TRANSPORT BEAM LINES FOR LASER-PLASMA ACCELERATORS

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Abstract

Compared to RF accelerators, laser-plasma interaction produces beams with significantly larger emittance, energy spread, and divergence, necessitating dedicated transport line designs. This study investigates beam dynamics in various transport line configurations between plasma stages and towards the end users. Design and optimization of these lines are performed according to the requests on the beam parameters. Their capabilities and limits are also discussed.

INTRODUCTION

The role of a transport line is to capture the beam with given parameters from a source or acceleration stage and delivers it to an application or subsequent acceleration stage while adjusting the beam parameters to the requirements of the next stage.

In the design of transport lines, the number of magnetic elements (such as quadrupoles) is dictated by the number of requirements on beam parameters at the exit. The geometry, whether straight, dogleg or chicane configuration, is determined by the site and users constraints.

Laser-wakefield accelerators (LWFAs) produce electron beams with specific properties, such as micron-scale transverse sizes, large emittance, energy spread, and divergence. Specific optimization of position, intensity and size of magnetic elements must be performed consequently. For multi-stage designs, preserving beam emittance requires additional constraints on the beam parameters at both the plasma entrance and exit.

In this article, after recalling the key role of the focusing gradient and how we simulate it, studies of two-, four-, six-, and dogleg configurations are described.

KEY PARAMETER: K (m^{-2})

Transverse beam dynamics in plasma stages is governed by the focusing gradient K (m^{-2}) defined as

$$K = \frac{e}{\gamma_{\rm rel} m_e c^2}\left(\frac{\partial E_r}{\partial r} - \beta_{\rm rel} c \frac{\partial B_\theta}{\partial r}\right)_{r=0},$$

where e and m_e are the electron charge and mass, c is the speed of light in vacuum, $\beta_{\rm rel}, \gamma_{\rm rel}$ are the relativistic speed and Lorentz factors, r the transverse coordinate and E_r, B_θ the radial electric and azimuthal magnetic field components. In this work, the profile of K along the plasma density plateau surrounded by two plasma ramps, is calculated from the wake fields E_r and B_θ, given by the Wake-T simulation code [1].

This plasma profile of K is then modeled with the TraceWin code [2] by using a series of plasmaquad elements [3] (referred to as QuadSpec in Ref. [4]), which provide simultaneous focusing in both transverse planes, unlike conventional quadrupoles that focus the beam in one plane while defocusing it in the other. This approach enables simulation and optimization of the full system, composed of plasma stages and transport lines, using a single transport code.

CONSTRAINTS ON BEAM PLASMA PARAMETERS

The beam accelerated in a plasma stage presents much larger energy spread and emittance compared to conventional accelerators. To avoid further emittance growth through a plasma density plateau, the injected beam is recommended to meet the matching condition for its Twiss parameters α_0 and β_0:

$$\alpha_0 = \alpha_{\rm M} = 0 \text{ and } \beta_0 = \beta_{\rm M} = 1/\sqrt{K}, \qquad (1)$$

so that the Twiss α, β remain constant throughout the plasma. However, this induces an emittance increase of several orders of magnitude, in the transport line upstream which is in charge of achieving the required matched beam, and downstream to which the matched beam is delivered. This is due to the large energy spread (%) combined with the tiny beam size (µm) and the huge beam divergence (mrad) induced by the large K values ($\simeq 10^6$ m^{-2}) reached on the plasma plateau. Studies in Ref. [5] show that this transport line emittance growth can be mitigated by reducing the Twiss parameter $\gamma_{\rm M} = \left(1+\alpha_{\rm M}^2\right)/\beta_{\rm M}$, required or given to it, by not considering the matching condition at the plateau, but that at the entrance or exit ramp surrounding the plateau, which can be much smaller when the ramp length is well adjusted. In Ref. [3,4], for a Gaussian density ramp with characteristic length L = 8 mm, the required Twiss parameter γ can be reduced from 2503 at the plateau entrance to 165 m^{-1} at the ramp entrance or exit. When backtracking the matched beam from the plateau (Eq. (1)), the matched condition at the ramp entrance can be obtained: $\alpha_0 = 3.2$ and $\beta_0 = 0.07$ m (γ_0 = 165 m^{-1}). This was obtained for an electron beam energy E = 200 MeV, charge Q = 30 pC, energy spread σ_p/p = 1 % and emittance $\varepsilon_x \times \varepsilon_y = 3 \times 1$ mm^2.mrad^2 (typical for an ionization injection plasma). These values were obtained by backtracking the matched beam from the matched conditions at the plateau entrance to the up-ramp entrance (method presented in Ref. [3,4]).

