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Staging optics considerations for a plasma wakefield acceleration linear collider

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ABSTRACT

Plasma wakefield acceleration offers acceleration gradients of several GeV/m, ideal for a next-generation linear collider. The beam optics requirements between plasma cells include injection and extraction of drive beams, matching the main beam beta functions into the next cell, canceling dispersion as well as constraining bunch lengthening and chromaticity. To maintain a high effective acceleration gradient, this must be accomplished in the shortest distance possible. A working example is presented, using novel methods to correct chromaticity, as well as scaling laws for a high energy regime.

1. Introduction

A demand for TeV-scale electron–positron colliders has resulted in linear collider design studies which, if built, will be tens of kilometers long and cost billions of dollars. This has motivated an interest in cheaper and more compact accelerator technologies seeking to provide higher acceleration gradients.

Plasma wakefield acceleration (PWFA) is one of several new concepts, in which two consecutive charged particle beams are sent through a plasma, quickly and efficiently transferring energy from one beam (the drive beam) to the other (the main beam). These beams need to be very small, both transversely and longitudinally, in order to excite a sufficiently large electric field (the wakefield) to form an accelerating cavity in the plasma.

In order for the main beam to reach energies significantly higher than that of the drive beam, this process must be repeated in multiple stages. The plasma cells must be separated by beam optics which swaps out the depleted drive beam and focuses the diverging main beam back into the next cell. Since a shorter optics section gives a higher effective acceleration gradient, it is important to minimize its length.

2. Requirements

A linear collider requires very low emittance beams to reach the luminosity target. In order to preserve these emittances, all the way to the interaction point, a number of requirements must be met by the optics section between plasma cells. The goal is to find the shortest lattice which satisfy all these requirements.

We will assume beam and plasma parameters as defined in the PWFA linear collider study [1], where plasma cells operate in the non-linear blowout regime [2]. The main beam has an rms energy spread σ_E around 1%, a bunch length of $\sigma_z = 20$ μm, and normalized emittances of $\epsilon_{N,x} = 10$ μm and $\epsilon_{N,y} = 35$ nm. The drive beam has energy $E_d = 25$ GeV, and the plasma has an electron density of $n_p = 2 \times 10^{16}$ cm^{-3}, providing a gain of $\Delta E = 25$ GeV per cell. The emittance budget requires each stage to preserve emittance to the 1%-level.

2.1. Drive beam injection and extraction

Injecting the drive beam only a few 100 μm in front of the main beam is too short for any kicker. However, dipoles can be used to combine and separate the two beams by utilizing their difference in energy.

2.2. Beta matching

The plasma cavity formed by the drive beam has strong linear focusing forces. If the β-function of the main beam is not properly

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matched [2], the beam envelope will oscillate and the projected emittance increases. The Twiss [3] matching condition at the plasma cell is

$$\beta_x = \beta_y = \beta_{mat} = \frac{\sqrt{2\gamma}}{k_p}, \tag{1}$$

$$\alpha_x = \alpha_y = 0, \tag{2}$$

where k_p is the plasma wavenumber and γ is the Lorentz factor. For our parameters, $\beta_{mat} = 2.3$ cm at 100 GeV.

2.3. Dispersion cancellation

The drive beam injection/extraction dipoles also disperse the main beam, due to its energy spread. Very small emittances require cancellation of dispersion:

$$D_x = D'_x = 0, \tag{3}$$

where D_x is the first-order dispersion. Higher order dispersions may also require cancellation to avoid emittance growth.

2.4. Isochronicity

The dipoles form a chicane with a non-zero longitudinal dispersion R_{56}. This leads to bunch lengthening or compression, which alters beam loading and the energy spread might increase. To avoid this we require

$$R_{56} \lll \frac{\sigma_z}{\sigma_E}, \tag{4}$$

which is $O(1\text{ mm})$ for our parameters.

