LOI for Snowmass 2021 on
Electron Beam Driven Plasma Wakefield Acceleration (PWFA)

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Perspective on Status of Plasma Wakefield Acceleration Experiments

The beam-driven Plasma Wakefield Accelerator idea was originally proposed by J.M. Dawson, P. Chen and others in the early 1980s [1]. First experiments carried out at the Argonne Wakefield Acceleration Facility (AWA) that showed that relativistic electron bunches propagating through plasmas could excite linear wakes but the electric field gradients were low because the bunches were long and the plasma densities were low [2]. The picture changed dramatically when a series of PWFA experiment were approved on the SLAC linac in 1997. This facility could provide both electron and positron bunches with energies up to 40+ GeV. In the first decade of the new millennium, the particle bunches were compressed to give high peak current bunches suitable for exciting high gradient wakes in high-density plasmas. Other medium/smaller scale $(100\ \mathrm{MeV} - 1\ \mathrm{GeV})$ facilities such as those the Advanced Test Facility (ATF at BNL), FLASHForward (DESY in Germany) and in particular AWA, continue make important contributions to basic science of PWFA. However, key results that have attracted the attention of accelerator physicists have come from a series of experiments carried out by the PWFA collaboration using the 20-40+ GeV, 4ps-50fs electron and positron bunches from the SLAC LINAC.

These experiments achieved a number of firsts and ultimately showed that 50 GeV/m gradients could be sustained over almost a meter-long plasma [3]. These experiments were followed by “two-bunch” experiments that demonstrated high-efficiency [4] and that a trailing bunch containing 28 pC charge gained a maximum energy of 9 GeV in 1.3 m with a <5% energy spread [5]. The longitudinal and transverse field structure of a fully blown-out wake cavity has been shown to be suitable for preserving the transverse beam emittance during acceleration [6]. The longitudinal emittance can be preserved by optimizing the beam loading so that the energy spread of the beam is not increased.

Current and future challenges

Following Snowmass 2013 and the subsequent P5, a community-driven long-term strategic planning report was generated [7] by the DOE that outlines near, medium and long term research goals that are expected to lead to a conceptual design report for a plasma-based linear collider by 2035. While recognizing that there are currently significant scientific unknowns that place the plasma-based accelerator field in the discovery science mode, the near term goals must address the outstanding science questions that will enable demonstration of a single stage of a multi-stage linear collider driven by electron bunches.

Near term challenges: A preliminary study of a future PWFA collider stage such as charge per bunch, energy gain, beam loaded acceleration gradient, repetition rate, energy spread, emittance and efficiency has shown that the beam requirements are so severe that no existing beam facility can attempt such a demonstration today. The problem therefore has to be broken down into a subset of basic science issues can be addressed using existing facilities while the remaining issues are addressed using computer simulations that have no physics limitations. The DOE’s flagship facility for PWFA is the FACET-II facility at SLAC that is expected to start operating in 2020. FACET-II will endeavor to demonstrate that a 10 GeV drive electron beam can be nearly fully depleted of its energy in exciting the plasma wake, while a trailing beam can gain at least the same amount of energy per particle without an increase in either its energy spread or emittance with a high (>40%) drive-trailing beam energy transfer efficiency [8]. In our opinion, this is a grand-challenge of the decade for the advanced accelerator community.

A parallel goal will be to generate ultra-high brightness beams needed for the next generation of colliders and coherent light sources. Towards this end one or more plasma-based technique(s) will produce in the first instance a low charge (10 pC) but sub 100 nm transverse emittance and <1 MeV.fs longitudinal emittance. Promising plasma-based approaches include downramp injection and ionization injection by two transversely colliding laser beams. Then there are also opportunities to investigate basic science issues such as the generation and acceleration of spin polarized beams, asymmetric emittance beams etc.

Medium Term Challenges: The key medium term (7-10 years) challenge is staging. In a multi-stage PWFA the drive bunch for each new stage has to be brought in on a curved trajectory using magnetic optics. This requires the two PWFA stages to be separated by 10 m or more for a typical drive beam energy of 10-20 GeV. Therefore, the loaded gradient in the plasma section has to be of about 15 GeV/m to achieve an average gradient of >1 GeV/m. This is the gradient goal of the FACET-II experiments. In future experiments the loaded transformer ratios will need to be improved from the current value of 1 to 3 or even greater to increase the effective average gradient [9]. Since the trailing bunch in the PWFA LC design always travels in a straight-line trajectory, if it bunch can be matched in and out of one stage, it can in principle be matched in and out of multiple identical stages. However, additional multi-stage issues such as spatio-temporal synchronization, tolerance to transverse misalignment and emittance growth due to transverse instabilities will need to be investigated.

Advances in technology needed to meet challenges

The generation of collider/5th generation light source quality bunches from a single PWFA stage requires collaborations and facilities capable of delivering the requisite high density plasmas and high-energy high peak-current electron beams. Developing interim applications of plasma-based acceleration will enable operational demonstrations that can then be scaled to TeV energies of a plasma-based linear collider on a further decade or two time-scale.

Some suggestions for Snowmass 2021 planning

Well before 2035, research into positron generation and acceleration of beam parameters suitable for the e+ arm of a PWFA LC will have to be carried out. If this cannot be done successfully, it will impact the current concept of PWFA LC in a drastic way. One would then have to think about a PWFA LC that is then an e-e- collider, an e-H+ PWFA collider, or a gamma-gamma collider where the gamma photons are generated by colliding the PWFA-produced electron beams with intense laser pulses or using undulators. Only focused research in the next decade will guide us in the right direction. One of the issues the AF6 subgroup of the Snowmass 2021 process ought to revisit is a plasma-wakefield based afterburner to a current linear collider concept. The community has a chance of having enough information based on experiments and full-scale computer simulations to propose an energy boosting afterburner for an existing e-e+ linear collider (such as the ILC) by 2035 in the opinion of the authors.

References

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