4 High-gradient plasma and laser accelerators

4.1 Executive summary

Novel high-gradient accelerators have demonstrated acceleration of electrons and positrons with electric field strengths of 1 to >100 GeV/m. This is about 10 to 1000 times higher than achieved in RF-based accelerators, and as such they have the potential to overcome the limitations associated with RF cavities. Plasma-based accelerators have produced multi-GeV bunches with parameters approaching those suitable for a linear collider. A significant reduction in size and, perhaps, cost of future accelerators can therefore in principle be envisaged.

Based on various R&D achievements, the plasma accelerator community is establishing the first user facilities for photon and material science in the European research landscape. The many national and regional activities will continue through the end of the 2020s with a strong R&D and construction programme, aiming at low energy research infrastructures, for example to drive a free-electron laser (FEL) or to deliver ultrafast electron diffraction (UED). Various important milestones have been and will be achieved in internationally leading programmes at CERN, CLARA, CNRS, DESY, various centres and institutes in the Helmholtz Association, INFN, LBNL, RAL, Shanghai XFEL, SCAPA, SLAC, Tsinghua University and others. New European research infrastructures (RI) involving lasers and plasma accelerator technology have been driven forward in recent years, namely ELI and EuPRAXIA, both placed on the ESFRI roadmap. The distributed RI EuPRAXIA as well as the aforementioned internationally leading programmes will pursue several important R&D milestones and user applications for plasma accelerators.

This work should be complemented by early tests and R&D activities targeted at high energy physics (HEP). Given that funding for ongoing activities is mostly from non-HEP sources, several HEP-related aspects are currently not prioritised, for example: staging to high energy; efficiency; acceleration of positron bunches and beam polarisation.

The Panel makes the following general assessment: Important progress has been made in demonstrating key aspects of plasma and dielectric accelerators, in particular in terms of energy and quality of the accelerated bunch from laser, electron and proton driven plasma accelerators. At the same time, rapid progress in underlying technologies, e.g. lasers, feedback systems, nano-control, manufacturing, etc. has also been made. Various roadmaps have been developed in the EU (EuroNNAc), the US (DOE) and world-wide (ALEGRO), defining R&D needs for a collider at the end of the 2040s. These roadmaps call for additional funding for HEP-oriented R&D in novel accelerators. It is expected that a plasma-based collider can only become available for particle physics experiments beyond 2050, given the required feasibility and R&D work described in this report. It is therefore an option for a compact collider facility beyond the timeline of an eventual FCC-hh facility.

The feasibility of a collider based on plasma accelerator schemes remains to be proven. Key challenges to reach the high energy frontier include a scheme for positron bunch acceleration in plasma, that still needs to be demonstrated on paper. Also, acceleration of bunch charge that is sufficient to reach the luminosity goal remains to be achieved. Emittance preservation at the nanometer scale and large overall efficiencies need to be developed. Staging designs of multiple structures with high energy gain and all optical elements remain to be demonstrated, including tolerances, length and cost scaling. High

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repetition rate and associated power-handling and efficiency issues need to be investigated in detail for luminosity reach in a possible collider.

The panel proposes a plasma and laser accelerator R&D roadmap that should be implemented and delivered in a three-pillar approach (Fig. 4.1). Dielectric laser accelerator (DLA) are in an earlier stage of development than plasma-based techniques, but are of potential interest on the longer horizon and are hence included for assessment. A feasibility and pre-conceptual design report (pre-CDR) study forms the first pillar and will investigate the potential and performance reach of plasma and laser accelerators for particle physics. In addition a realistic cost-size-benefit analysis is included and will be performed in a comparative approach for different technologies. A second pillar relies on technical demonstrations to prove suitability of plasma and laser accelerators for particle physics. A third pillar connects the work on novel accelerators to other science fields and to other applications. The proposed delivery plan for the required R&D work defines a minimal plan. The minimal plan executes work in seven work packages and will provide nine deliverables by the end of 2025. Among those deliverables are an integrated feasibility study and four experimental demonstrations. Required additional resources amount to needed funding for 147 FTEy (full-time equivalent-years) and 3.15 MCHF of investment. Additional in-kind contributions will be provided and have been specified. The minimal plan connects work and particle physics relevant milestones in 12 ongoing projects and facilities, all listed in the report. Beyond the minimal plan, the expert panel has grouped four additional high priority R&D activities into an aspirational plan. Execution of the aspirational plan will yield a scalable plasma source, that can achieve longer acceleration lengths as a path to high beam energy and first particle physics experiments. It will put into place a focused R&D effort on electron bunches with high charge and high quality, as well as the development of a low emittance electron source and a high repetition rate laser. The aspirational plan would require additional resources for 147 FTEy and 35.5 MCHF investment, beyond the minimal plan. We provide suggestions on organisational aspects in this report. Work package leaders and institutional participation shall be determined in a project setup phase. We note that the implementation of the proposed research requires an adequate mass of experts, as well as experimental and computational facilities. These have been considered in the present proposal, and their availability for the programme is ensured.

4.2 Introductory material

RF accelerator technology has been a major success story over the past 90 years, enabling the development of complex large-scale machines and applications in a variety of fields from high-energy physics and photon science to medical technologies and industrial tools. With more than 30 000 accelerators in use, accelerator-based technologies have been established as essential instruments all over the world today and will continue to play important roles in the future. The recently published 2020 Update for the European Strategy for Particle Physics by the European Strategy Group proposes clear challenges and development goals for the near- and long-term future of accelerators in particle physics. It emphasises in particular the importance of innovation in accelerator technology, listing it as “a powerful driver for many accelerator-based fields of science and industry” with “technologies under consideration includ[ing] high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures”. It points out the need to define “deliverables for this decade [. . .] in a timely fashion”.

Novel high-gradient accelerator technologies, as mentioned in the strategy and as addressed here, replace the metallic walls of established RF accelerators by dielectric walls or by dynamic plasma structures. In this report the term “plasma accelerator” relates to novel concepts that use the wakefields excited in a plasma for acceleration of charged particles (here electrons or positrons). A “beam-driven” plasma accelerator uses wakefields excited by charged particle beams typically consisting of pulses of electrons or protons. A “laser-driven” plasma accelerator uses wakefields excited by a laser. Dielectric accelerators are vacuum accelerators that rely on accelerating structures made from a dielectric material like silica, with no plasma. Dielectric structures powered by laser pulses are described as “dielectric

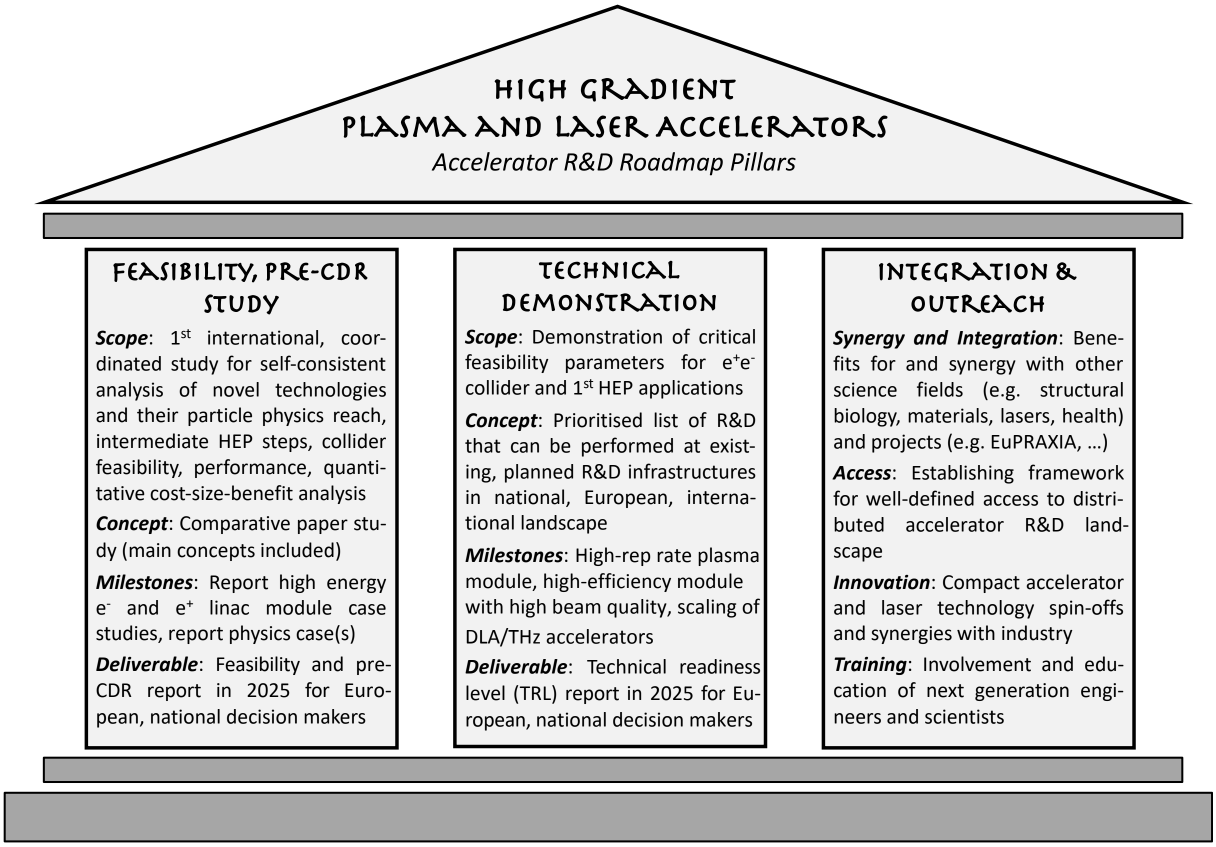

Fig. 4.1: Visualisation of the three pillars that are proposed to form the accelerator R&D roadmap for plasma and laser accelerators.

laser accelerators" or "DLA", or where clear from the context just "dielectric accelerators". Dielectric structures powered by THz pulses are described as a "THz accelerator".

The principle of a dynamic plasma accelerator structure is visualised in Fig. 4.2. Peak accelerating fields of 39 GV/m in laser-driven plasma [1] and of 50 GV/m in beam-driven plasma [2] exceed typical accelerating fields in operational RF accelerators by a factor 100 to 1000. An energy gain of 8 GeV in laser-driven, 43 GeV in electron-driven and 2 GeV in proton-driven plasma wakes has been demonstrated. The bunch charge for those experiments reaches from a few particles to 10s of pC. Dielectric laser accelerators have demonstrated peak accelerating fields of 1.8 GV/m with effective accelerating gradients of 0.85 GeV/m, energy gain of 18 keV and accelerated a fraction of a fC [3]. Although many hurdles have to be overcome, plasma and possibly also dielectric accelerators could potentially reach performance levels relevant for particle physics with a strong reduction in facility size and, potentially, cost, compared to future collider projects that fully rely on RF technology.

The availability of lasers based on Ti:Sapphire and chirped-pulse amplification (delivering few-femtosecond-long pulses with more than 100 TW of power) have made it possible to drive accelerating fields exceeding 100 GV/m in plasma. Recently, an energy gain of 8 GeV in only 20 cm of plasma was measured [1]. At the same time, linacs based on plasma accelerators delivering dense relativistic electron bunches are being used to drive FELs [4, 5]. Driven by this technology, a record energy gain of 42 GeV in only 85 cm of plasma was measured [2]. Proton bunches were used to accelerate electrons in plasma by 2 GeV [6]. Thus, the promise of high accelerating field ($>$ 10 GV/m) and large energy gain ($\gg$1 GeV) from novel accelerators has been demonstrated, as required for collider stages. Important progress in beam quality (low energy spread, small emittance, etc.) and stability was achieved in a

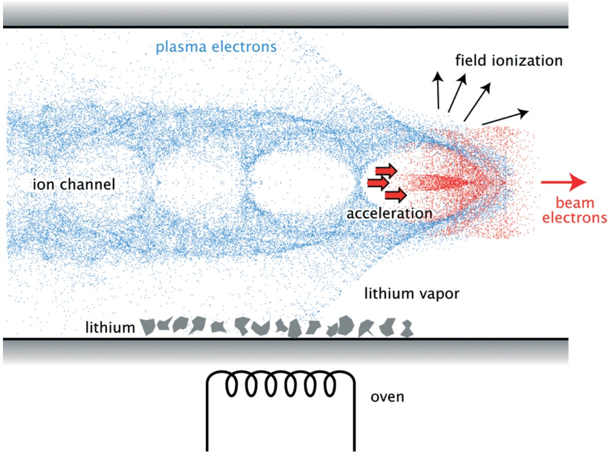

Fig. 4.2: Illustration of a dynamic accelerating structure that has been formed inside a plasma by a preceding driver pulse (here a short electron beam pulse). *(Image credit: R. Ischebeck, SLAC.)*

variety of experiments, as recently demonstrated by the first free-electron lasing (FEL) with a beam from a laser-driven plasma accelerator at SIOM [4] and from a beam-driven plasma accelerator at LNF/INFN [5]. The community is pursuing collaborative work in the EU-funded EuroNNAc network [7], in the ALEGRO activity [8], the AWAKE collaboration [9], and in the EuPRAXIA project for a European plasma accelerator facility [10], which was included in the ESFRI roadmap in 2021.

In parallel, micrometer-size, periodic dielectric structures powered by laser pulses have also demonstrated acceleration using GV/m fields [3], and terahertz-driven accelerators are making progress. In the initial experiments, the electron bunches from an RF gun were badly matched to the acceptance of the DLA structure. As a result, only a sub-fC charge has been accelerated by 18 keV. Significant progress in the manufacturing of structures with sub-micrometer accuracy, driven by the semiconductor industry, has enabled the fabrication and experimental verification of dielectric structures for particle acceleration ("accelerator on a chip"). These structures are designed to not only accelerate particles, but also focus the particle bunches longitudinally and transversely [11]. Work has proceeded in an international collaboration ACHIP and in individual efforts on dielectric laser and terahertz acceleration. Such an approach leveraging the international semiconductor and communications industries would provide a truly new approach to reducing the cost per GeV of an accelerator.

Other novel concepts and devices have been developed to complement accelerating structures: Plasma-based electron sources produce bunches, which may even be polarised, suitable to be injected in the accelerating structures; R&D on positron sources is making progress; active and passive plasma lenses help to transport and focus beams; and energy de-chirpers reduce energy spread. Novel instrumentation has been developed, in part to meet the requirements of the unique bunch properties produced by these sources. For example dielectric structures can act as optical beam position and bunch length monitors.

Different technological options for high gradient, novel accelerators are being pursued by the community, and these options have reached a different level of maturity. Arguably, the successes in reaching multi-GeV beam energy and demonstrating exponential gain in undulator-induced photon emission from both laser-driven and beam-driven plasma wakefield accelerators [4, 5] demonstrate the significant progress in this technology in recent years. Other technological options such as dielectric laser and terahertz accelerators have not reached this level of maturity, and further work is required to demonstrate readiness for first applications.

In plasma, the driver, the witness and the accelerating structure interact self-consistently, a situation that creates unique opportunities for the accelerated bunch parameters, but also challenges for the description and control of the system. The development of plasma and dielectric accelerators relies heavily on computer modeling and simulation. Significant progress has been made in fully-relativistic, electro-magnetic particle-in-cell (PIC) simulations that include 'all' of the known physics. These are critical to the development of new concepts and can be used to develop and test new concepts before proceeding to more expensive and time consuming experimental studies. In addition, the development of reduced simulation models can retain most of the physics for designing and optimising systems. Such numerical simulations can be used to train neural networks. These surrogate models run in a fraction of the time and can be used to guide the design and optimisation of accelerators [12].

These new types of accelerators produce particle bunches or radiation with unique properties. In particular, operation at high frequencies naturally generates small and short accelerated bunches, natural tools for ultra-fast science with sub-fs resolution. High fields in the particle source ("plasma photo-injector") can generate bunches with very low normalised emittance, reaching into the 10 nm regime and, in principle, enabling ultra-small beam size. These unique properties of the accelerated bunches make available a wealth of applications for high-gradient plasma and laser accelerators in science and technology, ranging from the direct use of the accelerated electrons for UED to medical applications and radiation generation.

Particle physics applications at the energy frontier are some of the most demanding, requiring dedicated R&D efforts, as described below. Some other envisioned particle physics experiments, for example in the search of weakly interacting massive particles, make use of beam parameters that could be more readily achieved with novel accelerating schemes. We detail such possible applications in Section 4.6.3.2.

While rapid progress has been made with novel high-gradient accelerator concepts, significant challenges remain to make them suitable for particle physics applications. Relevant parameters that were achieved individually (accelerating gradient, energy gain, charge, energy spread, emittance, etc.) must now be achieved together. Plasma accelerators will require tens to hundreds of stages to reach the relevant energies. First experiments show the staging of two plasma accelerators [13], but further research is required to preserve beam quality to collider-relevant levels. Staging of two dielectric laser accelerators has also been demonstrated [14], but an accelerator for HEP experiments will require tens of thousands of stages. Parameters reached in a single stage must be preserved (emittance, relative energy spread, etc.) or repeated (energy gain, handling of driver and accelerated bunches) from stage to stage. A global concept for a collider, possibly involving different advanced accelerator or conventional accelerator components must be developed. This also includes the particle detector, since beams from plasma and laser accelerators may generate high repetition rate collisions (kHz–MHz). However, at this stage of advanced accelerator development, no roadblock has been identified on the roadmap towards an e^+e^- collider.

This report develops a path to demonstrate the feasibility of a collider, that typically should deliver nC charge inside a bunch for both electrons and positrons, with about 100 nm normalised transverse emittance, at a final energy of TeV or higher and with a repetition rate of 15 000 Hz (parameters here for a plasma based accelerator). The path described in this report includes a feasibility study, mostly theory and simulation driven, plus technical R&D tasks with specific deliverables. The minimal plan aims at demonstrating important achievements by the time of the next European strategy, while the aspirational plan defines additional longer term R&D objectives. The programmes are complemented by work in ongoing projects and facilities that is also described and will demonstrate important additional deliverables. Those ongoing projects include work in the United States and work in other science fields.

