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2020 roadmap on plasma accelerators

Permalink

https://escholarship.org/uc/item/0538z8b3

Journal

New Journal of Physics, 23(3)

ISSN

1367-2630

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Publication Date

2021-03-01

DOI

10.1088/1367-2630/abcc62

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2020 Roadmap on Plasma Accelerators

2020 Roadmap on Plasma Accelerators

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2020 Roadmap on Plasma Accelerators 2

Abstract. Plasma-based accelerators use the strong electromagnetic fields that can be supported by plasmas to accelerate charged particles to high energies. Accelerating field structures in plasma can be generated by powerful laser pulses or charged particle beams. This research field has recently transitioned from involving a few small-scale efforts to the development of national and international networks of scientists supported by substantial investment in large-scale research infrastructure. In this New Journal of Physics 2020 Plasma Accelerator Roadmap, perspectives from experts in this field provide a summary overview of the field and insights into the research needs and developments for an international audience of scientists, including graduate students and researchers entering the field.

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1. Introduction

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Particle accelerators are widespread and critical tools for science, engineering and medicine. Plasma-based accelerators use the strong electromagnetic fields that may be supported by plasmas to accelerate charged particles to high energies. The electromagnetic fields in plasmas may be supported in near unrestricted oscillating mode structures, allowing for myriad accelerating and focusing configurations. This is in contrast to optical fields, which have strong restrictions on the mode structure. Electric field strengths supported in plasma scale with the square root of the plasma density, $E\,[\mathrm{GeV\,cm^{-1}}] \sim \sqrt{n\,[10^{18}\ \mathrm{cm^{-3}}]}$, and so within the range of sub-atmospheric to solid density plasmas, the accessible field strengths are thousands to millions of times stronger than those supported by conventional accelerating structures, which are limited to $\mathrm{MeV\,cm^{-1}}$ gradients. Being able to support stronger field strengths means that the accelerator size — and, potentially, cost — could be substantially reduced.

Plasma acceleration schemes date back to early theoretical work, which in the 1970s and 1980s led to laser [1] and beam [2] driven plasma wakefields being proposed. These schemes were not fully realized experimentally until the development of ultrashort duration high-current electron bunches on SLAC [3] and high-power, ultrashort-pulsed lasers [4]. The drive beam, whether a laser or particle beam, generates a plasma 'wake' with phase velocity close to the speed of light, which allows a relativistic 'witness' beam to remain in an accelerating phase of the wake and gain energy over long distances. The development of high power laser technology also resulted in the demonstration of ion acceleration from thin foil targets [5], which spurred interest in this acceleration scheme.

Research into plasma based acceleration schemes has made great progress, particularly over the last two decades, due to further advances in driver technology, target design and improved understanding of the underlying physics through the development of advanced simulation techniques. Interest has grown substantially, with significant investment in infrastructure around the world, including FACET-II [6] and AWAKE [7] facility developments for beam driven wakefield acceleration schemes and a substantial growth in the number of large scale high-power laser facilities, particularly in Europe and Asia, for example the billion dollar scale Extreme Light Infrastructure [51].

In recent years, organizations have been founded and roadmaps developed for plasma accelerators that layout detailed national and international priorities for the field, including funding recommendations and research focuses. In Europe, EuPRAXIA aids interactions between Universities and National Laboratories and provides integration and coordination of research efforts towards a near-term plasma accelerator design. ALEGRO is an international organization to promote Advanced and Novel Accelerators for High Energy Physics applications and supports the international community. There have been increased planning efforts over the last decade in the US, with the publication of the 2016 Advanced

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Accelerator Development Strategy Report [8].

The intent of this *2020 New Journal of Physics Roadmap* is to summarize the current state of the field and provide a broad overview and insight into research needs and developments for an international audience of scientists, including graduate students and researchers entering the field. *Note that this article is not a review paper*, and it therefore does not comprehensively cover all work in this area; for the latter the reader is directed to review articles, for example Refs. [9, 10, 11, 12, 13].
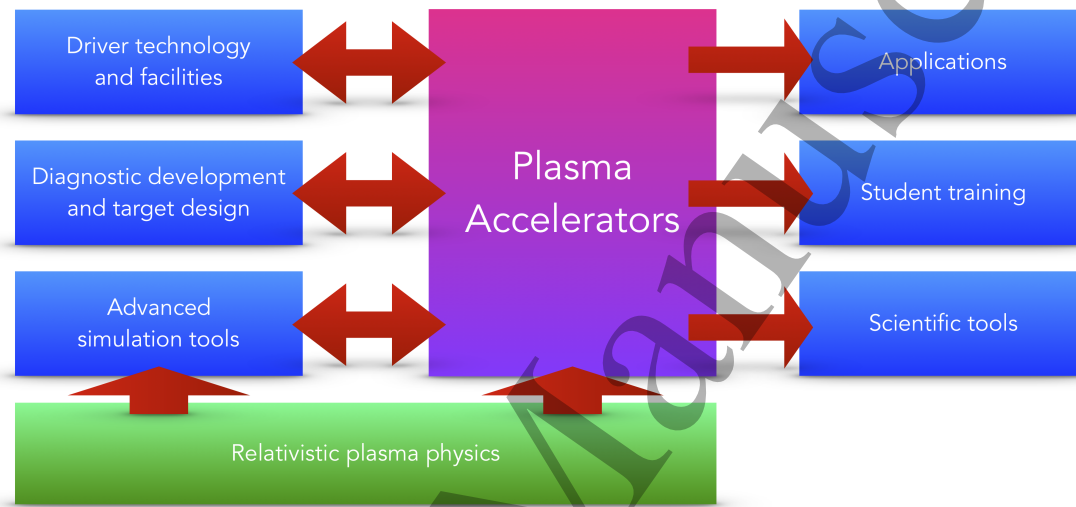
Figure 1. The critical needs and products of plasma accelerator research.

Fig. 1 illustrates the critical needs and products of plasma accelerator research, all supported by the foundational science of relativistic plasma physics (including the nonlinear optics of relativistic plasma). The diagram illustrates that plasma accelerators require advances in driver technology, target design and diagnostics to make progress, and simulation tools to both understand and design accelerator schemes. The arrows going both ways indicate that plasma accelerator research also feeds back into shaping the development of drivers/targets/diagnostics. Products include technological applications — such as new imaging techniques — tools for scientific discovery — such as ultrafast x-ray sources or extremely high energy lepton — and student training for workforce development in academia and industry.

This *2020 New Journal of Physics Roadmap* includes twelve perspectives from groups of experts in the field, who come from institutions across the US, Europe and Asia. The sections cover the topics of: electron and positron acceleration in plasma wakefields generated by laser pulses, relativistic electron and ion beams; applications of relativistic electron beams including secondary radiation production; ion beam acceleration with lasers; applications of ion beams including medical applications; as well as laser technology, diagnostic development and advanced theoretical/simulation tools. These perspectives address the critical issues highlighted in Fig. 1, and give an overview of the status of plasma accelerator research worldwide in 2020.

Alec Thomas and Stuart Mangles
Editors of the 2020 Plasma Accelerator Roadmap

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2. Electron Beam Driven Plasma Wakefield Acceleration (PWFA)

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2.1. Status

The beam-driven Plasma Wakefield Accelerator idea was proposed by P. Chen, J.M. Dawson et al. [2] in 1985 but was initially slow to take off experimentally, because there were and are a few high-current, highly relativistic electron beam facilities in the world suitable for plasma-wakefield acceleration research. On the other hand, until very recently, the linear accelerator (LINAC) at the SLAC National Accelerator laboratory was both the most versatile and powerful (> 10 GeV beams) facility for driving wakes using both electron and positron bunches for studying PWFA. Other medium/smaller scale (≤ 1 GeV) facilities such as those at Brookhaven National laboratory (ATF), DESY (FLASH Forward), INFN in Frascati and in particular Argonne National laboratory (AWA) [14], are making important contributions to basic science of PWFA. However, key results that have attracted the attention of high-energy physicists have come from a series of experiments carried out by the UCLA/USC/SLAC collaboration using the 20-40+ GeV, 4 ps-50 fs electron bunches from the SLAC LINAC.
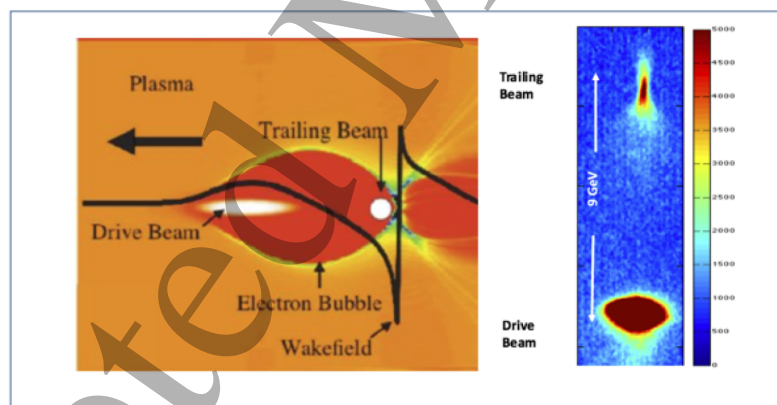
Figure 2. (a) In a PWFA a short but intense drive beam excites a wake (shown here as electron bubble) in plasma. An appropriately place trailing bunch gains energy from the electric field of the wake (black curve). (b) An initial 20+ GeV trailing bunch gained > 8 GeV in about 1.3 m long plasma in experiments at SLAC [15].

These experiments were the first to break the GeV energy gain barrier [16] using a relativistic plasma wave. They also showed that the energy can be increased simply by making the plasma longer. Then by increasing the drive beam energy to 42 GeV, this collaboration showed that 50 GeV/m gradients could be sustained over almost a meter-long plasma wake. In this experiment while most of the drive bunch particles lost energy in exciting the wake, some particles in the back of the same bunch doubled their energy [3]. These experiments were followed up by "double-bunch" experiments, where the first drive bunch was used to excite a wake and a second distinct trailing bunch was used to extract energy from the wake. If the charge in the trailing bunch was sufficient, and if for a given drive and trailing bunch

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separation the plasma density was optimized, the trailing bunch was seen to gain energy without a significant increase in the energy spread (see Fig.1). In the process a significant fraction, $> 20\%$, of the energy could be extracted from the wake [17]. To-date a trailing bunch containing 28 pC charge was observed to gain a maximum energy of 9 GeV in 1.3 m with a $< 5\%$ energy spread [18]. Another major accomplishment of the PWFA research community was to probe the longitudinal and transverse field structure of a fully blown-out wake cavity and show that the field structure of the fully formed wake does not change significantly and that it is ideally suited for preserving the transverse beam emittance during acceleration [15]. The longitudinal emittance can be preserved by optimizing the beam loading so that the energy spread of the beam is not increased.

2.2. Current and future challenges

A recent long term strategic planning report [19] by the United States Department of Energy (DOE) with input from the PWFA community, outlines near (5-7 years), medium (5-12 years) and long term (10-15 years) research goals that will lead to a conceptual design report for a PWFA-based linear collider by 2035. This comprehensive report recognizes that there are currently significant scientific unknowns that places the beam-driven plasma-based accelerator field still in the discovery science mode. Thus the near term goals must address the unanswered science questions that will enable demonstration of a single stage of a multi-stage linear collider driven by electron bunches.

Near term challenges: The beam requirements of a future-PWFA collider stage – such as charge per bunch, energy gain, beam loaded acceleration gradient, repetition rate, energy spread, emittance and efficiency – are so severe that no existing beam facility can attempt such a demonstration today. The problem therefore has to be broken down into what subset of basic science issues can be solved using the existing facilities and where more theoretical and simulations work is needed. With this in mind the DOE has funded the FACET II facility at SLAC that is expected to start operating in Fall 2020. The foremost near term challenge to the PWFA community is to demonstrate that the 10 GeV FACET II drive beam can be nearly fully energy depleted while the trailing beam can add at least the same amount of energy per particle without an increase in either its energy spread or emittance with a high ($> 40\%$) drive-trailing beam energy transfer efficiency [6]. Similar goals are being pursued at the FLASHForward facility. A parallel goal will be to generate ultra-high brightness beams needed for the next generation of colliders and coherent light sources. Towards this end, one or more plasma-based technique(s) will need to demonstrate that low charge (10 pC) but sub 100 nm transverse emittance and < 1 MeV.fs longitudinal emittance bunches can be generated using a PWFA. Two plasma-based approaches to achieve such bunches look particularly promising: downramp injection and ionization injection [20]. Beyond these two major areas of research, there are other important basic science issues such as generation and acceleration of spin polarized beams, and generation and acceleration of asymmetric profile beams, effect of ion motion on emittance growth etc. Medium Term Challenges: The key medium term challenge is staging. In a multi-stage PWFA the drive bunches have to be brought in on a curved trajectory using magnetic optics. For typical drive bunch energy of 10-20 GeV, envisioned in the conceptual design of a PWFA based linear collider (PWFA LC), this implies that the two PWFA stages have to be separated by as much as 10 m. This in turn has an implication for the minimum loaded acceleration gradient one must reach to achieve an average gradient of > 1 GeV/m to make a multi-stage beam-driven PWFA viable. The first FACET II experiments will be carried out with a loaded gradient of about 15 GeV/m to

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achieve this. In the future, the average gradient can be improved by increasing the transformer ratio by using shaped bunches [21]. The trailing bunch in the PWFA LC design always travels in a straight-line trajectory. So if the trailing bunch can be matched in and out of one stage without emittance growth, it can in principle be matched in and out of multiple identical stages. However, in a multi-stage PWFA there is the additional problem of spatio-temporal synchronization that must be addressed. Any transverse misalignment errors between the two beams in a multi-stage accelerator will lead to emittance growth and energy loss due to transverse instabilities and betatron radiation respectively. Finally, well before the long–term time scale approaches, a great deal of research into positron generation and acceleration to give beam parameters suitable for the e+ arm of a PWFA LC will have to be carried out. If this cannot be done, it will impact the current concept of PWFA LC in a drastic way. One would have to think about a future LC that has only a plasma-based electron arm but a conventional accelerator positron arm (likely not worth the additional complication), an e-e PWFA LC collider, an e-P PWFA collider, or a gamma-gamma collider where the gamma photons are generated by colliding the PWFA-produced electron beams with intense laser pulses or using undulators. Only focused research in the next decade will be able to guide us in the right direction. Perhaps e-beams from PWFA may find use in fixed target high-energy physics experiments in the first instance.

2.3. Advances in technology needed to meet challenges

The existing/planned smaller scale electron beam facilities are perfectly positioned to contribute in a very meaningful way to the generation of super low transverse and longitudinal emittance, polarized electron bunches as well as on innovative ideas for generating and accelerating positron beams. However, currently only FACET II and possibly FLASHForward and INFN seem suitable to address the generation of collider/Vth generation light source quality bunches from a single PWFA stage and efficiency issues. However, no current facility will be able to demonstrate a single stage of a PWFA LC at the required ($> 10\,\mathrm{KHz}$) repetition rate. This is why an important interim application of any plasma-based accelerator that will enable the long term development of the plasma-based linear collider on 5-10-year time-scale is considered important.

2.4. Concluding remarks

PWFA research has made great strides in the past two decades. Many of the milestones achieved in the plasma-acceleration field were either discovered or achieved using an electron beam as a driver. Many problems listed above are common to all the plasma accelerator concepts. Thus the different plasma-based accelerator sub-communities will greatly benefit from close collaboration.

