Accelerator Physics
# Accelerator Physics Table of Contents

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Overview of Proposed Projects on Accelerator R&D

The linear collider is an ambitious project. The center of mass energy will be a factor of 5 to 10 larger than that achieved at the SLC, and the required luminosity is four orders of magnitude larger than the SLC luminosity. The reliability required for performing high energy physics places difficult demands on the accelerating structures and their associated RF systems. The need for high luminosity places extreme demands on all of the accelerator systems due to the need to produce and maintain a very low emittance beams with very large bunch energy and beam power.

Two technological solutions have been extensively developed. One uses an innovative RF source at XBand with a normal-conducting structure design (NLC/GLC), and the other uses a more conventional RF source at Lband with a superconducting RF structure design. Most of the research and development work has been done at the large laboratories, which have the engineering resources for large-scale prototyping (of, for example, accelerating structures, modulators, klystrons, and RF distribution systems) and the resources to build large test facilities (e.g., FFTB, NCLTA and ASSET at SLAC, ATF at KEK, and TTF at DESY).

These test facilities have partly demonstrated that the concept of a Linear Collider may be feasible in reality. However, considerable additional work is required before a 0.5 to 1.0 TeV cms linear collider can be successfully constructed and operated. Challenges exist in beam dynamics, source technology, RF technology, magnet and kicker technology, ground motion characterization, vibration suppression and compensation, instrumentation and electronics, and control systems.

Summary of R&D Covered by the Proposal

The sub-proposals presented here represent an initial overlap of what university groups can do and what the lab groups have suggested is needed. Since linear collider construction is expected to be underway in less than about ten years, these sub-proposals are expected to bear fruit on a commensurate time scale.

Although these sub-proposals represent an early step in the development process, they span a rather significant part of the work that needs to be done. We present below a brief summary, organized by major topic, of how the sub-proposals meet the R&D needs of the Linear Collider program.

Among the topics still needing attention are ultra precise (~1 nanometer) beam size monitors for the interaction point, cryogenic sensors (for superconducting final doublet vibration control), and superconducting quadrupole vibration system tests.
Beam simulations and calculations

The linear collider must produce and maintain a beam with unprecedented low emittance, with low jitter, low losses, and few halo particles. It must also preserve the polarization of the electrons (and possibly positrons). Beam dynamics simulations and calculations are needed to learn to control the effects that cause emittance growth, jitter, particle and polarization loss, and halo production. The beam in the injector system, comprising sources (D), damping rings (E,F) and bunch compressors, is susceptible to space charge effects; dynamic aperture limitations from damping wiggler and chromaticity correction; emittance growth from misalignments and intrabeam scattering; instabilities from electron clouds, ions, and wake fields; and coherent synchrotron radiation (B,I). In the main linac the emittance must be preserved in the presence of wake fields and alignment errors (C,G). The transport and collimation of the beam halo is a serious concern for detector backgrounds (G, H). Each of these areas requires substantial additional calculational work before a linear collider can be successfully built and operated.

<table>
<thead>
<tr>
<th></th>
<th>LCRD</th>
<th>Project Description</th>
<th>Author</th>
<th>Institution</th>
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<tr>
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<td>2.27</td>
<td>Effects of Coherent Synchrotron Radiation in Linear Collider Systems</td>
<td>James Ellison</td>
<td>New Mexico</td>
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<td>C</td>
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<td>A Compact Wakefield Measurement Facility</td>
<td>Young Kee Kim</td>
<td>U Chicago</td>
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<tr>
<td>D</td>
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<td>Improved simulation codes and diagnostics for high-brightness electron beams</td>
<td>Court Bohn</td>
<td>Northern Illinois</td>
</tr>
<tr>
<td>E</td>
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<td>Damping ring studies for the LC</td>
<td>Sekazi Mtingwa</td>
<td>MIT and NCA&amp;T</td>
</tr>
<tr>
<td>F</td>
<td>2.34</td>
<td>Experimental, simulation, and design studies for linear collider damping rings</td>
<td>Joe Rogers</td>
<td>Cornell</td>
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<tr>
<td>G</td>
<td>2.30</td>
<td>Beam simulation: main beam transport in the linacs and beam delivery systems, beam halo modeling and transport, and implementation as a diagnostic tool for commissioning and operation</td>
<td>Dave Rubin</td>
<td>Cornell</td>
</tr>
<tr>
<td>I</td>
<td>2.42</td>
<td>Transverse phase-space measurements for a magnetic bunch compressor by using phase-space tomography technique</td>
<td>Feng Zhou</td>
<td>UCLA</td>
</tr>
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Electron and positron source technology

Positron sources for the linear collider could be of the conventional type, with several operating in parallel to avoid fracturing targets, or could be based on undulator radiation striking a thin target. The latter idea has advantages including the possibility of producing polarized positrons, but suitable undulator prototypes must be produced, and a beam test of the principle is desirable (A) Other work includes studies of photocathodes (B).
RF Technology

The design of the X-band main linacs is limited in accelerating gradient performance by electrical breakdown of the rf structures. On the other hand, the gradient performance of superconducting cavities is limited by the $Q$ of the cavities. The cost of the X-band design would be reduced if the power output capability of the X-band klystrons were increased. Understanding the sources of the breakdowns in the X-band structures and increasing the performance of the klystrons are important for demonstrating the technical performance of NLC main linacs and reducing their costs (A, B, C, E). Understanding the limitations of superconducting cavities and extending their performance will allow for an enhanced energy goal for the TESLA main linacs, reduced cost, or both (D).

Kicker and Magnet Technologies

One of the novel and controversial features of the TESLA design is its large damping rings which require fast kickers to inject and eject bunches one at a time. The circumference (and presumably the cost) could be reduced if faster kickers were available (A, D).

Permanent magnet technology is attractive for many parts of any linear collider complex. These include the fixed energy damping rings, beam transport lines, and the X-band main linacs. This technology offers the possibility of eliminating costs associated with electromagnets which require power supply systems, and may require cooling water systems. The performance capabilities of magnets based on permanent magnet materials (especially their radiation resistance) must be understood before considering them for reducing the costs of several subsystems throughout linear colliders (B).
Ground Motion, Vibration, and Mechanical Support Systems

The choice of a site for a linear collider will include consideration of the vibrations inherent at the site. The characterization of ground vibrations as a function of depth will help determine the depth at which a linear collider will have to be located (A).

The rf structures and magnets in the NLC main linacs will have to be accurately moved and, due to their great number, the development of an inexpensive system to do this will reduce costs. The final focus magnets in NLC and TESLA also require movers with even greater accuracy but their number is smaller (B).

Instrumentation and electronics

The very small vertical and longitudinal emittances of a linear collider beam are near or beyond present beam size resolution limits. The linear collider will require the development of monitors surpassing the performance of present designs (A, B, E, F, G). Sensitive monitors for transverse-longitudinal beam “tilt” would improve the ability to minimize emittance growth (D). Control of the beam halo requires a monitor which can detect low intensity halo despite the presence of a high intensity beam core.

The linear collider will have special requirements for electronics: radiation hardness, speed and depth of data acquisition, and reliability (C, I).
Control Systems

The international nature of the linear collider collaboration lends itself to the possibility of a truly global accelerator network for controlling the machine. Exploration of the capabilities of such a network and its basic unit (the virtual control room) will help demonstrate the feasibility of this technique (A).

Non-\(e^+e^-\) collisions

A major facility like the Linear Collider should enable a broad spectrum of physics programs. In addition to the high energy \(e^+e^-\) operation, other possible programs include Z-pole studies at a separate collision region, \(e^+e^-\) or \(\gamma\gamma\) at the high energy region, or Compton backscattered photons from the spent beams. In the latter case, there is a novel program with polarized photons on fixed target, and also a platform for prototyping the laser-beam issues for \(\gamma\gamma\) without disrupting the initial high energy \(e^+e^-\) program.

We now present the accelerator R&D sub-proposals.
2.1. Beam Halo Monitor & Instrumented Collimators (LCRD)

Accelerator Physics

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email: cremaldi@phy.olemiss.edu
phone: (662) 915-5311

Mississippi

Year 1: $28,270
Year 2: $30,650
Year 3: $30,650
BEAM HALO MONITOR & INSTRUMENTED COLLIMATORS
L. Cremaldi*, D. Summers, Igor Ostrovskii
University of Mississippi

I. OVERVIEW

Beam representing 1 part in $10^3 - 10^6$ of an $e^\pm$ beam or proton beam core is often the major cause of detector background and unwanted secondary radiation into beamline areas. Beam profile monitors generally focus on the core and loose sensitivity in the halo “tail” region where a large dynamic range of detection efficiency is necessary. Beams of order $10^{14}$ particles per beam are being proposed for future linear colliders. Although difficulty arises in placing monitoring instrumentation near the beam, it might be possible to instrument the collimator regions of the beam delivery system where halo fraction has dropped to $< 10^{-5} \Phi$ of core flux density.

Advanced collimator designs for the NLC are discussed in [1, 2], and express the need for replaceable collimation systems due to electron beam damage. A short radiation length spoiler is placed in advance to a long radiation length absorber. We are speculating on the instrumentation of the absorber with radiation tolerant technologies, as diamond, quartz, graphite. We believe that some instrumentation integrated in to the collimation system would allow for longer life, safer operation, as well as minimizing detector backgrounds. In addition the reduction of transverse wakefield destabilizing forces at the collimator jaws would gain from even crude position information of the beams. It is also expected that readback instrumentation would also have to be considered replaceable on a short time scale (1 yr); this to be determined.

In this proposal we discuss the instrumentation of collimators in the final beam delivery system with (1) CVD diamond or (2) quartz plate/fiber. (3) We also entertain the idea of gaining some calorimetric information from graphite and thermal sensors.

Figure 1: Sketch of a proposed 2 stage collimator with upstream spoiler and final instrumented absorber.
II. HALO RADIATION LEVELS

We can estimate the halo radiation levels due to the NLC beam delivery system assuming a nominal 3µm x 26µm beam ribbon

\[ I = (1.4 \times 10^{10} \text{ e/bunch}) \times (95 \text{ bunches}) \times (120 \text{ Hz}) = 1.6 \times 10^{14} \text{ e/s} \]

\[ \Phi = 1.6 \times 10^{14} \text{ e/s} / [\pi (0.0003)(0.0026)] \text{cm}^2 = 6.5 \times 10^{19} \text{ e/cm}^2 \cdot \text{s} \]

Assuming a uniform halo density range of \((10^{-3} - 10^{-6})\) \(\Phi\) out to \(50\sigma\) \((A = \pi 50\sigma 50\sigma)\), we obtain a halo flux density range of

\[ \Phi_{\text{HALO}} = 2.6 \times 10^{[14-11]} \text{ e/cm}^2 \cdot \text{s} \]

III. CVD DIAMOND PADS

CVD diamond is our most radiation hard semiconductor [3,4]. About 3000 eh pairs are produced per 100µm per minimum ionizing particle (mip). When used in a calorimetry setting an increase due to secondary shower electrons \(E_o/E_c \geq 10\) occurs. The primary or secondary ionization signals from diamond would be easily seen.

In Figure 2 we depict a simple measurement scheme in which 4 CVD pads sample opposing shower rates in X and Y. The DC current (rate) measurements, would be immune to high frequency \(RF\) noise expected in most beamlines. A null measuring circuit could be designed to indicate beam offset.

If the detectors are imbedded at 1-2 radiation lengths in to the absorber we expect a current \(\Phi_{\text{DET}} = \Phi_{\text{HALO}} \times 10 \times 3000\text{e/mip} \approx 8 \times 10^{[18-15]} \text{ e/s} \cdot \text{cm}^2 \approx 1.2\text{A per cm}^2\) in each detector. Detectors of cross sectional area 4mm\(^2\) would record currents of 50mA to 50\(\mu\)A. These current measurements would be sensitive to horizontal and vertical beam steering. Some gain adjustment is provided by the detector bias voltage.

The radiation tolerance of these devices has typically been tested to \(10^{15} \text{ n/cm}^2\) of integrated dose. Adding a reduction factor of 100 for electron/neutron damage

\[ \Phi_{\text{HALO}} \Delta t < 10^{17} \text{ e/cm}^2 \quad \text{or} \quad \Delta t < [80\text{s} - 80000\text{s}] \]

leading one to believe that in high radiation areas ionization and displacement damage would be a serious problem. Some factors of 10 can be gained by optimizing detector placement, but we conclude that such a device will only be useful in regions of lower halo flux density \(<10^6 \Phi\) nearer the IP or at larger radii in the absorbers. These issues can only be determined by simulation with input from beamline halo measurements.
IV. GRAPHITE

The Los Alamos LEDA Beam Profile Monitor [5] measures the displacement current due to a 100ma proton beam interaction (secondary emissions) in carbon wire and graphite scrapers. Sensitive low-current amplifiers were developed for this purpose[6]. These graphite wands may well be suitable for insertion in to the NLC secondary absorber structures. Some low current (<µA) electronics is necessary for these investigations.

Large temperature swings are expected in beamline spoilers and absorbers. Platinum resistors are sensitive to 0.1 °C changes in temperature and would be quite radiation tolerant. We will consider mounting PT1000’s on the CVD or Graphite wands for additional readback information.

![Diagram of spoiler and absorber with wands](image)

**Figure 2:** Small diamond wands inserted in to beam halo absorber at (1-2)R_L.

V. QUARTZ FIBER/PLATE/ROD ABSORBER READBACK

In moderate-to-high radiation environments quartz is used as a cerenkov radiator. The radiation induced attenuation at 450 nm is typically 1.5(10%) dB/m for 100 Mrad absorbed dose. Quartz fibers continues to be useful even to a doses of a few Grads. (1Grad ~ 5 x 10^{17} n/cm^2)

It is then likely that a “quartz wand” built with fibers, plate, or a rod could function as a suitable radiator when implanted in the secondary halo absorber, in a similar fashion to the CVD diamond wand. With the a low electron Cherenkov threshold quartz is very sensitive to the E&M component of the shower. Placement at the 1-2 R_L level would generate ample light to be piped out. In Figure 3 we depict a simple fiber quartz wand with fibers inserted in to a solid quartz cylinder. Four wands are inserted into the absorber.
(3mm holes) as in Figure 2. The quartz fibers pipe could pipe the light out into PMTs or PDs. Q-Q fibers would be the best candidate for radiation hardness and optimizing the light yield. The system would be easily replaceable if necessary.

![Quartz Fiber/Rod Readout concept.](image)

**Figure 3: Quartz Fiber/Rod Readout concept.**

**VI. CVD/QUARTZ ABSORBER SIMULATIONS**

In order to optimize performance of the CVD diamond and quartz devices we will perform GEANT simulations with proposed NLC absorber elements. These simulation would be complimentary to the NLC working group activities on Beam Delivery Systems.

**VII. BEAM TESTS**

A prototype device would have to be tested in a beamline configuration at SLAC. This test would occur in FY05-FY06 if preliminary source studies are fruitful. Below in Figure 4, we show a prototype Quartz Fiber/W calorimeter tested at SLAC in the 90’s for use by the SLD collaboration. The fiber bundles were read out though Hamamatsu R268 PMT. This prototype lead to the design of the CMS Hadron Forward calorimeters. The Q-Q fibers were replaced by less expensive and less radiation hard Quartz-plastic.

![Quartz-Fiber Calorimeter assembled in U. Mississippi Lab for SLD tests.](image)

**Figure 4: Quartz-Fiber Calorimeter assembled in U. Mississippi Lab for SLD tests.**
VIII. GOALS of INSTRUMENTED ABSORBER PROJECTS

<table>
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<th>Goal</th>
<th>04</th>
<th>05</th>
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<tbody>
<tr>
<td>1. Test CVD Diamond Pads with Sr90 beta source.</td>
<td>x</td>
<td></td>
<td></td>
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<tr>
<td>2. Develop CVD Diamond prototype “test wand”. for beam tests</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Begin Quartz setup with existing equipment</td>
<td>x</td>
<td></td>
<td></td>
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<tr>
<td>4. Determine if quartz is suitable to use in the moderate to high radiation areas environments of the NLC beam delivery system.</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>5. Determine if fiber/plate/rod would be more suitable for instrumenting halo absorbers.</td>
<td></td>
<td></td>
<td>x</td>
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<tr>
<td>6. Monte Carlo Studies. of CVD diamond and Quartz</td>
<td></td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>7. Test Quartz fiber/plate/rod configurations. Prototype-I</td>
<td></td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>8. Determine best method of readout, PMT, PD, etc. Prototype-I</td>
<td></td>
<td>x</td>
<td>x</td>
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<tr>
<td>9. Test quartz fiber/plate/rod before and after radiation Prototype-1</td>
<td></td>
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<td>x</td>
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<tr>
<td>10. Build Beamline Insertion Prototype.-II</td>
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<tr>
<td>11. Test fiber/plate/rod in beamline configurations.</td>
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IX. BUDGET – INSTRUMENTED ABSORBER

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<th>FY04</th>
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<tr>
<td>A. Electronics for CVD Beam tests</td>
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<tr>
<td>B. Low current amplifier for Graphite tests</td>
<td>1500</td>
<td></td>
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<tr>
<td>C. Optical Test Bench Equipment</td>
<td>5000</td>
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<tr>
<td>D. Quartz fiber/rod materials</td>
<td>4000</td>
<td>1000</td>
<td>1000</td>
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<tr>
<td>E. Student (partial support)</td>
<td>6000</td>
<td>6000</td>
<td>6000</td>
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<tr>
<td>F. Travel (SLAC, FNAL, LANL)</td>
<td>3000</td>
<td>5000</td>
<td>5000</td>
</tr>
<tr>
<td>G. Materials&amp;Supplies,Fabrication</td>
<td>2000</td>
<td>5000</td>
<td>5000</td>
</tr>
<tr>
<td>H. 2% Benefits on C.</td>
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<tr>
<td>I. 44% Overhead on D,E,F,G,H</td>
<td>6650</td>
<td>7530</td>
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</tr>
<tr>
<td>TOTAL</td>
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</table>
X. PROGRESS ON CVD DIAMOND HALO MONITOR

Our first step purpose to set up the triggered system depicted in Figure 5 so that signals from the diamond pad detector could be studied. A diamond pad detector 1cm x 1cm x 200µm was obtained from Rutgers University with evaporated gold pads. We attached wire contacts and have mounted the diamond on a circuit board. A PIN diode was also mounted in the apparatus and connected to a Canberra 2003B solid state preamplifier to act as an electron trigger from the Sr90 source. See photos in Figure 6.

After some initial triggering tests it is found that upon a PIN trigger a capacitively coupled noise pulse is observed on the Diamond pad output which is also housed in the same RF shield. We are in progress of isolating the PIN diode trigger from the diamond detector. An Sr90 scintillation trigger is also being assembled.

When this apparatus is working we will introduce thin absorbers in advance of the CVD diamond and measure charge depositions related to -dE/dX. A higher rate test at SLAC or FNAL similar to those performed at the TESLA TEST FACILITY(TTF) in Figure 7 are envisioned. At that time graphite tests with LEDA-like electronics may be attempted. envisioned.

We have in hand a second diamond crystal from Kiev and have options to purchase detectors from De Beers.

Figure 5: CVD Diamond Readout Apparatus.
Figure 6: Photos of original Diamond Pad test stand.

Figure 7: 250MeV e-beam at 0.5 nC bunch charge bunch profile measured at TTF.
XI. EXPERIENCE and INFRASTRUCTURE

Our group has been working with Si/Diamond pixel detectors for a number of years. We have developed mechanical and cooling schemes, worked with high Tc carbon materials and fibers. In 2000 we participated in a successful test beam run with Rutgers University (member of RD42), successfully reading out a 150µm x 150µm diamond tracker.

We work closely with Rutgers who have extensive experience with CVD diamond, metalization of pads, wire bonding, and working with vendors. Igor Ostrovskii, listed on the proposal, is a materials expert and able to obtain some CVD diamond detectors in Kiev. We also have physics equipment (amplifiers, ratemeters, etc.) to begin development of single detectors.

We are also involved with CMS HCAL fiber readout calorimeter and the SLD quartz fiber polarimeter project. We have also used an extensive laser/quartz-fiber calibration system at the Tagged Photon Lab for calorimeter and Cherenkov detector calibrations.

Machine shop time for fabrications would be donated by the department as well as some matching funds from overhead.

XII. REFERENCES


2.2. Beam Test Proposal of an Optical Diffraction Radiation Beam Size Monitor at the SLAC FFTB (LCRD)

Accelerator Physics

Contact person: Yasuo Fukui
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phone: (650) 926-2146

UCLA
SLAC
KEK
Tokyo Metropolitan
Tomsk Polytechnic

Year 1: $70,000
Year 2: $70,000
Year 3: $70,000
**Project name**  Beam Test Proposal of an Optical Diffraction Radiation Beam Size Monitor at the SLAC FFTB

**Classification**  Accelerator

**Institutions and Personnel**

University of California at Los Angeles, Department of Physics and Astronomy:
David B. Cline (Professor), Yasuo Fukui (Assistant Research Physicist),
Feng Zhou (Assistant Research Physicist)

Stanford Linear Accelerator Center:
Marc Ross (Staff Scientist), Paul Bolton (Staff Scientist)

KEK, High Energy Accelerator Research Organization, Japan:
Junji Urakawa (Professor), Makoto Tobiya (Assistant Physicist),
Toshiya Muto (Postgraduate Research Physicist)

Tokyo Metropolitan University, Physics Department:
Ryosuke Hamatsu (Associate professor), Pavel V. Karataev (Graduate student)

Tomsk Polytechnic University, Russia:
Alexander P. Potyliitsyn (Professor), Gennady A. Naumenko (Postgraduate Research Physicist),
Alexander S. Aryshev (Grad. Student)

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**Project Overview**

The goal of this project is to develop a non-invasive transverse beam size monitoring of a single electron/positron beam bunch at the SLAC FFTB with the beam energy at 28.5 GeV. In the Linear Collider, this method provides the transverse beam size information of an accelerator in its normal operation mode with the minimum disturbance to the beam quality. The incoherent Optical Diffraction Radiation (ODR) is generated when a charged particle bunch passes by inhomogeneous boundaries, and it is considered as the optical component of the wake field of a beam bunch. [1-3] By using a tilted conducting slit where a beam bunch passes through the center of the slit aperture, we can observe the interference pattern of the backward scattered ODR from two edges of the conductive slit. In the simplest picture, the ratio of the photon intensity at the peak of the interference pattern of the ODR and that at the valley of the photon intensity gives the information of the transverse beam size. Because the distances of the edges of the slit from the beam central trajectory is typically 10 times or larger than the transverse beam size, this beam size monitor is non-invasive.

With the 28.5 GeV e⁻/e⁺ beam at the SLAC FFTB (Final Focus Test Beam), the $\gamma$ factor of $5.8 \times 10^9$ allows us to use much larger aperture size than those with lower beam energy, which contributes to reduce the background photons significantly. But, because of the
same large $\gamma$ factor, the ratio of the photon intensity at the valley of the interference pattern of the ODR to that at the peak of the photon intensity is expected to be below the detector sensitivity. Also the interference pattern of the ODR photons from edges of the parallel slit is deformed significantly due to the pre-wave zone effect, which is parameterized by a fraction of the distance between the slit target and a detector to $\gamma^2\lambda$, where $\lambda$ is the ODR wave length. But by rotating the slit edges slightly, we can obtain the sensitivity on the transverse beam size of the high energy electron beam bunches, overcoming those two negative effects due to the large $\gamma$ factor of the beam. A conventional CCD camera is used to detect the interference pattern of the ODR photons.

Most of the experiments on the use of the ODR for a beam size monitor has been done only recently with electron beams up to around 1 GeV at TTF(Tesla), and at ATF(KEK) [4, 5]. The test of the beam size monitor by using ODR at the SLAC FFTB provides a unique condition for a non-invasive beam size monitor with the highest available test beam energy of electron and positron beam. The transverse RMS beam size of electron and positron beam at a focal point of the SLAC FFTB are 2 -10 $\mu$m in horizontal and vertical. The FWHM bunch length is 0.7 mm. The intensity of electron and positron beam is $1-3 \times 10^{10}$ particles/pulse. The normalized transverse emittances are $3 - 5 \times 10^{-5}$ m-rad in horizontal and $0.3 - 0.6 \times 10^{-5}$ m-rad in vertical. We expect the beam test in the calendar year in 2005 or 2006.

The international collaboration, with researchers at KEK, Tokyo Metropolitan University, and at Tomsk Polytechnic University who have done significant R&D on the beam size monitoring with the ODR at the KEK ATF in Japan with the 1.3 GeV electron beam [5], allows us to understand the dependence of the beam size measurement with the ODR on the beam energy and on the level of the background radiation. The experience of groups of UCLA and SLAC on the use of the SLAC FFTB in the recent E150 (plasma lens) Experiment benefits the design, preparation and the beam test of the ODR beam size monitor.

**Description of the project activities**

Figure 1 shows a top view of the experiment area in the SLAC FFTB beam line and a schematic diagram of the beam size monitor with the ODR interference pattern measurement and a conventional wire scanner for a cross calibration. Because the wavelength of the ODR photons, around 0.5 $\mu$m, is much shorter than the beam bunch length, 0.7 mm, the observed optical diffraction radiation is incoherent. The CCD camera is trigger-able with 1000×1000 pixels with 14-16 bits resolution in each pixel. The size of the CCD is $16 \times 16$ mm$^2$.

![Figure 1](image.png)  
**Figure 1** Top View of the Experiment Area in the SLAC FFTB Beam Line (left) and a Schematic Diagram(right)
The downstream end of the closest dipole and quadrupole magnets are 20 m and 1 m away from the target slit respectively. The total path length of the ODR photons between the target slit and the CCD camera is around 30 m where the CCD camera is located in a measurement room located outside of the FFTB tunnel shield wall.

Figure 2 shows a schematic of a conducting slit target where the top part and the bottom part are rotated by the vertical axis by $\alpha/2$ to opposite direction. [6] The target slit is made of crystalline wafer/block with 1-2 $\mu$m thick Au or Al conductor coating on the top plane. The minimum slit aperture is around 0.2 mm. Figure 3 shows the longitudinal polarization component of the backward ODR photon yield as a function of the opening angle without pre-wave effect (left) and with pre-wave effect (right) with parallel slit edges ($\alpha$ in Figure 2 is set at 0) with a slit gap of 0.2 $\lambda\gamma$ for $\gamma$ at 60000. The ratio of the peak of the interference pattern to that in the valley in the left figure of Figure 3 is $4 \times 10^4$. Due to the pre-wave effect, the interference pattern is deformed, which is shown in the right figure of Figure 3 with the detector at 5.6 m from the slit target. The parameter, $\gamma^2 \lambda$, which decides the range of the pre-wave zone, is 1.7 km for the SLAC FFTB case.

![Figure 2](image1.png)

**Figure 2** A schematic diagram of a target slit

![Figure 3](image2.png)

**Figure 3** Longitudinal polarization component of the backward ODR photon yield as a function of the opening angle without pre-wave effect (left) and with pre-wave effect (right) with parallel slit edges ($\alpha = 0$ in Figure 2) with a slit gap of 0.2 $\lambda\gamma$ for $\gamma$ at 60000.

Figure 4 shows the longitudinal polarization component of the backward ODR photon yield as functions of the opening angle and the transverse beam size with the dis-phasing rotation angle $\alpha = 0.05$, with the beam going through the center of the slit. Figure 5 shows the Ratio of the minimum yield and the peak yield, $\Delta$, as functions of the transverse beam size and the slit rotation angle $\alpha$. We can obtain the transverse beam size information with a slit with the dis-phasing rotation angle $\alpha$, where with a parallel slit the ratio of the photon intensity at the valley of the interference pattern of the ODR to that at the peak of the photon intensity is expected to be below the detector sensitivity, and the pre-wave effect causes significant distortion of the ODR interference pattern. [6]
Figure 4  Longitudinal polarization component of the backward ODR photon yield as functions of the opening angle and the transverse beam size with $\alpha = 0.05$, with the beam going through the center of the slit.

Figure 5  Ratio of the minimum yield to the peak yield, $\Delta$, as functions of the transverse beam size and the slit rotation angle $\alpha$.

The goals of the beam test for the beam size monitor with optical diffractive radiation at the SLAC FFTB are:

1. establish the measurement system of the transverse size of the 28.5 GeV electron and positron beam with the optical diffraction radiation,
2. obtain the size of the systematic error of the transverse beam size measurement by using the conventional wire scanner with multiple beam bunches, or by using the optical transition radiation from a single beam bunch off a slant target plate directly placed in the beam path,
3. optimize the slit plate angles, gap size, and the bandwidth of the optical diffractive radiation,
4. study on the measurement error of the transverse beam size due to the background photons into the CCD camera by:
   i) optical transition radiation off the target slit which is generated by the transverse beam tail particles,
   ii) scattered optical photons off the target slit material associated with the beam halo, and
   iii) synchrotron radiation at the upstream dipole magnets and quadrupole magnets. [7]

The key issues are to use conventional wire scanners and the optical transition radiation for cross-calibration of the beam size measurement, and to understand the background optical photons at the SLAC FFTB. The challenges of this beam test are to
obtain the transverse beam size information in the photon yield valley of the interference pattern with a large $\gamma$ factor. We plan to reuse as much available equipment of the completed E150 (plasma lens) experiment as possible.

**FY2003 Project Activities**

In FY2003, significant progress has been made in understanding the expected ODR photons out of a target slit when 28.5 GeV electron beam bunch pass through the opening. The size of the $\gamma\lambda$ determines the transverse area size of the target slit, and the ratio of the photon intensity at the peak of the interference pattern of the ODR and that at the valley of the photon intensity. We made better understanding on the “pre-wave zone” effect on the ODR interference pattern, which was determined by the distance size of $\gamma^2\lambda$. [8, 9] Most of the theoretical and simulation work has been done by the collaborators at the Tomsk Polytechnic University.

The experience and skill of the Tomsk Polytechnic University, Russia, and experience of the groups of SLAC, KEK, and Tokyo Metropolitan University at the KEK ATF has been and will be advantageous in this project. A contribution paper on this project was submitted to the PAC 2003 Conference at Portland, Oregon. [10]

A part of the approved budget in FY2003 will be carried over to FY2004 on works on making the target slit and the alignment system of the target, a vacuum chamber modification, recycling a gamma calorimeter, a part of the optics and laser alignment system.

**FY2004 - 2006 Project Activities and Deliverables**

**FY2004** A two day collaboration workshop on this project will be held at SLAC in December 2003. We will discuss on all aspects of the project, including a review of the theoretical work, the design of the target slit, the optics system, the alignment scheme of the target slit and the ODR photon path, calculation/simulation of the ODR photons by a beam bunch and the background photons. We will submit a letter of intent to the proposal approval committee of the SLAC FFTB facility. The FFTB is available for the beam test in the calendar years 2004 and 2005, and it is planned to be modified in the calendar year 2006. Because two major test projects, SPPS (Short Pulse Photon Source) and E164 (Plasma Wakefield Acceleration), use the beam time alternatively, not much beam time is available in the calendar year 2004.

A project design report will be published. We will start building elements of the beam size monitor, the vacuum chamber, and the target slit and its alignment system. We will purchase a CCD camera and its control system, which is the major part of the detection system.

**FY2005** Most likely, we will use the beam time at the SLAC FFTB in FY2005. We will install the mirrors in the ODR photon path, a part of the alignment system of the optics path, and a recycled gamma calorimeter in the downstream of the vertical bending magnet. This work will be done in the beam down time. Skill of Paul Bolton (SLAC) on the laser optics, and the experience of David Cline, Marc Ross, and Yasuo Fukui on using the SLAC FFTB beam line in previous experiments will benefit the project.

We will be ready to install a CCD camera, the vacuum chamber with a target slit, a conventional wire scanner in the beam line to have an initial test run of the beam test.
whenever a beam time is assigned to this project. After the first beam run, we will analyze the first set of data and make necessary improvements in the beam size monitor and in suppressing the background.

**FY2006** We will do the follow-up work of the experiment, based on the preliminary results on the ODR beam size monitor. The beam time may be available in FY2006. We also plan to test the ODR beam size monitor with the 28.5 GeV positron beam at the SLAC FTFB. Within 6 – 9 months after the last test beam run, we will complete the analysis of the beam data and the comparison with the simulation. We then publish results in major journals. This project can be thesis topics for graduate students. The FTE level of the UCLA collaborators is expected to increase in the period of FY2003-2006.

### Budget

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### References

2.3. Design and Fabrication of a Radiation-Hard 500-MHz Digitizer Using Deep Submicron Technology (LCRD)

Accelerator Physics

Contact person: K.K. Gan
email: gan@mps.ohio-state.edu
phone: (614) 292-4124

Ohio State
SLAC

Year 1: $85,360
Year 2: $130,720
Year 3: $130,720
Design and Fabrication of a Radiation-Hard 500-MHz Digitizer Using Deep Submicron Technology

Department of Physics, The Ohio State University

S. Smith
Stanford Linear Accelerator Center

Project Summary

The Next Linear Collider (NLC) will collide 180-bunch trains of electrons and positrons with a bunch spacing of 1.4 ns. The small spot size ($\sigma_y < 3$ nm) at the interaction point requires precise control of the emittance, which in turn requires the alignment of individual bunches in the train to within a fraction of a micron. Multi-bunch beam position monitors (BPMs) are to determine the bunch-to-bunch misalignment on each machine pulse. High bandwidth kickers will then be programmed to bring the train into better alignment on the next machine cycle. A multi-bunch BPM system using an 11-bit (effective) digitizer with 500 MHz bandwidth and 2 G samples/s is needed to distinguish adjacent bunches. The digitizers are also needed for the low level RF controls in the damping rings and main and injection linacs. Table 1 summarizes the number and requirements of the various NLC digitizers. Without the digitizers, a redesign of the low level RF technology will be needed.

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Table 1. Quantities and requirements for various NLC digitizers.

We propose to design a digitizer chip using the deep-submicron technology that has proven to be very radiation hard (up to at least 60 Mrad). This mitigates the need for costly shielding and long cable runs while providing ready access to the electronics for testing and maintenance. Once a digitizer chip has been successfully developed via several prototype runs, an engineering run at a cost of ~$150,000 will produce all the chips necessary for the NLC. We have extensive experience in chip design using Cadence. This proposal was reviewed by the Holtkamp Committee in 2002 and awarded a rank of 2 on the scale of 1 to 4 with 1 having the highest ranking. This proposal has been funded by DOE since June 2003. Some of the circuit blocks in the chip have been designed. We request funding for 2004-2005 to continue the design work and submit a prototype chip for some of the circuit blocks.

* Contact: K.K. Gan, 614-292-4124, gan@mps.ohio-state.edu
Project Plans

The digitizer chip is very challenging: large bandwidth (500 MHz), high precision (11 bits), and fast sampling speed (2 G samples/s). We plan to capitalize on the experience of our engineering staff that, over the last ten years, has designed radiation hard chips for ATLAS, CLEO III, and CMS. Our most recent design of the DORIC and VDC chips for the ATLAS pixel detector uses the IBM deep submicron technology with feature size of 0.25 μm to achieve radiation hardness². In addition, we have extensive experience designing fast analog electronics systems such as those used in high-resolution drift chambers.

We propose a 12-bit pipelined digitizer as shown in Fig. 1 to meet the requirements of Table 1. In this scheme the input is crudely digitized in the first stage (3-bit cell). The digitized value is then subtracted from the sampled input value, amplified by eight and presented to the second stage. This identical process is repeated for each of the four stages. A one-bit comparator follows the last stage so the final result can be rounded to 12 bits.

The 12-bit digitizer is somewhat beyond the state-of-the-art. However a less demanding design that meets the requirement of the LLRF Control will satisfy the specifications of all but 1,200 of the needed digitizers. This would demonstrate the feasibility of the current NLC design with the low level RF technology. The 1,200 multi-bunch BPM digitizers present a difficult challenge. However, there is one characteristic of the BPM that may ease the design requirements. The input to this system is a sequence of doublets occurring at the bunch spacing of 1.4 ns. Only one parameter is needed to completely specify a doublet. Thus the requirements could be met with a digitizer sampling at the bunch frequency (1/1.4ns or 714 MHz). By interleaving three digitizers, we can have a chip with 2 G samples/s to provide more redundancy. In the following, we first discuss the required precision of some of the circuits in the digitizer and then the control of the errors in order to achieve the desired precision.

![Figure 1. Schematic of a 12-bit pipelined digitizer.](image-url)
**Precision**

Submicron CMOS does not allow large power supply voltages, 2.5 V is common. This limits the internal signal swing. We can estimate the necessary precision by assuming that a 3 V full scale range can be achieved for the differential internal signals. This means the LSB is 3 V/4096 or 732 μV. Thus comparator thresholds must be stable and accurate to one half the LSB or 366 μV. Amplifier and sample/hold gains must be stable and accurate to about the same precision, 0.01% (~ 0.5/4096) of full scale. Charge injection errors in the sample/hold circuits must also be controlled to the same level of precision.

