ADVANCEMENTS IN SINGLE-SHOT ELECTRON DIFFRACTION ON VELA AT DARESBURY LABORATORY

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Abstract

Electron diffraction on VELA at Daresbury Laboratory was first demonstrated in 2014. Since then we have studied the machine parameter optimisation for single-shot diffraction patterns from single-crystal gold and silicon samples at bunch charges down to 60 fC. We present bunch length measurements for electron diffraction setups determined with a transverse deflecting cavity. We also discuss the current limitations of VELA for electron diffraction and the improvements to be made.

INTRODUCTION

The making and breaking of chemical bonds occurs on the sub-100 fs timescale. To understand the structural dynamics it is necessary to be able to follow the evolution of structure on this time scale. Ultrafast diffraction, either with X-rays or electrons, is the obvious experimental means of doing this. Both techniques allow a diffraction pattern to be obtained in a single shot, the former using an X-ray FEL on a multi-GeV accelerator and the latter using a much smaller scale multi-MeV electron accelerator. A recent DoE report recommends the provision of high quality accelerators for ultrafast electron diffraction [1].

Electron diffraction on VELA at Daresbury Laboratory was first demonstrated in 2014 [2]. At that time there was no means of measuring the electron bunch length to compare with the modelling of the electron diffraction experiment [3]. In this paper we present the first measurement of low charge bunch lengths using a transverse deflecting cavity (TDC) and discuss how to improve the time resolution for electron diffraction studies on VELA.

VELA

A full description of the electron diffraction system on VELA was given in [3]. A schematic of the system is shown in Fig. 1. A 2.5 cell S-band RF gun produces bunches at 4 MeV/c from a copper photocathode illuminated with a drive laser of pulse length 180 fs FWHM. The gun is operated at -18° from crest to minimise momentum spread. VELA is capable of producing higher momentum beams, but the momentum was deliberately kept low in order to reduce the amount of dark current produced.

Due to constraints imposed by VELA diagnostics requirements for initial commissioning of the accelerator, the sample chamber is located ~8.4 m from the cathode. The space charge expansion of the bunch length during this transport was discussed in [3]. Due to the long transport distance, a total of seven quadrupoles are used to focus the beam through the sample onto the screen, which is located a further 2.8 m from the sample chamber. No focussing is used between the samples and the screen. An insertable Faraday cup is located just before the screen to measure the bunch charge. The noise floor of this device is 60 fC.

The diffraction pattern is detected on a Lanex screen orthogonal to the beam and imaged with an Andor iXon3 image intensifying camera equipped with a fast Samyang 85mm f/1.4 lens. This system is capable of single photon detection. The image on the screen is transferred to the camera using a 45° mirror behind the screen. There is a central 3 mm diameter hole in the screen and mirror to remove the high intensity non-diffracted beam from the image. A second screen without such a hole but mounted on the same stage can be used for imaging the non-diffracted beam. It can also be viewed on a YAG screen downstream from the Lanex screen.

To shape the electron beam on the sample, and to remove unwanted dark current and halo, a series of apertures, ranging from 0.5 – 5.0 mm diameter, are located directly in front of the sample. Both the sample and aperture are on independent 2D transverse translation stages. A carousel allows up to 12 samples to be introduced into the vacuum chamber at once. A YAG screen is also located on the same stage as the samples to directly view the electron beam image as seen by the samples.

VELA features a transverse deflecting cavity (TDC) in order to measure the temporal profile of the electron bunches. The TDC is located approximately 2.8 m downstream of the cathode, the streaked beam being imaged on a YAG screen a further 3 m downstream. The first measurements were carried out in 2015 for bunch charges of tens to hundreds of pC [4]. At the low bunch charges used for electron diffraction experiments, the intensity of light from a YAG screen is too low for the standard VELA cameras to image. Therefore the Andor camera was used to view the post-TDC YAG screen.

