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Brigitte Cros, Nicolas Delerue, Matthieu Bardon, Arnaud Beck, Kevin Cassou, Sébastien Corde, Marie-Emmanuelle Couprie, Xavier Davoine, Sandrine Dobosz-Dufrénoy, Franck Falcoz, et al.

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# Roadmap toward a laser-plasma accelerator

Prepared in the framework of the GDR APPEL

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# 1 Foreword

This document is the outcome of discussions in the framework of the GdR APPEL<sup>1</sup>, launched in 2019 to bring together French researchers interested on the topic of laser plasma accelerators.

Establishing a roadmap on this topic is a challenging exercise, as part of the solutions to build plasma based accelerators still need to be explored. Part of the community is involved in the development of fundamental mechanisms, while some groups are studying and implementing technical solutions toward the development of machines. It is thus timely to start proposing global solutions for plasma accelerators, even with less than ideal properties and tackle technical challenges for their practical use, together with French companies joining this effort.

This document was edited by B. Cros and N. Delerue, based on contributions from the different authors listed as co-authors and mentioned in the document.

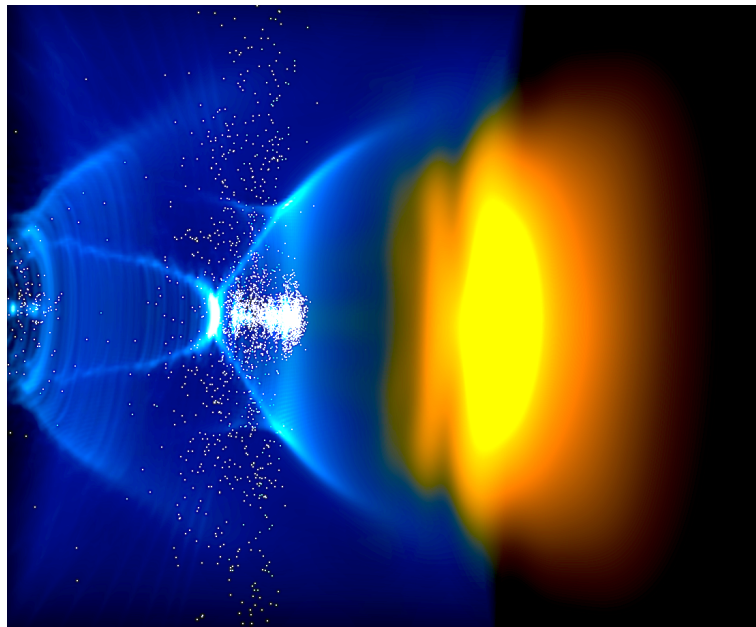


Figure 1: SMILEI simulation of Laser-plasma wakefield acceleration with injection by ionisation (hydrogen + nitrogen). Orange: envelop of the laser electric field. Blue/white: hydrogen electronic density. White dots: electrons from the ionisation. Image by F. Massimo.

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## 2 Executive Summary

### 2.1 Résumé et recommandations

Ce document présente un certain nombre de constatations résultant de l'analyse de la thématique et soulève quelques interrogations que nous tentons de résumer ici.

- Plusieurs sources d'électrons de bonne qualité seront démontrées d'ici 2027. La figure 2 résume les propriétés des sources d'électrons envisagées sur les installations françaises existantes ou en cours de développement.
- Les installations existantes ou en projet permettent à la communauté de d'avoir un rôle significatif dans des projets internationaux sur l'accélération d'électrons.
- L'accélération d'ions est dans une phase exploratoire ayant pour objectif de mieux identifier les concepts les plus prometteurs pour le développement d'accélérateurs.
- Le développement des accélérateurs d'ions est freiné par la taille de la communauté et par le manque d'installations. La communauté a besoin d'acquérir une taille critique pour mener l'étude jusqu'à un accélérateur. L'IN2P3 est l'institut qui peut avoir un rôle moteur dans le développement de ces accélérateurs.
- Le fonctionnement des installations existantes n'est pas parfaitement adapté aux besoins des utilisateurs pour le développement d'accélérateurs (critères et mode d'accès, organisation en projets indépendants, manque de ressources). Une solution pour pallier ces difficultés peut être de proposer des projets pluriannuels (APOLLON) pour la démonstration de concepts utilisant des dispositifs complexes. Cependant la mise au point d'accélérateurs fiables nécessite des développements techniques poussés, qui ne peuvent être réalisés que sur des installations dédiées.
- Les équipes françaises sont à l'origine des nombreux développements numériques et disposent de plusieurs codes performants pour décrire l'accélération laser plasma. Les efforts vont maintenant porter sur l'adaptation des outils numériques et leur utilisation pour la conception et la modélisation d'accélérateurs.
- Le calendrier et l'envergure des projets en cours sont très dépendants de moyens qui ne sont pas bien maîtrisés au niveau des projets. Les projets accélérateurs plasma ont besoin d'un cadre collaboratif stable à moyen terme (échelle de 10 ans) et avec des moyens (investissements et fonctionnement) qui ne dépendent pas uniquement de guichets multiples dont la sélection est faite en priorité sur la disruption et la nouveauté des concepts.
- Le développement des applications doit être effectué en étroite collaboration avec les communautés intéressées: la discussion est à poursuivre pour préciser les applications les plus pertinentes à développer et identifier les partenaires.

#### Recommandations

La qualité des travaux et des installations nationales sur l'accélération laser plasma permet aux équipes françaises d'avoir un rôle visible dans les projets internationaux et doit être soutenue à un niveau comparable à celui de nos voisins Européens (Le niveau d'investissement sur la thématique en France est en dessous de celui des pays européens comparables, Allemagne, Royaume-Uni, Italie).

La planification concertée d'investissements inter-instituts voire inter-établissements, de moyen à long terme, permettrait aux projets en cours d'avoir une meilleure vision des perspectives et de mieux fédérer les équipes, soit dans le cadre national, soit par la participation à des projets au niveau Européen.

L'appui des instituts à l'obtention d'une programmation thématique pluriannuelle sur l'IR APOLLON, IR permettant des démonstrations techniquement complexes, est indispensable.

Contact	Facility or project	Energy and spread E (MeV), dE (%)	Charge (pC)	Emittance mmmrad	Repetition rate (Hz)	Estimated date
K. Cassou	PALLAS	150-200, 10%	30	1	10	2024
J. Faure	LAPLACE HC	200, 1%	>10	<1	100	2026
S. Dobosz Dufrénoy	UHI100	300, 5% 200, <10%	20 100	1 <5	0.03	2024
B. Cros, A. Specka	APOLLON F2	300, <10% 1000, <10%	100 100	1 1	0.01 0.01	2024 2024
B. Cros, A. Specka	APOLLON 2et	10000, <10%	30	<1	0.01	2027
S. Corde	LAPLACE HE	200-500	500	1		2026

Figure 2: Parameter range of electron sources expected to be achieved by French teams by 2027. Dates are indicative and depend on the availability of resources.

## 2.2 Summary and recommendations

This document reports assessments following from a topical survey and analysis, and discusses some interrogations summarized as follows.

- Several good quality electrons sources are expected to be demonstrated by 2027. Figure 2 summarizes the properties of electrons sources planned at French facilities in operation or in under development.
- Existing or planned facilities in France are essential for the French community to be a relevant and significant partner in international projects on elcetron accelertation.
- Ion acceleration is in an exploratory phase with the goal to identify the most promising concepts for accelerator development.
- Ion accelerator development is slowed down by the small size of the French community and the lack of facilities. The community needs tor each a critical size to perform R&D towards an ion accelerator. IN2P3 is in a position to be the driving institute for this type of accelerators.

- The mode of operation of existing facilities does not fulfill the need of users for accelerator development (selection criteria, access duration, organisation as independent projects, lack of resources). To overcome some of these difficulties, proposal of experimental programmes extending of several years will be made at APOLLON facility programme committee, in order to demonstrate concepts involving complex, time consuming set-ups. However, reliable accelerator design requires advanced technical developments, which can only be achieved at dedicated facilities.
- French teams have pioneered a large number of numerical developments and several high performance codes are available to model and study numerically the physics of laser plasma acceleration. Future studies will include the adaptation of numerical tools and their use for the design and modeling of accelerators.
- The schedule and scope of ongoing projects is strongly dependent of resources which are not controlled at the project level. Plasma accelerator projects are in need of collaborative framework stable over a 10 year time-scale, and with identified funding for investment and operation; currently accessible research funding is attributed with low success rates on criteria based on novelty of concepts and disruption, which are not compatible for example with advanced technical developments to design new facilities.
- The development of applications should be performed in close cooperation with relevant communities: the most relevant applications and partners should be identified.

