

## 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 based accelerators is fixed by the relativistic plasma wavelength, the radiation sources based on these accelerators can be of the order of a femtosecond. Beam properties from laser-plasma accelerators have been traditionally thought not to be of sufficient quality to produce amplification. Our work shows that this is not the case.

### INTRODUCTION

Here we present a study of the beam characteristics of a laser-plasma accelerator. We also highlight the latest results on the compact Advanced Laser Plasma High-energy Accelerators towards X-rays (ALPHA-X) Free-Electron Laser (FEL). We will show how the beam properties of the ALPHA-X beam line have been optimized in order to drive a FEL. We discuss the implementation of a focussing system consisting of a triplet of permanent magnet quadrupoles [1, 2] and a triplet of electromagnetic quadrupoles. The design of these devices has been carried out using the GPT (General Particle Tracer) code [3, 4]. The latest measurements of energy spread and emittance will be presented: lately we have measured energy spreads less than 0.7% and, using a pepper pot, put an upper limit on the emittance of  $5 \pi$  mm mrad.

### FREE-ELECTRON LASER SIMULATIONS

To evaluate the conditions under which a FEL driven by a wakefield accelerator can work we have used the ALPHA-X undulator [5] parameters and optimized the beam parameters 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 [6], but has a friendly interface.

The initial beam parameters used in the simulations are

summarized in table 1 and the results are presented in Fig. 1.

Table 1: Initial Parameters used for FEL Simulations

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

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 perfect agreement with the theoretical prediction [7] of a saturation power of 21.44 GW at a distance 1.735 m. Also, the bunching factor is  $\approx 0.8$  (fig. 1b), as expected for a FEL.

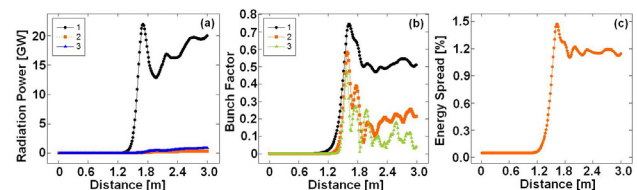


Figure 1: (a) Radiation power and (b) bunching factor for the first three harmonics and (c) energy spread.

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  $\rho$  parameter, as expected [8, 9].

### THE INITIAL 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 this, 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.

To evaluate these parameters for the ALPHA-X transport line, we have used GPT, which considers space charge effects and allows a realistic estimate of electron beam properties along the beam line.

The ALPHA-X beam transport line (Figure ) consists of plasma as an accelerator medium followed by a triplet of quadrupole electro-magnets and an undulator.

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Our simulations show that using the present beam line it is possible to focus beams with energies up to about 600MeV. At higher energies the maximum quadrupoles magnetic field is not sufficiently strong to focus the beam into the undulator and the transport becomes non-ideal.

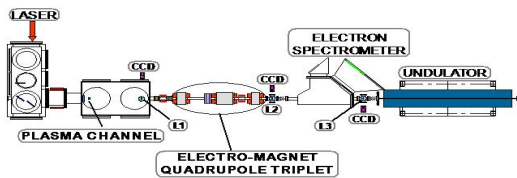


Figure 2: The initial ALPHA-X beam line.

The following plots (Figure 3a, 3b) 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.

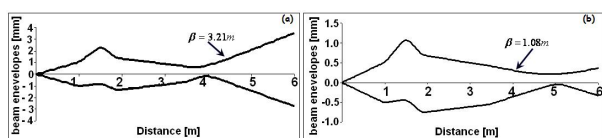


Figure 3: Horizontal and vertical beam envelopes for (a) 250 MeV and (b) 500 MeV using electromagnet quadrupoles.

The beta function provides an estimation of the electron beam waist diameter and the effective “Rayleigh” length, which, as we saw before, should be comparable with the undulator length. As can be seen in Fig 3, using the present beam line, we can focus beams with energies up to 600MeV into the undulator, but the beta function value at high energies becomes too small to drive a FEL. Our goal is to improve the transport through the beam line by increasing the beta function value to approximately the undulator length, for a larger energy range.

**THE UPDATED ALPHA-X BEAM LINE**

The main design objective of the new magnetic transport system for the ALPHA-X beam line is to provide a flexible system that is capable of focussing beams with energies ranging from 50 MeV to 1 GeV.

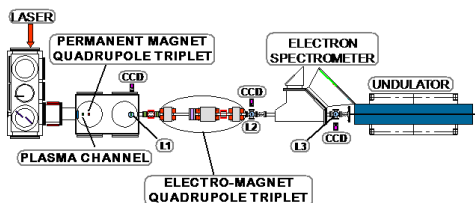


Figure 4: The updated ALPHA-X beam line.

