CONSIDERATIONS FOR A DRIVE BEAM SCHEME FOR A PLASMA WAKEFIELD LINEAR COLLIDER

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Abstract

The potential for high average gradients makes plasma wakefield acceleration (PWFA) an attracting option for future linear colliders. For a beam-driven PWFA collider a sequence of cells has to be supplied with synchronised drive beam bunches. This paper is concerned with the generation, transport and distribution of these drive beam bunches in a so-called drive beam complex for a 3 TeV collider. Based on earlier concepts, several modifications are suggested. The new design includes a superconducting linac and an optimised bunch delay system with a tree structure. To verify the feasibility for the overall complex, a lattice design and tracking studies for the critical bending arc subsystem are presented. Also the feasibility of a compact bunch separation system is shown. The result of these efforts is a drive beam complex that is optimised for construction cost and power efficiency that favours unified lattice solutions.

INTRODUCTION

The application of plasma wakefield acceleration technology (PWFA) [1–3] to future linear colliders allows reducing the overall length of these single pass machines significantly. A crucial subsystem of a beam-driven PWFA collider is the drive beam complex, since it has a strong impact on the overall cost and the power efficiency. In the drive beam complex, a train of N_b drive beam bunches is accelerated, transported and distributed to the individual plasma cells. In this paper, a design for such a drive beam complex for a 3 TeV collider is proposed, which is based on the concept presented at [4]. The design aims to minimise construction cost and power consumption and favours simple system solution. The proposed design is motivated by an analysis of advantages and disadvantages of earlier proposed schemes [5–7].

The chosen drive beam parameters are summarised in Tab. 1. They have been adopted from [6], where a detailed optimisation has been performed. The main difference is the bunch separation that has been reduced from 4 ns to 2 ns. The most critical parameter is the drive beam energy E_{DB}. Higher values lead to a larger main beam energy gain per plasma cell, but also to stronger synchrotron radiation effects and longer bending arcs.

DRIVE BEAM ACCELERATOR

Combiner Ring Option

The design [6] foresees a CW superconducting recirculating linac that accelerates the drive beam bunches with a bunch separation of 1.66 μs. This separation is then reduced to 4 nm by injecting the beam into an accumulator ring with 1 km circumference. This scheme is supposed to supply a 1 TeV collider, but it is difficult to adapt to higher collision energies. For a 3 TeV collider, the 25 GeV electron beam would have to be transported for 64 turns in the combiner ring, which would cause an average energy loss of 17%. Even more severely, the preservation of the bunch length and the beam quality in general is a very challenging task. Therefore, an alternative schemes is proposed in the following, where the electron bunches are already accelerated as a train with a 2 ns bunch separation, which avoids the use of a combiner ring.

Table 1: Drive Beam Parameters

Energy	E_{DB}	25 GeV
Emittance	ϵ_x, ϵ_y	10 μm
Bunch length RMS	σ_z	40 μm
Charge	Q	2×10^{10}
Repetition rate	f_{rep}	10 kHz
Bunch number	N_b	2×64
Bunch separation	ΔT_b	2 ns

Pulsed Beam with Superconducting Linac

The design of the superconducting linac is strongly influenced by the amount of necessary stored RF energy in the cavities. The accelerated 2×64 bunches of the drive beam contain a total energy of 9.6 kJ, but the stored RF energy has to be significantly higher. This is necessary to limit the energy spread along the drive beam train due to transient beam loading. To reduce the stored RF energy, the bunch repetition rate and the cavity frequency are slightly detuned to create a phase slip, which compensates the beam loading partially. Due to this technique, an energy spread of <1% can be reached with about 5×9.6 kJ of stored energy. The energy spread and/or the stored RF energy could be further reduced by linearising the energy spread with a few cavities operating at higher harmonic frequencies. ILC-type cavities [8] are proposed that are scaled to a frequency of 1 GHz. Assuming a quality factor Q_0 of 2×10^{10}, the linac has a length of 4.3 km and the necessary cryogenic cooling power is 10 MW. The effective gradient is 80% of 7.3 MV/m due to the beam loading compensation. A frequency reduction to 0.5 GHz has to potential to optimise the design due to the higher expectable Q_0 values.

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Delay Scheme

After the drive beam is accelerated, it is transported to the entry of the main linac. The last bunch of the drive beam has to be synchronised with the main beam bunch to create acceleration in the first plasma cell. The other drive beam bunches have to be delayed compared to the main beam bunch by $(n-1)\Delta T_b$, where n is the plasma cell index and ΔT_b is the drive beam bunch separation. A small ΔT_b is preferable to ease the delay task, but the bunch separation has to be large enough to allow the separation of individual bunches with kicker systems.

