# LASER-BASED PROFILE MONITOR FOR ELECTRON BEAMS*

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*Abstract*

High performance TeV energy electron / positron colliders (LC) are the first machines to require online, non-invasive beam size monitors for micron and sub-micron for beam phase space optimization. Typical beam densities in the LC are well beyond the threshold density for single pulse melting and vaporization of any material, making conventional wire scanners ineffective. Using a finely focused, diffraction limited high power laser, it is possible to devise a sampling profile monitor that, in operation, resembles a wire scanner. Very high resolution laser-based profile monitors have been developed and tested, first at FFTB (SLAC) and later at SLC and ATF. The monitor has broad applicability and we review here the technology, application and status of ongoing research programs.

## INTRODUCTION

Particle beam brightness and power have increased rapidly in the last decade with the advent of precision control and improved implementation of accelerator designs. Precision beam diagnostics for position and profile have proved vital. Present machines, such as the FFTB at SLAC [1], the ATF at KEK [2] and the SNS [3] have beams that require the use of new types of profile monitors because of their small size or power. Carbon wire scanners, perfected for use with the extremely small beams at SLC and FFTB [4], have been shown to have limited performance for high brightness beams. The debris resulting from wire failure in a superconducting linac, such as SNS, could harm the delicate niobium cavities. A laser-based profile monitor, in contrast, uses a transient pulse of photons that does not pose a real threat to the cavities. In addition, and more importantly for the linear collider, the laser beam can be focused to a size that is smaller than the smallest practical wire diameter, providing a minimum beam size measurement capability well beyond the wire scanner.

Interacting lasers and particle beams have long been used as experimental tools, notably for the production of neutral beams or in the measurement of electron / positron polarization [5,6]. Recent advances in laser and optical technology have made it effective to use very finely focused lasers to accurately probe, using a 90 degree collision angle, within particle beams in order to measure beam size and beam halo. In the last few years, several such probes have been constructed and operated successfully. In this paper we will review the design, operation and results from these devices, and outline issues for future work.

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Scattering of e+ / e- particles by laser photons is described by the Compton theory. While the Compton scattering amplitude for protons is much smaller, the photo-neutralization cross section for $H^-$ beams is not, and a laser-based monitor is similarly effective for use with those beams.

In the laser monitor, a low energy optical photon collides with a high energy electron resulting in a high energy gamma ray and lower energy electron. The boosted photon energy is characterized by a sharp endpoint, $y_m=\omega_m/E_b$, ($\omega_m$ and $E_b$ are the maximum gamma ray energy and the beam energy, respectively) corresponding to back scattering in the rest frame of the system, and a relatively flat cross section for lower energies. The total cross section, is large and this provides ample signal for the profile monitor, even when compared with conventional wire scanners.

As with conventional wire scanners, it is important to devise an efficient, low background method of detecting the scattered particles, either the degraded electrons or gamma rays, since this usually determines the system accuracy. The fraction of transferred energy at the kinematic endpoint, $y_m$, grows as a function of beam energy, making clean detection much easier at high energies. Figure 1 shows $y_m$ as a function of $E_b$ for two different laser frequencies, with the values typical of three laserwires indicated.

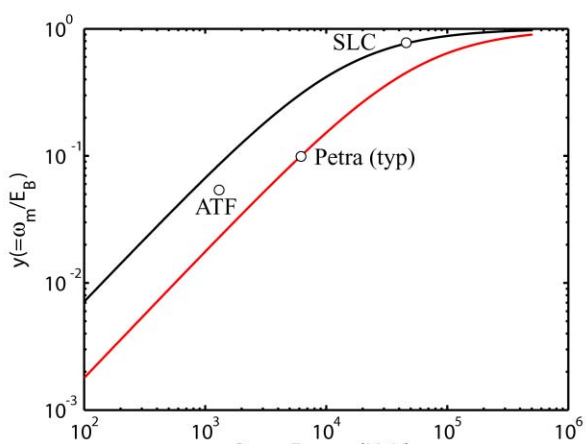


Figure 1: Relative Compton boosted gamma ray energy endpoint ($y_m$) as a function of electron beam energy for λ=1050nm (lower curve) and λ=350 nm (upper curve) lasers.

Whereas the fundamental physics of a laser-based monitor is straightforward, the implementation can be challenging and requires a detailed understanding of the technology. In this paper we examine the design and operation of five laser-based monitors, at 1) the SLC/SLD IP[7], 2) the KEK ATF[8,9], 3) DESY PETRA[10], the CERN CLIC Test Facility[11] and 4) the SNS (H-beam)[12]. In addition, since it was a pioneering device, we also include a reference to the FFTB nanometer interferometer monitor[13].

