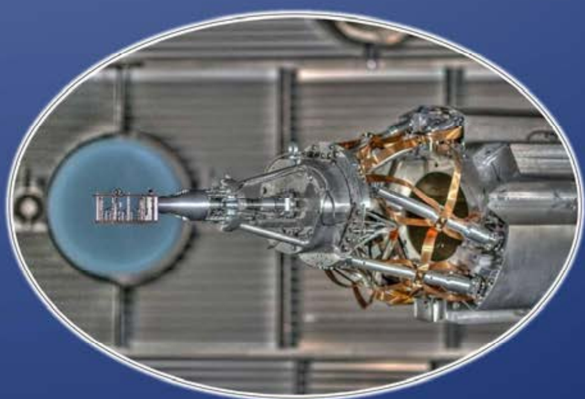

LMJ-PETAL User Guide

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Updated version available at http://www-lmj.cea.fr

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I- Introduction

The Military Applications Division of the French Alternative Energies and Atomic Energy Commission (CEA-DAM) has promoted for several decades collaboration with national and international scientific communities [1-31]. Regarding laser facilities, according to the decision of the French Ministry of Defense, the CEA-DAM has given access to the scientific communities to the LIL facility, the prototype of Laser Megajoule (LMJ), for a period of 9 years since 2005 until 2014. Ten types of experimental campaigns and a total of one hundred laser shots on targets in collaboration have been performed on the LIL during this period [32-37]. With the LMJ [38] and PETAL facilities [39], the CEA-DAM is once again in a position to welcome national and international teams, in perfect accordance with its legal obligations to confidentiality.

Figure I.1 : LIL and LMJ aerial view

The Laser Megajoule is part of the French “Simulation Program” developed by the CEA-DAM. The Simulation program aims to improve the theoretical models and data used in various domains of physics, by means of high performance numerical simulations and experimental validations.

LMJ offers unique capabilities for the Simulation Program, providing an extraordinary instrument to study High Energy Density Physics (HEDP) and Basic Science. A large panel of experiments will be done on LMJ to study physical processes at temperatures from 100 eV to 100 keV, and pressures from 1 Mbar to 100 Gbar. Among these experiments, Inertial Confinement Fusion (ICF) is the most exciting challenge, since ICF experiments fix the most stringent specifications on LMJ’s performances [40, 41].

The PETAL project consists in the addition of one high-energy multi-Petawatt beam to LMJ. This project is being performed by the CEA under the financial auspices of the Aquitaine Region ("maître d'ouvrage", project owner), of the French Government and of the European Union. PETAL will provide a combination of a very high intensity beam, synchronized with the very high energy beams of LMJ. LMJ-PETAL will be an exceptional tool for academic research, offering the opportunity to study matter in extreme conditions.

LMJ-PETAL will be open to the academic communities, as the previously mentioned LIL. The academic access to LMJ-PETAL and the selection of the proposals for experiments will be done by Institut Laser & Plasmas (ILP) through the PETAL international Scientific Advisory Committee.

This document provides the necessary technical references to researchers for the writing of Letter of Intent (LOI) of experimental proposals to be performed on LMJ-PETAL. Regularly updated version of this LMJ-PETAL User guide will be available on LMJ website at **http://www-lmj.cea.fr**.

II- LMJ-PETAL Overview

LMJ is now under commissioning at CEA-CESTA at a stage of 176 beams (44 quads).

LMJ is a flashlamp-pumped neodymium-doped glass laser (1.053 µm wavelength) configured in a multi-pass power amplifier system. The 1.053 µm light is frequency converted to the third harmonic (0.351 µm) and focused, by means of gratings, on a target at the center of the target chamber. LMJ will deliver shaped pulses from 0.7 ns to 25 ns with a maximum energy of 1.5 MJ and a maximum power of 400 TW of UV light on the target.

The main building includes four similar laser bays, 128-meter long, situated in pairs on each side of the central target bay of 60-meter diameter and 38-meter height.

The 176 square 37 x 35.6 cm^2 beams are grouped into 22 bundles of 8 beams. In the switchyards, each individual bundle is divided into two quads, the basic independent unit for experiments, which are directed to the upper and lower hemispheres of the chamber.

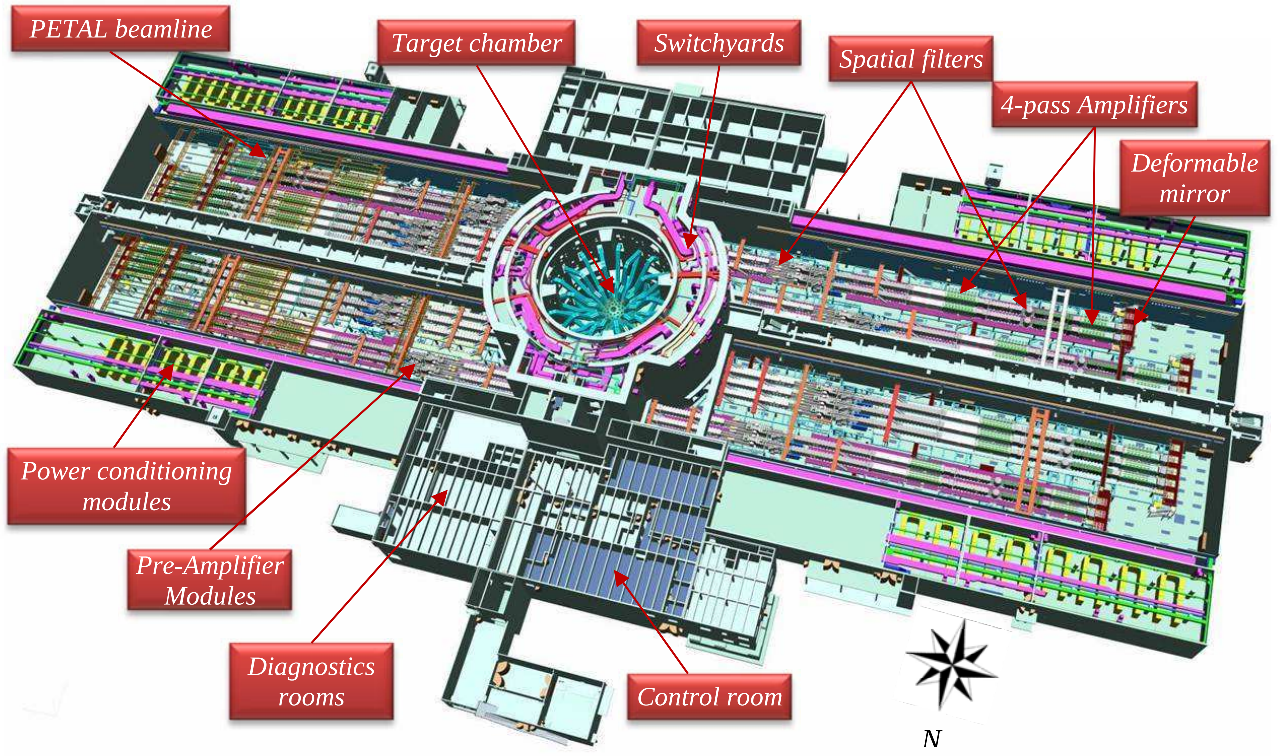


Figure II.1: Schematic view of the Laser Megajoule showing the main elements of the laser system

At the center of the target bay, the target chamber consists of a 10-meter diameter aluminum sphere, equipped with two hundred ports for the injection of the laser beams, the location of diagnostics and target holders. It is a 10 cm-thick aluminum sphere covered with a neutron shielding made of 40 cm thick borated concrete. The inside is covered by protection panels for X-ray and debris.

LMJ is configured to operate in the "indirect drive" scheme, which drives the laser beams into cones in the upper and lower hemispheres of the target chamber. Forty quads enter the target chamber through ports that are located on two cones at 33.2° and 49° polar angles. Four other quads enter the target chamber at 59.5° polar angle, and will be dedicated to radiographic purpose.

The 44 laser beam ports include the final optics assembly: vacuum windows, debris shield and device to check the damages on optics.

A lot of equipments is required in the target area:

- a Reference Holder (RH) is used for the alignment of all beams, diagnostics and target,
- a Target Positioning Systems (TPS) for room temperature experiments is operational,
- a cryogenic TPS for ignition target will be installed later,

- a set of visualization stations for target positioning (SOPAC stations, as System for Optical Positioning and Alignment inside Chamber),
- a set of about ten Systems for Insertion of Diagnostic (SID) will be installed, they will position 150-kg diagnostic with a 50-µm precision.

The PETAL project consists in the addition of one short-pulse (500 fs to 10 ps) ultra-high-power, high-energy beam (few kJ) to LMJ. PETAL will offer a combination of a very high intensity multi-petawatt beam, synchronized with the nanosecond beams of LMJ. PETAL will expand the LMJ experimental field on HEDP.

The PETAL design is based on the Chirped Pulse Amplification (CPA) technique combined with Optical Parametric Amplification (OPA). Furthermore, it takes the benefits of the laser developments made for the high-energy LMJ facility allowing it to reach the kilojoule level.

Over 30 photon and particle diagnostics are considered with high spatial, temporal and spectral resolution in the optical, X-ray, and nuclear domains. Beside classical diagnostics, specific diagnostics adapted to PETAL capacities will be available in order to characterize particles and radiation yields that can be created by PETAL [42]. The development of PETAL diagnostics takes place within the Equipex project PETAL+ funded by the French Research National Agency (ANR) within the framework of the “Programme d’Investissement d’Avenir” (PIA) of the French Government.

The first CEA-DAM physics experiments on LMJ have been performed at the end of 2014 with a limited number of beams and diagnostics. The operational capabilities (number of beams and plasma diagnostics) will increase gradually during the following years. The first academic experiments on LMJ-PETAL will be performed in 2017 with 16 beams (4 quads) and PETAL beam, 3 SID and 12 diagnostics.

History	***Date***
Beginning of the construction of the LIL facility	*1996*
First laser shots on LIL	*2002*
Beginning of the construction of the LMJ facility	*2003*
First target physics experiments on LIL	*2004*
Beginning of PETAL on LIL	*2005*
First academic experiments on LIL	*2005*
LMJ target chamber installed	*2006*
LMJ building commissioning	*2008*
Decision of coupling PETAL with LMJ	*2010*
Last academic experiments on LIL & closure of LIL	*2014*
First target physics experiments on LMJ with 2 quads	*2014*
First test shots on PETAL	*2016*
First academic experiments on LMJ with 4 quads and PETAL	*2017*

Table II.1: History of LIL, LMJ and PETAL facilities,
from the beginning of the LIL to the academic opening of LMJ-PETAL

III- Policies and Access to CEA-CESTA and LMJ facility

III.1- Driving directions and accommodations

The LMJ-PETAL facility is located at CEA-CESTA, 15 avenue des Sablières, CS 60001, 33116 Le Barp Cedex, France. GPS coordinates are given in the appendix.

In Figure III.1, directions are given for visitors traveling from either the Bordeaux Merignac Airport, or SNCF Bordeaux railway station. The A63 highway provides direct access to CEA-CESTA. The driving distance from Bordeaux is 35 km, approximately 30 minutes in normal traffic conditions. Note that it is compulsory that all visitors satisfy the badging policy described in the paragraph III.2-.

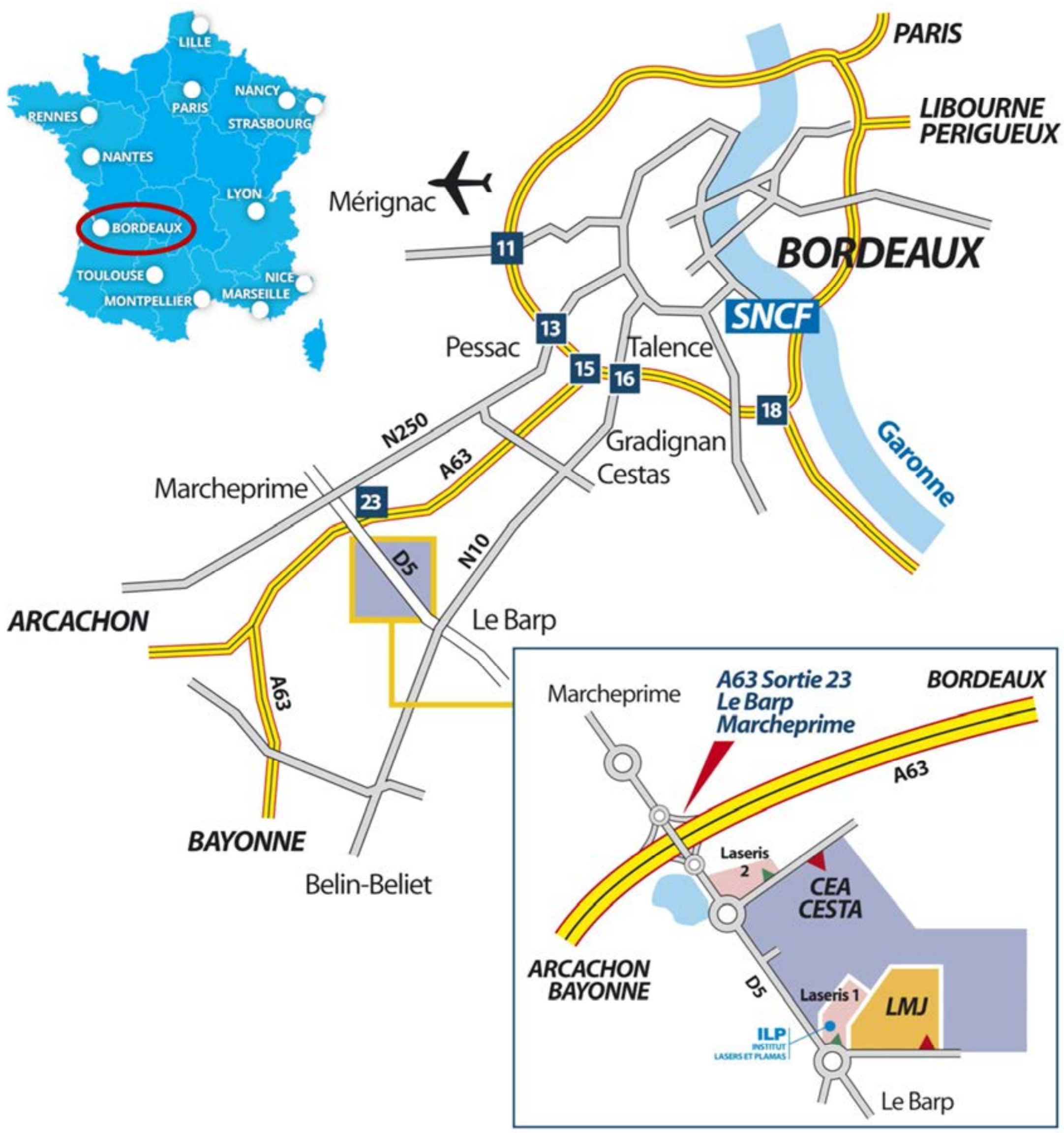


Figure III.1: Map of Bordeaux South area and transportation routes to CEA-CESTA and LMJ

There are some hotels close to CEA-CESTA, but numerous hotels can be found in the city of Bordeaux or in the area of Arcachon (seaside). A list of hotels is given in the appendix.

III.2- Office space at ILP Campus and Computer access

To provide comfortable working conditions to worldwide researchers preparing their experiments, the "Institut Laser & Plasmas" (ILP) and CEA-CESTA offer a large office space, Internet access and administrative assistance inside the ILP Campus Building. This building is located just outside CEA-CESTA. Meeting rooms are available as well as a 150 places amphitheater which could be used for workshops. The ILP building is located only 2 km away from LMJ Control Room. A cafeteria for lunch is also accessible at walking distance, as well as supermarket, restaurants and food services located in Le Barp city, 3 km away.

Figure III.2: Photograph of the ILP Campus building located on the open zone and only 2 km away from LMJ-PETAL building

III.3- CEA-CESTA Access and regulations

CEA-CESTA is a national security laboratory with regulated entry. Visitors must make prior arrangements at least 8 weeks before any visit. The experimental campaigns on LMJ-PETAL will be planned at least 6 months in advance, and the access to CEA-CESTA could be extended up to a 3 months period. In order to gain admittance, the requested information is the following:

Last name, first name, place of birth, nationality (dual nationality if any), nationality of birth, passport number and date of validity (CNI number and validity for French citizen), home address, name and address of employer, research institution, funding agency, professional phone number, professional email, contact in case of emergency.

Please notice that access to LMJ-PETAL is of CEA responsibility only. Acceptance of an experimental proposal by ILP doesn't automatically grant access to CEA for all of the collaborators. According to confidentiality rules, no justifications would be given in case of denied access to the facility.

Professional computers may be authorized on-site provided that the MAC address and physical address of the computer were given with the aforementioned personal information. Internet connectivity will be provided in a dedicated room; however no Wi-Fi capabilities are available inside CEA-CESTA.

