# DESIGN OF A TeV BEAM DRIVEN PLASMA WAKEFIELD LINEAR COLLIDER*

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*Abstract*

A novel design of a 500 GeV c.m. beam-driven PWFA linear collider with effective accelerating gradient on the order of 1 GV/m and extendable in the multi-TeV energy range is presented. The main bunches collide in CW mode at several kHz repetition frequency. They are accelerated and focused with several GV/m fields generated in plasma cells by drive bunches with very good transfer efficiency. The drive bunches are themselves accelerated by a CW superconducting rf recirculating linac. We consider the overall optimizations for the proposed design, compare the efficiency with similar collider designs like ILC and CLIC and we outline the major R&D challenges.

## INTRODUCTION

Accelerating gradients in beam-driven plasmas of more than 50 GV/m have been demonstrated experimentally [1]. We base the collider design on adopting parameters similar to ILC for the main beams and assuming a 25 GeV main bunch energy gain per plasma stage of on the order of one meter length, and a resulting effective gradient of 1 GV/m. Our concept for a PWFA-based Linear Collider is shown schematically in Fig. 1 with key parameters provided in Table 1. We adopt established concepts for the beam generation and focusing systems, taking advantage of the extensive R&D for conventional rf linear colliders during the last twenty years, especially ILC [2] and CLIC [3], with a potential for a comparably lower power consumption and cost. The acceleration in plasma is a single bunch process, and this provides flexibility in the interval between bunches. In the preferred scheme the main bunches collide in CW mode at several kHz repetition frequency (unlike the ILC which collides bunch trains at 5 Hz). The main bunches are accelerated and focused in multi-GV/m fields generated in plasma cells powered by drive bunches with high transfer efficiency. The drive bunches are accelerated by a CW superconducting rf recirculating linac taking advantage of the impressive progress of the rf technology developed by ILC and providing an excellent power efficiency with a high flexibility in the number of bunches. The CW-mode operation is advantageous from the point of view of both the plasma source and the accelerator complex. However, the time structure of the PWFA-LC could also be adapted for pulsed mode operation, without significant reductions of the efficiency of the accelerator complex. This could open the possibility of an ILC energy upgrade to multi-TeV energy range without significant modifications to the ILC facility. Our concept differs significantly from the work presented in [4] in particular by the SCRF based drive beam generation, the CW operation, the co-linear drive beam distribution and more detailed power calculations.

The 500 GeV design has main beam parameters as close as possible to ILC at 500 GeV thus taking advantage of the design and R&D effort already performed in the frame of ILC. Some changes to the main beam parameters have been made; they are: charge per bunch of 1x$10^{10}$ (2x$10^{10}$ in ILC), bunch length of 20 $\mu$m imposed by plasma constraints (300 $\mu$m in ILC), 20,000 bunches per second instead of 12,500 in ILC to compensate for the luminosity reduction induced by lower charge per bunch, vertical focusing of the beam at IP with $\beta_y$ = 0.1 mm as in CLIC instead of 0.48 mm in ILC taking advantage of the reduced charge per bunch. As a consequence the vertical beam size at IP is reduced from 5.9 to 2.7 nm. Finally the total luminosity and luminosity in 1% of the peak energy are 2.1x$10^{34}$/cm$^2$/s and 1.3x$10^{34}$/cm/s respectively, slightly larger than in ILC in spite of a somewhat larger beamstrahlung (a disruption parameter of $\delta_b$ = 0.07 instead of 0.04, but still in the low beamstrahlung regime).

## PLASMA OPTIMIZATION

The present design assumes an energy gain of 25 GeV per stage and a main beam bunch charge of $10^{10}$ particles. We present here an optimization based on PWFA of an $e^-$ driver and an $e^-$ witness bunch (the main beam) in the blow-out regime, for which it has been demonstrated that the beam loading efficiency can exceed 90% for shaped trailing bunches while maintaining low energy spread and emittance [5]. The results assume the plasma ions do not move. The drive beam parameters are considered as free variables, used to minimize the main beam energy spread, maximize the drive beam to main beam energy transfer efficiency, minimize power consumption and minimize the drive beam energy. The plasma density of 2x$10^{16}$/cm$^3$ has been minimized with the constraint of still yielding 25 GeV energy gain per cell for an acceptable plasma cell length (3.3 m). By adjusting the ratio of the main bunch to drive bunch charge, for a given distance between the two bunches, the beam loading of the main bunch flattens the wake field for uniform acceleration along the bunch length [5]. The distance between the two bunches determines the ratio of the flat part of the accelerating field to the peak

* This work is supported by the Research Council of Norway and U.S. Department of Energy under contract number DE-AC02-76SF00515.
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ISBN 978-3-95450-122-9

