BUNCH LENGTH MEASUREMENTS USING A TRANSVERSE DEFLECTING CAVITY ON VELA

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Abstract

The VELA facility at Daresbury Laboratory in the UK includes a 5 MeV/c 2.5 cell S-band photoinjector gun. This gun operates in the "blow-out" regime with a sub-200 fs length drive laser: the resulting bunch length is determined by space-charge effects. We present measurements made with an S-band transverse deflecting cavity to characterise the bunch length as a function of charge, and as a function of the gun operating phase.

INTRODUCTION

VELA at Daresbury Laboratory [1] contains a 2.5 cell S-band photoinjector gun, originally designed for the ALPHA-X project [2]. This is followed by a suite of beam diagnostics, as well as experimental stations in two separate user areas, in addition to further stations in the core facility, such as electron diffraction. VELA also stands as a technology test bed to lead to the construction of CLARA [3], a future FEL test facility whose first stage is currently under construction [4]. The photoinjector gun is also currently being replaced by a new 1.5 cell gun, designed to allow operation of CLARA up to 400 Hz repetition rate [5], an increase from the 10 Hz limit of the current 2.5 cell gun.

The front end of VELA is shown in Fig. 1. This consists of the photoinjector gun, which delivers bunches up to 250 pC and beam momenta up to 5 MeV/c, driven by a laser with pulse length 180 fs FWHM. The region after the gun is designed to investigate the 6D phasespace of the electron bunches. Transverse emittance can be measured using a series of quadrupole scans [6], and a spectrometer line allows momentum and momentum spread to be measured. The transverse deflecting cavity (TDC) allows the temporal dimension to be investigated. We report on the first bunch length measurements using the TDC on VELA.

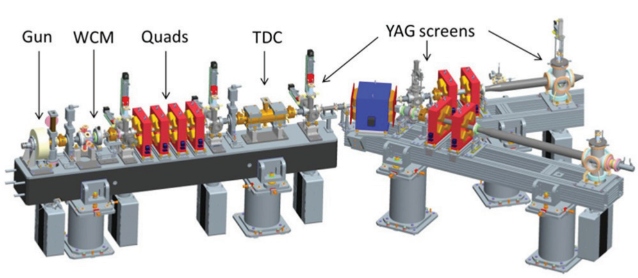

Figure 1: The beam diagnostics section of VELA.

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TRANSVERSE DEFLECTING CAVITY

The transverse deflecting cavity on VELA is a 9-cell, S-band standing-wave cavity, designed in-house in collaboration with Lancaster University [7] and shown in Fig. 2. The TDC, delivered by Research Instruments, Germany, arrived at Daresbury in 2014. RF commissioning was completed and first beam put through the cavity in December 2014. Tests showed that operation was as expected [8]. The cavity is fed by a 6 MW klystron driven by an in-house built modulator. The cavity was kept at a temperature of 57 °C to reach the operating frequency of 2998.5 MHz. Further beamtime with the TDC was not available until mid-2015 due to shutdown of VELA for installation work.

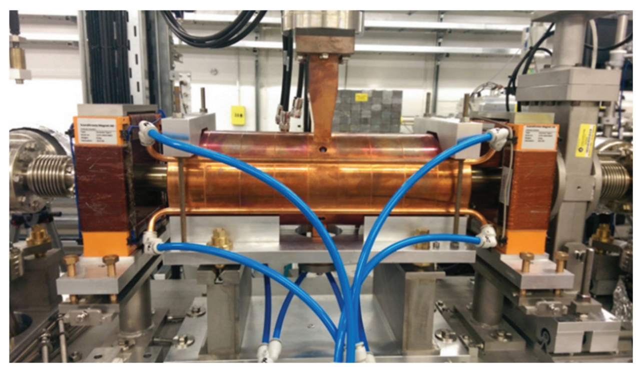

Figure 2: The VELA Transverse Deflecting Cavity.

Over the course of the commissioning there were multiple difficulties with operation of the TDC, in particular, crosstalk between the RF systems of the gun and TDC limited the ability to make measurements to characterise the performance of the TDC.