## DESIGN

The profile monitor consists of 4 subsystems, 1) the laser, 2) an optical transport to bring the light to the beamline vacuum chamber, 3) the interaction region, with its optics, and 4) a scattered radiation detector. Since its operation and design resemble that of a wire scanner, we will refer to the laser-based profile monitor as a 'laserwire'.

As with conventional wire scanners, the properties of the 'scattering object', used to sample the electron beam charge density, must match the beam parameters. Tightly focused laser waists have limited length, known as the Rayleigh range. For a linear collider, with flat $\varepsilon_y/\varepsilon_x<1\%$, beams, this can smear the overlap region and may force, for example, the use of a very short wavelength laser. Table 1 lists the laser wavelength, intensity, spot size, 'spot length' (Rayleigh range), detector types, and pulse structure of several laserwires. Figure 2 shows a laser 'waist' scan, showing the Rayleigh range of the ATF laserwire.

Table 1: Laserwire IP, laser, signal and beam energy.

| | Laser | | | IP (σ in μm) | | | | Nγ/e | E_beam (GeV) |
|---|---|---|---|---|---|---|---|---|---|
| | λ (nm) | P (MW) | $\sigma_t$ (ns) | $\sigma_{L\_\perp}$ | $\sigma_{L\_\|}$ | $\sigma_{b\ x}$ | $\sigma_{b\ y}$ | | |
| SLC/SLD | 350 | 10 | 0.1 | .4 | 12 | 3 | 0.8 | 1e4 | 46 |
| ATF | 532 | .0002 | CW | 5.7 | 760 | 50 | 7 | 0.005 | 1.3 |
| PETRA | 1064 | 25 | 2 | 20 | 2000 | 200 | 20 | 1000 | 4-12 |
| CTF | 1047 | 300 | 0.004 | 30 | 5000 | 150 | 150 | 100 | 0.05 |
| SNS ($H^-$) | 1050 | .03 | 2 | 100 | | | | | 0.000025 |

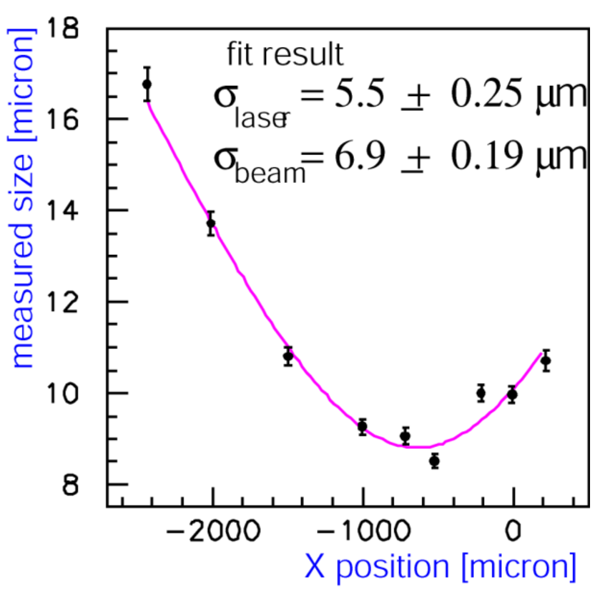


Figure 2: Laser waist scan (ATF damping ring) showing the laser Rayleigh range. The data are fit to the laser size (related to the Rayleigh range), the electron beam size (vertical in this case) and the centroid offset.

The monitor resolution depends on the relative size of the two beams and, if they are similar in size, on the accuracy with which the focused laser spot is known. It is important to note that, if the laser spot size is accurately known, it is subtracted in quadrature from the measured profile giving a monitor resolution lower than the laser size. This is the case with the ATF laserwire, where the properties of the CW laser focus are well measured and stable.

An interesting feature of the laserwire is the ability to control the effective density of the beam sampler. Taken together with a high dynamic range detector, this may be used to significantly extend the dynamic range of the monitor, allowing the extremes of the beam to be sampled. Prototype measurements with the SNS injector H- beam, where beam halo information is very important, have shown sensitivity to less than 0.1% of the core beam density.

### *Laser*

Recent advances in commercially available laser components have enabled laserwires. Affordable, reliable, high peak power components that allow billions of excellent quality pulses consistent with several years laserwire operation are available. However, reflective and transmissive component damage thresholds can vary widely and must be understood before use. A simple rule of thumb damage threshold is $1J/cm^2$. When the laser photon energy is increased, for example with the λ=350 nm SLC/SLD laserwire, bulk transmissive damage caused by non-linear optical harmonic generation is also possible. Most damage effects are self-degenerating, i.e. when they start, the damage site becomes partly opaque and the threshold drops rapidly. These and related topics are annually reviewed at the 'Boulder Damage Symposium' [14] and the best reference is [15].

