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Directions in plasma wakefield acceleration

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Introduction

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This introductory article is a synopsis of the status and prospects of particle-beam-driven plasma wakefield acceleration (PWFA). Conceptual and experimental breakthroughs obtained over the last years have initiated a rapid growth of the research field, and increased maturity of underlying technology allows an increasing number of research groups to engage in experimental R&D. We briefly describe the fundamental mechanisms of PWFA, from which its chief attractions arise. Most importantly, this is the capability of extremely rapid acceleration of electrons and positrons at gradients many orders of magnitude larger than in conventional accelerators. This allows the size of accelerator units to be shrunk from the kilometre to metre scale, and possibly the quality of accelerated electron beam output to be improved by orders of magnitude. In turn, such compact and high-quality accelerators are potentially transformative for applications across natural, material and life sciences.

This overview provides contextual background for the manuscripts of this issue, resulting from a Theo Murphy meeting held in the summer of 2018.

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This article is part of the Theo Murphy meeting issue 'Directions in particle beam-driven plasma wakefield acceleration'.

Introduction

For more than a hundred years, particle accelerators have been engines of discovery and for the advancement of mankind. They allow fundamental science challenges, such as the exploration and illumination of fundamental structural building blocks of matter, to be addressed. They are also enabling tools across natural, material and life sciences, with an extremely broad range of applications that have direct or indirect socio-economic relevance. For example, advanced modern light sources in the X-ray range, such as synchrotrons and free-electron lasers [1], are derived from high-energy and high-quality electron beams that are forced on circular or wiggling trajectories such that they emit (coherent) photon pulses. Such photon pulses, in turn, allow the resolution of ultrafast processes in molecules and atoms on their natural timescales. Such processes combine to produce macroscopic phenomena across chemistry, physics and biophysics. While radio-frequency-based electrically charged particle accelerators have been extremely successfully developed and applied over the decades, and their underlying importance cannot be overstated, there are ceilings to their capabilities and capacities. To a large degree, these result from the limited accelerating electric field gradients they can sustain to accelerate charged particles. In conventional accelerators, these limits result from ionization processes at the walls of the radio-frequency cavities that provide the electromagnetic power to accelerate the particle. Such processes result in plasma breakdown when accelerating electric fields are raised to more than a few tens of megavolt per metre. To satisfy the ever-increasing particle energy demands, therefore, the length of the accelerator has to be increased. This has led to kilometre-scale accelerators, e.g. for modern light sources such as hard X-ray free-electron lasers, and tens of kilometre-scale accelerators for high-energy physics. The associated costs of such accelerators, which can amount to billions of pounds, limit their application. In order to address these issues, various advanced accelerator concepts are being developed that can increase the accelerating gradient by orders of magnitude, with concomitant reduction in the size of accelerator systems, e.g. from the kilometre to the metre scale. These efforts are increasingly coming to fruition, as documented by recent reviews and roadmaps, e.g. in the USA [2] and UK [3,4], which summarize past achievements and ambitious goals for the future of these novel classes of accelerators.

Of all advanced accelerator concepts, plasma wakefield-based accelerators have reached the highest level of maturity. For these types of accelerators, the limiting factor of conventional accelerators, namely the occurrence of plasma discharges at too high electric fields, is rather the operating medium and principle. In plasmas, collective separation of plasma electrons and ions can generate time-varying electric fields that scale with the plasma density and can reach strengths of order teravolt per metre. Intense laser pulses or intense particle beams can generate such fields in their wake during propagation through plasma. The intense transverse electric field of a laser or particle beam driver then kicks plasma electrons out of its path. The remaining plasma ions can be considered stationary on the timescale of the electron motion. They re-attract the plasma electrons radially towards the driver propagation axis. At the same time, the driver pulse propagates forward through the plasma at almost the speed of light and consecutively blows out further plasma electrons. This constitutes an elliptical or spherical co-moving structure formed by a constantly replenished high-density plasma electron sheath surrounding a cavity almost free of electrons. This co-moving bubble-like structure is many orders of magnitude smaller than the metallic cavities used in classical accelerators. Its size can be seamlessly adjusted by varying the plasma density. Inside, it exhibits properties which are almost ideal to accelerate charged particles: linear focusing forces of the ion background are combined with forward-directed wakefields that are scalable, e.g. from gigavolt per metre-scale for millimetre-sized plasma bubbles to the teravolt per metre-scale for 10 µm-scale plasma bubbles. This structure is the centrepiece of plasma wakefield accelerators and is used to transfer energy from the driver pulse to injected electrically charged particle beams. The plasma electron oscillation can be driven by laser pulses, which is known as laser wakefield acceleration (LWFA), or by charged particle beams such as electrons, positrons or protons, which is known as plasma wakefield acceleration (PWFA). The status and perspectives of these two related novel plasma wave-based accelerator methods, specifically, have recently been summarized in a UK roadmap [4].