PROCEDURE FOR BUNCH LENGTH MEASUREMENTS

The TDC gives a vertical kick, *y'*, to the electrons depending on to their longitudinal position, *z*, in the bunch:

$$y' = \frac{\omega}{c}\frac{eV_T}{E}z$$

where V_T is the total transverse voltage of the cavity, ω is the RF angular frequency, and E the electron beam energy. With no quadrupoles turned on between the TDC and the screen, (a distance L downstream of the TDC), the vertical beam size on the screen is given by

$$\sigma_y = \sqrt{\sigma_{y0}^2 + \left(\frac{\omega eV_T L\sigma_z}{cE}\right)^2}$$

where σ_{y0} is the non-deflected vertical beam size.

If V_T, L, and E are kept fixed, altering the phase, φ, of the TDC should deflect the beam vertically on the screen by an amount Δy proportional to $sin(\varphi)$. Varying the phase by small amounts from the "zero-cross" phase and observing the shift in beam position gives a calibration relating the position on a screen image to time at the TDC. For small changes in phase, we can make the approximation $sin(\varphi) \approx \varphi$. Then, the calibration factor

$$\frac{\Delta y}{\Delta\varphi} = \frac{eV_T L}{E}$$

can be measured experimentally, and the bunch length, σ_t, found from:

$$\sigma_t = \frac{\sqrt{\sigma_y^2 - \sigma_{y0}^2}}{\frac{\Delta y}{\Delta\varphi}\omega}$$

With the TDC off, the quadrupoles before the TDC were adjusted to give minimum vertical beam size on the screen. The photoinjector gun is immersed in a solenoid field which leads to an x-y coupling of the beam due to non-zero magnetic field at the cathode. A bucking coil located behind the cathode can be used to cancel this field, and is adjusted to eliminate any tilt of the beam. Fig. 3 shows examples of the beam images with the TDC switched off and on, and Gaussian fits to the vertical projections. The Gaussian fits appear to offer a good characterisation of the beam size, even for non-Gaussian beams.

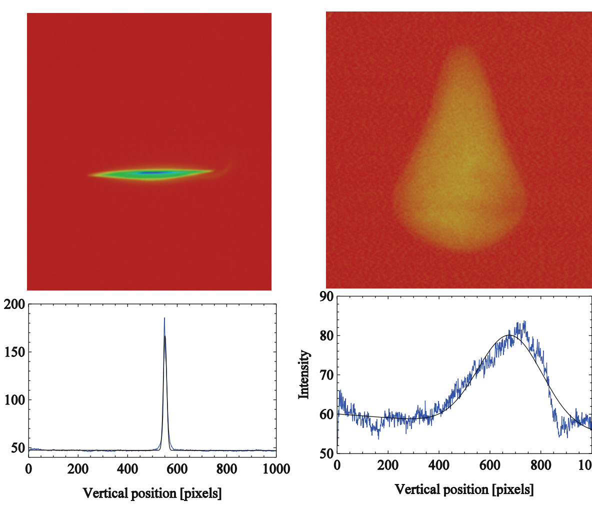

Figure 3: Example images of with the TDC off (left) and and TDC on (right) beams. The lower plots show the vertical projections with Gaussian fits.

To take jitter into account, 100 images were taken at each beamline setting. Gaussian fits were made to the vertical projections. The centroid positions and standard deviations of the Gaussian fits were averaged over the 100 images to obtain an estimate of the beam position and size for the given beamline setting, with error estimates based on the distribution of the Gaussian fit parameters. Images with a centroid position greater than 3 standard deviations away from the mean were removed from the analysis. Examples of the distributions of the Gaussian fit parameters are shown in Fig. 4. Even for large position jitter, the beam size jitter is reasonably small.

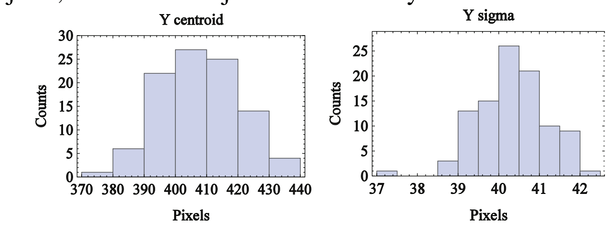

Figure 4: Example distributions of beam centroid and size over 100 shots.

