ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-THPRI013

A BEAM DRIVEN PLASMA-WAKEFIELD LINEAR COLLIDER FROM HIGGS FACTORY TO MULTI-TEV*

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Abstract

An updated design of a beam-driven Plasma Wake-Field Acceleration Linear Collider (PWFA-LC) covering a wide range of beam collision energy from Higgs factory to multi-TeV is presented. The large effective accelerating field on the order of 1 GV/m and high wall-plug to beam power transfer efficiency of the beam driven plasma technology in a continuous operation mode allows to extend linear colliders to unprecedented beam collision energies up to 10 TeV with reasonable facility extension and power consumption. An attractive scheme of an ILC energy upgrade using the PWFA technology in a pulsed mode is discussed. The major critical issues and the R&D to address their feasibility in dedicated test facilities like FACET and FACET2 are outlined, especially the beam quality preservation during acceleration and the positron acceleration. Finally, a tentative scenario of a series of staged facilities with increasing complexity starting with short term application at low energy is developed.

PWFA LINEAR COLLIDER CONCEPT

The concept of a beam-driven PWFA-based e^+/e^- Linear Collider [1], [2], is developed as an attempt to find a reasonable design that takes advantage of the PWFA technology, identify the critical parameters to be achieved and the necessary R&D to address their feasibility. Parameters covering a wide range of colliding beam energies from 250 GeV (Higgs Physics) up to 10 TeV, if requested by Physics for studies Beyond the Standard Model, are summarized in Table 1. A schematic layout at the extreme energy of 10TeV is shown on Figure 1. Geometric accelerating gradients on the order of 1 GV/m mitigate the extension of the facility and therefore its cost. The acceleration in plasma, being a single bunch process, provides great flexibility in the interval between bunches. In the preferred scheme, the main bunches collide in a continuous mode at several kHz repetition frequency allowing for beam-based feedbacks to stabilize the collisions. They are accelerated and focused with multi-GV/m fields generated in plasma cells powered by drive bunches with about 50% power transfer efficiency. The drive bunches are accelerated by a CW superconducting recirculating linac, taking advantage of the impressive progress in SCRF technology providing excellent power efficiency. As a result, the overall power consumption is significantly reduced (Fig. 2a) in respect with more conventional RF acceleration. The figure of merit defined as the ratio of the total luminosity to the power consumption is substantially improved especially in the multi-TeV colliding beam energy range (Fig. 2b). The above concept assumes similar behaviour of the electron and positron beams, which remains to be demonstrated.

