PROGRESS REPORT

Experimental, Simulation, and Design Studies for Linear Collider Damping Rings.

Classification (subsystem)

Damping rings

Personnel and Institution(s) requesting funding

G. Dugan, R. Helms, M. Palmer, D. Rubin, D. Sagan, J. Smith, J. Urban, Cornell University.
M. Ehrlichman, 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 and Cockroft Institute

Project Leader

D. Sagan
dcs16@cornell.edu
(607) 255-0918

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).

Development of simulation and modeling tools

The bulk of the simulations done is based on an existing object–oriented particle–tracking library, Bmad[1]. Bmad has been extensively tested against an operating machine, CESR and has shown good agreement with other simulation codes[2]. Bmad was created to enable programmers to develop programs without the need to code from scratch commonly used functions such as lattice file parsing and particle tracking. Using a subroutine library such as Bmad cuts down on the time needed to develop programs and reduces programming errors.

To facilitate the fast development of simulation programs, an accelerator design and analysis simulation program, based on the Bmad, has been developed called Tao[3] (Tool for Accelerator Optics). Tao implements the essential ingredients needed to solve many simulation problems. This includes the ability to design lattices subject to constraints, the ability to simulate errors and changes in machine parameters, and the ability to simulate machine commissioning including simulating data measurement and correction. The great strength of Tao is that it is designed to be easily customizable so that extending it to solve new and different problems is relatively straight forward.

The hardware at Minnesota to be used for ILC simulation and modeling is an Intel–architecture computing farm (`http://www.hep.umn.edu/~cleo3/`) consisting of a 100–CPU computer farm running Scientific Linux, which was assembled as the Monte Carlo farm of the CLEO-c experiment. The farm has sufficient capacity also to carry out accelerator simulations for this Linear Collider program and for the CESR-c luminosity improvement program.

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.

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.

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 continue 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 ILC configuration decision for a superferric wiggler in the damping ring was made in large part based on the results of our dynamic aperture studies. However a specific wiggler design has not been finalized, as the CESR-c superferric wiggler has been shown to provide more dynamic aperture than is necessary in the ILC damping ring.

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.

Alternate designs for the ILC damping rings

This effort aimed to reduce the proposed 17 km circumference of the ILC damping ring, without assuming improvements in kicker performance[4]. The concept was to store a compressed bunch train where RF deflecting cavities would distribute bunches between multiple transfer lines at the injection/extraction point. In principle, the circumference of the damping ring could be reduced by approximately a factor of four using this design without increasing the requirements for the injection/extraction kicker.

Broader Impact

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.

Progress Report

Studies of wiggler–related dynamic aperture limitations.

Work performed thus far has used conventional dynamic aperture calculations and newer frequency map calculations. These calculations were previously developed at Cornell for modeling CESR-c wigglers, implemented in Bmad, and optimized for application in wiggler–dominated damping rings.

With a wide array of tools at hand, all seven of the viable ILC damping ring designs were evaluated on their dynamic aperture using a number of different machine and wiggler models[5]. The dynamic aperture was measured for each design with and without realistic higher–order multiples on the main ring magnets and with and without non–linear wiggler models. Wiggler models used were a pure linear model, a full non–linear model, and an intermediate model with only idealized wiggler non–linearities.

Results from this work were that the TESLA permanent magnet wiggler provided insufficient dynamic aperture while the CESR-c superferric wiggler gave excellent dynamic aperture in a wiggler–dominated damping ring. The baseline ILC configuration decision for a superferric wiggler in the damping ring was made in large part based on the results of these studies.

Development of simulation and modeling tools

Bmad has been extended to include particle spin tracking. This implementation uses a spinor–quaternion approach [6] where the spin is described using the SU(2) representation with a complex spinor. The transport of spin can then be described through the use of a SU(2) transport matrix called a quaternion. Only three independent numbers are required to describe the rotation of spin through an element. This results in less floating point operations compared to using a SO(3) representation and without the loss of generality. The quaternions are found using the T-BMT equation of spin motion and the Lorentz equation. They are computed to second order and are represented by a taylor series in phase space. So far, quaternions have been computed for dipoles, quadrupoles, sextupoles, solenoids, combination quadrupole/dipole, solenoids and electrostatic quadrupoles. A numerical integrator has also been implemented for spin and orbit tracking that is based on the Boris integration scheme [7].

