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DESIGN OF AN ELECTRON ENERGY SPECTROMETER AND ENERGY SELECTOR FOR LASER-PLASMA DRIVEN BEAMS AT EPAC

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Abstract

The Extreme Photonics Applications Centre (EPAC) is a new national facility currently under construction at the Rutherford Appleton Laboratory, UK. EPAC is designed to enable a wide variety of user experiments with a state-of-the-art petawatt-class laser system. It is anticipated that early experiments will include laser-plasma acceleration of electrons to energies ranging from 100 MeV to 5 GeV or higher, with later experiments using these electrons as a beam once stable generation is achieved. EPAC is designed to be flexible, allowing users to select the relevant central electron energy for their experiment. To achieve this goal EPAC and the Accelerator Science and Technology Centre (ASTeC) at STFC Daresbury Laboratory have developed a beamline design to capture laser-plasma driven electrons with broad energy spread, measure their energy spectrum, perform selection of specific energies if necessary, and deliver these electrons to a user interaction point. We present here the conceptual design of the proposed spectrometer and energy selection system.

INTRODUCTION

The EPAC project will include a 1 PW laser operating at 10 Hz which will be used for a variety of experiments involving matter in extreme conditions. It is intended that by focusing this laser through a gas target, a Laser Wake Field Accelerator (LWFA) will be created that will generate bunches of electrons with energies ranging from 100 MeV to 5 GeV or higher depending on the parameters of the laser pulse used. The first experiments will focus on understanding and optimising this novel technique of accelerating particles, and experiments later in the facility life cycle will demonstrate the usefulness of such a beam for a wide variety of experimental purposes.

To facilitate this a beamline has been designed to capture, analyse and use the created electron bunches. Facilities based on LWFA technology are still in their early stages and so it is anticipated that electron bunches may initially be produced with significant energy spreads as much as ±10 %, accompanied by a long low-energy “tail”. Energy spreads as small as 1 % should be achievable at EPAC after sufficient beam commissioning, a value in line with other facilities [1–3]. To facilitate a range of user experiments the central electron energy of the EPAC beam can be varied. A baseline design energy of 1 GeV is specified; however, the beamline is adaptable over a range of at least 0.1 GeV to 5 GeV.

Measurement of the central energy and energy spread is a key requirement of any experimental work, as is the ability to spatially separate electrons of the desired energy from the other off-momentum particles. This will be achieved by a magnetic dogleg that can act as an electron energy spectrometer, by generating dispersion that will also allow energy selection of particles. The dogleg is preceded by an array of Permanent Magnet Quadrupoles (PMQs) to capture the beam [4], and an Electromagnetic Quadrupole (EMQ) array to condition the beam beta function into the spectrometer.

CONCEPT OVERVIEW

We present a double-dipole design similar to one recently proposed for SCAPA [5]. A pair of opposing-polarity dipole magnets spread electrons into parallel final trajectories and onto a detector which sits after the second magnet; the detector consists of a scintillator for broadband energy measurement and a YAG screen for precision measurements. The dipole fields are chosen such that the trajectory of the central energy is displaced downwards by 120 mm. A concept diagram is shown in Fig. 1.

The EMQ array (a triplet for a 1 GeV beam, or a sextuplet for 5 GeV) is essential to achieve useful resolution; LWFA sources are typically highly divergent and the beam beta functions must be minimised to ensure that beam spread on the detector is dispersion-dominated rather than divergence-dominated. Without EMQs, the central energy may be measured but the beam spread would prevent a spectrum measurement. The dipole width is set at 190 mm for acceptance of energies above 70 % of the central energy, and electrons below that value will be lost to the beam dumps in the floor. Selection of energies is achieved by increasing or decreasing the field strength. Widening the magnets to transmit energies below 70 % of the central energy would not be useful, since those electrons are expected to be few, and very likely to be collimated away by the PMQ and EMQ apertures. The EMQs will be accompanied by a pair of horizontal and vertical corrector magnets.

The layout of the EPAC experimental area requires that that final beam be parallel to the source trajectory; this is the motivation for a double-dipole design as opposed to the more single dipole. Such a layout allows both spectrometry and energy selection, to convert broadband beams

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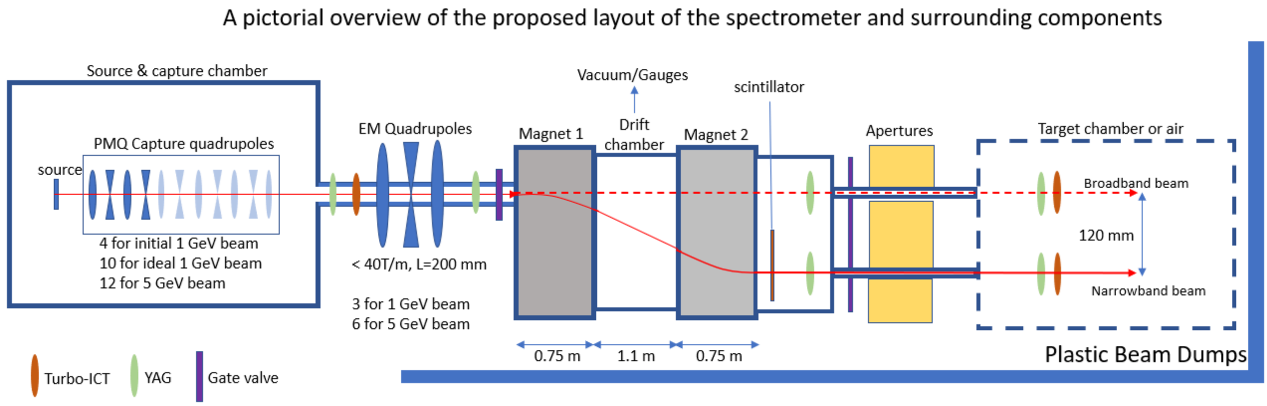