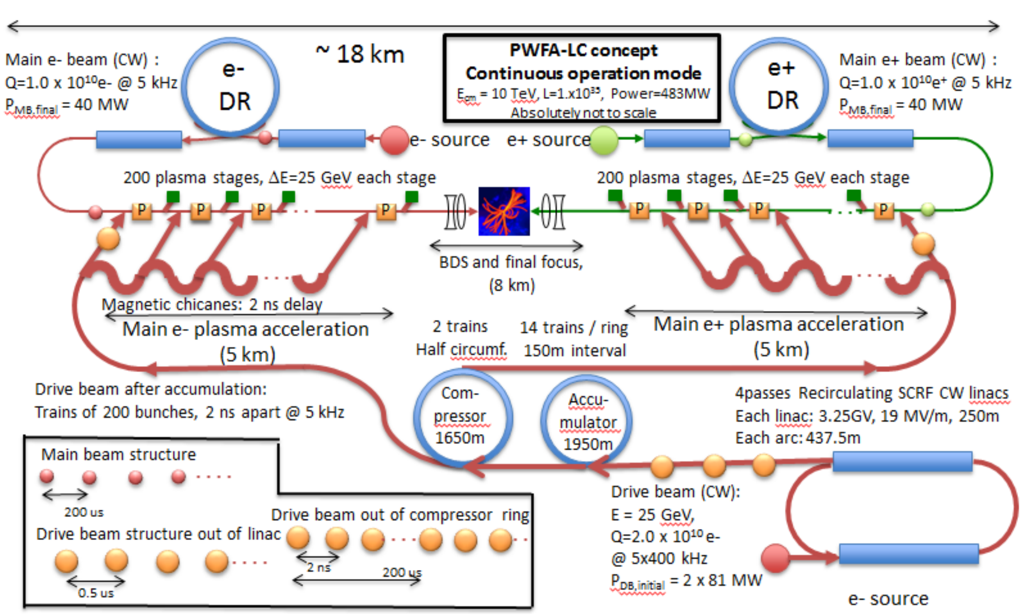

Figure 1: Layout of a PWFA-based 10 TeV Linear Collider

* Work supported by the U.S. Dept. of Energy under contracts DE-AC02-76SF00515

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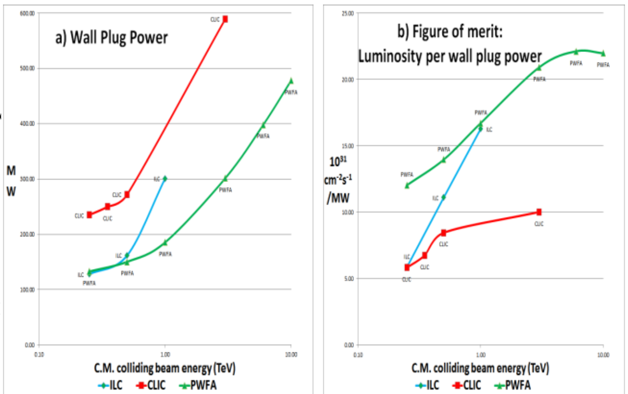

Figures 2a and 2b: Linear colliders wall plug power consumption and figure of merit defined as the ratio of the wall plug power consumption to total luminosity

Pulsed and After-Burner Modes with Application to ILC Energy Upgrade

Thanks to the flexibility of the interval between bunches, the PWFA technology can also be used in a pulsed mode to accelerate a beam with parameters and train structure similar to the one of the ILC except for the bunch length which is reduced by a factor 15 from 300 to 20 microns. After beam acceleration up to an initial energy with ILC technology, the beam could be further accelerated with PWFA technology at low cost and high efficiency. Alternatively and as first step of the ILC energy upgrade, the PWFA technology could be used as an ILC after-burner: Each ILC bunch would be split in two, one with 2/3 of the charge used as drive bunch and a second with 1/3 of the charge used as main bunch. The ILC beam energy could then be doubled without any drive beam injector complex and without substantial additional power (Table 2). Replacing the last 250 meters of ILC structures by PWFA allows TeV beam collisions without extension of the ILC tunnel (Figure 3). The ILC energy upgrade could then be pursued by adding a drive beam injector and progressive replacement of ILC structures by PWFA.

Table 1: Major PWFA-LC beam parameters

Colliding beam energy, CM	GeV	250	500	1000	3000	10000
N, experimental bunch		1.0E+10	1E+10	1.0E+10	1.0E+10	1.0E+10
Main beam bunches / train		1	1	1	1	1
Main beam bunch spacing,	nsec	3.33E+04	5.00E+04	6.67E+04	1.00E+05	2.00E+05
Repetition rate,	Hz	30000	20000	15000	10000	5000
n exp.bunch/sec,	Hz	30000	20000	15000	10000	5000
Beam power / beam at IP	W	6.0E+06	8.0E+06	1.2E+07	2.4E+07	4.0E+07
Effective accelerating gradient	MV/m	1000	1000	1000	1000	1000
Overall length of each linac	m	125	250	500	1500	5000
BDS (both sides)	km	2.00	2.50	3.50	5.00	8.00
Overall facility length	km	2.25	3.00	4.50	8.00	18.00
Drive beam						
Transfer efficiency drive to main	%	50	50	50	50	50
Drive beam power per beam	MW	12.2	16.2	24.3	48.6	81.0
Drive beam acceleration efficiency	%	39.9	42.0	44.3	45.0	45.3
Main beam acceleration efficiency	%	19.9	21.0	22.1	22.5	22.7
Wall plug to main beam efficiency	%	9.1	10.8	13.1	16.1	17.0
Total wall plug power	MW	132.9	150.4	185.5	301.3	477.9
IP Parameters						
Normalized horizontal emittance	m	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05
Normalized vertical emittance	m	3.50E-08	3.50E-08	3.50E-08	3.50E-08	3.50E-08
Horiziontal beam size at IP (1σ)	m	6.71E-07	4.74E-07	3.35E-07	1.94E-07	1.06E-07
Vertical beam size at IP (1σ)	m	3.78E-09	2.67E-09	1.89E-09	1.09E-09	5.98E-10
Bunch length at IP (1σ)	m	2.00E-05	2.00E-05	2.00E-05	2.00E-05	2.00E-05
Disruption parameter, Y		8.44E-02	2.39E-01	6.75E-01	3.51E+00	2.14E+01
delta_B	%	2.75	6.66	12.76	23.10	29.88
ngamma		0.57	0.73	0.88	1.05	1.14
Geometric Lum (cm^{-2} s^{-1})		9.41E+33	1.25E+34	1.88E+34	3.76E+34	6.27E+34
Total Luminosity (cm^{-2} s^{-1})		1.57E+34	2.09E+34	3.14E+34	6.27E+34	1.05E+35
Luminosity in 1% top energy (cm^{-2} s^{-1})		9.41E+33	1.15E+34	1.57E+34	2.51E+34	3.14E+34
Fig. merit:Luminosity/wall plug (10^{31}/MW)		11.8	13.9	16.9	20.8	21.9

