Institut national de physique nucléaire
& de physique des particules

Fiche projet de développement

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Titre / *Title* :	**Prototype accélérateur Laser Plasma (PALLAS) / *Prototyping Accelerator based on Laser-Plasma technology***
Résumé / *Summary*:	Conception d'un prototype accélérateur laser-plasma à 150 MeV avec des propriétés de contrôle et stabilité comparables aux accélérateurs RF / *Development of a 150 MeV laser-plasma injector with control and stability comparable to RF accelerator standards.*

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History

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Acronyms

ACU: air conditioning unit

CPA: chirped pulse amplification

CCA: control command and acquisition system

CSI: Conseil Scientifique de l'Institut.

CSL: Conseil Scientifique de Laboratoire

eBCL: electron beam characterization line

FTE: Full time Equivalent

HPC: High Performance Computing

KDP : key decision point

LBTL: laser beam transport line

LIF: laser injection focusing module

LPA: laser-plasma accelerator

LPI : laser-plasma injector

LWFA: laser wakefield acceleration

ML: Machine learning

PALLAS: prototype accelerator based on laser-plasma technology

PLSM: plasma module

PIC: particle in cell

STII: self truncated ionization injection

TRL : technology readiness level

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Summary

What scientific question does the project address?

Construction of a fully reliable and controlled LPI prototype for laboratory applications with e- beam having characteristics comparable to RF accelerators. Current systems are essentially looking towards ultimate performances but are still limited by e-beam quality and stability.

Before the project itself, what is the state of the art in the field concerned??

We aim at the transition between laser laboratory proof of principle experiment to accelerator prototype development. Present research activities are mainly concentrated on high accelerating gradients in order to reach high energy compact systems. A European project called EUPRAXIA is in the design phase, aiming to build a high-energy compact plasma accelerator based on two different approaches: laser-driven or beam-driven acceleration. The most advanced research activities for plasma wakefield acceleration are yet undertaken at DESY and LNF..

How did it get there?

In the recent years, lots of improvement in the control of the injection process and progress in laser technology made possible the scaling of laser-plasma based electron beams to higher average current and better energy efficiency. This definitely makes the LPA a promising technology for compact future e- accelerators.

How is the IN2P3 community mobilized and energized around these scientific issues (access to a GdR? IRN?),

GDR Appel (Accélérateurs Plasmas Pompés par Lasers) (http://gdr-appel.fr/: IN2P3/INP but mainly driven by IN2P3) is gathering the French community from various institutions working on the subject and proposes workshops, scientific animation, meetings on french strategy for laser plasma acceleration, etc.

What are the links with other research departments in CNRS (Sante, INSU, INP, ...).

There is a strong link with INP for coordinated R&D effort in the preparatory phase of EuPRAXIA, especially with people from LOA (Jérôme Faure) and SOLEIL (Marie Emmanuelle Couprie).

What is the impact and gain of visibility for IN2P3 teams with this project?

LLR team involved in the project has experience in LPA development in particular in exploring exp. @ >1PW level (on the APOLLON long focal length laser room) and has also a high visibility in PIC open source code development for LPA (Smilei code). The IJClab team has a strong experience in high intensity femtosecond lasers, optics, plasma physics, but also laser integration in accelerator systems and conventional accelerators.

How will this visibility be increased in the frame of the project? Explain the role of IN2P3 researchers and engineers (provide an organigram of the project).

The visibility of the IN2P3 on LPA activities will strongly be improved by a unique R&D platform devoted to LPI R&D as an accelerator test facility . The PALLAS project constitutes the first concrete machine prototype development in this field within an IN2P3 laboratory, led and developed by IN2P3 staff. Until now all experiments in France were developed in INP or CEA labs.

theme

IN2P3 theme for the project
◻ Particules et Hadronique (PH)
◻ Astroparticules et Cosmologie (AC)
☒Accélérateurs et Technologies (AT)
◻ Data & Computing (DC)
◻ Nucléaires & Applications (NA)

1. Project goals

1.1 Scientific and technical challenges

The PALLAS (Prototype Accelerator based on Laser-pLASma technologies) research project launched by CNRS-IN2P3 and the Université Paris-Saclay at the end of 2019 focuses on the development of laser-plasma accelerator (LPA): an extremely innovative and promising technique for future compact particle accelerators. PALLAS aims to achieve a real technological breakthrough within 5 years by building in Orsay a compact laser-plasma accelerator prototype capable of producing an electron beam with a level of stability and reliability comparable to conventional radio-frequency accelerators.

Laser wakefield acceleration (LWFA) represents a very promising path towards the construction of compact particle accelerators. Recently, impressive results have been achieved, with the world energy record of 8 GeV in 2018 at Berkeley University [1] and the longest continuous operation at 1 Hz[2], [3] in 2019 at DESY. Stable operation at high-repetition rate is now a key development for potential applications such as secondary X-ray sources[4]. However, the transition from LWFA experiment to an accelerator needs to overcome many remaining limitations. These include (i) reproducibility, which is mainly limited by the stability of the laser driver, and (ii) beam quality, which is highly dependent on the characteristics of the plasma and the matching to the electron transport line.

The PALLAS project aims to address these limitations by designing a laser-plasma accelerator test demonstrator running at a repetition rate of 10Hz. It consists in an electron laser-plasma injector (LPI) delivering a beam of 150 to 200 MeV, which is excited by an already existing high-intensity laser driver, a specially designed plasma target module and a transfer line with instrumentation measurement dedicated to the coupling to a potential future second acceleration stage for higher energy and for applications. The LPI will be studied as the first stage of a multi-stage GeV laser-plasma accelerator that could be added later on (in a second step of the project).

The performance goals of the LPI beamline are staged in 3 phases.

phase 1 [2020-2022]: simulations, definition of the optimized parameters for the laser driver, the plasma targetry and the characterization line. Construction of the laser beam transport, laser compression and laser injection and focusing. The plasma target will be designed as a module with a basic robust electron beam characterisation line constituting the minimal configuration of the LPI. The experimental R&D work is concentrated on plasma targetry and laser optimization and control. The main deliverable is the electron beam with parameters presented in table 1.

phase 2 [2022-2024]: implementation of a focusing section at the plasma output in the electron beamline . Upgrade of the laser driver to increase the beam brightness. Active control and improved metrology of the electron beam. LWFA tuning and optimization based on machine learning processes at 10Hz. Improvement of the electron beam quality and control at the exit of the plasma target is the main deliverable as presented in table 1.

phase 3 [2024-2026]: implementation of the electron transport for the injection in a second laser-plasma stage. Global tuning of the LPI. The complete LPI beamline optimized and ready for injection in the second stage towards higher energy is the main deliverable.

One can notice that parameters of the first phase are reasonable with respect to already demonstrated performances except for the reproducibility of the electron source. The third phase of the project is focussed on the development of the beam transport for the seeding of a laser-plasma accelerating stage or for direct applications[5].

The targeted parameters for the LPI are the following:

parameters	phase 1	phase 2	phase 3	unit
energy	150	200	200	MeV
charge	15-30	30	30	pC
repetition rate	10	10	10	Hz
energy spread	10%	<5%	<5%	-
emittance	1	<1	<1	mm.mrad
stability	5%	3%	1%	-
reproducibility	5%	3%	3%	-

Table 1: laser plasma injector electron beam main parameters for the different phases. For phase 3 parameters are considered at the end of the transfer line.

The construction of the laser-plasma injector test facility is based on the following scientific and technical axis:

- **PIC simulation optimization studies:** Intensive simulations with the PIC SMILEI code [6] will be performed to determine the optimized laser parameters, plasma density profile and transfer line, in order to obtain the best electron beam quality at the LPI output. Errors and tolerances will be analyzed to identify the most sensitive elements to which special attention must be paid in order to maximize beam stability in terms of energy, dispersion and pointing. All these elements will serve as guidelines for the design of the entire LPI. These objectives are in line with the development plan for the SMILEI code, an IN2P3, INP and CEA (Maison de la simulation) project.
- **Advanced laser control:** there are no intrinsic physical limitations preventing the stable operation of laser pulses in terms of energy, transverse profile and pulse length as long as the environment is stable and well characterized and disturbances are correctly anticipated

and compensated for. The control of the spatio-spectral (temporal) profile [7] of the laser pulse in the interaction volume is currently one of the technical issues to be addressed in order to allow stable and reliable laser-plasma acceleration needed to compete with conventional accelerators. A laser metrology system for characterizing the spatio-spectral phase [8]–[10] will be combined respectively with a new-generation acousto-optical modulator integrated at the beginning of the laser amplification chain to increase the correction capabilities of the spectral phase and with a large aperture deformable mirror located close to the plasma target (control on the spatial phase). This will give access to an on-line control of the laser properties (spatial, spectral and temporal) in the interaction zone. An elaborate control-command system will be developed to control, and finally to automate, systematic laser beam tuning and measurements to realize a "machine-like" optimization. The objective is to achieve an accurate control of the laser parameters at the target level including feedback loops for the pertinent ones.

- **Plasma target**: The objective is to design a plasma target with a tailored plasma density profile based on the results of PIC simulations with the support of fluid simulations. Plasma density profiles must be precisely matched to achieve the production of a good electron beam quality, by controlling the divergence and other phase-space properties [11]–[13]. A compact multi-zone plasma cell integrated as a beamline module will be developed using new opportunities in micromechanics and additive manufacturing tools. A test bench specially developed for plasma cell testing will allow the characterization of plasma electron density profiles by transverse optical interferometry. These developments should go beyond the scope of the PALLAS project and will also be useful for the development of the next generation targets for APOLLON and other laser-plasma accelerators.
- **Electron beamline, characterization and transport**: Development of a compact and scalable line of diagnostics. The electron beam diagnostics will be, as far as possible, single-shot and with an adapted dynamic range. On the basis of the first measurements and optimizations of the LPI, a section of beam re-focusing optics and an emittance measurement will be added. Then, the electron beam transfer line will be designed to capture the beam exiting the plasma and transport it to a second laser-plasma acceleration stage (not included at the present step of the project).

The project objectives are centered on the technical and theoretical key-components for the conception of a usable laser-plasma accelerator prototype.

1.2 Positioning

The aim of the PALLAS project is to make a transition from the laboratory experiment as carried out, up to now, on different power laser installations to the development of an accelerator. More specifically, it aims to design and produce a prototype laser-plasma injector, the first element of a "typical" machine based on laser-plasma technology delivering high-energy electron beams.

The project is based on the LASERIX platform, a 40TW, 10Hz laser system from the University of Paris Saclay installed since the end of 2015 in the premises of IJClab (formerly LAL) whose teams have just joined IJClab at the beginning of 2020. In addition, in mid-2019 IN2P3 and the University of Paris Saclay (ERM) financed the development of a plasma target test bench coupled to a laser beam from the LASERIX platform to test cells developed for the LPAs by studying, in particular, the time-resolved longitudinal and transverse density profiles of the plasma. The LLR, IN2P3's historical actor in laser-plasma acceleration, has expressed its interest in participating in the realisation of the electron beam characterisation line. In addition, the LLR team with its contribution to the development of the SMILEI code and its expertise in laser-plasma acceleration physics plays an indirect but major role in the PALLAS project. The PALLAS project is an opportunity for these two teams of IN2P3 labs to structure their collaboration for higher impact work in the field of LPA.

The LPA prototype will be developed in the way to efficiently control and optimize the electron beam parameters. This will be done thanks to a modular design and the implementation of a state-of-the-art control and data acquisition system: it indeed combines an innovative approach on the plasma target part combined with a complete online control of the laser pulse and the generated electron beam. Laser-plasma acceleration is based on non-linear and multi-parametric interaction. In order to get the laser characteristics and the plasma behaviour under control, advanced machine learning techniques will be used either at the modelling level and for the laser and, potentially, for the electron beam control level.