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 (Fig. 4). The new magnets have several excellent qualities. Firstly, they have very strong fields and are compact: the tip magnetic field is about 1.5 T and their dimensions are comparable with a 1 euro or 1 pound coin (Fig. 5).

Secondly, it is possible to place them just after the accelerator to avoid beam divergence and thus maintain a short bunch duration while improving the laser pointing instability. Eventually, in combination with the electromagnet quadrupole triplet, they will allow perfect matching of the beam to the undulator.



Figure 5: 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. 6c). Figures 4a and 4b show the magnetic field both inside and outside the quadrupole.

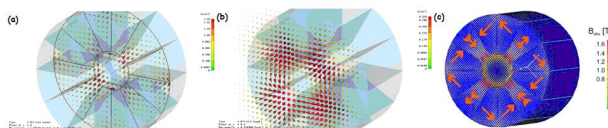


Figure 6: Magnetic field direction (a) inside and (b) outside a quadrupole, and (c) direction of magnetization.

To cover all energies in the range of 50 - 1000 MeV, the quadrupoles initially had an adjustable distance from the capillary that 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).

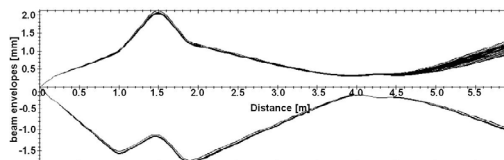


Figure 7: 150 MeV beam: horizontal and vertical beam envelopes for different initial positions.

Figure 7 shows the beam envelopes at 150 MeV. The different lines represent the different positions inside the quadrants.

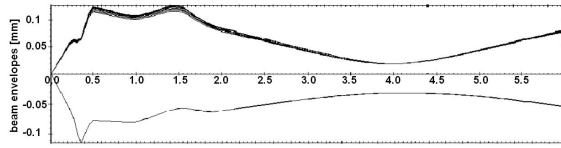


Figure 8: 1 GeV beam: horizontal and vertical envelopes for different angles.

In the second case (Fig. 8), 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. 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 and how they maintain beam parameters such energy spread, bunch length and beta function to values close to the ones used for FEL simulations. In both sets of simulations, the parameters given in Table 1 have been used:

Table 2: Initial Parameters Used for the Simulations

Bunch charge	50 pC
x & y emittance	1 $\pi$ mm mrad
Bunch radius	2 $\mu$ m
Bunch length	3 $\mu$ m
Relative r.m.s energy spread	0.01

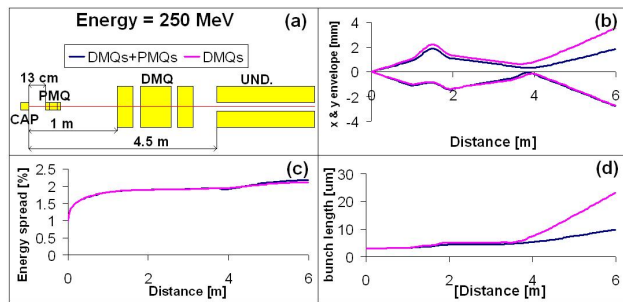


Figure 9: 250 MeV case: (a) geometry of the simulation, (b) beam envelopes, (c) energy spread, (d) bunch length.

Figure 9 shows the beam parameter evolution for a 250 MeV electron beam. Considering the beam envelope (Fig. 9b), it is clear that using both quadrupole triplets reduces the beam divergence. The permanent magnets also reduce bunch length stretching (Fig. 9d) [10]. The only

parameter that remains constant is the energy spread (Fig. 9c), which remains close to its initial value.

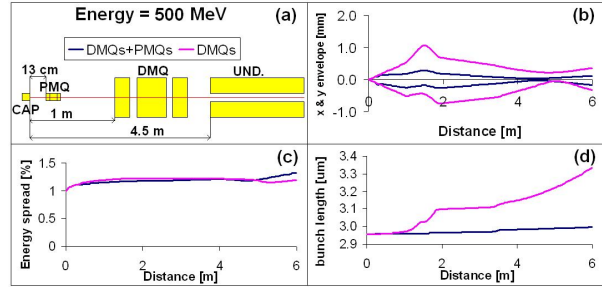


Figure 10: 500 MeV case: (a) geometry of the simulation, (b) beam envelopes, (c) energy spread, (d) bunch length.

For the high energy case (Fig. 10), an improvement is evident. Considering the beam envelope (Fig. 10b), 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. 10d), and, as previously, the energy spread remains close to its initial value (Fig. 10c).

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.