All types of cellular telephones are forbidden. This restriction also applies for CEA people inside restricted areas, like the LMJ-PETAL building. The cell phones should be kept secured in a cell phones garage at the badging center entry.

III.4- Confidentiality rules

The CEA-DAM would be pleased to promote a wide participation of the academic communities to the scientific and technologic researches which will be performed on the LMJ-PETAL facility. However, as an organism which is in charge for the control of scientific disciplines involved in nuclear deterrence, the CEA-DAM has to follow the protection rules regarding National Defense.

As a consequence, some information and data obtained from laser experiments have to be protected according to the "Guide on the sensitiveness of information in the field of Inertial Confinement Fusion"[*].

[*] General Secretary for Defense and National Security: Document #3235/SGDSN/AIST of May 30, 2012

That is why some indications are given below to prevent or reduce any risk of reject of proposal according to confidentiality rules.

Most of research themes can be carried out on LMJ-PETAL without any restriction: optics, laser-plasma interaction, plasma physics, particles transport, thermal conduction, mechanics in continuous media, general hydrodynamics, nuclear physics, etc.

Some other research fields are considered as sensitive: Equation of State (EOS), atomic spectra and opacities, constitutive relations and damage laws of materials, radiative hydrodynamics, turbulent hydrodynamics, X-ray radiation transfer, mixing physics in convergent flows, actinides studies, etc.

Some specific studies included in the previous list may be considered not sensitive. EOS and opacities are notably concerned.

Regarding EOS and constitutive relations and damage laws, simple elements or mixture can be studied at any pressure if their atomic number is lower or equal to 71. For atomic number between 72 and 91 (included), the pressure is limited to 1000 GPa. For atomic number greater than 91, the domain is considered as sensitive at any pressure.

Atomic spectra and opacities can be studied for any temperature for element whose atomic number is lower or equal to 36. For other elements, the temperature is limited to 50 eV.

The open domains for experiments are summarized in the figure III.3.

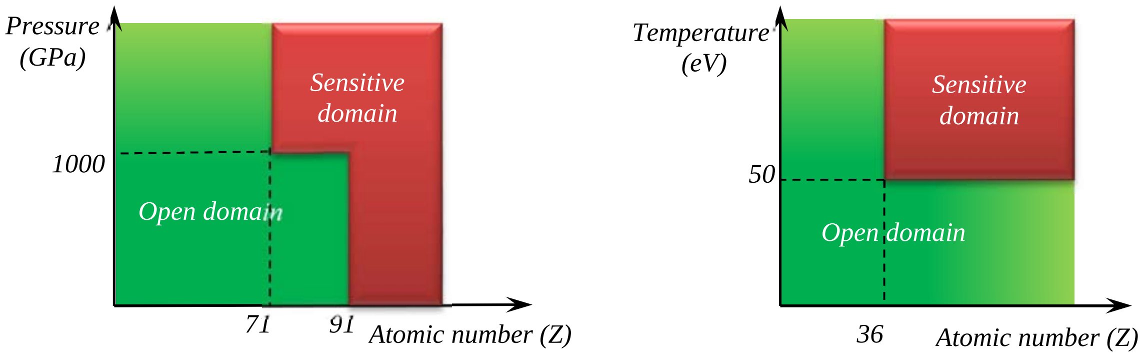


Figure III.3: a) Accessible pressure and atomic number for Equation of State experiments b) Accessible temperature for opacities experiments

III.5- Selection process

A call for proposals for experiments on the LMJ-PETAL laser facility will regularly be issued on an annual basis by ILP, CEA and Aquitaine Region.

Depending on the experiment complexity, experiments will be approved on a one-year or two-year basis. The more complex selected experiments will be given a few laser shots in the first year, intended to demonstrate the feasibility of the experiment. On the basis of the results of the campaign of the first year, more laser shots will be assigned on the second year.

The selection process for experimental proposals on LMJ-PETAL is the following:

- First a Letter of Intent (LOI) should be addressed by research groups to ILP (Z.A. Laseris – 1 avenue du Médoc – F-33114 Le Barp, **ILP-LMJ-call@cpht.polytechnique.fr**). This LOI should describe the purpose of the experiment, the research groups involved in the experiment, the laser requirements (energy, power, pulse shape, etc.), the diagnostic requirements, the target requirements, the number of laser shots requested (limited to 6 per campaign).

A pre-selection of the most pertinent experiments will be done by the International Scientific Advisory Committee of PETAL, established by ILP.

- Secondly, a full proposal should be sent to ILP (**ILP-LMJ-call@cpht.polytechnique.fr)** and CEA-DAM (**userLMJ@cea.fr**) by the pre-selected groups.

This report will include:

1. The experimental configuration at the target chamber center, including realistic target dimensions and position of additional targets (backlighter if any).

2. The laser configuration

2.1. *For LMJ beams*:

- The desired spot sizes (see Table V.2) and Optical Smoothing Conditions (2 GHz or 2 + 14 GHz);
- The laser pulse shape per quad (P (TW) as a function of time) and Energy (kJ) per quad (the Energy-Power diagram is presented in Figure V.9);
- The laser aim points per quad.

2.2. For PETAL beam:

- Pulse duration (between 0.5 and 10 ps);
- Energy (the current transport mirrors limit the available energy on target at 1 kJ for the 2017-2018 timeframe);
- Best focus position.

3. The Diagnostic Configuration

The primary and secondary diagnostics for the physics goal must be specified.

Concerning Diagnostics in SID: 3 SID are available in the 2017-2018 timeframe. The Table VII.1. indicates the available locations.

The fixed diagnostics, if needed, are: DMX in MS8, SESAME 1 and SESAME 2

4. The Target description

Sketch of the targets, including their dimensions, and the manufacturer of the targets must be provided. The CEA target laboratory will be in charge of the alignment of the targets at target center chamber (TCC).

5. The Preliminary Nuclear Safety analysis

In order to later fulfill the CEA LMJ nuclear safety rules, the following information are required:

- A rough estimate of the X-ray and/or electrons and/or ions emitted spectra, with their angular distribution;
- The list of all the constitutive target materials with estimated mass.

6. Preparation requirements

The list of the experimental capabilities which need to be commissioned prior to the physics experiment is requested: specific ns shaped pulse, PW laser contrast, characterization of specific hard X-ray or proton backlighting sources, etc.

7. Shots logic and Draft Failure Modes

The order of the shots (6 shots per campaign at maximum) is required, as well as the logic of the shots and the main possible failure modes (and back up plan).

Final selection of the most pertinent experiments is done by the International Scientific Advisory Committee of PETAL in accordance with CEA-DAM.

III.6- Experimental process

Once the experiments have been selected, the experimental campaigns are included in the schedule of the facility by the CEA-DAM Programming Committee. The selected groups are informed of this planning approximately 2 years in advance of the experimental campaign. At the same time, Experiment Managers from CEA (MOE, see III.7) are designated in order to prepare the experiment in close collaboration with the selected groups.

The key milestones in the PETAL-LMJ experimental process will include several reviews in order to evaluate the experimental preparations and readiness.

- The **Launch Review** is conducted approximately 24 months in advance of the experimental campaign. The selected group, assisted by the MOE, presents the experiment proposal in front of CEA-DAM experts. The primary purpose of this review is to ensure the proposed experiment meet the LMJ-PETAL requirements and to identify additional studies. CEA-DAM will analyze the proposals in terms of confidentiality rules, security rules and feasibility. At this point CEA-DAM could ask the research group to amend their proposal if it does not match the rules or if a feasibility matter is identified.

Following the Launch Review, the selected groups will prepare a detailed report to be sent to CEA-DAM (**userLMJ@cea.fr**) approximately 18 months in advance of the experimental campaign. This report will complete the full proposal with feasibility studies, simulation results (including X-ray and particles emissions), detailed target description, etc.

- A **Follow-up Review** occurs approximately 6 months later. The selected group exposes the advances of the experimental preparations and results of identified extra studies. This review is based on the abovementioned detailed report. Depending on the progresses made, other Follow-up Reviews may be scheduled.
- The **Design Review** is conducted approximately 12 months in advance of the experimental campaign. In addition to the previous specified data's (laser and diagnostic configurations, target description, shots logic …), this review provides all information required by the facility: consideration of target debris, nuclear safety analysis, diagnostics predictions, etc.
- The **Readiness Review** occurs approximately 1 month prior to the date of the experiment. It is the final check to ensure that all preparations for execution of the experiment are complete.

III.7- Responsibilities during Shot Cycle

Several people will be in charge of the management of the experiment, each of them having a specific responsibility.

The Principal Investigator (PI) is in charge of the scientific design of the experiment; he may be assisted by a co-PI from ILP (for ICF studies for instance).

The practical design of the experimental project, taking into account the facility capabilities and the expected results (laser energy, pulse shape, laser beams, diagnostics, alignment, debris from target, etc.) comes under the responsibility of the CEA Experiment Manager (MOE); he will work in close collaboration with the PI.

The making of the experimental campaign is under the responsibility of the CEA Experiment Coordinator (RCE); he is in charge of the target and laser bay functioning and performances taking into account all inherent risks for the operation crew and material.

The laser shots during the campaign are under the responsibility of the LMJ Shot Director who is responsible for the LMJ safety.

The PI will not be in direct contact with the LMJ Shot Director. Decisions related to the effective performance of the experimental campaign are taken according to the PI's wishes; however communications with the Facility and LMJ Shot Director are the sole responsibility of the MOE and RCE.

III.8- Access to LMJ-PETAL during shots

Access to the LMJ-PETAL facility requires half-day training to LMJ security rules and general information. This course is usually given on Monday.

To ensure personnel and equipment safety, it is mandatory that the LMJ Control Room remains a quiet area during shot operations. Shot preparation is a long process and will take a few hours which include some phases not relevant for physicists. A dedicated meeting room will be available close to the LMJ Control Room for the PI for the final shot phase when his presence is necessary.

To limit administrative duties and escort procedures, the number of external users allowed to follow one shot is limited to 4 people maximum, typically the PI, co-PI (if any), one PhD student and diagnostics expert (for PETAL+ diagnostics for instance). Those people could rotate during the week or the experimental campaign (providing the access procedures have been followed).

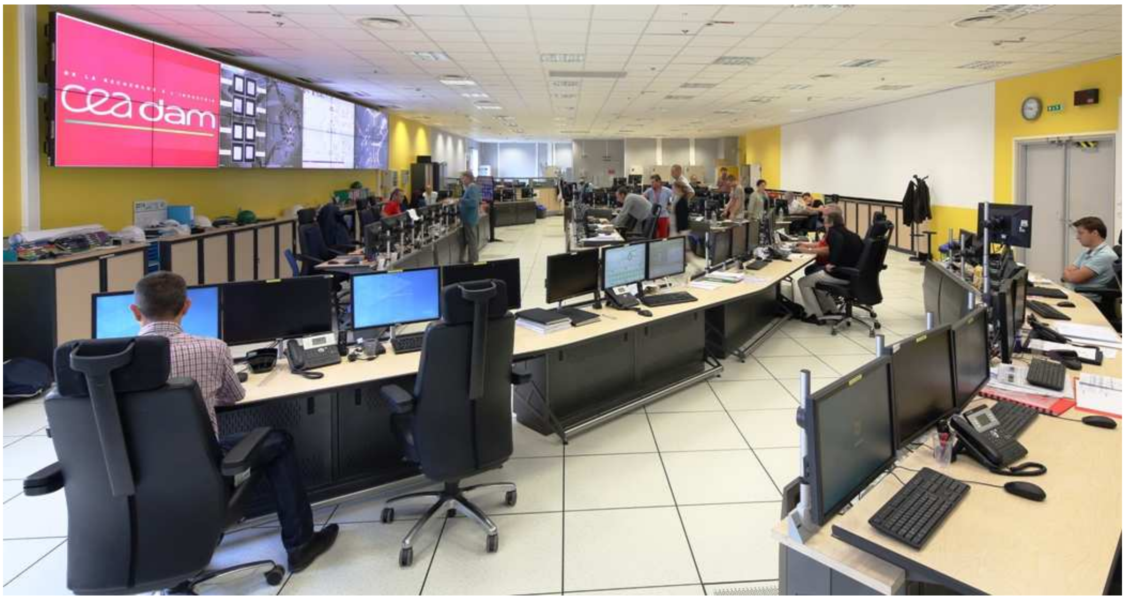


Figure III.4: View of the LMJ Control Room

III.9- Data access

The laser pulse shapes and raw laser energy are immediately observable after the shot, like X-ray images acquired on X-ray framing camera or streaked camera when they are directly recorded on electronic devices (CCD). The consolidated laser energy will be communicated at the end of the experimental campaign because it requires evaluation of the vacuum window transmission which could have been modified by laser-induced damages. For data requiring digitizing or scan (like Image Plate) the data release will not be possible immediately after the shot, but a few hours later. It is also the case for data depending on material handling inside target bay area, which is regulated by safety procedures for contamination control and radiation monitoring.

Raw experimental data and/or data translated into physics units will be accessible to the PI and his experimental team as soon as possible after the shot. The data release is of CEA responsibility. The release of detailed response functions of some diagnostics, like for example the detailed response functions of DMX-LMJ channels, may be considered as classified information. This is why only consolidated data in physics units will be delivered to the PI in such a case. By any way the CEA Experiment Manager will ensure that all essential physics data are delivered to the PI. He is responsible for the quality of the experimental data.

Data support will be either USB keys for the data directly available after the shot or CD-ROM for consolidated and scanned data. The baseline data format of LMJ data is a custom hdf5. CEA will provide hdf5 structure description and if necessary basic tools to extract the information.

III.10- Publications and Authorship practices

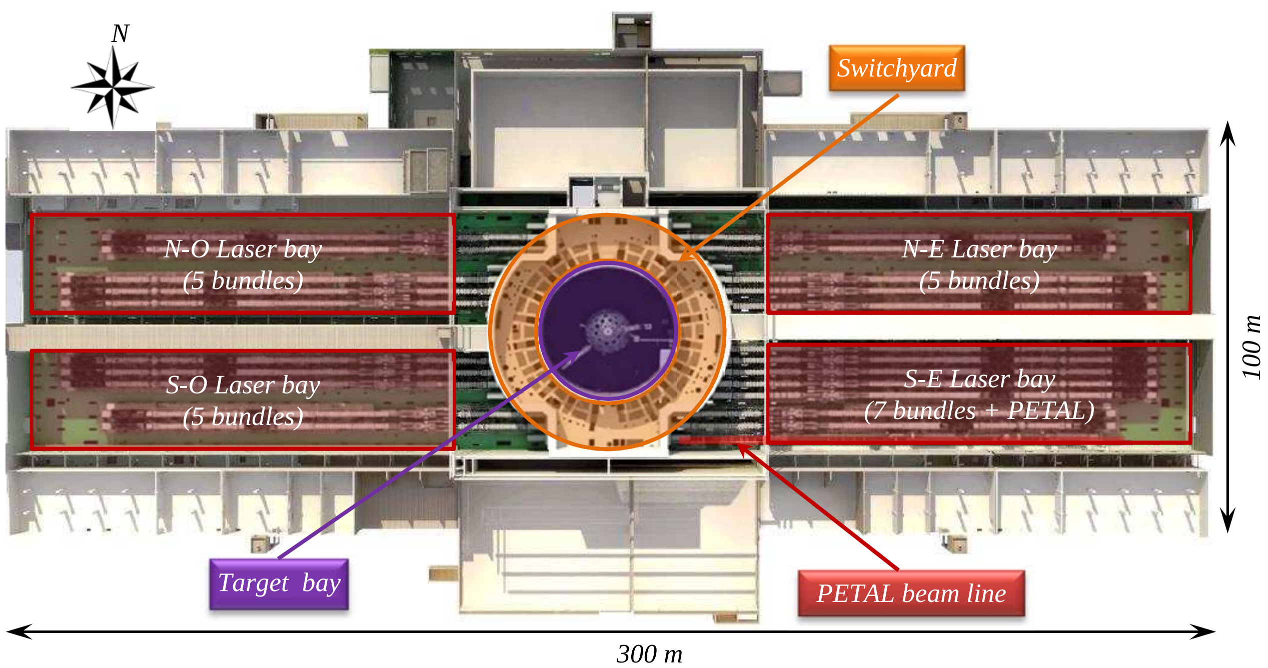
Results of LMJ-PETAL experiments are expected to be published in major journals and presented in scientific conferences. The PI should inform CEA-DAM of any publication a few weeks before any major conference (APS DPP, IFSA, EPS, ECLIM, ICHED, HEDLA, HTPD, etc.) using the email address **userLMJ@cea.fr**. It is of PI responsibility to judge who made a significant contribution (or only a minor) to the research study. However CEA Experiment Manager (MOE) and CEA Experiment Coordinator (RCE), as well as CEA Diagnostics leaders, should be co-authors of the first publications of the campaign they have been involved in. A statement acknowledging the use of LMJ-PETAL should be included in all publications. The sources of financial support for the project (ANR, ILP, ERC) should also be disclosed.

