SUB-MICROMETRE RESOLUTION LASERWIRE TRANSVERSE BEAM SIZE MEASUREMENT SYSTEM

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Abstract

We present the results from the laserwire system at the Accelerator Test Facility 2 (ATF2) during recent operation after relocation to the virtual image point of the ATF2 final focus. The characterisation of the 150 mJ, 77 ps long laser pulses at a scaled virtual interaction point is used to deconvolve the transverse laserwire profile demonstrating a 1.16 ± 0.06 μm vertical electron beam profile. Horizontal laserwire scans were used in combination with the vertical scans to measure the electron beam size using a full overlap integral model due to the problems presented by a large aspect ratio electron beam.

INTRODUCTION

A laserwire is a non-invasive method of measuring the transverse size of an electron beam where a high power laser beam is focussed to a small size and scanned across the electron beam. With a relativistic electron beam, the laser photons are Compton-scattered to a high energy and travel near-parallel to the electron beam. A bend further along the accelerator facilitates separation of the Compton-scattered photons and the electrons where the photons are detected. Unlike a conventional wire-scanner, the resolution of a laserwire is limited by the wavelength of light used, which is typically < 1 μm, therefore allowing a laserwire to provide greater resolution as well as avoiding damage from the electron beam. Such a diagnostic will be imperative for measuring low emittance electron and positron beams with high charge densities such as those of the ILC [1, 2] and CLIC [3].

A laserwire installation at the ATF2 [4] was upgraded and comissioned in 2010 demonstrating initial transverse beam size measurements of 8.0 ± 0.3 μm [5]. This system was moved to a different point in the ATF2 lattice where a micrometre scale beam could be realised. This paper presents the recent results of this laserwire system demonstrating high resolution measurements of the electron beam, even with a large aspect ratio beam that is conventionally thought to limit the use of a laserwire.

SETUP

The laserwire was relocated in summer 2011 to the beginning of the ATF2 final focus section where strong, closely-spaced matching quadrupoles allow a vertical electron beam size of ~ 1 μm to be achieved. A seeded Q-switched Nd:YAG laser with frequency-doubled output is used to deliver ~ 150 mJ pulses with a wavelength of 532 nm to the laserwire interaction point at the repetition rate of the ATF2 1.3 GeV electron bunches of 3.25 Hz. The laser pulses are $\sigma_\tau = 77$ ps long and the electron bunches are $\sigma_\tau = 30$ ps long. The laser is located outside the accelerator enclosure and transported into it in free-space with mirrors before being focussed by an aberration corrected fused silica lens to the laserwire interaction point.

The Compton-scattered photons are detected approximately 10 m downstream immediately after a dipole magnet. The detector consists of a $4 \times 4 \times 0.6$ cm lead plate followed by an Aerogel scintillator of the same size, a light tight and guiding pipe and finally a shielded photomultiplier tube. A data acquistion based system on EPICS is used to synchronously record data from the laserwire experiment, cavity BPM system [6] and ATF2 diagnostics.

The laser pulses and electron beam were synchronised for collisions using an optical transition radiation (OTR) screen mounted in the laserwire chamber [7]. The laser beam was directed below this and both the attenuated laser light and the OTR were detected in an avalanche photodiode. The laser timing was adjusted until both were overlapped. The OTR screen was also used as an alignment tool by comparing the bremsstrahlung radiation as the screen was lowered into the beam to the referenced position of the laser focus relative to the screen. This method allowed detectable collisions between the laser and the electron bunches to be detected immediately, which were subsequently optimised to maximise the Compton signal.

To perform laserwire scans, the vacuum chamber was moved on a two-axis mover system. As the laserwire lens is mounted to the vacuum chamber, the laser focus therefore moves exactly as the vacuum chamber does. Optical encoder readouts provide 50 nm resolution on the chamber position.

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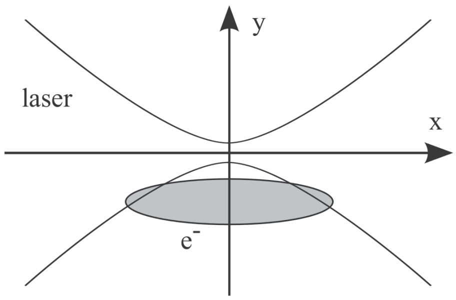

Figure 1: Schematic of laser propagation across a large aspect ratio electron beam (not to scale).