The above parameters, which are typical of a beam coming from an ionization-injection plasma, will be employed for the electron beam at the entrance of all the transport lines discussed in this study.

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TWO-QUADRUPOLE CONFIGURATION

In the context of a target irradiation application with two requirements on the transverse beam sizes, a transport line consisting of two 50 mm quadrupoles can be employed. Optimizations [6] conducted using the TraceWin software have shown that a 6-meter-long transport line is necessary to obtain a solution with low quadrupole forces (K = 2.3 m^{-2} and -1.5 m^{-2}), if beam sizes $\sigma_x \times \sigma_y = 5 \times 5$ mm^2 are required at the exit. The evolution of the RMS size of such a configuration is presented in Fig. 1. This transport line length is required to give to the beam sufficient distance to diverge, given the significant disparity between the micrometer beam sizes at the entrance and the millimeter sizes required at the exit.

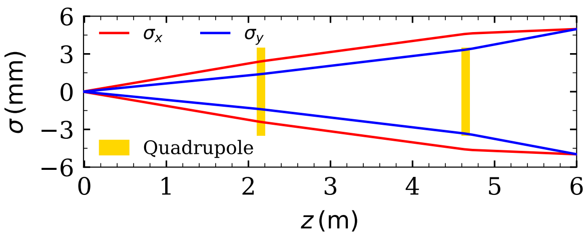

Figure 1: Evolution of the beam through the two-quadrupole configuration.

The flexibility of this configuration can be judged by its capability to achieve beam sizes at exit from ~ 0.5 mm to 5.5 mm [6]. Larger beam sizes can only be obtained either by lengthening the drifts, or by demanding for larger divergence or larger Twiss parameter γ_0 of the input beam. Another possibility to obtain larger beam sizes is to switch to a strong-focusing configuration, with much higher quadrupole forces, up to a factor of three. However, it induces pinches of the beam, which will imply stronger beam divergence at the target and more pronounced chromatic effects causing further emittance growth.

Beam divergence and emittance are the two other remaining transverse parameters that are not constrained in this target irradiation application. It could be nevertheless useful to note that the beam divergence is, in the y plane, of the order of 1 mrad in weak focusing, and 10 mrad in strong focusing. Depending on the target thickness, layers at different depths could be irradiated differently. Corresponding emittances up to 50 (resp. 500) mm.mrad are reached at the line exit, values that can be higher for larger energy spread or larger Twiss γ at beam input [6].

FOUR-QUADRUPOLE CONFIGURATION

When adding the requirement of a beam waist (Twiss $\alpha = 0$) at the line exit, two additional constraints are introduced, necessitating two more 50 mm quadrupoles. The line structure is adopted from the above two-quadrupole structure, by replacing each single quadrupole by a doublet spaced 500 mm apart. As now the maximum beam size must exceed 6 mm, the line needs to be lengthen to 7 m. The quadrupole gradients K are 0.9, -1.3, 6.1 and -5.3 m^{-2}. The evolution of the transverse size along the four-quadrupole line is presented in Fig. 2.

Discussions on the capacity and limits of this configuration, and comments on the emittance growth are similar as in the previous paragraph.