**Error Control**

There are three types of errors in the digitizer:
1. Offset errors: uncertainties in the comparator thresholds, fixed charge injection from the sample and hold, and amplifier offset.
2. Gain errors: uncertainties in the gain stages and sample/hold gain.
3. Dynamic errors: uncertainties in the timing and amplifier and sample/hold settling times.

Offset and Gain errors will be measured as part of the qualification test on raw chips. These errors do not have to be measured individually. For example the offset error from the comparator, the charge injection offset and amplifier offset will be measured as a single number. These values will be loaded into an on-chip memory. The raw digitized numbers will be used only as indices to tables of “correct values”, which will be used to calculate the true input value. The maximum number of these calibration values is estimated to be 72. With this scheme, we only require stability in the design and process. Based on experience, this level of stability should be achievable over a modest temperature range. In addition these devices can be recalibrated in the field.

Dynamic errors will be controlled by careful design. By means of simulation and prototyping we will design each of the internal functions to have sufficient bandwidth to settle in the required time.

**Process**

The proposed digitizer requires several amplifiers with a gain of eight. Let us assume that we allow half the bunch period (0.7 ns) to sample and the other half to hold. To settle to 12 bits with a precision of one half the LSB requires nine time constants (e^(-9) ~ 0.5/212) or a rise time of 171 ps (2.2τ with τ = 700 ps/9). To accomplish this the fabrication process must provide a product of gain (8) and bandwidth (1/2πτ) of 16.4 GHz. The IBM process SiGe BiCMOS 6HP/6DM is available through MOSIS and features 40 GHz NPN bipolar transistors along with 0.25 μm CMOS.

**Strategy**

Our goal is a design that meets the requirements of the multi-bunch BPM. This is a challenging project. However even if we initially fail to meet these goals we believe the resulting design will meet the requirements of all other NLC digitizers, 45,000 out of
46,200. Therefore we will gain the insight and experience necessary to meet the requirements of the multi-bunch BPM on future submissions.

**Description of First Year Project Activities**

We have designed some circuit blocks in the 3-bit cell. The internal structure of the 3-bit cell is shown in Fig. 2. The status of the design is as fellow:

![Figure 2. Schematic of a 3-bit cell.](image)

**Sample/Hold Circuit:**

A simplified drawing of the sample/hold is shown in Fig 3. We use AC coupled stages internally since the waveforms to be digitized have no DC component. This allows for a very simple sample/hold circuit with gain that is set by a capacitor ratio, C1/C2. The switch on resistance must be small enough to allow 9 time constants of charging in 700 ps. This is achievable with reasonable sized components. We need sampling circuits with a gain of 1 for buffering and gain of 8 for error amplification. A simulation of the sample/hold with an ideal op-amp having a gain-bandwidth of 16 GHz is shown in Fig. 4. There is an offset due to the injected charge from the sampling switches. The offset should be stable and thus can be removed by our calibration procedure. A high priority task is to both improve the performance of the circuit and to demonstrate our calibration scheme will recover the input signal to 11 bit accuracy.

![Figure 3. Schematic of a sample/hold circuit.](image)
Figure 4. Simulation of the response of a sample/hold circuit.

The DC operating point of the circuit is maintained by a slow feedback loop. The output of the feedback amplifier is driven by MOS transistors biased in the sub-threshold region. This results in very high output impedance. We are also considering a switched feedback loop as an alternative.

**Comparator Circuit:**

We have designed the comparator using ECL circuits and differential operation is maintained throughout, including the output latch. Our initial simulations show that the performance is adequate for 714 MHz operation.

**MUX Circuit:**

We have designed this conceptually simple circuit.

We have created numerous schematics using a mixture of ideal and real device models from the IBM 0.25 Micron SiGe BiCMOS 6HP/6DM process. Some of the drawings will be posted on the web to show that the design is proceeding in earnest. We plan to complete the design and simulation of the input amplifier/shaper stage and the 3-bit cell in the remaining eight months of the funding cycle.

**Goals for the Year 2004–5**

We plan to have well designed building block circuits by next year. The next natural step is to fabricate and measure their performance and perform radiation tests. We know from previous experience that the CMOS part of this process is rad-hard but the radiation hardness of the SiGe NPN transistors is unknown.

The design and development activities will include:

1. Layout, submission, and testing of the building block circuits
2. Radiation hardness tests
3. Continued system design of a prototype 12-bit digitizer

We plan to have one submission in this funding cycle.
Goals for the Years 2005-7

The design and development activities will include:
1. Layout, submission and testing of a 3-bit cell
2. Layout, submission and testing of a prototype 12-bit prototype
3. Continued system design of the full 12-bit digitizer

We plan to have two submissions for each funding cycle.

Budget Description

We believe that the design work is sufficiently complex and must be done by an experienced senior electrical engineer. The budget request pays for a senior electrical engineer that has retired from the Physics Department of The Ohio State University but works part time. He will be assisted part time by a research associate paid from our base program and by an engineer paid by the Physics Department. The travel budget allows the engineers to make one trip per year to SLAC to discuss the design/finding with our SLAC collaborator. The MOSIS cost for a run using the IBM 0.25 Micron SiGe BiCMOS 6HP/6DM process is $45,360

Budget

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Bibliography


3. The future link will be reached via www.physics.ohio-state.edu/~gan/research.html.
2.4. RF Beam Position Monitors for Measuring Beam Position and Tilt (LCRD)

Accelerator Physics

Contact person: Yury Kolomensky
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UC Berkeley
Notre Dame
SLAC

Year 1: $48,902
Year 2: $49,589
Year 3: $50,289
Project Description

Precision RF Beam Position Monitors for Measuring Beam Position and Tilt

UC Berkeley Senior Personnel
Yury G. Kolomensky (faculty)

Collaborating Institutions
Stanford Linear Accelerator Center: Marc Ross, Joseph Frisch (staff scientists)
University of Notre Dame: Michael D. Hildreth (faculty)

Contact Person:
Yury G. Kolomensky
yury@physics.berkeley.edu
(510)642-9619

1. Objectives

Controlling the beam emittance is important for future linear colliders as well as high-brightness light sources. There are two principal sources of emittance dilution in an X-band linac: transverse wakefields (from beam-to-RF-structure misalignments) and dispersion (from beam-to-quadrupole misalignments). Both lead to an emittance dilution that is correlated along the bunch length (i.e., the tail of the bunch is deflected relative to the head). The ability to detect beam pitch or yaw is important in order to identify the primary sources of emittance dilution. For single beam bunches at an NLC, 2 – 15 mrad beam tilt corresponds to 10% emittance growth. Detecting beam tilts in a few mrad range would also be useful for TESLA and high-brightness X-ray sources, such as ALS.

Similar to inducing single-bunch tilts, transverse misalignments can also create intra-bunch position variations, such as “banana” effects (head-tail position differences) and “beam breakup” effects (tail instabilities). Maintaining high luminosity at a future linear collider requires compensation of such intra-bunch effects before the interaction point. Intra-bunch IP feedback systems being designed require measurements of beam position along the bunch train with precision of a few micros. Such feedbacks are needed for both warm (NLC/JLC) and superconducting (TESLA) linear collider technologies. Also, since the overall size of the wakefield and quadrupole misalignment effects typically depends on the relative position of the beam centroid in accelerating or quadrupole structures, precise measurements of beam positions are needed along the length of the linac. For the NLC, the beam position along the linac needs to be measured with the precision of about 1 μm, while for TESLA design the requirements are looser.

In addition to measurements of the transverse beam offsets along the linac, measurements of the beam position and energy near the interaction point are of great importance for the physics program of the future linear collider. Measurements of the beam-beam deflections are proposed[1] to be used in the fast feedback systems to correct residual beam offsets at the 5-10 nanometer level. Energy spectrometers at the interaction point aim at measuring the energy of the colliding beams with the precision of 10^{-4} or better.[2] Such precision will require a measurement of the beam position before and after the spectrometer magnets with
the resolution of up to 20 nm, and comparable stability.

Resonant RF cavity beam position monitors\cite{3} can be used to measure the average position of the bunch train with high precision, as well as determine the bunch-to-bunch variations. In a single-bunch mode, \textit{i.e.} in the mode where the time interval between the bunches is significantly larger than the fill time of of the cavity, the same cavities can be also used to measure the head-to-tail position differences, or bunch tilts. In the following section, we will briefly describe the RF beam position monitors and associated electronics, and outline the R&D plans for the cavity system.

2. Beam Position Monitors

A typical beam position monitor consists of three copper cavities, two (X and Y) cavities for monitoring the horizontal and vertical displacements of the beam, a \(Q\) cavity to provide an \textit{in-situ} measurement of beam charge and phase. The position cavities are typically tuned to the dipole \(TM_{210}\) mode while the \(Q\) cavity uses the monopole \(TM_{110}\) mode. The BPMs constructed at SLAC in 1960s\cite{3} use three independent cavities which are easy to manufacture and tune, although some new monitors use a more compact single-cavity design.

The resonance frequency of the cavities is typically a multiple of the carrier RF frequency. To achieve good position resolution and stability, the cavities are tuned to a high value of \(Q > 1000\) which increases the resonant pickup. Custom RF electronics with I/Q demodulation\cite{4} provides information on both amplitude and phase of the beam-induced signals. Measuring both amplitude and phase of the RF signals reduces systematic effects and increases position sensitivity.

Resonant RF BPMs with the custom electronics providing I/Q demodulation have been successfully used in experiment E158 at SLAC. The cavities used in the test were standard SLAC linac cavities tuned to 2856 MHz, the carrier frequency of the SLAC linac. In a series of beam tests in the ASSET region at SLAC in 1999 and 2000, the pulse-to-pulse position resolution of better than 500 nm was achieved with dynamic ranges of 0.5 – 1 mm (better than 1:1000 resolution-to-range ratio) for \(\sim 300\) ns bunch trains. The phase resolution was about 0.5°.

3. Beam Tilt Measurement

One of the main objective of this proposal is to demonstrate that the RF cavities can be used for measuring small tilts of individual beam bunches. This can be done by measuring the imaginary part of the beam-induced RF pulse, or a phase difference between the RF signals from a dipole and \(Q\) cavities.

A short beam bunch of charge \(q\) centered the distance \(x_0\) from the electrical center \(O\) of the cavity (point \(O\) in Fig. 1) induces an RF pulse with voltage

\[
V(t) = Cq x_0 \exp(j\omega t)
\]

where \(C\) is some calibration constant, \(\omega\) is the resonant frequency of the cavity, and time \(t\) is computed from the time the center of the pulse passed through the cavity. If the bunch is pitched by amount \(\delta\) from head to

Fig. 1. Tilt of the bunch relative to the \(z\) axis of the cavity.
Fig. 2. Intermediate frequency signals produced by a single beam bunch at the ATF from BINP reference and position cavities. A fit to the data produces information about the amplitude and phase of the beam-induced signals.

tail, the RF voltage is instead

\[ V(t) = C q \exp(j \omega t) \left[ x_0 - j \frac{\delta \sigma \omega}{16c} \right] \]  

(2)

The beam tilt introduces a phase shift

\[ \Delta \phi = \frac{\Delta x}{x_0} = -\frac{\delta \sigma \omega}{16 c x_0} \]  

(3)

equivalent to an offset of \( \Delta x \approx 13 \text{ nm} \) for a typical beam size of \( \sigma = 400 \mu \text{m} \) and a tilt of \( \delta = 2 \mu \text{m} \). For small offsets of \( x_0 \approx 1 \mu \text{m} \), the phase shifts of \( \approx 0.7^\circ \) should be measurable. It is clear that for this measurement the phase information is vital: it would be hard to extract the small offset from the amplitude signal alone (e.g., by measuring the RF power). For the phase measurement, the challenge is to be able to keep the beam centered at the cavity with high accuracy, and to be able to maintain the phase stability. The former requires being able to position the electrical center of the cavity near the beam axis (by either moving the beam or the cavity), and the latter requires precise temperature and environment control, as well as good cancellation of the dominant monopole mode in the dipole \( X \) cavity.\[4\]

4. Scope of the Project

A high-resolution C-band beam position monitor has been constructed at BINP and is currently being tested at the Accelerator Test Facility (ATF) at KEK by the SLAC group of Marc Ross and Joseph Frisch. We are collaborating with them on the analysis of the cavity data. The demodulation scheme employed by the SLAC group involves down-mixing the RF pulse to an intermediate frequency of 15 MHz and digitizing the IF signals with a 100 MHz sampling ADC. Information on the amplitude and phase of the RF pulse is then obtained in the offline analysis of the IF data, shown in Fig. 2.

The main objective of the work at KEK is to gain operational experience with the precision BPM hardware and and demonstrate nanometer-scale position resolution and sensitivity of the beam-induced RF signals in the position cavities to beam tilt. The analysis of the data collected so far is still ongoing, but the
preliminary results indicate that the resolution of the current BPMs will need to be improved for the eventual use in a future Linear Collider. Further work on stabilization of the BPM structure is also required. LLNL group is currently constructing a precision support structure with movers that independently control cavity position and tilt relative to the beamline while minimizing low frequency vibrations of the apparatus. The demodulation of the BPM signals and digitization scheme is also likely to be modified for the eventual use in a high repetition rate environment to reduce data throughput.

Application of the precision RF BPMs to measuring beam parameters near the interaction point of the linear collider hinges on the assumption that the monitors can perform reliably in the presence of significant photon flux from the beam-beam interactions (beamsstrahlung) and can maintain high resolution downstream of the interaction point, where the transverse size of the beam is significantly increased. These aspects of the precision monitor operation will be tested in the experiments being proposed at SLAC. Berkeley group is part of this Letter of Intent, and we have extensive experience in design and operation of the precision beam position monitors in End Station A. We plan to contribute to the design and optimization of the BPM hardware and electronics for the beam tests being planned in FY05-07.

5. Progress Report and Future Schedule

This project is part of the national Linear Collider R&D program which is described in detail in “A University Program of Accelerator and Detector Research for the Linear Collider” by the US Linear Collider Research and Development Group. The project received funding from DOE for FY03. Our current proposal covers activities in FY04-06.

In the first two years of the project (2003-2004), we are working in collaboration with groups at SLAC, LLNL, and KEK in developing the prototype of the nanometer precision beam position monitor. The nanoBPM collaboration has finished two beam tests at the ATF facility at KEK with the precision C-band cavities constructed at BINP. The present structure consists of a three pairs of \((X, Y)\) BPMs and allows for the measurement of the position resolution. The resolution from the latest run in June 2003 was found to be in the range of \(40 - 50\) nm, limited by the electronics noise and potentially low frequency vibrations of the BPMs relative to each other. The former problem is being addressed by the improvements in electronics. The latter will be addressed by the BPM support system being developed by LLNL group. Our group is responsible for tests of the new RF processing electronics, developing the data acquisition and online monitoring system for the beam tests coming up in 2004 and for data processing and analysis algorithms, including beam-based alignment and calibration of the BPMs. Three beam tests are tentatively scheduled for 2004 at the ATF. The milestones for the tests include

- Demonstrating position resolution of the cavities of below 10 nm for a dynamic range of a few \(\mu m\).
- Demonstrating sensitivity of the BPMs to beam tilts in 10 mrad range.
- Commissioning the new LLNL active support structure including metrology system and the active stabilization feedback system.

In the second phase of the project, we plan to construct the high-frequency (X-band) cavities for position measurement with high quality factor \(Q\) and strong monopole mode suppression (e.g. by using symmetric outputs). Work on the cavity design will start this year with the grant awarded in FY03. The new set of cavities will be constructed for the beam tests at KEK in 2005, which will aim to demonstrate beam position stabilization between the two sets of BPMs mounted on independent girders.

A related project of demonstrating the performance of BPM-based energy spectrometer in the presence of large beam-induced backgrounds is being proposed at SLAC for FY05 and beyond. We will be involved in assembling a set of precision cavities with associated RF processing electronics for beam tests in FY05.
and FY06. The resolution and stability requirements for the energy spectrometer are similar to what is aimed at by the nanoBPM project, although the RF electronics will have to be re-optimized for the 300 nsec bunch train operation.

6. Budget

We are requesting an increase in funding for this project to $148,779 for three years (FY04-06). The project will support a graduate student for 6 month/year (0.5 FTE) and an undergraduate student working part-time during the school year (25% for 9 months/year) and full time during the summer (3 months/year). We are requesting funds in the amount of $10,000/year for RF electronics testing equipment to aid the nanoBPM project (FY04) and to build custom BPM processors in for the energy spectrometer tests in FY05-FY06. We are also requesting funds to travel to KEK to participate in beam test experiments (1 trip/year in FY04), travel to SLAC to set up beam energy spectrometer BPMs (average 1 trip/week for 6 months during FY05-06), and one trip per year to ALCGP meetings to report on results. The budget includes cost of living and fee increases for the graduate and undergraduate students (15% increase in FY04 mandated by the University, and 2%/year increases in FY05-06).

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References

1. See for example [http://hepwww.ph.qmul.ac.uk/ white/FONT/default.htm](http://hepwww.ph.qmul.ac.uk/ white/FONT/default.htm)
2.5. Non-intercepting electron beam size
diagnosis using diffraction radiation from a
slit
(UCLC)

Accelerator Physics

Contact person: Bibo Feng
email: bibo.feng@vanderbilt.edu
phone: (615) 343-6446

Vanderbilt

Year 1: $36,550
Year 2: $74,900
Year 3: $88,988
3.2 Non-intercepting electron beam size diagnostics using diffraction radiation from a slit

Personnel and Institution(s) requesting funding
B. Feng, W. E. Gabella, W. M. Keck Foundation Free-Electron Laser Center, and S. Csorna, Department of Physics and Astronomy, Vanderbilt University

Collaborators
J.T. Rogers and Charles K. Sinclair, Dept. of Physics, Cornell University

Project Leader
Bibo Feng
bibo.feng@vanderbilt.edu
(615)-343-6446

Project Overview
The Linear Collider presents new challenges for beam instrumentation. Some of the beam dimensions are of the order of a few nm (at the i.p.), and to be able to reach these small sizes, the beams have to be tightly controlled and understood from their very inception onward. A number of different techniques are available in the arsenal of beam size and beam emittance measurements (e.g. transition radiation, metal wire, laser wire, laser interferometry, cavity BPM). Experiments of electron bunch profile measurements have been conducted using coherent synchrotron radiation (CSR), coherent transition radiation (CTR), as well as coherent diffraction radiation (CDR) [1-3]. Because the CDR perturbs the electron beam less than CTR and CSR, it is a better choice for monitoring the electron beam bunch shape. The use of diffraction radiation (DR) for measuring the transverse beam dimension is a new non-invasive technique, only partially investigated at the present time [4-5]; for example transverse beam size and emittance measurements have not been performed even though it is apparently possible to make precision measurements of bunch length, emittance at low energies, and the transverse size. This collaborative effort involving physicists and facilities from Cornell and Vanderbilt is aimed toward a comprehensive investigation of the potential use of DR over the broad spectrum of energies to be found at the Linear Collider.

Diffraction radiation is emitted from relativistic electron bunches passing through an aperture in a metal screen. The simplest aperture is a circular hole or a slit. The DR, like the transition radiation, is in the forward direction along the electron path, and in the backward direction along the direction of specular reflection from the metal screen. The DR intensity is proportional to the square of $\gamma$, and it is distributed in angle as $1/\gamma$, where $\gamma$ is the electron energy factor ($E_{\text{beam}}/m_e c^2$); thus, both the intensity and the angular distribution can be used to deduce the beam energy[6]. The DR technique can be developed as a low cost, compact, and non-intercepting monitor which can be very useful for each element of the Linear Collider, starting with the injection linac, the damping rings and the main linac. DR has the potential capability to diagnose multiple beam parameters such as longitudinal and transverse beam sizes, energy, position, divergence and emittance. The DR technique also can be developed as a single shot measurement. As the DR technique measures the spectrum and angular distribution in the frequency domain, it has very high spatial and time resolution, and it is easy to satisfy the requirements of the Linear Collider facility. The goal in spatial resolution in this proposal is less than 1 $\mu$m in the longitudinal and transverse beam size measurement. From the analysis of measured data, the error on bunch length is estimated to be of the order of about 20%. One limitation that is apparent is due to the shrinking angular distribution with increasing $\gamma$, potentially limiting transverse beam size measurements to energy below 5 GeV (depending on background); however
other properties such as bunch length measurement improve with increasing beam energy making this technique very viable at the Linear Collider.

The coherent properties are included in the DR spectrum in which the radiation wavelength is nearly equal to the beam bunch length. In the case of the LC, 100 μm bunch lengths would produce radiation in the 0.1 mm wavelength region. The CDR has a fixed phase relative to the electron bunches, and the measurement of the coherent radiation gives the longitudinal bunch form factor $f(\omega)$ and hence provides information about the longitudinal bunch distribution function $S(z)$. Therefore, the electron distribution in a bunch can be obtained from the inverse Fourier transformation of the form factor. In addition, the angular distribution of the DR from an electron passing through a slit in a metal foil has polarization properties because of the interference effects between the two half-planes of the radiator. The polarization shows different properties with the electric field parallel and normal to the plane of slit plane. The electron beam transverse dimension can be measured through the analysis of the angular distribution of the diffraction radiation [4-5].

We propose the measurement of the coherent DR spectrum from a slit in a metal foil. The longitudinal profile will be evaluated from the fast Fourier transform of the autocorrelation function and the use of the minimal phase approximation. The results will be compared to that of intercepting CTR (Coherent Transition Radiation) and non-intercepting electro-optic measurement experiments conducted in the same environment.

In addition, we propose measure the electron beam transverse dimension through the analysis of the angular distribution of DR. A simple CCD camera can measure the angular polarization of DR. The total intensity of normal angular distribution has a minimum value when the beam passes through the center of slit. In practice, this property can be used to center the electron beam in the slit, and it may be a useful tool with which a cavity BPM can be centered on the beam.

It should be noted that much more accurate angular information of DR can be obtained by placing two slits. We also propose to measure interference from the forward radiation off one slit as it interferes coherently with the backward radiation from the other. Analyzing the whole angular distribution in the normal plane and fitting it to the theoretical prediction allows us to determine the transverse dimension of electron beams, beam energy and emittance.

The bulk of the design and construction of the apparatus will be done at the Vanderbilt FEL Center, where there are available experienced scientists, mechanical and design engineers and where, importantly, a minimum of eight hours of beam time per week will be made available to this project. Bibo Feng, who is the accelerator physicist at the Vanderbilt FEL, has performed CDR experiments at the Tohoku University Linac in Japan, and has experience measuring e-beam emittance, beam current as well as transverse and longitudinal beam profiles. Steve Csorna, a physics faculty member, who is a particle physicist, has worked with Don Hartill at Cornell in the measurement of the CESR beam’s transverse size from the two slit interference of synchrotron radiation. Bill Gabella, the associate director of the Vanderbilt FEL Center, is an accelerator physicist who has experience in measuring bunch length using coherent transition radiation.

**FY2004 Project Activities and Deliverables**

In the first year, we will conduct the simulation work of DR which applies to the fundamental description of the bunch length experiment and the beam transverse size experiments. The calculation of CDR and incoherent DR under different conditions will help to understand the principles and to direct the design work of the experimental devices. We will write the calculation codes as well as the data processing programs.
We will design and build a Martin-Puplett type interferometer which will be used for the CDR spectral experiments. Two Golay cell FIR detectors and some optical components are needed for this purpose. We will design and build a radiator as well as its housing chamber for the experiments. The two pieces of thin metal foils or aluminum coated silicon plates can be used as the radiator. The slit of the radiator should be moved to intercept the electron beam by an actuator. The slit width will be adjusted by moving the two half foils in the same plane. It emits transition radiation when the slit is closed, thereby allowing us to directly compare the results from DR and TR techniques.

The first year deliverables will be a Martin-Puplett type interferometer, the DR radiator, and a technical report for DR experiments.

**FY2005 Project Activities and Deliverables**

In the second year, the CDR measurement devices will be built and commissioned at the Vanderbilt linear accelerator. The linear accelerator at Vanderbilt is a Mark III type linac, which produces electron energy from 25 MeV to 45 MeV with average beam current 200 mA. By measuring the coherent radiation spectrum intensity we will be able to derive the beam bunch length and longitudinal intensity profiles.

We will also measure the DR angular distribution from the radiator to yield the beam transverse dimension according to the angular distribution theoretical calculation. We will measure the interference image from two DR screens with slits to obtain more detail information of the angular distribution of DR, and derive the electron beam properties such as beam transverse size, beam energy and beam angular spread.

The second year deliverables will be a technical report describing the coherent DR and incoherent DR experimental results at Vanderbilt.

**FY2006 Project Activities and Deliverables**

During in the third year, we will carry out the beam property experiments using coherent DR and incoherent DR at the Cornell accelerator facility with higher electron beam energy. The device for measuring the angular distribution will be designed and built for accommodating different wavelengths and radiation bandwidths corresponding to different beam energy and slit width of the radiator.

The third year deliverables will be a technical report describing the coherent DR and incoherent DR experimental results at Cornell accelerator facility.

**Budget justification**

The first years activities are limited to design and build an interferometer and a DR radiator, which will involve staff members (not included in the budget shown here). A minimal amount of travel funds is included to cover collaboration meetings.

We expect that the second and third year will be primarily devoted to studying the properties of the DR under varying beam conditions at Cornell and Vanderbilt. Low energy running (50 MeV) can be efficiently performed at Vanderbilt, high energy running will be at Cornell (CESR). The postdoc will have the primary responsibility for scheduling runs, acquiring data and doing a significant portion of the data analysis.

We expect that on the basis of what we learn during the first year, we will need to buy additional specialized equipment and electronics.

**Three-year budget, in then-year K$**
**Institution:** Vanderbilt University (Fringe benefits are calculated at 26.6% rate on total salaries, and indirect costs are calculated at 51% rate on total salaries, fringe benefits and travel)

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**References:**


2.6. Single-shot, electro-optic measurement of a picosecond electron bunch length (UCLC)

Accelerator Physics

Contact person: Bill Gabella
email: b.gabella@vanderbilt.edu
phone: (615) 343-2713

Vanderbilt

Year 1: $20,000
Year 2: $79,438
Year 3: $104,298
3.3 Single-shot, electro-optic measurement of a picosecond electron bunch length.

Personnel and Institution(s) requesting funding

William E. Gabella, Bibo Feng, John Kozub, Free-electron Laser Center, Vanderbilt University, Nashville, TN 37235.

Collaborators

Court Bohn, Department of Physics, Northern Illinois University.

Tesla Test Facility/DESY collaboration under discussion.

Project Leader

William E. (Bill) Gabella
b.gabella@vanderbilt.edu
615-343-2713

Project Overview

In next linear collider designs, the effort to create and maintain short electron/positron bunches requires a robust technique to measure bunch lengths. Designs have bunch lengths as short as 100 µm, or 330 fs, and a desirable goal is to measure the length to 10% or better. Short bunches have the advantage of avoiding the “bow-tie” degradation of the luminosity from the depth of focus while using strong focusing and small spots at the interaction region. The bunch length also needs to be short compared to the RF wavelength in the linac to avoid nonlinear effects from the accelerating gradient. Control of the bunch length in the magnetic bunch compressor after the damping rings requires accurate measurement of the length. The variation of length with position in the bunch train is also important to create uniform luminosity over the collision time and to correct any “long-range” wakefield or other effects on the bunch train which could lead to worsening of the effective emittance of the train.

Currently measuring electron bunch lengths with coherent transition radiation (or coherent diffraction radiation, or coherent synchrotron radiation), requires scanning a mm-wave interferometer and thus acquires signal over many electron pulses[1]. A technique using the perturbing effects of the passing electron bunch’s electric field on a crystal (electro-optic, or EO, effect) measured by a fast Ti:sapphire laser has been demonstrated at the free-electron laser center (FELIX) in the Netherlands[2]-[5]. A non-destructive, single shot measurement of a 1.7 ps long electron beam is performed with an estimated accuracy of 0.37 ps. The wakefields behind the electron beam are also measured with this technique. In Refs.[6, 7], there was difficulty in measuring the direct fields of the electrons because of the strength of the wakefields following the electron bunch; their charge was much greater than in the FELIX experiment. They plan to build a low-impedance structure to house the EO crystal for future measurements.1

The goal of this proposal is to perform EO measurements of both (FEL) laser and electron bunch lengths, but make several improvements. One is to use a shorter pulse Ti:sapphire laser, approximately 8 fs instead of 30 fs, and another is to increase the spectrometer resolution. This should yield an error of less than 180 fs on a single-shot measurement of a 1 ps electron beam (assuming a chirped pulse length of about 4 ps for good signal to noise); chirped for a shorter electron pulse of 0.3 ps (assuming a chirp of 1.2 ps) this would result in a resolution of less than 100 fs. Ref. [5] gives the minimum intrinsic resolution as \( \Delta t = \sqrt{t_0 t_c} \), where \( t_0 \) is the unchirped pulse length and \( t_c \) is the chirped pulse length.

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1 See the UCLC proposal by C. Bohn, Northern Illinois University and Fermilab.
length. Improvements toward the desired 30 fs resolution would come from improving the sensitivity and resolution of the spectrometer, and allowing shorter chirps closer to the actual electron bunch length.

It is important to point out that if timing jitter can be kept smaller than the probe laser pulse length, that length, 8 fs, would be the ultimate resolution in a sampling (many pulse) measurement. This is an important aspect of the research, synchronizing the probe laser to the electron bunch on the sub-100 fs level.

A Ti:sapphire oscillator will be installed at the Vanderbilt Free-electron Laser Center. It will be synchronized with the electron beam (and FEL laser beam). It appears that a laser with an 8 fs pulse length and approximately sub-100 fs synchronization are possible[8, 9]. The first measurements will be the longitudinal profile of the FEL laser pulse which is about 1 ps long. On a bench in the lab, refinements will be made to the spectrometer and pulse picker and resolutions estimated. The EO crystal holder and the laser beamline to our electron beam will be designed and built. The chamber design will be aided by the low-impedance chamber effort at Fermilab’s AO Photoinjector, a part of the UCLC proposal by Court Bohn. Electron bunch length measurements will follow.

For linac physics reasons, it is interesting to measure the evolution/change of the electron bunch through the bunch train. Single-shot EO measurements will be compared to coherent transition radiation measurements of the bunch length, as well as sampling measurements with the EO technique. At the FEL, a geometrically flat beam can be made with about 10:1 aspect ratio and the bunch length measured; the AO Photoinjector may be available for experiments on truly flat beams with aspect ratios of 50:1, or better. The electron beam at the FEL has a single pulse charge of 50 pC, however the monochromatic xray machine at the Center has single bunch charges of 1-5 nC in 8 ps and is available for experiments.

The current budget below includes approximately 50% of the cost of a synchronized, fast Ti:sapphire laser oscillator. The remaining burden will come from the FEL Center, subsequently the laser will be shared with the Center. Also identified at the Center is a high resolution CCD camera that should be useful for the spectrometer.

The EO measurement is sensitive to all externally applied electric fields, including the wakefield the electrons induce in the structure. This can be a novel way to measure the wakefields. It is important to point out the EO bunch length measurements on FEL’s do not seem to suffer from excessive wakefield effects; the bunch charge is typically less than 0.2 nC. While in the Fermilab experiment on the AO Photoinjector, the currents were 1-12 nC and the direct bunch signal was overwhelmed by the wakefields.

The Vanderbilt FEL Center has the needed expertise for these experiments. The Center routinely runs a 45 MeV electron linac with high average power as a driver for the FEL. The Center also runs a tunable, back-scattered xray source that uses a high-charge, 45 MeV electron bunch and a Ti:sapphire driven glass laser capable of 20 TW in 8 ps. The electrons and the laser are synchronized on the picosecond level. An optical parametric generator system capable of tunable light from UV to mid-IR is also run by Center personnel. That system is based on a Ti:sapphire oscillator and amplifiers driving nonlinear interactions in crystals to generate tunable wavelength light.

**FY2004 Project Activities and Deliverables**

**Activities:** Study which of several vendors’ fast Ti:sapphire laser oscillators would suit the experiment best in terms of price, speed and especially synchronization. Currently, for budgetary reasons, the laser will be purchased with the option of fast synchronization in its design, but the actual synchronization
hardware will be purchased in the following year. Install and begin testing the Ti:sapphire laser system without synchronization. Using a currently available CCD camera, build the spectrometer detector for the system.

Deliverables: Papers describing the studies of electro-optic measurements, for varying geometries of the crystal and the electron beam, for varying impact parameters, and for high resolution.

**FY2005 Project Activities and Deliverables**

Activities: Finish testing and characterizing the laser, especially the laser pulse length, jitter and stability. Purchase and install the synchronization hardware. Install the pulse picker which selects a single pulse out of the approximately 50 MHz laser repetition rate—needed to decrease measurement background. Build and test the variable pulse stretcher. Using the completed laser system, measure the FEL laser pulse length on a bench using the EO effect. Both single-shot and multi-shot measurements will be performed. Comparisons will be made to auto-correlator pulse length measurements. Design the laser beamline and the low-impedance vacuum chamber for electron EO measurements, use guidance from the Fermilab effort at the AØ Photoinjector.

Deliverables: Completed laser and associated hardware. Paper describing the laser characteristics and ancillary hardware. Design for the laser beamline and the low-impedance vacuum chamber for electron measurements. Description of first measurements of the FEL laser pulse.

**FY2006 Project Activities and Deliverables**

Activities: Measure the evolution of the FEL laser bunch length during the bunch train. Build and install the laser beamline and the vacuum chamber housing the EO crystal. Perform electron bunch length measurements: single-shot, multi-shot, and evolution during the train. Measure wakefields. Plan similar measurements at the AØ Photoinjector at Fermilab, or DESY, or SLAC, especially to investigate flat beams, shorter beams, and scaling to higher energy.

Deliverables: Papers describing the laser and electron bunch length measurements for a single-bunch and the variation over the bunch train. Paper detailing the wakefield measurements.

**Budget justification**

The first year of the budget is this proposal’s share of the fast Ti:sapphire laser oscillator needed for the experiment. The FEL Center director is very supportive of this line of research and is committed to helping with the purchase of the laser, as well as purchasing or loaning the pump laser that is needed. Current estimates are this should save about half the cost of the final synchronized oscillator, or about $30K. Also, to spread out the burden of the cost to this proposal, the basic oscillator designed with the possibility of synchronization is purchased in year 1, with the remaining synchronization hardware purchased in year 2. Two vendors have been identified that can supply the fast Ti:sapphire oscillator.

Already available at the FEL Center is a high-resolution CCD camera for building the spectrometer needed for the single-shot measurement.

In year 2, the previously planned/designated synchronization hardware will be purchased and installed. Much of the other needed ancillary laser hardware is either already available or will by purchased by the FEL Center for use in other experiments. The largest budget expense will be the hiring of a post-doctoral researcher or a graduate student whomever is available. This is important as year 2 is the busiest year in this proposal in terms of testing and building experimental components.

In year 3, again the major expense is for a researcher who will be designing and building the laser beamline and EO crystal vacuum chamber for, and then performing, the electron measurements. Plans for further measurements at other facilities will be made.
Three-year budget, in then-year K$

**Institution:** Vanderbilt University

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**References**


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Fringe rate used is 26.6%; indirect cost rate is 51%.
[8] H. Kapteyn, Dept. of Physics, University of Colorado, Boulder and KMLabs, LLC, *private communication.*

2.7. Fast Synchrotron Radiation Imaging System for Beam Size Monitoring (UCLC)

Accelerator Physics

Contact person: Jim Alexander
email: jima@lns.cornell.edu
phone: (607) 255-5259

Albany
Cornell

Year 1: $23,319
Year 2: $45,328
Year 3: $19,856
3.4 Design for a Fast Synchrotron Radiation Imaging System for Beam Size Monitoring

Personnel and Institution(s) requesting funding
Jim Alexander, Cornell University
Jesse Ernst, State University of New York, Albany

Project Leaders
Jim Alexander
date: jima@lns.cornell.edu
phone: 607-255-5259
Jesse Ernst
date: jae@mail.lns.cornell.edu
phone: 518-442-4538

Project Overview
With the high intensity, low emittance beams needed to reach the luminosity goals of the linear collider, beam size monitoring will play an important role in machine operation. In the damping rings, synchrotron radiation emitted by the bunch can provide a means of measuring transverse bunch size and shape [1]. With suitable imaging and high speed detection of the SR, bunch size, shape, and position may be determined with single bunch discrimination and minimal disturbance to the passing beam. A system fast enough to capture such a "snapshot" of a single beam bunch would be a useful addition to the Linear Collider diagnostics package and also be a valuable contribution to general accelerator physics and technology.

We propose to develop imaging and detection techniques that could be used to directly image the synchrotron radiation.

In the NLC(TESLA) designs of the damping ring, the vertical bunch size at the midpoint of the dipole magnets is \( \sim 5(7) \mu m \) and the horizontal size is \( \sim 35(45) \mu m \). Beam energy is \( \sim 2(5) \) GeV. The emitted synchrotron radiation is cast forward in a narrow cone of opening angle \( 1/\gamma \) and has a critical energy of about \( 3\gamma^3\hbar c/\rho = 8(6) \) keV. An imaging system working in the optical region would be diffraction limited and incapable of resolving the small vertical size of the beam, but wavelengths below 10 nm (i.e., X-rays above \( \sim 0.1 \) keV) will provide sufficient resolution [1]. An optimal choice for the working energy is thus constrained from below by diffraction, from above by critical energy, and must be chosen to permit maximal transmission by the optical components yet maximal absorption by the detector.

