THE ALPHA-X BEAM LINE: TOWARD A COMPACT FEL*

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Abstract

Recent progress in developing laser-plasma accelerators is raising the possibility of a compact coherent radiation source that could be housed in a medium sized university department. Furthermore, since the duration of electron bunches from laser-plasma wakefield accelerators (LWFAs) is determined by the relativistic plasma wavelength, radiation sources based on these accelerators can produce pulses with femtosecond durations. Beam properties from laser-plasma accelerators have been traditionally thought of as not being of sufficient quality to produce amplification. However, our work shows this not to be the case. Here, we present a study of the beam characteristics of a laser-plasma accelerator and the compact ALPHA-X (Advanced Laser Plasma High-energy Accelerators towards X-rays) FEL. We discuss the implementation of a focussing system consisting of a triplet of permanent magnet quadrupoles and a triplet of electromagnetic quadrupoles [1, 2]. The design of these devices has been carried out using the GPT (General Particle Tracer) code [3, 4], which considers space charge effects and allows a realistic estimate of electron beam properties along the beam line. We will present a study of the influence of beam transport on FEL action in the undulator, paying particular attention to bunch dispersion in the undulator. This is an important step for developing a compact synchrotron source or a SASE free-electron laser [5, 6].

SIMULATIONS FOR THE ALPHA-X FREE-ELECTRON LASER

To evaluate the conditions under which a FEL driven by a wakefield accelerator can work we have used the ALPHA-X undulator [7] parameters and optimized the beam parameters to model the FEL. The code chosen to model the FEL is SIMPLEX as it is easy to use and is similar to, and in a good agreement with, the well tested GENESIS code [8]. During the simulation we show here, we assumed that the electron beam energy is 100 MeV, with a total charge of 50 pC, a normalised emittance of 1 π mm mrad, in both transverse planes, and an energy spread of 0.1%. To model start-up we used a SASE model with a shot noise radiation wavelength of 241 nm and a FEL ρ parameter of 0.011. The results are presented in Figure 1.

Figure 1a shows 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 good agreement with the theoretical prediction [9] of a saturation power of 21.44 GW at a distance 1.735 m. Furthermore, the bunching factor is ≈ 0.8 (Figure 1b), as expected for a FEL at saturation.

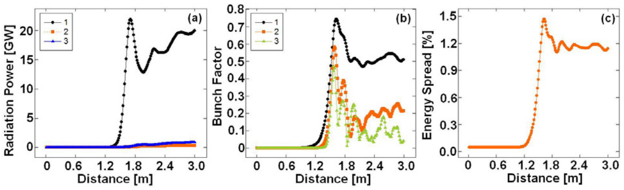

Figure 1: (a) Radiation power, (b) bunching factor for the first three harmonics and (c) the electron beam energy spread.

Figure 1c 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.

THE ALPHA-X BEAM LINE

In the previous paragraph we saw that using the ALPHA-X undulator, we are able to drive a FEL and reach a high saturation power. We also saw that in order to achieve such a result, we need to have a mono-energetic electron beam, a small emittance and a beta function that is at least comparable with the undulator length.

In order to estimate these parameters and see if they are close to the optimum values required for the FEL simulations, we have used a transport code to simulate the whole beam line.

The transport code we have choosen to use is GPT (General Particle Tracer), which considers space-charge effects and allows a realistic estimate of electron beam properties along the beam line.

We initially simulated the original ALPHA-X beam transport line (Figure 2), which consists of plasma as an accelerator medium followed by a triplet of quadrupole electro-magnets and an undulator.

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The simulations we have carried out show that using the present beam line it is possible to focus beams with energies up to about 600 MeV. At higher energies the quadrupoles magnetic fields are not sufficiently strong to focus the beam into the undulator and the transport becomes non-ideal.

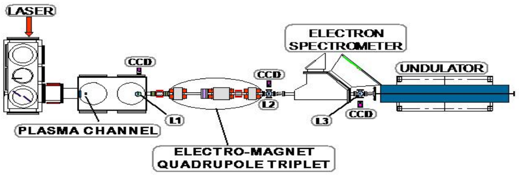

Figure 2: The original ALPHA-X beam line.

For these reasoning we have decided to design an additional triplet of quadrupoles to be placed very close to the accelerating medium (Figure 3) in order to reduce both the beam divergence and the diameter to ensure matched transport in the undulator. Moreover, one of the main design goals of the new magnetic transport elements for the ALPHA-X beam line is to have a flexible system to enable focussing of beams with energies ranging from 50 MeV to 1 GeV.

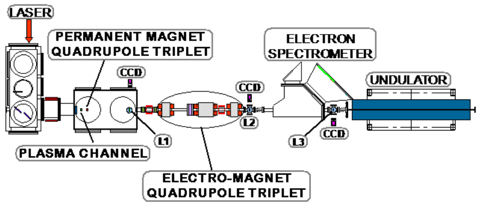

Figure 3: The updated ALPHA-X beam line.

To cover such a wide range of energies, we have designed a triplet of compact, high magnetic field quadrupoles to be placed very close to the accelerating medium. The new magnets have several excellent qualities. Firstly, they have very strong fields (1.2 T) and are compact (Fig. 4). Secondly, it is possible to place them very close to the accelerator to avoid beam divergence and thus maintain a short bunch duration. And eventually, in combination with the electromagnet quadrupole triplet, they allow perfect matching of the undulator to the beam.

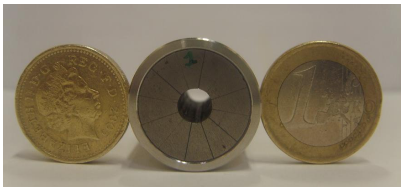

Figure 4: One of the quadrupoles compared with a 1 euro and 1 pound coin.

