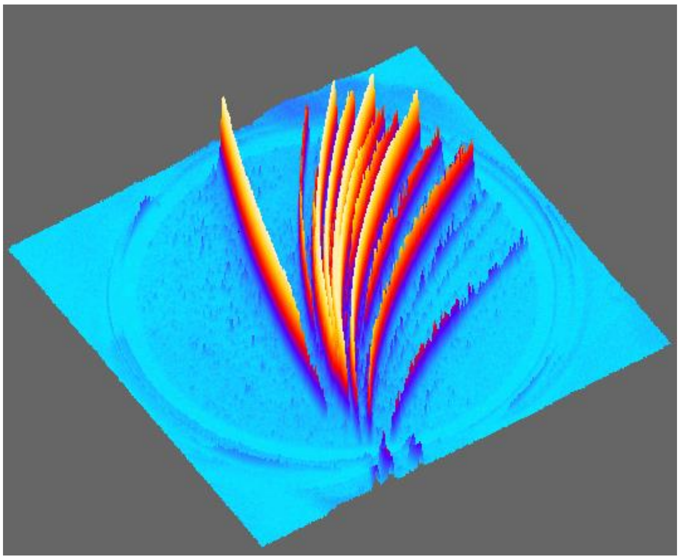


First two years
CILEX Scientific Program

Preamble

In this document we intend to present the scientific program to be developed in CILEX for the next two years. During this “PHASE 1”, we will mainly prepare the first set of experiments to be performed during “PHASE 2” on APOLLON.

At the moment, we are concentrating on three main topics:

Laser-Plasma Electron Acceleration (coordinator B. Cros)
Laser-Plasma Ion Acceleration (coordinator J. Fuchs)
Relativistic plasma-mirrors (coordinator F. Quéré)

For “PHASE2”, we intend proposing relatively straightforward experiments which will serve in qualifying the APOLLON laser properties, the experimental set-up, and diagnostics, while also being fully compatible with the long term program. Important information such as laser intensity on target and laser contrast will be extracted and will serve as feedback to laserists for corrections, if necessary.

Through 2017, the program takes place in three phases:

PHASE 1: 2013-2015
Upstream research program on satellite facilities
Global conceptual design of the experimental set-up for APOLLON
Numerical simulations for diagnostics design and PHASE 2 preparation

PHASE 2: 2015-2016
First tests on APOLLON at 1 PW and 5 PW
- Electron acceleration from a simple gas-jet in HE2
- Proton and ion acceleration from a simple thin foil in HE1
- Harmonics generation from a bulk target in HE1

PHASE 3: 2016-2017
Program processing and implementation of the application’s set-up

From the first SAC meeting in April 2013, we expect recommendations on the compatibility of PHASE 1 with i) other PHASES and ii) the long term objective program described in the document “CILEX general scientific objectives”.

We expect also recommendations on the general program itself: is-it scientifically sound and at the forefront of the physics development in this field?

It should be stressed that this document provides a snapshot of the CILEX scientific project at the present date. Each work group has its own priorities and there is no reason to expect uniform advances on all of the themes at this time.

This document comprises also an annex where the main laser characteristics are given for APOLLON and the satellite facilities and a map of the different experimental rooms.

Many laboratories are contributing and will contribute to this scientific project, coordinated at the scientific level within the framework of the ILP (Institute Laser Plasma). The teams are listed below with their main domains of expertise.

IRAMIS, UHI100 facility, expertise on plasma mirrors, ion and electron acceleration, laser diagnostics

IRFU, transport and focusing of electron beams, magnetic optics design

DAM, CALDER PIC code, simulation of non-linear laser wake-field and ionic acceleration

LLR, Electron beam transport and diagnostics

LPGP, modified WAKE, simulation in the quasi linear regime, PIC code (WARP) simulation of injector, laser guiding, plasma wave over long distance, X-ray laser

CPTh, WAKE laser wake-field modeling

LULI, ELFIE facility, expertise in ionic and laser wake-field acceleration

LOA, Salle-Jaune facility, X-ray lasers, laser wake-field acceleration, betatron and ionic acceleration

LAL, Electron diagnostics, bunch length, position monitors

Soleil, Magnet design, beam diagnostics

LUMAT : LASERIX facility

Contenu

A-Laser Plasma Electron Acceleration

GLOBAL SCIENTIFIC OBJECTIVE FOR 2013-2017

Electron acceleration by laser wake-field [Esarey] is a mechanism providing accelerating fields in plasmas up to 100 GV/m, 3 to 4 orders of magnitude higher than in conventional RF accelerators operating in vacuum. The achievement of GeV electron beams for the first time in 2006 [Leemans] was a breakthrough which attracted the attention of numerous groups, not only in the laser-plasma community but also from the accelerator community. With the development of multi-petawatt laser facilities ambitious programs on laser plasma acceleration are proposed worldwide.

The scientific objective defined in the frame of the CILEX project takes advantage of the specifications of the APOLLON laser which will provide (see annex) two laser beams at the PW level, a large radio-protected area prolonged by a 200m corridor devoted to electron acceleration, and of the know-how of the teams involved in the project ranging from plasma to high energy physics.

We intend to develop a two-stage laser-plasma accelerator which will serve as a work station for future studies on fundamental processes as non-linear Compton scattering, relativistic harmonic generation and betatron radiation, and as a prototype for future studies on multi-stage laser-plasma accelerator.

FUNCTIONAL SCHEME AND CONCEPTS FOR EXPERIMENTS

The rich scientific program addressed concerning electron acceleration imposes to develop versatile experimental blocks that will be finally arranged together. For each of them, the

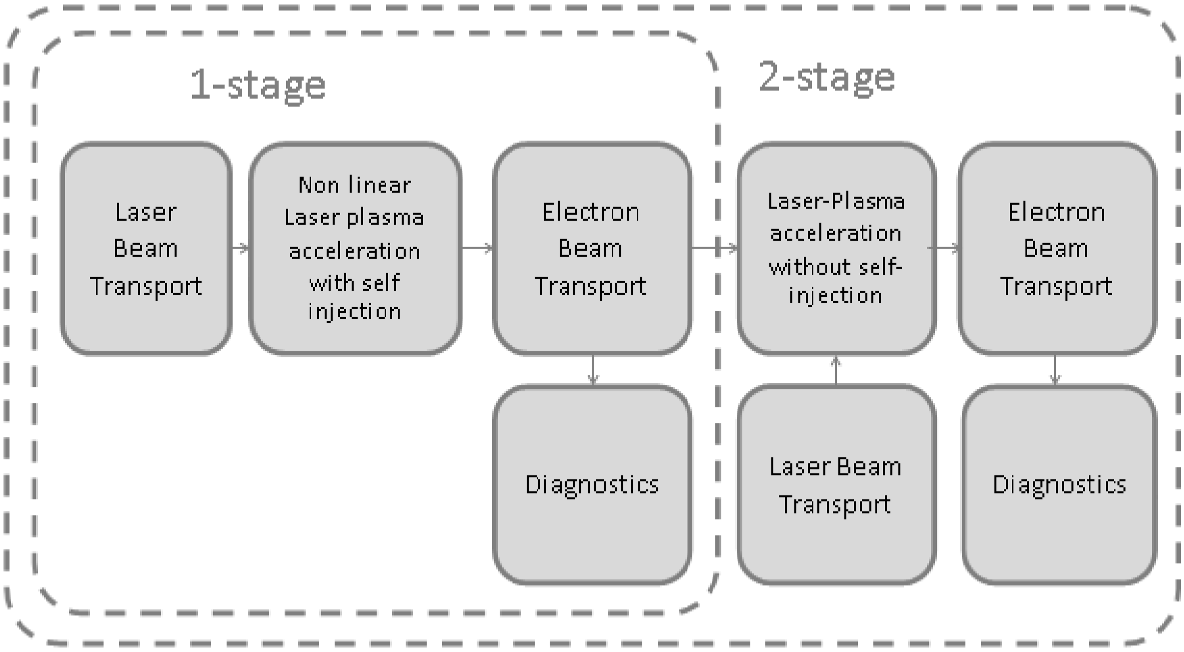


Figure 1: Functional blocks that will be developed and assembled to achieve the scientific program of laser wake-field electron acceleration

technical specifications are driven by scientific objectives. The different functional blocks assembly is reported in figure 1, with respect to the two main configurations, i.e. 1-stage and 2-stage acceleration.

Up to now, the scientific function of each block has been defined, and specific requirements have been identified. The technical solutions permitting to achieve the scientific requirements will be reported in the technical program (see Technical Advisory Committee document).

ACCELERATION STAGE 1

On APOLLON, the 1-stage configuration will be used for two purposes:

i) The non-linear regime of laser wake-field will be studied up to the ultimate achievable laser intensity in order to study regimes predicted theoretically by scaling laws. This will also serve to validate the in-situ laser intensity.

ii) In a lower intensity configuration, controllable schemes will be developed to generate the electron bunches that will be injected in the next accelerator stage.

i) Study electron acceleration in the extreme non-linear regime (10^{20}W/cm^2 and above). In the bubble or blow-out regime [Pukhov], simulations and scaling laws show that laser wakefield driven by PW, short-pulse laser beams at high intensity in plasmas with matched density, produce accelerated electrons with maximum energy peaked in the GeV range and an electron bunch with a charge of 10s of nC. This specific behavior occurs over short plasma lengths (typically less than 1mm), and is due to the fact that the ultra-intense laser interacts with the plasma directly in the bubble regime and does not need self-focusing to reach a high enough intensity to create a cavity free of electrons.

Scaling laws [Lu] have been proposed to predict the physics of laser-plasma acceleration in the highly non-linear regime and the first experiments using one 1PW beam of APOLLON will be devoted to the study of electron acceleration at intensities of the order of or above 10^{21}W/cm^2. Simulations in this regime are currently performed by CEA-DAM using the CALDER-CIRC PIC code [Lifschitz]. Preliminary results are shown in figure 2.

The plasma is taken as homogeneous with a density of 2x10^{19}cm^{-3}, after a 150µm long up-ramp at the entrance. The main feature of these preliminary results is that a strong charge can be accelerated in this regime: for the three cases of focusing conditions, the charge corresponding to electrons with energy larger than 100MeV is between 13nC and 17nC, obtained over a plasma length of the order of 700µm. The smaller focal spot focusing condition produces a larger charge. For the 10 µm and 20 µm cases the spectrum is peaked at energies above 500 MeV, whereas for 30µm the spectrum exhibits several peaks below 500MeV. The measurement of the charge and spectrum of the produced bunches will be performed as a function of the laser energy, pulse duration and for different focusing conditions, and used as a signature of the conditions of interaction, to validate the laser intensity.

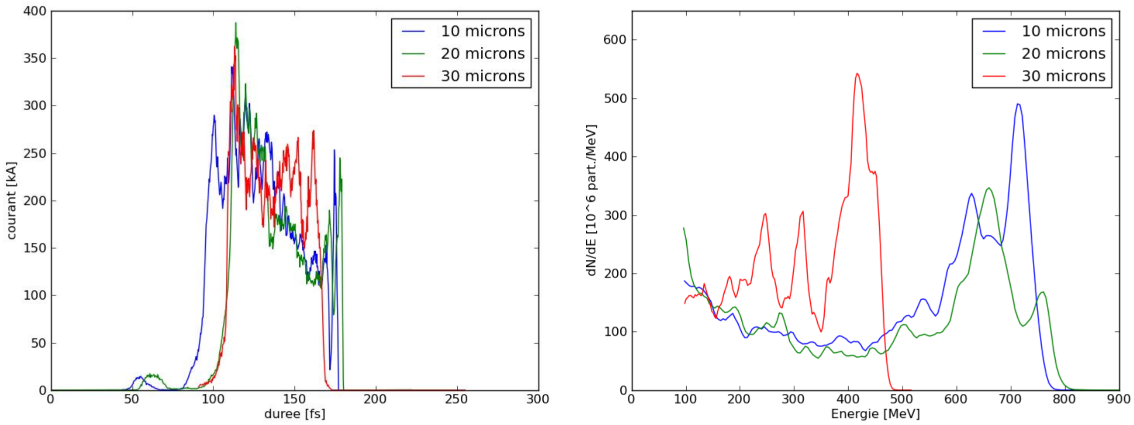


Figure 2: Accelerated electron bunch current (left hand graph) and spectrum (right hand graph) during the interaction of a 1PW, 15fs laser beam with a plasma of density 2x10^{19}cm^{-3}, for different focusing conditions indicated in the legends.

ii) For lower intensities (10^{18}-10^{19} W/cm^2), the first stage will be used as an injector in the framework of the two-stage acceleration, with the aim of reaching energies in the 100 MeV range. The laser will be focused in a centimeter scale low-density (few 10^{18}cm^{-3}) gas cell filled with He or H_2. The gas cell will have variable length, enriched with additional heavier gaseous elements. Alternatively a pulsed gas jet will be available. A probe relying on the F4 (see the annex in this document for beam definitions) beam (250 mJ, 20 fs, ϕ 50 mm) will diagnose the medium parameters.

Adjustment of the laser intensity with respect to the scientific objective will be achieved by focusing the APOLLON F2 beam (15 J, 15 – 200 fs, ϕ 140 mm) with appropriate focal lengths, from 3 m to 20 m approximately.

The outgoing electron beam as well as the outgoing laser beam and the electromagnetic radiation generated during interaction (especially betatron radiation) will be diagnosed. In a first step, wide-field, low-resolution devices will be designed in order to avoid any blindness to a particular energy range (10 MeV-5 GeV). In a second step, a more refined characterization of electron beam will be necessary to specify the transport and injection beam line into the second acceleration medium.

Hence, a precision below 1 % will be mandatory in the energy measurement. This demand will require the development of dedicated electron beam characterization diagnostics. It will have to be compact and able to support a large range of electron energy.

ACCELERATION STAGE 2

In the context of the 2-stage acceleration program, an electron beam transport line will be designed to couple the primary electron beam to the second accelerating stage driven by the F1 (150 J max, 15 fs-10 ps, ϕ 400 mm) main APOLLON beam. The dispersion of the transport line could be useful to select a given energy range, if the primary electron beam exhibits a large energy spread.

The main beam transport line will have to ensure the laser/electron beam coupling at the entrance of the accelerating medium, keeping the compactness of the laser-based accelerator, while focusing optics with focal lengths between 20m and 40m will be required. Thin plasma mirrors, letting the electrons originating from the first stage passing through and reflecting at 45° the laser beam dedicated to the creation to of the wakefield for the second could contribute to take up this challenge.

A long accelerating medium will be necessary to bring the electron beam energy from the 100 MeV range to the few GeV range. Meter scale capillary tubes and gas cells will be designed for this purpose. Plasma channels generated within a capillary discharge will also be tested.

The know-how acquired for the design of the first electron beam transport and diagnostic line (1-stage acceleration) will be invested in the design of the final instruments (2-stage acceleration). A change in the scale is expected, due to the high foreseeable electron beam energy. At the end, the diagnostics line will have to take in charge the beam dumping, lowering as far as possible the level of secondary radiation emission.

ORGANIZATION AND PRESENTATION OF SCIENTIFIC TASKS FOR 2013-2015

The experimental program, consisting in studying the elementary "bricks" for a future two-stage accelerator will be implemented on UHI100 facility in synergy with several numerical codes used for the design of experiments and data analysis (CALDER-CIRC, WAKE, WARP). Our goal is to test the electron injector and the electron beam line, as well as a short version of the second stage waveguide. After testing, these prototypes will be improved if necessary before implementation on APOLLON.

LASER BEAM TRANSPORT (LBT)

For each stage of laser plasma interaction the laser beam needs to be focused with a beam quality and reliability in relation with the requirement of the experiments, as the target can either be a gas jet, a gas cell or a capillary tube. The requirements of the synchronization of the two acceleration stages in terms of stability and precision will also be determined. Innovative solutions to preserve a high average gradient of the accelerator will be developed.