The huge accelerating fields that are supported by plasma wakefield accelerators do not only provide a path towards much more compact particle accelerators. They also allow, in principle, for much higher brightness of the accelerated lepton beams, usually known as 'witness' beams. The brightness of e.g. an electron beam is to a large extent defined by its emittance, which in turn is a measure of its compactness both spatially and in momentum space. At the very beginning of an accelerator, the particle source determines the minimum emittance and hence brightness ceilings of the emitted beam. In conventional accelerators, the sizes of the electron cathode and the accelerating cavities are comparably large, and the accelerating extraction fields are limited in comparison to plasma wakefield-based accelerators as described above. Electrons emitted from the thermal- or photo-cathode will repel each other due to their Coulomb fields, which leads to (transverse) momentum growth, and therefore to emittance growth. During the acceleration process, these transverse space-charge forces quickly reduce in importance, as the emitted electrons gain longitudinal momentum. The Lorentz force generated in the magnetic field of this forward current increasingly counteracts the beam's space-charge forces. Hence, rapid acceleration of injected electrons is desirable to achieve witness beams with low emittance and high current and brightness. This is crucial for applications such as high-energy physics colliders [5] and free-electron lasers [6]. Ingenious techniques such as emittance damping rings, optimization of electron guns, emittance compensation techniques etc. have therefore been developed that have enabled e.g. the realization of low-emittance and high-brightness beams in conventional accelerators. In plasma wakefield accelerators, the microscopic cavity structures and the dramatically higher accelerating fields naturally limit the detrimental effect of space-charge forces. In addition, the focusing force of the ions present inside the plasma cavity is very useful to contain emittance and to produce dense beams. These combined inherent features allow, in principle, electron beams with many orders of magnitude higher brightness than with conventional accelerators to be realized. Harnessing these features to produce ultrahigh-quality beams is now an increasing focus of the community.

Plasma-based wakefield acceleration driven by particle beams (PWFA) is particularly attractive, since it allows a constant phase relation between accelerating driver beam and accelerated witness beam, and long acceleration distances in a single plasma wakefield stage. This allows large energy gains to be reached while the relative position and the conditions experienced by the accelerated witness beam inside the bubble remain essentially constant. The witness beam can therefore be matched to the specific acceleration scenario and phase, e.g. in terms of its size and charge profile, which allows optimization of the quality of the output beam. PWFA-driven plasma blowouts [7] can also propagate with a velocity even closer to the speed of light than LWFA-driven plasma bubbles, due to the slowed down propagation velocity of laser light in plasma. This facilitates dark-current-free operation of PWFA. A further fundamental difference between electromagnetic waves and particle beam drivers is that particle beams have unipolar electric fields instead of oscillating ones. Only at very high laser pulse intensities and associated extremely high oscillating electric peak fields, does the ponderomotive force push the plasma electrons effectively outside, rather than merely making plasma electrons oscillate back and forth within the laser pulse envelope. By contrast, the non-oscillating, directed particle beam fields can achieve plasma electron blowout already at comparably modest field values, as the electric field vector constantly points radially outwards. This avoids tunnelling ionization of higher ionization levels during the plasma blowout excitation process by the particle drive beam. In turn, this allows unique ionization-based injection methods of cold electrons into the plasma bubble, for example, by spiking the system with focused laser pulses of modest intensity to liberate electrons from these higher levels, thus constituting plasma photocathodes (see this issue's cover).