3. Proton Beam Driven Plasma Wakefield Acceleration

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3.1. Status

For an accelerated bunch to reach high energies (TeV for $\sim 10^{10}$ particles) relevant for high-energy physics (HEP), the acceleration process has to occur over long distances (km). Laser pulses and electron bunches suitable to drive > 1 GV/m these wakefields carry limited amounts of energy (< 100 J) [3]. Staging of a large number ($\gg 10$) of plasma sections would thus be necessary to reach high energies. Relativistic proton bunches carrying tens (e.g., CERN SPS, 3×10^{11}p+, 400 GeV: 19 kJ) to hundreds of kilojoules (e.g., CERN LHC, 10^{11}p+, 7 TeV: 112 kJ) can in principle lead to energy gains in proportion of their energy [22]. They can drive wakefields over a single, long plasma, avoiding staging and its intricacies.
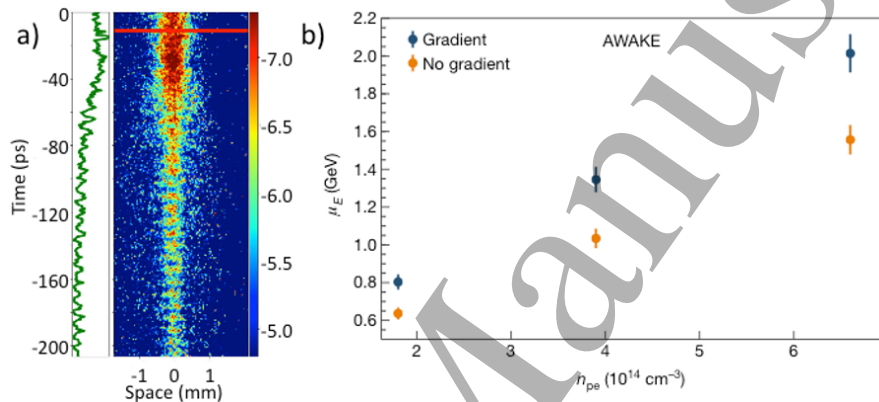
Figure 3. (a) Time-resolved picture of the self-modulated proton bunch (from [7], (b) energy gain as a function of plasma density without (orange symbols) and with (blue symbols) plasma density gradient (from [23]).

However, these bunches are long (6-12 cm) and require self-modulation (SM) [24] to drive wakefields of significant amplitude (GV/m). Self-modulation of CERN SPS proton bunches was demonstrated in the AWAKE experiment [7, 25] (see Fig. 3a). Most importantly, the SM process that was cast as an instability, i.e., potentially yielding outcomes with variations much larger than variations in the input conditions, was shown to be remarkably reproducible and "stable" against input parameters variations when seeded with sufficient wakefields amplitude. This is particularly important for this scheme since the wakefields are driven resonantly by the self-modulated bunch train and grow along the train. The witness electron bunch is thus injected in the Nth (30-100) wakefields period, or "bucket", from the seed point. Therefore, small variations in the wakefield period or phase could lead to electrons finding themselves in the decelerating phase of the wakefield and lose energy, or worse, in their defocusing phase and be lost. Acceleration of 19 MeV externally injected electrons to 2 GeV over 10 m was also demonstrated [23] (see Fig. 3b).

From the plasma point of view, a novel source was developed [26] that produces a long (~ 10m) very uniform rubidium (Rb) vapour density column (4cm diameter). The density uniformity is on the order of that of the temperature imposed along the source and is measured to be better than 0.3%. The excellent neutral vapour density uniformity is transformed into that of the plasma through laser ionization by a short (~ 120 fs), intense (~ 10 TW/cm^2, 1 mm radius) laser pulse. Plasma sources with such uniformity and transverse size may become necessary for all plasma-based accelerators for HEP applications.

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3.2. Current and Future Challenges

While previous experiments have shown wakefield generation, both transverse [25] and longitudinal [7], the next experiments must focus on the injection and acceleration of a good quality electron bunch to demonstrate the suitability of this scheme for high-energy physics. The steps to reach this goal are clear. First, the plasma source must be split into a self-modulator (SM'or) and an accelerator (Acc'or) section, see Fig. 4). The SM'or section must be sufficiently long for the proton SM process to saturate (∼10m). A short (∼30cm), vacuum electron injection section follows. Then an acceleration section (10m or more) allows for the electrons bunch to reach multi-GeV energies. The self-modulation section must include a plasma density step (%-level, ∼1 m into the plasma) shown by simulations to freeze the wakefields amplitude to a value close to that at saturation. Seeding of the SM process by a short electron bunch preceding the proton bunch (see Fig. 4) is most likely necessary in order to avoid SM of the front part of the proton bunch left un-modulated by the relativistic ionization front seeding method used to date. Second, an electron bunch shorter than the wakefields period must be injected on axis and with density n_b sufficient to create plasma electrons blow-out ($n_b/n_e \sim 35$) [27]. This guarantees that the fraction of the bunch (∼70%) travelling in the pure ion column, with focusing free of geometrical aberrations, can have its incoming emittance preserved. To preserve its emittance, its transverse size is matched to the plasma focusing force and beam loading is used to minimize its relative energy spread (<%-level) and therefore also chromatic effects.

3.3. Advances in Science and Technology to Meet Challenges

One of the possible limitations for long plasma-based accelerator is the development of the non-axi-symmetric mode known as the hose instability (HI). The growth rate for this mode is similar to that of the SM. Unlike the SM that is purposely seeded to avoid its (unstable) development from noise, HI could grow from noise and interfere with, or terminate the acceleration process. There are theory and simulation results that suggest that SM and HI compete and thus that SM could suppress HI. Also, development of HI strongly relies on its oscillation frequency being constant along the bunch. Therefore, wakefields not reaching the blow-out regime, as is the case with the SM process, energy spread along the proton bunch, etc., can act as detuning effects that would decrease or suppress the growth of HI. Observing and understanding HI is therefore important for the extension of the acceleration process over very long plasma lengths.
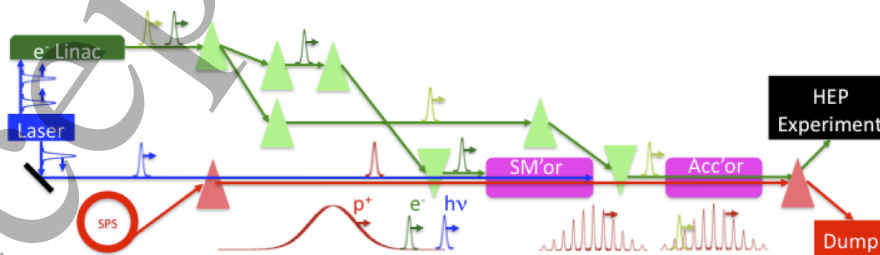

Figure 4. Schematic of a possible early use of the self-modulated, proton-driven plasma wakefield accelerator for an HEP experiment such as collision with a solid target. In this case SM seeding in the self-modulator is achieved using a short electron bunch. Elements not to scale: self-modulator (SM'or) ∼10 m-long, accelerator (Acc'or) 50-100m-long.

Long plasma sources, with longitudinally uniform plasma density represent a significant need for this acceleration scheme. While the laser-ionized, alkali vapour plasma source used so far and in the next round of experiments [26] satisfies all requirements; its length is limited by energy depletion of the ionizing laser pulse. Other possible sources include gas discharges and helicon sources. The helicon source is particularly appealing because of its geometric scalability [28]. It consists of a unit cell with RF coil antenna and magnetic field coil that can be stacked to form long plasma. However, density requirements are quite stringent and its longitudinal density uniformity remains to be demonstrated.

3.4. Concluding Remarks

The scheme of plasma wakefields driven by a self-modulated high-energy proton bunch is the newest that has been proposed. Remarkable progress has been made[7, 25, 23] since its birth [24]. The acceleration scheme requires a relativistic, high-energy proton bunch to drive wakefields. Its application is ideally suited for HEP laboratories that produce such beams (CERN, Brookhaven, Fermilab, etc.). HEP experiments could then be conducted in the short term with fixed targets, e.g., towards the search for dark photons. In the longer term, very high-energy (TeV) electron bunches, produced with one of the LHC beams in a plasma, could be collided with bunches of the other LHC beam [29]. These HEP experiments require neither positron bunch acceleration, nor production of electron bunches with very low emittances. This may speed up progress along a roadmap for HEP applications before a new particle collider will be built. This roadmap is rather clear and for now centred around the AWAKE experiment at CERN, the only experiment developing the proton-driven, plasma wakefields acceleration scheme.

4. Laser Wakefield Acceleration for High Energy Physics

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4.1. Status

With the advent of high-peak power short pulse lasers, LPAs started to produce quasi-mono-energetic beams in 2004. About a decade later, in 2016, the US Department of Energy published a roadmap [19] that aims at developing a laser- plasma (LPA) based collider at the TeV level of energies, with construction starting in the 2040's. As an essential element, this roadmap acknowledges the importance of early real-world applications to mature the underlying technology (see section 5). In addition, laser plasma accelerators are being considered as injectors for storage rings and next-generation diffraction limited light sources. This development, illustrated in Fig. 5, will clear the path towards a future collider [30], by far the most demanding application.

Over the past one and a half decades, the field of laser-plasma acceleration has greatly benefitted from the steady progress in drive laser performance. With the emergence of petawatt class lasers (see section 11), the maximum electron beam energy achieved has steadily increased from 1 GeV, to several GeV and, most recently, to electrons up to ~ 8 GeV from 20 cm long plasma structures [31]. The key element to this dramatic improvement in beam energy is

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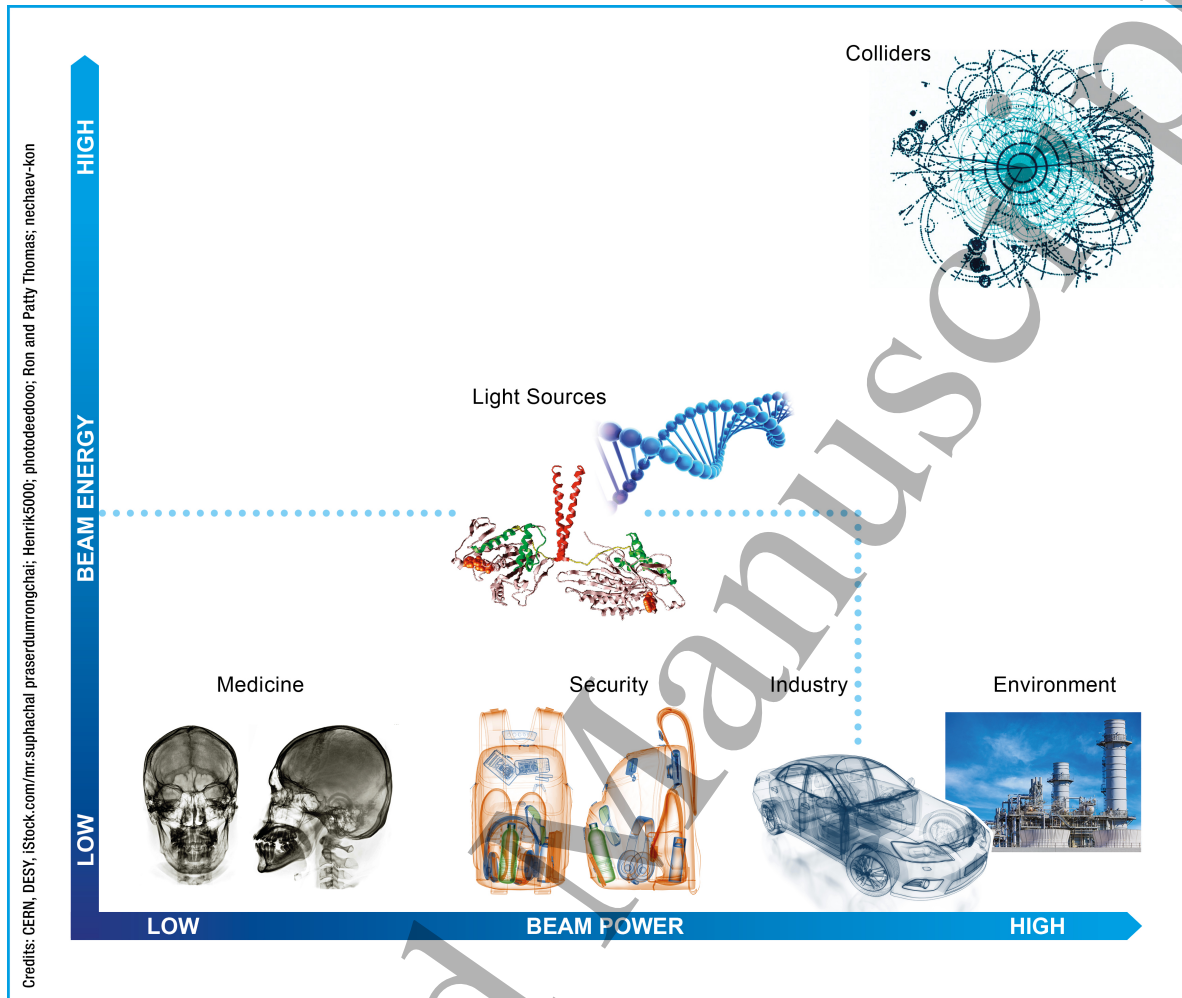
Figure 5. Application space for accelerators. The path for future laser plasma accelerators runs through earlier applications such as compact medical imaging and coherent light sources culminating in the most demanding use case – a plasma-based collider.

the development of guiding techniques and properly shaped plasma channels, and progress on mode matching into these structures, to confine PW-class laser beams over an extended interaction length [32]. Staging of two independently powered plasma modules, an essential ingredient of a realistic collider concept, has been demonstrated at the 100 MeV energy level [33]. In addition, methods to generate and conserve high-quality beams have been developed: Experiments have shown the reduction of electron beam energy spread from initially few percent to a few tenths of a percent [34]. Quality-conserving concepts to extract beams from the plasma and to match them into subsequent stages have been developed [35]. The initial beam quality is of particular importance for collider applications. Schemes have been developed that promise low-emittance beams [36]. Strong plasma-based focusing elements have been developed and optimized that provide symmetric high gradients at the few kT/m level [37] and preserve emittance [38], which provides confidence that the sub-micron emittance beams from a laser plasma accelerator can actually be transported Sophisticated diagnostics that are able to probe plasma profiles, accelerating and focusing fields as well as the properties of the emerging femtosecond electron beams with high temporal resolution are being developed (see

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section 10). As of today, laser-plasma accelerators can support continuous 1-Hz operation, producing hundred thousand consecutive shots of few-hundred MeV electron beams with few-percent energy spread and few-percent stability of central energy [39]. An understanding of the origin of the residual fluctuations in beam parameters has been obtained [39], permitting a path to feedback stabilization when increasing the repetition rate to the kHz level and beyond.

4.2. Current and future challenges

During the present innovation and discovery phase, which is expected to continue for the next ten years, and which will transition the field from a focus on academic research towards R&D of a technology with an advanced readiness level, the development of laser plasma accelerators will focus on demonstrating unique first applications of these devices in light source relevant applications. The associated milestones will include the first demonstration of an LPA powered free electron laser, compact high energy photon sources (> 10 keV) for imaging, and the injection of plasma-generated beams into storage rings. Successful demonstration of an FEL will benefit from reliable 24/7 operation and require GeV-class plasma-based accelerators producing high- quality, low-energy-spread ($< 0.5\%$), low-emittance (< 1 micron) electron beams with high charge (> 30 pC) in a few-femtosecond bunch length. To provide a competitive technology and to enable active stabilization – a key ingredient for all modern accelerators – significant efforts will be dedicated to the demonstration of high-average power operation for LPAs and, in particular, lasers operating at the multi-kW level and repetition rates at the kHz and beyond.

For collider applications, an essential stepping stone will be the reproducible demonstration of reliable 10 GeV electron beams with low energy spread (0.1-1%), low emittance and high charge (> 100 pC), from a single acceleration stage. While experiments have shown that those parameters can, in principle, be reached individually, it is still a challenge to generate a high- quality beam meeting all of those specifications at once. In addition, demonstration of highly efficient, beam-quality preserving staging at high energies and electron acceleration with independent drive lasers will be crucial. Methods to optimize the injection of electrons into the wake, including phase space manipulation to minimize energy spread and temporal shaping of the bunches need to be tested. Energy efficiency studies will be crucial for maximizing the conversion of laser power to particle-beam power, which is particularly important considering the 10s of MW power carried by a future TeV-level collider beam.