4.3 Motivation

Top class accelerator research and development relies on the initiative of outstanding scientists who often develop their ideas first on paper. Those ideas sometimes enable ground-breaking progress in science and society. A particularly important example is the invention of stochastic cooling by Simon van der

Fig. 4.3: A plasma cell is shown here in comparison to the superconducting accelerator FLASH at DESY. *(Image credit: H. Müller-Elsner, DESY.)*

Meer. This later enabled the construction of the SppS collider and the experimental discovery of the Z and W bosons. Simon van der Meer (together with Carlo Rubbia) received the Nobel prize for Physics in 1984 for his invention. Plasma and dielectric accelerators with their ultra-high gradients offer potential for another step-change in accelerator technology. In the following we introduce the motivation for the corresponding R&D, covering the technology, a potential ultra-compact collider and lower energy particle physics experiments.

4.3.1 Novel accelerator technologies for compact research infrastructures

Plasma and laser accelerators have intrigued the accelerator field through their potential for compact research infrastructures. Those infrastructures can be used for particle physics but also for other fields, including for example structural biology, materials, medical applications or even archaeological studies. The ongoing R&D is therefore highly motivated (and financed) by applications with lower beam energies, more easily reached. All ongoing efforts support the development of the novel accelerator technologies with quality and reliability appropriate for users. For example, plasma-based accelerators are planned to be used for free electron lasers, whereas DLA are envisioned for ultrafast electron diffraction. These novel accelerator technologies will then be an additional instrument in the toolbox of accelerator scientists. Particle physics developments can build on the ongoing R&D, complementing it with additional research topics that are required for colliders or other particle physics experiments. Of particular importance for particle physics are energy efficiency and luminosity (bunch charge, repetition rate and emittance). The energy efficiency is often of lesser importance for applications at lower energies.

4.3.2 Collider development roadmap – project phases

We note that there have already been various sketches of possible colliders relying on high-gradient plasma and laser accelerators. Those studies are valuable starting points for further design work, but do not include realistic designs of the accelerator layout (including in- and out-coupling of power drivers), nor solutions for multi-stage positron acceleration, or provide performance assessments from start-to-end simulations. The various published sketches provide an understanding of the required parameters for constructing a linear collider at the energy frontier, as listed in Table 4.1. The proposed design work here will include the first ever cost-size-benefit analysis for such an advanced collider based on simulation design work.

The work proposed would be the first step in a long term roadmap that would culminate in a compact collider, assuming all previous steps are successful. The long term roadmap is also visualised in Fig. 4.4. Steps in the long-term roadmap would include the following:

Table 4.1: Required parameters for a linear collider with advanced high gradient acceleration. Three published parameter cases are listed. Case 1 (plasma wakefield accelerator or PWFA) is a plasma-based scheme based on SRF electron beam drivers [15]. Case 2 (laser wakefield accelerator or LWFA) is a plasma-based scheme based on laser drivers [16]. Case 3 (DLA) is a dielectric-based scheme [17]. We note that the studies use different assumptions on emittance and on the final focus system, which explains differences in luminosity per beam power. Efficiency goals will be discussed in more details in Sections 4.6.4.2 and 4.6.7.

Parameter	**Unit**	**PWFA**	**LWFA**	**DLA**
Bunch charge	nC	1.6	0.64	4.8×10^{-6}
Number of bunches per train	-	1	1	159
Repetition rate of train	kHz	15	15	20 000
Convoluted normalised emittance ($\gamma\sqrt{\epsilon_h\epsilon_v}$)	nm	592	100	0.1
Beam power at 5 GeV	kW	120	48	76
Beam power at 190 GeV	kW	4 560	1 824	2 900
Beam power at 1 TeV	kW	24 000	9 600	15 264
Relative energy spread	%		≤ 0.35	
Polarisation	%		80 (for e^-)	
Efficiency wall-plug to beam (includes drivers)	%		≥ 10	
Luminosity regime (simple scaled calculation)	$10^{34}cm^{-2}s^{-1}$	1.1	1.0	1.9

- **2025** – Feasibility report and pre-CDR on advanced accelerators for particle physics. This includes an assessment of Technical Readiness Levels (TRL), taking into account results from technical milestones until 2025.
- **2027** – Definition of physics case and selection of technology base for a CDR, in accordance with guidance from the European Strategy. An update on the timeline will be provided appropriate to particle physics requirements and realistically achievable goals.
- **2031** – Publication of a CDR for a plasma-based particle physics collider.
- **2032** – Start of technical design report (TDR), prototyping and preparation phase. Eventual start of a dedicated test facility (to be defined in the pre-CDR).
- **2039** – Decision on construction, taking into account the results of the advanced accelerator R&D and the international landscape of colliders.
- **2040** – Start of advanced collider construction.
- **beyond 2050** – It is expected that a plasma-based collider can only become available for particle physics experiments beyond 2050, given the required feasibility and R&D work described in this report. It is therefore an option for a compact collider facility beyond the timeline of an eventual FCC-hh facility.

4.3.3 Lower energy particle physics experiments

The acceleration of electrons to energies in the tens to hundreds of GeV range opens up the possibility for new particle physics experiments: the search for dark photons, measurement of QED in strong fields and high-energy electron–proton collisions. In these experiments the critical parameters are the beam energy and intensity. Generally, the requirements on the beam quality are less stringent when compared to an e^+e^- collider at the energy frontier.

Preliminary studies show that the beam parameters for such particle physics experiments can be produced by novel advanced acceleration schemes. Therefore, plasma accelerators have the potential

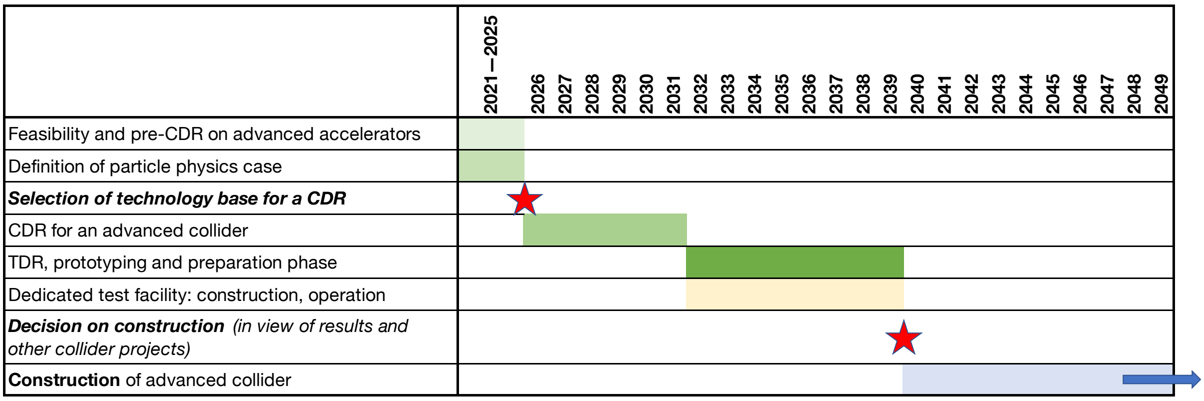

Fig. 4.4: Roadmap towards the development of a collider.

to support these lower energy particle physics experiments in the near-term, addressing particle physics goals that are new and unique. DLA and THz accelerators have unique possible applications in accelerating single electrons for fixed-target experiments or detector tests with reasonable efficiency, but further studies are required to assess viability. These near-term applications of novel accelerator concepts would then provide the opportunity to demonstrate the operational capability of the technology.

4.4 Panel activities

4.4.1 Mandate and scope

The expert panel "High Gradient Acceleration – Plasma, Laser" is charged with defining the roadmap in the area of plasma wakefield and dielectric acceleration. This includes as particular tasks: (1) Develop a long-term roadmap for the next 30 years towards a HEP collider or other HEP applications. (2) Develop milestones for the next ten years taking explicitly into account the plans and needs in related scientific fields, as well as the capabilities and interests of stakeholders. (3) Establish key R&D needs matched to existing and planned R&D facilities. (4) Give options and scenarios for European activity levels and investment. (5) Define deliverables and required resources for achieving these goals up to the next European strategy process in 2025, in order to inform the community as they make critical decisions on R&D areas for HEP.

4.4.2 Activity

The expert panel was formed during February 2021 and had its kick-off meeting on March 2, 2021. An extensive process of consultation with the advanced accelerator community was put in place, steered via twenty-two meetings of the expert panel. The activity was announced world-wide, and experts were invited to subscribe to an email list. By the end of May, 231 experts had registered to this list and were participating in the roadmap process. A first town hall meeting was held on March 30 and set the scene for advanced accelerators for HEP [18]. The meeting included talks on high-energy physics facilities or experiments at the energy frontier (linear collider) and at lower energies (dark matter search, highly non-linear quantum electrodynamics (QED), low energy gamma-gamma). HEP-relevant parameter examples and two possible case studies were assembled and distributed. Also, a number of questions were formulated by the panel and sent to the community, together with a request for input. A second [19] and a third [20] town hall meeting were held on May 21 and 31, where in total 48 speakers presented their input to the roadmap process. These meetings were attended by up to 135 participants at a given time. Finally, this strategy was presented at a town hall meeting at the European Advanced Accelerator Concepts workshop (EAAC) in Frascati [21].

4.4.3 International activities and integration

Particle physics is an international endeavor, and we recognise that a coordinated strategy will be the most successful. In parallel to the activities of this expert panel, there are ongoing international activities in the United States and Asia. In the US, the Particle Physics Community Planning Exercise (a.k.a. 'Snowmass') is set up by the Division of Particles and Fields (DPF) of the American Physical Society. Input to Snowmass is organised through ten different frontiers, including the Accelerator Frontier.

The Accelerator Frontier has several topical groups, including AF-6 'Advanced Accelerator Concepts' (AAC). Advanced Accelerator programmes are developing new concepts for particle acceleration, generation and focusing that could revolutionise the cost paradigm for future accelerators. The AAC Topical Group will focus on the concepts being developed worldwide, the potential impact they could have on the accelerator complex and future colliders, the major challenges that need to be addressed, and the development time and cost scales. The concepts considered in AF6 include the plasma and laser accelerators that are the topics of this report. To ensure the required international coordination and to arrive at a globally coherent roadmap for novel accelerators, the AF-6 convenors include membership from the Expert Panel and vice versa.

4.5 State of the art

Research on high-gradient plasma and laser accelerators is distributed across many universities and research laboratories. Close collaboration between the academic sector and government-funded laboratories has fueled many important advances in the field. Although the research is not coordinated by a single entity, it is characterised by an open exchange of ideas and personnel with individual groups focused in different areas. Existing research facilities are described in Section 4.8. Funding for this research comes from many sources; from governments and universities to a private foundation.

The field of advanced accelerator concepts encompasses a broad range of concepts. These include plasma-based concepts, where an intense laser or particle beam creates a wake in plasma. In the non-linear blowout regime, fields exceeding 100 GV/m can be used to accelerate electron bunches. The plasma channel can be generated by an electric discharge, or by field ionisation from a relativistic particle beam. Three types of drivers for the plasma wake are being exploited: femtosecond laser pulses, relativistic electron and proton beams, with each having unique advantages. It is common to speak of a *laser wakefield accelerator (LWFA)* when the wake is driven by a laser beam, and of a *plasma wakefield accelerator (PWFA)* when a relativistic particle beam is used. (see also Fig. 4.7). In laser-driven plasmas an energy gain of 8 GeV in only 20 cm of plasma was measured [1]. Electron-driven plasma accelerators have shown an energy gain of 42 GeV in only 85 cm of plasma [2]. Proton bunches were used to accelerate electrons in plasma by 2 GeV [6].

In parallel, researchers investigate the use of dielectric or metallic microstructures for particle acceleration. The accelerating fields can be generated by near-infrared lasers *(dielectric laser accelerators, DLA)*, or by terahertz radiation derived from short-pulse lasers or from the wakefields of an electron beam. This approach offers some unique features: the acceleration mechanism is inherently linear and occurs in a vacuum region in a static structure. Axial fields of 1.8 GV/m with 0.85 GeV/m average acceleration gradients have been demonstrated [3].

It is however clear that building an accelerator requires much more than demonstrating the accelerating gradient and energy gain. Specifically, the efficiency needs to be sufficiently high, and the energy spread and emittance need to be preserved to a large degree to enable a collider. There has been strong progress in addressing these aspects individually. These efforts are now addressed by several research groups, and first applications of novel accelerating concepts are emerging: exponential growth of radiation was observed in an EUV FEL driven by an electron beam generated in a laser-driven plasma wakefield accelerator at SIOM [4], and in a near-infrared FEL driven by a beam-driven plasma accelerator at LNF/INFN [5]; protons from laser-driven accelerators are considered for radiation therapy. At the same time, control of longitudinal and transverse focusing of the particle bunches in DLA [11] may be sufficient to enable ultrafast electron diffraction: measurements of hexagonal boron nitride have been performed, using an electron gun designed for a DLA and using DLA to characterise the electron pulses.

Applications in particle physics, in particular the design of a collider at the energy frontier, have significantly more demanding requirements on the electron beams. Many questions are still open, from the particle source to acceleration and beam delivery. In many cases, it is not yet clear what the best approach will look like—in some cases, it is even unknown what the best beam parameters are to address a certain particle physics questions, and consequently what technology would be best suited to generate and accelerate the beams.

There exist a number of rough parameter sketches and ideas for an e^+e^- or $\gamma\gamma$ collider based on plasma or dielectric technology (for example see Refs. [15–17]). In strong contrast to other novel concepts (for example the muon collider) there has never been a coordinated, pre-conceptual design study for such a collider. Such a coordinated study is required to address feasibility, perform supporting simulations and to estimate rough size and costs.

Some of the challenges on the road towards a linear collider at the energy frontier are:

- The particle energy will be in the TeV range, at least two orders of magnitude greater than the largest energy gain achieved in a plasma-based accelerator, and eight orders of magnitude above demonstrated acceleration in DLA.
- Achieving the luminosity goals for a linear collider will require ultra-bright beams, characterised by a high density of particles in phase space. Reaching these goals will require a suitable combination of bunch charge, repetition rate and emittance.
- A high energy efficiency is required for sustainability.
- Losses and beam tails must be controlled for several reasons: to avoid damage and minimise cooling when delivering the beams through the plasma channels or in the dielectric structures, respectively, to reduce detector backgrounds and to minimise the environmental impact of the facility.

In the following, we will outline present research activities directed towards first applications of high-gradient plasma and laser accelerators. In many cases, the relevant beam parameters are particle energy and beam brightness. Additionally, other figures of merit such as energy spread, reproducibility, reliability and energy efficiency have to be taken into consideration. The experimental programme is supplemented by the development of numerical and theoretical tools. These tools support the understanding of the experiments and guide the development of new concepts. The R&D objectives laid out in Section 4.6 build on the present research and address the issues most relevant for particle physics experiments.

4.5.1 Tests of complete accelerator systems

The systems outlined in this section aim at building an entire accelerator system which generates beams suitable for certain applications.

High quality beams: Electron-driven plasma-accelerator-based FEL in saturation –

Three test facilities in Europe, FLASHForward [22] at DESY, SPARC_LAB [23] at INFN-LNF and CLARA at Daresbury [24] (involving Strathclyde University ASTeC, UCLA and SLAC) are conducting experiments with beam-driven plasma accelerators in order to produce high quality beam parameters compatible with the observation of FEL gain. The EuPRAXIA@SPARC_LAB facility [25] at Frascati is aiming to operate a short wavelength SASE FEL by the end of 2029.

Great progress has been made in recent years in demonstrator experiments for the preservation of beam quality in terms of energy spread and emittance [26–30], and the first experimental evidence of the feasibility of a plasma photocathode has been shown [31]. Very recently, the first demonstration of

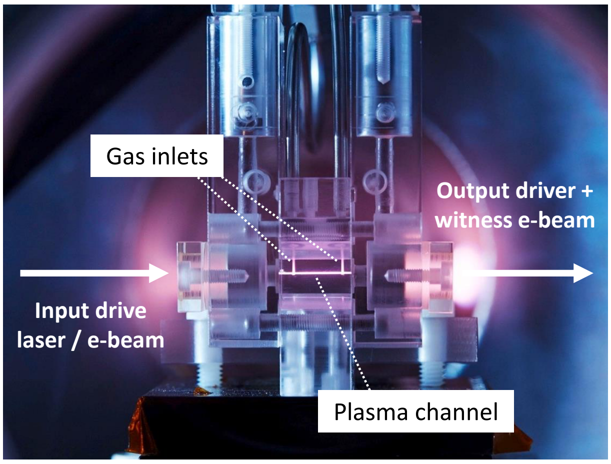

Fig. 4.5: Building blocks of a plasma wakefield accelerator: this setup, only a few centimeters in size, is used to generate a plasma channel. *(Image credit: H. Müller-Elsner, DESY.)*

exponential gain in a SASE FEL at 830 nm driven by a plasma accelerated beam has been reported from experiments at SPARC_LAB [5].

High quality beams: Laser-driven plasma-accelerator-based soft-X-ray FEL in saturation – Several proof-of-principle experiments for a laser-driven free-electron laser are being pursued in Europe, for example COXINEL at LOA/Soleil and LUX at DESY. In addition, experiments at SIOM in Shanghai, China, are making important progress, demonstrating exponential gain of extreme-ultraviolet (EUV) radiation in an undulator [4]. A new high quality plasma acceleration scheme has been proposed within the EuPRAXIA project [10,32]. In the US, FEL-oriented R&D with a laser-plasma accelerator is ongoing at LBNL.