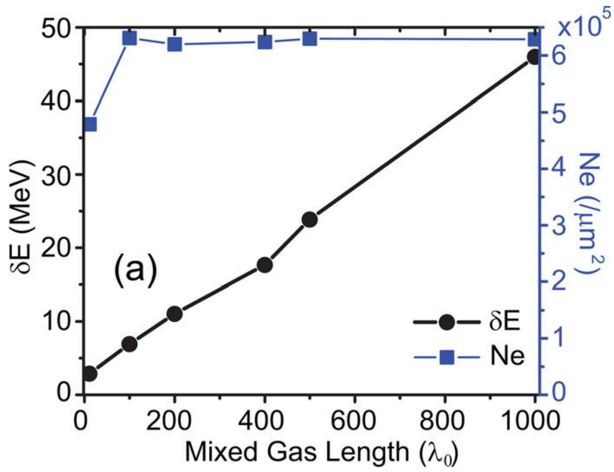
Scientific requirements identified for laser plasma acceleration impose severe specifications on the laser beam transport and determine which parameters need to be addressed specifically, such as the control in position, energy, wave front, contrast, and the shot to shot stability. We have identified several aspects of laser beam transport that will be studied:

- Dispersive-less high peak power laser transport line. The objective consists in focusing laser beams with a given Rayleigh length/beam radius within centimetric to meter-scale accelerating medium. Since the scientific program will require exploring a wide range of laser durations, the transport line has to be dispersive-less, allowing reaching the ultimate 15fs duration at focus. A scheme based on the use of 45° drilled mirrors used in conjunction with on axis spherical mirror is currently under investigation with the help of analytical modeling. In a second step, the detailed spot characteristic will be calculated by using the ZEMAX software taking into account the estimated laser beam profile of the APOLLON beams.
- Concerning the 1-stage program, focusing optics with focal length between 3m and 20 m will be used to cover moderate to extremely non-linear regimes. Up to 40 m will be mandatory for the two-stage configuration. To reduce the size of the optical arrangement, a combination of optics could be used. The design of a composite doublet including a conventional optic and a plasma mirror is under investigation and will be tested on the satellite facilities.
- Among the different kinds of accelerating medium, capillaries are exceptionally demanding in term of beam profile quality and beam pointing stability. Due to the long optical path along the laser chain, active devices will be designed and implemented to improve these two parameters. This implies to insert a diagnostic line characterizing the incident wave front, far field position, energy value and near field profile. A dedicated working group has been created to design the APOLLON diagnostic line. It will benefit from the experience acquired with the satellite facilities in this domain.
- In the two-stage configuration, the second laser beam will have to be precisely synchronized with the primary electron beam. We expect that a dedicated diagnostic and active correction will be necessary. The objective is to stabilize respectively the beam pointing and timing to less than 10% of the focal spot and time duration. Concerning the time domain, we plan to adapt the interferometric technique developed around the ELFIE satellite facility which consists in stabilizing the delay between beams using a closed loop mastered by optimization of the interferometric fringe pattern visibility given by the superimposition of the beams. In addition, during the next two years, a beam pointing stabilizer will be implemented within UHI100 satellite facility and any know-how transfer will be promoted.
- In the space domain an additional problem arises from the superimposition of the electron beam and the laser beam. This question can be addressed either via the laser beam transport point of view or via the electron beam transport design. The solution offered by the use of a thin plasma mirror reflecting the laser and transmitting the electron beam will be investigated. The design of such a tool is starting, gathering the experience of the UHI100 team on plasma mirrors for years and the conception capabilities of the LLR laboratory.
- For future applications, the transport line has to be as short as possible, to maintain the high accelerating gradient advantage of laser acceleration. Once more and as already stressed, plasma mirrors could bring an elegant solution to this issue. An experimental campaign will be dedicated to test this principle on a satellite facility.

DEVELOPMENT OF THE INJECTOR

The development of a controlled source of relativistic electrons for injection into a second stage will be undertaken. Among the possible methods that were proposed or tested to enhance reliability, the acceleration from a gas cell using the ionization of impurities to control the phase of electron injection, seems to be the easiest to implement for a first demonstration. Simulation results from [Chen], are shown in figure 3 (left hand side graph): the number of accelerated electrons and their energy spread can be controlled by varying the length of gas mixture, which should remain small to minimize the energy spread.

We plan to study the control of electron injection using first the UHI100 facility, and subsequently implement this mechanism with an optimized configuration on APOLLON facility. The injector will be developed using a gas cell of variable length, filled with Helium or Hydrogen with impurities of high Z atoms, to control the injection of electrons, and increase the beam charge. A gas cell permits to achieve a turbulence free medium with controlled pressure, and the variable length will be used to optimize the electron energy by varying the accelerating length within the limit of the depletion and dephasing lengths. This part of the project is already funded by the cluster -Triangle de la Physique (project ELISA - ELectron Injector for compact Staged high energy Accelerator) and brings together 3 teams from LPGP, SPAM and LULI.
The design of the gas cell is in progress (see figure 3, right hand side), and its implementation and optimization will be done on UHI100 laser facility at the summer 2013. A parametric study of the electron source will be performed, to characterize the electron beam properties (energy, divergence, duration, pointing stability, reproducibility) as a function of the experimental parameters (gas density, impurity density, nature of impurity, cell length, laser pulse duration, laser energy, spot size….).



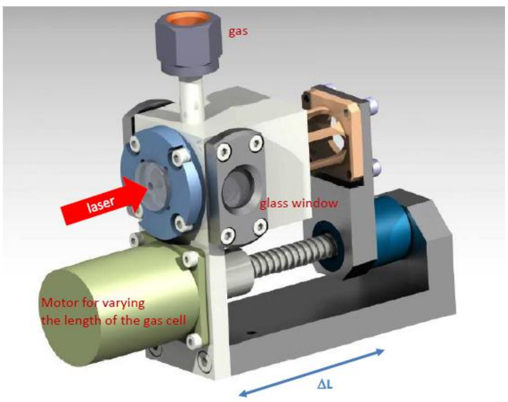


Figure 3 : Left: Simulation result from [Chen] showing the number of accelerated electrons and their energy spread as a function of the length of gas mixture. Right: drawing of the gas cell with variable length under conception for the injector (ELISA – funded by the Triangle de la Physique).

This will give us a complete set of parameters for numerical simulations that will be performed to adapt the design from UHI100 to APOLLON experiments. To analyze this regime accurately, we plan to use a PIC code, called WARP, developed at the Lawrence Berkeley National Laboratory (LBNL)

[Vay]. A collaboration between LPGP and LBNL groups has been initiated in order to adapt the WARP code for the injection and acceleration experiments. The first step will be to obtain an operational code in 2D cylindrical geometry.
Then the WARP code will be used for modeling beam-plasma interaction inside the injector. The code will be modified to treat injection through ionization in a mixture of gases and also, as for the WAKE code, to introduce the experimental characteristics of the incoming laser beam. Parametric studies will then be performed to determine the optimal configuration of the injector, mainly concerning the pressure and composition of the gas target, the target length and the focal length for the laser beam using expected laser parameters.

Electron Beam Transport (EBT)

The requirements of the electron beam line necessary to transport the beam from the injector and focus it at the entrance of the accelerator will be defined.

The addition of a laser plasma accelerator stage using a second laser beam requires a transport and focusing system, compact enough to maintain a high average accelerating gradient and able to accommodate the parameters of the produced bunches, and focus them at the entrance of the second accelerator stage, with a small enough size and divergence. Even if the distance between two stages can be reduced by the use of plasma mirrors to focus the laser beam, the versatility of the experimental set-up at the APOLLON facility may impose a meter scale distance between two successive stages. After such a distance, the electron beam diameter would reach a few millimeters, which is inadequate for coupling in a sub-millimeter accelerating stage. Thus, the matching of electron beam size from stage to stage imposes the design of a dedicated electromagnetic image-relay device. This work is presently jointly undertaken by teams from CEA-IRFU, LLR and LAL in the frame of CILEX. The DACTOMUS project (Diagnostic And Compact beam Transport fOr MUltiStages laser plasma accelerators) is partially funded by the Labex P2IO.

A first design study is underway for a set of parameters that are expected to be achieved reliably with the UHI100 facility: electrons with (50+/-5) MeV, 5mrad divergence, fs range duration. The aim of this test experiment will be to demonstrate that the electron beam produced in a laser plasma accelerator can be transported and focussed to a small enough spot to allow it to be injected in the next accelerator stage. A numerical study will provide the parameter space of feasible compact focusing transport lines for a given set of beam parameters and space constraints. Preliminary simulation results (see figure 4) show the electron distribution at the output of a transport beam line made by a combination of quadrupoles and sextupoles, allowing focusing 25% of the incident electrons within a 10µm diameter circle. The outcome of this parametric study will lead to a prototype setup that will be tested at the UHI100 laser facility.

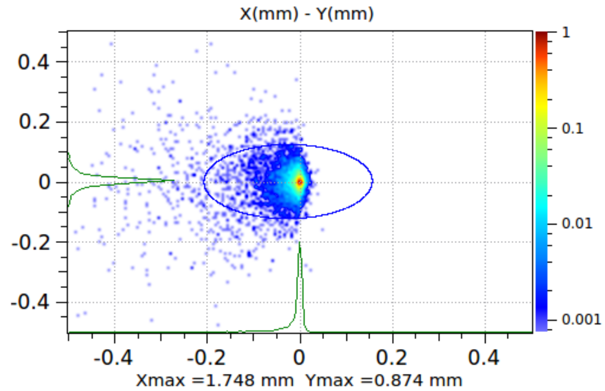


Figure 4: Example of the electron beam distribution in the perpendicular plane calculated at the output of a focusing beam line using a combination of quadrupoles and sextupole elements.

The requirement on the electron beam spot size for injection in the second laser plasma accelerator is of the order of 10 µm, and is very tight for a beam of that energy range and energy spread. On the principle, this electronic transport beam line could also be adapted to the injection in an undulator. We plan to characterize the electron spectrum as well as the transverse and longitudinal electron beam sizes from the transport line.

Laser Plasma Acceleration without self-injection using capillaries (LPA)

An accelerating stage will be designed and developed to produce accelerated electrons in the 10 GeV range, in a reliable way. Laser wake-field in waveguides permitting to reach meter scale distances will be studied in weakly non-linear regimes.

In the second accelerator stage, the electron will be trapped in a quasi-linear plasma wave created by focusing an intense laser pulse into a long guiding medium to reach high energy. The plasma wave will be created in a quasi-linear regime to avoid the self-injection of electrons, the injected electrons coming only from the injector.

Several schemes for plasma guiding will be studied and compared, starting with capillary tubes. Funding has been applied for to the French national research agency (ANR project PLASMEA - PLASma Media for Electron Acceleration) to develop and test the media for the accelerator stage, first on UHI100.

Capillary tubes allow creating plasmas with low density and length from 1cm to 1m scale. The LPGP- and CPhT teams have started a systematic study of the dynamics of electrons acceleration to several GeV in capillary tubes with the specified parameters of APOLLON using the code WAKE [Mora].

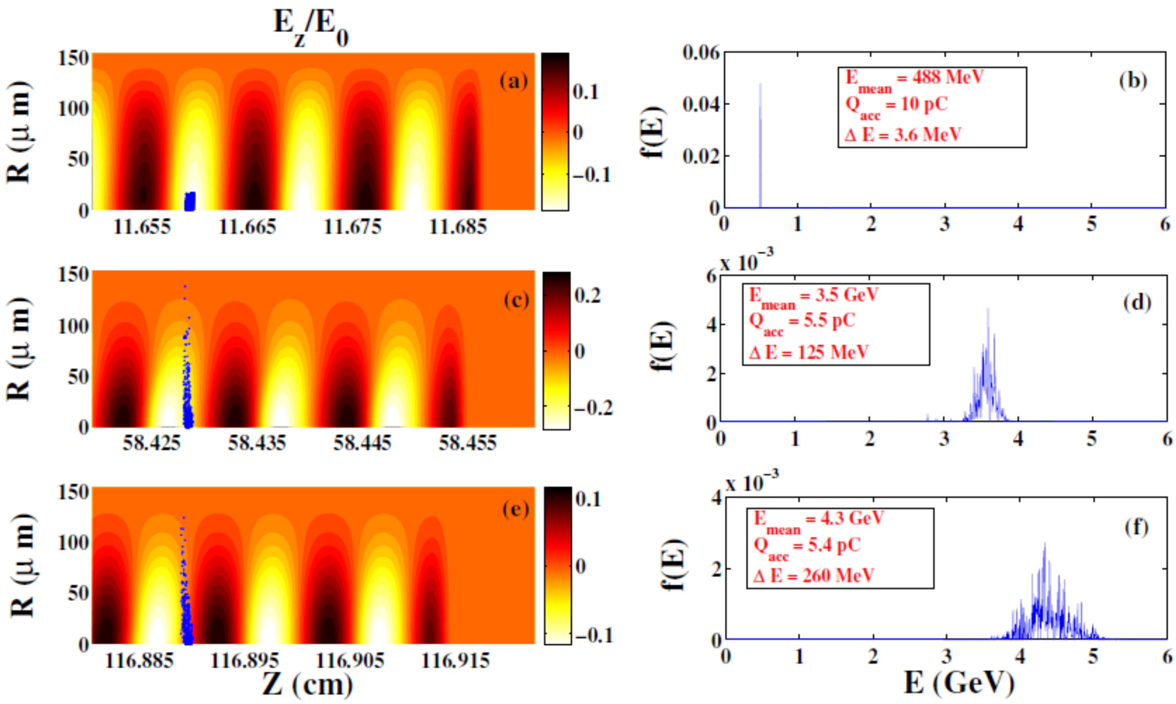


Figure 5: Acceleration of externally injected electrons in a capillary tube with low plasma density: left column Accelerating electric field, right column spectrum of accelerated electrons at three locations along the propagation: 11.6 cm, 58.4cm and 116.9cm.

Figure 5 shows an example of simulation for an intensity of 6×10^{18}W/cm^2, with a spot radius of 100µm focused at the entrance of a capillary tube with radius 154µm, filled with a plasma of electron density 10^{17}cm^{-3}. A 10pC, 50MeV mono-energetic external electron bunch (shown in blue) is injected with a spot radius of 10µm and duration 10fs into the accelerating and focusing phase of the wake-field. Very significant results are obtained from this simple simulation. They show that a regular wake-field can be generated over meter scale distance in capillary tube, and that the electrons can be accelerated up to the dephasing distance, about 1 m in this case. Furthermore the length of the plasma provides a simple control tool on the electron energy.

Capillary tube guiding will be developed by the LPGP team and tested at the UHI100 laser facility up to several tens of centimeters. Capillaries up to 30cm are commercially available and can be tested at existing facilities such as the Lund Laser Center (LLC) or UHI100. The development of a target alignment system adapted to the capillary tube length will have to be performed. Longer capillary tube lengths can be specially manufactured and will later be tested for transmission and beam quality, on a test bench at LPGP and at facilities offering enough space under vacuum and laser beam stability, like for example at the LLC. The plasma wave inside the medium will be characterized by the measurement of the modification of the laser spectrum created by the plasma wave excitation [Andreev] in the capillary tubes up to 30 cm long; the guiding of the laser over long distances inside the capillary tubes will be controlled by the measurement of the spatial profile at the entrance and the exit of the capillary.

If the pointing stability of the APOLLON laser prevents the coupling to monomode capillary tubes, we envisage, as a step backward, to confine the gas without guiding by choosing tube diameters several times larger than the focal spot size, over typically a Rayleigh length.

Diagnostics.

Diagnostics will be defined in relation with the other tasks. Laser: focal spot, energy, spectrum, before and after the interaction. 3 electron energy spectrometers: 100 MeV range for the injector, broad energy range, up to 1GeV, for the non linear regime, up to 10 GeV for the second stage, X-ray diagnostics to characterize the quality of acceleration, beam pointing/screens, pulse duration of electron bunch, charge.