Imaging and detecting these photons poses interesting technical challenges. A system suitable for damping ring use requires three principal components:

1. A point-to-point imaging optical system suitable for \( \sim 1 \) – 10 keV X-rays. Several technologies exist, including grazing angle mirror systems, diffracting aluminum or beryllium lenses, and Fresnel zone plates. Each has advantages and disadvantages. Grazing angle systems are inherently achromatic, but require high precision control of the surface figure. Diffracting lenses and zone plates are wavelength specific and would require a monochromator upstream, but are mechanically less demanding. (A monochromator has the useful side-effect of reducing flux and therefore reducing thermal load on the dimensionally sensitive optical elements.) Diffracting systems also introduce absorption which must be kept low by suitable choice of material.
2. A low-noise, high speed, high resolution two-dimensional detector with sufficiently fast response to cleanly separate the closely spaced bunches that one will encounter in a Linear Collider damping ring (1.4 ns for NLC, 20 ns for TESLA). Silicon pixel detectors are a plausible detector choice, offering 2-dimensional imaging and high granularity, as well as a low capacitance, low noise source adaptable to the needs of high speed readout. Careful study of the signal transmission characteristics, starting from the absorption processes, through the drift, diffusion, and charge collection in the detector, and the subsequent transport, switching, amplification, and measurement of the signal charge must be undertaken to fully understand the factors that determine achievable bunch resolution time. 1 ns resolution may be achievable in silicon, but subnanosecond resolution likely demands higher mobility materials such as GaAs. The intrinsic spatial resolution of the detector and the magnification of the optical system must be optimized together to achieve best resolution.

3. A high speed data acquisition system to extract signals from the detector, perform signal processing and pass results to accelerator control systems in real time. Appropriate software would be required to render the results in a form easily interpreted by an operator.

A well developed literature exists for X-ray optics of the varieties mentioned above [2]. Applications are typically related to focussing X-rays to maximize intensity. Techniques for high speed time-resolved detection of an imaged low emittance beam will require additional development. Further, conventional detection systems use florescent screens to convert X-rays to optical photons which are then detected by a standard CCD camera, offering no useful time resolution.

A system that would offer 10 ns resolution could usefully image single TESLA bunches, and is within the range of today's technology but not actually available. A system that would offer 1 ns resolution could image single NLC bunches, but would require technological development. A system that would offer 10 ps resolution could permit intrabunch resolution, i.e., bunch tomography, but will demand both technological advance and a deep understanding of the physical processes of the detection mechanism.

We propose to investigate a range of existing imaging technologies that could be applied to X-rays in the appropriate energy range. We also propose to study the detector and readout options that could be combined with this optical system to form a high speed bunch imaging device. We expect that the timing requirements on the detector and readout scheme will create significant technical challenges. We will study existing techniques, and where needed develop our own, including the possibility of combining a pixel detector with two amplifiers per channel to allow for a pair of closely spaced “snapshots.” For each option, we will explore in detail the fundamental physical processes that determine its ultimate time resolution.

We build on our ten years experience with silicon detectors and high speed data acquisition technology. We also have ready access to appropriate facilities, including Nanofabrication facilities at both Cornell and SUNY Albany, the X-ray lines at the Cornell High Energy Synchrotron Source (CHESS), and of course the CESR storage ring itself, whose energy and beam size parameters, and bunch spacings are relevant to the existing LC damping ring designs. We also expect to use readily available simulation tools include PISCES (for signal development and transport in solid state detectors), SPICE (for general electronics design), and SHADOW (for X-ray optics design). We will use these, or others as necessary, and will also develop our own Monte Carlo simulation of the entire chain from the point of radiation to the final step of detection. We also have available an extensive stock of small prototype silicon detectors and a well equipped detector development laboratory (including probe station, wire bonder, etc.) which can be used to empirically study general properties of signal development in silicon detectors and cross check the simulations and calculations.
**FY2004 Project Activities and Deliverables** Review existing techniques for X-ray imaging and use standard software to explore possible optical layouts for the most promising technologies. Evaluate relative merits of each and proceed to design the actual imaging system. Simultaneously, develop software tools and physics basis to simulate signal development in solid state detectors and signal processing electronics to design detector system with optimal response time. Write a technical report on results.

**FY2005 Project Activities and Deliverables** Pursue most promising design options and confirm essential details of simulations with empirical measurements on existing silicon detectors using available hardware and the CHESS X-ray lines. Write a technical report on results.

**FY2006 Project Activities and Deliverables** Optimize design details and write final design report.

**Budget justification**

We request funding for half-coverage of the cost of a large bandwidth oscilloscope (such as the Tektronix TDS 8000B with 80E06 insert) which will enable detailed studies of solid state detector performance at high speed. We also request funding for purchases of computers for the silicon readout systems.

The proposed travel budget covers travel for one of us (JAE) to come to Ithaca 4 times per year ($2K) and for one of us (JPA) to travel to Albany 4 times per year ($2K).
Three-year budget, in then-year K$

**Institution:** Cornell University

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(1) Includes 26% of first $25K subcontract costs

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References


2.9. Radiation damage studies of materials and electronic devices using hadrons (LCRD)

Accelerator Physics

Contact person: David Pellett
email: pellett@physics.ucdavis.edu
phone: (530) 752-1783

UC Davis
Fermilab
SLAC

Year 1: $40,725
Year 2: $39,465
Year 3: $39,465
Project Name

Radiation Damage Studies of Materials and Electronic Devices Using Hadrons

Classification (accelerator/detector:subsystem)

Accelerator

Institution(s) and personnel

University of California, Davis, Department of Physics:
Maxwell Chertok, David E. Pellett (professors)

Stanford Linear Accelerator Center:
James E. Spencer, Zachary R. Wolf (staff scientists)

Fermi National Accelerator Center:
James T. Volk (staff scientist)

Contact Person

David E. Pellett
pellett@physics.ucdavis.edu
(530) 752-1783

Project Overview

Many materials and electronic devices must be tested for their abilities to survive in the radiation environment expected at the proposed linear collider (LC). Radiation-sensitive components of the accelerator and detectors will be subjected to large fluences of hadrons as well as electrons and gammas during the lifetime of the accelerator. Examples are NdFeB permanent magnets which are being considered for the damping rings and final focus, electronic and electro-optical devices which will be utilized in the detector readout and accelerator control systems and CCDs which will be required for the vertex detector.

UC Davis has two major facilities which can be used to provide needed information on hadron radiation damage, the McClellan Nuclear Reactor Center (MNRC), located in Sacramento (approximately 50 mi. round trip from the Davis campus), and the UC Davis Crocker Nuclear Laboratory (CNL) cyclotron (on campus). These are described in an appendix to this document.

The initial study in this program concerns radiation damage due to neutrons in samples of NdFeB permanent magnet materials using the MNRC facilities.

Permanent magnet beam optical elements have been in use in the SLC damping rings at SLAC since 1985. They are also candidates for use in final focus quads, damping rings, wigglers, and possibly elsewhere in the LC. It would be advantageous to use NdFeB for such magnets due to its lower cost and its higher energy product, $(BH)_{\text{max}}$.
SmCo. Its Curie temperature, $T_C$, is lower than that of SmCo, however, so one must evaluate the degradation of its magnetic properties due to radiation damage.

Neutrons from photonuclear reactions are an important source of radiation damage to permanent magnets at LC in beam tunnels and damping ring enclosures. The radiation doses have been estimated in the NLC beam tunnel using a simulation based on electron losses [1]. These losses create showers of secondary particles dominated by electrons, positrons, photons and neutrons. The neutron energy spectrum is broad but peaked near 1 MeV. In a region under a magnet, approximately 25 cm below the beam line, the equivalent fluence of 1 MeV neutrons (normalized to radiation damage in silicon) was estimated to be $1.9 \times 10^{14}$ cm$^{-2}$ for 10 years of operation. The magnets themselves are likely to see much higher neutron fluences, especially in other locations, such as the damping rings.

Brown and Cost [2] have shown that the remanence of NdFeB permanent magnets may be reduced significantly for neutron fluences of this order of magnitude and higher when irradiated at an elevated temperature (350 K). The rate of reduction with fluence depended on the magnet operating point during irradiation, the intrinsic coercivity of the material and the manufacturer of the material. It is necessary to characterize candidate materials for LC NdFeB permanent magnets using neutron fluences comparable to those expected during the useful life of the magnet. Our planned measurements appear to be unique in their ranges of coercivity, loading and neutron energies and to complement the measurements of Ito, et al. using 200 MeV protons [3]. As Ito et al. make clear, there are discrepancies between available measurements with protons and the damage mechanisms which are not understood. Further, there also appear to be inconsistencies between the available neutron damage studies and the proton measurements. This work is needed if NdFeB magnets are to be considered for the baseline LC design.

High doses of gammas and electrons are also present in these locations, of course, but the associated radiation damage is expected to be much less than from the neutrons. SLAC is in a good position to verify this with bremsstrahlung on candidate materials. Samples of NdFeB and SmCo have been tested at SLAC (with Lockheed Martin) using $^{60}$Co gammas with no observable effects up to ~1 MGy, as expected [4].

Measurements of the radiation environment are in progress in the SLAC damping rings that will allow us to estimate the neutron fluences in the LC damping ring magnets. These are being done on a time scale that is consistent with our neutron damage measurements. The existence of significant neutron fluences have been demonstrated along the beam line in the SLC electron damping ring and their sources have been studied [5]. Fermilab is also estimating beam loss distributions and particle fluxes for LC collimation systems which will help specify the requirements elsewhere.

We do not propose to test SmCo samples in this program. There is already a proof of principle for the use of SmCo in the SLC and evidence from Ito et al. [3] that the material is considerably more radiation-hard than NdFeB. Further, SmCo presents a severe handling and disposal problem due to the copious production of the long-lived radioactive isotopes $^{155}$Sm and $^{60}$Co by thermal neutrons. We also note that SmCo
damage studies are continuing in the SLAC damping rings by the SLAC people in this proposal.

**Current Research Progress**

We are studying materials with two different values of coercivity and from two different manufacturers focusing on the damage due to 1 MeV-equivalent neutrons. The presence of $^{10}$B in the material with its large thermal neutron capture cross section greatly increases the radiation dose delivered for a given thermal neutron fluence relative to fast neutrons, so this of interest as well. Thus, magnet assemblies will be irradiated and measured at increasing doses using 1 MeV-equivalent neutrons, supplemented with separate thermal neutron irradiations. After each dose, the induced radioactivity will be monitored by MNRC personnel. SLAC personnel will then transport the magnet assemblies back to SLAC to evaluate changes in magnetic properties.

As an example, the times required at MNRC to reach a fluence of $10^{15}$ n/cm$^2$ are 7 hr for 1 MeV-equivalent neutrons and 30 min for thermal neutrons. An initial estimate shows that the radiation fields would be well below 1 mR/hr at a distance of 1 ft after such a thermal neutron irradiation for a 1 cm$^3$ sample of pure Nd$_2$Fe$_{14}$B. Some materials contain substantial percentages of Dy or Tb, however, which have large activation cross sections for thermal neutrons. This may limit our ability to irradiate samples with thermal neutrons in these cases.

We have evaluated the MNRC irradiation facilities in meetings with MNRC personnel. The initial irradiation will be done in the NIF area which provides shielding to strongly attenuate thermal neutrons and reduce the gamma flux. High dose radiation will likely require use of an alternate facility which would need modification to make it water tight and to reduce the thermal neutron flux.

Test assemblies of NdFeB magnet blocks with iron return yokes have been fabricated that fit into the reactor test chambers and provide as broad a variation in operating points over the different constituent blocks as possible. Details of the design of the magnet test assemblies and results of measurements of their magnetic fields are given in the report by Spencer and Volk [6].

An initial irradiation of a magnet assembly was performed directly downstream of a hydrogen target in a SLAC beam line, achieving a dose of 10 kGy of gammas and 1 kGy of 1 MeV equivalent neutrons (stated as tissue equivalent dose to simplify comparisons). The two most significant radioactive isotopes were $^7$Be and $^{51}$Cr from the B and Fe with the latter 20 times stronger but still less than one $\mu$Ci. The next strongest after these was down another factor of 4 from the $^7$Be. Half lives are of order one to two weeks. There was no evidence of radiation from the Nd derived isotopes nor from any substitution elements such as Dy, Pr or Tb. We are now preparing to irradiate the magnet assemblies at the MNRC reactor where we can significantly improve on the ratio of gammas to neutrons and increase the dose.
Proposed Research

This program will conclude the NdFeB damage measurements with 1 MeV equivalent and thermal neutrons now in progress. The latter part of the program will concentrate on testing electronic and electro-optical devices and materials for LC accelerator and detector applications using neutrons at MNRC or at CNL or 63 MeV protons in the CNL radiation test beam.

This proposal includes an estimated UC Davis budget, as follows:
- additional supplies will be required for the irradiations, such as high-level semiconductor dosimeters; supplies may also be needed for material to attenuate thermal neutrons in MNRC irradiation vessels;
- a student assistant is needed to help in performing and evaluating the irradiations and measurements at MNRC;
- travel funds are needed for trips by UC Davis personnel to MNRC and occasional trips to SLAC; also included are funds for one trip to a meeting to present results;
- funds are required to cover incidental MNRC costs associated with the tests. MNRC does not charge UC Davis for beam time.
- Also included are 20 hours of CNL beam time per year for proton or neutron irradiation of samples.

The cost of the student assistant is based on an undergraduate student working half time during the academic year and full time during the summer. The assistant must drive to and from the off-campus facility and be qualified to deal with the potentially radioactive samples.

UC Davis Budget for LCRD 2.9

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References


Appendix: Description of Relevant Facilities and Resources

As mentioned at the beginning of this document, UC Davis has two major facilities which can be used to provide needed information on hadron radiation damage, the McClellan Nuclear Reactor Center (MNRC), located in Sacramento (approximately 50 mi. round trip from the Davis campus), and the UC Davis Crocker Nuclear Laboratory (CNL) cyclotron (on campus).

The MNRC reactor has a number of areas for irradiating samples with neutron fluxes up to 4.5 x 10^{13} n/cm²s. A specialized area (NIF) allows irradiation with 1 MeV-equivalent neutrons in a flux of 4.2 x 10^{10} n/cm²s while suppressing thermal neutrons and gammas by large factors. Other areas allow irradiating very large objects at lower fluxes.

The CNL radiation test beam consists of protons of up to 63.3 MeV kinetic energy spread over a rather uniform beam spot 7 cm in diameter. A typical central flux is 4.2x10^{9} protons/cm’s (0.56 kRad/s (Si)). A secondary emission monitor calibrated with a Faraday cup is used to measure the beam fluence to an accuracy of better than 5%. The beam profile has been established by a variety of means, showing the dose to have fallen by only 2% at a radius of 2 cm. The facility can also produce a neutron beam with a flat energy spectrum extending to 70 MeV kinetic energy. We have used the CNL proton facility for a wide variety of tests on electronic devices and detector components.
2.10. BACKGAMMON: A Scheme for Compton backscattered photoproduction at the Linear Collider (UCLC)

Accelerator Physics

Contact person: S. Mtingwa
email: mtingwa@mit.edu
phone: (336) 334-7423

NCA&T

Year 1: $38,790
Year 2: $0
Year 3: $0
2.3 BACKGAMMON: A Scheme for Compton backscattered photoproduction at the Linear Collider

Personnel and Institution(s) requesting funding
S. Mtingwa, Department of Physics, North Carolina A&T State University

Collaborators
M. Strikman and E. Rogers, Dept. of Physics, Pennsylvania State University

Project Leader
S. Mtingwa
mtingwa@mit.edu

Project Overview

We propose to investigate the possibility of Compton backscattering low energy laser pulses off the spent electron and positron beams at the Linear Collider. The hot backscattered photons would then scatter off fixed targets for a rich variety of physics studies in a scheme dubbed BACKGAMMON, for BACKscattered GAMMas On Nucleons. The first objective would be to operate a heavy quark factory, since the cross sections for charm and bottom quark production would be favorable for producing large numbers of these flavors. Secondly, if the incident laser pulses are circularly polarized, the backscattered photons would be circularly polarized as well, allowing the possibility of producing polarized $\tau$ pairs on fixed targets. Also, BACKGAMMON’s polarized hot photons could scatter off polarized targets and play an important role in elucidating the spin structure of nucleons. Finally, there is the possibility of studying the photon structure function in spent electron beam scattering on laser photons.

The original idea for using the Linear Collider for producing Compton backscattered photon beams for operation of a heavy quark factory is described in [1]. There it is shown that, if one had an electron beam of hundreds of GeV energy, then one could produce greater than the $10^9$ B meson pairs per year that the theorists said were needed to elucidate CP violation in the B meson system. That was before the advent of the current generation of B factories using electron-positron colliders. Soon after the description of BACKGAMMON for heavy quark production, it became clear that this scheme could be used to operate a polarized $\tau$ factory as well. This and subsequent ideas are contained in References [2, 3, 4, 5, 6].

Milburn [7] and independently Arutyunian and collaborators proposed the original idea of using Compton backscattering in accelerators [8, 9, 10]. The detailed theory of Compton backscattering, incorporating the accelerator lattice functions of the initial electron beam, was derived in Reference [1]. The first practical application of Compton backscattering in a physics experiment was the measurement by Ballam et al. of $\gamma p$ hadronic cross sections in a bubble chamber at SLAC [11]. Since that initial experiment, there have been a number of studies using Compton backscattered photons, including the Brookhaven National Laboratory’s Laser Electron Gamma Source (LEGS) Facility [12, 13] and applications of Compton backscattered photon beams to measure the polarization of electron beams [14, 15, 16, 17, 18, 19]. Thus, Compton backscattering has enjoyed a rich history.

BACKGAMMON would be unobtrusive to the baseline Linear Collider design. It should be viewed as an add-on experiment to the Linear Collider that is worthy of further study. It would involve the following fixed target experiments:
Unpolarized laser pulses would be incident on the spent electron beam to produce unpolarized hot photons for the photoproduction of heavy quark flavors to study a variety of phenomena, including CP violation in the neutral B meson system, high precision studies of bottom and charm decays, searching for rare and forbidden bottom and charm decays, QCD studies using heavy quark pair events, heavy quark spectroscopy, heavy quark baryons, and other checks on the Standard Model.

While BACKGAMMON I is using the spent electron beam, circularly polarized laser pulses would be incident on the spent positron beam to produce circularly polarized hot photons for the photoproduction of polarized τ pairs, to study a variety of phenomena, including improving the τ neutrino mass limits from such decays as $\tau \rightarrow K^- K^+ \pi^- \nu_\tau$, searching for CP violation in the lepton sector of the Standard Model, searching for rare and forbidden τ decays, studying the Lorentz structure of τ decays, and other checks of the Standard Model.

At the conclusion of BACKGAMMON II, the polarized hot backscattered photons would be incident on polarized nucleon targets to measure the gluon contribution to the nucleon spin. An excellent discussion of this point is contained in [20]. The spin content of the nucleon still is not understood.

In Reference [5], the laser requirements of BACKGAMMON are briefly discussed. There, it is emphasized that the laser requirements in this scheme are less stringent than those for a $\gamma - \gamma$ collider. For the $\gamma - \gamma$ collider, the aim is to convert each electron in the collider bunch into a hot photon, leading to the requirement of 1 Joule per laser flash with a 1 kHz repetition rate. In BACKGAMMON, for $10^9$ electrons per bunch, only 1 mJ per laser pulse at 1kHz will produce the $10^9$ B pairs per year; while for $10^{10}$ electrons per bunch, as called for in the LC designs, $10^{10}$ B pairs per year would be produced. Moreover, if one could push the laser rep rate up to the 10 kHz called for in the LC designs, then one could produce up to $10^{11}$ B pairs per year. These B meson pairs would be produced in a much cleaner background than that of the hadron machines, such as the $10^{11}$ B pairs per year proposed for the BTeV experiment at Fermilab.

A specific laser design and implementation at BACKGAMMON could lay the groundwork for the $\gamma - \gamma$ collider laser system, with the main difference being the lower power requirements for BACKGAMMON. For the $\gamma - \gamma$ collider, it has been suggested that a diode pumped semiconductor laser is plausible [21]. However, for the high repetition rates needed in both these schemes, it may be necessary to time-multiplex a set of lasers. More R&D is needed to settle this issue.

During FY 2004, we will study the feasibility of using the disrupted beams after the electron-positron interaction point for Compton backscattering laser pulses. Initial discussions with TESLA accelerator physicists make the idea sound promising. We will study the backgrounds from the electron-positron interaction point to insure that they are manageable and design beamlines to bring the best quality electron and positron spent beams to the two interaction points with the lasers. Also, we will ascertain whether BACKGAMMON leads to high statistics physics data inaccessible by other means.

On the theoretical side, we will understand the details of the angular dependences of the polarizations of the photoproduced τ pairs, and we will perform theoretical studies of the physics issues as outlined above. This would involve both analytic approaches and simulations of the phenomenology. The results of our FY 2004 activities will be written in a detailed report, with specific attention given
to the question of whether the laser optics and beamlines and the gamma extraction beamlines are compatible with realistic linear collider extraction lines.

**Future Activities**

If the FY 2004 investigations show that BACKGAMMON is indeed feasible and has important advantages over other experimental methods, we will seek supplementary funding from UCLC for FY 2005 and FY 2006 to carry out detailed design studies for BACKGAMMON, focusing on the detector system and simulations of the fixed target photoproduction experiments enumerated above.

Finally, we will begin to investigate the possibility of using the doubly spent electron beam (after both $e^+e^-$ and $e$–laser interaction points) to scatter off a second low energy laser pulse and study the photon structure function. For a review, see [22].

**Budget justification**

The project will consist mainly of computational and theoretical calculations. The single-year budget mainly will support one graduate student and travel for the Principal Investigator (PI) and one collaborator to visit each other’s university for the purpose of working on the project. Computational equipment will be purchased for the graduate student.

Indirect costs are calculated at North Carolina A&T’s 40% rate on modified total direct costs, which excludes tuition.

**One-year budget, in then-year K$**

**Institution:** North Carolina A&T State University

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**References**


2.11. Ground Motion studies versus depth
(LCRD)

Accelerator Physics

Contact person: Mayda Velasco
email: mvelasco@lotus.phys.nwu.edu
phone: (847) 467-7099

Northwestern

Year 1: $41,000
Year 2: $41,000
Year 3: $41,000
Project name

Ground Motion studies versus depth\textsuperscript{1}.

Classification (accelerator/detector:subsystem)

Accelerator: Interaction region stability.

Institution(s) and personnel

Northwestern University, Department of Physics and Astronomy:
Michal Szleper (Research Associate)
Mayda Velasco (Assistant Prof.)

Contact person

Mayda Velasco
mvelasco@lotus.phys.nwu.edu
(847) 467 7099

Project Overview

Ground motion can cause significant deterioration in the luminosity of a linear collider, due to the vibration of numerous focusing magnets which cause the beam emittance to grow. For this reason, understanding the seismic vibration of all potential LC sites is essential.

The proposed studies will focus on how the ground motion varies with depth. This information is needed in order to decide how deep the LC tunnel should be at sites like Fermilab.

The measurements will be made in the NuMI tunnel at Fermilab. We will take advantage of the fact that from the beginning to the end of the tunnel there is a height difference of about 800 m and that there are about five different types of dolomite layers.

The proximity of Northwestern to Fermilab allows us to go to the tunnel every two weeks in order to change the location of the probes, exchange batteries for the equipment and program data taking for the next two week period. The members of the group have experience with NuMI (Laughton, Velasco, Szleper) and with seismic measurements (Seryi, Shiltzev).

\textsuperscript{1} Item ID 55: R & D list for NLC available at \url{http://www-conf.slac.stanford.edu/lcprojectlist/asp/projectlistbyanything.asp}. 
Description of the completed and ongoing project activities

Northwestern has already invested $25K in equipment toward this project using ICAR funds (see Table 1). All of the equipment is currently in the final phase of being tested and its performance studied. The data format provided by the data acquisition system of the GEOTECH equipment has been fully understood and an off-line Fourier analysis program, used previously in similar ground motion studies at SLAC (Seryi), has been adapted to work in a Linux environment and to input the required data format in order to obtain the seismic frequency spectrum. Software has been developed to facilitate data analysis (Szleper, Yasar).

Performance of the probes has been extensively studied in a series of measurements made in several locations on ground level at the Fermilab site (Szleper). Currently, the equipment is installed in the Aurora Mine, 200 ft below ground level, where measurements using a different equipment have already been made before (Shiltzev). A series of new measurements is expected to be completed by this summer and results will be compared. A few minor technical issues regarding the operation of the equipment are yet to be studied.

After data from the Aurora Mine are fully understood, we will start making measurements in the NuMI tunnel and the Minos near-detector hall. Given the number of measurements needed and that access is limited, the full set of measurements will take at least a half year to complete.

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Table 1: Equipment investments.

Budget

We have a grant from the state of Illinois to do accelerator development, ICAR. The grant provides $450K/year for five years, and we are now at the beginning of the fourth year. The grant is already approved for the fourth year. Most of this grant will go into the development of Multi-TeV dual beam linear collider (CLIC-type machines) as its ultimate goal, and \( \gamma \gamma \) colliders as a possible operating mode.
The grant covers all technical and post-graduate personnel and equipment cost for the project proposed here. However, this grant will not cover graduate students. We request DoE to cover that cost.

We have one PhD student on accelerator physics that is already analyzing data from the seismic measurements, and has moved to CERN to start focusing on the PhD work at CTF3-CLIC. A proposal for the thesis work at CTF3 was made by Hans Braun and accepted by Northwestern. See extra section.

**Thesis project on CLIC**

Draft outline from H.H. Braun (03/06/2003) for a PhD thesis project on CLIC drive beam machine protection in the framework of the Northwestern University contribution to the CTF3 collaboration.

The CLIC linear collider with $E_{CMS}=3$ TeV will use a high intensity drive beam of 80 MW average beam power to provide RF power to the main beam linear accelerators. To assure safe operation of the drive beam a sophisticated monitoring, feedback and interlock system will be mandatory to assure material protection and a high running efficiency. This system will be referred to as MPS (=Machine Protection System) in the remainder of this document. The CTF3 test accelerator facility, presently under construction at CERN by an international collaboration, aims to demonstrate the drive beam scheme of CLIC. The concepts of the CLIC drive beam MPS is among the various topics to be developed and tested with CTF3. This topic is well suited as a PhD thesis project since it allows the student to make a significant contribution to cutting-edge R&D for particle physics accelerators.

The thesis project should cover the following issues:

- Beam loss monitoring system based on radiation detectors outside of the beam vacuum envelope
  - Characterisation of type and intensity of beam loss induced radiation
  - Choice of detector type and readout
  - Verification with experiments in CTF3
- Drive beam failure modes
  - Analysis of possible failure modes
  - Examination of damage potential of failure modes
  - Detection capability
- Strategy for MPS
- Logic of interlock system
- Timing considerations
- Recovery scenarios

Although the developments will be done for CTF3, the scalability of the solutions to CLIC has to be assured.

Northwestern will provide for the student supervision, subsistence money, travel money, all material for the beam loss detector and readout prototyping and desktop computing facilities. It is also understood that Northwestern will take full responsibility for the purchase, installation and commissioning of the beam loss monitoring system for CTF3, even though this is not mandatory for the thesis project. CERN will provide assistance for the thesis, CTF3 beam time for thesis related tests and experiments, and office space. It is understood that the student will be a member of the CTF3 team during her PhD project with the possibility to participate in CTF3 machine commissioning and experiments and CTF3 related meetings.

Tentative roadmap for the project is show in Table 2.

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Table 2: Roadmap for the thesis project at CTF3.

Accelerator Physics

Contact person: Don Hartill
e-mail: dlh@lns.cornell.edu
phone: (607) 255-8787

Cornell
Ohio State

Year 1: $30,294
Year 2: $63,108
Year 3: $79,888
5 Accelerator Control

5.1 Investigation of GAN Techniques in the Development and Operation of the TTF Data Acquisition System

Personnel and Institution(s) requesting funding
D. Hartill, R. Helmke, T. Wilksen, Laboratory for Elementary Particle Physics, Cornell University
K. Honscheid, Department of Physics, The Ohio State University

Collaborators
K. Rehlich, Deutsches Elektronen–Synchrotron (DESY), Hamburg

Project Leader
Don Hartill
dlh@lns62.lns.cornell.edu
(607) 255-8787/-4097

Project Overview
It is generally agreed that a future Linear Collider can only be built and operated as a truly international project. The Global Accelerator Network was conceived as an idea to facilitate sharing of world-wide competence and resources. While the GAN idea is applicable to many aspects of the Linear Collider project we will concentrate on accelerator control and remote operation which are central to the GAN concept. At the first International Workshop on Global Accelerator Network concepts held earlier this year at Cornell University [1] it became clear that remote operation and control can be carried out with today’s technology — given enough resources. The challenge is to do this with existing resources so that these scarce resources, not necessarily all available at the same geographic location, can be used as efficiently as possible.

Parts of a technical solution that will allow the remote control and operation of a distant accelerator have been demonstrated at DESY, Cornell and elsewhere but a complete control system design using the GAN approach has not been carried out. We propose to evaluate existing collaborative tools required to carry out the system design and develop new ones where needed. To test these concepts, an upgrade program for the data acquisition system (DAQ) for the Tesla Test Facility (TTF) will be carried out so that remote access of TTF data is possible. With reliable remote access to the data, remote operation of the TTF to carry out significant machine studies by accelerator physicists located at remote sites can be effectively and safely conducted. With the upgraded data acquisition system in place, our goal is to carry out beam emittance measurements on the TTF from Cornell.

In addition to the proposed activities at the TTF, we are exploring possible possible collaboration with scientists at both the NLC Test Accelerator facility SLAC and at the Accelerator Test Facility at KEK in Japan. We hope to be able to contribute to the data acquisition and analysis systems at these two test facilities in much the same way as we plan with the TTF.

Tools that allow shared code development as well as documentation are critical for the success of these activities. Affordable video conferencing tools that work reliably in many different countries to exchange ideas across these geographical boundaries are also key to the success of such a collaboration. The effectiveness of these video conferencing tools will be evaluated as part of this project.

TESLA Test Facility
In 1992 the TESLA collaboration began construction of a test facility for a future linear collider. The TESLA Test Facility (TTF) [3] is located at the Deutsches Elektronen-Synchrotron (DESY) in Hamburg and has been in operation with prototype superconducting accelerator sections since 1998. In its current configuration, the TTF is a 300 m long linear accelerator with several cryostats equipped with 9 cell superconducting modules that routinely operate with accelerating gradients of up to 25 MV/m. A laser driven RF gun is the source of electrons. The facility can also be configured as a free electron laser.

The control system of the TTF is based on the Distributed Object–Oriented Control System DOOCS [4] developed at DESY in the early 90’s. This control system fulfills many of the requirements for a future linear collider control system. Its object–oriented design from the device server level up to the operator console makes it modular and flexible. The design uses the standard Ethernet communication protocol based on remote procedure calls (RPCs) that allows for remote operation of the TTF control system. The multi–protocol architecture for device servers permits the incorporation of any equipment contribution from an international collaborator without changing the interface to the control system. Remote operation of the TESLA test facility has been carried out from two collaborating sites demonstrating the GAN capabilities of this control system.

Not only will operation and control of the machine move from one institution to another in a GAN–enabled world but each remote site will require the ability to access and analyze the data collected during the operation of the TTF. Institutions that contribute essential hardware to the accelerator system will need to study the hardware behavior during operation and analyze the collected information. This is invaluable for detecting potential problems with the design and also for monitoring the long–term behavior in a real environment. For this, a data acquisition system similar to those in HEP experiments can provide an ideal solution. HEP experiments generate large amounts of data as well as high data rates which will be the case for the TTF and a future linear collider.

**TTF Data Acquisition System**

To meet these needs for the TTF, an accelerator data acquisition project was started in 1997 and began operating last year. It was considered as a proof–of–principle system with a final system to follow. This prototype system uses the well-known ROOT framework [5] from HEP experiments on top of DOOCS. ROOT has become, since its initial development in 1995, a full–fledged analysis tool. It is well suited for handling large amounts of data and the large file sizes that are expected for the LHC experiments. With full diagnostics and control the TTF data acquisition system will generate similar data streams. ROOT has very good histogramming and visualization capabilities with a large number of statistical functions. If these are not sufficient, the built–in C++ interpreter permits running any standard C++ code. Since it is used widely in HEP, support from other groups and laboratories is excellent. The current analysis tools in the prototype system, based on MatLab, will be complemented by tools based on ROOT.

The current TTF DAQ does not fit well into a GAN world since it is locally installed and is not easily used from remote sites. A better data storage concept is needed which supports remote access and remote usage of ROOT specific tools. We propose to take this existing system as a starting point and then develop and build GAN–enabled data acquisition parts into it. With the new data acquisition system in place, we plan to carry out beam emittance measurements on the TTF from Cornell.

**Collaborative Tools**

Central to the success of this project is the incorporation and evaluation of collaborative tools to accomplish both the distributed development and the remote operation of the the TTF DAQ system. We will explore the sociological and technical issues in this effort, keeping in mind the broader context...
of further linear collider research, development and operation.

Video conferencing will be the primary means of minimizing the effects of distance, to as great a degree as possible, between geographically distributed participants. We plan to use VRVS as an affordable video conferencing system at the core of our collaborative tool set. We will provide point-to-point and multi-point capability (i.e. a reflector) so that all members of the effort can be in optimal communication regardless of where they are working.

Besides video conferencing, we plan to evaluate several tools including whiteboards, documentation systems, code development environments and repositories. All these systems have to fulfill GAN specific requirements: easy accessibility from all collaboration sites, support for multiple platforms and languages, shared and restricted access levels, safe storage, and the capability of working on low-bandwidth connections (not withstanding the higher bandwidth requirements of video conferencing). Considerations of security will be important in the deployment of these tools. The ability to function through firewalls without opening up holes that might introduce vulnerability to the networks involved will be essential.

As the development and deployment of the TTF DAQ progresses, we will evaluate the effectiveness of these distributed collaborative techniques. We will be looking at sociological factors, the impact of latency inherent in the network, and other aspects of working over geographical distances.

**FY2004 Project Activities and Deliverables**

The first year will be dedicated to the evaluation of possible extensions to the existing prototype of the TTF data acquisition system. The main focus will be on global accelerator network specific enhancements. Data storage concepts which will allow for easy access to the recorded data by off-site collaborators will be developed. A first concept design will be carried out and a prototype system will be developed. Collaboration with scientists at the NLC TA and the ATF at KEK will be actively pursued to provide assistance on similar problems that these facilities face. In addition, the first stage of collaborative tools will be deployed including video conferencing tools as well as code design and development environments. Deliverables for the first year will be the prototype of a database and management system and a report on the effectiveness of using collaborative tools in an early project design and development stage.

**FY2005 Project Activities and Deliverables**

The main focus for this year will be further development of the database and developing tools needed for retrieving the data in a GAN environment. In addition, the first prototypes of visualization and analysis programs will be developed. Active collaboration with the NLC TA and/or the KEK ATF groups should be underway.

Deployment of collaborative tools especially for code management and documentation will be necessary for this part of the project. The documentation of the existing data acquisition and the added database will be carried out using these tools.

Deliverable items will be a usable database for the TTF DAQ as well as the first parts of a documentation system covering database and data retrieval. Remote operation of the TTF to carry beam emittance measurements will be attempted from Cornell.

**FY2006 Project Activities and Deliverables**

In the third year we will focus on the development of visualization and analysis tools. We will investigate if the standard HEP software package ROOT is suitable for this purpose and if it can be used in
parallel or even replace the commercial product MatLab. Collaboration with the NLC TA and/or the KEK ATF groups will continue.

A technical report on the use and exploration of collaborative tools during the three years of developing and implementing the software will be provided.

**Budget justification**

We have used current information and/or actual experience plus inflation rates of 5% for salaries and 3% for other expenses as appropriate. We have assumed a start date of October 1, 2003 in calculating indirect costs and fringe benefits. We have requested funds for a half time graduate student in the last year of the proposal at Ohio State University. We have requested funds for part time undergraduate students for the second and third years of the proposal at Ohio State University.

The computer related items are required to carry out the collaborative development program and consist primarily of desktop video conferencing tools. Required database software, and software management tools for the collaborative development of the data acquisition software are also included.

Travel funds for Ohio State University are requested to cover the cost of attending needed meetings among the collaborators to carry out the proposed program.

