Experimental, simulation, and design studies for linear collider damping rings.

Classification (subsystem)

Damping rings

Personnel and Institution(s) requesting funding

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Project Overview

Studies of wiggler-related dynamic aperture limitations.

Two classes of circular electron accelerators will generate damping almost entirely in wiggler magnets: linear collider damping rings and some low-energy e^+e^- factories, such as CESR-*c*. Wigglers 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 damping ring 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 International Linear Collider (ILC) 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 space charge effects.

The large density of particles in the ILC 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. To evaluate the effects of space charge, we will incorporate suitable algorithms into our particle-tracking simulations and modeling codes.

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 hardware to be used will be an Intel-architecture computing farm (`http://www.hep.umn.edu/~cleo3/`) consisting of 48 dual-processor systems in 1U rack-mount enclosures. An undergraduate student will be supported to act as operator and to participate in code development. While operating the farm for linear collider simulations, the high energy physicists at Minnesota will continue to develop expertise in accelerator physics to allow contributions to algorithm development and simulation-based benchmarking of designs for the damping ring project.

The modeling code is based on an existing object-oriented particle-tracking library, Bmad [1], that has been extensively tested against an operating machine, CESR. 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, 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 ILC damping rings.

Development of high-quality beam diagnostics systems

High-quality beam diagnostics are required for the measurement of small beam sizes and short bunch lengths, and are critical to the development of any linear collider damping ring. We plan to improve the following existing CESR diagnostic systems, which are also important for linear collider damping rings: high-resolution beam size diagnostics (interferometric technique), and streak camera bunch length and shape monitoring.

Review of ILC damping ring design and optics.

The large number of bunches (2820) and the relatively large inter-bunch spacing (337 ns) in the TESLA ILC 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 for the damping rings, and compare the advantages and disadvantages relative to the baseline design.

Investigation of the superferric option for the ILC damping ring wigglers.

The baseline design of wigglers for the ILC damping rings is based on permanent magnet technology. Superconducting wigglers were also considered. 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 ILC damping rings. We will re-evaluate the technical and cost advantages and disadvantages of each technology choice.

Studies of beam-based alignment and emittance correction algorithms.

The ILC 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, 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.

Broader Impact

Much of the research described in this proposal is synergistic with efforts to improve the performance of low-energy e^+e^- factories, such as CESR-c and DAΦNE. The simulation and modeling tools described above, as well as the diagnostic systems, will have applications in the design and operation of any high-performance circular electron accelerator systems, such as synchrotron radiation sources.

This proposal will support graduate and undergraduate students training in accelerator physics. Most accelerator work is carried out in national labs, which do not have the strong training mission of a university. The national shortage of accelerator physicists is related to the relatively poor representation of this discipline in the university community. This shortage affects not only high energy physics, but also many other fields, such as solid state physics, materials science, biophysics, and medical science, which have come to depend on accelerators as their front-line research tools. This proposal will contribute to the education of accelerator physicists, and consequently can have a broad impact on all these fields.

Results of Prior Research

Prior research in this area has been supported as part of the current grant NSF PHY-0355182, entitled "University-based Accelerator R&D for a Linear Collider", in the amount $128,315, covering the period 9/1/04-8/31/06. Under this grant, the specific activity entitled "Experimental, simulation, and design studies for linear collider damping rings" is supported at the level of $45,133. Results of this prior research are described below.

Studies of dynamic aperture of wiggler-dominated damping rings

Work performed thus far in studying the dynamic aperture of the various ILC damping ring designs has been focused on the development of simulation tools and methods to be used for the accurate calculation of the dynamic aperture of a wiggler-dominated ring. Using Bmad, we have optimized the application of conventional dynamic aperture calculations to a damping ring lattice. A new dynamic aperture calculation which we have also implemented to study the damping ring, is a frequency map analysis which shows the dynamic aperture while also highlighting the chaotic nature of the particle orbits.

These simulation tools have been used on the TESLA dog-bone damping ring lattice using a full non-linear representation of the wiggler magnets which are the predominant limiter of the dynamic aperture. The non-linear modeling of the damping ring wigglers has been done using the same techniques developed at Cornell for modeling CESR-*c* wigglers, now modified for application to the linear collider damping rings.

With simulation tools and algorithms in place, evaluating the robustness of the different ILC damping ring designs will be a straightforward application of the simulations. Future work will also be performed to maximize the dynamic aperture of a wiggler-dominated ring by varying the physical geometry of the wiggler magnets and studying these new wiggler magnets in the proposed damping ring designs.

Alternate designs for the ILC damping rings

We are investigating a method for manipulating a compressed bunch train in the damping ring using RF deflectors and multiple transfer lines. Bunches in the injection/extraction line are four times as far apart as bunches in the main ring, thereby reducing the size of the ring by approximately a factor of four without increasing requirements for the injection/extraction kicker.

