VELA MACHINE DEVELOPMENT AND BEAM CHARACTERISATION

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Abstract

Recent developments on the VELA (Versatile Electron Linear Accelerator) RF photo-injector at Daresbury Laboratory are presented. These are three-fold; commissioning/installation, characterising and providing beam to users. Measurements for characterising the dark current (DC), 4-D transverse emittance, lattice functions and photoinjector stability are presented. User beam set ups to provide beam for electron diffraction and Cavity Beam Position Monitor development are summarised.

INTRODUCTION

VELA is a facility designed to provide a high quality electron beam for accelerator systems development, industrial and scientific applications. It comprises of a 2.5 cell S-band photocathode gun with copper photocathode providing beam to experiments in the accelerator hall and 2 dedicated user areas. More information on the layout, design and early commissioning can be found in [1,2].

INSTALLATION & COMMISSIONING

As well as first commissioning of a second user area, Beam Area 2, in preparation for users in May 2015 a number of new devices were installed, including, a copper cathode, gun klystron, and transverse deflecting cavity (TDC).

New Gun Klystron

The RF power to the photo-injector gun is provided by a Thales TH2157 klystron, which is incorporated in a ScandiNova K2 klystron modulator. The modulator consists of a number of parallel solid state IGBT switching modules providing the primary voltage to a pulse step-up transformer which is capable of providing a 250 kV, 150 A flat top pulse of 0.5 – 3 µS at a pulse repetition rate between 1 – 400 Hz, with rate of rise for the pulse of between 150 – 215 kV/µs. The klystron is a 10 MW klystron operating at 2998.5 MHz, the original was a 10 year old klystron provided by Strathclyde University. During the first period of VELA commissioning it was noted that the electron beam momentum was low and did not align well with the measured RF cavity power. An investigation established that; the peak RF power capability was less than 10 MW and not all of the power entering the cavity was accelerating the beam. The new klystron provided an increase in momentum from ~4.9 to ~5.1 MeV/c. The power in the cavity is currently under investigation with further modelling work planned.

Cathode Replacement

The new cathode was diamond polished to a roughness of 100 nm, but this process has resulted in some peripheral diamond inclusions visible under SEM. Although not ideal, this cathode is now being used as the original cathode was not well polished and the effect of machining (i.e. turning) marks could clearly be seen in the downstream beam distribution, e.g. Fig. 1. Also, it was hoped that a smoother polished surface would reduce the DC, as described below.

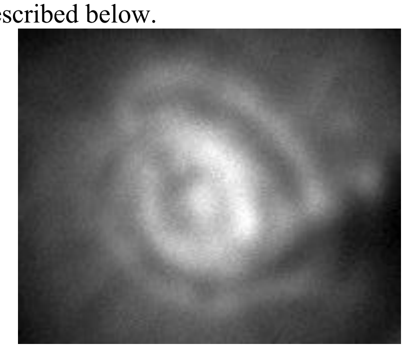

Figure 1: Beam image with rings attributed to machining marks on cathode.

Transverse Deflecting Cavity

The TDC, further explained in [3], is an S-band 9-cell copper cavity operating at 2998.5 MHz designed to provide a transverse kick of ~5 MV. Cold RF test characterisation has been performed and the cavity conditioned to 3.8 MW RF power at a repetition rate of 10 Hz and with a pulse width of 2.5 µs. Only a small number of vacuum events occurred during conditioning. An electron beam was then successfully transported through the TDC and first tests showed the expected behaviour: adjusting the TDC RF phase with constant RF amplitude moved the beam vertically on a downstream screen and increasing the RF gradient for a constant RF phase produced an increased vertical size of the beam image on the screen. Further characterisation of the TDC and electron bunch is planned for later in 2015.

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MACHINE DEVELOPMENT & BEAM CHARACTERISATION

Machine physics studies have concentrated on characterising the transverse 4D emittance, DC and investigating timing and synchronisation stability.

4D Emittance Measurements

Using an analysis technique that includes the effects of coupling and a linear approximation for space charge, quadrupole scan measurements on VELA, explained in more detail here [4], show normalised eigenemittances of order 0.5 µm at 10 pC bunch charge. The eigenmode emittances vary with the bucking coil current in a way that is broadly in line with expectations from a simplified theoretical model, shown in Fig. 2, although there remains some discrepancy between the observed beam sizes and those from the analysis. Further studies in 2015 will look at higher bunch charges, systematic errors and studying the impact of nonlinear and longitudinal effects of space charge.