While PWFA was conceptualized in its modern form more than 30 years ago [8] and was demonstrated experimentally for the first time soon after [9] at Argonne National Laboratory (ANL), its experimental development has only recently really taken off. This was catalysed by pioneering research and breakthroughs obtained in the USA, in particular at SLAC National Laboratory's FFTB and FACET facilities [10–15], at Brookhaven National Laboratory BNL and at ANL, and from increased technological readiness and the availability of sufficiently intense particle beam drivers. The latter, in turn, is on the one hand linked to the rise of free-electron lasers, which require short and intense kiloampere-scale electron beam drivers to convert electron energy into high brilliance photon beams in the magnetic undulator sections—a shared key requirement for PWFA drive beams. Today, additional facilities based on classical accelerator technology such as DESY FLASHForward [16,17], INFN SPARC_LAB [18,19], Daresbury VELA/CLARA [20] and Fermilab FAST/IOTA have started to engage in experimental and/or theoretical PWFA R&D, SLAC FACET-II is coming online in 2019 [21,22], and several sites in Asia, e.g. Tsinghua University, are making important contributions.

In parallel to the development of PWFA, tremendous progress has been achieved by LWFA research, driven by the maturing technological readiness of compact high-power lasers. A unique advantage of LWFA is the capability to produce ultrashort, intense electron packets with kiloampere-scale currents in especially compact set-ups. These electron packets can also be useful as beam drivers of PWFA stages in hybrid set-ups [23], an approach which is only just beginning to be systematically explored experimentally [24]. This avenue could multiply the availability of PWFA-ready systems and provide a further transformative step change for PWFA R&D. The main challenges here are the stability of LWFA electron-beam output, and controlled capture of these beams and insertion into PWFA stages as driver beams. High-power laser systems are also contributing underpinning technology for PWFA to selectively pre-ionize one or more components of the plasma target [12,25]. Also, hybrid LWFA-based PWFA systems in principle offer intrinsic synchronization between electron and laser beams, which is attractive for a wide range of applications, including plasma-photo-cathode injection techniques [26] as a path to ultralow emittance and ultrahigh brightness [27].

In addition to intense electron beams (either from linacs or LWFA stages) as drivers for PWFA, positively charged particle beams can also be employed as PWFA drivers. Positron beams can be used both as drivers and as witness beams [11,12], which is a very important step for research in high-energy physics towards potential electron–positron colliders [5,28–31]. Proton beams can also be used for PWFA [23,32,33]. This approach is followed in a unique experiment at CERN in the AWAKE project, fuelled by the availability of ultrahigh-energy proton beams at CERN, which can be self-modulated to resonantly excite the plasma wave [23]. Using a proton bunch as wakefield driver opens new opportunities for applications to so-called beam-dump experiments, searching for dark matter, as well as for high-energy electron–proton collisions.

The increased maturity and prospects which PWFA offers, and the increased PWFA R&D capacities today mutually reinforce progress in this highly dynamic field. In June 2018, the Royal Society held a Theo Murphy scientific meeting to discuss 'Directions in particle beam-driven plasma wakefield acceleration'. The future research goals under discussion included the increase in output beam quality, energy gain, repetition rate and control and stability of PWFA, and development of applications to harness these unique accelerator systems. The meeting was organized in four sessions on 'Linac-driven electron PWFA', 'Hybrid LWFA-driven PWFA', 'Positron and proton PWFA' and 'PWFA applications', thus reflecting the key areas of research and the thrust towards applications. In the 'Linac-driven electron PWFA' theme, past and future experiments at the pioneering PWFA research facility SLAC FACET and its future follow-on facility FACET-II were reported. The need for beam-quality preservation and improvement was highlighted, and first experiments which indicate the ability to harness PWFA to provide electron beams with a quality *even much better* than state of the art was discussed. This requires precise control of the transverse phase space (the emittance) and the longitudinal phase space (the energy spread). Programmes and first experiments at newer linac-based facilities such as DESY FLASHForward and INFN SPARC_LAB were introduced and discussed, which provide additional capacities and unique capabilities. In the 'Hybrid LWFA-driven PWFA' theme, fundamental motivating considerations, simulations and first experimental contributions were presented. While this path is still in its infancy, the conceptual approach and the prospects such as inherent synchronization of beams are so attractive that significant R&D contributions are to be expected over the next years. The approach is also potentially invaluable to provide a second generation of ultracompact PWFA systems to make the concepts and applications developed by linac-driven PWFA ubiquitous in the longer term. In the 'Positron and proton PWFA' theme, the special requirements, challenges and prospects of dealing with positively charged driver and witness beams were discussed. These areas are motivated by prospects of achieving higher particle energies for high-energy-physics particle colliders. The sheer size and cost of future colliders for high-energy physics based on conventional technology make them increasingly harder to realize, so that a reduction in size and cost is vital. In the 'PWFA applications' theme, selected applications such as high-energy physics and light sources were discussed. These applications depend crucially on the beam energy, quality, repetition rate and control of PWFA systems. Fortunately, high-energy physics and light sources such as free-electron lasers share many similar requirements on the particle beams which power them. In order to increase the luminosity and hence the event rate of high-energy physics experiments, low beam emittance, low energy spread, high beam charges and efficiency are essential, while e.g. for free-electron lasers, in addition, high brightness is required rather than high charge.

