SUB-MICROMETRE RESOLUTION LASERWIRE TRANSVERSE BEAM SIZE MEASUREMENT SYSTEM

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Abstract

The laserwire system at the Accelerator Test Facility 2 (ATF2) is a transverse beam profile measurement system capable of measuring a micrometre-size electron beam. We present recent results demonstrating a measured vertical size of 1.16 ± 0.06 μm and a horizontal size of 110.1 ± 3.8 μm. Due to the high aspect ratio of the electron beam, the natural divergence of the tightly focussed laser beam across the electron beam width requires the use of the full overlap integral to deconvolve the scans. For this to be done accurately, the propagation of the 150 mJ, 167 ps long laser pulses was precisely measured at a scaled virtual interaction point.

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 nearly parallel to the electron beam. A bend further along the accelerator separates the Compton-scattered photons from the electrons and the photons are detected at this point. Unlike a conventional wire-scanner, the resolution of a laserwire is limited by the wavelength of light used, which is typically < 1 μm, 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 [6]. 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.

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SETUP

The laserwire setup was relocated in summer 2011 to the beginning of the ATF2 final focus section where strong, closely-spaced matching quadrupoles provide a vertical electron beam size of ∼1 μm. 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 the laser beam is transported to the laserwire interaction point (LWIP) via a series of mirrors.

The Compton-scattered photons produced in the laserwire interaction are detected approximately 10 m downstream immediately after a dipole magnet. The detector consists of a 4 × 4 × 0.6 cm lead plate followed by an Aerogel scintillator of the same size, a light tight and guiding pipe and finally a shielded photo-multiplier tube. A data acquistion based system on EPICS is used to synchronously record data from the laserwire experiment, cavity BPM system [7] and ATF2 diagnostics.

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 moves exactly as the vacuum chamber does. Optical encoder readouts provide 50 nm resolution on the chamber position.

During operation, the laser pulses and electron bunches were synchronised using an optical transition radiation (OTR) screen mounted on a 4 axis manipulator arm inside the laserwire vacuum chamber [8]. The screen is lowered into the electron beam and the laser beam directed below it. The OTR and attenuated laser light are simultaneously detected in an avalanche photodiode. The timing of the laser system is adjusted with respect to the electron bunches until both are overlapped. The edge of the OTR screen is then used to align the laser focus spatially by first setting the it at the laser focus position (referenced offline) and then moving the laserwire chamber (and therefore the laser focus and OTR screen together) until the bremsstrahlung produced by the OTR screen falls to half its maximum value. Furthermore, a laser machined notch in the OTR screen al-

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lows horizontal alignment by observing the minimum in bremsstrahlung as the electron beam passes through the notch. This process allows the laser to be aligned to the electron beam so that collisions are immediately detectable. The alignment is subsequently optimised by performing successive horizontal, vertical and timing scans to maximise the Compton signal.

ANALYSIS

A laserwire scan is the convolution of the laser beam and the electron beam distributions. With knowledge of the laser beam, a laserwire scan can be deconvolved yielding the electron beam width. The principal difference between a wire-scanner and a laserwire is that the laser beam width varies throughout the its focus. The Rayleigh range is the length scale over which the laser changes significantly, and is defined as the distance from the focus until the laser waist expands from its minimum at σ_o by a factor of $\sqrt{2}$. In the case where the electron beam width is much less than the Rayleigh range, the laser beam width is effectively constant across the electron beam and the vertical laserwire scan is the simple convolution of the vertical laser photon and electron distributions - typically both Gaussian. However, if the electron beam has a high aspect ratio, this is not so. Even when the laser focus is displaced from the electron beam, the divergent laser beam away from the focus continues to interact with the electron beam as shown in Figure 1. This has the effect of producing a non-Gaussian scan shape with wings away from the centre.

