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Frontiers of Accelerator Instrumentation

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I. Abstract

New technology has permitted significant performance improvements of established instrumentation techniques including beam position and profile monitoring. Fundamentally new profile monitor strategies are required for the next generation of accelerators, especially linear colliders (LC). Beams in these machines may be three orders of magnitude smaller than typical beams in present colliders. In this paper we review both the present performance levels achieved by conventional systems and present some new ideas for future colliders.

II. Introduction

The field of accelerator instrumentation is large and growing. Instrumentation has been the focus of several recent workshops. One reason for this is the broad range of requirements that new machines place on these systems. This paper addresses mainly those accelerator instrumentation issues associated with electron-positron linear colliders.

The function of accelerator instrumentation is to provide a measure of subsystem performance. Through this the accelerator designer may verify component tolerances. Furthermore, the control system of the accelerator can use information provided by the diagnostics to perform online corrections through feedback. The next collider generation will require a substantial effort in the development of the feedback systems.

In parallel with recent improvements in the technology of signal processing and controls, the next generation of machines will rely heavily on instrumentation and controls improvements. It is therefore important to identify this aspect of accelerators as one which can yield significant benefit by relaxing effective tolerances in other subsystems.[1] Of course, this must be done carefully and may be difficult to prototype and test accurately.

The challenge of the instrument designer is to develop new technology and also to improve existing techniques. Through the use of new technology, conventional devices such as beam-position monitors and video-profile monitors have become more accurate and free from systematic errors that are harmful to feedback systems. Since a feedback loop processes and filters information from many sources, it requires an accurate model of both the accelerator system and its instrumentation.

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The next generation of colliders will require accurate beam-position measuring devices, high-resolution beam-profile monitors, and devices that directly monitor other aspects of the beam such as correlations between energy and longitudinal or transverse position. Present profile monitors project phase space onto one axis, and are therefore not sensitive to correlations. Since smearing effects, such as chromatic filamentation, can irreversibly increase phase-space volume, it is important to accurately monitor the ellipse orientation.[2]

Most work to date has focused on the serious challenge of measuring small-collider, interaction-region spots. However, accurate, durable phase-space monitors will be required throughout the LC in order to maintain the emittance.

III. Beam Position Monitors (BPM)

Present BPM systems can be grouped according to their bandwidth. Colliders, because of their low single-bunch passage rate, probably require high-bandwidth devices. Thermal noise considerations and low bunch spacing presently limit the performance of typical devices to:

$$\frac{V_n}{V_0} = \sqrt{4kTZ_0B}\,\frac{\sqrt{2\pi e}}{\varepsilon a}\,\frac{\sigma^2}{2t_0} \qquad (1)$$

Where $\sqrt{4kTZ_0B}$ is the thermal noise, about 25 μV at 25 MHz, a is the signal strength at the electrodes, about 2V ns for 10^{10} particles, ε is the efficiency of the signal collection cables and $2t_0/\sigma^2$ is the fraction of the signal from strip lines of length t_0 in the bandwidth (σ) of the signal processing filter. V_n/V_0 is about 1/5000 for 50 ns interbunch spacing. This is usually adequate since the vacuum chamber can be made to scale with the beam size at least in a coarse manner.

An example of a suitable BPM system is that being built for the Final Focus Test Beam Facility (FFTB)[3] at SLAC. This system has 1 μm resolution near the center of the aperture with intensities of 10^{10} e-, bandwidth of 25 MHz and 16-bit ADC's with noise margin of 3 dB. The absolute accuracy of the BPM is 30 μm. The FFTB BPM's are about 25 mm diameter.

Most BPM systems have significant systematic errors. These can be crudely classified as beam-quality related errors or electrode- and signal-processing errors. Among the former are:

• Beam-shape sensitivity

Beam-shape sensitivity has been studied[4] and can produce an error of about $3/r^2\left(\sigma_x^2 - \sigma_y^2\right)$ for a centered beam, with x and y in the planes formed by the pickup electrodes. Placement of the electrodes at 45° to the beam-coordinate system, or other electrode designs can reduce this error.

• Interference from beam electromagnetic fields

An interesting example of this is the experience[5] in the TRISTAN Main Ring where the wakefields left by the passage of the bunch were sufficient to cause multipactor breakdown near the button electrode.

