Journal of Instrumentation

TECHNICAL REPORT • OPEN ACCESS

Plasma-based particle sources

To cite this article: M. Fuchs *et al* 2024 *JINST* **19** T01004

Published by IOP Publishing for Sissa Medialab

Received: *March 20, 2023*
Accepted: *August 14, 2023*
Published: *January 17, 2024*

Snowmass'2021 Accelerator Frontier

Plasma-based particle sources

M. Fuchs,[a,*] G. Andonian,[b] O. Apsimon,[c] M. Büscher,[d,e] M.C. Downer,[f] D. Filippetto,[g] A. Lehrach,[h,i] C.B. Schroeder,[g] B.A. Shadwick,[a] A.G.R. Thomas,[j] N. Vafaei-Najafabadi[k] and G. Xia[c]

[a]*Department of Physics and Astronomy, University of Nebraska, Lincoln, Nebraska 68588, U.S.A.*
[b]*Department of Physics and Astronomy, University of California, Los Angeles, California 90095, U.S.A.*
[c]*University of Manchester, M13 9PL, Manchester, U.K.*
[d]*Peter Grünberg Institut (PGI-6), Forschungszentrum Jülich, Jülich, Germany*
[e]*Institut für Laser- und Plasmaphysik, Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany*
[f]*Department of Physics, University of Texas, Austin, Texas 78712, U.S.A.*
[g]*Lawrence Berkeley National Laboratory, Berkeley, California 94720, U.S.A.*
[h]*Institut für Kernphysik (IKP-4), Forschungszentrum Jülich, Jülich, Germany*
[i]*JARA-FAME (Forces and Matter Experiments), Forschungszentrum Jülich and RWTH Aachen University, Aachen, Germany*
[j]*Gérard Mourou Center for Ultrafast Optical Sciences and Department of Nuclear Engineering and Radiological Sciences, University of Michigan, Ann Arbor, MI 48109, U.S.A.*
[k]*Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794, U.S.A.*

E-mail: mfuchs@unl.edu

Abstract: High-brightness particle beams generated by advanced accelerator concepts have the potential to become an essential part of future accelerator technology. In particular, high-gradient accelerators can generate and rapidly accelerate particle beams to relativistic energies. The rapid acceleration and strong confining fields can minimize irreversible detrimental effects to the beam brightness that occur at low beam energies, such as emittance growth or pulse elongation caused by space charge forces. Due to the high accelerating gradients, these novel accelerators are also significantly more compact than conventional technology. Advanced accelerators can be extremely variable and are capable of generating particle beams with vastly different properties using the same driver and setup with only modest changes to the interaction parameters. So far, efforts have mainly been focused on the generation of electron beams, but there are concepts to extend the sources to generate spin-polarized electron beams or positron beams.

The beam parameters of these particle sources are largely determined by the injection and subsequent acceleration processes. Although, over the last decade there has been significant progress,

*Corresponding author.

https://doi.org/10.1088/1748-0221/19/01/T01004

the sources are still lacking a sufficiently high 6-dimensional (D) phase-space density that includes small transverse emittance, small energy spread and high charge, and operation at high repetition rate. This is required for future particle colliders with a sufficiently high luminosity or for more near-term applications, such as enabling the operation of free-electron lasers (FELs) in the X-ray regime. Major research and development efforts are required to address these limitations in order to realize these approaches for a front-end injector for a future collider or next-generation light sources. In particular, this includes methods to control and manipulate the phase-space and spin degrees-of-freedom of ultrashort plasma-based electron bunches with high accuracy, and methods that increase efficiency and repetition rate. These efforts also include the development of high-resolution diagnostics, such as full 6D phase-space measurements, beam polarimetry and high-fidelity simulation tools.

A further increase in beam luminosity can be achieve through emittance damping. Emittance cooling via the emission of synchrotron radiation using current technology requires kilometer-scale damping rings. For future colliders, the damping rings might be replaced by a substantially more compact plasma-based approach. Here, plasma wigglers with significantly stronger magnetic fields are used instead of permanent-magnet based wigglers to achieve similar damping performance but over a two orders of magnitude reduced length.

Keywords: Wake-field acceleration (laser-driven, electron-driven); Accelerator Subsystems and Technologies

2024 JINST 19 T01004

Contents

1 Introduction

Novel advanced accelerator concepts, such as plasma-based and advanced structure accelerators have the potential to become an essential part of future accelerator technology. In particular, laser-wakefield accelerators (LWFAs), which are based on laser-plasma interactions, can produce high-brightness femtosecond electron bunches with low transverse emittance from a compact setup (for current state-of-the art parameters see table 1). However, some parameters of LWFA electron beams, such as transverse emittance, energy spread, laser-to-beam conversion efficiency or pulse repetition rate can be even further improved and more specifically tailored to their application, such as for future particle colliders [1] or laser-driven free-electron lasers (FELs) [2]. The specific properties of future particle colliders are determined by the requirements of future high-energy physics experiments, which are currently being evaluated. However, it is expected that these experiments will require a center-of-mass energy of $\gtrsim 1$ TeV and a luminosity of $\gtrsim 10^{34}\,\mathrm{cm^{-2}s^{-1}}$. The beam energies can only be achieved by combining numerous acceleration stages. Considerations of power requirements and feasibility of plasma-based concepts indicate a demand for beams with high charge per bunch, low normalized emittances of < 0.1 µm and a relative energy spreads of $< 1\%$ [1]. FELs driven by plasma-based accelerators can be considered an intermediate step toward this goal as, depending on the wavelength of the FEL emission, the electron beam requirements are somewhat relaxed and the required beam energy can be achieved in a single accelerator stage. In particular, the quality of current plasma-based accelerators are sufficient to drive FELs at XUV wavelengths [3–5]. Recently, first experimental milestones have been achieved, notably the demonstration of FEL gain at 27 nm driven by an LWFA beam [6], FEL gain at 820 nm of a beam-driven plasma-accelerator [7] and seeded operation of a seeded LWFA-driven FEL at 270 nm [8]. However, FEL operation at X-ray wavelengths requires further improvements in beam quality, namely beam energies of a few GeV, transverse geometric emittances of < 0.1 nm, peak currents of few kA and relative slice energy spreads of well below 1% [9]. Both, colliders and FELs require an increase in the repetition rated and improvements in the shot-to-shot stability of the electron beams.

The parameters of LWFA electron beams are primarily determined by the electron injection into the accelerating plasma structure and the acceleration process itself. For simplicity, the majority of current LWFAs use a self-injection scheme [10–12], which leads to electron beams with a relatively large energy spread and that are typically less reproducible compared to conventional accelerator technology. To achieve electron self-injection requires a comparably high laser intensity, which is currently limiting the repetition rate at which LWFA beams can be produced. Different schemes of controlled injection have been demonstrated, including colliding laser pulses [13], plasma density modulations [14, 15] and ionization injection [16–18]. First promising results have been obtained and the methods have helped to significantly improve the beam parameters over the last decade (see table 1). However, these methods still require further improvements and some experimental implementations are challenging.