The challenge for the group is to develop technological expertise on laser-plasma accelerators at IN2P3 by promoting the LASERIX platform at IJClab, the SMILEI code and the associated teams in a unique scientific and engineering support framework. Historic collaborations with the local industrial companies, world leaders in laser systems for particle acceleration but also in high-intensity photonics, reinforce the interest of the PALLAS project.

The PALLAS project will be one of the French contributions to the next phase of the EuPRAXIA project - EuPRAXIA preparatory phase - 2020-2025 aiming at lifting the technical bottlenecks identified during the EuPRAXIA Design Study phase [14] The contribution of the CNRS will be articulated around 3 axes:

- LAPLACE [FEL demonstration injected by an LPA, development of LPA at kHz for applications] - (LOA-SOLEIL)

- APOLLON laser reliability studies towards high energy and high repetition rate - (LULI)

- PALLAS [LPI, high energy staging > GeV] (IN2P3/IJCLab+LLR, CEA IRFU).

It should be noted that the feedback from the development of plasma targets for PALLAS is foreseen to initiate future collaborations with the various laser-plasma labs (LOA, CEA, LPGP, LULI). The design and development of the beam transport and diagnostics will be done in collaboration with CEA-IRFU and LLR. A common PHD has started between the ML group for accelerators at IJClab and the LRI, giving the indispensabile expertise on automation and optimisation. The construction of a laser-plasma beamline test facility is a unique tool for the French accelerator R&D community. It will strengthen the participation of France in European projects like EuPRAXIA. The success of the PALLAS project will set IN2P3 as a major contributor in laser-plasma acceleration in France.

In terms of timing, the project is starting late with respect to the impressive recent progress made in DESY by the LUX team on the control and optimization of the electron source at 1Hz for the FEL applications. As detailed in the next section, the project had a slow start mainly due to funding issues. Nevertheless, the control of the electron beam charge, emittance and energy stability is still not mastered at the desired level of accuracy. We still believe with the present team and collaborations that the construction of a LPI test facility at 10Hz will push on the field. Beyond that, the project aims to make significant breakthroughs in the technological development in key-components of a

LPI by 2026. It will allow fostering French collaboration at the national level and serve as a dedicated test facility in the frame of the European EuPRAXIA initiative.

1.3 Project history and roadmap

The **scheduled deadlines,** events and **major milestones** of the project are the following:

- **2016-2019** - various attempts to mature laser-plasma acceleration projects, initially by coupling PHIL and LASERIX (K. Wang PHD[15]) in an original way with the ESCULAP[16] project aiming at external injection of a laser-driven plasma accelerator at low energy. The project has been discontinued for technical and financial reasons. Then the PALLAS and LAPLACE projects as French contributions to EuPRAXIA have been proposed within a national consultation process organised by the GDR APPEL. In the framework of these projects, the LASERIX platform has begun the necessary studies concerning the evolutions of the laser and the definition of the work required to transport the laser beam into the NEPAL radiation shielded area where the experiments will be carried out with the development of the LPI prototype.
- 01/2020 – meeting DAS/IJClab/LLR – (KDP0)
- 01/2020 – PALLAS project support for integration of envelope coupled to ionization in SMILEI.
- 04/2020 - creation of the master project PALLAS at IN2P3
- 06/2020 - Launch of renovation work in the NEPAL(PHIL) hall supported by the CPER fund.
- 07/2020 – first ionization injection simulation with 2-zone density profile - new version of SMILEI.
- 09-12/2020 – consortium agreement EuPRAXIA – preparatory phase.
- 09/2020 – key decision point on the financing of the air conditioning unit (grant for energy recovery sustainable system from the minister).
- 11/2020 - IJClab scientific council audition
- 12/2020 - PIA3 – PACIFICS ranked A, giving a critical opportunity for PALLAS funding – pending budget arbitration
- 12/2020 – installation of the plasma cell (target) test bench on a new beamline of LASERIX
- 01/2021 – application for authorization to the nuclear regulation safety French agency (ASN)
- 02/2021 – end of the civil work in the NEPAL radiation-shielded area, beginning of laser beam transport line installation
- 01/2021 – meeting DAS/DT/IJClab/LLR – (KDP1)
- **09/02/2021 – IN2P3 scientific council**
- 06/2021 – project review
- 09/2021 – laser delivered and optimized in the NEPAL experimental area, first plasma target prototype
- 11/2021 – installation of the plasma module
- 01/2022 – project review
- 02/2022 – installation of the first characterization beamline
- 03/2022 – feedback from the ASN and authorization to start the accelerator.
- **04-06/2022 – LPI beamline ready for the first electron generation**
- **12/2022: optimized LPI @ 150MeV – end of phase 1**

- **06/2023: optimized LPI @ 200MeV with laser upgrade >80TW – phase 2**
- **2024-2026: optimization of beam transport for staging – phase3**

This document concerns phase 1 of the PALLAS project. Phases 2 and 3 are subject to the arbitration of the additional PIA3-PACIFICS funding which will provide a major part of the required budget for a full realization. The final decision is expected at the beginning of 2021. The ASN firing authorization will give the starting point for electron beam production. An authorization occurring after 03/2022 will impact the project schedule. Despites the pandemic situation the project was slightly drifted by a few months in 2020.

The project roadmap is to achieve the development of the complete optimized LPI by 2026 and prepare the staging to go towards higher electron beam energy. Within the EuPRAXIA framework, participation in technical design reporting is foreseen to prepare staging and continue the R&D beyond the PALLAS project. In addition, the availability of a compact ultra-short and bright electron source reaching control and stability standards of conventional RF accelerators will open new applications, in medical sciences for example.

1.4 Technological R&D context

In this section, we detail the critical technological developments in the project and put into context the transition initiated by different groups towards laser-plasma accelerators. The benefits of the laser-plasma injector test facility proposed at IJClab based on the LASERIX laser driver are explained briefly. For more detailed technical information, the development plans are discussed in the project description (2.2, annex 4). The simplified product breakdown structure of the whole LPI in phase 1 is given in the section 2.1 with a more detailed approach.

Plasma cell target

A multi-zone tailored longitudinal density plasma profile plasma target is crucial to control the multiple physic coupled process occurring for:

1. Laser self-focusing
2. ionization injection control of electrons.
3. Electron bunch acceleration
4. Electron beam quality and matching to the beam transport

This is a technological development (TRL3->TRL6). The plasma target concentrates part of the innovation foreseen in the project. It is the heart of the "machine" and contains miniaturized gas cells constituting the medium for creating the plasma and the accelerating and focusing wake wave co-propagating with the laser. The development plan is based on the following cycle: determination of the ideal density profile by PIC simulation of laser-plasma interaction and acceleration (SMILEI); fluid/micro-mechanical design; tests and measurements of the density profile with the dedicated plasma cell testbench developed in the LASERIX room. Consequently fast prototyping of plasma targets prior to installation in the LPI beamline will be possible. Several groups in the field are working on plasma targetry development [17], [18] for laser-plasma acceleration. Our approach for the plasma cell design being close to the one developed in DESY [19] is also unique as the cell is directly integrated in the beam line as a component and offers a free optical access for transverse beam probing, without the need of a vacuum interaction chamber with differential pumping. This particular feature will enable accurate tuning of the longitudinal plasma profile, with easy exchangeable configuration.

This development is strongly linked to the development of the SMILEI code. As an example, the latest developments carried out by the SMILEI team at LLR and supported by the PALLAS project have made it possible to divide by 20 the computation time. The phasing between the PALLAS project and the SMILEI code development plan is excellent if the resources are confirmed in the future to reinforce the SMILEI team at the level of the institute. The few published comparisons between numerical simulations of LWFA and experimental data generally conclude that PIC simulations fail to reproduce accurately and quantitatively what is happening in the laboratory. The total injected charge (for injectors simulations) and final emittance of the accelerated electron beams are especially coarsely estimated. The reasons for this are now partly understood and a path towards high fidelity simulations emerges. First of all, the initial conditions of the simulation, and in particular the accurate characterization of the laser, are of paramount importance [20]. Then, it appears that a very high resolution is required in order to evaluate the emittance correctly [21]. At the level of IN2P3, we propose to leverage this collaboration opportunity between the numerical and experimental communities to achieve the following objectives

1. Improve simulations fidelity by developing new numerical techniques and confront them directly to experimental data.

2. Propose, realize and interpret numerical simulations to support experimental designs and understand the collected data.

Numerical simulation is playing a major role in the plasma physics community in general. Many active agents of "Plateau de Saclay" , but also at the international level, have already gathered around the project SMILEI [22] which aims at developing an open source simulation code relevant for our applications. With the first exascale supercomputers arriving at the horizon 2020, unprecedented possibilities will become available but standard numerical simulation methods have to be completely reshaped in order to fit the new architectures requirements. New approaches have to be developed in order to combine high performance and high fidelity. For 5 years now, the SMILEI community has tried to gather state-of-the-art techniques in a single, open source tool by constructing collaborations with other communities sharing a common numerical expertise. Within the SMILEI team, the LLR is in charge of the developments dedicated to plasma acceleration. A collaboration with Apollon's operators has started for realistic accounting of the laser initial conditions in the simulations and will also continue within the PALLAS project. SMILEI team is aiming to further improve simulation fidelity for LWFA by implementation of *perfectly matched layer* [23] boundary conditions and spectral solvers. This would be a major innovation and a step towards a more realistic evaluation of the beam emittance. Simulation performance will also be enhanced by extending the Cartesian adaptive vectorization technique to our quasi-cylindrical solvers and porting the code on GPU architectures.

High Intensity Laser Control

Laser intensity at the interaction area, beam pointing and spatial and spectral phase parameters are mandatory as inputs in the simulation. Many measurement subsystems for metrology are commercially available, but implementation and combination for single shot characterization at 10Hz is not obvious (*TRL5->TRL7*). Side project at the laboratory is aiming to implement a new combination of detectors for advanced control of the spatio-temporal laser pulse in real time

(P2IO-emergent project ML-COLA)[1]. The 40TW LASERIX beamline dedicated to the project is propagated under vacuum from the laser room to the NEPAL radiation shielded area where it is compressed down to 40fs in a large 300TW already existing compressor, then spatially corrected and focussed into the gas cell target. The laser beam wavefront correction is ensured by a large aperture deformable mirror[24] set at the immediate exit of the compressor. The femtosecond compressed laser pulse is then sent to laser injection and focusing high vacuum chamber where all the necessary laser diagnostics for accurate control are embedded and monitoring the laser beam on a leak behind the last folding mirror before the target.

Active laser control implementation of direct laser feedback on the electron beam is aimed. A continuous operation at 10Hz is aimed, which is substantially higher than previous works in this energy range [25], [26]. The key point, beyond complete single shot characterization of the laser pulse, is the control command running with common standards (Tango controls, high speed data network, time-stamping and data archiving).

Laser driver extraction, focusing/capture section and online diagnostics

Accelerated electrons exit the plasma target collinear to the high intensity laser beam making it difficult to insert close diagnostics, except for the dipole spectrometer which deviates charged particles thanks to a strong permanent magnetic field. Electromagnetic noise generated by the plasma and the intense laser pulse adds constraints. The implementation of the first electron beam optics and laser extraction strongly depends on the technical choice and the compactness notably imposed by the configuration of the experimental premises. One particular challenge is the matching between the focusing strength of the wakefield and the first electron beam optics of the line[13]. The control and design of the density ramp at the exit of the plasma cell is crucial. The plasma test bench will allow characterization of plasma density ramps and geometrical optimization.