- **Sensitivity to local beam loss**

This is certainly the least-understood of the above and will be a significant problem in future high-power machines. The electromagnetic shower generated when a few beam particles strike the vacuum chamber near or just upstream of the monitor can cause a strong secondary-emission signal. This signal, since it is lower-bandwidth than the coupled signal from the beam, can create a large offset error. Guidelines for avoiding this are to 1) recess the strip lines so that they cannot be struck directly by the beam, and 2) provide the appropriate amount of collimator protection upstream.

Other sources of BPM systematic error can be adequately addressed with careful calibration and appropriate data-handling codes. Some of these errors are listed here:

- **Electronic offsets and cable imbalance**

  Non-linear response

In the last ten years, processor speed and digital-signal processing (DSP) techniques have improved enough so that they may now be included in storage-ring feedback loops. In addition to noise-free signal processing, these techniques allow much greater control over the loop-gain and transfer function. Examples of feedback systems using digital signal processing are the tune-control system at LEP, [6] and the proposed longitudinal-feedback system for the SLAC B-factory.[7] An excellent DSP instrument that has been used for development of the SLC damping rings is the Tektronix 3052.[8]

Most LC designs require trains of closely spaced electron and positron bunches. A remaining challenge for LC BPM designs is a system that can, with the accuracy listed above, independently monitor the micro-bunches position. Using the 1.4 ns interbunch spacing of the NLC design, the expected kT noise is six times larger, about 1/1000. Advances in signal processing may help to reduce this. Techniques under development for use with the Fermilab bunched-beam cooling system[9] that use fiber optic signal-delay lines will allow the stripling signal to be repeatedly sampled.[10] [11] The use of the fiber optic signal-storage loop effectively lowers the bandwidth considerably.

Narrow-band BPM systems, used in storage rings, can perform much better. Furthermore, frequency-domain techniques allow greater control of electronic offsets. An SSC proposal[12] with 15 KHz bandwidth should have a limiting resolution of 100 nm.

E. Beam-Profile Monitors

The next generation of linear colliders present a serious challenge to the profile-monitor designer. Monitor performance can be characterized by beam-size resolution, (the minimum spot size measurable), and dynamic range, (the accuracy with which the distribution is determined). The first of these has been studied and some proposals for future devices will be outlined here. The second has received less attention but is important in order to gain an understanding of the sources background in high-energy physics-users detectors. Several attempts have been made to find an effective measure of the particle distribution in the beam's tails, especially in e+/e- storage rings.[13]

Most beam-size monitors use scattered radiation produced in the interaction between the beam and a target of some kind. As either the beam size is reduced or the intensity increased, the target may be destroyed in this interaction and must be regenerated before the next measurement. At small beam sizes and high beam current no solid will survive the impact of a single pulse. Gas- or plasma-based ionization monitors are also limited at very high intensities or very small spot sizes, where tunneling ionization, or the ionization of all atoms in the high-field region of the bunch, becomes an important effect. As a result, one must use a target that can be quickly regenerated or another mechanism altogether, such as a laser beam.

A. Review of existing techniques—Wire Scanners and Fluorescent Screens

1. Wires

Present wire scanners are limited to a range of currents and beam sizes because of single-pulse heating due to energy loss in the wire. These limits are roughly given by:

$$\frac{I}{\sigma} \leq 5 \times 10^9 / 2\mu m \qquad (2)$$

for small wires with diameter about the same as the beam size. At SLC, these limits are reached at the IP, and they will be exceeded throughout most of an LC.

The best wire-scanner resolution has been seen with the SLC IP wire scanner. Figure is an SLC interaction-region wire scan with a 4 μm wire.[14]