**Three-year budget, in then-year K$**

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(1) Includes 26% of first $25K subcontract costs
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**References**


[3] The TESLA Test Facility  
   [http://tesla.desy.de/](http://tesla.desy.de/)

   [http://tesla.desy.de/doocs/doocs.html](http://tesla.desy.de/doocs/doocs.html)

   [http://root.cern.ch](http://root.cern.ch)
2.15. Investigation of acoustic localization of rf cavity breakdown
(LCRD)

Accelerator Physics

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email: g-gollin@uiuc.edu
phone: (217) 333-4451

Illinois
SLAC

Year 1: $34,882
Year 2: $34,882
Year 3: $34,882
**Project name**

Investigation of acoustic localization of rf cavity breakdown (LCRD 2.15)

**Classification (accelerator/detector:subsystem)**

Accelerator

**Institution(s) and personnel**

University of Illinois at Urbana-Champaign, Department of Physics:
George D. Gollin (professor); Michael J. Haney (electrical engineer); Joseph Calvey, Michael Davidsaver, Justin Phillips (undergraduates).

University of Illinois at Urbana-Champaign, Department of Electrical and Computer Engineering:
William D. O’Brien (professor)

Stanford Linear Accelerator Center:
Marc Ross (staff scientist)

**Contact person**

George Gollin
g-gollin@uiuc.edu
(217) 333-4451

**Project Overview**

Electrical breakdown in warm accelerating structures produces electromagnetic and acoustic signals that may be used to localize (in a non-invasive fashion) the breakdown site inside a cavity. Other indications of breakdown (microwave, X-ray, and dark current measurements) have proven insufficient to elucidate the basic physics of cavity breakdown. During tests of the NLC design it will be important to record information describing electrical breakdown in order to understand why cavities break down, and how cavity design and operating conditions influence accelerator reliability.

The goal of this project is to understand the acoustic properties of heat-treated copper in order to relate the acoustic signatures of breakdown events to the underlying minor electromagnetic catastrophes taking place inside the accelerating structures. A wildly optimistic (and unlikely) outcome would be to develop a technique allowing derivation of an invertible acoustic Green's function for an individual copper structure. This Green's function could be used to predict the signals arriving at various sensors as functions of the acoustic excitation caused by a cavity breaking down. The inverse function, provided with data from a sufficiently large number of sensors, would yield information about the discharge. A more realistic outcome will be to determine how well acoustic information can be used to localize and classify different breakdown modes in NLC cavities.
Our first year of investigation has concentrated on building software tools and developing a small amount of laboratory infrastructure so that we can begin learning about the problems we are confronting. Since these effects are well described by classical mechanics, the research has proved ideal for participation by undergraduates. The students have been remarkably productive and insightful, and are continuing their involvement.

**Results of First Year Activities**

Since NLC structures are held at high temperature when they are assembled by brazing, the copper's grain size grows so that sound waves must propagate through a crystalline medium with irregularly shaped grains a few millimeters in size which are oriented randomly. The speed of sound in copper is about five millimeters per microsecond, so acoustic waves with frequencies in the MHz range (whose wavelengths are comparable to the grain size) are disrupted by scattering as they propagate.

In our first year of efforts we have been working with two sets of copper dowels on loan from the Fermilab NLC structure factory. The copper stock is from a shipment of material used to construct actual NLC test structures; one set of dowels has been heat-annealed to bring up its grain size, while the other has not and, consequently, has microscopic grains.

We have borrowed several 1.8MHz transducers (and associated signal conditioning electronics) from Bill O'Brien's lab as well as recently purchasing a pair of 500 kHz Panametrics transducers ourselves. A schematic diagram of our copper/transducer setup is shown in Figure 1. A variety of measurements for dowels of different lengths (including speed of sound, attenuation length, and beam spread) provide us with a nice set of experimental inputs with which to confront our acoustic models.

We have been developing a pair of models for the propagation and detection of acoustic waves in copper. Both describe copper as a (possibly irregular) grid of mass points connected by springs. We can vary the individual spring constants and the arrangement of interconnections to introduce irregularities representing grains into our simulated copper. The models may seem naïve, but they are able to support a variety of complex phenomena and it is a simple matter to tune various physical properties (such as the speeds of sound for compression- and shear-acoustic waves) through adjustments of the models' parameters.
Figure 1. Copper/transducer laboratory setup. We can listen for echoes returning to the transducer which fires pings into the copper, or listen to the signal received by a second transducer, or the sum of signals from the two transducers.

One of the models uses MatLab as a computational engine, generating an analytic solution to the coupled equations describing the forces acting on each mass point. The other, written by two of the students, performs a fourth-order Runge-Kutta numerical integration to compute the response of mass points to acoustic perturbations. We have found it invaluable to be able to compare the detailed predictions of the models in order to verify their accuracy: scattering off grains produces very complicated effects and it is important to confirm that our calculations are accurate. Our numerical integration model is able to handle considerably larger systems than is possible with MatLab. However, when applied to smaller systems (with a few hundred mass points), both models agree to an accuracy consistent with integration step size and machine precision.

Most of our model systems have been two dimensional grids of roughly $10^5$ points. We "drive" signals into them using a transducer model in which the piezoelectric device is described as a damped oscillator excited by shocks of short duration. Because of reflections at the ends of the cable used to drive the real transducers, the actual drive signal is complicated; we find we can model it adequately as a series of four closely-spaced impulses. Figure 2 shows a comparison of our simulation and measurements of the transducer signal for a pair of echoes in a copper dowel. We have used the first echo to guide our selection of drive parameters; the shape of the second echo is well-reproduced.
Propagation of a simulated acoustic wave in a homogeneous 250×650 point grid is shown in Figure 3a. The lateral spread of the pulse is a consequence of the relatively small number of mass points receiving the initial excitation.
We can simulate the transducer signal as a function of time by summing the amplitudes at the "face" of a transducer as it experiences the effects of the acoustic pulse. Results, shown in comparison with a real oscilloscope record of transducer signal vs. time are shown in Figure 3b. They are promising but need a considerable amount of refinement.

![Simulated transducer response to an acoustic pulse propagating in a homogeneous 250×650 point grid. The transducer is at the downstream edge of the array.](image)

Figure 3b. Simulated transducer response to an acoustic pulse propagating in a homogeneous 250×650 point grid. The transducer is at the downstream edge of the array.

The effect of inhomogeneities on an acoustic wave is dramatic, as can be seen in Figure 4, below. Spring constants in the parallelogram-shaped region are half as large as those used elsewhere in the grid. The disruption suffered by the pulse dumps a significant amount of acoustic energy into the "bulk" of the copper. The version of the simulation shown in the figure does not include any damping. Even so, the echo returning to the transducer is badly disrupted.

Notice the acoustic "glow" which washes over the transducer site due to scattering off the discontinuities in material properties evident in Figure 4. We see this sort of effect in the (real) heat-treated dowels when driving them with our 1.8 MHz transducers, as can be seen in Figure 5, below. Once our models are able to simulate copper with many grains it will be interesting to compare the glow predicted by our model with that seen in data.
Figure 4. Propagation of an acoustic wave through an asymmetry in a two-dimensional grid. Spring constants inside the region indicated by the parallelogram are half as large as they are outside the parallelogram.

Simulated signal in the transducer (which generates the initial pulse and then measures subsequent acoustic activity) is shown in the small graph below.
The amplitude of an acoustic pulse decreases because of attenuation as well as scattering of energy out of the pulse. Not surprisingly, a pulse bouncing back and forth in a heat-treated (grainy) dowel dies out more rapidly than does a pulse traveling in a dowel which hasn't been heat-treated. This is evident in Figure 6, which shows a comparison of the sizes of the first and second echoes for pulses traveling in short (2.5 cm length) copper dowels.

Figure 6. Pulses associated with the first and second echoes in short (2.5 cm) copper dowels. Note the relative sizes of the first and second echoes in each dowel; more energy is scattered out of the pulse traveling in the heat-annealed (grainy) copper. Horizontal and vertical scales are 2 µsec and 500 mV per division respectively.
We will continue to refine our models. For the time being it is productive to continue with two-dimensional models, though our numerical integration model is quite capable (at the expense of longer execution time!) of simulating materials in three dimensions. We are presently constructing software tools to allow us to insert multiple grains into our grid and beginning to learn how to interpret comparisons of data and simulations.

**Proposed Activities for a Three Year Program**

We would like to stress three points:

- Active participants in LCRD 2.15 are constrained by the academic calendar: Gollin teaches (although he will be relieved of teaching duties during the Spring and Fall 2004 terms in order to focus on Linear Collider work), while Calvey, Davidsaver, and Phillips are undergraduates with full course loads. Most of our progress occurs during the summer.
- Calvey and Davidsaver will graduate in 2006, while Phillips will graduate in 2005. They have all expressed a great deal of interest in continuing on LCRD 2.15, and will be even more productive than they were last summer.
- The proposed work is somewhat speculative: we don't yet know if the grain structure (which differs from structure to structure, naturally) will force us to work with lower frequency transducers. The resolution that can be obtained is not a simple function of the wavelength of the working frequency since the time-development of a pulse can be measured with great precision. There is information to be gleaned from the time structure of a pulse, not just from its integrated intensity.

It is sensible to propose increasing the density of instrumentation on our copper elements while improving our models. We will need to acquire more transducers, signal conditioning electronics, and digitizers to do this properly. As our ability to relate simulations and observations in simple geometries matures, we will machine the dowels into more complicated shapes and begin working with a nine-element section of NLC accelerating structure sent to us by Mark Ross.

The Runge-Kutta integration modeling tool presently runs on a fast PC. The University of Illinois HEP group computing infrastructure includes a large number of Linux workstations used to run production analyses for CDF, CLEO, and FOCUS; we will investigate porting the PC instantiation of the code (which is written in C++) to the Linux cluster. In addition, UIUC is the home to the National Center for Supercomputing Applications. NCSA is a terrific resource and is generally supportive of proposals for collaboration and access to supercomputer time. When our computing needs make it appropriate, we can begin discussing a joint effort with them.

We have had discussions with Mark Ross and Frédéric Le Pimpec at SLAC concerning our results; the UIUC approach complements work being done at SLAC nicely and we would hope to collaborate with them more closely than has been the case to date.

Our budget is simple, consisting primarily of salaries for three undergraduate students, the costs of additional instrumentation, and a small amount of travel money.

**UIUC Budget for LCRD 2.15**

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2.17. RF Cavity Diagnostics and Acoustic Emission Tests
(LCRD)

Accelerator Physics

Contact person: Lucien Cremaldi
email: cremaldi@phy.olemiss.edu
phone: (662) 915-5311

Mississippi

Year 1: $20,840
Year 2: $21,780
Year 3: $28,780
I. PROPOSAL

A number of groups [1,2,3] have now shown that HV breakdown in RF cavities and accelerator structures are accompanied by high frequency acoustic emissions (AE). Piezoelectric transducers are well suited to detecting the onset and breakdown at frequencies 500 kHz < f < 5MHz. Where background noise is filtered.

SLAC [1] has shown that by mounting a large number of sensors in the 2 MHz band some degree of breakdown localization (imaging) is possible. Golin [2] at U. of I. is performing materials tests and imaging as well.

(1) We propose to complement these tests by mounting 2MHz sensors on the RF cavity structures in Lab G at Fermilab. These are large 805 MHz cavities, parts of which were fabricated in Mississippi. The first sensors will be attached to 100KHz sampling electronics used for slow monitoring systems in Lab G. This data will be analyzed and correlated to cavity breakdown events. Some preconditioning /driver electronics may be necessary and under investigation.

AE data is typically recorded by systems designed to classifying the source of emission data, creep, shock, etc. . These systems can run in the $15K range and can provide a significant advantage to the inexperienced user. We will need to investigate such systems in the future and decide if there are advantages seen in our HEP applications.

(2) In anticipation of using 1000’s of sensors in true accelerator structure monitoring, the reliability of the piezo sensors can be questions. Radiation damage to the piezo-ceramic should be studied, as well as materials (epoxy-resins) used in assembly of the sensors. We would like to stress test sensors under different conditions of radiation, temperature cycling, humidity, etc. One would expect degradation in frequency response.

We want to set up a test stand which can record the frequency response between 20KHz and 30MHz using either an external frequency analyzer or PC-based system. Such a circuit may be used in situ to test degradation in real time by interrogating sensors with driver pulses and looking for readback distortion.

(3) Finally we would like to investigate the wireless transmission of data from the accelerator structures to base. The challenge here is to understand the protocol for transferring the monitor data in a safe and reliable way. Transfer rate may be an issue. A commodity wireless system would be set up in Lab G for this purpose in due time.
II. ACOUSTIC SENSOR MONITORING PROGRAM

<table>
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<th>FY03</th>
<th>FY04</th>
<th>FY05</th>
<th>FY06</th>
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<tr>
<td>Determine signal conditioning specs (sensor type, conditioning)</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Work with sensors on table top experiments</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wire AE sensors in to Lab G facility</td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
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<tr>
<td>Set up AE sensor frequency characterization system</td>
<td>x</td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Wireless implementation</td>
<td></td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Investigate Professional AE systems</td>
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<td>x</td>
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III. 3-YEAR BUDGET

<table>
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<tr>
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<th>FY05</th>
<th>FY06</th>
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</thead>
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<td>1000</td>
<td>5000</td>
</tr>
<tr>
<td>C. T-H Cycling Oven</td>
<td>2500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D. Frequency Characterization Sys</td>
<td>5000</td>
<td>5000</td>
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<td>E. AE Professional Sys</td>
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<td>F. Wireless Readback</td>
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<td></td>
<td>5000</td>
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<td>G. Materials&amp;Supplies</td>
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<td>2000</td>
</tr>
<tr>
<td>H. Wages (Student or Technician)</td>
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<td>6000</td>
<td>6000</td>
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<tr>
<td>I. 3% on H.</td>
<td>180</td>
<td>180</td>
<td>180</td>
</tr>
<tr>
<td>J. 44% IndirectCosts on G-I</td>
<td>3160</td>
<td>3600</td>
<td>3600</td>
</tr>
<tr>
<td>TOTAL</td>
<td>20840</td>
<td>21780</td>
<td>28780</td>
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</table>

IV. INFRASTRUCTURE

The National Center for Physical Acoustics (NCPA) is located on Campus with physics department faculty available for consultation. Condensed matter physicist Igor Ostrovskii, listed on this proposal, is an expert in acoustic, ultrasonics and surface physics. He is very familiar with AE monitoring techniques at reactors and facilities in the former Soviet Union. Our HEP group has experience with fabrication of RF cavities and surface smoothness issues. We have have wireless communications experts at the NCPA who routinely transfer data in the field to base stations for analysis.

V. REFERENCES

VI. PROGRESS REPORT

- A number of tabletop AE tests were performed in Fall 02 with existing equipment.

- This work was summarized at the Dallas workshop in a presentation by L. Cremaldi. http://www.phy.olemiss.edu/~cremaldi/NLC/

- No expectation of funding in Spring 03. No summer students secured for summer work.

- A proposal was submitted to the DOE in June 03 receiving adequate program funding.

- Funds were secured in August 03 after summer break.

- Nothing new to report at the Cornell Meeting.

- 5MHz Acoustic sensors obtained from International Transducer Corp., Santa Barbara CA, in September 03. Are identical to those used in SLAC tests.

- Plans made to install sensors in Lab G in November 2003, welcomed.

- Some bench testing of 5MHz sensors performed in Mississippi in preparation of Lab G installation. Work in progress.
2.18. Control of Beam Loss in High-Repetition Rate High-Power PPM Klystrons (LCRD)

Accelerator Physics

Contact person: Mark Hess
email: mhess@psfc.mit.edu
phone: (617) 253-8454

MIT
Mission Research Corp

Year 1: $60,000
Year 2: $60,000
Year 3: $0
Project name

Control of Beam Loss in High-Repetition Rate High-Power PPM Klystrons

Classification (accelerator/detector: subsystem)

Accelerator

Institution(s) and personnel

Massachusetts Institute of Technology, Plasma Science and Fusion Center
Chiping Chen (Principal Research Scientist) and Mark Hess (Postdoctoral Associate)

Mission Research Corporation
David Smithe, Lars Ludeking

Contact persons

Chiping Chen  Mark Hess  
chen@psfc.mit.edu  mhess@mit.edu  
617 253-8506  (617) 253-8454

Project overview

A major thrust in the Linear Collider (LC) program is the development of high-power X-band periodic permanent magnet (PPM) focusing klystrons. The required specifications are: 75 MW power output, 3 µs pulse length, 120 Hz repetition rate, and 100,000 hour lifetime. After nearly a decade of intense research and development at SLAC, KEK and elsewhere, the SLAC group achieved, in June 2003, the operation of a 75 MW XP-3 klystron with a pulse length of 1.6 µs and a repetition rate of 120 Hz [1].

Earlier PPM focusing klystrons had problems of various sorts because they were designed to operate either close to or above the threshold for bunched beam confinement. The threshold, which we derived recently using a point-charge, center-of-mass model, did not exist when these PPM klystrons were designed. In terms of the normalized current, the threshold is given by [2]

\[
\left(\frac{8e^2 I_b}{\omega_{c,rms} a^2 I_A}\right)_{cr} = \frac{\alpha}{\pi}
\]

where \( I_b \) is the beam current, \( \omega_{c,rms} = eB_{rms}/m_e c \), \( a \) is the beam tunnel radius, \( \alpha = 2\pi f / \gamma_b \beta_b c \), \( f \) is the operating frequency, \( I_A = \gamma_b \beta_b m_e c^3 / e \equiv \gamma_b \beta_b \times 17 \) kA is the electron Alfven current, \( \gamma_b = (1 - \beta_b^2)^{-1/2} \) is the relativistic mass factor of the electron beam, \( B_{rms} \) is the rms value of the PPM focusing field, \( c \) is the speed of light in vacuum, and \(-e\) and \( m_e \) are the electron charge and rest mass, respectively. Under the current LCRD funding, we have made improvements on the threshold in Eq. (1) by taking into account the effect of finite bunch size, which will summarized in detail in the next section.
Figure 1 Plot of the normalized current vs. the parameter $\alpha$ for five PPM focusing klystrons developed in the past decade for the LC program. The solid line corresponds to the threshold for bunched beam confinement given in Eq. (1). Detailed parameters and performances of the klystrons are listed in Table 1.

Table 1 Parameters and performances of five PPM klystrons developed for LCs

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>50 MW XL-PPM (SLAC)</th>
<th>75 MW XP-1 (SLAC)</th>
<th>75 MW XP-3 (2003 SLAC)</th>
<th>50 MW (Toshiba/KEK)</th>
<th>75 MW PPM-1 (BINP/KEK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f$ (GHz)</td>
<td>11.4</td>
<td>11.4</td>
<td>11.4</td>
<td>5.7</td>
<td>11.4</td>
</tr>
<tr>
<td>$I_b$ (A)</td>
<td>190</td>
<td>257</td>
<td>260</td>
<td>317</td>
<td>266</td>
</tr>
<tr>
<td>$\gamma_0$</td>
<td>1.83</td>
<td>1.96</td>
<td>2.00</td>
<td>1.69</td>
<td>1.94</td>
</tr>
<tr>
<td>$B_{cm}$ (T)</td>
<td>0.20</td>
<td>0.16</td>
<td>0.21</td>
<td>0.14</td>
<td>0.17</td>
</tr>
<tr>
<td>$a$ (cm)</td>
<td>0.48</td>
<td>0.54</td>
<td>0.54</td>
<td>0.90</td>
<td>0.55</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.75</td>
<td>0.77</td>
<td>0.74</td>
<td>0.79</td>
<td>0.79</td>
</tr>
<tr>
<td>$\frac{8e^2 I_b}{\omega_{cm} a^2 I_{\rm exp}}$</td>
<td>0.19</td>
<td>0.28</td>
<td>0.16</td>
<td>0.20</td>
<td>0.25</td>
</tr>
<tr>
<td>$\frac{8e^2 I_b}{\omega_{cm} a^2 I_{\rm obs}}$</td>
<td>0.238</td>
<td>0.244</td>
<td>0.234</td>
<td>0.251</td>
<td>0.251</td>
</tr>
<tr>
<td>Beam Power Loss</td>
<td>0.8%</td>
<td>significant but not measured</td>
<td>~1.0%</td>
<td>small but not measured</td>
<td>30%</td>
</tr>
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</table>
One reason for the SLAC group’s ability to achieve the breakthrough results in the XP-3 klystron may be attributed to the increases in both the radius of the beam tunnel and the strength of the PPM focusing field, allowing the device to be operating below the threshold (see Fig. 1 and Table 1).

Also included in Fig. 1 and Table 1 are four earlier PPM klystrons developed in the LC program. Three of the PPM klystrons operated at 11.4 GHz namely, the SLAC 50 MW XL-PPM [3,4] and 75 MW XP-1 [3,4], and the BINP/KEK 75 MW PPM-1 [5]. The other was the Toshiba/KEK 5.7 GHz 50 MW (C-Band) klystron [6].

Despite these experimental and theoretical advances, the lifetime and rf pulse length of high-power, high-rep rate klystrons remain an important, urgent issue in the near term for LC klystron R&D. Without reliable rf sources, other components and structures in the NLC cannot be tested experimentally. In general, the klystron lifetime decreases with increasing beam intensity. High beam intensity implies high cathode loading and high space-charge, which could cause cathode failure and beam halo production (or loss of electrons to the rf circuit), respectively. Loss of electrons, via halo production, must be controlled to order to avoid structural damage.

LC klystrons employ intense relativistic electron beams and bunch them to generate rf power. Because the beams are space-charge-dominated, a large rms-mismatch is induced as the beam undergoes a transition from an unbunched state to a highly bunched state, as shown in our earlier 2D simulation studies of the SLAC 11.4 GHz, 50 MW PPM focusing klystron [7,8]. The results of those studies were in qualitative agreement with the experimental observation of 0.8% beam power loss (or 4% electron loss) to the rf structure. At a higher average power, this level of beam loss could have a more pronounced effect on the lifetime.

This two-year research proposal requests funds to expedite the theoretical and computational research to improve our understanding of the mechanism and control of beam loss in LC klystrons. In particular, we will focus on the following tasks areas:

1. Complete the current investigation of the effects of finite-size and energy spread on the theoretical threshold for bunched beam confinement;
2. Study the characteristics of halo formation in LC PPM focusing klystrons;
3. Explore methods to control halo formation and beam loss in LC PPM focusing klystrons;
4. Continue our close consultation and close collaboration with the SLAC Klystron Department.

Current research progress

We have made significant progress on our understanding of beam loss in PPM klystrons since our LCRD proposal (FY 2003) was selected for funding. Our accomplishments have been two-fold. First, we have developed a more realistic bunched beam confinement model compared to the original model [2] by including in the effect of finite size beam bunches [9]. Secondly, we have started our numerical simulations of klystron beams using the MAGIC particle-in-cell code.

The new finite-size bunch model assumes that the electron bunches are periodic and slightly displaced from the axis of the beam tunnel, but may be composed of arbitrary radial and longitudinal distributions relative to the axis of the electron bunches. We have derived a beam confinement criterion within this model by calculating the center-of-mass
Fig. 2 Plot of (a) normalized current threshold vs. $\alpha$ for the point-charge and finite size bunches, and (b) a close-up of (a) together with the operating points of the five PPM klystrons listed in Table 1.

force on each bunch and applying a Hamiltonian analysis on the bunch’s motion in a similar fashion as in Ref. 2.

Figure 2(a) shows a comparison of the maximum value on the normalized current $8c^2I_b / \omega_{c,rm}^2 a^2 I_A$ versus $\alpha = 2\pi a \beta / \gamma_b c$ for three different distributions: the original point-charge model and two distributions which are uniform within a characteristic beam radius of $r_b/a = 0.5$ in the radial direction, and have Gaussian profiles in the longitudinal direction with rms spreads corresponding to 0 and 60 degrees with respect to the rf phase at 11.4 GHz, respectively. Also shown in Fig. 2(a) is the well-known Brillouin density limit for unbunched beams, i.e. $8c^2I_b / \omega_{c,rm}^2 a^2 I_A = 1.0$. By comparing the point-charge model with the one corresponding to the zero degree of bunching, we find qualitatively that an increase in radial bunch size lowers the threshold. However, by comparing two Gaussian bunch limits, we find that an increase in the longitudinal bunch size yields a higher threshold.

Figure 2(b) shows a magnification of the Fig. 2(a) but includes the operating points of the five PPM klystrons in Table 1. Based on the results of the MAGIC2D simulations, as well as klystron design considerations, we estimate that a typical PPM focusing klystron will have approximately 60 degrees of bunching. We find from Fig. 2(b) that the SLAC 75 MW XP-1 klystron is above the 60-degree threshold with $r_b/a = 0.5$, while all other klystrons are below. We should note here that these results are still preliminary since the uniform radial distribution function is only an approximation.

Proposed research

We now summarize in detail the proposed research outlined at the end of the Project overview section.

1. Investigation of the effects of finite-size and energy spread on the theoretical threshold for bunched beam confinement - The MIT group (Hess and Chen) will continue to improve the beam confinement criterion by including the effects of the self-consistent coupling between the 3D beam envelope oscillations and the beam centroid (center-of-mass) motion. The beam centroid and rms envelopes, which correspond to the
first- and second-order moments in the kinetic description of the beam, are coupled through the image charges induced on the beam tunnel. Once the coupled equations describing the rms beam envelope oscillations and the beam centroid motion are derived, we will carry out a normal mode analysis to determine the stability of the coupling, which will lead to an improved criterion for bunched beam confinement.

We will also include the energy spread, realistic magnetic field profile, and transverse rf fields in the proposed analytic studies.

We will compare results of analytic studies with self-consistent three-dimensional simulations using the Mission Research Corporation (MRC) MAGIC3D code simulations and the MIT Three-Dimensional Periodically Focused Beam (PFB3D) code [10]. MRC (Smithe and Ludeking) will continue to assist us in the MAGIC 3D simulations of PPM klystron tubes.

2. Study of the characteristics of halo formation in LC PPM focusing klystrons – We will use three methods to study the characteristics of halo formation. Among the halo characteristics, the most important ones are the maximum halo size, the rate of electron loss via halo formation, and their dependence on the system parameters. One method is to use a 3D particle-core model which would be naturally built upon the proposed analytic studies of the beam centroid and the rms beam envelope oscillations. The 3D particle-core model will give us the lowest-order estimates of the halo characteristics. The second and third methods will be the MAGIC3D and PFB3D simulations, respectively. Because the PFB3D code uses the Green’s function techniques, it may provide a higher resolution than the particle-in-cell MAGIC3D code. We will compare results obtained with the three methods.

3. Control of halo formation and beam loss in LC PPM focusing klystrons – Once the halo characteristics are determined, we will explore how to control halo formation and beam loss in LC PPM focusing klystrons. While there may always be some degree of beam halo present, the key in controlling beam loss in klystrons is to minimize halo production, so that the amount of beam loss can be kept well below a tolerable level. In this regard, the parameter dependence of the halo characteristics will be extremely useful in order to accomplish this task.

For example, it was found in our earlier 2D (PFB2D) simulations that a slight non-zero magnetic field at the cathode results in a delay in halo production as the electron beam propagates through the system [8]. Such a delay may be used as an effective technique to minimize beam loss at the rf structure.

4. Continue our close consultation and close collaboration with the SLAC Klystron Department – The SLAC Klystron Department (Caryotakis) [11] agreed to provide us with design specifications and experimental data on their latest klystrons when we submitted the first proposal. Recently, Dr. Daryl Sprehn of SLAC provided us with the detailed design and testing results on the XP-3 klystron, which contributed to the results shown in Fig. 1 and Table 1 [12]. SLAC is also designing a new PPM klystron with a weaker PPM focusing field. Their expertise in the construction and design of PPM klystrons, as well as, their data from klystron testing will continue to be extremely valuable in guiding our research. We will also request the latest klystron design data and test results from the KEK group for further comparison and evaluation.
Budget

<table>
<thead>
<tr>
<th>Institution</th>
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<td>MIT</td>
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<tr>
<td>MRC</td>
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References

2.20. Research in Superconducting Radiofrequency Systems (UCLC)

Accelerator Physics

Contact person: H. Padamsee
email: hsp3@cornell.edu
phone: (607) 255-5727

Cornell

Year 1: $9,740
Year 2: $22,380
Year 3: $272,280
4.2 Research in Superconducting Radiofrequency Systems

Personnel and Institution(s) requesting funding

H. Padamsee, M. Tigner, R. Geng, V. Shemelin, M. Liepe, Laboratory of Elementary Particle Physics, Cornell University

Project Leader

H. Padamsee
hsp3@cornell.edu
(607) 255-5727

Project Overview

Rapid advances in superconducting cavity performance have made RF superconductivity an important technology for a variety of accelerators, fulfilling the needs for high energy physics, nuclear physics, radioactive beams for nuclear astrophysics, intense proton accelerators for neutron spallation sources, muon acceleration for future neutrino factories and muon colliders, storage ring light sources, free electron lasers, fourth generation x-ray free electron lasers, and energy recovery linacs. Improved understanding of gradient-limiting mechanisms, together with technology advances, are responsible for the steady increases in performance [1]. Gradients of 25 MV/m at Q values of $10^{10}$ are now regularly achieved in one-meter long superconducting structures suitable for TESLA (TeV Energy Superconducting Linear Accelerator). To reach such gradients, high-purity, high thermal-conductivity niobium is used to prevent thermal breakdown of superconductivity, while high pressure rinsing and clean room assembly techniques are used to reduce field emission and voltage breakdown. LEPP research has played a major role in pushing cavity performance to these levels [2].

The goal of our future R&D program will be to push gradients towards the theoretical limit (50 MV/m), which is another factor of two higher than achieved levels. Advances in understanding gradient and quality factor (Q) limitations, together with progress in gradients will benefit the goals of TESLA and its upgrades to higher energies and luminosities. We also plan to explore improved cavity designs that lower surface fields thereby raising the maximum possible accelerating gradient. Preliminary explorations suggest designs that offer a 20% improvement, raising the theoretical accelerating field limit for superconducting structures to 60 MV/m.

We are also developing new techniques for cavity fabrication and treatment to lower production costs for 20,000 cavities needed for a 500 GeV CM linear collider. If such procedures are successful with smaller cavities, we aim to combine the less expensive fabrication and processing techniques with the improved designed and build multi-cell structures. Here we will need the help of industry.

The sophisticated techniques associated with fabricating, treating and testing superconducting niobium cavities now resides primarily in European industries. Having a US industry learn these high tech procedures would greatly improve the choices for US contributions to the linear collider. During the third year of the proposal we will transfer the high level of technology associated with fabrication, surface preparation and cryogenic testing of superconducting structures to one or more US firms while fabricating, treating and testing full scale structures with improved design and methods.

We assume that the on-going R&D under our regular NSF contract will continue to be funded at the levels we have requested in our five-year NSF proposal, 020278, also referred to as the Blue Book, CESRP 01-1. Much of the work described in the first two years will be carried out by graduate
students doing doctoral work. Funds are requested for equipment, materials, supplies and surface analysis work. Support for graduate students is paid for by our regular NSF contract.

**Basic studies of the sources of high field Q-slope and quench field in Nb cavities**

Two mechanism operate to reduce the Q of a superconducting cavity at accelerating fields above 20 MV/m. One is field emitted electrons from particulate contaminants in the high electric field regions of the cavity. This phenomenon is quite well understood and methods to control emission are in hand. High pressure water rinsing (at 100 bar) eliminates field emission by eliminating micron and sub-micron particles. The high power available for the beam can also be used to burn up any residual emitters that accidentally enter structures during the final stages of assembly. The other important field limitation is a phenomenon called the “high field Q-slope” [3]. In very clean cavities that show little or no field emission, there persists a steady decline in $Q_0$ above 20 MV/m, followed by a quench between 20 and 30 MV/m. Absence of x-rays corroborates absence of field emission. Temperature maps reveal that power dissipation occurs over high magnetic field regions of the cavity. Yet the losses are not uniform. Collaborative work at several laboratories shows that electropolishing, instead of the standard chemical etching procedure, substantially reduces the Q-slope and increases the quench field. Another cavity treatment (baking at 100°C for 48 hours) further improves the high field Q-slope of electropolished cavities, and raises the quench field substantially. Baking also has a slight beneficial effect on the Q-slope of chemically etched cavities, but no significant effect on the quench field. As a result of these new procedures accelerating fields of 35 MV/m are now realized in TESLA 9-cell structures as needed for the 800 GeV to one TeV upgrade.

An understanding of the Q-slope mechanism will point the way to treatments that can lead to even higher performance. There has been some recent theoretical progress as well as new models proposed for explaining why electropolishing and baking help to reduce the Q-slope. One mechanism is magnetic field enhancement at grain boundaries[4]. Surfaces prepared by buffered chemical etching tend to develop grain boundary steps and sharp grain boundary edges due to differential etch rates for different grains. Electropolishing eliminates steps due to higher etch rates at sharp features. A model for the benefits of baking involves the redistribution of oxygen in the rf layer[5].

Much experimental and simulation work remains to validate these explanations or to eliminate them. We plan to use our state-of-the-art thermometry system to identify hot regions responsible for the Q-slope, and premature quenches [6]. These studies will be carried on single cell cavities with surfaces prepared by a variety of methods, such as chemical etching, electropolishing, baking, and anodizing (electrolytic oxidation). After identifying lossy regions we will dissect the cavity and study the spots with surface sensitive techniques such as Auger, SIMS (secondary ion mass spectrometry), and XPS (x-ray photoelectron spectroscopy). Auger and SIMS will give surface sensitive elemental information, while XPS will help sort out differences in surface oxides. Use of other surface techniques may be warranted.

Graduate students will carry these studies. Students will also prepare niobium samples by the same techniques and carry out parallel measurements with surface analytic instruments.

**Improved Geometries, Fabrication and Preparation** Another way to tackle the high field Q-slope is to modify the cavity design to reduce the ratio of the peak magnetic field to the accelerating field. Although field emission is present in some cases, it does not present a brick wall limit because techniques exist to control it. This means that the peak surface electric field is less important than the peak surface magnetic field.
Preliminary studies using cavity design codes show that introducing re-entrant shapes offers the possibility of lowering the surface magnetic field by at least 10%, if we allow the surface electric field to rise by 20%. Since the cell-to-cell coupling factor of the re-entrant geometry is also higher, it is possible to reduce the aperture to make further reduction in the surface magnetic field. We expect to continue such optimization studies during the first year to determine the best cell length, aperture and higher order mode propagation properties.

The re-entrant shape leads to some technological complications for cavity fabrication, surface preparation and cleaning, which we intend to address at the single cell level during the second year.

Today, 9-cell TESLA cavities which are purified with Titanium at 1350°C and electropolished reach accelerating fields of 35 MV/m. High temperature treatment for purification of 9-cell structures calls for large and expensive UHV furnaces. Heat treatment is also a lengthy process, since the furnace cycle takes three days. Diffusion of titanium into the bulk demands removal of more than 100 µm of the surface, another time-consuming operation.

To reduce large scale production costs, we aim to explore heat treatment at the half-cell stage. Stacking cups interleaved with titanium foils can improve the packing fraction in a furnace by at least a factor of two, thereby reducing the investment in infrastructure and processing time. Preliminary tests show that optimization of the time/temperature cycle during heat treatment can also lower the diffusion length of the titanium from 100 µm to about 20 µm, yielding a substantial reduction in chemical processing time.

The present method of electropolishing involves a large and expensive facility that must rotate a cavity full of acids and carefully exhaust the hydrogen produced at the counter electrode. Hydrogen dissolved in the bulk niobium precipitates as normal conducting islands of niobium-hydride on cool down. If so contaminated, an electropolished cavity must be heated at 750°C for several hours to drive out the dissolved gas. Half-cell electropolishing is simpler, more open and poses less danger of hydrogen contamination.

In order for these proposed economical methods to succeed it is necessary to devise an electron beam welding procedure that produces an excellent final weld which requires very little post etching. The final weld operation must not contaminate the cavity surface. Preliminary welding studies show that both these conditions can be met.

During the first and second years, we plan to make several single cell cavities with the improved (re-entrant) shapes and prove out novel half-cell purification, electropolishing and final welding procedures.

**Transferring superconducting rf technology to US industries** During the 3rd year, the Cornell SRF group will work closely with US industries to build several multi-cell niobium structures of the advanced geometry with the more economical production and preparation methods. This will be an essential step for industry to develop large scale industrial process for 20,000 cavities. Cornell Research Associates, technicians and graduate students will collaborate with industrial personnel using Cornell facilities described below. As a result, industries will learn the special techniques involved in deep drawing, half-cell purification, half-cell electropolishing, electron beam welding, and final chemical etching. We plan to take the industries through the special procedures of high pressure rinsing and cold testing 9-cell cavities to TESLA gradients of 25 MV/m and above. By using Cornell infra-structure, industries would not have to make the large up-front investment in facilities. Manpower support for Cornell personnel will be paid for out of our regular NSF contract. We anticipate that industrial firms would expect Cornell to cover part of the costs of training time for industrial personnel as contracts.
SRF Infrastructure. Newman Laboratory at Cornell has extensive infrastructure for research and development in RF superconductivity as well as for production, preparation, and testing of superconducting cavities. These facilities have been used to build the prototype SRF cavities for CEBAF and TESLA, as well as all the cavities that power the present storage ring at Wilson Laboratory (CESR). Cavity production facilities include a 100 ton press for deep drawing niobium cavity cells, digital control milling machines for precise die machining, an electron beam welder large enough for TESLA scale cavities, and a large UHV furnace to purify cavity half cells at 1300 C. Cleaning facilities include open and closed cavity etching systems that can handle TESLA type cavities, high purity water rinsing systems, and high pressure (100 atmospheres) water rinsing. There is a new 1100 sq ft Class 100 clean room for cavity assembly and a smaller Class 100 area for preparing smaller test cavities. There are several portable clean room set ups for critical assembly. Test setups include three radiation shielded pits, two of which can accommodate 1300 MHz cavities. We have several cryostats, and cryostat inserts to test cavities from 200 MHz to 3000 MHz, several 200 Watt CW power sources and a 1.5 MW pulsed klystron for high pulsed power processing 1300 MHz cavities. High power testing capabilities exist for windows at 500 MHz and HOM loads at 2450 MHz. Research facilities include a rapid thermometry system for studying single cell 1500 MHz cavities, field emission apparatus, and dedicated scanning electron microscope with energy dispersive analysis for element identification installed in a class 1000 clean room. An Auger System with SIMS Analysis capabilities augments our surface analysis capabilities.

