TRANSPORT OF ULTRA-SHORT ELECTRON BUNCHES IN A FREE-ELECTRON LASER DRIVEN BY A LASER-PLASMA WAKEFIELD ACCELERATOR*

M.P. Anania#, D. Clark, R.C. Issac, A.J.W. Reitsma, G.H. Welsh, S.M. Wiggins, D.A. Jaroszynski##,
SUPA, Department of Physics, University of Strathclyde, Glasgow G4 0NG, UK.
S.B. van der Geer, M.J. de Loos, Pulsar Physics, Eindhoven, The Netherlands.
M.W. Poole, J. Clarke, B. Shepherd, Crockcroft Institute/ASTeC (SFTC) Warrington, UK

Abstract

Focussing ultra-short electron bunches from a laser-plasma wakefield accelerator into an undulator requires particular attention to be paid to the emittance, electron bunch duration and energy spread. Here we present the design and implementation of a focussing system for the ALPHA-X beam transport line, which consist of a triplet of permanent magnet quadrupoles and a triplet of electromagnetic quadrupoles.

INTRODUCTION

The use of compact permanent quadrupole magnets [1, 2] has several advantages over electromagnets for beam transport e.g. they can be placed very close to the accelerating medium to minimize divergence and avoid dispersion of the electron bunch; and eventually, with the help of electromagnet quadruple magnets they allow flexible matching of the electron beam transport in an undulator to give a matched beta function. The design of these devices has been carried out using the GPT (General Particle Tracer, a software package developed to study 3D charged particle dynamics in electromagnetic fields) code [3, 4], which considers space charge effects and allows a realistic estimate of electron beam properties to be obtained inside the undulator. We present a study of the influence of beam transport on free-electron laser (FEL) action in the undulator, paying particular attention to bunch dispersion in the undulator. This is an important step for developing a synchrotron source or a self-amplified spontaneous free-electron laser [5, 6] based on a laser-plasma wakefield accelerator.

THE PRESENT ALPHA-X TRANSPORT SYSTEM

The primary beam transport line is situated between the end of a plasma capillary channel or gas jet, which acts as the accelerator, and the start of the undulator. The main requirement of the transport line is to focus the electron bunches into the undulator for a wide range of energies (from 50 MeV to 1 GeV).

The present ALPHA-X beam transport line (Figure 1) consists of plasma as an accelerator medium followed by a triplet of quadrupole electro-magnets and an undulator. We have carried out transport simulations of this line using GPT, which show that using the present beam line it is possible to focus beams with energies up to about 600MeV. At higher energies the maximum magnetic field is not sufficiently strong to focus the beam into the undulator and the transport becomes non-ideal.

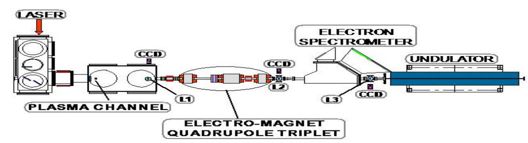

Figure 1: The current ALPHA-X beam line.

The following plots (Figure 2a and 2b) show the horizontal and vertical beam envelopes for two different energies (250 MeV and 500 MeV) indicating the beta functions of the electron beam at the undulator entrance.

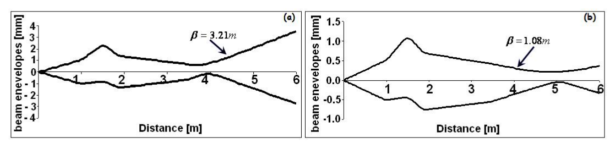

Figure 2: Horizontal and vertical beam envelopes for (a) 250 MeV and (b) 500 MeV using electromagnet quadrupoles.

The beta function provides an estimation of the electron beam waist diameter and the effective "Rayleigh" length, which should ideally be comparable to the undulator length (i.e. 3 m). As can be seen in Fig. 2, using the present beam line, we can still focus beams with an energy up to 600MeV into the undulator, but the beta function value at high energies becomes non-ideal, with a much reduced betatron length. Our goal is to improve the transport through the beam line, increasing the beta function value at least to the undulator length, over a much larger energy range.

THE UPDATED ALPHA-X BEAM LINE

The main design objective of the new magnetic transport elements for the ALPHA-X beam line is to have a flexible system (an effective zoom lens) to be able to focus beams with energies ranging from 50 MeV to 1 GeV. In order to cover such a wide range of energies, we have designed a

* This work was performed under the auspice of the U.K. EPSRC, the European Community - New and Emerging Science and Technology Activity under the FP6 "Structuring the European Research Area" programme (project EuroLEAP, contract number 028514), the Laserlab-Europe consortium and the Extreme Light Infrastructure (ELI) project. Authors want to thank Ulrich Schramm for his collaboration at this work.
# maria.anania@strath.ac.uk
dino@phys.strath.ac.uk

triplet of compact, high magnetic field quadrupoles to be placed just after the plasma channel. The new magnets have several excellent qualities. Firstly, they have very strong fields and are compact: the magnetic field is 1.2 T and their dimensions are comparable with a 1 euro or 1 pound coin (Fig. 3). Secondly, it is possible to place them just after the accelerator to avoid beam divergence and to maintain a short bunch duration. And eventually, in combination with the electromagnet quadrupole triplet, they allow perfect matching of the undulator to the beam.

