U.S. University Linear Collider R&D and Studies of Alternative TESLA Damping Ring Designs

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USA
U.S. University Linear Collider R&D
U.S. university HEP “social organization”

Most U.S. high energy experimentalists are employed either by national labs (Fermilab, SLAC, Argonne, Brookhaven, Lawrence Berkeley, …) or by universities.

Working at a U.S. university is different from working at a lab:

• We teach, develop new course material, serve on university committees. Unscheduled interactions with students are time consuming (and also rewarding).

• We can enlist the help of eager, talented undergraduates who are able to work productively on a wide range of laboratory projects.

• We have liberal access to the expertise (and sometimes hardware) of colleagues in other departments: engineering, for example.
U.S. university career path

- University undergraduate: 4 years; BA or BS
- Graduate school: 5-7 years; PhD
  - University postdoc
    - Assistant professor
      - Associate professor
        - Professor
  - National lab postdoc: 3-5 years
    - National lab staff
      - National lab senior staff

Diagram notes:
- Red circles indicate non-permanent positions.
- Green boxes denote permanent positions.

George Gollin, *U.S. University R&D and Damping Ring Studies*, DESY, April, 2004
U.S. university career path

University postdoc positions are not expected to lead to permanent (faculty) positions at the same university.

Postdoc $\rightarrow$ assistant professor step is toughest: there are not very many university faculty jobs available.

Candidates for assistant professor positions are expected to have

- shown considerable leadership in their HEP collaboration
- played a major role in producing physics from recent data.

$\therefore$ U.S. postdocs (and grad students) do not devote more than a fraction of their time to future experiments (LHC, LC).

This plays a significant role in how U.S. universities participate in LC.
U.S. HEP funding

Two independent agencies: Department of Energy and National Science Foundation.

- DOE funds Fermilab, SLAC,… and ~2/3 of the university groups.
- NSF funds CESR (CLEO) and ~1/3 of the university groups.

Though initially created as a DOE panel, HEPAP advises both agencies.

DOE and NSF cooperate, but they do not follow a “unified” national HEP policy. An example: the two agencies’ different interactions with university-based Linear Collider R&D initiatives in the U.S.

U.S. funding levels are strongly influenced by political currents.
Tensions

Graduate students and postdocs must work on near-term projects which yield particle physics results in order to advance professionally.

University faculty want to preserve autonomy and independence from administrative control by national labs. This is significant to us.

We receive mixed messages from DOE and NSF regarding LC funding (DOE is supportive, but NSF is less so).

We have various responsibilities in our currently-running/analyzing experiments.

So it’s complicated (but also very interesting)!
Engaging the university HEP community

January, 2002

• FNAL was focused on Run II problems. LC wasn’t on the lab directorate’s radar.

• Most university groups addressing LC issues were already affiliated with SLAC through SLD. Most work involved detector simulations.

• No serious planning to involve new university groups in LC R&D that were not already participating through SLAC.

That’s not good!

Fixing this: we’re professors, we’re not lab employees, we can do things without asking permission, they can’t fire us.
Fermilab, Cornell, SLAC workshops

April - May, 2002 workshops at FNAL, Cornell and SLAC:

• Introduce university physicists to R&D issues suitable for university groups. (We really like doing lab work!)
• NO Higgs sensitivity vs. stuff talks (at least not at FNAL).

Tom Himel (SLAC) was the hero of the workshops: he assembled a list of accelerator projects for us to consider. “The List” included NLC and TESLA projects.

These workshops led to a 50% increase in university participation in LC R&D.

About half of the new participants took on accelerator projects!
An example from Himel’s list

Sample DB entry

ID: 16   Priority: Medium   project_size: Large   skill_type: physicist

short project description: superconducting quadrupole vibration test

Detailed project description: There are two options for the final doublet magnets: permanent and superconducting. The main concern about the superconducting method is that coils will vibrate too much since a strong support to the cryostat would cause a big heat leak, and boiling helium may jiggle the coils. Either by calculation, or finding an appropriate magnet, convince people that the quadrupole fields center will move by less than a nm relative to the outside of the cryostat.

Needed by who: NLC and TESLA   present status: good idea needed

Needed by date: 6/1/2005

ContactPerson1: Joe Frisch   WorkPhone1: 6509264005
EmailAddress1: frisch@slac.stanford.edu

Note that the contact person is someone who knows more about the project. He’s not the person who will arrange who works on what.