The full characterization of the 6D bunch phase space distribution is extremely challenging and because of its ultrashort duration, so far it has been mainly possible to only measure bunch-integrated properties, such as energy spread and transverse emittance. However, there are measurements that indicate that some of the local bunch properties (slice emittance, slice energy spread) are smaller than that of the overall bunch and that they might be temporally correlated. For example, this includes the observation of micro-bunching of LWFA bunches at optical wavelengths [19], the demonstration of energy-chirp compensation through a tailored plasma density [20], and the observation of exponential amplification of a laser-driven free-electron laser (FEL) [6].

Novel approaches for an injector front-end for a future plasma-based collider or laser-driven light source are required to address these limitations. In particular, this includes methods that increase the laser-to-electron beam efficiency, enable shaping the phase-space of ultrashort LWFA electron bunches with high accuracy, the generation of beams for high luminosity, comprehensive simulations, and high-resolution diagnostics spanning a wide parameter range. It also requires addressing the scalability of the system and the availability of dedicated test facilities.

2 Background

2.1 Laser-plasma driven sources

LWFA in the bubble regime. One of the main challenges for LWFAs are improvements in the electron beam brightness, including the energy spread, transverse emittance and increasing the accelerator repetition rate. Due to simplicity, the majority of LWFAs are driven in the highly nonlinear (bubble) regime and use electron self-injection [10–12]. Operating in this regime requires laser pulses with relativistic intensities. Specifically, the normalized vector potential $a_0 = eE\lambda/2\pi mc^2 \simeq \lambda[\mu\text{m}](I_0[\text{W/cm}^2]/1.4\times10^{18})^{1/2}$ of the pulse, where E is the laser electric field, λ the laser wavelength, mc^2 the electron rest mass and I_0 the laser intensity, needs to be significantly in excess of 1. Furthermore, the laser pulse duration has to be significantly shorter than the plasma wavelength. To achieve these intensities with a matched laser spot size requires laser pulses with a power of hundreds of terawatts to petawatts [10, 21, 22]. This currently limits the repetition rate at which state-of-the art laser systems can operate, thus limiting the repetition rate of the accelerator. Note that the development of lasers with a high peak and a high average power is discussed in reference [23]. Furthermore, the highly nonlinear bubble regime increases the difficulty of control over the electron beam properties. This includes the control of the injection process and over the acceleration process. For the latter, this is because of the evolution of the laser pulse due to the laser-plasma interaction. This also leads to comparably low laser-to-electron-bunch efficiencies because of the stronger interaction of the laser with the plasma at higher intensities.

Electron injection in LWFAs. Self-injected electron beams have a finite transverse emittance because the injected electrons have an intrinsic transverse momentum at the time of injection [10–12]. In this case, a laser pulse with a sufficiently high laser intensity ponderomotively excites a plasma wave by transversally expelling plasma background electrons, leaving behind a fully evacuated ionic cavity (the bubble). The expelled electrons are attracted back towards the axis by the electrostatic fields due to the ion cavity. Most electrons that are transversely expelled by the laser from a region close to the axis wrap around the cavity in half circles. They compose a highly dense electron sheath around the bubble center. Electrons within a specific initial off-axis region propagate along trajectories where they obtain a sufficiently large longitudinal momentum to become trapped in the bubble. The bubble structure can become unstable due to extensive beam loading or because of laser pulse alterations through self-evolution of the pulse in the plasma. This can lead to an extension of the bubble, leading to subsequent electron injection and ultimately a decrease in beam quality [11].

Parameters of the electron beams can be controlled via injection mechanisms. The currently mainly used processes include colliding laser pulse injection, ionization injection and shockfront-assisted injection. (i) in the colliding laser pulse injection, two laser pulses with the same polarization collide, each with an intensity below the self-injection threshold [13]. The colliding pulses generate a beatwave, which allows background plasma electrons to cross the separatrix and become trapped. The manipulation of the electron energy and a reduction in the relative electron energy spread to approximately 1% have experimentally been demonstrated. (ii) ionization injection uses a gas mixture of low-Z and higher-Z atoms. As the ionization of the inner-shell electrons of the higher-Z atoms occurs during higher intensity part of the laser pulse, they can be "born" and injected into a suitable acceleration phase of the bubble [16–18]. This can lead to a decrease in transverse emittance and a localized injection along the accelerator. A variation on the ionization injection scheme uses two lasers with a large difference in wavelength. Here, the long-wavelength laser (e.g. a CO_2 laser at $\lambda = 10\,\mu$m) drives the wakefield and the short-wavelength laser (e.g. a Ti:Sapph laser at $\lambda \sim 1\,\mu$m) ionizes and injects the electrons into the wake. Because of the scaling of the normalized vector potential $a_0^2 \propto I\lambda^2$, the long-wavelength laser can achieve a high vector potential at a relatively low intensity as compared to a shorter-wavelength laser. As a result, the long-wavelength driver does not fully ionize the gas target and the short-wavelength injector pulse can ionize and specifically inject the remaining inner-shell electrons. LWFAs driven by long-wavelengths lasers typically operate at lower plasma densities and in plasma bubbles with a significantly bigger volume. This relaxes the required precision for injection and can help maintaining spin polarization and low energy spread.This "two-color ionization injection" scheme has been shown in simulations to produce beams with an emittance that is low enough to meet the requirements of a collider [24, 25]. (iii) in shockfront-assisted injection, electron injection is controlled via a longitudinal plasma density downramp inside the gas target [26, 27]. As the plasma wave propagates through a density downramp,

2024 JINST 19 T01004

its local phase velocity decreases. It can be reduced to approximately the plasma fluid velocity which leads to the injection of cold background plasma electrons.

3 Overview of recent key results

3.1 Laser-plasma driven sources

The parameters of LWFA beams have tremendously improved over the last decade in terms of beam energy, accelerated charge, energy spread and repetition rate (see table 1). Unlike previous decades when the beam improvements have heavily relied on advancements in laser technology, many of these improvements are due to improved injector and accelerator designs. The ultimate limits of these technologies still needs to be explored.

Table 1. Overview of the state-of-the art LWFA electron beam parameters. * Bunch-integrated measurements.

Bunch property	State of the Art	Other beam parameters	References
Bunch energy	8 GeV	5 pC, 0.2 mrad (up to 60 pC in 6 GeV peak)	Gonsalves et al., PRL (2019) [28]
Bunch charge	220 pC (dE/E = 14% FWHM*)	250 MeV, 7 mrad [ionization injection]	Couperus et al., Nat. Comm. (2017) [29]
	1.1 nC (dE/E = 18% FWHM*)	334 MeV, 2.5 mrad [shock injection]	Götzfried et al., PRX (2020) [30]
	700 nC (dE/E = 100%*)	Up to 200 MeV laser: OMEGA-EP, 100 J, 700 fs	Shaw, et al. Sci Rep 11 (2021) [31]
Energy spread*	0.2–0.4% (RMS)	800 MeV, 8.5–24 pC shockwave assisted injection	Ke, et al. PRL (2021) [32]
Bunch duration	1.4 fs (RMS)	15 pC, CTR (diagnostic limited)	Lundh et al., Nat Phys (2011) [33]
	2.5 fs (RMS)	Faraday rotation (diagnostic limited)	Buck et al., Nat Phys (2011) [34]
Emittance* **(normalized)**	0.2π mm mrad (@245 MeV)	Single-shot measurement	Weingartner et al. PRSTAB (2012) [35]
Repetition Rate	1 Hz	24-hour operation; 100,000 consecutive shots	Maier et al., PRX (2020) [36]
	1 kHz	up to 15 MeV, 2.5 pC	Salehi et al., PRX (2021) [37]
Efficiency **(laser-to-electron)**	9.6%	quasi-monoenergetic 3J in driver laser pulse	Götzfried et al., PRX (2020) [30]
	11%	dE/E = 100% 135J in driver laser pulse	Shaw, et al. Sci Rep 11 (2021) [31]