Three different delay schemes have been considered. The layouts of option A and B are illustrated in Fig. 1. Option A

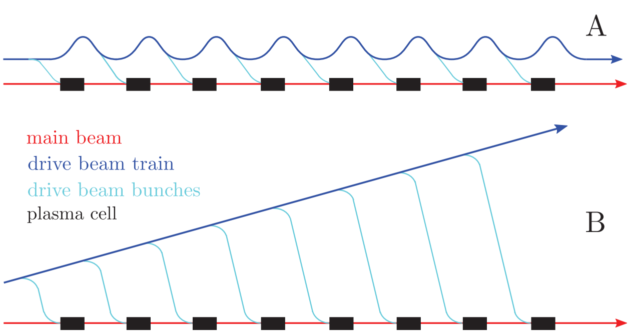

Figure 1: Illustration of the delay scheme options A and B (not to scale).

has already been suggested in [6]. It possesses the attractive feature that drive and main beam can be housed within one tunnel. The disadvantage of this scheme is that strong bending is required to delay the drive beam by 2 ns within the 31 m between two consecutive plasma cells. Even when assuming a filling factor of 100%, 5 T superconducting dipole magnets are needed to create the necessary bending radius of 1 m. The energy loss due to incoherent synchrotron radiation (ISR) is about 2% per arc, which is not compatible with the necessary utilisation of superconducting magnet technology. It should be mentioned that even though a constant plasma cell separation has been assumed, resent studies [9] show that this distance will most likely have to be prolonged with increasing main beam energy. Such a separation change can be incorporated in the presented delay scheme, however.

Option B is very similar to an earlier proposed scheme using turn around arcs [5]. It allows using larger bending radii, which enables the application of normal conducting magnet technology. At the same time, the energy loss due to ISR can be reduced. The disadvantage of this scheme is that every plasma cell is supplied via a separate tunnel, which causes a high facility cost.

Since option A suffers from strong ISR effects and option B requires a very long tunnel system, the intermediate option C is proposed as a solution, which is depicted in Fig. 2. The overall distribution system possesses a three layer tree structure. On each layer the drive beam is split into four parts such that $4\times4\times4=64$ plasma cells can be supplied.

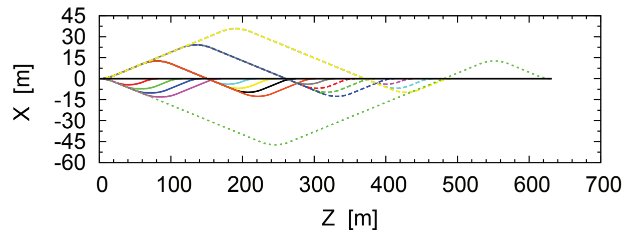

Figure 2: Footprint of the tree-like delay scheme option C for the first 20 bunches.

This reduces the drive beam tunnel length to 10.5 km of which 5.1 km are filled with bending arcs. All bending arcs are of equal length and bending angle, namely 40.5 m and 440 mrad, respectively. Each bunch passes 3.5 such bending arcs on its way, including a half arc just before the plasma cell. This corresponds to a constant path length offset for all drive beam bunches compared to the main beam. Therefore, for a main linac section of length L, only the corresponding straight drive beam section have to be considered to evaluate the the effective path length difference ΔL as

$$\Delta L = \left(\frac{1}{\cos(\theta)} - 1\right) L, \tag{1}$$

where θ is the angle between main and drive beam, which is 220 mrad for the chosen design. Since the bending arc is a critical subsystem, a lattice has been designed and tracking simulations have been performed.

Chicane Design

To verify the feasibility of option C, a corresponding chicane has been designed. The lattice is a double arc and accounts for 2 of the 3.5 bending arcs each bunch passed on its way to the plasma cell. The angle θ between the drive and main beams is set by the 2 ns requirement, however the length of each delay system is determined by the strength of the dipole magnets, the bending filling factor, assumed to be 1 T and 80% respectively, and the horizontal geometrical constraint. θ which is found to be 220 mrad, is provided by normal conducting magnets, due to radiation issues, which increases the length of the delay lines and the main beam line accordingly.

An array of *FODO* cells filled with 6 dipoles, to bend the beam by $+\theta$ and $-\theta$, conform half of the chicane. A short matching section with 2 quadrupoles is required to set $\alpha_{x,y} = \eta'_x = 0$ at the middle point of the beam line. The complete chicane is created by mirroring the first half. The obtained chicane by means of MAD-X [10] is isochronous (R_{56} < mm) and achromatic ($\eta_x < 100\,\mu$m). Each quadrupole is independently powered to reduce the fifth synchrotron radiation integral to $< 10^{-5}\, m^{-1}$ for minimizing the impact of incoherent synchrotron radiation (ISR). Additionally, 5 families of sextupoles have been optimized by means of MAPCLASS [11] to reduce $\Delta\epsilon_{x,y} \leq 2\%$ and the second order coefficient T_{566}. Figure 3 shows the Twiss functions throughout the chicane.