A laser-plasma based X-ray FEL in full saturation is expected to be achieved by 2030 at the latest, proving the generation of high quality electron beams at low repetition rate (up to 5 Hz). The EuPRAXIA project has produced a conceptual design of a 5 GeV plasma-based X-ray FEL facility including all required infrastructure. The location of the laser-driven plasma-based FEL will be decided by 2023, to start operation in 2029.

Proton-driven plasma wakefield acceleration – The energy of laser and electron drive beams is typically limited to less than 100 J, which in turn limits the maximum energy gain of electrons accelerated in a single stage. Therefore, in order to accelerate electrons to TeV energies in both laser- and electron-driver beam acceleration experiments, several stages are required. Proton drivers available today carry a large amount of energy, typically 10s to 100s of kJ, and can therefore, in principle, accelerate electrons to TeV energies in a single plasma.

The AWAKE Experiment, a world-wide collaboration of 23 institutes, has demonstrated at CERN for the first time that a long proton bunch, too long to drive large amplitude wakefields, self-modulates in a high-density plasma in a phase controlled way due to seeding, and then drives large amplitude fields [33, 34] (see also Fig. 4.6). In addition the acceleration of externally injected electrons to multi-GeV energy levels has been demonstrated [6]. Future experiments will address challenges of external injection and stability against the hose instability among issues common to all plasma-based accelerators. The final goal of AWAKE is to bring the proton driven plasma wakefield acceleration technology to a stage, where first particle physics experiments can be proposed.

Dielectric accelerator module with high quality beam for first applications – Dielectric laser-driven acceleration (DLA) refers to the use of photonic micro-structures made of dielectric and semiconductor materials. The acceleration is driven directly by infrared lasers to accelerate charged particles [17]. Structures scaled to terahertz (THz) frequencies offer the possibility to generate significantly higher

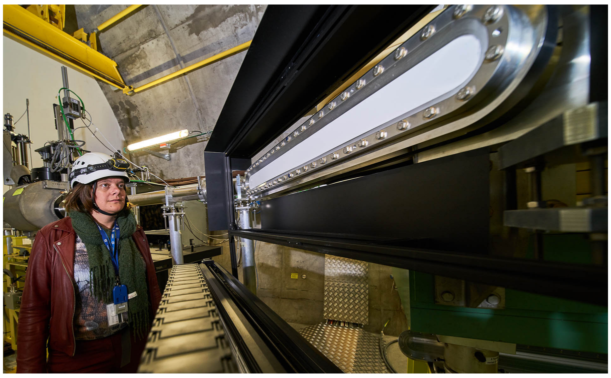

Fig. 4.6: Diagnostics for the accelerated electrons in the AWAKE experiment at CERN.
(Image credit: CERN.)

bunch charges, but the efficient generation of terahertz radiation remains a challenge. Dielectric materials have a damage threshold in the 1 to 10 GV/m range at THz to optical frequencies, and DLA structures have been shown to support electromagnetic fields of 1.8 GV/m, corresponding to an average gradient of 850 MV/m [3].

The bunch charge depends on the structure size, and the width of the accelerating channel is a fraction of the wavelength of the driving laser. Proof-of-principle experiments using near-infrared titanium sapphire lasers as drivers operate with bunches in the fC charge range, while terahertz accelerators operate with pC bunches [35].

Manufacturing of the structures makes use of the technology used in the semiconductor industry, supplemented by emerging free-form manufacturing methods with micrometer precision. Mass production using CMOS and MEMS fabrication methods can be envisioned. Recent advances include the use of inverse design to determine the optimum layout of the structure [36], and the demonstration of transverse and longitudinal focusing of the beams in a dielectric accelerating channel [11]. The community is exploring applications in ultrafast electron diffraction, medical physics and beam instrumentation [35].

4.5.2 Collider sub-system development

Elements of collider sub-systems are currently being investigated, and these programmes will inform more integrated designs such as proposed for WP 2 in Section 4.7.2.

Staging of electron plasma accelerators including in- and out-coupling – Staging of plasma accelerators is essential to reach high energies together with high efficiency and high repetition rate. A number of considerations make connecting plasma-accelerator stages non-trivial [13]. Major challenges arise from strong focusing in plasma and therefore highly diverging beams outside the plasma, as well as from the need to in- and out-couple the driver without disrupting the accelerated beam. In this context, conventional beam optics typically suffer from large chromaticity (energy-dependent focusing), which results in catastrophic emittance growth. Advanced beam optics including plasma lenses [37] and plasma ramps will therefore be key to staging. Managing sub-fs synchronisation and sub-μm misalignment tolerances [38], for example by deploying novel self-stabilisation concepts [39] is also essential. Strong focusing elements, such as plasma lenses, will be required to minimise the distance between stages, which also contributes to maintaining a high average accelerating gradient along the staged accelerator.

Experiments at LBNL have demonstrated first acceleration in two independent laser-driven stages, with pioneering use of both plasma lenses and plasma mirrors [13] to ensure a compact setup. These experiments also emphasised the above challenges: the charge coupling efficiency between the two stages was only about 3.5 % due to a significant chromatic emittance growth. Thorough theoretical analysis and simulations were carried out in the EuPRAXIA CDR phase for two stage plasma accelerator systems

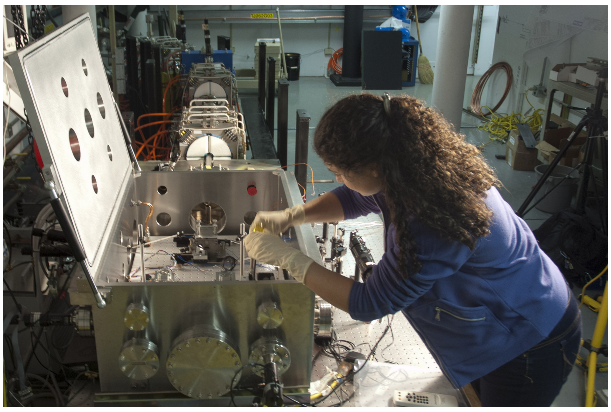

Fig. 4.7: Early laser acceleration experiments at SLAC: installation of the experimental chamber in the Next Linear Collider Test Accelerator. *(Image credit: R. Ischebeck, SLAC.)*

with chicane-based phase space rotation and minimised energy spread, including transfer lines between two plasma stages, as well as between a plasma stage and an FEL application.

Polarised electrons – The laser-driven generation of polarised electron beams in compact sources and the preservation of the polarisation state in a plasma wakefield is an open challenge for particle physics applications, which—unlike many R&D topics in the field—often benefit little from synergies with applications in other fields such as photon science. In combination with the development of advanced target technologies they are being pursued in the framework of the ATHENA consortium and EuPRAXIA [10]. Novel spin-polarised gas targets will be tested at different laser facilities, e.g., at DESY in the near future. The goal is to demonstrate in experiments the capability of plasma wakefields to maintain beam polarisation during the acceleration process and to measure the fraction of polarisation preserved after the plasma.

This was as yet only demonstrated in numerical simulations. A complementary approach is followed by the Forschungszentrum Juelich (FZJ), which builds on sources for laser-accelerated polarised hadron beams. These sources will be modified such that they can also serve as sources of polarised electrons [40].

Positron bunch acceleration – Results on the acceleration of injected positron bunches in a beam-driven plasma accelerator have been achieved at FACET. An overview and outlook for efficiency and beam quality has been reported [41]. Many techniques have been proposed and some have been studied experimentally that demonstrate individual elements of a plasma accelerator stage for positrons, e.g. multi-GeV/m gradients, but none of these techniques are envisioned to satisfy the requirements needed for a collider. In a DLA or a THz accelerator, conversely, the acceleration of positrons is inherently the same as the acceleration of electrons. Notwithstanding, the generation of positron beams with suitable transverse emittance is still unsolved, unless resorting to conventional damping rings, which in turn have relatively poor longitudinal emittance.

Advanced plasma photoguns with ultra-low emittance – Plasma photocathodes promise production of electron beams with ultra-low normalised emittance in both planes. Such beams may obviate the need for damping rings for HEP injectors. They would be compatible with plasma-based collider schemes, and could in the short term be used as test beams. The first plasma photogun was realised in proof-of-concept experiments at SLAC FACET [31], and next-generation experiments, e.g., at SLAC FACET-II aim to demonstrate the potential of the scheme towards normalised emittances of the order of 10 nm.

Hybrid laser-beam driver schemes: Demonstration and stability – LWFA-driven PWFAs utilise high peak-current (> 6 kA) electron beams from compact laser-driven wakefield accelerators to subsequently drive a PWFA stage. A European 'Hybrid' collaboration has been formed and has achieved major con-

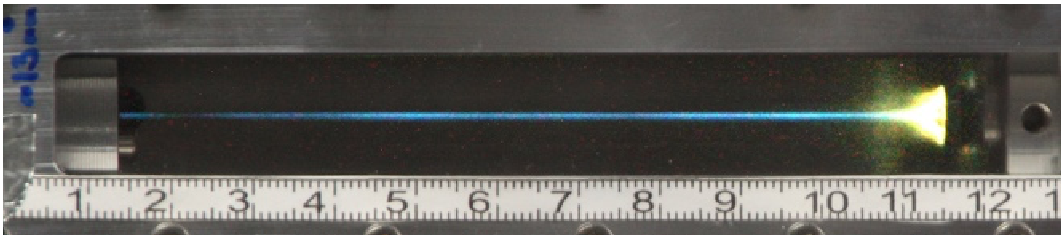

Fig. 4.8: Photograph of the visible plasma emission from a 100 mm long hydrodynamic optically-field-ionised (HOFI) plasma channel. The scale visible at the bottom of the image is in cm. Note that the apparent decrease in plasma brightness near a scale reading of 2.5 cm arises from blackening of the cell window in that region, not from non-uniformity of the plasma channel.
(Image credit: A. Picksley, Oxford.)

ceptual and experimental milestones in quick succession [42–46]. The hybrid concept aims at demonstrating an overall highly compact platform that combines the LWFA and PWFA schemes and delivers at the same time high quality electron beams.

Plasma lens R&D – Radially symmetric focusing with a magnetic gradient of the order of kT/m has been demonstrated for electron beams by means of plasma-based lenses. Several results have been obtained with active plasma lenses (APLs), showing emittance preservation [47,48] and the focusing of relativistic electron beams both from laser-plasma and RF accelerators [37,49–51].

High transformer ratio in PWFA for high efficiency and low energy spread – Shaping the current profile of the drive bunch (DB) and witness bunch (WB) can control the excitation of wakefields and maximise the energy transfer efficiency from the DB to the WB [52]. A DB longer than the plasma period and with, e.g., a triangular current profile, or a train of bunches with increasing charge can drive wakefields with accelerating fields much larger than decelerating fields. The ratio of these fields, the transformer ratio, as high as $\sim$8 has been demonstrated experimentally [53]. Shaping of the WB further allows for minimisation of the final energy spread through precise flattening of the wakefields, i.e. beam loading. This field flattening has been controlled to the percent level in experiment [28]. Bunch shaping techniques include tailoring of the laser pulse at the electron bunch source, beam masking, and emittance exchange. Conservation of the transverse normalised emittance requires precise matching of the WB to the focusing force of the plasma column.

Development of plasma sources for high-repetition rate, multi-GeV stages – Straw-person designs of future plasma-based colliders [54] indicate that to reach the luminosity, it is required to increase the repetition rate and the average power of the driver by orders of magnitude beyond the state of the art to $\mathcal{O}$(10 kHz) and $\mathcal{O}$(100 kW), respectively. Modern plasma sources are based on various technologies, e.g. capillary discharges, gas jets, plasma cells and laser-shaped channels. These sources have been robustly characterised and used in low-repetition-rate (Hz to kHz-level) acceleration experiments [1,28].

In order to push technology towards operation at high repetition rates, it is necessary to explore the fundamental limitations of each source. For example, the repetition rate is limited by the time it takes for the plasma to recover to approximately its initial state after the passage of the beams and the corresponding energy deposition. This recovery time is governed by effects such as dissipation of wakefields, plasma recombination, plasma expansion, replenishing of the background gas inside the plasma vessel and cooling of the plasma source. These physical and technological limits are largely unexplored and open for development.

High average power, high efficiency laser drivers and schemes – Currently Ti:sapphire, pumped with frequency-doubled diode lasers or flash-lamp-pumped Nd:YAG lasers, is the most commonly used laser technology for LWFA, DLA and THz accelerators. Commercial systems for wakefield acceleration operate at high peak power (10 PW at ELI-NP) and useful repetition rates (1 PW @ 1 Hz, BELLA). However, laser drivers for LWFA-based colliders would require much higher *average* power than is currently available. Two options for achieving this performance are being pursued: the development of new lasers and technologies which avoid the intrinsic limitations of Ti:sapphire lasers, and which operate at multi-kHz repetition rates with high wall-plug efficiency. Options for such new laser systems under development with the goal of producing high energy (> 10 J), high repetition rate (> kHz) pulses required for an HEP-relevant LWFA collider include: the combination of multiple low energy, high repetition rate Yb-doped fibre lasers, which has demonstrated pulses of tens of mJ and 100 fs, at tens of kHz [55–58]; Thulium-doped lasers operating at 2 µm that have been shown to produce GW pulses shorter than 50 fs [59]; and the Big Aperture Thulium (BAT) project developing Th:YLF lasers. In addition, alternative approaches are being investigated for modulating long (picosecond) laser pulses to drive plasma accelerators [60]. This would broaden the range of possible laser drivers for LWFA to include, for example, thin disk Yb-doped lasers generating joule-level pulses at kHz repetition rates [61, 62]. It is also important to note that research directed towards producing high-average-power lasers for LWFA should include developing new optics, for example, compressor gratings, with novel coatings that can withstand the increased fluence and thermal load of such lasers.

Many LWFA experiments employing low-repetition-rate lasers (typically $f_{\rm rep} = 1\,$Hz) have demonstrated the generation of electron bunches with energies of order 1 GeV [63], bunch charge of hundreds of pC [64], divergence of 0.1–1 mrad [65], energy spread $\Delta E/E < 1\%$ [61, 66] and emittance of 1 µm [67]. In recent years there has been a transition from demonstration and physics studies experiments to accelerator research and development. For example, continuous operation for 24 hours of an LWFA at a pulse repetition rate of 1 Hz, with bunch parameters of $E = 368\,\mathrm{MeV} \pm 2.5\%$; $Q = 25\,\mathrm{pC} \pm 11\%$; $\Delta E/E = 15\%$; $\Delta\theta = 1.8\,\mathrm{mrad}$ was reported [68].

Research on high average power lasers is pursued at DESY in the KALDERA project, as discussed in Section 4.8.1.6.

4.5.3 Numerical and theoretical tools

Computer simulations and theory have been providing critical support to the development of plasma-based accelerators for decades [69, 70] as illustrated in Fig. 4.9. In order to enable successful progress towards HEP applications, it is now of the highest importance to prepare an open-science model capable of taking full advantage of pre-exascale and exascale computers [71, 72]. Global and sustained effort is needed over the next decades in theory/numerical R&D activities, leading to accurate collider-relevant predictions.

The most used simulation model today is based on the PIC technique. PIC simulation codes are kinetic, electromagnetic and relativistic. In addition, these codes capture the single particle motion of plasma particles self-consistently. PIC simulations are accurate and predictive. For example, the generation of electron bunches with quasi-mono-energetic features from plasma [73–75], was first predicted in simulations [76].

PIC simulations are also computationally intensive. To reduce simulation time, PIC codes can rely on relativistic frames [77, 78] in conjunction with reduced physical models. Reduced models include envelope solvers for laser propagation [79], reduced dimensions [80] and quasi-static approximations [81]. In addition, recent research also focuses on the development of advanced field solvers (e.g. see Ref. [82]) and particle pushers (e.g. see Ref. [83]) to increase numerical accuracy and stability.

Significant effort has been put into including new models of relevance for HEP applications, of which advanced radiation diagnostics and quantum-electrodynamics models in PIC codes are key examples. PIC codes are now capable of predicting the spatio-spectral features of classical synchrotron emission, model classical and quantum radiation reaction physics [84], pair production [85] and spin physics [83]. PIC codes can be useful to model intermediate applications, such as coherent plasma light sources, contribute to the design of plasma accelerator-based machines for HEP such as e^+e^- and $\gamma\gamma$

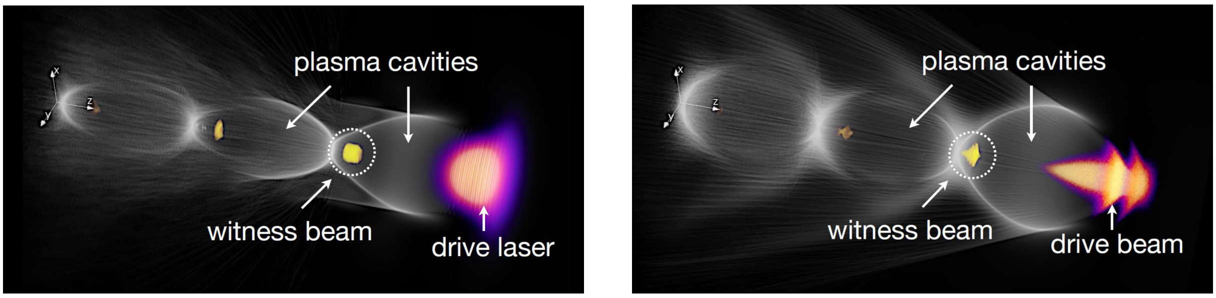

Fig. 4.9: Simulation of a LWFA *(left)* and a PWFA *(right)*, showing the formation of the accelerating cavities in the plasma. The witness beam is located at the point where the accelerating field is highest, just before the end of the first bubble.
(Image credit: EuPRAXIA Conceptual Design Report, A. Martinez de la Ossa [10].)

colliders, and are being prepared to also model the physics at the interaction point in lepton collisions.