The main diagnostics for the electron characterization are technically available, but the particularity of the electron beams produced by the LPAs requires dynamics adapted to the low charge but high peak current in single-shot or high-repetition rate (10Hz) operation. Specific R&D in beam instrumentation is therefore necessary to carry out advanced diagnostics of those beams. The compactness of the LPAs lines and the presence of an intense laser beam at the output of the plasma module are technological challenges. The availability of RF conventional operation electron accelerators at IJClab (PHIL, ThomX injector) is allowing on-site possible testing of the developed electron diagnostics.

Few groups have been working in the LPA beam transport for FEL application (COXINEL project)[27], [28] prototyping permanent quadrupole triplet for staging (Dactomus project) [29]. One has to mention the ongoing ARIES WP18 project to build a multi-stage LPA using both PW laser beam arms to reach >10GeV beam [REF].

We consider that the electron beam transport for staging is one of the technical challenges to achieve a LPI delivering high quality beam for an optimal matching to a second plasma stage. Several strategies are foreseen [30] based on possible linear chirp control of the electron bunch or

[1] ML-COLA project is aiming to develop a prototype of single-shot online spatio-spectral characterization of an intense femtosecond laser pulse combining spectral phase measurement, multi-spectral CMOS and machine learning for the full laser field reconstruction. Project is running for 2 years. The developed laser diagnostics is foreseen to be implemented in the laser diagnostics set embedded in the LIF module, see fig. 1 and fig. 3..

optimized matching of the Twiss parameters combining plasma ramps and apochromatic quadrupoles [31]. Nevertheless, at this step of the project the technical beam transport issues are not discussed. This will be addressed later on, after the beginning of phase 2 centered on the optimization of the electron beam at the immediate exit of the plasma cell. Feedback on the robustness of the control of the beam will be launched in a technical design study. The collaboration with CEA-IRFU, one active member of the EuPRAXIA conceptual design study on electron beam transport in the frame of the PACIFICS -PIA3 project, is strengthening the PALLAS project.

Beam time and LASERIX facility access

The LPI beamline is dedicated to the PALLAS project with a full power laser beam time availability of 22 weeks per year with a dedicated experiment area available all the time. This beamtime corresponds to the full power laser beam in the new laser beamline serving the NEPAL radiation shielded area.

2 Description and organization

2.1 Project breakdown structure

A simplified scheme of the LPI beam line is given in the figure 2 illustrating the LPI beamline.

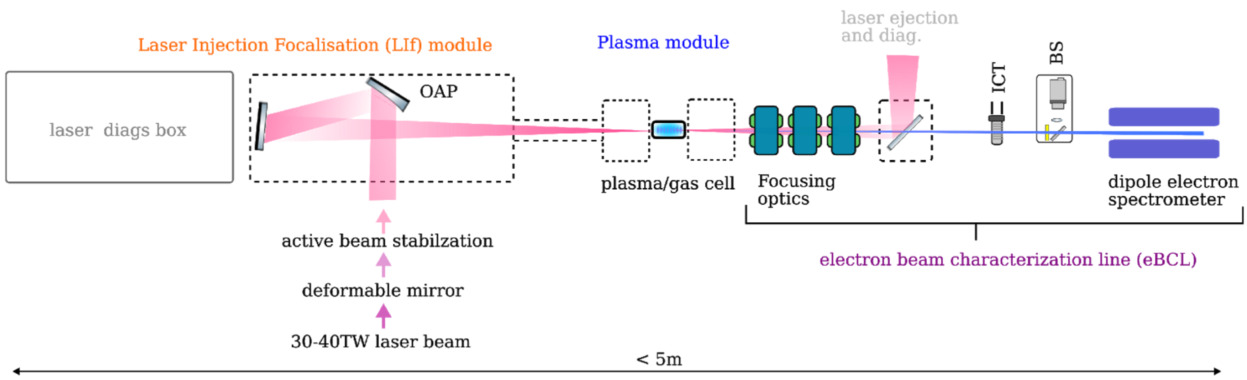
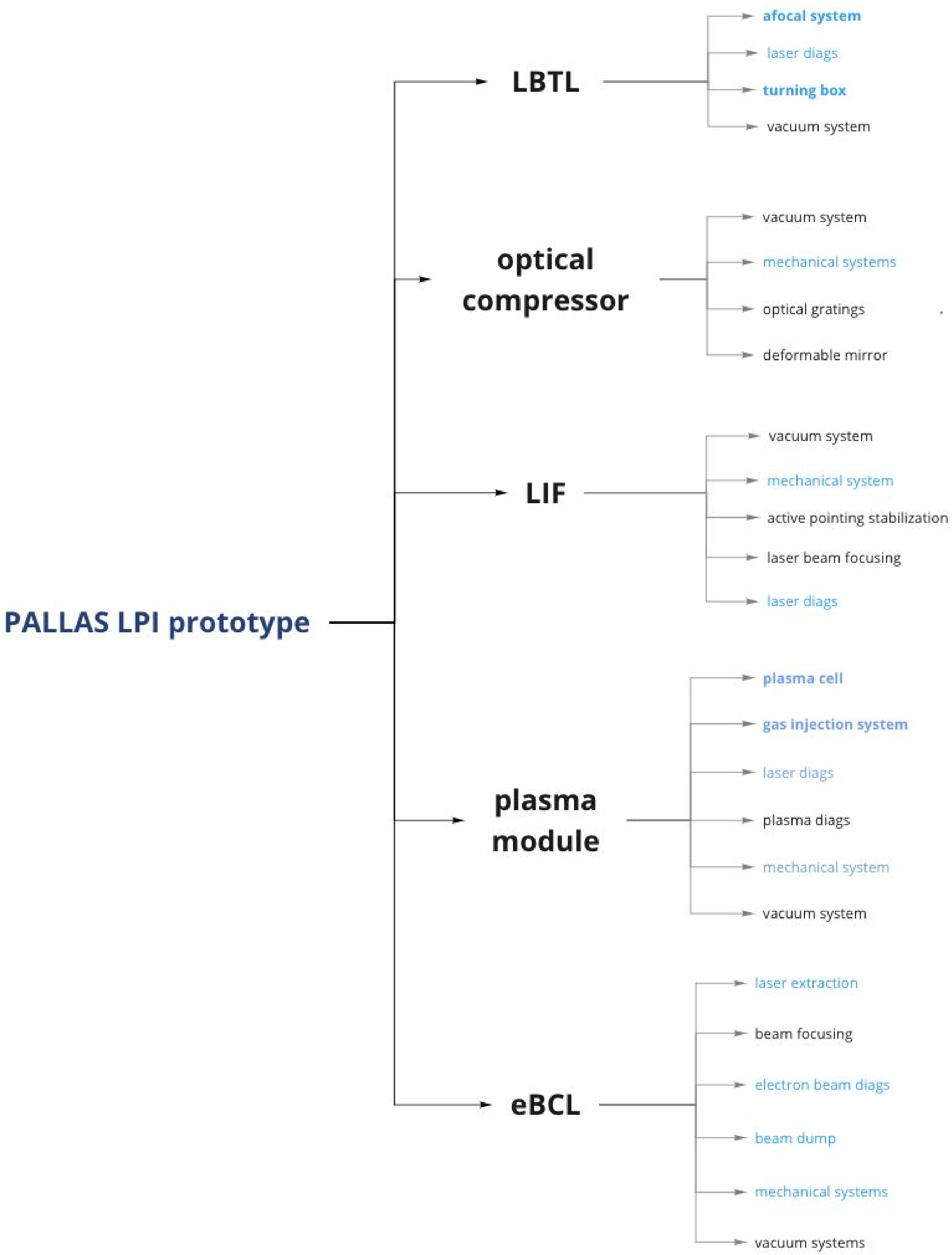


Figure 1 - simplified scheme of the LPI beamline in phase 1.

The simplified view of the product breakdown structure is shown below. In colored text the elements are realized internally and being subject to development.

The laser beam transport line (LBTL) and the optical compressor are the systems allowing the delivery of the high intensity laser beam to the LPI beamline which is composed by the laser and injection focusing (LIF) module, the plasma module and the electron beam characterization line (eBCL).


PALLAS LPI prototype
LBTL
afocal system
laser diags
turning box
vacuum system
optical compressor
vacuum system
mechanical systems
optical gratings
deformable mirror
LIF
vacuum system
mechanical system
active pointing stabilization
laser beam focusing
laser diags
plasma module
plasma cell
gas injection system
laser diags
plasma diags
mechanical system
vacuum system
eBCL
laser extraction
beam focusing
electron beam diags
beam dump
mechanical systems
vacuum systems

2.2 Technical approach

The project technical aspects are detailed for the phase 1 configuration of the LPI beamline.

2.2.1 Implementation of the PALLAS beamline

The LPI beamline is sharing the NEPAL radiation shielded experimental area with the PHIL photo-injector. The reserved area for the LPI beamline is 8mx(2-2.5)m. The experimental hall has been renewed with a AC unit for thermalization of the area and cleanliness (ISO8), closing and thermal isolation of the technical corridor and RF room ceiling.

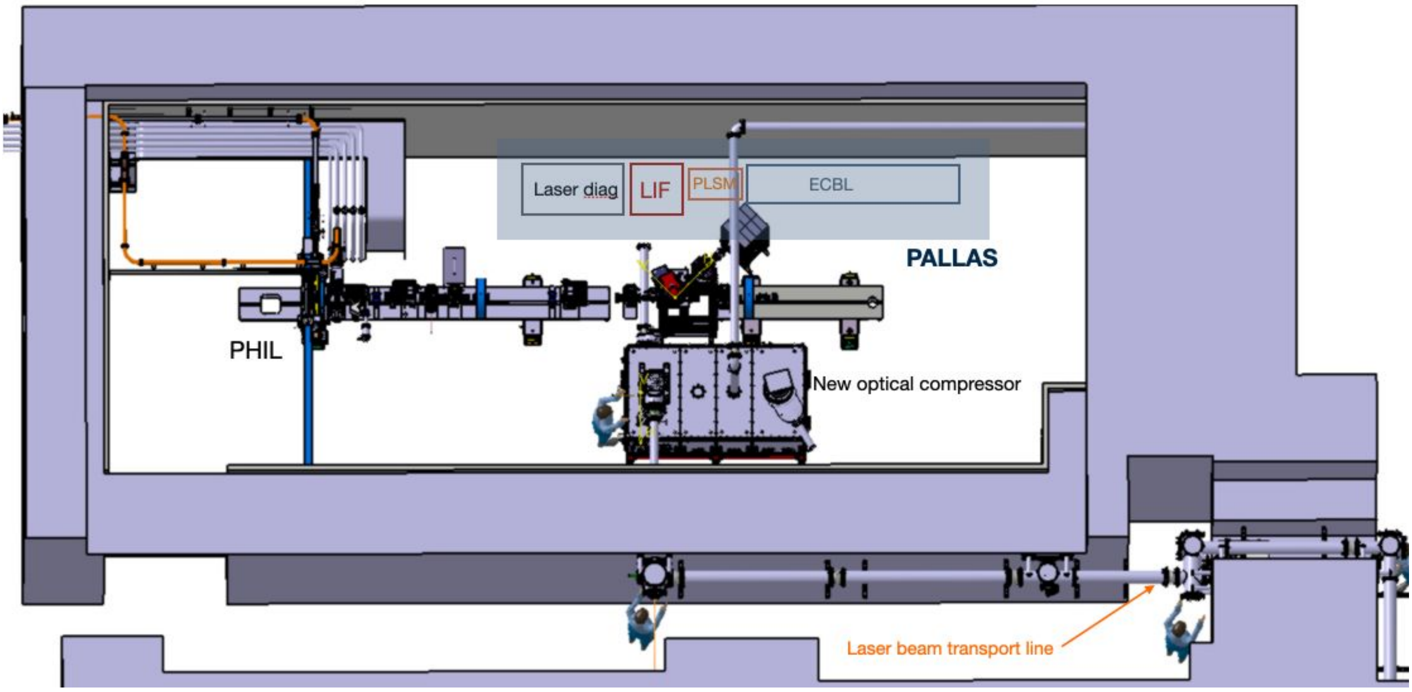


Figure 2 - :top CAD view of the NEPAL experimental hall with the PHIL accelerator and future implementation of the PALLAS LPI beamline with the new optical laser compressor and laser beam transport line

A new technical room (not visible on the figure 1, located on the top right corner) has been constructed to host a primary vacuum pump for evacuation of large vacuum vessel and plasma module differential pumping and the control command server, network switch and data storage. A new network for a high data rate acquisition is being installed in the NEPAL hall.

