# BEAM CHARACTERISATION AND MACHINE DEVELOPMENT AT VELA

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*Abstract*

An overview is presented of developments on VELA (Versatile Electron Linear Accelerator), an RF photo-injector with two user stations (beam areas BA1, and BA2) at Daresbury Laboratory. Numerous machine development, commissioning, beam characterisation and user experiments have been completed in the past year. A new beamline and a dedicated multi- purpose chamber have been commissioned in BA1 and the first experiments performed. A number of measures have been taken to improve the stability of machine by mitigating problems with a phase drift, laser beam transport drift and a coherent beam oscillation. The 6D phase space of the electron beam has been characterised through quadrupole scans, transverse tomography and with a transverse deflecting cavity.

## INTRODUCTION

VELA is a facility designed to provide a high quality electron beam for the research & development of accelerator systems and for industrial and scientific applications. It comprises a 2.5 cell S-band photocathode gun with copper photocathode providing beam to experiments in the accelerator hall and two user areas. More information on the layout, design and early commissioning can be found in [1, 2, 3, 4]. During 2015 VELA provided beam for ~14 different experiments over 9 different science areas. The experiments were run by collaborations of industrial users, UK academics and STFC staff. Some experiments took place in a new user area in BA1 which received first beam in 2015.

## MACHINE CHARACTERISATION

Machine physics experiments and studies have concentrated on characterising the dark current, electron beam 6D phase-space and beam stability.

### *Momentum and Momentum Spread*

Figure 1 shows a summary of many momentum measurements vs the difference between forward and reflected RF power at the gun cavity, with a line of best fit, systematic effects are attributed to re-calibrating RF power meters on different days. The maximum operating power of the gun klystron is 10 MW, giving a peak operating momentum for VELA of approximately 5.1 MeV/c. More detailed studies looking at ways of increasing the momentum and understanding the limitations of the system are described in [5]. The beam momentum spread at nominal operating beam momentum and RF phase conditions has been estimated at locations close to the two user areas and in the VELA spectrometer line, shown in Fig. 2. The data for BA1 may be due to poor charge transport and will be repeated next run.

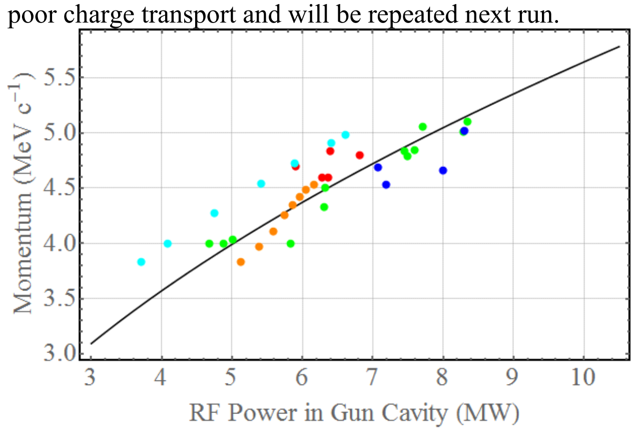


Figure 1: Beam momentum vs RF power, with trend line. Coloured points are different measurement sets.

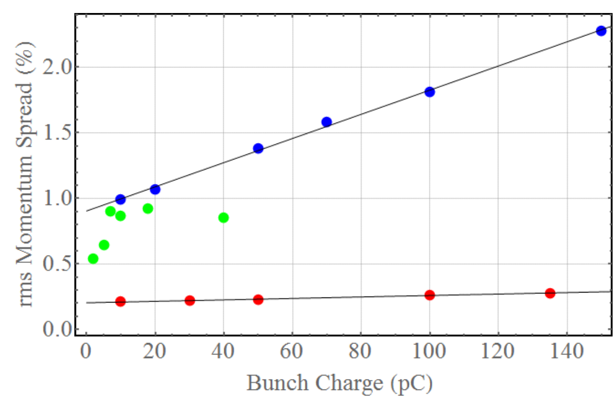


Figure 2: Momentum spread vs charge in spectrometer (red), BA2 (blue) and BA1 (green).

