THE EPAC ELECTRON TRANSPORT BEAMLINE - PHYSICS CONSIDERATIONS AND DESIGN

B.D. Muratori*, A.R. Bainbridge, J. Crone, J.K. Jones, H.L. Owen, T.H. Pacey,
UKRI-STFC Daresbury Laboratory and Cockcroft Institute, UK
D. Symes, N. Bourgeois, Central Laser Facility, Rutherford Appleton Laboratory, UK

Abstract

The Extreme Photonics Application Centre (EPAC) is a planned UK national facility, intended to use a 1 PW, 1 Hz laser system to drive laser-plasma acceleration with output energies ranging from 100 MeV up to at least 5 GeV. A design is presented in this paper for the capture and transport of the initially very divergent plasma-source electrons. We propose a unique, modular beam capture optics based on a FODO channel of Halbach permanent-magnet quadrupoles, which flexibly allows different-energy electron bunches to be captured and conditioned for experimental use. We show an engineering concept for the beamline that incorporates diagnostics and drive laser removal, and describe the effect of field errors and misalignments and their mitigation.

A MODULAR BEAMLINE

The Extreme Photonics Applications Centre (EPAC) is an ultra-short pulse (fs-scale), petawatt laser facility under construction at Rutherford Appleton Laboratory Site in the UK. LWFA electron bunches are foreseen to be generated with central energies varying from 100 MeV to 5 GeV or higher; the naturally-divergent bunches must be captured and conditioned for a range of experimental users.

Both laser-wakefield (LWFA) and plasma wakefield acceleration (PWFA) have seen substantial progress recently (as have other novel acceleration techniques). However, there has to date been less consideration of subsequent beam transport required to condition the bunches exiting such schemes (see for example [1, 2]). Beam conditioning of LWFA bunches is challenging due to the initial inherently large divergence and energy spread of such source; this makes capture difficult for electron energies above 1 GeV. Indicative Twiss parameters from a source might be $\beta_x = \beta_y = 5$ mm, together with a normalised emittance of around $\epsilon_N = 1\,\mu$m at the exit of the plasma, an energy spread perhaps $< \pm 25\%$ and a generated charge perhaps up to 1 nC.

To allow the flexible capture of a range of bunch central energies, we propose a modular capture system based on permanent-magnet quadrupoles (PMQs). PMQs of small aperture can be placed quite close to a plasma source, and can achieve the very high gradients needed [3–8]; however, above 1 GeV even small-aperture Halbach triplets will struggle to capture an LWFA bunch, and so we propose to use a FODO array that interleaves horizontal and vertical focusing [9]. An example is shown in Fig 1, where a FODO array of 500-T/m Halbach quads (with 10 cm drift space) are used to progressively capture a 1 GeV LWFA bunch (with properties given above). A doublet or triplet is unable to do that on its own. Using a FODO capture array allows a large energy bandwidth to be transmitted (albeit with different focal lengths); by varying the number of quadrupoles - whilst keeping them all the same strength- one can re-configure a capture beamline for different central energies or to produce a focal spot at different distances from the LWFA source.

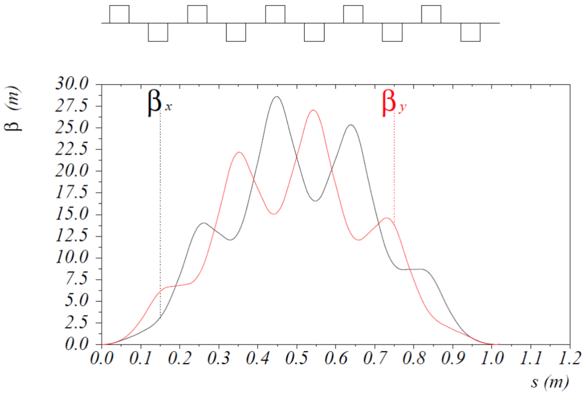

Figure 1: Beta functions, corresponding to a beam size of 120 μm, of an example high-acceptance beamline for a 1 GeV LWFA beam with initial parameters as given in the text. Here, the initial source is assumed to be formed at a beam waist. The FODO array progressively captures the divergent electron bunch over several FODO pairs and brings the central-energy electrons back to a focal spot approximately 1 m from the source.