Furthermore, understanding mechanisms for emittance growth and developing methods for achieving emittances that are compatible with colliders will be of central importance for focusing the generated electron beams to the sub-micron spot sizes required to reach high luminosity. Minimizing the length of the final focusing system by, e.g., relying on emittance conserving adiabatic plasma lenses, should be explored as an alternative to the current kilometer-scale system designs. The manipulation and preservation of spin-polarization of particle beams in plasma wakefield structures will have to be investigated. Demonstration and understanding of methods to accelerate a positron bunch with high efficiency and excellent quality, i.e., preserving the emittance of a plasma-accelerated positron bunch, is a unique challenge for an electron- positron collider: The well-studied non-linear plasma wave regime (i.e., bubble regime) in a homogeneous extended plasma is not suitable for positron acceleration. Tailored plasma geometries, e.g. hollow channels or channels with a finite radial extent, are being explored that would provide an extended accelerating and focusing phase and, simultaneously, must provide field properties allowing for high acceleration efficiency and

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emittance conservation. Novel positron capturing methods need to be studied where, e.g., a high energy primary electron beam produces electron-positron pairs in a dense solid target that is closely coupled to a plasma structure that is either electron or laser beam excited. Throughout this phase, continuous development of a comprehensive and realistic operational parameter set for a multi-TeV collider will be key to guide operating specifications.

4.3. Advances in science and technology to meet challenges

At its core, a laser plasma accelerator relies on just two key ingredients: a suitably tailored plasma structure and a high-quality laser pulse. Methods to develop transversely shaped plasma structures that can provide matched guiding at plasma densities of order 10^{17} cm^{-3} for spot sizes on the 20-50 micron level, and that can be longitudinally shaped to provide localized injection at the front of the structure and tapered (increasing) density to minimize dephasing are required. These plasma structures must then be able to operate reliably and reproducibly at repetition rates of a kHz and beyond for many billions of acceleration events and would enable the development of highly efficient 10 GeV single stages.

In addition, staging techniques need to be developed to re-accelerate beams in subsequent modules. The key challenges here are to merge a new laser beam that powers the next structure onto the path of the electron beam emerging from the previous structure, in the smallest possible space, and at the highest possible laser coupling efficiency without emittance degradation of the accelerating beam [33]. As discussed above, technology needs to be developed for positron production and capture, and for generating spin polarized electron beams.

On the laser driver side, in contrast to state-of-the-art lasers for experiments today (see section 11), which operate at the few tens of Watts and sub-percent wall-plug efficiency with 1-10 Hz of repetition rate, for colliders multi-kW (up to 10's and even 100's of kW), high repetition rate (1-10+ kHz) systems operating at peak power in excess of 100 TW are needed. Such systems must operate with high wall-plug efficiency ($> 10\%$) and hence rely on high efficiency diode pumping techniques of the gain medium. To minimize optical losses and for proper heat management, the gain medium must also have a small quantum defect. Workshops have been organized to document possible approaches. One approach for constructing such as system, which is based on readily available and well-established technology, is to rely on the traditional master oscillator power amplifier concept with chirped pulses and a broadband amplifier medium such as Ti:sapphire. The wall-plug efficiency, however, would be limited, and heat management poses a significant challenge to such an architecture. To reduce the losses associated with the large quantum defect of this gain material, new gain media are being researched including Tm:YLF. Alternative approaches, such as coherent pulse combining of ultrafast fibre lasers or the excitation of plasma waves using a laser pulse train, are also proposed and actively researched (see section 11).

Regardless of the design, the key for this next-generation drive laser is the reliable high-repetition rate operation for many consecutive hours and days. The transport and final focusing optics of the laser must provide high efficiency ($> 99\%$) and high damage threshold (both instantaneous and under prolonged exposure). These high-repetition rate systems will offer the possibility for advanced feedback and active stabilization and provide opportunities for machine-learning-based performance optimization and intelligent process control that hitherto was not possible.

4.4. Concluding remarks

Laser plasma accelerators have made tremendous progress over the past two decades. To a large extent this has been enabled by the emergence of lasers that perform far better than those available in the late 1980's and most of the 1990's. One and a half decades after the "Dream Beam results", few hundred MeV beams are generated for many hours with only percent-level fluctuations in beam parameters and energies up to 8 GeV have been produced [31]. The next decade will likely see the demonstration of coherent light from an LPA-powered FEL at the kHz repetition rate. This together with many other advances will elevate LPAs to emerge from the laboratory of experts into the world of applications. It will motivate major investments into further technical innovations and industrial developments and provide the foundation for the path towards a compact plasma-based collider.

5. Laser Wakefield Accelerated Electron Beams for Applications

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5.1. Status

In the past decade, Laser wakefield accelerators (LWFA) have steadily progressed by reaching a higher level of maturity and by moving beyond the proof-of-principle experiments of electron injection and acceleration that took place in the first decade of 2000. Electron beams at few hundreds of MeV, with a good normalized transverse emittance, $\varepsilon_n \approx 1 \ \mu$m, and relatively narrow energy spread, $\Delta E/E < 10\%$, are routinely obtained in many laboratories worldwide. Along with the improvement of the beam reproducibility and availability, several applications of these laser generated electron beams have emerged in the past decade. In addition to the high gradient accelerating fields, LWFA have other specificities that make them quite unique, such as a micrometre source size, a femtosecond bunch duration and a very high peak flux that make them attractive for several societal and scientific applications, even at moderate energy levels of sub-100 MeV. Applications relying on the direct use of LWFA electron beams can be divided into two types:

(i) applications that use the electron beam as a probe, mostly taking advantage of its femtosecond duration for probing ultrafast transient phenomena,

(ii) applications where the electron beam acts as a pump for irradiating materials or samples.

Electrons as an ultrafast probe: when the injection of electrons into the wakefield is well controlled, electron bunches can reach few femtosecond durations while, in principle, their shot-to-shot jitter with the laser pulse is extremely small, i.e. in the femtosecond range. This has the potential to reach ultra-high temporal resolutions in ultrafast probing experiments relying on a pump-probe scheme. Femtosecond LWFA electron beams have been used successfully for probing the dynamics of transient magnetic fields in plasmas [40], revealing sub-ps dynamics of an expanding plasma. More recently, LWFA beams were used to probe the electric field structure of a plasma wakefield with femtosecond resolution [41].

While probing transient fields in plasmas is of interest for plasma physicists, LWFA electron bunches could have a wider impact if used to probe condensed matter, in particular

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the solid state. With femtosecond duration and intrinsic synchronization to the laser pulse, their potential for probing materials at the atomic scale via ultrafast electron diffraction is high. A proof-of-principle experiment was performed recently using a LWFA operating at high repetition rate. These experiments successfully unveiled the lattice dynamics of a silicon nano-membrane with picosecond resolution [42].

Electrons as a pump beam: an advantage of using a plasma accelerator is that the beam properties can be easily tuned, e. g. by changing the plasma density or the laser parameters. Thus, it is relatively straightforward to produce a broad and Maxwellian-like energy distribution, mimicking closely the broadband radiation in the van-Allen belt. In this context, broadband LWFA electron beams were proposed as a test-bed for radiation hardness studies of on-board electronics that are essential in space missions. First experiments were carried out and demonstrated the potential of this method [43]. Electron beams have also been proposed as a source of ionizing radiation relevant for cancer treatment. In comparison with MeV-photons, electron beams produce a more uniform dose deposition in depth, thereby reducing the impact on healthy tissues surrounding the tumor volume. LWFA already provide electrons at the 150-200 MeV level, a range of energy that is relevant for developing Very High Energy Electrons (VHEE) therapy. First experiments provided evidence that a LWFA beam could provide an adequate dose deposition profile [44].
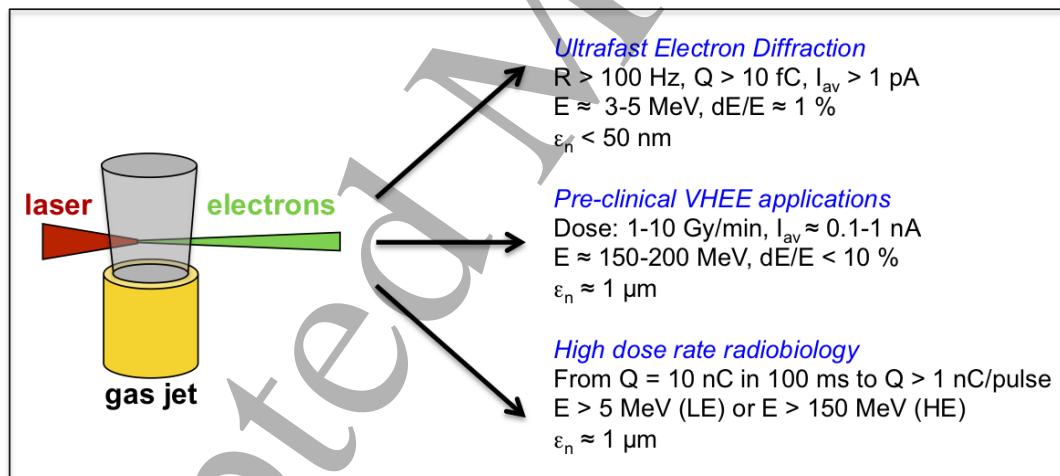
Figure 6. Required parameters for several possible applications of LWFA electron beams. R: repetition rate, Q: charge per bunch, I_{av}: average current, E and $\Delta E/E$: beam energy and relative energy spread, ε_n: transverse normalized emittance.

5.2. Current and Future Challenges

All these preliminary application experiments have remained at a proof-of-principle level and were carried out by researchers specialized in LWFA. A formidable challenge for this field will be to bring these initial experiments to a level where a laser wakefield accelerator can provide beam time to users. By touching fields such as material science, medicine, radiation biology and chemistry, laser-plasma accelerator technology could considerably extend its reach

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and impact. However, the use of LWFA can be meaningful only if the parameters of the electron beams are advantageous compared to what is achieved using conventional accelerator technology. For example, in ultrafast electron diffraction, modern RF electron guns deliver routinely electron bunches that are few tens of femtosecond long, with a very low emittance $\varepsilon_n < 20$ nm, high repetition > 100 Hz and excellent shot-to-shot stability, permitting percent changes in diffraction patterns with ≈ 100 fs temporal resolution to be resolved. Therefore, LWFA should not only provide significantly higher temporal resolution but also match the same level of emittance, stability and repetition rate. This can be done at low energy, say 5 MeV, so that the focus is no longer on high-gradient acceleration but rather on femtosecond duration, jitter and stability. Although some groups are actively working toward this goal, this performance is not reached at the moment.

When it comes to medical applications, LWFA electron beams do have unique properties over conventional sources: they not only provide very short bunches, but also dose rates as high as 10^9 Gy/s. Therefore, LWFA could be particularly relevant for the field of radio-biology, as their extreme duration and dose rates enable the study of possible modifications in ionizing radiation toxicity. They could permit irradiation dynamics tobe followed, starting from the chemistry of water radiolysis at the femtosecond level to the slower biological effects of fast-fractionation [45] and the FLASH effect [46]. These effects could be studied for both low energy (LE) electrons of 5-15 MeV and high-energy (HE) electrons, at 150-200 MeV, provided that the beam charge is high enough. Indeed, for VHEE therapy, a dose of 10 Gy needs to be deposited within a reasonable amount of time over a projected surface of 3 cm^2, implying that a total charge of roughly 10 nC should be delivered in less than a few minutes. In order to access FLASH irradiation conditions, the same charge should be delivered in less than 100 ms. At the moment, very few experiments have started to assess the toxicity of such high dose rates on biological samples [47, 48].

5.3. Advances in Science and Technology to Meet Challenges

Although each specific application requires various parameters and performance (see figure 6), research efforts should focus on transitioning LWFA from physics experiments to actual machines. Most of the applications described here require in general

(i) better stability, reliability and robustness of the beam parameters,

(ii) higher repetition rate,

(iii) better beam availability.

While it is possible that some of these problems are solved with new physics discoveries, a significant engineering effort is necessary. For example, better stability and reliability of the source also implies that the laser systems become highly reliable turn-key instruments. Future LWFAs need to be built for operating at high repetition – they are currently usually running at a few Hz at best. We anticipate that the next ten years will witness the emergence of high average power lasers at kHz repetition rate while still operating at high intensity, therefore enabling high repetition rate LWFA. Several groups have indeed started to demonstrate kHz operation of LWFA delivering few MeV electron beams [49]. High repetition rate should permit the implementation of feed-back control loop for better stability, faster data accumulation, better statistics and the delivery of high doses in short times, all of which are essential to applications such as ultrafast electron diffraction, or radio-biology. The problem of beam availability to users can be tackled by starting to envisage LWFA facilities dedicated to specific

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applications: a given experimental setup might need to become more specialized and focused on a particular application with a specific set of parameters, e.g. high dose rates at moderate charge for radio-biological applications. Dedicated facilities will permit the development of more complicated magnetic transport beam lines that are necessary for several applications. Finally, in addition to developing dedicated facilities and improving the laser technology, plasma targets (gas jets, gas cells etc.) still need to reach better performance for better control and stability of the electron beam. In particular, plasma targets adapted to high repetition rate operation and high average power still need to be developed.

5.4. Concluding Remarks

To conclude, applications linked to the direct use of electron beams from a LWFA are still in their infancy. The potential is very high as the above-mentioned applications could have a tremendous impact in several fields. This will only happen if an important engineering effort is directed toward the development of dedicated facilities with more reliable laser sources and well-optimized plasma targets. The pursuit of high repetition rate LWFA is also a research path that will enable the development of scientific and societal applications.

6. Laser-plasma Ion Acceleration

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6.1. Status

Since focusing of high power lasers onto solid targets has proven to generate intense high energy ion bunches of sub-ps duration and unique spatial characteristics, laser driven ion accelerators [50] received attention for a wide range of potential multidisciplinary and innovative applications (see section 7). This not only demands for an increase of achievable ion energies, but also for high beam quality and control of the spectral and spatial ion intensity distribution. In parallel to ongoing high power laser development which is now routinely approaching the petawatt (PW) level (intensities in the range of more than 10^{22} Wcm^{-2}) [51], continuous effort is dedicated to optimize advanced acceleration schemes together with sophisticated targetry [52] and laser pulse tailoring to improve key aspects of the ion beams.

The best established and most stable acceleration process, and as such considered the work-horse mechanism for experiments in the field is called TNSA (target normal sheath acceleration, centre of figure 7). In TNSA, protons and ions originating from the target surface contaminant layer gain energy along the target normal direction due to space charge fields (TV/m) set up by hot electrons, which were accelerated by the relativistic laser pulses at the front surface plasma. Intrinsically, proton and ion pulses feature broad, exponentially decaying spectra with high cut-off energies of up to many tens of MeV/u and an energy dependent divergence. When perfectly controlled, tailoring the target density profile at the

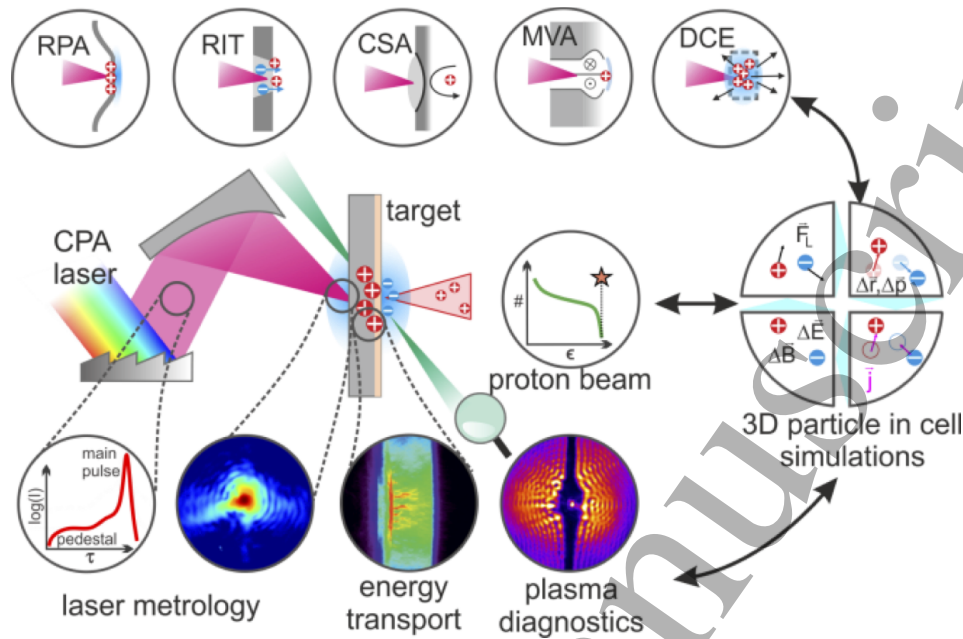CONTENTS   20

Figure 7. Schematic presentation of laser-driven ion acceleration experiments. The properties of the emitted ion beam strongly depend on the complex interplay of the microscopic laser plasma interaction conditions on large dynamic scales such as the temporal and spatial laser pulse shapes in the focal plane (laser metrology) and the plasma density distribution of the target. Depending on the specific laser and target configuration, different ion acceleration mechanisms can prevail (center: TNSA, top: RPA, RIT, DCE, CSA or MVA) [50], whereas discrimination often relies on large scale predictive simulation studies.

moment the peak of the main pulse arrives can lead to mechanisms enhancing the proton and ion acceleration performance. For thin targets the absorption into hot electrons can benefit from the onset of relativistic induced transparency (RIT), where the laser transfers its energy volumetrically to electrons and by that indirectly to the acceleration of ions. If on the other hand absorption is minimized (e.g. by using circularly polarized light), the laser by its light pressure can push an entire ultra-thin foil like a piston, which is referred to as radiation pressure acceleration (RPA). If the target is sufficiently small, the laser pushes away all electrons and the remaining ions are accelerated by repulsion forces, i.e. directed Coulomb explosion (DCE). Near critical plasma density profiles can be tailored in such a way that collisionless shocks are formed by which protons of the background plasma can be reflected to velocities twice as large as the shock velocity (CSA). Beneficially large magnetic fields can be generated to sustain the electrostatic fields in magnetic vortices (MVA) to drive proton acceleration from low density targets. In the laser plasma interaction, these multiple acceleration mechanisms may coexist and transitions between them can additionally enhance the acceleration efficiency [50]. As one example, the highest proton energy achieved so far of over 90 MeV was measured in a transparency-enhanced hybrid regime [53].