### *Dark Current*

Dark current from the VELA gun (in which a diamond-polished cathode has been installed since mid-2014) has been measured throughout its commissioning and operation [4], and these measurements have shown improved (i.e. lower) levels of dark current over time. New measurements of the dark current indicate another reduction compared to the previous measurements, with a dark current (maximised by solenoid settings) of about 130 pC per 3 µs RF pulse at a gradient of 70 MV/m that gave a beam momentum of ~4.7 MeV/c. The error on this measurement is tens of pC due mostly to the noise on the




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detector. At this level of signal noise, it becomes difficult to determine the effect of the gun solenoids on the dark current. The previous measurement (with the same diamond-polished cathode) gave a maximum value of around 280 pC per pulse for the same settings. The precise origin of the field emitters within the gun/cathode is not understood, but we observe a similar reduction in dark current due to the conditioning effect of continued gun operation which has been observed elsewhere [6].

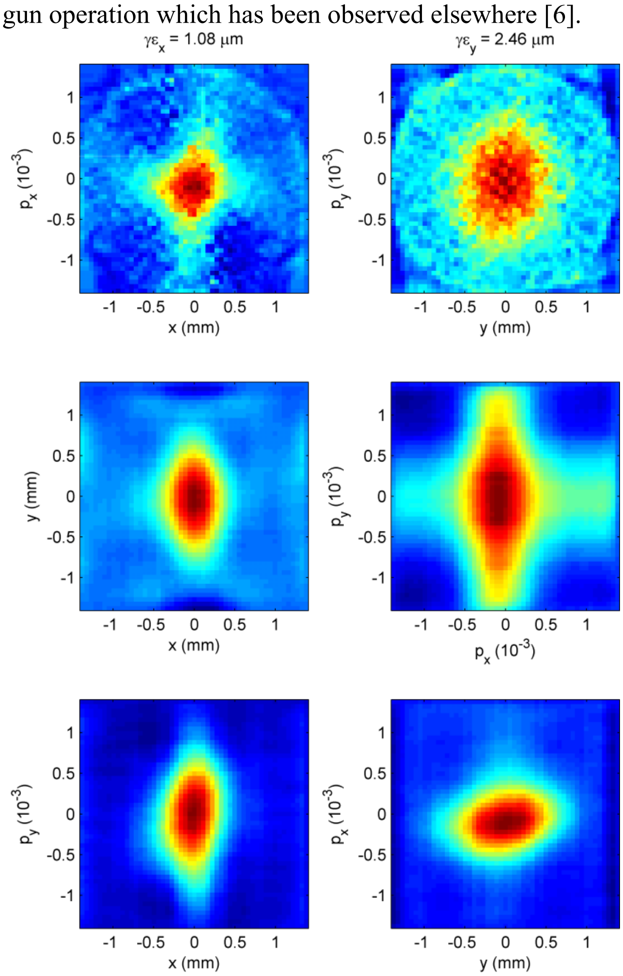


Figure 3: Transverse phase space tomograms.

## *6D Phase Space Characterisation*

Building on work characterising the 4D transverse emittances [7] first results have been obtained from transverse phase space tomography, shown in Fig. 3. The technique that has been used is a first demonstration of beam phase space tomography in two transverse degrees of freedom [8]: the results provide information on the beam distribution in the 4D transverse phase space, taking full account of any coupling between the horizontal and vertical planes. The images in Fig. 3 show projections of the 4D transverse phase space distribution at the position of the first YAG screen, just upstream of a set of four quadrupoles (followed by a second YAG screen) that are used for the tomography measurements. Measurements were made with 4.5 MeV/c beam momentum and 10 pC bunch charge: in this regime, space charge effects are expected to be significant, but not dominant. So far, the tomography analysis is performed without taking space charge into account. Work is in progress to include the effects of space charge: this will allow extending the measurements to higher bunch charges, providing a means to characterise in some detail space charge effects. Although the results are likely to change to some extent when space charge is properly taken into account, the emittances and lattice functions determined from the horizontal and vertical phase space projections are in line with expectations. There is some evidence (for example, from the tilt of the beam distribution projected onto the $p_x$ vs $y$ plane) for coupling in the beam, which may come from imperfect cancellation of the solenoid field on the cathode. The presence of coupling is consistent with independent measurements of the beam tilt as observed on YAG screens at various locations along the beamline. The bunch length and longitudinal phase space has been investigated with a transverse deflecting cavity built in collaboration with Lancaster University [9]. First results show the electron bunch length to be of the picosecond to sub-picosecond scale, depending on bunch charge and consistent with results from simulations [10].