As well as varying the number of quadrupoles in a FODO array formed of fixed-strength Halbach PMQs, one can also rotate individual PMQs to reconfigure F-quads to D-quads (or vice-versa) and to lesser effect the quadrupole separation can be varied. Several examples of this are shown in [9] where the same 500 T/m Halbach magnets are used to focus a 5 GeV bunch with equivalent parameters to the 1 GeV case. The same line, without rotating any magnets, would otherwise have been considerably longer and have attained a larger maximum beam size.

PMQ ARRAY ERROR ANALYSIS

Error analysis studies have been performed for both 1 and 5 GeV PMQ capture cases. Error studies were performed using the Elegant [10] tracking code using individual quadrupole offsets sampled from a Gaussian distribution of errors. Here, we consider misalignments of the PMQs in

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[*] bruno.muratori@stfc.ac.uk

each plane (x, y and z), roll, and fractional strength error (FSE), and initial beam misalignments and parameter variations. The Halbach PMQ design is discussed elsewhere [11], and is expected to achieve a magnet centre accuracy around 20 μm. Using an analysis over 100 error seed lattices, we have determined that transverse misalignments and FSE are the largest error sources. We envisage a transverse misalignment budget of 50 μm (based on previous magnet construction and survey experience) and a PMQ FSE of 1%; to achieve the latter, we utilise a novel 3-bit PMQ gradient tuning to overcome the accuracy limitations of conventional PMQs [11].

Indicative beam distributions at 1 and 5 GeV were generated using FBPIC [12] simulations of the EPAC LWFA source, which as would be expected predict a highly non-Gaussian beam with a large on-energy core of particles, a low-energy and a high-energy tail; an example is shown in Fig. 2. It is thought unfeasible to design an optical system that may transmit the entire beam, due to chromatic effects; however, it is possible to form a reasonably-small focal spot that encompasses as much as 10 % of the energy spread but as much as 80 % of the beam particles.

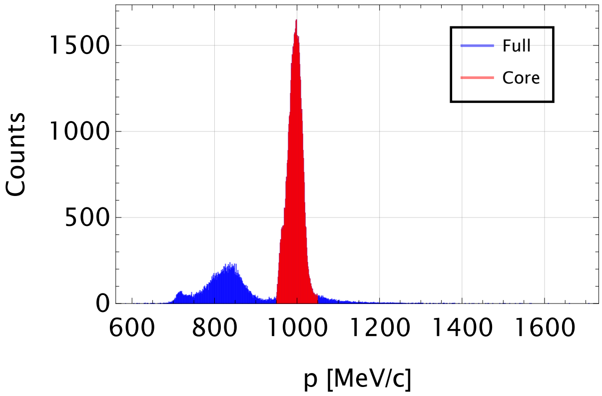

Figure 2: Energy distribution of the EPAC 1 GeV beam with the full distribution (blue) and 'on-energy' core (red).

To assess the beam aperture required through the PMQs and other equipment, we use a beam stay clear (BSC) defined as

$\text{BSC} = 2\Delta u_{95\%} + 2\sigma_{\text{u},95\%}$ where $u = x|y$, $\Delta u_{95\%}$ is the 95% quantiles of the electron trajectories, and $\sigma_{\text{u},95\%}$ is the rms beam size; a factor of 2 margin is applied. The BSC for the 1 GeV PMQ array is shown in Fig. 3. The BSC value can be defined as the maximum value of the BSC function (combined contributions) $\text{BSC}_{\text{CC}} = 2.92$ mm or by using the maximum value of the beam size and trajectory offset (independent contributions) $\text{BSC}_{\text{IC}} = 3.93$ mm. We may then set the PMQ radial aperture to be 4 mm, which is compatible with achieving a 500 T/m gradient [11].

The 5 GeV PMQ array was analysed similarly. At 5 GeV the BSC values are $\text{BSC}_{\text{CC}} = 2.74$ mm and $\text{BSC}_{\text{IC}} = 2.92$ mm.