The principal Minnesota accomplishments so far have been helping to port the Bmad simulation tools from the Compaq Tru64 architecture to Intel processors running Linux, and implementing parallel–processing versions of the simulation code on the Minnesota farm. The initial implementation, based on LAM/MPI, was limited in significant ways, and we have developed an alternative operational mode running parallel Bmad simulations under the PVM parallel processing package within the Condor management structure that is used for CLEO-c Monte Carlo. This enhances fault tolerance and facilitates allocation of resources in a manner compatible with the CLEO-c farm. This work was done by Ehrlichman, with local supervision by Poling and Smith, and technical guidance and support from Mark Palmer, David Rubin, and David Sagan.

It is now possible to perform accelerator simulations on the Minnesota farm in either mode. Ehrlichman acts as operator and maintainer of the facility, helping with operating system support and managing hardware repairs, ensuring maximum availability for simulations requested by the Cornell accelerator group. While carrying out these support tasks, Ehrlichman has also been learning accelerator physics, and during the remainder of FY2006 will work with Palmer and Sagan on further refinement and application of the simulations, as well as supporting the group's use of the farm.

Studies of space charge effects.

Routines for tracking with space charge forces have been added to the Bmad library. This feature has been used to calculate the space charge tune shift in various proposed designs for the Linear Collider damping ring, where it has been shown to be in good agreement with

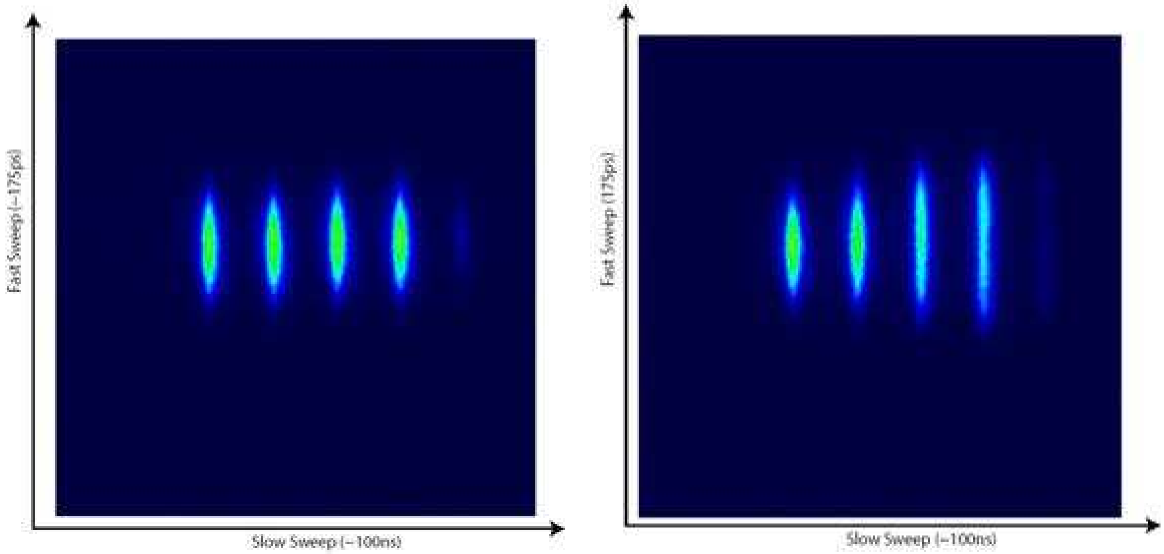

Figure 1: Streak camera images showing a stable 5–bunch train in CESR (left) and an unstable train (right).

analytic calculations.

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 system and beam profile monitor systems.