The work related to these tasks will be performed in parallel by the teams partner of the CILEX project, using satellite facilities as UHI100 or in collaboration with other groups, as for example the Lund Laser Center, Stanford Linear Accelerator,…. The PHIL Platform at LAL will also be used to do preliminary tests on some diagnostics. Diagnostics will be prepared and adapted to the specificities of experiments that will be performed on APOLLON.

In particular, we will need dedicated spectrometers for the electrons from the injector, which means in the 100's MeV range, and even higher after the second stage in the GeV range.

We will use beam monitors to characterize the pointing stability of the electron beam from the first stage, on UHI100 and APOLLON, and at the exit of the 2nd stage as well on APOLLON. We will also record the size and divergence of the electron beams and to complete the set of parameters, we will get access to the electron pulse duration, using either Coherent Optical Transition Radiation measurement or a single shot Smith-Purcell monitor adapted to the constraints of laser-plasma acceleration. LAL (N. Delerue) has recently received funding from the "ANR jeunes chercheurs" program to build such a longitudinal beam profile monitor.

We plan finally to set up some optical diagnostics, for the laser pulse itself, for each of the 2 stages of the accelerator. We need to characterize the laser plasma wave amplitude, the spectral broadening of the pulse as well as the pulse duration.

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B-Laser Plasma Ion Acceleration

Global scientific objectives for 2013-2017

Our goal is the development of a **work station dedicated to ion studies** for two purposes:

- **Fundamental studies** on acceleration processes under extremely high intensities.
- Development of a highly reliable **ion source at high repetition rate and with high numbers of particles (>10^{13} ions per bunch) ranging from low energies (sub-MeV) to multi-100 MeV,** for future studies on the application of ion sources in material sciences such as warm dense matter or time dependent radiation induced defects.

Presentation of the scientific tasks for 2013-2015

In parallel with the completion of the design of HE1, short focal length target area where the production of ion beams will be pursued and developed on APOLLON, and the study with simulations of the potential beam parameters that will be achieved, we will, in the first phase of the project, focus on the following points with the aim of optimizing the future production of high-energy ion beams on APOLLON for a wide variety of applications:

1. Pursue the **exploration of the ion acceleration physical mechanisms in order to improve ion beam energy and beam properties,** paying a special attention to **the reliability and reproducibility**.
2. **Prepare the applicative part** of the APOLLON ion station that will aim at exploiting the unique properties of the ion beam as a probe for a variety of applications (condensed matter, astrophysics, chemistry, nuclear physics, etc.). Although the extreme high intensity of APOLLON will allow exploring new territories (e.g. probing denser plasmas with increased ion energy beams and particle flux) that are not accessible using present-day facilities, we can nonetheless

use present-day beams to prepare the ground for such experiments by **testing geometries** (including multiple target assembly adapted to high-repetition rate of APOLLON) **and diagnostics**.

3. **Develop and test diagnostics and target insertion systems,** adapted to APOLLON conditions, namely in-line (i.e. which do not need to be retrieved out of the target chamber), at high-energy and high repetition rate. We plan for this to test various concepts in order to adapt the diagnostics to APOLLON conditions and ensure efficiency of operation.

INCREASING PROTON ENERGY USING ENGINEERED TARGETS ON UHI100

Fundamental studies on extremely high intensities using APOLLON require to continue and even to amplify the **exploration of the physical mechanisms, properties, and ways to control ion sources** on satellite facilities.
For example, emerging Radiation Pressure Acceleration (RPA) [Borghesi] and Light Sail (LS) [Macchi] mechanisms will be actively developed on APOLLON. However, we believe that many aspects of Target Normal Sheath Acceleration (TNSA) [Wilks] are still un-explored and satellite facilities (UHI100 and ELFIE in the present case) will be extensively used for testing strategies to enhance the laser absorption by using various target shapes or compositions. **This process will lead to the selection of the more interesting targets for their physical content and beam performances prior to the first experiments on APOLLON.**

One of the suggested ways to increase the proton energy is to use structured targets in order to increase the coupling efficiency of the energy delivered by the laser pulse. In this context, we recently explored three different kinds of targets: “foam targets”, “microsphere targets” and “grating targets”. Foam targets show a very low density ($\approx n_c$) micrometric layer on their irradiated size, allowing for a larger interaction volume at critical density and subsequent coupling efficiency increase. Microsphere targets have a monolayer of micrometer spheres arranged in a hexagonal matrix network modifying their surface geometry. This kind of structure has already shown to be able to increase the coupling efficiency (and TNSA proton maximum energy) as recently evidenced by an experiment which took place on the 100 TW laser facility at the Advanced Photonics Research Institute (APRI) in Gwanju [Margarone]. Finally, grating targets exhibit a grating-like structure allowing exciting surface waves. These waves, located at the interface plasma vacuum, are characterized by a strongly inhomogeneous resonant electric field able to accelerate the electrons in vacuum and inside the target, more effectively than the laser driven ponderomotive effect. 2D PIC simulations, carried out in an interaction regime between 10^{16} and 10^{20} W/cm^2, have shown that it is actually possible to resonantly excite a surface wave, SPW, in the relativistic regime, if the target surface is properly modulated. Note that this condition is mandatory and requests a very high contrast of the incident laser beam.

A significant increase in the laser energy absorption from 25 to 75% and a subsequent increase in the number and energy of emitted particles have been observed in recent experiments on the UHI100 facility at Saclay, using laser intensities slightly higher than 10^{19} W/cm^2, and grating targets with a period of 2λ. This was demonstrated by measuring, as a function of the angle of incidence, both the protons emitted in the direction normal to the target (whose maximum energy is a function of the density and temperature of the electronic population) and the reflection of the laser energy (see Figure 6).

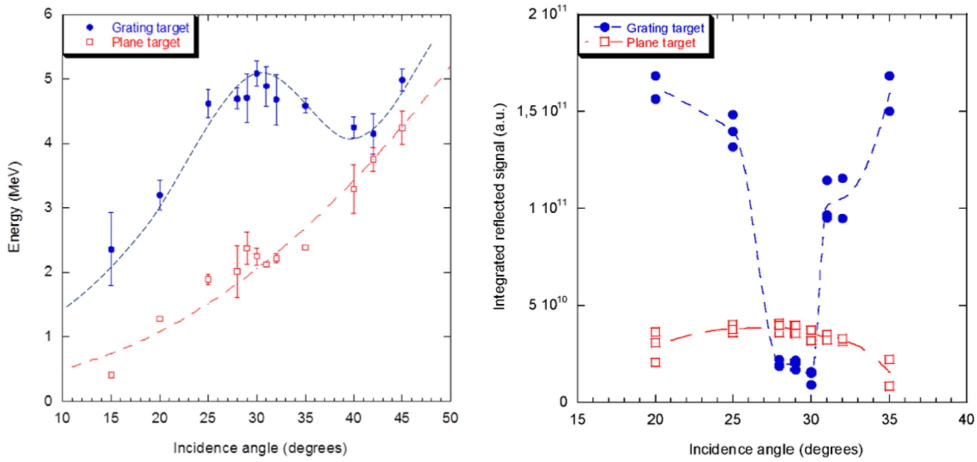

Figure 6: Maximum proton energy (left) and target reflected light (right) as a function of the laser incidence angle.

More generally, in order to operate **a selection for APOLLON** regarding the highly reliable **multi-100 MeV ion source,** we plan to launch a complete characterization of the behavior of thin foils covered by a monolayer of polystyrene microspheres with a diameter of the order of the laser wavelength, bi-layer targets (a thin plastic foil supporting a micrometric low-density foam slice) and grating structured targets with a period of the order of the laser wavelength (realized by thermal imprinting on mylar foils).

CONTROL OF DIVERGENCE OF IONS USING SELF-GENERATED MAGNETIC FIELD ON ELFIE

Standard TNSA-produced beams have a wide divergence that is energy dependent (from a 10s of degrees at low energy to a few degrees at high energy [Mancic]). However, many applications require that the **divergence of the ions beams is reduced and/or controlled**. In particular, to enhance the temperature that can be achieved by ion heating in order to be relevant for studies of warm dense matter [Patel], one needs to focus in a small spot as many particles as possible within the beam. Having also the ability to concentrate a high number of high energy protons in a small surface is also of strong interest for material studies, because the fluence produced in laser-generated beams could be comparable with the fluence received by the inertial Fusion Reactor Walls [Renk].

Several approaches have been studied in order to control/reduce the divergence of laser-produced ion beams. Inspired from particle accelerator technology, the use of an ion optical system consisting of permanent magnet miniature quadrupole in order to collimate the generated proton beam was tested [Schollmeier]. This scheme, however, suffers from a low transmission of the allowable number of generated proton through the magnet (0.1 %) and if a higher number of protons is sent through, the current associated with the beam would detrimentally perturb the magnetic field distribution intended to focus it. An alternative way based on plasma technology was also tested through the use of radial electric fields within a cylinder target and generated by an auxiliary high intensity laser pulse. This was shown to allow collimating MeV energy ions [Toncian], but at the cost of strong chromatic effects (only a small portion of the broad energy spectrum of the incoming ion beam can be focused) due to short time life of the electric field used.

Another alternative that will be tested within our present program will be **to exploit strong magnetic fields** produced at the front and the rear side of a solid target during its irradiation by a high intensity high contrast laser beam. The particular interest of magnetic field compared to electric ones (used in the scheme mentioned above) is that their diffusion time is much longer, hence one can envision exploiting fields which evolve slowly over the transit time of the whole ion spectrum. This would allow realizing an achromatic lens for focusing (if the magnetic field is dominant at the front side of the target) or defocusing (if the magnetic field is dominant at the rear side of the target) ions, or even other types of charged particles such as electrons or positrons. In general, magnetic fields are principally generated through two mechanisms: hot electrons current [Kolodner] and thermoelectric effect [Braginskii]. Since the idea would be here to exploit as high magnetic fields as possible to strongly collimate MeV energy protons on large time scale (several 10s of ps), the use of an ultra intense laser beam seems necessary. Indeed, during the interaction of a long pulse beam with solid targets, hot electrons currents are negligible and the magnetic field due to thermoelectric effect have a relatively low amplitude (1-2 MG) [Willingale] due to long density and temperature gradients. This is not a priori the case using an ultra intense, high contrast, laser beam where there exist steep density and temperature gradients on large time scales. Moreover, the strong dissymmetry in the plasma expansion induced by the interaction of such pulses with thin targets [Kar] leads to think that magnetic fields produced at the front and rear sides of the target through the thermoelectric effect are indeed very dissimilar. A first experiment performed in the summer 2012 at Titan (LLNL), illustrated below, shows that indeed the concept of using magnetic fields to focus a broader part of the energy distribution of a laser-generated ion beam is valid.

Our plan is now to (i) **analyse** this first experiment to understand and model the source of the magnetic fields producing the ion beam focus, (ii) **test various materials and irradiation conditions to optimize the induced focusing,** (iii) **model and test the damaging of such focusing device depending on the laser and target conditions** to prepare deploying it on APOLLON.

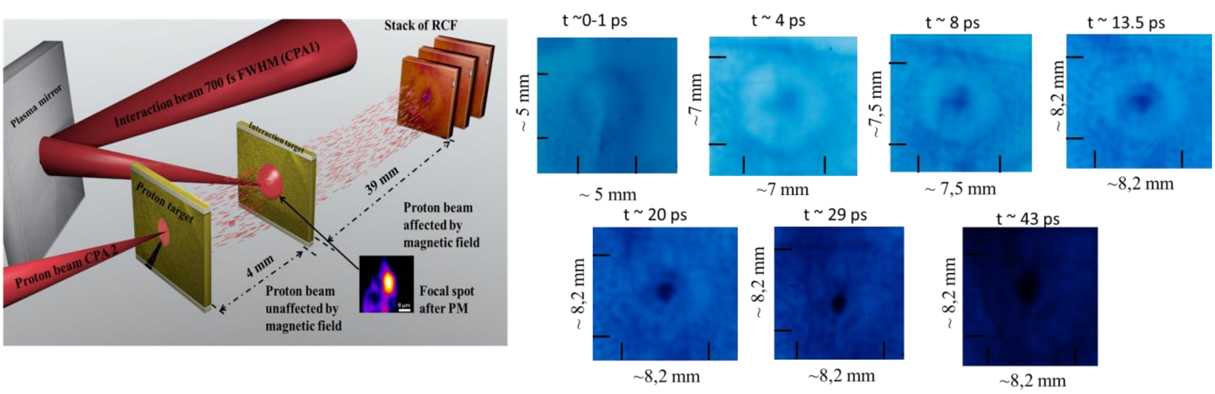

Figure 7: (left) Experimental set-up of a first experiment aimed at exploiting strong magnetic fields to focus achromatically laser-generated ion beams. (right) Typical result: 2D angular profiles of a proton beam sent through a 3 µm Al target on which magnetic fields are generated. The times indicated correspond to the time at which the protons in the film have transited through the Al target.

CONTROL OF DIVERGENCE OF ELECTRONS IN DENSE MATTER

Achieving a degree of control of the properties of the electron beam driving ion acceleration as it propagates through the solid is another important aspect of our program since it would also greatly enhance the prospects for applications by leading to higher density of electrons in the ion accelerating sheath, and hence to higher ion energies. The divergence of the electrons, and the consequent decrease of the sheath density as the target thickness increases, has been indeed shown to be one of the main causes of the observed decrease of TNSA ion energy for thicker targets [Fuchs, Ceccotti]. Recent schemes have demonstrated that electrons can be self-guided in composite targets having strong variations of resistivity [Ramakrischna], as an effect of the magnetic fields arising at the resistivity interface [Robinson].

We have explored a variation of this devoting attention to the use of **magnetic self-collimation of the electron beam** [Yuan]. As the beam propagates, its divergence may be mitigated to some extent by resistive magnetic field self-generated by the beam propagation itself. These fields are typically transverse, azimuthal with respect to the beam's propagation axis and, under the right conditions, can have a pinching effect on the beam, as exemplified by the simulations shown in the figure below. The interest here, compared to previous proposals exploiting resistivity changes in multi-layered targets, is that it does not involve complex target fabrication, but tweaking of the laser beam parameters in order to induce the proper resistivity gradients. We plan to continue exploring and optimizing this scheme by simulations, and then testing experimentally the optimum configurations.

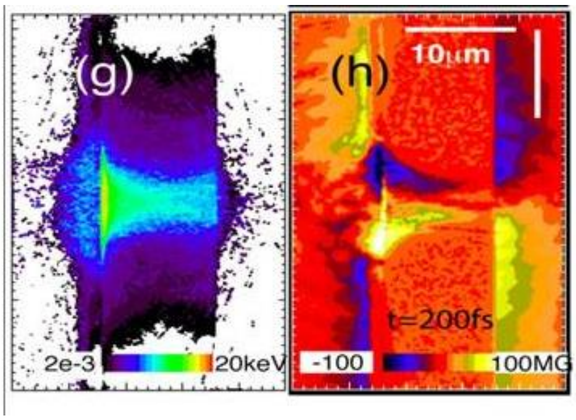

Figure 8: PIC simulations results of a 10 µm Au target (snapshot at 200 fs after the start of the laser irradiation with an intensity of 6 10^{19} W.cm^{-2} using a 300 fs duration pulse). (Left) Electron energy density showing the induced electron collimation by the (right) strong quasi-static magnetic fields produced by the resistivity gradients within the target (figure extracted from [Sentoku]).

Another possibility is offered by using external magnetic field in order to modify and control the propagation of superthermal electrons, which propagate parallel to the B-field axis. In this approach the electron confinement results from Larmor gyration of the electrons around the field lines [Yang]. A crucial tool for this work is the pulsed coil available at LULI [Albertazzi], which allows generating homogeneous B-fields of the required magnitude over a large spatial scale.