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 (Figure 5c). Figures 5a and 5b show the magnetic field both inside and outside the quadrupole.

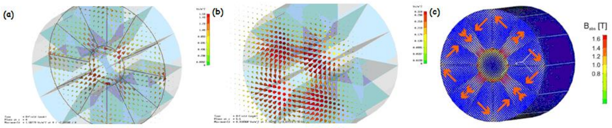

Figure 5: Magnetic field direction (a) inside and (b) outside a quadrupole, and (c) direction of magnetization.

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 ±2.5% 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.

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 normalised emittance	1 π mm mrad
Bunch radius	2 μm
Bunch length	3 μm
Relative energy spread	0.01

Figure 6 shows the evolution of beam parameters for a 250 MeV beam. Considering the beam envelope (Figure 6b), it is clear that using both quadrupole triplets the beam divergence decreases. The permanent magnets also reduce bunch length stretching (Figure 6d) [10]. The only parameter that remains constant is the energy spread (Figure 6c), which remains close to its initial value.

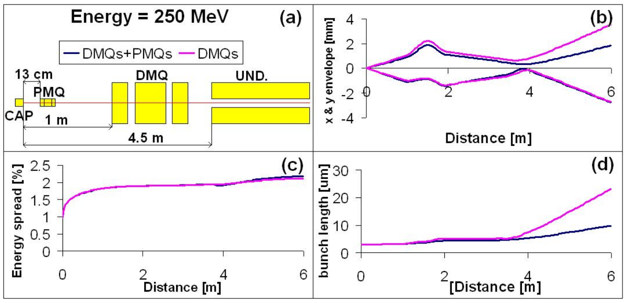

Figure 6: 250 MeV case: (a) geometry of the simulation, (b) beam envelopes, (c) energy spread, (d) bunch length

For the high energy case (Figure 7), an improvement is evident. Considering the beam envelope (Figure 7b), 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 (Figure 7d), and, as previously, the energy spread remains close to the initial spread (Figure 7c).

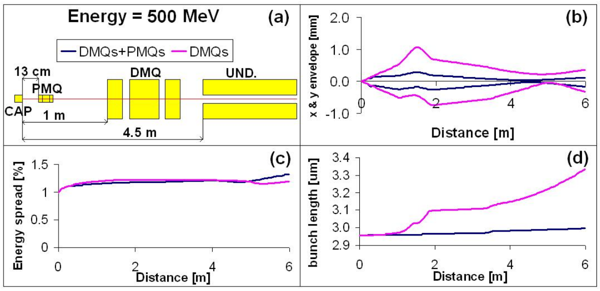

Figure 7: 500 MeV case: (a) geometry of the simulation, (b) beam envelopes, (c) energy spread, (d) bunch length

EXPERIMENTAL RESULTS

In this paragraph we present the experimental results obtained using the new permanent magnet triplet. The first result we will show is the image of the beam after about 60 cm from the accelerator without and with the permanent magnets (Figure 8) and after about 3 meters from the accelerating medium (Figure 9).

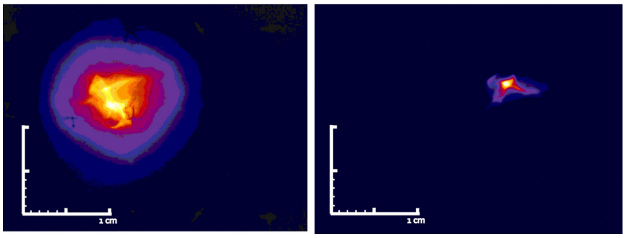

Figure 8: image of the beam after 60 cm (a) without permanent magnets ad (b) with permanent quadrupoles.

We can clearly see that the permanent magnets stretch the beam and make it much smaller in both the cases. Moreover, we can see in Figure 9 that the use of the permanent magnet is essential for transporting the electron bunch over a longer distance.

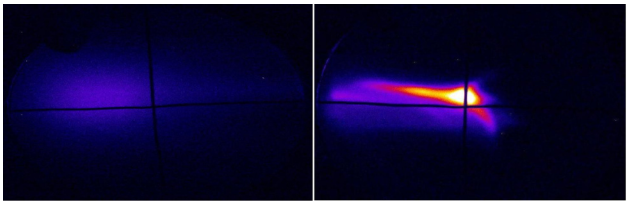

Figure 9: image of the beam after 3 m (a) without permanent magnets ad (b) with permanent quadrupoles.

We have also measured the beam energy and the energy spread. We can see in Figure 10 a snapshot of the electron spectrometer YAG screen. We have measured an energy of about 83 MeV with a very small energy spread (only 0.7%!).

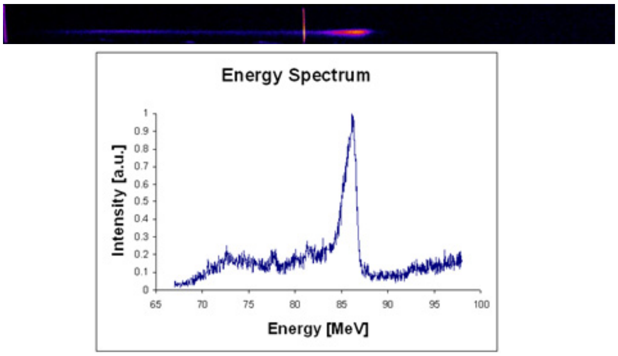

Figure 10: (a) Image of the electron spectrometer YAG screen and (b) electron energy spectrum.

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 towards 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 are able to focus the beam into the undulator, and furthermore there is a large angular and position off-set tolerance. Eventually, using both the triplet of quadrupoles we can improve the prospects 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.

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