Figure 1: Overview of the basic layout of the proposed energy spectrometer chicane and energy selector, showing the spectrometer concept, energy selection, and proposed surrounding components. (Dimensions not to scale.)

into near-monochromatic beams by passing the dispersed beam through an aperture; the spectrometer forms part of a longer beamline to allow some experiments downstream of it that require electron bunches with small energy spread. A potential updgrade may involve two further dipoles of reversed polarity to give a 4-dipole chicane that cancels the beam dispersion and provisions R_{56} (albeit with limited variability) [1]. Such chicanes have been used, for example, in Free-Electron Laser (FEL) experiments using LWFA beams.

DIPOLE MAGNET DESIGN

The magnetic design of the dipole magnets, and ray tracing of particles, were performed using OPERA [6]. The magnets are iron-dominated vertical C-dipoles, each 750 mm long with 1.1 m separation. The strength is 1.41 T when used with 5 GeV beam and 282 mT with 1 GeV. The yoke is modelled as AISI grade 1006 low-carbon steel using an Industeel XC06 BH curve. Coils either side of the magnet gap provide the flux, here water-cooled with 64 turns and each split into two pancakes that are powered in series but cooled in parallel. Operating currents are up to 246 A, and the magnetic efficiency at 1.41 T is ≥ 90%.

As C-dipoles with parallel faces naturally develop a quadrupole component when operating near saturation, asymmetric shimming is used to maintain homogeneity at all operating currents. A small error remains due to the finite permeability; this is managed using faceted roll-offs on the transverse and longitudinal edges of the gap that approximate the idealised Rogowski curve. The predicted magnet homogeneity at each operating energy are shown in Fig. 2. Poor homogeneity can give rise to an angular deflection of the electorn beam and jeopardising the ability to perform energy selection. To capture the full desired range of electron energies, the width of the good-field region is specified as ±95 mm above and below the magnet axis. The effective magnetic length is 775 mm.

The C-core yoke has the added benefit that the dipoles can be used to dump beams up to 10 GeV, by reversing the polarity of the second dipole such that electrons are directed through the open side of the yoke into the floor dumps.

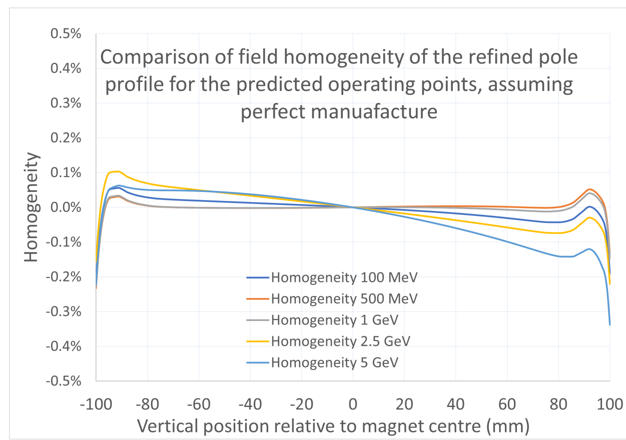

Figure 2: Transverse field homogeneity ($\Delta B/B_0$) for a magnet made from type XC06 steel, at the correct flux densities needed for the beam energies shown.

ENERGY MEASUREMENT

To achieve the target displacement of 120 mm, approximately 282 mT is required here per GeV of electron energy. This relationship is linear with flux density, but is slightly non-linear with current due to saturation. The calibration of energy vs. position is well defined and can be measured in a single shot. Crucially, provided the central energy is offset to 120 mm displacement, the spread above and below that central position (in percentage terms) is independent of the operating point. This is shown in Figs. 3 and 4.