In order to model these rings, we have implemented deflecting cavity elements in Bmad. These elements use realistic EM fields including spatial and temporal nonlinearities. We are currently testing this scheme in a 4 km ring based upon the TESLA dogbone design and the KEK-B deflecting cavities. Early results suggest that we can obtain the necessary emittance and damping time without a significant compromise of the dynamic aperture.

Development of simulation and modeling tools.

In the past year we have completed the assembly and commissioning at Minnesota of an Intel-architecture computing farm (`http://www.hep.umn.edu/∼cleo3/`) consisting of 48 dual-processor systems in 1U rack-mount enclosures. Funding for this system was provided by the Department of Energy and the University of Minnesota primarily to provide large-scale simulations for the CLEO-*c* experiment, but with a planned 10% share for linear collider accelerator simulations. The processors are Pentium 4 Xeons operating at ~ 2.5 GHz. with hyper threading enabled. Each worker node is equipped with 1GB of memory, modest local disk space (40GB), and Gbit Ethernet. Libraries, and input and output files reside on a dedicated 3.5-terabyte fiber-channel disk array. The operating system is Scientific Linux and all nodes are network-administered in a PXE boot environment.

CLEO-*c* simulations are currently carried out under the Condor system, while accelerator simulations are run in the LAM/MPI parallel computing environment. So far linear collider simulations on computers at Minnesota have been limited to demonstration jobs with Bmad and the TESLA Dog-Bone Damping Ring Lattice from W. Decking of DESY. CESR-*c* simulations are being run intensively, taking advantage of significant excess processing capacity beyond the current needs of the CLEO-*c* program.

Development of high-quality beam diagnostics systems

Improved beam diagnostics capability is critical to our understanding of CESR-*c* as a wiggler-dominated storage ring and for the measurement of small beams and short bunch lengths at CESR. A general upgrade of CESR instrumentation is presently underway. Two aspects of this upgrade that are particularly applicable to experiments for damping ring development are upgrades of CESR's streak camera and beam profile monitor systems.

The data acquisition system for our Hamamatsu C1587 streak camera has recently been upgraded. The camera is located at the end of an optical transport system which accepts synchrotron light from both the electron and positron beams in CESR originating from source points in two equivalent dipoles. The streak camera provides resolutions down to 1.6 ps for bunch measurements in CESR where bunches are spaced at 14 ns intervals. The device is presently undergoing *in situ* calibration and is in regular use for both low and high energy CESR operation.

Double-slit interferometer hardware, operating on the principle of the Michelson Stellar Interferometer, has been installed in the optics systems of both the electron and the positron vertical beam profile monitors in CESR. The system makes use of horizontally polarized synchrotron light originating in a standard CESR arc bend magnet. The depths of the observed interference fringes can be measured with a CCD camera and used to determine the vertical source size. With our current slit arrangement, a vertical resolution limit of approximately 50 μm is obtained. We are presently expanding the capability of this device for fast bunch-by-bunch readout by installing a new optics line for a Hamamatsu H7260 multianode photomultiplier. This device consists of a 32 channel linear array of anodes with 1 mm pitch and 0.6 ns rise-time. The fast response of this device makes it an excellent choice for distinguishing the 14 ns spaced bunches in CESR. With suitable imaging optics, our simulations indicate it is capable of making beam size measurements with a resolution of several percent in fewer than 10 passes of a single bunch. As such it can provide a unique probe of multi-bunch beam dynamics in CESR. Turn-by-turn multi-bunch readout electronics has been designed, built, and is currently being tested. We expect to start full system tests of the positron monitor prototype during the first half of 2005. The addition of an optics line and a second device for electron monitoring should follow shortly thereafter.

Due to the small beam sizes expected in a linear collider damping ring, beam profile measurement devices with improved intrinsic resolution are highly desirable. There is an ongoing effort at LEPP [2] to develop a beam profile monitor using Si and/or GaAs PIN diode devices to image X-rays. Our development of turn-by-turn multi-bunch readout electronics for our existing beam profile system will provide critical hardware for use in the testing of such devices. At present we are developing suitable analog front-end electronics to read out the proposed prototype detectors. The remainder of the electronics package will be a copy of that developed for our visible light beam profile monitor.

Facilities, Equipment and Other Resources

The facilities of the Cornell Laboratory for Elementary-Particle Physics (LEPP) include an accelerator complex (linac, synchrotron, storage ring, and insertion devices), the CLEO detector, substantial computer facilities with a computing support staff, an electronics shop equipped with a variety of sophisticated electronic test equipment, electronic design and fabrication support staff, machine shops, and other related facilities.