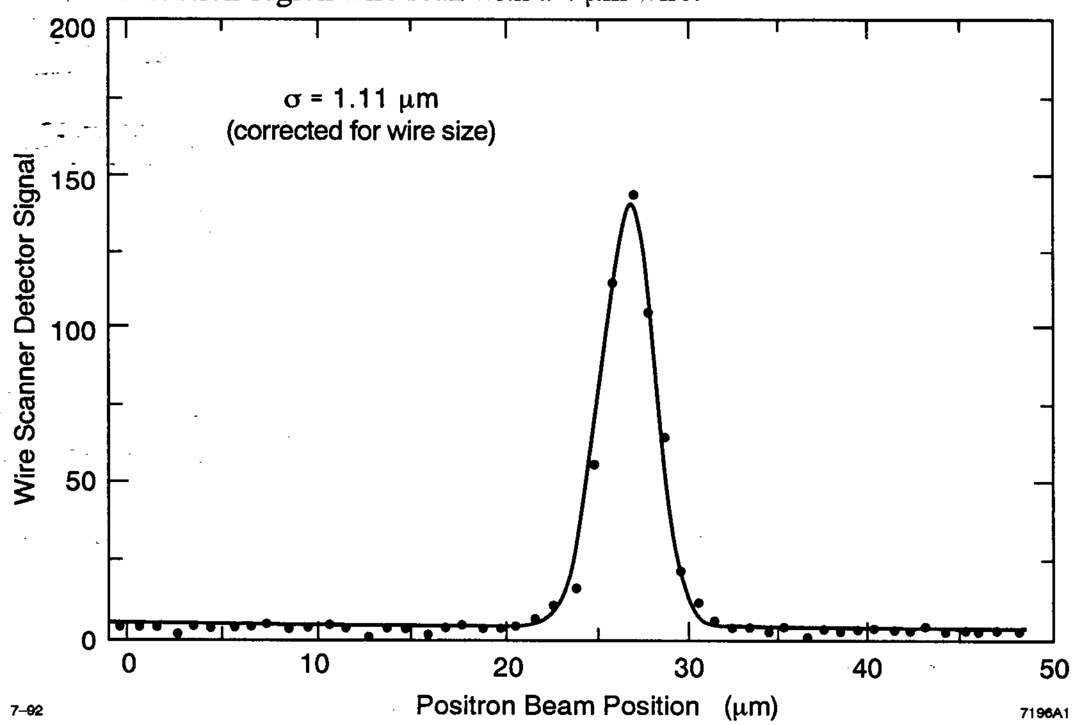

Figure 1. Wire scan results from the SLC interaction-region wire scanner. The reported beam size, after removing the contribution of the finite wire size, is 1.7 μm. This is probably the practical lower limit for this type of device.

Since a scanner samples the beam with a relatively hard process, giving good linearity, systematic errors are generally small. Figure 2 shows a high-resolution wire scan from the SLC. Most high-resolution wire scanner systems use hard, forward, bremstrahlung detectors. These detectors are often very far from the scanner and therefore have limited acceptance and have related systematic errors.

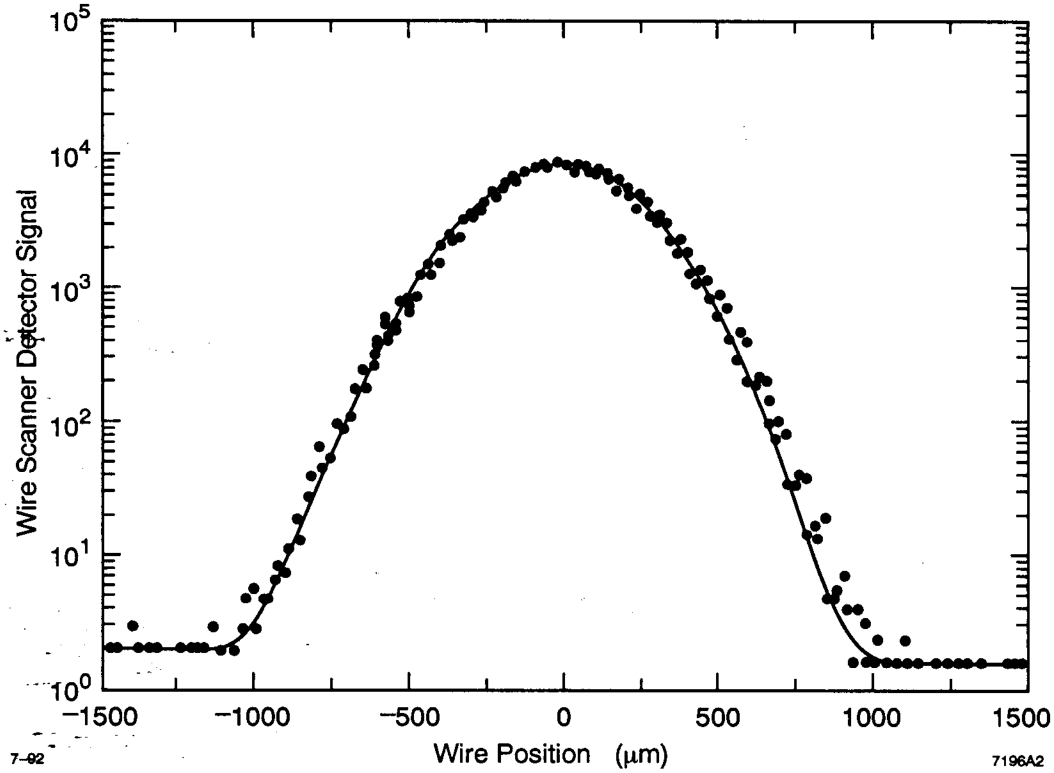

Figure 2. High-resolution SLC wire scan using hard-bremstrahlung detector. This device has an 80 dB signal to noise and can effectively measure the beam distribution to ± 5 σ.