2.2.2 Laser beam distribution to the NEPAL area

The 2 joules, 500ps stretched laser pulse is propagated under vacuum up to the 300TW compression chamber located in the NEPAL area. All opto mechanical mounts are decoupled from the vacuum for higher stability. The laser beam is up-collimated using a x2.5 imaging afocal arrangement installed in the propagation beamline. The laser pulse compression is realized down to 40fs (future improvement can reduce duration down to 30fs) then the laser beam is reflected by low incidence angle large aperture adaptive mirror. The laser beam is sent to the focusing module (LIF) with a set of large aperture lightweight SiC high reflectivity mirrors mounted on high bandwidth piezo actuators (resonant frequency ~ kHz). The LIF module is associated with an optical table arranged for real time beam control and characterization. It is designed to focus the beam with a high quality long focal off-axis parabola, with an optimized sampling for online complete spatio-spectro-temporal beam metrology (Fig. 3).

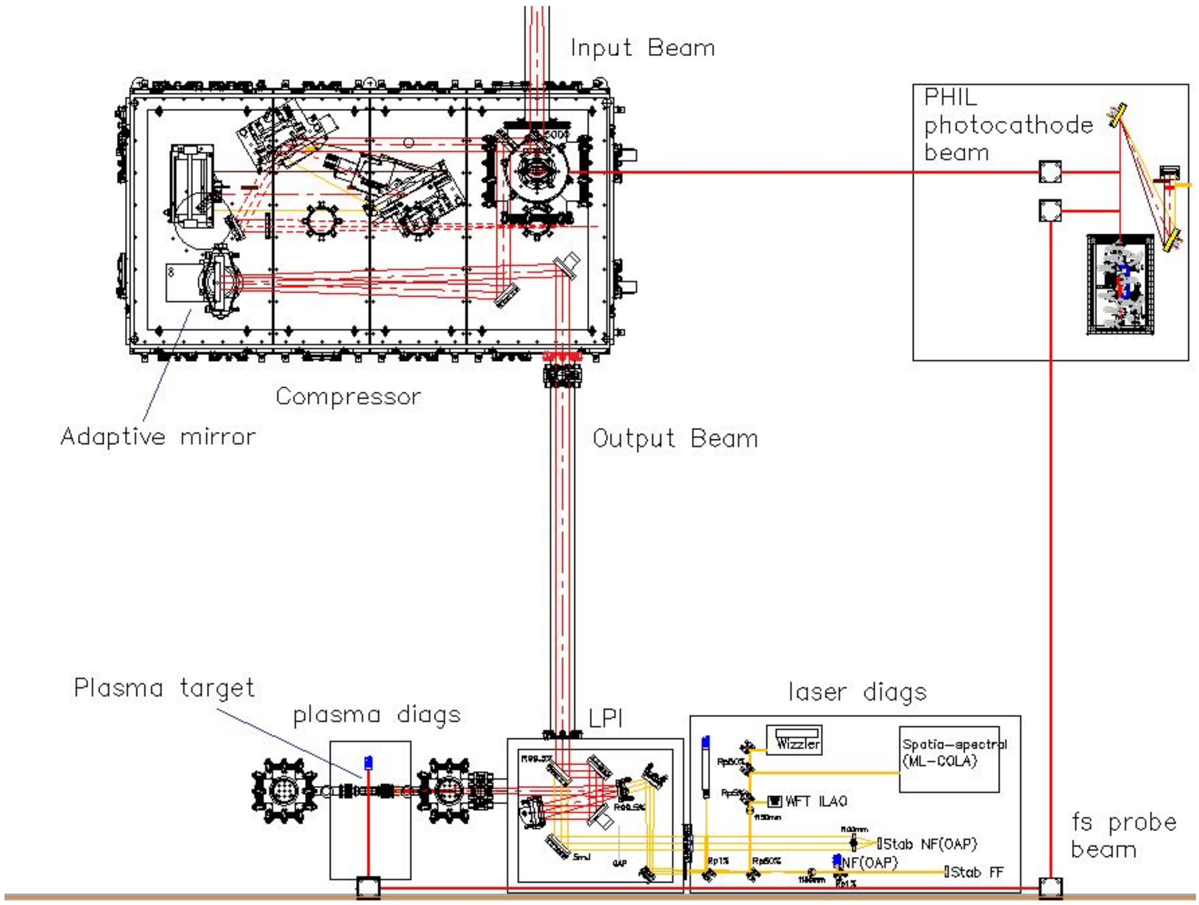


Fig. 3: Top-view of the laser compression and laser injection focusing module up to the target. The PHIL accelerator is hidden for convenience. The right part is dedicated for the PHIL photocathode excitation, with a beam coming directly from the LASERIX front-end. It allows a synchronous fs beam probe for plasma characterization if needed.

With such arrangement it is foreseen to achieve sub-urad beam pointing stability at the focal spot of the laser focusing optic and maximum drift at the few urad level.

The foreseen laser parameters for phase 1 on target are given in the table (tab. 2) .

laser parameters	value phase 1	value phase 2,3	error/tolerance	units
central wavelength	815	815	+/- 3	nm
energy [2]	1.46	2.92	+/-0.12 (0.21)	J
waist	18	18	+/-2	um
Rayleigh length[3]	1.27	1.27	+/-0.26	mm
pulse length	40	30	-5/+0	fs
Intensity on target	3.	8.3	+/-1 (3)	10^{18} W/cm^2
a_0 in vacuum	1.18	1.9	0.2	

tab. 2 - laser parameter on target for different project phases .

It is important to note that the error or tolerance is on the setting value due to uncertainty coming from the tuning of the laser beam transport and compression giving the most stable beam on target. The objective is to achieve 1% (rms) stability on the pulse duration ,<1% (rms) stability on the integrated energy and push phase and spot size stability to less than 3% (rms) by careful tuning of the in-line wavefront sensor-deformable mirror close loop.

One important feature of the laser is the ability to produce a pre-pulse collinear to the main pulse with controllable delay and contrast. In the considered laser upgrade of phase 2, a pre pulse can be used to stabilize laser self focusing and reduce beam pointing instability of the electron beam. This laser configuration has been developed and operated for years on the LASERIX facility for the EUV x-ray laser beamline[32].

2.2.3 Control command system

The control command system will be designed specially for PALLAS, based on the framework TANGO controls [33].

This design will take into account different points :

- Dedicated network
- Local storage and data policy
- TANGO based system
- Preparation for advanced optimization and coupling to external system like machine learning solution

[2] on the off axis parabola. Assumption an optimized wavefront correction at focus giving a strehl ratio of 0.8

[3] Assuming a gaussian transverse envelop with the corresponding waist

The network has to manage more than a hundred connected devices. Some items, like cameras, have high data rates and need 10Gb/s links. The core infrastructure is a 10 Gb/s full link switch with links to the three main concentration points and with direct connection to the servers.

The system Infrastructure will embed a data storage server to bufferize all produced datas and hosts databases needed for TANGO and data logging also. Datas produced are temporarily stored on a local data server before copying to IJCLab main computing room and probably to CC IN2P3 Lyon.

We chose TANGO system to mutualize development with other IJCLab experiments and speed up development and deployment. TANGO is based on a low level device server which controls equipment and is designed to add an upper level device server which adds intelligence to the system. The main issue of this project is to monitor finely multiple parameters with their correlations, this kind of adaptive topology is fully adapted to the present problem.

The TANGO solution will collect data and provide an entry point for complex systems which can be used to detect automatically errors or incoherencies based on machine learning solutions. With the TANGO system, we have the possibility to add easily specific device servers, dedicated to this need. Through TANGO, this specific device server has access to all PALLAS controlled parameters, without adding incoherency in the system.

2.2.4 Plasma cell targetry

Our approach is based on the following assumptions:

- control the ionization injection by unmatched laser condition $k_p \neq 2\sqrt{a_0}$ [34] and tailored plasma density profile, laser focus in vacuum position after the target [35].
- continuous steady state gas flow, geometry preserving laminar flow condition
- mobile target, fixed laser beam
- pumping speed matching staged pumps at the input and output of the plasma cell target
- scalable to high repetition rate
- “chair-like” longitudinal density profile

The main constraints are :

- target stands for at least one day of operation (>10^6 shots) with cells aperture $d_i > 10w_0$
- integration of first the focusing beam optics
- optical transverse access for interferometry measurement of the plasma density.

The plasma density profile used in the preliminary simulation studies is inspired from various publications [36]–[38]. An illustration is given in figure (Fig. 4). The simulations using SMILEI with envelope approximation [39] and the laser cylindrical symmetry show a localised injection and control of acceleration and charge injection. First CFD simulations using achievable geometry from a mechanical point view, show chair-like density profiles similar to the ideal profile used in the preliminary studies, except for the input gradient which is smoother.

The preliminary studies (CFD, conductance calculation and PIC simulations) and already published works confirmed that our technical approach is based on realistic assumptions.

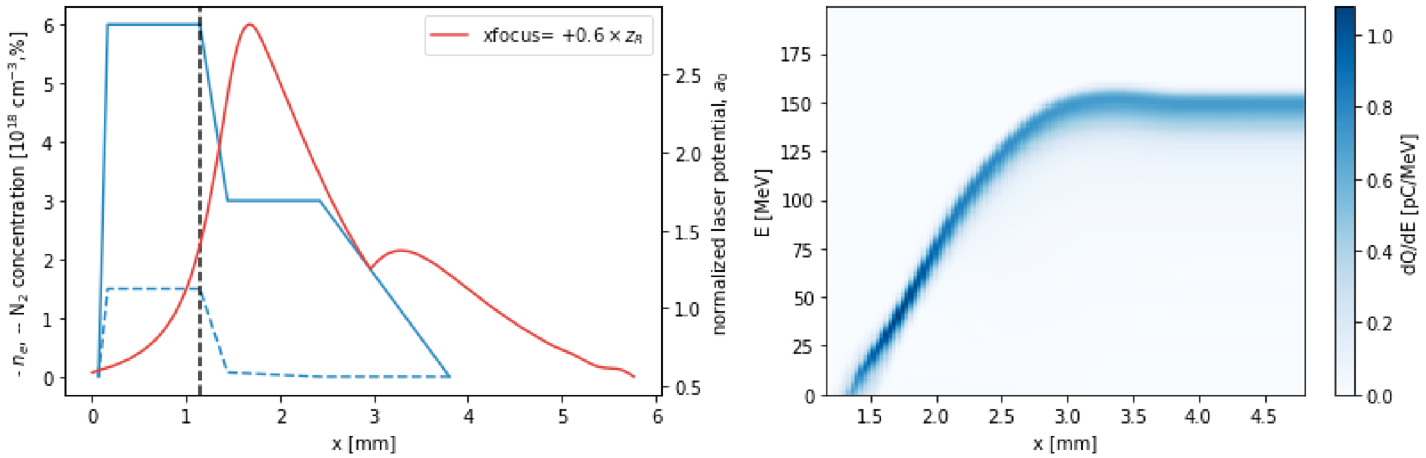


*Fig. 4 - : as an example preliminary results (left) a longitudinal plasma density profile and evolution of the normalized potential vector of the laser. The dopant concentration of N_2 is plotted in a dashed line is localized on the first zone due to injection in the only in the zone 1. The laser evolution corresponds to an offset of 0.6*zR in vacuum of the laser waist with respect to the beginning of the down ramp (vertical dashed black line) . (right) the corresponding energy spectrum of the accelerated bunch.*

The plasma target development plan will start with the realization of some first prototype cells for the benchmarking of the fluid simulation. Typical cell geometry and corresponding gas flows (sharp down ramp between two density plateaus, smooth linear and quadratic out ramp …) will be tested. In the meantime, the test cells developed will be used to evaluate concepts for the micro-assembly of the central body of the target and the optical diagnostic windows. Then after validation of essential geometry, the prototype cells for the LPI will be developed.

