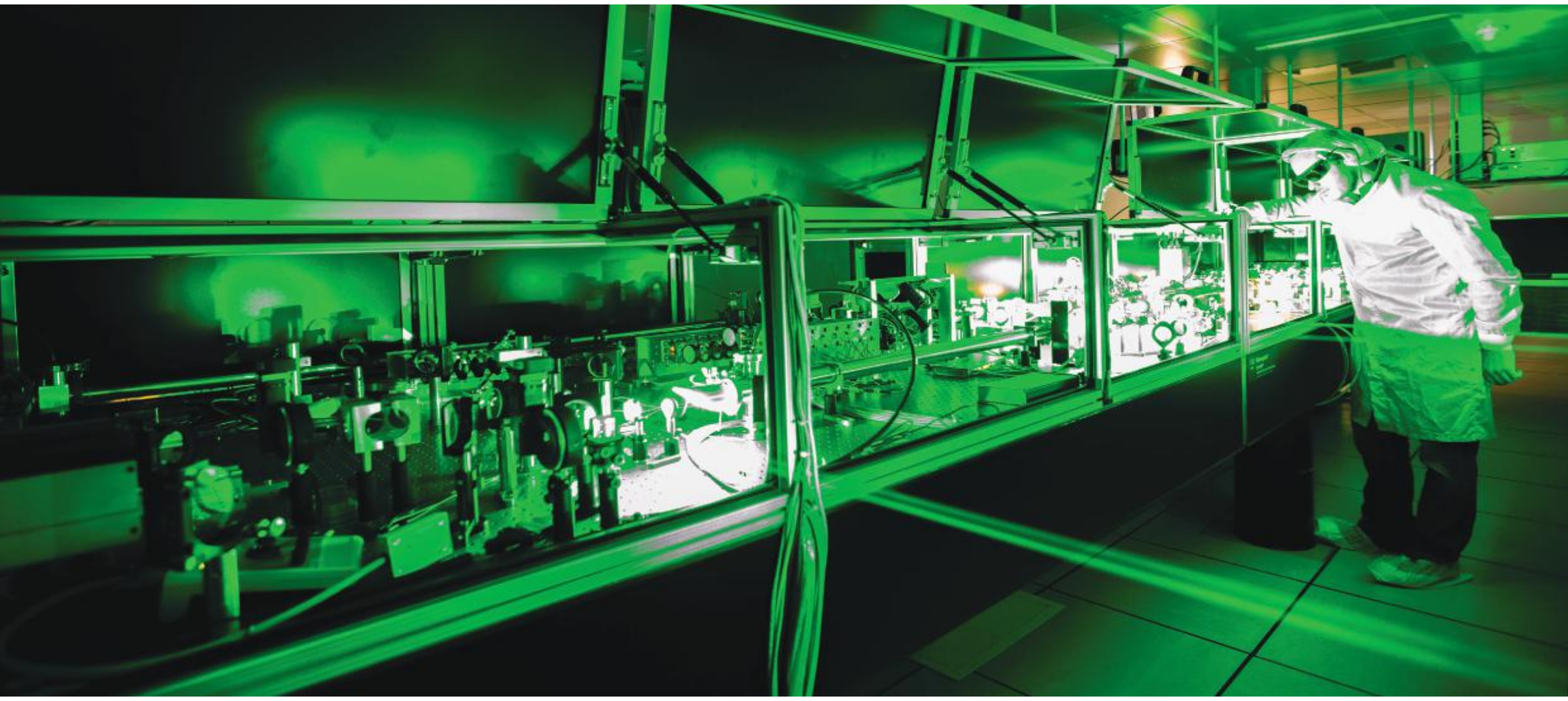
