CONCEPTUAL DESIGN OF THE DRIVE BEAM FOR A PWFA-LC*

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Abstract

Plasma Wake-Field Acceleration (PWFA) has demonstrated acceleration gradients above 50 GeV/m. Simulations have shown drive/witness bunch configurations that yield small energy spreads in the accelerated witness bunch and high energy transfer efficiency from the drive bunch to the witness bunch, ranging from 30% for a Gaussian drive bunch to 95% for bunch with triangular shaped longitudinal profile. These results open the opportunity for a linear collider that could be compact, efficient and more cost effective than the present microwave technologies. A concept of a PWFA-based Linear Collider (PWFA-LC) has been developed by the PWFA collaboration. Here we will describe the conceptual design and optimization of the drive beam, which includes the drive beam linac and distribution system. We apply experience of the CLIC drive beam design and demonstration in the CLIC Test Facility (CTF3) to this study. We discuss parameter optimization of the drive beam linac structure and evaluate the drive linac efficiency in terms of the drive beam distribution scheme and the klystron / modulator requirements.

INTRODUCTION

To study new insights of the universe working principle, energy regimes beyond the reach of today's accelerators need to be explored. The International Linear Collider (ILC) [1] will reach ½ to 1 TeV C.M. energy with superconducting (SC) microwave technology which provides an acceleration gradient of 35MV/m. For Next Linear Collider (NLC) [2], normal conducting (NC) microwave technology was adopted with reliable gradient of 65MV/m for collider-ready structures. The technology for a Multi-TeV Linear Collider, CLIC [3] is being developed by a world-wide multilateral collaboration of volunteer institutes with NC structures and 100 MV/m accelerating gradients. Plasma Wake-Field Acceleration (PWFA) holds much promise for advancing the energy frontier because it can potentially provide a 1000-fold or more increase in gradient. The experiments conducted at SLAC FFTB have demonstrated a gradient in excess of 50GeV/m can be sustained in an 85 cm-long plasma [4]. Relativistic plasmas can be robust, stable and disposable accelerating structures at ultra-fast timescale (λ ~ 100 μm) compared with SC and NC conventional ones (λ ~ 1-30 cm). There is no beam break up (BBU) but there is the two-stream instability. Simulations have shown drive/witness bunch configurations that yield small energy spreads in the accelerated witness bunch and high energy transfer efficiency from the drive bunch to the witness bunch, ranging from 30% for a Gaussian drive bunch to 95% for shaped longitudinal profile. Although there may be a tight aligning tolerance between the drive and witness bunches, a plasma accelerator is still one of the most promising routes to a cost-effective TeV-scale linear collider.

We developed a concept of PWFA-based Linear Collider (PWFA-LC). Here we will describe the conceptual design and optimization of drive beam, which includes the drive linac and distribution system. We apply experience of the CLIC drive beam design and demonstration in the CLIC Test Facility (CTF3) [5] to this study. We discuss parameter optimization of the drive linac structure and evaluate the efficiency in terms of the drive beam distribution scheme and the klystron / modulator requirements.

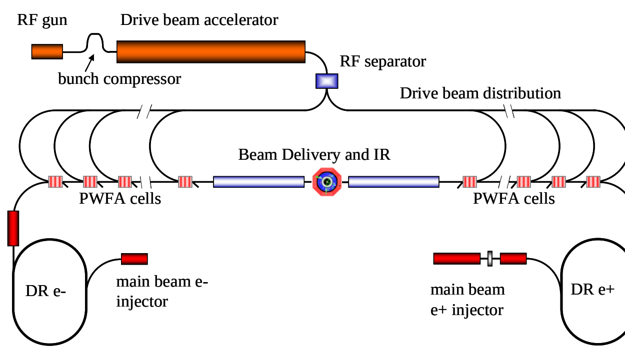

Fig. 1: Concept for a multi-stage PWFA Linear Collider.

PWFA-LC CONCEPT

Several ideas for a PWFA-LC have been suggested in the past based on the "afterburner" concept [6], which can be single stage or multi-stage [7]. Based on an attempt to find the best design that takes advantage of the PWFA and conventional linear collider concepts with a reasonable set of R&D milestones that would be realized over the next ten years, we proposed the concept shown in Fig. 1, key parameters corresponding to a TeV Linear Collider can be found in Ref. [8]. The PWFA-LC design consists of a conventional 25 GeV electron drive beam accelerator, which produces drive bunches distributed in counter-propagating directions to the 2×20 PWFA cells for both the electron and positron arms of the collider. Each cell provides 25 GeV energy to the main beam over about a meter long plasma cell. A geometric accelerating gradient of 250 MV/m is assumed when taking into account the plasma cell filling factor along the linac. Thus, the length of each 500 GeV linac is ~ 2 km.