Realistic magnetic fields implementable in laboratory experiments are of the order of a few tens of Tesla (up to 40 T are obtainable with the LULI coil). If one can neglect, to leading order, the effects of collisions with background electrons and ions and the effect of resistively generated fields as compared with the effect of the axial field, the fast electron motion will be equivalent to free electron gyration in a constant magnetic field. Under these conditions, the maximum transverse extent of the electron beam should be given by $r_{max}=r_0+r_g$ where r_0 is the beam radius at the injection point (e.g. the laser spot radius) and r_g is the Larmor radius, with $r_g=\gamma m_e v_f \sin[\theta_{1/2}]/(eB)$, where γ is the relativistic factor, v_f is the electron velocity at injection and $\theta_{1/2}$ is the angular divergence of the beam. Already from the simple formula above, one can infer that, with 40 T, it should be possible to confine electrons with energies up to a few 100s of keV within a radius r_g~ 100 µm (while MeV electrons would require larger fields). This would be suitable for applications that would not require very high energy ions, but flatter accelerating sheath to improve the produced beam divergence.

Numerical simulation carried out using an hybrid code [Yang] have shown that the assumptions made on the basis of the simple formulas above hold substantially, although they show that resistively driven magnetic fields in the target have some effects on the detailed beam dynamics. The figure below shows the beam density 2 ps after injection for the case without an axial magnetic field (a) and with an axial magnetic field of 20 T (b). The colour scale corresponds to $\log_{10}(n_e)$, and the electron beam is injected in the simulation in a plastic target with an injection half-angle of 30 degrees. In the case (a), it is seen that resistive fields partially collimate the beam for the first 100 µm of propagation, but the beam diverges deeper into the target due to the decrease of the resistivity of the background plasma, induced by the temperature increase. The presence of the axial magnetic field prevents, as expected, the transverse beam spread and the beam density is maintained high deeper into the target. The situation further improves as the B-field is increased.

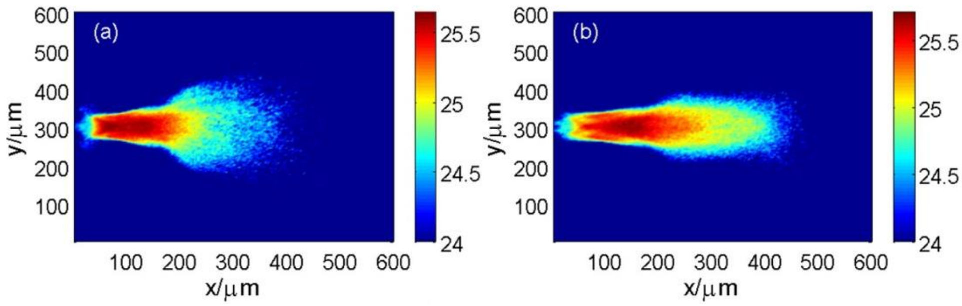

Fig. 9 – Fast electron density profiles (plotted in log10 color scale) for the cases without magnetic field (a) and with a 20 T axial magnetic field (b). Snapshots refer to about 2 ps after electrons begin to be injected in the target according to a temporally Gaussian profile. For details, see ref [Yang]

Overall the data indicate that in a range of parameters easily accessible on the ELFIE system, there should be clear (and perhaps dramatic) effects on relativistic electron collimation within extended targets. Provided we can get access to LULI (which is conditional to acceptation by the scientific committee), we propose to test this novel regime of magnetized, relativistic laser-matter interaction, and to characterize the behavior of the electron beam with a range of established diagnostics. We also plan to test the effect of the expected enhancement of electron density on the acceleration of protons via TNSA in thick targets.

ENERGY SELECTION OF ION BEAMS FOR APPLICATIONS

Short pulse laser produced ion beams are inherently broadband. There are many advantages to this characteristic (isochoric heating of thick materials, etc.), but there are cases where monoenergetic ion beams are required. Many groups have since designed active and passive devices to select smaller bandwidths from the original beams (as e.g. the plasma micro-lens [Toncian]). However, existing devices either require additional beams that would complicate an experiment or are extremely large. A development that we are undertaking within the frame of this program is to design a compact passive magnetic device that “selects” a portion of the original ion beam with the use of a series of slits. The advantage of such a device is that the beam enters and exits on the same axis regardless of the particle energy.

Inspired from accelerator technology, a first prototype of such a device has been already built and tested in 2011 at Elfie. It is 20 cm long and 10 cm wide. There is a series of four sets of magnets as shown in Figure 10. The first set disperses the energy of the beam. The second set, of opposite polarity, continues the dispersion, but changes the direction of the beam back to the forward direction. The third and fourth sets are identical and are a mirror image to the first two, which reverses the dispersion and the particles exit as a beam once more. There is an entrance slit (that could be replaced by a pinhole) to sample a small portion of the beam. There is a second slit in between the second and third sets of magnets that performs the energy selection of the final beam.

Figure 10 shows an example of the functionality of the magnetic selector. The device was set to select a proton beam with a central wavelength of 180 keV with a bandwidth of 75 keV, i.e. a range suitable for ion stopping in plasma studies. In Fig. 11, the top figure shows the standard broadband proton beam that entered the device and the bottom one shows the output beam spectrum.

In the coming years, we plan to continue such developments by developing smaller, even more compact models for higher energy ion beams for use in the HE1 experimental chamber.

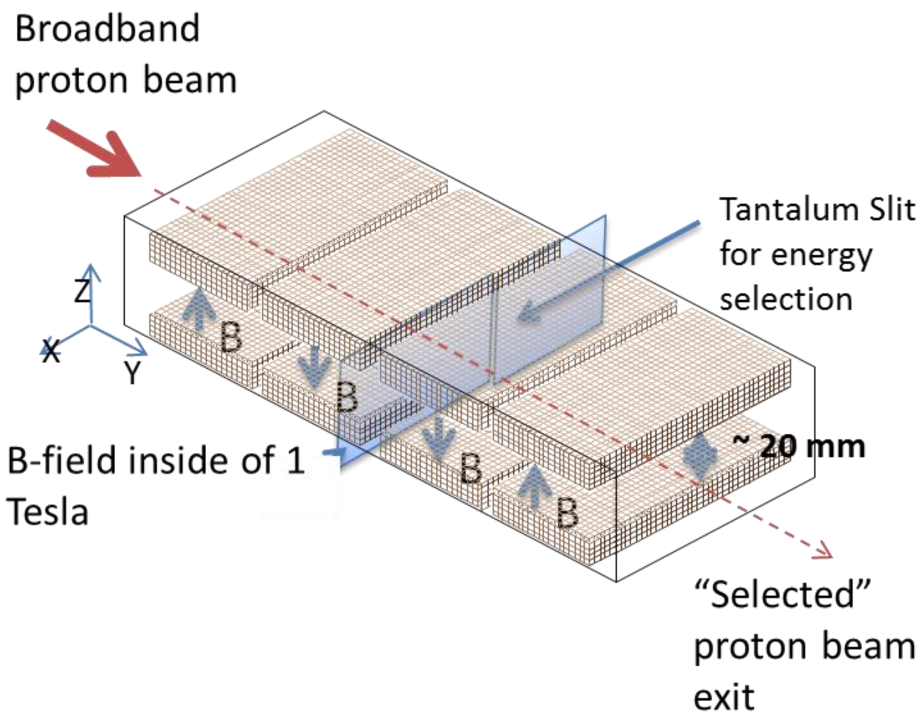

Figure 10: The ion beam selector device is composed of 4 sets of magnets in series. The broadband proton beam created by the short pulse laser solid interaction enters through an entrance slit and is dispersed in energy. The energy selection occurs in the middle of the device using a tantalum slit. The main advantage of this device is that the beam exits close to the same axis of the entering beam regardless of selected energy.

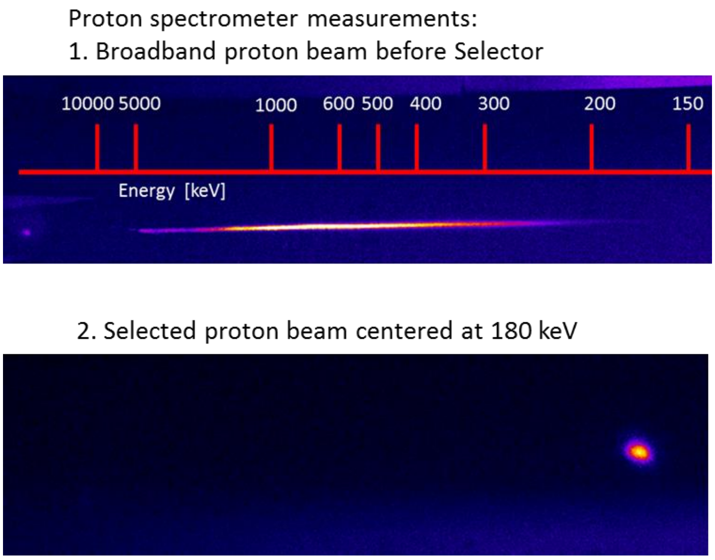

Figure 11: Sample data to illustrate the capabilities of the magnetic device. The top figure shows a sample proton spectrum entering the device. The bottom figure shows the selected beam exiting the device with a central energy of 180 keV with a bandwidth of 75 keV.

Testing low-density ion acceleration at Salle-Jaune and ELFIE

There are right now some issues/limitations linked with using solid targets for ion acceleration: 1) targets need to be aligned precisely for each shot, 2) laser temporal contrast needs to be controlled, 3) debris is produced, 4) repetition rate is limited. These limitations would all be greatly alleviated if one could use gas jets as the laser interaction medium. In such medium, shock acceleration [Palmer, Harberger] could be used to accelerate ions not only very efficiently, but also with a larger number of ions than TNSA. The basic idea behind it is that lower density targets can improve the absorption of the laser energy. Hence both the laser-to-ion conversion and the ion energies can be enhanced. However, to reach such optimum working point, precise interaction conditions need to be met. For this, an important point is to be able to use dense, shaped and thin gas jets. Up to now, gas densities from jets used in laser-plasma interaction were however limited to about 10^{20} cm^{-3} and the jets were rather large (mm-scale). Recent developments allow gaining more than a factor of 10 in atomic density while reducing the gas jet length by a factor of 3 [Sylla], allowing to reach an unexplored range of densities from tens of percent of the critical density to a few times the critical density. The reduction in size of the jet to submillimetric dimensions, coupled with the possibility of density variation over several orders of magnitude, also gives access to Rayleigh-range-long plasmas (even for tightly focussed lasers) from low-density laser transparency to high-density laser opacity regimes. Such a perspective opens systematic investigations of laser-plasma interactions and of ion acceleration.

PIC simulations for ion acceleration using APOLLON parameters

In parallel with the experimental efforts detailed above, a number of 2-D particle-in-cell (PIC) simulations have been performed by means of the code CALDER to predict the properties of the ion beams generated by the F1 beam (i.e. the main beam on APOLLON, see annex) as well as the F2 beam. We have considered fully ionized carbon (C^{6+}) foils of solid density ($n_e = 170 n_c$ at the laser wavelength $\lambda = 0.8$ µm) and thickness d ranging from 50 to 500 nm. Both the (steep-gradient) target front and rear sides are coated with a 1.3 nm-thick, $10n_c$ -dense proton layer that mimics the hydrogenated contaminant layer. The linearly-polarized, normally-incident laser beam has Gaussian space- and time-profiles with 1.9 µm and 15 fs FWHM, respectively. Two values of the on-target laser intensity have been considered: $I_0 = 5\times10^{21}$ Wcm^{-2} (corresponding to F2) and 1.8×10^{22} Wcm^{-2} (corresponding to F1). Collisions and synchrotron-like radiation loss have been neglected.

At such extreme intensities, the thinnest targets turn out to be significantly transparent to the incoming light. For d = 50 nm, the laser transmission reaches 50% for $I_0 = 5\times10^{21}$ Wcm^{-2} and 80% for $I_0 = 1.8\times10^{22}$ Wcm^{2}. It drops to 6% and 50%, respectively, for d = 100 nm. This behavior is illustrated in Fig. 12, which displays, for various laser and target parameters, the 2-D map of the magnetic field at a time following the on-target laser maximum.

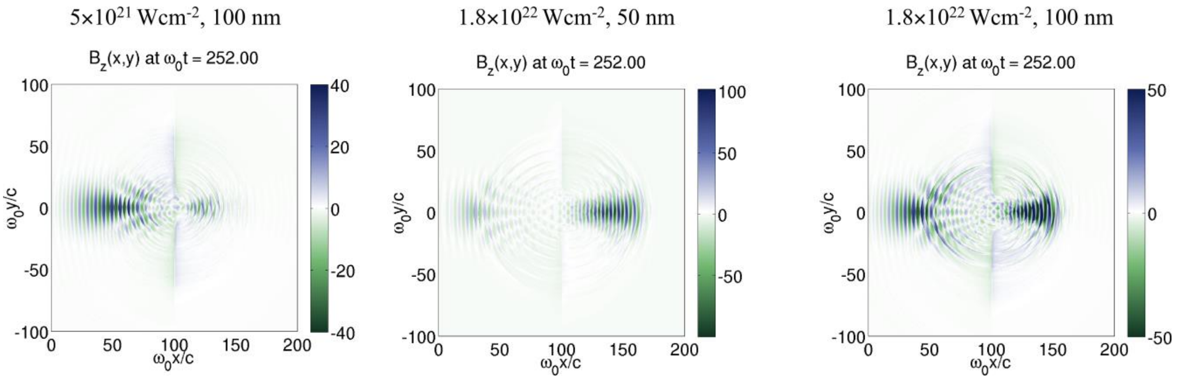

Figure 12: Map of the magnetic field for different configurations at t = 252ω_0^{-1} (the on-target laser maximum is reached at t = 205ω_0^{-1}). Space, time and field units are c/ω_0 = 0.13µm, ω_0^{-1} = 0.42 fs and $m_e\omega_0/e = 1.34\times10^4$ T, respectively.

Figure 13 plots the maximum ion kinetic energies for $I_0=1.8\times10^{22}Wcm^{-2}$ over a broader range of target thicknesses. As a result of enhanced laser absorption (from 7 % to 20 %), the peak proton energy increases from 140 MeV to 250 MeV when d is varied from 50 nm to 100 nm. The proton energy remains unchanged for d = 200 nm, yet severely drops beyond 500 nm. A closer analysis reveals that, whereas the proton acceleration is mostly ruled by volumetric electron heating up to d = 200 nm, it enters the standard TNSA regime beyond d = 500 nm.

Typical proton momentum and energy distributions are plotted in Fig. 14 for d = 100 nm. In the p_x-p_y space, the fastest protons are located over an elliptical shell centered at $p_x \approx 0.3m_pc$ and $p_x \approx 0.5m_pc$ for $I_0 = 5\times10^{21}$ Wcm^{-2} and $I_0 = 1.8\times10^{22}$ Wcm^{-2}, respectively. In both cases, the energy distribution of the forward-going protons presents a similar shape, featuring two peaks at the low- and high-energy ends, and, in-between, a plateau extending over up to 200 MeV (in the high-intensity case).

The easiest experiment that could be performed on APOLLON during the PHASE 2 is thus probably testing the behavior of the maximum proton energy with the foil thickness. This is reported in figure 15 for 1.8×10^{22} Wcm^{-2}. The curve passes through a maximum that is reached when the foil is quasi-transparent to the laser field. For 200 nm, the maximum energy is about 250 MeV and the corresponding spectrum is shown in Fig.13. Note that the spectrum is relatively flat and does not exhibit some “monochromatic” component as expected from the RPA regime. At 1.8×10^{22} Wcm^{-2}, energies about 100 MeV are obtained for 100 nm thick targets. Note also that the energy from the front side of the target is relatively uniform and about 50 MeV proving that the recirculation of the electrons [Ceccotti] trough the target is not efficient in this regime.