Having noted above the successful use of PIC codes to model current experiments, we add that the needs for simulating a TeV collider with nm emittance bunches are demanding and require further development in this area.

4.6 R&D objectives

4.6.1 Challenges to be addressed

4.6.1.1 Challenges for plasma accelerators

The impressive success in the field notwithstanding, there are still many fundamental research issues that have to be solved before high-gradient plasma and laser accelerators can be used for particle physics experiments. The primary challenges associated with using plasma acceleration in a linear collider are listed below:

1. **Efficiency and small energy spread at nominal bunch charges** – A critical issue for linear colliders is achieving beams with high charge and small energy spread ($<1\%$) with high acceleration efficiency to reach the design luminosity. In simulation it is possible to achieve high transfer efficiency from the drive bunch or drive laser pulse to the colliding electron beam with sub-% energy spread. However, few full start-to-end simulations for a plasma stage have been completed. In experiments, high instantaneous transfer efficiency (30 to 50%) has been demonstrated with low (10 to 100 pC) bunch charge [1, 28, 29, 86]. We note that the quoted transfer efficiency has been obtained with a small energy gain and an energy transfer much smaller than that of the driver. In concept, the total efficiency could be improved by lengthening the plasma cells. Future experiments are planned to study these limits and full simulation studies will be made to understand the limitations. In addition, understanding beam losses and energy recovery concepts will be used to improve the total transfer efficiency.

2. **Preservation of small beam emittances** – Linear colliders require the acceleration of beams with normalised final emittances of roughly 0.1 µm. There are many challenges to emittance preservation in plasma accelerators including the matching in and out of the plasma stages and suppression of beam hosing due to the two-stream instability. Several concepts have been suggested, although it is not clear if these are well matched to the changing beam parameters along a linear collider. The demonstrations of lasing in FELs imply transport of beam emittances that are $\sim$2 µm in a short single stage system, a normalised emittance that is still well above that required for a linear collider. Solution to this challenge requires detailed simulation including all the relevant physical processes and including beam parameters representative of different points along the linear accelerator. The studies should include realistic variation in beam and plasma parameters as well as tolerances and

correction schemes to ease the tolerances. Experiments should be used to validate the simulations although reproducing the exact linear collider parameters and configurations are likely not necessary. The preservation of the small beam emittances is probably the most challenging issue for the plasma accelerators and must be addressed rigorously.

3. **Staging of multiple plasmas** – Accelerating beams to high energy requires multiple plasma stages with each stage accelerating the beam by between a few GeV to a few tens of GeV. The inter-stage sections must couple the drive bunch or laser pulse in and out of the plasma, must match the colliding beam between stages, and must provide all the diagnostics required to tune the beam's 6D phase space. Care will be required to transport and match the beam between stages in a way that avoids significant emittance dilution. As an example of the challenge, a proof-of-principle multistage LWFA experiment was completed at LBNL. It suffered from large chromatic emittance dilution which limited the transmission to a few % of the beam. Mitigation strategies will also be needed for expected sub-micron transverse alignment tolerances and sub-fs timing tolerances. Concepts have been proposed for compact staging solutions, but these require components that have not yet been developed and/or need to be tested for high energy beams. Once a solution is proposed it will need to be verified in simulation to understand the expected performance across the range of parameters in the linear accelerator and then the simulations should be benchmarked with careful experiments.
4. **High repetition rate, stability and availability** – To achieve the desired luminosity, plasma-based linear colliders will need to operate with repetition rates of tens of kHz. Studies of plasma cooling and plasma stability are needed as there will be large energy deposition (100s kW/m in typical parameters) into the plasma. As multiple timescales exist and simulation can be difficult, experimental demonstration at high rate will be needed. The high repetition rate will also allow for feedback systems to stabilise the plasma accelerators, reducing the pulse-to-pulse variation. Finally, typical RF linear accelerators are designed for high availability and can continue operation even through failure of multiple components. A detailed analysis of failure modes and mitigation methods is required. Demonstration of routine operation of a plasma linac will be required to address concerns.
5. **Positrons** – At this time there is not a complete solution to accelerate a bunch of positrons with an emittance required for a linear collider that has been developed conceptually, in simulation, or in experiment. Concepts that are verified by simulation and then experimentally are required. If a solution for accelerating positrons could not be developed, a $\gamma\gamma$ collider based on colliding electron beams could be considered instead of an e^+e^- collider. This will require an additional study and a demonstration of the laser-Compton IPs, backgrounds, detector integration, etc.

As noted, an integrated feasibility study is needed to put these concepts together and illustrate to the community that a plasma-based accelerator is a realistic option for a future collider. The study should provide detailed examples of how the main challenges will be addressed. While experimental demonstrations are not needed for all components to support such a study, key demonstrations should be supported to validate detailed simulations of the relevant sub-systems. The feasibility study will include enough detail to make cost estimates. Bottom-up estimates will be needed for the new technology and components that have tight tolerances.

A strong benefit of a plasma-based linear collider is that it takes advantage of 40 years of linear collider development. One of largest obstacles in developing a new large HEP facility is that new concepts usually require demonstration of integrated subsystems as well as development of new technologies. These large subsystem demonstrations can be a large fraction of the facility cost. In a linear collider there are three main subsystems that would require demonstration: beam generation, beam acceleration, focusing and collimation. Fortunately, the construction and operation of the Stanford Linear Collider as well as the many 100s of MCHF that have been invested in linear collider test facilities have verified many of the critical linear collider concepts including the beam generation and transport, beam acceleration, final focus systems, as well as the critical beam-based diagnostics and feedback systems. Most of these demonstrations are directly relevant to a plasma-based collider, simplifying the development path greatly. In the case where plasma is used to replace the linear accelerators, only a relatively compact demonstration of a few plasma stages is required to address the issues described in items 1–5 above. These demonstrations should be sufficient to benchmark detailed simulations and allow low risk extrapolation to the full high-energy linear accelerator and the linear collider.

4.6.1.2 Challenges for DLA / THz accelerators

At present, beam parameters of particle bunches accelerated by dielectric laser and terahertz accelerators are still far from practical applications in particle physics. In addition, several aspects such as reliability and repeatability have not yet been addressed, and the technical readiness for building an accelerator still remains to be demonstrated in an application. In particular, we note the following challenges on the road towards a linear collider:

1. **Generation of beams with suitable parameters for a linear collider** – The acceptance phase space of dielectric laser accelerators is significantly smaller in comparison with radio frequency linacs. This determines the charge that could be accelerated in a DLA (e.g. the 5 fC from Table 4.1). Terahertz accelerators offer a larger acceptance volume. In particular the generation of positron beams with sufficiently small emittance is an open issue. Generating beams with suitable parameters (low bunch charge, sub micron normalised emittance, low energy spread, few fs length, at up to 20 MHz pulse repetition rate and with multi-bunch acceleration within a pulse — see Table 4.1) is a challenge: present experiments accelerate bunches with $\mathcal{O}$(aC) charge.
2. **Staging** – While the acceleration of electrons in multiple DLA stages has recently been demonstrated, these structures were driven by the same laser system. A high-energy linear collider would require multiple drive lasers, which have to be synchronised to a fraction of the period, i.e. to sub-femtosecond precision.
3. **Energy efficiency** – The high energy efficiency of solid-state lasers (up to 50%) lays a good basis for the laser-based acceleration schemes. An efficient transfer of this energy in a dielectric structure (e.g. 50% compared to presently less than 0.1%) would require either a significant beam loading, or the re-circulation of the laser energy inside the oscillator. When using terahertz frequencies, the efficiency of conversion of visible light to THz frequencies imposes an additional challenge.
4. **Transverse and longitudinal stability** – The phase space evolution of the particle bunches from the source to the final energy needs to be modelled, including tolerances in the manufacturing process. This will give a good understanding of the expected particle losses, which has to be taken into account considering radiation damage, environmental impact, heat load and detector backgrounds.
5. **Heat load and particle containment** – Linear collider parameters require an unprecedented beam energy to be contained in the accelerating structure that has a much smaller clearance than RF accelerators. In a dielectric-based collider (see Table 4.1) a 15 MW beam should pass through a micrometer size hole, or should be divided into multiple parallel accelerators. In addition, losses of the driver energy in the structure must be dissipated. Assuming losses of 7.5 MW over a 1 km length of the accelerator (1 TeV beam energy with 1 GV/m gradient), then power at the level of 7.5 kW/m would need to be be evacuated without major deformations of the accelerating structure. In addition, possible radiation damage should be considered. This issue will require major R&D for assessing feasibility and scalability to high energy. It should be addressed in the 2025 feasibility report.

Dielectric laser accelerators leverage the significant effort that the laser and semiconductor industries have invested into the efficient generation of coherent light, and into manufacturing structures with sub-micrometer accuracy. They promise the possibility to accelerate beams with extremely low emittances to relativistic energies. Generating beams of relativistic electrons that are coherent in a quantum-mechanical sense, this technology could thus have the potential for applications in the emergent field of ultrafast electron diffraction.

Matching the capabilities of dielectric laser and terahertz accelerators to the particle physics experiments would certainly entail choosing different beam parameters as compared to radio frequency or plasma wakefield accelerators. A careful optimisation of beam parameters will have to be performed, including considerations of beam loading, wakefields and beamstrahlung at the interaction point.

4.6.2 Three pillars of the near-term R&D roadmap

The panel has discussed and agreed on a roadmap that is based on three pillars that should be pursued in parallel (see also Fig. 4.1). The three pillars of our roadmap are

1. **The first international feasibility and pre-CDR study** for high-gradient plasma and laser accelerators and their particle physics reach. This paper study will lead to a comparative report on various options, a feasibility assessment, performance estimates, physics cases, intermediate HEP applications and a cost-size-benefit analysis for high energy.
2. **A prioritised list of technical R&D topics** that will demonstrate a number of technical feasibility issues of importance for particle physics experiments.
3. **Integration and outreach measures** that exploit and ensure the very high synergistic potential with other fields and large projects, like EuPRAXIA. It enables access to distributed R&D facilities under clear rules and supports innovation with closely connected industry. Finally, it connects to the next generation of scientists in close collaboration with other activities in I-FAST and the European Network for Novel Accelerators (EuroNNAc).

4.6.3 R&D objectives of the feasibility study and pre-CDR

The expert panel proposes the first international feasibility and pre-CDR study for high gradient plasma and laser accelerators and their particle physics reach. As a first step, we will evaluate the state of the art in detail, and provide an honest assessment of the field. We will determine theoretical limits and collect experimentally achieved parameters for collider-relevant aspects: energy gain, energy gradient, bunch charge, emittance and energy efficiency. We will attempt to assess the reliability and stability of the technology, the suitability for positron acceleration, and the preservation of polarisation.

We have worked out common study cases for a comparative feasibility study that includes all technical options, so a decision on continuation can be taken in 2025. DLA and THz accelerators are a promising technology and the panel believes this should be part of the roadmap. Its status is less mature than plasma wakefield acceleration (beam- and laser-driven), however the proposed work is expected to advance the technology significantly.

4.6.3.1 High-energy common study case

A high-energy study case will assess the feasibility in the high-energy collider regime. CLIC has already established an optimised set of parameters for radio frequency technology. We adapt here the CLIC parameters of the final 15 GeV of the CLIC 380 GeV main linacs [87]. A self-consistent concept for a linear collider at the energy frontier does not exist for any of the technologies considered. We note that the best way to reach a required luminosity target with optimum energy efficiency will result in a different beam parameter set, depending on whether plasma, DLA or THz accelerators are used. The parameters will thus be optimised to take into account the constraints and opportunities presented by plasma and laser technology, while attempting to maintain final particle energy and luminosity. The

Table 4.2: Specification for an advanced high energy accelerator module, compatible with CLIC [87]. Additional CLIC design values are listed for reference in the second part of the table.

Parameter	Unit	Specification
Beam energy (entry into module)	GeV	**175**
Beam energy (exit from module)	GeV	**190**
Number of accelerating structures in module	-	≥ 2
Efficiency wall-plug to beam (includes drivers)	%	≥ 10
Bunch charge	pC	833
Relative energy spread (entry/exit)	%	≤ 0.35
Bunch length (entry/exit)	µm	≤ 70
Convoluted normalised emittance ($\gamma\sqrt{\epsilon_h \epsilon_v}$)	nm	≤ 135
Emittance growth budget	nm	$\leq$ **3.5**
Polarisation	%	80 (for e^-)
Normalised emittance h/v (exit)	nm	900/20
Bunch separation	ns	0.5
Number of bunches per train	-	352
Repetition rate of train	Hz	50
Beamline length (175 to 190 GeV)	m	**250**
Efficiency: wall-plug to drive beam	%	58
Efficiency: drive beam to main beam	%	22
Luminosity	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.5

relevant study case is the design of an advanced accelerator module (two or more acceleration stages) accelerating electron or positron beams from 175 GeV to 190 GeV. All required components for in- and outcoupling of the drivers (e.g. laser, electron, or proton pulses that drive the accelerating fields) will be included. The specification is listed in Table 4.2.

We note that this high-energy study case is a required step towards the TeV beam energy regime, which is the final goal for a collider and will be pursued in further studies. We have chosen the 190 GeV energy to reduce difficulty while addressing several high-energy feasibility issues, although proposed solutions will have to be shown to work across the energy range of the accelerator. For example, solutions to compensate the two-stream hosing instability with ion motion may not work as the beam energy and thereby the beam size changes along the linac.

4.6.3.2 Low-energy common study case

The potential for low-energy particle physics applications will be assessed by considering a parameter regime for fixed-target experiments, which could be realised in the nearer future with more relaxed beam parameters compared to colliders at the energy frontier. The relevant study cases are therefore the design of an advanced accelerator (that can include the injector) to accelerate electrons to a final beam energy in the regime of 15 GeV to 50 GeV and to be used for first HEP experiments.
Table 4.3 summarises the parameters we use for an electron beam, generated by a dielectric laser accelerator (inspired by the eSPS specifications [88]). Electron bunches from a plasma accelerator for an LHeC-like collider [89] and for the LUXE experiment [90] are also summarised. These experiments are the following:

Single electron tagging experiments – High-quality electron beams in the energy range 15–20 GeV are scarce, but have potential application in HEP. A case for an experiment to search for dark photons has been made based on electrons in the SPS (eSPS). In order to tag each incoming electron, single

Table 4.3: Specification for an electron beam for fixed-target (FT) experiments, generated by a dielectric laser accelerator (inspired by the eSPS specifications [88]) as well as for electron bunches from plasma accelerators for PEPIC [91–93], a low-luminosity LHeC-like collider [89] and for the LUXE experiment [90]. Such bunches (for PEPIC and LUXE) can also be used for a beam-dump experiment to search for dark photons. Note that the number of bunches per train in the European XFEL is 2700, but for LUXE only one is used.

Parameter	Unit	single e FT	PEPIC	LUXE
Bunch charge	pC	few e	800	250
Final energy	GeV	20	70	16.5
Relative energy spread	%	< 1	2−3	0.1
Bunch length	µm	-	30	30−50
Normalised emittance	µm	100	10	1.4
Number of bunches per train	-	1	320	1
Repetition rate	-	1 GHz	0.025 Hz	10 Hz
Luminosity	10^{27} cm^{-2} s^{-1}	-	1.5	-

electrons enter the experiment, with a suitable time structure so that a large number of electrons on target are collected, $10^{14} - 10^{16}$. Such a scheme allows for the full reconstruction of the event and hence the possible decay of dark photons to 'invisible' dark matter candidates as well as, e.g., e^+e^- pairs. For a possible list of parameters, see also Table 4.3.

A DLA could provide the required electron energy over the same same foot-print as a 3.5 GeV X-band electron linac, and avoid the need for a storage ring such as the SPS as a booster accelerator. It would thus completely decouple the project from the SPS. In addition, since the DLA naturally provides low charge (fC) bunches at very high repetition rate (MHz), it could provide electrons 24/7 as a dedicated source. However, the proposed particle energy is many orders of magnitude beyond present capabilities of dielectric laser accelerators.

Electron bunch experiments – In a bunched scheme, the individual incoming electrons cannot be tagged and thus signatures like the decay of dark photons to e^+e^- pairs in beam-dump mode are sought. The AWAKE experiment has done a study of using such bunched electron beams with energies of 50 GeV and above [91–93]. Note that at the lower energy of about 20 GeV, the sensitivity to higher masses of the dark photon is reduced, but the possibility to investigate an unexplored region remains. However, in the AWAKE scheme, in which scalable plasma technologies are being pursued, energies of 50 GeV and beyond should be achievable. Other novel accelerator technologies should also study the possibility of providing such high energy bunched electron beams.

The use of bunched electrons in the 15 to 20 GeV range is also proposed in the LUXE experiment using the European XFEL electrons [90]. This experiment will investigate non-linear QED by colliding the electron bunches with a high-power laser. This is then a natural application for plasma wakefield accelerators.

The AWAKE study [91–93] also considered an electron-proton collider based on bunches of electrons at $\sim$50 GeV (PEPIC) or 3 TeV (VHEeP [94]). Using $\sim$50 GeV electrons is akin to the proposed LHeC project. Typical parameters are shown in Table 4.3 Although a significantly shorter electron accelerator is expected, much lower luminosity is also expected in the AWAKE scheme. Aspects that should be further considered are:

- Further study and optimisation of the AWAKE scheme, in particular to increase the luminosity.
- Application of novel accelerator schemes to the LHeC.

- Experiments at other electron beam energies as required by the HEP community.