2.5. Chromaticity cancellation

Placing quadrupoles immediately before and after the plasma will focus the drive and main beams differently due to their energy difference, hence injection/extraction dipoles should be placed between the plasma and quadrupoles. However, this allows tightly focused main beams to diverge significantly after exiting the plasma, resulting in a large chromatic amplitude W. Since emittance growth from chromaticity is given by $\Delta\epsilon/\epsilon_0 = 1/2W^2\sigma_E^2 + O(\sigma_E^4)$, we require

$$W_x = W_y = 0, \tag{5}$$

in which case the σ_E^4-term will dominate chromatic emittance growth.

3. Drive beam injection and extraction

3.1. Symmetry between injection and extraction

After plasma interaction, particles in the rear of the drive beam will have lost a significant fraction of their energy, but those in the front will remain at the injected energy. We assume that injection and extraction may be treated as inverse processes using the same optics, but in reverse order. This enforces either a mirror symmetric (C) or rotationally (S) symmetric chicane (Fig. 1). The C-chicane has less total bending, producing less synchrotron radiation, whereas the S-chicane places injection and extraction on opposite sides, freeing up space for beam dumps and diverting radiation away from drive beam distribution and injection systems.

3.2. Injection/extraction dipole length

In order to reduce chromaticity, the distance to the first quadrupole should be minimized. The two beams will separate in the dipole by a distance

$$\Delta x = \frac{1}{2} l_d^2 Bce \left(\frac{1}{E_d} - \frac{1}{E_m} \right), \tag{6}$$

where l_d is the dipole length, B is the dipole magnetic field strength, and E_m is the main beam energy.

A defocusing quadrupole placed next to the dipole can be used to further separate the beams, hence shortening the necessary dipole length. However, it also focuses the drive beam and leads to larger dispersion. Injector/extractor design has not been studied in detail in this work.

3.3. Dispersion cancellation

Although C and S-chicanes intrinsically cancel dispersion, they do not in the presence of quadrupoles. This can be corrected by either appropriately matching quadrupoles or by introducing extra dipoles. However, quadrupole dispersion matching is not independent of beta and chromaticity matching, further complicating their simultaneous matching. Adding extra dipoles allows dispersion cancellation independently of quadrupole matching.

Using a mirror symmetric quadrupole lattice, a single extra dipole per side is necessary, satisfying $D'_x = 0$ for C-chicanes or $D_x = 0$ for S-chicanes at the point of symmetry.

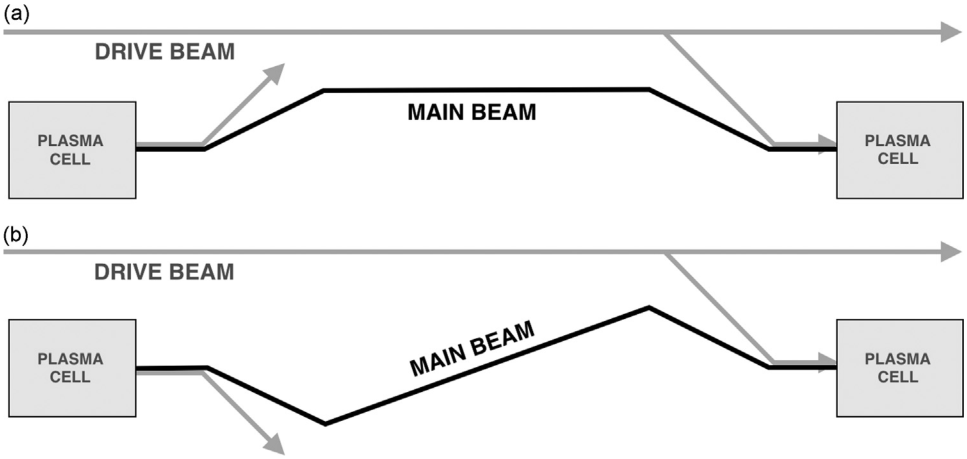

Fig. 1. Symmetric layouts for injection/extraction dipoles. A mirror symmetric C-chicane is shown in (a), and a rotationally symmetric S-chicane is shown in (b).