Tests of a High Resolution Beam Profile Monitor*

J. Norem, J. Dawson, W. Haberichter, R. Lam, L. Reed, X-F. Yang
HEP Division, Argonne National Laboratory, Argonne, IL, 60439, USA

J. Spencer
Stanford Linear Accelerator Center, Stanford University, Stanford, CA, 04309 USA

Abstract

High energy linear colliders require very small beams at the interaction point to produce high luminosities, and these beams must be measured and monitored. We have developed and tested a technique where the profile can be obtained from an extension of pinhole camera optics using thick, single sided collimators and slits. Very high resolutions (a few nm) should be possible. Gamma beams can be obtained from bremsstrahlung, Compton or beamstrahlung radiation. We describe tests of the technique using bremsstrahlung from an 800 MeV electron beam at Bates/MIT, Compton scattered photons from 47 GeV Final Focus Test Beam (FFTB) at SLAC, and other applications, such as linear colliders.

I. Introduction

The next generation of linear colliders will require very high precision diagnostics to be able to tune and maintain the small beams required for high luminosity operation. Present designs require beam spots with a vertical height of $\geq$ 2 - 4 nm [1]. The smallest beam spots which have so far been produced and measured have had beam heights, σ = 70 nm [2].

The proposed system uses non-imaging gamma ray optics to measure the position, profile and width of an electron or positron beam, where the "profile" is the electron distribution folded with the interaction that produces the outgoing photons. Bremsstrahlung, Compton scattering and beamstrahlung from beam-beam collisions, introduce negligible divergence at high energies. The optics are essentially a "pinhole camera" with a single sided collimator and a slit, inclined at a slight angle to the single sided collimator, so a scan along the slit is equivalent to a scan through the penumbra of the first collimator [3].

II. Resolution

The resolution for monochromatic photons is approximately equal to

$$\delta = \sqrt{\lambda L} / 2,$$

where λ is the wavelength of the photon, ~10^{-16} - 10^{-17} m, and L is the distance between the source and the first collimator, which could be of the order 10 m in the NLC. This would give a measurement resolution of a few nm.

Assuming targets convert ~1% of the beam energy, 10^{10} e$^-$/bunch would yield 10^8 equivalent γ's in a ~1 mm beam at 10 m, giving roughly 500 γ's through a 5 nm slit. About 1000 photons would be detected, assuming a conversion efficiency of ~10 pairs/equivalent γ and 0.2 Cherenkov photons /pair.

III. Experimental Problems

We expect that the primary experimental problems in reaching resolutions in the nm range would be component alignment and backgrounds in the detector. Preliminary measurements using this system, with beams at MIT / Bates and the final focus test beam at the FFTB at SLAC, have demonstrated the system and produced experimental data on alignment techniques and a variety of different background mechanisms.

Operation of this system using 10 MW beams at the Next Linear Collider (NLC) will be complicated by target damage and/or collimator stability. Thin foil bremsstrahlung targets can be moved between beam bunches. Compton scattering from real photons is preferred because it would not require foils, and would provide a photon spectrum peaked at higher energies, giving better resolution. Beamstrahlung, from virtual photons in beam-beam collisions, also provides a useful spectrum as a by product of normal operation, however during tuneup, low intensity beams would produce weak fluxes of long wavelength γ's. We note that all these processes are intimately related.

Collimators could be protected with absorbers upstream, however they would inevitably heat up and deform. We assume they could be mechanically and thermally isolated from their surroundings. Although useful measurements can be done with single bunches, the use of low expansion mounts should permit essentially continuous operation of this system at high power.

IV. Test Measurements

We tested some aspects of the system at the MIT / Bates 1 GeV electron linear accelerator using a 25 μm beam defined by collimators and a prototype detector optics to measure the beam profile.

The geometry is shown in Fig. 1. Just before the beam dump, a thin window was used to produce a bremsstrahlung beam with a maximum energy equal to that of the beam, 799.1 MeV. This photon beam was then collimated using a pair of tungsten blocks ground flat on one face and separated by 25 μm shims. Downstream, we assembled a system consisting