4 Proposed concepts and development path

4.1 Laser-plasma driven sources

While LWFAs have demonstrated the generation of beams with high brightness, many of the parameters listed in table 1 have not been realized simultaneously. In addition to further improvements

2024 JINST 19 T01004

in each of these parameters, methods to control the beam phase-space that allow the generation of high-brightness beams that combine multiple of these record bunch properties are needed. This not only requires the development of new injection and control methods but also the development of diagnostics with high spatial and temporal resolution that allow measurement of the bunch parameters with sub-bunch length precision. Furthermore, it requires a combined experimental and theory efforts that includes the development of novel experimental and simulation methods. High-resolution diagnostics will allow the comparison of experimental results with simulation to a high degree and can help improve the ability for predictions based on simulations.

Finally, the requirements on the driver laser to achieve beams with high luminosity at a high repetition rate and with high efficiency also requires the determination of the properties for a best-suited driver laser, which are likely going to be different for an injector front-end and the subsequent acceleration stages.

Beam control and phase-space shaping. The generation of LWFA electron bunches with high beam quality requires control over the beam phase space with sub-femtosecond temporal and sub-micrometer spatial precision. This includes control over both, the electron injection process and the acceleration process. This can be achieved by achieving separate control over injection and acceleration processes through decoupling the injection from the acceleration stage. As described above, this has been demonstrated and has resulted in improvements in the LWFA parameters, however further improvements are required.

Efforts to shape the electron bunch phase-space include the development of advanced methods of electron injection including beam tapering and the investigation of acceleration in different regimes, such as a more linear regime [38]. This includes advanced injection schemes that have the potential for more control, such as using two, multi-color laser pulses [25] or laser pulses with higher-order spatial modes [39] that have been proposed but are lacking experimental investigation. It also includes a detailed study of the effect of the electron bunch onto the accelerating plasma structure (beam loading), for which initial theoretical [40] and experimental [30] studies exist.

Also of interest are methods to control the electron bunch phase space using shaped high-power laser pulses with control over the laser spatial and temporal higher-order shapes, multiple pulses, potentially of different colors or the incoherent addition of multiple pulses for example from fiber lasers and control over the laser evolution during the laser-plasma interaction.

Furthermore, novel advanced target designs have the potential to increase the beam quality and shot-to shot stability.

Increase in efficiency and stability. A high laser-to-electron bunch efficiency is crucial to ensure economic accelerator operation at a high repetition rate. A high reproducibility of the electron bunch parameters are crucial for stable operation. The efficiency and stability of LWFAs can be improved through control over the injection process, the acceleration and the regime of the acceleration process. While most of the current LWFAs are driven in the highly-nonlinear bubble regime, the quasilinear regime, in which the plasma waves are driven only moderately relativistically and the wakefield is approximately sinusoidal, can lead to a more efficient acceleration [38]. The quasilinear regime also has the advantage that the accelerating and focusing phase regions for electrons and positrons are nearly symmetric. Unlike the bubble regime where only a single wakefield bucket is excited,

2024 JINST 19 T01004

multiple buckets can be driven in the quasilinear regime. This allows, for example, the acceleration of bunch trains with the advantage of optimal beam loading of each bucket. The bunch structure of the pulse train is also advantages for a future collider as the short duration of each bunch decreases Beamstrahlung effects [38], while delivering an overall macrobunch with a high charge. This, however, requires advanced injection techniques to control the shape of the injected particle bunches. This scheme can be combined with using multiple driver laser pulses (multi-pulse laser wakefield acceleration) for efficient wake generation and high repetition rate operation [41]. As described above, novel advanced target designs have the potential to increase the efficiency and the shot-to shot stability.

The subsequent acceleration process can be strongly impacted by the evolution of the driver laser pulse through laser-plasma interactions [11]. To increase the stability and efficiency requires control over the laser evolution, for example through pre-shaped laser pulses, the use of multiple laser pulses [42] and specific tailoring of the plasma density profile.

Optimal driver laser properties. The performance and properties of LWFAs is greatly impacted by the laser pulse properties. Optimized operation of different accelerator regimes, such as the bubble regime or the quasilinear regime, require specific laser pulse properties. Furthermore, as described above, advanced controlled injection and acceleration schemes require specific laser pulses, such as higher-order spatial and temporal modes, multiple laser pulses, multi-colors, incoherent addition. The requirements on the repetition rate of the driver laser to achieve a sufficiently high beam luminosity also requires the determination of a (set) of properties for a best-suited driver laser, which are likely going to be different for an injector front-end and the subsequent acceleration stages.

Diagnostics. Despite ever-more sophisticated attempts to measure the LWFA electron bunch phase space [43], it is still far from being fully characterized. In particular, the sub-femtosecond time resolution that is required to characterize the electron beam with sub-bunch resolution is very challenging. The determination of the success of certain approaches requires novel diagnostic methods for the accelerated electron bunch inside the plasma, during and after the plasma-vacuum transition as well as the accelerating plasma structure itself. These methods need to have a (sub-)femtosecond temporal and (sub-)µm spatial resolution and ideally work in a single shot. Furthermore, they need to be capable of measuring the full 6D phase-space distribution of the electron bunches, including their temporal energy distribution with sub-bunch resolution.

Because of their few-femtosecond duration and sub-micron source size, LWFA electron bunches pose a unique diagnostic challenge. The plasma acceleration community has met this challenge by developing innovative diagnostic methods [43]. Multi-octave spectroscopy of coherent optical transition radiation (COTR) that LWFA bunches radiate on transiting thin metal films has emerged as a minimally-invasive approach for recovering their longitudinal structure in one shot [44]. Specialized spectrometers record COTR spectral intensity from ultraviolet to long-wave-infrared [45], a range that spans wavelengths close to the dimensions of the e-bunch itself, in which the key structural information resides. Since intensity measurements lose phase information, iterative algorithms [46] guided by physical constraints and independent measurements reconstruct the longitudinal profile from recorded spectra. Recently high-resolution imaging of COTR from a generating foil to a multi-spectral detector array has augmented longitudinal with transverse structural information, enabling the first 3D spatial reconstructions of LWFA e-bunches [47]. COTR interferometry, in

2024 JINST 19 T01004

which COTR from two tandem foils interferes, producing fringes that are sensitive to intra-bunch divergence [48], shows promise for diagnosing electron velocity distributions. Thus a combination of COTR spectroscopy, imaging, and interferometry appears to be the most promising diagnostic of the full 6D phase-space distribution of LWFA electron bunches. Stringent tests of the uniqueness of reconstructed profiles and optimization of reconstruction speed are among future challenges.

These diagnostics will also allow a comparison of experimental results to high-fidelity simulations to validate and improve the simulation codes.