2. Fluorescent screens

Fluorescent screens remain a simple, reliable method for measuring beam size. Significant improvements in video technology now allow 16-bit amplitude vertical resolution and spatial resolution beyond other (e.g., optical) practical limits. Accuracy and dynamic range limits are mostly unknown. Excellent radiation hardness has been proven with these devices.

3. Comparison

Wire scanners and video-based profile monitors are in many ways complementary as illustrated in Table 1.

Table 1. Advantage and disadvantage comparison between video based fluorescent screens and wire scanners.

- Disadvantage + Advantage	+/-	Fluorescent Screen		Wire Scanner
Resolution	-	Finer than 20 μm not possible [15]	+	1.5 μm has been achieved and is probably the limit.
Systematic errors	-	Large systematic errors Dominated by optical and phosphor response problems[16]–hard to test	+	Simpler systematic errors Detector non-linearity–relatively easy to test Detector acceptance limits performance of many wire scanners
Dynamic range	-	Camera non-linearity and optical aberrations		
	-	Limited dynamic range without new cooled-CCD technology	+	Wide dynamic range, up to several orders of magnitude
Longevity	-	Phosphor desensitization after prolonged use, motorized systems and frame grabbers can improve	-	Thin wire fragility, wire failure mechanisms not understood
Signal processing	-	Complex frame-grabber data acquisition and background subtraction–quickly improving with new video technology	+	Many possible signal detectors - increases reliability and flexibility
	+	Single-pulse capture at low machine repetition rate	-	Multi-pulse sampling required, difficult to unfold beam jitter
	+	Full two dimensional display	-	Only projections are available. Hard to get detailed information about x-y coupled non-gaussian beams
		Visual presentation, rich intuitive content, real time display		
	-	Image lag and slow scan speed	+	Time resolve closely-spaced bunches (60 ns at SLC)
Radiation resistance	-	Camera and optics radiation sensitivity (<100 KRad without complex optics)[17]	+	Rugged scanner hardware
			-	Scattered particle detector may not be able to operate in high-radiation environments
Operability	-	Invasive–requires the use of kicker magnets for pulse snatching	+	Non-invasive upstream of background suppression collimators. Minimally invasive downstream with pulsed-beam dumpers

4. Wire scanner phase space monitor

An advantage of using narrow forward scattering can be seen when the beam angular divergence or correlation (α) is large compared to $1/\gamma$, the opening angle of the bremstrahlung. The scan results may be sensitive to the x–x' correlation at the wire, and the steering and position changes at the wire. This may be used to advantage with segmented detectors and allow an estimate of angular divergence. The placement of the device and the optics surrounding it can greatly improve its utility.

5. Wire failure

One significant drawback of a wire scanner is the fragility of the wire. Even well below the threshold for single-pulse breakage listed above, there are other wire-breakage mechanisms. Much work has been done on this problem at the SLC Linac where wire failure has been a problem.

The SLC Linac wire scanners[18] use 40 μm tungsten wire to measure high-intensity (two or three bunches of 3.5 x 10^{10}) 100 μm beams. The single-pulse heating is well below the wire-melting point. The wire is wrapped around cylindrical studs that are set in a ceramic holder. All fractures occur at the point where the wire approaches the stud. Micrographs of the broken wire suggest that high-electric field and a resultant arc to the stud are responsible for these failures. Since the wire and the stud are both in good electrical contact and well-grounded, a strong transient pulse from the beam must cause the arc. About 1 mJ is required. Figure 3 is a micrograph of the broken end of a wire. Similar wire failures have been seen at LEP. In both cases the failure rate has been improved by using only ceramic materials in the support.