6.2. Current and Future Challenges

Since the beginning, one of the most important challenges for laser ion accelerators has been the limited knowledge about the exact temporal pulse shape of the high power laser pulse at focus.

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The temporal pulse intensity ultimately determines the initial condition of the target, and subsequently the temporal evolution during the main pulse interaction process. Intrinsically, high power laser pulses always show additional background light represented by pedestals, distinct pre-pulses or too slowly rising main laser pulse edges (Fig. 7), all potentially resulting in an uncontrollable transition of the initially cold target into a pre-plasma state. This so-called temporal pulse contrast ratio between peak intensity and intensity of pedestals (Fig. 7 left) can nearly be ideal up to 10s of picoseconds before the peak of the main pulse. This tremendous progress of the last decades [51] is the result of implementing advanced cleaning methods to the laser systems often complemented by fast plasma-based temporal filters (i.e. plasma mirror devices) in the vicinity of the final focus. This enabled ion acceleration experiments with ultra-thin and near critical density targets.

Improvement of the natural rising edge of the pulse on the ps-timescale, however, is still a matter of ongoing development. As an example for the strong influence of laser contrast, Fig. 8 shows a collection of proton cut-off energy thickness scans taken from literature [54]. Usually, the cut-off energy is introduced as the highest achievable proton energy (star in the spectrum of Fig. 7) and serves as a characteristic parameter for the largest occurring accelerating fields. Moreover, it is used to distinguish between acceleration mechanisms and for benchmarking experimental with numerical results. As can be seen by the color code, higher laser energy in general yields higher proton cut-off energy, whereas the acceleration efficiency can strongly depend on other interaction conditions. As long as the rear surface density gradient generated due to pre-plasma expansion remains steep enough, TNSA cut-off energies are maximized for thin targets. For these, the diverging electron distribution flowing from the target front to the rear yields the highest electron density responsible for the accelerating sheath fields. Due to this effect, TNSA features stronger sheath fields for thinner targets [50]. This trend is illustrated by the grey scaling model curves in Fig. 8, stagnating at around 100 nm when the thickness gets much smaller than the focal spot size. If pre-plasma formation at the target rear can be suppressed sufficiently, even thinner foils can be irradiated and potentially RIT occurs when $a_0 \gg \omega_p^2 l/2c\omega_L$ [55] (with plasma frequency ω_p and laser frequency ω_L, target thickness l and normalized laser field amplitude a_0). There, volumetric heating potentially enhances the acceleration. If not, the cut-off energy usually drops for thinner targets as shown by several data sets.

Fig. 8 highlights the challenge of the field: understanding is deduced from macroscopic observations of basic properties of charged particle beams or secondary radiation, integrated over time and space. Microscopic insight about the instant plasma evolution from over-dense to near-critical states or the development of instabilities in the bulk is only inferred from numerical simulations, for which the input parameters often rely only on reasonable assumptions.

6.3. Advances in Science and Technology to Meet Challenges

By developing novel real-time laser and plasma diagnostic concepts with high spatial and temporal resolution, the field has initiated tremendous efforts to improve this situation (see section 10). Matching this new input to realistic, full-scale and full-density 3D simulations is indispensable, representing an entire research field in itself (see section 12). Here, continuous advances in predominantly four domains are required.

(i) Technologies to precisely characterize the high-power broad band laser pulses at the focal plane are necessary. This comprises measurements of spatio-temporal couplings as well as spatially-resolved temporal pulse contrast [56].

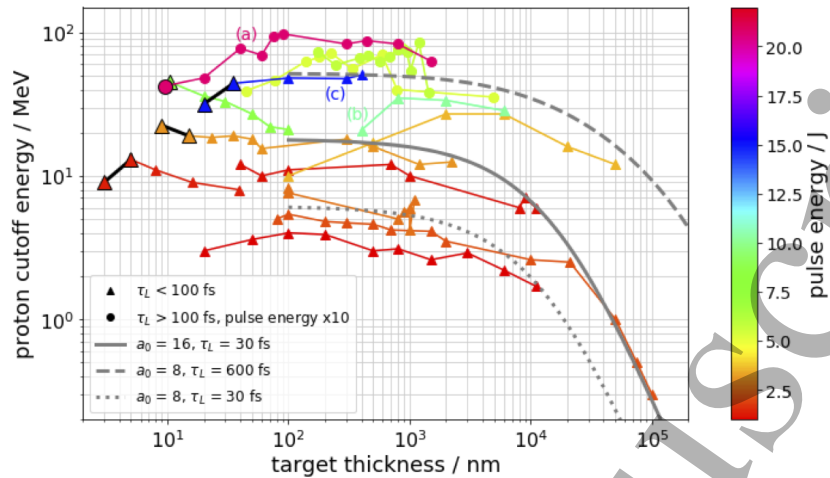CONTENTS   22

Figure 8. Selected target thickness scans from literature adopted from [54] for linearly polarized pulses of different sets of pulse duration updated by recent data (a) from [53] as well as (b) from J-Karen and (c) from Draco PW for aluminium and plastic targets, respectively. Laser pulse energy is colour coded, whereas for $\tau > 100$ fs (circles) a correction factor of 10 has to be applied. For thicker targets, TNSA thickness scan models described in [50] for different laser parameters (grey lines) show good agreement to the trend of the data. Potential onset of transparency estimated applying the criterion introduced by [55] and is indicated with bold symbols.

(ii) Equally important are methods to diagnose the microscopic plasma evolution by ultra-fast probing techniques using probes in the optical or X-ray regime [57] to study the plasma density around or inside solid targets, respectively. This also includes detection systems for particle and secondary radiation [58].

(iii) Debris and contaminant free, stable target supply systems are mandatory, providing high repetition rate [59] which enable experiments with high statistics and more reliable data sets [52].

(iv) A further increase of the laser peak intensity in general, a technique to freely control and tailor mainly the temporal pulse structure on a logarithmic scale between ionization level and peak intensity in order to realize any desired plasma dynamic could advance the field significantly on a more long-term scale.

6.4. Concluding Remarks

With the new high repetition-rated PW-class laser infrastructures complemented by the combination of novel diagnostic concepts and quantitative, predictive simulation capabilities developed during the last decade we expect a higher level of understanding and by that better performance of laser-plasma ion accelerators for the years to come. This will enable a wide range of potential interdisciplinary applications as outlined in the next chapter of this Roadmap.

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7. Applying laser-plasma based ion acceleration

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7.1. Status

The relativistic laser-plasma ion source, in particular a high power laser-irradiated thin foil target, can be viewed as a back-illuminated photoanode. Due to the point-like source size, its performance is quantified by the number of particles contained in a single bunch within a certain kinetic energy bin and emission divergence angle (cone). This differential spectrum is the outcome of the acceleration mechanism dominating an experimental realization (see section 6) and contains the primarily interesting information to devise any subsequent applications. Plasma acceleration experiments contribute new data frequently and are regularly monitored at https://www.alpa.physik.uni-muenchen.de/. The excerpt in Fig. 9 reveals that particle yield and bunch energy increase with laser pulse energy on target (colour-coded) and peak power. With typical differential numbers of $10^6 \ldots 10^8/(1\% E_{kin} \mathrm{msr})$ and half divergences between 20 and 200 mrad a single bunch contains $4 \times 10^7 \ldots 4 \times 10^{12}$ particles. Bunch repetition rates are limited by the laser and target positioning system. MeV ions have been demonstrated at kHz rates [60], 10–50 MeV at rates up to Hz and higher kinetic energies are accessible with single laser shots on demand (see section 6).
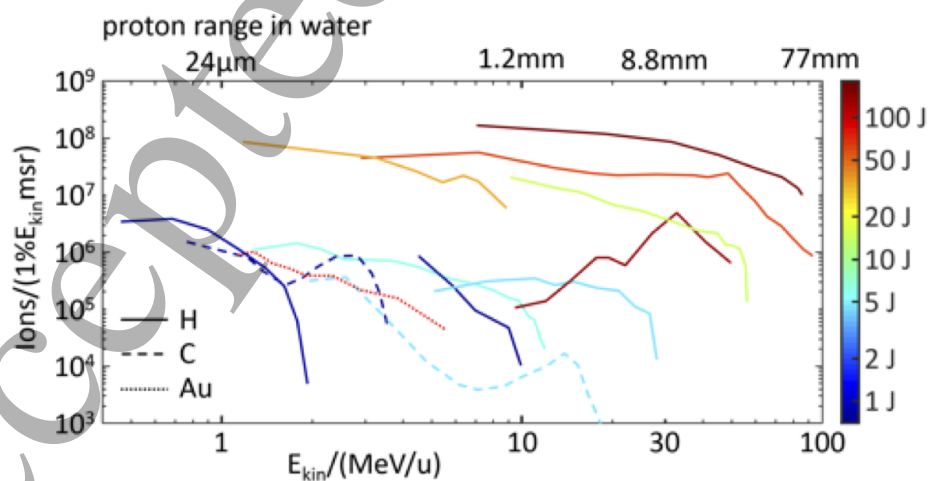

Figure 9. Typical single bunch differential energy spectra of protons, carbon and gold ions. Colour indicates laser energy on target. Penetration depth in water indicates application ranges.

Motivated by the compactness of laser-driven acceleration, applications that experience

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constraints by the size of established accelerator technology such as ion beam tumour therapy have been proposed as illustrated in Fig. 10d [61]. They represent a motivating long term goal that can drive maturing laser-plasma sources with increasing ion energies [62]. En-route, radiation biology studies have been carried out (Fig. 10e) in cell samples and are currently being extended to small animals. Orthogonal applications that also require relatively low average ion flux move into the focus of researchers. Material science, in particular proton induced X-ray emission as an analysis tool in cultural heritage studies [63] is one such example (Fig. 10f). The distinct features of 'laser-driven', the micrometre source size, the femtosecond acceleration interval, the high particle number per bunch (and the intrinsic synchronization with the laser pulse and additional radiation bursts that can be derived) readily enabled new frontiers that have not been accessible by established accelerator technology. When integrating the application close to the ion source, picosecond proton pump plus femtosecond optical probe geometries (Fig. 10a) were demonstrated [64]. Similarly, picosecond proton probing of electromagnetic fields in plasmas has become a standard tool (Fig. 10b) with external [65] and internal probes [59]. The short ion bunch duration also enables high peak flux that is interesting for material stress testing, isochoric heating of warm dense matter and the generation of short poly-energetic neutron bunches. Recently, efficiently accelerated deuterons were converted, in secondary Beryllium targets, into directed neutrons (Fig. 10c) at the 10^{10} n/sr level [66] with energy adequate for demonstrating single bunch time-of-flight based neutron radiography.
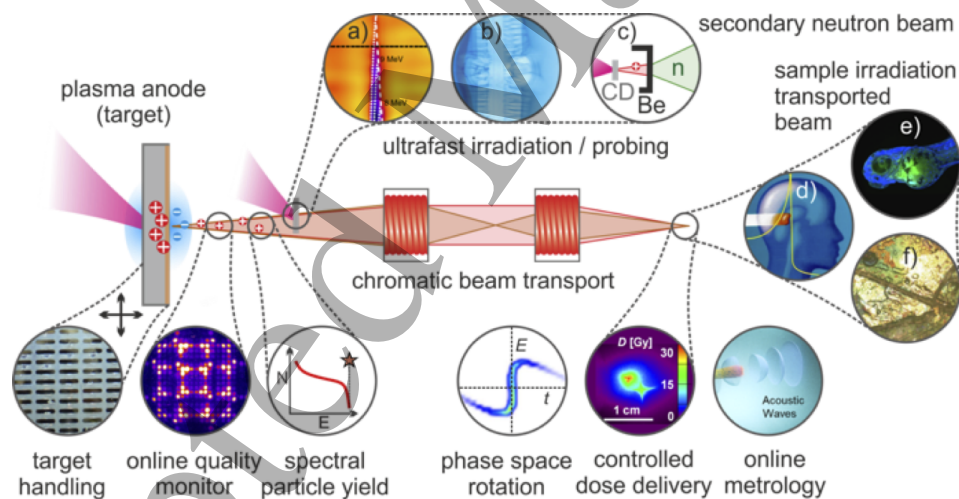
Figure 10. Key elements of laser-plasma ion accelerators for distinct applications. Unique ultra-fast pump-probe experiments become possible (a-c) close to the well characterized source ideally operating at high pulse repetition rate, while dedicated beam transport and shaping (here with pulsed coils and bi-chromatic) enables controlled dose delivery for medical applications and analytics (d-f).

7.2. Current and Future Challenges

Performance of laser-ion acceleration is today predominantly measured in achievable maximum ion energies. Increasing this value, primarily through higher laser pulse energy on target, remains a key challenge and enables applications that require deeper penetration (Fig. 9). The important quantity of interest though is the particle yield within a well-defined energy bin and emission cone (i.e. the differential spectral amplitude). This yield is currently not

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well understood, it can be difficult to predict quantitatively, and it is not stabilized to the desirable percent level.

High instantaneous fluxes and electromagnetic disturbances remain prime challenges for single bunch recording and characterisation. Adequate online techniques progress well (for example with iono-acoustic [67], electronic and scintillator based sensing (Fig. 9, lower row) in combination with time-of-flight measurement), but they do not yet yield detailed and complete information similar to that available through offline methods such as dose sensitive film stack exposure.

Taking advantage of the small source size, short bunch duration, and high peak flux currently requires integrating an irradiated sample that is placed very close to the source. This poses severe constraints on application fields as well as monitoring and control of irradiation conditions. On the other hand, the conventional RF cavities for phase-space rotation [68] and chromatic transport optics [69] that have been demonstrated so far (Fig. 9) are not yet well enough matched and therefore typically unable to recreate small foci and short bunches at a remote platform for applications. Long-term operation of the laser-ion source remains a remarkable challenge, in particular when aiming both at high energy and stable yield. By the time most influential laser and target parameters will have been identified, other technical aspects such as debris handling will become a foreseeable limitation.

7.3. Advances in Science and Technology to Meet Challenges

Fig. 10 visualizes key elements of interest for laser-driven ion source applications and currently investigated solutions. A stably operating high power laser system is prerequisite. Experience has proven that increasing the laser power alone is insufficient for an effective gain in ion yield at higher kinetic energies. Stable yields at energies of 100 MeV/u and beyond are mandatory for ion beam therapy and will require significant advances in knowledge and spatio-temporal control of the laser pulse shape with micrometre and femtosecond resolution over an intensity range from plasma formation ($\sim 10^{13}$ W/cm^2) to peak intensity ($\sim 10^{24}$ W/cm^2). Target positioning systems must be developed that support the laser repetition rate and attain positioning accuracy better than the focal volume (μm^3) [52]. Those systems ideally should contribute adequately low debris levels, as are currently only reached by novel cryogenic gas targets [59]. In addition debris mitigation measures must be explored and integrated. Spectral yield monitors must be operated online with direct readout and complemented by non-invasive acceleration diagnostics, for example through temporally resolved probing techniques. Ideally, these monitors will direct feed back to the laser-ion source via the laser pulse and target controls. Such controls that will enable active stabilisation of the ion yield in the future remain to be identified in multi-parametric studies.

