ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPGW070

DESIGN OF THE COCKCROFT BEAMLINE: ADJUSTABLE TRANSPORT OF LASER WAKEFIELD ELECTRONS TO AN UNDULATOR*

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Abstract

The Cockcroft Beamline is being designed to transport 1 GeV electrons from a laser wakefield accelerator (LWFA) to an undulator at the Scottish Centre for the Application of Plasma-based Accelerators (SCAPA) in Glasgow, UK. To demonstrate undulator radiation in the X-ray spectral region and potentially free electron laser (FEL) gain, electrons should be transported between the LWFA and the undulators with high fidelity. In this paper we present the design of an adjustable beam line to transport LWFA electrons to the undulator for a range of energies, from 0.5 GeV to 1 GeV, while preserving the electron beam properties and matching the undulator-beam coupling.

THE SCAPA FACILITY

The SCAPA facility [1] at the University of Strathclyde, Glasgow is a research facility focused on the development and application of laser plasma accelerators. Experimental areas on the ground floor are driven by high intensity laser systems located on the floor above. The Cockcroft Beamline in Bunker A will be driven by the facility's 350 TW Ti:sapphire laser with a repetition rate of 5 Hz [1]. Laser light is directed into a vacuum chamber and then focused onto a gas target to produce high energy electrons from a laser wakefield accelerator (LWFA) [2]. The optics layout sets the position of the LWFA electron source to be 0.5 m from the end of the vacuum chamber. This space is reserved for in-vacuum electron beam focusing components. Phase A of the beam line design enables transport of 0.5 GeV to 1.0 GeV electrons from the LWFA, to a pair of planar undulators to generate 2 nm to 10 nm XUV radiation.

LASER WAKEFIELD BUNCHES

Laser wakefield acceleration utilises plasma to produce extremely large electric fields that can accelerate particles with much higher accelerating gradients (over 100 GV/m) than the maximum possible in RF cavities (100 MV/m). Plasma is already broken down and therefore is not limited by breakdown that occurs on RF cavity surfaces [3]. The properties of LWFA bunches make them promising drivers of synchrotron sources [4] and free electron lasers (FELs) [5]: LWFAs can produce high energy (GeV), high peak current (kA), low emittance (<1 µm) [6] and femtosecond duration electron bunches [7] at the plasma exit [8]. However, they are also characterised by relatively large (mrad) divergence and sub % energy spreads, making the bunches challenging to transport and utilise. However, the beam should have a smaller divergence and emittance at 1 GeV, which would reduce bunch lengthening. Many groups are currently working on improving the beam properties of LWFA electron bunches [9].

Phase A of the beam line design is for demonstrating transport of LWFA electrons with current bunch parameters [8]. The initial bunch produced at the plasma exit is modelled as a cylinder with transverse Gaussian profile and properties shown in Table 1. Two representative sample bunches, with Lorentz factor (γ) of 1000 and 2000, are used to demonstrate the flexibility of the beam transport.

Table 1: Initial Bunch Parameters

Lorentz factor (γ)	1000	2000
Central energy	0.51 GeV	1.02 GeV
Energy spread	0.1 %	0.1 %
Bunch length (r.m.s.)	1.2 µm (4 fs)	1.2 µm (4 fs)
Total bunch charge	20 pC	20 pC
Norm. emittance	1 µm	1 µm
Bunch radius	0.5 µm	0.5 µm

BEAM LINE DESIGN

Focusing the Beam

Strong focusing is required near the plasma exit to collimate the divergent beam. We propose using a high gradient 250 T/m permanent quadrupole magnet (PMQ) triplet. The PMQs alternate in polarity, have an aperture radius of 3 mm and lengths of 5 cm, 10 cm and 5 cm, respectively. The first magnet is located 5 cm from the plasma exit and the whole triplet fits within the vacuum chamber. Each PMQ is placed on a separate translator inside the chamber so that their relative longitudinal position can be adjusted (as shown in Fig. 1). This telescopic movement allows focussing to be tuned to the beam energy. The remainder of the beam line consists

* Work supported by U.K. STFC (Grant No. ST/G008248/1), EuPRAXIA (Grant No. 653782), ECs LASERLAB-EUROPE (Grant No. 654148), U.K. EPSRC (Grant No. EP/J018171/1, EP/J500094/1 and EP/N028694/1).
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ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPGW070

of four electromagnetic quadrupole magnets (EMQs), each with an aperture radius of 25 mm and length 25 cm, to match the beam into the undulator section.

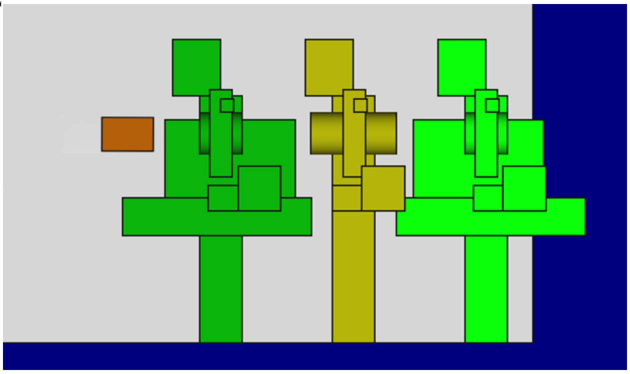

Figure 1: Schematic of the PMQ triplet inside the vacuum chamber. Each magnet is mounted on a separate translation stage (PMQ1: dark green, PMQ2: brown, PMQ3: light green) downstream of the LWFA electron source (red).