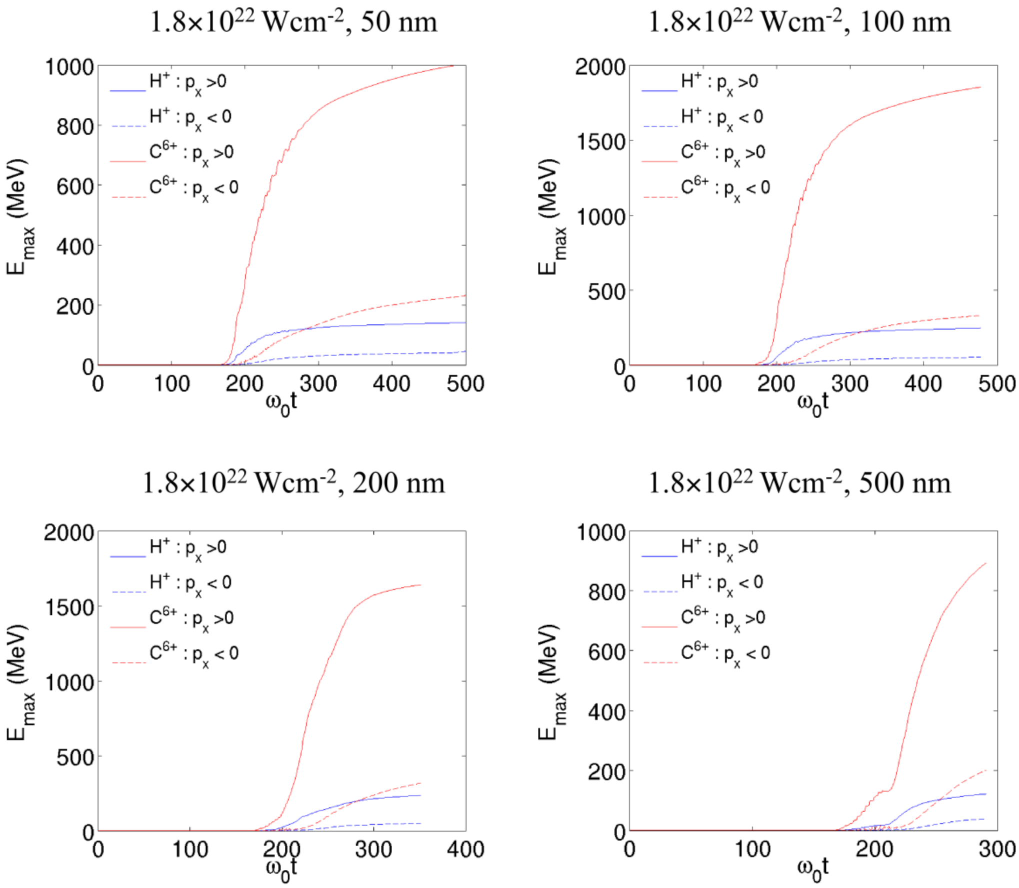

Figure 13: Time history of the maximum H^+ and C^{6+} kinetic energies at 1.8×10^{22} Wcm^{-2} as a function of the direction of propagation and the target thickness. Time is normalized to ω_0^{-1} (= 0.42 fs).

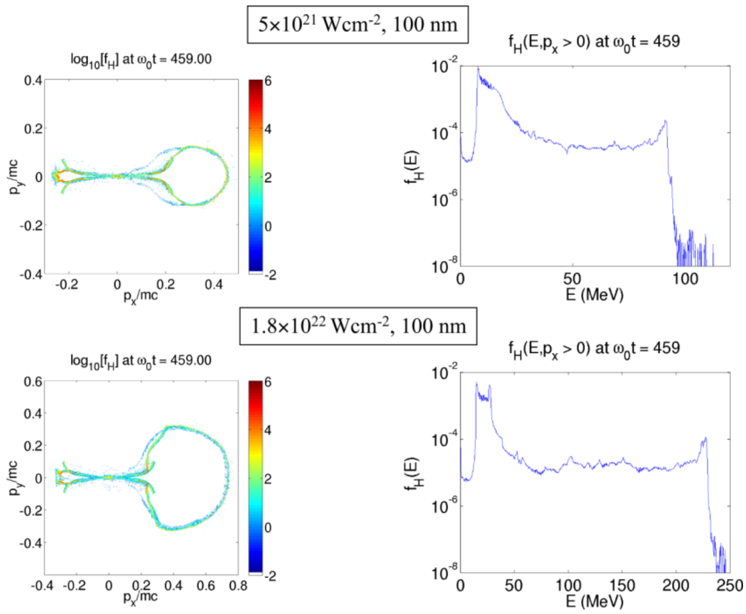

Figure 14: Proton momentum distribution (left) and energy distribution (right) at the final simulation time for $I_0 = 5\times10^{21}$ Wcm^{-2} (top) and $I_0 = 1.8\times10^{22}$ Wcm^{-2} (bottom). The target size is d = 100 nm

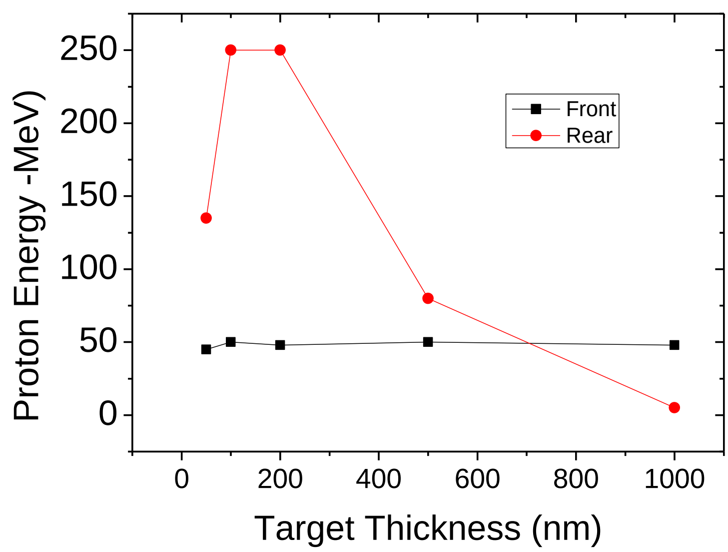

Fig 15: Max proton energies as a function of the thickness

DIAGNOSTIC FOR ION BEAM CHARACTERIZATION AND TARGET SYSTEMS

EMISSIVITY MEASUREMENTS

As mentioned above, one of the main research trends for any future proton source application is the possibility to tailor the spatial profile of the proton beam. A reliable measure of the intrinsic beam spatial properties -divergence and emittance- turns out to be therefore necessary. In the past, we already estimated these two parameters on the proton bunches we have produced using the UHI100 laser facility [Andreev, Ceccotti2] and ELFIE [Fuchs].

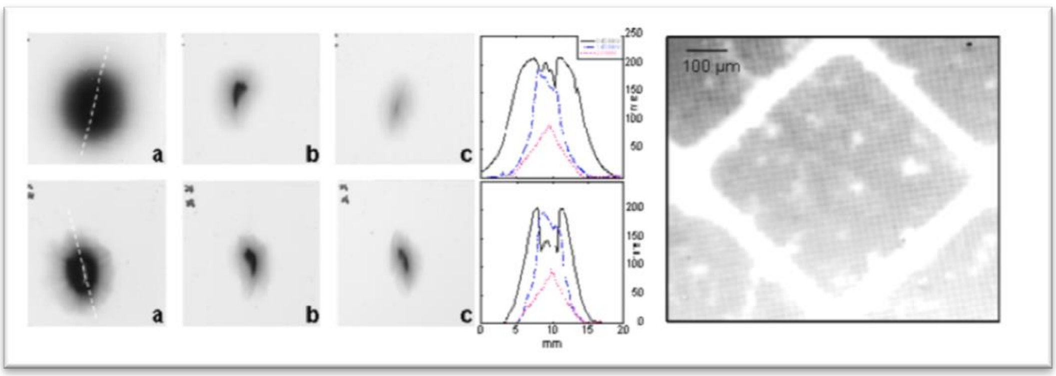

Fig 16 : (Left) Radiochromic film profiles in the BWD (top) and FWD (bottom) direction for the same shot. The recorded energies are 0.45MeV (a), 1.45MeV (b) and 2MeV (c). Images are obtained adding an aluminum layer of 0.8µm, 25µm and 40µm, respectively, on the RCF. The white dashed lines show the direction of the line-outs reported to the right of the picture. Profile clipping at the center of the curves is due to the alteration of the outermost films by the high proton doses; (right) shadow of grid meshes (periods: 500 and 12.7µm) impressed in the 0.45MeV BWD proton beam profile.

In the framework of a collaboration with the CEA/IRFU, we are planning to develop a diagnostic able to measure the proton beam emittance for the overall proton energy distribution (and not a restricted proton energy range as previously). The main concept, roughly schematized in the following Fig.17, will be to introduce an energy dispersion via a couple of permanent magnets in such a way as to observe the emittance variation as a function of proton energies.

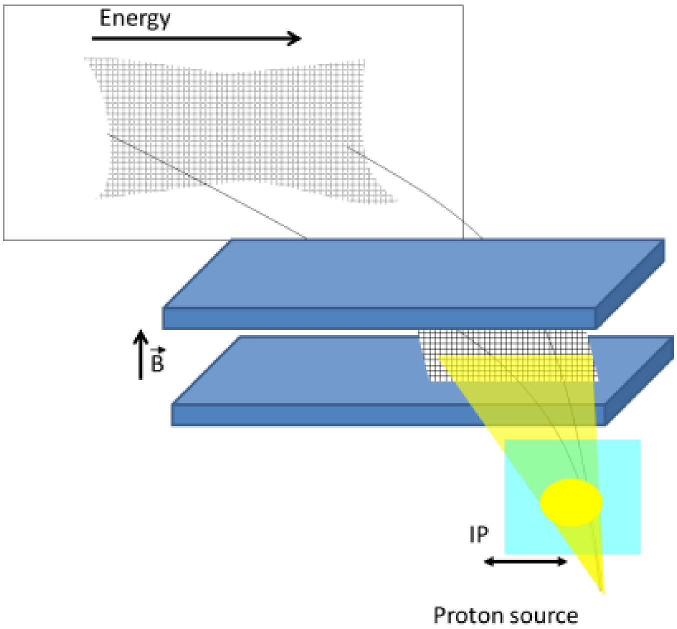

Fig 17: The proposed basic set-up for the measurement of energy resolved proton beam emittance

Such measurements must go with an energy resolved estimate of the virtual point source size. In order to do that, a properly screened IP will get an image of the intrinsic proton beam spatial distribution and divergence, before this latter be dispersed by the magnets. Nonetheless, before being able to turn such a concept into a real system, we must still face up to several points. For instance, it is mandatory to separate the proton signal from the one produced by other accelerated ions. As a consequence an experimental campaign on the UHI100 facility will be carried out to validate this innovative emittance diagnostic concept.

HIGH ENERGY THOMSON PARABOLA

The simulations performed by L. Gremillet (see above) show that the future APOLLON facility will be able to accelerate protons with energies of about 250 MeV. This value is of the same order of the proton energies expected on the PETAL facility (http://petal.aquitaine.fr/-The-PETAL-laser-facility-.html). As members of the workgroup PETAL+, devoted to the conception and implementation of ion diagnostics for the future experimental activity on PETAL, we have already designed a Thomson parabola with the appropriate spectral range and resolution for such high energy protons.

A preliminary concept (illustrated below) foresees to actually use two parallel Thomson parabolas, each one covering a specific energy range in order to record the spectral distribution between about 500 keV and 250 MeV. Moreover, this particular set-up allows recording the electron distribution too, in the energy domain between 500 keV and 100 MeV. In order to adapt such a diagnostic to APOLLON, several modifications need to be taken into account. First of all, as the size of the experimental hall will be obviously smaller than the PETAL facility, several parameters need to be modified to assure the same spectral resolution on a reduced size scale. On the other hand, a study about the nature of the charged particle detector to be used must be made, as the repetition rate of the APOLLON facility is hardly compatible with passive detectors like CR39 or IP. At the same time, the conversion efficiency of MCP detectors for such high energy has to be precisely defined. As a consequence we plan to carry out the development of this diagnostic in order to make it fit the APOLLON set of specifications.

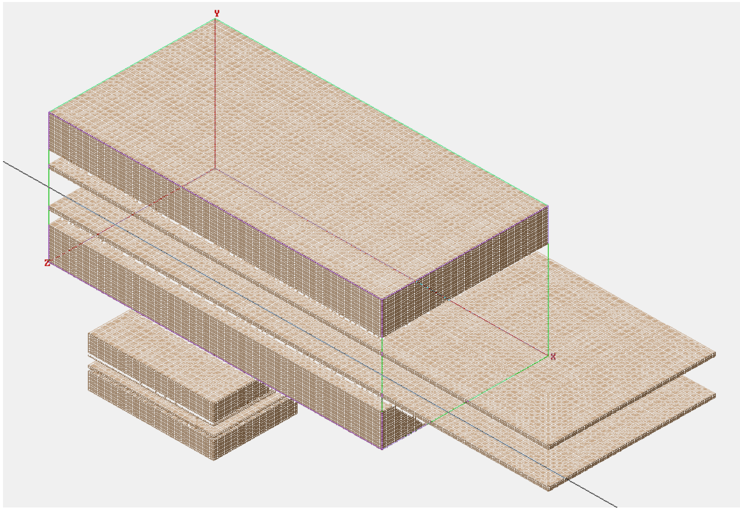

Fig 18: the basic set-up of the proposed Thomson parabola. Two sets of magnetic and electric fields vertically shifted, each one detecting an energy range.

HIGH REPETITION RATE TARGETRY

To take advantage of the high repetition rate avaliable at APOLLON (compared to other ultra-high intensity short pulse laser facilities), targets must be avalaible at the same or similar rate. Targets, such as those used to produce single ion beams can be mounted on a wheel, ladder, etc. However, complex experiments involving multiple beams (as used in pump/probe experiments) will typically involve multiple targets in extemely close proximity (on the order of several hundred microns). Then the challenge becomes to perform multiple target alignment inside and outside the experimental chamber in a timely manner. Figure 19 shows an illustration of a target assembly that includes three targets (one at the end of each glass stalk) and that was used in previous pump-probe experiment. In that experiment, two short pulse laser beams irradiated two of the targets (these were 250 μm diameter gold disks). They produces ion beams that irradiated the triangular target (the third target, positionned 500 μm from the two disks) to produce WDM.
We will develop a prototype for being able to insert a series of such multiple target assembly within a vacuum chamber without having the need to vent it, and take advantage of various experiments that will be performed on Elfie in the coming years to test it (in a “piggy-back” mode)

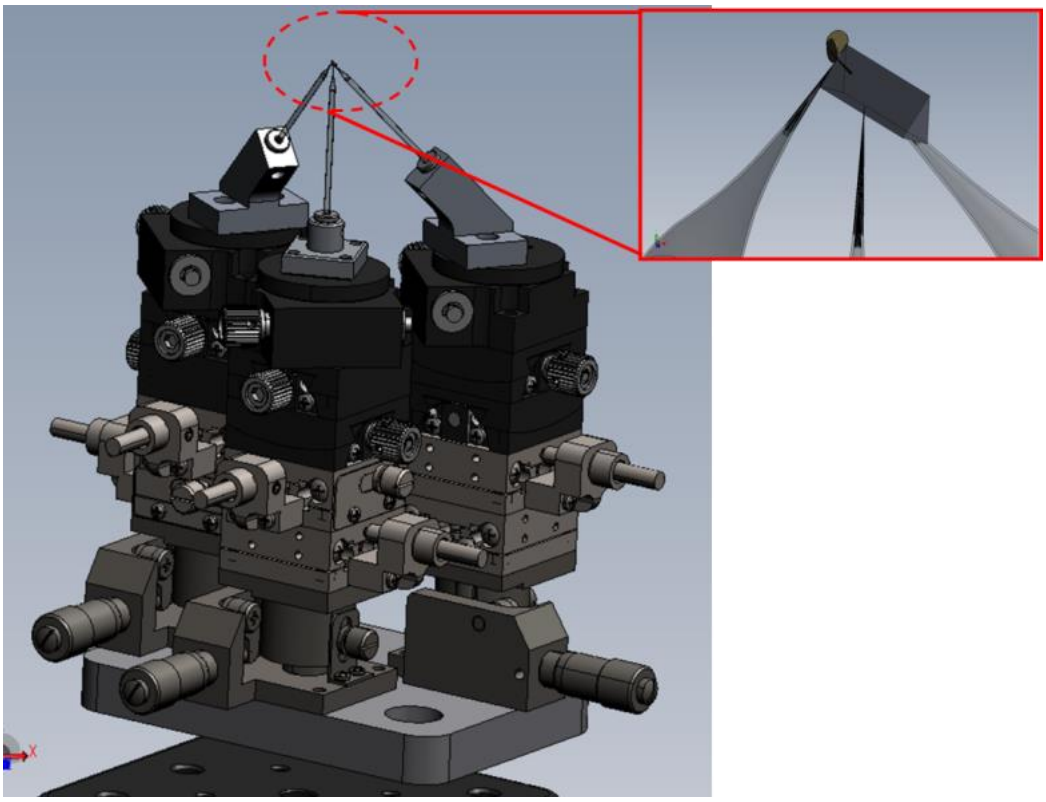

Figure 19: A target manipulator holding two 250 µm gold disks and a carbon triangle for a pump-probe experiment. All the targets are within several hundred microns of each other.