CESR's Hamamatsu C1587 streak 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 camera provides resolutions down to 1.6 ps for bunch length measurements in CESR. Recent improvements to the system have included the addition of a new computer for system control, an new CCD camera, and updated software. These upgrades have allowed for full remote control of the system. Other improvements have included the development of a new software package to Analise the streak camera data. An important feature of the new software is that it supports interfacing between the Windows PC which provides data acquisition and control for the streak camera and the OpenVMS–based CESR control system. This will allow significantly more sophisticated beam monitoring. Figure 1 shows two images taken in conditions with a stable train (left) and an unstable train (right) in CESR. In addition, a pair of gated cameras with 2 ns gates will soon be integrated into the optics setup presently supporting the streak camera. These cameras will be used for transverse beam measurements.

A new line has been installed in the optics of CESR's electron vertical beam profile monitor. This line services a Hamamatsu H7260 multi–anode photomultiplier (PMT). This PMT has a 32 channel linear array of anodes with 1 mm pitch and 0.6 ns rise–time. Readout is provided by a 72 MHz custom digitizer which provides turn–by–turn multi–bunch readout for CESR's

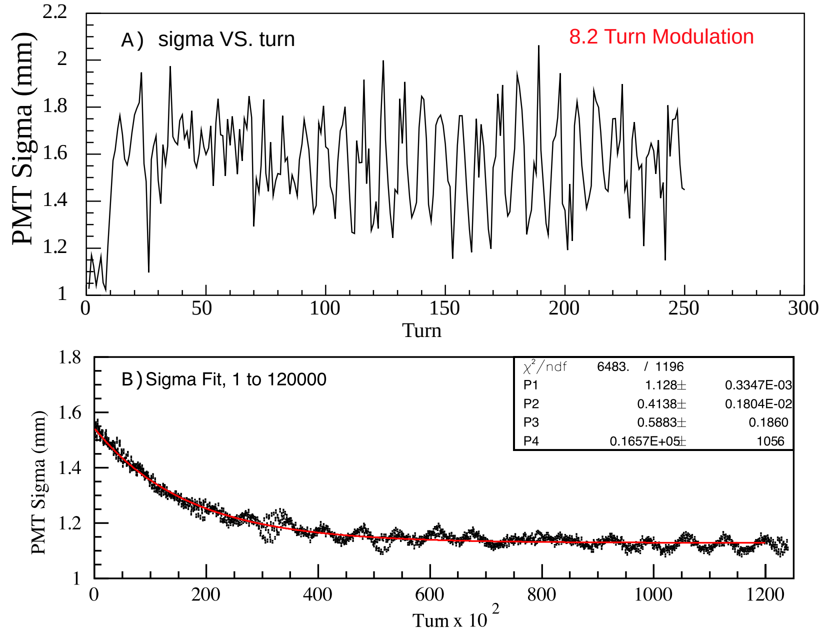

Figure 2: Two vertical beam profile measurements after resonant excitation of a single electron bunch. In each case, synchrotron light from the beam was projected directly onto the face of the multichannel PMT. A) Turn–by–turn measurement where the beam excitation was begun at turn 10 and was approximately 70 turns in duration. From roughly turn 80 onwards, a rotation of the vertical phase space ellipse is observed through the oscillation of the vertical size. B) The long term incoherent damping of a similar excitation of the beam. In this case 100 turn averaging of the PMT signals was applied. The vertical axes for both plots are in units of the image size on the PMT face.

14 ns spaced bunches. Initial applications have included looking at bunch–to–bunch vertical beam size variations, high bandwidth monitoring of beam stability, and measurements of incoherent damping of a resonantly excited beam. Figure 2 shows two different measurements of the response of the beam to resonant excitation. In 2A an excitation of the beam starting around turn 10 and lasting approximately 75 turns distorts the (y, p_y) phase space of the beam. Afterwards, rotation of the resulting mismatched phase space ellipse, consistent with a fractional tune of $Q_y = 0.56$ is observed. Figure 2B shows the much longer timescale incoherent damping of a similarly excited beam. Preparations are currently underway to install a similar device to monitor the positron beam.

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 [8] to develop a beam profile monitor using Si and/or GaAs PIN diode devices to image X–rays. The first prototype device (GaAs technology) will be tested during a high energy (5.3 GeV) run at the end of January 2006.

