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A laser-wire system for the International Linear Collider

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Abstract. A new laser-wire has been installed in the extraction line of the ATF at KEK. It aims at demonstrating that laser-wires can be used to measure micrometre scale beam size. In parallel, studies have been made to specify a laser suitable for the ILC laser-wires.

Keywords. Laser-wire; accelerator test facility; laser; optical system; Compton; beam emittance; MOPA; fiber laser.

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1. Laser-wire at the ILC

The international linear collider (ILC) will require a large number of non-invasive beam size measurements to extract the phase space of the electron and positron beams before focussing at the collision point. The large charge and energy densities $\sim 10^{10}$ electrons per bunch at 250 GeV and ~ 1 μm vertical beam size of the ILC beams preclude the use of traditional beam size diagnostics, such as wire scanners and screens. These problems are solved by using a high power focussed laser beam, the laser-wire (LW), instead of a conventional solid wire.

Different technologies may be used in different sub-systems of the ILC. In the ATF damping rings, a system based on a precise optical cavity has been used to good effect [1] and an alternative approach based on a high-power pulsed laser is being pursued at PETRA. For the ILC beam delivery system, the single-shot nature of the electron beam requires the use of high-power pulsed lasers, which is the approach adopted here; the first such device was commissioned at the SLC [2].

In the LW, the laser photons are Compton scattered with electrons from the beam, the total rate of Compton scatters is proportional to the spatial overlap between the laser photon density and electron beam density and given by [3]

$$N_\gamma = N_{\rm b}\frac{P_{\rm L}\sigma_C\lambda}{c^2 h}\frac{1}{\sqrt{2\pi\sigma_s}}\exp-(\Delta y/2\sigma_s)^2, \tag{1}$$

where $N_{\rm b}$ is the electron bunch population, $P_{\rm L}$ is the peak laser power, λ is the laser wavelength, Δy is the vertical offset between the centres of the laser and electron beams and is the quadratic sum of electron and laser Gaussian widths. By measuring the Compton rate (N_γ) as a function of relative displacement Δ_y, σ_s can be determined. Provided the laser beam size is known precisely, the electron beam size can, in principle, be extracted. In practice, however, additional machine-related errors may dominate; one of the purposes of a LW experiment at ATF/ATF2 [4] is to quantify and control all the various sources of error that will contribute to an emittance measurement at the ILC.

2. The ATF extraction line laser-wire

2.1 *Experimental conditions*

A laser-wire has been installed in the extraction line of the ATF (accelerator test facility) at KEK. At the ATF the electron bunches are repeated at 1.56 Hz with an energy of 1.28 GeV. The emittance of the ATF beams is 5×10^{-11} mrad (vertical) and 1.6×10^{-9} mrad (horizontal). The laser used is seeded by a passive mode-locked Nd:VO_4 laser producing pulses at 357 MHz. Pulses are selected by two Pockels cells at the ATF extraction frequency. They are then amplified in a Nd:YAG q-switched cavity and further amplified in Nd:YAG rods. These pulses are frequency doubled in a KD*P crystal. At the exit of the laser the pulses have a length of approximately 150 ps$\times$ c with an energy of 400 mJ at 532 nm. Several mirrors are used to bring the laser light to the interaction point. An indium sealed high quality fused silica window is used to bring the light in the vacuum. A lens is used to focus the laser beam at interaction point.

Compton photons were converted to electron positron pairs in a 4 mm thick lead plate on the front of an aerogel Cherenkov detector, placed 10 m downstream of the IP.

2.2 *Results and analysis*

After establishing collisions between the electron beam and laser beam, the signal was maximised by adjusting the laser waist position vertically (y) and horizontally (x) and the timing of the laser system. In order to make a beam size measurement the laser was scanned vertically across electron beam. An example of a vertical waist scan is shown in figure 1.