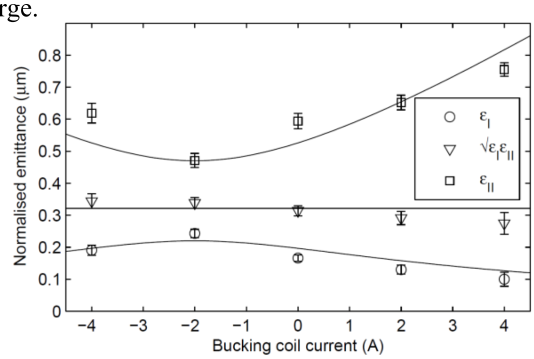

Figure 2: Measured (points) Eigenmode emittance with bucking coil current and theory (lines)

Dark Current Measurements

DC from the VELA gun was measured quantitatively in 2014, when the original cathode from first beam in 2013 [5] was still in place. These measurements used a Wall Current Monitor (WCM) after the gun and indicated that the amount of DC leaving the gun, for fixed gun gradient and RF pulse length, depended heavily on the fields in the main and bucking solenoids. A maximum DC level of over 1 nC per RF pulse was measured at the nominal gun power of 6.5 MW and pulse length of 3 µs. The DC measurements were repeated in 2014 with the new cathode installed, exploring the same parameter space but now including the higher gun RF power. A substantial reduction in DC level was observed in comparison with previous results as illustrated in Fig. 3. The DC measured was of the order of tens of pC, comparable to the measurement noise of the WCM. In fact, due to the now rather poor signal/noise ratio, the dependence of the magnitude of DC on the solenoids was difficult to determine. The DC magnitude as a function of the gun gradient was also measured for a fixed value of the solenoid strengths. At the maximum forward power to the gun from the new klystron, 8.4 MW, a DC of around 400 pC per pulse was measured. The DC can be used to estimate the field enhancement factor of the cathode using the Fowler-Nordheim model of field emission, this, being commonly done for other similar RF electron sources. The procedure in [6] was followed by fitting a straight line to the values of $\mathcal{J}/E^{2.5}$ vs. $10^{-6}/E$ where $\mathcal{J}$ is the average DC in one RF period and E is the gun gradient in MV/m. The data and straight line fit are shown in Fig. 4. From this data a field enhancement factor of β=150 is extracted from the slope, using a value of 4.6 eV for the bulk work function of copper, consistent with the other RF cavity data, as outlined in [6].

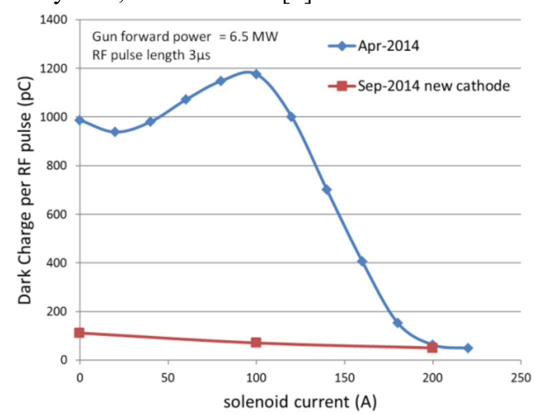

Figure 3: DC measured on WCM-01 with the original (April 2014) and new (Sep 2014) photocathode.

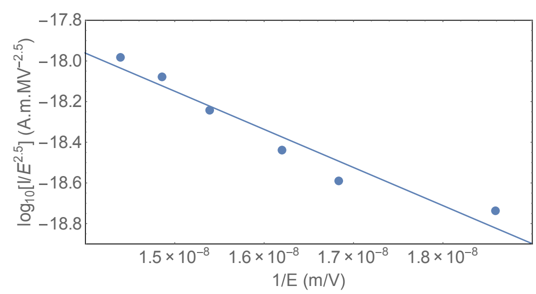

Figure 4: Fowler-Nordheim plot of normalised DC from the VELA gun.

Photoinjector Laser Stability

The VELA photoinjector laser and transport system provides 180 fs FWHM pulses at 266 nm, delivering user-defined pulse energies in the range of approximately 200 nJ to 200 µJ at the cathode for control of bunch charge. High shot-to-shot and long term stability of the laser pulse energy delivered to the cathode is the prerequisite for delivering stable bunch charge from the cathode. The stability of the laser pulse energy at the cathode has been inferred by measuring the intensity of the laser beam image on the virtual cathode screen. Figure 5 presents the results recorded over a six hour period and 300 shots and shows stability within ~1 % over both periods. The same level of stability was measured at the output of the UV generator in the laser room and this shows the transport system does not add additional pulse energy fluctuation to the laser beam. A dedicated research effort is currently underway into the quantification and stabilisation of the VELA distributed timing system. As part of these efforts, measurements into the synchronisation between the photoinjector laser oscillator and RF master oscillator (Coherent: Synchronisation AP, active at 81 MHz) have been performed using phase noise measurement apparatus (Agilent, E5505A). Results indicate phase stability within 400 fs RMS which is consistent with commercial specifications; spurious contributions from cavity power optimisation routines within the photoinjector laser oscillator have been identified to contribute to more than 1 ps jitter when active.

