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A BEAMLINE DESIGN TO TRANSPORT LASER WAKEFIELD ELECTRONS TO A TRANSVERSE GRADIENT UNDULATOR*

K. A. Dewhurst†[1], H. L. Owen[1], The University of Manchester, Manchester, UK
B. D. Muratori[1], STFC Daresbury Laboratory and ASTeC, Daresbury, UK
E. Brunetti[1], D. A. Jaroszynski[1], S. M. Wiggins[1]
The University of Strathclyde and SUPA, Glasgow, UK
[1]also at The Cockcroft Institute, Daresbury, UK

Abstract

The Cockcroft Beamline is to be installed at the Scottish Centre for the Application of Plasma-based Accelerators (SCAPA). The beamline is designed to transport 1 GeV electrons from a laser wakefield acceleration (LWFA) source to a pair of transverse gradient undulators. The project aims to produce X-ray undulator radiation in the first phase and free-electron laser (FEL) radiation in the second phase. The total beamline will be less than 23 m long, thus the Cockcroft Beamline has the potential to be the UK's first compact X-ray FEL. Here we present the main features of the beamline design.

INTRODUCTION

Laser wakefield acceleration (LWFA) uses high accelerating gradients set up in a plasma, around 10-100 GV/m, to generate and accelerate electron bunches. Therefore they can allow high energy accelerators to be designed on a significantly smaller scale than using RF cavities, with some hope of working toward table-top devices [1].

The electron bunches produced by LWFA have promising characteristics for application to FEL radiation production [2], including high energy (GeV) electrons, short (fs) bunch lengths, and small (<10 µm) transverse spot size at the plasma exit. However, LWFA bunches are often highly divergent with significant energy spread. The divergence causes the transverse size to increase quickly and the energy spread leads to chromatic effects which make beam transport difficult. Work on improving these bunch parameters by adjusting the laser-plasma interaction is currently being researched by other groups [3]. In our design we focus on how to ameliorate these bunch properties using beam transport techniques. We present an initial design for the Cockcroft Beamline transport line at SCAPA, to potentially provide the UK's first LWFA FEL accelerator.

SCAPA FACILITY

The SCAPA facility is located at the University of Strathclyde, Glasgow in a purpose-built extension to the physics building. The first floor houses three laser labs including the 350 TW laser system which will drive the wakefields for the Cockcroft Beamline. The beamline will be located in experiment Bunker A on the floor below. Table 1 shows the properties of the driver laser. Laser light is directed through the ceiling and into a vacuum chamber containing the plasma interaction point, suitable for both gas jet and gas channel experiments.

Table 1: Ti:Sapphire Laser Properties

Peak power	350 TW
Central wavelength	800 nm
Energy per pulse (after compression)	8.75 J
FWHM pulse duration	25 fs
Pulse repetition rate	5 Hz

The first three vacuum chambers containing laser optics tables and the plasma interaction point are already on-site. The LWFA electrons will be transported to two 1.5 m transverse gradient undulators, originally designed for the ALPHA-X experiment [4, 5]. After allowing enough room for detectors and the undulators, there is up to 13.9 m available for beam transport.

LWFA ELECTRON BUNCHES

Until the beamline is installed and the first measurements can be taken, we rely on particle-in-cell (PIC) simulations to predict the expected electron bunch distributions. Using the PIC software FBPIC [6] and varying laser and plasma parameters, we find that most bunches comprise of three sections longitudinally; first a large energy-spread "head" of the bunch, followed by a fairly mono-energetic middle section and in some cases a final chirped low-energy "tail". A typical simulated LWFA bunch is shown in Figs. 1 and 2 with these three parts labelled; the corresponding bunch properties are listed in Table 2.

INITIAL FOCUSING

Quadrupole Set Up

The divergent electron bunch requires strong focusing as close to the plasma exit as possible. For the Cockcroft Beamline the first focusing magnets would ideally be located within the same vacuum chamber as the plasma-interaction point. These quadrupoles need to be compact, vacuum compatible and to have a high gradient magnetic field up to 100 T/m. For these reasons we have chosen permanent mag-

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† kay.dewhurst@cockcroft.ac.uk

Table 2: Simulated LWFA Electron Bunch Properties

Central energy	1.060 GeV
Horizontal normalised emittance	5.73 μm
Vertical normalised emittance	0.446 μm
RMS energy spread	13 %
Absolute bunch length	6.7 μm (22 fs)
Bunch charge	770 pC
RMS horizontal beam size	0.925 μm
RMS vertical beam size	0.208 μm