ANALYSIS

To deconvolute the laserwire scans, knowledge of the focussed laser spot size is required. In the case where the horizontal electron beam size is much less than the Rayleigh range (the distance over which the laser waist expands from its minimum at focus σ_o to $\sqrt{2}\sigma_o$), the laser size can be assumed to be constant and the scan is easily deconvoluted when both the laser and electron beam have Gaussian profiles. However, with a large aspect ratio electron beam such as that at the laserwire location at ATF2 (∼100:1 - horizontal:vertical), the natural laser divergence from the focus across the width of the electron beam produces a non-Gaussian convoluted scan. This originates from the wider laser beam outside the focus area still interacting with the electron beam even when the focus of the laser beam is no longer in overlap with the electron beam as depicted in Figure 1. Therefore, both knowledge of the laser focussed spot size and the laser divergence is required to accurately deconvolute the laserwire scans using the full overlap integral of the measured laser propagation with the 3 dimensional Gaussian electron beam described in [1]. The laser propagation is described in each axis by

$$\sigma(x) = \sigma_o\sqrt{1+\left(\frac{(x-\Delta_x-x_{\sigma o})\lambda M^2}{4\pi\sigma_o^2}\right)^2} \qquad (1)$$

where σ_o is the minimum laser beam size, Δ_x the displacement of the laser focus from the electron beam, λ the wavelength of the light and M^2 the spatial quality factor. When the laser propagation is at an angle θ to the lab frame, the projection is calculated using

$$\sigma_l = \sqrt{(\sigma_{horizontal}\ \sin\theta)^2 + (\sigma_{vertical}\ \cos\theta)^2} \qquad (2)$$

RESULTS

The laser propagation was characterised using a larger scale focus generated by an $f = 1$ m plano-convex lens. A scaled focus was used as the micrometre size laser focus is beyond the measurement resolution of accurate CCD-based laser beam profilers. Beam profiles of the laser were recorded at various locations through the focus and the 4σ diameters used to fit the data to the M^2 model [8]. This model was then scaled to the laserwire interaction focus using the measured input beam profile to the laserwire lens. The laser propagation for both axes of the laser beam is shown in Figure 2.

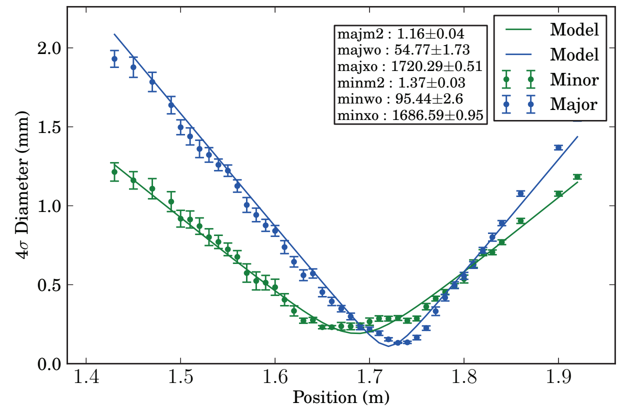

Figure 2: Measured laser propagation in both axes.

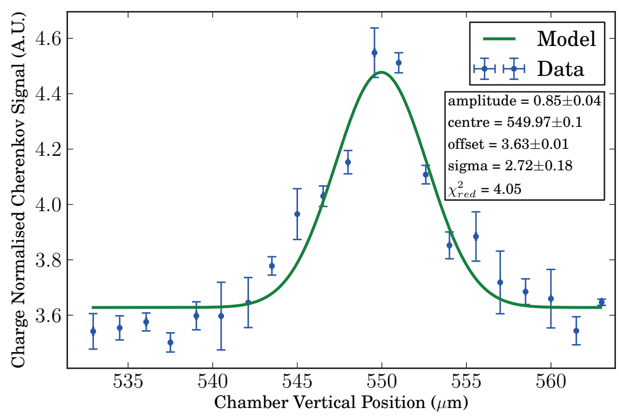

Figure 3: Initial vertical scan of the electron beam.

The laser propagation was found to be different in the two transverse dimensions and rotated by $17.5 \pm 1.0°$ to the lab frame. The propagation model of each axis was used to calculate the projected vertical laser propagation in the lab frame that is relevant for deconvoluting the laserwire scans.

When performing alignment with the OTR screen, a laser machined notch in the edge of the OTR screen allowed horizontal alignment as well as vertical alignment to be performed and for the system to be aligned within 10 μm of the optimal vertical position. After the initial alignment using the OTR screen, Compton scattered photons were detectable and the collisions were then optimised.

To achieve an accurate measurement of the electron beam size, the laser focus must be centred on the electron beam, so the laserwire is first coarsely scanned vertically, then horizontally to centre the laser focus before finally performing a detailed vertical scan. The initial coarse vertical scan is shown in Figure 3 with a measured beam size of 2.72 ± 0.18 μm.

