Path towards a Beam-Driven Plasma Linear Collider

Spencer Gessner,[1] Erik Adli,[2] Weiming An,[3] Sebastien Corde,[4] Richard D'Arcy,[5] Eric Esaray,[6] Anna Grassellino,[7] Bernhard Hidding,[8] Mark Hogan,[1] Ahmad Fahim Habib,[8] Axel Heubl,[6] Chan Joshi,[9] Wim Leemans,[5] Rémi Lehe,[6] Carl Lindstrøm,[5] Michael Litos,[10] Wei Lu,[11] Warren Mori,[9] Sergei Nagaitsev,[7] Brendan O'Shea,[1] Jens Osterhoff,[5] Hasan Padamesee,[7] Michael Peskin,[1] Sam Posen,[7] John Power,[12] Tor Raubenheimer,[1] James Rosenzweig,[9] Marc Ross,[1] Carl Schroeder,[6] Paul Scherkl,[8] Navid Vafaei-Najafabadi,[13] Jean-Luc Vay,[6] Glen White,[1] and Vitaly Yakimenko[1]

[1]*SLAC National Accelerator Laboratory*
[2]*University of Oslo*
[3]*Beijing Normal University*
[4]*LOA, ENSTA ParisTech, CNRS, Ecole Polytechnique*
[5]*Deutsches Elektronen-Synchrotron DESY*
[6]*Berkeley National Laboratory*
[7]*Fermi National Accelerator Laboratory*
[8]*University of Strathclyde*
[9]*University of California, Los Angeles*
[10]*University of Colorado, Boulder*
[11]*Tsinghua University*
[12]*Argonne National Laboratory*
[13]*Stony Brook University*

(Dated: August 31, 2020)

I. INTRODUCTION

Research on beam-driven plasma wakefield acceleration is motivated by the ultimate goal of creating a linear collider that is affordable, highly-efficient, and operates at the highest possible energies. While there are many challenges on the path to a plasma-based linear collider (PLC), the field has shown steady progress on multiple fronts since the last Snowmass in 2013. Amongst many highlights are the first demonstration of highly-efficient plasma acceleration of electron beams [1], acceleration of positron beams in the non-linear regime [2], proton beam-driven acceleration [3], staged laser-plasma acceleration [4], plasma photocathodes for generating ultralow-emittance beams [5], and emittance preservation in an active plasma lens [6]. In this Letter of Interest, we highlight some of the challenges currently being addressed in Plasma Wakefield Acceleration (PWFA) research. We also discuss possible paths toward a PLC and the context for building such a machine.

II. CHALLENGES

The challenges associated with the development of a PLC have been identified in a variety of papers, workshops, and strategy sessions [7–14]. We enumerate some of them here:

1. High-efficiency, high-quality acceleration in a single plasma stage.
2. Coupling between plasma stages.
3. Positron acceleration in plasma.
4. Preservation of beam polarization.
5. High repetition-rate plasma acceleration and energy deposition in the plasma source.
6. Final focusing and alignment of beams at the collision point.

Each of these challenges come with their own list of challenges. For example, to achieve high-efficiency, high-quality acceleration, we need to simultaneously have strong beam loading while minimizing transverse instabilities [15]. This leads to tight constraints on drive-witness offset tolerances [16]. Ion motion is a possible suppression mechanism for transverse instabilities [17], but ion motion is also associated with emittance growth [18]. This illustrates an overarching challenge: these issues may be addressed individually, but we need an integrated approach to solve all of them simultaneously.

Moreover, for a PLC to be considered worthwhile, we cannot introduce new costs above and beyond those associated with a linear collider based on traditional technology. Our task is to develop a revolutionary new technology that drastically extends the energy and luminosity reach of a linear collider while reducing construction and operations costs.

III. PATHS TO A PLASMA LINEAR COLLIDER

Advocates for linear colliders are primarily interested in electron-positron collisions. This is because electron-positron collisions are "clean": collisions between electrons and positrons have a well-defined center of mass

(CM) and zero initial quantum number. In addition, the CM energy and beam polarization can be scanned to precisely probe physics near a particle resonance.

Electron-positron collisions require high-energy positron beams, and this presents a unique challenge for the PLC. The acceleration of positron beams in nonlinear plasma wakefields is different from the electron beam case. Some approaches, like the quasi-linear [9] and hollow channel regimes [19], try to symmetrize beam-plasma interactions, but these approaches have their own challenges. Research is underway to develop self-consistent solutions for high-efficiency, high-quality acceleration of positron beams in plasma [20].

An alternative for the PLC that does not require positron acceleration is to construct a γ-γ collider, that is, an e^-e^- collider with conversion of the e^- beams to γs near the interaction point. This conversion can be done by Compton scattering from a low-energy laser beam [21]. A scheme using highly compressed e- bunches is also being studied [22]. A γ-γ collider at the Higgs boson resonance would be interesting in the near term; this would require only 80 GeV/e- beam, assuming 80% energy transfer to the γs. For longer-range goals, a γ-γ collider would be just as effective as an e^+e^- collider in exploring new particles with masses in the energy region of 10 TeV and above.