PROPAGATION AND SELECTION

Propagation of a realistic LWFA beam (generated by FBPIC [7] simulations with central energy 1 GeV) has been performed through the spectrometer with an array of 4 Halbach quadrupoles [4] and 3 electromagnetic quadrupoles; the quadrupole apertures are 40 mm and 8 mm diameter for

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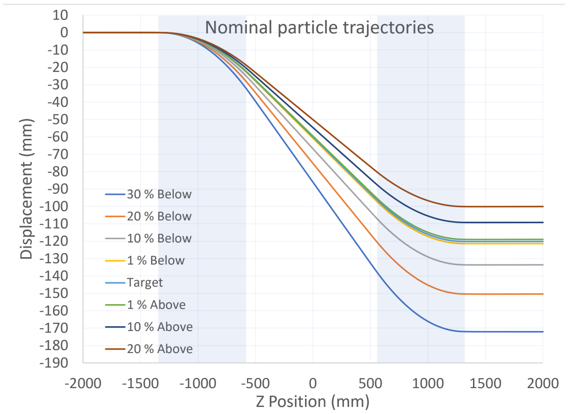

Figure 3: Simulated electron trajectories through the dipoles (shaded) showing the relation between electrons of the target energy and electrons of certain percentages above and below the target, assuming the field is chosen such that the central energy is displaced by 120 mm.

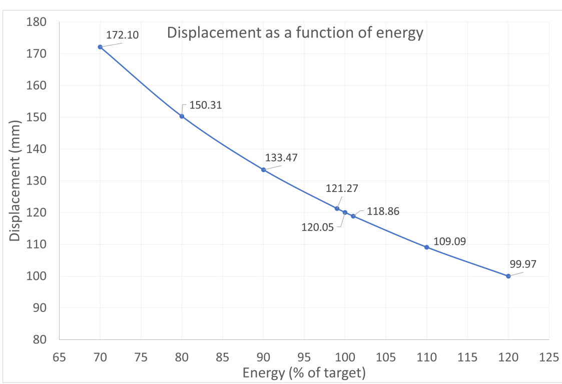

Figure 4: Relation between energy and displacement of electrons, assuming the correct field settings are employed for the target energy.

the EMQs and PMQs respectively. Propagation is shown in Fig. 5; this beam has an on-energy core and a low-energy tail as shown in Fig. 6. Nearly all the beam core propagates to the screen (99.9 % transmission), as shown by the dashed lines in Fig. 5. However, a large fraction of the low-energy tail (which may be of interest when benchmarking) is lost on the quadrupole apertures (solid line in Fig. 5) with a total transmission around 76 % of this example 108 pC bunch. The dipoles are designed to be wide enough to accept any electrons in the low-energy tail that do propagate. The EMQs are realistic, operating below 40 T/m at 200 mm length.

Energy selection has been simulated using a 15 × 2 mm vertical slit placed after the last spectrometer dipole. Shown in Fig. 6, "blue" electrons in the low-energy tail have a high chance of being lost in the quadrupole arrays, whereas the "red" electrons in the core are transmitted. After passing though the slit a highly monochromated beam (green) remains, with an expected bunch charge of 18 pC and an RMS energy spread of 0.4 %.

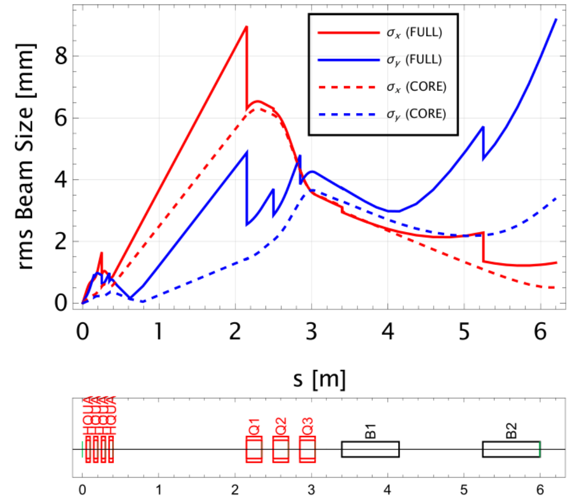

Figure 5: RMS beam sizes for a realistic 1 GeV beam generated from an FBPIC simulation, as shown in Fig. 6. Discontinuities in beam size correspond to locations of beam loss.

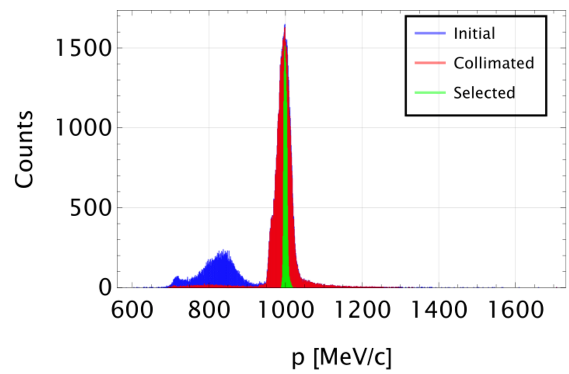

Figure 6: Expected FBPIC generated energy spectrum of a 1 GeV beam, with a core (higher energy on the right) and a low-energy tail (at lower energy).

CONCLUSION

A spectrometer beamline has been designed for the EPAC facility that will allow single-shot measurements of the energy spectra of LWFA-driven electron beams with central energies up to a 1 GeV baseline, extending to 5 GeV with additional quadrupoles. This beamline has the additional benefit of acting as an energy selection device, allowing broadband beams to be monochromated for user experiments.

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