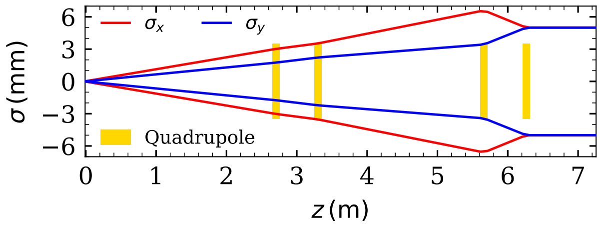

Figure 2: Evolution of the beam through the four-quadrupole configuration.

SIX-QUADRUPOLE CONFIGURATION

We study now the case of a transport line joining two plasma stages, which are identical, having the same density profile. The precedent user target is now replaced by a plasma stage. A transport line with six quadrupoles is required in order to transport and satisfy the six requirements α, β and ε in the two transverse planes at the second plasma stage entrance. Indeed, α and β must satisfy the matching conditions (Eq. (1)) at the plasma plateau entrance, which, as specified above, correspond to $\alpha_0 = 3.2$ and $\beta_0 = 0.07$ mm at the plasma ramp entrance; while the normalized emittance ε is asked to be preserved as much as possible.

In such a configuration, the beam parameters should be similar at entrance and exit, then the entrance/exit symmetry is chosen for the transport line structure. Studies in Ref. [5] show that to mitigate emittance growth in the transport line, the first quadrupoles must be very thin, very strong permanent magnets, positioned very close to the first plasma exit. We therefore adopt a structure with three 50 mm long permanent magnets at each end, separated one from another and from the plasma by 50 mm. The quadrupole gradients K are 322.2, -239.2, 92.6, 129.9, -245.5 and 214.3 m^{-2}. These two triplets should be separated by a few-meter long drift to allow installation of diagnostics and laser beam removal/injection devices.

We first optimized the transport line to meet the target parameters at the plasma up-ramp entrance as stated above. Requirements on α, β can be obtained without difficulties. The emittance ε has increased due to chromatic effects, although a compensation of these effects has been optimized with the two additional quadrupoles. The emittance $\varepsilon_x \times \varepsilon_y$ = 3×1 mm^2.mrad^2 initially has grown to 3.7×2.2 mm^2.mrad^2. The growth in ε_x is rather moderate. The larger growth in ε_y has been "sacrified" as there is no reason to keep an emittance well lower in a given plane when injecting to a cylindrically symmetric plasma. This emittance growth can be further mitigated. Indeed, studies in Ref. [3] have shown that when the matching condition at the ramp entrance is relaxed by 25 %, the induced emittance growth is only of

10 %, while a strict application of this matching condition can induce higher emittance growth in the transport line.

Performing now an optimization of emittance over the whole structure composed of the transport line and the plasma stage (plateau surrounded by the two ramps), we obtain the final emittance $\varepsilon_x \times \varepsilon_y = 3.1 \times 1.4$ mm^2.mrad^2. Figure 3 presents the optimization results for the beam parameters α, β and ε obtained after optimizations.

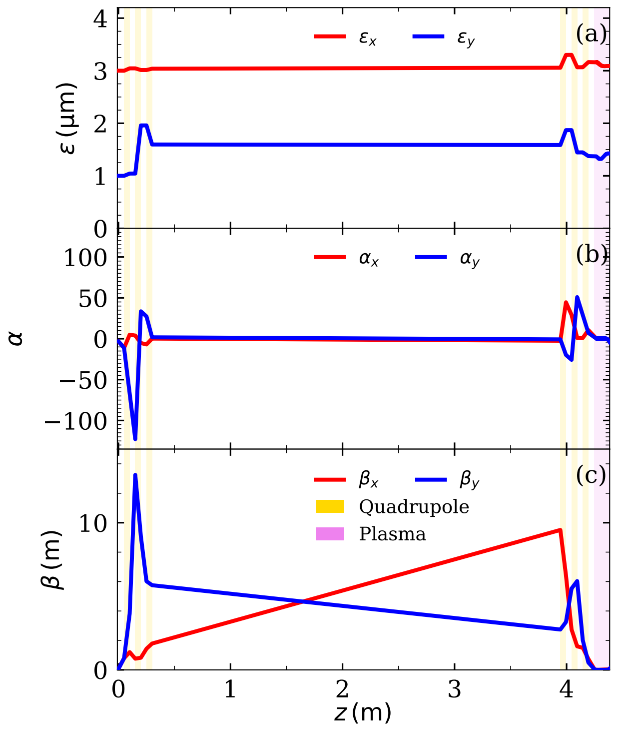

Figure 3: Evolution of the beam through the six-quadrupole configuration and second plasma.