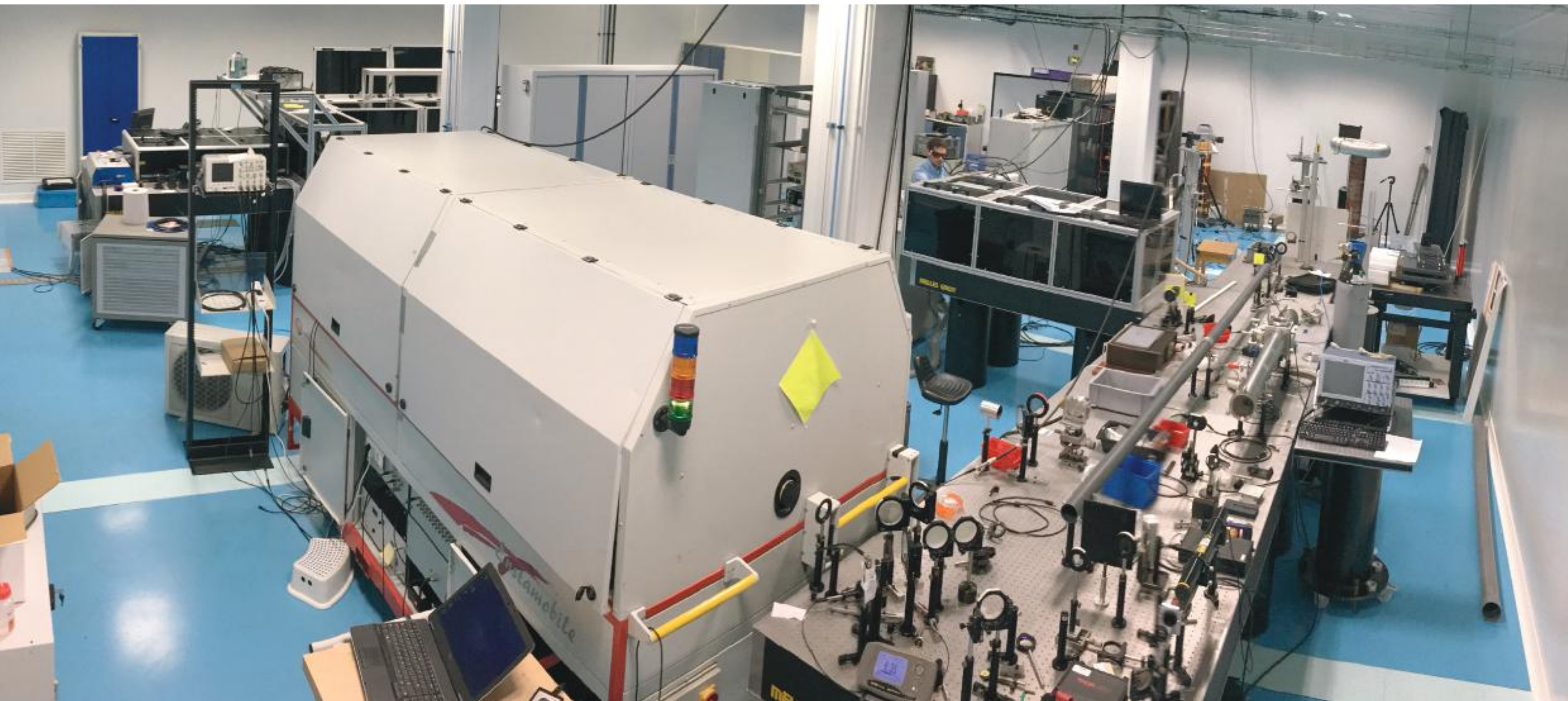
laboratoire d'optique appliquée