IV- LMJ Building description

The LMJ building covers a total area of 40 000 m^2 (300 m long x 100 to 150 m wide). It includes four similar laser bays, 128 meters long, situated in pairs on each side of the central target bay. The target bay is a cylinder of 60-meters diameter and 38-meters height, with a 2-meters thick concrete wall for biological protection.

At the center of the target bay, the target chamber consists of a 10-meters diameter aluminum sphere, fitted with two hundred ports for the injection of the laser beams and the location of diagnostics and target holders. The four lasers bays, completed by the end of 2013, are now equipped with all the supporting optics infrastructures and the final optical components are currently being installed.

The PETAL laser beam takes the place of one classical LMJ bundle inside the South-East laser Bay.



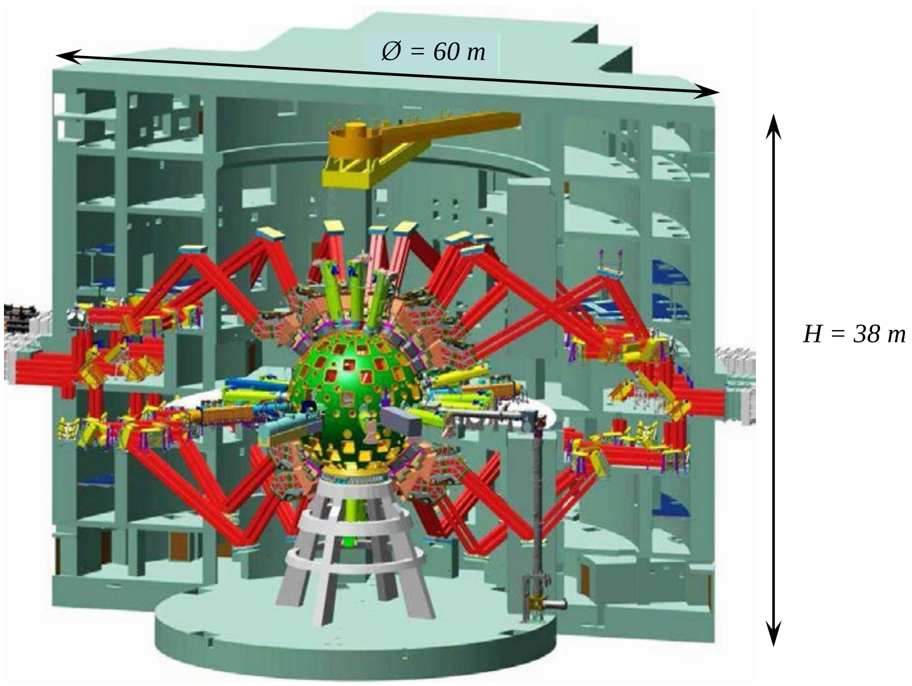


Figure IV.1: a) Drawing of the building with total dimensions

b) CAD of the target bay with transport of the beams, the experimental chamber and its equipment: target positioning system, plasma diagnostics

V- LMJ Laser system

V.1- Laser architecture

LMJ is under commissioning at CEA-CESTA at a stage of 176 beams. LMJ is a flashlamp-pumped neodymium-doped glass laser (1.053 µm wavelength) configured in a multi-pass power amplifier system. The LMJ 3100 glass laser slabs will be capable of delivering more than 3 MJ of 1.053 µm light, that is subsequently frequency converted to the third harmonic (0.351 µm) and focused on a target at the center of target chamber. LMJ will deliver shaped pulses from 0.7 ns to 25 ns with a maximum energy of 1.5 MJ and a maximum power of 400 TW of UV light on target.

The architecture of one beamline is shown on Figure V.1. The front end delivers the initial light pulse and provides its temporal and spatial shape as well as its spectrum and enables synchronization of all the beams. The front end is made of four sources (one per laser hall), which deliver the first photons (about 1 nJ), and 88 Pre-amplifier Modules (PAM, 1 per 2 beams), including a regenerative cavity and an amplifier, which deliver a 500-mJ energy beam to the amplification section.

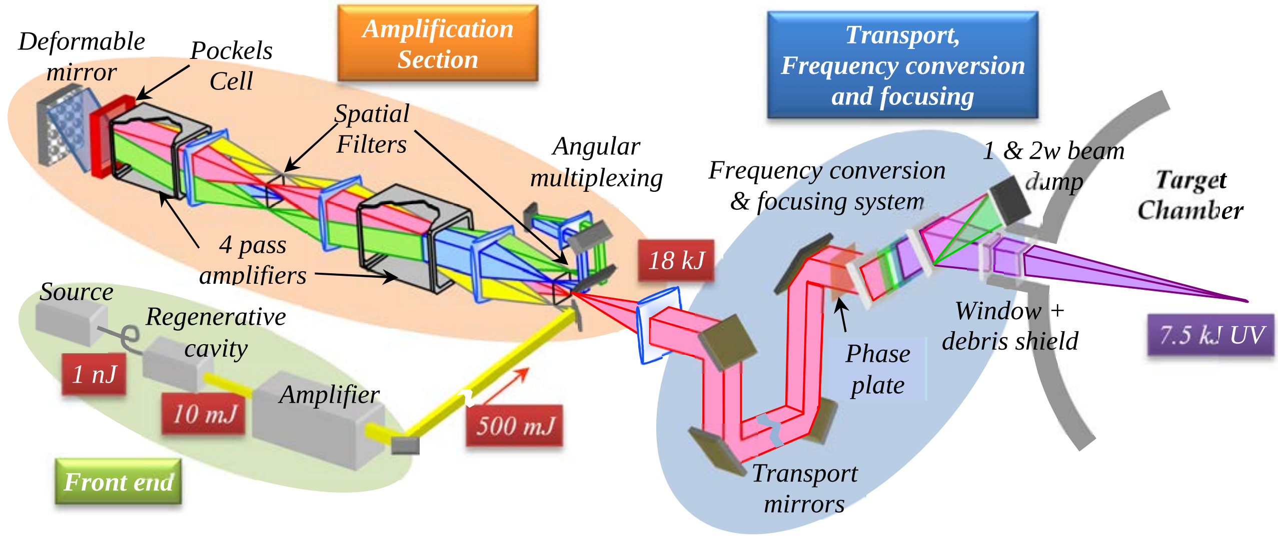


Figure V.1: Architecture of one LMJ beamline.
The basic unit for experiment is a quad made of 4 identical beamlines

Figure V.2: PreAmplifier Module in the North-East Laser Bay

Figure V.3: South-West Laser Bay equipped with 5 amplification sections

In the amplification section, the beams are grouped in bundle of 8 beams and they are amplified 30 000 times to reach energy of 15-18 kJ per beam. The amplification section includes two 4-pass amplifiers, two spatial filters, a plasma electrode pockels cell, a polarizer and a deformable mirror for wavefront correction.

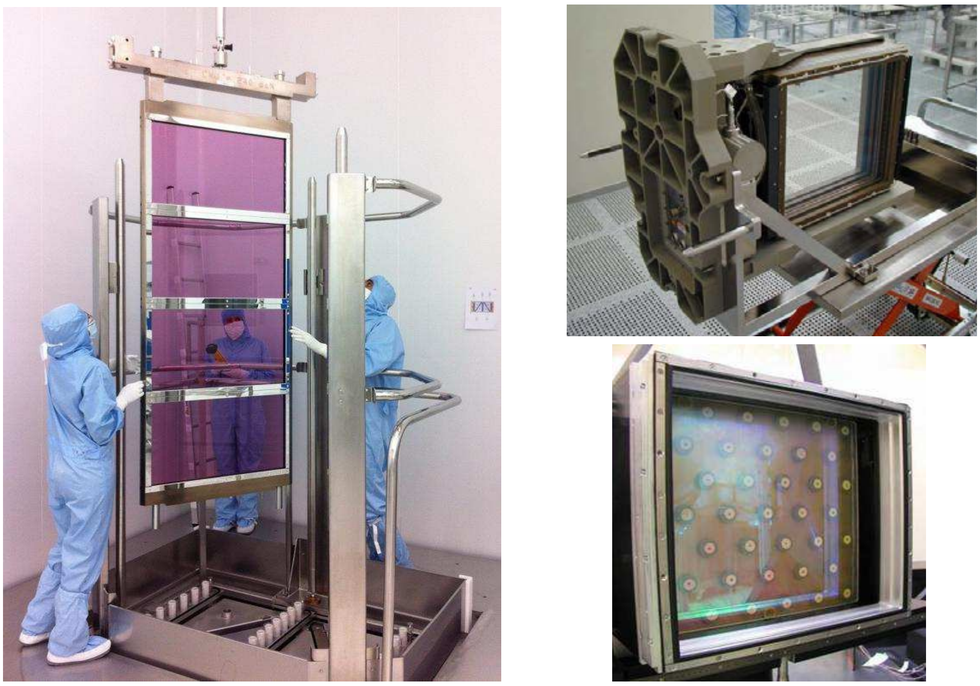


Figure V.4: Mounting of 4 laser slabs, plasma electrode pockels cell and deformable mirror

In the switchyards, each individual bundle is divided into two quads, which are directed to the upper and lower hemispheres of the chamber by the mean of 5, 6 or 7 transport mirrors. The quad is the basic independent unit for experiments.

The LMJ target chamber is arranged with a vertical axis. LMJ is configured to operate usually in the "indirect drive" scheme [41], which directs the laser beams into cones in the upper and lower hemispheres of the target chamber. Forty quads enter the target chamber through ports that are located on two cones at 33.2°

and 49° polar angles. Four other quads enter the target chamber at 59.5° polar angle, and will be dedicated to radiographic purpose (see Figure V.5).

The PETAL beam enters the experimental chamber in the equatorial plane.

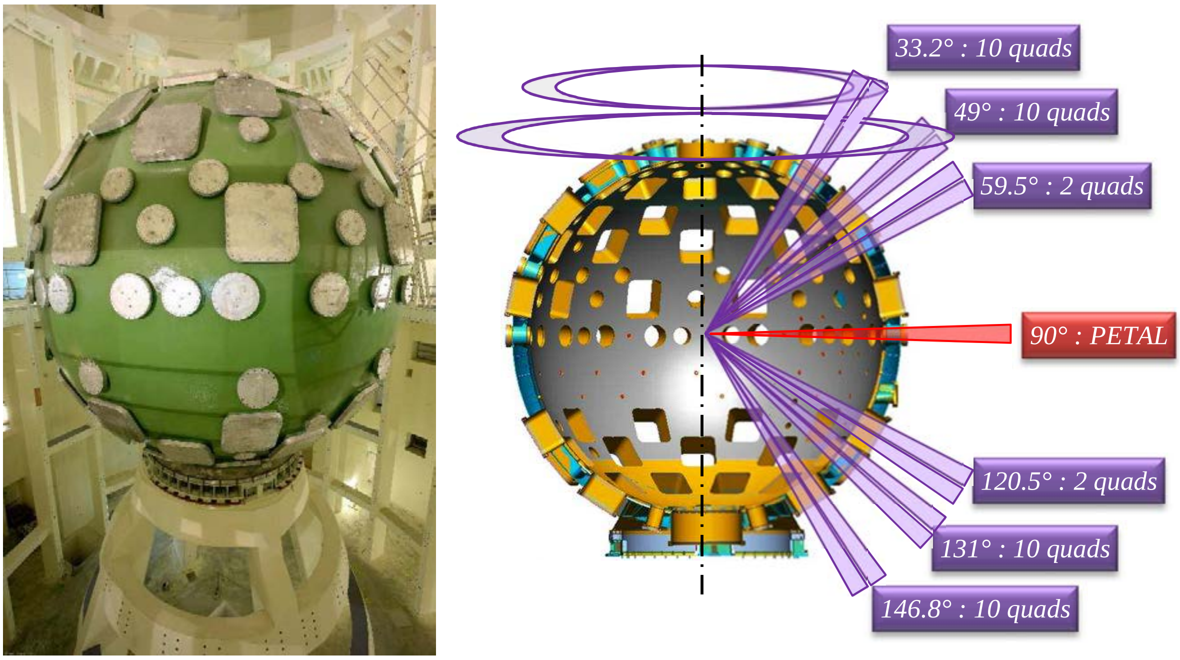


Figure V.5: Target chamber and geometry of the LMJ irradiation

A detailed configuration of irradiation geometry is given in Figure V.6 and the spherical coordinates of all beam ports are given in Table V.1.

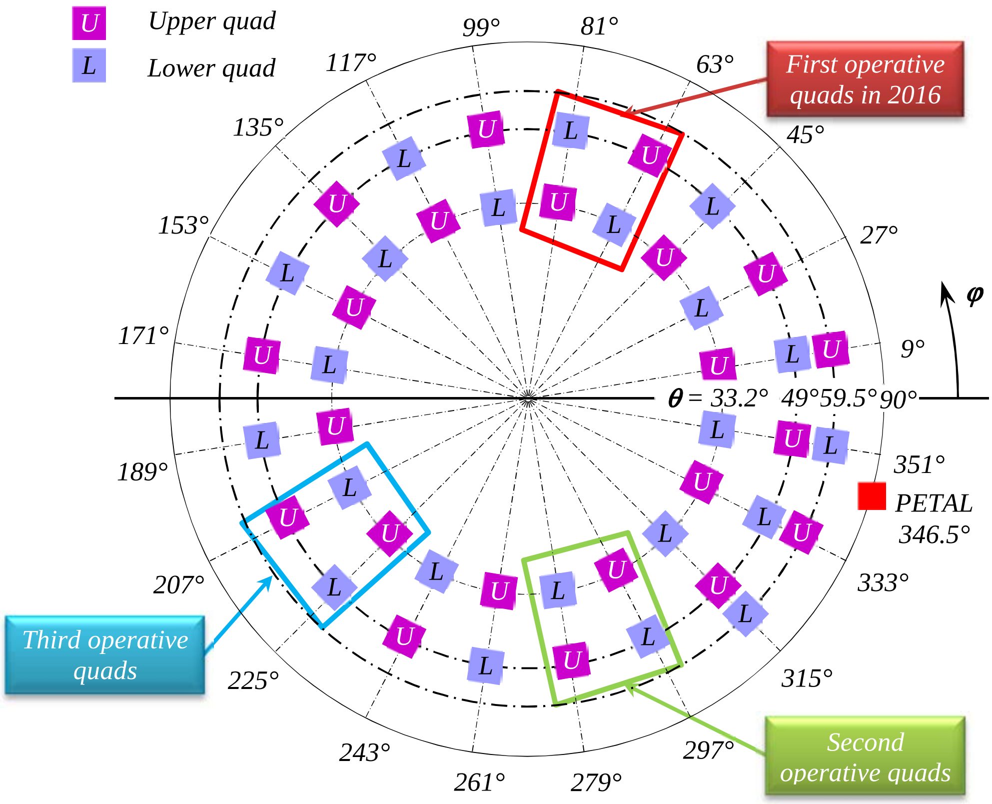


Figure V.6: Irradiation geometry of LMJ quads and PETAL beam. The first operative quads are indicated

Beam Port	θ	φ	Beam Port	θ	φ	Beam Port	θ	φ	Beam Port	θ	φ
First quads operative in 2016											
28U	33.2°	81°	28L	131°	81°	29U	49°	63°	29L	146.8°	63°
PETAL	90°	346.5°									
Next operative quads											
17U	33.2°	297°	17L	131°	297°	18U	49°	279°	18L	146.8°	279°
10U	49°	207°	10L	146.8°	207°	11U	33.2°	225°	11L	131°	225°
Subsequent quads											
5U	49°	135°	5L	146.8°	135°	6U	33.2°	153°	6L	131°	153°
22U	49°	351°	22L	146.8°	351°	24U	33.2°	9°	24L	131°	9°
19U	59.5°	333°	19L	120.5°	315°	23U	59.5°	9°	23L	120.5°	351°
13U	33.2°	261°	13L	131°	261°	14U	49°	243°	14L	146.8°	243°
26U	33.2°	45°	26L	131°	45°	25U	49°	27°	25L	146.8°	27°
2U	33.2°	117°	2L	131°	117°	3U	49°	99°	3L	146.8°	99°
7U	49°	171°	7L	146.8°	171°	9U	33.2°	189°	9L	131°	189°
21U	33.2°	333°	21L	131°	333°	20U	49°	315°	20L	146.8°	315°

Table V.1: Spherical coordinates of beam ports

V.2- LMJ Frequency conversion and focusing scheme

The optics assembly for frequency conversion and focusing is composed of a 1ω grating, two KDP crystals for Second and Third Harmonic Generation, and a 3ω focusing grating. The 1ω grating deflects by an angle of 50° the incoming 1ω beam. An angular dispersion of the spectrum is introduced by the grating which allows broadband frequency tripling. The frequency converters use a Type I-Type II third harmonic generation scheme. The 3ω grating deflects back the 3ω beam by an angle of 50°, while the unconverted light is stopped by absorbers. As a consequence no volume restrictions and additional shielding for unconverted light issues have to be taken into account in the making of the experiments.