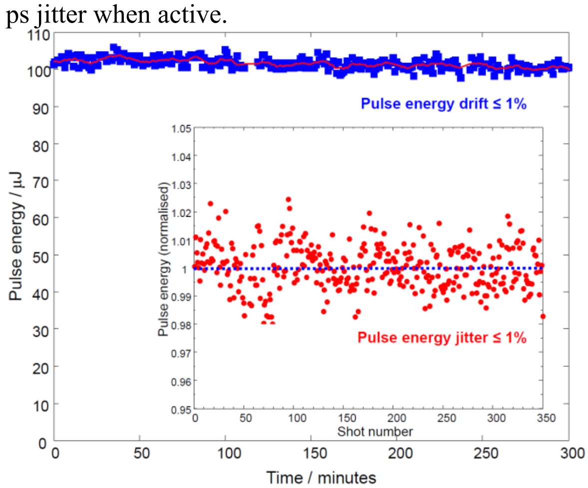

Figure 5: Laser pulse energy variation delivered by the VELA photoinjector laser and transport system to the photocathode, measured over a typical operating period of six hours (main figure, blue; 10 minute average, red) and over 350 shots (at 10 Hz). Both the long and short variation is within 1 % of the pulse energy.

EXPLOITATION

Two user experiments took place, on cavity Beam Position Monitors (BPMs) and the successful proof-of-principal of electron diffraction.

Cavity BPMs

The development of cavity beam position monitors is an industrialisation project between RHUL, FMB-Oxford and Daresbury Laboratory. It aims at making the cavity BPM technology widely accessible to small and middle size accelerator and FEL facilities. Usually, several of these devices are required in undulator sections of FELs or for precision low-charge operation of an accelerator. The development cost of high performance cavity BPMs may be inadequate in a budget of a smaller accelerator, and often the developers settle for a compromise. We are working on providing reliable, easy to operate cavity BPMs that could be adopted for a particular facility. At VELA, we are testing cavities, signal processing, data acquisition and control solutions. The preference in DAQ and control is for open source industry standard environments such as EPICS, and also open source hardware platforms for greater flexibility, maintenance and easy adaptation to a particular environment of a new machine. So far, a motorised cavity BPM test bench has been commissioned at VELA with a 200 pC electron beam and an existing cavity [7]. The VELA test location is ready for taking new cavities, processing electronics and DAQ systems that are currently being bench tested and will be installed in VELA in 2015.

Electron Diffraction

Ultrafast Electron Diffraction (UED) allows the study of dynamic structural changes on the atomic and sub-100 fs scales. Multi-MeV electron diffraction has been carried out on VELA with a setup of typically 4MeV/c electron bunches and $\ll$1pC of charge. A range of single crystal and polycrystalline samples were studied, including gold, platinum and graphite. Only a few 10s of fC of charge were necessary to obtain a clear diffraction pattern with a single electron bunch, an example, from polycrystalline platinum is shown in Fig. 6a. A fitted background was also subtracted and expected positions overlaid onto the image, shown in Fig. 6b. Full details of these experiments are given elsewhere in these proceedings [8].

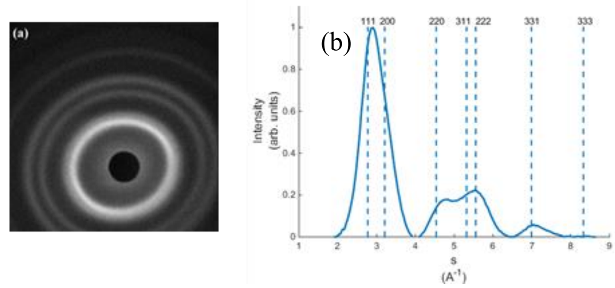

Figure 6: (a) 1000 shot accumulated diffraction pattern of polycrystalline platinum, and (b) Azimuthal integration of polycrystalline platinum diffraction with expected diffraction peaks overlaid as dashed lines.

SUMMARY AND FUTURE PLANS

This past year VELA has been significantly upgraded with a new cathode, gun klystron and TDC installed. The DC has been significantly reduced, attributed to the new cathode. The new klystron has enabled an increase in beam momentum, although further studies are required as the momentum is still lower than expected. Beam characterisation of the full 4D emittance including space charge has demonstrated a sub-micron beam and further studies are planned, complemented with longitudinal studies using the TDC. As well as trying to commission hardware and develop the machine a user exploitation programme is well under way with industrial and academic users. These will increase over the next year, with around 75% of available beam-time being made available, the rest being reserved for machine development.

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