### Recommendations

The quality of the achievements of French teams and of existing facilities relevant for laser plasma acceleration, places French teams in a position to have a significant role in international projects. This activity should be supported at a level comparable to their European partners (the investment in France on this topic is below the level invested in Italy, Germany or the UK).

Coordination between institutes or institutions for medium to long term funding of the topic would be beneficial for a long term project vision, and would foster collaboration between teams at the national level, or through contributions to European projects.

The support of French institutions to a pluri-annual programme at APOLLON facility is needed to achieve complex, technically demanding experimental demonstrations.

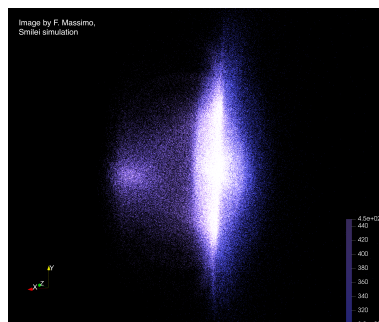


Figure 3: SMILEI simulation of a bunch for the EARLI project. Image by F. Massimo.

### 3 Context

The GdR APPEL was created in 2019 to bring together the French community involved in laser plasma acceleration, to foster cooperation with the conventional accelerator community, and to propose a perspective for the development of plasma based accelerators.

In this document, an accelerator is defined as an equipment delivering a beam of accelerated particles (e.g. ions or electrons) with a set of pre-defined parameters (energy, charge, bunch duration, emittance,...), in a reproducible and repetitive manner (with minimum repetition rate of the order of the Hz, and minimum operation duration of a few hours or days), with properties such that the beam can be used (transported, focused,...) for academic or industrial applications.

While laser plasma acceleration has accomplished tremendous progress since the theoretical proposal of 1979 [1], there is to date no operating accelerator based on this technology. Since 2006, the European community has supported several collaborative projects on advanced plasma acceleration developments. These efforts have contributed to develop the accelerator community awareness and led to subsequent joint projects such as ARIES and EuPRAXIA to mention only the latest. EuPRAXIA delivered in October 2019 a conceptual design report (CDR) for a facility built around a plasma based accelerator [2]. EuPRAXIA has been selected in June 2021 as a facility of the ESFRI and is the first plasma project on this road map. Following this decision EuPRAXIA Preparatory Phase project was submitted and approved on April 2022. The French teams are involved in EuPRAXIA as a "laser plasma excellence center", contributing to scientific and technical developments and to EuPRAXIA project management and plans for the future Laser Plasma Accelerator (LPA).

The interaction of a very high intensity laser with a gas or solid target produces energy beams of ions and electrons and provides secondary sources compact of X-rays and neutrons. All European projects related to laser driven ion acceleration have the ambition to demonstrate the acceleration of protons up to several hundred MeVs for medical and radio-biology applications, in particular ELIMED in Prague, ATHENA (Helmholtz Germany), A-SAIL in the UK, a collaboration between several universities and laboratories for studies of mechanisms of ion acceleration in laser-plasma interaction for an accelerator and for applications, and LAIA in Spain. In France, at LOA, a line of protons for radio-biology was tested until 2020 as part of the SAPHIR project, initiated by the company Amplitude, who provided a 200 TW, 5 Hz repetition rate laser, used for proton acceleration experiments. Promising results were achieved on the effects of large dose deposits carried out over short periods of time compared to the conventional duration of irradiation with medical accelerators.

These developments are of interest for mid-term applications, the most studied being radiation sources or secondary particles, where specific properties such as compactness and extremely short duration can be taken advantage of. Various test experiments are under way to achieve an FEL that is driven by laser-driven wavefield accelerators (LWFA) and beam-driven wakefield accelerators (PWFA) [3].

The first FEL demonstration using a plasma accelerator was achieved by the SIOM group (Shanghai, China) [4]. The output laser energy has been measured up to 50 nJ/pulse. The saturation level of FEL was not obtained. This first result is an important milestone in the progress made with this type of laser sources. The second FEL demonstration with a plasma accelerator was achieved by the INFN-Frascati collaboration (Italy) using a particle-beam-driven plasma accelerator in the infra-red with an exponen-

tial amplification in six successive undulator segments [5]. The COXINEL line, after extensive studies at LOA, has been transported to HZDR, and has recently achieved FEL in the seeded configuration [6].

The path towards long term applications for high energy physics (HEP) is starting to be explored: the ALEGRO collaboration has been formed in 2007 with the purpose of promoting advanced accelerator concepts for HEP and proposing a roadmap towards the design of an Advanced Linear Collider (ALIC). These communities have proposed contributions [7] discussed in the framework of the update of the European strategy for particle physics (ESPP). Recommendations following the ESPP update published in June 2020 [8] include pursuing plasma based accelerator R&D as a high priority future initiative. Following this recommendation, an expert panel on “High Gradient Acceleration (Plasma/Laser)” has been formed, to discuss and propose a roadmap for high priority demonstrators at the European level. 18 experts contributed to this panel, 5 of them are affiliated to French laboratories, demonstrating the interest of the French teams for this objective and the relevance of the French contributions.

The general assessments of this expert panel can be summarized as follows:

- Advanced accelerators have made important progress in demonstrating key aspects of those technologies: energy and quality for laser/electron/proton driven.
- Rapid progress is needed in underlying technologies, e.g. lasers, feedbacks, nano-control, manufacturing, . . .
- Various roadmaps have been proposed in EU (EuroNNAc), US (DOE) and internationally (ALEGRO), defining R&D needs for having a collider at the end of the 2030s or in the 2040s; however, the schedule is regularly slipping due to missing funding for particle physics oriented R&D in novel accelerators.
- The feasibility of a collider remains to be proven. For example, a scheme for positrons in plasma accelerators still needs to be demonstrated on paper; staging designs for high energy need to be calculated in detail and with all elements, including tolerances, length and cost scaling; repetition rate issues and efficiency approach need to be investigated in detail.

The next steps for the international community, as mentioned in the report of this expert panel on accelerator R&D following the ESPP report in 2021 and Snowmass meeting in 2022, are a collider Integrated Design Study to advance overall technical maturity, combined with strengthened R&D including test facilities and near term applications. These include alignment and jitter tolerances, matching/coupling between many’s of stages, optimized beam delivery systems and final focus, and stepping stones leading to a demonstrator for future colliders.

In this context it is timely for the French community to define their position in relation to the various objectives. The French community contributing to this topic is attached to national institutes of CNRS (IN2P3, INP), institutes of CEA (IRAMIS, IRFU, DAM, Grenoble), Universities (Paris Saclay, Bordeaux) and Engineering schools (ENSTA, Ecole Polytechnique), with the help of leading industry in laser development. A coordination toward common objectives is highly desirable to achieve a visible input at the international level, benefit from international projects, and reach a critical mass for major plasma accelerator developments.

## 4 State-of-the-art

Plasmas are able to sustain accelerating gradients up to hundreds of GV/m and are thus attractive media for accelerators. Particle acceleration results from the non linear interaction of an intense laser beam with gas or solid material. Protons up to 100 MeV and electrons close to 10 GeV have been achieved experimentally. These recent achievements are the fruit of a decade of intense developments, accompanied by the availability of PW class laser facilities worldwide, driven by plasma physicists for the exploration of various applications. Relativistic electrons are achieved by focusing a short pulse laser beam in an under-dense plasma and are comparatively easier to generate than protons, as they require lower laser peak power.

Laser driven wakefield is the easiest-to-implement mechanism to accelerate electrons in plasmas and has been widely used to generate relativistic electrons in the non-linear regime [9, 10]. In the quasi linear regime it excites a plasma wave, or accelerating structure, propagating at the speed of light in the plasma, without injecting plasma electrons [11].

Since the early work in the nineties [12], it has been recognized that the decrease of the laser beam intensity along its propagation limits the acceleration length. For two decades laser guiding has been developed, leading to the perspective of meter scale plasmas.

Separating the injector from the accelerator sections is one of the key elements to improve the quality of the electron beam in laser wakefield acceleration. Intense electron bunches can be generated by mechanisms such as ionization injection over short plasma lengths [13]; the acceleration of these bunches can subsequently be performed in a long plasma in the absence of further electron trapping.

Controlling these mechanisms separately and coupling the electron bunch created in a first plasma into a second plasma with a high efficiency is one of the main challenges for developing plasma based accelerators to high energies.

The most recent achievements to date include acceleration of electrons to 8 GeV, the current energy record for laser wakefield acceleration, in a laser heated plasma discharge waveguide at LBNL [14], demonstration of 24 hour operation of a laser plasma accelerator at DESY [15], optimization of the properties of the electron beam through machine learning at CLF by a UK -DESY consortium [16].