This special issue provides manuscripts prepared by speakers at the conference across these four themes. We are grateful to all who contributed to the conference and to this volume.

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References

1. 2019 Theme issue: Fifty years of synchrotron science: achievements and opportunities (eds S Samar Hasnain, C Richard, A Catlow). *Phil. Trans. R. Soc. A* **377**. London: Royal Society Publishing.
2. US DOE Advanced Accelerator Development Strategy Report. 2016 See https://science.energy.gov/~/media/hep/pdf/accelerator-rd-stewardship/Advanced_Accelerator_Development_Strategy_Report.pdf.
3. UK STFC. 2017 Accelerator strategic review report. See https://stfc.ukri.org/files/2017-accelerator-strategy-review-report/.
4. Plasma Wakefield Accelerator Research 2019–2040. 2019 A community-driven UK roadmap compiled by the Plasma Wakefield Accelerator Steering Committee (PWASC). (https://arxiv.org/abs/1904.09205).
5. Rosenzweig JB, Barov N, Murokh A, Colby E, Colestock P. 1998 Towards a plasma wake-field acceleration-based linear collider. *Nucl. Instrum. Methods A* 410, 532. (doi:10.1016/S0168-9002(98)00186-7)
6. Di Mitri S. 2015 On the importance of electron beam brightness in high gain free electron lasers. *Photonics* **2**, 317–341. (doi:10.3390/photonics2020317)
7. Rosenzweig JB, Breizman B, Katsouleas T, Su JJ. 1991 Acceleration and focusing of electrons in two-dimensional nonlinear plasma wakefields. *Phys. Rev. A* **44**, R6189–R6192. (doi:10.1103/PhysRevA.44.R6189)