To obtain a measurement of the calibration factor, $\Delta y/\Delta\varphi$, between four and eight different values of the TDC phase were used. An example of a linear fit of beam position to TDC phase is shown in Fig. 5.

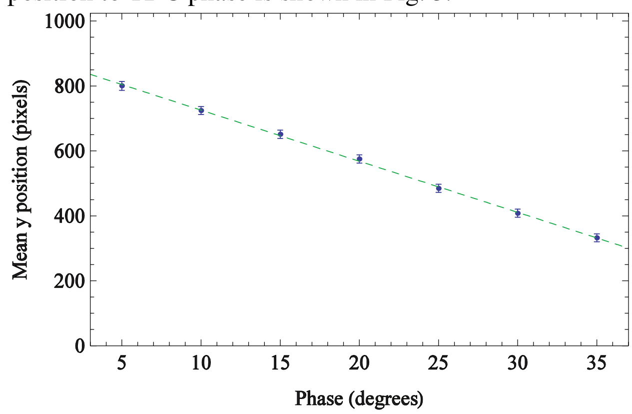

Figure 5: Example phase scan of the TDC. The gradient of a linear fit (dashed line) gives the calibration factor, $\Delta y/\Delta\varphi$.

The bunch length can be calculated using the beam sizes found from the same images collected during the phase scan. An average over the images from all the phases was taken, since (for phases close to the zero-crossing) the vertical beam size on the screen should be independent of the TDC phase.

DEPENDENCE OF BUNCH LENGTH ON BUNCH CHARGE

VELA uses a drive laser with pulse length 180 fs FWHM. In this mode, the beam operates in the so-called "blow-out" regime where space charge forces cause the beam to expand longitudinally directly after being emitted. Measurements were performed to characterise the bunch length as a function of bunch charge.

The VELA gun was set to give a beam momentum of 4.8 MeV/c and operated "on-crest" i.e. at the phase of maximum momentum. The charge was varied from 2 pC to 215 pC and bunch length measurements taken, as detailed above. The bunch charge was measured on a wall current monitor shortly after the gun, with the mean value and standard deviation taken over 100 shots.

The results of the measurements are shown in Fig. 6. The dashed lines show preliminary ASTRA [9] simulations of the bunch length at the centre of the TDC. The transverse laser spot was assumed to have a Gaussian profile, with the size as a free parameter in the simulation. Images of the laser spot were collected from the virtual cathode but the images are highly saturated and show significant substructure, thus an accurate measurement of the photoinjector laser profile cannot be obtained. In the “blow-out” regime, the initial transverse profile of the electron bunch has a strong effect on the longitudinal profile at the exit of the gun.

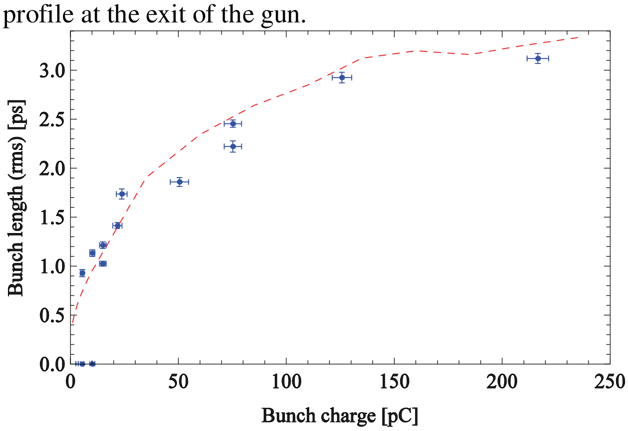

Figure 6: Measured bunch length as a function of bunch charge. The dashed line indicates preliminary simulation results.

Further bunch length measurements were carried out at lower charges, down to 60 fC. Hardware changes were implemented to allow imaging of the low charge beam, primarily done for ultrafast electron diffraction experiments. The beam momentum was significantly lower for these measurements, so cannot be directly compared to the measurements above. Results of bunch length measurements at low charge can be found in [10].

