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HIGH ACCEPTANCE BEAMLINE FOR THE CAPTURE OF A LASER WAKEFIELD ACCELERATED BEAM

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Abstract

Laser wakefield acceleration, together with other types of novel acceleration techniques, has seen considerable progress of late. Together with this progress comes a question, which has only recently started to be addressed, of how to transport and utilise such beams. This is a challenge because of the high initial divergence of these beams. There are several approaches to this problem and we concentrate on one in this paper and look at the implications of it in some detail.

INTRODUCTION

Laser wakefield acceleration (LWFA) has seen substantial progress recently as have other novel acceleration techniques. However, there have been few in-depth discussions about what kind of transport is required for the accelerated bunches exiting such schemes; see for example [1,2]. Beam transport is non-trivial, as the divergence and energy spread of these bunches is much larger than from RF accelerators. Indicative initial Twiss parameters might be:

$$\beta_x = \beta_y = 0.2 \text{ mm}, \quad \alpha_x = -0.008, \quad \alpha_y = -0.043, \quad (1)$$

together with a normalised emittance of about $\epsilon_N = 30\mu$m, an energy spread of roughly $< \pm 25\%$ and an arbitrary charge.

There are two main philosophies behind the transport systems proposed for LWFA bunches. The first, and most well-known one, relies on the identification of a suitable part of the accelerated bunch with conventional parameters. This is then transported, via a standard transport line, to its end destination whilst the rest is collimated away in various ways. Most of this collimation typically takes place in the first or second centimeter after the exit of the plasma, before the start of the transport line. The second, and the one discussed in this paper, attempts the transport of the entire bunch. This means the beam quality will not be as good as that shown in [3] but the charge will be considerably higher and it may be possible to correct the quality further down the beamline. The scope of the paper is to examine the feasibility of such a beamline at 1 GeV and then to extend it to 5 GeV, if possible.

A HIGH ACCEPTANCE LINE

The present idea of a high acceptance beamline for an LWFA bunch originates in a ns-FFAG style transport used on the world's first non-scaling FFAG, EMMA [4,5] and is illustrated at the top of Fig. 1. The squares conventionally represent a number of permanent magnet quadrupoles and are arranged in a FODO style with all quadrupoles of the same strength and length. The stronger the quadrupoles are, the more efficient they will be in capturing a divergent beam. However, as we will see, there are limits. There is also a need for the FODO channel to start as close to the plasma exit as possible as this is where most of the beam is usually lost [1]. For this paper, this was assumed to be 1 cm, however, it is possible to start later but this has increased aperture implications because the beam will have blown up more by then. There are several possibilities for these permanent magnet quadrupoles, but the easiest one seems to be to make them of Halbach type as this has been shown to allow for very strong fields as well as a large apertures [6–11].

Ideally, the beam exiting the plasma cell of a laser wakefield accelerator should be focused as soon as possible [12]. In the best possible case, the focusing should start when the beam is still inside the plasma. This could mean surrounding the plasma with a plasma lens. Such ideas have been mentioned on several occasions [13–15] but are not easy to implement. Therefore, perhaps the easiest thing to do is to let the beam go into a channel with as large as possible an acceptance and address any resulting quality issues after it has been captured. An example of such a channel is shown in Fig. 1 below:

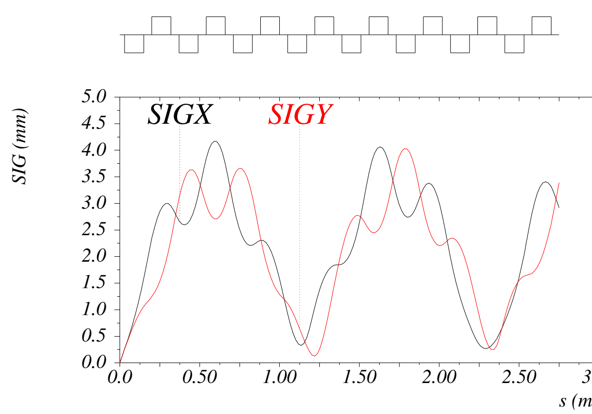

Figure 1: MAD8 modelling of an example high acceptance beamline with permanent magnet Halbach quadrupoles for a 1 GeV beam with initial parameters given by equation (1) and a normalised emittance of 30μm. The Halbach quadrupoles are 12 cm long with a 200 T/m strength and a 5 cm drift between them.

From Fig. 1, one can see that there is the usual periodicity due to the FODO channel quadrupoles as well as a super-periodic component which is just over a metre in the case shown. The first cell of the super-period starts and ends with a waist, the first of these waists starts inside the plasma, and the location of the second waist, 1.2 m away from the start

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of the line, is largely independent of the initial divergence and beam size conditions, though a higher divergence or an even smaller initial spot size clearly require a larger aperture beamline. Because the initial beam parameters (1) almost repeat themselves at the second waist, it should be possible to capture the beam at this location thereby preventing it from blowing up a second time and hence transport it in a conventional way.

