SIMULATIONS OF 25 GEV PWFA SECTIONS: PATH TOWARDS A PWFA LINEAR COLLIDER*

C. Huang, W. An, C. Clayton, C. Joshi, W. Lu, K. Marsh, W. Mori, M. Tzoufras,
UCLA, Los Angeles, CA, USA
T. Katsouleas, Duke University, Durham, NC, USA
I. Blumenfeld, M.J. Hogan, N. Kirby, T. Raubenheimer, A. Seryi, SLAC, Menlo Park, CA, USA
P. Muggli, USC, Los Angeles, CA, USA

Abstract

Recent Plasma Wake-Field Acceleration (PWFA) experiments at Stanford Linear Accelerator Center has demonstrated electron acceleration from 42 GeV to 84 GeV in less than one meter long plasma section. The accelerating gradient is above 50 GeV/m, which is three orders of magnitude higher than those in current state-of-art RF linacs. Further experiments are also planned with the goal of achieving acceleration of a witness bunch with high efficiency and good quality. Such PWFA sections with 25 GeV energy gain will be the building blocks for a staged TeV electron-positron linear collider concept based on PWFA (PWFA-LC). We conduct Particle-In-Cell simulations of these PWFA sections at both the initial and final witness beam energies. Theoretical analysis of the beam-loading [1] in the blow-out regime of PWFA and simulation results show that highly efficient PWFA stages are possible. The simulation needs, code developments and preliminary simulation results for future collider parameters will be discussed.

PWFA-LC CONCEPT

The next linear collider at TeV scale will require high energy (500 GeV) electron and positron beams with high luminosity, high beam power and high quality. For electron beam acceleration, the blowout regime of the plasma wakefield acceleration has demonstrated the possibility of electron acceleration by accelerating the tail of a 42 GeV electron beam to 84 GeV in plasma [2]. Such an experiment can be further refined by splitting the beam charge into two distinct bunches using a collimator during the bunch compression stage. Ideally these two bunches should be separated with distance close to the plasma wake wavelength. The first bunch (drive beam) will excite the plasma wakefield while the second bunch (main beam) will be placed in the appropriate accelerating phase in the wake. The goal is to at least double the energy of the main beam within a short distance while achieving small energy spread and emittance preservation. Two linear collider designs based on PWFA in the blow-out regime are currently envisioned, PWFA afterburner and PWFA-LC. In PWFA afterburner design, both bunches have initial energy of 250 GeV. The second bunch can be accelerated to 500 GeV in about 25 meters in a plasma of density $n_0 = 5.7 \times 10^{16}\mathrm{cm}^{-3}$ in a single stage [3]. The PWFA-LC design adopt a multi-stage approach and a beam train format similar to the Compact Linear Collider (CLIC) that is based on two-beam acceleration concept. Here the acceleration is done in plasma while RF acceleration structure is used in CLIC. In the PWFA-LC concept, the non-linear beam-plasma interaction inside the plasma cell essentially determines characteristics of the accelerated beam. Some of the central questions that need be addressed for such a PWFA stage are :

- large acceleration gradient ($>$ GeV/m),
- sufficient main beam charge ($\sim 10^{10}$ electrons),
- high beam quality with low energy spread ($0.1\% \sim 1\%$),
- high total efficiency ($30\% \sim 90\%$) from drive beam to wake and then from wake to main beam.

In this paper we present a preliminary study of electron acceleration in individual PWFA stages for a TeV linear collider. All drive beams have nominal energies of 25 GeV. The main beam will obtain 25 GeV energy gain in each PWFA stage. Detail simulations using quasi-static Particle-In-Cell code QuickPIC [4] are performed to test the design of a single 25 GeV PWFA stage. With 19 such PWFA stages, the main beam will reach 500 GeV required for collider.

DESIGN OPTIONS

Staging

Staging reduced the technical difficulty for creating and using long PWFA sections, it also provides benefit for reducing the hosing instability as hosing induced in a single stage can be properly corrected between successive stages. Furthermore the hosing growth scales as $(k_\beta L)^{-1/2} e^{(k_\beta L)^{1/3}}$, where k_β is the betatron wavenumber and L is the length of each stage. For fixed total acceleration distance NL, where N is the number of stages, shorter PWFA stages have smaller amount of total hosing growth due to the exponential dependence of hosing on L.

Plasma Density

Current state-of-art facility can produce electron beams with about 2×10^{10} electrons and bunch length on the order of $10 \sim 100\,\mu$m . For two-bunch experiment, bunch

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separation is around 100 μm. These parameters indicate that the plasma wavelength needs to be a few hundreds of μm in order to place both bunches at the right phase of the wakefield. We use $n_0 \sim 10^{16}\,\mathrm{cm}^{-3}$, which gives a non-relativistic plasma wavelength of $2\pi c/\omega_p \sim 300\ \mu$m and a accelerating field of $E_+ \sim 10$ GeV/m.