The development plan of the plasma component for the LPA and LPI is illustrated on the figure (Fig. 5). The results of the PIC simulation studies will provide a reference density profile as input to generate a rough internal volume definition. The rough geometry is elaborated using simple analytical conductance and gas flow conservation between sub-cells in laminar regime. The fluid simulation will be performed using OpenFOAM with the snappyhexmesh routine for the geometry import and meshing definition and the rhoPimplefoam solver [40]. The cell geometry will be optimized to get the longitudinal density to fit the reference density profile.

Measurements on the plasma cell test bench (fig. 5) will be confronted with both CFD and PIC simulations.

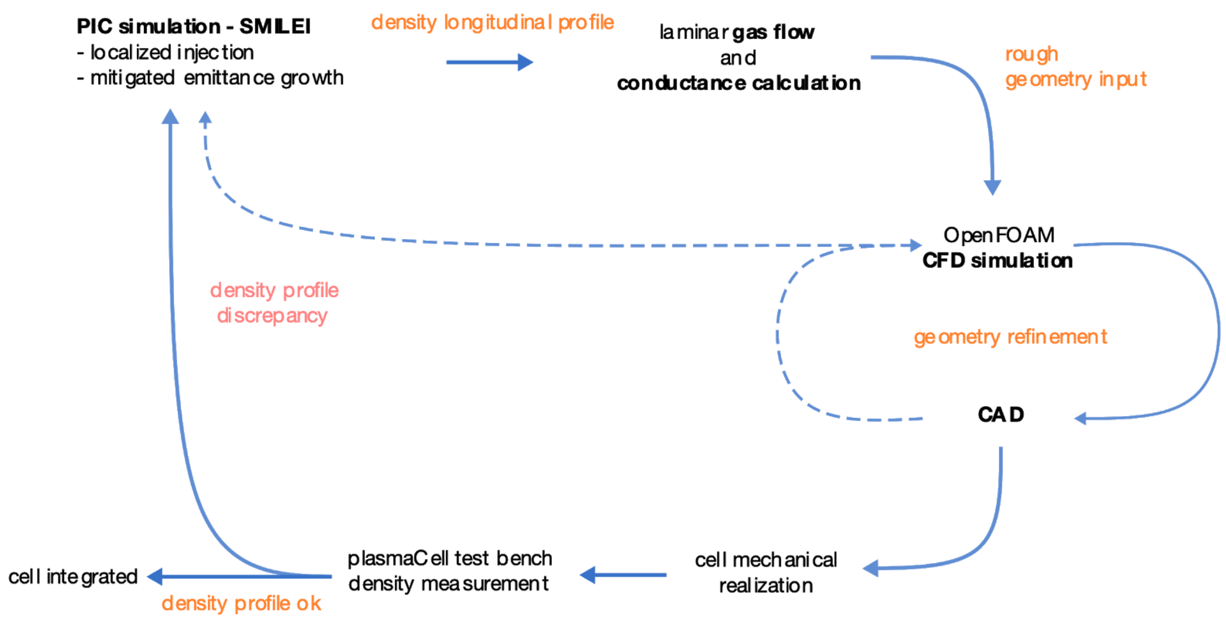


Fig. 5 : process of plasma cell optimization

One important tool is the availability of the plasma cell test bench (fig. 6) with dedicated laser

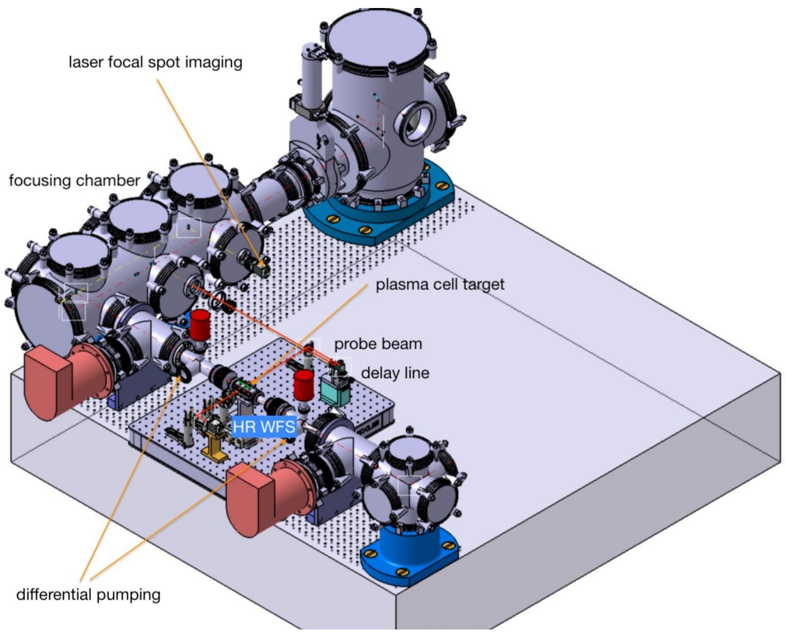


Fig. 6. Plasma cell test bench CAD view

beam line to measure longitudinal profile with wavefront sensor-based density measurement [41] giving access to density measurement with a few tens of micrometer resolution in space and electron density measurement sensibility of $3 \times 10^{17} cm^{-3}$ [42]. The plasma cell test bench has two

40fs pulse duration laser beams synchronized at the femtosecond level: the main beam with an energy of 250mJ reaches $8x10^{16}$ $W.cm^{-2}$ at the target test area. The probe beam can be delayed up to 300ps with a step of 5fs. This setup can be replicated later on in the NEPAL installation if needed as represented in figure (fig. 3). The plasma cell test bench is being commissioned at IJClab.

2.2.5 Electron beam characterization line

The usefulness of the characterization line of the electron beam from the plasma laser accelerator is twofold : (i) it must be able to characterize the performance of the laser-plasma acceleration including for the first experiments during which the beam will be unstable shot to shot. This phase is crucial, since it will allow us to refine the parameters of the target plasma cell and the laser to increase the shot-to-shot stability. For this, we need to provide a "simple" and versatile line with elementary and robust diagnostics allowing us to measure the orbit, the charge, the energy, the divergence as well as the energy dispersion. (ii) It must be able to match the electron beam for a second stage of laser plasma acceleration. A new line able to compensate the electron pointing instability, to match the electron beam duration, and the twiss parameter to the second stage should be designed following the first characterization and optimization done.

The strategy is to start from SMILEI simulations of the plasma cell by taking a consistent margin factor for twiss parameters and energy dispersion. The first step will be to refocus the beam either at the source on the same principle as the photoinjectors, or with electromagnets as close as possible to the plasma cell. The constraints of space, cost, infrastructure and feasibility of magnets will be taken into account from this first step, as the laser pollution and a way to suppress it from the electron path. Simple diagnostics will be installed such as YAG screens, lanex large enough to visualize the divergent and unstable beam in position, faraday slices (which are much more accurate than ICT) and ICT for shot-to-shot charge measurements. Three consecutive screens will allow us to measure the divergence and estimate the emittance of the shot-to-shot beam. A spectrometer with a wide acceptance in energy and beam diameter will allow us to qualify the accelerator gradient and the energy dispersion. Ideally, the alignment of the electromagnets should be controlled. Correctors and BPM should be foreseen at this first stage to manage the orbit with matrix response as in the Coxinel line [28] . Even if it is not an online correction, but, shot after shot, it enables an increase of the number of beams to be diagnosed.

This first electron beam characterization will have to be correlated with the plasma and laser characterization in order to search in an iterative and intensive way the key parameters for a shot-to-shot stability and control of the beam. At this stage, strategic development based on machine learning should be used with the collection of shot to shot characterisation and adapted numerical correction. Finally, we will insert additional diagnostics previously tested on conventional accelerators (PHIL being ideal with the use of the same laser and its own inherent jitter and intensity fluctuations) to characterize the duration and the profile of the shot-to-shot electron bunch, since it is a key parameter for the realization of the transport to the second stage. Single shot electrooptical sampling and THz streaking methods are considered. THz streaking has the advantage combined with a spectrometer to directly access the longitudinal phase space. These two methods also have the advantage of using the same laser as for acceleration with a natural synchronization.

Once we have the first reliable measurements of the beam properties at the plasma exit (pointing, twiss, energy, energy dispersion), as well as the adaptation needs, we will be able to start designing the line for the second stage assuming a duration and a chirp. In a classical way, the line must take into account the specificity of laser-plasma accelerator, i.e. strong divergence, shot-to-shot instabilities of the pointing and properties, strong energy dispersion. The electron bunch will thus undergo an elongation due to the difference in the path of the particle trajectory during focusing, and due to the energy dispersion. The chromatic effects will be important and will have to be compensated. As for the space charge force, the more energetic the beam will be, the less sensitive it will be, an energy of 200 MeV is expected. However, if the energy gain is at the expense of stability and energy dispersion, a compromise will have to be made to optimize the second stage. Diagnostics will also have to be placed at the end of the transport in order to verify the expected properties such as Twiss parameters, dispersion and duration, based on similar diagnostics as those used for the first characterization. We will use adapted calculation codes based on the 6D phase space expected by the plasma laser simulations, which will be in agreement with the first characterizations of the beam. We can cite Astra, robust for the space charge force, the code co-developed with Soleil CODAL (used for ThomX) for which we master the physical models of the different effects: space charge force, CSR (Murphy or Zhou), impedances, energy broadening (often neglected in the codes), as well as robust tracking. We will of course do cross simulations with other codes such as tracewin or elegant. Attention will be paid to chromaticity, its correction, and to the multipolar orders of magnets.

2.2.6 Task list

A list of tasks organized according to the PBS is given in annex 1. Integration tasks are not shown. For the initials and abbreviations refer to the list of project members and service acronyms. The CP column indicates the tasks on the critical path.

2.3 Responsibilities

The responsibility assignment matrix is given in annex 2.

2.4 Organization

The initial phase of the project is based on a strong commitment from the different IJCLab divisions. In the long term LLR may have a more important role according to the load on the APOLLON long focal laser-plasma acceleration experiment now starting.