High power short pulse lasers, which are readily available and provide a great deal more power than CW lasers, are the best for low repetition rate, high background linac environments. Of the laserwires listed in table 1, only the ATF damping ring laserwire works with a non-pulsed, CW, laser. While providing much more power, pulsed lasers have two important drawbacks, 1) the details of the pulse structure may cause large fluctuations [16] and 2) adjustment of the time difference between the laser and the beam can greatly complicate the basic task of finding collisions, depending on the collision angle and pulse length.

A number of transverse laser modes are have been planned or tested. The simplest, lowest order mode of a laser is the monopole (‘00mode’) or gaussian mode. The laser energy is most tightly confined in this mode and it is relatively easy to generate in the laser itself by choosing an appropriate laser medium and using a limiting pinhole aperture. In this case the laser is diffraction limited and has the minimum possible emittance. The next highest mode is the dipole mode that has a central null. The characteristic size of the null is smaller than the minimum of the monopole mode, allowing measurement of smaller beams. The extreme case is the interferometer used at FFTB, where the laser beam was split and recombined so that a regular static fixed pitch interference pattern was formed. By adjusting the recombination angle, it was possible to vary the pitch of the pattern and allow measurement of beam sizes as low as 50 nm.

## *Optics*

Optics are needed to match from the laser, (in an accessible part of the machine complex), to a transport line and to receive the beam from the transport and focus it to the IP. Additional low power optics may be needed for monitoring the laser transport and focus. Figure 6 shows the IP optics of the SLC/SLD laserwire.

The smallest possible ’00 mode’ laser spot is generated using very low *f* number optics. A rule of thumb, where we assume that the incoming beam optic is sized to match the input beam (+/- $3\sigma_{in}$), is $\sigma_0 \sim 1/2\ f^{\#}\ \lambda$. Consequently great care must be taken to make sure the optical system is aberration-free and constructed to the proper tolerances. The mechanical tolerances of the SLC/SLD IP are around 2 microns. It is not possible to directly measure the dimensions of the high power beam spot. Low power tests were done and a re-imaging system, capable of operation at full power, was used to monitor the performance of the optics and verify the incoming beam conditions.

Laser linear polarization, together with a Brewster angle plate, can be used as a ‘switch’ that directs the light either to the vertical IP or the horizontal IP.

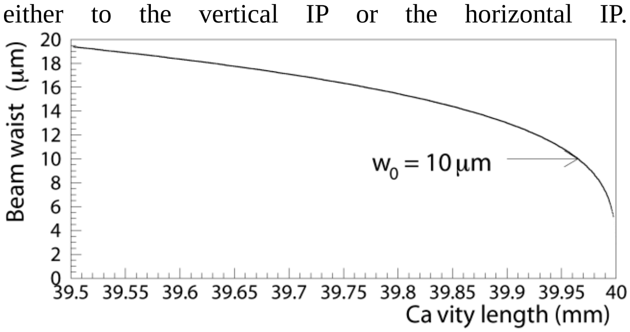


Figure 3: Laser spot size $\sigma_0$ as a function of D for spherical mirrors with radius D/2. The operating point for the ATF laserwire is indicated.

## *ATF Damping Ring Laserwire*

The optical system used at ATF is quite different since it relies on a high gain, strongly focused resonant Fabry-Perot cavity. The cavity gain, x600, and requirement for a small waist (5um) determine the cavity design. Very high (99.9%) reflectivity spherical mirrors are used in an active, position feedback-controlled, mount to maintain high average power. The precision with which the cavity length (*D*) must be controlled is illustrated in figure 3 and 4, which shows the laser spot size at the waist minimum as a function of *D*.

The stiff flexure-based mirror mounts are shown in figure 5. The entire system is inside the ring vacuum system. A beam sleeve with two small holes for the optical resonator is used to control the ring vacuum chamber impedance.

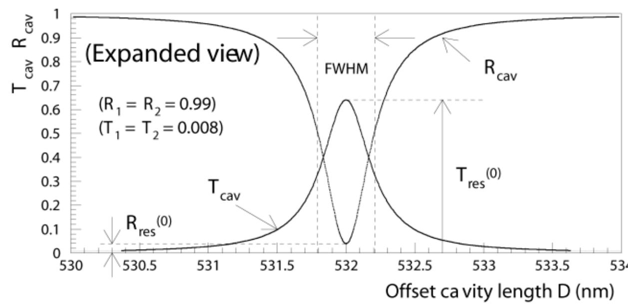


Figure 4: The Airy function for the ATF laserwire resonant cavity, showing the reflection and transmission of the cavity system.

