Design for a 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 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 known yet, the older NLC and TESLA designs indicate a range of possibilities. In the NLC(TESLA) damping ring designs, 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 and the critical energy is about $3\gamma^3\hbar c/\rho = 8(6)$ 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 ~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 $\sim 1 - 10$ 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 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 (1.4 ns for NLC, 20ns for TESLA). 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. (Commercial photodiode receivers for 10GBit/sec ethernet systems exhibit 30ps rise and fall times.) 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 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 may require some 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 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-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 "Design for a Fast Synchrotron Radiation Imaging System for Beam Size Monitoring" is supported at the level of $21,082. Results of this prior research are described below.

In the past year we have developed simulation and calculational tools for studying key issues and optimizing design features of a high-speed xray camera and associated xray optics. In particular we have investigated the impact of xray energy choice, which in our design is a tunable parameter to be determined by a monochromator, on signal size, S/N ratio, achievable precision in beam size, shape, and centroid parameters, and radiation damage. A serious issue emerging from this study is that of radiation damage, and we have mapped out the ratio of signal size to radiation dose as a function of xray energy to find optimal conditions. As a function of energy, both the xray flux and the absorption characteristics are changing, and a problem for radiation dose arises as xray energies decrease and the energy deposition in the semiconductor, though smaller per photon, is nevertheless more and more concentrated in smaller and smaller volumes of material and leads to serious dose rate issues. For silicon the signal/dose ratio is maximized just below the K-shell edge at 1.836 keV, but in absolute terms the dose rate remains very high. In GaAs the situation is similiar but the absolute dose rate is even more severe. We are now developing concepts for a mechanical shutter system to limit the duty cycle of exposure since the natural signal acquisition duty cycle in a damping ring application will be low and radiation impinging on the detector outside the signal acquisition times contributes only to damage. In the proposed activities for FY05 (see below) we will deploy a real detector in CESR and among other things be able to explore the radiation damage issues.

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.

FY05 Project Activities and Deliverables

We propose a one year program to build and install a prototype beam size monitor in the CESR accelerator to acquire hands-on experience with this kind of system.

Because the timing constraints in CESR are relatively relaxed (14ns between bunches) we can use existing silicon strip detectors for the front end. We need to build readout electronics for the detectors, and for this purpose we have designed and submitted for fabrication a circuit board which will hold the detectors and the frontend preamplifiers, and we will build a backend digitization and data acquisition system which is cloned directly from existing designs that currently are used to process bunch-by-bunch signals from fast BPMs and other beam monitoring devices in CESR. The silicon strip detectors are 6.4mm × 6.4mm prototypes left over from old CLEO III detector development projects. Their size and response characteristics are well matched to the CESR parameters. We have designed and are building a new analog front end preamp to match the detector output to the 72MHz digitization system. In this initial prototype study we will use simple pinhole optics for imaging the synchrotron radiation on the detector and will deploy the apparatus in an existing CHESS xray beamline. As this system is built primarily from existing designs and existing hardware where-ever feasible, the costs are well understood and have been kept as low as possible. The details are laid out in the budget justification below.

Budget justification

We ask for funding for the following electronics components needed for a 32-channel readout system.

preamp board	$1200
analog boards (4)	$3200
timing board	$600
I/O board	$450
digital board	$1400
power supply	$1000
timing pickup module	$300
cables, connectors and misc.	$500
xray pinhole structures (3)	$2400
xray filters	$750
beryllium vacuum window	$400
miscellaneous expenses	$800
mechanical shutter system:	
control board	$1350
pulsed power supply	$950
monitor and feedback	$300
materials	$1000
Total	$16,600

In addition, we request travel funds for Jesse Ernst who will travel to Ithaca 6 times at an average cost of $350 per trip, and funds for other miscellaneous expenses incurred at SUNY Albany in the execution of the project.

Budget tables: all figures in K$.

Institution: Cornell University

Item heightOther Professionals	0
Graduate Students	0
Undergraduate Students	0
Total Salaries and Wages	0
Fringe Benefits	0
Total Salaries, Wages and Fringe Benefits	0
Equipment	14.8
Travel	0
Materials and Supplies	1.8
Other direct costs	0
Albany subcontract	4.65
Total direct costs	21.25
Indirect costs (58%)	2.253
Total direct and indirect costs	23.503

Institution: State University of New York, Albany

Item heightOther Professionals	0
Graduate Students	0
Undergraduate Students	0
Total Salaries and Wages	0
Fringe Benefits	0
Total Salaries, Wages and Fringe Benefits	0
Equipment	0
Travel	2.1
Materials and Supplies	1.0
Other direct costs	0
Total direct costs	3.1
Indirect costs(50%)	1.550
Total direct and indirect costs	4.65