CAPTURE AND TRANSPORT OF ELECTRON BEAMS FROM PLASMA INJECTORS

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Abstract

Electron beams produced by laser-plasma interaction are arousing a strong interest in the conventional accelerator community, considering their high initial energy and their strong beam current. Using adequate beam shaping might make their characteristics comparable to those obtained in traditional accelerator facilities based on RF technology. Moreover, the advantages of using laser-plasma electron beams can be expressed in terms of size and cost of the global accelerating infrastructure. However, improvements are still necessary since, currently, the laser-accelerated beams are characterized by a large energy spread and a high beam divergence that degrades quickly the good initial electron beam properties and makes these sources not yet suitable to replace conventional accelerators.

In this paper, we report on the progress of the study related to capture, shape and transport of laser generated electrons by means of tracking codes. In particular, our study has focused on laser-generated electrons obtained nowadays by conventional multi-hundred TW laser systems and on numerical predictions. For this, we have analyzed different lattice structures, working on the optimization of the capture and transport of laser-accelerated electrons. Results are shown and discussed, together with open problems.

INTRODUCTION

In the last years, substantial research has been carried out regarding the production of laser-generated electrons as new electron sources. While firstly researchers were concentrating on increasing the particle energy, reaching the GeV frontier, nowadays more and more effort is put to control those beams ("dream beams"), in order to make them suitable for different applications and gradually make them become reliable and innovative particle sources. Little has currently be done to control the electron beam with traditional accelerator devices which could potentially allow a stronger control of the electron beam and solve some of the issues that laser-generated electron beam present in order to be considered as sources. In this paper we will describe a possible beam transport of laser-generated particles using conventional accelerator devices. In particular, we will focus on the capture and transport of electrons generated by 100 TW class lasers, since this is the new generation of lasers currently establishing worldwide in different labs and being a test bet for larger scale facilities currently in development phase such as 10 PW lasers (APOLLON in France, VULCAN in the UK).

BEAM TRANSPORT WITH QUADRUPOLES

We have used the PIC code ALaDyn [1] to simulate the plasma-laser interaction and to obtain the electron bunch distribution at the exit of the interaction point between gas-jet and laser beam. The output parameters of the simulation have been taken as input for the capture and transport of the electron beam within the conventional accelerating structures. In this paper we focus the study to a 200 TW laser with wavelength λ=0.8 µm, pulse duration (FWHM) τ=30 fs, and waist=15.5 µm, delivering an intensity of I=5x10^{19} W/cm^2, similar to what we would expect to obtain by the FLAME laser currently under commissioning at the Frascati National Laboratories [2]. For the gas jet, we have considered the gas jet that will be installed at the FLAME laser, and in a configuration that generates a plasma of length 4.1 mm and electron density 3x10^{18} 1/cm^3. The main output parameters of the electron beam, in its almost monochromatic part of the bunch, as given by the PIC code are shown in Table 1. As a general comment we can see that, besides the good characteristics of the beam dimensions, the energy spread and the beam divergence are higher than those obtained in the conventional electron beam sources, especially when we consider the high beam energy of the laser-plasma bunches. Consequently an approach for beam transport different from those used for conventional beams is needed. We also underline that the obtained current might be slightly higher than what has currently been measured by experiments with similar laser characteristics, but this does not modify the conceptual design of the structure.

Table 1: main beam parameters from ALaDyn PIC code

Electron charge	707 pC
Beam energy	910 MeV
Energy spread (RMS)	6.4 %
Bunch length (RMS)	2 µm
Transverse beam size (RMS)	0.5 µm
Transverse divergence (RMS)	3 mrad
Transverse normalized emittance (RMS)	2.5 mm mrad

The capture, transport and optimization of the laser-generated electron beam with conventional accelerator devices has been designed with the use of the well established codes, TRACE 3-D [3] and TSTEP [4], the first one being an optical transport code, the latter being a macroparticle tracking code, derivative of PARMELA[5]. We have first studied the transport of a beam by using a conventional quadrupole line for controlling the transverse bunch dimensions. From the beam parameters of Table 1, we have extrapolated an initial distribution to give as input to TRACE 3-D for conventional quadrupoles optimization. In Fig. 1 the obtained optimized beam line is shown.

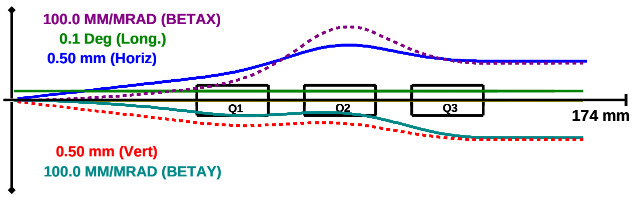

Figure 1: matching transport line with quadrupoles. Axis limits for the different shown parameters are indicated by the normalized ordinate in figure.