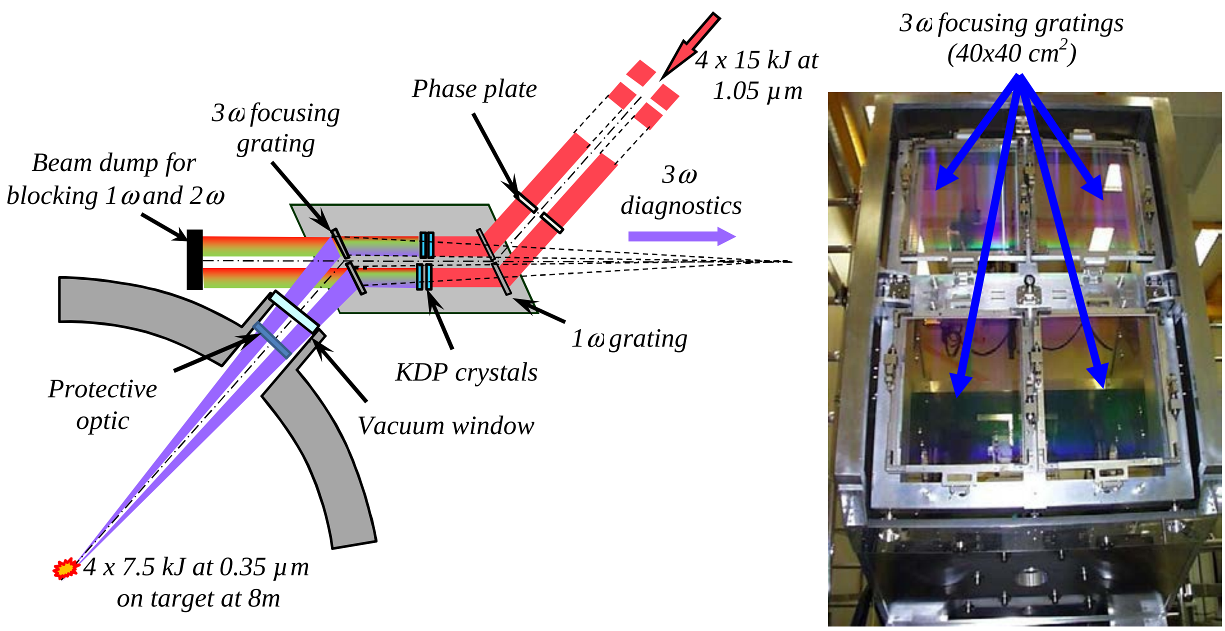


Figure V.7: LMJ frequency conversion and focusing by gratings

The pointing accuracy of LMJ quadruplets depends on the aim point. Two pointing volumes have been defined. The finest accuracy (50 µm rms) is achieved inside a 30 mm diameter x 30 mm high orthocylinder (see Figure V.8). Outside this first cylinder the pointing volume can be described by two other imbricated cylinders with a 75 to 100 µm pointing accuracy. These capabilities have to be considered for the positioning of X-ray backlighters for instance.

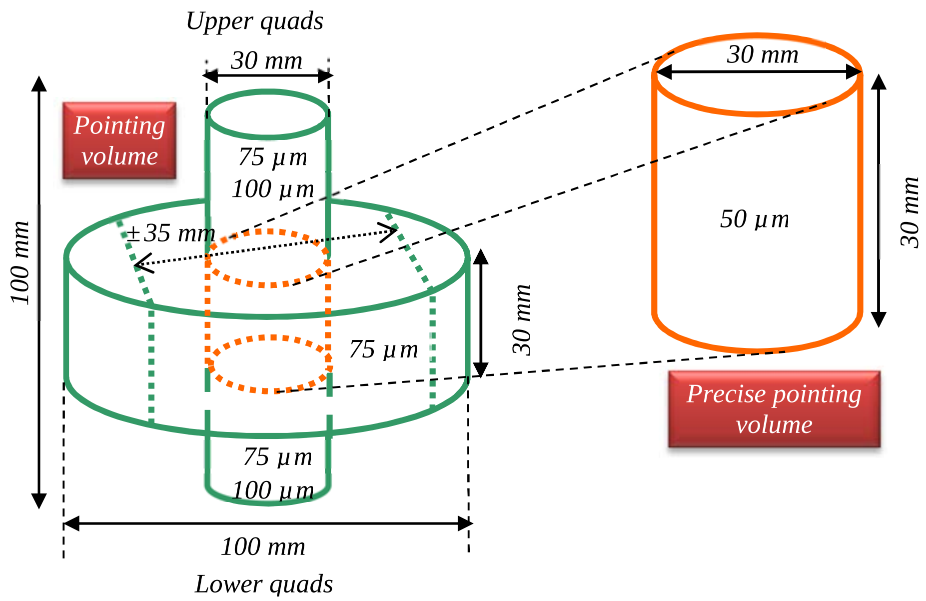


Figure V.8: LMJ pointing volume and expected pointing accuracy (rms)

V.3- Beam Smoothing

To reduce the peak intensity of the light on the target, several techniques are available on LMJ: continuous phase plate (see paragraph V.4) and smoothing by spectral dispersion.

Two phase modulations at 2 GHz and 14 GHz around the central wavelength are realized. The first one (2 GHz) is used to raise the threshold of appearance of the Brillouin effects in optics at the end of the laser chain. The second one (14 GHz) is dedicated to Smoothing by Spectral Dispersion (SSD). The full bandwidth available with both frequency modulations is 0.5 nm at 1ω in order to reduce the contrast in the speckles of the focal spot on the target down to 20% [43].

Due to the specific LMJ focusing system, the movement of speckles in the focal spot is along the laser axis (longitudinal SSD) instead of being perpendicular to this axis (transverse SSD) as in standard laser facilities.

Another smoothing technique, polarization smoothing, will be installed later for ignition experiments.

V.4- Spot sizes

Various Continuous Phase Plates (CPP) could be considered for the spot sizes. Three types have been defined for the first phase of operations with circular focal spots, called CPP Type D, Type E and Type F.

The nominal phase plate is the Type D for heating the target. The Type E provides a larger focal spot for uniform irradiation (direct drive EOS experiments or large backlighter). The Type F provides a smaller focal for radiography purposes.

The peak intensity on target for a 5 TW pulse, the diameters of focal spots at 3 % of the peak intensity and the order of the super-Gaussian describing the intensity profile are given in the Table below.

CPP	Diameters at 3 % (µm)	Intensity (5 TW) (W/cm^2)	Super-Gaussian Order
Type D	940	$1.8\ 10^{15}$	2.6
Type E	1500	$5.8\ 10^{14}$	3.5
Type F	630	$6\ 10^{15}$	TBD

Table V.2: Characteristics of standard Continuous Phase Plates

V.5- Energy and Power

The available laser energy for user experiments is constrained by optical damages on gratings [44] and vacuum windows and operating costs. Whereas LMJ nominal laser energy is designed for 30 kJ per quad for ignition experiments, a lot of CEA experiments will be performed at limited laser energy to reduce the optical damages on final optics. Experimental designs with 10 to 15 kJ per quad are to be considered.

The maximum sustainable laser energy for a given pulse shape will be refined with feedbacks from laser scientists [45, 46] during the preliminary design review of an experiment. Operational limits depend on the exact pulse shape and the type of CPP.

The figure V.9 gives the maximum performances and the recommended setting as a function of pulse duration for square pulses.

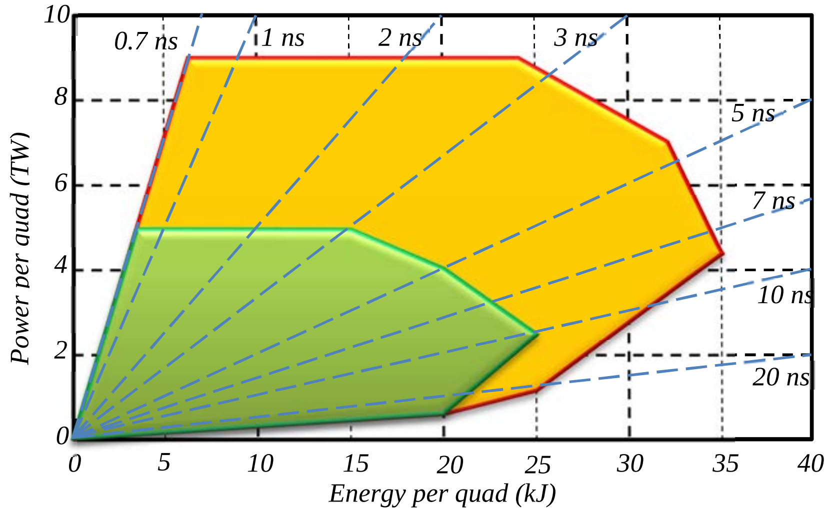


Figure V.9: LMJ sustainable operational energy and power limits. The red line is the maximum performances; the green line is the recommended setting in order to limit damage on optics [9]

During the first experiments performed in 2014, the LMJ facility has proved a shot to shot repeatability of the delivered energy per quad better than 3 %.

V.6- Pulse shaping capabilities

The LMJ source (master oscillator) is designed to deliver complex ignition pulse. As a consequence, a wide variety of pulse shapes can be produced on LMJ, with a minimum duration of 0.7 ns and a maximum duration of 20 ns. Complex pulse shapes (rising pulse, decreasing pulse, multiple pulse, with pedestal, etc.) can be fashioned, but will required some test laser shots for a fine tuning [46]. Some examples of pulse shapes are given in figure V.10 and V.11.

All the LMJ beams will be synchronized at the center of the target chamber within a standard deviation of 40 ps.

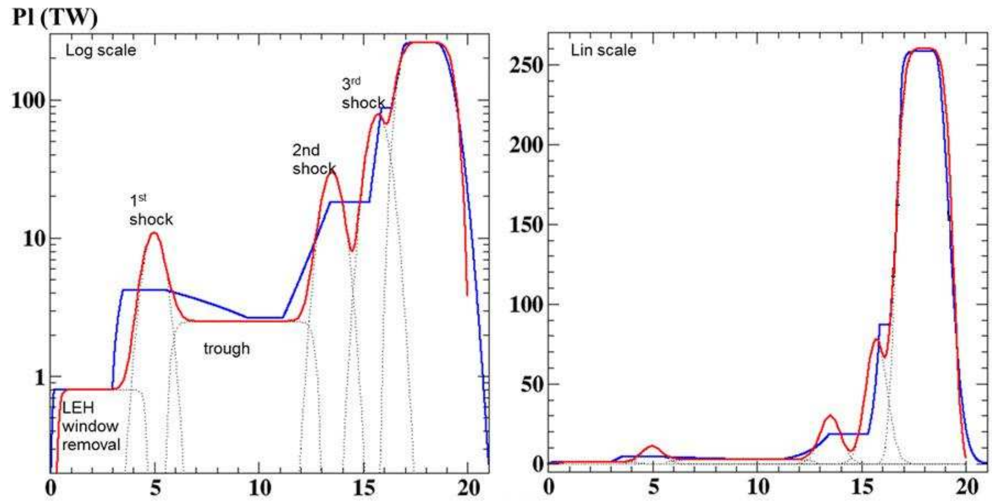


Figure V.10: Different envisioned pulses shapes for ignition target (in red and blue). The dashed black lines are supergaussian used to fit each specific part of the pulse

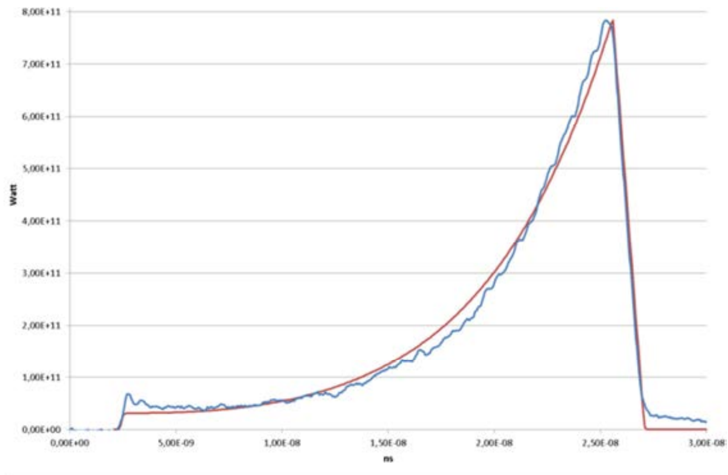


Figure V.11: Typical pulse shape realized on the LIL facility for isentropic compression experiments [37] (request in red)

On LMJ, the Pre-Amplifier Module (PAM) is common for two beams within one quadruplet. However as the two PAMs of a single quadruplet share the same master oscillator (see Figure V.12), only one pulse shape is available per quadruplet. This versatility in pulse shaping will be beneficial for Polar Direct Drive Shock Ignition [47]. Delays between quadruplets could be defined for example to use one quadruplet as the main driver and one quadruplet to irradiate an X-ray backlighter. The maximum available delays are currently limited to 100 ns.

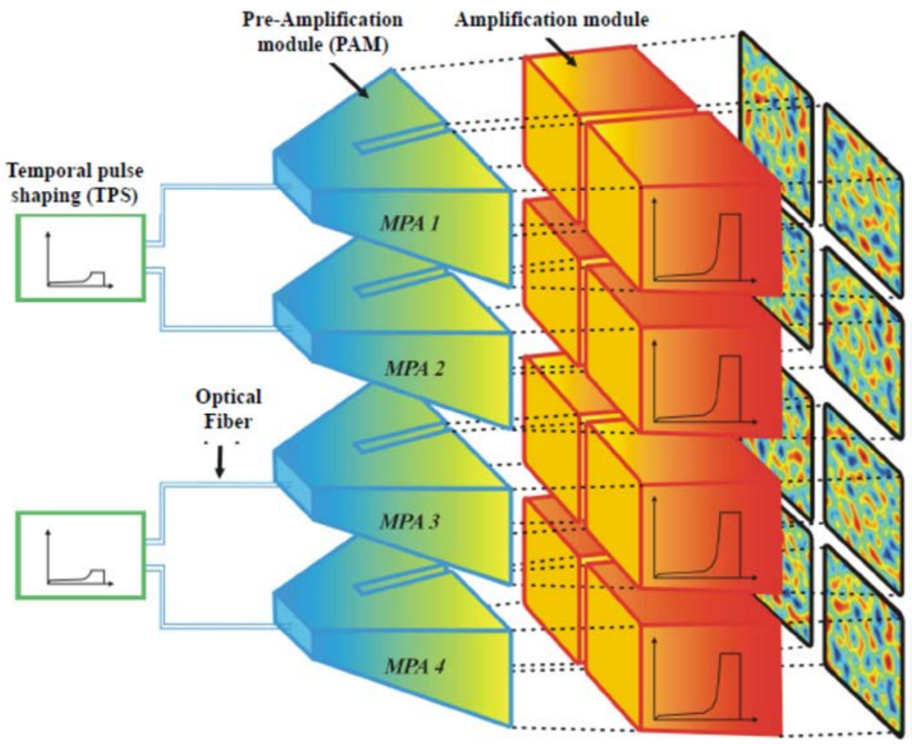


Figure V.12: Schematic of the pulse shaping capability within a LMJ bundle (2 quads, 8 beams)

V.7- Laser performances

The first LMJ experiments were carried out in October 2014, with the 8 initial beams (28U and 28L). They revealed good performances of the whole system.

The pointing accuracy of the quad was 50.6 ± 23 µm (compare to a 100 µm specification), and the beams synchronization was about 20 ps (compare to a 100 ps specification).

The figure V.13 shows the history of energy delivered on the target for the eight shots of this first physics campaign. The mean energy obtained over the eight shots is 19.92 kJ ± 0.16 per chain, to compare with the 20 kJ (2.5 kJ x 8) required.