Irradiation studies close to the source, for example ion-pump optical-probe studies of fast dynamics in materials or unprecedented time and space resolved ion radiography, require online detectors for three-dimensional dosimetry and bunch duration measurements. Disposable film and other offline detection methods that require tedious post processing must be gradually replaced. For a 200 J laser driving a thin-foil deuteron source at 10 Hz repetition rate, generation of secondary radiation, in particular directed neutron bunches for radiography and spectroscopy can become competitive by providing 10^{13} neutrons per second.

Many applications require irradiation under controlled and clean conditions in air. Studies must therefore shift from the mm source proximity to platforms of a meter-scale remoteness. Retrofitting conventional beam transport and bunch manipulation systems for controlled dose delivery can be a starting point. They will be necessary for radiation therapy related studies

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in its current form, where beams are primarily scanned in position and energy, but inadequate for the long term. Recreating the ion bunch parameters that the source can generate and taking advantage of them requires solutions that are adapted to the bunched nature of laser acceleration. Pulsed beam transport systems, advances represented by dedicated macroscopic [68, 69] and target-integrated microscopic [65] pulsed coils, must further mature to become not only compact energy filters but adaptive shaping tools for broadband bunches [61], in particular for the irradiation of live samples in the context of tumour therapy research where precisely applied depth dose profiles are mandatory within a minimum number of bunches and where ultra-high peak dose rates might open new therapeutic windows in the frame of the novel FLASH irradiation concept.

7.4. Concluding Remarks

Laser-driven acceleration represents a natural evolutionary step in accelerator development that has lasted for more than a century. The plasma ion source is one promising approach for converting laser pulse energy into particle kinetic energy. With new driver and acceleration schemes come distinct ion bunch characteristics. Many applications today, in particular medical, request parameters that have evolved over decades of experience at conventional accelerators. This approach likely limits the motivation for laser-driven accelerators to the future compactness of the system. Ideal applications integrate laser-driven ion accelerator systems [62] and in concert will match, outperform or complement established conventional devices. Starting with doable, niche fields of research that promise high discovery potential must guide our efforts and provide a solid basis en route towards applicable, compact laser-ion accelerators.

8. Betatron X-rays and Compton Sources

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8.1. Status

One of the most promising applications of laser wakefield acceleration (LWFA) is the generation of sources of x-rays and gamma-rays that have the potential to offer complementary alternatives to synchrotrons and other sources based on RF accelerator technologies [11, 12]. The two most mature LWFA-based sources, with applications in imaging for medical and industrial applications, nuclear physics, material and high energy density science already underway, are based on betatron motion and Compton scattering processes (Fig. 11). When an intense laser ($I > 10^{18}$ W/cm^2) interacts with an underdense plasma (electron density in the range $10^{17} - 10^{19}$ cm^{-3}), the ponderomotive force drives an electron plasma wave that traps electrons and accelerates them to relativistic energies (with a current record at 8 GeV [31]). When such electrons are trapped off the main laser axis, or with initial transverse momentum, they also experience transverse restoring forces due to space-charge separation, prompting them to execute transverse oscillations as they are accelerated. This betatron motion generates a bright source of x-rays, first observed in 2002 in a beam driven plasma accelerator [70] and in 2004 in a laser-driven one [71], with similar properties to those of a

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synchrotron (a broadband spectrum with photon energies up to a few tens of keV, a collimated beam of a few tens of milliradians, and a micron source size).
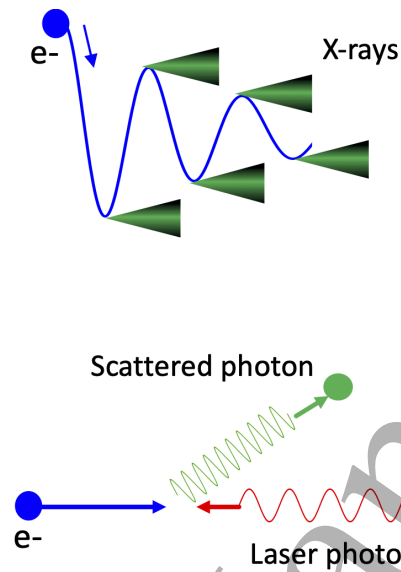

Figure 11. Schematic representation of Betatron x-ray radiation (top) and Compton scattering (bottom) from electrons accelerated through laser-wakefield acceleration.

The two additional benefits are a femtosecond-scale pulse duration and the intrinsic synchronization between the drive laser beam, the generated particle bunch, and the secondary radiation. These features make LWFA light sources unique for applications. For higher energy photons, Compton scattering, where laser photons are scattered off the LWFA electrons and upshifted to higher energies (up to a factor of 4 times the square of the electron relativistic factor for a head-on collision), is a better alternative. The scattered photons can either be from the LWFA-drive beam reflected on a plasma mirror [72], or from a second beam [73, 74], which was first demonstrated in 2012 and 2006, respectively. For a given electron beam energy, Compton scattering will scale to much higher photon energies (the maximum at present is 18 MeV [75]) than betatron radiation. Fig. 12 summarizes the peak brightness of these two sources and compares them with conventional technologies.

8.2. Current and Future Challenges

Most of the research efforts of this field are currently aimed at applications, and thus the development of these sources and their key parameters (energy, photon flux, spatial and temporal resolution) must be done in close coordination with applications in high energy density, biological, planetary, material and astrophysical sciences, and nuclear photonics. In terms of source development, the photon flux, overall laser conversion efficiency (currently around 10^{-5}) and shot-to shot intensity/energy stability need to be improved. Some applications, such as x-ray phase contrast imaging of biological objects and laser-driven shocks, as well as time-resolved x-ray absorption spectroscopy, have already been demonstrated. These should likely become routine applications for betatron radiation in a near future, where it can be coupled to high power or free electron lasers capable of driving matter to extreme states. Other techniques, such as x-ray scattering or diffraction, will require at least 3 orders of magnitude more photons. Compton scattering provides higher photon energies, is easier to
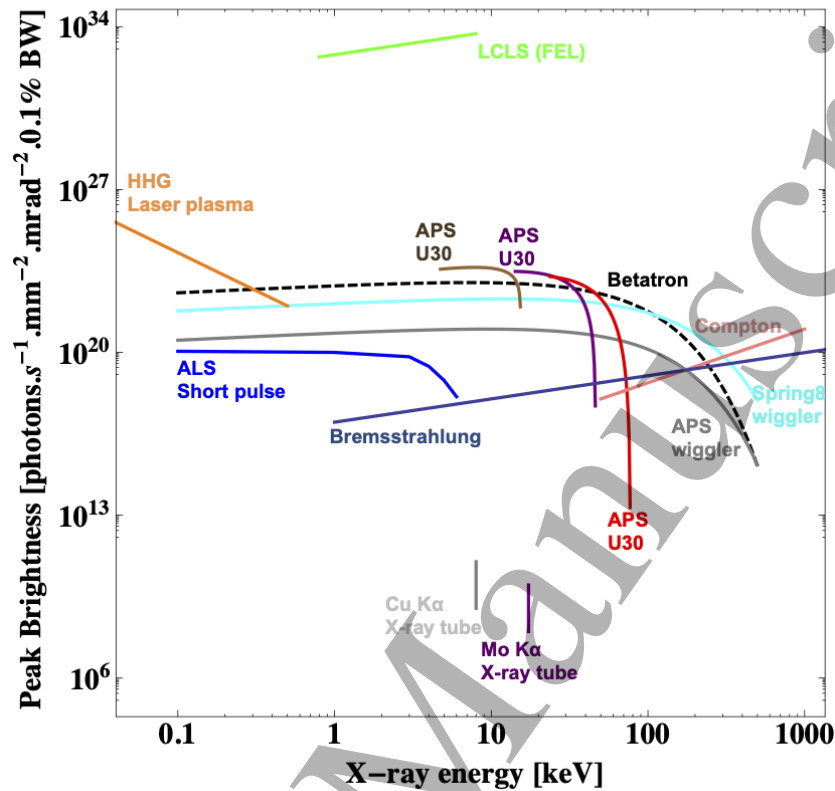
Figure 12. Peak brightness of betatron, Compton and bremsstrahlung radiation from LWFA compared to other types of sources in the same energy range. Sources included in this plot are: The APS synchrotron U30 undulator for harmonics 1, 3 and 5 (Argonne National Laboratory, USA), the ALS synchrotron (Lawrence Berkeley National Laboratory, USA), the Spring8 synchrotron (RIKEN, Japan), x-ray tubes (Copper and Molybdenum K_α), the LCLS free electron laser (SLAC, USA), and high harmonics generation from laser-produced plasmas. Figure reproduced from Ref [12].

tune, and can have a narrower bandwidth (provided the electron energy spread is small and the source operates in the linear regime where the scattering laser intensity is well below 10^{18} W/cm^2) than betatron radiation. Hence, applications are naturally more geared toward gamma-ray radiography, photofission, and possibly nuclear resonance fluorescence. Most of these applications have yet to be demonstrated with a LWFA-based Compton source.

8.3. Advances in Science and Technology to Meet Challenges

The development of LWFA-driven light sources is tied to progress in laser, target, and diagnostic technologies. At present, most of the applications have been (and can continue to be) demonstrated at a Hz-level repetition rate. However, most research directions mentioned in this roadmap ultimately require high repetition rate (kHz and above), both to enable application science and active laser feedback for precision control. A near term development would be a few-joule kHz system (with stabilization and temporal/spatial pulse shaping) enabling precision LWFA via stabilization and thus controlled light sources. Although many

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new, petawatt-class short pulse laser facilities are now emerging around the world [76], and should spur improvements in flux and brightness of betatron and Compton light sources, experimental techniques to improve the source parameters should still be pursued. Examples include methods of initiating electron trapping that offer the potential to improve the beam quality (emittance, brightness and energy spread), tapering the electron plasma density, guiding and other methods to improve the overall efficiency. Progress will also be enabled by coupling high intensity, short pulse lasers with multiple other laser beams. These include

  (i) long wavelength,

 (ii) high energy long pulse (ns) systems to drive matter to extreme conditions,

(iii) X-ray free electron lasers (X-FELs).

In this context, a LWFA-based XFEL, also discussed in this roadmap, would be a game changer well beyond the plasma-based particle acceleration community (see section 9). Large facilities that are emerging throughout the world need to be supported by smaller scale groups with flexible research efforts, and have a balance between user facilities where new ideas can be tried, and dedicated engineered beamlines where high performance and control can be advanced for applications of LWFA light sources.

8.4. Concluding Remarks

In summary, Betatron radiation and Compton scattering sources based on laser wakefield acceleration have the potential to provide photons with unique properties for applications. Their key properties are: photons from a few keV to a few MeV, a broadband spectrum (with some width and energy tunability for Compton scattering) a directional beam (mrad), a small source size (micron), a femtosecond-scale pulse duration, and an intrinsic synchronization with the drive laser system for dynamic studies. They should become standard diagnostic tools at large-scale user facilities (high intensity, high energy and XFELs), but also improved side by side with new, high repetition rate (kHz) laser technology, diagnostic and target development.

9. Laser Plasma Accelerator based Free Electron Laser

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9.1. Status

Free Electron Lasers (FEL) [77] use relativistic electrons wiggling under vacuum in the periodic magnetic field created by an undulator as a gain medium. The interaction between the electrons and their spontaneous emission produced in the undulator, the so-called synchrotron radiation, induces an energy modulation of the particles, that converts into a density modulation, enabling coherent radiation emission and further radiation amplification. The spectral range can be tuned by a mere change of the electron energy or undulator field. FELs were first operated down to the UV range in the oscillator configuration, for which the spontaneous emission is stored to be amplified. In the Self Amplified Spontaneous Emission

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(SASE) configuration, the spontaneous emission is amplified in a single pass (see Fig. 13). The injection of an external laser tuned at the undulator resonant wavelength enables to speed up the energy modulation and to improve the FEL longitudinal coherence. The recent advent of coherent tuneable X-ray FELs [78], providing record GW peak powers with mJ, few fs to attosecond duration pulses, leads a major revolution for matter investigation, enabling to decipher ultra-fast dynamics, explore X-ray non-linear processes, and scrutinize matter in various conditions. Operated at MHz repetition rates, with simultaneous delivery to several FEL branches, X-ray FEL user facilities reach a very high level of reliability (up to 98 %) on a 24-hour operation. The achievement of X-ray SASE FELs, 35 years after the first mm range SASE one, benefited from the improvement of the electron beam quality driven by collider accelerators development.

Driving an FEL with a Plasma Accelerator (PA), in particular a Laser Plasma Accelerator (LPA), will qualify this advanced accelerating technology with a demanding application in terms of electron beam quality and constitutes a milestone towards future colliders. Thanks to the large plasma acceleration gradient, it will also pave the path towards compact FELs. Besides, using the extremely short electron bunches produced by LPAs, the FEL could be operated in the single spike regime, particularly adapted for providing femtosecond to attosecond pulses. The natural synchronization of the electrons with a laser system is well suitable for pump-probe two-colour applications.
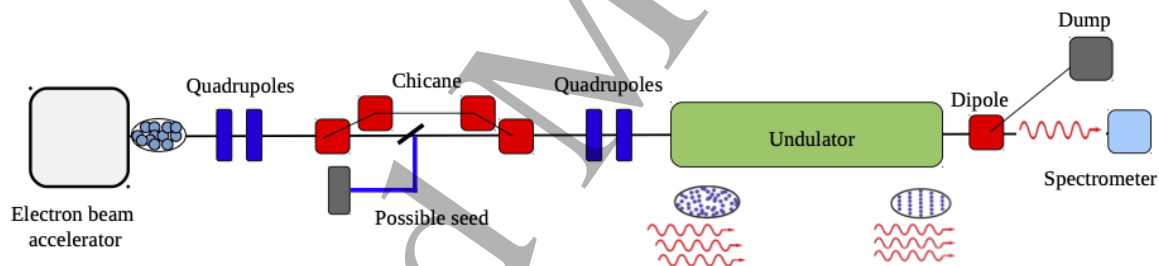

Figure 13. Scheme of a Free Electron Laser.

9.2. Current and Future Challenges

The hopes resting on PA to drive undulator radiation and FEL light sources are challenged by PA performance that still do not meet conventional linear accelerator (CLA) state-of-the-art ones. Indeed, while CLAs deliver μrad divergence and per mill relative energy spread beams, LPAs present milliradian divergence and energy spread usually above the percent level. As a consequence, the chromatic effects in the transfer lines [79] (scaling as the square of the divergence and linearly with the energy spread), usually negligible on CLAs, have to be mitigated on LPAs not to cause a dramatic emittance growth and afferent beam quality degradation.

The large divergence requires strong focusing in the immediate vicinity of the electron source, using high gradient permanent magnet quadrupoles or plasma lenses. The imprinting of the energy modulation enabling for FEL amplification sets a requirement on the slice energy spread to be smaller than the Pierce parameter, typically of the order of 10^{-3} and inversely proportional to the FEL gain length. With presently available LPA beams, two strategies can be adopted to reduce the initial large energy spreads. Electrons travelling in a decompression magnetic chicane follow different paths in the dipolar magnetic fields according

to their energy, ending up longitudinally sorted in energy [80]. The resulting slice energy spread reduction however comes along with a peak current drop and a bunch lengthening. This bunch lengthening is also required for intermediate FEL wavelengths, to avoid the radiation escaping the electron bunch due to slippage (electrons and photons propagating at a different velocity). Still, advantage can be taken from the energy–position correlation introduced by the chicane for synchronizing the electron beam focusing and the radiation pulse progress along the undulator [81, 82]. Another approach employs a transverse gradient undulator [83] combined with dispersive optics to maintain the undulator resonant wavelength condition along the transverse direction. Whatever the adopted strategy, the presently low repetition rate and short term stability of LPAs are also an issue.