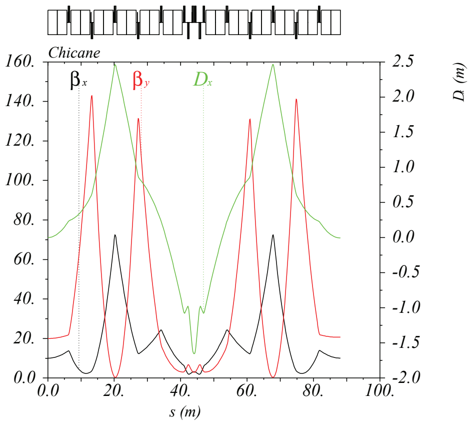

Figure 3: Twiss functions throughout the chicane that corresponds to two bending arcs, which are the basic building blocks of the delay system.

PLACET has been used to estimate the impact of ISR and coherent synchrotron radiation (CSR). Gaussian beam distributions have been assumed for the transverse planes, whereas for the longitudinal plane, a characteristic $z - E$ distribution obtained after compressing the beam to 40 μm, has been considered in order to realistically estimate the effect of CSR. The assumed beam parameters are $\gamma\epsilon_{x,y} =$ 10 μm, $\sigma_z(core) = 40\ \mu m$, $\frac{\Delta p}{p} = 1\%$ and $2{\times}10^{10}$ particles. Table 2 summarises the obtained spot sizes and emittances whether ISR and CSR are activated or not for 200000 e^-. A total $\Delta\epsilon_x$ of 164 μm has been found. Considering that the design corresponds to 2 bending arcs, a final ϵ_x of about 300 μm is expected for the full transport through 3.5 bends.

Table 2: Obtained emittances and spot sizes at the exit of the chicane whether ISR and CSR are switched on/off.

ISR	CSR	ϵ_x	ϵ_y	σ_x	σ_y	σ_z
		$[\mu m]$	$[\mu m]$	$[\mu m]$	$[\mu m]$	$[\mu m]$
OFF	OFF	12	10	53	66	40
ON	OFF	141	10	151	66	40
OFF	ON	59	10	121	66	41
ON	ON	174	10	184	66	41

Bunch Separation

The individual drive beam bunches are separated from the rest of the drive beam train via kicker systems. The rise time of these kicker systems determines the minimal drive beam bunch separation ΔT_b and is therefore a critical parameter for both the drive beam accelerator and the drive beam delay system. A bunch separation ΔT_b of 2 ns was chosen, which corresponds to the fastest available kicker system [12]. Adding ten individual kickers to a combined 2 m long system allows deviating the 25 GeV beam by 0.05 mrad.

Considering a septum width of 2 mm and a necessary bunch to septum separation of 1 mm, a transverse bunch-to-bunch distance of at least 4 mm has to be created with this kick. Additionally, the bunch-to-septum separation has to be $\geq 3\,\sigma_x$, to minimise losses, where σ_x is the horizontal beam size. The most stringent space constraint is present at the lowest level of the drive beam tree structure due to the plasma cell separation of 31 m. Therefore, a preliminary system has been designed that is capable of separating the corresponding four beams within a distance of 21 m. Three kicker systems each of 2 m length are positioned behind each other. While the first kicker system applies a kick of 0.05 mrad only to the last of the four bunches, the second kicker system kicks the last two bunches, and so on. The kicker systems are followed by a series of focusing and defocusing quadrupole magnets that create a bunch-to-bunch separation of 4 mm and a relative bunch-to-septum separation of 3.15 σ_x. The β-functions along this system are between 6 m and 130 m, the final dispersion is 12.7 mm, and the bunch lengthening is negligible.

CONCLUSIONS

The design of a drive beam complex for a 3 TeV linear collider based on PWFA is presented. A superconducting linac accelerates the drive beam trains already with the final bunch separation of 2 ns, which avoids the use of a combiner ring. The accelerated bunches are transported and delayed in a distribution system with tree structure with a total tunnel length of 10.5 km. A sample lattice for the critical bending arcs of the distribution system has been designed, which employs 1 T normal-conducting dipole magnets and has a total length of 40.5 m. Tracking studies show that the impact of especially ISR increases ϵ_x strongly to about 300 μm. Future plasma simulations will have to verify if this value is acceptable. Using a low-emittance lattice cell for the arc design instead of a FODO lattice could also mitigate some for the emittance growth. Also, a design for the bunch separation scheme is presented. It is capable of satisfying the stringent space limitations imposed by the plasma cell separation. A reduction of the drive beam energy, which would require a higher transformer ratio, could ease many aspects of the drive beam complex design, at the price of tighter plasma cells tolerances.

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