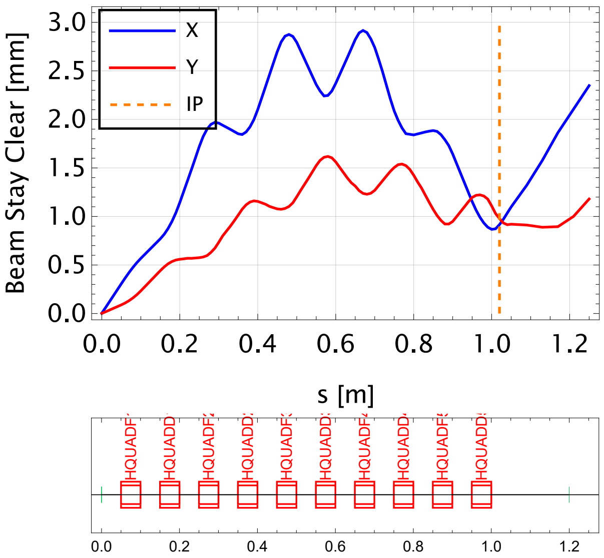

Figure 3: Beam stay clear as a function of distance in both planes for the 1 GeV PMQ array. IP position (orange) at ~ 1 m.

ENGINEERING LAYOUT AND DIAGNOSTICS

Our engineering concept is to provide a modular mounting and adjustment system for the PMQs in groups; a first group of PMQs is currently being manufactured. Each 4-quadrupole plate (2 FODOs) allows quadrupoles to be mounted as either F- or D-quads, and to be transversely adjusted (manually). Fiducial plates provide alignment references to the measured magnetic centres. An example modular plate is shown in Fig. 5; several plates may combine more FODOs to accommodate increasing electron central energies. Longitudinally there is inherently a limited adjustment, but there is sufficient space (around 45 mm) between any two quadrupoles that allows two important components to be inserted: a roller-driven tape target that acts as a plasma mirror to reflect and remove the waste LWFA laser light; insertable diagnostic screens that are mounted on a separate adjustment rail. These are both illustrated in Fig. 6.

EXTENSION OF THE BEAMLINE

Initial experiments will utilise a short PMQ array to capture the c.1 GeV electron bunches and focus them within the main plasma source chamber. However, many later experiments will require conditioned electron bunches with perhaps smaller electron energy spread and also larger energy. A longer beamline is envisaged as shown schematically in Fig. 4

Extension of the beamline beyond the initial vacuum chamber is required to tailor the electron beam to experimental requirements and for proper characterisation of the electron beam because full diagnostics (spectrometer etc.) cannot be contained within the PMQ array which cannot be tuned. The extended beamline uses a series of electromag-

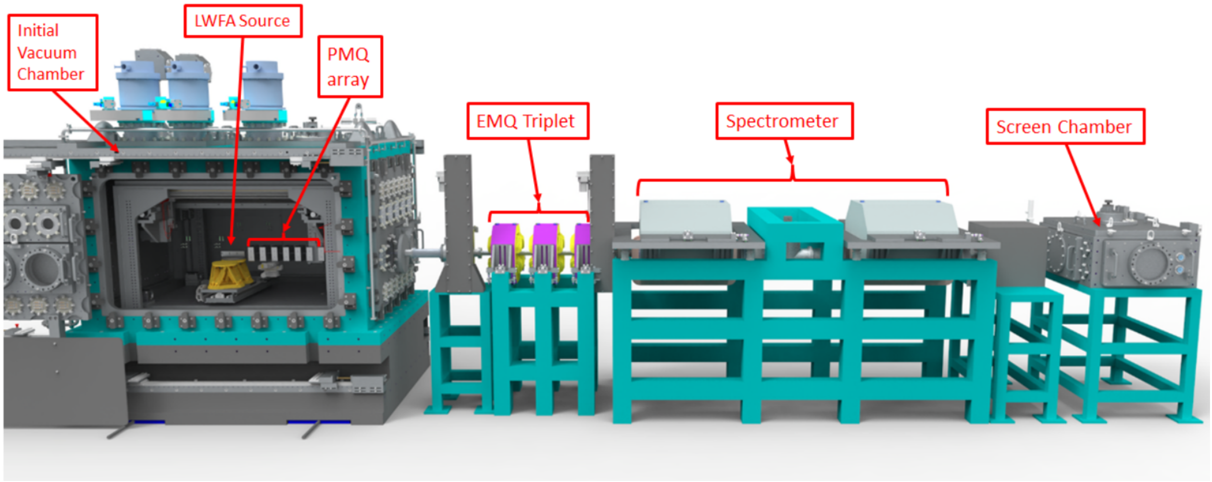

Figure 4: Schematic of the full, extended EPAC beamline in the 1 GeV configuration. Use of a downstream conventional EMQ triplet can tailor the electron beam for spectrometry and/or energy selection within a double-dipole spectrometer [13].