Several national projects at the 100 MEuros level of investment, are under active development in Europe [17]; for example, EPAC in the UK (application beam lines for electrons, ions, and radiation) is under construction; a kHz plasma based electron injector for Petra IV (DESY) is pushing forward the development of laser technology at kHz repetition rate in Germany.

In France, APOLLON research Infrastructure, a tool to study acceleration mechanisms in the GeV range, and multi-stage acceleration, is being progressively commissioned. The F2 beam was commissioned at the 0.5 PW level in 2021; the F1 beam is expected to come on line in 2023. Some projects have emerged from discussions in the framework of the GdR APPEL: LAPLACE and PALLAS projects, based on the upgrade of existing facilities, have plans for electron acceleration studies and accelerator development.

Laser ion acceleration is commonly achieved by irradiating a thin target with an ultra-short, highly focused laser at intensities exceeding  $10^{19}$  W/cm<sup>2</sup>. The main known ion acceleration mechanism is Target Normal Sheath Acceleration (TNSA) in which ions present on the surface of solid targets are set in motion by the electric fields (TV/m)

induced by the movements in and out of the target of electrons accelerated in the plasma. The intensity of these fields decreases as protons (ions) are accelerated out of the target, which gives them a continuous energy distribution (decreasing exponential) up to a maximum energy.

Protons (ions) are emitted within 30 to 45 degrees angular opening cones; their maximum energy does not exceed one hundred MeV with petawatt class lasers and the total number of protons accelerated over the entire energy range of the spectrum is at most of the order of  $10^{12}$  to  $10^{13}$  by shot. The maximum energy of protons accelerated by TNSA depends not only on the energy contained in the laser pulse but also on its duration and on the thickness of the targets used (from a few nm to a few tens of  $\mu\text{m}$ ). It reaches almost a hundred MeV for protons and a few tens of MeV for light ions.

Other mechanisms of acceleration by radiation pressure (RPA), and electrostatic shocks (Collisionless Shock Acceleration, CSA) are also predicted. All these mechanisms can be paired during the same interaction and combined with helical coil (HC) targets in order to post-accelerate, focus and bunch the proton beam. The HC targets post-acceleration scheme involves a single laser pulse without the need of an extra driver to trigger focusing and post-acceleration processes.

Some of the most recent results are listed here.

- Deuteron energies close to 100 MeV per nucleon were obtained using the TRIDENT laser at the Los Alamos National Laboratory using the combination of two acceleration steps in a solid target, followed by a low density plasma. This laser has an energy of 120 J delivered in 500 fs, i.e. a power of 250 TW, and an intensity on target in the order of  $10^{20}$  W/cm<sup>2</sup>. The intensity contrast of the laser is  $10^{-10}$  [18].
- Maximum proton energies close to 85 MeV were obtained at GSI, Darmstadt on the PHELIX laser ( $10^{20}$  W/cm<sup>2</sup>, 500 fs) with targets a few microns thick in the TNSA regime.  $10^9$  ions per MeV were measured at these energies [19].
- Proton beams with a maximum energy around 93 MeV were observed on the 2 PW laser from GIST in South Korea by irradiating an 800-nm 30-fs laser in circular polarization with an intensity of  $6.1 \times 10^{20}$  W/cm<sup>2</sup> on 15 nm thick plastic targets in the RPA regime [20]
- Very recent experiments carried out on the VULCAN laser in the United Kingdom have demonstrated a maximum proton energy close to 100 MeV with ultra-thin targets. The laser parameters were  $2.6 \times 10^{20}$  W/cm<sup>2</sup>, 500 fs [21].
- Recent experiments performed at the LULI2000 facility have demonstrated that the use of helical coils shows a 30% increase in the proton cut-off energy, a fluence multiplied by a factor 7, and also several bumps in the proton spectrum at the end of the coil.

Finally, it should be noted that the French community has pioneered theoretical aspects of laser plasma interaction and PIC code development and is strongly involved in the development of numerical tools such as:

- Codes simulating laser beam amplification and transport, describing laser beam properties and aberrations when reaching the target.

- Hydrodynamic (plasma) codes that can simulate the pre-plasma expansion/modification induced by the laser pre-pulse. This effect can be important for laser-solid interaction (ion acceleration).
- PIC codes used to simulate plasma acceleration (such as SMILEI, CALDER, ...).
- Codes to simulate charged particle transport.
- Monte Carlo codes, or nuclear physics codes, or other codes that can be used to describe the charged beam interaction with a target.
- Codes simulating the diagnostics.

The work planned for the next ten years is building on the strengths of the laser plasma community and should greatly benefit from reaching out to accelerator development experts.

The next sections highlight the proposed work related to electron and ion accelerator developments.

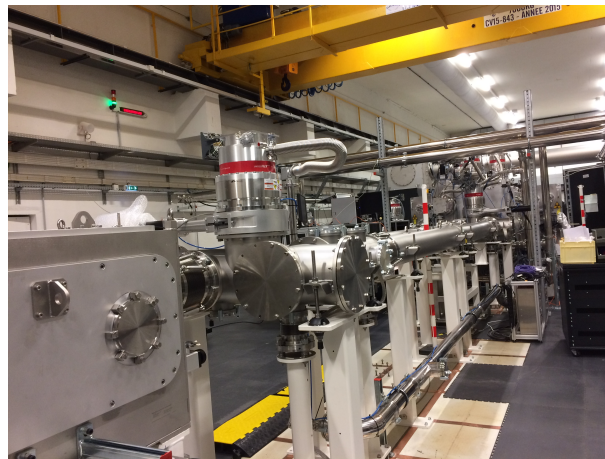


Figure 4: The APOLLON Long Focal Area, April 2022.



## 5 R&D towards plasma based electron accelerators

### 5.1 Main objectives

The main objective of the proposed research is to pave the way towards the **construction of an accelerator center based on laser-plasma acceleration technology**, capable of delivering electron beams to communities of users, as would a conventional accelerator center.

The proposed method for plasma based accelerator design relies on a global machine design through simulations and an evaluation of the developments needed for every component to reach the requirements of the accelerator. Research activities relevant to a Laser Plasma electron Accelerator (LPA), including exploratory experiments or component R&D as well as theoretical or conceptual studies, will be conducted using existing laser French facilities and those in project, and additional facilities or structures as necessary.

The accelerator structure and parameters depend on the application(s) it is dedicated to. One of the first tasks to be done is thus to identify applications that would benefit from LPA technology leading to the construction of an accelerator within the next 10 to 20 years.

In parallel to the identification of specific applications, the development of the present roadmap is firstly based on rough ranges of parameters and properties, which will be refined as work progresses. The values of the following quantities need to be taken into account as a parameter set, to be achieved together and for a significantly large number of occurrences, to define the accelerated beam: beam energy, charge, length, emittance, energy spread; repetition rate; reliability, repeatability, reproducibility; energy efficiency; flexibility. The repetitive achievement of a parameter set makes the difference between exploratory single shot experiments and accelerator demonstration. Reliability and efficiency need to reach values comparable to those of conventional accelerators. They need to be evaluated for present mechanisms and taken into account in the design of future accelerators, in addition to the development of laser driver technology.

Table 1 gives 2 examples of parameter sets and properties that can be taken as objectives to be targeted for an LPA at the French national level:

Table 1: Examples of parameter sets to be considered as objectives for electron accelerator R&D

Parameter	SET 1	SET 2
Beam energy	1-5 -10 GeV	200-300 MeV
Beam charge	100 pC	100 pC to 1 nC
Beam length	10 fs	100 fs
Beam emittance (normalized)	1 mm.mrad	1 mm.mrad
Beam energy spread	$1 \times 10^{-3}$	$1 \times 10^{-3}$
Repetition rate	100 Hz (in 10 years)	1 kHz (in 20 years)

One of the main challenges in accelerator R&D for the next 10 years is to build a plasma based laser driven accelerator to accelerate a 100 pC electron beam to the 10 GeV range, with a good beam quality, typically an energy spread at the 1% level, and micro-radian emittance.

The activities proposed by French groups involved in this research over the next ten years are summarized in the remainder of this section. Main objectives, deliverables or milestones are mentioned together with the relationship with international or national projects.

## 5.2 Developement of numerical tools

Advanced Particle-In Cell (PIC) codes have demonstrated their ability to describe the essential features of laser plasma interaction in the regimes relevant to plasma based accelerators. The current challenges for modeling accelerators are now to achieve, on one hand, ultra-fast simulations capable of “real-time” results in synchronism with the high repetition-rate experimental time-scale, and on the-other-hand, ultra-realistic simulations capable of describing all aspects of the experiments in a quantitative manner. Several PIC codes are available worldwide, including opensource codes maintained by large communities of users and developers. The French teams are mainly involved in the development of SMILEI [22], WARPX [23] CALDER [24], and also use FBPIC [25].