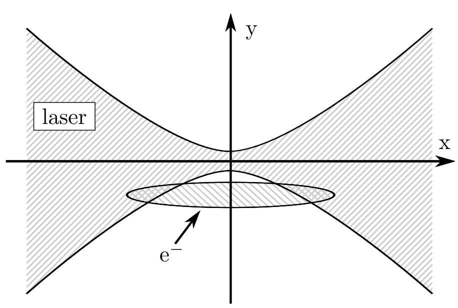

Figure 1: Schematic of laser focus across electron beam depicting the residual interaction between the two even when the laser focus is displaced from the electron beam.

In this case, the full overlap integral must be used [1]. The laser propagation is measured and used with the horizontal electron beam size to analyse the vertical laserwire scans.

RESULTS

To deconvolve the laserwire scans, the laser propagation must be measured. As it is not possible to precisely measure the micrometre size focussed laser spot with commercially available diagnostics, a scaled focus generated by a $f = 1$ m plano-convex lens at a virtual LWIP in the laser lab was used. The virtual LWIP is a separate laser beam line with precisely the same length from the laser as the main beam line and represents a duplicate of the input laser beam to the laserwire lens but with sufficient space for laser diagnostics unlike the LWIP as well as the convenience of being outside the accelerator enclosure. With a scaled laser focus, a high resolution CCD laser beam profiler can be used to measure the propagation of the laser beam and the measured laser propagation is shown in Figure 2.

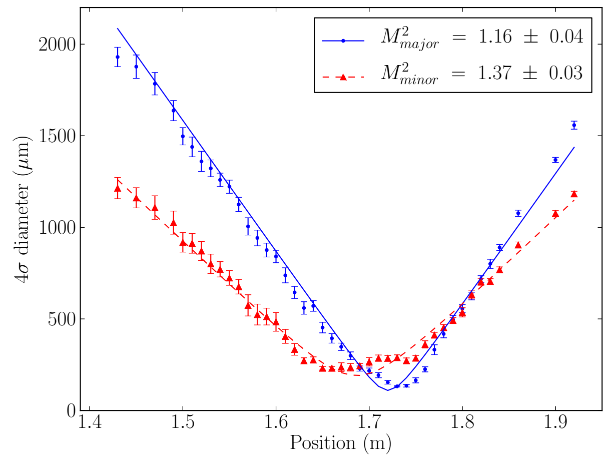

Figure 2: Laser propagation measured at scaled focus analysed along the two axes of the laser beam.

The laser propagation was found to be asymmetrical with two orthogonal axes of propagation rotated with respect to the lab frame. These are individually described by the M^2 model [9], which describes the measured laser propagation in comparison to that of a laser beam with a perfect Gaussian transverse intensity distribution. For a given input laser beam size to a lens, the focussed spot size is a factor of M^2 bigger, where $M^2 \geq 1$. Using the parameters from this model, the laser beam can be accurately described throughout the focus at the LWIP in each dimension by

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

where σ_o is the minimum laser beam size, Δ_x the displacement of the laser focus from the electron beam centre, λ the wavelength of the light and M^2 the measured spatial quality factor for that axis. The two laser propagation axes are combined to calculate the relevant vertical projection in the lab frame using

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

where θ is the angle of the laser axes with respect to the lab frame, which was measured to be $17.5 \pm 1.0°$.

Once the alignment procedure was performed and Compton-scattered photons were detectable, the dependence of the laserwire signal on electron bunch charge and laser pulse energy was measured. For several laser settings the electron bunch charge was varied as shown in Figure 3.

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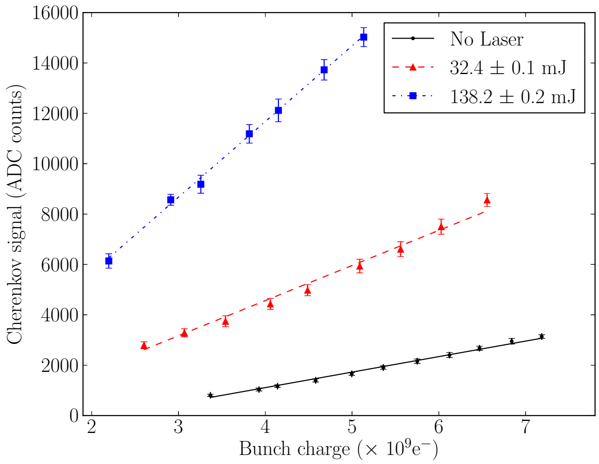

Figure 3: Laserwire signal dependence with varying electron bunch charge for various laser levels.