IV. CONTEXT

Why build a Plasma-based Linear Collider? The most pressing need in High Energy Physics is a "Higgs Factory" for precision studies of the Higgs boson and the electroweak scale. There are currently four proposals for a Higgs factory which are considered viable: The linear collider concepts ILC [23] and CLIC [24] and the circular collider concepts FCC-ee [25] and CEPC [26]. The study of the Higgs boson is important as an opportunity to demonstrate that there are new fundamental interactions beyond the Standard Model and to learn some their properties. However, it is unlikely that these experiments, or possible new particle discoveries at the HL-LHC, will reveal those new interactions in detail. Current models of new fundamental interactions increasingly are based on new particles in the 10 TeV energy region and above.

One route to this energy scale is with proton-proton collisions. The proposed colliders FCC-hh [27] and SppC [28] plan to use 16 T dipole magnets to produce proton collisions at 100 TeV CM (about 15 TeV CM for parton-parton interactions). The high-field dipole magnet development program is predicted to last at least 20 years to produce practical 16 T accelerator magnets and longer to produce affordable higher-field high-Tc magnets.

PWFA technology will give us the ability to probe physics at multi-10 TeV energies using electron linear colliders. There are many challenges to overcome, so it is unlikely that the PLC will be ready in the next decade to supplant the ILC or CLIC in addressing the current imperative to study the Higgs boson with high precision. If a large linear collider such as ILC or CLIC is constructed for that purpose, the PLC can be the next step for that facility. Re-using the tunnel and most of the infrastructure, it will be able to directly explore the physics of multi-10-TeV particles.

V. THE NEXT STEPS

Experiments to demonstrate high-efficiency, high-quality electron acceleration in plasma are currently underway at FLASHForward at DESY and preparing to start at FACET-II at SLAC. These experiments will demonstrate the viability of PWFA technology and establish the tolerances for producing high-quality beams. Experiments at FLASHForward will also study high-repetition rate PWFA, while experiments at FACET-II will cover positron acceleration in plasma and beam focusing based on thin plasma lenses. Both FLASHForward and FACET-II need to be modified in order to demonstrate staged PWFA, which is a high priority for the field.

In parallel with ongoing experimental work, an integrated design study is required to inform PLC parameter choices and to compare the performance of a PLC to existing linear collider projects. Improving the maturity of the PLC concept will further guide experiments and keep the field on track with timelines proposed by the DOE [11] and ICFA [12].

[1] M. Litos *et al.*, Nature **515**, 92 (2014).
[2] S. Corde *et al.*, Nature **524**, 442 (2015).
[3] E. Adli *et al.*, Nature **561**, 363 (2018).
[4] S. Steinke *et al.*, Nature **530**, 190 (2016).
[5] A. Deng *et al.*, Nature Physics **15**, 1156 (2019).
[6] C. Lindstrøm *et al.*, Physical Review Letters **121** (2018), 10.1103/physrevlett.121.194801.
[7] J. Rosenzweig *et al.*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **410**, 532 (1998).
[8] A. Seryi *et al.*, in *Particle Accelerator Conference (PAC 09)* (2010) p. WE6PFP081.
[9] C. B. Schroeder *et al.*, Physical Review Special Topics - Accelerators and Beams **13** (2010), 10.1103/physrevstab.13.101301.
[10] E. Adli *et al.*, arXiv e-prints , arXiv:1308.1145 (2013), arXiv:1308.1145 [physics.acc-ph].
[11] DOE, *Advanced Accelerator Development Strategy Report: DOE Advanced Accelerator Concepts Research Roadmap Workshop*, Tech. Rep. (2016).

[12] B. Cros and P. Muggli, *Towards a Proposal for an Advanced Linear Collider, Report on the Advanced and Novel Accelerators for High Energy Physics Roadmap Workshop*, Tech. Rep. (2017).

[13] E. Adli, Phil. Trans. Royal Society A **377**, 20180419 (2019).

[14] B. Cros and P. Muggli, arXiv e-prints (2019), arXiv:1901.08436 [physics.acc-ph].

[15] V. Lebedev *et al.*, Physical Review Accelerators and Beams **20** (2017), 10.1103/physrevaccelbeams.20.121301.

[16] G. White and T. Raubenheimer, in *10th International Particle Accelerator Conference* (2019) p. THPGW087.

[17] T. Mehrling *et al.*, **121** (2018), 10.1103/physrevlett.121.264802.

[18] W. An *et al.*, Physical Review Letters **118** (2017), 10.1103/physrevlett.118.244801.

[19] S. Gessner *et al.*, Nature Communications **7** (2016), 10.1038/ncomms11785.

[20] S. Diederichs *et al.*, Physical Review Accelerators and Beams **22** (2019), 10.1103/physrevaccelbeams.22.081301.

[21] V. Telnov, arXiv e-prints , hep-ex/9810019 (1998), arXiv:hep-ex/9810019 [hep-ex].

[22] V. Yakimenko *et al.*, Physical Review Letters **122** (2019), 10.1103/physrevlett.122.190404.

[23] L. Evans and S. Michizono, arXiv e-prints (2017), arXiv:1711.00568 [physics.acc-ph].

[24] CERN, "Cern yellow reports, vol 4 (2016): Updated baseline for a staged compact linear collider," (2016).

[25] A. Abada *et al.*, The European Physical Journal Special Topics **228**, 261 (2019).

[26] The CEPC Study Group, arXiv e-prints (2018), arXiv:1809.00285 [physics.acc-ph].

[27] A. Abada *et al.*, The European Physical Journal Special Topics **228**, 755 (2019).

[28] J. Gao, International Journal of Modern Physics A **32**, 1746003 (2017).