DOGLEG CONFIGURATION

Studies of a dogleg transport line have been performed [7] in the context of a LWFA injector for the AWAKE run 2c experiment, where the objective was to connect two plasma stages. The beam parameters given at the line entrance and those required at the line exit ($\alpha, \beta, \varepsilon$ in the two transverse planes) are not the same as in this study, but similar.

In the straight parts, six quadrupoles are used, distributed into a permanent-magnet quadruplet at entrance and a permanent-magnet doublet at exit. In between, an achromat is inserted, comprising electromagnetic elements, distributed into two dipoles and five quadrupoles. As expected, the major challenge is the preservation of the emittance. This is done by adding four sextupoles placed within or very close to the quadrupoles where the dispersion function is high enough.

This dogleg configuration allows to meet all the requirements of high beam charge and quality concerning AWAKE, with a certain degree of flexibility. However, in the more general context, the final bunch length must also be as short as a few micrometers to optimize beam acceleration in the second plasma. In the present context, it is not necessary to control this parameter, which is free to increase from 3 to 70 µm. This lengthening is due to the passage through the dipoles. Studies are currently done to insert a magnet chicane to reduce this bunch length.

Figure 4 presents the optimization results for the beam parameters α, β and ε obtained after optimizations.

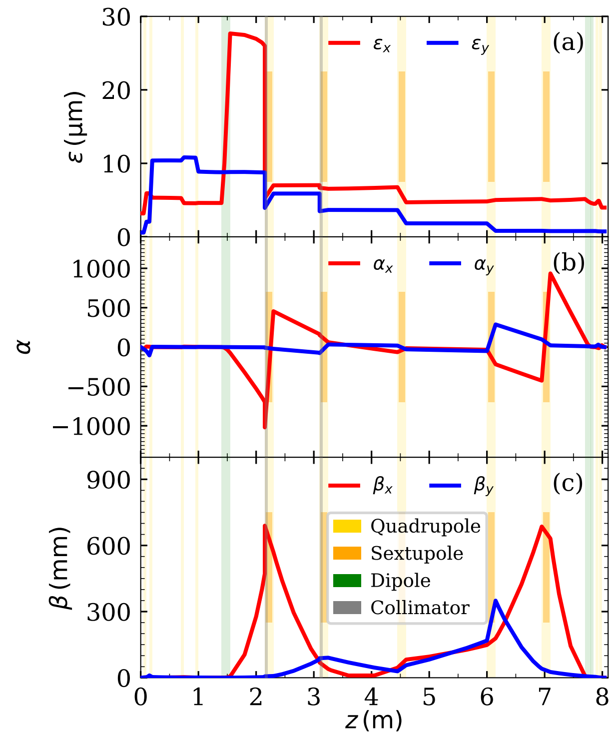

Figure 4: Evolution of the beam through the dogleg configuration.

CONCLUSION

The above studies of various transport lines demonstrate the capacity of classical magnetic elements configurations to drive the LWFA electron beams toward an application or a next acceleration stage, while meeting the beam requirements. This opens the path to multistage LWFAs.

The plasmaquads prove to be efficient tools capable of describing the transverse beam physics of plasma stages and transport lines at once.

Above all, the most important feature that appears and should be recommended is that beam physics studies and optimizations for LWFAs must be done in an integrated way, including studies on plasma stages and transport lines. This is the case for the present studies [8], as for the EuPRAXIA project [9] and for the AWAKE run 2c experiment injector project [7].

ACKNOWLEDGEMENTS

The authors are grateful to the CEA DACM team for fruitful discussions, especially Barbara Dalena and Nicolas Pichoff.

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