Starting from very low Twiss beta values, of the order of 0.2 mm, by using a matching system of three quadrupoles, with a total length of 174 mm, we manage to obtain at the end of the transport line a bunch with Twiss parameters α=0 and β=45 m. Such final parameters can eventually be transported with a periodic FODO system without particular problems. Also the transverse dimensions of the bunch allow a conventional transport after the matching line.

These results have been confirmed with the code TSTEP. In Fig. 2 we show the transverse beam sizes along the matching line as given by the particle tracking code. The bunch remains confined below 0.35 mm and the behaviour of the transverse beam size agrees with what is shown in Fig. 1.

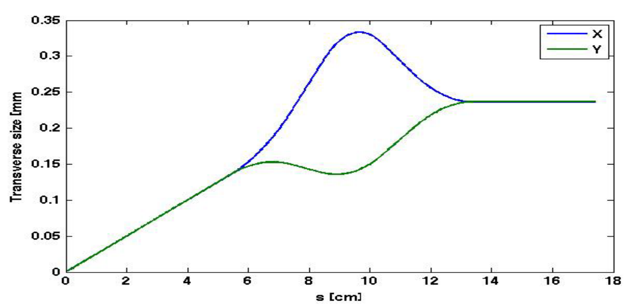

Figure 2: transverse beam size along the quadrupoles line.

Some problems however arise from this kind of transport system. If we consider the behaviour of the normalized emittance ε_n, we obtain the plot of Fig. 3. The two cases refer to an ideal Gaussian bunch distribution with the initial parameters of Table 1 and the ALaDyn particle distribution. On can see that the normalized emittance reaches values of up to 250 mm mrad, an excessively high value for an accelerator.

Another problem is related to the strength of the quadrupole gradient necessary to contain the divergence of such beams: it reaches high values as 5000 T/m, a factor 10 higher than the maximum gradient currently available and obtained using PMQs [6]. This is due to the fact that the beam is generated inside a plasma where the magnetic field is extremely high, thus producing a bunch with a very low Twiss beta function. As the bunch comes out of the plasma and finds a drift space, however, the divergence of the order of mrad produces a rapid increase of the transverse bunch dimension σ and even more of the Twiss beta function β, since $\beta = \sigma^2/\varepsilon$. As example, after a drift of 1 cm the transverse size of the bunch increases by a factor of about 60 with respect to the initial value. This means that the quadrupole gradient must be very strong to counteract this rapid expansion thus giving a strong focusing kick in one direction (e.g. x) and a defocusing one in the other direction (y). As a consequence, the bunch experiences strong perturbations, and it becomes difficult to control it.

The conclusion is that, even if the quadrupoles choice represents a simple and economic way to transport a beam, if the beam parameters remain of the order of magnitude of those in Table 1, it is not possible to use such a transport beam line.

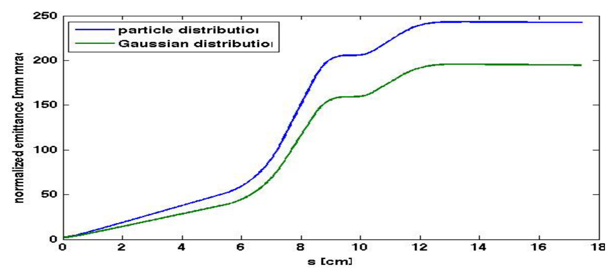

Figure 3: transverse normalized emitance along the quadrupole line.

BEAM TRANSPORT WITH SOLENOIDS

An alternative to quadrupoles in order to contain the transverse bunch dimensions is the use of solenoids that, acting over a longer distance, allow a smoother control of the bunch transverse size increase. As in the previous section, we have first optimized the beam line by using TRACE 3-D. A solenoid of about 20 cm very close to the laser-plasma interaction point is able to control the beam size and the Twiss beta function.

The same results have then been confirmed with TSTEP. The magnetic field of a solenoid allows an easier control of the transverse bunch size, which reaches a final value similar to that obtained with the quadrupoles line. Even in this case the magnetic field must be very high, of the order of 50 T. However such high field solenoids, differently from the quadrupole gradients, have been under investigation and their feasibility seems possible [7]. Also in this case the normalized emittance reaches very high values as shown in Fig. 4, where a final normalized emittance of about 200 mm mrad is shown.

The reason of the step behaviour at the exit of the solenoid is due to the fact that we have used in the simulations an ideal solenoid with a step field at the entrance and exit. In order to generate a more realistic output, we have also run the simulations using a magnetic field of a solenoid, shown in Fig. 5, as given by Poisson code [8]. With this more realistic magnetic field, the normalized emittance is a bit worse than when using an ideal solenoid, reaching values of the order of 400 mm mrad (see Fig. 6).

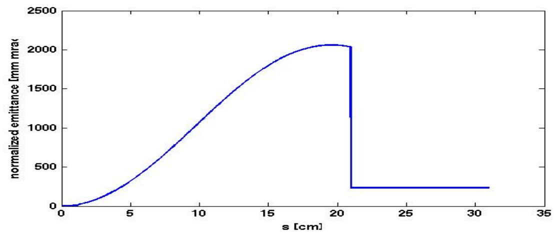

Figure 4: transverse normalized emittance along the solenoid transport line.

