A CONCEPT OF PLASMA WAKE FIELD ACCELERATION LINEAR COLLIDER (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 a shaped longitudinal profile. These results open the opportunity for a linear collider that could be compact, efficient and more cost effective that the present microwave technologies. A concept of a PWFA-based Linear Collider (PWFA-LC) has been developed and is described in this paper. The drive beam generation and distribution, requirements on the plasma cells, and optimization of the interaction region parameters are described in detail. The R&D steps needed for further development of the concept are also outlined.

A PWFA-LC CONCEPT

The requirements for an electron-positron linear collider in the TeV energy range are well understood from 20 years of conceptual design work based on conventional rf cavity acceleration systems. The high gradients possible with plasma wakefield acceleration may provide a path to a new lower cost approach to achieving these energies. However, a practical collider must also meet the luminosity requirements imposed by the physics goals, which is the order of $10^{34}cm^{-2}s^{-1}$. To achieve this high luminosity requires beams of about ten MW average power, which are low emittance and can be focused to nanometre size for collisions. A practical collider technology must also have high power transfer efficiency into the beam.

Several ideas for plasma wakefield-based linear colliders (PWFA-LC) have been suggested in the past. The "afterburner" [1] is an approach that uses short plasma sections to double the energy of a conventional rf linear collider just before the collision point. Each beam is split into pairs of microbunches with the first driving a plasma wake that accelerates the second. Luminosity of the energy-doubled collider is maintained by employing plasma lenses to reduce the spot size before collision. A multiple-stage PWFA-LC concept has been suggested at the 2006 Advanced Accelerator Workshop [2], which is essentially a multi-stage afterburner employing a high-charge beam with multiple bunches and multiple plasma cells to reach high energy. One implementation would use a 100 GeV drive beam and five (four if the incoming witness bunch also has 100 GeV) plasma stages to accelerate the main beam to 500 GeV.

The design presented here is an attempt to optimize the advantages of PWFA and conventional linear collider concepts, based on a reasonable set of R&D milestones that could be realized over the next ten years. This approach benefits from the extensive R&D for conventional linear colliders and has relatively relaxed requirements on the plasma acceleration systems while still potentially lowering the cost. These considerations led to a larger number of PWFA stages and imposed specific requirements on the parameters for the main and drive beams. This PWFA-LC concept addresses these requirements, and, in contrast to the approaches discussed above, uses an electron drive beam for both electron and positron main beams. This design will evolve with better understanding of plasma wakefield physics based on future experimental results and simulation studies. Therefore, it is crucial to maintain flexibility in the parameter space for a PWFA linear collider.

The design for a PWFA-based Linear Collider is shown schematically in Figure 1 and the key parameters are in Table 1. This approach uses established concepts for the particle and drive beam generation and focusing systems based on twenty years of linear collider R&D. However, this constrains the plasma acceleration systems if they are to provide the needed high beam power and efficiency. These constraints are summarized in Ref. [3] which describes a 10 TeV linear collider design. The proposed plasma wakefield research program at FACET is designed to demonstrate the viability of this concept.

This PWFA-LC design uses a conventional 25 GeV electron drive beam accelerator, to produce trains of drive bunches distributed in counter-propagating directions to 20 PWFA cells for both the electron and the positron arms of the collider to reach energy of 500 GeV for each beam. Each cell provides 25 GeV of energy to the main beam in about a meter of plasma. The layout and parameters were chosen to optimize PWFA performance while also providing feasible parameters at the interaction point and a practical design for the main beam injector and the drive beam acceleration and distribution system. The drive beam system is very similar to the CLIC drive beam concept which is being tested at the CTF3 test facility [4].

The main beam bunch train consists of 125 bunches, each separated by 4 ns. The drive beam train consists of 20 mini-trains each with 250 bunches separated by 2 ns (as described in details in [11]). An RF separator splits the drive beam before it is sent to the distribution system. There are 100 ns gaps between each mini-train in the drive beam train, to accommodate the kicker rise time. To

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allow for the counter-propagation distribution of the drive beam, the distance between PWFA cells must be equal to half of the distance between mini-trains, i.e. 600 ns/2 or about 90 m.