PROGRESS REPORT
LOA 2013-2018

ENSTA-ParisTech, Ecole Polytechnique,
CNRS UMR7639

Contents





SHORT HISTORY OF LOA

The Laboratoire d'Optique Appliquée (LOA) is a Joint Research Unit (UMR 7639) CNRS - Ecole Polytechnique (EP) - ENSTA-Paristech. It is hosted at the Palaiseau-Yvette research centre of ENSTA-ParisTech, inside the campus of Ecole Polytechnique. LOA was created in 1972 from a research team called "Studies of lasers and their applications" established in 1960 at Ecole Polytechnique. Associated with INSERM in 1984 (U 275), and with CNRS in 1989 (Associated Research Unit URA 1406), the LOA became an UMR in 1997. The laboratory gathers 80 to 90 people. 50% of the staff are permanent among which 25% are researchers. Its annual running budget is 6 M€ full cost.

LOA has played a pioneering role in the development of ultrafast laser-plasma science. In the early 1980s, it became the French precursor of ultrafast lasers and their applications. It is one of the very first laboratories to have successfully developed a laser with femtosecond pulse duration. These new light sources allowed LOA researchers to quickly launch the first applications in this emerging science, all related to ultrafast phenomena, and mainly for the study of femtosecond processes in solid state physics. Thanks to the research support actions of the European Community, the laboratory was then funded to develop a femtosecond laser source with an increased laser energy, and with the goal to study atoms under intense electromagnetic fields ("Stimulation for Science" program). This was the start in the early 1990s of a continuous increase of laser energies of LOA systems over the years, and a jump of several orders of magnitude for femtosecond laser intensities available on target compared to the existing systems worldwide. A whole new set of LOA research topics has then been launched with the creation of new research teams, all related to laser-plasma physics, ultrafast non-linear optics and the generation of innovative ultrafast and intense laser-based sources of energetic particles and radiations. This has led to almost 30 years of leading activities in these research areas and to a series of scientific breakthroughs in line with the longstanding tradition of LOA to tackle scientific problems from curiosity-driven basic laser-plasma science to interdisciplinary applications. As few examples:

- The first X-ray source with femtosecond pulse duration (Phys. Rev. E 1994 & Nature 1998)

- The direct observation of atomic movements at their characteristic femtosecond time scale (Nature 1997 & Nature 2001 & Rev. Mod. Phys. 2001)

- The generation of filaments over long distances in air (Science 2003)

- The first amplified injected laser in the XUV spectral range (Nature 2004)

- The electron acceleration by laser fields and the creation of femtosecond electron beams (Science 2002 & Nature 2004 & Nature 2006)

- The firsts collimated X-ray sources from laser-produced plasmas (Phys. Rev. Lett. 2004 & Nature Photonics 2012)

- The attosecond control of plasmas (Nature Physics 2012 & Nature photonics 2012)

- Positrons acceleration from plasmas (Nature 2015)

- The generation of femtosecond laser-based X-ray lasers (Nature photonics 2015)

- The vacuum laser acceleration of relativistic electron beams (Nature physics 2015)

- The demonstration of high repetition rate laser-plasma accelerators (Nature photonics 2017)

The early partnership with European institutions has positioned LOA as leading partner promoting the field. In 1992, LOA became a European pole of excellence for intense femtosecond lasers, ultrafast phenomena and ultrafast laser-plasmas, being selected within the "Human Capital and Mobility" program. This position was confirmed in 1996 by taking part in the first European laser program ("Lasernet" that has later given birth to "LaserLab") which included the 5 major European laser infrastructures. The LOA is still part of this program, which has been extended to many other partners and will now enter into its 5th phase of scientific cooperation. LaserLab now brings together 33 leading institutions in laser-based inter-disciplinary research from 16 countries. In addition to key partnerships in all major national programs like recently the two French "Equipement d'Excellence" CILEX and ATTOLAB from the national "Investissement d'Avenir" program, LOA has throughout the years actively participated in steering national and international projects through memberships of several boards, developing joint research activities as well as transnational access to the laser installations with the aim of reinforcing the national and European leadership in laser-plasma research and applications.

The LOA has now the mission to advance knowledge and educate students in ultrafast laser-produced plasma physics, and other related topics that will best serve academic, societal and industrial applications. In each team of the LOA research centre, we seek to develop carefully chosen and cutting-edge advanced programs with the ability and passion to work wisely, creatively, and effectively for the establishment of a bridge between academic laser-plasmas physics and societal needs.

THE RESEARCH UNIT

The LOA research infrastructures lie in a single site located at the ENSTA-Yvette research centre where laboratories and offices are spread over a total surface of 5200 m^2. LOA provides uniqueness instrumentations in the field of ultrafast laser-plasmas, pushing high intensity lasers to pulse durations down to an optical cycle and to high repetition rates, providing systems with multiple beams synchronized at the femtosecond time-scale, beamlines with fixed experimental set-up for dedicated topics or mobile terawatt ultrafast lasers.

The LOA scientific activity is operated by 7 research groups.

<u>Application of ultrafast sources to solid state physics (APPLI)</u>

The APPLI group is dedicated to the development of new femtosecond particle and radiation sources and to their use for probing ultrafast dynamics in solids. A special emphasis is set on developing high-repetition rate and reliable sources that can truly be used for probing ultrafast phenomena at the femtosecond time scale. Part of the group is focused on material science to study the dynamics of electrons, spins, phonons and their mutual couplings in a large range of materials, from metals to strongly correlated systems and nanomaterials. Another part of the group is pushing the development of innovative femtosecond electron sources and their use to probe structural dynamics in solids via ultrafast electron diffraction (UED) with unprecedented time resolution.