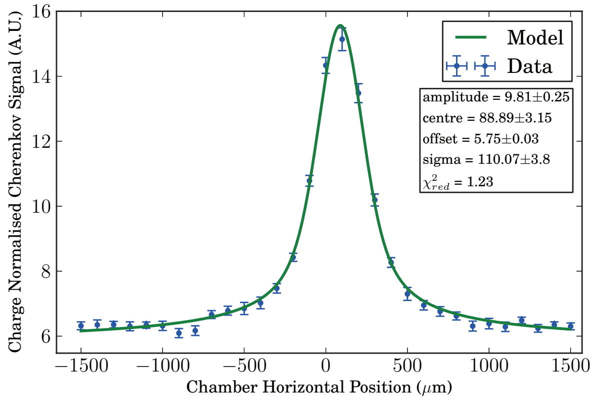

Figure 4: Horizontal scan of the electron beam.

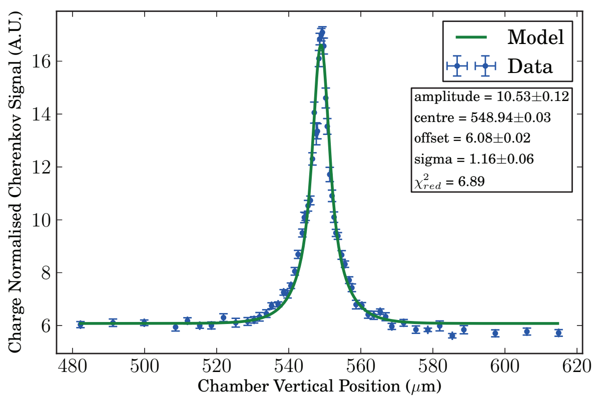

Figure 5: Detailed nonlinear vertical scan of the electron beam.

The initial vertical scan is fitted to a Gaussian function, which although not an accurate description, allows the centre and approximate size to be initially determined. To deconvolute the horizontal scan using the necessary overlap integral model, knowledge of the vertical beam size is need. Similarly, to deconvolute the vertical scan, knowledge of the horizontal is needed. To overcome this circular problem, the two are fitted iteratively together until convergence is reached. The required horizontal scan of the electron beam is shown in Figure 4.

As the divergent laser beam continues to interact with the electron beam even when the laser focus is displaced from the electron beam, the vertical laserwire scans must cover a scan range significantly greater than the vertical size of the electron beam for accurate fitting. However, the central part of the scan contains a very narrow peak. Therefore, a scan with nonlinear step sizes was crucial in performing accurate laserwire scans in the minimum time possible. In Figure 5, 61 laser positions were used and 20 machine samples were recorded at each location in the vertical scan..

From the iterative fitting process of both the horizontal and the vertical laserwire scans, the measured horizontal beam size was 110.1 ± 3.8 μm and the vertical beam size was 1.16 ± 0.06 μm.

CONCLUSIONS

Micrometre scale electron beam profiles with a resolution of less than 1 μm have been demonstrated with a visible wavelength laser. The often cited problem of laser divergence with a laserwire with a very large aspect ratio electron beam has been overcome to accurately measure both the horizontal and vertical dimensions.

The general background level as well as the background encountered due to the horizontal defocussing of the electron beam as a consequence of the necessary strong vertical focussing presents a challenge to successfully operating this laserwire installation. With higher background levels, higher energy laser pulses are required to overcome this as well as a greater number of samples being required to overcome statistical variations. With lower background conditions, a more precise fit to the data could be achieved and future work is under way to develop suitable electron beam optics for this purpose.

The development and demonstration of such a laserwire is a significant step forward to achieving a precise and reliable diagnostic for future linear colliders such as the ILC.

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REFERENCES

[1] I. Agapov *et al.*, Phys. Rev. ST Accel. Beams 10 (11) (2007) 112801

[2] N. Phinney, N. Toge and N. Walker, International Linear Collider Reference Design Report Volume 3 (2007)

[3] M. Aicheler, P. Burrows, M. Draper, T. Garvey, P. Lebrun, K. Peach and N. Phinney A Multi-TeV Linear Collider based on CLIC Technology: CLIC Conceptual Design Report CERN-2012-007

[4] S. T. Boogert *et al.*, Phys. Rev. ST Accel. Beams 13 (12) (2010) 122801

[5] L. J. Nevay *et al.* "Micron-Scale Laser-wire at the ATF-II at KEK Commissioning and Results", IPAC '11, San Sebastian, 2011 TUPC158

[6] Y. I. Kim et al., Phys. Rev. ST Accel. Beams 15 (4) (2012) 042801

[7] P. Karataev *et al.*, Phys. Rev. Lett. 107 (17) (2011) 174801

[8] T. F. Johnston Appl. Optics, 38 (21) (1998) 4840

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