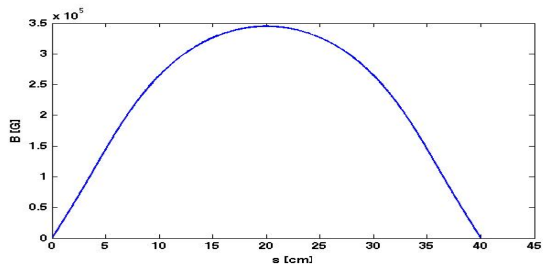

Figure 5: Longitudinal magnetic field of the solenoid.

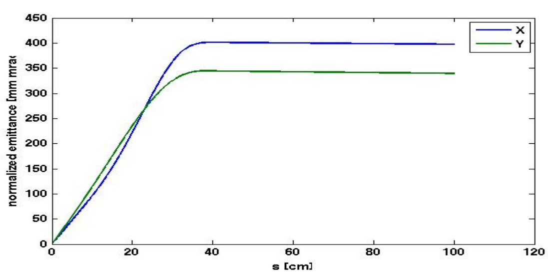

Figure 6: normalized emittance with a solenoid magnetic field.

Despite the high normalized emittance, the conclusion that we can draw is that with state of the art superconducting solenoids, a transport of a laser plasma beam with characteristics as those reported in Table 1 could be possible. However, laser-beam shaping needs to be done reducing the energy spread and the beam divergence. In fact these two parameters are responsible of the significant initial normalized emittance increase of Fig. 6 as demonstrated in the following paragraph.

NORMALIZED EMITTANCE GROWTH

The normalized emittance for a bunch with high energy spread and high divergence cannot be approximated by the expression $\varepsilon_n = \gamma\varepsilon$ with γ the relativistic factor. In fact, if we use the definition

$$\varepsilon_n^2 = \langle x^2 \rangle \langle \beta^2\gamma^2 x'^2 \rangle - \langle x\beta\gamma x' \rangle^2 \qquad (1)$$

being β e γ the relativistic factors, x and x' the transverse position and its divergence, and supposing that there is no correlation between the energy and the transverse coordinate, using the definition of the relative energy spread σ_ε

$$\langle \gamma \rangle^2 \sigma_\varepsilon^2 = \langle \beta^2\gamma^2 \rangle - \langle \beta\gamma \rangle^2 \qquad (2)$$

then eq. (1) can be written as

$$\varepsilon_n^2 = \langle \gamma \rangle^2 \left(\sigma_\varepsilon^2 \sigma_x^2 \sigma_{x'}^2 + \varepsilon_0^2\right) \qquad (3)$$

where σ_x is the transverse beam size, $\sigma_{x'}$ the beam divergence, and ε_0 is the un-normalized emittance. For conventional electron beams with β=1, the calculation of the normalized emittances reduces to the second term of eq. (3). Anyway the first term cannot be neglected if the energy spread and the beam divergence are high. Generally the initial beam divergence in a conventional accelerator is as low as some tens of μrad at energies of hundreds of MeV, a factor 100 lower than what reported in Table 1, thus giving a negligible first term on the RHS of eq. (3). In our case, on the contrary, we have that in the drift immediately following the plasma-laser interaction point the beam parameters are such that the normalized emittance growths at a rate of about 1000 mm mrad/m. This is uncommon for conventional accelerators: in laser-plasma accelerators there is a strong 'geometric' increase of the normalized emittance in the drift space following the interaction point that is the main responsible of the high emittance values reported here.

CONCLUSIONS

We have demonstrated that capture of laser-generated with conventional accelerator devices is in principle feasible. However, while the use of quadrupoles requires technical specifications that are currently not available, with the solenoids, one needs to push technical specification to the limits of what is currently existing as prototype. We have also shown that a drift space worsens the normalized emittance of the laser-generated beam due to the high energy spread, an apparent impossible behaviour in conventional accelerators.

ACKNOWLEDGMENTS

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REFERENCES

[1] C. Benedetti, et al., IEEE - Transactions on Plasma Science 36/4, 1790-1798, (2008).
[2] http://ilil.ipcf.cnr.it/flame.
[3] K. R. Crandall, D. P. Rusthoi, LA-UR-97-886, 1997.
[4] L. M. Young, priv. comm.
[5] L. M. Young, Los Alamos National Laboratory report LA-UR-96-1835.
[6] S. Becker, et al., Phys. Rev ST - A&B - 12, 102801 (2009).
[7] S.A. Kahn, et al., Proceedings of EPAC08, Genoa, Italy, 2455 – 2457 (2008).
[8] J. H. Billen and L. M. Young, Los Alamos National Laboratory Report No. LA-UR-96-1834, 2001.