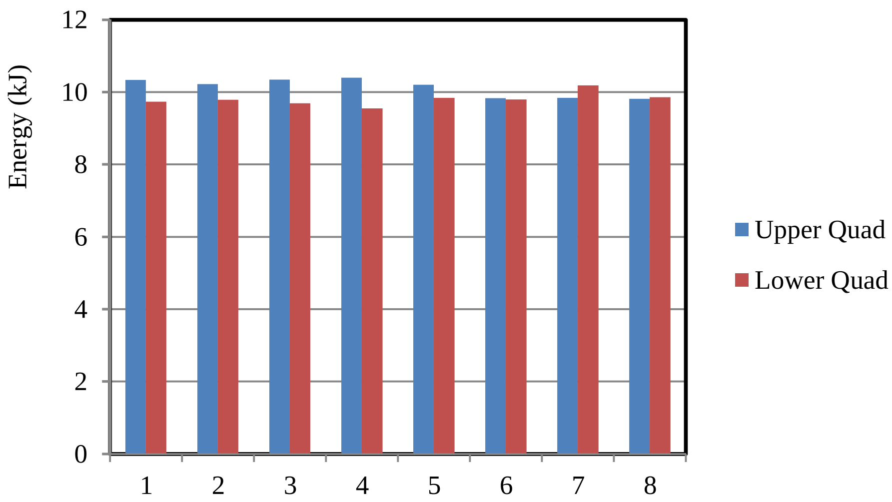


Figure V.13: History of the energy delivered on the target for the eight first shots (October 2014)

For these 8 experiments, the achieved pulse durations present a good reproducibility: 2.85 ± 0.1 ns (see Figure V.14).

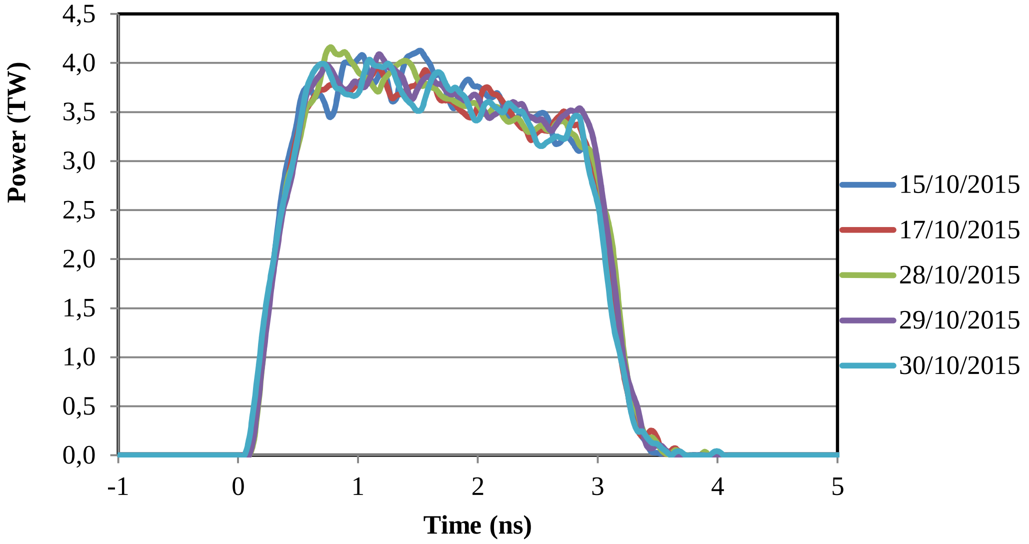


Figure V.14: Pulse shapes of the first physics campaign on LMJ (for clarity only 5 of them are shown)

VI- PETAL Laser system

The PETAL design is based on the Chirped Pulse Amplification (CPA) technique combined with Optical Parametric Amplification (OPA) [48-50]. Moreover, it takes the benefits of the laser developments made for the high-energy LMJ facility allowing it to reach the kilojoules level.

Figure VI.1 shows the implementation of PETAL in the LMJ facility. The PETAL beamline occupies the place of a LMJ bundle in the South-East laser bay. The compressor stages are situated at the bottom level of the target bay, and after a transport under vacuum, the beam is focused in the equatorial plane of the LMJ chamber via an off-axis parabolic mirror.

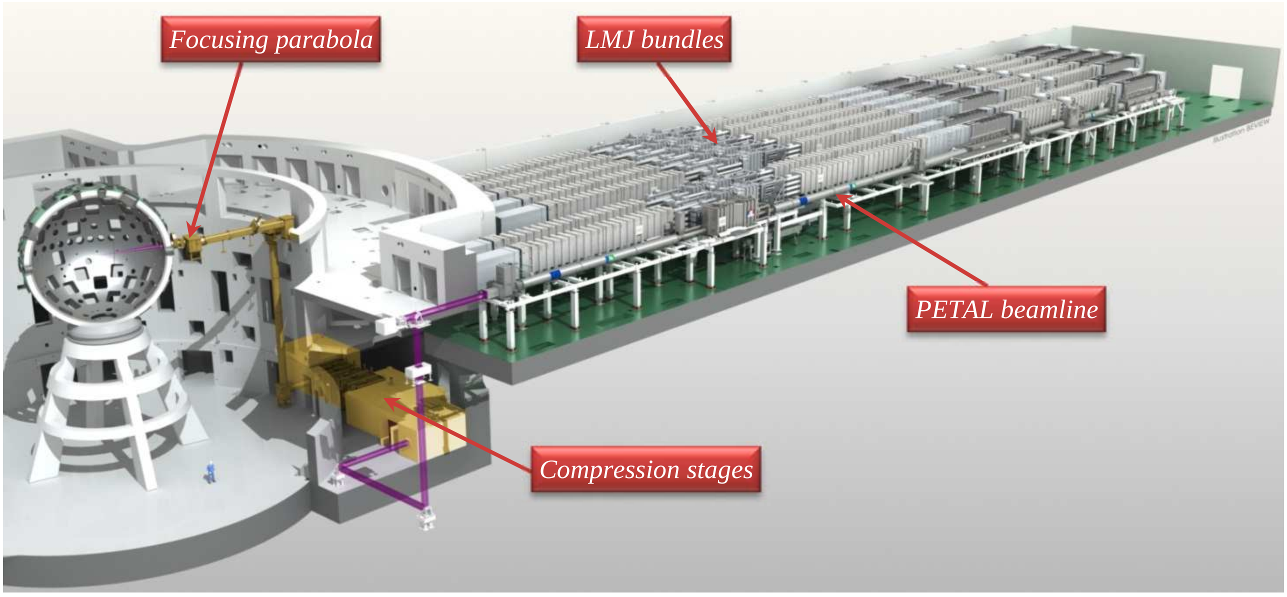


Fig. VI.1: Implementation of PETAL in the LMJ facility.
The PETAL beam is focused in the equatorial plane of the target chamber

The front end consists in a standard Ti:sapphire mode locked oscillator delivering 3nJ /100 fs / 16 nm pulse at 77.76 MHz and 1053 nm wavelength. The pulse is stretched to 9 ns in an Öffner stretcher in eight passes. Then the pulse is sent to the Pre-Amplifier Module (PAM) including OPA stages and pump laser. The OPA scheme consists of two cascaded LBO crystals and a BBO crystal. A 150 mJ amplified signal pulse with a shot-to-shot stability of less than 2% has been demonstrated on the LIL facility [49, 50].

The PETAL amplifier section has the same architecture as the LIL/LMJ amplifier section using a single 37 × 35.6 cm^2 beam. It is a four-pass-system with angular multiplexing and a Reverser. It uses 16 amplifier laser slabs arranged in two sets and delivering up to 6 kJ. At this stage, due to gain narrowing, the bandwidth is reduced to 3 nm and duration to 1.7 ns. The main differences with the LIL/LMJ power chain are the wavefront and chromatism corrections [51].

The compression scheme is a two-stage system (see Figure VI.2). The first compressor, in air atmosphere, reduces the pulse duration from 1.7 ns to 350 ps in an equivalent double pass configuration. The output mirror is segmented in order to divide the initial beam into 4 sub-apertures which are independently compressed and synchronized into the second compressor in a single pass configuration under vacuum [52]. These sub-apertures are coherently added using the segmented mirror with three interferometric displacements for each sub-aperture. The pulse duration is adjustable from 0.5 to 10 ps.

The focusing system consists in an off-axis parabolic mirror with a 90° deviation angle, followed by a pointing mirror (see Figure VI.3). The focal length is 7.8 meters, and the focal spot goal is a 50 µm diameter, this will result in intensities above 10^{20} W/cm^2 on target. Due to the 4 sub-apertures of the beam [53], a multi-beam option could be available: a segmented pointing mirror could redirect the beams towards up to 4 separate focuses. This option will be studied in detail if required.

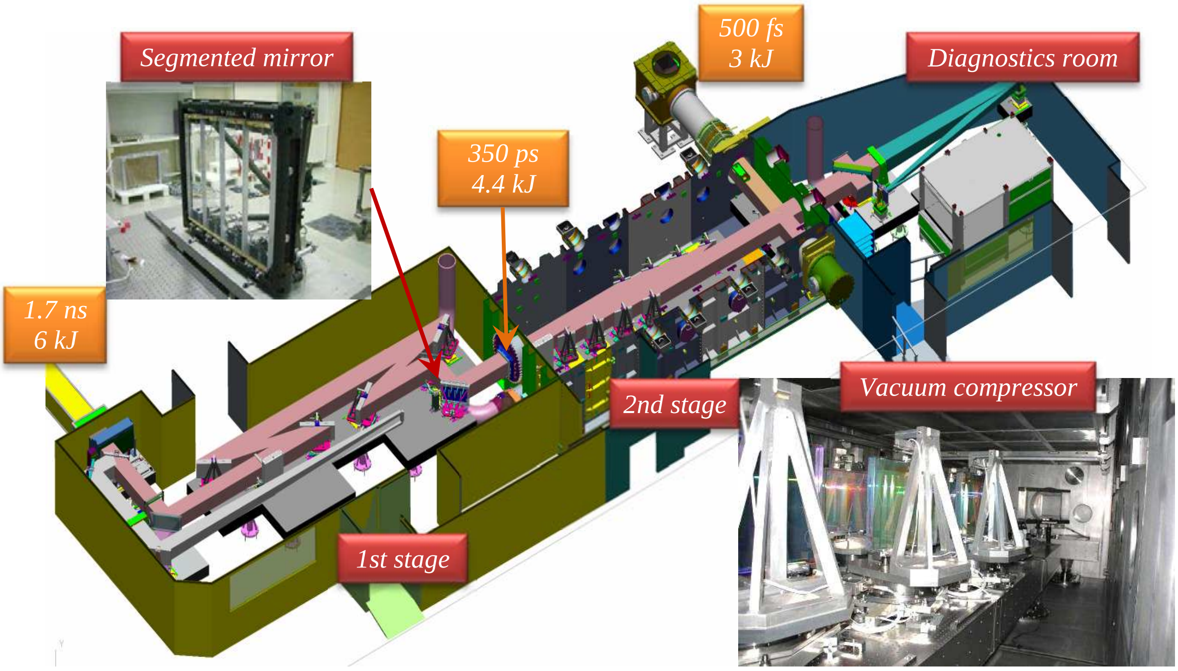


Figure VI.2: Compressor stages with a subaperture compression scheme: first stage in air and second stage in vacuum with 4 independent compressors

Figure VI.3: PETAL beam and LMJ bundles in the South-East laser bay, and PETAL focusing scheme

The PETAL performances depend on the damage threshold of optics. Great efforts have been made on gratings in order to improve their strength. The effect of electric field on damages has been demonstrated [54], and the groove profile of PETAL multilayer dielectric gratings has been optimized in order to obtain a damage threshold above 4 J/cm² in the ps range. But in fact, the transport mirrors may not sustain more than 2 J/cm² compared to the 4 J/cm² specified value required for a 3 kJ output level. **Therefore, the current mirrors will first limit the available energy on target at a 1 kJ level**. New technologies are required to increase this value and the intensity on target. Several ways of improvement are identified and are being explored.

VII- Target area and associated equipments

As shown previously in Figure IV.1, the target bay area occupies the central part of the building. There are 8 floors. A detailed CAD of the target chamber with the major target bay equipments is shown in Figure VII.1.

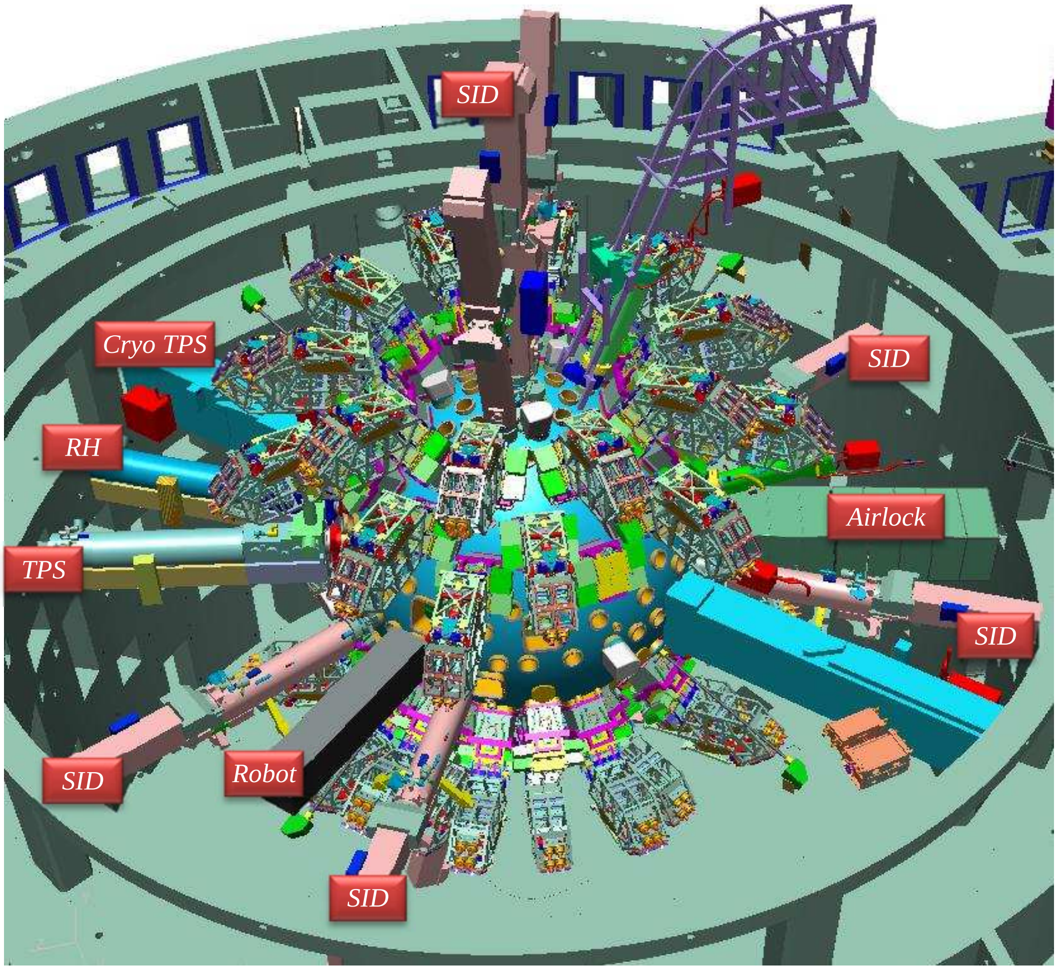


Figure VII.1: CAD of the target area

The radius of LMJ target chamber is 5 meters. Beam and diagnostics ports cover the full surface. A SID is provided on several different port locations for inserting diagnostics used to make measurements during a target experiment on LMJ. A SID is a two-stage telescoping system that provides a precise positioning of a diagnostic close to the center of target chamber. Two kinds of SIDs are available: the LMJ SIDs are designed for ignition experiments, they provide the best positioning accuracy for imaging system, can be positioned on polar axis, and use electronic detectors; the PETAL SIDs are dedicated to PETAL diagnostics which use passive detectors due to electromagnetic perturbations induced by PETAL shots, and cannot be positioned on polar axis. About 10 SIDs are envisioned for the LMJ.

The port locations of the target handling equipment (Reference Holder (RH), Target Positioning System (TPS) and cryogenic TPS, SOPAC viewing stations) and the possible port locations for the different SID are listed in the Table VII.1. Three Specific Mechanisms ports are also available, 2 of them (MS8 and MS9) being reserved for DMX Broadband time-resolved spectrometer.

The diagnostics insertors locations are schematically drawn in Figure VII.3. Additional target chamber ports for fixed diagnostics exist and may be considered for future diagnostics developments.