Note: current URL is http://www-conf.slac.stanford.edu/lcprojectlist/asp/projectlistbyanything.asp
Sample accelerator projects

Here are some of the ~90 items from Tom’s list:

- low level RF Digital Feedback Hardware
- Exception Handling for RF System
- TESLA Wave Guide Tuner Control
- Structure Breakdown diagnostics
- active vibration stabilization of Final Doublet
- Linac accelerator structure cooling without vibration
- Acoustic sensors for structure and DLDS breakdown
- beam profile monitor via Optical Transition Radiation
- Very fast injection/extraction kickers for TESLA damping ring
- RF BPM electronics, including tilt
- 5-10 kW magnet power supply
- flow switch replacement
- robot to replace electronic modules in tunnel
- Programmable Delay Unit
- linac movers: 50 nm step, rad hard
- Low Level RF 500 MHz digitizer
Constructing a coherent R&D program

LCRD (DOE) proponents write short project descriptions

UCLC (NSF) proponents write short project descriptions

ALCPG working group leaders offer suggestions for revision, collaboration with other groups, etc.

LCRD proponents write “subproposals”

UCLC proponents write “project descriptions”

Proposal coordinators create one unified document combining LCRD and UCLC projects

Separate accelerator and detector committees review proposed work for both agencies

LCRD proponents revise subproposals

UCLC proponents revise project descriptions

Proposal coordinators create new document combining revised LCRD and UCLC projects, then transmit to DOE and NSF.
Here come the professors!

The result:

• 71 new projects
• 47 U.S. universities
• 6 labs
• 22 states
• 11 foreign institutions
• 297 authors
• 2 funding agencies
• two review panels
• two drafts
• 546 pages
• 8 months from $t_0$

Funded by NSF* and DOE

*planning grant only
## Scope of proposed work

<table>
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<tr>
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<th># (03)</th>
<th>$ (03)</th>
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<td>$149 k</td>
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<td>$194 k</td>
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<td><strong>Total</strong></td>
<td>71</td>
<td>$2,354 k</td>
<td>68</td>
<td>$3,208 k</td>
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</table>

**Funding received from DOE**

- ~$900 k

**Funding received from NSF**

- ~$150 k
ITRP poster

...graphics from 15 of 69 projects
Some of the projects

There are a lot of projects!

Most involve collaboration between one or two university groups and Fermilab and/or SLAC.

Many are well-suited to undergraduate student participation.

Here is a small amount of information about a few of the accelerator physics projects…
RF Beam Position Monitors for Measuring Beam Position and Tilt

(Yury Kolomensky, UC Berkeley)

LCRD 2.4: funded FY03, $30k.

Some analysis of test beam data from KEK ATF using SLAC-built device.
Ring-tuned, permanent magnet-based Halbach quadrupole
(James Rosenzweig, UCLA)

LCRD 2.23: funded FY03, $35k.

Good progress, both in modeling and in fabrication of prototypes for studies.
Beam Test Proposal of an Optical Diffraction Radiation Beam Size Monitor at the SLAC FFTB
(Yasuo Fuki, UCLA)

LCRD 2.2: funded FY03, $40k.
Simulation work so far.

ODR Yield in 0.1/γ angle range
σ: rms transverse beam size
Design and Fabrication of a Radiation-Hard 500-MHz Digitizer Using Deep Submicron Technology
(K. K. Gan, Ohio State)

LCRD 2.3: funded FY03, $40k.

Some of the circuit functional blocks have been designed, but none fabricated for test yet.

Figure 2. Schematic of a 3-bit cell.
Fast Synchrotron Radiation Imaging System for Beam Size Monitoring
(Jim Alexander, Cornell; Jesse Ernst SUNY Albany)

UCLC 2.7: exploring possible parameters, configuration for device.

Design for a Synchrotron Radiation Camera for Beamsize Measurement

Basic concept:
1. Refocus SR in the damping rings to make a projected image of the passing bunch.
2. Diffraction limit on source size forces us into the x-ray regime

Goals:
1. definite: Measure $\sigma_x$ and $\sigma_y$
2. possible: Single-bunch resolution
3. optimistic: Intrabunch measurement (i.e. z)
   - Don't yet know if this will be possible.
   - Still working on ideas for this.