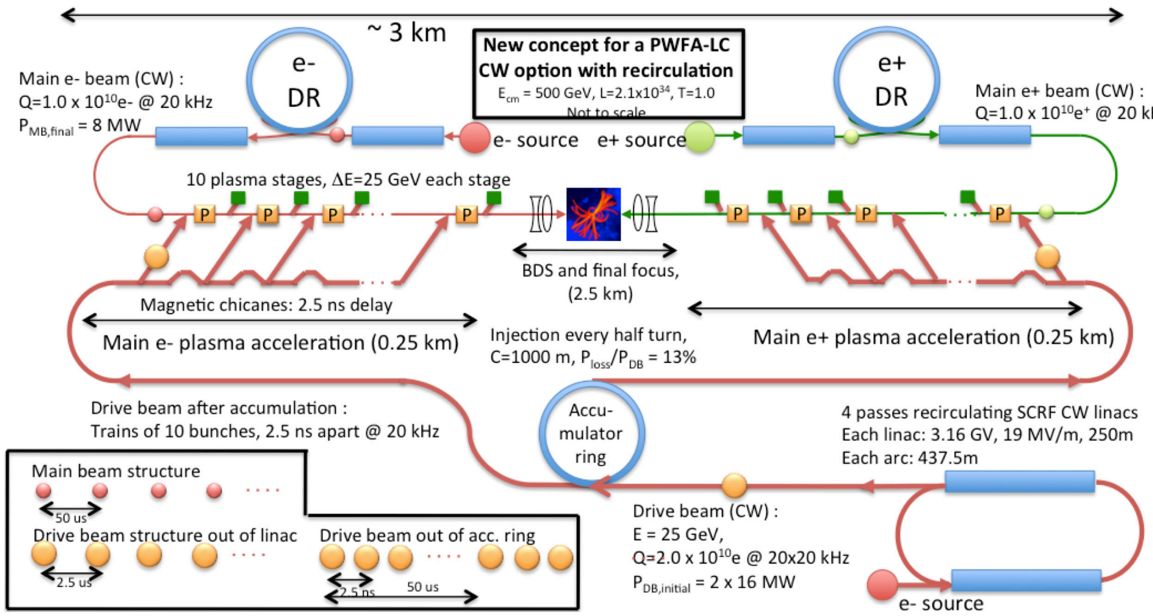


Figure 1: Layout of a 500 GeV PWFA Linear Collider. Each main bunch is accelerated by 25 GeV in each of ten plasma stages. The plasma is driven by $e^-$ bunches, generated by a SCRF CW recirculating linac, and distributed co-linearly with the main beams.

decelerating field; the transformer ratio. We design for a transformer ratio of 1[1]. A transformer ratio higher than 1 would reduce the drive beam energy, but tighten the main bunch injection tolerances, as the main bunch needs to be positioned closer to the trailing edge of the bubble. Using Gaussian beam current profiles, the optimization yields [6] a drive bunch charge of $2 \times 10^{10}$, drive bunch length of 40m (approx. the plasma wavelength/$2\pi$), a distance between the drive bunch and the main bunch of 187 um and a final main bunch energy spread of a few %. Assuming operation in the PWFA blow-out with the stated parameters and electron bunches with a Gaussian charge profile, an overall drive bunch to main bunch power transfer efficiency of 50% is achieved in QuickPIC [7] simulations. The drive to plasma transfer efficiency is 77% and the plasma to main bunch transfer efficiency is 65% [6]. For positron acceleration other regimes such as the near hollow channel proposed most recently by [8] shows promise, however precise efficiency calculations have not yet been performed for this regime.

## DRIVE BEAM GENERATION

The plasma cells are powered by trains of bunches produced using recirculating linac acceleration. Each drive bunch powers one single plasma cell accelerating one single main bunch by 25 GeV, and is then ejected to a dump. The process starts with a CW SC linac for optimum efficiency and a recirculating beam line to reduce the overall drive beam linac length and the associated cost and cryogenics power. The bunches are fed into an accumulator ring to generate the time structure required to power the plasma stages, see Fig. 1. When enough bunches to accelerate a single electron and positron bunch to their final energy have been accumulated in the ring, they are extracted and distributed to the plasma cells from a co-linear distribution system. This system uses fast kickers, small angle bends and magnetic chicanes as delay lines to satisfy the time constraints. Due to the co-linear drive beam, and exploiting the energy difference drive beam and main beam, the kick angle required for drive beam injection before a plasma stage is at most 9 mrad (varying with energy), and we foresee that a solution based on conventional technology (septa and kickers) will fulfill the timing requirements of the PWFA-LC. More details about the drive beam generation and injection/extraction can be found in [9].

[1] In the blow-out regime the transformer ratio could be chosen to be significantly larger than 1.