FY2005 Project Activities and Deliverables

During the first year we plan to:

1. Develop a space charge element for particle tracking simulations.

2. Make active use of the streak camera bunch length and shape monitor, and complete upgrades to the interferometric beam size monitor, including integration into the CESR control system.
3. Continue to investigate alternative damping ring solutions for the ILC.
4. Continue to 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*.
5. Perform an evaluation of the technical and cost advantages of permanent magnet and superferric wigglers for the ILC damping rings.
6. Continue to develop the infrastructure for supporting accelerator simulations on the Minnesota farm. This will include investigating the MPICH implementation of multi-processor parallel computing under Condor. This will have the benefit of more effective utilization of resources within a cluster that is serving both CLEO-*c* and accelerator simulations, and will allow the linear collider simulations to take advantage of the fault tolerance, administrative resources, and other features of high-throughput computing that Condor provides.

The first year deliverables are technical reports on the items described above.

FY2006 Project Activities and Deliverables

During the second year we plan to:

1. Complete the benchmarking of our design algorithm and particle-tracking code for a wiggler-dominated ring.
2. Using this code, perform a complete simulation (tune plane scan) of candidate ILC damping ring designs, including wiggler nonlinearities and space charge, to determine the optimum operating points and particle loss rates.
3. Develop well-optimized correction algorithms for BBA and vertical dispersion and coupling correction that can be applied to the ILC damping rings and to tests in CESR-*c* and possibly ATF.
4. Continue to develop the infrastructure for supporting accelerator simulations on the Minnesota farm.

The second year deliverables are technical reports on the items described above.

Budget justification: Cornell University

The activities will require the involvement of Cornell LEPP staff members and graduate students. One graduate student will be supported half-time from this grant in the first year, and full-time in the second year. The activities at Cornell will require travel funds for consultation with collaborators at DESY, SLAC, KEK, and LBNL. Indirect costs are calculated at Cornell's 58% rate on modified total direct costs.

Three-year budget, in then-year K$

Institution: Cornell University

Item	FY2005	FY2006	Total
Other Professionals	0	0	0
Graduate Students	9.067	19.767	28.834
Undergraduate Students	0.0	0.0	0.0
Total Salaries and Wages	9.067	19.767	28.834
Fringe Benefits	0.0	0.0	0.0
Total Salaries, Wages and Fringe Benefits	9.067	19.767	28.834
Equipment	0.0	0.0	0.0
Travel	4.0	4.0	8.0
Materials and Supplies	0.0	0.0	0.0
Other direct costs	9.183	17.964	27.147
Minnesota subcontract	13.5	13.5	27.0
Total direct costs	35.75	55.231	90.981
Indirect costs*	11.089	16.775	27.864
Total direct and indirect costs	46.839	72.006	118.845

* Includes 26% of first $25K subcontract costs

Budget justification: University of Minnesota

The budget for the Minnesota component of the project assumes that all support for scientific personnel (Poling, Smith) will be provided by the Department of Energy through grant DE-FG02-94ER40823. This grant also covers maintenance and software-licensing costs for the Minnesota simulations farm. Salary support is requested for one undergraduate work-study student to aid in programming and operation of this facility for linear collider applications. The budget is based on the expectation of 10 to 15 hours of work per week during the academic year and double that during the summer. A typical level of work-study support is assumed. Funds are also requested for travel to three or four linear collider meetings per year. DOE-supported travel to Cornell for CLEO-*c* work will also provide opportunities to consult with collaborators. Indirect costs are computed using the University of Minnesota's rate for on-campus research (49.5%). Undergraduate student salaries do not incur fringe-benefit costs.

Three-year budget, in then-year K$

Institution: University of Minnesota

Item	FY2005	FY2006	Total
Other Professionals	0	0	0
Graduate Students	0	0	0
Undergraduate Students	5.0	5.0	10.0
Total Salaries and Wages	5.0	5.0	10.0
Fringe Benefits	0	0	0
Total Salaries, Wages and Fringe Benefits	5.0	5.0	10.0
Equipment	0.0	0.0	0.0
Travel	4.0	4.0	8.0
Materials and Supplies	0	0	0
Other direct costs	0	0	0
Total direct costs	9.0	9.0	18.0
Indirect costs	4.5	4.5	9.0
Total direct and indirect costs	13.5	13.5	27.0

References

[1] D.L. Rubin and D. Sagan, "CESR Lattice Design", Proc. 2001 Particle Accelerator Conference, Chicago, paper RPPH121 (2001).

[2] J. Alexander, J. Ernst,"Design for a Fast Synchrotron Radiation Imaging System for Beam Size Monitoring", a component of the grant NSF PHY-0355182, "University-based Accelerator R&D for a Linear Collider"