ATF EXTRACTION LINE LASER-WIRE SYSTEM*

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Abstract

The ATF extraction line laser-wire (LW) aims to achieve a micron-scale laser spot size and to verify that micron-scale beam profile measurements can be performed at the International Linear Collider beam delivery system. Recent upgrades to the LW system are presented together with recent results including the first use of the LW as a beam diagnostic tool.

INTRODUCTION

The need for a non-invasive transverse beam size monitoring system for the International Linear Collider (ILC) is well established [1]. The LW systems at the ILC will form an essential part of the emittance measurement and beam parameter optimisation. The aim of our program is to develop a laser-wire system capable of measuring beam sizes that are vertically $1\mu\mathrm{m}$. We reported the first operation of the laser-wire in Summer 2006 [2]. This contribution outlines the progress made at the ATF extraction line laser-wire experiment.

EXPERIMENTAL CONDITIONS

The ATF laser-wire is shown schematically in Figure 1. The interaction chamber is located in the extraction line of the ATF damping ring, at a location where the beam optics can be modified to produce electron beam sizes of between $\sim 50\mu\mathrm{m}$ down to the ILC-like $20 \times 1\mu\mathrm{m}$. The ATF provides bunches of 2×10^{10} electrons, at 1.56 Hz repetition frequency [4].

High energy green ($\lambda = 532\mathrm{nm}$) laser pulses are produced by amplifying a single pulse from a passively mode-locked seed laser. The seed laser is frequency locked to the ATF RF distribution system at $357\mathrm{MHz}$. The laser pulses are $\sim 150\mathrm{ps}$ in duration and have a total pulse energy of $\sim 30\mathrm{mJ}$.

The laser pulses are transported to the extraction line by a series of mirrors, collimated, and aligned with respect to the accelerator by two well separated irises. The laser light is then steered onto the final focusing lens by two mirrors. The second mirror (scanner in Figure 1) is fixed to a remotely controllable mount that can be tilted in both horizontal and vertical directions.

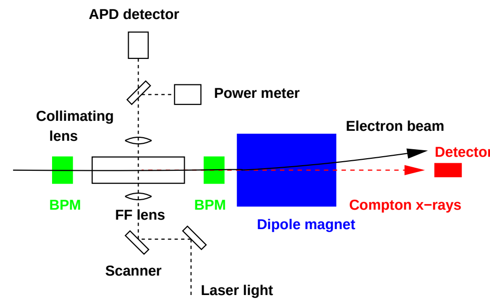

Figure 1: Schematic plan of the interaction region.

The laser beam is focused by a plano-convex singlet lens (FF in Figure 1) with nominal focal length 150 mm before the beam passes through a 6.36 mm thick fused silica window. The focus lens is mounted on a three axis translation system so the position of the incident laser beam can be optimised and the laser waist can be translated. The angle of incidence of the laser on to the final lens can be changed using the scanner.

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]

$$N_\gamma = N_b \frac{P_L \sigma_C \lambda}{c^2 h} \frac{1}{\sqrt{2\pi}\sigma_s} \exp\left(-\frac{\Delta y}{2\sigma_s^2}\right) \qquad (1)$$

Where N_b is the bunch population, P_L is the laser pulse power, σ_C is the Compton cross section, λ the laser wavelength, $\Delta y = y_l - y_e$ the vertical position difference between electron and laser beam centres and σ_s is the quadrature sum of the electron and laser beam sizes $\sigma_s^2 = \sigma_e^2 + \sigma_l^2$. The maximum energy of scattered photons is given by $E_{\gamma,max} = 2E_b\epsilon/(1+2\epsilon)$, where $\epsilon = \gamma hc/(\lambda m_e)$. Then by measuring the modulation of the Compton rate (N_γ) as a function of relative displacement (Δy) the quadrature beam size (σ_s) can be extracted. Provided the laser beam size (σ_l) is known the electron beam size (σ_e) can be extracted.

The Compton scattered photons from the laser-electron beam interaction are separated from the charged beam in

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the next dipole magnet. The Compton photons exit the beam pipe through a 1 mm aluminium window and are detected by an Aerogel Cerenkov light detector, which counts the number of charged particles, and then a lead-glass calorimeter.