Combined experimental and theoretical/simulation efforts. The successful design and fielding of a plasma-based particle source will require significant advances in the current state of the art in the numerical simulation of such systems. Currently, high fidelity numerical modeling of these systems is beyond the capabilities of even leadership-class computing facilities. Hybrid models, allowing for the optimization of computational cost versus physical accuracy will be necessary. That is, it is not viable to have a single global physics model in a simulation. Each region of phase space will have to be optimally treated based on its intrinsic importance to the overall system. In this way, computational resources can be allocation to provide uniform physical fidelity. For example, the bubble sheath could be treated with a high-order kinetic model (either Lagrangian or Eulerian) whereas areas of the plasma further removed for the "action" might be treated, with sufficient accuracy, as a fluid. Sampling "noise" associated with macro-particle models [49] will have to be kept under tight control and new, low-noise algorithms may have to be developed. Machine learning will be an essential element in this optimization process and we expect that the very optimization will, by identifying the critical regions of phase space, provide additional insight into the details of the underlying physical processes. To achieve this level of fidelity will require tight integration of experimental and theoretical efforts, each guiding advances in the other. Diagnostics sensitive to details of phase space will be required to probe simulations results with enough precision to guide model development and the computations cost optimization process. Macroscopic diagnostics such as energy spread and emittance are not likely sufficient constraints on simulation models. In addition, precise characterization of the gas jet profile and incident laser pulse will be necessary to provide sufficiently accurate simulations [50]. As a consequence of the model optimization process, we expect to derive high-performance reduced models that allow for predictive simulations to run concurrently with experimental campaigns without requiring leadership-class computing systems. Such a capability could provide the tight-coupling feedback needed to quickly advance the experimental program.

Polarized electrons. The acceleration of polarized electron beams by means of laser-driven acceleration promises to be cost-efficient and highly effective. Before a technical implementation can be envisaged, some principal issues need to be addressed theoretically, for example: (i) is it possible to alter the polarization of an initially unpolarized target through interaction with relativistic laser pulses or (ii) are the spins so inert during the short acceleration period that a pre-polarized target is required (see ref. [51] for a recent review)? Starting from the work by Hützen et al. [52], which proposes the use of pre-polarized targets for proton acceleration, Wu et al. [53] and Wen et al. [54] have developed a scheme to generate kA polarized electron beams via the interaction of an accelerating laser pulse with a pre-polarized plasma, which is produced through photo-dissociation of a dense halide (e.g. HCl) gas-jet by a circularly polarized ultra-violet (UV) laser pulse. A specifically

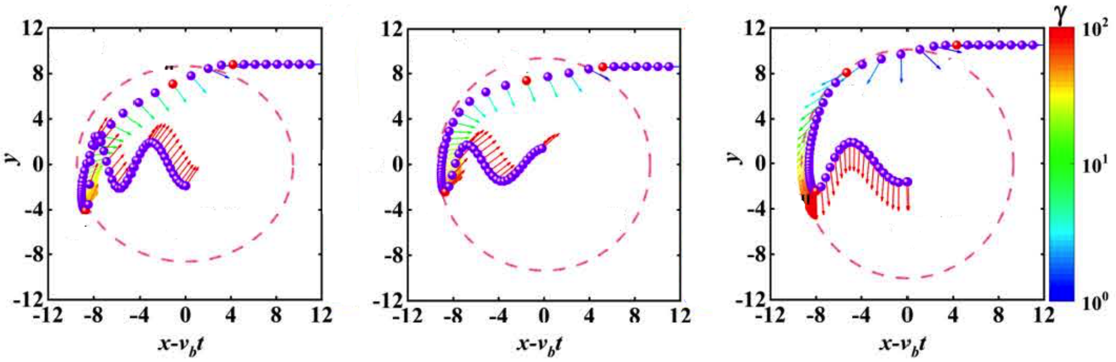

Figure 1. Temporal development of the spin orientations (arrows with color-coded electron energies) of test electrons (pink dots) during bubble acceleration. It can be seen that slight changes of the bubble geometry (prolate, spherical, oblate; indicated by the dashed red lines) leads to large differences of the originally longitudinally polarized electrons. The accelerating laser pulse propagates the simulation box from left to right (not shown in the figure). Adapted from [56]. © The Author(s). Published by IOP Publishing Ltd. CC BY 4.0.

configured ionization injection scheme has also been shown in simulations to produce significant populations of polarized electrons [55]. Obviously, for positrons (which are not discussed here in detail) other approaches are required, see e.g. reference [51]. These mostly rely on spin-selective radiation reactions of pre-accelerated, unpolarized electron beams with ultra-intense laser pulses.

Detailed theoretical studies (see for example reference [56]) reveal that intense highly-polarized electron beams can be accelerated to multi-MeV energies via the “standard” bubble mechanism with 100-TW class lasers. It has been shown that the final spin direction strongly depends on the self-injection process (see figure 1) and, thus, a careful tuning and control of the laser and target parameters is mandatory. As a consequence plasma-based accelerators promise to readily control the degree of polarization and the preferred spin direction according to the experimental needs (e.g. longitudinal or transversal polarization). Once energies above a few MeV have been reached, the beam polarizations are very robust during post-acceleration in subsequent plasma stages [57].

On the experimental side, the polarization of protons accelerated from an unpolarized foil target has been measured at the Arcturus laser at Düsseldorf [58]. A polarized ^{3}He gas-jet target [59] that has been used for a first experimental campaign at the Phelix laser facility at GSI Darmstadt. A polarized HCl target for proton acceleration has been prepared at Forschungszentrum Jülich [52]. It is planned to upgrade this target to deliver also polarized electrons. On the European scale, similar studies are under way in the framework of the EuPRAXIA consortium [60].

Plasma photocathode in beam-driven wakefield. In the plasma photocathode concept, electrons are generated directly within a beam-driven plasma wakefield accelerator, by the ionization of neutral gas particles using a high intensity laser pulse [61]. The electric fields generated in a plasma wakefield accelerator can exceed those of traditional photoinjectors by many orders of magnitude. Beam emittance is dependent on the injection properties of the plasma electrons into the accelerating phase of the plasma wave. Once injected at the proper phase of the plasma wave, the electrons are subject to ~GV/m accelerating fields, as well as focusing electric fields inside the plasma blowout, reducing the space charge effects that typically lead to an increase in the beam emittance at low electron energies. The plasma photocathode thus offers a path for the generation of high brightness beams. In particular, XFEL applications require low emittance [9] and low energy spread for efficient lasing. The electron beams from the photocathode process are well suited for the XFEL as they inherently provide low emittance and energy spread bunches [62]. In this regard, simulation studies on plasma photocathodes have shown electron bunches with normalized emittance on the 10^{-9} m-rad scale [63] and, using a novel modification of wakefield loading from another beam, relative energy spread on the 0.01% level [64]. In addition, the femtosecond electron bunch duration implies multi-kA currents for extreme charge density applications including colliders and other radiation sources [62].

Decoupling of beam injection and acceleration is accomplished using different plasma sections, such as a dual species gaseous media. In a mixture of both low-ionization-threshold and higher-ionization-threshold gas components, the higher-ionization-threshold components are still present in neutral (i.e., unionized) form within a plasma cavity. The plasma photocathode concept is based on the release of electrons via ionization of these higher-ionization-threshold states with a focused laser pulse at an appropriate position directly within the accelerating plasma blowout.