## MACHINE DEVELOPMENTS

Machine developments this year include: first beam and experiments in BA1, beam stability improvements and the development of an application programming interface, (API): the '*Mid-Level Control System*'.

## *A New Multi-Purpose Chamber in Beam Area 1*

A new beam line, as shown in Fig. 4, has been installed and commissioned in BA1. The beam line comprises a multi-purpose chamber providing a flexible space to allow rapid re-configuration of experiments on an optical breadboard inside a large vacuum vessel. The chamber also provides the capability to combine the electron beam with a 20 TW laser. The 20 TW laser can be brought to a focus towards the centre of the experimental chamber using an F/19 off-axis parabola, enabling, amongst other things, the generation of the high fields required for laser-driven particle acceleration. The chamber includes translation stages useful for installing user equipment/diagnostics. A quadrupole doublet located before the chamber allows electron beam focussing at the experimental target location. Two quadrupole doublets located after the chamber allow flexible beam transport through the spectrometer beam line for measurements of momentum and momentum spread of the post-experiment beam. First user experiments were carried out to enable tests of experimental hardware, timing and synchronisation and measurements of some beam parameters. The quality of the space-charge dominated low energy beam transported the long distance (~22 m) from the cathode highlighted issues such as coupling from the gun, which will be investigated in the next run. After the CLARA Front End is commissioned in 2016 [11], higher energy beams will be delivered to BA1. Considering this in addition to the requirements from users on flexibility and knowledge of beam parameters for a wide range of experiments, some modifications to the beam line have been suggested. These will be implemented in the near future.

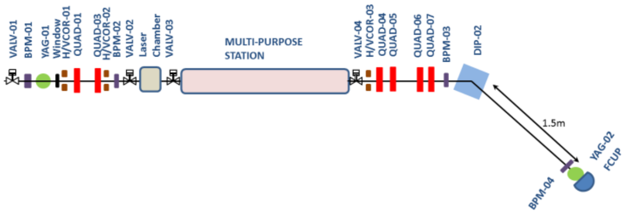


Figure 4: Schematic of beam line in Beam Area1.

### *Stability Improvements*

The position of the laser beam on the cathode, as viewed on a virtual cathode, shows a slow drift, mainly in the vertical direction. An interim solution to this has been implemented using a commercial beam stabilising servo system (Newport GuideStar). This system acts to stabilise the beam path of the HeNe alignment laser that co-propagates with the UV beam, since the system cameras are not sensitive in the UV. Correlation of the UV and HeNe drift has been found to be very good and the system has no problem keeping the mean UV beam position stable (measured on the virtual cathode) to within 300 microns. A similar stabilising system acting directly on the UV beam will be implemented. Estimates of jitter from various sources have been made with simulations and experiments. Simulations have estimated the effect of laser spot jitter and RF amplitude/phase jitter on downstream BPM signals and beam momentum. As an example, Fig. 5 shows the simulated and measured momentum distributions. So far, there is poor agreement between the simulations and the measurements, suggesting there are some significant effects not yet included in the model. Further work may look at incorporating misalignment errors in the simulations and investigating the high momentum tail in the measurements.

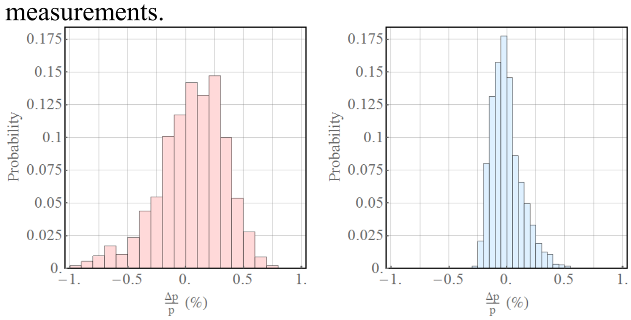


Figure 5: Simulated (left) and measured momentum distribution.