Port	θ	φ	Remark
Target equipment			
RH	90°	238.5°	Reference holder
TPS	90°	255.5°	Target Positioning System
Cryo TPS	90°	220.5°	Cryogenic TPS, unavailable
SOPAC	16°	9°	Target viewing station
SOPAC	24°	243°	Target viewing and lighting station
SOPAC	90°	13.5°	Target viewing station
SOPAC	90°	103.5°	Target viewing station
SOPAC	90°	193.5°	Target viewing station
SOPAC	90°	283.5°	Target viewing station
SOPAC	164°	9°	Target viewing and lighting station
SOPAC	164°	189°	Target viewing station
Diagnostics insertors			
S1	16°	333°	Close to polar axis, unavailable
S2	164°	279°	Close to polar axis
S3	16°	153°	Close to polar axis, unavailable
S5	90°	112.5°	Unavailable
S7	164°	99°	Close to polar axis, laser injection and collection for EOS Pack
S12	90°	148.5°	
S16	90°	58.5°	
S17	0°	0°	Polar axis
S20	90°	292.5°	Optical system of EOS pack
S22	90°	328.5°	PETAL+ SPECTIX diagnostic, Opposite S12
S26	90°	180°	PETAL+ SEPAGE diagnostic
Specific mechanisms			
MS 8	24°	99°	DMX position 1
MS 9	70°	72°	DMX position 2
MS 18	90°	222°	Activation diagnostic, unavailable
SESAME 1	90°	166.5°	PETAL+ SESAME diagnostic position 1
SESAME 2	90°	121.5°	PETAL+ SESAME diagnostic position 2

Table VII.1: Spherical coordinate of target equipment and diagnostics insertors. The unavailable locations for experiments in 2017-19 are indicated

Figure VII.2 : Reference holder and Target positioning system

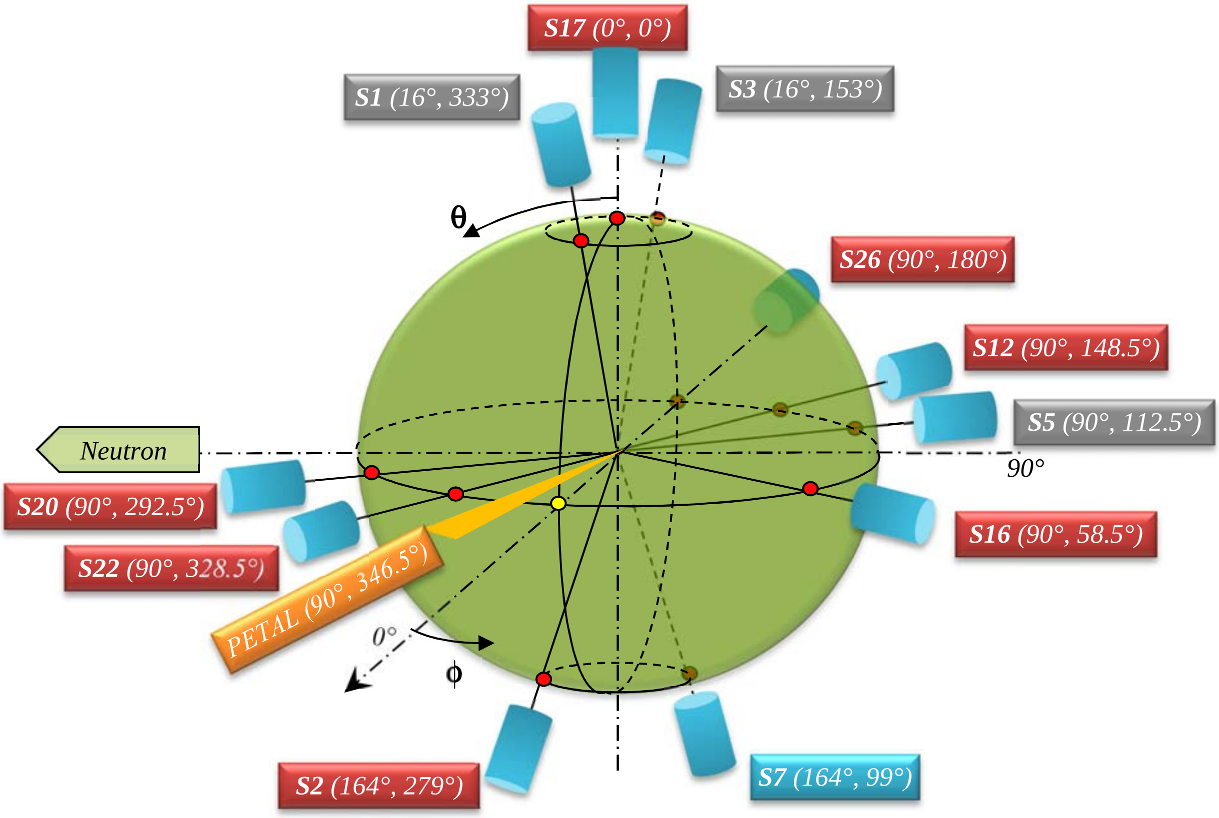


Figure VII.3:3D view of the SIDs location on the target chamber. S1, S3 and S5 are unavailable in 2017-19. S7 is dedicated to laser injection and collection for EOS Pack

Figure VII.4: View of the upper part of the target bay

VIII- LMJ Diagnostics

Over 30 diagnostics are considered with high spatial, temporal and spectral resolution in the optical, X-ray, and nuclear domains. Plans for LMJ diagnostics began with LIL laser facility and rely on decades of expertise in the design, fabrication and commissioning of advanced plasma diagnostics. The OMEGA laser facility has also been used and will continue to be the test bed for the development of CEA nuclear diagnostics. The early diagnostics, designed using the feedback of LIL's diagnostics, consist of:

- four hard and soft X-ray imaging systems (30 eV to 15 keV range) with a 15 to 150 µm spatial resolution and a 30 to 100 ps time resolution, providing 30 imaging channels,
- a diagnostic set for hohlraum temperature measurements including an absolutely calibrated broadband X-ray spectrometer (30 eV - 20 keV), a grating spectrometer, a time resolved imaging system of the emitting area,
- an absolutely calibrated broadband X-ray spectrometer (30 eV - 7 keV),
- an optical diagnostic set dedicated to EOS measurements including 2 VISAR (Velocity Interferometer System for Any Reflector), 2 SBO (Shock Break Out), a pyrometer and a reflectivity measurement,
- a Full Aperture Backscatter System, and a Near Backscatter Imager to measure the power, spectrum, and angular distribution of backscatter light to determine the energy balance.

The main characteristics of the first set of diagnostics are described in Table VIII.1.

X-ray Imagers				
Diagnostics & Setting	*Characteristics*	*Spectral range*	*Spatial resol. (µm) / Field of view (mm)*	*Temp. resol. (ps) / dynamic (ns)*
GXI-1 *Gated X-ray Imager (high resolution) SID*	*Magnification = 4,4*			
	2x4 toroidal mirror channels	*0.5 - 10 keV*	*30 / 3 (15 / 1.5)*	*75 / 20*
	4 pinhole channels	*2 - 15 keV*	*40 / 3*	*75 / 20*
	1 time integrated mirror channel			*without*
SHXI *Streaked Hard X-ray Imager (medium resol.) SID*	*Magnification = 1 or 3*			
	2 streaked toroidal mirror channels	*0.5 - 10 keV*	*150 / 15 or 50 / 5*	*30-100 / 5-25*
	2 time integrated lenses channels	*5 - 10 keV*	*130 / 20 or 50 / 6,5*	*without*
GXI-2 *Gated X-ray Imager (medium resolution) SID*	*Magnification = 0.9*			
	2x4 toroidal mirror channels	*0.5 - 10 keV*	*150 / 15 (100 / 10)*	*50 / 20*
	4 X-ray lenses channels	*6 - 15 keV*	*150 / 15*	*"*
	1 time integrated mirror channel			*without*
SSXI *Streaked Soft X-ray Imager (high resolution) SID*	*Magnification = 1 & 3*			
	2 toroidal mirror channels	*0.05 – 1.5 keV*	*30 / 5 & 50 / 15*	*50 / 5 to 250 / 25*
	Spectral selection by grating			
X-ray Spectrometers				
Diagnostics & Setting	*Characteristics*	*Spectral range*	*Spatial resol. (µm) / Field of view (mm)*	*Temp. resol. (ps) / dynamic (ns)*
DMX *Broad-band X-ray spectrometer Specific mechanics*	*20 broad-band channels*	*0,03 - 20 keV*	*- / (2-5)*	*100*
	Grating X-ray spectrometer Δλ<1Å	*0.1 – 1.5 keV 1.5 – 4 keV*		*50*
	Laser Entrance Hole Imager	*0.5 - 2 keV*	*100 / 5*	*500*
	X-ray Power	*0.1 - 2 keV 2.0 – 4.0 keV 4.0 – 6.0 keV*	*- / (2-5)*	*100*
Mini-DMX *Broad-band X-ray spectrometer SID*	*16 broad-band channels*	*0.03 – 7 keV*	*- / 5*	*100*

Optical diagnostics				
Diagnostics & Setting	*Characteristics*	*Spectral range*	*Spatial resol. (µm) / Field of view (mm)*	*Temp. resol. (ps) / dynamic (ns)*
EOS pack *Diagnostics set for EOS experiments SID (microscope)*	*2 VISAR (Infra-Red and Green)*	*0.5 - 200 km/s*	*30 / 1 to 100 / 10*	*50 / 5 to 500 / 100*
	Shock Break Out (SBO)			
	Pyrometer	*> 0.1 eV*		*< 10 or < 50 ps*
	Reflectivity	*0.01 à 1*	*10 / 1 to 50 / 5*	*50 / 5 to 500 / 100*
	Image 2D : 2 or 4 images	*> 1 eV*	*100 / 10*	*75 - 200 / 5 - 20*
FABS *Full Aperture Backscattering Stations Focusing system*	*Brillouin spectrometer $\Delta\lambda$ < 0.05nm*	*346-356 nm*		*50 / 5 to 250 / 25*
	Raman spectrometer $\Delta\lambda$ < 5 nm	*350-750 nm*		
	2 Brillouin power channels	*< 360 nm*		*250 / 25*
	2 Raman power channels	*350-750 nm*		
NBI *Near Backscatter Imager Chamber wall*	*2 Brillouin power channels*	*346-356 nm*	*2°/16°*	*1000/10*
	2 Raman power channels	*350-750 nm*		

Table VIII.1: LMJ diagnostics names and their main characteristics

Companion Table-top laser facilities [55] or X-ray sources [56] are used to perform metrology of the X-ray diagnostics before any plasma experiment.

VIII.1- X-rays imagers

The development of grazing-incidence X-ray microscopes is one of the skills of CEA diagnostics development laboratory. On LMJ, shrapnel [57] and X-ray loading [58] impose to place any imager as far away from the source as possible, which would degrade the spatial resolution. Grazing incidence X-ray microscopes allow overpassing this limitation. Compared to standard pinhole imagers, they offer also the best solution in terms of resolution versus signal to noise ratio. The design of LMJ X-rays imagers benefits from years of expertise either on OMEGA [59] or LIL X-rays imagers [60, 61].

These imagers, either gated (GXI-1 and GXI-2) or streaked (SHXI and SSXI) share a common mechanical structure (see Figure VIII.1) with the X-rays optical block itself, a telescopic extension and the optical analyzer (X-ray framing camera or streaked camera) working inside an air box mechanical structure (see Figure VIII.2) [62]. Diagnostics development takes into account the harsh environment [63] which will be encountered on LMJ, as well as the electromagnetic perturbations induced by PETAL [64].

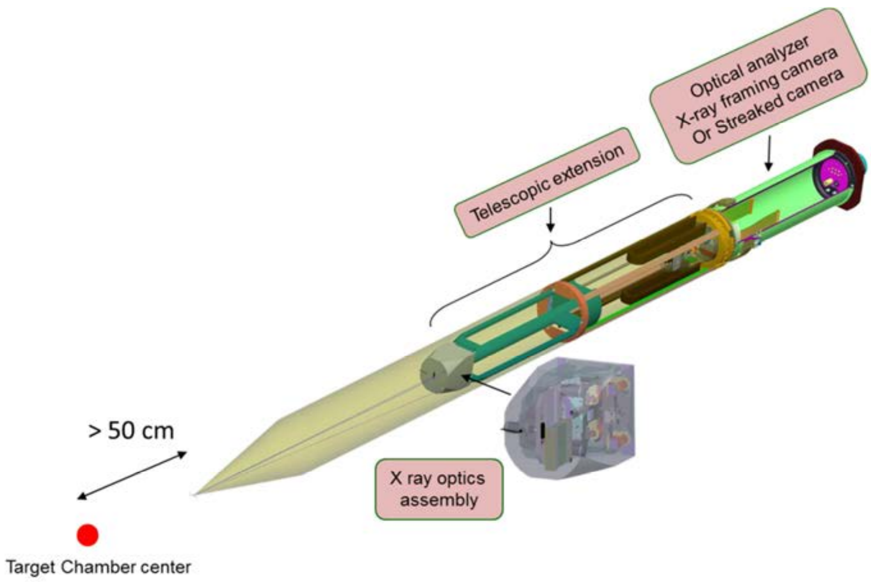


Figure VIII.1: Common mechanical structure of LMJ X-rays imager.

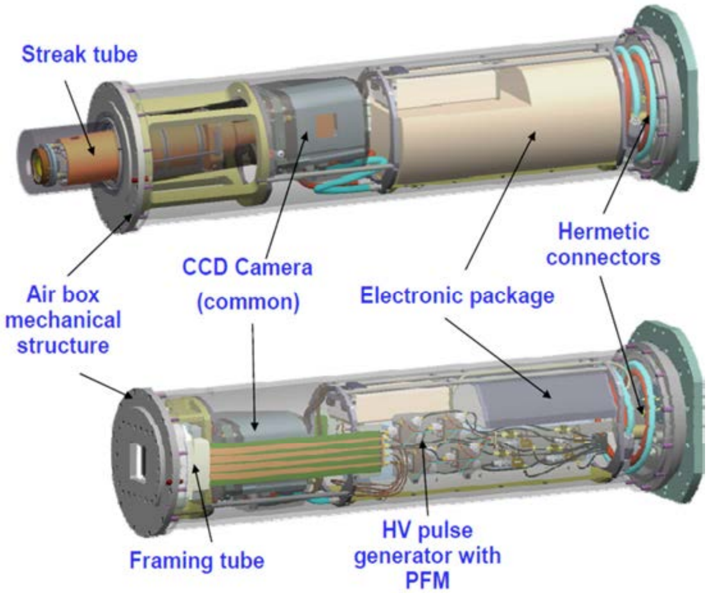


Figure VIII.2: Current design of LMJ optical analyzers [62]

The first LMJ X-ray imager GXI-1 has been commissioned on the facility in 2014. The optical block of the diagnostic includes an integrated unit, consisting of three alignment lasers (see Figure VIII.3). The optical scheme of the diagnostic is based on grazing incidence mirrors [65-68] together with a classical pinhole imaging in the central part of the system. 12 time-resolved images and 1 time integrated image will be acquired at the end, with different filtering options (see Figure VIII.4). Actual photographs of the GXI-1 diagnostic are displayed in Figure VIII.5.

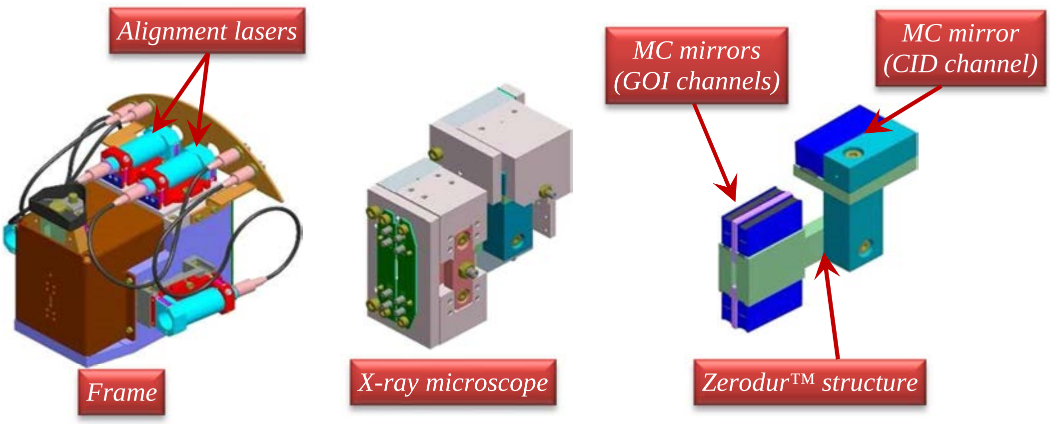


Figure VIII.3: Current design of the optical block of LMJ GXI-1

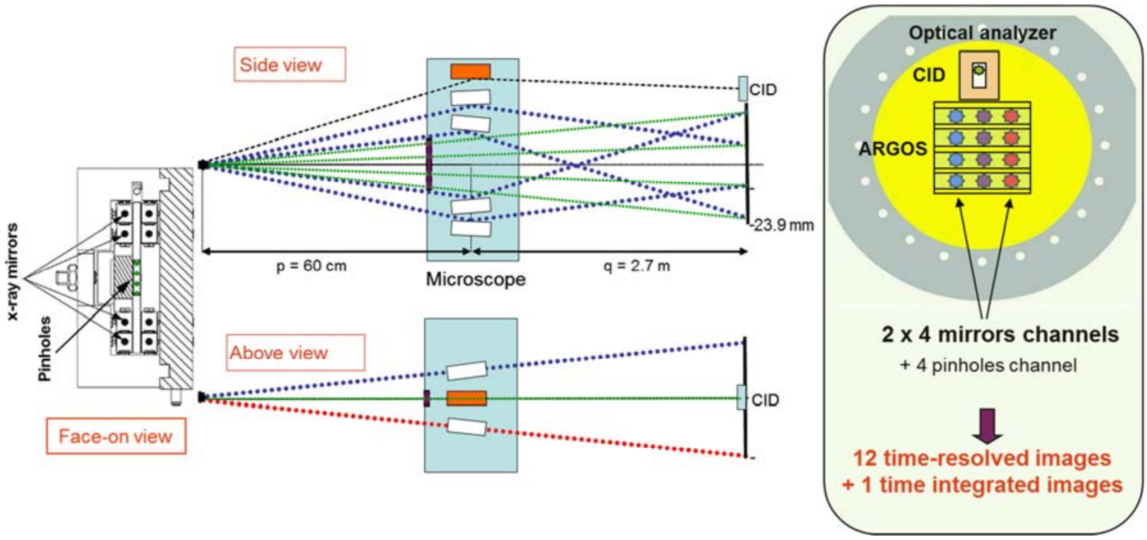


Figure VIII.4: Details of the acquisition channels of LMJ GXI-1

Figure VIII.5: Photograph of GXI-1 and zoom on the optical block

VIII.2- DMX-LMJ: Soft X-ray broadband time-resolved spectrometer

DMX is a primordial diagnostic for hohlraum energetic performance measurements [69].