The optically initiated injection and acceleration of electron bunches, generated in a multi-component hydrogen and helium plasma employing a spatially aligned and synchronized laser pulse, was demonstrated in an experiment at SLAC FACET [65]. In the experiment, a pre-ionized plasma channel is formed in a hydrogen-helium gas mixture. A 20.35 GeV electron beam, with charge of 3.2 nC and pulse length of 30 μm, drives a wakefield in the hydrogen plasma, but does not ionize the helium gas. A laser pulse (800 nm wavelength, 10^{15} W/cm^2 intensity) is focused within this plasma wakefield, to liberate the helium electrons. The properties of the beam depend on the specific injection mechanism. When the laser pulse arrives before the drive bunch, known as the plasma torch mode, the plasma wave is distorted due to the presence of ionized helium particles. If the laser pulse arrives directly after the drive bunch, the plasma photocathode regime is achieved, without distortion of the plasma wave [66]. The two injection modes depend on the synchronization between ionization laser and drive bunch. The experimental demonstration of the plasma photocathode is a significant milestone and offers a path towards the production of electron beams with nanometer-radian normalized emittances [66].

The plasma photocathode concept based on plasma waves can further be modified, to relax both beam and laser requirements by using a dielectric wakefield accelerator in place of the plasma wakefield. In this conceptual scheme, a drive beam propagates axially through the center of a dielectric lined waveguide that is filled with a neutral gas. The beam generates a wakefield due to the retarding nature of the dielectric medium, but the beam fields do not ionize the gas. An incoming, co-propagating laser is focused behind the drive beam, which locally ionizes the gas, generating a witness beam similar to the plasma wave scenario. Although the gradients provided by the dielectric wakefields are not as intense as in the plasma case, dielectrics still enable gradients on the order of GV/m [67], before the onset of breakdown, or other high-field effects [68, 69]. Additionally, the fundamental accelerating mode supported in the dielectric structure is longer than the plasma wavelengths used in the previous plasma photocathode experiments, which relaxes the stringent requirements of both beam and laser properties, and synchronization required for precision injection. Dielectric wakefield accelerators are solid-state structures, so there is also reduced complexity of generating, operating, containing, and characterizing a preionized plasma column and associated complexities therein. Experimental efforts to demonstrate the proof-of-concept are currently being undertaken at the Argonne Wakefield Accelerator [70]

2024 JINST 19 T01004

Plasmonic photocathodes. Nano-structuring the surface of plasmonic material has been demonstrated to resonantly couple light to the vacuum-metal interface, inducing strong local near-field enhancement [71]. Upon laser illumination, a properly engineered surface supports electromagnetic traveling waves confined at the metal-dielectric interface, called surface plasmon polaritons (SPP). SPP modes are driven by electron charge-density oscillations in the material, which exhibit shorter wavelengths with respect to the illuminating laser. Therefore, mediated by SPP, the optical field energy can be transported and concentrated in areas of sub-wavelength size, leading to large local field enhancement. The nanostructured surface can be precisely engineered to obtain the amplitude and phase profile required for optimized electron beam generation and acceleration of electron pulses. Although metals sustain higher losses with respect to dielectric systems, the large field enhancement relaxes the requirements on the incident laser intensity for the same accelerating gradient. Furthermore metals offer strong control of the electromagnetic field at the subwavelength scale essentially due to the high index of refraction, and are not affected by common problems, such as beam charging. Realization of SPP nano-cavities for electron generation has been experimentally demonstrated to generate very large field enhancements [72, 73]. Here the nanostructure is acting as a high-Q Fabry-Perot resonator for the SPP waves, matching the speed of the (slow) surface plasmon along the surface of the structure with the incident laser wavelength. While these structures can achieve very high field enhancements, the very high power density stored locally can quickly generate damage, especially at high repetition rates. An alternative path is to make use of non-resonant structures. The intrinsically low quality-factor Q of the geometry results in lower field enhancement, but also decreases the energy density stored locally and, therefore, the potential for structure damage. In this configuration SPP waves travel along the surface until they are either absorbed by the surface through electron scattering or are radiated into the vacuum through surface defects. Interference between traveling SPP can also be exploited to generate large field enhancements in specific areas of the structure that not necessarily spatially coincident with a nanoscale feature. Recently, non-resonant nano-structuring of plasmonic materials have demonstrated the ability to focus light into nanoscopic areas [74]. Large local enhancement of electric field can be achieved through SPP interference, leading to broadband (i.e. ultrafast), highly confined multiphoton photoemission from a flat surface, therefore avoiding aberrations from curved surfaces and burning issues of tip-like photocathodes in high field environments.

Such photoemitters will provide unprecedented electron brightness through a combination of high field and spatial localization, but the total charge per pulse would still be limited to the few-to-thousands electrons, depending o the actual source size. On the other hand, the amount of laser energy needed for multi-photon photoemission is in the single nano-joule scale, enabling the direct use of laser oscillators with tens of MHz repetition rates for photoemission, potentially bringing the average current close to the micro-amperes. In addition, multiple plasmonic sources could be fabricated on the same metallic cathode plane multiplying the exit peak current of a single emitter by the number of sources. In the future, such sources could therefore provide the right combination of peak brightness, charge and average current to be employed as photocathodes in Free Electron Lasers and linear colliders.

Advanced transverse emittance cooling technique. Improvements in the electron beam properties can also be achieved through conditioning during acceleration. For example, in order to achieve high luminosity, the ILC [75] conventional collider design relies on emittance cooling via damping

2024 JINST 19 T01004

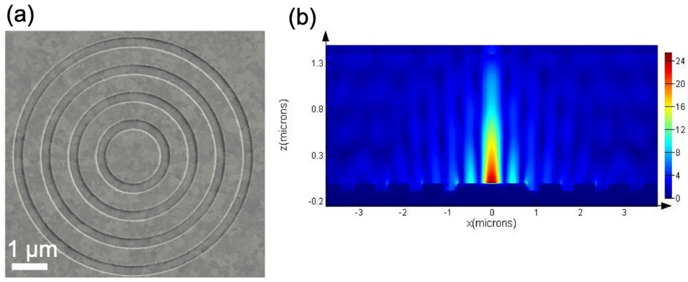

Figure 2. SPP-based photocathode; (a) structure fabricated with FIB technique; (b) distribution of field enhancement along a cut-out of the structure. From reference [74]. Reprinted (figure) with permission from [17], Copyright (2019) by the American Physical Society.

rings followed by a long transfer line from ring to main linear accelerator followed by beam delivery system to the final interaction point. Emittance cooling is achieved through radiation damping due to synchrotron radiation emitted from beam particles moving along curved trajectories of a circular accelerator (damping ring) that has a circumference of a few hundred meters to kilometers. Particles emit synchrotron radiation depending on the local curvature of the orbit within a cone of angle $\theta \propto 1/\gamma$, where γ is the relativistic Lorentz factor. As a result, the particles lose longitudinal and transverse momentum. As only longitudinal momentum is restored by radio-frequency cavities in the ring, transverse momentum is damped on every turn until radiation damping and quantum excitation are equal and an equilibrium is reached [76], which typically takes milliseconds [77, 78]. A higher damping rate is achieved by increasing the energy loss per turn by adding high field periodic magnetic structures (wigglers or undulators, depending on the magnetic strength) [79].