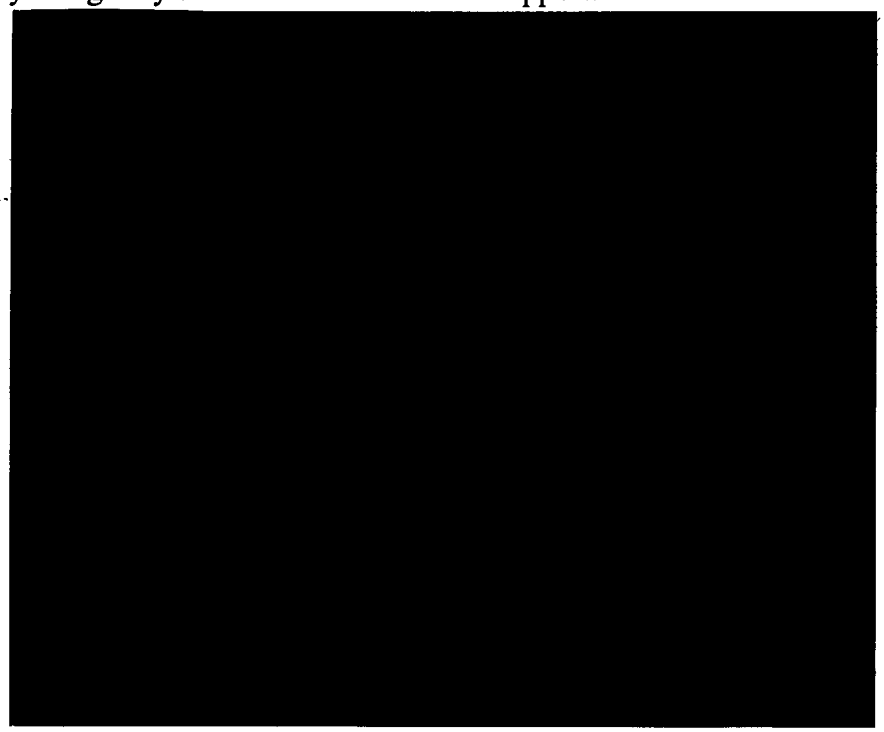

Figure 3. Electron microscope picture of a 40 μm tungsten wire break. This wire was installed in an SLC linac wire scanner.

6. New wires for FFTB

Most designs for an LC use large-aspect ratio beams with $\varepsilon_x \sim 100\varepsilon_y$, a new regime for accurate-profile monitors. At several locations in FFTB, during optics tuning, σ_x may be 1000 σ_y. An accurate measurement of σ_y will require novel scanner construction techniques. One proposed technique is to use a radial fan of wires at small angles to one another in order to optimize the angular resolution. Short-stub scanners will probe the beam distribution at several places in x. This data will provide information about the higher-order distortions in the beam matrix.

B. New Techniques

1. Final Focus Test Beam at SLAC

Several novel profile monitors will be tested at SLAC, at the Final Focus Test Beam facility (FFTB). The purpose of the FFTB is to test the optics and tuning tools required for the next generation of linear colliders. This will be done using 10^{10} 50 GeV electrons from the SLC linac. Interaction Point (IP) beam sizes are expected to be $\sigma_x = 0.9$ μm and $\sigma_y = 60$ nm.

2. Ionization Beam Size Monitor

The Orsay/SLAC Ionization Beam-Size Monitor,[19] shown schematically in Figure 4, measures the peak electric field of the beam using the scattered-ion angular distribution and velocity. This device allows the introduction of a controlled amount of gas into a volume surrounding the IP. The periphery of the chamber is equipped with ion detectors, in this case microchannel plates. Low Z He ions will receive a strong impulse from the field of the beam.