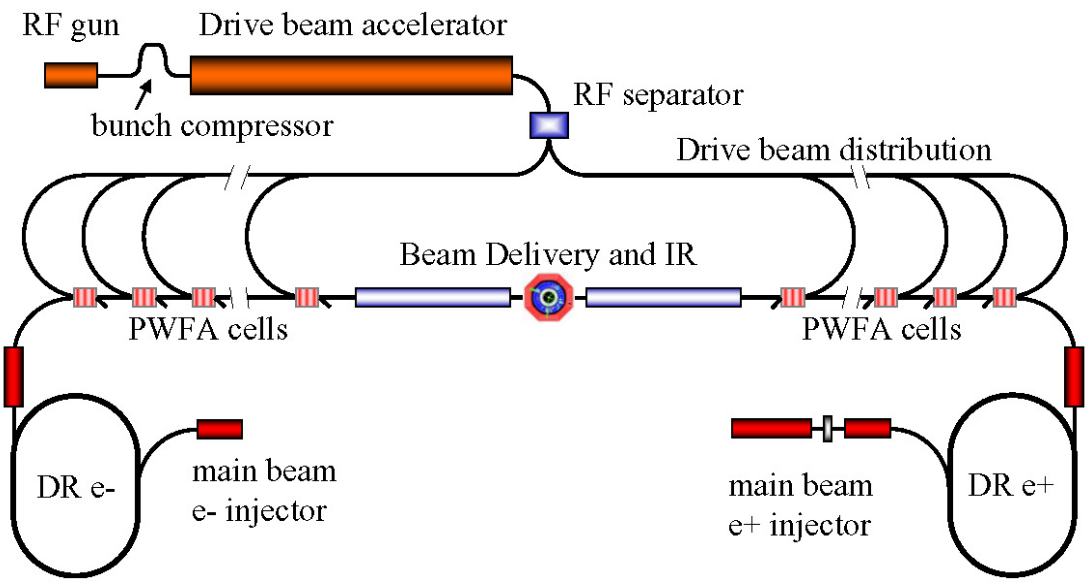

Figure 1: Concept for a multi-stage PWFA-based Linear Collider.

Table 1: Key Parameters of the Conceptual Multi-Stage PWFA-based Linear Collider

Main beam: bunch population, bunches per train, rate	1×10^{10}, 125, 100 Hz
Total power of two main beams	20 MW
Drive beam: energy, peak current and active pulse length	25 GeV, 2.3 A, 10 µs
Average power of the drive beam	58 MW
Plasma density, accelerating gradient and plasma cell length	1×10^{17}cm^{-3}, 25 GV/m, 1 m
Power transfer efficiency drive beam=>plasma =>main beam	35%
Efficiency: Wall plug=>RF=>drive beam	50% × 90% = 45%
Overall efficiency and wall plug power for acceleration	15.7%, 127 MW
Site power estimate (with 40MW for other subsystems)	170 MW
Main beam emittances, x, y	2, 0.05 mm-mrad
Main beam sizes at Interaction Point, x, y, z	0.14, 0.0032, 10 µm
Luminosity	3.5×10^{34} cm^{-2}s^{-1}
Luminosity in 1% of energy	1.3×10^{34} cm^{-2}s^{-1}

Properties of the drive and main beam bunches have been optimized by particle-in-cell simulations using the code QUICKPIC [5,13]. The main beam bunch charge is 1.0×10^{10} particles with a Gaussian distribution. A plasma density of 10^{17}cm^{-3} and a drive bunch charge of 2.9×10^{10} were chosen to achieve a power transfer efficiency from the drive beam to the main beam of 35% with a gradient of roughly 25 GV/m. The drive beam bunch length is 30 µm while the main beam bunch length is 10 µm and the drive-main beam bunch separation is 115 µm. The separation between the two bunches must be approximately equal to the plasma wavelength.