As an example, ILC project proposes a machine with 250–500 GeV centre-of-mass energy with an approximately 31 km footprint [80]. Electrons and positrons emerging from different sources undergo an initial acceleration up to 5 GeV before they are injected into a their respective damping rings with a circumference of 3.2 km, housed in the same tunnel. ILC damping rings are designed in a race track shape to accommodate two straight sections. A radiative section comprising 54 super-ferric wigglers is located in one of these straight sections. Each wiggler is 2.1 m long and generates a 2.16 T peak magnetic field when operating at 4.5 K and radiates 17 kW radiation power [80]. This straight section also houses a superconducting radio-frequency system to replenish the longitudinal momentum of the beam.

A novel, significantly more compact cooling method shows great promise by replacing the magnetic wigglers in a damping ring with a plasma-based approach to provide high-brightness beams for future linear colliders. Here, a plasma-based insertion device with significantly larger field strength than current wigglers will reduce the footprint and cost of the ring. There are several plasma-based methods for generating radiation using a relativistic particle beam, such as betatron emission [81, 82], Compton scattering [83, 84], Bremsstrahlung [85], undulator radiation [86, 87] and transition radiation [88]. We propose to incorporate the concept of plasma wiggler as radiators in a damping ring to benefit from their large effective magnetic fields and compactness. There are various concepts to conceive a plasma wiggler [82, 89–92]. Following the approach proposed by Rykovanov et al. [89], a plasma wiggler is formed when a short laser pulse is injected into plasma channel off-axis or at an angle that causes the centroid of the laser pulse to transversely oscillate.

Given that the product of the plasma wave number and the characteristic Rayleigh length of the laser is much larger than one, the ponderomotively driven plasma wake will follow this centroid. This oscillating transverse wakefield works as a wiggler forcing particles to follow sinusoidal trajectories and emit synchrotron radiation. In addition, the damping time is inversely proportional to the square of the magnetic field of the damping device. It is numerically demonstrated that a plasma wiggler can generate an order of magnitude larger effective magnetic fields than conventional wigglers. Specifically, the plasma-based emittance cooling scheme is compared to the current ILC-like baseline, where an injected emittance of 6 mm mrad is considered to be decreased to 20 nm (μm mrad) and the equilibrium emittance is reached in below 200 ms. The ILC-like baseline case consists of a total radiative length of 113 m. The advanced emittance cooling scheme can either be optimized for reduction in damping times to below 1 ms (using the same radiative length), for a reduction in length of radiative section to 1 m with a still acceptable damping time of 80 ms, or for a radiative section of less than 10 m and damping times of about 5 ms [93].

5 Conclusion

Particle injectors are critical elements of high-energy colliders and particle-beam based light sources. In particular advanced accelerator concepts require injectors that can generate particle bunches with carefully tailored characteristics. While there has been tremendous progress over the last years, many of these properties are yet to be realized in the laboratory. This includes not only particle beam parameters to increase the beam brightness, but also the beam stability and energy efficiency of the process. Developing the necessary injector technologies will require a combined effort to advance the forefront of phase space control and diagnostics, laser technology, computational modeling of injection, and basic plasma physics.

Acknowledgments

Work by M.F. and B.A.S. was supported by the U.S. Department of Energy (DOE), Office of Science, Office of High Energy Physics under Award Number DE-SC0021132.

References

[1] C.B. Schroeder et al., *Linear colliders based on laser-plasma accelerators*, 2023 *JINST* **18** T06001 [arXiv:2203.08366].

[2] C. Emma et al., *Snowmass 2021 Accelerator Frontier White Paper: Near Term Applications driven by Advanced Accelerator Concepts*, in the proceedings of the *Snowmass 2021*, [arXiv:2203.09094].

[3] F. Grüner et al., *Design considerations for table-top, laser-based VUV and X-ray free electron lasers*, *Appl. Phys. B* **86** (2007) 431 [physics/0612125].

[4] C.B. Schroeder et al., *Free-electron laser driven by the LBNL laser-plasma accelerator*, *AIP Conf. Proc.* **1086** (2009) 637.

[5] C. Emma et al., *Free electron lasers driven by plasma accelerators: status and near-term prospects*, *High Power Laser Sci. Eng.* **9** (2021) e57.

2024 JINST 19 T01004

[6] W. Wang et al., *Free-electron lasing at 27 nanometres based on a laser wakefield accelerator*, Nature **595** (2021) 516.

[7] R. Pompili et al., *Free-electron lasing with compact beam-driven plasma wakefield accelerator*, Nature **605** (2022) 659.

[8] M. Labat et al., *Seeded free-electron laser driven by a compact laser plasma accelerator*, Nat. Photon. **17** (2022) 150.

[9] C. Pellegrini, *The History of X-ray Free-Electron Lasers*, Eur. Phys. J. H **37** (2012) 659 [SLAC-PUB-15120].

[10] A. Pukhov and S. Gordienko, *Bubble regime of wake field acceleration: Similarity theory and optimal scalings*, Phil. Trans. Roy. Soc. Lond. A **364** (2006) 623.

[11] S. Kalmykov, S.A. Yi, V. Khudik and G. Shvets, *Electron Self-Injection and Trapping into an Evolving Plasma Bubble*, Phys. Rev. Lett. **103** (2009) 135004.

[12] I. Kostyukov, E. Nerush, A. Pukhov and V. Seredov, *Electron Self-injection in Multidimensional Relativistic Plasma Wakefields*, Phys. Rev. Lett. **103** (2009) 175003 [arXiv:0905.2528].

[13] J. Faure et al., *Controlled injection and acceleration of electrons in plasma wakefields by colliding laser pulses*, Nature **444** (2006) 737.

[14] C.G.R. Geddes et al., *Plasma-Density-Gradient Injection of Low Absolute-Momentum-Spread Electron Bunches*, Phys. Rev. Lett. **100** (2008) 215004.

[15] K. Schmid et al., *Density-transition based electron injector for laser driven wakefield accelerators*, Phys. Rev. ST Accel. Beams **13** (2010) 091301.

[16] C. McGuffey et al., *Ionization Induced Trapping in a Laser Wakefield Accelerator*, Phys. Rev. Lett. **104** (2010) 025004.

[17] A. Pak et al., *Injection and Trapping of Tunnel-Ionized Electrons into Laser-Produced Wakes*, Phys. Rev. Lett. **104** (2010) 025003.

[18] C.E. Clayton et al., *Self-Guided Laser Wakefield Acceleration beyond 1 GeV Using Ionization-Induced Injection*, Phys. Rev. Lett. **105** (2010) 105003.

[19] A.H. Lumpkin et al., *Coherent Optical Signature of Electron Microbunching in Laser-Driven Plasma Accelerators*, Phys. Rev. Lett. **125** (2020) 014801 [arXiv:1907.05078].

[20] A. Döpp et al., *Energy-Chirp Compensation in a Laser Wakefield Accelerator*, Phys. Rev. Lett. **121** (2018) 074802 [arXiv:1806.03338].

[21] T. Tajima and J.M. Dawson, *Laser electron accelerator*, Phys. Rev. Lett. **43** (1979) 267.