FY2004 Project Activities and Deliverables
Studies of the sources of high field Q-slope and quench field in Nb cavities: This work will span the entire three year proposal period. As gradients in superconducting cavities continue to rise toward the theoretical upper limit, we expect new loss mechanisms to arise that will need investigation.

Improved Geometries, Fabrication and Preparation: The first year's deliverables will be progress reports and papers to conferences and journals on studies to optimize the shape of cavities.

FY2004 Project Activities and Deliverables
Studies of the sources of high field Q-slope and quench field in Nb cavities: This work will continue in the second year. The second year's deliverables will be single cell cavities with improved shapes and test results, as well as progress reports and papers.

Improved Geometries, Fabrication and Preparation: The second year's deliverables will be progress reports and papers.

FY2006 Project Activities and Deliverables
Studies of the sources of high field Q-slope and quench field in Nb cavities: This work will continue in the third year. There will be a final report.

Improved Geometries, Fabrication and Preparation: Through the technology transfer program to US industry, we will fabricate two to three multi-cell niobium structures and test these structures at 2K. There will be a final progress report.

Budget justification and three-year budget, in then-year K$
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Equipment: Computers for thermometry data acquisition RF for cavity testing
Materials & Supplies: helium, nitrogen, niobium, acids, In the third year, funds are provided for niobium cavity fabrication.
Surface Analysis: Hourly rate to Evans East for SIMS, XPS
Industrial personnel for technology transfer program in third year

References


2.21. RF Breakdown Experiments at 34 Ghz (UCLC)

Accelerator Physics

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phone: (203) 432-5428

Yale

Year 1: $15,001
Year 2: $40,000
Year 3: $40,000
4 RF structure R&D

4.1 RF Breakdown Experiments at 34 GHz

Personnel and Institution(s) requesting funding
J. L. Hirshfield(PI),
Beam Physics Laboratory, Yale University

Collaborators
Chris Adolphsen (SLAC), W. Wuensch (CERN), O.A. Nezhevenko, V.P. Yakovlev

Project Leader
J.L. Hirshfield
jay.hirshfield@yale.edu
(203)-432-5428

Project Overview
An experimental program is proposed to study rf breakdown in mm-wavelength accelerating structures, with the aim of understanding the basic mechanisms that lead to breakdown. Availability of the recently-commissioned 45-MW, 34-GHz magnicon amplifier at the Yale Beam Physics Laboratory makes these experiments possible. This research is expected to have relevance to fundamental issues in accelerator structure design, as well as to near-term issues for NLC.

Rf breakdown limits the accelerating gradient and thus determines the collider length. One of the most important questions in collider design is the frequency dependence of the maximum achievable accelerating gradient, and studies at frequencies other than 11.4 GHz are expected to help understand limitations faced by NLC. Presently, some experimental breakdown data are contradictory, incomplete, and inconclusive, notably:

(a) Experiments by Loew and Wang [2, 3, 4] demonstrated a square root dependence of maximum surface gradient on frequency in the microsecond pulse length range; independent experiments on single cavities under similar conditions show maximum surface fields of 190 MV/m for S-band and 350-400 MV/m for X-band, in conformity with the square root dependence [8, 13].

(b) For X-band accelerating structures such as those under extensive study in several research groups at SLAC, the maximum surface field is always lower than in a single cavity, and the spread of maximum surface gradient depends on the structure type and parameters. Some recent theoretical investigations at SLAC also indicate that one may expect an increase of the gradient with frequency [5, 6, 7].

(c) CERN experiments [9, 10, 11] do not match the SLAC results, as follows. In cavities designed for 21, 30 and 39 GHz, the maximum surface gradient for a single cavity excited by the beam doesn’t appear to depend on cavity size, and equals about 380 MV/m for very short pulse width[12] (At SLAC, the same surface gradient was achieved in a single X-band cavity for pulse width more than 10 times longer). These differences are not understood, but it is suggested that direct comparison may be elusive, since the CERN experiments were done using a train of bunches to shock excite the fields internally, as compared to other experiments performed at SLAC, KEK, and Budker INP, where the fields are externally driven. In further contradiction to the SLAC
results, no significant difference was found at CERN between the maximum surface field for single cavities and various accelerating structures.

It is not possible to develop the next generation (multi-TeV) linear collider without careful investigations of the maximum achievable accelerating gradient for higher frequencies. This point has been enunciated repeatedly, within the accelerator community (e.g., Snowmass2001). This knowledge is important for NLC because deeper understanding of the limiting breakdown mechanism and its variations, for examples with different metals and alloys, could enable operation with higher acceleration gradients. Moreover, exact information on the maximum accelerating gradient available and what the optimal operating frequency should be, may allow design of a collider upgrade to a center-of-mass energy which enhanced X-band technology will not allow. In addition, the breakdown investigations under way at SLAC include development of models of this phenomenon, and validation of these models will require experiments over a range of frequencies including frequencies higher than X-band, but carried out under similar conditions. To be able to compare measurement results for S, X and Ka bands and to exclude extraneous effects, these measurements must be done using the same method used at SLAC (in contrast to the method used at CERN): high-power rf amplifier, waveguide system, pulse compressor, variable pulse width, flexibility of conditioning process, etc. The Yale Beam Physics Laboratory’s 34-GHz program to establish a Ka-band accelerator test facility satisfies these requirements. The main component of this facility is the 34 GHz, 1 \( \mu \)sec magnicon amplifier with the design power of 45 MW \[1\]. The tube has already undergone preliminary rf conditioning wherein, after about 60 hours of operation, an output power of about 10.5 MW was achieved in 0.25 \( \mu \)sec pulses. rf conditioning is to continue up towards the rated output level, although the present output is sufficient for providing \( >500 \) K pulsed temperature excursions in a dedicated test structure under construction for surface fatigue studies; such studies have direct application to NLC. Furthermore, support from DoE has been secured for a range of Ka-band high-power rf components, including rf windows, needed to transmit and couple the magnicon output power to test structures under evaluation. The first set of these components has been delivered. During the proposed experiments, coordination with SLAC is planned.

In order to achieve the maximum gradient, one should make correct choices for details of the accelerating structure. We propose to develop a test structure with both strong defenses against rf electrical breakdown, and low peak surface magnetic field (in order to minimize pulse heating leading to metal fatigue). The improvements are based on the following innovations:

(a) elliptical irises which reduce the maximum surface electric field: elliptical irises were suggested by the authors \[14, 15\];

(b) the first cell of the structure \[16\] will operate in the TM_{020} mode, so as to eliminate an additional overvoltage caused by the input coupler. Also, there is no magnetic field enhancement near the coupling slot.

The structure has a group velocity \( v_{gr} = 0.05c \). This turns out to be a reasonable choice in light of experiments with various X-band accelerating structures at SLAC. Details of the current structure design are given in \[16\].

It is important to emphasize that some of the design features of the test structure can be directly applied to the NLC X-band structure, namely elliptical irises that will reduce surface electric fields and consequently may allow an increase in accelerating gradient of up to 15-20\%, and the use of a
coupling cell operating in the TM_{020} mode that will allow lowering the risk of breakdown and over-heating. It is possible that fabrication of an X-band version of the structure will be undertaken with future funding; data obtained from experimental tests of this structure at the NRL-operated X-band accelerator test facility using the Omega-P/NRL X-band magnicon will also be analyzed in the context of the proposed program.

Successful operation of the aforementioned 34-GHz magnicon, as is already well underway, will allow development to proceed for the 34.272 GHz accelerating structure even before the availability of a full set of high-power Ka-band components such as pulse compressors, mode converters, etc. This is possible because it is proposed to apply the technique commonly used in evaluation of accelerating structures, namely to operate the structure first in a standing-wave mode. In the standing-wave mode, it is expected that surface fields and accelerating gradients of 690 MV/m and 180 MeV/m can be realized using 30 MW of rf drive power fed directly to the structure from the magnicon. At a surface gradient of 690 MV/m in the traveling-wave mode, the accelerating gradient would be more than 340 MeV/m. These experiments will be possible when future funding permits, in which case data obtained from operation of this structure will be analyzed in the context of the proposed program. The major opportunity for analysis of breakdown data will occur when experiments at 34 GHz commence with high power, long pulse excitation of CLIC structures, in a planned collaboration with CERN; this work could begin in late 2003 or 2004, at CERN’s discretion.

The research team has decades of rich experience which includes design, building and putting into operation three magnicons in the decimeter and centimeter wavelength domains having up to 10’s of MW’s of output power; and design, building and operating of electron accelerators based on various structure designs. Individual resumés are available upon request. During all years of the proposed project, student participation is planned, including part-time employment of graduate students and undergraduate participation through senior research projects and contiguous summer employment. During the second and third years, part-time work by a postdoctoral research associate is planned, at a level equivalent to 25% of full-time.

**Description of Available Facilities**

The Yale Beam Physics Laboratory is well equipped to carry out the proposed research. A cold-test lab for low-power rf tests is equipped to perform scalar analyzer measurements at frequencies from 2 to 50 GHz. High-power tests at 34 GHz will be carried out using a 45-MW magnicon amplifier which, during recent commissioning at reduced gun voltage, produced over 10 MW of output power (a record level) after only about 100,000 conditioning pulses. High-power components at 34 GHz, being designed and developed under another program should be available for the tests of CLIC structures; these components include high-power loads, dual directional couplers, mode converters, windows, tapers, power combiners, and pumping sections. Other facilities could become available during the 3-year span of this project, that include a 19-cell high-gradient standing-wave accelerating structure, a resonant ring to obtain \times 10 effective peak power enhancement to >400 MW with full 1-\mu sec pulse width, and a quasi-optical pulse compressor.

**Education and Outreach**

Education in laboratory-based accelerator physics within the context of the proposed program will take place in the Yale Beam Physics Lab at three levels: undergraduate, graduate, and post-doctoral. It is required for Yale physics majors to carry out an independent senior research project. The budget for the proposed program will allow the academic year senior project (for which there are no earnings) to
be enhanced by summer employment between the junior and senior years; in the past, this arrangement has been shown to greatly increase the student’s familiarity with research laboratory practice, and to obtain better results by the end of his/her senior year. Graduate students will be given the opportunity, with support under the proposed program, to find summer employment preceding matriculation and between their first and second years. (Normally, Yale graduate students have University fellowships during their first and second years.) This opportunity for summer employment helps students select a long-term area of research towards their Ph.D.’s, and provides important hands-on experience in an accelerator physics research laboratory. Postdoctoral education occurs when young professionals have the opportunity to broaden their skills by working side-by-side on multi-year projects with senior staff associated with the proposed program. Outreach activity that is possible within the context of this program includes a summer visiting appointment for an area high-school physics teacher, field trips for high-school students, and conduct of high-school senior projects (as just completed for the valedictorian of the Hopkins School graduating class in New Haven, who will matriculate as a physics major at MIT in September 2003.) All of these outreach activities have taken place at one time or another in the laboratories of the Principal Investigator during his tenure since 1962 at Yale.

**FY2004 Project Activities and Deliverables**

During the first year, we will begin to develop a design of the test stand, which besides the accelerating structure will include a 34-GHz high power feeding system and diagnostics. The test stand will be configured to accommodate CLIC structures that will be fabricated at CERN specifically for testing at 34.3 GHz, rather than at the CLIC frequency of 30 GHz. An annual report will be presented and engineering drawings of the accelerating structure will be completed.

**FY2005 Project Activities and Deliverables**

During the second year, the manufacturing of the CLIC test structure is to be completed, and fabrication and cold test of the structure can be anticipated. Tests of CLIC structures will continue, and data analysis will begin—with the aim of deepening understanding of the underlying breakdown mechanisms. An annual report will be presented. The accelerating structure will be completed and delivered.

**FY2006 Project Activities and Deliverables**

During the third year, analysis of data from CLIC structures will continue, and the accelerating structure will be assembled and connected to the magnicon, provided its fabrication was completed during FY2005. Then, the structure conditioning and experiments will be started. The components of the test stand will be assembled together with the accelerating structure. Using data accumulated from tests at Yale on CLIC structures, from the 34-GHz-accelerating structure described above as tested at Yale, and from an X-band version of the latter tested at NRL, attempts will be made to develop a model for helping to understand the basic mechanisms that govern rf breakdown in accelerating structures. The final report will be presented.

**Budget justification**

The first year’s activities are limited to design studies which involve staff members with the aim of configuring the experimental facilities to accommodate CLIC structures and (possibly) the 34-GHz accelerating structure. This activity will be partially supported with funds for undergraduate and graduate student participation. During the second year, breakdown tests on CLIC structures will be performed and fabrication and cold test of the 34-GHz accelerating structure could be carried out.
using base program funding. This activity will be partially supported with funds for undergraduate and graduate student participation, and for support of 25% of an Associate Research Scientist. During the third year, breakdown tests will continue, and data will be analyzed. This activity will be partially supported with funds for undergraduate and graduate student participation, and for support of 25% of an Associate Research Scientist. Indirect costs are 63.5% MTDC (normally excluded categories include equipment over $2000, graduate student tuition, subcontracts over $25,000). Fringe benefits are 10.0%, 11.0% and 12.0% on undergraduate wages in BY-1, BY-2, and BY-3, respectively; are zero on graduate student wages; and are 40.0%, and 42.0% on Associate Research Scientist salary in BY-2 and BY-3, respectively.

Three-year budget, in then-year K$

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References


[15] O. Nezhevenko, D. Myakishev, V. Tarnetsky, V. Yakovlev,“TW accelerating structures with minimal electric field”, PAC95, Dallas, p. 1076

2.22. Investigation of Novel Schemes for Injection/Extraction Kickers
(LCRD)

Accelerator Physics

Contact person: George Gollin
email: g-gollin@uiuc.edu
phone: (217) 333-4451

Cornell
Fermilab
Illinois

Year 1: $22,822
Year 2: $16,822
Year 3: $16,822
**Project name**

Investigation of Novel Schemes for Injection/Extraction Kickers (LCRD 2.22)

**Classification (accelerator/detector:subsystem)**

Accelerator

**Institution(s) and personnel**

University of Illinois at Urbana-Champaign, Department of Physics:
George D. Gollin, Thomas R. Junk (professors); Michael J. Haney (electrical engineer); Guy Bresler, Keri Dixon (undergraduates)

Fermi National Accelerator Laboratory:
David A. Finley (staff scientist), Chris Jensen (engineer), Vladimir Shiltsev (staff scientist)

Cornell University, Department of Physics:
Gerald F. Dugan (professor), Joseph T. Rogers (professor), David L. Rubin (professor)

**Contact person**

George Gollin

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(217) 333-4451

**Project Overview**

The injection/extraction kicker systems for damping rings in both the NLC and TESLA linear collider designs pose interesting challenges of speed, stability, and reproducibility.

The NLC damping ring design presently requires kickers with rise/fall times of ~60 ns, and “flat top” fields which are stable for ~270 ns in order to inject, and then extract, a train of 192 bunches from the main damping ring. The entire train will orbit inside the damping ring with the same 1.4 ns bunch spacing as when the train travels down the NLC linac.

The 2820 bunches of a TESLA pulse would require an unacceptably large damping ring if the 337 ns linac bunch spacing were used in the damping ring. As a result, the TESLA 500 GeV design calls for 20 ns bunch separation in a 17 km circumference damping ring; a fast kicker will deflect individual bunches on injection or extraction, leaving the orbits of adjacent bunches in the damping ring undisturbed. A number of the kicker designs which have been considered involve the creation of individual magnetic field pulses of sufficiently short duration so that only one bunch is influenced by a pulse. The demands of short rise/fall times and pulse-to-pulse stability are challenging. A system capable of generating shorter pulses would allow the construction of a smaller damping ring.
It is interesting to consider a different design in which the pulsed kicker is replaced by a set of rf cavities whose amplitudes, frequencies, and phases correspond to the Fourier components of a periodic pulse train which will kick one bunch while leaving a large number of following bunches undisturbed. The most naïve version of this kicker employs cavity frequencies which are the lowest terms in the representation of a periodic $\delta$ function; more sophisticated schemes can overcome many of the disadvantages of this particular design. Instead of energizing the system only when a bunch was about to be injected (or extracted) to the damping ring, the cavities would run continuously. This would allow their frequencies, phases, and relative amplitudes to be determined with great precision. With a properly chosen set of parameters, the system would kick every $M$th bunch in a train, leaving undisturbed the train’s other $(M - 1)$ bunches. Injection (or extraction) of an entire bunch train would be completed by the end of the $M$th orbit through the system.

Our first year of investigation has concentrated on modeling the naïve kicker scheme and learning about its deficiencies, in combination with an exploration of alternative methods of choosing cavity parameters. The most significant problem with the naïve scheme is the unacceptably large difference in the effects on the head and tail of unkicked bunches passing through the kicker. We have found a technique which allows the selection of cavity amplitudes and frequencies that make both the kicking impulse and its first derivative identically zero when bunches (which are not to be disturbed) pass through the kicker.

Since the physics of the kicker is entirely classical, the research has proved ideal for participation by undergraduates. The students have been remarkably effective! In addition, the work is the subject of Keri Dixon's undergraduate senior thesis.

Results of First Year Activities

Mode of operation; selection of amplitudes and frequencies

A Fourier-series kicker system could be installed in a bypass section of the damping ring, as shown schematically in Figure 1. During injection, a deflector system would route the beam through the bypass. Once injection was completed, each deflector could be turned off during the passage of a gap between the last and first bunches in the orbiting train. The train would then orbit in the damping ring, bypassing the kicker. At extraction, the deflectors would be energized again, routing the beam through the kicker for extraction.
We have been refining our ideas about the kicker design during our first year of investigation. Imagine that we build an $N$ element kicker so that the transverse momentum it imparts can be written

$$p_T(t) = \sum_{k=0}^{N} A_k \cos[(\omega_{\text{base}} + k\omega_0)t]; \quad \omega_0 = \frac{2\pi}{337 \text{ ns}}.$$ 

Our initial studies concerned a device which employed identical amplitudes $A_k$ and a base frequency $\omega_{\text{base}} = 0$ so that it delivered

$$p_T(t) = A \left[ \frac{1}{2} + \sum_{k=1}^{N} \cos[k\omega_0 t] \right].$$

This expansion comprises the first terms in the Fourier decomposition of a periodic $\delta$ function and is graphed in Figure 2 for the case $N = 16$.

The sum can be evaluated analytically; one finds that

$$p_T(t) \sim \frac{\sin\left[\left(\frac{N + 1}{2}\right)\omega_0 t\right]}{\sin(\omega_0 t/2)}$$

so that the spacing between the kicking spike and first zero is the same as the spacing between successive zeroes. A bunch passing through the kicker at $t = 0$ would be ejected from the damping ring, while successive bunches (which pass through the system when the net impulse is zero) would continue to orbit inside the damping ring.
The principal difficulty with this approach is the rapid change in $p_T$ for zeroes close to the kicking peak. The kicker’s residual impulse when “off” should be less than $7 \times 10^{-4}$ of its "on" impulse. The 6 mm rms bunch length in the TESLA damping ring corresponds to a flight time of 20 ps. A slope at a zero crossing in the field integral of 2 Gauss-meters/ns would produce a kick error of 0.04 Gauss-meters, somewhat smaller than the tolerance of 0.07 Gauss-meters. However, the number of passes a bunch makes through the kicker system ranges from 1 (for a bunch which is kicked immediately) to $2N + 1$ (for a bunch which is kicked during the train’s last orbit through the kicker system). As a result, an analysis of the effects associated with finite bunch length will need to take into account the cumulative effects of multiple passes through the kicker and the synchrotron oscillations of an electron (or positron) in the direction of motion of the bunch as the train travels through the damping ring. The safety margin is slim and it is sensible to consider an improved scheme which avoids the problem entirely.

An additional (practical) problem is the large number of cavity designs required: in the above example the frequencies range from 3 to 48 MHz.

One way to address the matter of too many cavity distinct designs is to operate the system with a much higher "base" frequency so that the 3 MHz frequency separation is obtained through tuning of individual cavities which are otherwise identical:

$$p_T(t) = A \sum_{k=0}^{N} \cos \left[ (\omega_{\text{base}} + k \omega_0) t \right].$$

A plot of $p_T(t)$ for a simple system of this sort is shown in Figure 3; note that the envelope of the high frequency oscillations pinches down at times when unicked bunches
pass through the system. As a result, the slope of $p_T(t)$ at the "major zeroes" is no worse than for the $\omega_{\text{base}} = 0$ version of the kicker.

![Kicked bunches are here...](image)

Figure 3. Field integral vs. time (ns) in a 10-element system with base frequency 300 MHz. Individual cavity frequencies are 300 MHz, 303 MHz, 306 MHz, ... 327 MHz.

However, this type of design still does not address the problem of reducing the difference in the fields experienced by the heads and tails of bunches passing through the kicker. Guy Bresler, one of the undergraduate participants, developed a remarkable technique which solves this problem. His algorithm calculates a set of cavity amplitudes for which both $p_T$ and $dp_T/dt$ are zero at times when (evenly spaced, unkicked) bunches pass through the system.

A set of amplitudes for a 29-cavity system running with base frequency 300 MHz is shown in Figure 4, while the resulting $p_T(t)$ is shown in Figure 5. The "major zeroes" aren't quite at the obvious symmetry points any more, but are still spaced uniformly. An enlargement of the central portion of Figure 5 is shown in Figure 6. The nine major zeroes visible in Figure 6 are indicated by arrows and vertical lines.
Figure 4. Cavity amplitudes for a 29-element system with base frequency 300 MHz. Individual cavity frequencies are 300 MHz, 303 MHz, 306 MHz, ..., 327 MHz. With these amplitudes, both $p_T$ and its first derivative are zero when (unkicked) bunches pass through the system.

Figure 5. $p_T(t)$ for a system employing the cavity amplitudes show in the previous figure.
Most bunches pass through the kicker several times after injection, or before extraction. There are a variety of effects which enter into a calculation of the kicker’s influence on a bunch which orbits the damping ring several times during the injection/extraction cycle. A bunch arrives at the kicker one “click” earlier each time it begins its next orbit of the damping ring until finally being ejected. As a result, it passes through the kicker during zeroes which are progressively closer to the kicking peak (located at $t = 0$ and $t = 337$ in Figure 5).

Tune effects will cause the position of an electron inside a bunch to vary from orbit to orbit. Even if in a worst-case scenario (a mysterious conspiracy among various effects keeps an electron in the head of a bunch each pass through the kicker), Bresler's algorithm reduces head-to-bunch-center effects to an acceptable level for all bunches. This can be seen in Figure 7.
Cavity geometry and tune effects

Most of our investigations have ignored the question of cavity geometry and its role (especially when coupled with tune effects) in spoiling the precision of the kicker. We began investigating this last summer, using *Mathematica* to model simple cavities and including tune effects in studies in which electrons made multiple passes through the system. These efforts are ongoing, and will form the core of Keri Dixon's undergraduate thesis.

We have also begun studying effects associated with errors in cavity placement, amplitude, and phase.

Proposed Activities for a Three Year Program

We will continue to refine our models and finish coding a simple orbit tracing program for use in detailed studies of tune and cavity effects. Note that the demands on the orbit tracing code are different from those which apply to storage ring simulations: the beams make a small number of passes through the kicker before extraction. The program is a straightforward piece of code to write.

It seems likely that a Fourier series kicker built with perfectly stable, error-free cavities could work as a TESLA damping ring kicker. As a result it is productive to continue with our kicker modeling, turning our attention towards inclusion of realistic, imperfect cavities.

The accuracy with which the phases and amplitudes of cavities can be set must be understood before a viable system can be built. In addition, the long term stability of this kind of system must be studied. Since this sort of activity is ideal for collaborative investigation with a national laboratory, George Gollin has accepted a year-long Fermilab
Guest Scientist appointment, which will begin in January, 2004. He will be excused from teaching during this time and will spend two days a week at FNAL, working on damping ring kicker issues with Shekhar Mishra and other lab scientists.

We would like to stress two points:

- Active participants in LCRD 2.22 are constrained by the academic calendar: Gollin teaches (although he will be relieved of teaching duties during the Spring and Fall 2004 terms), while Bresler and Dixon are undergraduates with full course loads. Most of our progress occurs during the summer.
- Dixon will graduate in 2004 and her summer plans are, as yet, unclear since she will be applying to graduate school. Bresler is younger and has expressed a great deal of interest in continuing on LCRD 2.22. It is important to have at least two students working on the project.

It is sensible to continue working with the students to improve our models. In addition, integrating them into the Fermilab-based work as much as their schoolwork permits is crucial. As a result, our budget is simple, consisting primarily of salaries for the undergraduate students, funds for a pair of fast PC's (we had borrowed machines from an undergraduate teaching facility last summer), and a certain amount of travel money associated with bringing them to Fermilab for short blocks of time during the summer.


### UIUC Budget for LCRD 2.22

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2.23. Ring-tuned, permanent magnet-based Halbach quadrupole (LCRD)

Accelerator Physics

Contact person: James Rosenzweig
e-mail: rosen@physics.ucla.edu
phone: (310) 206-4541

UCLA
Fermilab

Year 1: $38,950
Year 2: $38,950
Year 3: $38,950
Project name

Ring-tuned, permanent magnet-based Halbach quadrupole

Classification

Accelerator

Institution(s) and personnel

University of California, Los Angeles, Department of Physics and Astronomy:
James Rosenzweig (professor), Gil Travish (research scientist), Jae Lim (graduate student), Ryan Glasser (undergraduate student)

Fermi National Accelerator Laboratory:
James Volk (staff scientist)

Contact person

James Rosenzweig
rosen@physics.ucla.edu
(310) 206-4541

Project Overview

Interest in the use of permanent magnet quadrupoles (PMQs) in main accelerators, damping rings, and transfer lines of a linear collider (LC) has been driven by the promise of significant operational cost savings over the life of the project. It is notable that a similar logic has already been employed to proceed with the construction of the Recycler antiproton ring at FNAL. Promising work has been performed at Fermilab in designing and fabricating permanent magnet-based quadrupoles. Four different types of permanent magnet-based designs have been investigated at the prototype level. They are: the wedge design, the corner-tuner design, the sliding shunt design, and the counter-rotating quadrupole. Needed tunability of quadrupole gradient in the counter-rotating design has been demonstrated in prototypes, while simultaneously holding the effective magnetic center steady to less than 1 µm as required for utility in the beam-based alignment process in the LC linac. On the other hand, this approach introduces skew-quadrupole components that need to be cancelled in quadrupole arrays, thus constraining their implementation. The wedge and sliding shunt approaches are close to giving acceptable performance, but more work would be needed; the inelegant addition of coils to these devices has been suggested. Additional unresolved problems in application of permanent magnet-based quads may arise due to radiation damage; radiation lifetime measurements have been proposed by another university group in the context of this joint proposal.

Experimental prototyping work has not, until the onset of this project, progressed to investigate one of the more promising designs, the ring-tuned Halbach (US patent number 4,549,155) quadrupole — or, simply, ring quadrupole. The ring quadrupole, as shown in Fig. 1, is a mechanically simple, robust design, with a high level of symmetry. With the elegant rotating ring of permanent magnets around the main magnet assembly,
this device has the promise of very fine-scale tunability. Further, because of its open near-pole geometry, added permanent magnet material may easily be added in order to strengthen the magnet gradient.

![Figure 1. PANDIRA simulation of a Halbach permanent magnet-based quadrupole.](image)

In addition to those already mentioned, a further linear collider application may be considered — that of the final focus. While it is not currently on the NLC agenda, permanent magnets in the final focusing system are part of longer-range projects, such as CLIC\(^1\). It is clear that in order to produce smaller $\beta$-functions at the interaction point in the future, one must press the magnet technology with either permanent magnet-based, or superconducting-based devices. The UCLA group is interested in such ultra-high gradient applications for additional reasons based on application to advanced acceleration and beam physics projects. Thus we have embarked on a new program to develop permanent magnet-based quadrupoles at UCLA, of which the ring-tuned quadrupole is a centerpiece. The projects that we have undertaken are linked by several common themes: 1) obviously, they are based on correct deployment of permanent magnet materials; 2) they present challenges in measurement resolution of field center, gradient and quality; 3) the design and construction of the magnets require use of the three-dimensional magnetic field modeling codes.

The ring quadrupole project is straightforward to undertake, as nearly all of the scientific infrastructure and materials needed are in hand or under active development at the present time. Fermilab had already procured the permanent magnets for a prototype of such a design, and performed a full mechanical design, based on the magnet shown in Fig. 1. UCLA has completed the fabrication of the prototype parts, utilizing the leverage that the departmentally-subsidized, expert machine shop offers. This shop has

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\(^1\) F. Zimmermann, R. Assman, G. Guignard, D. Schulte, O. Napoly, “Final-Focus System for CLIC at 3 TeV” EPAC 2000 (Vienna).
constructed, over the last decade, a number of precision magnets: dipole spectrometers, several styles of electromagnetic quadrupoles, permanent magnet quadrupole, sextupole, and hybrid as well as pure-permanent magnet undulators. These magnets have been implemented in state-of-the-art experiments in advanced accelerators and light sources at UCLA, LLNL, BNL, ANL, Fermilab, and DESY. Their ubiquitous use is derived from both their quality and low cost. This quality is based not only on the machine shop, but on serious design efforts, performed mainly by UCLA, using advanced three-dimensional modeling codes.

As such, for this project, UCLA has developed a three-dimensional computer model of the Halbach quadrupole using the code RADIA. This effort will aid, after the sorting of the magnets, in understanding tuning systematics, and finite-length effects in this device. Testing of the quadrupole during and after construction and tuning is possible at UCLA magnet lab, as well as at the Fermilab and/or SLAC magnet-testing laboratories. The UCLA facilities for magnet testing have been upgraded recently for this and other PMQ-based quadrupole projects, to allow both Hall-probe and pulsed-wire measurement techniques, with rotating coil expected to be added in the coming year. A combination of prototyping, testing and computational analysis will allow us to optimize the Halbach ring quadrupole for LC linac, damping ring, and transfer line use.

The plan we outline below is for an integrated, three-year program that will allow UCLA to continue, and to deepen, its research and development of tunable permanent magnet quadrupoles. Before we proceed with the planned work, we must first discuss the progress made in the work thus far.

![Component parts for ring-tuned, PM-based quadrupole at UCLA magnet measurement lab.](image)

**Figure 2.** Component parts for ring-tuned, PM-based quadrupole at UCLA magnet measurement lab.

**Progress to date**

In the beginning of the first year — approximately 4 months after the initiation of the project, significant progress can be reported. The FNAL design for the Halbach ring-tunable quadrupole prototype is now nearing completed fabrication at UCLA. FNAL has
provided final drawings, Nd:Fe permanent magnet pieces, and machined stock. UCLA has been responsible for the final machining of components (iron parts as well as non-magnetic supports) and development of a rotation control system. The prototype machining is now finished (see parts array in Fig. 2), as can be assembled once the testing of each magnet piece is measured — a process now under way — and the numerical sorting of the magnets within the device is completed.

![Figure 3.](image)

**Figure 3.** (a) Rendered picture of Halbach ring-tuned permanent magnet-based hybrid quadrupole, from 3D magnetostatic simulation code RADIA. (b) Arrow plot of magnetic field in symmetry plane of the quad.

The numerical sorting of the PMQ pieces is accomplished through 3D simulation of the full quadrupole geometry using the measured magnetization of each piece; the goal of the sorting process is the stabilization of the quadrupole magnetic center. In order to perform this type of analysis, UCLA presently uses RADIA, as well as the commercial code AMPERES, to make 3-D computational models of magnets developed in our beam physics program. RADIA has been found to give good results in modeling permanent magnet-based quadrupoles and undulator magnets. Therefore, to advance the modeling of the Halbach quad, we have constructed a 3-D RADIA model of the device. This model, a preliminary version (uniform, ideal magnetization) of which is shown in Fig. 3, will allow detailed comparison with the gathered data. In addition to the predictive value of the numerical sorting, the testing serves to benchmark the RADIA model, giving a tool for optimization of the design, and allowing its extension to higher gradient versions.

The full device is expected to be assembled by the end of calendar 2003, and tested and tuned in the UCLA magnet lab, using Hall probe maps. We will then perform initial centerline stability tests at UCLA using our pulsed wire measurement system, shown in Fig. 4. This system, employed in short pulse “first integral” mode, has been recently calibrated using detailed, automated Hall probe maps of one or our standard 2” bore quadrupoles. It was then employed to give approximately 10 micron resolution centerline tests on our recently developed 5 mm bore, 300 T/m pure PM (“pizza-pie” design, also originally attributable to Halbach) quadrupoles. This resolution is good enough for the present application of these pure PMQ devices, which are not individually tuned in actual use, but placed on longitudinal movers to tune the entire focal length of a specially designed quadrupole triplet. This process is expected to produce beam sizes around 7 µm
at the LLNL/UCLA PLEIADES Thomson scattering source experiment, and so the resolution is appropriate. On the other hand, we are presently not able to produce 1 µm resolution in the pulsed-wire system, as demanded eventually by the NLC tunable quad system requirements.

![Figure 4](image)

**Figure 4.** (left) Two-axis pulsed-wire measurement system in UCLA magnet test lab; (right) high gradient (300 T/m) “pizza-pie” PMQ now under test in system.

As can be seen from the discussion above, this project is synergistic with the present UCLA program in ultra-high strength, compact PMQ development. The UCLA group has need for powerful quads in plasma acceleration experiments, for matching beams to the very strong intra-plasma fields, as well as for Thomson scattering experiments — where one is creating an electron-photon “collider” that has luminosity demands reminiscent of LCs, and is in fact the scenario behind photon creation in the γ–γ collider. In both cases, we have introduced ultra-high strength quadrupoles to both achieve very small β-functions, and to mitigate the effects of aberrations, by allowing small initial beam sizes.

We emphasize that the Halbach ring design is not only tunable, but also could produce quite strong gradients when scaled to small bores and enhanced permanent magnet geometries. Development of an ultra-high strength version of this quad for potential use in the LC final focus will also be studied at UCLA, as well as in Thomson scattering-based polarized positron sources, which demand quite small spot sizes as well. The student who is presently responsible for the development of the LLNL ultra-high strength quadrupoles, Jae Lim, will work half-time on this project in its first year of work.

The challenges facing both the pre-existing UCLA and newly begun LC ring quad work are similar. Both projects require very precise fabrication, and measurement. We thus are eager to learn from the lead national labs (FNAL and SLAC) how to approach the magnetic measurements in the tunability testing of the ring quads. As such, we will utilize rotating coil measurements that are unavailable at UCLA, and work with the labs on improving our approach to pulsed-wire testing. We then hope to be able, within two years, to take on the full testing duties, including rotating coil, of the ring-tuned quad, as well as other magnets of interest to the NLC program. Rotating coil development will be undertaken in collaboration with SLAC. Initial discussions have been made with Z. Wolf
concerning this work. The direction of the subsequent tunable PM-based quads will be subject to consultation with J. Volk of FNAL, the investigator responsible for most of the previous work on PMQs within the NLC collaboration.

**Description of proposed activities**

We include below a point-by-point summary of the proposed work for this project at UCLA and collaborating laboratories. Because of funding uncertainties, the activities are designed to be modular in time, each year ending with clear milestones that form the basis for the next year’s work.

**Year 1:** Completion of PM magnetization measurement (strength and direction characterization), numerical sorting with now-established RADIA model using measured values as input. Construction of magnet system based on sorting results. Testing at UCLA, including mapping of fields with automated Hall probe scanning, and pulsed-wire. Continued testing of magnets at FNAL (pulsed-wire) and SLAC (rotating coil). Re-evaluation of mechanical and magnetic design, leading to new design for fabrication.

**Year 2:** Full pre-testing, sorting and fabrication, as in initial year, of second-generation model of ring-tuned PMQ. Refinement of pulsed-wire system at UCLA with FNAL, and development of high resolution rotating coil apparatus at UCLA with SLAC. High resolution testing of second-generation quad at UCLA. Design of ultra-high gradient version of ring-tuned PMQ.