DMX diagnostic is composed of a set of four diagnostics:

- a time resolved Soft X-ray Large Band spectrometer made of 20 measurement channels combining mirror, filters and X-ray diodes,
- a time resolved Soft X-ray spectrometer with gratings and streaked camera,
- a time resolved Soft X-ray Laser Entrance Hole Imaging with X-ray diodes array,
- a time resolved X-ray Power measurement spectrally integrated.

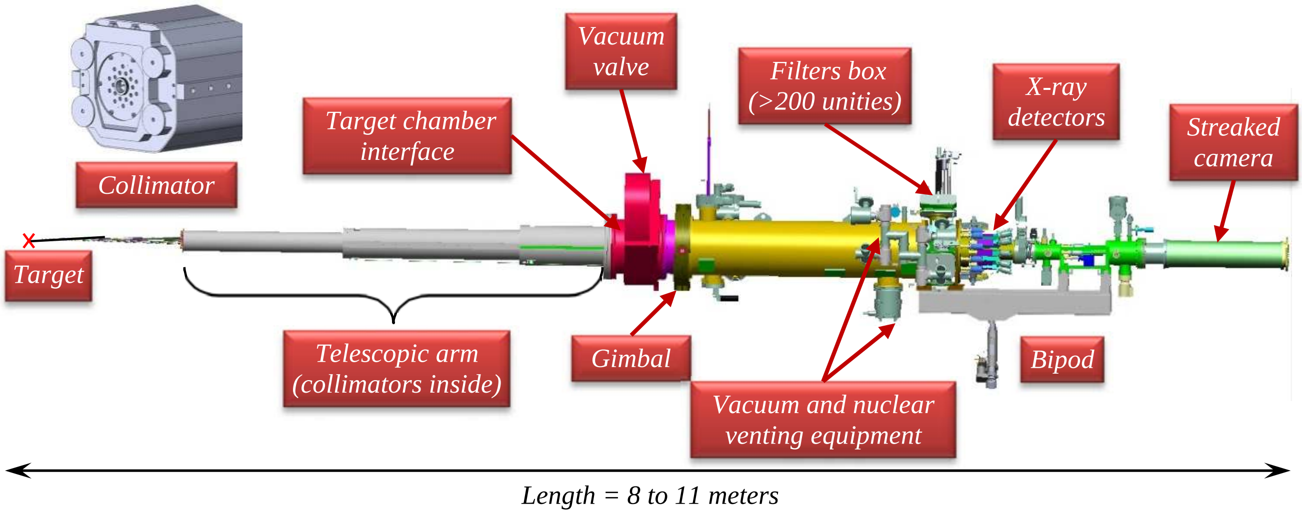


Figure VIII.6: DMX diagnostic

Beside standard soft X-ray measurements devoted to hohlraum energetics, the filtration of the channels could be adapted for specific purpose, such as conversion efficiency characterization of backlighters [70-72].

However as those measurements may require additional filters metrology on synchrotron beam lines (synchrotron SOLEIL at Saint Aubin), the request should be done well in advance.

Multilayer mirrors with spectral bandwidth are also under development for flat-response X-ray channels [73].

Figure VIII.7: Photograph of DMX during qualification test

VIII.3- Mini-DMX: Soft X-ray broadband time-resolved spectrometer

Mini-DMX is a second hohlraum energetic performance measurements axis on the LMJ facility.

This diagnostic is composed of 16 broadband channels combining filters, mirrors and coaxial detectors. It is positioned at its working distance (1000 mm or 3500 mm) by an insertion device manipulator (SID). This diagnostic like DMX, is absolutely calibrated.

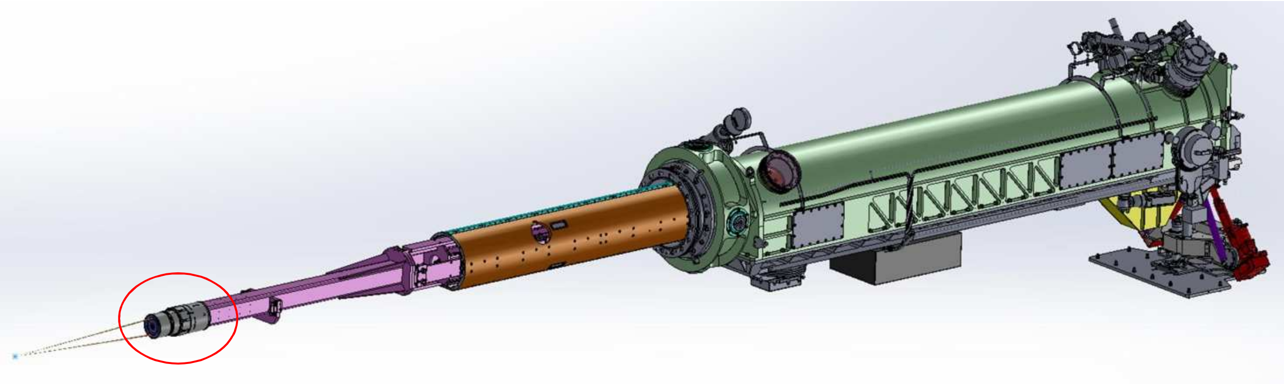


Figure VIII.8: Mini-DMX diagnostic positioned at working distance with SID

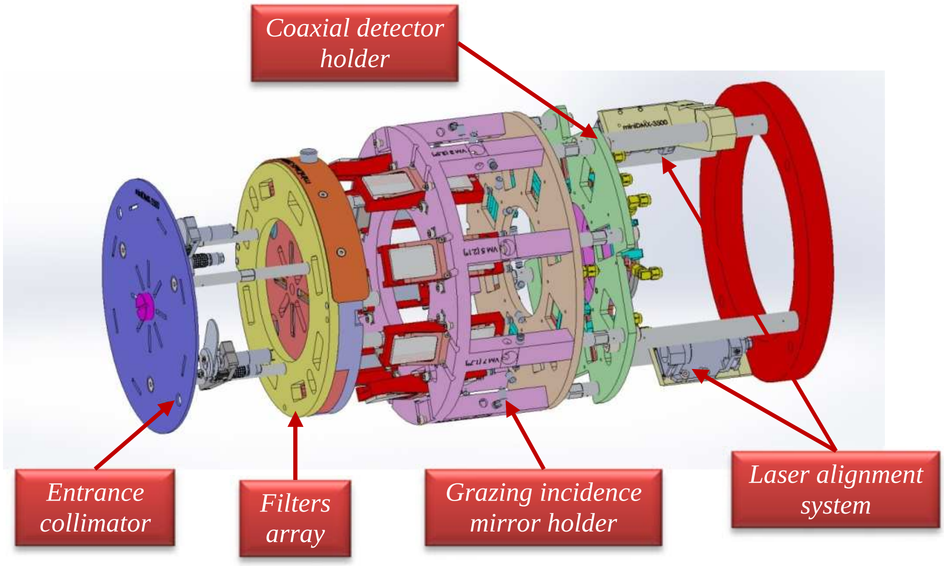


Figure VIII.9: Details of mini-DMX diagnostic

VIII.4- EOS Pack

The development of the EOS pack takes into account the feedback of the same kind of diagnostic that was in operation on the LIL facility [74]. The diagnostic (laser and optical analyzers) will be hardened and protected against EMP inside a Faraday cage. The goal is to be fully operational with PETAL so that simultaneous EOS measurements and side-on shock radiography may be possible.

The different acquisition channels are listed in the Table VIII.1. A two-dimensional Gated Optical Imager (GOI) will be added together with the 2 VISAR at 532 nm and 1060 nm.

The use of the EOS pack requests the S20 location for the insertion of the optical system inside the chamber and the S7 location (see Table VII.1) for laser injection and laser collection (see Figure VIII.10).

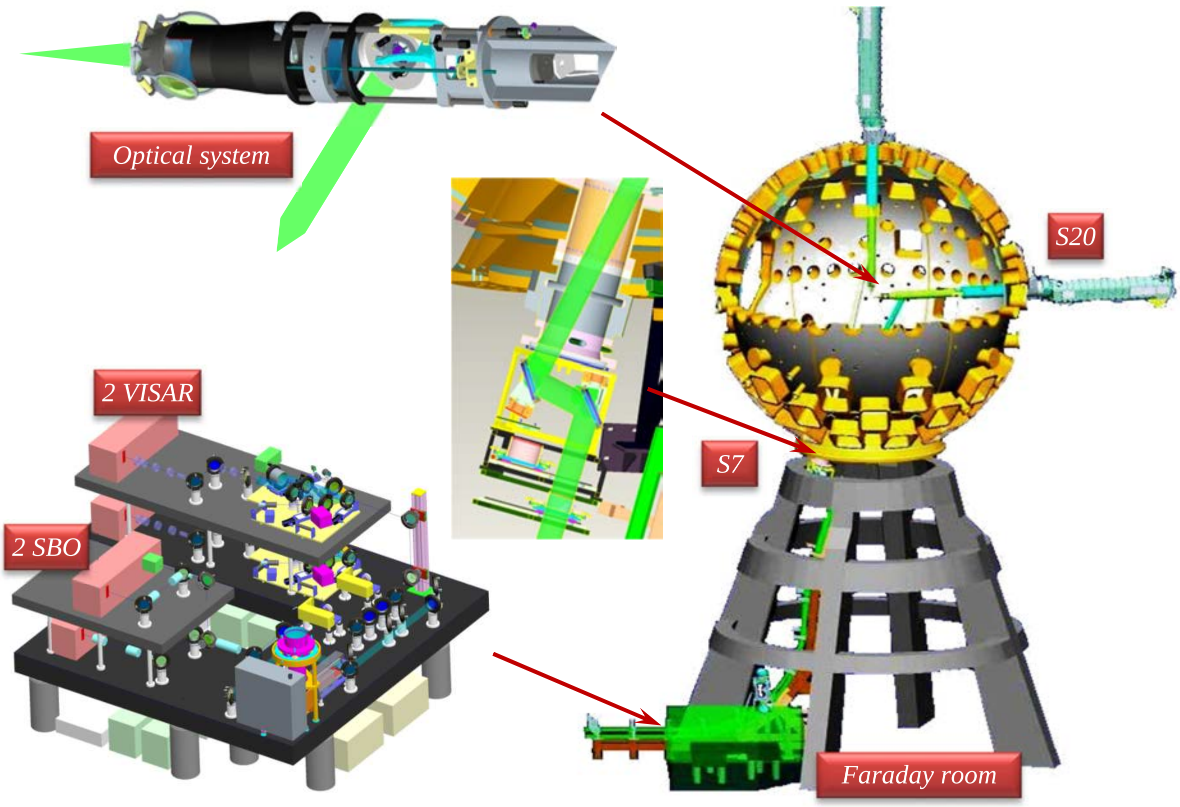


Figure VIII.10: EOS pack location and closer view on the analysis Table

VIII.5- Backscattering stations

A Full Aperture Backscattering Stations (FABS) will be operational in 2017 on the upper quadruplets 28U; a second one will be installed later on the upper quadruplets 29U (see Table V.1). They will allow power and spectral measurements of the Brillouin and Raman scattering light within the focusing aperture of LMJ quadruplet.

Power measurements in the Raman and Brillouin range outside the focusing aperture (Near Backscattered Imager, NBI) will be operational soon after.

VIII.6- Diagnostics in Conceptual Design Phase

The future LMJ diagnostics in Conceptual Design Phase include:

- Enhanced resolution X-ray imager
- Spatially resolved spectrometer
- Gated soft X-ray imager
- Activation diagnostic
- Neutron Imaging and Neutron Time-of-Flight Detectors [75, 76]
- Neutron Spectrometer

…

The delivery of these new diagnostics will begin in 2019.

IX- PETAL diagnostics

Beside classical LMJ diagnostics, specific diagnostics adapted to PETAL capacities are being fabricated in order to characterize particles and radiation yields that can be created by PETAL [42]; this is the PETAL+ project. PETAL+ is an academic project, coordinated by the University of Bordeaux. It is funded by the French Agency for National Research (ANR) within the framework of the National program EquipEx devoted to scientific equipment of high quality.

The set of equipment, which will be delivered in 2016, is developed by the CEA and consists of:

- one spectrometer for charged particles (electrons and ions),
- two electrons spectrometers,
- one hard X-ray Spectrometer,
- diagnostics insertors (SID).

IX.1- Electron and proton spectrometer - SEPAGE

The SEPAGE diagnostic includes an ion spectrometer for energy from 100 keV to 200 MeV, an electron spectroscopy for energy from 100 keV to 150 MeV, and an imaging module for proton-radiography.

It is made of two Thomson Parabolas (TP) for low and high energy particles:

	Electrons	*Protons (ions)*
Low energy TP	*0,1 – 20 Mev*	*0,1 – 20 MeV*
High energy TP	*8 – 150 MeV*	*10 – 200 MeV*

Table IX.1: Spectral ranges of SEPAGE

The imaging module is made of a set of Radio Chromic Film for particle energy from 1 to 200 MeV.

A CAD drawing of the diagnostic is shown in Figure IX.1. The preferred working location of SEPAGE is in SID position S26, opposite to the PETAL beam with an angle of 13.5°.

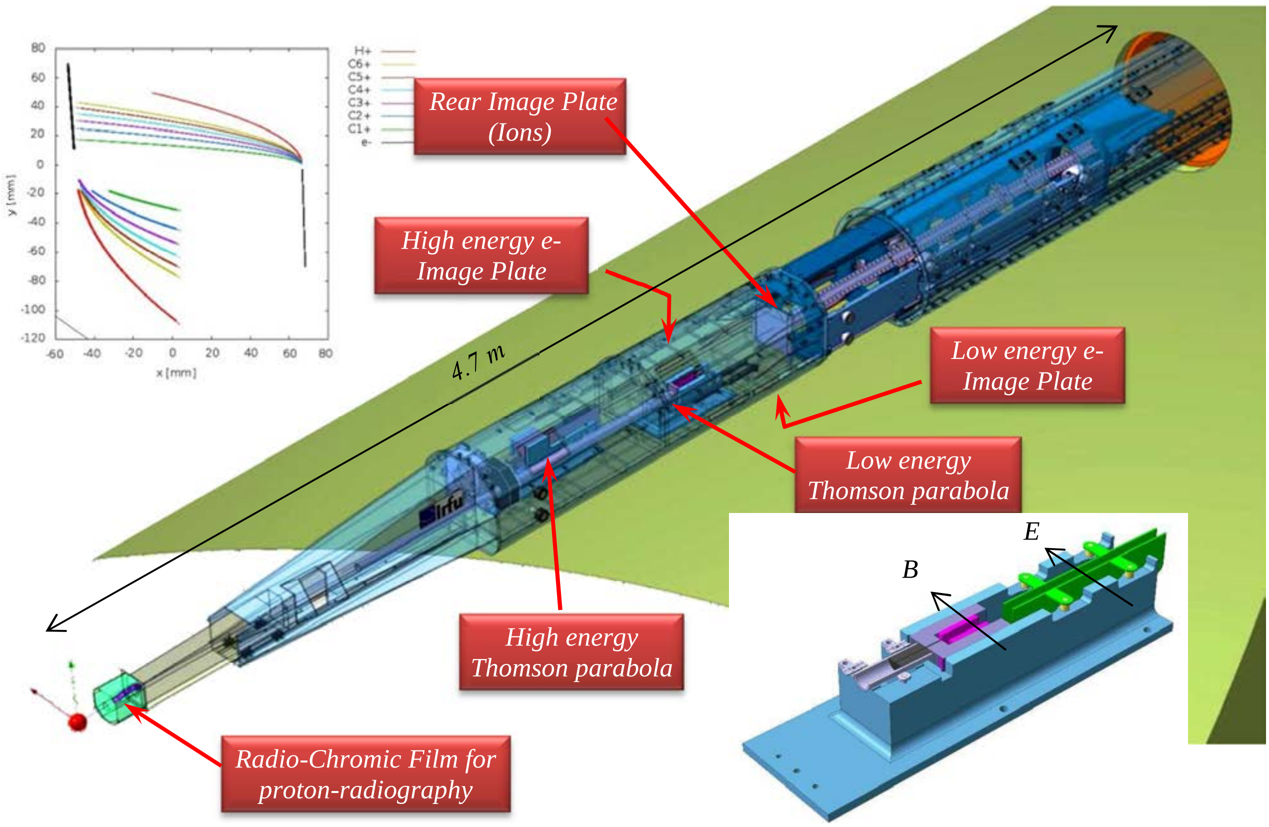


Figure IX.1 : Current design of SEPAGE diagnostic

IX.2- Electron spectrometers - SESAME

Complementary to the SEPAGE spectrometer, two additional electron spectrometers will be added at fixed location on the target chamber (see Table VII.1). SESAME 1 will allow electrons spectra measurements at 0° of PETAL axis whereas SESAME 2 will work at 45° of PETAL axis.