of a single sided collimator and a slit constructed with optically flat tungsten mirrors separated by shims, both remotely controlled by encodermotors with a minimum motion of about 0.1 μm. These elements, which defined the beam, were followed by a detector which consisted of a pair converter (a 1.25 cm W plate), a Cherenkov radiator (10 cm air), a periscope and camera consisting of an image intensifier and a linear CCD. The collimators were surveyed in using a transit and levels and this alignment was then checked using the beam. In fact, the initial alignment was excellent, so that the first two data pulses straddled the beam centerline.
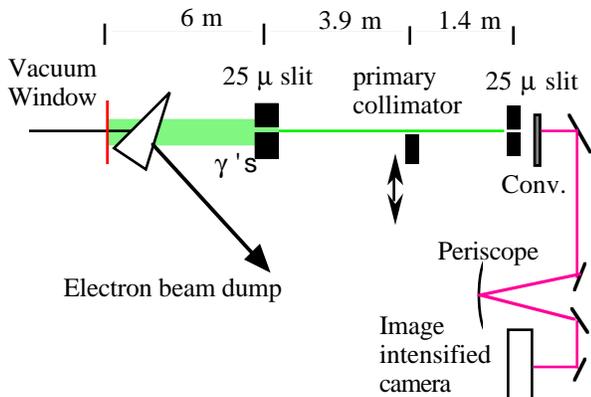
Figure 1. The experimental setup at Bates / MIT.
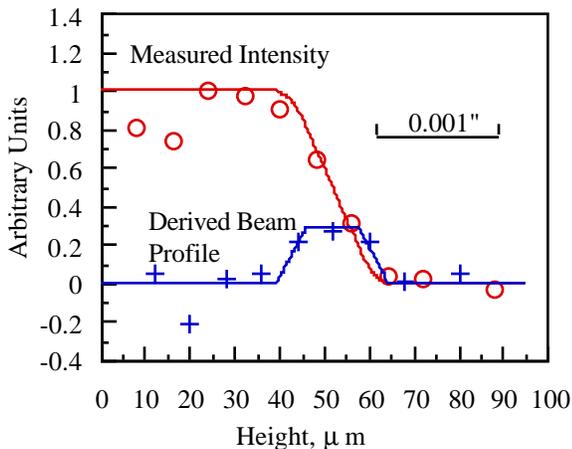
Figure 2, Measured beam profile.

A plot of the beam profile as measured by the system is shown in Fig. 2 As the beam intensity changed somewhat during the run, and we had no precise beam intensity monitor, we normalized the intensity of beam through the slit to the background, which seemed to be roughly proportional to the beam intensity. Since the limiting resolution in this application is 0.1 μm, the measurements errors are determined by statistics. Profiles are obtained by differentiating the intensity as a function of collimator position. The magnitude of errors due to normalization of the beam intensity, and to statistical error in the signal is difficult to determine independently.

With the beam dumped at the first collimator, it was possible to look at "single" photons in the camera, and thus to normalize the camera sensitivity. Using the primary beam energy and intensity, a calculation of the fringe field of the dump magnet, the radiator thickness, slit widths, and pair conversion and Cherenkov efficiencies calculated by Monte Carlo, we were able to calculate the magnitude of the signal which should be seen in the detectors. The primary uncertainty in this calculation is the initial direction of the electron beam after the ~1.2 mrad deflection in the fringe field before the gamma converter, which is larger than the divergence of the photon beam from the radiator. We obtained good agreement between the calculated and measured rates.

Scans were also taken with the active stripe of the CCD camera oriented parallel and perpendicular to the detector slit, the latter orientation permitted measurement of the effective width of the Cherenkov source, as well as the distribution of background light. Scans were taken while moving the position the front collimator, and with the beam dumped at the front collimator and the final slit. Typical data are shown in Fig. 3., where the image intensifier was operated with a microchannel plate voltage of 1550 V, which gave about 1/10 of the maximum gain possible gain. The observed width of a point Cherenkov source should be $\sim l\theta_C/2 = 0.8$ mm, where l is the length of the Cherenkov radiator and θ_C is the Cherenkov angle. Both l and θ_C can be controlled by simple adjustments of the light collection optics.
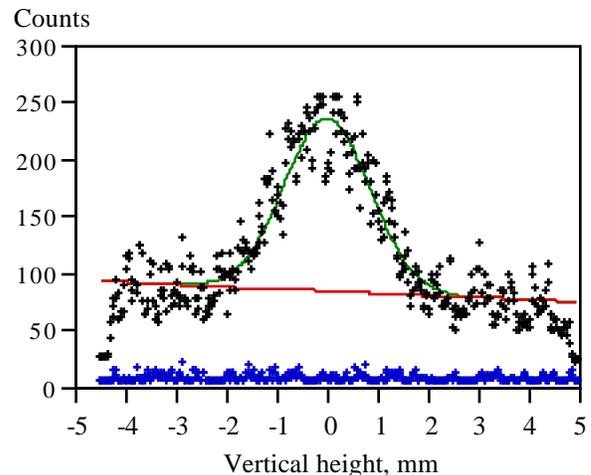
Figure 3, Vertical profile of Cherenkov Source.