<u>Laser Matter Interaction (ILM)</u>

The activities of the ILM group are mainly devoted to experimental physics, covering every aspect of the nonlinear propagation of intense ultrashort lasers in transparet media from the understanding of fundamental phenomena such as the lasing effect of Nitrogen inside filaments to the demonstration of new concepts of applications based on laser filaments (remote underwater sonar, THz plasma antenna, aeronautic laser spike to name a few).

Femtosecond Bio-radical Chemistry (FCB)

The research of the FCB group is developed at the interface of physical chemistry and biomedical sciences, using ultrashort laser facilities and time resolved spectroscopic techniques. They concern the innovative domain of Bioradical Femtochemistry for which photo and radio-induced radical events are investigated at the time scale of small molecular motions, typically in the temporal range 10^{-13} - 10^{-11} s.

Laser-based Femtosecond X-ray sources (FLEX)

The FLEX group investigates fundamental physical processes of high intensity laser-plasma interaction related to the generation of ultrafast radiation sources ranging from EUV to γ-rays. Studies mainly concentrates on secondary light sources like High harmonic generation, XUV lasers, energetic X-γ-ray sources generated by relativistic electrons and on the development of the associated metrology. The group also develops specific applications of these short wavelength sources for medical imaging, tomography and ultrafast x-ray spectroscopy like time-resolved femtosecond dynamics of transient atomic structures, high resolution phase contrast imaging, XUV holography and ptychography.

Optics-Photonics-Health (OPS)

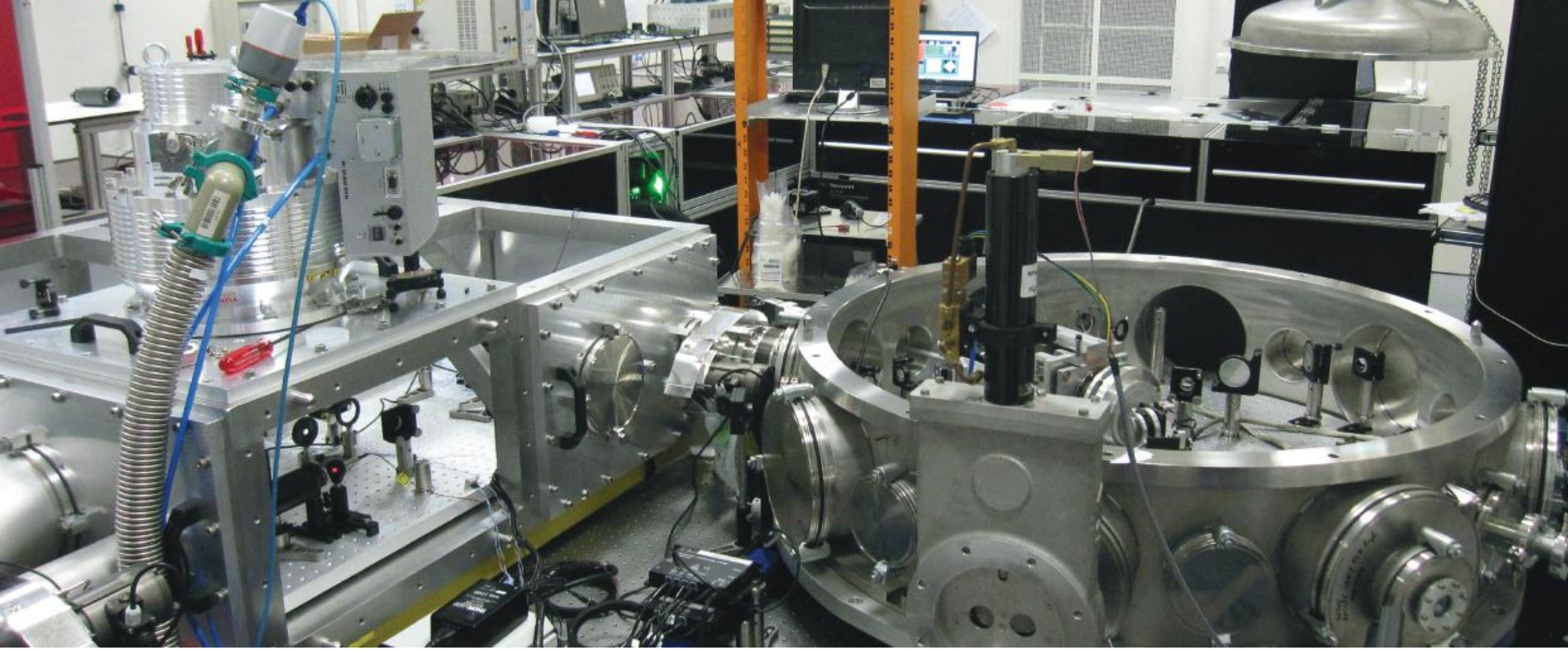
The OPS group works on ultrashort pulse laser surgery of the anterior segment of the eye, notably for corneal grafting and glaucoma surgery. In both cases the intervention has to be performed in an optically scattering medium. The activities of the group cover research in tissue optics as well as the development of laser sources optimised for surgery. In collaboration with other partners the group also works on multiphoton and nonlinear imaging and optical coherence tomography of the anterior segment of the eye.