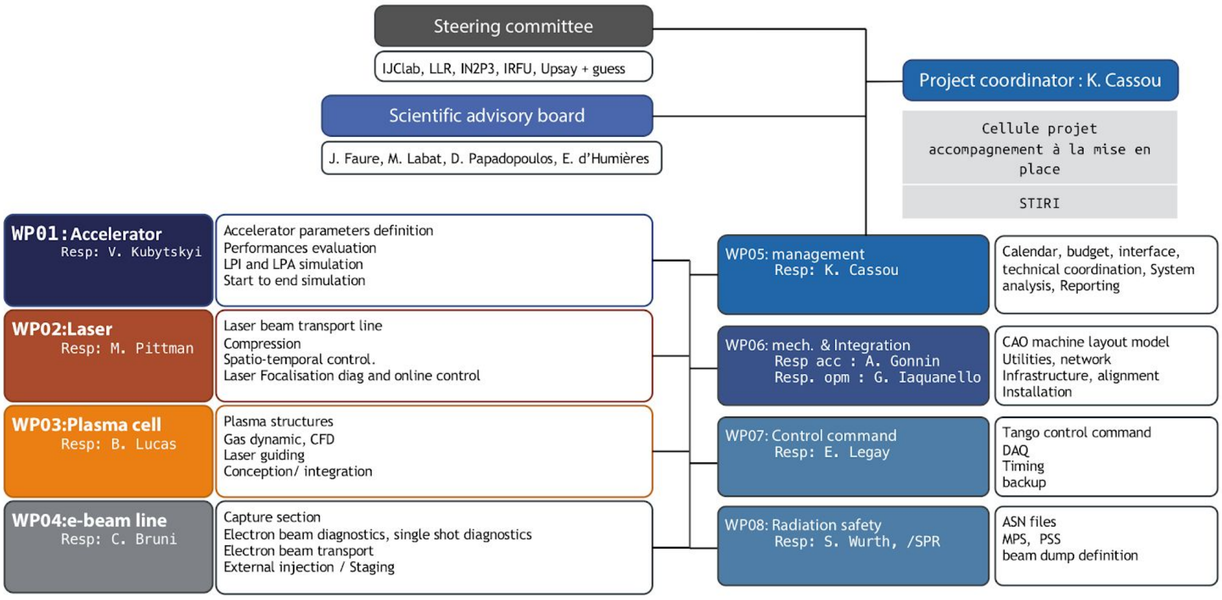


Table 4: PALLAS project organization, work package and main task and subject.

Monthly meetings bringing together the entire project group for general information and follow-up on specific issues are necessary. Thematic/technical meetings are organized with external actors and guests at the necessary frequency. The reporting is currently ensured by the project coordinator. The centralization of the documentation has started on ATRIUM. The project having really started during the COVID19 period, a rhythm has to be found for the group. The monitoring of the project will be carried out in a collaborative way on the cloud based OpenProject platform. A mailing list is set up for all the actors of the PALLAS project.

The validations are carried out by the technical coordinator and the person in charge of each WP. A steering committee is to be set up with a representative of IN2P3, University Paris Saclay, Accelerator department management, representative of the directors of external laboratories (LLR, LCP, IRFU) and companies in case of a joint laboratory. The steering committee will evaluate the phases and authorize the continuation of the project according to the funding. It will validate requests for changes in scope or program presented by the project team.

The scientific committee board is to be appointed, it is consultative and will have the role of advising the project team, especially during reviews on the scientific and technical aspects of the project. This committee will be composed of the following experts: J. Faure (LOA: world known laser plasma accelerator experimental expert), M. Labat (Soleil: specialist of free electron lasers and magnetism, member of the COXINEL project), D. Papadopoulos (LULI: laser expert, head engineer of the APOLLON laser), E. d'Humières (Université Bordeaux Aquitaine: expert in numerical simulation of laser plasma interaction).

2.5 Risk analysis

A first risk analysis is presented. It does not include the obvious risk of limited resources, which implies that the leaving of one person may compromise the proper execution of the project.

Procurement risks are not indicated at this stage, but some are already well identified. The closure of the workshop may complicate the installation phases and increase subcontracting costs. The project is based on the LASERIX platform of the University Paris Sud whose support via the MRM program is an annual operating budget of 130k€ (including ~75k€ for maintenance contracts). With the creation of the University Paris Saclay the visibility on the continuation of the support at its historical level is not clear for the moment but the direction of IJClab is aware of this key aspect and will defend the project inside the new Paris Saclay structures.

In addition, with the PALLAS project the LASERIX platform creates a new high energy laser beam line (transport line + compressor) whose maintenance and operation are not covered by the MRM. An additional 25k€ support arrowed towards the platform (covering the maintenance of the independent air conditioning and air treatment unit, maintenance contract for the vacuum pump and optics of the laser transport to the bunker) has been requested from the laboratory within the framework of the yearly funding call of the CNRS institute at the lab level.

ID	O	risk class*	events	description / causes	effects	C	actions	resp.
1	2	F,E	CTA non installé avant 03/2021	labs is not eligible to the CEE funds	delay laser commissioning		temporary operation is possible with the 2x50kW old colling group.	MP
2	2	F	strong cut in the PIA3	budget available at IN2P3 and labs can not cover the starting fund necessary	loosing interest in the international competition		PALLAS scope as to be redefined, centered on simulation and plasma cell development	all
3	1	B	optical grating of the compressor damaged	new gratings but stored for 10 years	> 12 month delay		quick inspection asap, budgeted spare in PIA3	MP
4	3	B	laser oscillator unstable	original oscillator (femtosource) complety customized	limiting beam availability, limiting engineer availbility for other task		budgeted new industrial high stability fs oscillator in the PIA3	MP
5	2	B	not achieved performances on plasma cell	not standing laser damage, evolution of ramp in time, uncontrol in/out pressure gradient	unstable e- beam, performances not reached		test bench developed on purpose to limit risk. Alternative design are foreseen. PHD on this task	BL, SK
6	2	B	laser performances not reached	WF spatial quality, defect in the optic line, Strehl ratio < 0.8, pointing instability not corrected	unstable e- beam, performances not reached		risk is mitigated, strong effort in 2021 in laser commissioning and characterization, replacement of the some optics	MP, KC
7	3	E	delay in ASN authorization	file processing time, visibility	delay in starting the LPI		anticipation files submission 14 months before firing date	SW

8	4	A,C	resources	insufficient resources : magnet beam optic , beam dynamic, control command acquistion. Smilei development group must be reinforced	delay in starting the LPI, project visibility		position request, seeking for collaboration.	
9	4	C,D	Thomx project delay	Most of the actors in PALLAS are involved in thomx	delay are expected in 2021 and 2022		link to risk 8	

Table 5 : Risk analysis , O-occurrence, C-criticity

*risk class * : A - politic/strategic risk, B - technical risk, C - organizational/social risk, D - management risk, E- risk legal/administrative, F - financial risk*

CRITICITE	*Gravité*			
Occurrence	*1*	*2*	*3*	*4*
1	*1*	*2*	*3*	*4*
2	*2*	*4*	*6*	*8*
3	*3*	*6*	*9*	*12*
4	*4*	*8*	*12*	*16*

The risk id1 is well identified, following the internal project review (CODEC), it has been decided to decouple the installation of all the utilities and local air conditioning units from the 2x75kW cooling group upgrade. A possible grant has been confirmed by the Energy Saving Commission (commission aux économies d'énergie -CEE) of the Ministry of "Transition écologique". The required cooling system is already defined and will come to replace the present cooling system installed for LASERIX alone. Based on a customized system it allows the ambient control of different rooms (temperature stabilization, hygrometry limitations and cleanliness for ISO-8 rooms) together with the cooling of the machines at a different temperature. For this reason, the system has to be installed by the same company. The required upgrade can be made in accordance with the earth warming impact program by using a natural gas cooling group (GWP=3 instead of 2000 for R404a) combined with a warm air recycling towards cool areas located around the installation. Such installation can benefit from co funding from CEE, reducing the total remaining budget in the range 55-65 k€ (instead of about 80 k€). All the inner installation has already been financed.

2.6 Development plan

The development plan in terms of calendar is represented in annex 4 for the phase 1 with details and with main deliverables and milestones for all the phases.

2.7 Tracking and documentation

To be updated with the CeMAP of IJClab.

3 Resources

The resources for the PALLAS project rely mainly on the IJClab. The accelerator department is strongly involved (ALEA, BIMP teams, Surfaces and vacuum service and RF service). The engineering department is mainly involved in all the mechanical design, integration, alignment and installation. The IT service is following the procurement and installation of the 10Gb/s network. The online service is in charge of the control command system development and commissioning.

The LLR has critical knowledge on SMILEI code development and expertise in LWFA physics and PIC modeling. In addition, LLR will participate in the design of the LPI beamline from the optimization of injection and acceleration processes to compact electron diagnostics.

person names	corp.	statut	2020	2021	2022	2023	Total (FTE)
IJCLAB			5,95	9,60	8,70	7,65	32,10
Baynard	IT	IE	20%	20%	20%	20%	0,80
Bruni	CH	CR	10%	20%	20%	20%	0,70
Cassou	IT	IR	75%	85%	85%	80%	3,25
Cayla	IT	AI	10%	10%	5%	5%	0,30
Chaumat	IT	AI	10%	15%	30%	30%	0,85
Coacolo	IT	IR	10%	50%	30%	30%	1,40
Demailly	IT	AI	30%	30%	30%	30%	1,20
Douillet	IT	IR	20%	35%	10%	10%	0,75
Drobniak	PHD	-	25%	100%	100%	75%	3,00
Dupraz	ENS/CH	MCF	10%	10%	0%	0%	0,20
Gonnin	IT	AI	30%	40%	20%	15%	1,05
Gouttiere	PHD		0%	50%	60%	25%	1,35
Guler	IT	IT	25%	25%	30%	30%	1,10
Iaquanello	IT	IE	30%	20%	0%	0%	0,50
Jenzer	IT	IR	10%	10%	0%	0%	0,20
Kazamias	ENS/CH	PR	25%	25%	25%	25%	1,00
Kubytskyi	IT	IR	30%	40%	50%	50%	1,70
Legay	IT	IR	30%	30%	20%	20%	1,00
Lucas	ENS/CH	MCF	25%	25%	25%	25%	1,00
Mercier	IT	IR	10%	10%	0%	0%	0,20
Neveu	IT	IE	10%	50%	50%	50%	1,60
Peinaud	IT	AI	0%	50%	40%	15%	1,05
Pittman	IT	IR	60%	60%	60%	60%	2,40
Razafimamonjy	IT	IE	20%	20%	5%	0%	0,45
Wurth	IT	IR	20%	20%	5%	0%	0,45
POLE-I-MEK-Monteurs	IT	T	10%	30%	0%	20%	0,60
POLE-I-SI	IT	VAR	10%	20%	0%	0%	0,30
POLE-I-ServiceOnline	IT	CDD	0%	25%	50%	50%	1,25
Infras	IT	VAR	10%	10%	0%	0%	0,20
PHD2-BIMP	PHD	-	0%	25%	100%	100%	2,25

LLR							**0,7**
Beck	IT	IR	5%	15%	10%	10%	0,40
Specka	ENS/CH	CR	5%	5%	10%	10%	0,30
LCP							**0,70**
Glotin	ENS/CH	MCF	0%	10%	10%	10%	0,30
Prazeres	ENS/CH	DR	10%	10%	10%	10%	0,40
IRFU							**TBD**
Boizon	IT	ING.	0	TBD	TBD	TBD	
Chance	IT	ING.	0	TBD	TBD	TBD	
Nghiem	IT	ING.	0	TBD	TBD	TBD	

Table 6 : List resources of project PALLAS for the phase 1.

The project needs reinforcement on the following aspects: laser wakefield acceleration theory, magnetism, beam dynamics. PALLAS development plan is based on a simulation and theory activities carried out in preliminary studies (EuPRAXIA, LPGP esculap collaboration...etc) that will need to be reinforced at IN2P3 if we want to give this project a significant scope in the coming years. At the IJClab, we no longer have a magnetism service. This point is critical for any accelerator project in house and clear weakness of our department. The senior beam dynamics experts are overloaded by the ongoing projects.