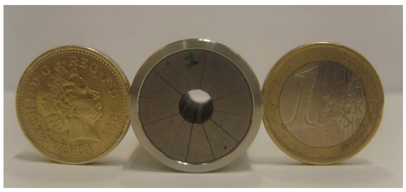

Figure 3: One of the quadrupoles compared with a 1 euro and 1 pound coin.

The design of the quadrupole magnets has been carried out using CST, an electromagnetic simulation software suite for 3D magnet design and optimization.
The quadrupoles are simulated by splitting a cylinder into 12 segments and magnetizing each segment with a magnetic field of 1.2 T (Fig. 4c). Figures 4a and 4b show the magnetic field both inside and outside the quadrupole.

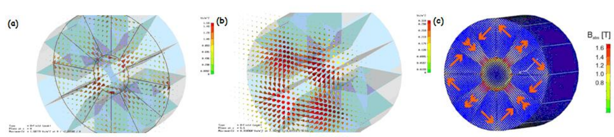

Figure 4: Magnetic field direction (a) inside and (b) outside a quadrupole, and (c) direction of magnetization.

To cover all energies in the range of 50 - 1000 MeV, the quadrupoles initially had an adjustable distance from the capillary, which depended on the beam energy. However, it was soon realized that the position of the quadrupoles was very critical, i.e. a small error produced large differences in the beam focal point, causing loss of the beam! Therefore, as the beam energy fluctuates from shot to shot by ±5% it was decided to place the permanent magnets at a fixed position and utilise the electromagnets to focus the beam to the desired point along the undulator by changing the electromagnet current.

OFF-AXIS PROPAGATION

The use of high field quadrupoles also helps with controlling off-axis propagation. Here we present GPT simulations of the behaviour of the electron beam for two cases: i) a beam propagating with an initial position displaced from the quadrupole axis and ii) an electron beam propagating at an angle of up to 10 degrees from the axis.
For the first set of simulations, the bunch is displaced by a distance equal to the capillary diameter (250 µm).

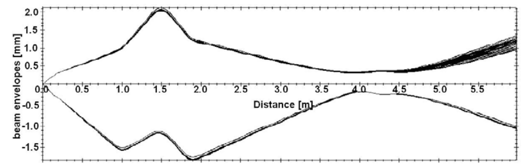

Figure 5: 150 MeV beam: horizontal and vertical beam envelopes for different initial positions.

Figure 5 shows the beam envelopes at 150 MeV. The different lines represent the different positions inside the quadrants.
In the second case (Fig. 6), a variety of angles of propagation to the beam have been chosen between 0 and 10 degrees. The different lines represent beams at different angles.

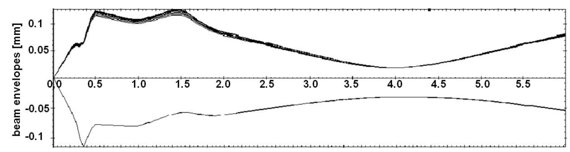

Figure 6: 1 GeV beam: horizontal and vertical envelopes for different angles.

As the results show, the quadrupoles can focus an off-axis electron beam both when the bunch position is offset and when the beam propagates at an angle of a few degrees with respect to the axis.

BEAM PARAMETER ANALYSIS

The new quadrupoles enable better electron transport along the beam line. Here we show how they can be combined with the electromagnets to enable complete control of the electron beam transport. In both sets of simulations, the parameters given in Table 1 have been used:

Table 1: Initial Parameters Used for the Simulations

Bunch charge	50 pC
x & y emittance	1 π mm mrad
Bunch radius	2 µm
Bunch length	3 µm
Relative energy spread	0.01

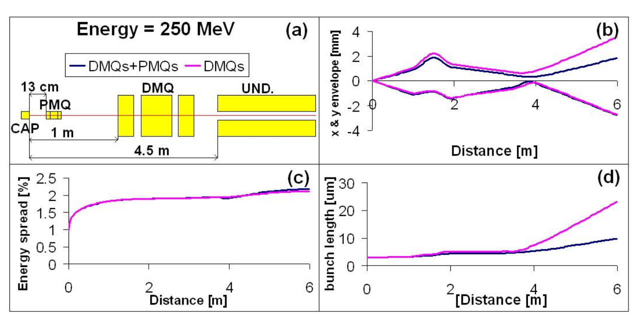

Figure 7: 250 MeV case: (a) geometry of the simulation, (b) beam envelopes, (c) energy spread, (d) bunch length.

Figure 13 shows the beam parameter evolution for a 250 MeV electron beam. Considering the beam envelope (Fig. 7b), it is clear that using both the quadrupole triplets the beam divergence decreases. The permanent magnets also reduce bunch length stretching (Fig. 7d) [7]. The only parameter that remains constant is the energy spread (Fig. 7c), which remains close to its initial value.