MACHINE OPTIMISATION

To optimise the VELA machine setup for electron diffraction, the camera was zoomed in to focus only on a few diffraction spots. Then the shape and size of the diffraction spot and its intensity above the background intensity were used to judge quality of setup.

Simulations, carried out using ASTRA [5], suggest a trade-off between transverse and longitudinal emittance is possible by varying the strength of the magnetic elements along the beamline, particularly that of the solenoid around the gun. Fig. 2 shows that this can have a large effect on momentum spread.

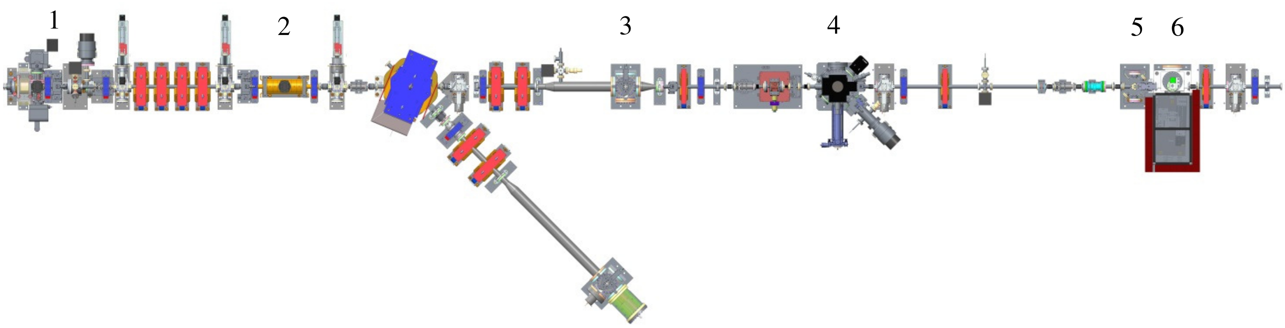

Figure 1: VELA schematic layout, showing: 1. Photoinjector gun, 2. Transverse deflecting cavity, 3. YAG screen used for bunch length measurements, 4. Sample chamber with independent stages for sample and beam shaping apertures, 5. Insertable Faraday cup, 6. Lanex screen used for imaging diffraction patterns.

Momentum spread of the low bunch charges could not be measured on the VELA spectrometer line due to insufficient image intensity for standard VELA cameras. This could be addressed in future by again using the image intensifying Andor camera.

To measure the effect of momentum spread on the size of the diffraction spots, the mean momentum of the electron beam was varied and the change in position of the spots on the screen recorded. This gave a movement of 1 mm per 1 MeV/c net change in momentum. Since the diffraction spots could be optimised to a FWHM of 0.3 mm on the screen for a 60 fC bunch, it was assumed the diffraction spot width was dominated by transverse focusing, not momentum spread. Thus optimisation was solely achieved through transverse focussing.

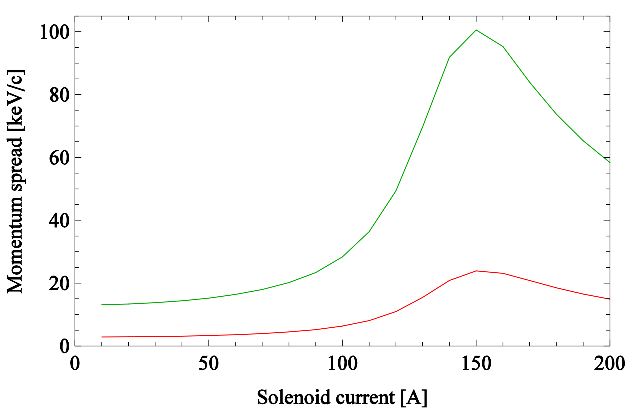

Figure 2: Simulated momentum spread at the sample as a function of solenoid current for a 1 pC beam (rms of distribution in red, full spread in green).