Longitudinal Beam Pofile

The longitudinal current profile of both the drive and main beams are of importance for efficient transfer of energy between the beams and the plasma. It is shown that in the non-linear blow-out regime, a wedge or trapezoidal shaped beam with a profile described by Eq. (5) in [1] is best for a constant wakefield within the beams.

In our simulation for PWFA-LC, the drive beam current rises linearly from the head to the tail with a trapezoidal shape. A triangular precursor is added to ensure that Eq. (5) of [1] is valid within the main body of the drive beam. This profile gives a constant decelerating wakefield inside the beam except for the region of precursor (see Fig. 1). The main beam with a properly chosen trapezoidal profile can flatten the longitudinal field in the region where the beam resides, reducing the final energy spread of the main beam.

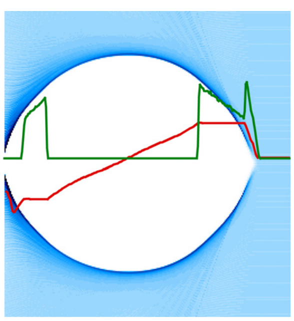

Figure 1: The longitudinal profiles (green curve) of the drive and main beams and the longitudinal wakefield (red curve) produced by these beams. The blue and white background are plasma and the ion channel, respectively.

Transverse Beam Profile

The transverse profile of both drive and main beams are Gaussian. The spot sizes of the beam are chosen to be matched to the focusing strength of the ion channel in the PWFA blow-out regime. The emittance chosen in the simulation is consistent with the recent PWFA experiment conducted at SLAC. However, such a matched emittance will cause significant head erosion for the drive beam [3]. Either using a larger spot size or a smaller emittance at the beam head may reduce the head erosion. Here for simplicity we choose the latter option.

Beam Charge and Transformer Ratio

In principle, the charge of the main beam can be as high as $N_{main} = N_{drive}/R$, where N_{main}, N_{drive} are the charge of the main and drive beams respectively. $R = |E_+/E_-|$ is the transformer ratio, E_+ and E_- are the accelerating and decelerating fields, respectively. For smaller R, more charges can be accelerated. However generally R should be larger than 1 to ensure sufficient energy gain by the time the drive beam energy is depleted. Moreover, the acceleration process could be terminated before energy depletion by beam head erosion if not controlled. Therefore in the simulation, R is chosen to be 1.22. The hosing instability could potentially cause main beam to lose charge starting from its tail, and shorter main beam is less susceptible to hosing instability, so we intentionally shorten the bunch length to make trade-off for stable acceleration.

SIMULATION SETUP

The physical simulation parameters are listed in Table 1. Two simulations are conducted, corresponding to the first/last stage of a 19 stages PWFA-LC. The initial main beam energy in these two simulations are 25 GeV and 475 GeV, respectively. Other parameters are identical for these two simulations. Both simulations use 1024 $\times$ 1024 $\times$ 256 grids with 8.4 $\times$ 10^6 particles for each beam and 4 particles per cell for the plasma. The simulation box size is $1000 \times 1000 \times 247\,\mu\mathrm{m}^3$. The time step is 60 ω_p^{-1} and the total number of time steps is 440.

Table 1: Simulation Parameters for PWFA-LC

	Drive beam	Main beam
Charge	$(0.82 + 3.6) \times 10^{10}$	1.73×10^{10}
Bunch Length	$(13.4 + 44.7)\ \mu$m	$22.4\ \mu$m
Emittance	10 / 62.9 mm·mrad	62.9 mm·mrad
Spot size	$3\ \mu$m	$3\ \mu$m
Plasma density	$5.66 \times 10^{16} cm^{-3}$	
Plasma Length	0.59 m	
Transformer ratio	1.22	
Loaded wakefield	42.7 GeV/m	

SIMULATION RESULTS

The simulation results are shown in Figs. 2 and 3. Figure 2 shows the beam/plasma evolution in the simulations in a window co-moving with the beams in the +z direction. Head erosion can be seen for the drive beam, however the accelerating structure remains stable during propagation. Even though the initial beam spot size and emittance are matched to the plasma density, beam spot sizes still oscillate as the beam energies are either decreased or increased. This effect is due to the energy dependence of focusing on a beam and can be seen in Fig. 2. Overall the main beams have gain 25 GeV in the simulation with small energy spread (0.4% / 0.3% for the 25 / 475 GeV stage respectively) (see Fig. 3). The efficiency for energy transfer from the drive beam to the main beam is 51%.