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C-Relativistic Plasma Mirrors

GLOBAL SCIENTIFIC OBJECTIVE FOR 2013-2017

Our goal is the development of **fundamental studies in relativistic optics**, where plasmas are coherently driven by laser fields of extremely high intensities, and high order harmonic generation is used as a diagnostic of the interaction.
When an intense ultrashort laser pulses hits a solid target, ionization by the laser field leads to the creation a dense plasma at the surface, within a few femtoseconds, which efficiently reflects the incident laser pulse. For a femtosecond pulse, plasma expansion during the interaction remains negligible: in these conditions, the field is specularly reflected, and its spatial quality is preserved. Such a dense plasma with a sharp interface with vacuum is called a plasma mirror (PM) [Thaury1&2, Dromey]. These are relatively simple systems, where laser propagation effects are very limited, and which constitute ideally-simple testbeds for models of high-intensity laser-plasma interaction and relativistic optics. In addition, plasma mirrors have a major role to play as active high-intensity optical elements, to manipulate the temporal and spatial properties of intense laser beams.

In the time domain, when the laser intensity is high enough, the non-linear response of the PM to the field results in periodic modulations in the reflected field. These modulations are associated in the frequency-domain to high-order harmonics of the incident laser. This harmonic signal constitutes a very fine in-situ probe of the laser-plasma interaction. Moreover, once the initial laser frequency and its low-order harmonics are filtered out of the reflected beam, these modulations produce trains of attosecond pulses. Schemes have been proposed and demonstrated to isolate single attosecond pulses from such trains, which could potentially be used for pump-probe experiments on the dynamics of electrons in matter. In this perspective, one of the most promising HHG mechanisms is called the Relativistic Oscillating Mirror, where the laser-driven relativistic oscillation of the plasma surface induces a periodic Doppler effect on the reflected beam, leading to HHG. This has been claimed to generate harmonic orders as high as several thousands, using laser intensities that will be well within the accessible range of the APOLLON laser. Other generation mechanisms can be involved and are actively studied worldwide.

Plasma mirrors can be used to also manipulate the spatial properties of the reflected beam, either at the initial laser frequency or its harmonics, for instance by geometrically shaping the initial solid target on which the PM is created. At moderate intensities, elliptical PMs have thus recently allowed extremely tight focusing of a high-power laser beam [Naka]. In the relativistic regime, curved PMs have been proposed as a way to focus the very high generated harmonic orders to a spot size w $\ll \lambda_L$ (where λ_L is the laser wavelength). Combined with their attosecond temporal bunching, this is a promising –although challenging- path to boost the peak intensity of ultrashort lasers.

The study of plasma mirrors thus has two major motivations:

- Studying the basic physics of high-intensity optics, in particular in the relativistic intensity regime. In this perspective, key information can be extracted from the generated harmonic signal.
- Manipulating the temporal and spatial properties of intense laser fields, in particular to generate intense attosecond pulses of light, and to reach unprecedentedly high light intensities.

Studying the physics of plasma mirrors - either theoretically, numerically using Particle-in-Cell (PIC) codes, or experimentally using existing high-power femtosecond laser facilities- is crucial to prepare the future experiments on APOLLON that will explore these two avenues. Such studies have already made it possible to clearly identify some of the main physical processes that are involved, and to measure and understand some of their properties.

An intensive theoretical and experimental program has in particular been pursed in the Physics at High Intensity group (CEA) for the last 8 years. On the theoretical side, this program has been based on two PIC codes, the 1D code EUTERPE and the 3D code CALDER, both developed within CEA. On the experimental side, it has exploited the 10 TW UHI10 laser until 2008, and since then its successor UHI100, a state-of-the-art 100 TW laser satellite facility.

In the next two years, this program will in particular aim at gathering the information and gaining the physical insight required for the future experiments on plasma mirrors with the APOLLON laser. This will be achieved by again using the combination of theory/simulations and experiments.

Theory and Simulations

The main goal of the theoretical and numerical work will be to gain further insight into the physics of plasma mirrors. So far, 1D and 2D particle-in-cell simulations have made it possible to clearly identify the main mechanisms that are involved in HHG, which are Coherent Wake Emission (CWE) and the Relativistic Oscillating Mirror (ROM) effect. For experiments with APOLLON, the most relevant process is clearly ROM, although CWE might also be useful as an in-situ diagnostic of the plasma.
The main ingredient that has been missing so far for ROM is a reliable analytical model that would be able to predict the harmonic generation efficiency as a function of the interaction parameters. This is

especially important to identify the optimal interaction conditions for HHG. Although a few models have been proposed by different groups, they remain to be studied in more details, and to be extensively compared to PIC simulations. This is one of the important tasks to be carried out by the PHI group in the coming years.

While no model is available to calculate the amplitude of the ROM signal, its phase properties on the other hand are now well understood, thanks to a model that we developed in the last two years. This model has been validated by PIC simulations as well as experiments. Knowing these phase properties is in particular essential to determine the divergence of the harmonic beam, which is a key parameter in experiments, e.g. to generate attosecond lighthouses. We have also shown that this divergence can be controlled to some extent by using the phase properties of the driving laser. This model for the phase of ROM harmonics can also be used to calculate the focusing of the beam reflected by a plasma mirror. This will be a precious tool to prepare and analyse future experiments on APOLLON.

PIC simulations are also very useful to study different schemes to generate isolated attosecond pulses. This is how we validated the principle of the attosecond lighthouse effect in 2012, which has then enabled the generation of the first isolated attosecond pulses from plasma mirrors, in the CWE regime [Wheeler]. In the coming two years, we will need to combine these different assets to determine in what conditions attosecond lighthouses based on ROM could be obtained with APOLLON.

Finally, other mechanisms for the generation of harmonics and attosecond pulses have recently been proposed recently in the literature, such as Coherent Synchrotron Radiation. They will require more detailed studies using PIC simulations, to determine in what conditions these mechanisms can be investigated experimentally with APOLLON, and whether they can provide interesting light sources.

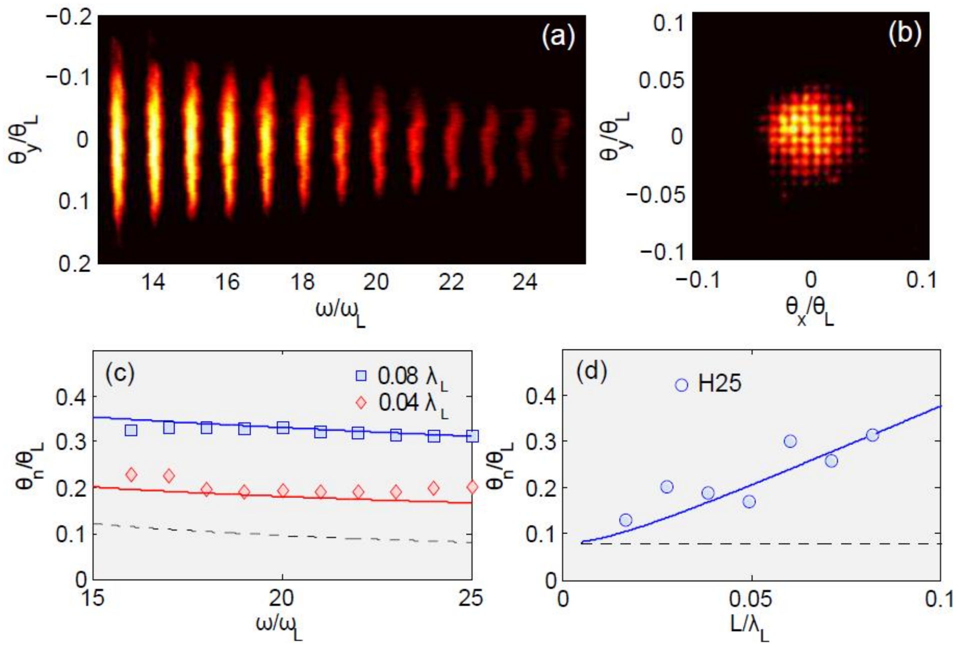

Figure 20: Measurements of high-order harmonics beams produced by a relativistic oscillating mirror. (a-b) Typical raw images obtained with the UHI100 laser. Image (a) shows the angularly-resolved harmonic spectrum measured in the far-field, for a peak intensity of I = 3.5x 10^{19} W=cm^2 (a_0 = 5.6), and an initial density gradient L = λ/20. Image (b) displays the full far-field spatial profile of the beam

corresponding to the superposition of harmonics 20 to ≈35 (close to the maximum order observed in this experiment), measured in similar interaction conditions. From these images, quantitative information on the harmonics spatial properties can be extracted. Panel (c) thus shows the spectrally-resolved divergence (in units of laser divergence θ_L) as a function of harmonic order, for two values of the density gradient L. The plot in (d) is the divergence of the 25th harmonic as a function of L. In both panels, the full lines show the results of the model that we have developed for the spatial properties of the harmonics, resulting from the laser-induced curvature of the plasma mirror. A fully-consistent set of parameters was used for all curves. There was no free parameter: the unknown physical quantities involved in the model were extracted from PIC simulations. From H. Vincenti et al, submitted (2013).

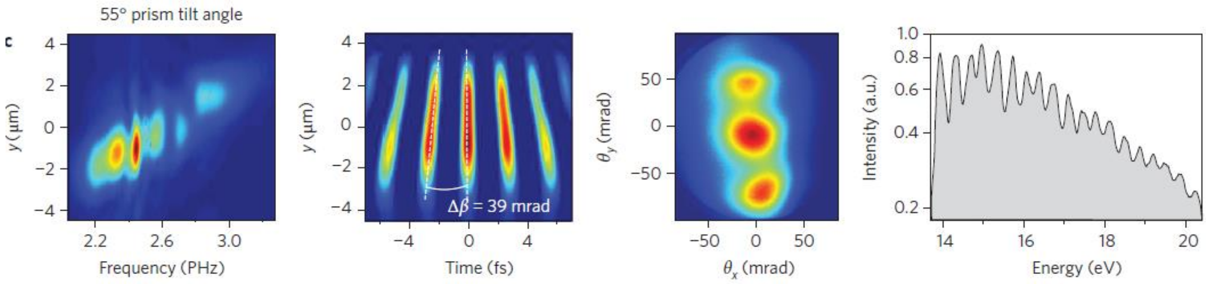

Figure 21: Experimental observation of the attosecond lighthouse effect in CWE regime. Left image: spatially resolved spectrum of the driving laser field at focus for a 55^o tilt of the prism pair. Second image: calculated laser electric field E(y,t) at focus (with the blue-to-red colour scale corresponding to values of E≥ 0, while all values of E<0 are displayed in dark blue), deduced from the first column by a Fourier transform with respect to frequency, assuming a constant phase in space and frequency. Third image: measured spatial EUV beam profile for a fixed arbitrary value of the CEP of the laser. Rightmost image: corresponding EUV spectrum recorded at the centre of the spatial beam profile. From J. Wheeler et al, Nature Photonics 6, 829 (2012).

RESEARCH ON HIGH-ORDER-HARMONIC GENERATION ON UHI100

The two major requirements for future experiments on plasma mirrors with APOLLON are:

- An excellent control of the interaction conditions on target,
- Suitable diagnostics, in particular for the harmonic emission.

The tools required for this will be developed and tested on smaller facilities such as UHI100. Moreover, experiments on such lasers can already provide tests of models, and evaluate the feasibility of some experiments.

CONTROL OF THE INTERACTION CONDITIONS

Controlling the interaction conditions implies, on the one hand, controlling the incident laser field on target, and on the other hand, the target conditions at the onset of the interaction.

As far as the first point is concerned, our goal in the next two years is to learn how to measure, and ultimately how to control, the whole spatio-temporal structure of the incident laser field on target. Methods to measure the exact temporal structure of the laser field at one point of the beam (prior to focusing) are already available (e.g. SPIDER or FROG). However, high-power lasers such as UHI100 or APOLLON are expected to exhibit significant spatio-temporal couplings (STC), i.e. a spatial dependence of their temporal properties. When uncontrolled, such couplings can significantly degrade the performances (in particular the peak intensity) of the laser at focus. But, if they are moderate and well-controlled, STC can be exploited to drive new physical effects, in particular in HHG, such as the attosecond lighthouse effect. A prerequisite to control is of course the ability to accurately measure STC. But at present, no simple method is available for such a spatio-temporal characterization. We are presently developing such techniques, which should be extremely useful to optimize APOLLON.

We are also working on the control of the laser properties. Well-established techniques are already available to control the temporal (acousto-optic modulator) and spatial (adaptative optic system) of fs lasers. We are collaborating with a French company, Imagine Optics, to develop better methods for the spatial control, which will enable to really optimize the spatial properties of the beam on target. Control of the full spatio-temporal structure is of course much more challenging, as this involves many more degrees of freedom. However, some basic STC can be induced and controlled in very simple ways: for instance, a small rotation of a grating on the compressor results in a temporal wavefront rotation at focus, which is precisely what is needed to induce the attosecond lighthouse effect. We will test such control schemes on UHI in the coming years.

As far as the control of the interaction is concerned, a crucial parameter for plasma mirrors is the scale length of the density gradient at the plasma-vacuum interface just before the arrival of the main pulse, which strongly influences the response of the plasma mirror to the laser field [Rodel]. Tuning this parameter is in particular necessary to optimize the ROM efficiency. Provided the main beam has a high enough temporal contrast, this can be achieved by ionizing the target using a small prepulse (with a minimum intensity of $\approx 10^{15}$ W/cm^2), at a controllable delay before this main pulse. We have tested on UHI100 a very simple scheme to introduce this prepulse, which consists in using a small fraction of the main beam. First experiments with this scheme have shown that it is very stable, produces a prepulse with a focal spot size much larger than that of the main beam, and enables to vary the delay very easily, even to negative values (i.e. no more prepulse). The real difficulty here is in fact not in controlling this density gradient, but rather in measuring it. This will be addressed in the next section.

Another interesting parameter to control is the maximum density of the plasma mirror, which in practice requires controlling the electron density of the initial solid target. Reaching densities approaching the critical plasma density at the laser frequency is particularly interesting, as this has been predicted to lead to higher HHG efficiencies. This can in principle be achieved using targets such as foams or aerogels. However, the difficulty is that the target has to remain homogeneous on the scale of the laser wavelength, and that its surface has to be of optical quality. So far, no suitable low-density target has been identified in experiments. Further prospecting and experiments will be performed to find suitable targets of different densities for future experiments on APOLLON.