Figure 3 shows a typical diffraction pattern from single crystal gold sample, using a bunch with 600 fC transmitted through a 2 mm aperture. The horizontal streaking is due to CCD readback. Fig. 4 shows a single shot diffraction pattern from a 100 nm thick Si(100) single crystal membrane (Norcada Inc.). Here the beam is apertured to 2 mm diameter immediately in front of the sample. 1.7 pC is transported to the aperture through which only 160 fC is transmitted.

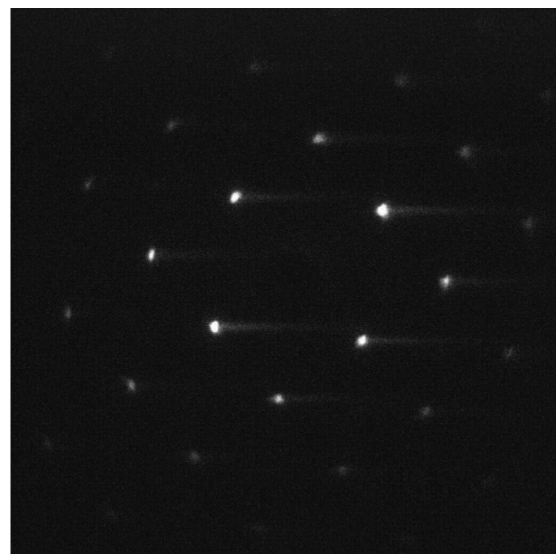

Figure 3: Single shot diffraction pattern from a single crystal Au(100) sample.

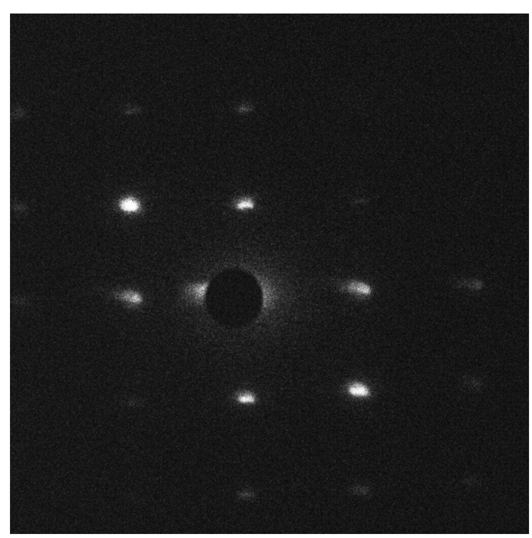

Figure 4: Single shot diffraction pattern from 100 nm thick Si(100).

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BUNCH LENGTH MEASUREMENTS

Bunch length measurements for low bunch charges are shown in Fig. 5. A description of the measurement procedure is given in [4]. The measured bunch lengths at 2.8 m from the cathode are similar to those expected from simulations. This shows that to achieve the shortest bunch lengths it is necessary to operate at the lowest bunch charge which still gives sufficiently good signal to noise in the diffraction pattern. It is thus important not to lose too much charge on the beam shaping apertures. The excess charge that is removed by the aperture does not contribute to the diffraction pattern but does increase the bunch length at the sample.

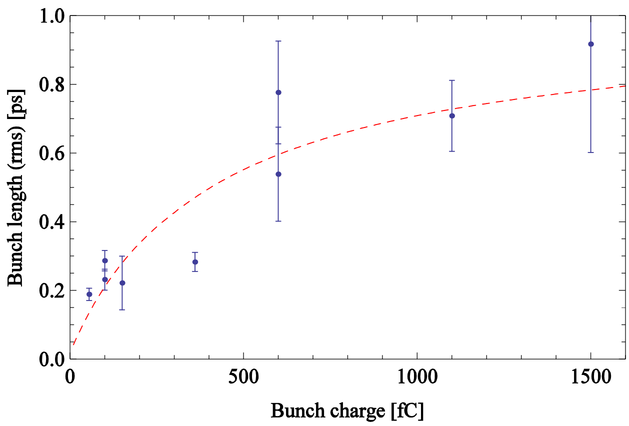

Figure 5: Bunch length measurements, compared to simulations (dotted line).