DRIVE BEAM

The main beam bunch train consists of 125 bunches with 10^10 e^-/e^+ per bunch, each separated by 4ns. To

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reduce the cost, only one drive linac is used. Correspondingly, the drive beam train should be composed by 20 mini-trains (20 plasma cells) each with 250 (125 × 2) bunches separated by 2ns. One RF deflector can be used to split the drive beam with the scheme shown in Fig. 2, there is 180° phase shift between the drive beam to the electron and positron arms of the linear collider.

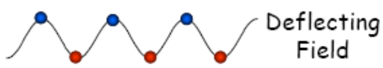

Fig. 2: Drive beam separation by transverse deflector.

Klystron / modulator requirements

Klystron / modulator requirements set up the maximum allowable drive beam pulse length. The drive linac was selected to run at 2856MHz of S-band. The SLAC 5045 klystron and modulator can achieve reliable 67 MW at 3.5 μs / 120Hz [9]; the SLAC built S-band klystron used at S-band Test Facility at DESY has performance of 150 MW at 3μs / 50Hz [10]. The scaling of the SLAC 5045 klystron to longer pulse length suggests 26MW with 0.1% duty cycle (8 μs@125 Hz) would be straightforward [11].

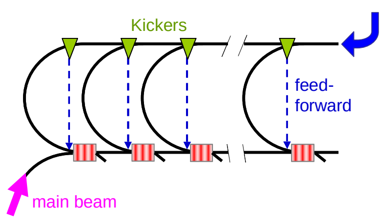

Fig. 3: Drive beam distribution system and PWFA cells.

Drive Beam Distribution System Requirements

The minimum drive beam pulse length is limited by the drive beam distribution system shown in Fig. 3. Similar to CLIC, the drive beam propagates in the opposite direction with respect to the main beam, so the mini-train spacing between 1st bunch of current mini-train to that of the next mini-train for the drive beam must be equal to two times of the PWFA cell spacing (90m or 600ns/2 in our conceptual design). The mini-train spacing should also be long enough to accommodate the rise time of the kickers of the distribution system; a reasonable value of 100 ns kicker gap was selected based on the SLAC / NLC kicker design of ~60ns rise / fall times [2]. The arcs shown in Fig. 3 are used for dispersion correction, matching and beam diagnostics for position feed-forward.

Drive Beam Linac

Considering the future development and reliability of both klystron / modulator and kicker technologies, the drive beam train configuration with bunch population 2.9×10^10 shown in Fig. 4 was chosen. Klystron / modulator were selected to run at ~ 30 MW, ~ 12μs (active pulse length ~ 10 μs), 100Hz.

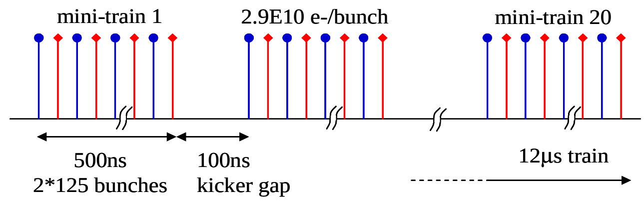

Fig. 4: Drive beam train configuration.

High beam power and efficiency are necessary for any realistic linear collider. 35% power transfer efficiency from the drive beam to the main beam was chosen with a gradient of ~ 25 GeV/m. To get high overall wall plug to main beam efficiency, the RF to drive beam efficiency should be as high as possible with ~50% wall plug to RF efficiency. Based on the successful demonstration of 95% RF to beam efficiency for fully loaded accelerating structure in the CTF3 [5] and PWFA-LC drive beam train configuration shown in Fig. 4, a novel type of Slotted Iris Constant Aperture (SICA) structure similar as CLIC drive linac [12] shown in Fig. 5 with ~ 90% RF to drive beam efficiency will be used. SICA structure has 4 radial slots in each iris, which are designed to have neglectable effect on the fundamental (FM) mode properties, while are used to damp the dipole modes. After passage of beam through this kind of structure, the induced dipole mode will be transported to the ridged waveguides by the slotted irises, and finally be absorbed by the SiC loads. The dipole modes' Q_{ext}'s in SICA structure are designed to be very low (~ 20). To further suppress the dipole mode, nose cones with different sizes can be introduced to each cell to create detuning [13]. Combing both damping and detuning, the dipole mode induced by one bunch will only have a very small tolerable effect on the following bunches.

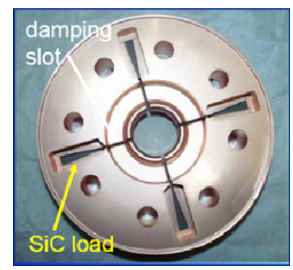

Fig. 5: SICA structure.