Another compelling application yet to be considered using a novel accelerator scheme is a $\gamma\gamma$ collider, with a centre-of-mass energy of 12 GeV [95]. The current design is based on the use of the European XFEL electron beam but would require additions to the complex to run a collider. A LWFA accelerator based on a few stages facing each other in a collider-like arrangement would decouple the idea from the over-subscribed FEL beam and provide an ideal test-bed for the development of a mini collider towards a larger scale scale collider.

4.6.3.3 Theory and simulation

The proposed feasibility study will include a strong effort on theory and simulation, both for plasma-based accelerators, and for DLA/THz structures. A beam physics and simulation framework will be set up that addresses all system aspects of a high-energy physics machine. The work will include the preparation of numerical and simulation tools, as required for simulating multi-stage setups at high and low energy for the various options, both for electrons and positrons. For typical densities, bunches with transverse sizes as low as a few tens of nm, may be required. The disparity between the transverse bunch size and the plasma or laser wavelength are numerically and theoretically challenging and make collider-relevant numerical models very computationally intensive. Sustained development and use of reduced physics/lower dimensions numerical models, combined with artificial intelligence (AI) / machine learning (ML), and possibly under simplifying configurations, are priorities for collider modelling.

Research milestones thus include setting up of simulation tools for electron and positron case studies ($\geq$ 2 stages) with certain approximations. Strong emphasis should be given to the accuracy, stability and efficiency of the numerical models. This will allow start-to-end simulations of many acceleration stages. More specifically, these tools will make it possible to study emittance and energy spread preservation for electron and positron bunches with collider-relevant parameters. Spin preservation and beam-disruption mitigation strategies also need to be developed.

The following provides a summary with key research and development priorities for high-gradient plasma and laser collider simulations.

1. **Sustained simulation development** – The nm-scale transverse witness bunch dimensions is a bottle-neck for the modeling of a plasma accelerator based collider. The development of accurate, stable and computationally efficient electromagnetic field solvers and particle pushers for particle-in-cell codes are key goals. Codes need to be prepared to take advantage of recent computer architectures at the (pre-)exascale. The codes need to be able to include physics beyond the beam-plasma electromagnetic interaction such as incoherent synchrotron radiation, ionisation processes and other scattering effects. The field would strongly benefit from sustained efforts over the coming years and decades and from links with supercomputing centers. Developing tools based on reduced physical or numerical models (e.g. based on the quasi-static approximation [96], boosted frames [77], envelope models, reduced beam propagation models etc.), potentially combined with AI/ML will be important to provide a suite of approximate but fast models ready to perform systematic parameter scans.

2. **Positron and electron acceleration** – Recent experiments demonstrated lasing in a free-electron-laser powered by sub-percent energy spread GeV-class electron bunches from plasma-based accelerators. Such an energy spread is compatible with requirements for collider applications. Scaling these results to 10-100 GeV is a main research goal. Intense effort is also needed to develop positron acceleration in plasma. Several positron acceleration concepts recently emerged (e.g. relying on drivers with advanced spatiotemporal profiles [97] or hollow channels [98] in linear or nonlinear regimes [41]). Expanding such concepts, and even developing new concepts towards collider-relevant conditions, is a requirement for plasma-based linear collider design.

3. **Emittance preservation** – Collider physics requires bunches with normalised emittance as small as $\simeq 10\,\mathrm{nm}$ for plasma accelerators, and sub-nanometer for DLAs. A conceptual demonstration of high-efficiency acceleration and emittance preservation within these tolerances is vital. Research needs to focus on emittance preservation during the acceleration and plasma-vacuum transitions, considering collider relevant parameters, for both electrons and positrons. Emittance preservation in plasma-vacuum transitions at the nm level was demonstrated in theory and simulations in a single stage and considering 100 MeV electron bunches [99, 100]. It is important to build on such studies to scale results to 10-100 GeV energies, and prove their validity for positron bunches. We note that these studies will also benefit intermediate applications such as coherent radiation emission in plasma [101].

4. **Efficiency and stability** – To maximise efficiency in a plasma accelerator, accelerated beams may be several orders of magnitude denser than the background plasma [102]. Despite recent work on hosing suppression in plasma-based accelerators [96, 103–106], demonstrating suppression of the hosing instability under such large witness to plasma density ratios remains a key research goal. Driver and witness bunches with advanced spatiotemporal and phase-space structures also promise to circumvent some limits of plasma accelerators, such as depletion and dephasing [107–109]. Research demonstrating their effectiveness for collider-relevant scenarios is, however, still required.
   Efficiency of a DLA hinges on strong beam loading, or on the recovery of the laser pulse energy by including the accelerating structure in the laser cavity [110]. A stable accelerating bucket can be achieved with alternating phase focusing [111].

5. **Physics at the interaction point (IP)** – The electron and positron bunches undergo an intense interaction just before the collision of the particles: the pinch originating in the electromagnetic interaction between the bunches results in a significant increase in luminosity. At the same time, synchrotron radiation generated by this interaction results in beamstrahlung, which leads to a noticeable increase in energy spread. These effects depend strongly on beam parameters such as the normalised emittance, charge and bunch length, and generally become more pronounced at higher energy. For DLA, the optimisation of the parameters favours the interaction of bunches with very low charge; the luminosity is maintained through the high repetition rate, and through the interaction of bunch trains [112].
   Spin preservation in plasma accelerators has been demonstrated conceptually. Previous studies [113], however, did not consider in full the extreme conditions that are required for collider physics. A spin-preservation acceleration regime in more realistic plasma collider settings is thus an important research goal. Furthermore, recent developments [84, 114, 115] enable radiation reaction, synchrotron emission (beamstrahlung) and disruption studies during acceleration in plasma. Applying existing and developing new simulation tools to capture spin-physics, beam disruption, radiation reaction and pair production to model collider-relevant bunches is an additional and important key goal. These advances will also be important in designing other plasma-based collider concepts, such as a $\gamma\gamma$ collider [16].

4.6.4 Technical R&D objectives in the minimal plan

The plan for a conceptual feasibility study is complemented by a prioritised list of R&D topics that will demonstrate a number of technical feasibility issues of importance for particle physics experiments. Here we present a limited number of objectives that have been defined as highly important objectives. All those topics shall have deliverables ready by the end of 2025, in time for the next update of the European Strategy for Particle Physics.

4.6.4.1 *High-repetition rate plasma accelerator module*

PWFA or LWFA stages suitable for collider applications would need to operate at multi-kHz pulse repetition rates for considerable periods of time without the need for replacement or servicing. This is a challenging requirement given the high average power deposited in forming the plasma and/or by the drive particle or laser beams. For example, from Table 4.1 a 5 GeV LWFA stage operating at on-average 15 kHz, and with 40% wake-to-bunch efficiency would need to handle ∼50 kW power remaining in the plasma after particle acceleration.

The development of long-lived, high-repetition-rate plasma accelerator modules is therefore a key requirement. To drive this development we have defined a milestone for end 2025 of the demonstration of a plasma module capable of $>$ 1 kHz operation for at least a billion shots. For this milestone demonstration of high-repetition-rate particle acceleration will not be attempted in the modules.

Two approaches will be explored: (i) all-optical plasma channels based on hydrodynamic optically-field-ionised (HOFI) [116]; (ii) high-voltage-discharge ignited plasma channels. For the latter, a focus will be placed on the development of the necessary high-repetition-rate, high-voltage electronics, plasma-capillary designs capable of fast refilling times or, alternatively, mitigation of expulsion into vacuum, and plasma sources durable enough to survive billions of plasma-generation events at high-repetition operation.

4.6.4.2 *High-efficiency, electron-driven plasma accelerator module*

The efficient transfer of energy from the driving to the trailing beam in plasma-wakefield schemes is essential in order to build a sustainable PWFA-driven linear collider. The maximisation of efficiency will require a careful interplay with other optimisations inherent to the PWFA process such as beam-quality preservation and transformer ratio optimisation. The grand goal of a highly efficient beam-driven plasma-accelerator stage is explored by several facilities, e.g. at INFN, SLAC and DESY, and in association with university groups.

Recently, a focus has been placed on maximising the transfer of energy from the wake to the trailing beam through careful longitudinal bunch shaping (facilitated by the third harmonic cavity and compression chicanes in the FLASH linac). Through this, the plasma wake was flattened with unprecedented accuracy in the region of the trailing bunch such that the in-going energy spread was preserved at the 0.1% level and the trailing beam extracted 42% of the energy in the wake. It is aimed to expand the pre-existing infrastructure of FLASHForward in the near future to include longer plasma capillaries for larger energy gain of the trailing beam and energy loss of the driving beam. Increased control of beam and plasma parameters will be necessary to eliminate the detrimental impact of beam-plasma instabilities such as hosing. By optimising the involved processes, a landmark goal of 40% overall efficiency may be achieved by the end of 2025, if sufficient funding is available to catalyse the required research.

At SPARC_LAB a multi bunch scheme is being explored for maximising energy transfer and efficiency by means of the ramped bunch train scheme. This method consists of using a train of equidistant drive bunches, for example having 1 ps separation. The charge increases along the train (e.g. 50–150–250 pC) producing an accelerating field with higher transformer ratio (>2) while maintaining a high-quality witness beam. For this application it is essential to create trains of high-brightness micro-bunches, each tens of fs long, with stable and adjustable length, charge and spacing. Preliminary tests were performed at SPARC_LAB, but were limited by the time jitters along the train. Better performance is expected with an upgraded system for synchronisation between the photo-cathode laser and the RF, able to reach fs range stability. This requires dedicated funding.

4.6.4.3 *Scaling of DLA/THz accelerators*

The primary focus of HEP-directed research in dielectric laser and terahertz accelerators lies in the increase of structure length, both through confinement and active focusing in longer acceleration channels

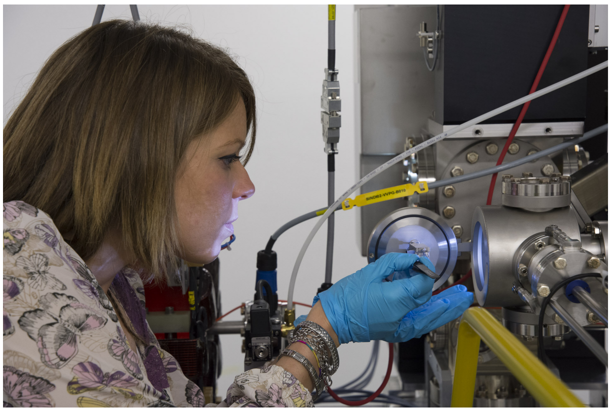

Fig. 4.10: Test of instrumentation for dielectric laser accelerators in SwissFEL at PSI. *(Image credit: R. Ischebeck, PSI.)*

and in the staging of multiple structures. As a first goal, we aim for an energy gain of 10 MeV in a staged setup. The number of stages will depend on the energy gain per stage. It is expected that the interaction length in a single stage can be extended from the present sub-millimeter range to several millimeters. This would correspond to an energy gain of about one MeV per stage, accounting for the length required for transverse and longitudinal focusing.

While particle focusing and longitudinal stability will become easier at highly relativistic energies, the wakefields generated by the ultra-short bunches require special attention. Ultimately, the energy lost in wakefields will limit the bunch charge in DLA/THz accelerators, thus a detailed understanding of the fields is central to the accelerator design. Another aspect that will become important for longer accelerators is instrumentation, such as beam position and profile monitors [117, 118] (see also Fig. 4.10), and feedback from the monitors. They will have to be integrated into the structures, read out and processed by edge computing.

4.6.4.4 Spin-polarised beams in plasma

While impressive progress has been made in improving beam quality over the last decades, the topic of spin-polarisation of plasma-accelerated electron beams has not yet been addressed experimentally. For serious consideration as injectors or accelerator modules in linear colliders, the demonstration of the generation of spin-polarised beams from plasma and also the conservation of polarisation in plasma accelerators is urgently required.

To date, only theoretical work has been performed, with simulations demonstrating that the generation and subsequent acceleration of polarised beams in a laser plasma accelerator are feasible. The proposed scheme involves the realisation of a pre-polarised plasma source, where some background electrons have their spins aligned co-linearly with the propagation direction of the incoming laser pulse. Creating a polarised plasma relies on photo-dissociation of the pre-aligned diatomic molecules by laser pulses in the deep UV. The degree of polarisation of the plasma source depends on the ion species. For example nearly 100% polarisation can be achieved using hydrogen.

Since the pre-alignment of hydrogen ions is technically challenging, the first observation of plasma-based polarised beams could be performed with hydrogen halides to experimentally demonstrate polarisation fractions between 10% and 20%. First work in this direction is currently underway at DESY in the LEAP project. It will be feasible to demonstrate polarisation in hydrogen halides and acceleration in plasma by the end of 2025 with additional resources. A concept can be developed to extend the pre-polarised plasma source technology to enable > 80% overall beam polarisation, with a later experimental demonstration of these high polarisation fractions.

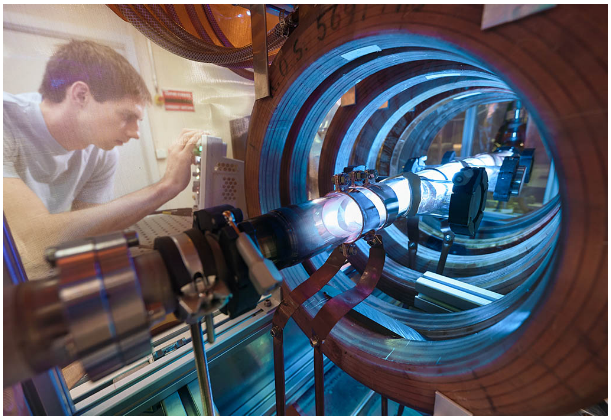

Fig. 4.11: 1 m prototype of a scalable Helicon plasma source. *(Image credit: CERN.)*

4.6.5 Technical R&D objectives in the aspirational plan

4.6.5.1 Scalable plasma source

For high energy physics applications, where electrons are accelerated up to the TeV energy level, the energy of the wakefield driver must be in the range of kJ. As the energy of laser and electron drive beams is limited to ≈100 J, multiple plasma stages are required to accelerate electrons to the required energy. However, current proton beams provide the required driver energy (10s of kJ) and therefore electrons can be accelerated, in principle, in a single plasma stage. It is therefore of great importance to develop plasma source technologies that are scalable from tens to hundreds of meters paving the way for first high-energy physics applications in the intermediate time scale.

In the AWAKE experiment the longest plasma source has been used so far, a 10 m long rubidium vapour source, and provides the required density and uniformity. However, the length of these laser-ionised, alkali metal vapour sources is limited by depletion of the laser pulse energy, to a few tens of meters.

Helicon plasma sources (see Fig. 4.11) and discharge plasma sources are based on a modular scheme that can be adjusted to different lengths. It was shown that the plasma density range suitable for AWAKE can be reached in meter-long prototypes. However, both source types still have to demonstrate sufficient density uniformity. A strong plasma source development programme has been established in collaboration with plasma physics institutes and CERN: IPP, Greifswald, CERN, University of Wisconsin, Madison and EPFL-SPC, Lausanne jointly working on a design proposal for a several meter long helicon plasma cell with the required density and uniformity parameters. The discharge sources are developed by IST, Lisbon and Imperial College, London and are also included in a CERN laboratory test-stand. In a scaled-up version of the AWAKE experiment these scalable sources can then be used to produce beam for fixed-target experiments as a first application.

4.6.5.2 High-charge, high-quality plasma injector/accelerator module driven by laser pulses

In the high energy linear accelerator a laser-driven plasma accelerator module will need to take an incoming electron bunch of high charge (1 nC) and low transverse emittance (100 nm) and accelerate efficiently to higher beam energy, while preserving the charge and beam quality. Presently relevant experiments are performed on modules that include the electron source, injection and acceleration. Those experiments either focus on high charge or small emittance. They provide important insights towards future experiments on a pure accelerator module and define the state of the art. At some point experiments on a high charge, plasma accelerator-only module will be required. High charge and high quality are the priority in this R&D objective with lower priority given to emittance.

Single stage LWFA injection and acceleration of electrons deliver sub-nC charge bunches with peak currents exceeding 10 kA in the sub GeV energy range, benefiting from the availability of > 3 J energy laser pulses with pulse duration < 30 fs on target. Various electron injection schemes are known to influence beam quality (6D phase space density) and charge. The state-of-the-art is the generation of bunches with 5 pC/MeV/mrad optimised for driving light sources or hybrid acceleration plasma stages. A systematic, multi-center based investigation of the coupling of parameters and injection techniques and their physics-based limits is lacking. Investigations that address this absence have to be closely accompanied by numerical studies and novel machine learning based concepts for optimisation.

Additionally, still based on a compact cm-scale setup, the recently established hybrid plasma acceleration scheme offers independent optimisation options. In this scheme a high current LWFA drive beam drives an independent yet spatially close PWFA stage. As both stages operate with independent plasma densities that can be individually optimised for current and quality a multitude of cold injection schemes can be realised in the PWFA stage. This scheme also promises improved emittance after the PWFA stage. The hybrid schemes are currently investigated under cross-center defined conditions in the Hybrid collaboration (HZDR-LMU-LOA-Strathclyde-DESY). The collaboration is based on internal funding of the partners. This collaboration thus offers an optimal ground for the systematic study required to investigate the fundamental limits of beam quality in single stage plasma accelerators optimised for high bunch charge. This study will require additional resources listed in the aspirational plan.

Various injection concepts in LWFA or hybrid LWFA-PWFA aimed at generating high charge will be studied numerically first, followed by experimental demonstrations carried out at several LWFA laser labs (HZDR, LMU, Strathclyde, DESY, CNRS, CEA, Oxford, Lund, etc.). The goal of theoretical studies will be to identify mechanisms and parameter ranges to achieve nC-class charge (> 0.5 nC) and sub-micrometer normalised emittance (< 1 µm); experimental demonstrations of feasibility will subsequently be carried out with existing facilities, for example those listed above.