Due to the non-relativistic nature of the electrons, the bunch will expand a further 2-3 times by the time it reaches the sample chamber, as shown by simulations in Fig. 6. This limits the time resolution available in the current VELA configuration. Options to reduce this bunch length are discussed in the next section.

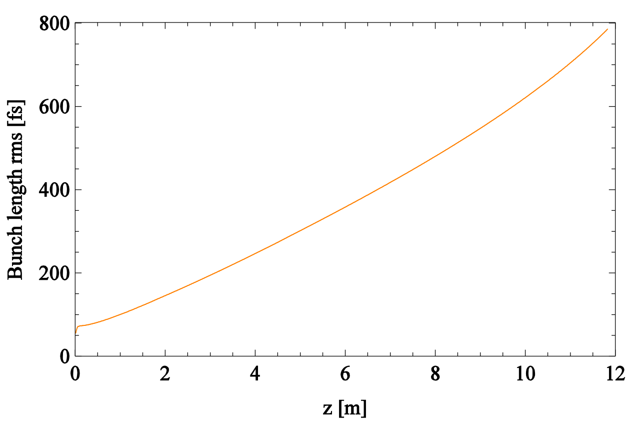

Figure 6: Simulation of bunch length growth over the length of VELA for a 1 pC bunch.

FUTURE DEVELOPMENTS

The completion of programmes to commission VELA and to develop a higher repetition rate gun for CLARA [6] could allow the possibility to reconfigure the layout to optimise for ultrafast electron diffraction. The sample chamber could be positioned at only 1 m from the cathode, thus reducing the bunch lengthening. This would give bunch lengths close to the 180 fs FWHM of the current photoinjector laser pulse to be obtained at the sample.

It is instructive to consider what would happen if the photoinjector laser pulse length could be reduced. The laser beam is transported from air, through a CaF_2 window into the of the vacuum transport line. If the incident pulse is short and therefore spectrally broad, dispersion in the window will substantially lengthen the pulse. Fig. 7 shows the theoretical lengthening of a Gaussian laser pulse after transmission through a 2 mm thick CaF_2 window as a function of the incident pulse length, assuming only dispersion and no non-linear effects. It can be seen that there is little to be gained from going below a 40 fs FWHM incident laser pulse. At this value we can obtain 44 fs at the cathode.

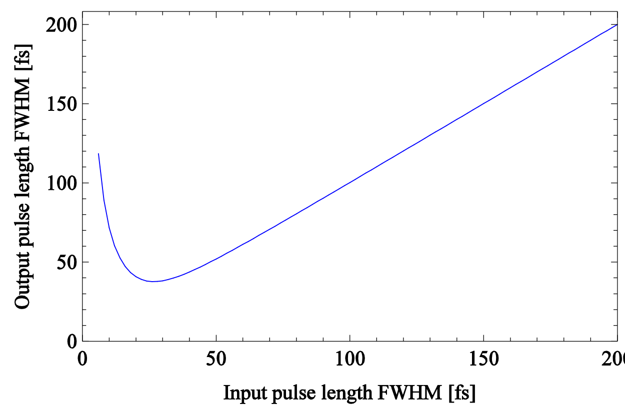

Figure 7: Laser pulse length after transport through 2 mm CaF_2.

The full implementation of the ultrafast electron diffraction facility will also require synchronised time advanced laser pump. A suite of lasers is available at the facility and implementation of laser-to-laser synchronisation forms part of the CLARA research and development programme [7].

With the sample chamber located after the photoinjector gun, but before the transverse deflecting cavity, it will also be possible to use the deflecting cavity to perform single-shot time-resolved electron diffraction. In this mode, a long electron pulse is used, and a slit is used to slice a horizontal portion of the diffraction pattern after the sample chamber. The cut beam is then passed through the transverse deflecting cavity, which imparts a vertical position on the electrons depending on the time it passes through the cavity, as described in [8]. Thus, in a single-shot, one can view the temporal evolution of the diffraction pattern of a sample.

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