Table 2: ILC energy upgrade by PWFA after-burner

Parameter	Unit	ILC	ILC	ILC + PWFA
Energy (cm)	GeV	500	1000	PFWA = 500 to 1000
Luminosity (per IP)	$10^{34}cm^{-2}s^{-1}$	1.5	4.9	2.6
Peak (1%)Lum(/IP)	$10^{34}cm^{-2}s^{-1}$	0.88	2.2	1.3
# IP	-	1	1	1
Length	km	30	52	30
Power (wall plug)	MW	128	300	175
Lin. Acc. grad.(p/eff)	MV/m	31.5/25	36/30	7600/1000
# particles/bunch	10^{10}	2	1.74	0.66
# bunches/pulse	-	1312	2450	2450
Bunch interval	ns	554	366	366
Pulse repetition rate	Hz	5	4	15
Beam power/beam	MW	5.2	13.8	13.8
Norm Emitt (X/Y)	$10^{-6}/10^{-9}$radm	10/35	10/30	10/30
Sx, Sy, Sz at IP	nm,nm,μm	474/5.9/300	335/2.7/225	286/2.7/20
Crossing angle	mrad	14	14	14
Av # photons	-	1.70	2.0	0.7
δb beam-beam	%	3.89	9.1	9.3
Upsilon	-	0.03	0.09	0.52

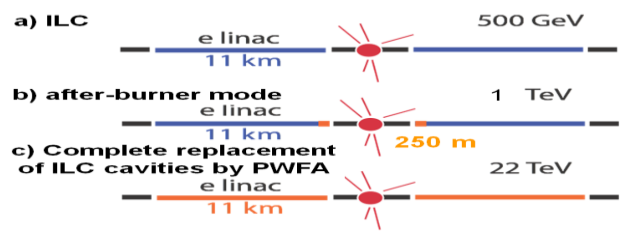

Figure 3: ILC energy upgrade by PWFA technology in the 500 GeV ILC tunnel (a), in after-burner mode (b), in the extreme case of PWFA technology use only (c).

MAJOR ISSUES AND R&D

The PWFA-LC concept is based on novel technology with key beam and plasma physics challenges, which remain to be carefully studied before the concept presented above can be validated, in particular:

- Beam acceleration with small energy spreads,
- High beam loading with both electrons and positrons,
- Development of a concept for positron acceleration with high beam brightness,
- Electron beam emittance preservation and mitigation of effects resulting from ion motion, Positron beam emittance preservation and mitigation of effects resulting from plasma electron collapse,
- Beam quality preservation with betatron radiation energy loss especially large at high energy
- Transverse and longitudinal tolerances
- Average bunch repetition rates in the 10's of kHz,
- Synchronization of multiple plasma stages and effect of alignment errors between stages,
- Optical beam matching between plasma acceleration stages and from plasma to beam delivery systems.
- Magnetic chicane with a delay of 2ns for relative phasing of the drive and main bunches

Promising performances of up to 50 GV/m fields have already been demonstrated [3]. Critical issues are presently being addressed by extensive R&D and experimental facilities such as FACET [4] presently and FACET2 [5] in the future with excellent performances already demonstrated in field, momentum spread and power transfer efficiency [6] as summarized below.