Permanent magnets are used to deflect particles toward Imaging Plates Detectors (IPs). The range of these electron spectrometers is 5 to 150 MeV.

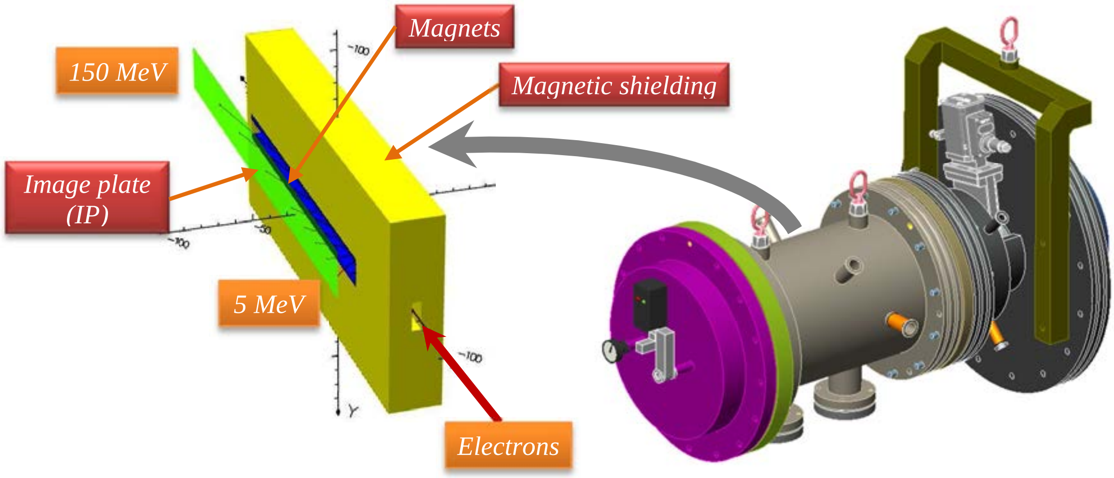


Figure IX.2: Principle and current design of SESAME diagnostic

IX.3- Hard X-ray spectrometer - SPECTIX

The SPECTIX spectrometer is a hard photon spectrometer intended to be complementary with the photon spectrometers (DMX) that will be working for the first LMJ shots. The energy range (6 to ~ 100 keV), the resolving power (≥ 100) and the signal dynamics (10^{10} to 10^{13} photons/sr) lead to choose a transmission Cauchois-type optics [77, 78].

The concept of SPECTIX is based on the combination of a spherical crystal used in transmission/refraction and a mechanical collimator. The refraction properties of the crystal are combined geometrically with the collimator in order to correlate the positions of the photons with their energies. In this scheme, the dispersion of the spectrometer convoluted with the size of the collimator provides the resolving power of the device. Identification of contributors to the background noise in such type of hard X-ray spectrometers, and shielding optimization were performed with the help of Monte-Carlo simulations [79].

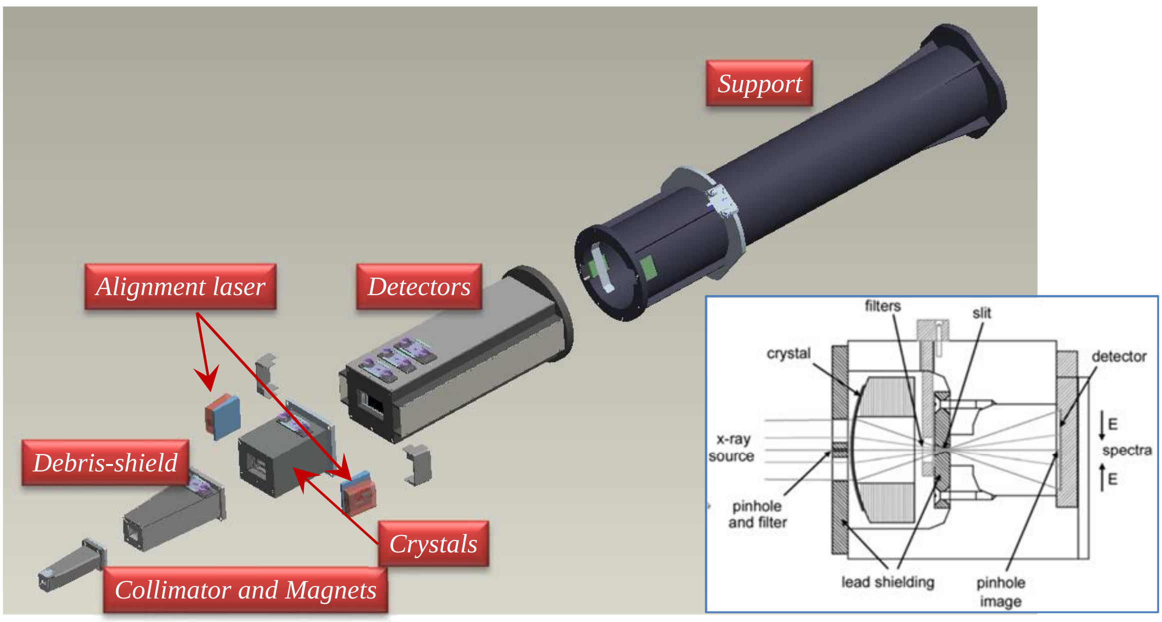


Figure IX.3: Current design and principle of SPECTIX diagnostic

X- First experimental configuration

X.1- Laser beams characteristics

By the end of 2016, the experimental configuration of the LMJ facility will include 4 quads and the PETAL beam. The spherical coordinate of these beams and the angles between the quads and PETAL are given in Table X.1.

Beam Port	θ	φ	Angle vs. PETAL
28U	33.2°	81°	92.5°
28L	131°	81°	93.4°
29U	49°	63°	79.9°
29L	146.8°	63°	82.7°
PETAL	90°	346.5°	

Table X.1: Angle of the first LMJ quads and PETAL beam

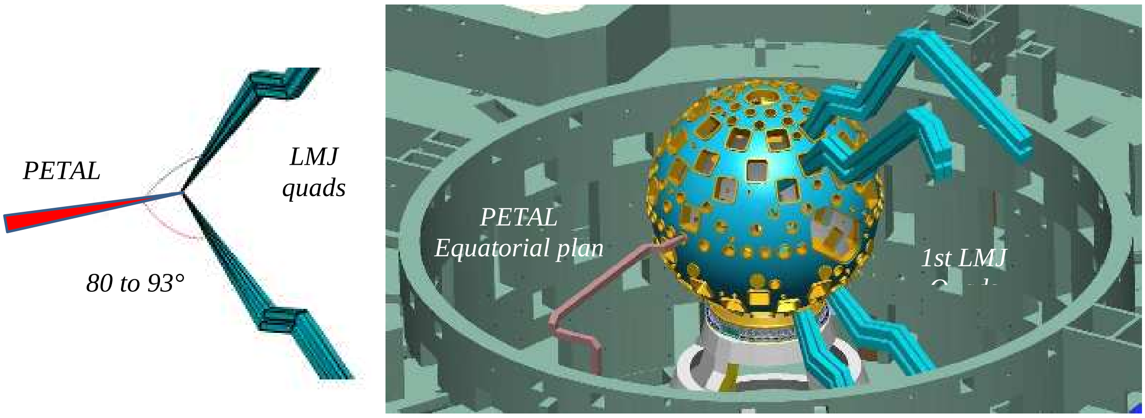


Figure X.1 : First LMJ-PETAL experimental configuration

The CPP Type D (see section V.4) will be available for all quads; the CPP Type E will be available for two quads; the CPP Type F will be available for two quads.

Concerning the Smoothing by Spectral Dispersion, the 2 GHz modulation will be activated for all shots, and the 14 GHZ modulation will be activated if required.

X.2- Target bay equipment

About 10 SIDs are envisioned for LMJ but by the end of 2016, only 3 of them will be available: 1 LMJ SID and 2 PETAL SID.

According to the first LMJ-PETAL configuration, the ILP has chosen in 2012 the preferred SID locations for the PETAL diagnostics. As a consequence and for sake of minimizing the number of Facility reconfiguration, the operational positions available in the 2017-2019 timeframe will be:

- S12, S16, S20, S22, S26 in the equatorial plane for LMJ or PETAL SIDs,
- S2 and S17 close to the polar axis for LMJ SIDs.

The proposed experimental configurations should take these constraints into account.

The available LMJ diagnostics by the end of 2016 will be: GXI-1, SHXI, GXI-2, SSXI, DMX and EOS pack.

FABS and NBI will be available by the end of 2017.

XI- Targets

XI.1- Assembly and metrology capabilities

The target laboratory at CEA-CESTA is responsible for the mounting of the user-supplied targets on the structure necessary for the alignment at target center chamber (TCC). The metrology of the targets prior to the shot will also be performed in this laboratory. Depending on the target geometry, a precision better than 10 µm rms can be reached. A CAD drawing of the target (step file) must be provided to CEA before any target part fabrication in order to check the feasibility of alignment, diagnostics line of sight, etc. The SOPAC stations will provide various targets views at TCC. The target engineer and CEA Experiment Coordinator (RCE), together with the PI and CEA Experiment Manager (MOE), will define the alignment reticles necessary to match the requested alignment precision.

Figure XI.1: Examples of SOPAC views and alignment reticles (in red)

XI.2- User-supplied targets

To comply with nuclear and facility safety procedures, the exhaustive list of materials (and masses) of the target has to be provided to CEA. The targets should arrive at CEA targets laboratory well in advance of the shot to allow proper time for assembly and metrology. Targets redundancy should be sufficient to allow fulfilling the shot plan (6 shots).

XII- References

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XIII- Acknowledgements

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PETAL+ is an Equipex project of the University of Bordeaux funded through the PIA by the ANR (French National Research Agency).

XIV- Glossary

ANR: French Agency for National Research
APS DPP: Meeting of the Division of Plasma Physics of the American Physical Society
CAD: Computer Assisted Design
CEA-DAM: Military Applications Division of CEA
CPA: Chirped Pulse Amplification
CPP: Continuous Phase Plates
DMX: Broad-band X-ray spectrometer
ECLIM: European Conference on Laser Interaction with Matter
EOS: Equation of State
EOS Pack: Diagnostics set for EOS experiments
EPS: Conference on Plasma Physics of the European Physical Society
ERC: European Research Council
FABS: Full Aperture Backscattering Stattion
GOI: Gated Optical Imager
GXI1: Gated X-ray Imager
GXI2: Gated X-ray Imager
HEDLA: Conference on High Energy Density Laboratory Astrophysics
HEDP: High Energy Density Physics
HTPD: Conference on High Temperature Plasma Diagnostics
ICF: Inertial Confinement Fusion
ICHED: International Conference in High Energy Densities
IFSA: Conference on Inertial Fusion Sciences and Applications
ILP: Institut Laser & Plasmas
IP: Imaging Plate
LIL: Laser Integration Line
LMJ: Laser Megajoule
LOI: Letter of Intent
LPI: Laser Plasma Interaction
MOE: CEA Experiment Manager
NBI: Near Backscattered Imager
OPA: optical parametric amplification
PAM: Pre-Amplifier Module
PETAL: Petawatt Aquitaine Laser
PETAL+: PETAL diagnostics Project funded by ANR (Equipex Projects)
PFM: Pulse Forming Module
PI: Principal Investigator
PIA: Programme d'Investissement d'Avenir (French National program for promising investment)
RCE: CEA Experiment Coordinator
RCF: Radio Chromic Film
RH: Reference Holder
RMS: Root mean square
SBO: Shock Break Out
SEPAGE: Electrons and protons spectrometer for high energy
SESAME: Electron spectrometer for medium energy
SHXI: Streaked Hard X-ray Imager

SID: System for Insertion of Diagnostics
SOLEIL: French Synchrotron facility located at L'orme des Merisiers, 91190 Saint Aubin
SOP: Streaked Optical Pyrometer
SOPAC: System for Optical Positioning and Alignment inside Chamber
SSD: Smoothing by Spectral Dispersion
SSXI: Streaked Soft X-ray Imager
TBD: To be determined
TCC: Target chamber center
TP: Thomson Parabola
TPS: Target Positioning System
VISAR: Velocity Interferometer System for Any Reflector

XV- Appendix

GPS coordinates:

- CEA-CESTA : 44° 39’ 30’’ N / 0° 48’ 29.8’’ W
- LMJ : 44° 38’ 08.8 ‘’ N / 0° 47’ 12’’ W
- ILP building : 44° 38’ 13’’ N / 0° 47’ 54.1’’ W

List of hotels close to CEA-CESTA, in Bordeaux and Arcachon.

Close to CEA-CESTA	Bordeaux
Hôtel-Restaurant LE RÉSINIER 68, av. des Pyrénées – RN10 33114 LE BARP Tel. : +33 5 56 88 60 07 Fax : +33 5 56 88 67 37	Hôtel Quality Suites Bordeaux aéroport 4* 83 avenue JF Kennedy 33700 MERIGNAC Tel : +33 5 57 53 21 22 reservation@qualitybordeaux.com
Domaine du Pont de l’Eyre 2 route de Minoy 33770 Salles Tel : +33 5 56 88 35 00 Fax : +33 5 56 88 35 99 dom.pont.de.leyre@wanadoo.fr	Hôtel Best Western « Bayonne Etche-Ona » 3* 15 cours de l’Intendance 33000 BORDEAUX Tel : +33 5 56 48 00 88 Fax : +33 5 56 48 41 60 bayetche@bordeaux-hotel.com
B&B MIOS 6 avenue ZAC 2000 Parc d’activités MIOS Entreprises 33380 MIOS Tél : +33 8 92 70 20 70 or +33 5 56 77 33 11 bb_4527@hotelbb.com	Hôtel TENEO gare Saint Jean 4 cours Barbey 33800 BORDEAUX Tel : +33 5 56 33 22 00 bordeaux@teneo.fr
Hôtel CAMPANILE A63 – aire de repos de CESTAS Tel : +33 5 57 97 87 00	
Arcachon	
Hôtel LE DAUPHIN 7 avenue Gounod 33120 ARCACHON Tel : +33 5 56 83 02 89 Fax : +33 5 56 54 84 90	Hôtel Park Inn 4 rue du Professeur JOLYET 33120 ARCACHON Tel : +33 5 56 83 99 91 Fax : +33 5 56 83 87 92 info.arcachon@rezidorparkinn.com
Hôtel AQUAMARINA 82 boulevard de la Plage 33120 ARCACHON Tel. : +33 5 56 83 67 70 Fax : +33 5 57 52 08 26	Hôtel Quality Suite Arcachon 4* 960 avenue de l’Europe 33260 LA TESTE DE BUCH Tel : +33 5 57 15 22 22 reservation@qualityarcachon-spa.fr
Hôtel LES VAGUES 9 boulevard de l’Océan 33120 ARCACHON Tel. : +33 5 56 83 03 75 Fax : +33 5 56 83 77 16	

XVI- Revision log

Rev No	Date	Main modifications	Brief description
1.0	12 Sept 2014	-	Initial release (Jean-Luc Miquel, Alexis Casner, Emmanuelle Volant)
1.1	28 April 2015	p6: III.4- Confidentiality rules p7-8: III.5- Selection process p8: III.6- Experimental process p16: V.4- Spot sizes - Table V.2. p19: V.7- Laser performances p26: VIII- LMJ Diagnostics - Table VIII.1 p30-31: VIII.3- Mini-DMX	Rearrangement of section III (precisions on Selection process, addition of Experimental process). Modification of spot sizes. Addition of Laser performances. Addition of Mini-DMX. (JLM, EV)

All Photos: @CEA

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