## *Mechanical*

It is well known that environmental contaminants, such as dust or organic residue, are often involved in the initiation of optical component damage. For this reason, high power lasers are often housed in expensive, cumbersome, clean rooms. This is more important for short wave lasers and is critical if high reliability for a large number of pulses is required.

The most fragile part of an optic is its surface. Two different types of anti-reflective (AR) coatings were considered, a conventional narrow-band multi-layer sputtered dielectric and a ‘Sol-gel’ wide-band (AR) coating. Sol-gel is an active getter for organic vapors and must be protected from them in a clean ultra-high vacuum quality environment.

For all laserwires, bringing diffraction limited d high quality wavefronts into the vacuum enclosure requires innovative engineering. The surface figure required for the SLC/SLD vacuum chamber windows (λ/10) forced a repolishing and coating of the windows after the attachment of the vacuum system weld eyelet.

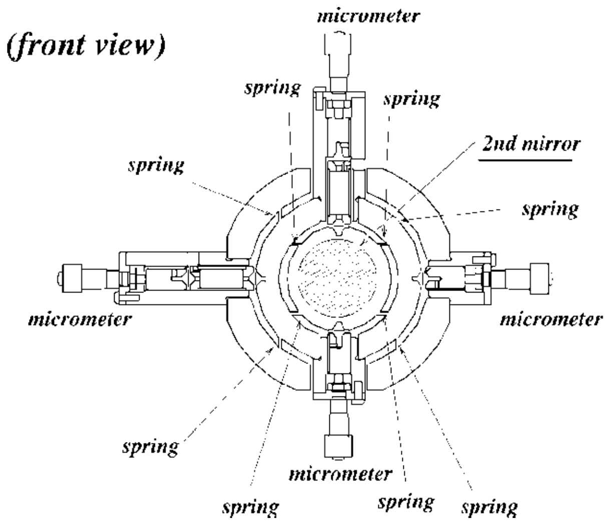


Figure 5: Intra-cavity view, facing one of the two spherical mirrors, of the Fabry-Perot resonator installed in the ATF damping ring. The electron beam passes from right to left and the opposing mirror, through which the light is injected, is mounted on a feedback-controlled drumhead flexure. The springs noted in the figure denote flexure couplings.

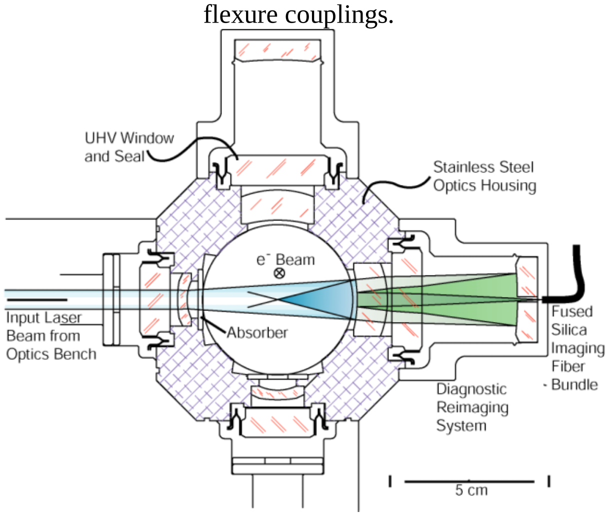


Figure 6: SLC/SLD Laserwire interaction point [17]. The laser beam enters from the right of the figure.

### *Data Acquisition*

In high repetition rate environments, such as the ATF storage ring, counting rate based acquisition systems are possible. At ATF, where the average number of gamma-rays per bunch crossing is much less than one, single photon techniques allow precision timing so that multi-bunch profiles can be quickly collected. In the ATF storage ring, where the beam repetition rate is 2.2MHz, an average number of 200 revolutions occurs between counts. However, since the probability of multiple events in a single crossing is very small, it is possible to set an energy threshold. Since energy and emission angle are correlated in the 2-body Compton process, this is a very powerful way to control backgrounds.

## OPERATION

For pulsed laser operation, a three-parameter (time, *x* and *y*) search must be done in order to begin scanning. This is in sharp contrast to the effort required to 'find' the carbon or tungsten wire. Several diagnostics are required in order to aid scanning set up. At SLC, a pair of matched length cables carried a signal from a monitor diode and a capacitive pickup (figure 7) to a sampling scope for monitoring. Once the residual 0.3 ns offset was found, this provided an important timing reference (the SLC laser pulse length $\sigma_t$=0.1ns and the beam bunch length $\sigma_z$=3ps).