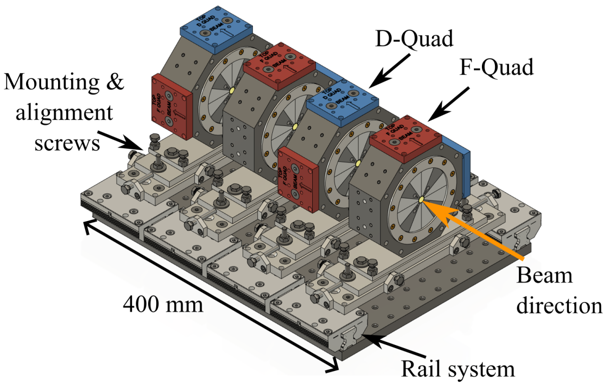

Figure 5: Engineering concept of modular PMQ FODO array and mounting plate. Fiducial plates (in red and blue, and on two sides of each quadrupole) provide references to the quadrupole magnetic centres. The mounting plates allow in principle other optical configurations such as triplet or asymmetric arrangements.

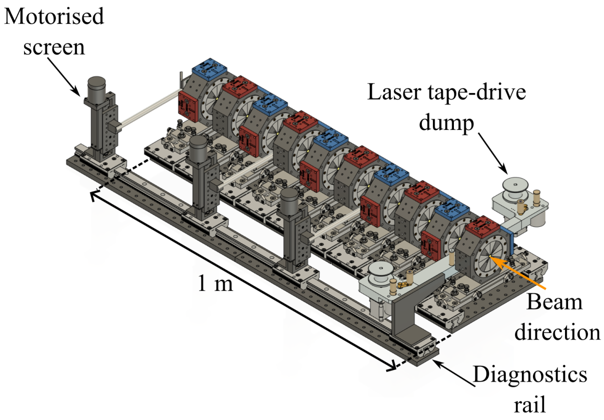

Figure 6: Engineering illustration of a 10 quadrupole capture array that may bring a 1 GeV electron bunch to a focus within around 1 m distance. Individual quadrupoles will be pre-aligned to around 50 μm relative accuracy (to the plasma source and to each other. One possible location for the tape drive beam dump is shown (between the first and second PMQ); also shown are the separately-mounted diagnostic screens and mounting mechanisms.

netic quadrupoles (EMQs) to focus to a variety of IP distances, for high resolution spectrometry [13] and for further diagnostics. Modular beamline design enables arrangements of different combinations of identical components (PMQs, EMQs, spectrometer etc.) to satisfy a wide range of experimental energies and configurations. A schematic of the beamline is shown in Fig. 4; a conventional electromagnetic (EMQ) triplet may be used to condition the Twiss functions either to an adjustable long-throw interaction point or (as shown) into a double-dipole spectrometer, described in a separate paper [13].

At 1 GeV a 4-PMQ capture and an EMQ triplet (post-chamber) may be used to focus the beam to a small spot at a series of IPs (from 3 to 15 m). The EMQ gradients are readily achievable (< 40 T/m). Core beam spot sizes at the IP of ~ 1 mm are attainable. For example, a beamline for the shortest 3 m long focus would have $\sigma_x = 0.28$ mm and $\sigma_y = 0.26$ mm at the IP.

Similarly, at 5 GeV an 8-PMQ capture and 6-EMQ conditioning system are used to focus the on-energy beam core to a variable interaction point position from 6 to 15 m. The PMQ and EMQ magnets are identical to the 1 GeV case, but the required EMQ gradients vary ($G < 40$ T/m). Spot sizes of ~ 1 mm are achievable for each IP distance. For example, at an 6 m IP $\sigma_x = 0.49$ mm and $\sigma_y = 0.48$ mm.

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