The laser was moved vertically in steps of several microns and the Compton signal was recorded for 20 machine cycles at each step and averaged. The average beam

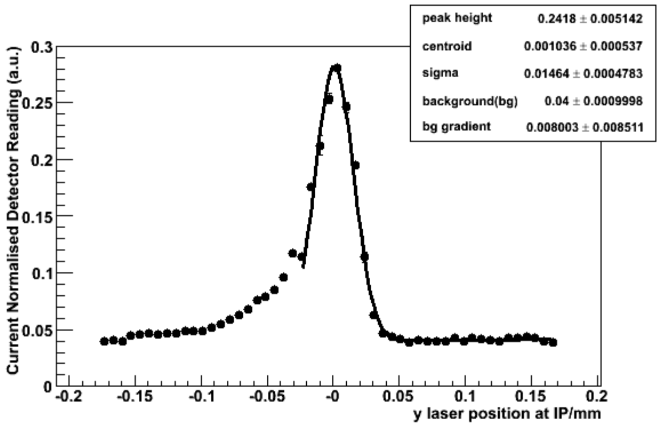

Figure 1. Example of a vertical scan with the ATF extraction line LW system.

charge was also measured and used to normalise the Compton signal to remove variation due to bunch charge variation from the ATF. The signal as a function of laser position at the IP is approximately Gaussian with a width of (15.2 ± 0.1) μm. There is a clear asymmetry in the signal, which can be attributed either to the transverse profile of the laser pulse or to possible aberrations in the lens such as coma. The current (interim) lens is not expected to provide a laser focus sufficiently small to measure the electron beam size as described above. The width of the measured signal was expected to be dominated by a combination of spherical aberrations from the lens and the M^2 of the (imperfect) laser beam.

3. Laser R&D

Table 1 summarises the parameters required for an ILC laser-wire. The laser beam quality has to be excellent for the laser beam to be focussed down to its diffraction limited size by a specially designed aberration-free focussing optics. High laser pointing is necessary for reliable particle beam size measurements. The laser wavelength (λ) choice is a compromise among, small focussed beam size, for better spatial resolution, large Rayleigh range, R for flat laser wire condition and small Compton X-section, requiring more laser power for the same the number of Comptons at reduced λ. The laser peak power is decided by the numbers of Comptons produced for measurement with a very small error. The larger the peak power, the better the accuracy of the final results.

The laser system has to be an oscillator and amplifier architecture (MOPA), as a single laser cannot generate 50 MW IR peak optical power at MHz rep. rate required to obtain about 10 MW power at UV by non-linear frequency conversion. Several possible gain mediums have been investigated and discussions are on-going with possible suppliers to select the best solution.

Table 1. Laser parameters.

Laser parameters	Guidelines/Values
Repetition rate	ILC repetition rates with Sync. to reference RF ≤ 1 ps rms
Pulse duration	ILC bunch length, 1 ps
Overall temporal structure	ILC time structure, 900 μs@ 5 Hz
Beam quality	TEMoo mode, $M^2 \simeq 1$, Gaussian beams, high pointing stability
Wavelength	Focus laser beam size and Compton X-section, 250–500 nm
Peak power	Number of Comptons, 10 MW/250 nm

4. Conclusions and outlook

The ATF extraction-line LW has seen first collisions between the 30 ps ATF beam pulses of 1.28 GeV electrons and 150 ps, 532 nm laser pulses. The results are consistent with a fine electron beam being scanned by a larger laser beam; this situation will reverse once the technology has developed, as discussed below. The quadrature beam size, σ_s, measured at the laser beam waist was 15.3 μm. The aim of the ATF system is to verify that beam size measurements of $\sim$1 μm electron beams can be performed in the ILC BDS. The first step in this programme has been achieved; the next step is to improve the resolution of the system by improving the transverse mode quality of the laser and upgrading from the commercial lens to a custom-built system with f#/2 optics. Longer term, an f#/1 system will be designed and it may also be necessary to investigate the use of shorter wavelength light.

In parallel several possible solutions have been studied to build a laser compatible with the ILC requirements.

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