The parameters to optimise in such a FODO channel are: the quadrupole length and strength together with the length of the drift between them. For the parameters considered, the maximum RMS beam sizes of 4 mm shown in Fig. 1 imply an aperture, using a $\pm 5\sigma$ criterion because LWFA bunches are very unlikely to be Gaussian in any dimension, of around ±20 mm. The initial values (1) are the ones shown in all figures contained in this paper. Of importance in this capture is the waist of the super-period, together with its location away from the plasma exit. Despite this having been found not to depend on the initial beam parameters, it was found to have a weak dependence on the length of the quadrupoles and the drifts between them. Both of these were varied together while modelling the line in MAD8 and keeping the integrated strengths the same. The results are shown in Fig. 2, where the maximum beam size is shown. The quadrupoles were varied from 4 cm at 600 T/m to 24 cm at 100 T/m. The distance between quadrupoles was varied from 0.0 cm to 10 cm. Fig. 2 shows that the best option would be the shortest quadrupole with the highest gradient.

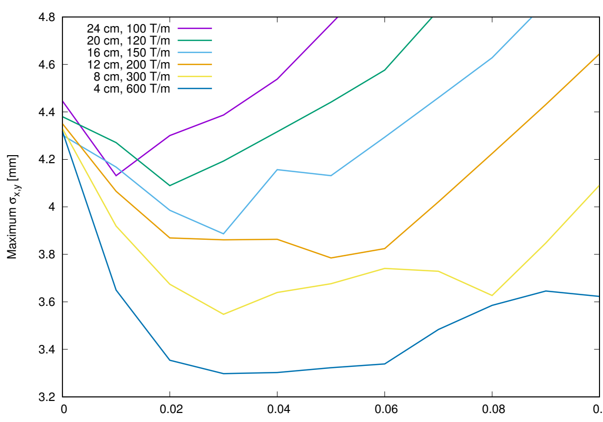

Figure 2: Maximum beam size $\sigma_{x,y}$ (at 1 GeV vs. drift length for different Halbach quadrupoles types with the same integrated strengths. The mid-point (5 cm) on the brown curve corresponds to the case shown in Fig. 1

However, a gradient of 600 T/m, with a 4 cm length is not yet realistic and the same can be said about the next option of quadrupole (8 cm and 300 T/m), therefore, we choose the 12 cm long quadrupole at 200 T/m. With a waist of the super-period at around 1.2 m, together with a drift length of 5 cm between quadrupoles, this appears to be a good option to keep the aperture requirements down whilst still focusing the beam in the most effective and physically realisable way possible. Note that the options with very short drifts between the quadrupoles of the channel do not improve things at all as larger apertures would be required, together with the requirement for a longer beamline as the second waist would be further away.

Note that the line is chromatic and different energies reach the second horizontal waist in different places. A ±25% energy spread results in a second horizontal waist spread over 1.2 ± 0.35 m at 1 GeV together with a difference in maximum beam size of ±25%. This could be compensated through the use of sextupoles but would require a non-zero dispersion throughout the line and is the subject of further investigations [16]. The whole beamline could be curved, for example, like a ns-FFAG arc gantry, this could also be done with two oppositely curved sections so as to have zero net bending if required. Several achromatic FFAG beamlines have already been considered [17–19].

Once the beam has been brought to converge at a second waist, some longitudinal distance away from the plasma, it should be possible to introduce variable gradient quadrupoles so as to prevent the beam from blowing up again. These could be electromagnetic and interspersed with the Halbach permanent magnets but this would severely restrict the space available for diagnostics. Alternatively, variable gradient, permanent magnet quadrupoles presented in [20, 21], could be used instead of the Halbach ones.

VARIABLE ENERGY HIGH ACCEPTANCE LINE

Energies ranging from 1 to 5 GeV were considered and, with some aperture implications, it was possible to transport all of them, assuming the initial parameters are the same as those given in the 1 GeV case (1). In Fig. 3 below we show how a 5 GeV beam behaves in exactly the same beamline that was used for 1 GeV earlier. The location of the waist changes and is now at around 6 m rather than 1.2 m so a longer FODO channel is required. With the parameters given at the entrance of the line, this gives a maximum RMS beam size of 18 mm, which would require a beam pipe aperture of around ±90 mm. As this would imply a very large aperture beamline, together with all the associated non-linearities due to the beam being too large, the settings were further investigated. As expected, the higher energy beam requires higher gradients and, whilst these cannot be provided, the same gradients can be present for a longer distance. Given that the chosen quadrupoles are permanent magnets, their polarity cannot be changed.