These codes are complementary and have different advantages depending on the environment, qualification of user or conditions of simulations. WARPX is a fully open source Particle-In-Cell (PIC) code, which has been entirely ported to GPU and CPU architectures and scaled at exascale on the largest machines worldwide. WarpX is a fully open source exascale Particle-In-Cell (PIC) code mainly developed through a longstanding collaboration between the team of J-L Vay at Berkeley Lab and the team of H. Vincenti at CEA-LIDYL, collaboration that has been awarded the Gordon Bell prize in 2022. WarpX also benefits from a strong support of a large community of international developers from major academic institutions (DESY, LLNL, FermiLab, SLAC, RIKEN) and key industrial partners (Arm, Atos, GENCI). SMILEI is benefiting from a strong French support and expanding international collaborations, and is dedicated to provide open source numerical tools for teaching and research activities.

The main efforts envisaged over the next five years can be described as follows:

- **Developments of numerical tools for high-fidelity laser-plasma modelling:** First, WARPX will be used at (pre)-exascale to model in full 3D a novel accelerator concept dubbed ‘the hybrid solid-gas’ target. These simulations will be done on Frontier and Lumi with mesh refinement capabilities to support experiments planned at Salle Jaune, UHI100 and APOLLON laser facilities in 2023/2024. Second, new numerical methods will be implemented and optimized in the WARPX code to simulate extreme QED plasma states occurring in Doppler-boosted beams interaction with matter at intensities beyond  $10^{25}$ W/cm<sup>2</sup>. These simulations will be run at (pre)-exascale to design, guide and interpret experiments planned at 100TW and multi-PW laser facilities at Horizon 2027. contact [H. Vincenti](#) (LIDYL); CALDER to model accurately plasma acceleration and accelerator applications involving plasma, contact [X. Davoine](#) (CEA).
- **Acceleration of numerical tools**, contact [A. Beck](#) (LLR). One of the main objectives of the SMILEI team up to 2023 is to optimise numerical methods and adapt the codes to the highest performance machines to accelerate simulations and for example simulate 1 cm of propagation per minute. A new version of SMILEI will be optimized for high performance GPU architectures (2023), including GPU NVIDIA (2022); GPU AMD (2023); and ARM/RISC (2022/2023). Optimization

of the performance of SMILEI to reduce the size of the simulation and increase its efficiency will be achieved through: implementation of perfectly matched layers for Maxwell and envelop solvers (2022); optimisation of particle merging laser wakefield acceleration (2023); local mesh refinement (2024); and boosted frame (2024).

- **Coupling between codes** simulating different part of the accelerator, A. Beck (LLR), P. Nghiem, D. Minenna (IRFU), F. Massimo (LPGP).
- **Ultra-fast simulation for optimisation** based on machine learning and support to experiments, V. Kubytsky (LOA), F. Massimo (LPGP).

### 5.3 Global design of Laser plasma accelerator

Start-to-end design and determination of particle beam parameters will be performed through simulations by the IRFU teams and collaborators, contacts P. Nghiem, D. Minenna. Other contributions from IRFU can be envisaged for transport lines and diagnostics.

Two types of designs are envisaged:

- **New facility** such as EuPRAXIA or EARLI (see below)
  - Optimisation through simulations to achieve the required particle beam parameter sets for planned applications;
  - Determination of physical parameters of all required equipments, such as driving laser, plasma medium, transport line, together with static and dynamic tolerances of these parameters.
  - Determination of physical parameters of necessary diagnostics, their range of operation, and resolution.
  - Definition of beam commissioning plan, and contribution to the commissioning activity until demonstration of nominal parameters.
- **Existing facility or project** such as APOLLON, PALLAS
  - Simulations to determine achievable particle beam parameter taking into account the physical parameters of existing equipments such as driving laser, plasma medium, transport line, and their range of operation and fluctuations;
  - Simulations to achieve parameters as close as possible to the required ones, taking into account tuning range and of existing equipment.
  - Participation to experiments until a good agreement between simulation and experiments is reached. Based on this agreement, a numerical duplicate of the machine can be defined and used to monitor and control operation.

### 5.4 Demonstration of physics concepts for plasma based accelerators

Several facilities are available to French groups for exploring fundamental concepts essential for the future development of accelerators, either in the frame of objective driven projects such as PALLAS (IJCLAB) and LAPLACE (LOA) or opened to users such as APOLLON (LULI) and UHI100 (CEA).

### 5.4.1 Demonstration of good quality electron beams

Several teams share the objective to explore methods to achieve good quality electron beams as this is one of the keys to accelerator development, as the first brick to build an accelerator. The main objectives and milestones can be summarized as follows:

- **Development of a good quality electron source with PALLAS**, contact K. Cassou (IJCLAB). The main objective is to achieve by 2024 a high quality plasma injector, with electron energy in the range 150 – 250 MeV, a charge of 30 pC, a relative energy spread smaller than 10%, an emittance of 1mm.mrad, operating at 10Hz. This will be followed (2025) by an improvement of beam properties (increase in charge, improvement of emittance and slice energy spread). The last step will be to build a transport beam line to complete the demonstration of a good quality injector.
- **Development of a good quality electron source with LAPLACE HE**, contacts J. Faure, C. Thaury (LOA). A versatile source will be developed with a tunable energy in the range 100 MeV – 1.5 GeV, operating at 0.5 Hz. An energy spread smaller than 5% is targeted. The expected charge will range from several hundreds of pC at 100 MeV to a few tens of pC at the GeV level.
- **Development of a good quality electron source with UHI100**, Contact S. Dobosz Dufrénoy (LIDYL); two types of sources will be studied, a 300 MeV, 10 – 20 pC, 5% energy spread, mrad emittance beam in collaboration with LPGP (B. Cros), and a 200 MeV , 100 pC, energy spread < 10%, emittance < 5 mrad, in collaboration with LOA (Adrien Leblanc)
- **Development of a good quality electron source with APOLLON**, contact B. Cros (LPGP), collaboration with A. Specka (LLR), S. Dobosz-Dufrénoy (LIDYL), D. Minenna (IRFU), N. Delerue (IJCLAB). The objective is to achieve high quality electron beams using methods scalable to high electron energy. The team (IRFU, LLR, LPGP) will perform start-to-end simulations of the two stage experiment planned at APOLLON, including the electron source, beam transport, second acceleration stage. The first simulations will identify the most promising schemes with expected laser parameters. More detailed simulations will be performed following results from the first experiments.

This works spans over several years (typically 5 years) and is conditioned to the attribution of sufficient beamtime through the facility programme committee over the years. The main steps are envisaged as follows:

- Development of electron sources in plasma cells with high quality, i.e. small energy spread and high charge) will be studied for several energy ranges, 200 – 300 MeV relevant for injector development at APOLLON, and around the GeV relevant to a wealth of applications of the electron beam in the Long Focal Area. The development of the injector will be followed by tests of the transport line and beam diagnostics.
- Development of the accelerating stage includes the demonstration of long plasma waveguides adequate for laser guiding over distances in the range 0.1 – 1 m, and the characterisation of laser wakefield in these waveguides.

- Experimental demonstration and plasma diagnostics can be for example performed at UHI100 prior to testing with APOLLON F2 or F1 beam during commissioning.
- Development and implementation of laser/electron diagnostics is crucial to the success of these experiment

These efforts are expected to demonstrate the external injection of electrons and acceleration in a second stage at APOLLON at the multi GeV level.

- **Development of a good quality electron source with the EARLI project.** Contacts: D. Minenna (IRFU), B. Cros (LPGP), P. Nghiem (IRFU) and F. Massimo (LPGP). The EARLI project (high-quality Electron Accelerator driven by a Reliable Laser for Industrial uses) aims to design and test one of the first industrial compact LPA. EARLI design is expected to be used as an injector for future plasma accelerators (such as EuPRAXIA, AWAKE or other relevant multi-stages LPA). EARLI consists of a laser system, a plasma cell and a transfer line able to produce and transport to users a high-quality electron beam with combined low energy spread, low emittance and high charge, that is reliable during long runs. Conventional accelerators methods are applied to the LPA physics and focus is made on the final beam characteristics (see Section 5.3).

#### 5.4.2 Development of beam driven plasma stage

A Plasma wakefield Accelerator (PWFA) high efficiency module for high quality electron beams will be developed, contact S. Corde (LOA).