4 Costs and fund

The cost is given for the 3 phases of the project. The assumption for the funding is based on the full grant from PACIFICS PIA3 project, continuity of the IN2P3 commitment for the master project PALLAS, direction commitment of IJClab from the last CODEC[see reference documents] and the support of the Université Paris Saclay to the LASERIX platform covering most of the operation and maintenance cost.

The project had the opportunity of an exceptional financial support in 2020 which allowed to launch the construction of the laser transport line, anticipation of elements with long delivery time and the renovation of the NEPAL zone.

The details of cost and corresponding funds are given for the phase 1 in table (tab. 7). The whole equipment cost per budget line is summarized in the annex 3.

Module	sub-elements	categorie	WP	cost [k€]	year	Funds
LBTL	mirror mounts	optomechanics	WP2	7	2020	IN2P3
LBTL	mechanical support and vacuum chamber	mechanics	WP2	45,4	2020	labo
LBTL	vacuum pumping system	vacuum	WP2	23,4	2020	labo
LBTL	laser tracker update	various	WP2	1,6	2020	IN2P3
LBTL	lenses	optics	WP2	14,1	2020	labo

LBTL	mirror mounts support	optomechanics	WP2	10,2	2021	IN2P3
LBTL	CCD detector for laser monitoring	detector	WP2	7,9	2021	IN2P3
LBTL	alignment and stabilisation source	laser	WP2	5	2021	IN2P3

Module	sub-elements	categorie	WP	cost [k€]	year	Funds
CCA	datastorage	CCS	WP7	3,5	2020	IN2P3
CCA	control command min development	CCS	WP7	0,3	2020	labo
CCA	control command network switch	CCS	WP7	10,4	2020	labo
CCA	cabling fiber high bandwidth network	CCS	WP7	5	2021	labo
CCA	control command tango server	CCS	WP7	15,4	2021	labo
CCA	time stamping event generator / CCS laser up.	CCS	WP7	21,3	2021	PIA3

Module	sub-elements	categorie	WP	cost [k€]	year	Funds
LIF	OAP#1	optics	WP2	18	2020	labo
LIF	OAP#2	optics	WP2	16	2020	labo
LIF	optical table diags	optomechanics	WP2	8,8	2020	labo
LIF	mirror mount	optomechanics	WP2	18	2021	IN2P3
LIF	module support	granite guider	WP2	11	2021	labo
LIF	vacuum chamber	mechanics	WP2	50	2021	IN2P3
LIF	pumping system	vacuum	WP2	16,3	2021	IN2P3
LIF	optics various	optics	WP2	8	2021	IN2P3
LIF	laser embedded energy diag	detector	WP2	4,2	2021	labo
LIF	motorized flip	motorization	WP2	16,7	2021	PIA3
LIF	various	various	WP2	0,6	2021	labo
LIF	spatio spectral phase measurement NF	detector	WP2	75	2021	PIA3
LIF	pulse front tilt measurement	detector	WP2	47,7	2021	PIA3
LIF	laser beam profiler	detector	WP2	9	2021	PIA3
LIF	HR spectrometer for machine protection	detector	WP2	6,9	2021	PIA3
LIF	active high speed pointing stabilization system	motorization	WP2	29,5	2021	PIA3
LIF	high energy quater wave plate	optics	WP2	32,5	2022	PIA3

Module	sub-elements	categorie	WP	cost [k€]	year	Funds
PLSM	plasma cell test bench - vac + diag	various	WP3	53	2020	IN2P3
PLSM	plasma cell test bench - mechanics	mechanics	WP3	20	2020	ERM
PLSM	differential pumping roots unit	vacuum	WP3	13,6	2020	IN2P3
PLSM	plasma cell prototype	mechanics	WP3	15	2021	labo/PIA3
PLSM	plasma module chambers	mechanics	WP3	18	2021	PIA3
PLSM	target movers	mechanics	WP3	15	2021	IN2P3

Module	sub-elements	categorie	WP	cost [k€]	year	Funds
eBCL	laser remover vacuum chamber	mechanics	WP4	15	2021	PIA3
eBCL	laser remover vacuum chamber	optics	WP4	8	2021	PIA3
eBCL	laser remover vacuum chamber	optomecanics	WP4	10	2021	PIA3
eBCL	guider support	mechanics	WP4	8	2021	PIA3
eBCL	vacuum chamber diag beamline	vacuum	WP4	15	2021	PIA3
eBCL	vacuum chamber diag beamline	mechanics	WP4	9	2021	PIA3
eCBL	spectrometer / dipole	magnet	WP4	14	2021	PIA3
eCBL	beams screen station	detector	WP4	15	2021	PIA3
eCBL	Turbo ICT 1	detector	WP4	19,6	2021	PIA3
eCBL	readout ICT 1 wavecatcher	DAQ	WP4	4	2021	PIA3
eCBL	spectrometer / power supply	electronics	WP4	37,5	2022	PIA3
eBCL	spectrometer detector screen	dipole magnet	WP4	13	2022	PIA3

tab. 7 - equipment cost details of the module of the LPI beamline base configuration

The list of mandatory infrastructure work is detailed in the table (*tab.8*) .

Element	sub-elements	categorie	WP	cost [k€]	year	Funds
maçonnerie	SOBEMA, ouverture, support faux plafonds	infra	WP6	7	2020	CPER
ceiling wall	CRIP, revetement murs et plafonds, isolation	infra	WP6	37	2020	CPER
painting	peintures mur et sols	infra	WP6	9,4	2020	CPER
PMR plateforme	acces PMR installation et monte charge matériel	infra	WP6	12,8	2020	CPER
AC unit	traitement de l'air et thermalisation salle bunker exp et salle laser.	infra	WP6	76,1	2020	CPER

AC unit	cooling group 2x75kW	infra	WP6	36,5	2021	CPER?
AC unit	cooling group 2x75kW	infra	WP6	31	2021	MRM
radioprotection system	mise à jour système de radioprotection (* chiffrage précis en cours)	infra	WP8	50	2021	CPER?

tab. 8 - equipment cost details of the infrastructure renewing work for the NEPAL experimental area

The PALLAS project relies on the LASERIX laser facility of Université Paris Saclay. The operation costs of the LASERIX facility extended with the NEPAL are given in table (*tab. 9*) per year.

LASERIX	description	categorie	cost [k€]	Funds
laser operation	maintenance contract laser	operating costs	85	MRM
laser/exp operation	maintenance contract ACU	operating costs	7	MRM
laser & distribution	consumables optics	operating costs	28	MRM
distribution operation	maintenance vac system	operating costs	7	MRM
distribution operation	consumables various	operating costs	10	MRM
		total	137	

tab. 9 - operation cost details of the laser driver facility and experimental area.

The main fundings for the PALLAS projects are the equipex+ PIA3, the IN2P3 and IJClab for equipment, Université Paris Saclay for the operation and CPER for infrastructure work.

	Phases	**1**		**2**		**3**			
	Fundings	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**total**
equipment									
	IJClab / CODEC	0	46	25					71
	ERM Plasma cell	20							20
	IN2P3 Plasma cell	34							34
	IJClab/ IN2P3 COV19 bonus	141							141
	IN2P3 PALLAS	45	150	*144*	*146*	*120*	*30*	*30*	665
	PIA3-PACIFiCS	0	*393*	*826*	*73*	*388*			1680
	Total (pré-acquis)	**240**	**196**	**169**	**146**	**120**	**30**	**30**	931
	Total	**240**	**589**	**995**	**219**	**508**	**30**	**30**	**2611**
operation									
	MRM (Univ. Paris Saclay)	130	130	130	130	130	130	130	910
	Soutien plateforme (SPL)	0	8	25	25	25	25	25	133

	Total	**130**	**138**	**155**	**155**	**155**	**155**	**155**	1043
Infrastructure									
	CPER 2020	143							143
	CPER 2021		*90*						90
	Total	**143**	**90**	**0**	**0**	**0**	**0**	**0**	233

tab. 10 - fundings details; The orange colored numbers are validated by IJClab direction. The yellow are the foreseen budget within commitment with IN2P3 master project PALLAS and requested budget for the PIA3 PACIFICS grant. All in k€

The total cost of the PALLAS project is given underlying the unique opportunity for the institute to participate in an innovative accelerator R&D with accessible investment taking into account already engaged funds and anticipation in previous CPER funds of the LASERIX facility to expand its activities to laser-plasma R&D.

Element	description	costs [M€]
Laser	laser driver and upgrades	5,0
Laser compressor	new compressor for NEPAL	0,4
Laser deformable mirror	large aperture ILAO	0,1
Plasma cell	LAL closed project material recycling	0,1
PALLAS LPI beamline	see table. 10	2,6
Laser operation	see table. 10	1,0
Infrastructure	see table. 10	0,2

Validation of laboratories direction and visas

Project review by scientific council and project	**Yes**

The project was examined by the CODEC. A different version of the maturing project had been auditioned in 2019 during a joint LAL-IPN scientific council. The CODEC decided the following support to the PALLAS project:

- support of 129k€ in COV19 budget line in 2020
- support of 46 k€ from IJClab in 2021
- support of 8 k€ from IJClab in 2022

The PALLAS project has been examined by the IJClab scientific council recognizing that *"the scientific and technical challenges [of PALLAS project] are very relevant "*

Laboratory	Director name	Visa
IJCLAB / accelerator department	Achille Stocchi / Sébastien Bousson	at the accelerator department
LLR	Yves Sirois	

5 Reference documents

The list of documents attached to this project document are:

PALLAS-riskanalysis_all-v04.xlsx

PALLAS-WBS-v04.xlsx

PALLAS-matrice-RACI-v04.xlsx

PALLAS-HR-v04.xlsx

PALLAS-budget-livrables-funds-v0X.xlsx

PALLAS-IJClab-revue_3888632.pdf

6 Project deliverables

The deliverables of the PALLAS project are:

- A **state of the art test and development platform for laser-plasma accelerators at IN2P3** : plasma cell test bench, and new laser beamline distribution to the NEPAL area.

- Plasma cell development for other LPA facilities.

- A **150-200MeV laser-plasma injector** operating at **10Hz** and delivering the performance and control comparable to an RF accelerator.

The LPI developed will foster and serve as a test machine demonstrator for the community.

7 Evaluation of the next step costs

The natural continuation of the project is the construction of a laser-plasma acceleration stage to reach the electron beam with GeV energy. It will imply to move the LPI beamline and the LASERIX facility in a new building or extend the NEPAL area. This is required by :

- space missing for the installation of the last high energy amplifier of the LASERIX laser system.
- space is missing to install the laser-plasma accelerating stage and beam characterization line.
- radiation safety has to be reviewed.

Proposal has been made and included in the next CPER call for the renewing of the so-called “chapeau gendarme area“ building.

The financial estimation has not been carefully performed. This next step is considered as a new project resulting from the PALLAS success that we hope to be in phase with the European R&D LPA effort in EuPRAXIA.