Status:
Have started simple simulations for studying
optics and detector choices:
1. Optics
   - point-to-point with sufficient magnification
   - Zone plates are one candidate
2. Detection
   - small pixel array is one candidate

Relevant times

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<tr>
<td>bunchlength</td>
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<td>13ps</td>
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Ground Motion studies versus depth  
(Mayda Velasco, Northwestern)

• LCRD 2.11: Has used state-of-Illinois funds to purchase equipment, some installed.

Linear collider R&D: Preparing ground motion study in NUMI  
noise versus depth

• Northwestern University joined the study, is providing equipment and will participate in the study

• Measurements needed to determine the best depth to locate the next linear collider

• Test at Aurora Mine already done

• Next... Numi Tunnel  
  ➔ This was classified as a high priority project (1.5)  
  Szleper, Velasco, Serye
Investigation of Acoustic Localization of rf Cavity Breakdown

(George Gollin, Univ. Illinois)

Can we learn more about NLC rf cavity breakdown through acoustic signatures of breakdown events?

At UIUC ("UC" = Urbana-Champaign):
George Gollin (professor, physics)
Mike Haney (engineer, runs HEP electronics group)
Bill O’Brien (professor, EE)
Joe Calvey (UIUC undergraduate physics major)
Michael Davidsaver (UIUC undergraduate physics major)
Justin Phillips (UIUC undergraduate physics major)

Marc Ross is our contact person at SLAC.
An interdisciplinary university collaboration...

Haney’s PhD is in ultrasound imaging techniques

O’Brien’s group pursues a broad range of acoustic sensing/imaging projects in biological, mechanical,… systems

Ross is our contact at SLAC and participates in related work taking place there.

National labs can undertake large projects which demand significant industrial infrastructure but universities are ideally suited to initiate investigations which require a broad, interdisciplinary knowledge base.
Students have been exceptionally productive

The project involves classical mechanics (no quantum!) and is ideally suited for student participation.
A piece of NLC to play with

Ross sent us a short piece of NLC and some engineering drawings specifying the geometry.

We need to understand its acoustic properties.

Start by pinging copper dowels with ultrasound transducers in order to learn the basics.
Copper dowels from Fermilab NLC Structure Factory

Harry Carter sent us a pair of copper dowels from their structure manufacturing stock: one was heat-treated, one is untreated.

NLC structures are heat-brazed together; heating creates crystal grains (domains) which modify the acoustic properties of copper.

Ross also sent us a (small) single crystal copper dowel.

#2 is heat-treated…

…#1 is not.

We cut each dowel into three different lengths.
Transducer 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.
Pinging the shortest heat-treated dowel

Two transducers: fire a ping, then listen for signals in both transducers. The initial excitation is complicated (note the protection diodes).
Transducer phenomenology

“sum of 1-4” is our four-δ model after hand-tuning its parameters using the first echo.
Grain structure

Closeup of one of the (heat-treated) dowel #2 sections.

Note that grain patterns visible at the copper’s surface.

Grain structure is not visible on the surface of dowel #1.
Speed of sound at 1.8 MHz in copper

The speed of sound is different in the two kinds of copper dowels. It’s 5.2% faster in the grainy (heat treated) copper. (You can hear it!)

Blue points: dowel #2 (heat treated)

\[ v_s = 4985 \text{ m/sec} \]

\[ \lambda \sim 2.8 \text{ mm} \]

Red points: dowel #1 (not heat treated)

\[ v_s = 4737 \text{ m/sec} \]

Single crystal:

\[ v_s = 4973 \text{ m/sec} \]

(4.973 mm/μsec)

Air: \(~331\text{ m/sec}\)

Water: \(~1482\text{ m/sec}\)
Scattering/attenuation at 1.8 MHz in copper

A “ping” launched into a copper dowel will bounce back and forth, losing energy through

- absorption in the transducer (large acoustic impedance mismatch between the transducer and the copper: not much energy crosses the copper/transducer boundary)
- scattering of acoustic energy out of the ping
- absorption of acoustic energy by the copper.

---

[Diagram showing a ping of approximately 15 mm inside a 69 mm dowel, with a 25 mm gap at one end.]
Scope shots

Single transducer: ping, then listen for echoes. Adjust ping energies so that first echoes are approximately equal in amplitude.