The objective is to demonstrate an efficiency between the accelerated beam and driving beam of 20%, in two different configuration: (i) a driver with 10 GeV, 2 nC, 20 mm.mrad and external injection of witness beam at FACET-II or (ii) a driver with 200-500 MeV, 0.5 nC, 1 mm.mrad and internal injection of the witness beam in an hybrid scheme at a laser facility (LAPLACE, HZDR, LMU). The following steps are planned

- demonstration of driver depletion with driver to plasma efficiency larger than 40% (2022-2023) ;
- demonstration of witness beam acceleration with more than 40% plasma to witness beam efficiency (2023-2024);
- same demonstration an a ratio of energy spread over energy gain lower than 5% (2024-2025);
- demonstration of a PWFA module PWFA with an efficiency larger than 20% (2024-2026). Note that for FACET-II this demonstration should preserve the witness beam emittance.

#### 5.4.3 Development of high repetition rate electron sources

High repetition rate electrons sources are planned at LAPLACE-HC, contact J. Faure (LOA).

The main objective is to achieve a laser driven electron source in plasma operating at 100 Hz, with integrated control system providing 10 Hz acquisition of machine parameters, together with active feedback systems such as laser pointing. This project is undertaken

through a collaboration LOA-THALES in the frame of the joint laboratory HERACLES3 supported to Ecole Polytechnique, CNRS and THALES. The following steps are planned:

- 2023-2024: Implementation of the laser plasma accelerator operating at 100 Hz, driven by a 200 mJ - 100 Hz laser system. Expected electron beam parameters are either in the energy range 50-100 MeV, with a large charge of more than 100 pC, for electron energy above 50 MeV, and no requirement on beam quality; or of high quality with an energy spread lower than 5% for an energy in the range 50-100 MeV, with a charge of 10 pC, and an emittance of the order of 1 mm.mrad;
- 2025-2026 : Upgrade of the accelerator to a laser driver of 1 J. Objectives for high quality electron beam parameters are around 1 % energy spread at 200 MeV, emittance lower than 1 mm.mrad, and a charge larger than 10 pC. Studies will be performed to determine the parameters needed to achieve high charge beams.

#### 5.4.4 Acceleration of positron beams in plasmas

Acceleration of positron beams in plasmas combining energy efficiency and beam quality will be studied, contact S. Corde (LOA). Theoretical and numerical studies will be undertaken including tool developments to describe emittance with a resolution relevant to high energy collider design. An experimental demonstration at FACET requires a positron beam with charge 10-100 pC, emittance 10 mm.mrad, energy gain 1-5 GeV, plasma to witness beam energy efficiency of 10%. Preparatory numerical studies for FACET-II experiments are planned in 2022-2024 period, and experimental demonstration expected over 2025-2026.

### 5.5 Development of components and diagnostics for accelerators

Plasma components are essential parts of plasma based accelerators and dedicated efforts are necessary to achieve reliable plasma media with tailored properties. The work is planned as follows:

- **Development of structured plasma target**, contact B. Lucas (IJCLAB). Longitudinal shaping of density profile for localised injection and preparation for 1 kW operation. Optimisation workflow combining mechanical testing, fluid simulation and plasma characterization using a dedicated test bench with a laser beam intensity larger than  $10^{16}$  W/cm<sup>2</sup>. Studies in preparation for testing components at kW level and modelling taking into account thermal and hydrodynamic effects.
- **Development of plasma cell** for Laser Plasma injector (LPI), contacts B. Cros, S. Dobosz-Dufrénoy. Plasma cells will be designed and build to optimize electrons sources in the energy range 0.1-1 GeV driven by UHI100 and APOLLON laser beams. Each cell design will be optimised for the laser input parameters and the desired properties of the electron bunch. The design includes hydrodynamic simulations, PIC simulations, experimental characterization of the gas and plasma density, and characterization of the electron source.
- **Development of long plasmas** for Laser Plasma Accelerator (LPA) modules, B. Cros (LPGP). Long plasmas suitable laser plasma accelerator modules will be designed and build. The objective is to demonstrate tailored low density plasma

modules optimised for external injection and acceleration of electrons; schemes suitable for laser guiding and electron acceleration will be explored for plasmas of length 0.1 to 1 m, relevant for APOLLON experiments. Simulations will be performed as well as laser guiding using UHI100 and APOLLON facilities.

- **Developpement of long plasmas for injection and acceleration**, contact C. Thaury (LOA). Optical laser-guiding will be developed to extend the acceleration length, up to several tens of cm. The long plasma where the guide will be generated will be produced using a gas cell, a gas jet or a combination of both. Targets will be tested at different facilities, such as the Salle Jaune, LAPLACE HE or APOLLON.
- **Developpement of gas jets**, contact C. Thaury (LOA). Long gas jet systems, between 1 and 20 cm in length, will be designed, built and tested. They may comprise several gas inlets, and various devices for producing density gradients.
- **Development of particle beam diagnostics**, contacts N. Delerue (IJCLAB), C Simon (IRFU). Diagnostics for routine measurements at laser-plasma facilities will be identified and tested.
  - Existing diagnostics readiness for LPA will be evaluated; test campaigns to validate them and characterize their performances at plasma accelerators will be performed. These include current transformers, Faraday cups (aiming for 0.5 pC resolution), beam position monitors (strip-line BPMs and cavity BPMs, aiming for 0.5 mm resolution), transition radiation screens (for transverse profile measurements with 0.2 mm resolution, emittance measurements and bunch length measurements).
  - Temporal diagnostics will be tested for electron- laser timing, in order to measure the arrival time of the electron bunch with respect to the laser with a resolution below 100 femtoseconds. This diagnostic is required for synchronization between the laser and the electron beams in two stages acceleration schemes.

## 5.6 Development of laser drivers for plasma accelerators

Specific developments are planned for plasma accelerators as laser quality strongly determines electron properties.

### 5.6.1 Developments at facilities

- **Demonstration of stabilisation techniques for APOLLON 1 PW**, contact F. Matthieu (LULI). The objective is to improve the beam stability on target, including beam pointing and beam quality.
  - Stabilisation of 1PW APOLLON beam in the Long Focal experimental Area (LFA) aims at reducing pointing fluctuations by a decade, from  $2.5 \mu\text{rad}$  to  $0.25 \mu\text{rad}$  RMS. This is planned through the following steps: Characterisation of pointing stability at laser focus vacuum chamber in 2022; implementation of passive stabilisation system in 2023, and measurement of pointing stability.

- Stabilisation of focal spot distribution on target, with the objective to achieve a Strehl ratio fluctuation in the range 0.65 to 0.75. The following steps are planned: Implementation of passive systems to minimize instabilities, implementation of active system to correct remaining instabilities in 2023; a diagnostic will be implemented as close as possible to the focal plane to measure instabilities and correct them using a feedback loop to control a mirror.
- **Advanced PALLAS laser control**, M. Pittmann (IJCLAB) The objectives are to achieve active pointing stabilisation better than  $1 \mu\text{rad}$  in the bandwidth 0 – 400 Hz, wave front distortions lower than 20 nm (RMS), and study of spatio-temporal distortion on single shots using machine learning reconstruction from multiple diagnostics.
- **Increase of average laser power (LAPLACE HC)**, contact J. Faure (LOA). A laser system with 100 to 200 W average power will be build by LOA and THALES in the frame of the joint laboratory HERACLES3, Ecole Polytechnique/CNRS/Thales.
  - The first phase is scheduled for 2022-2023: implementation of the laser in LOA clean room: 200 mJ, less than 25 fs, 100 Hz, leading to an average power of 20 W;
  - In a second phase (2024-2025), the laser will be upgraded to reach 1 J, less than 25 fs, 100 Hz, or possibly 200 Hz, equivalent to 100 to 200 W average power.

### 5.6.2 Development of laser technology

- **Development of laser technology for LAPLACE HC**, contact C. Simon-Boisson (THALES).

Laser technology for LAPLACE HC is based on Titanium Sapphire CPA using diode-pumped frequency doubled Nd:YAG lasers.

All technology necessary for the first step at 200 mJ – 100 Hz is already available and has been entirely experimentally validated at full scale.

Regarding the upgrade to 1 J-100 Hz expected to be operational at LAPLACE-HC in 2025:

- Pump lasers are already available as fully qualified products (THEIA product) as they will be the same as the pump laser used for the 200 mJ stage. Several lasers will be used.
- Technology for TiSa crystal has been also already validated for the 200 mJ stage. This is a new technology based on a disk geometry and modified thermal management : TiSa disk acts as an active mirror with heat extraction from the rear face aiming to enhance a mostly longitudinal temperature gradient. Up-scaling from 200 mJ to 1 J will be moderate (larger beam aperture and splitting in 2 disks).
- High average power compression is certainly the most challenging part of this roadmap towards 100 W average power. However already accumulated experimental data combined with powerful simulation tools suggest that such power level should be properly managed while keeping gold-coated gratings for short pulse operation, either through current designs with optimized grating substrates and opto-mechanics configuration or through introduction of active cooling.