4.6.5.3 Stable low-emittance electron source

We will need to address the challenge of generating an appropriate electron bunch for the collider, that simultaneously delivers nC charge, 100 nm normalised emittance, few permille energy spread and few fs length electron bunches at 15 kHz. While charge has been prioritised in the previous deliverable, this deliverable aims at demonstrating 100 nm scale transverse normalised emittance with ultra-short bunch length. The low emittance electron beam for an advanced collider could be provided either from conventional electron sources or plasma sources. As a conventional source of this type does not exist today (and will probably involve multi-stage bunch compression and damping schemes), a plasma source R&D path is included in our aspirational plan. The first intermediate steps for a low-emittance electron source are to reach a normalised slice emittance of 100 nm at a charge in the 10–100 pC range. The work shall demonstrate the advantage in compactness compared to conventional setups (including damping rings and compressors), as well as scalability of this source to the required high repetition frequency. Also, the stability of the injector shall be qualified and compared to tolerances in a collider setup. Experimental priorities differ from the high charge goal as addressed in the previous topic. It is felt important that both priorities are pursued in parallel.

4.6.6 R&D objectives in ongoing projects of high relevance for particle physics

The field of plasma and laser accelerators in Europe has received significant funding from other science fields in which first applications are expected. Those applications are mainly targeted at lower energy or other parameter regimes. However, those ongoing developments are drivers of progress and will demonstrate important features of advanced accelerators. Conversely, major experiments are ongoing in the US, funded mainly by particle physics and planning for several ground-breaking deliverables in the next decade.

4.6.7 Sustainability

The United Nations has defined seventeen interlinked Sustainable Development Goals (SDG) that are intended to be achieved by the year 2030 [119]. The SDG were developed as a "blueprint to achieve a better and more sustainable future for all" [120]. In the following, we outline how we are planning to align the proposed research with these goals. In particular, relevant work pertaining to the following goals is envisioned:

SDG 3: Good health and well-being – Particle accelerators are ubiquitous tools in medicine. Developing compact accelerators producing particle bunches and radiation bursts for medical applications could enable a wealth of opportunities. This includes cancer therapy (e^- and p^+ flash therapy) and phase contrast X-ray imaging for medical diagnostics. Instruments based on compact acceleration technologies could in the long term become accessible to patients with modest financial resources, and potentially allow off-grid applications.

SDG 4: Quality education – Strong links between the research laboratories and universities ensure that students have access to education that is based on the latest research, and that will allow them to make meaningful contributions to the field. Education in university courses and summer schools is complemented by internship programmes at national laboratories, where students can gain first-hand experience in novel accelerating techniques.

SDG 5: Gender equality – We are aiming at improving the gender balance in our research groups as outlined in Section 4.9.4. An improved diversity has many advantages, including increased innovation [121].

SDG 10: Reduced inequalities – Applications of novel accelerators may include the generation of radiation pulses from the terahertz to the X-ray regime with unique properties (ultra-short, ultra-bright), which could enable a wealth of new scientific results. Compact and more cost-effective accelerators could become accessible to university groups with modest space and financial resources. This will enable the construction of a distributed network of facilities that provide localised access to research infrastructures. This reduces the need for CO_2-intensive travel by enabling experiments to be performed at local facilities and contributes to an innovative and green Europe.

SDG 12: Responsible consumption and production – The use of natural resources (ground, steel, concrete, cables, ...) for construction of the research infrastructure could strongly be reduced by the significantly smaller length and transverse size of novel accelerator technologies.

SDG 13: Climate action – The energy efficiency of particle accelerators is a key aspect of research in high-gradient plasma and laser accelerators. Solid state lasers reach excellent energy efficiencies of up to 50%. The efficient transfer of the energy from the plasma wake to the particle beam is at the core of the studies outlined in Section 4.6.4.2. The use of permanent magnets and the effect of the focusing forces in the plasma will further contribute to reducing the need for magnet power supplies. As a result, the electricity consumption and the operational CO_2-footprint of the research facility will be minimised.

In summary, the CO_2 footprint and sustainability of any proposed particle physics collider will be major criteria for future decisions. High gradient accelerators have an advantage due to their more compact size, reduced use of materials and reduced CO_2 footprint in construction. However, electricity consumption during operation only depends on the average beam power and the efficiency of the acceleration process (wall plug to driver to collider beam). Plasma and dielectric acceleration schemes still need to demonstrate the required efficiency. For beam-driven plasma accelerators the efficiency for producing the driver beams is similar to existing RF accelerators (about 60%) and can be considered as proven. On the other side the efficiency of operational high peak power lasers (Ti:Sa) for laser plasma accelerators needs to be increased by orders of magnitude. The efficiency of the total power transfer from the drive pulse to the collider beam must reach 20% to be competitive with the CLIC scheme. This remains to be proven. This report defines the R&D goal in the minimal plan to show 40% transfer efficiency for the beam-driven plasma accelerator (to be compared to 20% in CLIC), see Section 4.6.4.2. If this can be achieved then electrical power consumption of a plasma-based collider could in principle be half to that of CLIC, depending also on achievable bunch charge (R&D goal in itself). For the PWFA parameters in Table 4.1 about 200 MW would be required to accelerate two beams to 1 TeV beam energy (2 TeV center-of-mass) with an overall efficiency of 24% (Acceleration only. Wall plug to beam driver: 60%. Beam driver to collider beam: 40%). It is noted that those are R&D goals and not yet achieved. Required R&D work for laser driven plasma accelerators must focus on the development of energy efficient, high peak power lasers, advancing their efficiency by orders of magnitude.

4.7 Delivery plan

4.7.1 Summary delivery plan and resources

The proposed work on plasma and laser accelerators shall be implemented and delivered in a three pillar approach, as visualised in Fig. 4.1. A feasibility and pre-CDR study will investigate the potential of plasma and laser accelerators for particle physics. A second pillar relies on technical demonstrations in experiments aimed at particle physics. A third pillar connects to the work on novel accelerators in other science fields and for other applications.

The delivery plan defines a minimal plan that consists of seven work packages and will achieve nine deliverables by end of 2025. This plan requires additional financial resources for 147 FTEy and 3.15 MCHF of investment. Additional in-kind contributions will be provided and are specified. The minimal plan relates to work and particle physics relevant milestones in 12 ongoing projects and facilities. Beyond the minimal plan, the expert panel has identified four additional high priority R&D activities into an aspirational plan. The aspirational plan would require additional resources for 147 FTEy and 35.5 MCHF of investment, beyond the minimal plan. We provide suggestions on organisational aspects in this report. Work package leaders and institutional participation shall be determined in a project setup phase. We note that adequate facilities, sufficient critical mass and expertise has been considered and are available for the proposed work topics.

4.7.2 Minimal plan

Given the status of the field, a coordinated feasiblity and pre-CDR study is defined as the highest priority. The proposed study will investigate the detailed case studies defined in Section 4.6.3 in a mostly theoretical and simulation-based setup. The proposed advanced accelerator methods (LWFA, PWFA and DLA/THz) will be simulated for the same case studies. In addition, several ideas at an early stage, e.g. for positron acceleration and staging of many accelerators, will be developed in design and simulation work to provide reliable predictions of the achievable system performance.

The minimal plan includes four experimental milestones, explained in technical detail in Section 4.6.4, and aim to present technical progress by the next European strategy update in 2025, and to foster collaboration with the researchers in the field. These four highest priority milestones have been selected by the expert panel out of 56 technical milestones, proposed by the community through townhall meetings.

4.7.2.1 Work packages and tasks in the minimal plan

The work shall be organised in seven work packages, as listed in Table 4.4.

4.7.2.2 Deliverables in the minimal plan

The work packages shall provide deliverables, as listed in Table 4.5. The experimental milestones were selected due to their immediate relevance for high energy physics. In particular, we note that we lack sufficient scientific studies and data to exclude the applicability of any of the novel accelerating technologies for high energy physics at this point in time.

Table 4.4: Work packages and tasks in the minimal plan.

WP	Task	Short description	Invest Personnel
COOR		Coordination Plasma and Laser Accelerators for Particle Physics	—
FEAS		Feasibility and pre-CDR Study on Plasma and Laser Accelerators for Particle Physics	300 kCHF 75 FTEy
	FEAS.1	Coordination	
	FEAS.2	Plasma Theory and Numerical Tools	
	FEAS.3	Accelerator Design, Layout and Costing	
	FEAS.4	Electron Beam Performance Reach of Advanced Technologies (Simulation Results - Comparisons)	
	FEAS.5	Positron Beam Performance Reach of Advanced Technologies (Simulation Results - Comparisons)	
	FEAS.6	Spin Polarisation Reach with Advanced Accelerators	
	FEAS.7	Collider Interaction Point Issues and Opportunities with Advanced Accelerators	
	FEAS.8	Reach in Yearly Integrated Luminosity with Advanced Accelerators	
	FEAS.9	Intermediate steps, early particle physics experiments and test facilities	
	FEAS.10	Study WG: Particle Physics with Advanced Accelerators	
HRRP		Experimental demonstration: High-Repetition Rate Plasma Accelerator Module	1200 kCHF 30 FTEy
HEFP		Experimental demonstration: High-Efficiency, Electron-Driven Plasma Accelerator Module with High beam Quality	800 kCHF 10 FTEy
DLTA		Experimental demonstration: Scaling of DLA/THz Accelerators	500 kCHF 16 FTEy
SPIN		Experimental demonstration: Spin-Polarised Beams in Plasma Accelerators	350 kCHF 16 FTEy
LIAI		Liaison to Ongoing Advanced Accelerator Projects, Facilities, Other Science Fields	—

4.7.2.3 *Resources for the minimal plan*

Particle physics-focused R&D on plasma and laser accelerators will require significant funding. It will profit strongly from facilities and groups that have been set up over the recent years in Europe, many funded from other science fields. However, the existing groups have fixed deliverables and cannot absorb the additional work load arising from particle physics focused R&D. The required additional resources are summarised in Table 4.6 and Fig. 4.12, also listing in-kind support and committed funds. The needs of the minimal plan are on top of what the individual facilities and ongoing projects have as approved budget or will request in the future to their funding institutes. The committed funds relate to ongoing investments in European facilities and projects. The proposed particle physics-oriented R&D projects will benefit from these investments, enabling an excellent return-to-cost ratio.

In-kind contributions should ensure coordination of WP COOR (coordination of plasma and laser accelerators for particle physics) and WP LIAI (liaison to other science fields). The host lab for the feasibility and pre-CDR study should provide resources for overall coordination (WP FEAS.1) of this

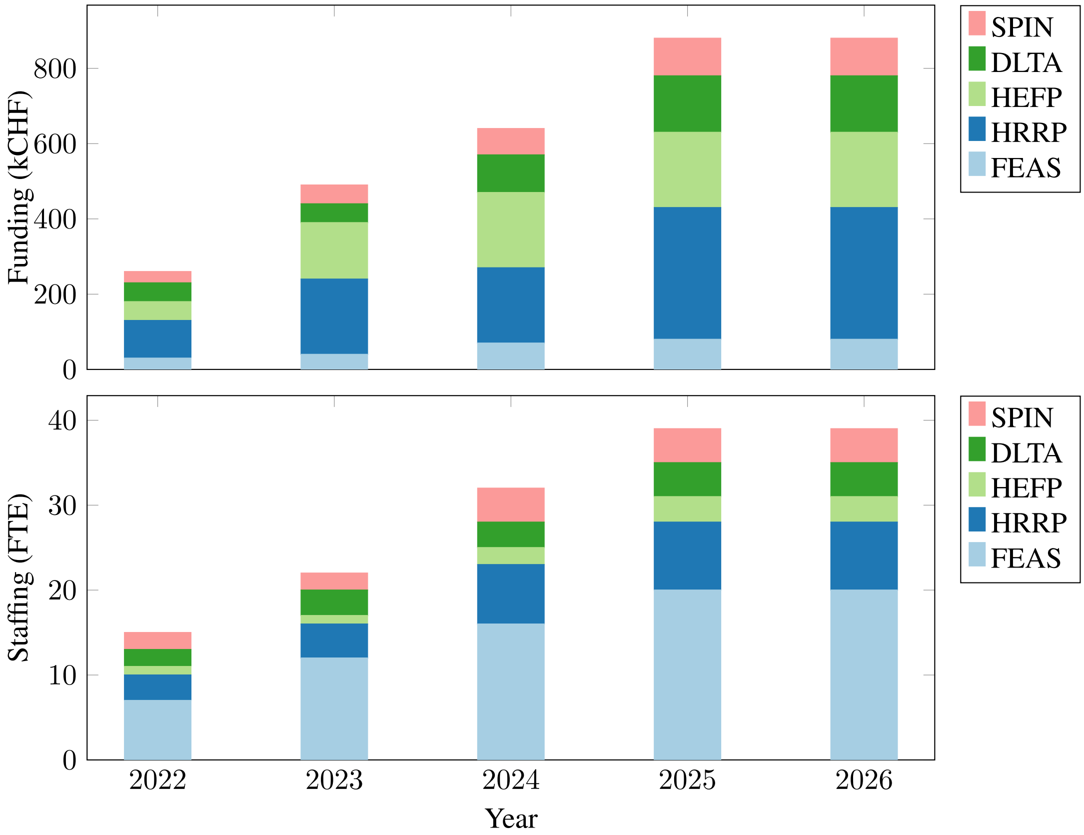

Fig. 4.12: Resource-loaded schedule for the minimal plan.

important theoretical and simulation effort.

We note that within the minimal plan a feasibility and pre-CDR study (WP FEAS) is of highest priority and should be fully implemented under any funding scenario.

4.7.2.4 Facilities with adequate infrastructure for work packages HRRP, HEFP, DLTA and SPIN

The work packages HRRP, HEFP, DLTA and SPIN address important technical deliverables as part of the minimal plan. As written before, the feasibility of those deliverables has been assessed by checking that adequate facilities (see Table 4.7), critical mass of groups and expertise are available to deliver on time and on budget. This shall not preempt a proper project setup phase that invites additional groups and facilities to join the required work.

4.7.2.5 Notes on simulation requirements

The proposed study will be largely based on theoretical and numerical explorations. Emittance preservation in a plasma accelerator is possible by matching the witness bunch transverse size to its emittance in the plasma focusing force. The main bottle-neck for these simulations comes, precisely, from the need to accurately resolve the witness transverse profile. Hence, fully self-consistent three-dimensional simulations of a single 15 GeV stage of 10 nm emittance witness beams are probably not possible today in practice. It then becomes important to focus on reduced models (e.g. quasi-static, boosted frames), reduced dimensions (e.g. 2D) and other approximations, e.g. reduced beam propagation models [122] to perform those simulations. Modeling a single plasma stage up to 15 GeV, considering a witness bunch with 10 nm normalised emittance, and in 2D, requires $\sim$ 5 million core-hours. These requirements can be substantially relaxed by considering a 100 nm normalised emittance witness bunch. In that case, simulations would take less than a thousand core hours, which potentially enables modeling of several consecutive stages, for example.

Key physics aspects can also be investigated by focusing on specific sections of the plasma to reduce computational costs. Consider emittance growth in plasma-vacuum transitions, for instance. Here, simulations could be setup to focus on the plasma-vacuum transition only. Other approximations could rely on modelling dynamics under prescribed fields. In summary, modeling specific sections of a single collider stage, and even coupling between two full collider stages appear possible, at least under certain approximations.

The simulation of DLA and THz accelerators appear feasible as well, because the accelerating structures are stationary. Certain aspects, however, merit special attention: the simulation of many million cells, the sub-nanometer emittance growth budget and the effect of surface roughness and fabrication tolerances.

4.7.2.6 Organisational aspects

We envisage that the minimal plan and its work packages will be organised similar to an EU project with a steering committee, a governing board and regular reporting of scientific progress and funding. The deliverables and work packages defined above are supported by a large number of facilities and groups, that provide the necessary infrastructure, critical mass and expertise for executing the work within the foreseen resource envelope and timeline. Work package leaders and institutional involvements are not detailed here in order to not preempt a proper project setup phase with open calls for participation and a negotiation phase. The most suited and interested groups and facilities shall be selected in the process, also taking into account the level of in-kind contributions. Importantly, the project shall be coordinated and integrated with US and Asian effort, to the maximum possible extent.

The feasibility and pre-CDR study (Work Package FEAS) will need a host lab from particle physics that acts as project coordinator and as central hub. As indicated in the work package and task list, the minimal plan requires a physics case study group and support from particle physicists.

4.7.2.7 Integration and outreach: milestones at existing facilities and ongoing projects

The field of high-gradient plasma and laser accelerators consists of multiple groups at universities and research laboratories, which perform research with different applications in mind, funded by various funding sources. The minimal plan connects to those activities through its Work Package LIAI, addressing the goals of integration and outreach. Below we list some of the major technical challenges identified in Section 4.6 and ongoing projects and facilities with relevant milestones in this R&D area.

In the following, we list major milestones (only if they are relevant for particle physics developments) for several existing projects and facilities in some more detail. They connect to Work Package LIAI of the minimal plan. It is noted that those projects and facilities are funded from other fields and sources. The US efforts are funded mainly by particle physics inside DOE. We note the importance of those milestones for the progress of the field and for demonstrating several feasibility issues for particle physics usages. The expert panel therefore recommends full funding of those projects and facilities.

Table 4.5: Deliverables in the minimal plan.