[22] W. Lu et al., *Nonlinear theory for relativistic plasma wakefields in the blowout regime*, Phys. Rev. Lett. **96** (2006) 165002.

[23] L. Kiani et al., *High average power ultrafast laser technologies for driving future advanced accelerators*, 2023 *JINST* **18** T08006 [arXiv:2204.10774].

[24] X.L. Xu et al., *Low emittance electron beam generation from a laser wakefield accelerator using two laser pulses with different wavelengths*, Phys. Rev. ST Accel. Beams **17** (2014) 061301 [arXiv:1402.5322].

[25] L.-L. Yu et al., *Two-Color Laser-Ionization Injection*, Phys. Rev. Lett. **112** (2014) 125001.

[26] C.G.R. Geddes et al., *High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding*, Nature **431** (2004) 538.

2024 JINST 19 T01004

[27] A. Buck et al., *Shock-Front Injector for High-Quality Laser-Plasma Acceleration*, Phys. Rev. Lett. **110** (2013) 185006.

[28] A.J. Gonsalves et al., *Petawatt Laser Guiding and Electron Beam Acceleration to 8 GeV in a Laser-Heated Capillary Discharge Waveguide*, Phys. Rev. Lett. **122** (2019) 084801.

[29] J.P. Couperus et al., *Demonstration of a beam loaded nanocoulomb-class laser wakefield accelerator*, Nat. Commun. **8** (2017) 487.

[30] J. Götzfried et al., *Physics of High-Charge Electron Beams in Laser-Plasma Wakefields*, Phys. Rev. X **10** (2020) 041015 [arXiv:2004.10310].

[31] J.L. Shaw et al., *Microcoulomb* ($0.7 \pm \frac{0.4}{0.2}$ *µC) laser plasma accelerator on OMEGA EP*, Sci. Rep. **11** (2021) 7498.

[32] L.T. Ke et al., *Near-GeV Electron Beams at a Few Per-Mille Level from a Laser Wakefield Accelerator via Density-Tailored Plasma*, Phys. Rev. Lett. **126** (2021) 214801.

[33] O. Lundh et al., *Few femtosecond, few kiloampere electron bunch produced by a laser-plasma accelerator*, Nat. Phys. **7** (2011) 219.

[34] A. Buck et al., *Real-time observation of laser-driven electron acceleration*, Nat. Phys. **7** (2011) 543.

[35] R. Weingartner et al., *Ultralow emittance electron beams from a laser-wakefield accelerator*, Phys. Rev. ST Accel. Beams **15** (2012) 111302.

[36] A.R. Maier et al., *Decoding Sources of Energy Variability in a Laser-Plasma Accelerator*, Phys. Rev. X **10** (2020) 031039.

[37] F. Salehi, M. Le, L. Railing and H.M. Milchberg, *Laser-Accelerated, Low-Divergence 15-MeV Quasimonoenergetic Electron Bunches at 1 kHz*, Phys. Rev. X **11** (2021) 021055 [arXiv:2010.15720].

[38] C.B. Schroeder et al., *Physics considerations for laser-plasma linear colliders*, Phys. Rev. ST Accel. Beams **13** (2010) 101301.

[39] L.-L. Yu et al., *Emittance control of electron and positron beams in laser plasma accelerators*, Proc. SPIE **9514** (2015) 95140P.

[40] M. Tzoufras et al., *Beam loading in the nonlinear regime of plasma-based acceleration*, Phys. Rev. Lett. **101** (2008) 145002 [arXiv:0809.0227].

[41] S.M. Hooker et al., *Multi-Pulse Laser Wakefield Acceleration: A New Route to Efficient, High-Repetition-Rate Plasma Accelerators and High Flux Radiation Sources*, J. Phys. B **47** (2014) 234003 [arXiv:1401.7874].

[42] S.Y. Kalmykov, B.A. Shadwick and X. Davoine, *All-optical control of electron trapping in plasma channels*, in the proceedings of the *19th IEEE Pulsed Power Conference (PPC)*, San Francisco, CA, U.S.A., 16–21 June 2013 [DOI:10.1109/ppc.2013.6627518].

[43] M.C. Downer et al., *Diagnostics for plasma-based electron accelerators*, Rev. Mod. Phys. **90** (2018) 035002.

[44] M. Heigoldt et al., *Temporal evolution of longitudinal bunch profile in a laser wakefield accelerator*, Phys. Rev. ST Accel. Beams **18** (2015) 121302 [arXiv:1406.6653].

[45] O. Zarini et al., *Multioctave high-dynamic range optical spectrometer for single-pulse, longitudinal characterization of ultrashort electron bunches*, Phys. Rev. Accel. Beams **25** (2022) 012801.

[46] F. Bakkali Taheri et al., *Electron bunch profile reconstruction based on phase-constrained iterative algorithm*, Phys. Rev. Accel. Beams **19** (2016) 032801.

[47] M. LaBerge, B. Bowers, Y.-Y. Chang, A. Couperus Cabadag, J.and Debus, A. Hannasch, R. Pausch et al., *3D structure of microbunched plasma-wakefield-aceelerated electron beams*, submitted for publication, 2023.

[48] A.H. Lumpkin et al., *Coherent Optical Signature of Electron Microbunching in Laser-Driven Plasma Accelerators*, Phys. Rev. Lett. **125** (2020) 014801 [arXiv:1907.05078].

[49] E.G. Evstatiev, J.M. Finn, B.A. Shadwick and N. Hengartner, *Noise and error analysis and optimization in particle-based kinetic plasma simulations*, J. Comput. Phys. **440** (2021) 110394.

[50] J. Ferri et al., *Effect of experimental laser imperfections on laser wakefield acceleration and betatron source*, Sci. Rep. **6** (2016) 27846.

[51] M. Büscher, A. Hützen, L. Ji and A. Lehrach, *Generation of polarized particle beams at relativistic laser intensities*, High Power Laser Sci. Eng. **8** (2020) e36 [arXiv:2006.06974].

[52] A. Hützen et al., *Polarized Proton Beams from Laser-induced Plasmas*, High Power Laser Sci. Eng. **7** (2019) e16 [arXiv:1810.02247].

[53] Y. Wu et al., *Polarized electron-beam acceleration driven by vortex laser pulses*, New J. Phys. **21** (2019) 073052 [arXiv:1904.03431].

[54] M. Wen, M. Tamburini and C.H. Keitel, *Polarized Laser-WakeField-Accelerated Kiloampere Electron Beams*, Phys. Rev. Lett. **122** (2019) 214801 [arXiv:1809.10570].

[55] Z. Nie et al., *InSitu Generation of High-Energy Spin-Polarized Electrons in a Beam-Driven Plasma Wakefield Accelerator*, Phys. Rev. Lett. **126** (2021) 054801 [arXiv:2101.10378].

[56] H.C. Fan et al., *Control of electron beam polarization in the bubble regime of laser-wakefield acceleration*, New J. Phys. **24** (2022) 083047 [arXiv:2201.02969].

[57] J. Thomas et al., *Scaling laws for the depolarization time of relativistic particle beams in strong fields*, Phys. Rev. Accel. Beams **23** (2020) 064401 [arXiv:2001.07084].