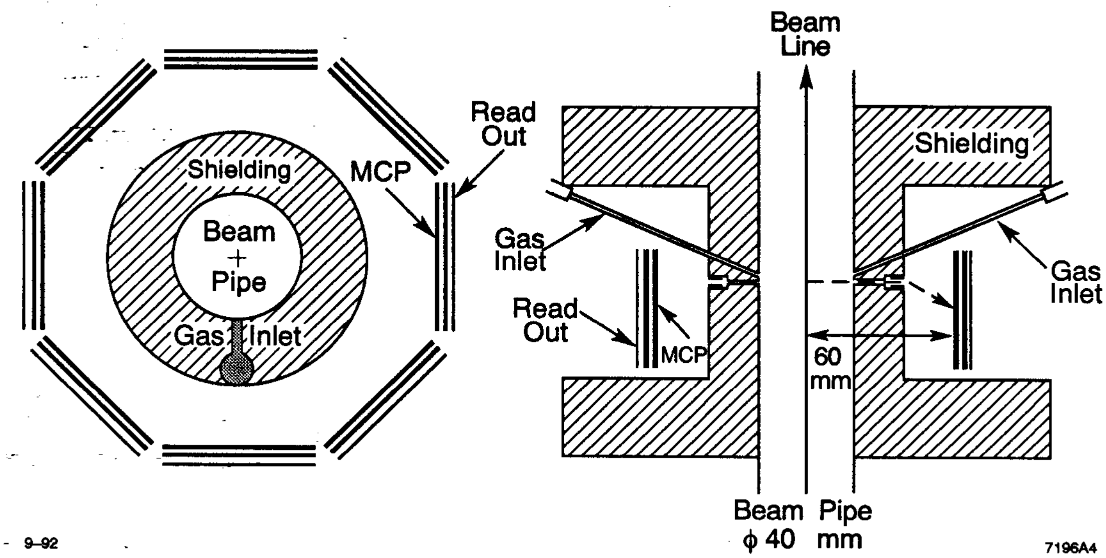

Figure 4. Gas ionization beam size monitor.

At the FFTB the beam will enter an Argon filled volume with a pressure of a few 10–4 mm Hg and ionize through dE/dx. The principle of the device is to measure the maximum velocity of the Argon ions using time of flight. The endpoint of the TOF spectrum is used to derive an estimate of the beam size in the minimum direction (σ_y). To find the beam size in the other plane, He ions are used. Since the He ions are much lighter, they are trapped in the beam, and oscillate with an amplitude that is related to their position with respect to the bunch center at the time they were ionized. The angular distribution of the He ions is related to the aspect ratio of the bunch. This technique does not work very well for positrons, since they are not trapped in the beam. The expected resolution of the device is about 5% for a few (10) pulses at nominal FFTB currents of

1E10. It will function up to a few μm where cross-calibration may be done with respect to the nearby wire scanner.

At an LC, this device will have to use multiply-ionized atoms due to tunneling ionization.

There may be significant background problems with this device since the signal from the ions is small. There are only a few hundred Ar ions detected per beam crossing. With care in beam tuning it can be setup, but under severe conditions it is clear that there may be problems.

3. Laser-Compton scattering profile monitor

The laser-compton profile monitor[20] is another new concept that provides a measure of the beam size using the interaction between the beam and a high-power, standing-wave pattern created by a laser. The beam size is determined by measuring the depth of modulation of the compton-scattered photons as the beam is scanned across the laser-interference fringes. In order to measure a large range of beam sizes (50 nm to a few μm), it is necessary to use several different laser wavelengths. This method has the advantage that the signal is strong, several thousand high-energy photons for typical FFTB parameters, and will therefore be less susceptible to low-level backgrounds. Systematic errors will arise from a poorly-focused laser spot and the resultant large interference zone. The accuracy is expected to be about 20% of the beam size on average. Systematics may also occur when the laser wavelength is changed. The ultimate limits of this device are reached when the beam size becomes comparable to the shortest wavelength laser for which there is enough power and available windows. This is about 130 nm λ and a beam size of about 10 nm, still somewhat larger than the expected σ for some of the proposed LC.

4. Liquid Jet Scanner

The liquid jet scanner [21] will use a small-diameter liquid metal jet delivered from a high pressure nozzle to scan across the beam. A pressure of 95,000 psi is required for a 1 μm-diameter jet of a eutectic alloy about 1 mm long, although the smallest jet seen to date is 4 μm. It may be possible to make jets as small as 0.2 μm. At the smallest orifice size, proper filtering will be difficult.

5. Bremstrahlung edge profile monitor

The principle of operation of this device is a bit more complex.[22] A bremstrahlung beam is produced at the IP using a thin radiator. The x-ray beam is carefully collimated using a nearby collimator and transported through a significant rotation of phase space. The edge is scanned and used to estimate beam size. Diffraction limits the ultimate resolution of this device. Both this device and the Compton-laser scattering scanner rely on long-base line alignment and alignment stability.

C. Synchrotron Light Monitors

Synchrotron light systems have also improved as a result of the development of new technology.[23] An application of synchrotron light at SLC is the use of a fast-gated video camera to monitor the beam profile on successive turns in the damping ring in order to minimize transverse-emittance blowup due to optical mismatch and other errors.[24] Figure 5 shows results from this system.