The Cerenkov detector is placed 10.6 m downstream of the interaction point. Using a Geant 4 simulation 12% of the photons are converted to electrons and positrons in a 7.35mm thick lead plate on the front of the aerogel which itself produces Cerenkov light in proportion to the number of charged particles. A periscope sends the light down to a photomultiplier tube (PMT). The aerogel is 100×100 mm wide and 55mm thick with a refractive index of 1.015, giving a Cerenkov threshold of 2.983 MeV.

The calorimeter is placed 11.4m downstream of the interaction point. The lead-glass is 365mm long and it's horizontal×vertical width is 113×123 mm at the front and 137×123 mm at the rear window where a photomultipllier tube is placed.

Signal pulses from the PMTs are digitised using a multi-channel gated integrating analogue to digital converter.

RECENT RESULTS

The laser-wire has been operated on numerous occasions during 2006/7; here we report the results from two consecutive ATF experimental shifts.

Scans and laser optics tuning

Since the installation of the laser-wire the laser beam alignment with respect to the final focusing lens has been optimised. Previously a significant asymmetry was observed in the laser-wire signal [2]. A recent scan is shown in Figure 2, which is fitted to the sum of a Gaussian and first order polynomial, which is clearly symmetric and Gaussian.

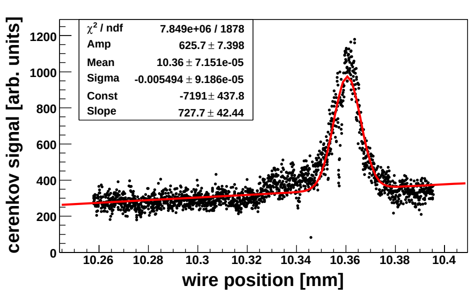

Figure 2: Cerenkov detector signal as a function of laser beam vertical position.

For effective laser-wire operation it is essential that the laser-beam waist is located centrally on the electron beam. The laser beam waist is translated along the propagation direction by moving the final focusing lens. At each lens position the laser beam is scanned vertically across the electron beam and a beam size is extracted. The fitted sizes are plotted as a function of lens position and fitted to the equation below.

$$\sigma(z) = \sigma_0 \sqrt{1 + \left(\frac{z}{z_R}\right)^2} \tag{2}$$

The vertical electron beam size is typically $\sim 1\mu\mathrm{m}$ so the measured σs is a good estimate of the laser beam size. The fit results (Table 1) show that at the laser waist, $\sigma_s \sim 7\mu\mathrm{m}$.

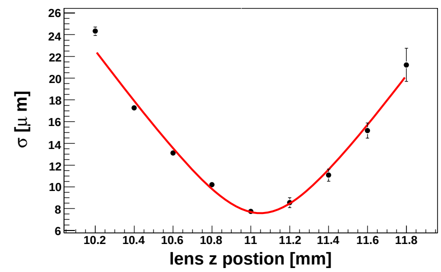

Figure 3: Laser waist scan using the Cerenkov detector.

Detector	$\sigma_0[\mu m]$	$z_R[mm]$
Cerenkov	7.6 ± 0.2	0.30 ± 0.01
calorimeter	6.8 ± 0.3	0.27 ± 0.01

Table 1: Laser waist scan fit results. σ_0 is the minimum beam size and z_R is the Rayleigh range.

As a cross check, a calorimeter was placed behind the Cerenkov detector so that they could simultaneously measure the LW Compton photons. A laser scan using the calorimeter detector is shown in Figure 4. The signal to noise ratio of the calorimeter is 0.8, whilst for the Cerenkov detector it is 1.8. As the aerogel detector has a Cerenkov threshold $\sim$ 3MeV it does not detect particles below this energy, which include low energy background particles. The calorimeter measures both compton and background particles below this threshold, so is more sensitive but suffers from greater backgrounds.

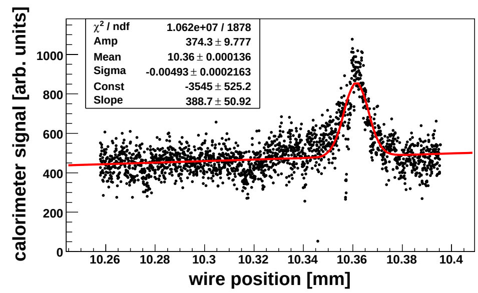

Figure 4: Calorimeter detector signal as a function of laser-beam vertical position.