## POWER ESTIMATES

The estimated total wall plug power consumption of the complex is summarized in Fig. 2. It assumes 50% drive to main bunch efficiency as discussed above, a realistic power supply efficiency of 90% and a klystron efficiency of 65% (based on LEP or CEBAF experience with CW operation). With these efficiencies the rf power to accelerate the drive beam up to the requested energy of 25 GeV varies from 26 MW to 114 MW at center of mass energy of 250 GeV and 3 TeV respectively. In addition 1 MW to 13 MW have to be provided to compensate for synchrotron radiation losses in the accumulator ring. Thus the wall plug power for drive beam acceleration varies from 61 MW to 211 MW corresponding to the lion's share of the total wall power consumption. The cryogenic power of the SC linacs is only 15.7 MW using recirculation. The resulting drive beam wall-plug to drive beam efficiency is 40%, and the total beam acceleration efficiency of about 20% is particularly high thanks to the CW operation of the superconducting drive linac combined with the very good drive to beam transfer efficiency of the plasma. A power consumption ranging from 56 MW to 70 MW is added for the main and drive beam injector complexes based on CLIC estimations. The corresponding total wall plug to beam efficiency ranging from 9.1% at 250 GeV to 16.4% at 3 TeV are comparable to that of the ILC at low energy and attractive at high energy as compared with CLIC (4.8% at 3 TeV). As a consequence, the total wall plug consumption ranging from 137 MW at 250 GeV to 297 MW at 3 TeV are comparable to ILC at low energy and attractive at high energies compared with CLIC.

## CHALLENGES

The main challenges for a PWFA-LC are directly related to the beam acceleration mechanism in a plasma, in particular demonstrating proof of principles for $e^-$ and $e^+$ acceleration with high efficiency, small energy spread and small emittance dilution. At present there exists no study that demonstrates preservation of ILC level emittances in plasma for neither positrons nor electrons. The primary issues are ion motion in the plasma (which favors small main bunch densities or hollow channels) and multiple scattering (which favors small transverse bunch sizes or hollow channels) [8]. Transverse and longitudinal injection tolerances also need to be studied further. In addition, there are technical challenges for the plasma sources, as for example the several hundred kW of drive beam power deposited in each plasma stage.

## CONCLUSIONS AND OUTLOOKS

A PWFA based linear collider has the potential for high luminosity $e^-e^+$ collisions in the Multi-TeV range with reasonable power consumption, due to the very good drive to main bunch transfer efficiencies in plasma. A reasonable set of design choices for a plasma based linear collider benefits from the years of extensive R&D performed for the beam generation and focusing subsystems of conventional rf linear colliders. The linear collider concept presented here highlights the key PWFA challenges that must be addressed by further theoretical studies and experimental facilities such as FACET [10]. Over the next four years the FACET experimental program will address efficient two bunch acceleration with small energy spread and small emittance growth. Multi-stage PWFA experiments are proposed for the FACET-II facility. An extensive design and simulation effort must proceed in parallel with the experimental studies at FACET to fully develop the PWFA-LC design concepts outlined here.

## ACKNOWLEDGMENTS

We acknowledge Marc Ross for stimulating discussions. QuickPIC simulations are performed on the Hoffman2 Cluster at UCLA.

Table 1: PWFA-LC parameters for 500 and 3,000 GeV. Parameters are also available for 250 and 1,000 GeV [9].

| **Main parameters** | | |
|---|---|---|
| $E_{CM}$ [GeV] | 500 | 3,000 |
| Effective gradient [MV/m] | 1,000 | 1,000 |
| Number of bunches [$1 \times 10^{10}$] | 1 | 1 |
| Bunch spacing (CW) [$\mu$s] | 50 | 100 |
| Main beam power per beam [MW] | 8 | 24 |
| Linac length [km] | 0.25 | 1.5 |
| Overall facility length [km] | 3 | 8 |
| **IP parameters** | | |
| $\sigma_x$ [$\mu$m] | 0.47 | 0.19 |
| $\sigma_y$ [nm] | 2.7 | 1.1 |
| $\beta_x$ [cm] | 1.1 | 1.1 |
| $\beta_y$ [cm] | 0.01 | 0.01 |
| $\sigma_z$ [$\mu$m] | 20 | 20 |
| Total $L$ [$10^{34}$/cm$^2/s$] | 2.1 | 6.3 |
| $L_{1\%}$ [$10^{34}$/cm$^2/s$] | 1.3 | 3.8 |
| **Efficiency and power** | | |
| Drive to main bunch efficiency [%] | 50 | 50 |
| # of plasma stages per linac | 10 | 60 |
| Drive linac bunch rep. freq. [kHz] | 400 | 1200 |
| Drive beam power per beam [MW] | 16.2 | 48.6 |
| Total wall plug power [MW] | 150 | 297 |
| Beam acceleration efficiency [%] | 21 | 23 |
| Wall plug to main beam efficiency [%] | 11 | 16 |

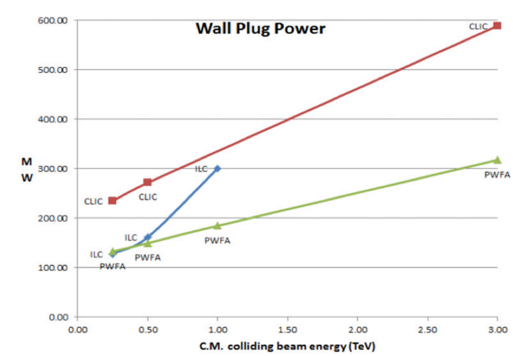


Figure 2: Total wall plug power for a PWFA-LC at various energies, assuming a drive to main bunch efficiency of 50% in the plasma, compared to ILC and CLIC.

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ISBN 978-3-95450-122-9