Fast Synchrotron Radiation Imaging System for Beam Size Monitoring

Classification (accelerator/detector: subsystem) Accelerator: Beam Monitoring.

Personnel and Institution(s) requesting funding

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Overview of Project

With the high intensity, low emittance beams needed to reach the luminosity goals of the linear collider, beam size monitoring will likely play an important role in machine operation. In the damping rings synchrotron radiation (SR) emitted by the bunch can provide a means of measuring transverse bunch size and shape. 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.

Although the details of the damping ring of the future ILC are not fixed yet, the recommended Baseline Configuration design indicates a 6km ring with 2800 bunches at 5GeV. Although the lattice design is not yet settled, previous damping ring designs would lead us to anticipate a vertical bunch size at the midpoint of the dipole magnets around $\sim 5\mu m$ and a horizontal size around $\sim 40\mu m$. with a critical energy in the range $5 \sim 10$ keV. Synchrotron radiation is cast forward in a narrow cone of opening angle $1/\gamma$. 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 1nm (ie X-rays above $\sim$1keV) will provide sufficient resolution. 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 $1 \sim 10$ 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 minimizing 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 (7ns in the present recommended baseline configuration). Solid state 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. Commercially available GaAs photodiode receivers for 10GBit/sec ethernet systems exhibit 30ps rise and fall times, so subnanosecond detectors are already available off-the-shelf. Initial calculations indicate that radiation hardness is also likely to be a significant factor. 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, and high speed time-resolved detection of an imaged low emittance beam will require additional development. 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 1ns resolution could usefully image single damping ring bunches, and is within the range of today's technology but not actually available. 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 technologies applicable to Xray imaging in the appropriate energy range, and to the development of a high speed bunch imaging device. 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 the Cornell Nanofabrication Facility (CNF), 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. 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 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.

Results from Prior Support

Prior research in this area has been supported as part of the current grant NSF PHY-0528059, entitled "University-based Accelerator R&D for a Linear Collider", in the amount $118,843, covering the period 9/15/05-8/31/06. Under this grant, the specific activity entitled "Design for a Fast Synchrotron Radiation Imaging System for Beam Size Monitoring" received one year of support at the level of $21,337. Results of this prior research are described below.

In the past year we have designed and built a detector with readout electronics and data acquisition software, and will be deploying the device in CESR in January 2006 for initial testing. The detecting elements are GaAs photodiodes (Emcore 8485-1055) which are read out by a high-speed low-noise amplifier (Maxim MAX3655). The data acquisition operates at 72MHz, suitable for single-bunch resolution in the CESR ring where the bunch spacing is 14ns. Much of our effort has been directed at developing this data acquisition system, which is now fully operational and is in regular use by another beam monitoring system in CESR. The funding from the prior support noted above was mainly used to purchase electronics components and circuit boards for the front end and the data acquisition system.

The January 2006 test is an engineering run in which we plan to study general performance of the system under beam conditions, evaluate the signal-to-noise ratio and the time resolution of the detector and front end electronics, and measure the vertical profile of the CESR beam. These studies will be carried out with the CHESS facilities and support of the CHESS staff. The main effort is directed at studies of detector operation and performance characteristics, and x-ray optics required for point-to-point imaging are kept as simple as possible, consisting only of an adjustable aperture pinhole.

Broader Impact

We are involving graduate students in this project – including a theory student working on his thesis in general relativity – and intend to bring in undergraduates starting in the summer. Commissioning the device and analyzing the data are excellent projects for students, and overall this enterprise is like an entire HEP experiment in miniature, comprising signal detection, signal processing and data acquisition, calibration, data quality control and monitoring, data analysis, quantitative results – and a publication at the end. In these days when HEP experiments are multi-decade endeavours, this kind of project offers excellent short term training opportunity.

FY06 Project Activities and Deliverables

We propose a one year program to extend the prototype beam size monitor studies described above to include a 32-channel, 2-dimensional detector array and more sophisticated x-ray imaging optics. We will continue to use the data acquisition system developed during the past year, which is optimal for use in CESR and for the time being needs no further improvement, and will also continue to use the CHESS facilities for testing.

The main focus of the coming year will be to make the system function as an actual beam monitoring device. This implies, as noted above, both a larger array of detector pixels as well as improved optics. For the rather large CESR beam a pinhole suffices to image synchrotron radiation onto the detector plane, but as our long-term goal is to use these devices to monitor low emittance beams in the future, we will need to advance the optical components of the system. We plan therefore to purchase and install zone plate lenses.

The details are laid out in the budget justification below. The main expenditures are for additional GaAs photodiode arrays and for zone plates. Because zone plate optics require monochromatic beams, and zone plates themselves have transmission efficiency $\sim 20\%$, we expect significantly lower photon flux. Therefore we also include in our plans an upgrade of the front-end electronics for improved S/N performance. By making use of the local CHESS facilities, other devices such as monochromators (needed for zone plates), mechanical components (stages, shutters, etc.), and general x-ray monitoring and shielding equipment are already available. Finally we request travel funding to cover one foreign and two domestic trips. This will allow us to explore possible future collaboration with the Caltech group that is submitting a related proposal and plans to test its devices at the ATF in Japan.

Budget justification

We ask for funding for the following items. There is no overhead charge on expenditures for capital equipment.

1×12 GaAs PIN Photodiode Arrays (3 + 3 spares)	$2900
preamp board	$1200
low noise pre-amps (32 channels at $30/channel)	$1000
zone plate (320μm dia., 800 zones, 2-9 keV)	$15000
travel (2 domestic, 1 to Japan)	$5500
Total	$25,600

Budget tables: all figures in K$.

Institution: Cornell University

Item	FY2006
Other Professionals	0
Graduate Students	0
Undergraduate Students	0
Total Salaries and Wages	0
Fringe Benefits	0
Total Salaries, Wages and Fringe Benefits	0
Equipment	20.1
Travel	5.5
Materials and Supplies	0.0
Other direct costs	0
Total direct costs	25.6
Indirect costs (58%)	3.19
Total direct and indirect costs	28.79