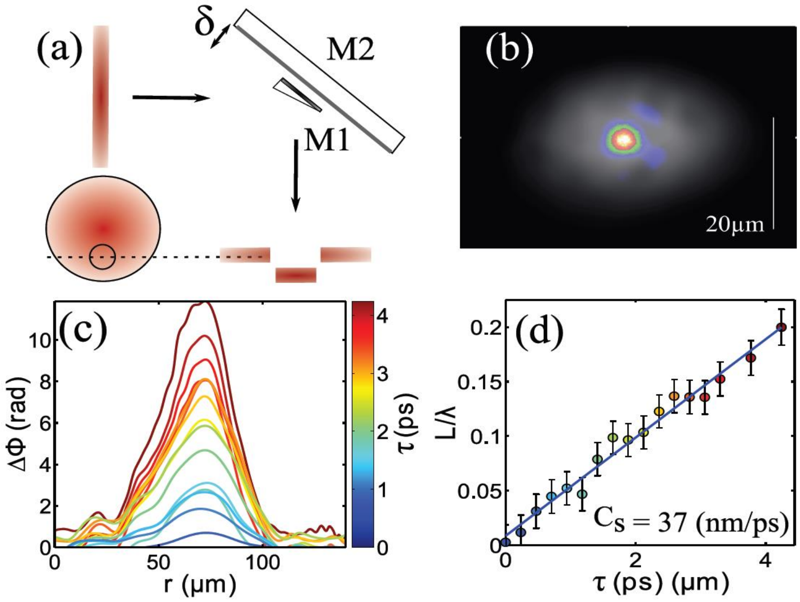

Figure 22: (a) Experimental scheme for density gradient control. Two mirrors M1 and M2 are used to separate the prepulse and main pulse in time, before the focusing parabola. Side and front views of the full laser beam are shown in red. (b)Resulting intensity distributions of the prepulse beam (gray scale) and main beam (coloured scale) at focus. (c) Temporal evolution of the spatially-resolved phase shift induced on the FDI probe pulse by the plasma expansion trigerred by the prepulse. (d) Temporal evolution of the density gradient scalelength L at the center of the prepulse beam, as deduced from the measured phase shifts. From S. Kahaly et al, accepted at prl (2013).

DIAGNOSTIC DEVELOPMENTS

Thanks to the experiments carried out on UHI10 and UHI100 over the last 8 years, some excellent diagnostics are already available for the study of plasma mirrors, and in particular HHG. These essentially consist of:

- An imaging XUV spectrometer, that consists of the combination of a torodal mirror and a flat varied-line spacing grating, both used at grazing incidence, which provides a spectrally-resolved image (with a resolution of a few tens of microns only) of the harmonic source on a MCP detector.
- A non-imaging XUV spectrometer that consists of a spherical varied-line spacing grating, used at grazing incidence. This provides the angularly-resolved harmonic spectrum, measured on a MCP detector.
- A spectral filtering optical line, that selects a group of harmonics, which 2D spatial profile is then measured on a MCP detector.

All these diagnostics are routinely used for experiments with the UHI100 laser, and have provided detailed information on HHG from plasma mirrors. Adapting these diagnostics to experiments on APOLLON is not trivial, due to the large size and high power of the laser beam. In addition, if very high harmonic orders are produced with APOLLON, up to the X-ray range, new diagnostics suited to this different spectral range will be needed, in particular with a better spectral resolution. This will probably require spectrometers based on Bragg crystals. In the next two years, we will work on ways to adapt the existing diagnostics to the laser conditions corresponding to APOLLON, and on new diagnostics suited to higher harmonic orders.

In the past two years, we have also developed a Fourier-domain interferometer, to determine the density gradient at the surface on the plasma mirror by measuring the phase shift induced on a weak probe beam. We have successfully used this device to measure the density gradient created by the prepulse mentioned in the previous section. Our next goal is to use it to measure the density gradient during the interaction with the main pulse. The challenge here is to limit the noise in the probe interferogram, due to scattered light from the main pulse, which could prevent an accurate measurement of the phase shift. This problem becomes all the more critical as the main beam is intense. We will soon attempt such measurements on UHI100, and these measurements should make it possible to assess the feasibility of density gradient metrology with FDI in the presence of the main pulse of the APOLLON laser.

Two other diagnostics need to be developed and tested on UHI100 in the next two years.

i) The first one is a set-up to reliably measure the laser to harmonic conversion efficiency. This set-up will have to efficiently eliminate the laser frequency, filter one or a group of harmonics, and use a calibrated detector to measure the energy contained in the filtered radiation. To obtain the conversion efficiency on target, the losses induced on the selected harmonic(s) by the spectral filtering system will have to be accurately determined. The main issue is not to get a signal, but to make sure that this signal is reliable: the challenge here is the huge amount of laser light that is present in the experimental chamber (already with UHI100, and even worse with APOLLON). The use of a solar-blind calibrated detector will probably be necessary.

ii) The second diagnostic to be developed is a system to measure, or at least evaluate, the duration of the emitted attosecond pulses. Most temporal measurement techniques developed until now (initially for attosecond pulses generated in gases) are multi-shot techniques, which require scanning a delay. The feasibility of implementing such techniques on APOLLON will have to be studied. This however seems rather unsuitable, as these techniques are already extremely challenging (and demonstrated only once so far) to use with multi-TW lasers. Alternative techniques need to be studied, such as photonic streaking, which uses a temporal rotation of the laser wavefront on target, just like attosecond lighthouses. We will have to determine whether the streaking speed that can be achieved with a laser such as APOLLON can provide the temporal resolution required to measure attosecond pulses.

MODEL VALIDATIONS AND FEASIBILITY STUDIES

The experiments performed on UHI100 in the next two years will also aim at validating the models developed to describe the physics of plasma mirrors, and test the feasibility of different experiments, in the relativistic regime that is accessible with this laser ($a_0 \leq 10$). The APOLLON laser will then make it possible for the first time to extent these studies to the ultrarelativistic regime ($a_0 \approx 100$).

In the last year, we have already validated experimentally the model that we have developed for the phase properties of the ROM harmonics. In the near future, we will perform additional measurements, where we will in particular try to test this model at even higher intensities. In these experiments, we will also collect data to test the models that have been proposed for the ROM harmonic generation efficiency.

Another important experiment that will be attempted is the generation of an attosecond lighthouse in the relativistic regime, using laser pulses of 25 fs duration. Although theoretical studies and measurements of the spatial properties of the harmonic beam suggest that this should be possible, our first attempt was unsuccessful. We will try this experiment again in better conditions, and use these tests to assess the feasibility of such an experiment on APOLLON. The shorter duration of the pulses provided by this laser (15 fs) is highly favorable, since it gives access to larger wavefront rotation velocities on target.

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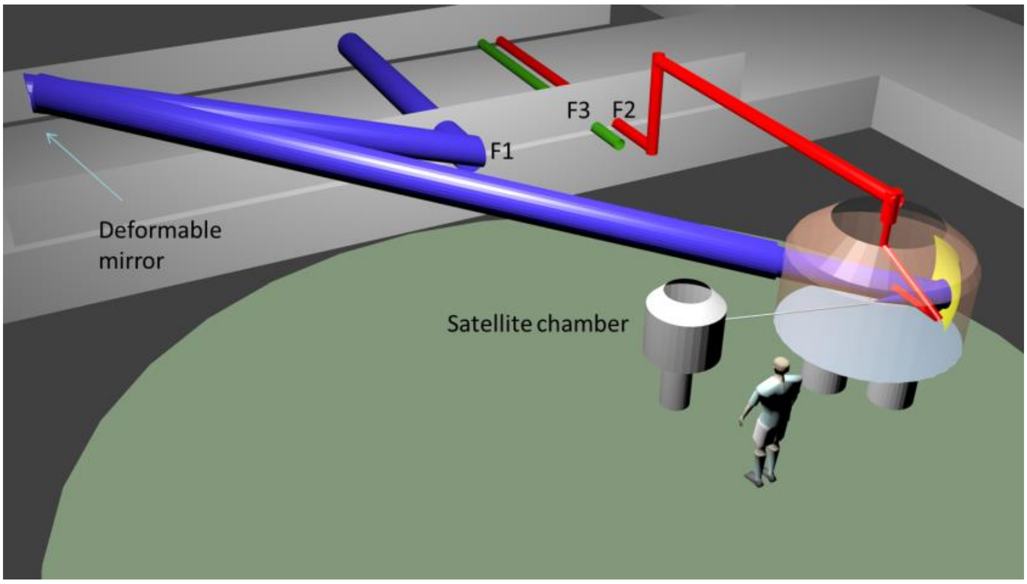
D-Conceptual Design of He1

Below we present *the present state* of the design of the HE1, short-focal length room, integrating the needs *of ion beam development, as well as the ones of high-photon-energy* and *high brightness beams of X-rays* (exposed in previous sections). Refining this design will continue, with the goal of finalizing the design in the summer 2013 so that, accounting for procurement, manufacturing, and set-up in the HE1 room, equipment will be ready for first light in mid-2015.

Room Layout

This experimental room will house several vacuum chambers with a primary chamber for the laser plasma interaction and smaller chambers for secondary interactions. A possible layout of the main chamber and beamlines is illustrated below



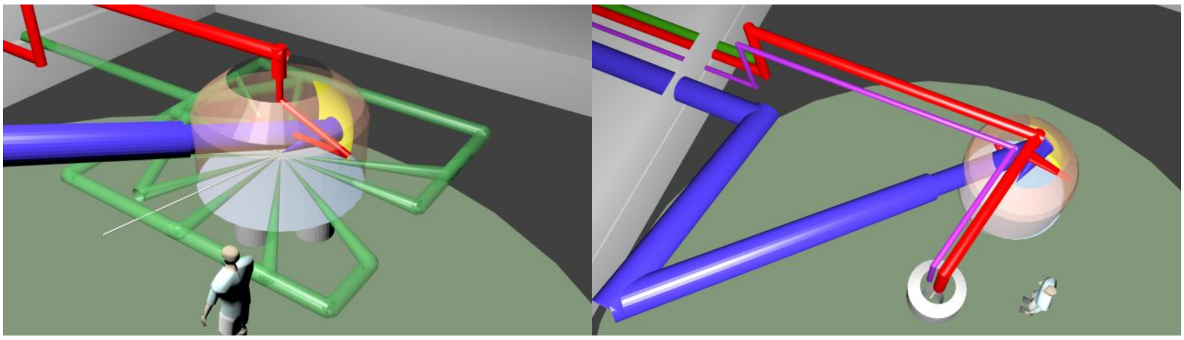
Top view of the two experimental chambers and possible beam layout, and F1 & F2 beams.

Light Transport

The two short pulse beams, after pulse compression, will be directed to the HE1 experimental room. The beams have an option of contrast improvement with a system of plasma mirrors. Another option will be to have a deformable mirror after the plasma mirror setup and before the last turning mirror to correct for profile distortions from compression and the plasma mirrors. The main short pulse (F1) beam enters the chamber at the off axis angle of the f/2.5 parabola such that the reflected beam onto the target is horizontal as illustrated above. The second short pulse beam (F2) will enter from the top and will have the flexibility of being directed to any angle (~310˚ movement possible) that permits a secondary parabola on the chamber breadboard.

The long pulse beam (F3) enters the room and is directed to the chamber on the horizontal plane as defined by the users. The beam can enter the chamber through any of the ports on the horizontal plane. It will be focused by a lens and phase plates will be used to define the beam profile on target.

The probe beam (F4) will be transported from the compressor into the target chamber. The beam will be transported in vacuum to preserve the low jitter. Both F2 and F4 will have the possibility to be redirected to the satellite chamber to maximize the number of possible beam configurations.

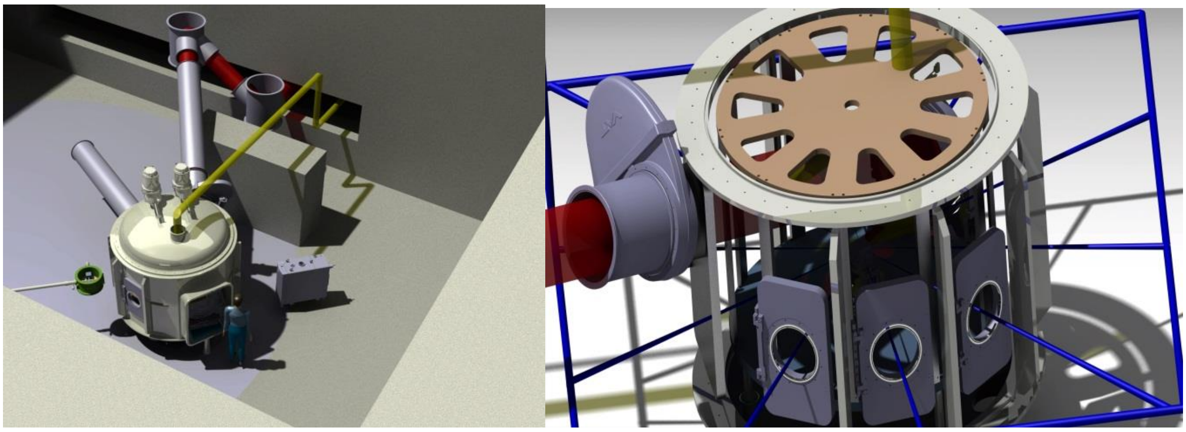


(left) Beam layout of F1, F2 & possible configurations of F3. (right) Redirection of the F2 (in red) and F4 (in purple) beam to the satellite chamber.

Target Chamber

The design of the target chamber is modeled after the chamber at the Titan laser at Jupiter Laser Facility (USA). It has many advantages over existing chamber at other facilities:

- Access from all angles with large doors
- All ports are angled to TCC for re-entrant diagnostics
- Large enough to accommodate for many diagnostics without compromising pumping

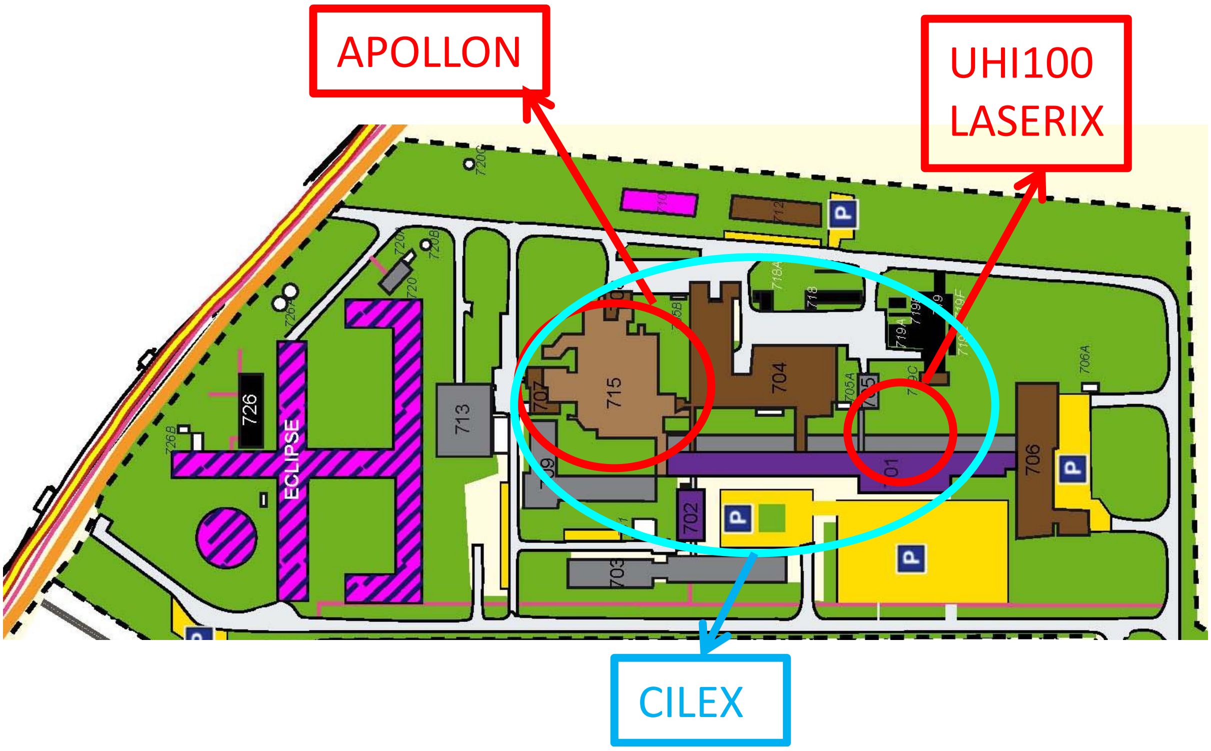


The target chamber will be 2 meters in inner diameter. The material of the chamber will be aluminum for activation precaution and since the walls of the hall will serve as the primary radiological protection. The main short pulse beam will enter the chamber through a port in the side wall at the parabola off-axis angle. The second short pulse beam will enter through the vertical port on the lid of the chamber.