This shows that when there is no laser present, the detector background level linearly increases with the bunch charge. With laser pulses present, the signal also varies linearly with bunch charge as expected.

To accurately deconvolve the vertical laserwire scans, the horizontal size must be known as well as the horizontal offset of the laser focus from the electron beam. To measure this, a horizontal scan was performed in addition to a vertical scan. Similarly, the horizontal scan shape and size vary with a vertical offset of the laser focus to the electron beam. To overcome this a small vertical scan with a low number of samples was performed to provide vertical centering before performing a detailed horizontal scan. After this, the laser focus was centred horizontally and a detailed vertical laserwire scan performed. An example intial vertical laserwire scan is shown in Figure 4.

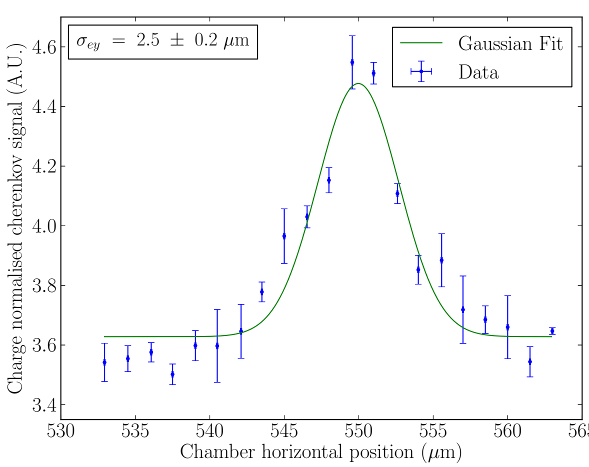

Figure 4: Initial vertical laserwire scan for centering purposes fitted to a Gaussian model.

A Gaussian model is used to fit the data and although it is not an accurate model, it is sufficient to achieve the desired centering. A more detailed horizontal scan taken following this as shown in Figure 5, and after this a detailed vertical scan, shown in Figure 6. Both are shown with the fit to the laserwire overlap integral model.

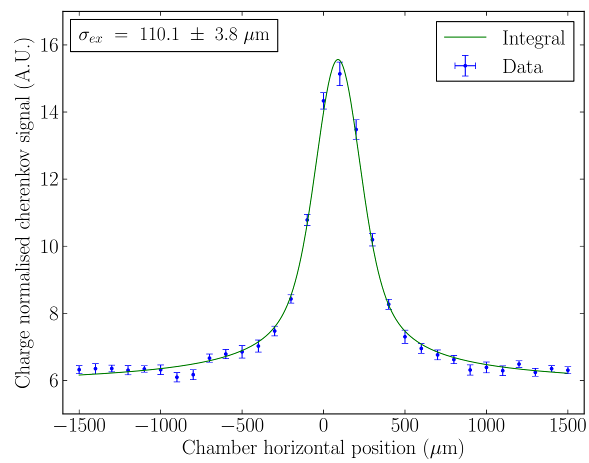

Figure 5: Horizontal laserwire scan of the electron beam.

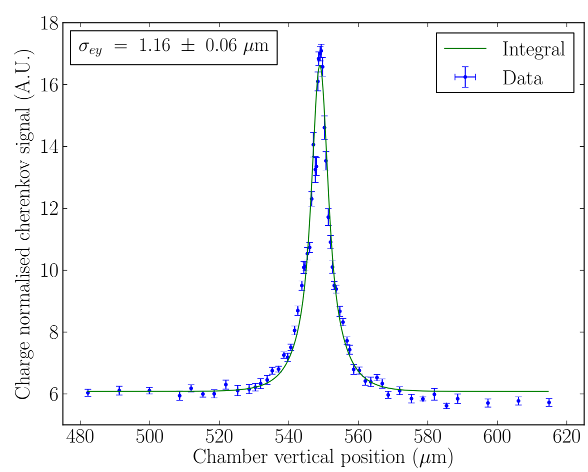

Figure 6: Detailed nonlinear vertical laserwire scan of the electron beam.