Review of ILC damping ring design and optics

The Cornell group has participated in the ILC damping ring design reviews and has made contributions to the preparation of the damping ring baseline recommendation. Involvement included a comparative appraisal of superconducting vs permanent vs warm technologies for the wigglers as well as an evaluation of wiggler field quality, and the effect of wiggler nonlinearity on the dynamic aperture of the proposed lattices. In addition, an analysis was performed on a configuration in which RF kickers are used to separate closely spaced bunches for compatibility with a finite width injection/extraction kicker.

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

A comparison of technologies proposed for the ILC damping ring wigglers was carried out as part of the process of reaching a baseline configuration decision. Issues which were reviewed included: field quality, physical aperture, power consumption, radiation resistance, construction costs, auxiliary requirements, flexibility, and availability. The two dominant issues were found to be the field quality and physical aperture. Proposed wiggler designs with excessive lateral field roll–off have been found to seriously degrade the dynamic aperture performance of the damping rings. At present, only the superferric option has been demonstrated to have sufficiently good field quality such that dynamic aperture is not degraded. A large physical aperture is required for satisfactory acceptance of a large injected positron beam. The present specification is that a minimum vertical aperture of 32 mm is required in the wiggler for this reason. A larger aperture also lessens the impact of electron cloud and resistive–wall effects. These issues strongly favor the superferric wiggler design due to the large pole gap. For all other issues, the superferric design was found to be an acceptable solution.

Alternate designs for the ILC damping rings

Implementation of this design required augmenting the Bmad library with the capability of tracking through RF deflecting cavities. Software was written to calculate the electromagnetic fields in such a cavity, with realistic space and time dependence. Moreover, the cavities were implemented in a generic way, and may be useful in other contexts where cavities of various sizes or shapes, or operating in various modes, are desired.

The Bmad library itself has been extended to facilitate tracking through rings with multiple transfer lines. This project has also thoroughly exercised Bmad's flexibility in manipulating reference orbits through multiple transfer lines.

Lattice files have been created demonstrating two–line and three–line versions of this damping ring. The sensitivity to RF stability has been evaluated and has been shown to be negligible. In comparison with other proposed ILC damping rings, however, the multi–line rings suffer from relatively poor momentum acceptance. Given the ILC community's increasing focus on developing a fast kicker, no further work on this project is planned at this time.

Next year FY2006 Project Activities and Deliverables

Studies of wiggler–related dynamic aperture limitations.

Future work in this area will proceed using a superferric wiggler with the ILC baseline and alternative damping ring designs. Detailed studies of dynamic aperture and frequency map performance will continue, and new studies of injection efficiency and particle distribution effects are planned. Studies involving varying wiggler model non–linearity and ring magnet errors will continue to be key component to fully understanding the dynamic aperture limits in a realistic machine environment.

Development of simulation and modeling tools

Bmad and Tao are continually expanding to meet simulation and modeling. The eventual aim is to be able to provide a "complete," flexible, injector to collision point to detector simulation tool. In particular planned work includes developing a Touschek Lifetime module in Bmad and creating a custom version of Tao for modeling ILC damping ring designs.

Studies of space charge effects.

Further investigation will verify the accuracy of the space charge module in the context of multi–particle tracking, and explore the implications of space charge forces on emittance in the damping ring.

Review of ILC damping ring design and optics

Cornell plans to continue its involvement with the ILC damping ring working group. In particular the characteristics of the 6km baseline configuration will be studied in more detail, with a wiggler designed specifically for a damping ring (rather than the CESR-c wiggler).

Development of high–quality beam diagnostics systems

Work will continue to complete the installation of the new visible light beam profile monitor hardware, and to develop an operational x–ray beam profile monitor. Data acquisition software upgrades will be implemented so that the beam profile monitor and streak camera systems can be more fully integrated into CESR operations. Our primary focus will be on the application of these systems to improving our understanding of a wiggler–dominated ring.

Studies of beam–based alignment and emittance correction algorithms.