9.3. Advances in Science and Technology to Meet Challenges

The advances towards plasma electron beam driven FELs are twofold: first, attempts to improve the initial beam quality are followed and second, the beam is manipulated with present electron beam performance. Strategies of improvement of the electron beam quality are investigated, such as control of the electron injection and plasma exit, shaping of the plasma density, hybrid schemes (Trojan horse [84], external RF injection), or electron beam chirp removal in a magnetic chicane after an injection stage [85]). Besides, FEL demonstrations are attempted with the presently available beam quality. Proof-of-principle LPA based undulator radiation at different wavelengths set the first milestone towards FEL light [86]. The quality in terms of spectral purity and stability was far from that achieved on synchrotron light sources, and the electron beam properties could not enable any FEL process. A second step has been achieved with the proper transport of an LPA electron beam along a dedicated FEL manipulation line on COXINEL (Synchrotron SOLEIL, LOA, PhLAM, France) [84]. Relying on variable high gradient permanent magnet quadrupoles, a decompression chicane, additional quadrupoles to implement chromatic optics in an undulator and an original Beam Pointing Alignment Compensation method, the electron beam properties along the line were finely controlled. Benefitting from the improved beam quality, the emitted undulator radiation exhibits good wavelength stability and a high level of spectral purity [87]. Depending on the charge density value, FEL amplification could be within reach, as illustrated in Fig. 14 in the UV range.

Progress is also under way on other test experiments; the decompression chicane concept is also adopted at LBNL (USA) and LUX (CFEL/Univ. Hamburg), which is improving the electron beam stability and performance produced using 200 TW lasers with numerous diagnostics [87]. Different LPA set-ups are developed at SCAPA (Strathclyde Univ., UK), SIOM (China) and LAPLACIAN (Japan) with a booster scheme and a very short 4 mm period undulator. The set-up at F. Schiller Univ., Jena/KIT (Germany) uses a dedicated transport line with a superconducting transverse gradient undulator. The PA based FEL demonstrations should be done by steps progressively shortening the wavelength of operation. The FEL gain decreases with the wavelength, finally requiring an excellent beam quality for the hard X ray domain (nC charge level, 0.01 % energy spread, 1 πmm.mrad emittance).

9.4. Concluding remarks

The large efforts devoted to the improvement of the plasma acceleration electron beam quality will benefit the FEL application. PA operation also becomes more reliable, thanks to numerous diagnostics, transforming an accelerating concept into an accelerator. Presently,
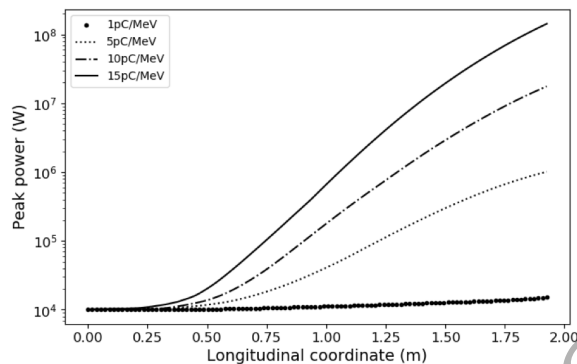
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Figure 14. Peak power along the undulator for different levels of charge per MeV. Simulation with GENESIS of a seeded FEL at 267 nm, using an initial beam with 155 MeV central energy, an emittance of 0.2 mrad, a divergence of 1 mrad, a 18 mm period undulator with a deflection parameters of 1.85. Transport to the undulator using a decompression chicane with compression factor of 1.5 mm and a chromatic optics with two sets of quadrupoles, simulated with transport matrices up to the second order.

several test facilities are aiming at demonstrating the first FEL amplification, with electron beam manipulation through dedicated transfer lines. A proper transport with beam pointing alignment compensation and fine energy tuning already enabled stable observation of LPA based undulator radiation. Simulations with reasonable LPA beam parameters predict FEL amplification on the various test experiments. UV-VUV LPA based FEL, to be demonstrated in the coming years, will answer a real Grail quest. The demonstration of PA based X-ray FEL will then rely on the newly proposed schemes which should deliver high electron beam quality. These new developments will open the route to ultra-short plasma based FEL in the next decades.

10. Diagnostics for plasma accelerators

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10.1. Status

Diagnostics link micron- or nanometer- (nm-) scale morphology and femtosecond- (fs-) scale dynamics of plasma-based accelerator structures to accelerated beam properties, and observable accelerator properties to theory and computer simulation. Laser- [88] and particle-beam-driven [89] electron accelerators are based on under-dense plasmas (density $10^{16} < n_e < 10^{19}$ cm^{-3}) that are transparent to optical probes, and support wakes with natural feature size of order $\lambda_p \sim 10 - 100$ microns. Researchers in this area, far from simply carrying over diagnostic methods from conventional rf electron accelerators, have invented an entire new

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generation of diagnostics capable of measuring the ultra-short duration (few fs) and ultra-small normalized transverse emittance ($\varepsilon_n < 0.1$ mm mrad) of plasma-accelerated electron bunches, and of visualizing the evolving structure of light-speed plasma wakes, all in a single shot [13]. Consequently many plasma electron acceleration studies now routinely include, along with electron energy distributions and charge measurements, e.g. a fs longitudinal bunch profile (Fig. 15a) derived from optical transition radiation spectroscopy [90], a sub-micron transverse beam profile derived from betatron x-ray radiation spectroscopy, or snapshots/movies of the transient plasma wake that produced them (Fig. 15b), derived from fs shadowgraphic [91], holographic or radiographic probes [13]. Increasingly, diagnostics invented for plasma accelerators are even finding their way back into conventional accelerator technology.

Ion accelerators, in contrast, are based on over-dense plasmas ($10^{21} < n_e < 10^{24}$ cm^{-3}) that are opaque to optical probes, and have nm-scale plasma-density and field structures [10]. Currently standard Thomson parabola ion spectrometers, imaging plates, and film stacks diagnose ion beams from such accelerators, while scintillating screens characterize both ions and accompanying electrons that emerge from the laser-irradiated target. Analysis of drive and probe laser beams reflected from the front or back surface of the overdense-plasma target diagnoses laser absorption and laser-surface interaction. Ultrashort particle probe beams map electro- and magneto-static fields, particularly at the target rear, spatially and temporally. Currently such techniques usually measure properties before and after the interaction. Detailed knowledge of nm- and fs-scale internal plasma structures during the interaction (see Fig. 16), which govern accelerated ion beam properties, is largely lacking. High-flux plasma self-emission ranging from x-ray to optical frequencies complicates detection and interpretation of diagnostic probe data.

10.2. Current and Future Challenges

Plasma-accelerated electron-beam diagnosis faces several challenges. With current methods, uniqueness of reconstructed bunch durations and form factors (e.g. Fig. 15a) is not guaranteed, and uncertainties of converged results remain challenging to quantify. Moreover, as plasma accelerators produce even shorter (sub-fs) and lower-emittance bunches, existing techniques may need to be refined or superseded. One of the biggest future challenges is to develop single-shot methods for recovering not only few-fs longitudinal bunch density profiles (Fig. 15a), but simultaneously transverse density and 3D momentum structure. Such 6D diagnosis must be minimally invasive, applicable throughout beam transport lines and sufficiently low-cost to be replicated over many accelerator stages. The main challenge for plasma wakefield structure diagnosis is achieving single-shot 4D visualization — i.e. 3D structure plus time evolution, the laboratory equivalent of particle-in-cell (PIC) simulation output. Methods already developed to visualize wakes in $n_e \sim 10^{19}$ cm^{-3} gas-jet plasmas must be adapted to $\sim 10^{17}$ cm^{-3} plasmas of meter length, since they underlie contemporary GeV accelerators. However, low n_e poses the challenge of reduced sensitivity for many optical methods. Finally, we must learn to incorporate advanced diagnostics and their results directly into computations during a simulation, when all physics is available in memory.

For ion accelerators, diagnosing and controlling interaction of the low-intensity laser pre-pulse with the hydrodynamically evolving pre-plasma, prior to the main relativistic laser interaction with over-dense plasma, is one major challenge. Incomplete knowledge of this pre-interaction probably accounts for consistently higher simulated than measured ion beam energies. Methods of quantitatively diagnosing critical-density surface dynamics of intensely irradiated thin foil targets are therefore needed. A second major challenge is spatially and
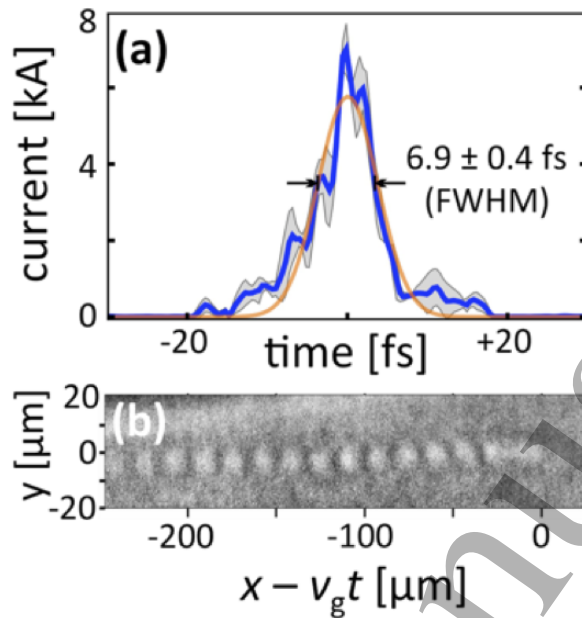
Figure 15. State-of-the-art diagnostics of plasma-based electron accelerators: (a) longitudinal profile (blue curve) of 250 MeV, 62 pC electron bunch from laser wakefield accelerator, reconstructed from its optical transition radiation spectrum based on methods in Ref. [90]. Grey: rms deviation; Orange: Gaussian fit (picture from O. Zarini); (b) shadow of plasma wake driven in pre-ionized $n_e = 4.5 \times 10^{18}$ cm^{-3} plasma by electron bunch from a laser-driven wakefield accelerator, traveling left to right and illuminated transversely by a few-fs near-IR probe pulse based on methods in Ref. [91] (picture from S. Schöbel).

temporally resolving dynamics of the relativistically irradiated optically opaque plasma, in order to identify absorption mechanisms, plasma instabilities, resonant plasma excitations and atomic dynamics that control ion acceleration. Developing advanced methods for diagnosing and controlling laser pulses at full petawatt power is a key component of this challenge.

10.3. Advances in Science and Technology to Meet Challenges

Coherent transition radiation (CTR) methods show promise for the task of minimally invasive, low-cost 6D profiling of plasma-accelerated e-bunches. Different CTR incarnations — multi-octave spectroscopy, imaging, interferometry — have separately characterized longitudinal structure, transverse structure and transverse momentum, respectively, of plasma-accelerated bunches with high resolution outside of the accelerator [13]. We must now find ways to combine these capabilities. Promising ways forward include diffraction radiation from bunches passing through non-interceptive, μm-scale apertures, and Smith-Purcell radiation from bunches passing over a grating. Both add an angular dimension to spectral data, which can facilitate simultaneous reconstruction of longitudinal and transverse bunch profiles.

Computational advances in solving the inverse e-bunch reconstruction problem using data from diverse diagnostics, despite missing information (e.g. spectral phase of emitted radiation), are also needed. Single-shot 4D visualization of mm-scale light-speed refractive index test objects has been demonstrated in dense media using spectral tomography and multiplexed transverse probe trains [13], but must now be extended to μm-scale plasma wakes

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in $\sim 10^{17}$ cm^{-3} plasma. This will require generation, detection and management of wide-bandwidth, mid-infrared probe pulses.

For ion accelerators, single-shot methods of diagnosing peak-to-prepulse contrast, dispersion and spatio-temporal mode of ultra-intense petawatt laser pulses with high fidelity and dynamic range will be essential for controlling pre-pulse and main-pulse target interactions. Simultaneously, synchronized ultrashort XUV and x-ray probe pulses will be needed for penetrating the target's optically opaque plasma, and for resolving nm-scale surface and internal structure and its fs dynamics using e.g. time-resolved Thomson scattering and small-angle x-ray scattering [57, 92]. Ultrashort x-ray free-electron lasers (FELs), including conventional large-scale facilities (LCLS, SACLA, European XFEL) and compact laser-plasma-accelerator-driven FELs, are promising sources of coherent ultrafast x-rays, while ultrashort electron and proton probe bunches from tabletop plasma-based accelerators can produce bright, incoherent diagnostic x-rays pulses via betatron emission, bremsstrahlung radiation or inverse Compton scatter [11, 93]. Such particle bunches can also profile internal fields of the laser-irradiated target directly via shadowgraphy. Advances in high-performance computation will be needed to combine these multifarious diagnostic data, and incorporate them into forward and inverse models of the target's evolving plasma accelerating structure, and to evaluate uniqueness and uncertainty of these models.
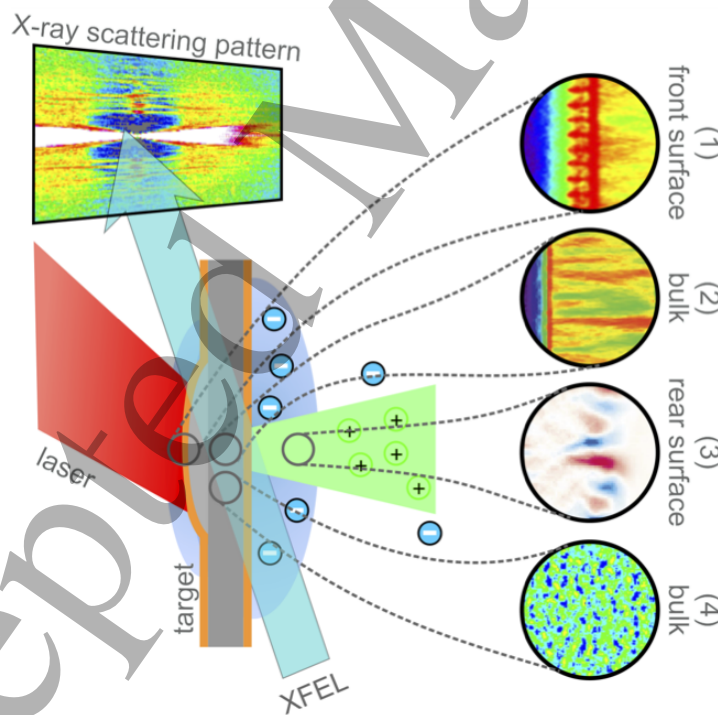

Figure 16. Typical small-scale structures in over-dense ion acceleration targets as modeled by PIC simulations. Insets at right show (top to bottom): (1) electron density modulation at 10-100nm spatial scale from nonlinear Rayleigh-Taylor instability at the front surface; (2) bulk electron density modulation at μm spatial scale, originating from a Weibel-instability; (3) time-averaged quasi-static magnetic fields at μm spatial scale, from Weibel-instability at the target rear surface; (4) excited plasma waves within ion accelerators within the bulk at 10-100 nm spatial scale. The upper left inset shows a simulated small-angle x-ray scattering image of an ion accelerator (picture from T. Kluge).

10.4. Concluding Remarks

Innovative optical and e-beam diagnostics enabled high-resolution imaging of plasma wakes and micron-/fs-scale plasma-accelerated electron bunches in the laboratory for the first time [13]. Multiplexed, wavelength-scaled versions of these diagnostics will monitor the performance of future multi-GeV, multi-staged plasma electron accelerators on an industrial scale. Continued advances in plasma-based ion acceleration now depend on developing analogous visualization capabilities for the denser, more finely structured plasmas that accelerate them. Future ion accelerator diagnostics will rely on x-ray tomography and frequency-domain techniques to penetrate the over-dense plasma and to resolve plasma and atomic dynamics at nanometer and fs-scales. Advanced simulation capabilities and large-scale data analysis and reconstruction techniques will complement these laboratory techniques. Progress in laser-plasma electron accelerators and secondary XUV/X-ray radiation sources will also advance diagnostic techniques for ion accelerators and warm dense matter targets.

11. Laser drivers for plasma accelerators

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11.1. Status

Recently, major advancements in laser wakefield acceleration (LWFA) have been achieved, see sections 4 and 5. Applications of such laser-driven accelerators are currently limited by the repetition rates of laser drivers, typically below 10 Hz. However, several promising schemes for LWFA have emerged that predict particle beams at repetition rates of the order of 100 Hz with GeV energy, pC or higher charge per pulse, low energy spread and low emittance – parameters essential to meet the demands of real world applications, as shown in Fig. 17.