	Due	Title	Description
DEL2.1	6/24	Report: Electron High Energy Case Study	Plasma accelerator design from 175 to 190 GeV, including: full lattice; in/out-coupling; all magnetic elements; correctors; diagnostics; collective effects; synchrotron radiation effects; estimate of realistic performance; estimate of realistic footprint; estimate of realistic benefits in cost and size; and understanding of scaling with beam energy for different technologies (laser-driven, electron-driven, proton-driven, DLA/THz).
DEL2.2	6/24	Report: Physics Case of an Advanced Collider	Report from common study group with particle physicists on physics cases of interest at the energy frontier (e^+e^- collider, $\gamma\gamma$) and at lower beam energies (e^-p collider, dark matter search, …).
DEL2.3	6/25	Report: Positron High Energy Case Study	Equivalent to 2024 report on electron accelerator (see above).
DEL2.4	6/25	Report: Low Energy Study Cases for Electrons and Positrons	Assessment of the low energy regime around 15-50 GeV including: achievable performance; foot print and cost; schemes and designs for first particle physics experiments with novel accelerators; needed R&D demonstration topics for low energy design and needed test facilities. Includes studies on a low energy, high charge plasma injector.
DEL2.5	12/25	Pre-CDR and Collider Feasibility Report	Input for decision point of European strategy, bringing together work/reports achieved (see earlier) and complemented by report on Technical Readiness Levels (TRL report) for collider components and systems. Includes: comparison of performance and readiness for different technologies (laser, electron, proton driven plasma, DLA/THz) for a possible focus on the most promising path for particle physics; design of a staging experiment; report on intermediate steps and need for a dedicated facility and project plan for a CDR of an advanced collider.
DEL3.1	12/25	High-Repetition Rate Plasma Accelerator Module	Demonstrates: at least 1 kHz characterised; robust lifetime ($> 10^9$ shots); only the plasma cell; without full repetition rate beam test but including cooling and power handling assessment. Long-term goal: 15 kHz repetition rate.
DEL4.1	12/25	High-Efficiency, Electron-Driven Plasma Accelerator Module with High Beam Quality	Beam demonstration of high efficiency PWFA module. 40% transfer efficiency from driver beam stored energy to witness beam stored energy
DEL5.1	12/25	Scaling of DLA/THz Accelerators	Staged dielectric laser or THz accelerator with 10 MeV energy gain, transverse and longitudinal focusing and at least two stages. Long-term goal: Massively scale-able design printed on a chip.
DEL6.1	12/25	Spin-Polarised Beams in Plasma Accelerators	Demonstration of polarised electron beams from plasma with 10–20% polarisation fraction. Long-term goal: Polarisation 85%.

Table 4.6: Integrated resources for the minimal plan. Committed funds in the LIAI work package relate to funding in relevant ongoing projects and facilities (see Tables 4.9, 4.10 and 4.11)

WP	Task integrated resources			In-kind contributions	Committed funds
	FTEy	MCHF	G-core-h	FTEy	MCHF
COOR	0	0	0	2.5	0
FEAS	75	0.3	1.6	75	0
HRRP	30	1.2	0	3	0
HEFP	10	0.8	0	1	0
DLTA	16	0.5	0	2	0
SPIN	16	0.35	0	2	0
LIAI	0	0	0	2.5	∼280
Sum	*147*	*3.15*	*1.6*	*88*	*∼280*

Table 4.7: Facilities for work packages HRRP, HEFP, DLTA and SPIN. Non-European facilities are listed in *italics.*

Work Package	Facilities
HRRP	DESY, Oxford, INFN-LNF, CERN, *LBNL*, ...
HEFP	INFN-LNF, DESY, *SLAC*, ...
DLTA	PSI, FAU Erlangen, University Hamburg, DESY, *Stanford, UCLA*, ... (ACHIP Laboratories), Cockcroft, ...
SPIN	DESY, FZJ, ...

Table 4.8: Technical challenges addressed in ongoing projects and facilities.

Technical Challenge	Facility with Relevant Milestones
Efficiency and small energy spread at increased bunch charges	*FACET-II,* FLASHForward, SPARC-Lab, ACHIP Laboratories, BELLA, HZDR, CALA, APOLLON, PALLAS
Preservation of small beam emittances	AWAKE, SPARC-Lab, FACET-II, BELLA, ACHIP Laboratories, FLASHForward, SCAPA, CLARA
Staging of multiple advanced accelerator modules	*BELLA,* CLARA, AWAKE, PETRA-IV Injector, EuPRAXIA
High repetition rate, heat load, stability and availability	ACHIP Laboratories, KALDERA, EuPRAXIA, *BELLA,* FLASHForward, PETRA-IV Injector
Positrons	*FACET-II,* Queens University

Table 4.9: International programmes and facilities. Funding line states the present funding situation and is not a funding request included in the minimal plan.

AWAKE (CERN)	
External funding	26 MCHF (CERN) + 11.4 MCHF (in-kind collab.) Cost and schedule review end of 2021
Milestones for 2025	Demonstrate the seeding of the proton bunch self-modulation process with an electron bunch. Optimise the process of generation of wakefields using a plasma density step to maintain large wakefields at the GV/m level and accelerate electrons to multi-GeV energies.
Milestones envisioned beyond 2025	Demonstrate the acceleration of an electron witness bunch to 10 GeV in 10 m with control of the incoming normalised emittance at the 10 µm level and percent-level energy spread. Develop scalable plasma sources 50–100 m long, and demonstrate acceleration in a scalable plasma source (helicon or discharge) to 50–100 GeV energies.
Access modalities	Collaboration-based access. In operation.
EuPRAXIA (European ESFRI project)	
External funding	569 M€ (110 M€ secured)
Milestones for 2025	Status report TDR for plasma electron accelerator, FEL and positron user facility. Interim report from EU funded preparatory phase project (laser-based site, legal model, financial model, access rules, innovation model).
Milestones envisioned beyond 2025	2029: Electron beam-driven EuPRAXIA FEL at Frascati in operation with users. 2030: EuPRAXIA laser-driven facility operates at several GeV with users. EuPRAXIA laser at 800 nm wavelength (few kW) [3]: pulse energy 50–100 J, repetition rate 20–100 Hz, pulse duration 50–60 fs, energy stability (RMS) 0.6–1%, pointing stability (RMS) 0.1 µrad. Two stage, 5 GeV HQ e- bunch, FEL operation.
Access modalities	Proposal driven and excellence based access to the EuPRAXIA user facility under European rules and standards. In construction at Frascati site.
International ACHIP Programme: ARIES (DESY), FAU Erlangen, Pegasus (UCLA), Stanford, SwissFEL (PSI)	
External funding	ACHIP funding (4 M$/year) from the Gordon and Betty Moore Foundation will end in 2022. Additional funding has been granted to individual university groups.
Milestones for 2025	Control of transverse & longitudinal phase space in dielectric laser accelerators; Staging of multiple DLA/THz structures, preserving normalised emittance; Acceleration high repetition-rate (> 100 GHz) bunch trains (10 bunches at 10 ps spacing, 10 pC/bunch). 10 MW, 100 GHz gyrotron source at > 50% efficiency; 100 MW, 400 GHz, laser-THz source. Inverse design of dielectric structure on a chip with efficient laser coupling.
Milestones envisioned beyond 2025	100 MeV energy gain in stageable structures; mm-wave structures manufactured for 1 metre of (staged) acceleration
Access modalities	National labs are typically very open to international collaborations. Some of the facilities are part of the ARIES trans-national access programme. Access to university groups is typically decided on a case-to-case basis. In operation.

Table 4.10: National programmes and facilities in Europe. Funding line states the present funding situation and is not a funding request included in the minimal plan.

APOLLON (France)	
External funding	60–100 M€
Milestones for 2025	Feasibility study of LWFA electron source at 100 pC level; tunable energy range up to GeV; physics study of positron source from LWFA electrons
Milestones envisioned beyond 2025	None scheduled. There is potential for demonstration of 10 GeV LWF acceleration module, and 2 stage multi-GeV experiment; effective implementation is limited by insufficient laser beam availability for this type of programme.
Access modalities	Proposal-driven access. In operation.
CLARA (UK)	
External funding	£33.4 M (£27.9 M secured)
Milestones for 2025	2023: CLARA Phase 2 + FEBE beamline construction completed. 2024: Beam commissioning and first user access period completed. 2024–2027: user-led science programme with programmatic access: 1) plasma acceleration (beam-driven wakefield, external injection laser-driven wakefield) and structure wakefield acceleration; 2) post-acceleration beam capture and 6D phase-space characterisation; 3) tailored multi-bunch delivery to FEBE for beam-driven acceleration; 4) beam-driven acceleration at 400 Hz.
Milestones envisioned beyond 2025	2027+: Demonstration of plasma-driven FEL on FEBE beamline.
Access modalities	Access by competitive application judged by a beam access panel. Trans-national access will be supported. In construction.
FLASHForward (DESY, Germany)	
Milestones for 2025	Single, beam-driven plasma-booster stage with beam-quaity preservation at 0.1% energy spread, 2 µm norm. emittance and 40% overall efficiency at the 1 to 2 GeV energy level and 100 pC witness charge (FEL quality); exploration of plasma physics for the kHz to GHz repetition rate regime; development of high-average power plasma sources; active feedback / feedforward stabilisation (including machine learning techniques)
Milestones envisioned beyond 2025	Booster stage average power extended to 10 kW level drive beam in ILC-like bunch pattern; application as FEL booster module for FLASH to extend photon science reach
Access modalities	Access to FLASHForward may be available through collaboration agreements. In operation.
KALDERA (DESY, Germany)	
Milestones for 2025	kW average power drive laser for LWFA; application-ready FEL-quality LWFA injector: GeV-scale electron beam energy, sub-percent energy spread; active feedback/feedforward stabilisation (including machine learning techniques)
Access modalities	Access to KALDERA may be available through collaboration agreements. In construction.

Table 4.11: National programmes and facilities in Europe (continued). Funding line states the present funding situation and is not a funding request included in the minimal plan.

PALLAS (France)	
External funding	5.5 M€ (3.12 M€ secured) for phase 1
Milestones for 2025	High quality laser-plasma electron injector for staging with 10 Hz, 10–50 pC, 150–250 MeV, $\leq$ 1 µm emittance, including advanced laser control, laser driver pointing stabilisation to $<$ 1 µrad on 0–380 Hz BW, and percent control of critical laser parameters; long operation test; high charge optimisation test; beam active feeback and optimisation (including machine learning techniques), conceptual design study for laser driven plasma acceleration stage > 1 GeV.
Milestones envisioned beyond 2025	GeV-level laser driven plasma stage module injection at 1–10 Hz (depending on budget possibilities). Note this depends on large investment (building extension laser driver and plasma acceleration stage module)
Access modalities	The beam time availability should be about 20 weeks per year of beam time, if university and institute support on operating cost is maintained. Open to collaborative participation with memorandum of understanding. In construction.
Plasma Injector for PETRA IV (DESY, Germany)	
Milestones envisioned beyond 2025	6 GeV LWFA PETRA-IV injector with sub-per-mille energy bandwidth-jitter-envelope, 24/7 operation, and up to 3.2 nC/s charge delivery
Access modalities	Access to the Plasma Injector for PETRA IV may be available through collaboration agreements. In design.
SPARC-LAB (Italy)	
External funding	7 M€ (6 M€ secured)
Milestones for 2025	High efficiency, electron-driven plasma accelerator module driven by a train of four drivers, with ramped bunch charge, total charge up to 300 pC, GV/m accelerating gradient and fs scale synchronisation. High repetition rate plasma accelerator module with off-line capillary discharge/vacuum system characterisation at kHz repetition rate. High charge, high quality plasma accelerator module, driven by laser pulses. LWFA module with external electron bunch injection suitable to test, as well as staging configuration with fs scale synchronisation.
Milestones envisioned beyond 2025	To be defined in the framework of EuPRAXIA@SPARC-LAB collaboration
Access modalities	Collaboration-based access. In operation.

Table 4.12: National facilities in the US. Funding line states the present funding situation and is not a funding request included in the minimal plan.

BELLA (LBNL, United States)	
Milestones for 2025	Multi-GeV electron staging of two LWFA modules with high coupling efficiency and emittance preservation; 10 GeV high-quality electron beams from a single stage; high brightness electron beams from laser-triggered injection; active feedback stabilisation of LWFA with machine learning/AI techniques; high efficiency multi-kHz lasers to the few hundred mJ level; studies of positron capture and acceleration in plasmas; demonstration of LWFA-driven light sources (XUV FEL, gamma-ray Thomson source); conceptual design studies of a plasma-based colliders.
Milestones envisioned beyond 2025	High efficiency multi-kHz lasers at the J level and beyond; operation of a user facility based on multi-kHz LWFA; R&D to further improve electron beam quality and stability from LWFAs; positron acceleration and staging in plasmas; science experiments using LWFA-driven sources of particles and photons; integrated design studies of plasma collider.
Access modalities	Access to BELLA facilities is available either through collaborative use arrangements, or via the LaserNetUS facility network. In operation.
FACET-II (SLAC, United States)	
Milestones for 2025	Single plasma stage with combined parameters: 10 GeV energy gain of witness bunch in one meter plasma, charge > 100 pC, normalised emittance preservation at few micron-rad level, percent level energy spread and more than 30% overall energy transfer from drive to witness bunch; Development of ultra-high brightness plasma-based injector with tens of nm emittance as proxy for collider level emittance beams; characterise mechanisms for emittance growth in PWFA and demonstrate mitigations; measurement of plasma target recovery time to inform maximum repetition rate in collider designs; development of single shot ML/AI virtual diagnostics for extreme beams; construction of facility upgrade to deliver 10 GeV positrons and electrons to experimental area.
Milestones envisioned beyond 2025	Commissioning of facility upgrades that deliver 10 GeV electrons and positrons to the experimental area within one plasma period for studies of electron-driven plasma acceleration of positrons.
Access modalities	National User Facility with proposal driven experimental programmes and external peer review by FACET-II Program Advisory Committee. In commissioning.

Table 4.13: Aspirational plan.

WP	Topic	Needed funding	Needed work-force	Milestones to be achieved by 2025	Far term goal
SCPS	Scalable plasma source	3 MCHF	17 FTEy	Several metres long prototype with required plasma density and stability	Ten to hundreds of metres of plasma source
HCPL	High-charge, high-quality plasma accelerator module driven by laser pulses	6.5 MCHF	30 FTEy	Detailed specification of the parameters for a self-consistent demo remain to be finalised	Accelerator module with 1 nC high quality beam (outcome feasibility study)
SESP	Stable low-emittance electron source	4 MCHF	20 FTEy	Electron beam extracted with 50–250 MeV, 10–100 Hz, sub-micron emittance, 30–100 pC	15 kHz, > 500 pC, < 100 nm emittance, fs bunch length, sub % energy spread
HRLA	High-rep rate, high peak power laser	22 MCHF	80 FTEy	Demonstration of kW average power (e.g. 100 Hz, 10 J, < 100 fs or 1 kHz, 1 J , < 100 fs or another combination/scheme) Ti:sapp laser pulse	15 kHz rep rate, 100 Tera-Watt, 30% wall plug efficiency
Sum		35.5 MCHF	147 FTEy		

4.7.3 Aspirational plan

Particle physics requirements on luminosity impose very stringent challenges for high energy, repetition rate, bunch charge and power efficiency. While some issues are addressed already in the minimal plan and at ongoing projects and facilities, in particular in the US, additional projects would ensure the required particle physics focus and fast progress towards demonstrating collider feasibility in experiments. The aspirational plan lists four strongly recommended and highly important R&D tasks in addition to the minimal plan. Those additional projects, which are described in details in Section 4.6.5, have been selected out of the 56 proposed activities. The scalable plasma source offers a path to longer acceleration lengths, longer stages, higher beam energy and first particle physics experiments. The high charge and high quality project establishes a focused work effort on understanding the highest possible bunch charge at required low emittance, a crucial input to the achievable instantaneous luminosity. The stable electron source investigates a possible path to 15 kHz injectors, while the laser work package in the aspirational plan develops laser technology for high repetition rate and acceptable durability and lifetime.

Executing the aspirational plan in addition to the minimal plan would ensure that additional collider-relevant aspects of the research are covered and would allow a maximum rate of progress.

It is noted that the expert panel considers those activities of very high priority and endorses them fully. Required additional resources for the aspirational plan amount to a total of 35.5 MCHF and 147 FTE-years. The components of the aspirational plan are listed in Table 4.13. It is noted that depending on where the work is done, significant resources might already be available for the laser development. Further analysis is required to identify the incremental budget from particle physics to address collider needs (e.g. the 15 kHz repetition rate with sufficient laser component lifetime and power efficiency).

4.8 Facilities, demonstrators and infrastructures

4.8.1 Accelerator R&D facilities

The ongoing R&D for advanced, high-gradient accelerators is being performed at accelerator or laser facilities that are located at research centers and universities. Access possibilities range from limited access, through collaboration-based access models to user facility operation with excellence-based access after committee review. We provide a selected list, aimed at facilities or projects with particular importance for high energy physics related research:

4.8.1.1 AWAKE (CERN, Europe)

The Advanced WAKEfield Experiment, AWAKE, at CERN is the only facility in the world using proton beams to drive plasma wakefields for electron acceleration. AWAKE is an international collaboration, with 23 member institutes world-wide and aims to bring the R&D development of proton driven plasma wakefield acceleration to a point where particle physics applications can be proposed and realised. AWAKE at CERN profits from the opportunity of being embedded in the high-energy physics laboratory, enabling combination of the expertise of CERN's high energy physics and accelerator scientists with plasma wakefield acceleration specialists.
During its first run period (2016–2018) AWAKE demonstrated for the first time strong wakefields generated by a 400 GeV/c SPS proton bunch in a 10 m long Rb plasma as well as the acceleration of externally injected electrons to multi-GeV energy levels in the proton driven plasma wakefields.
AWAKE Run 2 has started in 2021 and will run for several years. Four phases are planned, with the goal of demonstrating the acceleration of electrons to several GeV while preserving the beam quality as well as the scalability of the experiment.