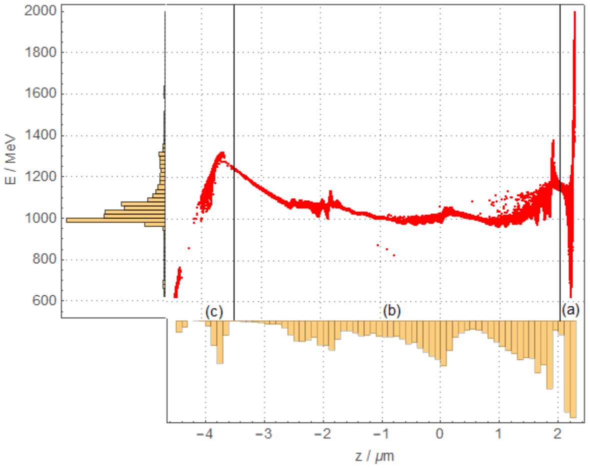

Figure 1: The longitudinal profile of a simulated LWFA electron bunch. The characteristic sections are labelled; (a) large energy spread head section, (b) mono-energetic middle, (c) low-energy chirped tail. The histogram on each axis shows the charge distribution. Most of the 770 pC charge is concentrated about the mean energy 1.060 GeV.

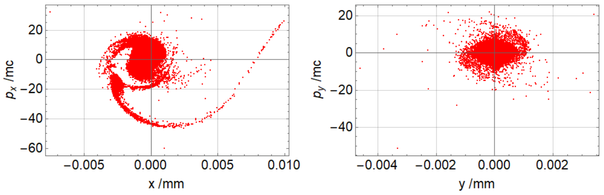

Figure 2: The transverse phase spaces of the LWFA electron bunch shown in Fig. 1; for both x (left) and y (right) planes.

net quadrupoles (PMQs), which have been used successfully for LWFA electron bunch focusing at other facilities [7, 8].

Adjustment of the initial focusing will be necessary when calibrating the machine; this is usually achieved by moving the quadrupoles longitudinally. However, this will not be possible in our case due to the short length of the vacuum chamber. Instead we propose the use of adjustable PMQs such as the QUAPEVA [9] or ZEPTO [10] magnet designs. These have mechanical adjustments to rotate or wind in and out magnetic material from the pole pieces, and so the field strength can be varied without altering the aperture size. The beamline at COXINEL makes similar use of a QUAPEVA triplet for the initial focusing of their lower-energy bunches [11].

Simulations carried out using MAD8 show that at least three quadrupoles are required to control the divergence. Two adjustable PMQs can be mounted inside the vacuum chamber with a separation of 100 mm: with this constraint it is more feasible to use a set of four quadrupoles for initial focusing. The second quadrupole pair only requires half the field strength (50 T/m) and will be located outside of the vacuum chamber, without the associated size limit. Therefore the initial focusing section will comprise two adjustable PMQs and two electromagnetic quadrupoles.

Particle Tracking

The electron bunch shown in Figs. 1 and 2 was tracked through the initial focusing section using the particle tracking code ASTRA [12]. Figure 3 shows the variation of the β-function in this region, with the growth due to divergence overcome, in both planes, on or before the fourth quadrupole.

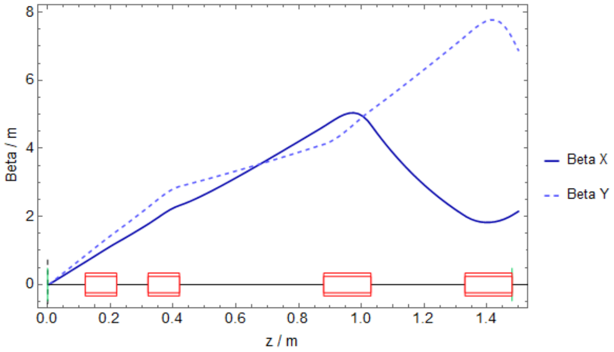

Figure 3: Variation of the Twiss parameter β through the initial focusing section. The red boxes depict the positions and lengths of the four quadrupoles.

The bunch profiles after tracking through this section are shown in Figs. 4 and 5, with the bunch properties listed in Table 3. There is no change in the energy of the particles as there are no accelerating or decelerating mechanisms present. However, we observe significant increases in the transverse beam size, absolute bunch length and normalised emittance.

The increase in beam size is due to the large initial divergence. The absolute bunch length has increased due to low-energy particles travelling slower compared to the high-energy particles and particles on the bunch edge having a longer path length compared to those in the centre. The emittance growth is the result of a chromatic effect due to the large energy spread. Different energy regions of the bunch rotate by different amounts in transverse phase space during transport; this increases the total area occupied by the bunch in phase space and therefore the projected emittance [13]. The normalised emittance in the first 1.48 m of beamline increases by a factor of 1000. If this were to continue along the rest of the 13.9 m transport section the bunch would no longer be suitable for matching to the undulators.