Ongoing modeling is planned as part of the low emittance transport simulations and also as part of the design work to convert CESR to an ILC damping ring test facility.

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

Future work will involve designing an optimized ILC superferric wiggler based on the CESR-c superferric wiggler design. Reducing the size of the CESR-c wiggler in any or all dimensions, has the potential to reduce the total cost of the damping rings due to the 100–500 meters of wiggler in each ring. An optimized superferric wiggler design will be sought with a smaller width, gap, and length without sacrificing the physical aperture (gap), the dynamic aperture (length), and the field quality (width). Mapping out the dependence of these lattice non–linearities on the physical description of a wiggler will provide a better understanding of wiggler magnets which can be used in the ILC damping ring as well as the many other wiggler rings around the world.

Work in the following year will begin at Cornell to construct a prototype ILC superferric wiggler. The infrastructure and expertise honed at Cornell during the construction of the

CESR-c wiggler will be taken advantage of for the ILC wiggler in a very similar procedure.

Budget justification: Cornell University

The activities will require the involvement of Cornell LEPP staff members and graduate students. One graduate student will be supported full–time for the year. The activities at Cornell will require travel funds for consultation with collaborators at DESY, SLAC, KEK, and LBNL. Budgeted is one trip to KEK at $2.5K per trip, two trips to Europe at $2.0K per trip and 3 trips to SLAC/LBNL at $1.5K per trip. Indirect costs are calculated at Cornell's 58% rate on modified total direct costs.

Also covered by the budget is hardware for beam profile monitor additions including a Shutter unit and controller, control interface and overcurrent trip electronics boards, and upgraded beam expansion optics.

Institution: Cornell University

Item	FY2006	Total
Other Professionals	0.000	0.000
Graduate Students	28.187	28.187
Undergraduate Students	0.000	0.000
Total Salaries and Wages	28.187	28.187
Fringe Benefits	0.000	0.000
Total Salaries, Wages and Fringe Benefits	28.187	28.187
Equipment	4.600	4.600
Travel	9.000	9.000
Materials and Supplies	0.000	0.000
Other direct costs	17.909	17.909
Minnesota subcontract	13.500	13.500
Total direct costs	73.196	73.196
Indirect costs*	21.658	21.658
Total direct and indirect costs	94.854	94.854

* 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. 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.

Institution: University of Minnesota

Item	FY2006	Total
Other Professionals	0.000	0.000
Graduate Students	0.000	0.000
Undergraduate Students	5.000	5.000
Total Salaries and Wages	5.000	10.000
Fringe Benefits	0.000	0.000
Total Salaries, Wages and Fringe Benefits	5.000	5.000
Equipment	0.000	0.000
Travel	4.000	4.000
Materials and Supplies	0.000	0.000
Other direct costs	0.000	0.000
Total direct costs	9.000	9.000
Indirect costs	4.500	4.500
Total direct and indirect costs	13.500	13.500

References

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

[2] J. Urban , L. Fields, D. Sagan, "Linear Accelerator Simulations with Bmad," Proc. 2005 Particle Accelerator Conference, Knoxville, Tennessee (2005).

[3] D. Sagan and J. C. Smith, "The Tao Accelerator Simulation Program," Proc. 2005 Particle Accelerator Conference, Knoxville, Tennessee (2005).

[4] R. W. Helms and D. L. Rubin, "A Compact Damping Ring Using RF Deflectors for the International Linear Collider," Proc. 2005 Particle Accelerator Conference, Knoxville, Tennessee (2005).

[5] J. Urban and G. Dugan, "CESR-c Wiggler Studies in the Context of the International Linear Collider Damping Rings," Proc. 2005 Particle Accelerator Conference, Knoxville, Tennessee (2005).

[6] G. Hoffstaetter, *A Modern View of Polarized Proton Beams*, Springer Tracts in Modern Physics, Springer, 2004

[7] P.H. Stoltz and J.R. Cary, *Efficiency of a Boris-like integration scheme with spatial stepping*, PRST–AB **5**, 094001 (2002).

[8] J. Alexander, J. Ernst, M. Palmer, "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".