**Year 3:** Full pre-testing, sorting and fabrication of high-gradient, small bore model of ring-tuned PMQ. High resolution testing of high-gradient PMQ at UCLA. Studies of use of high gradient PMQs in final focus, and in Thomson-based polarized positron sources. Evaluation of higher order multipoles in PMQs, and their effects on beam use in NLC short focal-length scenarios.

**Budget**

The budget given below includes UCLA overhead on relevant items at the 26% (off-campus research) rate.

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² FNAL is providing already procured Nd:Fe material worth over $7k to this project, and is expected to continue its support at this level.
2.25. Investigation and prototyping of fast kicker options for the TESLA damping rings (UCLC)

Accelerator Physics

Contact person: Gerry Dugan
email: gfd1@cornell.edu
phone: (607) 255-5744

Cornell

Year 1: $7,900
Year 2: $171,762
Year 3: $98,766
2.5 Investigation and prototyping of fast kicker options for the TESLA damping rings

Personnel and Institution(s) requesting funding
G. Dugan, J. Rogers, D. Rubin, Laboratory of Elementary Particle Physics, Cornell University

Collaborators
D. Finley, C. Jensen, G. Krafczyk, V. Shiltsev, Fermilab
G. Gollin, T. Junk, University of Illinois at Urbana-Champaign
W. Decking, DESY

Project Leader
G. Dugan
gfd1@cornell.edu
(607)-255-5744

Project Overview
The large number of bunches (2820) and the relatively large inter-bunch spacing (337 ns) in the TESLA linear collider design give a bunch train which is more than 200 km long. A damping ring of this size would be very costly, and so the bunch train is damped in a compressed form, with a bunch spacing of 20 ns, leading to a damping ring with a circumference of 17 km.

In the TESLA baseline, the rise and fall time of the damping ring injection and extraction kickers determine the circumference of the ring. There is considerable leverage in developing faster kickers, as this translates directly into a smaller circumference ring. The baseline system for 500 GeV (cm) parameters has a 20 ns specification for the kicker pulse width; this becomes about 12 ns for the 800 GeV (cm) parameters. Designs and prototype results exist [1] for conventional kickers with widths of 7 ns, and designs have been developed for more novel ultrafast schemes [2] using electron beams.

We propose to further explore the feasibility of the kicker designs described in the references cited above, particularly the very fast stripline kicker[1]. We will also develop new ideas for fast kickers. For example, we will explore the possibility of the use of the ponderomotive force from a high-intensity laser pulse to provide a very short kick to the beam. We will work closely with our collaborators from the University of Illinois and Fermilab in exploring their novel fast kicker concept.

In the TESLA baseline design, both the injection and extraction kickers must be fast. The injection kicker is considerably more difficult than the extraction kicker, because of the larger beam size at injection. We will investigate the possibility of single-turn injection of beam into the damping rings, which would eliminate the need for a fast injection kicker.

It should be noted that, in addition to the small pulse width (of order ns) required for the kicker, extremely good pulse-to-pulse reproducibility is required in order to avoid beam jitter at the collision point. The fast intra-train feedback at TESLA cannot compensate for pulse-to-pulse jitter introduced by the extraction kicker. Part of the evaluation of the feasibility of any new kicker scheme must include an evaluation of the expected pulse-to-pulse jitter.

If a new fast kicker scheme is found to be technically feasible on paper, we propose to do an engineering design of a prototype, build the device, and test it using a high energy electron beam.

If the development of a fast kicker is successful and the ring size can be reduced, the average current will go up and at some point multibunch beam stability becomes the limiting factor to a further reduction in the ring size. This has been explored for two specific cases in prior work [3], for an earlier
set of TESLA beam parameters. We propose to update and expand on these considerations, including our current understanding of critical stability issues such as the electron cloud, and to determine the minimum ring size permitted by beam dynamics considerations.

**FY2004 Project Activities and Deliverables**

During the first year, we will review fast kicker schemes which have been proposed in the past, and explore the feasibility of new kicker schemes. We will investigate the possibility of single-turn injection of beam into the damping rings. We will determine the minimum ring size permitted by beam dynamics considerations. This work will be done by one of the scientific staff members, together with a graduate student.

The first year deliverables will be 3 technical reports: on the feasibility of fast kicker schemes, the feasibility of single-turn injection for the TESLA damping rings, and on the minimum allowable ring size as set by the beam dynamics.

**FY2005 Project Activities and Deliverables**

Assuming that we have found a feasible design for a fast kicker scheme, in the second year we will execute an engineering design for a prototype kicker, and build the prototype. Although it may not be a full scale device, we will include in the prototype all the features needed to address the principal technical challenges of the device. The work will be done by scientific and engineering staff members, and the graduate student.

The second year deliverable will be the prototype kicker.

**FY2006 Project Activities and Deliverables**

In the third year, we will test the performance of the kicker. This will involve electrical measurements such as peak current, rise and fall time, and pulse-to-pulse reproducibility. We will also test the kicker in a high energy electron beam, either at CESR or a similar facility with an available beam. The work will be done by scientific and engineering staff members, and the graduate student.

The third year deliverable will be a technical report describing the results of the kicker prototype tests.

**Budget justification**

The first year’s activities are limited to design studies, which will involve staff members and one graduate student (not included in the budget shown here). Travel funds are included to cover trips for consultations with collaborators and to DESY.

During the second year, the design and construction of the prototype will be supported by 1/2 FTE of engineering and technician manpower. The graduate student support will continue.

During the third year, the testing of the prototype will be supported by 1/4 FTE of technician manpower, together with a graduate student.

Indirect costs are calculated at Cornell’s 58% rate on modified total direct costs.

**Three-year budget, in then-year K$**

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References


2.26. Continuing Research and Development of Linac and Final Doublet Girder Movers (LCRD)

Accelerator Physics

Contact person: David Warner
email: Warner@lamar.colostate.edu
phone: (970) 491-1035

Colorado State

Year 1: $48,300
Year 2: $47,300
Year 3: $55,200
Continuing Research and Development of Linac and Final Doublet Girder Movers

David Warner
Colorado State University

Abstract:
This proposal is a continuation of the magnet mover R&D which was supported in the 2003 LCRD program. We envision a three-year R&D program, which will continue the investigations we began in the current R&D program to determine the resolution attainable with mechanical movers and reduce the costs associated with manufacturing them, study the mounting of piezoelectric movers to the mechanical mover to achieve the resolution required for the final doublet, and finalize mover designs with an emphasis on manufacturability and cost reduction.

Introduction
Every magnet and structure girder in the NLC linac will sit on movers to allow it to be positioned accurately. Depending on the requirements of the component in question, the movers will be required to position the beam components in either three degrees of freedom (two linear positions and one angle) or five degrees of freedom: (two linear positions and three angles). Two varieties of movers are required: Linac component movers and final doublet movers. These mover types are distinguished primarily by their resolution (by which we will mean both the accuracy with which the position of the mover is known after a move and the minimum distance you can move it in a controlled fashion) and the number of units required by the project.

Linac Component Movers
Linac component movers will typically be adjusted every few minutes to few hours, and must have a resolution (“step size”) of approximately 50 microns. This positioning will be relative, with the motion required determined by beam monitors. Since approximately 10,000 movers will be required, cost reduction, manufacturability and reliability are critical for this component.

Gordon Bowden (SLAC) has developed and produced movers used in the FFTB which have been demonstrated to meet the requirements for linac component movers except for resolution (they were measured to achieve a position resolution of approximately 300 microns) and cost (a 5-degree of freedom mover would probably cost at least $3000 each to manufacture in their current design, at least in small quantities). These movers are mechanical, utilizing a kinematic support concept providing motion by rotation of bearings mounted on an eccentric shaft in contact with a wedge-shaped component support. Rotation of the shaft is accomplished by means of a 200 step per rotation stepper motor driven through a 100:1 harmonic drive. Mechanical movers such as these
have several desirable features, including low cost, reliability, and the ability to retain a set point without active compensation. Position monitoring can be accomplished by simply mounting a rotary encoder on the shaft.

In order to meet the 50 nm step size requirement, the rotation of the eccentric shaft must be controlled in approximately 60 microradian intervals, or about 100,000 steps per rotation. This is challenging. One possibility for achieving the desired position resolution with the existing mover design is to increase the step resolution of the stepper motor to 2000 steps per rotation, which can be achieved with a micro-step motor controller. This concept remains untried, and testing is required to determine if a purely mechanical mover of this type can provide 50 nm resolution.

The stepper motors and the harmonic drives are the cost drivers for this system. Any cost reduction effort for the mover must begin here. One way to accomplish this is to use stepper motors more efficiently, with less expensive mechanical reduction to replace the harmonic drives or smaller-step stepper motor drivers. Another option is to use other mechanical options for driving the shafts with the required precision, such as DC actuators or combinations of stepper motors with worm gears, vertical wedges, piezoelectric inchworm movers or other systems. The cost reduction benefits here must be weighed against the cost to the system precision and reliability.

If the mechanical prototype can be demonstrated to provide the required resolution and repeatability, then this phase of the project would consist of fine-tuning the existing design, particularly cost reduction and design-for-manufacturability issues. These issues are critically important for the design to be successful.

If the mechanical motion alone is not accurate enough to accomplish the 50 nm resolution required, then a combination of the mechanical mover and a piezoelectric stack will be investigated. This approach is also envisioned for the final doublet movers.

**Final Doublet Movers**

The final doublet movers are a higher-precision device, requiring 10 nm resolution, excellent stability against vibration, and possible operation in a cryogenic environment. Similar resolution and vibration isolation have been accomplished for other applications using a combination of a mechanical mover (for coarse adjustment) and a piezoelectric stack, although we have not yet discovered a similar system in use in a cryogenic environment. Piezoelectric stacks are notoriously unstable, and require a constant feedback and adjustment to maintain the set position. We will investigate using a mechanical mover similar to the linac movers investigated above, with a piezoelectric stack for precision movement and a strain gauge, interferometer, or precision capacitance meter providing continuous feedback to keep the system at the set point. Note that we would not envision using the interferometer or capacitance meter for absolute position measurement—that would be accomplished by beam monitoring. This metrology would be used solely to maintain the position of the mover.
Project Status and Overview of Plans

In September 2003 the Technical Design facility at CSU received funds from the Linear Collider R&D program to develop linac magnet movers and final doublet girder movers. At that time, work began on procuring a prototype mover, refining our understanding of metrology techniques which will be used to qualify the mover, and exploring other shaft drive options that might prove more cost-effective.

In early October 2003, Warner visited SLAC and discussed the mover issue with Gordon Bowden and Tom Himel to see if any changes had been made to the requirements and design specifications for the magnet movers. No changes being found, we have begun work according to the R&D plan which was funded by the DOE, scaled back to meet the actual funding provided.

Prototype mover system:

Unfortunately it was not possible to get an existing mover from SLAC, so we are replicating a modified, up to 5-motor version of the mover. We have received a set of drawings for the three-axis mover from SLAC and have begun discussions about how we might modify the design for our purposes. Our variant of the mover is designed to initially include only three motors (as in the original FFTB mover), which will allow us to control two linear dimensions and one angle (X and Y and roll), but can be expanded to 5 motors which will allow us to control all three angles (Pitch, yaw and roll) and two linear dimensions (X and Y, not along the beam axis). The prototype mover will combine harmonic drive reducers and a 10-times micro-stepped stepper motor (2000 steps per rotation) to drive the mount shafts, which will theoretically allow us to achieve the required step resolution.

Currently we are beginning to place orders for components of the mover (harmonic drives, shafts, bearings, stepper motors, rotary encoders), and we will begin assembling the mover prototype in December.

Metrology:

We are developing a metrology system based on capacitive position measuring, using a system from Lion Precision that will allow measurements with a precision of approximately 10 nm over a range of 50 microns. Additionally, the stepper motor shaft (before the 100:1 harmonic drive) will be read out using rotary encoders with 3mr resolution mounted to the stepper motor. Together, this will allow us to measure the entire range of motion of the mover.

We have a quote on a one sensor system that we will buy for our initial measurements, and plan to expand to a full 5 sensor system after we have proven the system works.
Description of the Proposed Project

The work already funded by the LCRD program in our first proposal will be completed by May 2004. Our new proposal expands on the work already funded, taking advantage of the FFTB mover and metrology equipment we will build, and the experience we will have gained to move towards final mover designs.

**Year one** of this new proposal expands the scope of the initial project primarily by investigating the rotary motion drivers and motion encoders in an attempt to find a cost-effective solution. We expect to have an operational prototype mover by the end of January 2004, and to have the metrology equipment in place to allow us to measure its motion. By May, we will have determined if we can meet the step resolution required with a purely mechanical three-motor microstepped mover. At this point, we will investigate the resolution attainable with other mechanical reduction devices or alternate motor options, such as DC actuators or piezoelectric inchworm devices to try to reduce costs by eliminating the harmonic drive.

Additionally, we plan to purchase a full 5-axis capacitive position measuring system (actually an expansion of the system we are ordering for 1-axis measurements under our current grant) in order to be able to fully monitor the 5-axis movement of the stage simultaneously.

**Year two** of the project is to improve the resolution attainable by the mover by incorporating piezoelectric movers and active feedback, perhaps based on the capacitive metrology system we are investigating for measuring the system performance.

The information we will learn during the first year of the project will give us a solid understanding of the limitations of the mechanical mover, and based on this platform we will develop a piezoelectric stack to attach to the mover, and begin to investigate the resolution, vibration isolation, and stability achievable with such a system.

It is becoming clear that the final focus elements will likely be cryogenic, and so developing a system which will allow us to move the support girder precisely without providing a huge thermal leak will be another considerable challenge we will begin to investigate.

**Year three** of the project will be to move towards manufacturability of the linac mover at a low price, involving redesign of the components in collaboration with manufacturing firms to reduce price and to determine the most cost effective option for the driver system.

Year three will also include continuing development of mounts for the final focus mover.

The deliverables at the end of the project will be:

Year 1 (Note that some of the year one goals are partially funded by the existing project):
-Measurements of the resolution achievable using the micro-step driven FFTB mover, both for three-motor and five-motor configurations.
-Development of a metrology system capable of measuring the 5-axis motion of the mover with better than 50 nm precision.
-Results from feasibility of alternate shaft driver options.
-Designs for magnet mounts for a five-motor system.

Year 2:

- A design for a feedback system to stabilize a piezoelectric stack add-on to a mechanical mover capable of achieving 10 nm precision.
- A prototype mover system including these additions, and measurements of the resolution and stability achievable by such a system.

Year 3:

- An optimized-for-manufacturability design report for the beam line movers, including an optimized shaft driving system, measurements of system performance, and projected costs
- A final design for a final focus element mover.

This project must be coordinated with the magnet support work underway at FNAL. Our contact there is Harry Carter, and we will work in cooperation with him to make sure the movers are designed in conjunction with the supports.

This project is an excellent fit to the capabilities of the technical design facility at Colorado State University. The facility has been involved in manufacturing many components for HEP applications that require cost optimization due to the large number of items to be procured, as well as a great deal of prototype development and fixturing work. Through Prof. Wilson, The CSU HEP group has a long history of participation in the Linear Collider Detector development. The group is fully supportive of the technical design facility proposals to contribute to Linear Collider Accelerator development. Additionally, there is a precision measurements group in the department working on laser atom lithography projects lead by Prof. Siu Au Lee, which can provide advice and assistance as required.
Budget

There is no HEP base program grant support for Warner. All costs, including travel, associated with this proposal must be provided by the project.

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Institutions and personnel

Colorado State University, Department of Physics:
David W. Warner (engineer)

Stanford Linear Accelerator Center:
Gordon Bowden (staff scientist)

Contact person

David Warner
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(970) 491-1035
2.27. Effects of Coherent Synchrotron Radiation in Linear Collider Systems (LCRD)

Accelerator Physics

Contact person: James Ellison
email: ellison@math.unm.edu
phone: (505) 277-4613

New Mexico

Year 1: $35,000
Year 2: $35,000
Year 3: $35,000
Project Name: Effects of Coherent Synchrotron Radiation in Linear Collider Systems

Classification(accelerator/detector:subsystem): Accelerator

Institutions and personnel:

James A. Ellison, Professor of Mathematics, U. of New Mexico
Gabriele Bassi, PostDoc, Mathematics Department, U. of New Mexico
Robert Warnock, SLAC Physicist Retired and Current Visiting Scientist, also Adjunct Professor of Mathematics, UNM

Contact Persons: James A. Ellison, ellison@math.unm.edu, (505)277-4613
Robert Warnock, warnock@slac.stanford.edu, (650)926-2870

Motivation

There are two points at which coherent synchrotron radiation (CSR) could be of concern in linear colliders. First, it may cause transverse $x$-emittance degradation in bunch compressors, since energy changes due to CSR get mapped into transverse coordinates through dispersion. Second, it might cause longitudinal bunch instabilities in the damping rings at high current, possibly leading to a quasi-periodic, sawtooth behavior of the bunch length. Damping ring designs contain many meters of wigglers (for instance 46 m at NLC and 432 at TESLA), to reduce the damping time to a manageable value. The coupling impedance from CSR in the wigglers, combined with that from bending magnets, could induce the feared instability.

Bunch Compressors and Computation of CSR from Arbitrary Orbits

Preliminary estimates of emittance growth in bunch compressors have been made by Emma and Woodley [1]. They have done calculations for the Stage 1 and Stage 2 compressors (BC1 and BC2) of the NLC and for the Tesla bunch compressor (TBC) [2]. For BC1, BC2, and TBC their figures for emittance growth $\Delta \varepsilon_x/\varepsilon_x$ due to CSR were 2.4%, 5.5%, and 1%, respectively. Although these values are regarded as reasonably small compared to other sources of emittance growth, they are based on a simplified model of the CSR field, and cannot be considered a definitive conclusion. The field calculation, as implemented in M. Borland’s code ELEGANT, treats the source of the radiation as a line charge. In a macroparticle simulation the transverse
charge distribution is projected onto a longitudinal line to produce an effective radiation source. Moreover, the formula for the field is for a source moving on a trajectory which is straight except for a single bend. Consequently there is no proper integration of single bends to make a true chicane orbit. Actually, there should be a residual field after a bend which does not decay completely before the next bend is reached.

There exist large codes to compute CSR from an arbitrary charge/current distribution on fairly general orbits (by Dohlus et al. at DESY and Rui Li at JLAB), but these have proved to be cumbersome for actual design work and are not much used for that purpose. We have devoted considerable effort to finding a better calculational method, intended to be useful both for bunch compressors and rings, and perhaps also for wigglers.

**Ongoing and Proposed Work on Bunch Compressors and Computation of CSR from Arbitrary Orbits**

One approach that we have explored in recent months is to make a Fourier analysis of fields and sources in all spatial dimensions, with account of the large-wavelength shielding of CSR by the vacuum chamber (in a parallel plate model). This avoids the tricky integrations over singularities of the Green function that make the usual approach in space-time quite difficult. The price to pay is in dealing with fast oscillations of the integrand in the inverse Fourier transform to compute the field. We hoped that this problem could be handled by the method of stationary phase, but it turns out that this method is only partially effective. Since it still might be used in combination with other procedures, we are currently writing a careful report on our experience.

We have recently made what appears to be great progress by using a Fourier series only in the vertical coordinate $y$, perpendicular to the plane of the orbit. This makes it trivial to satisfy the field boundary conditions on the parallel plates that model the vacuum chamber. The resulting 2D wave equation has a "mass" term, the mass being the vertical wave number, and a remarkably simple Green function with a softer singularity than the usual Green function for the 3D wave equation. We think that this should provide an efficient and simple numerical method, and propose the implementation of such a method as a main item of research. We will first study a chicane bunch compressor with the charge/current source coming from a bunch with energy chirp, evolving only in response to the fields of the dipoles. Horizontal transverse spread of the charge distribution is fully accounted for, whereas the vertical distribution is arbitrary but constant in time. Later we hope to make the calculation self-consistent, allowing the phase space distribution to be affected by CSR. This could be done in a macroparticle simulation, or preferably in a less noisy Vlasov treatment if that could be done in reasonable computation time.

**Damping Ring Instabilities**

A representation of the impedance for CSR in wigglers has been proposed by Wu, Raubenheimer, and Stupakov (WRS)[3]. Wu, Stupakov, Raubenheimer and Huang (WSRH) [4] have combined this impedance with the usual impedance for CSR in dipoles to discuss the longitudinal instability threshold in damping ring designs for NLC and TESLA, and for the existing prototype damping ring at the KEK ATF. The instability study is done with coasting beam the-
ory for a line-charge beam, and without shielding of CSR. The conclusion is that the instability is indeed worrisome. The threshold is close to the nominal current for NLC and ATF. On the other hand, the dipole and wiggler impedances scale differently with frequency, and that leads to a possibility of optimizing the damping ring design to raise the threshold, perhaps by a factor of 4.

Proposed Work on Damping Ring Instabilities

Although the work of WSRH is a valuable first survey of the problem, it involves some serious assumptions that one would like to avoid. We propose to pursue the following improvements:

1. Avoid coasting beam theory by applying our program for numerical integration of the nonlinear Vlasov-Fokker-Planck (VFP) equation [7, 6]. We would begin with the Haßinski equilibrium distribution, and see whether it becomes unstable under time evolution by the VFP integrator. As the authors WSRH point out, the coasting beam theory is doubtful in this instance, because the Bousard criterion does not apply: the bunch length is not much larger than the unstable wave lengths.

2. Study possible saturation of any instability, again using the VFP code. That code has proved to be very useful for long term simulations, giving plausible results over several damping times.

3. Include shielding of CSR, which will be necessary in studying dynamics of unstable cases, and may have some effect on thresholds as well. We are not yet sure how to describe shielding for the wiggler radiation, and there is the complication that the vacuum chamber has different sizes in bends and wigglers. Some innovative approximations will certainly be necessary.

4. Criticize the mathematics and physics of the model of the wiggler impedance in WRS. This is for an infinite wiggler, and takes as its starting point results of Saldin et al. [5]. As far as we know the complicated Saldin analysis has not been verified by other authors, and in any case there are some puzzling singularities in the result that we would like to understand. After becoming familiar with the problem, perhaps we can treat the case of a wiggler of finite length, which of course would be more relevant for the prediction of thresholds.

5. Try to include non-zero transverse extent of the bunch. This would relate to work on the 2D Green function mentioned above.

Budget and Personnel

Warnock is a retired SLAC physicist with several years experience in CSR, see, for example,[6]. The proposal is based on his recent work, our joint progress over the last few months, and discussions with other experts at SLAC. Ellison has some modest experience with radiation by moving charges from his work on channeling radiation at CERN and Aarhus in the late eighties and is now deeply involved in the basic issues of CSR from particle bunches on more or less
arbitrary orbits. Bassi has been hired as a PostDoc, as of mid June, after completing a Ph.D. at DESY and the University of Bologna. He is making a substantial contribution to our CSR work.

Warnock is not asking for financial support; he finds it sufficient to get theoretical and numerical collaboration from Ellison and Bassi. Ellison is not asking for financial support either as CSR is one item in the research of his current DOE grant - DE-FG03-99ER41104 for "Investigations of Beam Dynamics Issues at Current and Future Accelerators". In addition, Ellison has funds in his DOE grant to partially support the CSR work of Bassi. We are requesting $35K/year for the 3 year period April 1, 2004 to March 31, 2007 to fill out the support of Bassi’s CSR work and to partially support a graduate research assistant. The $35K includes salary, fringe benefits, tuition, health insurance and the 50% indirect cost rate. Our current LCRD/DOE funding arrived too late to support a graduate student in the fall, however we have just hired a student who will begin work in mid December.

The proposal outlines an ambitious program that we find quite challenging.

References


2.29. Improved simulation codes and diagnostics for high-brightness electron beams
(UCLC)

Accelerator Physics

Contact person: Courtlandt L. Bohn
e-mail: clbohn@fnal.gov
phone: (815) 753-6473

NIU

Year 1: $65,621
Year 2: $57,572
Year 3: $59,006
3 Beam diagnostic monitors and electron sources

3.1 Improved simulation codes and diagnostics for high-brightness electron beams.

Personnel and Institution(s) requesting funding

C. Bohn, Department of Physics, Northern Illinois University.

Collaborators

H. Edwards, Fermilab
P. Piot, Fermilab
D. Mihalcea, Northern Illinois University
I. Sideris, Northern Illinois University
S. Voronov, University of Rochester and Northern Illinois University
U. Happek, University of Georgia
W. Gabella, Vanderbilt University

Project Leader

Courtlandt L. Bohn
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Project Overview

The first component of this proposal is the development of improved simulation codes for high-brightness photoinjectors. The ultimate goal is to have a fast, accurate simulation code that (1) couples the longitudinal and transverse dynamics, (2) accounts for rapid evolutionary time scales, and (3) quantifies details in the beam structure, such as beam halo. The Fermilab/NICADD Photoinjector Laboratory [FNPL; NICADD denotes the Northern Illinois Center for Accelerator and Detector Development headquartered at the Department of Physics, Northern Illinois University (NIU)], of which H. Edwards is the Facility Manager, is an electron injector like that used at the TESLA Test Facility; it provides an excellent basis for testing new codes against laboratory experiments. The second component of the proposal is development of interferometric and electro-optic diagnostics for measuring bunch lengths and density profiles. The diagnostics will be tested and improved at FNPL, and they will be used in conjunction with bunch-compression experiments.

Linear colliders call for an injected electron beam with high bunch charge, low normalized transverse emittance, and short bunch length. A generic desire is to optimize the beam brightness to minimize the need for beam “cooling” like that done with a damping ring. This is the underlying motivation for the flat-beam experiment that is being conducted at FNPL [1]. Ideally, the injected beam would have bunch charge well exceeding 1 nC, a normalized emittance of order 1 µm, and a bunch length of a few mm (which gets compressed by an order of magnitude at higher energies). These parameters push the beam-brightness frontier. Accordingly, to understand the underlying beam dynamics likewise pushes the frontier of injector-simulation tools. For example, one must account more accurately for intricacies of space charge and wakefield effects. As a matter of principle this can be done with an $N$-body code, but $N$ would need to be large and the computational time correspondingly long. To explore the parameter space in developing first designs of injectors, fast codes are needed, and to be used with confidence, these codes must comprise sufficiently accurate models of the beam physics. This is the context of the simulation effort discussed herein.
We propose to explore the possibility of developing a new code based on wavelets. The use of wavelets in the context of $N$-body simulations that involve long-range $1/r^2$ Coulomb interactions between particles is new. There is apparently only one related paper, and it was just published in June 2003 [2]. This paper demonstrates that wavelet denoising in the context of $N$-body simulations of two-dimensional disk galaxies results in a hundred-fold improvement in performance. The early stages of evolution in Coulomb systems are driven by long-range collective interactions as opposed to short-range collisional encounters; whether the two-body forces are attractive or repulsive should be relatively unimportant. Because the gravitational and electrostatic forces have identical long-range scaling, the findings of Ref. [2] should carry over to charged-particle beams. Our idea, conceived prior to the appearance of this paper, is to apply wavelet decomposition/denoising to three-dimensional beams with space charge. The basic advantage is that wavelets provide a multiscale “image” of the beam. Because noise arising from the use of macroparticles is present on all scales, the use of wavelets removes most of the noise without altering the beam’s inherent structure. In developing new code, C. Bohn will generally do the underlying theoretical work, and I. Sideris (a postdoctoral computational physicist) will generally do the programming. A NIU physics graduate student (who possesses a doctorate in mathematics) has begun to explore this topic as the basis for his Ph.D. dissertation in physics. We request funding to support this graduate student.

Preserving a hierarchy of scales in the time-dependent space-charge potential is dynamically important. Our recent research has revealed that nonlinear, time-dependent forces commonly establish large populations of globally chaotic orbits in beams that are out of equilibrium, and such orbits can even be present in thermal-equilibrium beams [3,4]. When present, these chaotic orbits mix exponentially throughout their accessible phase space with a time scale of only a few orbital periods, i.e., very much faster than collisional relaxation. We have also found that the presence of colored noise due to space-charge fluctuations and/or machine imperfections can, when combined with parametric resonance associated with low-order oscillatory modes, generate much larger halos than would be inferred from parametric resonance alone [5]. Thus, all scales are potentially important to the dynamics. The use of wavelets will generate potential-density pairs that preserve these scales, thereby enabling accurate computations that apply well beyond predictions of conventional root-mean-square beam properties. The new wavelet-based algorithm would apply anywhere collisionless processes are important. For example, as concerns linear colliders, it would apply not only to injectors, but also toward a better understanding of the dynamics in the TESLA damping rings.

The length of an electron bunch is an important parameter for high-energy linear colliders. Wakefields depend on the bunch shape and are a limiting performance factor. Plus, the luminosity at the interaction point depends on the phase spaces of the colliding beams. One approach for measuring the longitudinal density profile of the bunch is to measure and analyze the coherent radiation produced either by transition, diffraction, or synchrotron radiation. A generic instrument for doing so is an interferometer [6]. In addition, monitoring and controlling nonlinear influences on a beam, such as wakefield effects, requires excellent time resolution. Linear-collider applications call for a time resolution of about one-tenth the root-mean-square bunch length, which for the NLC works out to be $\sim10\ \mu$m. Moreover, single-shot capability is required for monitoring bunch-to-bunch fluctuations. Conventional techniques, such as streak-camera measurements, have much coarser time resolution, typically $\sim1$ ps, i.e., $\sim300\ \mu$m. The same comment applies to existing interferometers, in that they typically operate in the wavelength region above $\sim200\ \mu$m, which means accessing bunch lengths shorter than $\sim500$ fs has not been possible. Accordingly, these interferometers are also limited in their ability to distinguish fine structure in the longitudinal density profile.

Prof. Uwe Happek and his group at the University of Georgia have designed a number of Michelson interferometers; they are in operation at Cornell, Vanderbilt, UCLA, Argonne, and Jefferson Labora-
Interferometric diagnostics are high-bandwidth far-infrared (FIR) devices. Their implementation is generically “flexible” in that they can be used to measure, e.g., transition radiation emitted as the beam passes through a thin foil (an invasive measurement), or diffraction radiation emitted as the beam passes through a hole in the foil (a noninvasive measurement), or synchrotron radiation emitted during bunch compression (also a noninvasive measurement). NICADD recently procured from Happek a new Michelson interferometer that is designed to push down the lower limit of the accessible bunch length by an order of magnitude, i.e., to about 20 µm. D. Mihalcea (a postdoctoral experimental physicist) developed the control software and has been testing the new instrument. However, it averages over many bunches; it is not single-shot.

A next-generation single-shot interferometer that combines a multichannel detector with a Fresnel mirror to measure electron-beam-induced coherent radiation will be developed in connection with this proposal. The Fresnel mirror is used to divide the wavefront of the incoming coherent radiation; an interferogram forms in the focal plane due to the different path lengths of the resulting wavefronts. The Fresnel mirror eliminates the moving parts inherent to the Michelson design and results in a rugged instrument. This is an important advantage, particularly for a UHV instrument wherein the moving parts would require special bearings or vacuum feedthroughs.

Development of the single-shot instrument relies on the availability of a suitable multichannel detector. We propose to consider two options: a room-temperature array of mirage detectors and a cryogenically cooled array of superconducting transition-edge detectors. Either option could be used for a conventional interferometer with a single-element detector; the cryogenic detector is attractive in that it offers the possibility to design a windowless, ultrahigh-vacuum (UHV) device.

The mirage detector is based on the use of a thin metal film as a spectrally flat absorber. The film heats the air above its surface, and a diode-laser beam probes the heated air. Changes in the refractive index deflect the laser beam, and a position-sensitive photodetector monitors the beam’s location. The device’s sensitivity is accordingly limited by thermal fluctuations, similar to a Golay cell. Multichannel detection is achieved by focusing the laser beam with a cylindrical mirror to a line above the absorbing surface, with subsequent detection of the beam deflection by an optical multichannel detector (CCD, photodiode array, or position-sensitive detector array). A room-temperature mirage detector has the additional advantage of being compatible with the use of fiber-optic cable for remote detection, eliminating the ubiquitous electrical noise associated with linear accelerators. Disadvantages are its slow response time, limited sensitivity due to thermal fluctuations, and for an UHV device, the need for a vacuum window that would inherently limit the transmitted coherent radiation spectrum.

To monitor bunch-to-bunch beam dynamics for electron bunches emitted at a high repetition rate, we will develop a multichannel detector based on superconducting transition-edge bolometers. While the operation of these detectors is complicated by the need for cryogenics, they are both fast and sensitive. Moreover, the transition-edge detector array can be used in a UHV-compatible instrument connected directly to the beamline, thereby circumventing the need for a vacuum window.

To summarize, the plan is to develop a multichannel interferometer that will permit studies of single bunches, as opposed to properties averaged over many bunches. Existing multichannel FIR detectors are very large and cumbersome, making their use in accelerator beam lines impractical. By contrast, a single-shot interferometer based on the Fresnel mirror design (or equivalent approaches such as a Lloyd’s mirror) combined with a multichannel detector would enable compact devices, of roughly the size of the new Michelson interferometer (30 cm x 15 cm x 15 cm) recently procured from Happek. A portion of the funding for materials and supplies will likely be used in developing mirage detectors for interferometric applications. Prof. Happek will do most of the hardware development for the single-shot instrument; commissioning and testing will take place at FNPL.
Electro-optic (EO) sampling is a noninvasive technique offering picosecond time resolution of the electric field at the EO material [7]. It is based on the Pockels effect. When an electric field is applied to a certain class of crystals the refractive-index ellipsoid is modified, and as a result retardation (phase shift) is introduced between two orthogonally polarized components of a pulse of light traversing the crystal. This retardation can be detected by observing the change in the polarization of laser light transiting through the crystal. By using short laser pulses and varying the delay between the “probe” pulse and the pulse that produced the electron bunch, the “pump” pulse, one can sample the time dependence of the electric field.

In principle, the EO technique permits direct time-domain measurements of both beam-induced wakefields and the electric field from a single bunch itself. The technique was recently applied at FNPL in the former connection, specifically, to measure the beam-induced wakefield of a six-way cross [8]. The direct field of the bunch itself could not be resolved; the prevailing conjecture is that it was concealed by the arrival of the early-time wakefield at the crystal. The conjecture makes sense from simple time-of-arrival considerations pertaining to the geometry of the cross and the location of the crystal within the cross.

The design of the vacuum chamber housing the EO crystal is key to measuring the direct field of the beam. One possibility is to use a tapered vacuum chamber for low wakefields. We propose to design, build, and (in collaboration with Fermilab personnel) implement such a chamber, and thereby access the beam field. Part of the program will be to cross-correlate the density profile extracted from the EO-measured field against that from the interferometer and the projected longitudinal density obtained by use of a deflecting-mode cavity (once it is installed). These cross-correlations should go far toward validating the interferometric and electro-optic techniques. C. Bohn will do the theoretical work to design the vacuum chamber for the EO diagnostic. S. Voronov, a newly hired postdoctoral laser and optics expert will be key in commissioning and operating the new diagnostics. We request funds to purchase components for the interferometric and electro-optical diagnostics and to support a graduate student in commissioning the devices. In addition, we will collaborate with Dr. Bill Gabella of Vanderbilt University toward improving the time-resolution of the electro-optic diagnostic. In particular, Dr. Gabella will be working to develop an improved short-pulse probe laser.

Plans at FNPL are to install a third-harmonic deflecting-mode cavity to enable direct measurement of the beam’s longitudinal phase space. Once this diagnostic is available, we will use it as a cross-check of the interferometric and electro-optic diagnostics. Measurements with the full diagnostic suite at FNPL will be applied toward benchmarking the new simulation code.

**FY2004 Project Activities and Deliverables**

Activities: Develop theory for wavelet-based space-charge algorithm. Design the single-shot interferometer based on tests of multichannel detectors. Design low-impedance vacuum chamber for the electro-optic diagnostic and begin its fabrication.


**FY2005 Project Activities and Deliverables**

Activities: Develop and demonstrate the wavelet-based space-charge algorithm. Construct the single-shot interferometer and begin testing it at FNPL. Finish the low-impedance chamber and install it in FNPL; configure electro-optic diagnostic and begin testing.

Deliverables: Initial wavelet-based simulation code, single-shot interferometer, low-impedance vacuum chamber.
FY2006 Project Activities and Delievables

Activities: Benchmark the wavelet-based simulation code against FNPL experiments. Characterize beam with the interferometric and electro-optic diagnostics and cross-correlate their results. Improve the temporal resolution of the electro-optic diagnostic pending the successful development at Vanderbilt of a short-pulse probe laser.

Deliverables: Benchmarked simulation code. Papers on experiments involving the interferometric and electro-optic beam diagnostics.

Budget Justification

Successful completion of this proposal requires dedicated participants, both professional staff (not budgeted here) and two graduate students. It also requires modest hardware investments for the interferometric and electro-optic diagnostics, mostly toward the former. Most of the hardware costs appear in the first year (for the interferometric multichannel detectors and the electro-optic vacuum chamber). Modest funds for design modifications are requested for the second and third year as part of bringing the diagnostics to maturity.