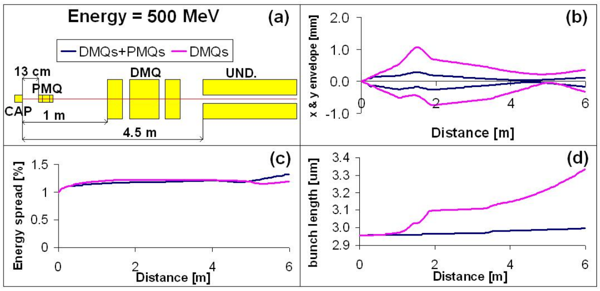

Figure 8: 500 MeV case: (a) geometry of the simulation, (b) beam envelopes, (c) energy spread, (d) bunch length.

For the high energy case (Fig. 8), an improvement is evident. Considering the beam envelope (Fig. 8b), we see that the beam size is much smaller for both sets of quadrupole triplets. Also, the bunch length remains constant for the permanent quadrupoles (Fig. 8d), and, as previously, the energy spread remains close to the initial spread (Fig. 8c).

The results given here show that using both the quadrupole triplets, we can provide matched transport into the undulator for a beam with an energy up to 1 GeV.

FREE-ELECTRON LASER SIMULATIONS

The beam transport simulations demonstrate that the new permanent magnet quadrupoles are suitable for producing beam parameters that are ideal for driving a FEL. To evaluate the conditions under which a FEL driven by a wakefield accelerator can work we have used the ALPHA-X undulator [8] parameters and the beam parameters calculated above to model the FEL. The code chosen to model the FEL is SIMPLEX as it is similar to, and in a good agreement with, the well tested GENESIS code [9], but has a friendly interface.

The simulation, using the initial beam parameters in table 2, is presented in Fig. 9.

Table 2: Initial Parameters used for FEL Simulations

Electron Energy	100 MeV
Bunch charge	50 pC
x & y emittance	1 π mm mrad
Energy spread	0.01
x & y beta function (avg)	1.5 m
Seeding (SASE)	Shot noise □ = 241 nm
FEL ρ parameter	0.01114

In Fig. 9a, there is the radiation power of the first three harmonics. We can see that the saturation power for the first harmonic is about 20 GW, at a saturation distance of about 1.8 m, in perfect agreement with the theoretical prediction [10] of a saturation power of 21.44 GW at a distance 1.735 m. Also the bunching factor is ≈ 0.8 (fig. 9b), as expected for a FEL.

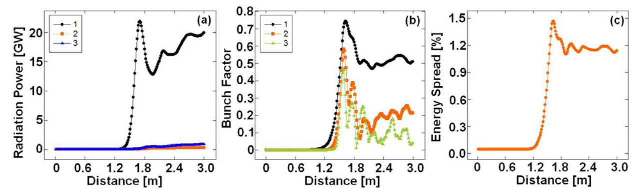

Figure 9: (a) Radiation power and (b) bunching factor for the first three harmonics and (c) energy spread.

Fig. 9c shows that the energy spread, which is initially 0.1%, reaches a value of about 1.5% at saturation, which is of the order of the FEL ρ parameter, as expected.

CONCLUSIONS

Using the present ALPHA-X beam line, we are able to focus electron beams with energies up to 600 MeV. However, as the energy increases, the beam becomes larger and the focal point moves toward the end of the undulator, giving a shorter beta function, and a non-optimal match. To avoid this problem, we have designed a triplet of compact and high field permanent magnet quadrupoles. Simulations demonstrate that adding the new quadrupoles we will be able to focus the beam into the undulator with a large angular and position off-set tolerance. Eventually, using both the triplet of quadrupoles we can improve the prospect of an FEL. With the beam parameters obtained, we have simulated the ALPHA-X undulator as a FEL and results show that the FEL amplification is possible giving a saturated power of about 20 GW.

REFERENCES

[1]. Eichner, T. et al., Phys. Rev. ST – Accel. Beams **10**, 082401, 1-9 (2007).
[2]. Lim, J. K. et al., Phys. Rev. ST – Accel. Beams **8**, 072401, 1-17 (2005).
[3]. De Loos, M .J. and Van der Geer, S. B. , "General Particle Tracer code: design, implementation and application", doctoral thesis (2001).
[4]. Van der Geer, S. B. and De Loos, M .J., "The General Particle Tracer Code", doctoral thesis (2001).
[5]. Marshall, T.C. [Free-electron Laser], Macmillan (1985).
[6]. Luchini, P. and Motz, H. [Undulators and Free-electron Laser], Oxford Science Publications (2005).
[7]. De Loos, M.J. at al, Phys. Rev. ST – Accel. Beams **9**, 084201, 1-7 (2006).
[8]. B. J. A. Shepherd and J. A. Clarke, Proc. EPAC'06, (2006) 3580.
[9]. V. Khacjatryan, et al., "PSI XFEL simulations with SIMPLEX and GENESIS", Proc. EPAC08, MOPC012, 91-93 (2008).
[10]. Wiedemann, H., [Particle Accelerator Physics], Springer Publications (2007).