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. Despite the necessary long range, the central part of the scan contains a very narrow peak that must be sufficiently sampled for a precise scan. Therefore, a scan with nonlinear step sizes was crucial in performing accurate laserwire scans in the minimum time possible. In Figure 6, 61 laser positions were used and 20 machine samples were recorded at each location in the vertical scan.

To deconvolve the horizontal scan, the vertical electron beam size must be known and vice versa for the vertical scan. To overcome this circular problem the two

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scans were fitted iteratively together until convergence was reached. The measured horizontal electron beam size was 110.1 ± 3.8 μm and the vertical beam size was 1.16 ± 0.06 μm with the overlap integral model fitting very well to the data.

In previous laserwire operations, a Gaussian model had been used to fit the horizontal laserwire scans. The horizontal scan is a convolution of the laser intensity along its propagation axis with the Gaussian electron distribution and in the case where the Rayleigh range of the laser is significantly less than the electron beam width, which was the initial assumption, the convolution is dominated by the Gaussian electron beam and the fitted sigma will be accurate to < 2 %. The Gaussian model is attractive as it does not depend on the vertical electron beam size, which considerably simplifies the deconvolution of the vertical laserwire scans. A comparison of the two models is shown in Figure 7.

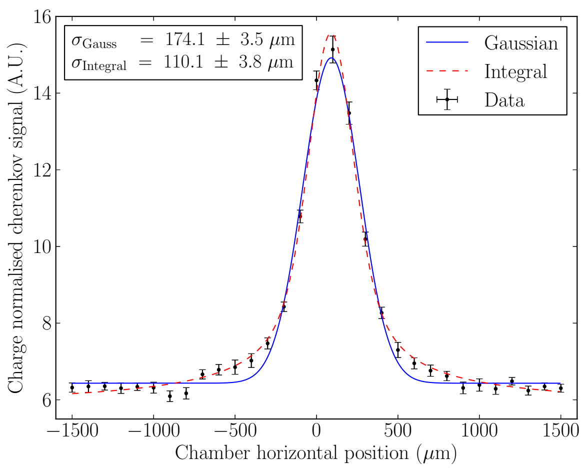

Figure 7: Comparison of different fit models for a horizontal laserwire scan.

The two models agree closely in shape with only a slight difference at the peak and in the wings. However, the size from each differs by $\sim$ 40 %. Deconvolving the vertical scans using an inaccurate horizontal size leads to a similar or greater level of inaccuracy in the extracted size from the vertical scans. Despite the apparent agreement in form, the overlap integral is clearly more accurate and must be used.

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 measuring a very large aspect ratio electron beam has been overcome to accurately measure both the horizontal and vertical dimensions.

In the past a simple Gaussian model had been used for both the horizontal and vertical scans. However, with a large aspect ratio electron beam the vertical scan is non-Gaussian and the overlap integral model must be used. A comparison of the Gaussian and overlap integral models was performed for the horizontal scans showing that despite a very similar shape, the measured size is very different, which in turn has a strong impact on the deconvolution of the vertical scan. Further study of this and other systematic uncertainties is underway.

The detector background level encountered is due to the horizontal defocussing of the electron beam that causes a small fraction of the electron bunch to generate bremsstrahlung radiation as it intercepts the beam pipe after the LWIP. This is a consequence of the necessary strong vertical focussing in this particular experiment and highlights that the background environment is highly important when using a laserwire. Higher background levels reduce the precision of the scan and necessitate higher energy laser pulses to achieve the same statistical precision. As many transverse scans are required to make an emittance measurement, it is desirable that individual scans have a high degree of precision.

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

ACKNOWLEDGMENTS

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