Three-year budget, in then-year k$

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References


2.30. Beam simulation: main beam transport in the linacs and beam delivery systems, beam halo modeling and transport, and implementation as a diagnostic tool for commissioning and operation (UCLC)

Accelerator Physics

Contact person: Dave Rubin  
email: dlr@cesr10.lns.cornell.edu  
phone: (607) 255-3765

Cornell

Year 1: $16,060  
Year 2: $21,060  
Year 3: $32,640
2 Beam dynamics calculations and experiments, and accelerator design

2.1 Beam simulation: main beam transport in the linacs and beam delivery systems, beam halo modeling and transport, and implementation as a diagnostic tool for commissioning and operation.

Personnel and Institution(s) requesting funding
G. Dugan, L. Gibbons, M. Palmer, R. Patterson, J. Rogers, D. Rubin, D. Sagan
Laboratory of Elementary Particle Physics, Cornell University

Collaborators
A. Seryi, P. Tenenbaum - SLAC

Project Leader
D. Rubin
dlr@cesr10.lns.cornell.edu
(607)-255-3765, -8183

Project Overview
This project will cover simulations of main beam transport in linear colliders, with an emphasis on integrated damping ring to IP simulations; studies of the sources and transport of beam halo from its origin to the IP; implementation of modeling tools as a diagnostic for addressing commissioning and operational issues. Each of these topics is discussed in turn in the following paragraphs. Complete and robust simulation and modeling tools are critical to the evaluation of design and commissioning of NLC and TESLA, and our goal is to develop software with the flexibility to investigate the properties of both machine.

Main beam transport
One of the most essential features of a linear collider is the need for the preservation of a very small vertical emittance during beam transport from the damping ring to the IP. The best estimate of what is required to do this comes from integrated simulations of beam transport from the damping ring to the IP. Elaborate simulation programs have been developed at SLAC, DESY and CERN for the linear collider projects, in which errors can be incorporated, and realistic tuning algorithms can be explored, based on the expected performance of diagnostic systems. The errors are both static and dynamic, and include initial alignment errors, instrumentation resolution, ground motion and mechanical noise. Dynamic stabilization schemes and linac-based and IP feedback can be incorporated.

The worldwide effort in this area could benefit from additional manpower working in collaboration with the existing investigators to refine the simulation tools and develop improved tuning algorithms. We propose to join these ongoing beam simulation efforts, providing additional manpower, as well as fresh perspectives.

We will work closely with our collaborators, who have extensive experience in beam simulation, to identify critical issues which, in the context of the worldwide effort, require attention.

Particular areas of interest to us include the exploration of the tolerance of the baseline emittance preservation schemes to diagnostic faults, realistic modeling of the bunch compressors, and the effects of lattice mismatches. Also, one of our aspirations is to develop the machine model so that it can
eventually interact with the control system in such a way that we can use it to diagnose and correct machine errors. Until a real control system exists, we can simulate that as well and begin to understand how the operational problems will become evident and then how they might be addressed.

We would also like to explore the utility of simulations of beam transport from the source to the damping ring.

Our group has considerable experience developing computer models to study the properties of stored and accelerated beams, and for the evaluation of machine performance and diagnosis and correction of guide field errors etc. We have done extensive simulation of single particle dynamics, beam-beam interaction, long range interaction of multiple bunch beams, and of the injection process for both CESR (5.3GeV) and for CESR-c(1.9GeV). We also created a detailed simulation of the positron production process in our linac in order to improve efficiency, and a rudimentary model of a superconducting linac to explore the dependence of single and multi-bunch stability on cavity parameters. We are well equipped to contribute to the effort to model beam transport in a high energy linac.

**Beam halo modeling and transport**

Understanding and control of beam halo is a crucial issue for linear colliders. The extent of the beam halo impacts the design of the collimation systems and muon spoilers, which in turn determine background conditions at the detector. The collimation systems are also an essential part of the machine protection system, a key issue for machine reliability.

One of the principal open issues in the baseline linear collider designs is the absence of a fully developed pre-linac collimation system. Working with our collaborators, we propose to develop a realistic design for such a system.

Beam halo typically explores regions of the vacuum chamber far from the central axis, where magnetic field nonlinearities, often ignored in main beam transport simulations, may be important. We propose to study the transport of halo particles, represented as longitudinal and transverse beam distribution tails, from the damping ring to where the halo is intercepted, exploring, for example, the effects of nonlinear field errors.

The baseline linear collider collimation systems have been designed to cope with a relatively high level of beam halo, based on previous linear collider experience. This level is typically much larger than simple estimates would indicate. A more basic understanding of the origin of beam halo would allow a better optimization of the collimation system design. We propose to simulate the sources of beam halo (e.g., due to scattering processes in the damping rings, dark current in the linac cavities, etc.) and track these particles from their sources to the collimation systems, where they are removed from the beam. Comparisons will be made to the assumed halo used for the design of the baseline collimation systems for NLC and TESLA, and to the SLC beam halo experience.

**Machine commissioning and operation**

During machine commissioning, interpretation of measurements of beam position monitors, beam size monitors, cavity higher order modes, etc. will be critical to identification of component failures and implementation of correction algorithms. Typically a simulation is used to compute the effects of the guide field on the beam so that the consequence of various field errors, misalignments, etc. can be anticipated. But during commissioning we must first measure the guide field errors, so that with the help of the models, appropriate corrections can be determined. We plan to develop the modeling tools to extract information about the guide field from the beam instrumentation, so that we can simulate the diagnosis and optimization of machine performance.

**Project Activities and Deliverables**

2.30.3 UCLC project description 181
The descriptions of year-by-year activities provided below are representative of one possible course of action which seems plausible at this juncture. It should be appreciated that, as we develop a more mature understanding of the issues, and the roles that are most suited for us, and as the needs of the worldwide linear collider effort evolve, it may turn out that the order in which tasks are undertaken is different from what is described below. For example, the beam halo work, described below as being done in the second and third years, could in fact start in the first year, if that turns out to be advantageous. If such a reordering occurs, we expect to produce the same deliverables as specified below, but in different years.

**FY2004 Project Activities and Deliverables**

During the first year, we will work with our collaborators to assemble, at Cornell, a suite of the existing main beam simulation tools. We will develop expertise in the use of these tools, initially by studying already-solved problems and simple examples. This will allow us to tackle unsolved problems. We will then use the existing codes to address one of the outstanding issues noted above. The exact choice will be determined by the needs and priorities of the worldwide linear collider simulation efforts at that time.

Evidently, a single code, with the capability of modeling damping rings, bunch compressors, linear acceleration, including wake effects, and beam delivery system, does not exist. At present, damping ring to IP simulations are based on mating different codes with emphasis on different physics. We plan to extend the capability of the code that has been developed for modeling CESR and CESR-c dynamics (BMAD) so that we can build a complete end to end simulation, including the beam beam interaction.

To become familiar with the issues involved in the control of beam halo, and to address a known issue in collimation system design, we will undertake a detailed design of pre-linac collimation systems for NLC and TESLA.

The deliverables for the first year will be the capability to use the existing main linac and beam delivery systems simulation routines, and a technical report addressing an outstanding issue in beam simulation. We will also provide improvements to, and/or cross-checking of, some of the existing simulation codes. Finally, we will write a technical report specifying a design for pre-linac collimation systems for NLC and TESLA.

**FY2005 Project Activities and Deliverables**

In the second year, we will continue to address main beam transport code improvements, and will tackle several other simulation issues which are high priority, and which are suitable for our expertise and interests.

In this year, we will begin to consider what is needed in code development or modification for halo transport. We will build upon existing codes whenever possible. We expect to be able to produce useful results on beam halo transport this year.

We will also develop a strategy for understanding the sources of beam halo.

The deliverables for the second year will be technical reports describing additional code improvements and studies of main beam transport issues. We will also produce codes to do beam halo transport in the main linacs and beam delivery systems. We will write a technical report on the first results from our beam halo transport studies. We will also write a technical report outlining our strategy for understanding and simulating sources of beam halo.
**FY2006 Project Activities and Deliverables**

In the third year, we expect continue to address outstanding high priority issues in main beam transport.

Based on the halo source strategy developed in the previous year, we will develop codes which simulate the sources of beam halo, and couple these to our halo transport codes. We will compare the results of this work with the assumed halo used for the design of the baseline collimation systems for NLC and TESLA, and to the SLC beam halo experience.

The deliverables for the third year will be additional technical reports describing studies of main beam transport issues. We will produce a technical report documenting our studies of halo sources and halo transport, and the comparisons with linear collider halo design assumptions and SLC experience. Finally, we will write a technical report documenting the diagnostic capability of our codes, including, for example, evaluation and correction of orbit, optical and coupling errors based on beam position monitor data.

**Budget justification**

This work will be carried out primarily by the personnel noted above from Cornell, with help from our collaborators. We have requested support for one graduate student in the first year of the activity, growing to 1.5 and then 2 in the subsequent years (not included in this budget). Computing equipment support for the student(s), and a small travel allowance for meetings with our collaborators and conference attendance is included.

Indirect costs are calculated at Cornell’s 58% rate on modified total direct costs.

**Three-year budget, in then-year K$**

**Institution:** Cornell University

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2.32. Damping ring studies for the LC (UCLC)

Accelerator Physics

Contact person: S. Mtingwa
email: mtingwa@mit.edu
phone: (336) 334-7423

NCA&T

Year 1: $45,840
Year 2: $51,070
Year 3: $56,300
2.2 Damping ring studies for the LC

Personnel and Institution(s) requesting funding
S. Mtingwa, Department of Physics, North Carolina A&T State University

Collaborators
K. Kubo, KEK, Tsukuba, Japan

Project Leader
S. Mtingwa
mtingwa@mit.edu

Project Overview
The goals for the beam emittances of the proposed Linear Collider (LC) are far smaller than those achieved at existing accelerators. Thus, the obstacles to be encountered will be substantial, although hopefully not insurmountable. A major limitation on the performance of the LC will be the damping rings and the emittances achieved there. Experiments have been performed, or are planned, at a number of facilities, including the ATF at KEK and CESR at Cornell. We propose to travel to the ATF for a two-week period and to CESR for a two-week period per year for the next three years to assist in gaining a theoretical understanding of the results of their experiments.

The NLC/JLC design normalized horizontal emittance coming out of the damping rings is 3 mm-mrad, with the normalized vertical emittance being two orders of magnitude smaller. The beam charge is about $10^{10}$ particles per bunch. The most important limitation on achieving the design emittances in the damping rings is that of intrabeam scattering (IBS). Thus, it will be important to understand more fully the challenges that intrabeam scattering will present. With James Bjorken, we developed the theory of IBS for strong focusing accelerators and spent a number of years at Fermilab analyzing beam emittance growth rates from IBS in the Antiproton Source’s Accumulator Ring. Also, we worked with David Finley and Alvin Tollestrup in analyzing IBS growth rates for the Tevatron upgrade. In this project, we will revisit IBS within the context of the LC damping rings. The results will be important for the TESLA design as well.

FY2004 Project Activities and Deliverables
Intrabeam scattering involves multiple small-angle Coulomb scatterings of particles within a bunch. The theory in Reference [2] does not specify the precise minimum scattering angle of the particles and only estimates it. Some work on this effect is contained in Reference [3]. During the first year, we propose to work more on this issue. Also, we will begin our studies of the data from prototype damping ring experiments at ATF, CESR, and the Advanced Light Source. Our results will be written in a detailed report and published.

FY2005 Project Activities and Deliverables
The vertical emittance in a damping ring is largely determined by vertical dispersion and horizontal-vertical coupling; thus, one wants to minimize these effects in the accelerator lattice design. Even so, the operating regime of the ATF demands a better understanding of the coupling among the three degrees of freedom and its effects on intrabeam scattering. An excellent start in this direction is contained in Reference [3], where they extended the theory contained in Reference [2]. During the
second year, we propose to analyze this effect further and compare with the data from the prototype experiments. Our results will be written in a detailed report and published.

**FY2006 Project Activities and Deliverables**

Armed with a better understanding of the predictions of intrabeam scattering, during the third year, we will concentrate on the wealth of data that should have been collected by that time and fine tune our understanding of the ability to achieve the small design emittances of the various linear collider designs. Others are studying various other effects that could compromise the damping rings’ performance. These include such effects as electron cloud build-up, residual gas ionization, the injection efficiency of the damping rings, the interaction of the beam with radiation, and the influence of newly injected pulse trains on ones previously stored. During the third year of this project, we plan to use the results from those other studies to achieve a quantitative understanding of how to unravel those other effects from that of intrabeam scattering. Our results will be written in a detailed report and published.

**Budget Justification**

The entire project will consist mainly of theoretical and computational calculations. The first year’s budget will mainly support one graduate student and travel for the Principal Investigator (PI) to spend two weeks at the ATF in Japan and two weeks at CESR at Cornell University. Computational equipment will be purchased for the graduate student.

During the second year, we include the same funds as requested the first year, increased mostly for inflation. Also, computational equipment will be purchased for the PI.

During the third year, we include the same funds as requested the second year, increased mostly for inflation. Also, additional computational equipment will be purchased for the PI.

Indirect costs are calculated at North Carolina A&T’s 40% rate on modified total direct costs, which excludes tuition.

**Three-year budget, in then-year K$**

**Institution:** North Carolina A&T State University

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2.33. A Compact Wakefield Measurement Facility (LCRD)

Accelerator Physics

Contact person: Young-Kee Kim
email: ykkim@hep.uchicago.edu
phone: (773) 834-9131

ANL
Chicago
Fermilab

Year 1: $47,900
Year 2: $89,300
Year 3: $74,300
**Project name:** A Compact Wakefield Measurement Facility  
**Classification (accelerator/detector: subsystem):** Accelerator  
**Institution(s) and personnel**  
University of Chicago: Kwang-Je Kim and Young-Kee Kim  
Argonne National Laboratory: Wei Gai and John Power  
Fermi National Laboratory: David Finley and Nikolay Solyak  
**Contact person:** Young-Kee Kim

**Project Overview**

A fundamental concern for the NLC is the beam-induced wakefield effect. In general, the short-range wake acts back on the beam and degrades its quality, while the long-range wake deleteriously affects subsequent bunches. Specifically, wakefields can be divided into four classes: (1) the short-range transverse wakefield that causes single-bunch emittance dilution and drives the single-bunch beam breakup (SBBU) instability; (2) the long-range transverse wakefield that causes integrated emittance dilution and drives the multibunch cumulative beam breakup (MBBU) instability; (3) the short-range longitudinal wakefield that induces a correlated energy spread on each bunch that, left uncorrected, will give rise to dispersive emittance growth; and (4) the long-range longitudinal wakefield that is responsible for beam loading.

Wakefield effects such as due to RMS structure misalignment and schemes to suppress these effects (e.g. emittance bumps) have been studied mainly with numerical calculations and with previous machines, such as the SLC. These techniques, however, will work at the NLC only if the structure wakefields are below certain thresholds. For example, the RMS structure misalignment must be less than 20 μm to avoid resonant instabilities. For **quality control** reasons it is imperative that the wakefield characteristics of each NLC structure be accurately measured before being installed into an NLC accelerating module. Traditionally, a GeV scale electron beam is used for mapping transverse wakefields in NLC structures (ASSET), but we suggest that this can also be done more easily, quickly, and cheaply with a dedicated low energy facility if the electron beam brightness is sufficiently high. High brightness electron beams can be generated by laser-driven RF photocathode guns.

We propose to demonstrate that a state of the art, direct wakefield measurement can be made using an inexpensive and flexible, photoinjector-based, 10 MeV accelerator. We plan to use the Argonne Wakefield Accelerator (AWA) facility at ANL to build a prototype version of this facility to prove the validity of this concept. In addition to having a transverse wakefield measurement resolution comparable to ASSET, this facility will also be able to measure longitudinal wakefields and emittance dilution. If successful, a dedicated facility could be constructed to serve as an NLC quality control center.

This project will be a collaborative effort by the University of Chicago, ANL, and FNAL. The University of Chicago students will participate in the modeling and testing of the diagnostic devices and in the wakefield measurement. The prototype facility will be assembled and tested at the AWA facility, taking advantage of the extensive experience...
on wakefield measurement by its staff. The Technical Division at FNAL will provide additional accelerator components, RF expertise, and the NLC structures.

**High Brightness Electron Beam Generation at the AWA**
Although a 1 GeV beam has been used in the past to measure the wakefields of NLC structures, a low energy electron beam could also be used if the beam brightness, which is given by beam current divided by emittance squared, were sufficiently high. A new 1 ½ Cell L-band (1.3 GHz) photocathode gun at the AWA facility has recently been commissioned. The primary purpose of this gun is to generate high-intensity beams, with a bunch charge of about 100 nC, for studying wakefield acceleration schemes. The beam produced by the gun in the high-intensity mode is not suitable for characterization of NLC structures due to the large normalized beam emittance of about 100 mm-mrad. However, preliminary studies have shown that the gun can be operated in a high brightness mode (bunch-charge of 2 nC and emittance of 2 mm-mrad) that is suitable for the measurement of wakefields in NLC structures. We plan to carry out a detailed simulation study of the AWA gun to determine the optimum configuration for the high-brightness mode.

**The Wakefield Measurement System at the AWA**
Once the high-brightness mode of the AWA L-Band gun is established, both numerically and experimentally, this beam can be used to drive wakefields in X-Band structures. A zeroth order design of this system was presented at the 2003 Particle Accelerator Conference (J. G. Power et al., “A Compact Wakefield Measurement Facility”, PAC2003), but only a brief summary is given here.

**Beam Dynamics**
The existing AWA configuration can be used to directly measure both the transverse and longitudinal wakefields. At the AWA facility the ‘drive’ beam (ED = 10-20 MeV) is used to excite a structure and the ‘witness’ beam (EW = 3-5 MeV), following the same trajectory as the drive beam, is used to probe the wakefield. If we assume: (1) the drive energy = ED = 10 MeV, (γ~20), the drive normalized emittance = εD,n = 2 μm; (2) the witness energy = EW = 5 MeV (γ~10), the witness normalized emittance = εW,n = 1 μm; and (3) βD* = βW* = 1 m is the beta function at the center of the structure; then the unnormalized emittance = εD = 2 μm/20 = εW,n = 1 μm/10 = 10⁻⁷ m. This means that both beams can easily be matched into the same transport beam line passing through the tube. In both cases, the beam at the center of a L = 1 m structure is σ* ~ 310 μm and the beam at the exit is σ ~ 340 μm both of which are significantly smaller than the inner iris of an NLC structure, radius ~ 3 mm.

**Transverse Wakefields**
In general, for an NLC structure, the transverse kick from the dipole wake, W' (z), ranges between 0.1 (long-range wake) and 100 V/pC/m/mm (short-range wake) where z is the separation between the drive and witness beam. The transverse wakefield measurement resolution at ASSET, or the minimum measurable dipole wake, is 0.1 V/pC/m/mm. Using: (1) the AWA drive beam is 2nC so the net transverse kick from the minimum dipole wake is (2000 pC)* 0.1 V/pC/m/mm = 200 V/mm/m; and (2) the witness beam energy is 5 MeV so the angular deflection for a drive beam offset of 1 mm and a structure
length of \(L = 1\) m we have \(\Delta \theta_y = 0.2kV/5000kV = 40\mu rad\). At a distance 1 meter downstream this produces an offset of 40 \(\mu\)m, well within the range of a typical BPM resolution. The drive beam is separated from the witness beam by taking advantage of the energy difference between the beams (10 MeV vs. 5 MeV) and passing them through a bending magnet.

**Longitudinal Wakefields**

The longitudinal wakefields can be very simply measured by placing the existing AWA high resolution spectrometer (~0.1%) at the end of the witness beamline. For a 5 MeV witness beam this would mean that we could observe absolute energy changes of 5 keV. Thus, for an \(L=1\)m structure, we could detect integrated longitudinal wakes of 5 kV. Such a small longitudinal wakefield would be nearly impossible to observe at ASSET since the minimum observable energy change would be 0.1% of 1 GeV, which is 1 MeV.

**Emittance Dilution**

The emittance dilution of the drive beam will be measured in two ways: (1) measure the correlated 4-d transverse emittance before and after the structure; and (2) measure the slice emittance. The latter is especially important for understanding the head-tail instability. To do these characterizations we will need to develop new, high-precision diagnostic hardware. We plan to develop a diagnostic with the ability to map the full 4-d correlated transverse phase space (not the usual 2-d emittance) by using a ‘pepper pot’ with a hole pattern that reveals the 4-d information, a YAG phosphor screen, and a scientific grade camera. We plan to develop the slice emittance diagnostic by using a pepper pot, a Cherenkov radiator, and the existing AWA streak camera.

**Beam Centering Measurements**

We speculate that it is possible to implement a system for finding the electrical center of all cells within an NLC structure by using the technique developed at SLAC [M. Seidel, SLAC-PUB-7519]. The method works by measuring the dipole power spectrum coupled out through the damping manifolds of the NLC structure. This power spectrum of all the cells is known and is centered around 15.1 GHz with a Gaussian detuned width of 2.9%. (Although the NLC structure design is still changing, the power spectrum for any particular design can be calculated, and the range given here is thought to be representative of the final design.) By stepping the drive beam across the vertical plane and monitoring the power emitted from a particular cell (by measuring the amplitude of its dipole mode resonant frequency), we can find the minimum power position and thus have found the electrical center of that cell. To do this measurement we can make use of ANL’s existing 70 GHz HP Spectrum Analyzer and only need to purchase some simple rf circuitry.

**Work and Deliverables**

These are all ideal projects for student training. The funding requested is mainly for student support for 2-3 years and diagnostics installation.

**Year One Project Activities**

Since the resolution of the wakefield measurement system depends strongly on the BPM (beam positioning monitor) system, the first year of work will be on this system. We will
supervise two undergraduate students, working together, on a hardware oriented project based on the BPM system. Their goal will be to (1) study the various options for the BPM system (e.g. stripline BPM, button BPM, phosphor screen and camera, etc.) and (2) develop the BPM system most suitable for the wakefield measurement system. If, for example, a stripline BPM is chosen, they will begin by familiarizing themselves with the standard literature where they will learn the basic principles, such as how to calculate the field pattern in an ideal stripline BPM. They will then learn how to run an electromagnetics code to simulate the device, learn how to use a wire-based technique to calibrate, install the BPM in an UHV beamline, and finally write a computer control program for the BPM data acquisition. The work plan will follow this same basic outline for any of the systems chosen.

**Year Two Project Activities**

In the second year, our two undergraduates will begin working with a new graduate student, and together, they will turn the zeroth order design of the facility into a thoroughly designed facility. They will also begin acquiring the hardware needed from either FNAL or outside vendors. To do this they will perform the following tasks: (1) a detailed numerical parameter study of the AWA photocathode guns; (2) simulation of the emittance dilution in an NLC structure; (3) simulation of the beamline optics; and (4) a mechanical design of the wakefield measurement system. The tools that will be used for the simulation of the gun dynamics and emittance dilution are PARMELA and MAFIA.

We will examine the output beam quality vs. laser profiles (spot size, laser pulse length, etc.), the RF injection phase, and magnetic field settings. The beamline optics will be designed with COMFORT, TRANSPORT, TRACE-3D and PARMELA. Since the drive beam will be space charge dominated, it is important that PARMELA is used to verify the beam transport results of the other codes. In the case of the witness beam transport, the charge will be about 10 pC and is therefore emittance dominated. The development of the wakefield measurement system will consist of a translation stage, under the control of the software control system that can step the structure transversely to the beam.

Towards the end of the second year we will begin beam characterization experiments of the photocathode gun based on the simulation results obtained for the low charge operating mode.

**Year Three Project Activities**

In the third year we plan to complete the beam characterization experiments and begin wakefield measurements of NLC structures. We will characterize the drive beam at (1) the beginning of the beamline (i.e. the exit of the gun); (2) along the beamline path, including the structure location, to monitor for beam quality preservation; and (3) the end of the beamline at the offset BPM and spectrometer to estimate stability. A similar characterization of the low charge witness beam in this new beamline will also be necessary, but will be much simpler since the witness beam is already well understood.

Once the gun and beamline are operational, we can use this system to measure beam-induced transverse and longitudinal wakefields in the NLC structures. Toward the end of the third year we plan to install an NLC structure in the AWA shielding bunker and begin wakefield characterization of the structure. This will include transverse and longitudinal wakefields measurements. By continuing to develop the diagnostics made during the first
year, we plan to measure emittance dilution of the beam after passing through the structure. Finally, we will implement the beam centering rf circuitry developed at SLAC using the AWA HP Spectrum Analyzer.

Based on the lessons learned during the three years of this project, we will finish by writing a technical design report for building a production level, wakefield measurement facility in the third year. In addition to producing this report, work to characterize NLC structures will continue.

**Budget**

**Justification**
Most of the resources needed are already part of the ANL and FNAL infrastructure, including: (1) the expertise and the computing resources needed to run the above codes; (2) access to MAFIA and LIAR; (3) the expertise at designing high quality beam diagnostics; (4) diagnostic infrastructure including a streak camera, ICTs, profile monitors, etc. Much of the resources that ANL does not have, such as BPM electronics, magnets, EM software will be made available by FNAL. The funding requested is mainly for student support (two undergraduate students from the University of Chicago, Ya-chieh Hsin and Jonathan Walsh) and some additional diagnostic hardware. Although most of the diagnostics already exists at the AWA, some of it will have to be modified to become suitable for beam measurements at lower charge. Diagnostic hardware required includes a gated, intensified, high resolution camera, a pepper pot, a quartz radiator, vacuum support hardware; etc. These diagnostics will be designed and ordered during the second year – some of them will be installed into the system. Additional effort will be primarily for installation of the beamline components and the diagnostics. This will require substantial assistance from a technician in addition to student support (two undergraduate students, Ya-chieh Hsin and Jonathan Walsh, and one graduate student). Again, much of the existing ANL and FNAL infrastructure can be leveraged for this proposal including magnets for the beamline, video processing software, spectrum analyzer, etc.

**Detailed Funding Request**

**FY 2004 (Then year dollars)**

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**FY 2005 (Then year dollars)**

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FY 2006 (Then year dollars)

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<td>one U of C graduate student:</td>
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<tr>
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<td>Tuition</td>
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2.34. Experimental, simulation, and design studies for linear collider damping rings (UCLC)

Accelerator Physics

Contact person: Joe Rogers
email: jtr1@cornell.edu
phone: (607) 255-4093

Cornell
Minnesota

Year 1: $70,557
Year 2: $130,193
Year 3: $37,422
2.4 Experimental, simulation, and design studies for linear collider damping rings

Personnel and Institutions requesting funding
R. Poling, A. Smith, University of Minnesota.

Collaborators
W. Decking, DESY
S. Mtingwa, North Carolina A&T State University
M. Ross, SLAC
J. Urakawa, KEK
A. Wolski, LBNL

Project Leader
J. Rogers
jtr1@cornell.edu
(607)255-4093

Project Overview

Studies of wiggler-related dynamic aperture limitations. Two classes of circular accelerators will generate damping almost entirely in wiggler magnets: linear collider damping rings and some low-energy $e^+e^-$ factories, such as CESR-c. Wiggles are unlike typical accelerator magnets in that they have longitudinal magnetic fields which are comparable to their transverse fields. Also, the design orbit has an angle and a displacement relative to the wiggler axis. The combination of the longitudinal field and the angle through the wiggler produces an effective field error, as does the combination of the field roll-off near the wiggler edge and the displacement from the wiggler axis. The effective field nonlinearity is quite strong, severely limits dynamic aperture in linear collider designs, and may decrease the damping rate for large-amplitude particles. We intend to develop and test a design algorithm for wigglers and lattices which preserves the dynamic aperture, and test this algorithm with beam measurements in CESR-c. We will apply the same techniques to the various linear collider damping ring designs to demonstrate that they have adequate dynamic aperture and amplitude-dependent damping rate (or optimize those designs until they do).

Studies of beam-based alignment and emittance correction algorithms. The linear collider damping rings designs have an unprecedented low vertical emittance. Coupling and vertical dispersion must be very well corrected. It is likely that beam-based alignment (BBA) will be needed to reference the beam position monitors to the magnets with high precision. We plan to model BBA and correction algorithms in the ATF damping ring at KEK and in CESR-c with the simulation code BMAD (see below), with special attention to the role of systematic errors in BBA. We will compare the simulation results with observations at ATF and at CESR-c. The goal is to produce improved BBA and emittance correction algorithms.

Studies of intrabeam scattering. At the high particle densities of the linear collider damping rings, intrabeam scattering (IBS) will cause an increase of the emittance of the beams. In the NLC main damping ring the achievable emittance may be limited by IBS. Several theoretical models [1], [2], [3] have been used to calculate IBS emittance growth rates. These models agree well with each other, but may be in disagreement with experiments at the ATF. We plan to use CESR-c in a low-emittance mode to measure the IBS emittance growth, evaluate the theoretical models, and to compare with the
Studies of space charge effects. The large density of particles in the linear collider damping rings creates a significant space charge tune shift. The tune shift is not the same for all particles, and the area of the tune “footprint” is significant. If this tune footprint overlaps strong resonance lines, particles may be lost, or the emittance may grow. We want to determine if it is possible to operate a storage ring with the large space charge tune shift of the linear collider damping rings without excessive losses or emittance growth. To do this, we will operate CESR-c in a low emittance mode and scan the tune plane while monitoring beam lifetime, radiation, and beam size. These observations will be compared to particle-tracking simulations including space charge.

Investigation of collective effects relevant for damping rings. Several beam stability issues are of particular importance for the damping rings of future linear colliders. Each will be investigated by machine studies in CESR-c. These are: the instability threshold for the electron-cloud effect in a low emittance, wiggler dominated ring; the instability threshold for the fast-ion instability in a low-emittance ring; and impedance-driven instabilities at the short bunch lengths of the linear collider damping rings. We will also investigate strategies for electron emission suppression (e.g., by the use of coatings such as TiN).

High-quality beam diagnostics are required for the measurement of small beam sizes and short bunch lengths. We plan to improve the following existing CESR diagnostic systems: high-resolution beam size diagnostics (interferometric technique); and streak camera bunch length and shape monitoring.

Development of simulation and modeling tools. We have begun the development, at Cornell and at Minnesota, of simulation and modeling tools to support the measurements in CESR-c and the analysis of ATF data. The modeling code is based on an existing object-oriented particle-tracking library, BMAD [4], that has been extensively tested against an operating machine, CESR. We are constructing an Intel architecture, Linux operating system computing farm at Minnesota, approximately 10% of which will be dedicated to linear collider accelerator work, with the remaining 90% for the CLEO-c program. Funding for this facility has been obtained from the Department of Energy and the University of Minnesota. Ten 2-GHz processors are currently installed, with acquisition of 60 faster processors planned for late summer 2003. An additional 60 processors are planned for acquisition by summer 2004. The porting of the simulation tools from Tru64 (Compaq Alpha Unix) to Linux should be completed by fall, and preliminary testing is already under way of the management system for running tracking computations in a multiprocessor environment.

To understand the significance of measurements in CESR-c, we will make detailed comparisons of the simulated properties of the linear collider damping rings with CESR-c, including dynamic aperture with wiggler nonlinearities, intrabeam scattering, space charge, and other collective effects. We will also use the models to explore coupling and dispersion correction schemes that can then be tested in CESR-c. Our study will include an independent evaluation of the characteristics of the NLC and TESLA damping rings.

Review of TESLA damping ring design and optics. The large number of bunches (2820) and the relatively large inter-bunch spacing (337 ns) in the TESLA design gives a bunch train which is more than 200 km long. A damping ring of this size would be very costly, and so the bunch train is damped in a compressed form, with a bunch spacing of 20 ns, leading to a damping ring with a circumference of 17 km. This ring is still quite large, and, apart from the cost issue, has some technical disadvantages (such as large space charge effects) related to its large size. We will investigate other technical solutions (such as vertically stacked rings) for the damping rings, and compare the advantages and
disadvantages relative to the baseline design. Many of the constraints on the ring design are determined by fast kicker technology. We propose investigating and prototyping a fast kicker in another section of this proposal.

Investigation of the superferric option for NLC and TESLA damping ring wigglers. The baseline design of wigglers for NLC and TESLA is based on permanent magnet technology. Superconducting wigglers were also considered in both cases but not chosen. At LEPP, we have experience both with permanent magnet systems, and, in connection with CESR-c, have developed expertise in the design and fabrication of superferric wigglers. We will re-examine the possibility of superferric wigglers for the linear collider damping rings. We will re-evaluate the technical and cost advantages and disadvantages of each technology choice.

**FY2004 Project Activities and Deliverables**

During the first year we plan to:

1. Complete the development of a design algorithm which maximizes the dynamic aperture of a wiggler-dominated ring;
2. Calculate the intrabeam scattering growth rate for the ATF, NLC, and TESLA damping rings and a low-emittance configuration of CESR-c using multiple theoretical models [1], [2], [3] (including development of codes when not currently available);
3. Develop a space charge element for particle tracking simulations;
4. Complete development of an Intel architecture, Linux operating system computing farm at Minnesota with a 10% share for linear collider research.
5. Complete the port of the Cornell accelerator simulation tools from Tru64 to Linux and implement parallel processing on the Minnesota computing farm.
6. Start upgrades of the streak camera bunch length and shape monitor and the interferometric beam size monitor, including integration into the CESR control system;
7. Perform an independent evaluation of the robustness of the NLC and TESLA damping ring lattices; and
8. Investigate and report on alternative damping ring solutions for TESLA.

The first year deliverables are the publicly available simulation codes of item 3 above and four technical reports on items 1, 2, 7, and 8.

**FY2005 Project Activities and Deliverables**

In the second year we plan to:

1. Benchmark the design algorithm and particle-tracking code for a wiggler-dominated ring by measuring the dynamic aperture, orbit-dependent tune shifts, decoherence, phase space distortion, and amplitude-dependent damping rate in CESR-c;
2. Measure the intrabeam scattering growth rate in a low-emittance configuration of CESR-c and document the implications of this measurement for analysis of the ATF data and for the linear collider damping rings;
3. Perform a complete simulation (tune plane scan) of the NLC and TESLA damping rings and CESR-c, including wiggler nonlinearities, intrabeam scattering and space charge, to determine the optimum operating points and particle loss rates;
4. Complete upgrades of the streak camera bunch length and shape monitor and the interferometric beam size monitor, including integration into the CESR control system;
5. Develop well-optimized correction algorithms for BBA and vertical dispersion and coupling correction that can be applied to the NLC and TESLA damping rings and to tests in CESR-c and possibly ATF;
6. Perform an analysis of the ATF BBA and emittance correction data; and
7. Perform an evaluation of the technical and cost advantages of permanent magnet and superferric wigglers for the NLC and TESLA damping rings.

The second year deliverables are six technical reports on items 1, 2, 3, 5, 6 and 7 above and the upgraded instrumentation of item 4.

**FY2006 Project Activities and Deliverables**

In the third year we will complete this program. We plan to:

1. Apply the design algorithm for optimizing the dynamic aperture in a wiggler-dominated ring to the NLC and TESLA designs and optimize the NLC and/or TESLA designs if their safety margin is found to be inadequate;
2. Perform an experimental tune-plane scan in a low-emittance mode of CESR-c while monitoring beam lifetime, particle loss, and beam size to benchmark the particle-tracking code;
3. Implement and test the algorithms for BBA and vertical dispersion and coupling correction in a low-emittance configuration of CESR-c;
4. Measure the instability threshold for the electron-cloud effect, the fast-ion instability, and impedance-driven single-bunch instabilities at short bunch length in a low-emittance configuration of CESR-c.

The third year deliverables are four technical reports on items 1 through 4 above.

**Budget justification:** Cornell University

Each year’s activities will require the involvement of Cornell LEPP staff members and one graduate student (who are not included in the budget shown here).

The first year’s activities at Cornell will require travel funds for consultation with collaborators at DESY, SLAC, KEK, and LBNL. Construction of the upgraded instrumentation will require funding for materials and supplies.

The second year’s activities at Cornell will require travel funds for consultation with collaborators. Construction and installation of the upgraded instrumentation will require funding for materials and supplies and 1/4 FTE technician manpower.

The third year’s activities at Cornell will require travel funds for consultation with collaborators. Indirect costs are calculated at Cornell’s 58% rate on modified total direct costs.

**Three-year budget, in then-year K$**

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</table>

(1) Includes 26% of first $25K subcontract costs

**Budget justification:** University of Minnesota

The budget for the Minnesota component of the project assumes that scientific personnel (Poling, Smith), who receive base support from the Department of Energy, will be partially redirected from other activities to linear collider research. High energy physics graduate students who have not yet embarked on a thesis project will be recruited to participate in this effort for roughly one year each. This will provide an accelerator-physics option as part of the training of HEP students, a model that could help to address workforce needs both within our field and in other areas where accelerator science has application. For the first year of the project, while the group continues its ramp-up and development of expertise, support is requested for one student only for the summer of 2004. In the second and third years full support is requested for one student during the summer and half-time support is requested for one student during the academic year. It is expected that one undergraduate student at a time will also be involved in this research, with support from University of Minnesota undergraduate research programs. Currently Benjamin Rancourt, a senior physics major, is participating in the project. The first-year travel budget covers two to three trips each for Poling and Smith to linear collider meetings and to work with collaborators. The second and third years include additional funds to support one trip each for the graduate and undergraduate students.