Note the difference in sizes of the second echoes as well as the different amounts of baseline activity between the echoes.

No grains
- larger 2\textsuperscript{nd} echo
- less “fuzz”

Yes grains
- smaller 2\textsuperscript{nd} echo
- more “fuzz”
RMS baseline activity in scope shots

Single transducer: ping, then listen to baseline “noise” as pulse travels into copper, pumping energy into acoustic baseline “glow.”

Here’s the baseline glow, 5 mV and 100 µsec per division. Scope shot from heat-treated (grainy) long dowel.
Beam spread

Two transducers: ping using #1 (centered), then listen using #2.

Move #2 off center and measure signal size in different length dowels: we see very little beam spread in non-heat-treated dowels.

Relative signals at far ends of dowels vs. off-axis distance of receiver

![Graph showing signal amplitude vs. displacement from center for dowels of different lengths.](image)
Measurements and modeling

The plan: work up a simple phenomenological model (based on sensible physics) which includes scattering off grain (and other) boundaries and includes attenuation.

If we can model the copper cylinders adequately, perhaps we will be able to describe the NLC structure’s acoustic properties.

Technical language: we would like to be able to understand how to describe the (acoustic) Green’s function for our Copper structures.
Condensed matter, as done by folks in HEP

Initial models: regular (rectangular, 2D or 3D) grids of mass points connected by springs.

Speeds of propagation for pressure and shear waves are determined by $k_1$, $k_2$, and $k_1/k_2$.

We can vary spring constants arbitrarily.

Grain boundaries are modeled as sets of mass points with different spring constants.
Propagation of a pressure wave in a homogeneous grid

~250 × 650 uniform grid
Pressure wave propagation: stills from the movie…
More stills from the movie…
More stills from the movie…
More stills from the movie…
More stills from the movie…
Simulated transducer response
Propagation of a pressure wave through a grainy crystal

Change the spring constants inside thin domain walls around randomly shaped grains to see effects on pulse propagation. Crystal now has 200 grains.
Propagation of a pressure wave through a grainy crystal

Transducer at the far end of the crystal sees direct pulse, then acoustic “glow,” then reflected pulse.
What we are working on now

• We have a really good method for placing grains in our simulated copper. We haven’t yet worked on selecting parameters to tune the simulation so that it reproduces data.

• Refinement of description of transducer-copper coupling. (Transducer absorbs some of the energy which arrives at its point-of-coupling.)

• Modeling of more complicated (2-D, 3-D) shapes (not yet).

• Porting code to NCSA supercomputers

• In the future: Inverting the simulation to uncover what we can learn about the underlying acoustic “event” from sensor data.
We are having a lot of fun

This particular project is well suited for undergraduate participation.

The students are very good! Joe and Michael are only in their second year, while Justin is a junior.

All three students will continue the work this summer.
Studies of Alternative TESLA Damping Ring Designs
Damping ring introduction

TESLA damping ring fast kicker must inject/eject every $n^{\text{th}}$ bunch, leaving adjacent bunches undisturbed.

Minimum bunch separation inside damping rings determines size of the damping rings.

It’s the kicker design which limits the minimum bunch spacing.

Would a different extraction technique permit smaller bunch spacing?

This would allow exploration of a larger “parameter space” when doing cost/performance/reliability optimizations.
Thinking in new ways

We’re investigating a few speculative ideas for different kickers and injection/extraction schemes.

In tandem, we’re pursuing design studies for a smaller damping ring.

Kicker schemes:

• multiple bunch trains with inter-train gaps
• longitudinal RF followed by a dispersive section
• Fourier series kicker
• chirped waveform pulse compression kicker
Multiple bunch trains with inter-train gaps
(Joe Rogers, Cornell)

It is easier to turn a kicker on than it is to turn it off.

Beam in DR would be grouped into trains separated by gaps. Eject the last bunch in each train.

Kicker needs to turn on during inter-bunch interval, but can turn off (and settle) during gap between trains.
Multiple bunch trains with inter-train gaps

Always inject and eject the last bunch in a train.

If necessary, use a two-ring scheme to keep loading of DR RF constant. (It’s a little complicated to explain quickly.)