However, it should be possible to add a mechanism to the outside of some of the magnets so that they can be rotated by 90°, this means that, whilst the field cannot be changed, the polarity of the rotated magnets can be effectively reversed. Hence, it is now possible to focus the beam for longer in each plane whilst at the same time bringing the second horizontal waist closer to the plasma exit. There are several ways this can be done. The first is by creating alternating focusing and defocusing doublets and is presented in Fig. 4. This

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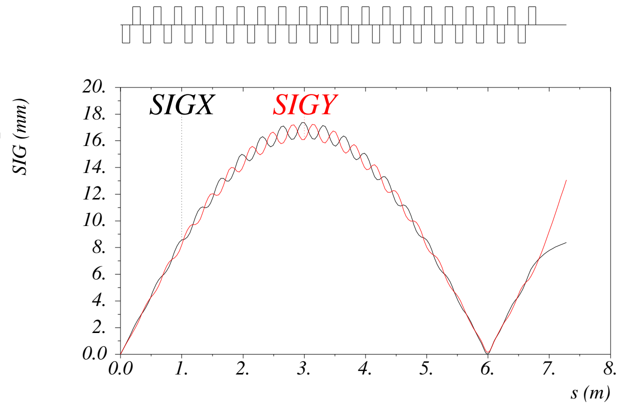

Figure 3: MAD8 modelling of an example high acceptance beamline with permanent magnet Halbach quadrupoles for a 5 GeV beam with initial parameters given by equation (1) and a normalised emittance of 30μm. The Halbach quadrupoles are 12 cm long with a 200 T/m strength and a 5 cm drift between them.

brings the second waist from 6 m to 3.5 m and reduces the aperture requirement from around ±90 mm to around ±55 mm. The second is done by creating alternating focusing and defocusing triplets and is presented in Fig. 5 for the first cell only. This brings the second waist even closer to roughly 2.3 m but the aperture required remains almost identical at ±50 mm. Any longer focusing or defocusing n-tuplets were found to be ineffective at focusing the beam in both planes simultaneously. Further, the last option leads to the second horizontal waist not taking place in both planes at the same time.

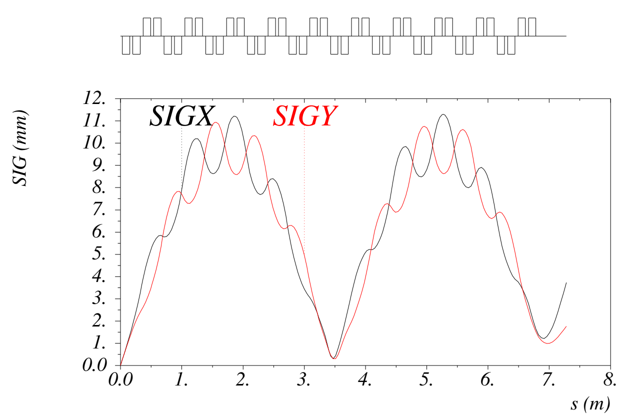

Figure 4: MAD8 modelling of an example high acceptance beamline with permanent magnet Halbach quadrupoles for a 5 GeV beam with initial parameters given by equation (1) and a normalised emittance of 30μm, with doublet focusing. The Halbach quadrupoles are 12 cm long with a 200 T/m strength and a 5 cm drift between them.

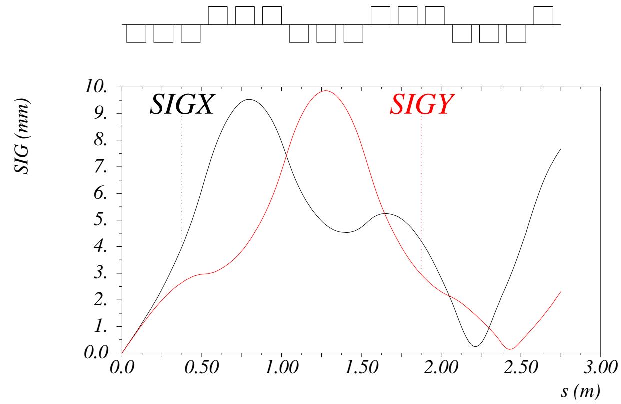

Figure 5: MAD8 modelling of an example high acceptance beamline with permanent magnet Halbach quadrupoles for a 5 GeV beam with initial parameters given by equation (1) and a normalised emittance of 30μm, with triplet focusing. The Halbach quadrupoles are 12 cm long with a 200 T/m strength and a 5 cm drift between them.

CONCLUSIONS

A possible high acceptance beamline for LWFA was presented. It comprises of a quadrupole FODO channel, whose length is to be determined, and can be operated anywhere from 1 GeV to 5 GeV. Higher energies can also be accommodated, even if the quadrupole gradients remain the same, as long as there are corresponding aperture and focusing length increases. The number of quadrupoles required to bring the beam to a waist from where it can hopefully be handled in the same way as a traditional beam, changes according to the energy. Therefore, if very different energies are required, it is important to be able to both add and take away quadrupoles with an additional requirement that some of the quadrupoles be motorised so as to rotate them by 90°.

The line could be realised by having a sufficiently large beam pipe, all in vacuum, and with Halbach quadrupoles placed on a longitudinal rail inside it. The rail could have small perpendicular crosses at regular intervals, where the quadrupoles can be pushed out of the way of the beam, as required. Further, screens can be added, also on this rail, so that the location of the waist can be determined experimentally. The clear advantage being that it will be possible to amend the beamline to the existing LWFA bunch exiting the plasma rather than fixing it to a particular design one from the start.

After the beam has been brought back to a waist, it should be possible to replace the Halbach quadrupoles with standard variable electromagnetic ones or variable gradient permanent magnet quadrupoles [20, 21].

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