The parameters and luminosity at the interaction point (IP) were optimized for the high beamstrahlung regime, which is inherent to short bunch length colliders [6]. The luminosity within 1% of the nominal center-of-mass energy is 1.3×10^{34} cm^{-2}s^{-1}, which is similar to that in the International Linear Collider (ILC) design [7]. The relative energy loss due to beamstrahlung is about δ_B = 30%. The main beam emittances are typical for TeV collider designs, and the β-functions at the IP are $\beta_{x/y}$ = 10/0.2 mm. These IP parameters are quite close to those for CLIC [8]. Previous physics studies for the interaction region and detector design, background and event reconstruction techniques [9] are all applicable.

The main beam generation complex could be similar to that of the CLIC design with a polarized electron source and a conventional positron source. The plasma acceleration process maintains beam polarization, and would also accommodate a polarized positron beam. The damping rings would store multiple trains of bunches, one of which would be extracted on each 100 Hz machine cycle. The extracted beams would be compressed in multi-stage bunch compressors before injection into the plasma linac. Provided that the beam emittances can be preserved in the PWFA linac, the requirements on the main beam generation complex are not very different from that of the CLIC design.

The drive beam accelerator is a heavily loaded linac that achieves a high efficiency of power transfer to the beam by using a high peak current and a low gradient. Various options are possible; in particular, the design of the CLIC drive linac [8] has similar features. With the S-band structure (see [11] for details), a peak current of 2.3 A gives a 6.7 MV/m loaded gradient and 90% RF to beam efficiency. A slotted-iris, constant aperture (SICA) structure significantly reduces the dipole Q and decouples the dipole motion of the drive beam bunches. This accelerator structure is very similar to those operating in the CTF3 test facility where 95% rf to beam efficiency has been demonstrated [4]. The drive beam for PWFA-LC is described in mode detail in [11].

The drive beam distribution system consists of kickers with a 100 ns rise time that distribute drive beam mini-trains into return arcs followed by dogleg magnetic combiners. These combiners use the difference in energy of the drive and main beams to merge the two before the PWFA cells. Similar doglegs are installed at the exit of the cells for beam separation. A preliminary design has shown that an isochronous magnetic combiner is feasible, with emittance growth less than 0.3 mm-mrad at maximum beam energy. The combiners also focus the beams to the matched β-functions at the entrance of the PWFA cell, with $\beta_{x,y}$ = 2.3 cm for a plasma density of n = 1×10^{17}cm^{-3} at 500 GeV energy, and scaling as $(E/n)^{1/2}$, where n is the plasma density.

Although the alignment and timing tolerances in the PWFA-LC system have not yet been studied in detail, the design is based on conventional linear collider concepts, and the scale of the tolerances in the beam generation and focusing systems are similar to those in the conventional designs. Furthermore, the drive beam determines the plasma channel when using field ionization, so the primary tolerances will be related to the *relative* alignment and timing between the drive and main beams and to the plasma stability. These tolerances are expected to be very tight and will require advanced feedback and stability control [3,10]. The damping rings and drive beam delivery paths provide an opportunity for feedforward and these systems should be able to maintain the sub-picosecond timing requirements. Similarly, transverse feedforward systems and fast intratrain feedback systems should be able to stabilize the relative transverse positions of the drive beam and main beam at the required sub-micron level. These requirements are not so different from those in the conventional rf linear collider designs.

The option of a superconducting drive linac with a longer rf pulse length would simplify the intratrain feedback stabilization and will be investigated. Tolerance issues will also be studied as part of a more detailed design.

Further plans for development of the concept, both theoretical and experimental, at the FACET facility, are outlined in [12].

CONCLUSION

A concept of a PWFA-based Linear Collider (PWFA-LC) has been developed and is described in this paper. The scheme of the drive beam generation and distribution, requirements on the plasma cells, and optimization of the interaction region parameters are given. The research and development steps needed for further development of the concept are also outlined.

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