Large ring ~6 km, filled by transfers of undamped trains from the ~100 m ring

Kicker ideas being discussed at Fermilab.
Longitudinal RF followed by a dispersive section (Dave Rubin, Cornell)

Split the energies of successive bunches, then send bunches down energy-dependent (separate, equal-length) paths.

- kicker rise, fall times can be $4 \times$ bunch spacing
- could be combined with Joe Rogers’ idea to accommodate longer fall-time kicker
Fourier series kicker
(George Gollin, Illinois)

Kicker is a series of \( N \) transverse RF cavities tuned to frequencies which differ by \(~3\) MHz.

- proper adjustment of amplitudes and phases kicks one bunch while leaving the next \((N-1)\) undisturbed.
- intelligent choice of amplitudes permits \( p_T = 0 \) and \( dp_T/dt = 0 \) for unkicked bunches.
- transverse kick minimizes beam-induced fields in cavities.
Fourier series kicker

Cavities can be run at high frequency (so that there is one basic design, with individual cavities “tuned” to the proper frequency).

The “major zeroes” aren’t quite at the obvious symmetry points.

Note that zeroes also satisfy $dp_T/dt = 0$. 
Chirped waveform pulse compression kicker
(Joe Rogers, Cornell)

Dispersive wave guide compresses chirped RF signal.

Commercial broadcast RF amplifier ~100kW, but compression generates large peak power for kicking pulse in low-Q cavity.

![Diagram of chirped waveform pulse compression kicker](image)

- Function generator
- RF amplifier
- (dispersive) wave guide
- Kicker cavity

Wave guide group velocity vs. frequency

- 340 ns
- 10 ns
Chirped waveform pulse compression kicker

In effect, the amplifier launches different frequencies down the waveguide at different times. Slowest-traveling frequency is injected first, fastest-traveling frequency last.

All frequencies arrive simultaneously at the cavity.

Unlike Fourier series kicker, in which bunches “sum” the effects of different frequencies, this design uses the cavity to form the sum.

System is linear, so low-power tests can be used to evaluate concept. (Fermilab is interested in pursuing this.)

Programmable function generator can be reprogrammed to compensate for drifts and amplifier aging.
Testing our kicker ideas

A0 photoinjector lab at Fermilab produces a relativistic (16 MeV now, 50 MeV in a few months), bunched low-emittance electron beam. (It’s rather like a TESLA injector.)

This should be an excellent facility for kicker studies!
What might a damping ring, small enough to fit into the Tevatron or HERA or tunnels, look like?

We had a small workshop in March at Fermilab to think about this.

Participants: ANL, LBNL, SLAC, Cornell, DESY, FNAL…

6 kms, 6 straight sections, 25 wigglers.
\( \beta \)-functions and dispersion

![Graph of \( \beta \)-functions and dispersion](image-url)
Comparison of the two designs

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<th>Small ring ((e^+/e^-))</th>
<th>Dogbone ((e^+/e^-))</th>
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<td>Energy</td>
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<td>Circumference</td>
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<td>Transverse damping time (\tau_d)</td>
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<td>Current</td>
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<td>Energy loss/turn</td>
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<tr>
<td>Radiated power</td>
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<td>Tunes (Q_x, Q_y)</td>
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<td>Chromaticities (\xi_x, \xi_y)</td>
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<td>-125, -68</td>
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<tr>
<td>---------------------------------</td>
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<tr>
<td>Revolution frequency</td>
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<td>RMS bunch length</td>
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<td>Bunch area:</td>
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<td>Current/bunch</td>
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<td>Peak current</td>
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## Other small-ring parameters (2)

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<td>Electrons per bunch</td>
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<td>Current/bunch</td>
<td>0.15697 mA</td>
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<td>Peak current</td>
<td>63.87 A</td>
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<td>Space charge tune shift (horizontal)</td>
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<td>Space charge tune shift (vertical)</td>
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<tr>
<td>Longitudinal microwave instability limit</td>
<td>$Z/n = 0.14496 , \Omega$</td>
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<td>Transverse coupled-bunch instabilities driven by resistive wall (Al beam pipe)</td>
<td>0.990 ms, 0.045 damping time</td>
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<td>Fast-ion instability growth time, beam particles uniformly distributed along train</td>
<td>2.3 ns</td>
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<tr>
<td>Fast-ion instability growth time, inter-train gaps clear trapped ions completely</td>
<td>26 ms</td>
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Comments about damping rings

It will be interesting to see how various optimizations turn out if it is possible to remove the 20 ns minimum bunch spacing requirement.