[58] N. Raab et al., *Polarization measurement of laser-accelerated protons*, Phys. Plasmas **21** (2014) 023104.

[59] P. Fedorets et al., *A High-Density Polarized ^{3}He Gas-Jet Target for Laser-Plasma Applications*, Instruments **6** (2022) 18 [arXiv:2201.13071].

[60] R.W. Assmann et al., *EuPRAXIA Conceptual Design Report*, Eur. Phys. J. ST **229** (2020) 3675.

[61] B. Hidding et al., *Ultracold Electron Bunch Generation via Plasma Photocathode Emission and Acceleration in a Beam-Driven Plasma Blowout*, Phys. Rev. Lett. **108** (2012) 035001.

[62] F. Habib et al., *Plasma accelerator-based ultrabright x-ray beams from ultrabright electron beams*, Proc. SPIE **11110** (2019) 111100A.

[63] Y. Xi et al., *Hybrid modeling of relativistic underdense plasma photocathode injectors*, Phys. Rev. ST Accel. Beams **16** (2013) 031303.

[64] G.G. Manahan et al., *Single-stage plasma-based correlated energy spread compensation for ultrahigh 6D brightness electron beams*, Nat. Commun. **8** (2017) 15705.

[65] B. Hidding et al., *First Measurements of Trojan Horse Injection in a Plasma Wakefield Accelerator*, in the proceedings of the 8^{th} *International Particle Accelerator Conference*, Copenhagen, Denmark, 14–19 May 2017, pp. 1252–1257 [DOI:10.18429/JACoW-IPAC2017-TUYB1].

[66] A. Deng et al., *Generation and acceleration of electron bunches from a plasma photocathode*, Nat. Phys. **15** (2019) 1156.

2024 JINST 19 T01004

[67] B.D. O'Shea et al., *Observation of acceleration and deceleration in gigaelectron-volt-per-metre gradient dielectric wakefield accelerators*, Nat. Commun. **7** (2016) 12763.

[68] B.D. O'Shea et al., *Conductivity Induced by High-Field Terahertz Waves in Dielectric Material*, Phys. Rev. Lett. **123** (2019) 134801.

[69] M.C. Thompson et al., *Breakdown Limits on Gigavolt-per-Meter Electron-Beam-Driven Wakefields in Dielectric Structures*, Phys. Rev. Lett. **100** (2008) 214801.

[70] G. Andonian et al., *Dielectric Wakefield Acceleration with a Laser Injected Witness Beam*, in the peroceedings of the *12th International Particle Accelerator Conference*, Campinas, SP, Brazil, 24–28 May 2021, pp. 481-484 [DOI:10.18429/JACoW-IPAC2021-MOPAB138].

[71] E.N. Economou, *Surface Plasmons in Thin Films*, Phys. Rev. **182** (1969) 539.

[72] A. Polyakov et al., *Plasmonic light trapping in nanostructured metal surfaces*, Appl. Phys. Lett. **98** (2011) 203104.

[73] R.K. Li et al., *Surface-Plasmon Resonance-Enhanced Multiphoton Emission of High-Brightness Electron Beams from a Nanostructured Copper Cathode*, Phys. Rev. Lett. **110** (2013) 074801.

[74] D.B. Durham et al., *Plasmonic Lenses for Tunable Ultrafast Electron Emitters at the Nanoscale*, Phys. Rev. Appl. **12** (2019) 054057.

[75] ILC collaboration, *ILC Reference Design Report Volume 1 - Executive Summary*, arXiv:0712.1950.

[76] A.W. Chao and M. Tigner, *Handbook of Accelerator Physics and Engineering*, 1st edition, World Scientific, Singapore (1999).

[77] A. Xiao and L. Emery, *International linear collider damping ring lattice design*, in the proceedings of the *22nd Particle Accelerator Conference*, buquerque, NM, U.S.A., 25–29 June 2007, pp. 3450–3452.

[78] P. Emma and T. Raubenheimer, *Systematic approach to damping ring design*, Phys. Rev. ST Accel. Beams **4** (2001) 021001.

[79] H. Wiedemann, *An Ultralow Emittance Mode for PEP Using Damping Wigglers*, Nucl. Instrum. Meth. A **266** (1988) 24.

[80] C. Adolphsen et al., *The international linear collider technical design report*, Tech. Rep. ANL-HEP-TR-13-20, BNL-100603-2013-IR, IRFU-13-59, Cockcroft-13-10, CERN-ATS-2013-037, CLNS-13-2085, DESY-13-062, FERMILAB-TM-2554, IHEP-AC-ILC-2013-001, ILC-REPORT-2013-040, INFN-13-04-LNF, JAI-2013-001, JINR-E9-2013-35, JLAB-R-2013-01, KEK-Report-2013-1, KNU-CHEP-ILC-2013-1, LLNL-TR-635539, SLAC-R-1004, ILC-HiGrade-Report-2013-003, CERN, Geneva (2013).

[81] A. Rousse et al., *Production of a keV X-Ray Beam from Synchrotron Radiation in Relativistic Laser-Plasma Interaction*, Phys. Rev. Lett. **93** (2004) 135005.

[82] R. Rakowski et al., *Transverse oscillating bubble enhanced laser-driven betatron X-ray radiation generation*, Sci. Rep. **12** (2022) 10855 [arXiv:2202.01321].

[83] H. Schwoerer et al., *Thomson-Backscattered X Rays From Laser-Accelerated Electrons*, Phys. Rev. Lett. **96** (2006) 014802.

[84] K. Ta Phuoc et al., *All-optical Compton gamma-ray source*, Nat. Photon. **6** (2012) 308 [arXiv:1301.3973].

[85] R.D. Edwards et al., *Characterization of a gamma-ray source based on a laser-plasma accelerator with applications to radiography*, Appl. Phys. Lett. **80** (2002) 2129.

2024 JINST 19 T01004

[86] H.-P. Schlenvoigt et al., *A compact synchrotron radiation source driven by a laser-plasma wakefield accelerator*, *Nat. Phys.* **4** (2008) 130.

[87] M. Fuchs et al., *Laser-driven soft-X-ray undulator source*, *Nat. Phys.* **5** (2009) 826.

[88] J. van Tilborg et al., *Temporal characterization of femtosecond laser-plasma-accelerated electron bunches using terahertz radiation*, *Phys. Rev. Lett.* **96** (2006) 014801.

[89] S.G. Rykovanov et al., *Plasma Undulator Based on Laser Excitation of Wakefields in a Plasma Channel*, *Phys. Rev. Lett.* **114** (2015) 145003.

[90] I.A. Andriyash et al., *An ultracompact X-ray source based on a laser-plasma undulator*, *Nat. Commun.* **5** (2014) 4736.

[91] S. Corde and K. Ta Phuoc, *Plasma wave undulator for laser-accelerated electrons*, *Phys. Plasmas* **18** (2011) 033111 [arXiv:1104.2186].

[92] R.L. Williams, C.E. Clayton, C. Joshi and T.C. Katsouleas, *Studies of classical radiation emission from plasma wave undulators*, *IEEE Trans. Plasma Sci.* **21** (1993) 156.

[93] O. Apsimon et al., *An Innovative Transverse Emittance Cooling Technique using a Laser-Plasma Wiggler*, arXiv:2112.08163.

2024 JINST 19 T01004