Diagnostic packages are designed to provide comprehensive information about system performance in preparation for and during a target shot. Measurements will be made of the beam energy, pulse shape, near-field and far-field spot profiles, full-aperture beam wavefront, and contrast. Also, a beam timing interferometer will be setup to monitor the delay of the beams relative to F1.

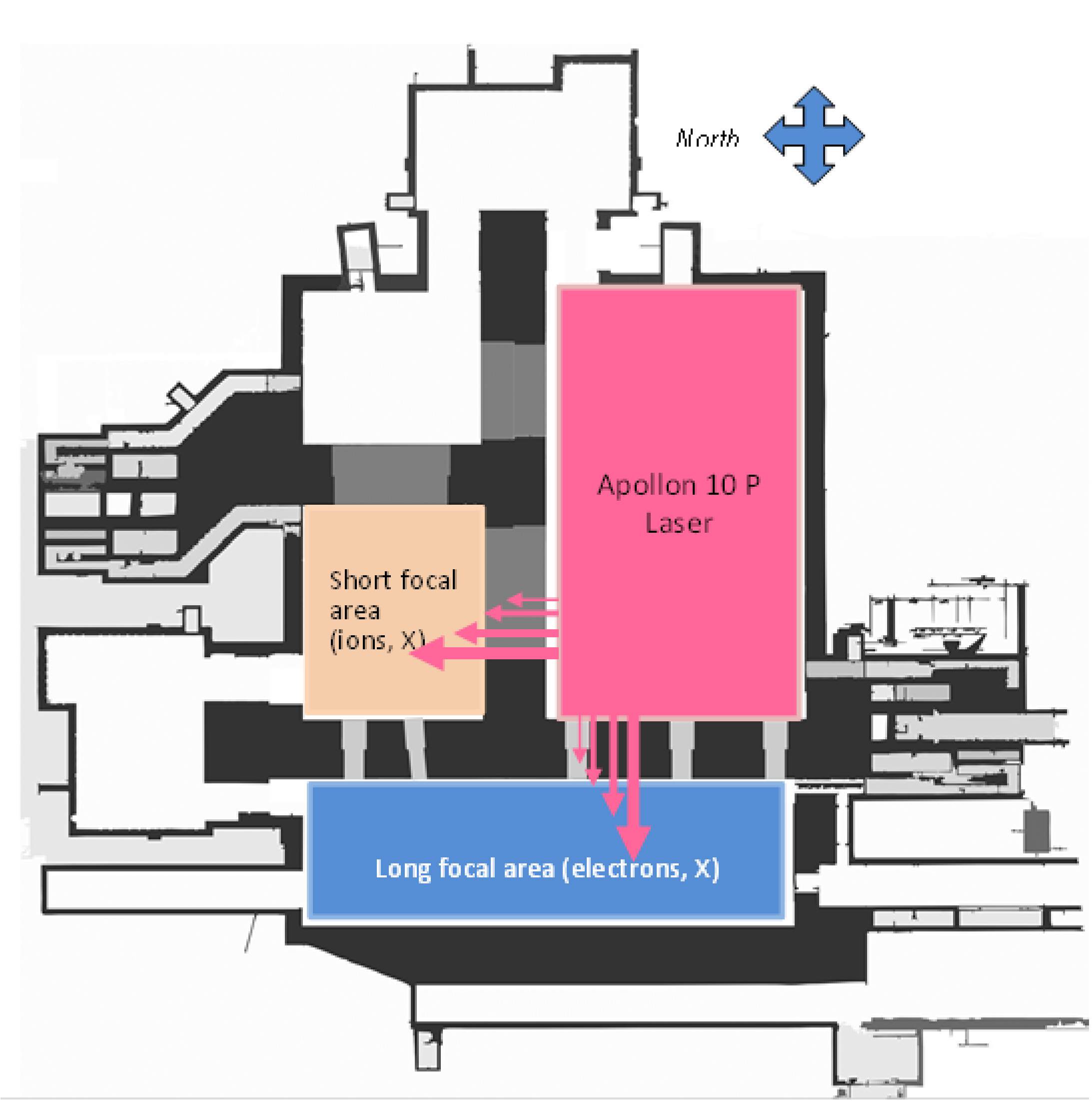
E-Annexe

CILEX Overview



CILEX APOLLON laser as well as the satellites facilities UHI100 and LASERIX will be located at l'Orme des merisiers within the Campus Paris-Saclay.

APOLLON



The Cilex/APOLLON laser facility will distribute up to 4 laser beams within one of the 2 experimental areas. The respective delay between the different pulses will be adjustable. The beam characteristics are the following:

F1: Main short pulse beam**:** 150 J max, 15 fs – 10 ps, 400 mm diameter.

The amount of energy within the λ= 800 nm pulse will have to be selected between the 4 predetermined values: 150J, 75J, 50J, 25J. The pulse duration will be continuously adjustable from 15fs to 10ps. The flat top profile will have a 400 mm diameter. The beam pointing jitter will lead to a maximum spot jitter at focus corresponding to the dimension of the focal spot.

F2 : Secondary short pulse beam**:** 15 J, 15 – 200 fs, 140 mm dia.

The second short pulse beam will have a maximum energy of 15 J at 800 nm. A lower energy, namely 10J, 5J or1J will be affordable. The duration will be adjustable from 15 fs to 10 ps.. The beam diameter before focusing is 140 mm.

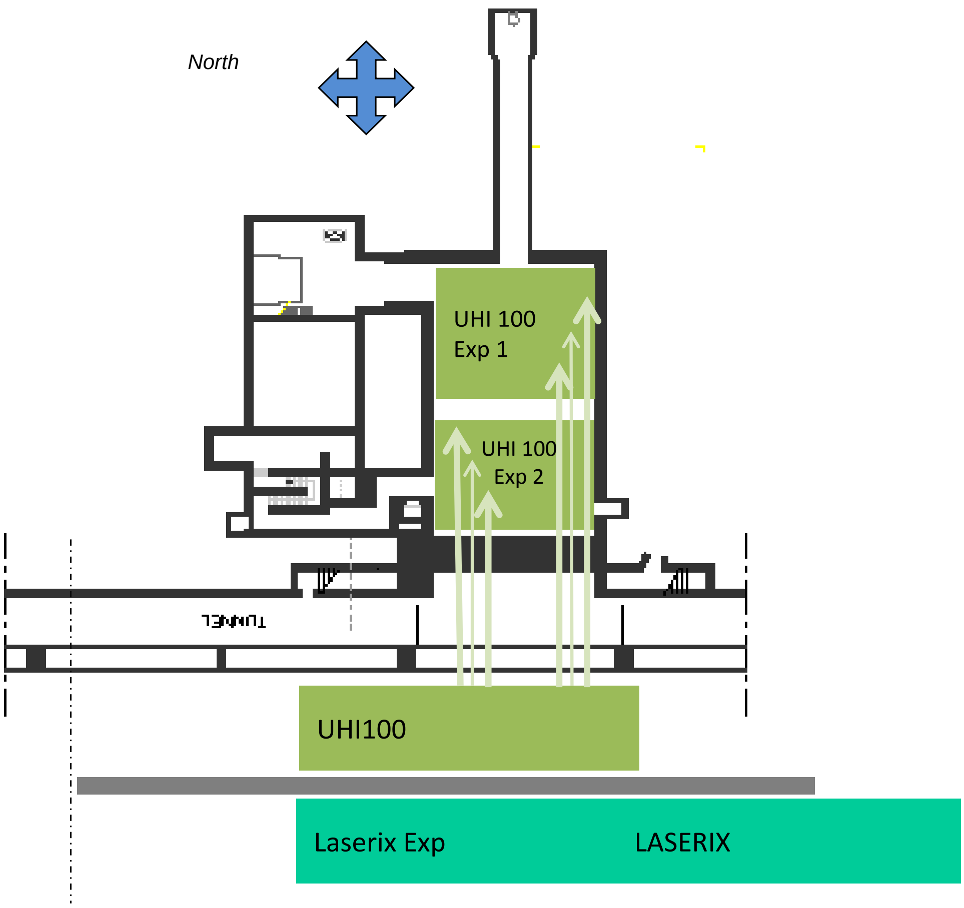
F3 : Long pulse beam**:** 300 J max, 1 ns, 140 mm diameter.

The energy of the F3 beam will be the complement of the F1 beam energy, before compression (300J). The pulse duration will be 1 ns, the beam diameter will be 140 mm with a flat top profile.

F4 : Probe pulse beam**:** 250 mJ < 20 fs, 100 mm diameter.

The delay of each of the 3 subsidiary beams pulse can be adjusted with respect to the main F1 from -5ns to +5 ns with a precision of 30% of the pulse duration at first. In a second step, the precision will reach 10% of the pulse duration.
The pointing error of the 3 subsidiary beams will be 20% of the focal spot size.

UHI100



The UHI100 laser facility delivers up to 3 beams within one of the 2 associated experimental areas.

- **Main beam** : The main beam will reach up to 2,5 J. The duration can be adjusted from 25 ps down to 25 fs duration at λ=800 nm.

- **Second beam** : The main pulse can be divided in two independent beams, carrying half of the total energy available (1,25 J). The two optical compressors will allow the adjustment the duration of each of the pulses.
- **Probe** : A probe beam will be available, with a maximum energy of 25 mJ.

Within the first two years of the program, the main beam and the probe beam of UHI100 are already available within CEA-Saclay facility.

LASERIX

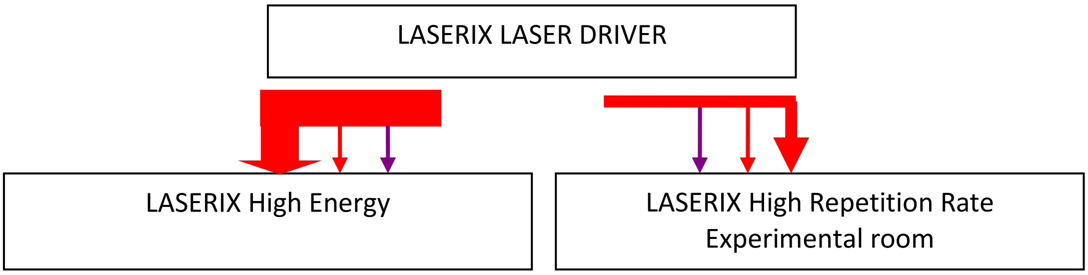
The LASERIX facility of Paris-Sud Orsay university is dedicated to laser based Soft X-ray laser (SXRL) experiments. It is yet installed on the ENSTA campus close to Laboratoire d'Optique Appliquée and is providing one soft X-ray laser beamline (in the 10 to 40nm range) assisted by femtosecond laser and high order harmonic probes for pump-probe experiments.

The SXRL beamlines are excited by combination of laser pulses coming from a main laser driver. This laser delivers broadband near infrared pulses in the joule range at 10 Hz seeding a first beamline and in the 10 joules range at up to 0.4Hz for a second beamline. Both beams are compressed down to 1ps to 10ps under vacuum for low density plasma production generated at average intensity (< 10^{15} W/cm^2) on metal targets. Low energy sampling of these two laser beamlines are used to generate femtosecond probe beams situated in the NIR by direct use of compressed pulses and in the XUV range by high harmonic generation.

At full term LASERIX will provide two SXRL beamlines running in parallel located in two different experimental rooms separated from that of the laser:

- **One high energy beamline** running at up to 0.4 Hz will be created by high-energy picosecond laser pulses (1 to 10 ps) in the 10 J range
- **One high repetition rate** beamline running at 10 Hz will be created be average energy picosecond (1 to 10ps) pulses in the joule range

The two beamlines will be assisted by optically synchronized secondary low energy femtosecond pulses for pump-probe experiments in the millijoule range for direct compressed laser beams and sub microjoule range for soft-X ray probing with high harmonics.



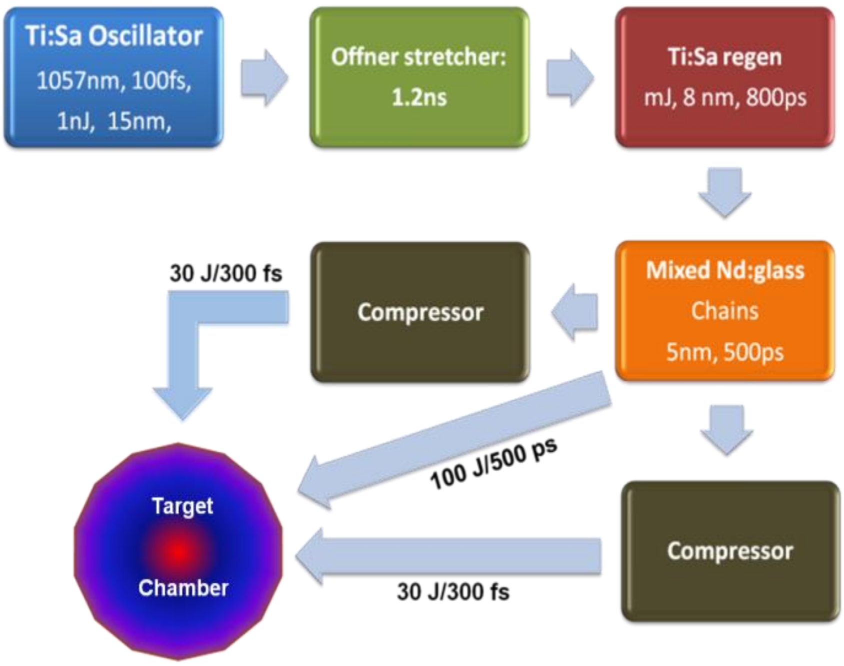
ELFIE

The ELFIE laser facility, based in Ecole Polytechnique, has four main beams available (more can be produced by beam splitters, etc.) and one experimental area. All beams can be frequency doubled (or tripled for the probe beam).

Two short pulse beams: 10 J in each beam. The duration can be adjusted from 10 ps down to 350 fs duration at λ=1.057 μm.

Long pulse beam: The long pulse beam has energy 50 J. The duration is 600 ps at λ=1.057 μm.

Probe: The probe beam has energy 100 mJ with duration 10 ps to 350 fs at λ=1.057 μm



SALLE-JAUNE

The salle-jaune facility, based in ENSTA, has up to 3 synchronized beams on target after compression (or not).

Two short pulse beams: 60 TW-30 fs, 1.8 J in each beam. The duration can be adjusted from 30 fs to 25 ps down at λ=800 nm. The laser frequency of one beam can be doubled.

Long pulse beam: The long pulse beam has energy 0.5 J. The duration is 500 ps.

Probe: The probe beam has energy 50 mJ.