The use of sextupoles to correct some chromatic effects is currently being explored. However, as the expected bunch

Table 3: Bunch Properties After Initial Focusing

Central energy	1.060 GeV
Horizontal normalised emittance	8640 µm
Vertical normalised emittance	417 µm
RMS energy spread	13 %
Absolute bunch length	436 µm (1.5 ps)
Bunch charge	770 pC
RMS horizontal beam size	3020 µm
RMS vertical beam size	1210 µm

charge is high compared to other LWFA sources, an effective way of improving these parameters would be to remove unwanted particles from the bunch. The histograms in Fig. 4 show most (88% or 680 pC) of the charge is located in the first 40 µm of the bunch. Selecting for this core region would be a feasible option to improve the bunch properties before the first undulator.

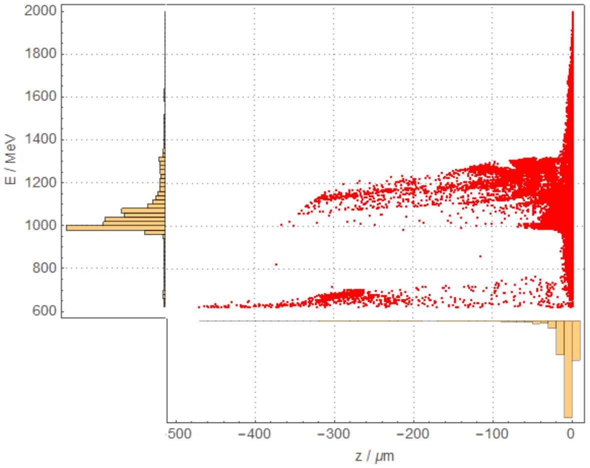

Figure 4: The longitudinal profile after tracking through the first four quadrupoles. The histogram on each axis shows the charge distribution. Most of the charge is concentrated about the mean energy and in the leading 40 µm (130 fs).

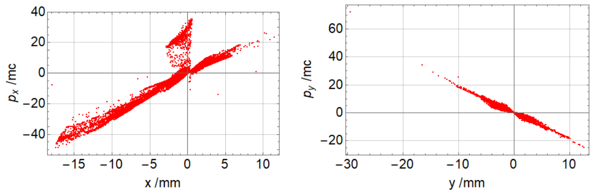

Figure 5: The transverse phase spaces of the electron bunch shown in Fig. 4; for both x (left) and y (right) planes.

DOGLEG SECTION

The initial focusing section will be followed by a shallow angled (0.75 degree) dipole pair: the dogleg. This bending section will separate any remaining driver laser light from the path of the electrons, thus preventing this light from influencing radiation production in the undulators.

The dipoles will also introduce a small dispersion to the beam. In areas of higher dispersion, different energy particles will travel along different trajectories. Here, collimators will be inserted to remove the highest and lowest energy particles, reducing the energy spread and decreasing chromatic effects such as emittance growth. Areas of dispersion are also required if sextupoles are to be incorporated into the design.

Additionally, the dipoles can be used to introduce a small amount of dispersion in the following, final part of the beamline: the undulator matching section. The plan for this final section is to use four electromagnetic quadrupoles to match the beam to the undulators. The undulators are transverse gradient and so require the incoming beam to be transversely dispersed. The group working at KIT use the same technique (a dogleg to introduce dispersion) for matching to their transverse gradient undulator [8]. The complete layout of our proposed beamline is shown in Fig. 6.

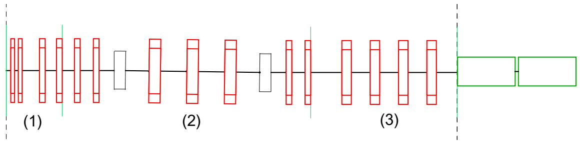

Figure 6: The layout of the Cockcroft Beamline, with sections (1) inital focussing, (2) dogleg, (3) undulator matching.

FURTHER WORK

The project is currently in the planning stage. So far the focus has been on the first section of the beamline and achieving good capture of a bunch from the plasma. Next we will consider the inclusion of sextupoles and collimators in the dogleg section, and how these components will be incorporated into the current design. Investigations will also be carried out on matching to the transverse gradient undulators, as this is key to producing high intensity radiation.

CONCLUSION

The Cockcroft Beamline at SCAPA will produce LWFA electron bunches with energies around 1 GeV. The current beamline design includes initial focusing quadrupoles, a dogleg and a matching section for two transverse gradient undulators. Work so far has focused on the initial capture of the bunch, where we propose to use two adjustable PMQs and two electromagnetic quadrupoles. Simulations in ASTRA have demonstrated that this arrangement will transport the whole bunch along the first 1.48 m of beamline, and bring the initially high divergence under control. Work will continue on designing the dogleg section to improve the bunch parameters. Chromatic effects of the large energy spread may be compensated by introducing sextupoles and collimators. Finally, more work needs to be done to complete the design stage and properly match the beamline to the undulators in order to produce the desired undulator and FEL radiation.

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