On a longer term beyond 2024-2025, next steps of the roadmap could be foreseen with extension of TiSa technology up to kW average power level, dedicated to several societal applications and large projects such as EuPRAXIA:

- Increase of energy up to 10 J while keeping 100 Hz operation;
- Increase of repetition rate to 200 Hz or 500 Hz or 1 kHz, with possible increase of energy in the same time.

Regarding the technology building blocks required:

- There are already some assets for the pump laser technology because the THEIA technology has been already validated in the lab up to an average power of 400 W (800 mJ at 500 Hz). Obviously for larger energies, new pump lasers should be developed providing higher energy per pulse from a single unit.
  - Compression at kW level could be feasible by using either dielectric gratings or hybrid (metal-dielectric) gratings. Such components can improve the thermal issues related to the high average power but attention must be paid in the laser damage threshold of the coatings and in achieving large enough bandwidth for short pulse compression.
- **Increase of average power of PW system** , Contact [F. Falcoz](#) (Amplitude).

Amplitude is involved in the increase of the average power of high energy system since 2012. In the frame of ELI ALPS, they have already reached the level of 100 W of average power on a 500 TW at 10 Hz (20 fs) and they should be above 300 W in the next 2 years. These results are possible thanks to the development of a new range of pump laser based on Nd:YAG liquid cooled disk laser head. Today using flashlamp pumping they have already demonstrated pump laser generating 500 W (50J/10Hz) in the green (Premiumlite product). In the next few years, the use of diode pumping will allow them to further increase the repetition rate while keeping high energy per pulse. This new development has started at Amplitude in 2022 and their roadmap is the following:

- 2024 : demonstration of a nanosecond pump laser delivering 1.5J/200Hz @ 532 nm (300W)
- 2026 : demonstration of a nanosecond pump laser delivering 10J/200Hz @ 532 nm (2kW)
- 2027 : demonstration of a nanosecond pump laser delivering 4J/500Hz @ 532nm (2kW)

In parallel to this roadmap they are also working on important topics that are needed to manufacture a high repetition rate multi 100's of TW TiSa laser with the level of reliability and ease of use needed for plasma accelerator:

- 2022-2023 : Implementation of data collection and time stamping on large TiSa system. Data such as beam pointing, pulse duration, or phase, will be used to optimize the performances of the laser regarding a specific application (for example particle acceleration).

- Improvement of TiSa cooling able to withstand thermal load above 2kW. A first version has been developed in 2019 in the frame of the HIBEF system (400TW at 5Hz).
- Optimization of grating compressor design and cooling of the compressor optics to ensure the best stability of the beam parameters.

## 5.7 EuPRAXIA

EuPRAXIA is the European Flagship project that will enable the demonstration of plasma technology for accelerators.

**Several French group are partners of EuPRAXIA Preparatory Phase, approved for funding in April 2022 (2 Meuros, 2022-2026).**

French groups will contribute to a laser plasma excellence center in the frame of EuPRAXIA Preparatory Phase. CNRS (IJCLAB, LLR, LOA, LPGP, LULI), and CEA (LIDYL) are the main partners of EuPRAXIA PP. French contributions are planned in the following work packages (WP):

- WP3: Organisation and Rules, coordinator A. Specka (LLR), Will contribute to develop an organisational model.
- WP6: Membership Extension Strategy, coordinator B. Cros (LPGP). The objective is to enlarge EuPRAXIA membership. This WP will outreach, define the extension approach, and contribute to EuUPRAXIA integration into international landscape.
- WP8 Theory & Simulation, coordinator H. Vincenti (LIDYL), will steer the scientific and technical progress on Theory & Simulations of Plasma Accelerator and related applications.
- WP10 Plasma Components & Systems, coordinator K. Cassou (IJCLAB), will assess the current design of plasma components and related systems and provide a sustainable roadmap to fulfil the EuPRAXIA scientific goals.
- WP13 Diagnostics for particle and photon beams, contributor A. Specka (LLR), to develop the required structures in detail (excellence centers, scientific programs, R&D). Specify required funding needs. Steer scientific and technical progress towards EuPRAXIA implementation.
- WP14 Transformative Innovation Paths, contributor S. Corde (LOA), to develop high quality hybrid scheme PWFA electron sources, through for example plasma cathode scheme. Target parameters: energy 50 to 250 MeV, charge 10 to 100 pC, normalized emittance < 100 nm.

## 5.8 Industrial accelerators

The objective of SourceLab, contact F. Sylla, is to **develop and sell turnkey electron sources** with the following parameters: electron energy tunable in the range 1 to 150 MeV, a charge larger than 10 nC in the range 1-10 MeV, and larger then 1nC in the range 10-150 MeV; divergence and stability of the electron beam need to be studied. The planned developments also include some underlying technology developments such as target nozzles, spatio-temporal diagnostics, or data management systems. Several specific designs are planned:

- present - 2023 : Develop and sell a compact beamline including a kHz laser, a post-compressor and the KAIO system for the generation of high repetition rate relativistic electrons. This beamline targets both academic customers and industrial customers with specific exploratory applications.
- 2023-2025 : Development of a reliable accelerator for non destructive testing (NDT) using Bremsstrahlung and inverse Compton scattering, by increase in technical readiness Level (TRL) of the existing SHERIL Platform. The laser driver needs to be defined; it could be a reliable version of the current 10 TW-10 Hz - laser driver or a post-compressed, kHz, Yb:YAG commercial laser.
- 2025-2027 Development of a demonstrator for ex-vivo X-ray medical imaging by inverse Compton scattering

## 5.9 Electron beamline for specific applications

The accelerator structure depends on the application(s) it is dedicated to. One of the first tasks to be done is thus to identify applications that would benefit from LPA technology leading to the construction of an accelerator within the next 10 and 20 years.

### 5.9.1 LPA as electron injectors

Contact D. Minenna (IRFU). LPA can be used as very high energy (typically around 200 MeV) electron sources for a variety of applications. One of the most immediate applications is as electron injectors for current or future accelerator facilities intended for scientific or industrial applications. For example, LPA electron injectors, such as the ones developed in the EARLI project, can be used for plasma accelerators such as AWAKE or the first stage of EuPRAXIA. It is expected that LPA injectors will have a smaller footprint and may eventually become competitive with current conventional electron sources. In the long term, LPA injectors may be the initial element of multi-stage LPA collider facilities for high-energy physics.

### 5.9.2 Quantum Electrodynamics (QED) studies

Contact M. Grech (LULI). The advent of multi-petawatt (PW) laser facilities and development of laser-plasma accelerators open new opportunities for the study of fundamental processes at the frontier of relativistic plasma physics and (strong-field) quantum electrodynamics (SF-QED). Several experiments are envisioned that will allow the study of processes that were long thought to be the playground of elementary particle physics. Many of these experiments consider the head-on (or near head-on) collision of a laser wakefield accelerated (LWFA) electron beam with a PW to multi-PW laser pulse. This geometry is indeed known for maximizing the importance of two processes which are among the most exotic processes expected on multi-PW facilities, and as such, have been the focus of a coordinated effort of the laser-plasma and SF-QED communities:

1. Nonlinear inverse Compton scattering and radiation reaction: An electron dynamics in a strong (laser) electromagnetic field will not be fully captured by the standard Lorentz force when the electron starts emitting high-energy radiation in the form of gamma photons (nonlinear inverse Compton scattering). These emissions - associated with loss of energy and momentum by the radiating particle - will impact the electron dynamics, a process known as radiation reaction.

2. Nonlinear Breit-Wheeler pair production: The high-energy gamma photons can interact back with the laser field. This purely quantum effect leads to the production of an electron-positron pair, a process known as multi-photon (or nonlinear) Breit-Wheeler, the high-energy gamma photon interacting with many photons of the background laser field.

The study of nonlinear inverse Compton scattering, and radiation reaction (RR) in particular, will require the use of high-quality ( $\Delta E/E \sim 1\%$ ,  $\Delta\theta < 1$  mrad) LWFA electron beams at moderate energy (few 100's MeV). For this type of experiment, the effect of RR will be imprinted onto the electron spectrum and starting from a high-quality electron beam is of utmost importance to study various effects of RR [31]. At the same time, the total charge of the beam is not so important here (few 10's pC can be considered).

In contrast, to study nonlinear Breit-Wheeler pair production, it is important to increase both the electron beam energy to few GeV and the total charge to several 100's pC up to few nC. For this line of study, requirement on the beam quality is not too important [32].

In all cases, control of the electron beam stability and careful alignment and timing with the colliding laser pulse will be important. It will be interesting to work at the highest repetition rate allowing for this control.