Adjustable Transport

The particle tracking code GPT [10, 11] has been used to model the beam line. GPT's inbuilt optimiser allows the ideal positions for the three PMQs to be found for each energy case; within the spatial constraints of the vacuum chamber. Further optimisation has been carried out to establish the natural positions of the four EMQs, so that their positions can be fixed for all energy settings. A solution is found that allows the magnetic strength of each EMQ to be within a conservative maximum of 15 T/m. Combined, this allows for fully adjustable transport in the expected LWFA bunch energy range of 0.5 GeV to 1 GeV; by adjusting only the positions of the PMQs and the strengths of the EMQs.

Particle Tracking

The two bunches, with parameters given in Table 1, are tracked through a matched beam line set up using GPT. The properties of each bunch after transport are shown in Table 2. Space charge effects are included in the tracking, but do not significantly change the output bunch properties. No particles are lost during transport, but the beam size, emittance and bunch length increase.

Table 2: Post-Transport Bunch Parameters at the Undulator Entrance

Lorentz factor (γ)	1000	2000
Central energy	0.51 GeV	1.02 GeV
Energy spread	0.1 %,	0.1 %
Bunch length (rms)	10.4 µm (35 fs)	3.9 µm (13 fs)
Total bunch charge	20 pC	20 pC
Norm. emittance (x,y)	6.8, 10.9 µm	1.8, 4.8 µm
Beam size (rms) (x,y)	342, 105 µm	118, 188 µm

Bunch length growth occurs due to the relatively large initial divergence. This is caused by outer, more divergent particles having longer path lengths through the quadrupoles, compared with central particles. The emittance growth is due to the energy spread: different energy segments of the bunch rotate by different amounts in phase space, thus increasing the total phase space area occupied by the bunch [12].

Figure 2 shows the phase space particle distributions for the 0.5 GeV bunch at the entrance to the undulator. The 0.1 % energy spread bunch is shown in red, behind this in black is the result of tracking a similar bunch with 1.0 % energy spread to demonstrate the effect of energy spread on the emittance growth. Figure 3 shows the equivalent plots for the 1.0 GeV bunch. The effect of energy spread on emittance (area in phase space) can be seen by the difference in area between the red and black regions. The emittance values for the black particles in Figs. 2 and 3 are around 8 times larger than those for the 0.1% energy spread bunches.

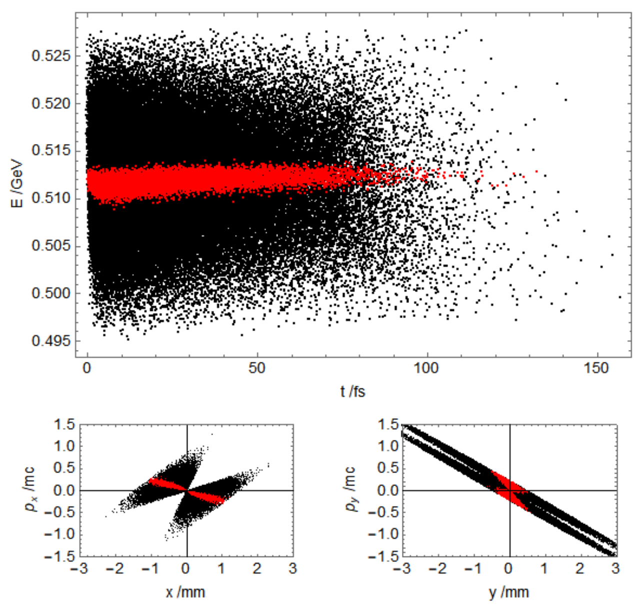

Figure 2: Phase-space plots for the 0.5 GeV electron bunch at the undulator entrance. Red: Results for the 0.1 % energy spread bunch. Black: An equivalent bunch with a larger (1 %) energy spread to demonstrate the resultant emittance growth.

RADIATION PRODUCTION

A pair of 1.5 m planar undulators, which are part of the ALPHA-X project [13], will be used for radiation studies using the beam line. The K-values of the undulators are individually adjustable; for these simulations we chose to use the maximum value of $K = 1$. The parameters for a single undulator section are listed in Table 3.