The structure consists of ~ 40 cells and approximately 1.5 m long with FM mode's Q_0 of 13000. It will operate at 2π/3 mode with average beam current 2 A (peak current 2.3 A). For NC constant gradient (CG) traveling wave (TW) structure, the RF to beam conversion efficiency can be expressed as [14]

$$\eta_b^{RF} = \frac{2g(\tau)}{\left[1-\frac{e^{-2\tau}}{g(\tau)}\right]} \times \frac{k_b \Delta_b \omega}{Q\left[1+\frac{(k_b-1)\Delta_b \omega}{2Q\tau(1-\delta)^2}\right]} \times \frac{\delta}{(1-\delta)} \qquad (1)$$

To get high η_b^{RF}, beam loading parameter δ should be ~ 50%, which means fully loaded, no power goes to the load and the loaded gradient G_a is half of the unloaded gradient G_u. For PWFA-LC, the bunch number k_b can be looked as infinite, and then η_b^{RF} can be simplified as

$$\eta_b^{RF} = \frac{2\tau g(\tau) J}{\left[1+\frac{J}{2}\left(1-\frac{e^{-2\tau}}{g(\tau)}\right)\right]^2} \tag{2}$$

When $\eta_b^{RF} = \eta_{b,\max}^{RF}$, we have

$$\frac{d\eta_b^{RF}}{d\tau} = 2J_u e^{-2\tau_{opt}}\left(1-J_u\tau_{opt}\right) \Rightarrow \tau_{opt} = \frac{1}{J_u} = \frac{1}{J(1-\delta)} \tag{3}$$

$$\eta_{b,\max}^{RF} = J_u\left[1-g\left(\frac{1}{J_u}\right)\right] = J_u\left[1-\frac{J_u}{2}(1-e^{-(2/J_u)})\right] \tag{4}$$

Since $\eta_b^{RF} \approx 90\%$, the normalized unloaded and loaded beam currents $J_u = J(1-\delta) \approx 5.98$, $J \approx 11.96$. The optimized attenuation factor will be $\tau_{opt} \approx 0.17$. Based on the following relation,

$$L_s = \frac{2Qv_g\tau_{opt}}{\omega} = \frac{2Qv_g}{\omega J(1-\delta)} \tag{5}$$

The group velocity can be calculated to be $2\%c$, which is about 60% of that for CLIC 3 GHz SICA structure [15]. The structure's filling time is ~250 ns. Due to $v_g \propto (a/\lambda)^3$, the iris diameter will be ~31 mm. According to the definition of normalized current,

$$J = \frac{R'q_b}{G_a\Delta_b} = \frac{R'I_b}{G_a}, J_u = J(1-\delta) = \frac{R'q_b}{G_u\Delta_b} \tag{6}$$

Where q_b is bunch charge, Δ_b bunch spacing, R' shunt impedance ($R' \propto \omega^{1/2}$ for normal conducting structure, here R'~40.8 MΩ/m), the loaded gradient G_a and unloaded gradient G_u will be 6.7 MV/m and 13.4 MV/m with ~ 15% margin considered. Table 1 lists all of the drive linac structure parameters. To bring the drive beam energy to 25GeV, the drive linac should be consisting of ~2500 structures with total length ~ 4 km.

Table 1: Drive Linac S-Band SICA Structure Parameters

Frequency	2856MHz
Operating Mode	2π/3
Attenuation Factor	~ 0.17
Structure Type	Slotted Iris Constant Aperture
Filling Time	~ 250 ns
FM Mode's Q_0	~ 13000
Dipole Mode's Q_{ext}	~ 20
Peak Current	2.3A
Loaded Gradient	6.7MV/m
RF to Beam Efficiency	90%

SUMMARY

Conceptual design and optimization of PWFA-LC drive linac have been made. The drive beam spacing can be doubled by addition of a RF deflector and delay beam line at the end of drive beam linac but keeping the drive linac configuration, if the main beam bunch spacing was found to be too short. Increasing the bunch spacing by orders of magnitude could be done with a stretching ring, where the entire drive train would be stored and then bunches would be extracted one-by-one with fast rise time kicker. Alternatively, a SC linac can be used for very long bunch spacing as well.

To get the best performance, the fully loaded structure usually operates with pulsed continuous beam [12], i.e. no mini-train spacing during each beam pulse. Nonetheless, in our PWFA-LC concept, the drive beam is not pulsed continuous but with 100 ns mini-train spacing, the best performance of 90% RF to drive beam efficiency might be compromised, further studies still need to be made. One way to cure this is to operate the drive linac with pulsed continuous beam but with the beam during the 100ns spacing dumped at the nearby of RF separator or the end of both the electron and positron arms, which will not be transported to the plasma cells for wakefield generation.

ACKNOWLEDGEMENTS

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