To date, the UK and US laboratories and the European laser industry (e.g. Amplitude Technologies and Thales) have produced most of the PW-class lasers used at International Laboratories and Facilities working in the field of accelerators. Experimental results and theoretical modeling to date show a good understanding of laser-driven phenomena and have highlighted the important role of relevant laser parameters to maintain effective particle acceleration; in particular the stability of laser intensity on target, the quality of the focal spot profile, and the beam pointing stability. Many challenges remain, however, with improvements in the quality of laser-driven plasma-based GeV beams and repeatability of laser performance needed to meet the requirements of accelerator applications. Finally, the pulse repetition

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rate of laser-driven sources needs to be increased for exploitation at user facilities and other
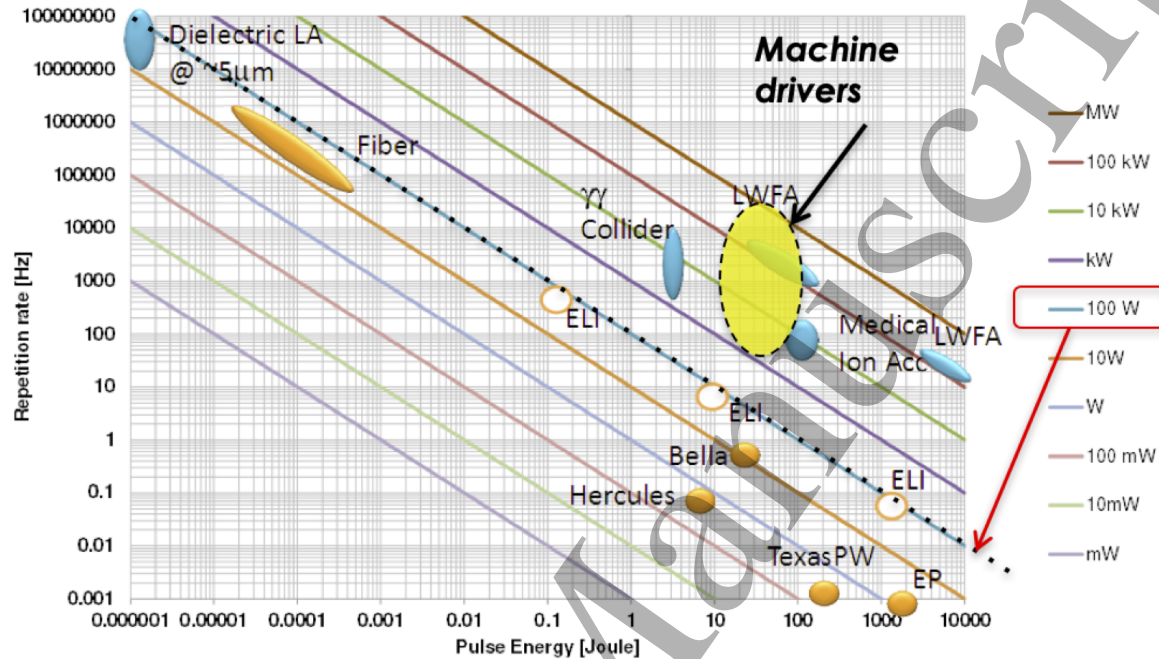prospective laser-based industry and space applications.

Figure 17. Repetition rate vs. pulse energy of high intensity laser systems. The
dotted line separates the existing systems with average power below approximately 100
W, with systems envisaged for applications and for laser-plasma acceleration drivers.

11.2. Current and future challenges

Over the past 15 years, a significant number of ultra-intense laser facilities have been
constructed worldwide based on a variety of laser architectures. These have been operated,
or will be operational soon, in a wide range of fields not only for laser-particle acceleration or
high field applications. Many of them use indirect (laser-pumped-laser) CPA architectures
based on high-energy Ti:Sapphire (Ti:Sa) amplifier technology. These include: Apollon
(France), ELI-NP (HPLS Romania), Qiangguang II 'Intense Light' and SULF (SIOM, China),
PULSAR I&II (ETRI) and GIST (South Korea), BELLA (LBNL USA), ELI-ALPS (Hungary),
ELI-Beamlines (L3-HAPLS, Czech Republic), Gemini (RAL, UK), and J-KAREN[P] (KPSI,
Japan)[51]. The pulse duration of these facilities is around 30 fs at a wavelength centered
around 800 nm with average power ranging from a few W ($\sim$0.1 Hz) to 400 W (10 Hz). They
have already demonstrated acceleration of high-energy particles in the GeV range and schemes
for producing TeV energy particles in more compact facilities via multiple staging of multi-
GeV modules have been proposed. An important next step in this field is the demonstration
of higher pulse rate operation of the order of 100 Hz or more.

Increasing the pulse repetition rate of existing facilities is limited by the pump laser
technology and, specifically, the ability to manage the corresponding increase in thermal load
on the gain medium (Ti:Sa crystals), beam propagation optics, and the compressor diffraction
gratings. Most existing facilities use pump lasers based on inefficient flashlamp technology. The
HAPLS [94] (ELI-Beamlines L3) laser developed by Lawrence Livermore National Laboratory

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(LLNL) in the US is the exception to this and is the first PW-class laser to take advantage of the improved efficiency provided by diode pump laser technology. The HAPLS pump engine has a design pulse energy of around 70 J at 527 nm generated from two Nd:glass, multi-slab amplifiers operating at 1053 nm and pumped with 885 nm diodes at 10 Hz, both cooled by helium gas at room temperature. A similar architecture and cooling approach is adopted in the final Ti:Sa amplifier. The system has recently been commissioned at ELI-Beamlines and has demonstrated 16 J pulses at 28 fs and 3.3 Hz (53 W average power).

Progress on flashlamp based pump lasers has also been achieved with Amplitude Technologies P60 pump system on ELI-ALPS demonstrating 53 J at 532 nm with over 3 million shots at up to 10 Hz [95]. Here flashlamps are used to pump multiple ceramic Nd:YAG thin disk amplifier modules in an active-mirror configuration, cooled by liquid at room temperature. The final Ti:Sa amplifier also uses a room temperature liquid coolant.

Direct CPA architectures, which combine the advantages of direct diode pumping of a broad bandwidth gain medium, offering the potential of higher efficiency, are also being developed [51]. The PENELOPE (HZDR, Germany) and POLARIS (HI-Jena, Germany) lasers use crystalline Yb:CaF2 and a mixture of Yb:glass/Yb:CaF2 gain media, respectively, both pumped with diodes at 940 nm. However, the smaller bandwidth of Yb:CaF2 compared to Ti:Sa limits the shortest pulse duration to 150 fs. PENELOPE is designed to produce an average power of 150 W (150 J at 1 Hz) at 1030 nm.

Alternative OPCPA architectures exploiting optical parametric amplification within large-aperture lithium triborate (LBO) crystals are also under development [51]. These include two diode-pumped lasers at the ELI-Beamlines facility, L1 ALLEGRA (100 mJ at 1 kHz) and L2 AMOS (100 TW, 2 to 5 J between 10 and 50 Hz), and the Shenguang II Multi-PW beamline (SIOM, China). The OPCPA pump laser at the heart of the AMOS system is based on DiPOLE diode-pumped ceramic Yb:YAG multi-slab amplifier technology, cooled by cryogenic helium gas, developed by the Central Laser Facility at the STFC Rutherford Appleton Laboratory in the UK. DiPOLE pump lasers have demonstrated efficient and stable operation with average powers of over 1 kW (100 J at 10 Hz) at 1030 nm, pumped by 940 nm diodes [96].

Existing facilities focus their attention on improving key laser parameters, in particular the energy per pulse and its stability, pulse duration and contrast, and beam pointing stability, typically ranging from 1.5 to 10 μrad. With the refinement of laser diagnostics, new phenomena including the relationship between spatial phase and temporal effects have been revealed. These spatio-temporal effects are now an important field of study in laser technology aimed at establishing a correlation between electron beam specifications and laser parameters.

11.3. Advances in science and technology needed to meet challenges

Although progress over the past decade has been significant, with kW pump systems emerging (e.g. P60 and DiPOLE), laser driver technology for particle accelerators will require a further increase in average power of at least one order of magnitude, to 10 kW, and an increase in pulse repetition rate to greater than 100 Hz. To meet these requirements, all measures leading to a gain in efficiency will be crucial, especially if scaling to high-energy accelerators is foreseen. Just for comparison, in RF accelerators there is a great attention to the wall plug efficiency of RF power coupling to the accelerator cavity that is typically above 60%. To aim at such values, all the losses of efficiency will have to be tackled and diode pumping is definitely the first step. The major challenge here will be to increase the lifetime of the diodes while reducing the cost, possibly exploring new approaches that natively support higher frequency operation

and production techniques that can scale to larger numbers to reduce costs. Key institutional and industrial partnerships are emerging in this context such as the collaboration between the Ferdinand-Braun-Institut-Berlin (FBH) and Trumpf. Potential improvements in diode laser efficiency and peak power scaling can also be achieved by cooling diode bars to near-cryogenic temperatures. A recent R&D project Cryolaser at FBH demonstrated 1.7 kW peak power (1.2 ms, 10 Hz) from a single bar at 940 nm with over 60% efficiency when cooled to 223K [97]. Increasing diode power density, and therefore reducing the number of bars required, offers another approach to cost reduction for higher power pump systems.

The recent announcement of the construction of the Extreme Photonics Applications Centre (EPAC) at STFC in the UK over the next 5 years, will provide a unique capability to study applications of 10 Hz PW laser-driven accelerators and test strategies for power and pulse rate scaling. This includes a pathway to exploit 100 Hz DiPOLE pump technology currently under development at STFC [98], which would push PW-class lasers to an average power of 3 kW at an output energy of 30 J. On a similar trajectory, Amplitude Technologies is working on pathways to extend the repetition rate of the P60 pump laser to 50 Hz, and possibly 100 Hz, with minimum investment, and no impact on thermal management, by replacing the flashlamp cassette by a diode cassette. With these performances it is possible to imagine using up to 6 of these next generation pump lasers, possibly exploiting pulse interleaving techniques, to pump a Ti:Sa amplifier system and deliver sub-100 fs pulses with 10 kW (100 J, 100 Hz) average power before compression. Similar performances have been envisaged for the EuPRAXIA project and conceptual design of the required beamlines has already been delivered [99].

First steps towards these goals are underway in projects like k-BELLA at LBNL (USA) and KALDERA at DESY (Germany) aiming to deliver 3 J in 30 fs at 1 kHz, a first attempt to hit the kHz barrier. The architecture of this laser has not yet been chosen and there are several possibilities, all based on indirect Ti:Sa amplifier schemes, either cryo-cooled to improve efficiency and thermal management and pumped by Yb:YAG based lasers, or as thin disks with an active mirror geometry, pumped by incoherently combined fiber lasers cryo-cooled with gas jets. Ti:Sa lasers have proven reliability and higher Technology Readiness Level compared to other technologies and as a result are the most widely used systems for laser-plasma acceleration. With the desire to develop higher average power systems both the optical-to-optical and the overall wall-plug efficiency of the laser become a concern as the laser cooling capacity, and complexity of the laser design, scales with the amount of energy converted into heat in the laser gain medium. For indirect CPA architectures the efficiencies for each laser, wavelength converter, and all optical transfer stages must be taken into consideration and will eventually become a limiting factor due to prohibitive electrical power requirements. For this reason, a baseline Ti:Sa design requires the most effective strategies to reduce power consumption to an acceptable level while providing a viable solution compatible with mid-term application goals.

For scaling pulse repetition rate to the kHz level and beyond, electrical power consumption can be significantly reduced by adopting a direct diode-pumped CPA architecture. This offers the potential of higher wall-plug efficiency, lower complexity, dramatically lower thermal loading, and improved Mean-Time-Between-Failures. We stress that reducing the thermal load has a two-fold beneficial effect on wall-plug efficiency lowering the cooling power requirements. One approach under investigation by LLNL (USA) uses direct diode pumping of a gas-cooled Tm:YLF amplifier and is being designed to provide high scalability in both pulse energy and repetition rate, as well as high efficiency. This Big Aperture Thulium (BAT) laser concept[100] operates at a longer wavelength near 2 μm and can be pumped by existing commercial diodes emitting around 800 nm. The quantum defect due to the difference between pumping

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wavelength and emission wavelength is a concern when aiming at very high efficiency. In this architecture it is somewhat compensated by well known cross-relaxation effects in Tm, thus leading to estimated overall wall-plug efficiency as high as 30%, a major gain if compared to current systems.

Projects are also underway to exploit coherent combination of very large numbers of fibre amplifiers for energy scaling. The XCAN project in Europe [101], a collaboration between Ecole Polytechnique (LULI) and Thales (TRT) in France, has begun a proof-of-concept demonstration that aims to combine over 60 fibres delivering 10 mJ in 350 fs pulses at 50 kHz in its first phase. To date the project has successfully combined the output from 37 fibre amplifiers. More recently the Jena group achieved coherent combination of 96 fibers delivering 23 mJ and 674 W in a 235 fs pulse [102]

Besides the pumping strategy and management of thermal load in the gain medium, the endeavor to high efficiency will also have to address losses and the corresponding thermal load, and aging of compressor gratings. A number of studies have already been published on the influence of thermal load on grating and compressor performance and the likely need for cooling. The results show that a major role is played by the choice of grating coating technology [103] with several options, including, gold coating, gold coated with resin, and mixed metal dielectric (MMLD) coatings under investigation for higher power operation. At present no facility based CPA systems employ grating cooling, so practical experience is limited. Some very preliminary studies show that for pulse duration over 30 fs, heating with an average power of 1 kW had no visible effect on the pulse duration, but it does affect the far field That said, recent results from Gemini TA2 indicate that while you can compensate for the thermal effects on the far field, the capability of driving high-quality electron beams, in some cases, is affected as laser repetition rates go beyond a few Hz. Further studies in real operational environments are required to be conclusive. Understanding the impact of thermal management on system performance will require significant effort and will need to be extended to the entire optical chain, including both passive components and active deformable mirrors used for wave front correction. Another important consideration is the damage threshold of mirrors in the beam transport from the compressor to the focal point. Although there have been significant improvements in the short-pulse damage threshold of coatings, their behaviour at high repetition rates, where memory effects with colour centres etc. can play a role, is still an unknown.

Finally, the stability of laser parameters that determine the intensity in the focal spot will need to be improved by a level well beyond that achievable today at existing facilities. Progress in this direction has already begun and will increasingly exploit high repetition rate systems for the implementation of feedback loops to provide automatic stabilization. The new high power PW-class laser facilities coming on line over the next 5 years (ELI-L3-HAPLS and EPAC) will have an important role to play in improving the understanding and providing practical experience of all the phenomena which affect future power scaling.

11.4. Concluding remarks

Laser-driven plasma acceleration is now entering the transition phase to deliver particle accelerator and light source user facilities based on this novel technology. Technology issues still remain and should be tackled using an accelerator-oriented approach, focusing on accelerator needs with developments towards improved stability, reliability and efficiency. A comprehensive approach looking at laser drivers as accelerator components will be needed and is expected to deliver soon the performances required for an intermediate level accelerator

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demonstrator, using moderate upgrades of existing technology. At the same time, longer-term driver developments will look at more scalable approaches to fulfill efficiency, lifetime and cost requirements of future higher luminosity accelerators.

12. Numerical methods for plasma accelerators

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12.1. Status

Computer simulations have had a profound impact on the design and understanding of past and present plasma-based particle acceleration experiments, and will be a key component for turning plasma-based accelerators from a promising technology into a mainstream scientific tool.

The workhorse algorithm for plasma-based particle accelerator modeling is the Particle-In-Cell (PIC) methodology, where beams and plasmas follow a Lagrangian representation with electrically charged macroparticles while electromagnetic fields (and structures) follow a Eulerian representation on (usually Cartesian) grids. Exchanges between macroparticles and field quantities involve interpolation at specified orders of accuracy. The standard "full PIC", three-dimensional implementation has historically often been too computationally demanding because of the large disparities of space and time scales that are involved. Fluid approximations [104], scaled parameters [105], or reduced dimensionality under certain geometries (2D planar or expanding the fields into a truncated series of azimuthal modes [106]), provide significant computational savings but at the cost of generality.