Model independent matrix and statistical analysis methods were used to look for correlations between different signals, including BPMs, RF power, etc. The results are consistent with rms phase and amplitude jitter in the gun RF of ~0.5° and 0.11% respectively [12]. Model-fitting approaches rely on the correctness of the model and are more suitable when the beam dynamics are well understood, the machine is stable, and a reasonably complete and accurate machine model exists. Work is in progress to develop a VELA model that provides a good representation of the observed machine behaviour [13].

A small, but for some experiments significant, coherent beam oscillation has been observed on screens and BPMs. This was removed by synchronising the timing system to the mains electricity supply. Further investigations are planned for future runs to identify the exact source. This will be important for the future running of VELA/CALRA with higher repetition rates up to 400 Hz.

### *Mid-Level Control System*

To facilitate the development of high level software on VELA an API, the *Mid-Level Control System*, has been developed with the aim of providing a simple to use system for the creation of '*any conceivable high level application*,' including operating procedures, beam measurements, data acquisition and monitoring. The API needs to be easily re-configurable and extendable, as VELA/CLARA is being built in phases and hardware is continually being changed and/or added. The API provides an interface to a suite of hardware controllers allowing easy communication with the main types of hardware on VELA controlled and monitored through the EPICS control system: magnets, cameras, RF, BPMs, charge monitors, vacuum gauges etc. Each hardware controller has a set of simple, human readable function names and parameters that completely screen end-users from the intricacies and peculiarities of lower level systems. For example, the magnet controller has a function that knows how to degauss each magnet type on VELA. As well as basic control and data access, standard, routine analysis techniques are also implemented, such as processing camera images to estimate the beam size. The source code is written in c++ (so can easily be included in any c++ application) but, crucially, has also been compiled into Python modules that can be imported into any Python script. This is one of the most promising aspects of this project: Python is a very easy to use scripting language that can be used by novices, but that is also suitable for more complex and advanced applications. Extensibility and re-configurability was achieved by having all offline data, e.g. EPICS process variable names, number and type of magnets, YAG screen and BPM calibrations, etc. read in at run-time from plaintext configuration files. As systems change and new hardware is added, all that needs to be updated is the configuration file with no re-compiling. First prototype applications using the API have, for example, been built to auto-crest RF cavities, take data for 4D emittance and tomography scans and monitor BPM signals. Further developments may include compilation of the source code for other languages, e.g. Matlab, Mathematica, Labview.




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## REFERENCES

[1] J.W. McKenzie *et al.,* MOPFI065, in *Proc. IPAC '13*, Shanghai, China, 2013.

[2] P.A. McIntosh *et al.,* WEPME083, in *Proc. IPAC'14*, Dresden, Germany, 2014.

[3] B.L. Militsyn *et al.,* THPRO052, in *Proc. IPAC'14*, Dresden, Germany, 2014.

[4] D.J. Scott *et al.,* TUPJE056, in *Proc. IPAC'15,* Richmond, USA, 2015.

[5] L. Cowie *et al,* THPOW017, presented at IPAC'16, Busan, Korea, 2016.

[6] L. Monaco *et al.,* WEPLS051, in *Proc. EPAC'06*, Edinburgh, UK, 2006.

[7] B.L. Militsyn *et al.,* MOPWI005, in *Proc. IPAC'15*, Richmond, VA, USA, 2015.

[8] K.M. Hock and A. Wolski, "Tomographic reconstruction of the full 4D transverse phase space", *Nuclear Instruments and Methods in Physics Research A*, vol. 726, pp. 8-16, 2013, http://dx.doi.org/10.1016/j.nima.2013.05.004

[9] A.E. Wheelhouse *et al.,* WEPHA054, in *Proc. IPAC'15,* Richmond, USA, 2015.

[10] J. McKenzie *et al,* MOPMR035, presented at IPAC'16, Busan, Korea, 2016.

[11] J. Clarke *et al.,* MOP011, in *Proc. FEL'15*, Daejeon, Korea, 2015.

[12] J. Jones *et al*., TUPOW027, presented at IPAC'16, Busan, Korea, 2016.

[13] M. Toplis *et al.,* TUPOW028, presented at IPAC'16, Busan, Korea, 2016.