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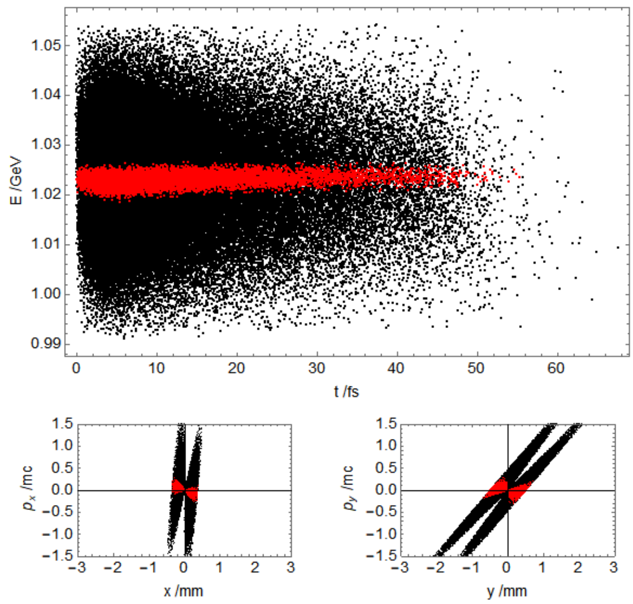

Figure 3: Phase-space plots for the 1.0 GeV electron bunch at the undulator entrance. Red: Results for the 0.1 % energy spread bunch. Black: An equivalent bunch with a larger (1 %) energy spread to demonstrate the resultant emittance growth.

Table 3: Undulator Parameters [14]

Number of periods	100
Period length (λ_u)	15 mm
Operating gap	3.5 mm
K-value (K)	1

The expected radiation wavelength (λ_r) produced on-axis by an undulator can be calculated using

$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right). \tag{1}$$

Hence, we expect 11.25 nm radiation for the 0.5 GeV bunch and 2.81 nm for the 1.0 GeV bunch; both in the XUV spectral region. A 1.0 GeV beam produces radiation in the water window region of the spectrum, and therefore would be suited to biological imaging applications [15].

The radiation production in the ALPHA-X undulators has been modelled using GENESIS1.3 [16] version 4 [17]. The particle distributions from the GPT simulations are used as input bunches for GENESIS1.3. Version 4 of the code is chosen as the distribution contains many off-energy particles, and this version allows such particles to move between slices in the bunch as it propagates. The pair of 1.5 m undulators are modelled as a single 3 m long planar undulator. Time-dependent simulations are carried out to take account of the short (fs) bunch lengths involved.

Figure 4 shows the radiation pulse profile produced by the 1.0 GeV bunch at the undulator exit. Short pulses (fs) with high numbers of photons per pulse (10^6) are obtained from every simulation. Our simulations successfully demonstrate

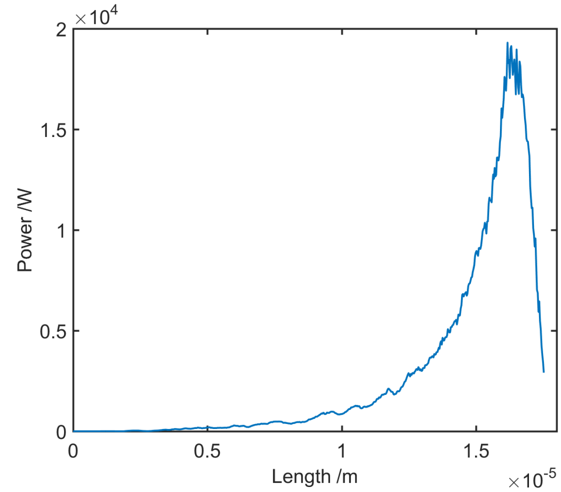

Figure 4: Radiation pulse produced at the fundamental wavelength (2.81 nm) for the 1.0 GeV electron bunch at the undulator exit. The peak power is 19.3 kW, with pulse length FWHM 1.9 µm (6 fs), and 1.73 × 10^6 photons per pulse.

the production of soft X-ray, short pulse, undulator radiation from a LWFA electron source in less than 10 m of beam line. Short pulses are produced (23 fs and 6 fs for the 0.5 GeV and 1.0 GeV cases respectively) with a high number of photons per pulse (1.06 × 10^6 to 1.73 × 10^6) at a repetition rate of up to 5 Hz. This is consistent with previous measurements undertaken using the undulators on the ALPHA-X project using 130 MeV beams [8, 18] and compares favourably with production from femtoslicing synchrotron radiation which has higher repetition rate (kHz), but can only produce 100 fs bunch lengths with around 1000 photons per pulse [19] from a large scale accelerator in comparison to our small scale beam line.

SUMMARY

We have presented the Phase A design for the Cockcroft Beamline at SCAPA. The design consists of three permanent magnet quadrupoles with adjustable longitudinal position, and four electromagnetic quadrupoles with adjustable strength. The beam line is capable of transporting LWFA electrons from the source, over 6.4 m, to a pair of 1.5 m planar undulators for energies in the range 0.5 GeV to 1.0 GeV. Simulations suggest that the current design is capable of producing high power XUV undulator radiation in femtosecond pulses that could be used for biological imaging experiments. This first Phase of the beam line builds on work carried out on the ALPHA-X project and is a stepping stone toward demonstrating FEL gain at SCAPA.

Data associated with this paper is available at: doi:10.15129/489a22a0-f2c5-45af-9380-7ce84db8af19.

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