V. Backgrounds

At the 800 MeV Bates linac, the primary background seemed to be due to Cherenkov light uncorrelated with the beam transmitted by the slit. Additional shielding around the first collimator and stopping the beam in front of the slit both reduced the background intensity. The source of this background thus seemed to be showers produced at the primary collimator and slit, creating secondaries which produced Cherenkov radiation in the periscope. Because of the geometry of the slit mounting and the volume of the sensitive region of

the periscope, (2 m long and 10 cm in diameter at the largest point), it was difficult to shield this background completely. Reductions of a factor of 10 were obtained however.

At SLAC, measurements will require thick targets in the beam and probably detectors inside the shielding of the FFTB. We have tested a prototype detector inside the shielding of the FFTB using 47 GeV electrons on 0.003" Al flags as target as well as laser Comptons. The image intensifier and CCD were shielded by about 0.05 - 0.10 m of Pb from the Collimator immediately below them that functioned as a beam dump for electrons that lost more than about 1/3 of their energy. Three components were seen: dark current in the CCD, pulses from the image intensifier that seemed to be in time with the photon beam, and photon like pulses that seemed to occur even with the image intensifier gated off. We assume that the last source of background is due to ionization in the structure of the image intensifier. Backgrounds were comparable to dark current with the CCD running at 20° C. With thicker targets, a 0.1 radiation length bremsstrahlung converter, for example, backgrounds would be larger.

VI. Possible Experiments

We hope to be able to measure the size, profile and stability of the Compton conversion spot for SLAC experiment E144 [4] on the FFTB using a system of collimators which will be inserted into the photon dump line downstream of the final focus. This apparatus should also be able to measure the final focus beam spot with a resolution of $\delta \sim 20$ nm.

In principle it should also be possible to use a streak camera to measure the time (or z) dependence of bunch parameters with resolution of perhaps ~ 0.1 ps [5]. Correlations could be studied on a bunch to bunch basis [3]. Comparing measurements made with the apparatus on-axis and off-axis, for example, it should be possible to look at chromatic effects at the final focus, since these would cause the different momenta to focus at different points, producing a larger effective beam width for off axis electrons. Seismic effects have been examined experimentally and should be correctable at the level of 1 - 3 nm [3].

Measurements of plasma focusing should also use this technique, which offers the possibility of time and space resolution comparable with the expected range of nonlinear plasma effects [6].

Since the resolution increases with increasing energy, this technique should also be useful for measurements at the NLC [7]. Bremsstrahlung, Compton scattering or beamstrahlung could be used to produce photons which would give high resolution, with diffraction width of about 5 nm. Assuming targets that convert as much as 5 - 10% of the the beam energy, as many as 20% of electrons produce a photon greater than 100 GeV for 500 GeV collisions, and 10% would have energies greater than 250 GeV for bremsstrahlung. Above 250 GeV, the beamstrahlung spectrum would give typically 2.5 %,

and we would expect 25% for Compton scattering from laser wavelengths selected to avoid pair production. Of all these processes, the latter two are the most practical, due to the difficulty of working with solid targets in highly constrained environments.

A significant complication at NLC energies is that beam power and beam brightness both increase with energy, producing very high power densities on all components, particularly the primary collimator. We should be able to begin to explore some aspects of high power densities on components in FFTB experiments.

It is also interesting to point out, on the 100th anniversary of Roentgen's discovery of X-rays [7], that this radiation was determined to be wavelike and electromagnetic by means of diffraction experiments which showed wavelengths on the order of 10^{-10} m.   NLC collider data would involve photon wavelengths of $2 \cdot 10^{-18}$ m, many orders of magnitude shorter than any previous diffraction experiment. We believe it is also interesting to study diffraction phenomena at these wavelengths to verify well understood ideas at these small distances.

VII. Conclusions

This technique offers the possibility of very good spatial resolution at the SLAC / FFTB and NLC, with the added advantage of time resolution compatible with the best streak cameras. Measurements of a variety of correlations, such as chromatic effects, should be possible as well as experiments with plasma focusing We have made preliminary measurements of beam profiles using non-imaging γ optics with resolutions of a few μm. We have also looked at alignment and backgrounds in realistic beam environments and isolated some sources of background signals.

VIII. Acknowledgements

IX. References

[1]   R. Palmer, Annu. Rev. Nucl. Part. Sci. 40, (1990), 529
[2]   CERN Courier, 34(7), (1994), 15
[3]   J. Norem, J. Dawson, W. Haberichter, R. Lam, L. Reed, X-F. Yang, J. Spencer, Nucl. Instr. and Meth. (to be published, 1995).
[4]   K. McDonald, A. Melissinos et al, private communication, 1991
[5]   Hamamatsu Corporation, Bridgewater NJ.
[6]   P. Chen and D. Cline et al. private communication 1993
[7]   J. Spencer et al., The SLAC NLC Extraction and Diagnostic Line, these proceedings.
[8]   W. C. Roentgen, Nature, 53, (1896), 274