A small damping ring could be built and tested before linac construction was complete. (Independent tunnels) This is an appealing idea! It could allow beam to be injected into the linac as soon as the main linac was under construction.

Exploration of technical issues associated with damping rings is becoming a major focus of LC activity at Fermilab.
Comments about a small damping ring

The present lattice design of the small damping ring uses 25 wigglers, so the beam dynamics issues associated with wigglers will be less complex.

Preliminary studies (results in the tables a few slides back) indicate that the small ring is stable.

The present lattice has six straight sections. This will allow inclusion of distributed correction schemes which address dispersion, coupling, higher order multipole corrections, and so forth.
Fermilab TESLA Damping Ring effort

Fermilab’s EE Department has assigned an engineer (with significant experience in kicker design and fabrication) to develop ideas for a small damping ring’s kicker system.

Fermilab’s Magnet Design Group is also investigating kicker designs.

Beam Physicists at FNAL are developing detailed maps of wigglers for damping ring beam dynamics calculations.

We are collaborating with physicists from ANL, BNL: their light source experience and modeling tools will aid in the development of an improved lattice as we study the properties of a small damping ring.

Fermilab expects to develop a full design for a small damping ring (including design of accelerator components and cost estimates), in order to allow meaningful comparison with the present TESLA damping ring design.
Fermilab Accelerator Physics Activities

In addition to the performance of the damping ring, successful low emittance transport (LET) of the beam from the damping ring to the interaction region is crucial to the luminosity preservation.

Fermilab is currently developing local expertise in simulation of the main linac.

At the moment, we are working with the NLC linac lattice, but experience gained through these studies will aid our efforts in studying the TESLA main linac.

Fermilab is interested in playing a significant role in design studies of the TESLA linac, including (naturally) LET.
Comments from a university professor

I am not a Fermilab staff scientist. They can’t fire me….

In recent times Fermilab has been concentrating its resources on Run II. The Tevatron’s performance has improved considerably in recent weeks.

In the past, the Linear Collider effort at Fermilab has been much smaller than is desirable.

This is changing now. As far as I can tell, this is the real thing.

Shekhar Mishra is now leading an LC effort which will be ambitious in scope. Initial commitment of resources: 6 to 12 full time (mostly accelerator) physicists.
Fermilab engages

Director’s statement to HEPAP in 2001:

We propose to the U.S. and to the international HEP community that we work together to build a linear collider at or near the Fermilab site.

Shekhar’s presentation at SLAC ALCPG04 meeting (1/04):

Fermilab would like to take the lead in organizing an international effort to design warm/cold ETF once goals are set. We assume that the emerging design would go to the International Design Group as a proposal. Fermilab would be eager to host such a facility at Fermilab.
Fermilab engages

“ETF” stands for “Engineering Test Facility.” Some of the possibilities presented include:

ETF could be 1% demonstration machine for the technology chosen by ITRP.

It could have an Injector, Linac (5 GeV), Damping Ring, post damping ring Linac

This is a significant change in Fermilab’s level of engagement with the Linear Collider.

An early step: March 15 – 18 working meeting studied schemes for a smaller TESLA damping ring. It was a very productive meeting. No PowerPoint talks. Lots of calculating.
ETF speculation... (from Shekhar)

- A0 photo injector that can be used for at least TESLA type beam.
- There are several discussions on front end of the warm Linac for other applications.
- A 5 GeV Linac can be designed to inject beam into either the Main Injector/Tevatron tunnel.
- In the Main Injector Tunnel one can imagine using either the Main Injector or the Recycler as a damping ring.
- One can build a damping ring using Recycler permanent magnet technology in either the Main Injector or the Tevatron tunnel.
- Beams after the damping ring can be extracted in existing long transfer lines, measured and/or accelerated.
Other comments...
Summary/conclusions

The participation of North American university groups in Linear Collider R&D has increased by 50% in the last two years. This may help increase the sense of engagement (and responsibility) felt by LC participants.

Fermilab’s LC involvement has begun to increase dramatically.