DEPENDENCE OF BUNCH LENGTH ON GUN PHASE

Since the VELA beam has relatively low energy, any energy chirp will lead to velocity bunching/debunching. As space charge leads to a positive chirp, the beam will expand along the VELA beamline. In VELA, the only means of changing the energy chirp is by adjusting the operating phase of the gun.

Measurements were taken with the gun set to a momentum of 4.5 MeV/c “on-crest”. The $\Delta y/\Delta\varphi$ calibration was only performed at the “on-crest” phase, ideally a new calibration would have been made at each gun phase, but this was not done due to time limitations. As the beam momentum changes with gun phase, the transverse kick to the beam from the TDC also changes. To account for this, the beam sizes can be scaled using the known relation between gun phase and momentum (shown in Fig. 7), which has previously been compared to measurements in [11].

The bunch charge can change with the gun phase, because the variation in electric field on the cathode changes the effective work function. To compensate for this, the attenuation of the photoinjector laser was adjusted to keep a constant bunch charge, as measured on the wall current monitor. The phase scan was performed at both 10 pC and 100 pC; with the results shown in Fig. 8. The behaviour seems to be as expected, with positive phases giving a larger energy chirp to the bunch, thus increasing the length. Simulation results are also shown, which indicate a similar trend to the measurements. Again, the initial laser transverse size was used as a free parameter in the simulations, though it was kept the same for the two charge regimes.

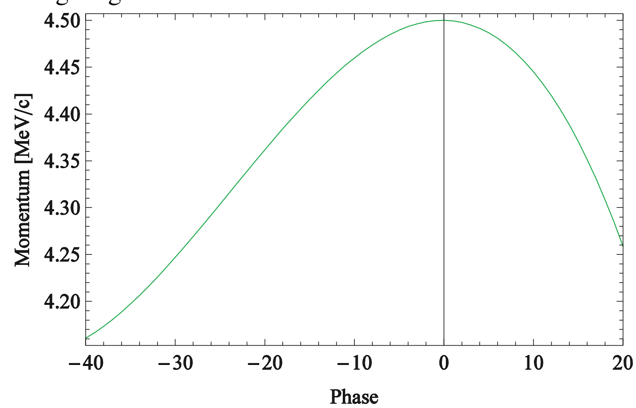

Figure 7: Simulated beam momentum as a function of gun phase.

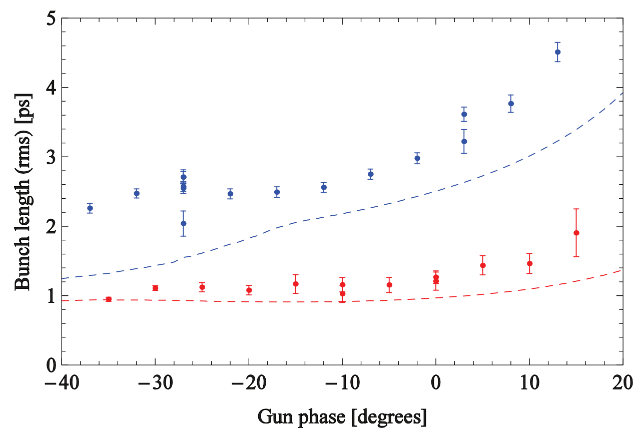

Figure 8: Measured bunch length as a function of gun phase for bunch charges of 100 pC (blue) and 10 pC (red). The dashed lines show preliminary simulations.

SUMMARY AND FURTHER WORK

A transverse deflecting cavity on VELA has been used to characterise the bunch length in the “blow-out” regime. Measurements have been made to determine the dependence of the bunch length on the bunch charge and gun phase. Direct quantitative comparisons with simulations are difficult because of the nature of the “blow-out” regime, in which the bunch length has a strong dependence on the transverse profile of the photoinjector laser, which has not been characterised in detail. The TDC will be used to characterise the behaviour of the new 1.5 cell RF gun when it is installed. Further investigations will combine use of the TDC with the spectrometer line for slice energy spread measurements and for direct observation of longitudinal phase space of a bunch. Further work will also enable transverse slice emittance measurements to be made.

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