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Annex 1 : Task list

deliverables	task	resp.	assign.	pers.mois	CP	start	duration	end
renovation NEPAL								
	worksite monitoring	MP	MP	0,5		24/06/2020	219,00	29/01/2021
	workiste acceptance	MP, SI	ext.	0,1		29/01/2021	3	01/02/2021
CTA and cooling group								
	preparation files	MP	MP	0,3		01/02/2020		
	worksite monitoring	ext	MP	0,3		15/01/2021	25	09/02/2021
	workiste acceptance	MP,SI	MP	0,1		20/02/2021	2	22/02/2021
Radiation safetry problem								
	requirement definition	SW	SPR, KC	0,3		15/09/2020	45	30/10/2020
	beam dump design	SW	SPR, AG	2		01/12/2020	60	30/01/2021
	follow up dump	TBD	TBD	0,2		TBD	TBD	TBD
	installation of the RS system	SPR,SW	ext.	TBD		01/06/2021	TBD	TBD
ASN files								
	files preparation	SW	SPR	1		01/09/2020	150	29/01/2021
	submission and follow up	SW	SPR	1		01/12/2020		
LBTL - laser transport								
	design	GI	MP, KC, GI	3		15/03/2020	200	01/10/2020
	realization follow up	GI	GI,KC	0,3		01/11/2020	120	01/03/2021
	installation	MP	JD,monteurs	3		21/03/2021	30	20/04/2021
	commissioning	MP	MP, KC, EB	0,6		20/04/2021	35	25/05/2021
optical compressor								
	installation	MP	GI, JD, EB	1,6		15/01/2021	10	25/01/2021
	commissioning	MP	EB, MP	1,6		20/04/2021	25	15/05/2021
	laser 40fs, stability test, Ph2,3 / LE-HE	MP	BL, EB, KC	4,3		05/04/2021	45	20/05/2021
Laser-plasma injector study								
	paramters definition	VK	KC, SK	2		01/06/2020	150	29/10/2020
	simulations	VK	FG, PB,KC	12		01/06/2020	240	27/01/2021
	optimization studies	VK	VK, PB, FG	24				
LIF laser injection focalisation								
	design	DD	KC, MP	5		15/06/2020	120	13/10/2020
	follow up realisation	DD	KC, MP	0,3		20/10/2020	150	19/03/2021
	installation	DD	JD, MP, KC	0,2		23/03/2021	10	02/04/2021
	commissioning	DD	JD, KC, MP	3		02/04/2021	40	12/05/2021
	laser 18um, 40fs, <3urad	KC	MP, BL, KC	3		12/05/2021	90	10/08/2021
plasma cell								
	installation of the test bench	BL	AG, JD, KC, SJ	0,6		15/12/2020	30	14/01/2021
	CFD simulation	KC	PB, KC	8		01/11/2020	120	01/03/2021
	calibration of the test bench	BL	PB, SK, JD	4		14/01/2021	30	13/02/2021
	development of multizone cell	BL	PB, KC, SK, YP,SJ	9		14/01/2021	150	13/06/2021
	design plasma module	AG	PB, BL	3		01/03/2021	90	30/05/2021
	follow up realisation	AG	AG	0,3		30/05/2021	90	28/08/2021
	installation plasma module	AG	AG, JD, BL, PB	0,3		07/09/2021	10	17/09/2021
	commissioning	BL	PB, KC, SK	4		17/09/2021	40	27/10/2021
	operational plasma cell	BL, KC		TBD				
electron beam characterization line								
	review of EuPRAXIA LPI diag line	CB	AS, VK, SK, KC	3,6		15/09/2020	80	04/12/2020
	design	AG	CB, AS, HG,VC	6		04/12/2020	120	03/04/2021
	follow up procurement	AG	AG	0,3		03/04/2021	150	31/08/2021
	test diags en faisceau	HG	HG, AS, VC	4		31/08/2021	180	27/02/2022
	assembly installation	AG	ND, VC	1,6		31/08/2021	30	27/02/2022
	commissioning	CB	ND, BL, SK, AS, PB	6		27/02/2022	30	29/03/2022
	Diags E, Q, profil single shot acquisition	CB						
Control command system								
	definition	EL	JFC, ON, VK, SI, HG,K(	3,6		01/09/2020	45	16/10/2020
	conception	EL	EL, ON, JFC, SI	6		16/10/2020	60	15/12/2020
	installation HW	SI	SI, ext.	3		01/02/2021	60	02/04/2021
	tango gateway laser	ON	ON, KC	2		01/02/2021	30	03/03/2021
	device server development	JFC	ON, CDD	12		01/11/2020	240	29/06/2021
	GUI development	ON	ON, CDD	8		15/01/2021	280	22/10/2021
	aquisition	EL	EL	??				
	data storage	EL	SI, EL	??				
	CCA opérationnel	*EL*		*TBD*				
Management								
	project tracking, reporting	KC	CellProj	4		01/01/2020		31/12/2022
	interface	KC	WP resp.	3		01/01/2020		31/12/2022
	review organisation	KC	CellProj	1		01/01/2020		31/12/2022
	priority / technical arbitration	KC	WP resp.	-		01/01/2020		31/12/2022
experimental studies & operation								
	optimisation E_max / dE/E	TBD	AS,BL, MP, PB, VK, K(	28		15/04/2022	90	14/07/2022
	optimisation charge dQ/dE	TBD	AS, BL, MP, PB, VK, K	28		15/09/2022	20	05/10/2022
	laser-electrons stability control studies	TBD	AS, BL, MP, PB, VK, K	14		01/12/2022	15	16/12/2022
	beam parameters phase 1	*all*		*TBD*				18/12/2022

Annex 2 : RACI matrix

(R=responsible, A=accountable, C=consulted, I=informed).

deliverables	taches	resp. task	resp. projet (WP5)	WP1: ACC	WP2: LAS	WP3: PLASMA	WP4: eBEAMLINE	WP6: INTEGRATION	WP7: CCA	SPR (WP8)	CeMAP	Steering committe	Infra
renovation NEPAL aera													
	worksite monitoring	MP	C	I	R	I	I	C	I	I	I	I	C
	worksite acceptance	MP	A	I	R	I	I	C	I	I	I	I	C
AC groups													
	preparation of the files	MP	I	I	R	I	I	C	I	I	I	I	C
	installation monitoring	MP	I	I	R	I	I	C	I	I	I	I	C
	AC acceptance	MP	A	I	R	I	I	C	I	I	I	I	C
Radiation safety													
	requirements definition	SW	R	C	C	I	C	C	C	R	I	I	I
	upgrade of the system	SPR	I	I	I	I	I	I	C	A	I	I	C
	new RS system acceptance	SPR	I	I	I	I	I	C	I	A	I	I	C
dossier ASN													
	files preparation	SW	C	C	C	I	C	I	I	A	I	I	
	submission and follow up	SW	I	I	I	I	I	I	I	A	I	I	
laser beam transport line													
	design	GI	C	I	A	I	I	R	C	I	I	I	
	fabrication follow up	GI	I	I	R	I	I	R	I	I	I	I	
	installation	MP	C	I	R	I	I	R	C	I	I	I	C
	commisssioning	MP	C	I	R	I	I	R	R	I	I	I	
laser compressor													
	installation	MP	C	I	A	I	I	R	I	I	I	I	C
	mise en œuvre	MP	C	I	A	I	I	R	I	I	I	I	
	laser 40fs, stability test, Ph2,3	MP	A	I	R	I	I	I	C	I	I	I	
LPI studies													
	parameters definition	VK	A	R	C	C	C	I	I	I	I	I	
	simulations	VK	R	A	C	R	C	I	I	I	I	I	
	studies&performances evaluation	VK	R	A	R	R	R	I	I	I	I	I	
laser injection focalisation													
	design	DD	R	C	A	C	C	R	C	I	I	I	
	fabrication follow up	DD	I	I	A	I	I	R	I	I	I	I	
	commisssioning	KC	R	I	A	I	C	R	R	I	I	I	
	laser 18um, 40fs, <3urad	KC	A	C	R	C	I	I	C	I	I	I	
plasma cell													
	installation banc test	AG	C	C	R	R	I	R	I	I	I	I	
	simulation CFD	PD	R	C	I	R	I	I	I	I	I	I	
	cell design	YP	C	C	I	A	I	R	C	I	I	I	
	cell prototype test	BL	R	R	R	R	I	I	I	I	I	I	
	plasma module design	BL	C	R	C	A	C	R	C	I	I	I	
	follow up fabircation	BL	C	I	I	A	I	R	I	I	I	I	
	installation	BL	R	C	C	R	C	A	I	I	I	I	I
	commisssioning	BL	C	C	R	A	C	I	R	I	I	I	
	cellule 2 zones opérationnel	BL	A	C	C	R	C	I	C	I	I	I	
ligne caracterisaton e-													
	review of EuPRAXIA LPI diag line	CB	C	R	R	C	A	R	I	I	I	I	
	line design	CB	C	C	C	C	A	R	C	I	I	I	
	procurement follow up	AG	C	C	C	C	R	R	I	I	I	I	
	test diags	HG	R	R	C	C	R	I	C	I	I	I	
	assembly installation	AG	C	C	C	C	R	R	R	I	I	I	I
	commisssioning	HG	R	R	R	R	A	I	I	I	I	I	
	Diags E, Q, profils SS	CB	A	C	C	C	R	I	C	I	I	I	
contrôle commande acqu.													
	definition	EL	R	R	C	C	R	C	A	I	I	I	I
	design	EL	C	C	I	I	I	C	R	I	I	I	I
	installation HW	EL	I	I	I	I	I	C	A	I	I	I	C
	test tango gateway for the laser	EL	A	C	C	C	I	I	R	I	I	I	
	development DS	ON	C	C	C	C	C	I	R	I	I	I	
	development IHM	ON	A	C	C	C	C	I	R	I	I	I	
	acquisition	EL	A	C	C	C	C	I	R	I	I	I	
	data storage	EL	C	C	C	C	C	I	R	I	I	I	
Management													
	project tracking	KC	R	C	C	C	C	C	C	C	R	A	I
	interface	KC	A	C	C	C	C	C	C	C	I		C
	review organisation	KC	A	R	R	R	R	R	R	R	R	I	C
	quality	CP	C	C	C	C	C	C	C	C	R	I	
	technical arbitrage	KC	A	R	R	R	R	R	R	R	C	C	I
Beam optimisation													
	optimisation E_max / dE/E	VK	R	R	R	R	R		C			I	
	optimisation charge Q	VK	R	R	R	R	R		C			I	
	beam control test, stabilty	VK	R	R	R	R	R		C			I	
	longitudinal phase space meas.	CB	R	R	R	R	R		C			I	

Annex 3 : equipment cost per budget line

all in k€

equipment / funding budget line	ERM 2020	Total ERM	IN2P3 2020	IN2P3 2021	IN2P3 2022	IN2P3 2023	IN2P3 2024	Total IN2P3	labo 2020	labo 2021	labo 2022	Total labo	PIA3 2021	PIA3 2022	PIA3 2023	PIA3 2024	Total PIA3	Total général
1	**20**	**20**	**79**	**156**	**112**			**347**	**141**	**46**	**25**	**213**	**393**	**147**	**55**		**595**	**1174**
Control command			4					4	11	20		31	21				21	56
Laser diags													167				167	167
Laser oscillator upgrade													131				131	131
Laser pulse shortening upgrade														65			65	65
LBTL			9	23				32	83			83						115
PHIL spectro 2									5	5		10						10
LIF module				92				92	43	16		59	17	33	55		104	255
e- beamline phase 1				0	112			112					57	50			106	218
PlasmaCell test bench	20	20	53					53										73
Plasma module			14	41				54		5		5						59
LPI											25	25						25
2					**20**	**146**		**166**						**678**	**19**		**697**	**863**
Control command						20		20										20
Laser energy upgrade														493			493	493
Laser optical compressor														110			110	110
LIF module															19		19	19
e- beamline phase 2					10	126		136										136
Plasma module					10			10										10
LPI														75			75	75
3							**120**	**120**								**388**	**388**	**508**
e- beamline phase 3							120	120								388	388	508
Total général	**20**	**20**	**79**	**156**	**132**	**146**	**120**	**633**	**141**	**46**	**25**	**213**	**393**	**826**	**73**	**388**	**1679**	**2545**

Annex 4 : Project schedule with major milestones

For a sake of clarity and details we provide an access to the online project schedule of the PALLAS project to the reviewer on request :

https://ijclab-accel.openproject.com/

Please contact us to get temporary login.