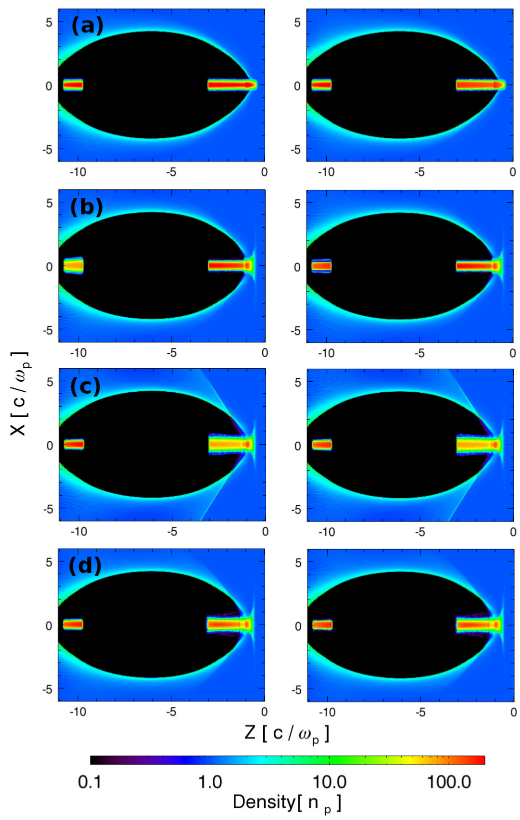

Figure 2: Beam and plasma density at four different locations in 25 GeV (left column) and 475 GeV (right column) PWFA-LC stages. (a) propagation distance s = 0m; (b) s = 0.2 m ; (c) s = 0.38 m ; (d) s = 0.59 m. Beams are shown in red, plasma and ion channel are shown in blue and black, respectively.

SIMULATION NEEDS AND CODE DEVELOPMENTS

In the case of a future collider beam with very low emittance, the spot sizes are extremely tight. To simulate the required transverse dimensions of the main beam in an actual linear collider, the transverse resolution needs to be 1000 times higher compared to current simulation resolution. For example, transverse beam size in a conceptual PWFA-LC design [5] is $140 \times 3\ \mathrm{nm}^2$, while the simulation box size would be on the order of $200 \times 200\ \mu\mathrm{m}^2$, therefore one needs roughly $4000 \times 200000 \times 500$ grids. This means that the requirement on time step will be prohibitive if one would use a full PIC model. It also represents a significant challenge for quasi-static PIC code. We are currently extending the pipelining algorithm [6] to allow QuickPIC to scale to Petaflop computing platform. Separating the resolutions for the beam and the plasma would also be an option to reduce problem size.

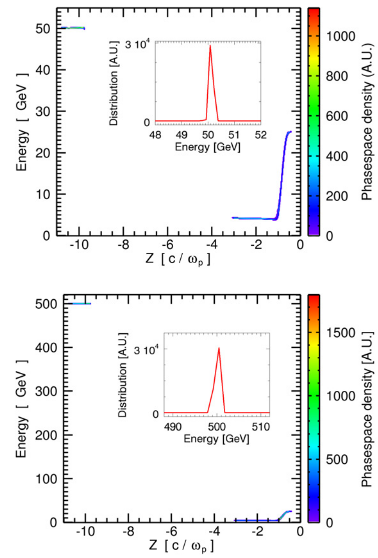

Figure 3: Phase space of the drive and main beams at the end of the acceleration in the 25 GeV (upper plot) and 475 GeV (lower plot) PWFA stages. The insets are the energy spectra of the main beams after acceleration. The FWHMs of the spectra are estimated to be 0.4% and 0.3%, respectively.

CONCLUSION

Designing PWFA-LC for a TeV collider scenario is challenging. Theoretical understandings of the blow-out regime and beam-loading make it possible to optimize PWFA-LC designs for this goal. The nonlinear dynamics of the electron beam-plasma interaction in the PWFA-based Linear Collider (PWFA-LC) concept has been investigated using quasi-static PIC code QuickPIC. A preliminary design of the plasma and electron beam parameters in PWFA stages with initial main beam energy of both 25 GeV and 475 GeV energies is examined for a one TeV PWFA-LC. The simulation results show that it is possible to accelerate high quality beam in PWFA-LC with narrow energy spread with high efficiency. Modeling tools which include all the relevant physics such as beam-loading, hosing, head erosion, ion motion, and radiation loss are needed and being developed for further investigation.

REFERENCES

[1] M. Tzoufras et al., Physical Review Letters 101, 1-4 (2008).

[2] I. Blumenfeld et al., Nature 445, 741-4 (2007).

[3] C. Huang et al., Proceedings of PAC 2005, pp. 2666-2668, 16-20 May 2005.

[4] C. Huang et al., Journal of Computational Physics 217, 658-679 (2006).

[5] A. Seryi et al., this proceedings.

[6] B. Feng et al., Journal of Computational Physics, In Press, DOI: 10.1016/j.jcp.2009.04.019.