### GPT AND TRANSPORT COMPARISON

In this section, we will show that the simulations carried out also agree with the code TRANSPORT, which is designed to model the propagation of charged particle beams in transport systems [11]. The effect of the beam line on a charged particle trajectory is represented by first-, second-, and third-order matrices. Figures 11 and 12 show the beam envelopes for two different energies (250 MeV and 450 MeV) calculated using the two codes.

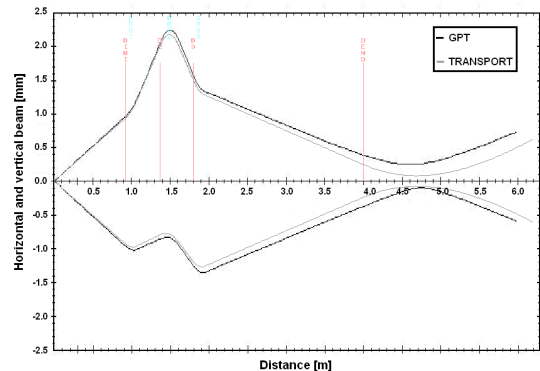


Figure 11: 250 MeV case: GPT and TRANSPORT comparison.

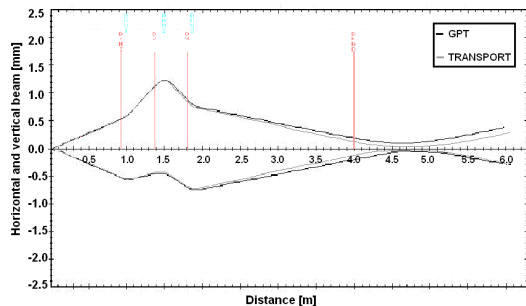


Figure 12: 450 MeV case: GPT and TRANSPORT comparison.

The two codes define the magnetic devices along the beam line slightly differently. GPT uses the field strength (T/m) to define quadrupoles, while TRANSPORT defines the field by the maximum value (T). However, we find a good agreement between the two codes, as the previous plots show (Fig. 11 and 12). We see that varying the beam energy, the beam envelopes calculated by the two codes are in good agreement, with minor discrepancies due to space charge effect, which TRANSPORT does not account for.

### LATEST EXPERIMENTAL RESULTS

In this paragraph we present the first experimental results obtained using the new permanent magnet triplet. The first result shown is the image of the beam after about 60 cm from the accelerating medium with and without the permanent magnets (Fig. 13). We can clearly see that the permanent magnets reduce the divergence and produce a slightly squashed beam profile.

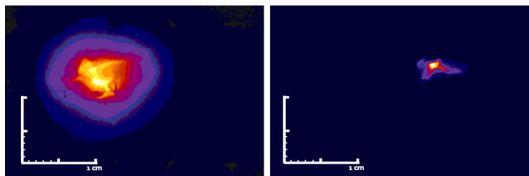


Figure 13: Image of the beam after 60 cm (a) without permanent magnets and (b) with permanent quadrupoles.

These results are in good agreement with the GPT simulations of a beam after propagating 60 cm.

During the latest experimental campaign, we have also measured the electron beam energy and the energy spread.

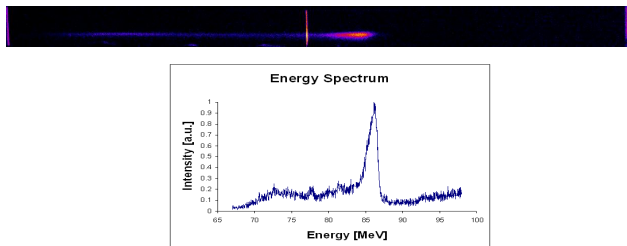


Figure 14: (a) Image of the electron spectrometer YAG screen and (b) electron energy spectrum.

In Fig. 14 we show a snapshot of the electron spectrometer YAG screen. This shows a measured mean energy of about 86 MeV and an energy spread of only 0.7%! Notice that the measured energy spread is smaller than that used to simulate the FEL.

### CONCLUSIONS

The simulations show that using the ALPHA-X undulator as a FEL, we can obtain amplification, with a saturation power of 20 GW at a radiation wavelength of 240 nm. To drive a FEL, we require a small energy spread ( $\approx 1\%$ ), a small emittance ( $\approx 1 \pi$  mm mrad) and a beta function that is comparable to the undulator length. Transport simulations show that the initial beam line, consisting of the accelerating medium, a triplet of electromagnet and an undulator, is not suitable for obtaining a long beta function over a wide range of energies (from 50 MeV to 1 GeV). For this reason we have designed a triplet of compact and high field permanent magnet quadrupoles. Simulations demonstrate that adding the new quadrupoles the beam will focus into the undulator while accepting a large angular and position off-set tolerance. The latest experimental results show that ALPHA-X accelerator and beam line produces very small energy spread, even smaller than that used for FEL simulations.

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