8. Chen P, Dawson JM, Huff RW, Katsouleas T. 1985 Acceleration of electrons by the interaction of a bunched electron beam with a plasma. *Phys. Rev. Lett.* **54**, 693. (doi:10.1103/PhysRevLett.54.693)
9. Rosenzweig JB, Cline DB, Cole B, Figueroa H, Gai W, Konecny R, Norem J, Schoessow P, Simpson J. 1988 Experimental observation of plasma wake-field acceleration. *Phys. Rev. Lett.* **61**, 98. (doi:10.1103/PhysRevLett.61.98)
10. Blumenfeld I *et al.* 2007 Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator. *Nature* **445**, 741–744. (doi:10.1038/nature05538)
11. Litos M *et al.* 2014 High-efficiency acceleration of an electron beam in a plasma wakefield accelerator. *Nature* **515**, 92–95. (doi:10.1038/nature13882)
12. Corde S *et al.* 2015 Multi-gigaelectronvolt acceleration of positrons in a self-loaded plasma wakefield. *Nature* **542**, 442–445 (doi: 10.1038/nature05538)
13. Gessner S *et al.* 2016 Demonstration of a positron beam-driven hollow channel plasma wakefield accelerator. *Nat. Commun.* **7**, 11 785. (doi:10.1038/ncomms11785)
14. Clayton CE *et al.* 2016 Self-mapping the longitudinal field structure of a nonlinear plasma accelerator cavity. *Nat. Commun.* **7**, 12 483. (doi:10.1038/ncomms12483)
15. Corde S *et al.* 2016 High-field plasma acceleration in a high-ionization-potential gas, *Nat. Commun.* **7**, 11 898. (doi:10.1038/ncomms11898)
16. Aschikhin A *et al.* 2016 The FLASHForward facility at DESY. *Nucl. Instrum. Methods A* **806**, 175–183. (doi:10.1016/j.nima.2015.10.005)
17. D'Arcy R *et al.* 2019 Tunable plasma-based energy dechirper. *Phys. Rev. Lett.* **122**, 034801.
18. Alesini D *et al.* 2017 The EuPRAXIA@SPARC_LAB project. See http://www.lnf.infn.it/~campana/ExecutiveSummary.pdf.
19. Ferrario M *et al.* 2018 EuPRAXIA@SPARC_LAB Design study towards a compact FEL facility at LNF. *Nucl. Instr. and Meth. A* **909**, 134–138. (https://arxiv.org/abs/1801.08717)
20. Clarke JA *et al.* 2015 The status of CLARA, a new FEL test facility. In Proc. 37th Int. Free Electron Laser Conf. 2015, Aug. 2015, MOP011, Daejoon, Korea. JACoW. http://accelconf.web.cern.ch/AccelConf/FEL2015/.
21. Yakimenko V *et al.* 2016 FACET-II: accelerator research with beams of extreme intensities. In Proc. 7th Int. Particle Accelerator Conf. IPAC 2016, May 2016, TUOBB02, Busan, Korea. JACoW. http://accelconf.web.cern.ch/AccelConf/ipac2016/.
22. 2016. Technical design report for the FACET-II Project at SLAC National Accelerator Laboratory, SLAC-R-1072.
23. Hidding B, Königstein T, Osterholz J, Karsch S, Willi O, Pretzler G. 2010 Monoenergetic energy doubling in a hybrid laser-plasma wakefield accelerator. *Phys. Rev. Lett.* **104**, 195002. (doi:10.1103/PhysRevLett.104.195002)
24. Gilljohann MF *et al.* 2019 Direct observation of plasma waves and dynamics induced by laser-accelerated electron beams. *Phys. Rev. X* **9**, 011046.
25. Adli E *et al.* 2018 Acceleration of electrons in the plasma wakefield of a proton bunch. *Nature* **561**, 363–367. (doi:10.1038/s41586-018-0485-4)
26. Hidding B *et al.* 2012 Ultracold electron bunch generation via plasma photocathode emission and acceleration in a beam-driven plasma blowout. *Phys. Rev. Lett.* **108**, 035001. (doi:10.1103/PhysRevLett.108.035001)
27. Manahan GG *et al.* 2017 Single-stage plasma-based correlated energy spread compensation for ultrahigh 6D brightness electron beams. *Nat. Commun.* **8**, 15705. (doi:10.1038/ncomms15705)
28. Seryi A *et al.* 2009 A concept of plasma wake field acceleration linear collider (PWFA-LC). In Proc. 2009 Particle Accelerator Conf., WE6PFP081, May 2009, Vancouver, Canada. https://accelconf.web.cern.ch/accelconf/pac2009/.
29. AWAKE Collaboration. 2013 A beam driven plasma-wakefield linear collider: from Higgs factory to multi-TeV. arXiv:1308.1145v2 and SLAC-PUB-15426.
30. Muggli P, Cros B. 2018 ALEGRO, the Advanced LinEar collider study GROup, IPAC TUPML036.
31. Cros B, Muggli P. 2019 ALEGRO input for the 2020 update of the European Strategy. Preprint at (https://arxiv.org/abs/1901.08436).
32. Katsouleas T. 1985 Physical mechanisms in the plasma wake-field accelerator. *Phys. Rev. A* **33**, 2056. (doi:10.1103/PhysRevA.33.2056)
33. Caldwell A, Lotov K, Pukhov A, Simon F. 2009 Proton-driven plasma-wakefield acceleration. *Nat. Phys.* **5**, 363–367. (doi:10.1038/nphys1248)