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FACET EXPERIMENTS

At FACET, PWFA two-bunch acceleration experiments were started in 2013 and are currently on going. The main goal is demonstration of high-efficiency, high-gradient witness beam acceleration, with small energy spread and emittance preservation. The chirped FACET electron beam is separated into a drive beam and a trailing beam using a finger collimator in a dispersive region. A heat-pipe oven produces a Lithium vapour with variable densities in the $10^{16}/cm^3$ - $10^{17}/cm^3$ range. The vapour is pre-ionized by a 10 TW Ti:Sa laser system. The drive to witness beam separation and charge ratio can be varied in order to adjust the beam loading and thus the efficiency. In 2013, experiments at FACET demonstrated witness beam acceleration in the blow-out regime, with an energy gain of 1.6 GeV in 36 cm of plasma, thus a gradient of 4.4 GV/m. The energy transfer efficiency from the wake to the witness beam approached 50%. The witness beam final energy spread was in the % range. The experimental results were in good agreement with PIC simulations, demonstrating a high level of understanding of the two-beam acceleration process. Preliminary results are published in [6]. The FACET electron beam emittances are about 100 µm in the horizontal plane and 10 µm in the vertical plane. PWFA emittance preservation on this level is currently being investigated experimentally in FACET. Simulations, however, indicate that due to ion motion, nm emittance preservation for electron beams is challenging in the blow-out regime. Recently, theoretical and simulations results indicate that in the quasi-hollow channel regime [7], nm emittance preservation is possible for both electron and positron witness beams.

POSITRON ACCELERATION

Unlike conventional RF accelerators, which treat electron and positron beams symmetrically, the plasma accelerator is more naturally suited to accelerate electron beams. Plasma wakes can sustain extremely large accelerating gradients when operated in the nonlinear “bubble” regime. The bubble is the region of the plasma wake where all plasma electrons have been expelled and the heavy background ions remain. The background ions contribute a strong, linear focusing force on electron beams propagating through the plasma. For positron beams, the force is defocusing. We therefore seek an alternative method of accelerating positrons in plasma that provides large accelerating gradients without transverse focusing forces.

Hollow channel plasmas offer a possible solution to this problem. In a hollow channel plasma, the plasma is confined to an annular region centred on the beam propagation axis. An electron or positron beam traveling through the centre of the channel will excite a wake in the plasma wall which provides radially uniform longitudinal fields inside the channel. A positron beam, trailing at the correct phase of the wake, will experience a large accelerating gradient. The first experiments that will probe this scheme are already underway at FACET.

CONCLUSION

Beam driven Plasma Wake-Field Accelerators (PWFA) provide an attractive novel technology with large accelerating fields and excellent power efficiency for a number of applications ranging from Photon Science to High Energy Physics. The PWFA-LC concept drives number of key beam and plasma physics challenges, which remain to be carefully studied before the concept can be validated. Many of the critical issues are being addressed at the FACET test facility at SLAC and the remaining issues may be addressed in the proposed FACET-II facility. Together these facilities will carry out the specific R&D aimed at a feasibility assessment within a decade. The promising PWFA technology may then be used for applications with strong physics interest and gradually increasing complexity in a staged approach. An informed decision about possible low energy applications could be made soon after critical issues will have been addressed in FACET-II starting to operate by 2018. One attractive low energy application could be a compact X-ray FEL with high repetition rate and high brightness based on PWFA technology (Fig. 4). Such low energy applications with possible use by mid of next decade would help to further develop and validate the technology by integration of the various systems and to get operational experience which is necessary before a more complex or higher energy application can be envisioned in the following decade.

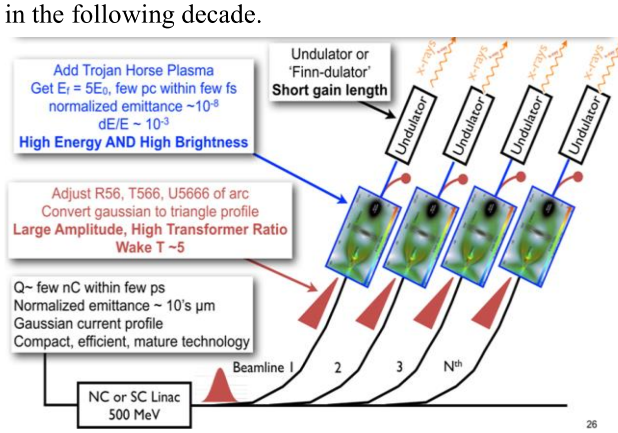

Figure 4: Layout of a PWFA based X-FEL

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