4.8.1.2 EuPRAXIA—European Plasma Research Accelerator with Excellence in Applications (European ESFRI project)

The EuPRAXIA consortium formed in 2015 to design and construct a distributed European Plasma Accelerator facility with excellence in applications. A conceptual design report was completed at the end of 2019 [10] and the project was placed on the ESFRI roadmap in 2021 after a vigorous application and selection process [123], involving support of several European governments. Presently the consortium includes 50 organisations from fifteen countries as Members and Observers. EuPRAXIA with its large-scale consortium will advance critical accelerator R&D on plasma accelerators in a coordinated, European approach. It will continue to bring together existing European infrastructures in this domain, establish the first pilot applications for plasma accelerators, strengthen the links to the important European laser industry, and build two scientific flagship projects for start of operation by the end of the 2020s. One construction site will be in the metropolitan area of Rome in Italy and will deliver critical and much-needed photon science capabilities for research into materials, bacteria, viruses and health. The laser-driven plasma accelerator site of EuPRAXIA will be decided in 2023 among various candidates. The high-tech EuPRAXIA innovation project can thus drive scientific advance in Europe with medium electron beam energies and can contribute to a sustainable economical development with highly qualified jobs and possible spin-off companies, while being a critical technological stepping stone to future particle physics colliders based on plasma acceleration.

4.8.1.3 SPARC-LAB (Italy)

SPARC-LAB (Sources for Plasma Accelerators and Radiation Compton with Lasers and Beams) is a test and training facility devoted to advanced accelerator research and development. It was born from the integration of a high brightness photo-injector, able to produce high quality electron beams up to 170 MeV energy with high peak current (>1 kA) and low emittance (<2 μm), and of a high power laser (>200 TW), able to deliver ultra-short laser pulses (<30 fs). A plasma interaction chamber for PWFA experiments, placed at the end of the linac, is fully equipped with diagnostics, both transverse and longitudinal, based on electro-optical sampling and THz radiation, with a H_2 plasma discharge capillary and permanent quadrupole magnets for beam matching in and out of the plasma. At the end of the linac a diagnostics and matching section allows characterisation of the 6D electron beam phase space and matching of the beam to the downstream undulator chain for FEL experiments. During summer 2021 the first demonstration of SASE and Seeded lasing of an FEL driven by a PWFA module was achieved. A second beam line for plasma acceleration experiments in the LWFA configuration with external injection of high quality electron beams will be ready by the end of 2022. The SPARC-LAB test facility is expected to enable LNF in the next five years to establish a solid background in plasma accelerator physics and to train a young generation of scientists to meet all the challenges addressed by the EuPRAXIA@SPARC-LAB project.

4.8.1.4 CLARA (United Kingdom)

The Compact Linear Accelerator for Research and Applications (CLARA) is an ultra-bright electron beam test facility being developed at STFC Daresbury Laboratory. CLARA is a unique facility for user-led experiments across a wide range of disciplines, including advanced and novel accelerator concepts. A dedicated full-energy beam exploitation (FEBE) beamline has been designed and incorporated into the facility allowing user access while the accelerator is running. FEBE incorporates two consecutive large-scale vacuum chambers, beam diagnostics, and functionality for 100 TW laser-electron beam interactions (laser funding being sought). First beam for commissioning on FEBE is expected in 2023.

4.8.1.5 PALLAS (France)

The PALLAS project is aiming to develop 10 Hz, 150–250 MeV, $\geq$ 30 pC, 1 μm, high quality compact laser-plasma injector prototype for staging with stability, control and reliability comparable to a conventional accelerator. The laser plasma injector is designed as a test facility for laser-plasma based technology. The project focuses on the study and implementation of technological solutions to increase the performance of laser-plasma injectors, particularly in terms of repetition rate and stability at an intermediate average power and repetition rate allowing immediate testing with a state of the art available laser driver.

4.8.1.6 KALDERA (DESY, Germany)

KALDERA is DESY's flagship project to develop a laser-plasma accelerator driven by a 100 TW laser at 1 kHz repetition rate. This repetition rate will enable active stabilisation and feedback of key laser parameters, providing a clear path to competitive FEL-quality electron beams of sub-percent energy spread energy stability. Since established modern technologies such as room-temperature or super-conducting RF acceleration operate at repetition rates well above the 100 Hz level, increasing the repetition rate of laser-plasma accelerators is necessary to transform laser-plasma acceleration into a competitive technology. Particle physics applications will benefit in several ways from KALDERA. Although the domain of KALDERA is primarily in photon science, it will demonstrate that plasma acceleration can act as a reliable driver for applications. Furthermore, KALDERA will require developments such as kW-capable targetry, novel diagnostic tools and kHz-ready novel beam optics such as active plasma lenses.

4.8.1.7 FLASHForward (DESY, Germany)

FLASHForward is an electron-beam driven plasma wakefield accelerator, which makes use of the beam from the FLASH soft X-Ray FEL facility. The goal for the accelerator over the next five years is to develop a single, beam-driven plasma-booster stage with longitudinal- and transverse-beam-quality preservation at the level of 0.1% energy spread and 2 μm normalised emittance, respectively. These beams will be accelerated to the 1–2 GeV energy range, and are expected to be of sufficient quality to drive a free-electron laser. Furthermore, a goal of 40% overall energy-transfer efficiency is set. Beyond the timeline of the next European strategy update, the milestones of FLASHForward will be centred around maximising brightness and luminosity. Specifically, the advances in plasma-source technology for operation at high repetition rate, as well as the physical limits characterised through experimentation, will be leveraged to demonstrate a plasma-booster stage with $\mathcal{O}(10\text{ kW})$ drive beam average power accelerated with a bunch pattern suitable for utilisation at a future particle collider.

4.8.1.8 Plasma Injector for PETRA IV (DESY, Germany)

The Plasma Injector for PETRA IV (PIP4) project explores the possibility of realising a compact and cost-effective injector system for the PETRA IV storage ring, based on a LWFA. The challenge for a plasma-based injector is to feed the storage ring at its nominal energy of 6 GeV, at a maximum charge injection rate of 3.2 nC/s during the initial filling. It is anticipated that an LWFA injector reaching 6 GeV and sufficient charge rate within the required energy bandwidth will require a sub-PW-class laser system at > 5 Hz repetition rate, operating over 20 cm long plasma targets with enhanced control over the witness beam injection event and laser-guiding capabilities.

4.8.1.9 ACHIP Laboratories (international programme)

Research on dielectric laser and terahertz acceleration is performed by many relatively small groups at universities and research laboratories, as a relatively small initial investment is necessary for fundamental research on this topic. Many of the groups working on DLA are united in the *Accelerator-on-a-Chip International Program* (ACHIP), funded by the Gordon and Betty Moore Foundation. Additional grants from universities and national governments fund research on THz acceleration, and they will extend research on DLA beyond the ACHIP funding.

4.8.1.10 BELLA (LBNL, United States)

The BELLA (Berkeley Lab Laser Accelerator) Center focuses on the development and application of laser-plasma accelerators (LWFAs) for future plasma based colliders as well as for light sources and other applications. It houses three state of the art laser systems. Commissioned in 2013, the 1 Hz BELLA PW laser recently set an 8 GeV acceleration record in just 20 cm. A second beamline will enable experiments on multi-GeV staging as well as other techniques such as laser formed waveguides and positron acceleration. In 2018, two 100 TW class laser systems were commissioned. The first focuses on a compact gamma ray source via Thomson scattering, with other experiments through LaserNetUS. The second powers a beamline towards an EUV free electron laser. Both support synergistic experiments important to future colliders including advanced injectors, phase space manipulation and beam characterisation. Short pulse fiber laser combining is being developed to provide the average power, repetition rate, and pulse durations required for future drivers of LWFAs.

4.8.1.11 FACET-II (SLAC, United States)

FACET-II is a National User Facility at SLAC National Accelerator Laboratory providing 10 GeV electron beams with µm-rad normalised emittance and peak currents exceeding 100 kA. FACET-II operates as a National User Facility while engaging a broad User community to develop and execute experimental proposals that advance the development of plasma wakefield acceleration aligned with the goals of the 2016 US DOE Advanced Accelerator Development Strategy Report. Phased upgrades to FACET-II are expected to provide high-intensity positron bunches around 2025, a capability unique in the world, to experimentally investigate the optimal technique for high-gradient positron acceleration in plasma.

4.8.1.12 Other facilities

We note that other groups or facilities not mentioned here also contribute to the development of original ideas and closely collaborate with many of the described facilities and projects. Several of them are mentioned and listed under the relevant work topics and deliverables.

4.8.2 Possible advanced accelerator test facility for HEP-specific aspects

At present time the expert panel believes that the immediate focus must be put on a common, coordinated pre-CDR study for high energy physics applications of high-gradient plasma and laser accelerators, as well as R&D on selected technical milestones. For the coming years we will rely on the existing national, European and international facilities for performing the proposed R&D work.

The study will be the theoretical and simulation-based demonstrator of feasibility for an advanced e^+e^- collider with a relevant particle physics case. In its deliverable report, the study will also specify possible new facilities or demonstrator projects needed to make progress towards a collider.

4.9 Collaboration and organisation

4.9.1 Collaborative activities

The field is driven by a rapidly growing, diverse and young community with strong links to universities, research centers and industry. There are growing links to users in the fields of Free Electron Lasers, ultrafast electron diffraction, health and lower energy particle physics experiments. The community has grown together in the EU-funded EuroNNAc network [7], in the ALEGRO activity [8], the AWAKE collaboration [9] and in the EuPRAXIA conceptual design study for a European plasma accelerator facility [10].

It is important to grow links to the High Energy Physics community in parallel. Only with support from HEP can the promise of a more compact and more cost-effective collider be realised on the 30-year time scale, opening up the energy-frontier for particle physics.

4.9.2 Connections to other fields

There are a large number of connections between research in high-gradient plasma and laser accelerators and other fields of research and industry. These connections are yielding fruitful collaborative activities:

Free electron lasers and X-ray science – Free electron lasers and other sources of coherent X-Rays demand very high-brightness beams. As such, scientists have long sought to use electrons from plasma wakefield accelerators for this application. In particular, the short pulse length offers possibilities in time-resolved X-ray studies.

Beam instrumentation and diagnostics – Novel accelerators will require novel diagnostics concepts. A close collaboration with scientists working on instrumentation for free electron lasers is resulting in the development of diagnostics for ultra-short and ultra-small electron beams.

Laser development – Work on laser development for wakefield accelerators should be organised with the following priorities: 1) Delivery by commercial partnership with national laboratories, probably using Ti:sapp based laser technology. 2) Parallel research across possible laser media and technologies carried out at university and national labs for more than five years, with a selection of one or two options to develop to the 10 J, 1 kHz level and taken forward at international collaboration level involving industry. 3) Selection of technology choice for HEP laser driver, developed by international collaboration between industry and national labs.

High-performance computing – Simulation and theory activities, already well developed in plasma-based acceleration physics, should be developed in a coordinated manner with the target to master the design, the commissioning and the operation of a plasma-based accelerator intended for HEP applications. Three aspects should be targeted: a) Beam physics should be managed by a single group with double expertise in plasma acceleration and transport lines, to be able to perfectly master the particle beam from injection to IP; b) Strong collaboration between simulators and experimenters should be established to check consistency between simulations and measured results, not on one operating point but on several ones and also around them; c) Simulation codes should be able to support all the phases of accelerator development, for example by offering rapid-turnaround simulations (envelope approximation) intended for massive optimisations in the design phase, high-precision simulations for describing the most realistic possible the acceleration physics during the operation phase, and an intermediate mode allowing rapid computation of small deviations to ideal configurations. Ultimately, the beam physics team should set up a numerical model (avatar) of the accelerator with which the latter will be operated.

Electron imaging and diffraction – The development of structures that couple a laser field directly to an electron beam is opening new possibilities in electron imaging and ultrafast electron diffraction experiments at attosecond time scales.

Advanced manufacturing – The manufacturing of dielectric laser accelerators is closely linked to the methods used in the semiconductor industry, ranging from electron beam lithography for first prototypes to photolithography in standard MEMS and CMOS processes that are already explored. In addition, there are important applications of free-form manufacturing techniques to building prototypes of plasma cells and terahertz accelerators.

X band high gradient RF structures – A strong link exists in the usage of compact and highly accurate RF structures. For example, X band accelerating structures are used for building compact electron beam drivers, for example in EuPRAXIA and in AWAKE.

Machine learning / artificial intelligence – The field of plasma and laser accelerators is exploring the use of machine learning (ML) and other methods in artificial intelligence (AI). To name only a few, inverse design algorithms are used to design couplers and dielectric structures for acceleration [36] and radiation generation [124]; genetic algorithms are used to apply adaptive feedback [125], and bayesian optimisation is used to optimise a LWFA [126].

4.9.3 Conferences and workshops

The field communicates through the biannual EAAC conference with up to 250 participants. EAAC is a European and EU funded effort of the advanced accelerator community and is one of the world-leading discussion fora. The community presents and discusses results also at accelerator conferences like IPAC, FLS and AAC, as well as at laser conferences.

4.9.4 Training and human resources

Training – To train the next generation of accelerator scientists, the advanced accelerator community has established a close collaboration with universities. Students perform Bachelor's, Master's and PhD theses in accelerator physics, both at their universities, as well as at the laser and accelerator laboratories. Summer student internships give students an additional opportunity to gain some first experience in the field. Education in novel accelerator concepts is taught in courses at universities, as well as in specialised schools. In many cases, the students can use the ECTS credits they earn in these classes for their degree.

Collaboration with industry – A strong connection between the European laser industry and the groups performing research on novel accelerators is driving innovations in pulse length and longitudinal pulse shaping, energy efficiency, the synchronisation of the laser pulses and the generation of terahertz frequencies. The companies are directly involved in the research, they send their scientists into the research groups and they accept internships by the students. This close collaboration benefits both sides, and it gives students an opportunity for employment after they finish their degrees. The universities and research laboratories hold a number of patents relevant to particle acceleration and beam manipulation, which can be licensed if there is an interest. Structure-based dielectric laser and terahertz accelerators have an additional collaboration with manufacturing companies, both in lithography and in three-dimensional free-form manufacturing on the micrometer scale [127].

Communication and outreach – The primary method of communication of our research is in peer-reviewed scientific journals. Additionally, we are supported by the outreach and media groups at the universities and research laboratories in bringing novel accelerator research to the public.

Open access – The scientific results of the proposed work will be published with an open access license, to allow a broad availability of the research. Software developed for the modeling of the beam dynamics will be published as open source software (OSS), and hardware developed in the framework of this programme will be put under an Open Hardware license.

Facility access Facility access is an important aspect of collaboration, especially between research centers and university groups. The access rules are strongly developing towards facilitated access modes and have been included in facility descriptions in Section 4.7.2.7.

Diversity – Diverse teams have demonstrated better performance in innovative tasks so we are aiming to maximise diversity in our teams. While hiring for the proposed projects will be done by the universities and research laboratories, we will make sure that people responsible for hiring students and research associates are aware of this topic, and we will communicate best-practice examples within our community. The field attracts young and brilliant students from all over Europe and the world. We note that the field has several women in leadership positions.

4.10 Conclusion

The field of high-gradient plasma and laser accelerators offers a prospect of facilities with significantly reduced size that may be an alternative path to TeV scale e^+e^- colliders. Though presently at an earlier development stage than the other fields, first facilities in photon and material science are now feasible and are in preparation. These accelerators also offer the prospect of near term, compact and cost-effective particle physics experiments that provide new physics possibilities supporting precision studies and the search for new particles.

The expert panel has defined a long term R&D roadmap towards a compact collider with attractive intermediate experiments and studies. It is expected that a plasma-based collider can only become available for particle physics experiments beyond 2050, given the required feasibility and R&D work described in this report. It is therefore an option for a compact collider facility beyond the timeline of an eventual FCC-hh facility. A delivery plan for the required R&D has been developed and includes work packages, deliverables, a minimal plan, connections to ongoing projects and an aspirational plan. The panel recommend strongly that the particle physics community supports this work with increased resources in order to develop the long term future and sustainability of this field.

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Table 4.14: Tasks breakdown for high-gradient plasma and laser accelerator (minimal plan). The needs of the minimal plan are on top of what the individual facilities and ongoing projects have as approved budget or will request in the future to their funding institutes.

Tasks	Begin	End	Description	MCHF	FTEy
PLA.FEAS.1	2022	2026	Coordination		
PLA.FEAS.2	2022	2026	Plasma Theory and Numerical Tools		
PLA.FEAS.3	2022	2026	Accelerator Design, Layout and Costing		
PLA.FEAS.4	2022	2026	Electron Beam Performance Reach of Advanced Technologies (Simulation Results - Comparisons)		
PLA.FEAS.5	2022	2026	Positron Beam Performance Reach of Advanced Technologies (Simulation Results - Comparisons)		
PLA.FEAS.6	2022	2026	Spin Polarisation Reach with Advanced Accelerators		
PLA.FEAS.7	2022	2026	Collider Interaction Point Issues and Opportunities with Advanced Accelerators		
PLA.FEAS.8	2022	2026	Reach in Yearly Integrated Luminosity with Advanced Accelerators		
PLA.FEAS.9	2022	2026	Intermediate steps, early particle physics experiments and test facilities		
PLA.FEAS.10	2022	2026	Study WG: Particle Physics with Advanced Accelerators		
PLA.FEAS			**Total of Feasibility and pre-CDR Study**	0.3	75
PLA.HRRP	2022	2026	High-Repetition Rate Plasma Accelerator Module	1.2	30
PLA.HEFP	2022	2026	High-Efficiency, Electron-Driven Plasma Accelerator Module with High beam Quality	0.8	10
PLA.DLTA	2022	2026	Scaling of DLA/THz Accelerators	0.5	16
PLA.SPIN	2022	2026	Spin-Polarised Beams in Plasma Accelerators	0.35	16
			Total	**3.15**	**147**

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