Two types of facilities are planned to be used. Firstly, several multi-PW, multi-beams laser facilities providing an electron beam driven by LWFA and a PW to multi-PW laser beam in a colliding geometry will become available (e.g. APOLLON, CoReLS and ZEUS facilities are designed to deliver multiple light beams with duration in between 15 and 30 fs FWHM and peak power from 1 to 10 PW). Secondly, experiments at FACET-II and LUXE will couple conventional electron accelerators with high-intensity (100 TW-class) ultra-short laser pulses for QED experiments [33].

APOLLON multi-PW beam is scheduled to come on line at the 3 PW level from 2024.

### 5.9.3 Medical applications

Medical applications of electron beams and associated radiation at low (MeV range) or very high energy (up to 200 MeV), seem to be within reach of plasma accelerators. Their specific contribution relies on the energy tunability, short burst duration and the availability of multiple sources within the same facility. Several groups in France are investigating plasma electron sources : at LIDYL, developing 150 MeV, mrad emittance, 1Hz repetition rate electron beams; at LOA developing electron and secondary radiation sources (betatron, compton).

### 5.9.4 Free electron Laser

Contact M-E. Couprie (SOLEIL). Free Electron Laser relies on the amplification of synchrotron radiation emitted in an undulator creating a periodic permanent magnetic field by a bunch electron beam, resulting from the energy exchange between the electron and photon beams. The short wavelength free-electron laser (FEL), in X-ray spectral range, generally uses a single pass configuration for the electron bunch through an undulator, i.e. without optical cavity, in the Self-Amplified Spontaneous Emission (SASE) or seeded configuration [26]. The radiation wavelength results from the electron beam energy and the undulator parameter, according to  $\lambda = \lambda_u(1 + K_u^2/2\gamma^2)/2\gamma^2$ , with  $\lambda_u$  the undulator

magnetic period and  $K_u$  its deflection parameter. The electron beam is usually provided by a linear RF accelerator; FEL can be a good application to qualify a plasma accelerator, and various test experiments are under way. An example in [3] gives typical electron beam parameters required for the FEL at 74 eV (16.7 nm) and is summarized in table 2.

Table 2: Exemple of electron beam parameter sets required for the FEL from simulations from Emma et 2021, and achieved parameters by SIOM group (Shanghai).

Parameter	simulation from Emma 2021	SIOM from Wang2021
electron energy	500 MeV	490 MeV
energy spread	1%	0.5%
charge	50 pC	30 pC
bunch duration	5fs	25 fs
transverse size at focus	20 $\mu\text{m}$	35 $\mu\text{m}$
undulator period	18 mm	25 mm
deflection parameter	1.26	1.41
FEL wavelentgh	16.7 nm	27 nm
FEL energy per pulse	5 nJ	50 nJ

Various test experiments are under way to achieve an FEL that is driven by laser-driven wavefield accelerators (LWFA) and beam-driven wakefield accelerators (PWFA) [3]. The first FEL demonstration using a plasma accelerator was achieved by the SIOM group (Shanghai, China) [4] driven by a laser plasma accelerator with measured parameters reported in table 2. The second FEL demonstration with a plasma accelerator was achieved by the INFN-Frascati collaboration (Italy) using a particle-beam-driven plasma accelerator in the infra-red with an exponential amplification in six successive undulator segments [5].

In France, **the project COXINEL has been launched** in the frame of a Synchrotron SOLEIL/ Laboratoire d'Optique Appliquée (LOA) collaboration, aiming at demonstrating a seeded FEL driven by a plasma plasma accelerator. The line has been designed [27] to focus the electron beam, at the exit of the gas jet, by a triplet of high gradient variable permanent magnets quadrupole (QUAPEVA) [28], a chromatic transport scheme improving the electron bunch quality and allowing for a variable focusing of the beam, on the longitudinal axis in the undulator section, according to the electron energy. The electron beam transport has been mastered [29] and the undulator spontaneous emission controlled [30]. The line has been moved to HZDR to take advantage of larger charge densities and smaller energy spread. It enabled to demonstrate FEL in the seeded configuration at 267 nm [30]. Detailed FEL characterization will be studied further at HZDR, before bringing back to line to France when electron beams of required quality will be available.

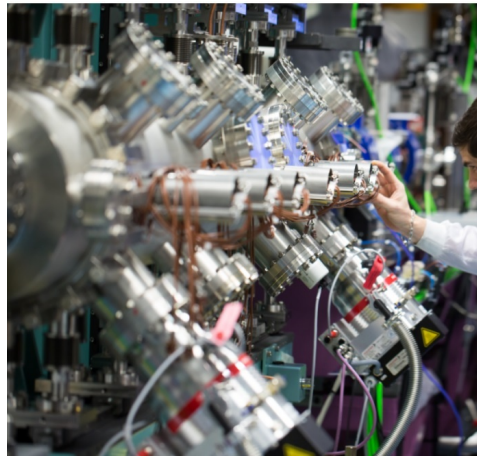


Figure 5: Coxinel- (ERC funded project) transport line for 200 MeV for a laser plasma accelerator and undulator for FEL radiation at 200nm implement at LOA for and experiment. courtesy J. Faure, ME Couprie

## 6 R&D related to ion acceleration

Electric fields generated by high power lasers in plasmas reach hundreds of GV/m, reducing the length to accelerate particles to a few tens of microns. High power lasers systems (100 TW to 10 PW) with high repetition rate capable of generating such fields are now quite compact and relatively inexpensive. The same laser-plasma acceleration device can make it possible to produce sources of photons, neutrons, ions of different species, in various ranges of energies. We propose to **strengthen the current programs at IN2P3 and INP in order to build a prototype plasma ion accelerator in France.**

The main ion acceleration mechanism known from solid targets (CH, Al ... of a few  $\mu\text{m}$ ) is the TNSA but there are other ion acceleration processes with targets of small dimensions more complex to implement and renew with each shot laser. The required protocol, if it is commonly performed on single-shot lasers (rate lower than 1 shot per 30 min), is not suitable for high rate laser shots.

Depending on the desired application, the characteristics of laser accelerated ion beams (maximum energy, energy dispersion, divergence and beam intensity) must be controllable. These characteristics are directly determined by the mechanisms behind the acceleration of ions during the interaction of laser with the target.

### 6.1 Laser ion acceleration using gas jets

The availability of high repetition rate lasers led to **research into ion acceleration from dense gas jets or liquid targets.** Several volumic acceleration mechanisms in very high pressure gas jet targets are predicted. In these mechanisms the laser can penetrate deep into the target volume and induce displacements of electrons. These are able to accelerate large amounts of ions to speeds higher than those observed in the TNSA regime (by the processes of "hole boring" or shock acceleration).

Pioneering theoretical studies are carried out to define the parameters of the interaction that optimize the energy and the number of ions accelerated. Experimental data are still scarce, the first published results were obtained in the USA in 2011 with a CO<sub>2</sub> laser and reported proton spectra with an energy average of several MeV and a dispersion of 5%. S. Chen et al. [34] reported in 2017 proton energies of a few hundred keV in shots carried out on the TITAN laser at LLNL.

Three experiments at LULI (Ecole Polytechnique) and at CLPU (Univ. Salamanca, Spain) were conducted in 2018 by a collaboration of CENBG, CELIA and LULI teams. On the one hand, they validated a gas jet system based on two compressors of 400 and 1000 bars and tested different types of nozzles, some designed and simulated in these laboratories then micro-machined by external companies, others developed and sold by SourceLab. The results obtained in LULI demonstrated for the first time with an infrared laser, the acceleration of protons to energies of 5 MeV and Helium to energies of 10 MeV. These experiments have also made it possible to refine the roadmap to improve the gas jets created in order to achieve the conditions required to observe almost monoenergetic ion spectra expected during acceleration through the CSA process.

### 6.2 Laser ion acceleration using helical targets

For applications such as neutron production or proton isochoric heating, the proton beam resulting from the TNSA process suffers from two major drawbacks: a large divergence angle ( $\sim 40$  degree), and an exponentially decreasing energy distribution. **HC targets can**

**simultaneously focus, collimate, post-accelerate and bunch the proton beams generated by the TNSA process.** Experiments performed at LULI2000 allowed to clarify the physics of HC operation. It was demonstrated that the laser-accelerated proton bunch is modified through the following multi-stage process. Escaping electrons are charging positively the target, which drives a discharge current through the helix attached to the target backside. In turn, this transient current generates an electromagnetic pulse (EMP) which focuses, post-accelerates and energy selects the protons. Due to the coil induction, the discharge current propagation in the helix is dispersed and its intensity is modulated. This leads to the proton bunching in groups with different energies. These complex phenomena limit the proton post-acceleration efficiency and yield.