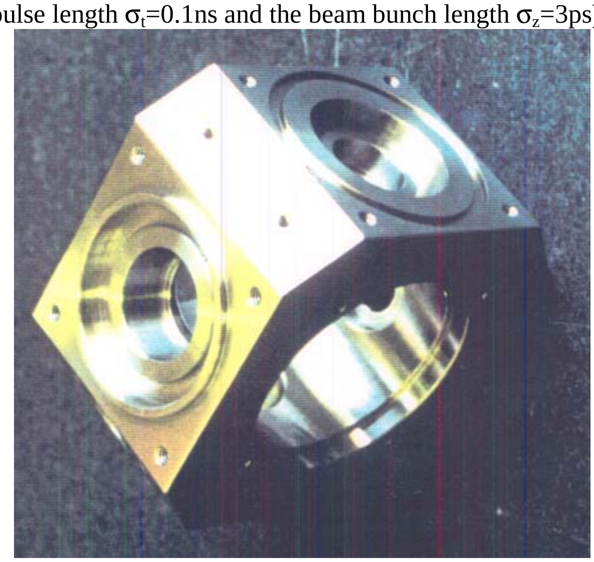

Figure 7: SLC/SLD Laserwire IP vacuum chamber. There are 8 faces that house 5 ports (input for vertical and horizontal, output for monitoring horizontal and a timing capacitive pickup (barely visible in the lower left of the figure).

The search procedure for starting laser collisions, once the timing is set correctly, uses the asymmetry of the focused laser waist. Given enough power, the collision signal can be measured far from the waist (in SLC ~ 0.5mm), along laser the direction. Once that dimension has been determined, only one parameter remains to be found and this is readily done using a laser 'waist' scan. After collisions have been established, a laser imager diagnostic can be used to prove that the laser is in the same position as it was for earlier measurements. This diagnostic is shown in figure 7.

## RESULTS

Laserwire systems have proven very important for the studies at two linear collider test facilities, FFTB and ATF. At SLC/SLD, the laser scanner was more of a demonstration than a tool for machine operation. It was used to prove that the single beam sizes were as anticipated by the use of the beam-beam deflection scan. The scanner was commissioned relatively late in the life of the linear collider. Figure 8 shows a sample vertical scan. Since the laser beam size is estimated to be $\sigma_l$ =400 nm, we infer that the beam size $\sigma_y$=1.0um.

At the ATF, the laserwire has undergone several tests for systematic errors, including steering, detector acceptance and laser beam size tests. When compared with the other monitors developed for the low emittance beam, the laserwire seems the most accurate and repeatable and has proven a vital tool for understanding the ring.

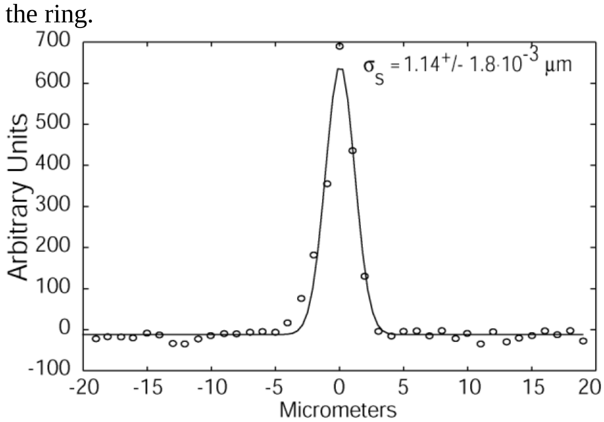


Figure 8: Sample scan from the SLC/SLD laserwire. The laser beam size and particle beam size, combined in quadrature, $\sigma_s$=1.14um.

## DEVELOPMENT PROGRAMS

One of the most serious challenges facing laserwire developers is to control the cost and complexity of the installation. Both the CW laserwire, with complex feedback and the pulsed laserwire with synchronization and amplification stages, often require specialists to facilitate operation.

Laser technology, however, is quite advanced and a number of attractive features can be included in a lasewire design: 1) matching of the laser time structure with that of the beam, 2) 'fast scanning' of a multi-bunch beam such that a profile is developed in a single pulse, 3) scanning in time as well as position, 4) varying the laser pulse amplitude during the scan in a manner correlated with the expected signal in order to extend the dynamic range and make the process less invasive, 5) measuring bunch length using a mixture of two laser signals with almost the same wavelength and 6) adaptation of the interferometer or '01' mode.

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