Indirect costs are computed using the University of Minnesota’s rate for on-campus research (48.5%). Graduate student fringe benefits are exempt from indirect costs. The fringe rates for graduate students include health benefits and tuition during the academic year, and health insurance and FICA during the summer. Annual salary increases of 3% have been assumed.

**Three-year budget, in then-year K$**

**Institution:** University of Minnesota
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References


2.37. Undulator-Based Production of Polarized Positrons (LCRD)

Accelerator Physics

Contact person: William Bugg
email: bugg@slac.stanford.edu
phone: (865) 974-7799

South Carolina
Tennessee
Princeton

Year 1: $85,500
Year 2: $100,500
Year 3: $0
Undulator-Based Production of Polarized Positrons
(SLAC Experiment E-166)

Steve Berridge\textsuperscript{UTK}, William Bugg\textsuperscript{UTK, 1}, Yuri Efremenko\textsuperscript{UTK}, Thomas Handler\textsuperscript{UTK}, Yuri Kamynchok\textsuperscript{UTK}, Changguo Lu\textsuperscript{PU}, Kirk T. McDonald\textsuperscript{PU, 1} Milind Purohit\textsuperscript{USC}, Stefan Spanier\textsuperscript{UTK}, Achim Weidemann\textsuperscript{USC, 1}

\textsuperscript{PU} Joseph Henry Laboratory, Princeton University, Princeton, NJ 08544
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Executive Summary

This proposal seeks 2 years of support for members of three universities for work on SLAC experiment E-166 \cite{1}, an accelerator-physics project involving 15 institutions to demonstrate undulator-based production of polarized positrons for a linear collider. This proposal is an extension of a proposal \cite{2} that was funded as part of the FY03 Linear Collider Accelerator Physics R&D Program.

The full exploitation of the physics potential of future linear colliders such as the JLC, NLC, and TESLA will require the development of polarized positron beams. In the scheme under study in experiment E-166 a helical undulator is employed to generate photons of several MeV with circular polarization which are then converted in a relatively thin target to generate longitudinally polarized positrons.

To characterize the success of this technique, the experiment includes diagnostics of the polarization of both the MeV-scale photons and positrons, based on the polarization dependence of the rate of transmission of photons through magnetized iron. The three universities will play major roles in the construction of the detectors used in these polarimeters, as well as in the construction of the magnetic transport for the positrons.

Experiment E-166 will have a test run in Winter/Spring of 2004, with data taking expected in Winter/Spring 2005. As the experiment is expected to run through FY05, we present here a two-year budget request. The total request is for $85.5k in FY04, and for $100.5k in FY05, apportioned among the three universities as described in sec. 3. Of this, $25k is already funded as the 2nd year of our FY03 LCRD proposal \cite{2}.
Section 1 presents some relevant extracts from the E-166 proposal [1]. Section 2 presents the scope of work of the present LCRD proposal, and sec. 3 presents our budget requests.

1 Introduction

The full exploitation of the physics potential of future linear colliders such as the JLC, NLC, and TESLA will require the development of polarized positron beams.

In the proposed scheme of Balakin and Mikhailichenko [3] a helical undulator is employed to generate photons of several MeV with circular polarization which are then converted in a relatively thin target to generate longitudinally polarized positrons.

To advance progress in this field, a new experiment, SLAC E-166 [1, 4] (approved June 30, 2003), will test this scheme to determine whether such a technique can produce polarized positron beams of sufficient quality for use in future Linear Colliders. The experiment will install a 1-meter-long, short-period ($\lambda_u = 2.4$ mm, $K = 0.17$), pulsed helical undulator in the Final Focus Test Beam (FFTB) at SLAC. A low-emittance 50-GeV electron beam passing through this undulator will generate circularly polarized photons with energies up to a cutoff energy of about 10 MeV. These polarized photons are then converted to polarized positrons via pair production in thin targets.

1.1 Undulator Based Production of Polarized Positrons

A polarized positron source for a Linear Collider was first proposed by Balakin and Mikhailichenko in 1979 in the framework of the VLEPP project [3]. The concept, schematically sketched in Fig. 1, sends the high energy ($\geq 150$ GeV) electron beam of a Linear Collider through a (\sim 200 m-long) helical undulator to produce circularly polarized photons with energies of about 11 MeV. While the electrons are further accelerated and brought into collision after passing through the undulator, the photons are converted in a thin target into electron-positron pairs. Here the polarization state of the photons is transferred to the positrons and electrons. Only the on-axis photons of the helical undulator radiation are completely circularly polarized; the degree of polarization is decreasing with increasing emission angle. Hence, the polarization of the photons and of the generated positrons can be increased at the expense of the total number of positrons by collimation. The positrons are captured behind the target similarly to the case of a conventional positron source [5, 6], and fed into a linac.

This undulator-based positron source concept offers the additional advantage that the heat load on the target is less than that of a conventional source, and so the former is very well suited for the production of high intensity positron beams [7]. An undulator-based polarized positron source can in principle be realized independently of the linac technology, i.e., independently of the details of the required pulse structure, because the number of produced positrons scales with the number of the electrons in the drive linac, and the pulse structure of the electrons is directly copied to that of the positrons. In this sense it is an option for all Linear Collider projects.
1.2 Physics Opportunities at a Linear Collider with Polarized Electrons and Polarized Positrons

Polarized electrons have been a part of each of the different Linear Collider proposals for a long time. Recently much scrutiny has been given to the case for polarized positrons in addition to polarized electrons. A consensus has emerged that polarized positrons are a highly desirable option for a Linear Collider.

The importance of beam polarization in general was demonstrated e.g., at the SLAC Linear Collider (SLC). Because of the high degree of electron polarization (during its last run in 1997/98, an average longitudinal beam polarization $P_{e^{-}} = 74\%$ was reached [8]) one of the world’s most precise measurements of the weak mixing angle at $Z$-pole energies was performed.

Having both beams polarized offers a number of advantages:

- Higher effective polarization.
- Increased signal to background in studies of Standard Model Physics.
- Enhancement of the effective luminosity.
- Precise analysis of many kinds of non-standard couplings.
- The option to use transversely polarized beams.
- Improved accuracy in measuring the polarization.

1.3 The Need for a Demonstration Experiment

The aim of the proposed experiment E-166 is to test the fundamental process of polarization transfer in an electromagnetic cascade. For this, a simplified version of the scheme shown in Fig. 1 will be used, in which a 50-GeV electron beam passes through a 1-m-long undulator as shown in Fig. 2. The resulting photon beam of MeV energy is converted to positrons (and electrons) in a thin target, after which the polarization of the positrons (and photons) is analyzed.

While the basic cross sections for the QED processes relevant to polarization transfer were derived in the late 1950’s, experimental verification of the polarization development in
an electromagnetic cascade is still missing. From this point of view, the proposed experiment has some general scientific aspects in addition to its importance for Linear Colliders.

Each approximation in the modeling of electromagnetic cascades seems to be well justified in itself, but the complexity of polarization transfer in cascades makes the comparison with an experiment desirable, so that the decision whether a Linear Collider should be built with or without a polarized positron source can be based on solid grounds. The achievable precision of the proposed transmission polarimetry of 5-10% is sufficient for this purpose. This experiment, however, will not address detailed systems issues related to polarized positron production for a Collider, such as capture efficiency, target thermal hydrodynamics, radiation damage in the target, or an undulator prototype suitable for use at a Linear Collider; such issues are well within the scope of R&D by a Linear Collider project that chooses to implement a polarized positron source based on a helical undulator.

1.4 Overview of Experiment E-166

The goal of the experiment is

- To measure the yield and polarization of the photons produced by passing an electron beam through a helical undulator.
To measure the yield and polarization of the positrons produced by conversion of undulator photons in a thin target.

To compare the results to simulations.

A schematic layout of the experiment is shown in Fig. 2 with emphasis on the particle beams, while Fig. 3 shows the layout of the detectors to measure the flux and polarization of the photons and positrons.

The experiment uses a low-emittance, 50-GeV electron beam in the SLAC Final Focus Test Beam (FFTB) plus a 1-meter-long, short-period ($\lambda_u = 2.4$-mm, $K=0.17$), pulsed helical undulator, to produce circularly polarized photons of energies up to 10 MeV. These polarized photons are then converted to polarized positrons through pair production in a Ti target which has a nominal thickness of 0.5 rad. len. The polarizations of the photons and positrons are measured by the Compton transmission method using a magnetized iron absorber [9].

This experiment is a demonstration of undulator-based production of polarized positrons for Linear Colliders at a scale of 1% in length and intensity:

- Photons are produced in the same energy range and polarization as in a Linear Collider;
- The same target thickness and material are used as in the Linear Collider;
- The polarization of the produced positrons is expected to be in the same range as in a Linear Collider.
• The simulation tools being used to model the experiment are the same as those being used to design the polarized positron system for a Linear Collider: EGS4 [10] and GEANT3, both modified to include spin effects for polarized $e^+$ production, and BEAMPATH [11] for collection and transport.

1.5 The Photon Polarimeter

Measurements of the circular polarization of energetic photons are most commonly based on the spin dependence of Compton scattering off atomic electrons [12, 13]. One can either observe the scattered electrons and/or photons emerging from a thin, magnetized iron foil [14], or measure the transmission of unscattered photons through a thick, magnetized iron absorber [9, 15, 16]. Experiment E-166 uses the latter technique, which is sketched in Fig. 4. The basic components are a magnetized iron absorber and a detector that measures the photons that penetrate through the absorber.

![Figure 4: The concept of transmission polarimetry, in which the survival rate is measured for photons that pass through a magnetized iron absorber.](image)

On reversing the sign of the magnetization of the absorber, an asymmetry $\delta = P_\gamma P_e A_\gamma$ is measured in the rate of transmitted photons, where $P_\gamma$ is the photon polarization, $P_e^-$ is the polarization of the electrons in the iron, and $A_\gamma$ is the so-called analyzing power which is proportional to the spin-dependent part of the Compton scattering cross section [1].

The implementation of the photon polarimeter for E-166 is sketched in Fig. 3. The photon polarimeter will include two types of photon detectors, a total absorption calorimeter and a Čerenkov detector.

1.5.1 Silicon-Tungsten Calorimeter

The total absorption calorimeter for the transmitted photons is a silicon-tungsten sampling calorimeter, similar to that employed in SLAC experiment E-144 [18]. As shown in Fig. 5, this device consists of 20 plates of tungsten, each 1 rad. len. thick, separated by silicon detectors in the form of a $4 \times 4$ array of pads, each $1.6 \times 1.6$ cm$^2$ in area. The pads are read out in longitudinal groups of 5, for a total of 64 readout channels. The resulting transverse and longitudinal segmentation of the calorimeter will permit confirmation that the energy deposited in the calorimeter has the profile expected from the signal of undulator photons, rather than that of possible backgrounds of scattered electrons and photons.

The resolution of a similar sampling calorimeter has been measured to be [18]

$$\sigma_\varepsilon^2 = (0.19)^2 \mathcal{E} + (0.4)^2,$$

(1)
where $E$ is the electron energy in GeV. For a pulse of $10^{10}$ electrons, some $4 \times 10^7$ photons of average energy 5 MeV reach the calorimeter, depositing about 200 TeV. Hence, the relative error on that energy of only 0.06 %.

### 1.5.2 Aerogel Flux Counters

A complementary measurement of the transmitted photon flux will be made with a pair of aerogel Čerenkov counters with index of refraction $n = 1.009$ [19]. This extremely low-index material is available from the BELLE experiment. The two flux counters are deployed before and after the magnetized iron absorber, as shown in Fig. 3.

The signal in the aerogel flux counter is generated by conversion of undulator photons in the aerogel, after which electrons and positrons of energy greater than 4.3 MeV will emit Čerenkov light. This light is observed in a photomultiplier that views the aerogel through an air light pipe, as shown in Fig. 6.

Because of their threshold energy of 4.3 MeV, the aerogel flux counters are insensitive to synchrotron radiation in the beam. Hence, a pair of aerogel flux counters that are placed upstream and downstream of the magnetized iron absorber, as shown in Fig. 3, can confirm the attenuation of this absorber on photons of energy above 5 MeV, independent of possible backgrounds of lower-energy photons.

The conversion probability of an undulator photon in the 1-mm-thick Al cover plate of the detector will yield about 1 electron or positron per 300 photons, but only 1/3 of these will have energy above Čerenkov threshold. The number of photons of energy that penetrate the iron absorber is about $4 \times 10^7$ per pulse of $10^{10}$ electrons, so the number of useful conversions is about $4 \times 10^4$. There will be about $50 \theta_C^2 \approx 5$ optical Čerenkov photons per conversion, leading to about 1/2 photoelectron per conversion in a photomultiplier whose photon collection efficiency times quantum efficiency is 10%. Hence, the expected signal
in the Čerenkov counter downstream of the magnetized iron absorber is about $2 \times 10^4$ photoelectron per electron beam pulse.

1.6 The Positron Polarimeter

The measurement of positron polarization is to be made by first transferring the polarization to photons, and then using a photon-transmission polarimeter [17]. Measurements of the asymmetry $\delta = P_{e^+}P_{e^-}A_{e^+}$ in the rate of transmitted photons can be related to the positron polarization $P_{e^+}$ and the polarization $P_{e^-}$ of the electrons in the magnetized iron absorber via a calculable analyzing power $A_{e^+}$ [1].

The layout of the positron polarimeter has been shown in Fig. 3, and is shown again in Fig. 7. A double 90°-bend magnet transports a ±20% momentum bite of the positron spectrum to the reconversion target (0.5 rad. len. of tungsten). The photons that emerge from the target are then incident on an 7.5-cm-long magnetized iron absorber. The photons that are transmitted through the absorber (≈ $10^3$ per pulse) are detected in a CsI array. The latter device was chosen, rather than a Si-W calorimeter, because the typical energy of photons reaching the detector in the positron polarimeter is only about 1 MeV; the energy resolution of a CsI calorimeter for such energies is about 2.5%, compared to 20% for a Si-W device.

1.7 Data-Acquisition System

For the measurements forseen by E-166, several parameters need to be set and data from
the apparatus need to be recorded. As the channel count and trigger frequency (30 Hz) are rather modest, an existing SLAC-provided PC running LabView is sufficient. This PC is interfaced to a CAMAC crate housing the front-end electronics (ADC's and such) with a GPIB card; other in- and output may be done with a PCI I/O board also installed in the PC.

The DAQ system is synchronized to the SLC/FFTB timing through a SLC PDU (Programmable Delay Unit), which provides trigger pulses with a programmable delay, either generated only when beam is present ("TRIG"), or always present ("TRBR"). For data-taking with beam, trigger pulses are used to make gates pulses for the ADC conversions; after a suitable delay the PC will read out the digitized data from the CAMAC crate, display them, and write them to disk on the PC. The data will then be transferred to a SLAC Unix storage for later off-line analysis.

A separate LabView process can read out a ‘Smart Analog Module’ (SAM) also present in the CAMAC crate, asynchronously with the beam; the SAM collects beam data (energy, positions, flux) from the SLAC Control System.

2 Proposed Scope of Work

E-166 is to be carried out in 3 phases:

1. T-467 (now underway) is a parasitic run in the FFTB to test detectors and the DAQ system for E-166. The detectors now being tested are:

   (a) A CsI crystal read out with a PMT (supplied by SLAC).
(b) A silicon-tungsten calorimeter (GCAL, supplied by UTK).
(c) A silicon-G10 detector stack (SiC, supplied by UTK).
(d) A silicon-tungsten calorimeter (the PCAL of E-144 [18], supplied by UTK).
(e) Two aerogel Čerenkov detectors (supplied by Princeton U.).

All detectors except the PCAL are placed near the end of FFTB, outside the electron beam line and outside the line of sight of photons possibly produced by upstream scraping or objects in the beam line. The final E-166 polarimetry detectors will eventually be installed in this location.

PCAL is located above the FFTB dump magnets in a position to detect positrons made by beam tails scraping at upstream collimators or the undulator tube.

The first results are that background “signals” in our detectors decreased by a factor of about 10 from the time of turn-on to a week later, when some material was removed from the beam line, and the beam better tuned.

In Nov. 2003 we will also use a Princeton-U.-supplied PC to read out all detectors into CAMAC ADCs. This system will then evolve to become the data-acquisition system for the dedicated backgrounds run in 2004.

2. A dedicated background test (mandated by EPAC and SLAC management) to be run in Spring, 2004. The major purpose is to establish that the FFTB beam can be steered through a 0.9-mm-diameter undulator tube without creating excessive background from beam tails. This phase will utilize the entire complement of detectors to be used in phase 3, but without the polarimeter magnets and the undulator itself. The GCAL of phase 1 will be replaced by a new Si-W calorimeter, built at Tennessee, that has better resolution.

3. E-166 proper, to be run in 2005. The undulator, all polarimeter magnets and counters will be in operation. A run of approximately 6 weeks is expected.

2.1 Princeton University
K. McDonald is Co-Spokesperson of E-166 (along with J. Sheppard of SLAC).

Princeton University has responsibility for design and construction of the aerogel flux counters used in the photon polarimeter (see Fig. 6), as well as for the construction of the two 90° bend magnets in the positron polarimeter (see Fig. 7). The aerogel flux counters will be delivered during FY04; construction of the 90° bend magnets will begin in FY04, with delivery in FY05. Princeton also proposes to purchase two CMC080 16-channel, 12-bt (18-bit effective) CAMAC ADCs to be used for the CsI detector readout.

2.2 University of South Carolina
A. Weidemann is deputy spokesperson for the parasitic test run, T-467, prior to E-166.

The work on the background test and the final experiment will give students an opportunity to work on hardware, data-acquisition, and simulation projects close to the installed
hardware. The South Carolina request in this proposal is mainly for a housing and travel subsidy for students to work at SLAC with A. Weidemann (who is resident at SLAC) on the following projects:

1. Continuation of the T-467 effort.
2. Development of the Data Acquisition and Control for the dedicated background test and the final E-166 experiment.
3. Experimental operation, data taking and analysis.
4. Simulation (GEANT4) of the detectors.

A. Weidemann has also been intimately involved in the organization of the E-166 effort; he created and maintains the E-166 web site, http://www-project.slac.stanford.edu/lc/local/PolarizedPositrons/ as well as the E-166 mailing list.

2.3 University of Tennessee

The Tennessee group has the responsibility for the construction, preparation and installation of a set of detectors for the measurement of the flux asymmetry of the undulator generated 2-10-MeV photons passing through the magnetized iron. One of these detectors is a silicon-tungsten calorimeter (GCAL, see Fig. 5) to measure the energy-weighted asymmetry, and the other is a layered silicon-G10 sandwich (SiC) that responds approximately linearly to the number of photons above 5 MeV. Since the experiment does not directly measure the photon spectrum it is important to sample the asymmetry with different weighting factors as a check on systematic errors in the polarization measurement.

The Tennessee group is recommissioning another silicon-tungsten calorimeter (PCAL), which they built for experiment E-144 [18] and which will detect positrons deflected by the FFTB dump magnets, to assist in tuning the electron beam through the small aperture of the undulator.

In addition to detector construction Tennessee participates in the basic design of the experiment, and in development of DAQ and simulations.
3 Proposed Budgets

Experiment E-166 will have a test run in Winter/Spring of 2004, with the main run in Winter/Spring of 2005. At present, we anticipate that the E-166 program will conclude at the end of FY05. Hence, we present a 2-year budget scenario in this proposal. Should the experiment continue into FY06, we will submit a supplementary proposal at a later date.

3.1 Princeton University

[Indirect costs are included in the budget items shown for Princeton U.]

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3.2 University of South Carolina

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Travel $4.2k
Indirect costs (Off-site rate = 25%) $3.1k
**FY04 total** $15.5k

FY05:
Graduate Student housing subsidy $8.2k
Travel $4.2k
Indirect costs (Off-site rate = 25%) $3.1k
**FY05 total** $15.5k

3.3 University of Tennessee

$25k of the $30k request of UTK for FY04 is already funded as a 2nd year of our FY03 LCRD proposal [2].

FY04:
Travel $14k
Materials and Supplies $8k
Labor (machine shop) $2k
Indirect costs (Off-site rate = 25%) $6k
**FY04 total** $30k

FY05:
Travel $20k
Student (half time) $8k
Materials and Supplies $8k
Indirect costs (Off-site rate = 25%) $9k
**FY05 total** $45k

4 References

[1] G. Alexander et al., Undulator-Based Production of Polarized Positrons. A Proposal for the 50-GeV Beam in the FFTB (June 7, 2003; approved as SLAC E-166 on June


2.40. Development of Polarized Photocathodes for the Linear Collider (LCRD)

Accelerator Physics

Contact person: Richard Prepost
email: prepost@hep.wisc.edu
phone: (608) 262-4905

Wisconsin
SLAC

Year 1: $34,600
Year 2: $34,600
Year 3: $34,600
Development of Polarized Photocathodes for the Linear Collider

Accelerator Physics - New Proposal

Contact Person: Richard Prepost
University of Wisconsin, Madison, WI 53706
EMail: prepost@hep.wisc.edu
Phone: 608 262-4905
Proposal to the University Consortium for a Linear Collider

October 21, 2003

Proposal Name
Development of Polarized Photocathodes for the Linear Collider

Classification
Accelerator (New Proposal)

Personnel and Institution requesting funding
Richard Prepost, University of Wisconsin, Madison WI 53706

Collaborators
SLAC
J. Clendenin
E. Garwin
R. Kirby
T. Maruyama

Contact Person
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prepost@hep.wisc.edu
608 262 4905

Project Overview
The development of high current polarized photocathodes is very important for the Linear Collider (LC) project. Physics requirements call for highly polarized electron beams with a goal of at least 90% polarization. A Wisconsin-SLAC collaboration has been developing and studying polarized photocathodes which have been used for the SLAC SLD and fixed target programs. A more recent goal is the development of photocathodes with a polarization in excess of 90% which meet the NLC charge requirements. This work started as a SLAC-Wisconsin collaboration (E. Garwin, T. Maruyama of SLAC and R. Prepost of Wisconsin) and has evolved into a formal SLAC collaboration called the Polarized Photocathode Research Collaboration (PPRC).
SLAC personnel now also include J. Clendenin, R. Kirby, D. Luh, A. Brachmann, and S. Harvey

To date, well over 80% polarization has been achieved with strained gallium arsenide photocathodes which have been used in past SLAC experiments. The 1994-1998 SLC operation with the SLD detector and subsequent fixed target experiments E-142, E-143, E-154, E-155, and E-155X used strained gallium arsenide cathodes which produced at least 80% polarization at the source. More recently, a newly developed high current polarized photocathode used for SLAC experiment E-158 achieved a polarization of about 85% with a charge approaching that required for the NLC.

These applications were the world’s first use of strained photocathodes specifically designed for a polarized electron source, resulting in record polarization for a high intensity electron linac. The research and development program will continue to focus on studying the properties of these cathodes with respect to spin relaxation, quantum efficiency, and charge saturation, with the goal of developing photocathodes for use with the LC.

Early research efforts focused on the development of strained photocathodes since electron spin polarization higher than 50%, approaching 100%, is theoretically possible using cathode structures which have less crystal symmetry than unstrained GaAs. As long as GaAs or any zinc blende type structure is used for cathodes, the electron polarization is limited to $\leq 50\%$ due to the degeneracy of the valence bands.

Since the seminal studies with strained InGaAs, research has been carried out with strained GaAs epitaxial layers grown on a GaAsP buffer layer. Electron spin polarizations approaching 85% were observed at low quantum efficiency (QE), decreasing to about 80% at high QE. A variety of layer thicknesses and strains were studied using MOCVD grown samples commercially obtained from the SPIRE Corporation in Bedford, MA. The samples were of high quality, and all samples studied to date have shown a significant polarization enhancement in excess of the unstrained maximum polarization of 50%. The epitaxial layer thicknesses varied from 0.1 $\mu$m to 0.3 $\mu$m and the strains of approximately 1% resulted from phosphorous concentrations ranging from 21% to 28%. Even the 0.3 $\mu$m thick sample, well in excess of theoretical estimates for the critical thickness for pseudomorphic growth, reached an electron spin polarization of 75% at low QE and 70% at high QE, demonstrating significant persistance of lattice strain.

We have continued R&D efforts on cathode structures to address certain issues, specifically 1) fundamental properties of materials, 2) higher polarization, and 3) higher charge limit. The cathode charge limit, was not a limiting factor for the SLAC SLD and fixed target programs but is an issue for a LC polarized source with an NLC micro-bunch structure. The LC with an NLC micro-bunch structure requires higher peak current than can be obtained from the photocathodes that were used for the SLAC SLC program. Provided that the photocathode output charge is not limited by the space charge limit of the electron gun, the output charge is limited by charge saturation of the photocathode itself. Charge saturation occurs because a photovoltage develops at the cathode surface at high currents acting as a potential barrier for further charge emission.

One possible cure for this problem is to increase the p-type doping in the epitaxial surface
layer. Over the past two years systematic studies have been made of strained GaAs samples where the electron polarization was measured as a function of the high doped surface layer thickness. The results showed, as expected, that the polarization increases as the high doped layer thickness is reduced. From these studies it was concluded that greater than 80% polarization could be obtained with about 5-10 nm of a surface layer doping of $5 \times 10^{19} \text{ cm}^{-3}$.

High surface layer doped samples have been grown to our specifications by the Bandwidth Semiconductor Corporation (former SPIRE Corporation). The basic structure was a 0.1 $\mu$ GaAs active layer highly doped for the first 10 nm of surface and strained by a GaAsP buffer layer. The highly doped surface layer is kept very thin so as not to decrease the electron polarization. The high doping surface layer has the effect of decreasing the band gap near the surface, resulting in a small potential barrier. A small amount of phosphorus (5%) was added to the active layer to compensate the energy difference in the conduction band resulting from the high gradient doping.

This structure was tested with a long pulse laser system to simulate the NLC 190 microbunch train of total length 266 ns. The NLC charge requirement for the source is 2.2 nC in each microbunch for a total of 420 nC, about 25 times the SLC maximum charge. A short YAG-Ti laser pulse was superimposed on the long flash-Ti laser pulse to simulate the peak charge requirement of a single microbunch. The resultant measurements of extracted charge vs laser energy showed no charge saturation up to the maximum laser energy. Both the microbunch peak charge and the total charge of the macrobunch nominally approach the NLC charge requirements. This new cathode structure was used for the first two runs (2002) of the fixed-target experiment E-158 which required about 80 nC in a 300 ns pulse, a higher charge requirement than previous cathodes have been able to deliver. The electron polarization was in excess of 80%, in accord with polarization measurements measured in the test lab.

Another approach to obtain higher photocathode output charge is to increase the thickness of the photocathode active layer, ordinarily limited to about 0.1 $\mu$. Larger thickness of the active layer results in serious degradation of the strain. Superlattice structures can in principle overcome the inherent thickness limitation of single heterostructures. Molecular Beam Epitaxy (MBE) superlattice structures have been grown for us by SVT Associates through an SBIR award with SLAC as the technical partner. Measurements of these structures during 2002-2003 have shown both good QE and high polarization. These measurements are continuing during 2003-04 with the goal of fine-tuning the superlattice parameters. To this date, peak polarizations of 85% and QEs of about 1% have been achieved. Fig. 1 shows polarization and QE vs. laser wavelength for several different SVT photocathode structures with varying superlattice parameters. The peak polarizations and QE are consistent with superlattice computer simulations. The superlattice structures shown here are typically 16 periods of 3-4 nm GaAs$_{1-x}$P$_x$ barriers alternating with 3-4 nm GaAs wells with a phosphorus fraction of $x = 0.35$. The extracted charge nominally meets NLC peak charge requirements. One of these superlattice photocathodes was used successfully for the final run of E-158 in 2003.
Another problem which has been addressed during 2003 is the dopant loss and strain relaxation during the relatively high temperatures used for heat-cleaning. This factor tends to prevent the achievement of ultimate performance from the photocathodes. To this end we have tested an atomic hydrogen cleaning system based on a Jefferson Lab design. The goal of atomic hydrogen cleaning is to achieve high QE using a heat cleaning temperature of 450°C. This temperature is in contrast to the normal heat cleaning temperature of 600°C which results in the degradation effects mentioned above. Our studies have shown that when hydrogen ions are prevented from reaching the photocathode, the performance goals are achieved.

**Description of Project Activities**

The research and development program divides into several well defined parts as follows:

1. **Fabrication**
   The cathode structures are grown by a commercial or academic partner who has the
facilities required for structure growth. Currently we receive structures from SVT Associates with whom SLAC currently has a Phase II SBIR award, now in the final year, and from a Russian group at St. Petersburg Technical University with whom SLAC shares a CRDF grant.

2. **Photocathode Characterization**
   The parameters of the photocathodes must be measured, requiring a variety of techniques including, but not limited to, X-Ray Bragg measurements, Electron Microscopy, Secondary Ion Mass Spectroscopy (SIMS), Auger analysis and Photoluminescence measurements.

3. **Measurement of Polarization, Quantum Efficiency (QE), and Charge Limits**
   SLAC has the facilities for these measurements using a cathode test system (CTS) for measurements of polarization and QE, and a HV gun test lab for measurement of charge saturation properties.

4. **Structure Design**
   The design of a photocathode structure requires computer programs to calculate the parameters for a band structure which calculations show have the desired polarization and charge. The analysis of X-Ray curves also requires X-Ray simulation software.

**Project Activities and Deliverables—FY2004-2006**

Research will continue with the goal of producing photocathodes which have polarization in excess of 90% and a peak output charge meeting the charge requirements of a LC with the microbunch structure of the NLC LC. Some of the structures studied to date are excellent candidates for meeting these requirements. The current research is with superlattice structures. Superlattice structures are particularly difficult to design since there are many parameters, making it difficult to simultaneously optimize QE and polarization. The target parameters for a structure are not always met during the fabrication process, making it very important to have many samples and high quality characterization techniques. One of the key studies is how to achieve maximum possible polarization while still satisfying the peak charge requirements.

Work will also continue with studies of atomic hydrogen cathode cleaning which results in being able to use lower heat cleaning temperatures. Lower heat cleaning temperatures result in lower dopant loss, dopant diffusion, and strain relaxation. We propose to build a hydrogen cleaning system with a load-lock system which will enable the transfer of cathodes between test systems.

**Budget Justification**

We propose a budget for the following items:
1. **Purchase of photocathode structures from a commercial source** The commercial source is presently SVT Associates which has the facilities for MBE growth with Be doping. The request for each FY is for 5 cathode structures @ 3K$ each, representing about 1/2 of the research requirements.

2. **Facility Upgrade** We plan to upgrade the photoluminescence facility which Robin Mair, a former Wisconsin student, used for his PhD work on the study of strained photocathodes. The photoluminescence facility has proven to be very valuable for structure characterization. The photocathode structures discussed above require an expanded wavelength range which will be accomplished by obtaining more diode laser heads. The request is for two laser heads for year 1 with a similar amount for additional photoluminescence diagnostic equipment in years 2 and 3.

3. **Characterization Studies** X-Ray and SIMS analyses are done off-site and payment is required. We have in the past done X-Ray analyses at Wisconsin and currently use a facility on the Stanford campus. We run the analyses but pay to use the facility. SIMS analyses are done by a commercial vendor. SIMS analyses measure the doping profile of the samples. The request is for 1/2 of the anticipated research needs.

4. **Travel** The travel request is for 1/2 of the Prepost trips to SLAC.

**Budget (K$)**

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**References**


2.42. Transverse phase-space measurements for a magnetic bunch compressor by using phase-space tomography technique (LCRD)

Accelerator Physics

Contact person: Feng Zhou
email: zhouf@bnl.gov
phone: (631) 344-2042

UCLA
BNL
Thomas Jefferson Lab

Year 1: $28,500
Year 2: $30,000
Year 3: $32,000
Project name

Transverse phase-space measurements for a magnetic bunch compressor by using phase-space tomography technique

Classification (accelerator/detector: subsystem)

Accelerator

Institution(s) and personnel

University of California at Los Angeles, Department of Physics & Astronomy:
David Cline (Professor), James Rosenzweig (Professor), Feng Zhou (Assistant research scientist)

Brookhaven National Laboratory:
Vitaly Yakimenko (Staff scientist)

Thomson Jefferson National Accelerator Facility:
Rui Li (Staff scientist)

Contact person

Feng Zhou
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(631) 344-2042

Project Overview

Future linear colliders and the fourth generation light sources will require sub-picosecond r.m.s electron bunches. The length of bunch produced by electron sources, RF photoinjectors, usually is in order of pico-second due to restrictions of large space-charge effects. One of the most common approaches to compress the bunch down to sub-picosecond is to use magnetic bunch compressors, which when combined with proper off-crest acceleration in linac allow rearrangement of the electron’s longitudinal position. With proper correlation between electron’s position and energy, the bunch length can be effectively compressed. However, this bunch shortening comes at a sacrifice that the significantly created Coherent Synchrotron Radiation (CSR) can distort both longitudinal and transverse phase spaces. Recently, some labs in the world made large efforts to experimentally understand CSR effects in a bunch compressor, but most of them only focused on measuring the transverse emittance and/or momentum changes [1-3]. The beam’s phase spaces in a compressor may be significantly distorted, and thus only emittance values may not completely represent a beam. UCLA group used horizontal slits to derive horizontal phase space in a compressor and observed significant bifurcations in horizontal phase space under full compression [4].

Our project is to measure and analyze transverse phase spaces to understand beam physics at a magnetic bunch compressor. Our measurements will be carried out at Brookhaven National Laboratory Accelerator Test Facility (BNL-ATF). The ATF can
provide a high-quality electron beam with sub-micron normalized emittance at 0.5 nC bunch charge without installing magnetic bunch compressor. Recently, a magnetic bunch compressor has been installed at the ATF by Prof. Rosenzweig’s group. According to the design, the minimum bunch length of sub-picosecond can be achieved with full compression. The transverse phase spaces in both planes at a magnetic bunch compressor can be reconstructed by a phase-space tomography technique, which was developed at the BNL-ATF [5]. The bunch compressor is located downstream of the linac sections. The linac can be operated at the energy of 50-70 MeV and thus the space-charge effect could be less serious, which allows us to understand CSR induced phase-space distortions with weak space-charge effects. One triplet located upstream of the compressor allows us to change beam twiss parameters in the compressor and thus we can measure the phase spaces with twiss parameters. The bunch length at the entrance of compressor can be varied from 1-ps to 10-ps by changing RF-gun phase and the bunch charge can be varied from 50 pC to 1 nC at the ATF, which allows us to study CSR effects with different initial bunch lengths and bunch charges. We may observe and analyze some interesting phenomena (such as bifurcations in phase spaces) at various beam conditions.

**Description of project activities**

A schematic diagram of the ATF beam line with bunch compressor is shown in the following figure. The first triplet is used to match different twiss parameters in the compressor. The second triplet is used for matching the compressor with other beam line.

![Schematic diagram of the ATF beam line](image)

The tomography technique to reconstruct transverse phase spaces in both horizontal and vertical planes with bunch compressor is achieved by phase rotations using quads scans. Total phase advances in both horizontal and vertical planes are 180 degrees, respectively. For each phase rotation, the beam image is taken at a beam profile monitor (BPM 2) in the downstream of these quads. These beams are projected to both planes $(\phi, \lambda)$ and then phase spaces $\mu(x, x')$ can be reconstructed using “filtered projection”, $\lambda^*(\xi)$:

$$
\lambda^*(ms) = \frac{1}{4s} \lambda_\phi(ms) - \frac{1}{2\pi s} \sum_{m-n=odd} \frac{\lambda_\phi(ns)}{(m-n)^2}, \quad \mu(x, x') = \int_0^\pi \lambda^*(\xi)d\phi \bigg|_{\xi=x\cos\phi+x'\sin\phi}
$$

The procedures for a measurement is summarized as:
- To measure twiss parameters at Point A
- Prepare for beam optics for each phase rotation starting from Point A
- Project beam images taken at BPM 2 to both horizontal and vertical planes
- Use “filtered projection” to reconstruct transverse phase spaces in both planes
We will investigate the transverse phase spaces with linac off-crest RF phases and/or different $R_{56}$, linac energy, twiss parameters in the compressor, initial bunch lengths and bunch charges.

**FY 2004 Project Activities and Deliverables**

We will make efforts 1) to modify transverse phase space tomography program, which has been available at the ATF; 2) build up a computer based program to automatically measure the twiss parameters at each location (especially at Point A) in the beam line; and 3) we can use the measured twiss parameters at point A to prepare the beam optics for each phase rotation. In late of FY 2004, the test measurements for transverse phase spaces at a magnetic bunch compressor will be carried out.

**FY 2005-2006 Project Activities and Deliverables**

At each beam condition, the twiss parameters at point A could be different and thus the beam optics preparation and measurements work will be tremendous. During this period, we mainly focus on extensive transverse measurements and analysis to understand beam physics of a magnetic bunch compressor.

**Budget**

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**References**