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Detector linearity

Bunch charge was measured using both a wall current monitor (WCM) and an integrating current transformer (ICT). The wall current monitor is located upstream near the laser-wire interaction point (IP) and the ICT is located at the end of the extraction line near the beam dump. With the beams optimally overlapping at the laser waist, 20 minutes of data were taken. During this run the bunch charge was varied by changing the charge produced by the ATF electron gun from 0.1×10^{10} to 1.4×10^{10}. The response

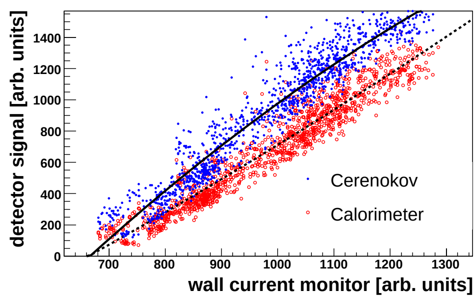

Figure 5: Cerenkov and calorimeter signals plotted as a function of beam charge

of both detectors as a function of bunch charge is shown in Figure 5.

The detector responses are fitted to $signal = p_0 + p_1 q + p_2 q^2$ where q is the charge measured in the WCM. The fit parameters obtained are summarised in Table 2

Detector.	$p_0/10^3$	p_1	$p_2/10^{-3}$
Cerenkov	-2.6 ± 0.1	4.5 ± 0.3	-1 ± 0.2
calorimeter	-1.2 ± 0.1	1.6 ± 0.3	0.3 ± 0.1

Table 2: Detector linearity fit for calorimeter and Aerogel Cerenkov detectors.

Both detector systems are reasonably linear over a large range of Compton signals. The parameter p_2 is larger for the Cerenkov detector, indicating some non-linear effect. The spectrum of the Compton signal is bunch charge independent but the backgrounds from the ATF might have some dependence.

For data taken with the scan in Figure 2 the charge variation in the WCM was 5.5% and the charge variation in the ICT was 8.8%. The fluctuation in the Cerenkov and calorimeter detector signal when the beams were not in collision was 13%. In future running laser power and bunch charge, as well as laser and electron beam positions, will be monitored in order to better normalise the LW signal.

Quadrupole scan

The electron beam size at the laser-wire interaction point was changed using two upstream quadrupole magnets (QD4X and QF4X). The beam size measured at our IP as a function of QD4X current is shown in Figure 6 and is fitted to $\sigma = a + bI + cI^2$ where I is the QD4X current in amperes. The measured vertical beam size varied from $\sim 35\mu\text{m}$ down to a minimum of $\sigma = 5.4\mu\text{m}$. At large beam sizes the signal to noise becomes significantly lower and fitting a Gaussian to the data becomes more difficult.

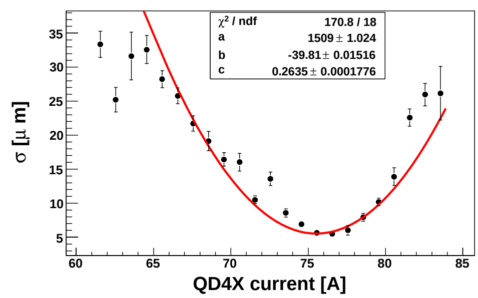

Figure 6: LW measured vertical beam size as a function of quadrupole QD4X current.

CONCLUSIONS

We presented our latest results of the ATF extraction line laser-wire. The smallest electron beam size measured was $5.4\mu\text{m}$. When the electron beam size is varied via a quadrupole scan clear variation is seen in the measured size.

A second detector, a lead-glass calorimeter, has been installed to measure Compton x-ray signal. The calorimeter suffers from more low energy background than our default detector, which measures Cerenkov light produced using aerogel. Our studies indicate that the calorimeter is slightly more linear than the Cerenkov detector. Both detectors are acceptable for the beam size measurement.

The LW system installed has recently been upgraded to allow studies of near diffraction limited focusing optics, which should allow the system to reach the ILC design goal of $1\mu m$ transverse beam size measurements [5]. The upgrade consisted of rigidly fixing the focusing lens to an upgraded vacuum chamber, which can now be moved with respect to the electron beam.

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