For LWFA and PWFA, the large disparities of space and time scales between the driver beams, the wakes and the plasma column can be mitigated by either performing the simulation in a Lorentz boosted frame (which lowers the range of space and time scales) [107] or using the quasistatic approximation to decouple fast and slow time scales [108]. Additional algorithmic speed-up can be provided by approximations such as ponderomotive guiding center (PGC) models [109]. Orthogonal to these efforts and crucial for laser-ion acceleration, advanced multi-physics modeling for fundamental processes beyond Maxwell's equations are needed to approach a regime of high-energy-density physics beyond the local thermal equilibrium (non-LTE). Such processes include high-frequency driven, non-LTE ionization physics, QED effects, radiation transport, collisional physics, among others, which further increase the computational costs of a PIC simulation.

Even in light of all the recent, ongoing and projected progress in algorithms, software and hardware, computational studies of plasma accelerators will continue to be a very challenging endeavor. The advent of exascale computing, coupled with the computational complexity brought on by emerging computer architectures and languages, poses both opportunities and challenges for high-fidelity, predictive modeling of plasma accelerators.
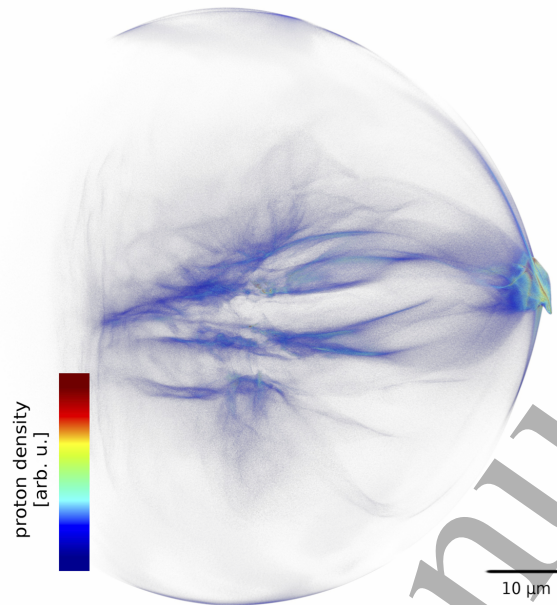
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Figure 18. Laser-ion acceleration from near-critical, mass-limited targets can provide favorable ion beam properties [110]. In the PIConGPU simulation shown here, only fully-dimensional treatment of the laser interaction with a spherical target and proper estimation of the early expansion due to laser contrast provided predictive capabilities. A volume rendering of the three-dimensional proton density shows a narrow proton bunch on the right that was accelerated by a pulse of the PHELIX (GSI) laser. Credit: Axel Huebl (Simulation), Peter Hilz (Experiment), Michael Matheson (Visualization).

12.2. Current and Future Challenges

The development of plasma-based accelerators depends critically on high-performance, high-fidelity modeling to capture the full complexity of acceleration processes that develop over a large range of space and time scales.

The simulations of plasma-based electron or positron accelerators are extremely computationally intensive, due to the need to resolve the evolution of a driver (laser or particle beam) and an accelerated beam into a structure that is orders of magnitude longer and wider. Studies of various effects, including injection, emittance transport, beam loading, tailoring of the plasma channel, and tolerance to nonideal effects (jitter, asymmetries, etc.) that are needed for the design of a plasma-based high-energy collider, will necessitate a series of tens or hundreds of runs. The current state of the art enables the simulation of only one to a few multi-GeV stages; chains of hundreds to thousands of stages will be required for TeV to tens of TeV colliders.

Plasma-based ion acceleration requires massive computational resolution in order to resolve the short-scale plasma dynamics inside overcritical targets while also providing a fully-dimensional description [110] (see Fig. 18). The overall laser-plasma interaction time, including modeling of realistic laser contrast and expansion dynamics, is six to nine orders of magnitude longer than the plasma dynamics inside the target. Important laser-target coupling occurs on an intermediate scale at the critical density, whereas electron transport inside the target takes place on the ultrashort scale. Experimental diagnostics for initial target conditions, e.g. realistic density profiles at peak laser intensity, as well as in-target processes

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are very challenging and simulation efforts often require hundreds of systematic simulations for sound predictions. Approaches probing the target conditions with novel X-FEL sources require first principle additions to the PIC cycle such as non-LTE evolution of ionization-recombination dynamics, as well as electron and radiation transport inside the target under collisional plasma effects, which are beyond a description provided by Maxwell's equations.

12.3. Advances in Science and Technology to Meet Challenges

Manycore computing is now driven predominantly by general-purpose graphics processing units (GPGPUs) that provide significantly higher energy efficiency than conventional central processing units (CPU) architectures. With a very high degree of parallelism (1000 times more threads than a CPU), manycore hardware can only be utilized well with nested levels of algorithmic parallelism and communication-avoiding design patterns.

These new computer architectures are increasingly favorable to high "arithmetic intensity," a measure of floating-point operations (FLOPS) performed by a given code (or code section) relative to the amount of memory accesses (Bytes) that are required to support those operations. This motivates a rethinking of the algorithms that historically have been used for plasma simulations in favor of higher-order algorithms, e.g. high-order Maxwell solvers, (semi-)implicit solvers, adaptive time-stepped particle pushers or advanced control of numerical instabilities. In addition, adaptive mesh refinement [111] has the potential to fit the resolution to the local conditions of the laser-plasma interaction (see Fig. 19).

Tightly linked to large-scale simulations on supercomputers is the adequate handling of data input and output (I/O), the bandwidth of which evolves more slowly than the computing power generating scientific data. Data reduction techniques [112] that derive physical quantities of interest for plasma-based accelerators, instead of systematically writing high-resolution numerical quantities to disk at high frequency, are promising for bridging the bandwidth gap, both with "in situ" as well as "in transit" techniques, but encounter challenges of easy programmability and reproducibility that must be addressed.

Developing fast tools that can be used to guide the parameter scans will be essential. Models within those will be guided by theory and fits to the PIC-based simulations and experimental results. For the latter, the community can benefit from standardized data exchange descriptions such as openPMD [113] that can be used to combine plasma codes with beam transport, light source and QED codes. One should start taking advantage of machine learning, developing surrogate models based on accumulated data from simulations and experiments. For example, both generated data could train and establish a knowledge base for laser-plasma beamlines without the need of long-time storage of vast amounts of data.

12.4. Concluding Remarks

Simulation codes that can exploit the power of the new computing architectures, from the desktop level to midscale computer clusters and all the way up to the largest supercomputers, are needed. When realized, these new tools will bring us toward the ultimate stretch goal of fast turn-around, virtual experimentation of entire plasma-based accelerators or collider sections in times short enough that the code can cross-fertilize feedback loops with experiments [111]. The development of such simulation tools requires teams, which consist of individuals with various skills, scientific backgrounds, affiliations, and responsibilities. This includes roles such as scientific code builders/developers, maintainers, and users. Avoiding excessive duplication of identical capabilities, it is important to foster the sharing of modules and

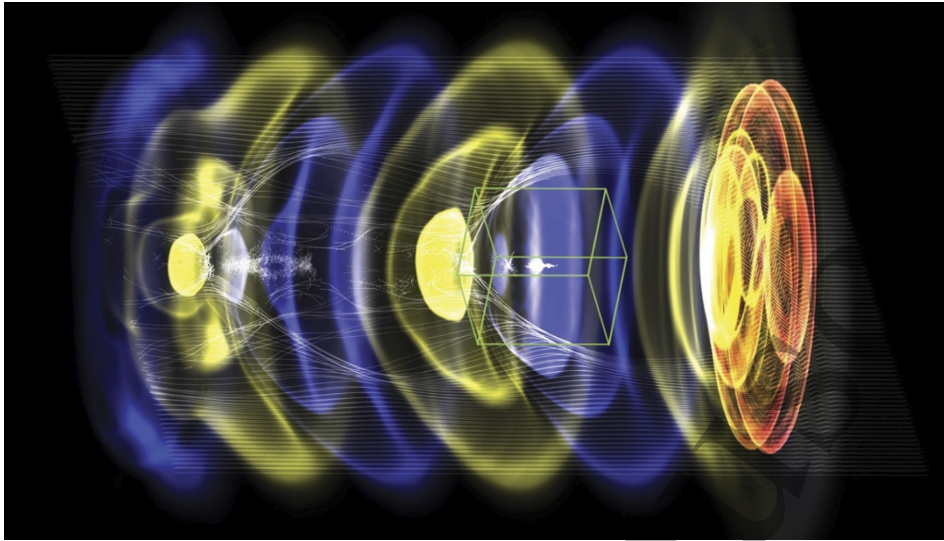CONTENTS   44

Figure 19. Snapshot from a WarpX 3D simulation of a laser-driven plasma accelerator. The laser (red) propagates from left to right and creates a plasma wake (yellow and blue) that accelerates a small electron beam (white) to high energy. A mesh refinement patch (green box) is used to increase the resolution and accuracy around the electron beam. Credit: Maxence Thévenet.

improve code interoperability. The development of open source libraries for algorithms and physics modules should be encouraged, as well as the development of open standards for simulations input/output and data structures.

13. Strong field QED in plasma accelerators

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13.1. Status

The recent spectacular rise in laser intensities accompanied by the ongoing construction of new laser facilities (ELI, APOLLON, CoRELS, etc) will place intensities above 10^{23} W/cm^2 within reach. Combining the extreme laser intensities with plasma accelerators brings new research fronts as it allows for studying the interplay between QED and collective effects in pair plasmas. This could lead towards advances in extreme astrophysics, where the interplay naturally occurs in the magnetosphere of some compact objects.

Which effects do high fields bring? The first effect to consider is the electron slowdown due to extensive radiation emission. The energy lost to radiation becomes a notable fraction of the initial electron energy when $\chi > 0.1$, where the Lorentz-invariant $\chi = |p_\mu F^{\mu\nu}|/mcE_C$ represents the ratio of the field strength in the electron rest frame to the Schwinger critical field E_C. The value of χ depends on the laser intensity, the geometrical configuration of the laser-electron interaction and the energy of the electrons. The most favourable configuration

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is the head-on collision, and two experiments have already observed the electron slowdown in this setup (Fig. 20).

Ultra-intense lasers will give an opportunity to explore the radiation-dominated regime [114], that has never been achieved in the laboratory before. Furthermore, it will open a possibility to study in detail the transition between the classical and quantum radiation reaction [115, 116, 117].

When $\chi \sim 1$, a lepton experiences an electric field $E \sim E_C$ in its rest frame. This field can perform a work equal to a lepton rest energy over a Compton wavelength, i.e. strong enough to trigger e_+e_- pair creation. The seminal E-144 experiment at SLAC (Fig. 20) has shown that a laser-electron scattering (46 GeV beam and a laser of 10^{18} W/cm^2) can produce positrons, albeit at a low rate. With the next generation of lasers, an abundance of pairs can be created using two colliding lasers [118]. For the first time we would be able to study collective effects in electron-positron-photon plasmas and possibly achieve over 80% conversion efficiency of the laser energy to the new particles and hard photons [119].
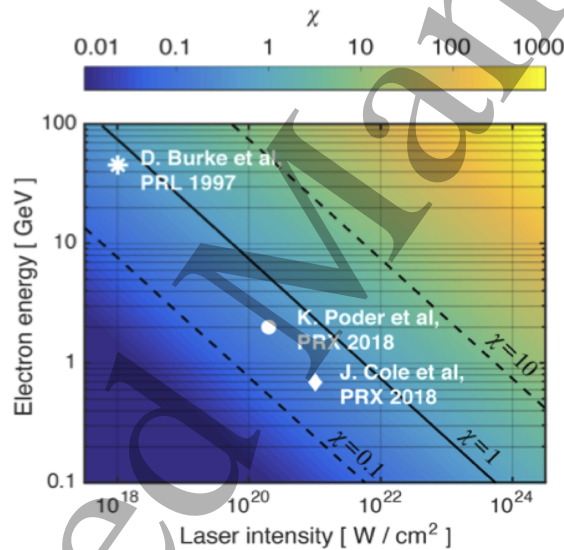

Figure 20. The parameter χ as a function of the laser intensity and electron energy for a head-on collision. The points represent the E-144 experiment at SLAC and experimental campaigns performed with the Gemini laser at Rutherford Appleton Laboratory, as summarised in Ref. [120].

13.2. Current and Future Challenges

Various technical and theoretical challenges remain to be elucidated. We restrict ourselves to discuss the most important ones.

(i) The first challenge is to explore the radiation-dominated regime of interaction and compare the electron beam properties to what is predicted by the classical and QED theory. This aims to confirm our current theoretical understanding of the transition between the classical and quantum description of radiation reaction, as well as to allow predicting the conversion efficiency of electron energy to radiation in the hard X-ray or gamma-ray spectrum.

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(ii) The second challenge is to create positrons. Producing and accelerating enough positrons to obtain a beam of good quality is one of the grand challenges for future electron-positron colliders.

(iii) The third challenge is to create electron-positron plasmas with sufficient density and size to exhibit collective effects. Electron-positron-photon cascades can be triggered by several quantum processes and in several different configurations, but in order to produce a pair plasma, it becomes necessary that the cascade develops in a confined environment. One ought to conceive a special electromagnetic configuration that on the one hand prevents secondary particles to escape the zone of production and on the other hand allows to re-accelerate every new generation of particles to sustain the cascade (e.g. optical traps).

(iv) The fourth challenge is to study collective effects in such plasmas. QED theories are developed and verified in a perturbative regime, considering that the background fields are well below the critical field, do not change rapidly and the amount of matter created is small enough not to perturb the background field. In a cascade, self-created plasma could potentially completely absorb the laser field. In fact, there may be a limit to the maximum attainable laser intensity due to the development of such cascades [121].

(v) The fifth challenge is to create "fireball" beams, quasi-neutral beams composed of electrons, positrons and photons, and study their propagation in background plasmas.

13.3. Advances in Science and Technology to Meet Challenges

This is a young growing and promising field and there is still a long way ahead towards addressing the main challenges put forward. On the experimental side, it is required to improve the quality of the electron beams produced with laser-plasma technology. It is not necessarily required to pursue higher energy (for higher yield of photons and pairs), but rather to provide reproducible beams with low energy spread to perform well-controlled experiments. This closely connects with the need to develop reliable diagnostics, both for particle beams and laser pulses. For example, access to non-disruptive diagnostics that could measure the electron beam spectrum before and after interaction with the laser would allow the requirements on the electron beam reproducibility to be relaxed. One also needs to achieve higher laser intensities, better stability and improved techniques that could provide laser diagnostics at focus.

A better understanding of the plasma dynamics in the presence of extreme fields is evidently a crucial goal. Theory and simulations show unexpected plasma behaviour in such conditions. For example, above a certain amplitude, Gonoskov et. al [122] showed that radiation damping causes particles to become trapped in, rather than expelled from the areas of the maximum field. The QED effects may strongly affect the laser interaction with solids at intensities of the order of 10^{23} W/cm^2 [123]. Simply increasing the laser intensity in a laser-electron beam head-on scattering may not always lead to an increased χ parameter: a strong radiation reaction could slow down the electrons before they interact with the peak of the pulse [124]. For choosing a best configuration to address each scientific challenge, one should explore different interaction geometries, using structured or composite targets to make the most of the available laser technology and probe different physics. Combining other technologies such as XFELS with optical lasers and electron beams could provide additional opportunities for further study of these topics, and open a possibility to study other effects, e.g. spin precession in LWFAs.

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13.4. Concluding Remarks

Relativistic pair plasmas are ubiquitous in the high-energy universe but such plasmas have rarely been studied experimentally in the laboratory. This landscape is rapidly changing due to the advance in ultra-intense lasers, which brings the laboratory creation of these plasmas closer to reality. Nonetheless, if pair plasmas will be routinely produced in the near future, it is still unclear whether we can generate relativistic electron-positron pair plasmas that mimic extreme astrophysical scenarios and that could unveil some of the mysteries associated with them in the laboratory. Further research is required for gamma-ray sources, e_+e_- cascade seeding, and the exploration of various configurations to make the most of the available laser technology for cascades and particle acceleration. The high-field laser-plasma community is growing and some of these challenges will be addressed in the next few years.

14. Acknowledgements

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