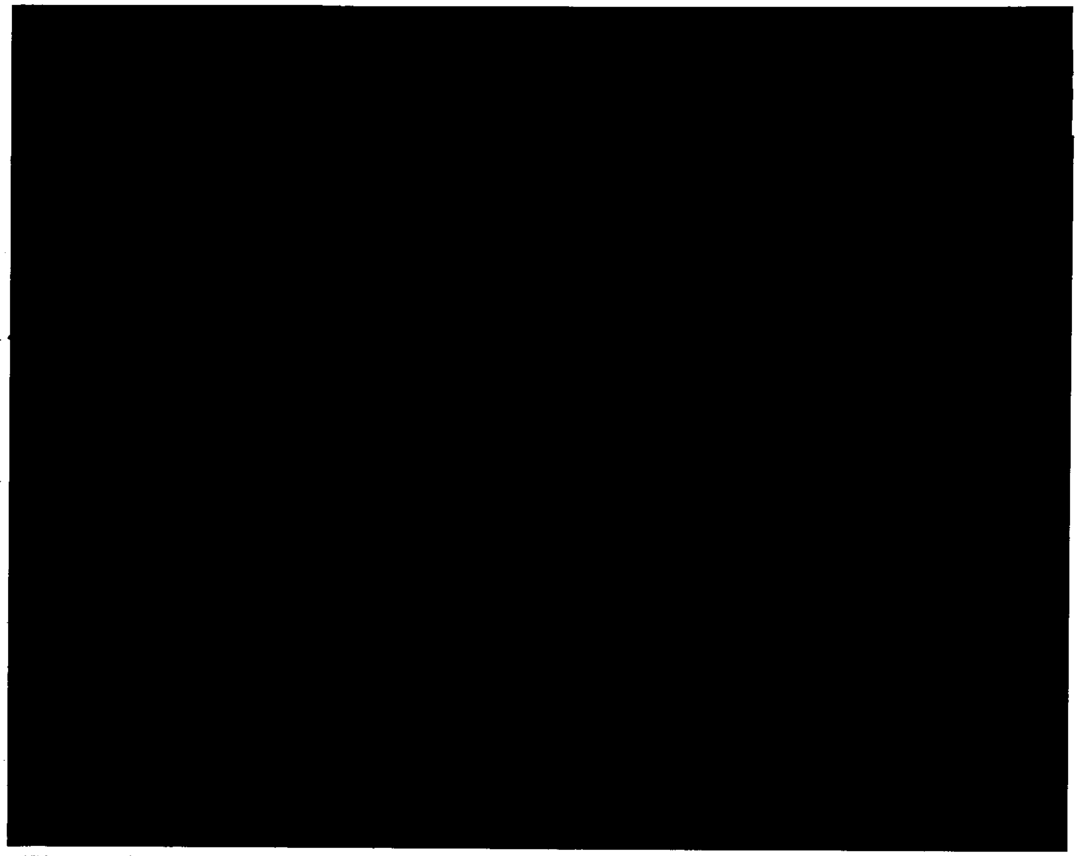

Figure 5. Synchrotron light measurements from the SLC damping ring showing the beam profile on the first four turns.

V Bunch-Length Monitors

1. Energy-Spread Monitors

An example of a non-gaussian beam shape which must be determined in detail is the energy profile of a single collider bunch emerging from the linac. Because of the strong dependence of the energy-spread distribution, especially the extremes of the distribution, on the bunch shape, it is important to measure the shape carefully. Figure 6 shows SLC linac energy-spread wire-scanner data.

