Proposal to the University Consortium for a Linear Collider

August 28, 2002

Proposal Name

Fast Synchrotron Radiation Imaging System for Beam Size Monitoring

Classification(accelerator/detector: subsystem)

Accelerator: Beam Monitoring.

Personnel and Institution(s) requesting funding

Jim Alexander, Cornell University
Jesse Ernst, State University of New York, Albany

Contact Person

Jim Alexander
email: jima@lns.cornell.edu
phone: 607-255-5259

Jesse Ernst
email: 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[The ZDR for the NLC; SLAC report #474, pg. 237]. 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 10nm (ie X-rays above ∼0.1keV) will provide sufficient resolution [The ZDR for the NLC; SLAC report #474, pg. 237]. 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, 20ns 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. 1ns 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 [see for instance Handbook of Optics, Vol III, Michael Bass, Ed. and references therein]. 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 flourescent 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 10ns 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 1ns resolution could image single NLC bunches, but would require technological development. A system that would offer 10ps 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 Xrays 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 year's 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 xray 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.

FY2003 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.

FY2004 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 Xray lines. Write a technical report on results.

FY2005 Project Activities and Deliverables Optimize design details and write final design report.

We request funding only for purchases of computers for design and simulation efforts and for the silicon readout systems. The proposed travel budget covers travel for one of us (JAE) to come to to Ithaca 4 times per year ($2K) and for one of us (JPA) to travel to Albany 4 times per year ($2K).

Cornell University

Item	FY2003	FY2004	FY2005	Total
Other Professionals	0	0	0	0
Graduate Students	0	0	0	0
Undergraduate Students	0	0	0	0
Total Salaries and Wages	0	0	0	0
Fringe Benefits	0	0	0	0
Total Salaries, Wages and Fringe Benefits	0	0	0	0
Equipment	5	10	5	20
Travel	2	2	2	6
Materials and Supplies	2	2	2	6
Other direct costs	0	0	0	0
Total direct costs	9	14	9	32
Indirect costs (57%)	5	8	5	18
Total direct and indirect costs	14	22	14	50

Institution: State University of New York, Albany

Item	FY2003	FY2004	FY2005	Total
Other Professionals	0	0	0	0
Graduate Students	0	0	0	0
Undergraduate Students	0	0	0	0
Total Salaries and Wages	0	0	0	0
Fringe Benefits	0	0	0	0
Total Salaries, Wages and Fringe Benefits	0	0	0	0
Equipment	5	10	5	20
Travel	2	2	2	6
Materials and Supplies	2	2	2	6
Other direct costs	0	0	0	0
Total direct costs	9	14	9	32
Indirect costs (49.9%)	4	7	4	15
Total direct and indirect costs	13	21	13	47