Two approaches for improving the quality and efficiency of the HC have been proposed: either the use of multiple acceleration stages by aligning a sequence of several HC along the normal axis to the target, or the use of coils with variable radius and pitch. In the latter approach, we face a problem of the current dispersion. It can be resolved by an accurate tuning of the coil and laser pulse parameters. Such tuning will be performed with a new current propagation model that has been developed. **Optimized designs will be tested in future experiments.** If the features of the proton beam generated by these HC targets are confirmed by these experiments, one will be able to work on the application of this scheme to high repetition rate lasers. In particular, the use of hydrogen rubans at the entrance of the coils will studied and tested experimentally.

### 6.3 Perspectives on laser ion acceleration

A great difficulty of this program lies in the diversity of existing laser installations and their access modes which do not allow to guarantee the conditions for quantitative parametric studies within a reasonable period of time. TNSA has been studied by several teams around the world for almost 20 years, the accumulated data and calculations have enabled a good mastery of the phenomenon. Much less data exist on other more complex mechanisms because in particular they require targets that are still difficult to produce today. Nevertheless, there is fierce international competition around laser ion acceleration in plasmas because its applications "achievable in the medium term" are promising from radio-isotope production and radiobiology to the production of compact bright neutron sources.

In the future, studies around laser plasma acceleration will take place with the laser APOLLON in Paris area and with European lasers at ELI and CLPU. Even though major advances are expected regarding the demonstration of new mechanisms of acceleration, due to the unique characteristics in intensities of these lasers, a laser plasma ion accelerator as a machine delivering beams of particles that can be used for applications cannot be developed with lasers that do not offer a laser line dedicated and guaranteed laser time over a reasonable period of time for a research program.

The GDR APPEL roadmap is an opportunity to clarify the strategy of CNRS, IN2P3 and INP for the next 10 years, to specify our ambition on the subject (research on the interaction plasma laser or plasma laser accelerator) and discuss the means necessary for its production. Several proposals are currently being studied.

The work planned for the next 10 years on ion acceleration can be summarized under the following main items:

- Efforts will be dedicated to identify the ion acceleration mechanisms that will achieve a peaked energy distribution, reproducible from shot-to-shot, and with a center



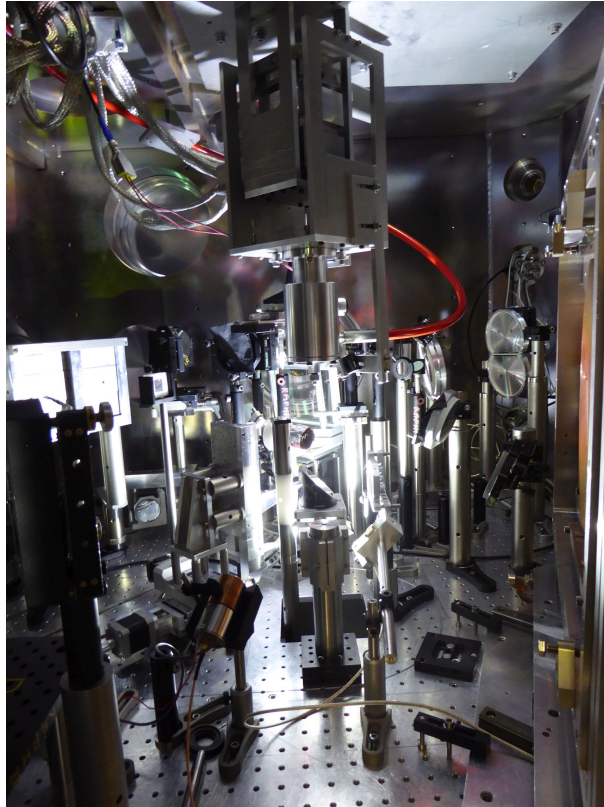


Figure 6: Ion acceleration experiment at Phelix (GSI). Image by Medhi Tarisien.

energy tunable from 10 MeV to 100 MeV for most applications, and up to 10 GeV for spallation, and with emission peaked around a small aperture angle for beam manipulation.

- Simulation tools will be developed and used to identify parameter ranges suitable for specific acceleration mechanisms: hydro codes to investigate the interaction of the ASE/prepulse with various types of targets, SMILEI for the interaction of the main pulse.
- Parametric studies at high repetition rate (APOLLON) will be performed to investigate the target properties favoring the desired acceleration mechanism.
- High repetition rate diagnostics, compatible with beam properties and laser plasma environment will be developed, together with beam transport and shaping for kA, ultra-intense ion beams.
- Applications able to motivate and provide funding scenario for the construction of a plasma based laser driven ion accelerator should be identified. Among others, neutron generation, flash radiotherapy with ions, production of radio-isotopes for uses such as beam diagnostics, medical uses, or laboratory astrophysics, will be envisaged.

## 7 Outlook

A particle accelerator based on plasma acceleration will have several outstanding features compared to conventional ones. For a long time the use of plasma technologies for accelerators was seen as a far away goal, but as highlighted in this document, this may become a reality in France over the course of the next decade.

The work on laser-plasma based electron accelerators is well advanced and France is a key contributor to the EuPraxia project. In France, the APOLLON laser will allow the community to study the physics of plasma acceleration at the power frontier. Lower power facilities such as LAPLACE, PALAS or UHI100 will pioneer construction and operation of laser-plasma accelerators for specific applications.

For ion acceleration, important studies have to be carried out to identify the best possible ion acceleration mechanism. The APOLLON facility will be instrumental in these studies as well as other facilities worldwide.

The work on both types of particle will strongly benefit from the progress expected in simulations tools which must be supported.

The main challenges identified by the community are the access modes to the facilities which often do not allow to build a program over several years. Limited resources (especially human resources) in comparison with other large European countries may slow the progress toward laser-plasma accelerators.

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## Glossary

### A

**A-SAIL** Advanced Strategies for Accelerating Ions with Lasers,  
<https://www.qub.ac.uk/research-centres/A-SAILProject/>. 7

**ALEGRO** Advanced LinEar collider study GROup,  
 . 8

**APOLLON** French laser research facility opened to international user,  
<https://apollonlaserfacility.cnrs.fr/presentation/>. 4

**ARIES** Accelerators Resaerch and innovation for European Science and Society. 7

**ATHENA** Helmholtz Accelerator Research and Development Distributed Test Facility,  
<https://www.helmholtz-ard.de/e26746/>. 7

### C

**CALDER** Particle-In-Cell code for plasma simulation. 11

**CDR** Conceptual design Report. 7

**CLF** Central Laser Facility of the Science and Technology Facilities Council, UK  
<https://www.clf.stfc.ac.uk/pages/home.aspx> . 9

**COXINEL** The ERC Advanced Grant COXINEL aims at demonstrating free electron laser at 200 nm, based on a laser-plasma accelerator . 8

### D

**DESY** Deutsches Elektronen-Synchrotron,  
 . 9

### E

**ELIMED** ELI-Beamlines MEDical and multidisciplinary applications,  
<https://web.infn.it/ELIMED/index.php/en/>. 7

**ESFRI** European Strategy Forum on Research Infrastructures, <https://www.esfri.eu>. 7

**ESPP** European Strategy for PArticle Physics, <https://www.esfri.eu>. 8

**EuPRAXIA** European Plasma Research Accelerator with eXcellence in Applications. 7

**EuroNNAc** European Network for Novel Accelerators, part of ARIES projet.. 8

### F

**FACET** Facility for Advanced Accelerator Experimental Test at SLAC, Stanford National Accelerator laboratory. 17

**FEL** Free Electron Laser. 7

**G**

**GdR** Groupement de Recherche. 7

**H**

**HEP** High Energy Physics. 8

**HZDR** Helmholtz-Zentrum Dresden-Rossendorf, <https://www.hzdr.de>. 8

**I**

**IN2P3** Institut National de Physique Nucléaire et de Physique des Particules. 4

**IR** Installation de Recherche. 5

**L**

**LAIA** Laser Acceleration of Ions and Applications,  
<https://www.i3m-stim.i3m.upv.es/research/laser-ion-acceleration-and-applications-laia/> . 7

**LAPLACE** Centre d'accélération laser-plasma,  
<https://loa.ensta-paris.fr/fr/2020/11/20/laplace-un-projet-pour-un-centre-dacceleration-laser-plasma-au-loa/>. 9

**LBL** Lawrence Berkeley National Laboratory, <https://www.lbl.gov>. 9

**LPA** Laser Plasma Accelerator. 7

**LWFA** Laser-driven WakeField Accelerator in plasma. 7

**P**

**PALLAS** Prototyping Accelerator based on Laser-Plasma technology. 9

**PWFA** Plasma (particle beam-driven) WakeField Accelerator . 7

**S**

**SMILEI** Open Source Particle-In-Cell code for plasma simulation,  
<https://smileipic.github.io/Smilei/>. 11