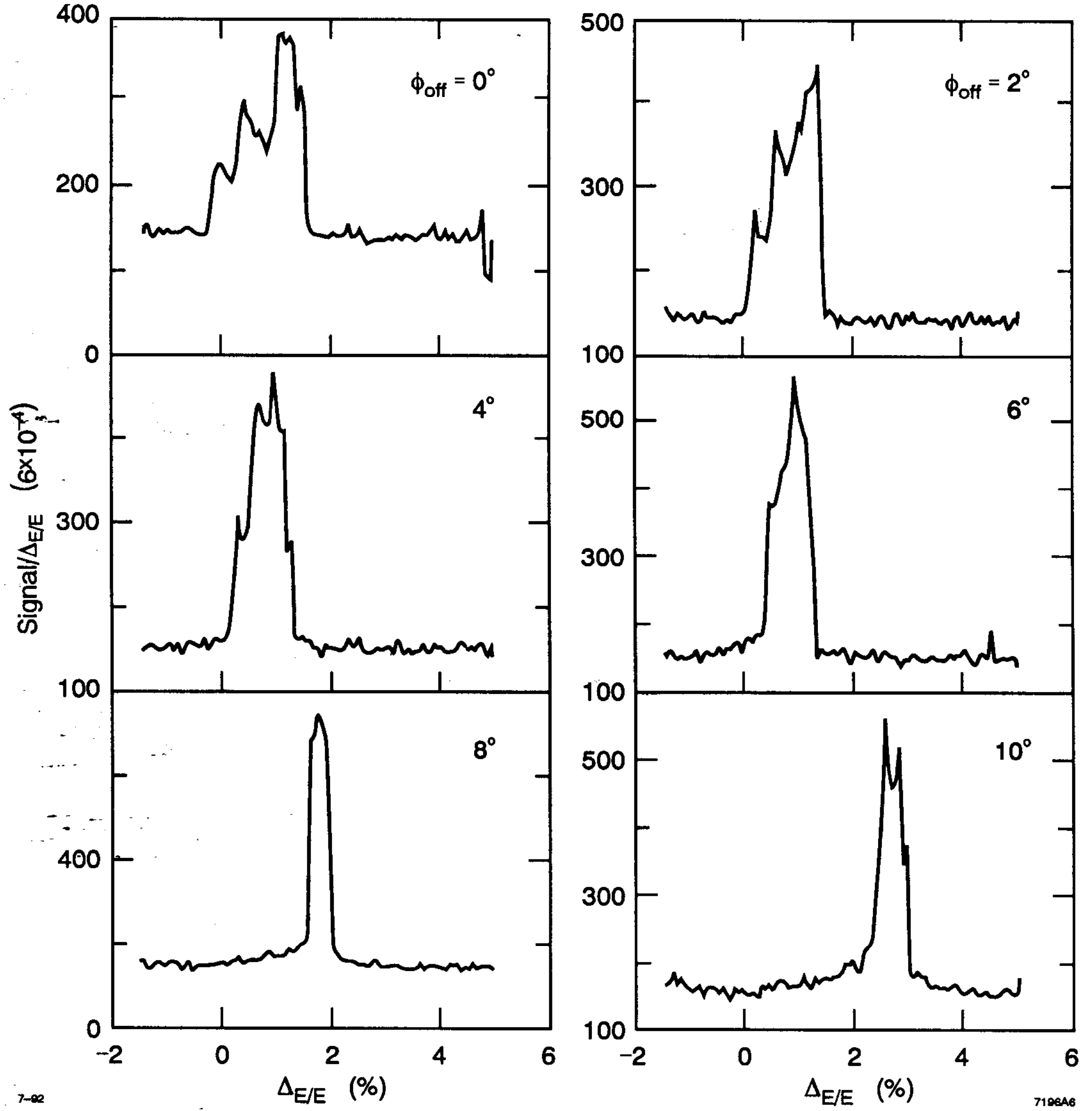

Figure 6. SLC linac energy-spread distributions. These data were produced from wire scans taken as the overall phase of the linac was varied. The data agree with simulations that assume a gaussian, longitudinal bunch distribution, and use a computed higher-order waveguide mode distribution.[25] It is important to measure the energy spread properly in order to predict the performance of downstream optical systems.

2. Coherent Synchrotron Radiation

Coherent synchrotron from a linac beam was first reported in 1989.[26] Coherent synchrotron radiation is the radiation emitted from the bunch as a whole and depends on N^2. In storage rings it is suppressed because the wavelength of the radiation is large compared to the size of the vacuum chamber. The spectrum of coherent radiation can be used as an estimate of the bunch length and for this reason it may be considered a useful beam diagnostic tool. For the nominal operating intensity of $5*10^{10}$, the expected radiated energy is 0.04 μJ or 5 μW at 120 Hz. Experiments done at the Cornell linac[27] with a pneumatic, Golay-cell, thermal-infrared radiation detector.

VI. Conclusion

Table 2 shows a summary of the profile monitor schemes to be tested at the FFTB.

Table 2. Comparison of profile monitor techniques to be used at the FFTB at SLAC.

Device	Gas Ionization	Laser Compton	Fluid jet	Edge scanner	FFTB Wire
	J. Buon	T. Shintake	F. Villa	J. Norem	C. Field
Principle	Field strength	Compton scattering from standing wave	low-melting-point metal	phase space rotation of brems	wire scanner
Min σ at FFTB	60 nm x 1μm	10 nm	jet radius /2 (50 nm)	3 nm	1μm
I limit (at that size)	few 10^{10} (beyond which it operates in a new regime)	none	none	none	$5x\ 10^9$
+	not position sensitive; few pulse measure.	large signal	large signal		
-	weak signal	multi-pulse scan difficult alignment	multi-pulse scan	measures integral of beam size, difficult alignment	multi-pulse scan wire failure

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