Physics at the Optical Cycle time scales (PCO)

The PCO group investigates charge dynamics in laser-induced plasmas on the femtosecond to the attosecond time scale. High repetition rate laser systems capable of producing few-optical-cycle pulses with peak-powers close to few TeraWatt are developed. By precisely controlling the interaction between the ultra-intense laser field and the plasma, they study the generation of ultrashort photon (VUV to XUV) and particle (electrons, ions) beams that can be used to probe the real-time ultrafast motion of electrons in matter.

Laser-based particle sources (SPL)

The SPL group develops new technology for compact particle accelerators. They are based on laser-produced plasmas to provide intense electric fields of the order of TV/m. Detailed studies of relativistic laser-plasma interaction processes has enabled the production of beams of particles with innovative properties compared to the state of the art. The group is concerned with fundamental physics, particle beams generation (electrons and ions) and applications (bio-medical, chemistry, materials, new phenomena on ultra-short (fs) time scales).



THE RESEARCH TOPICS

LOA has been recognized for 30 years as a research centre for fundamental and applied physics in ultrafast science, with the mission to understand and reveal the properties of matter under strong excitation and at the shortest time or space scales. To excite, control and probe at the highest resolution, teams have developed programs in non-linear ultrafast optics and laser-plasma physics. There is also a longstanding tradition to perform applications in other academic fields and to address key societal issues.

The quality of the research in the laboratory is based on highly competitive teams, with scientists being part of the international leaders of their field. They have a clear understanding of key technical and scientific challenges that may be addressed in these fast-evolving topics. One of the strengths of our scientific strategy is the remarkable transverse relationship between internal teams that merge their expertise to consolidate and boost the development of sub-topics as can be seen in Table 1 which shows the laboratory organization that covers 6 research areas.

The first topic is related to the production of the shortest time duration laser pulses to provide the highest laser intensity with compact (table-top) and high repetition rate laser systems. This leads to the development of high-temporal contrast, high peak power few-optical-cycle pulses to drive relativistic-intensity laser-plasma interactions. The second topic is related to the fundamental aspects of laser plasma interaction at high femtosecond laser intensities to develop compact particle accelerators (compared to conventional technologies) and the applications of the beams they produce. X-ray sources generated from these particle beams or from hot laser-produced plasmas are the scope of the third topic. The teams are studying how to produce and control intense and ultrafast radiations over a large range of spectral wavelengths and X-ray properties. The fourth topic covers every aspect of the nonlinear propagation of ultrashort lasers in transparent media, like in air, to understand fundamental phenomena related to laser-based filamentation.

The first objective of the research teams is advancing better fundamental knowledge in ultrafast laser-plasma science. This is done on the best effort basis, with dissemination of the results at national and international conferences, publication in top-ranked and wide-range journals or more specialized ones. Participation in many collaborative research programs within the local environment and at the European level boosts LOA projects. The properties of the secondary sources and ultrafast plasmas also provide unique opportunities to develop transverse application, most of the time in close collaboration with academic and industrial teams from these fields. Already remarkably addressed by the LOA teams during the last periods of evaluation, the development of applications has been further accelerated and is a key issue of our scientific strategy.

The fifth topic then focuses on high resolution imaging, taking advantage of the compactness, small source size, short pulse duration and perfect time synchronization of the laser, particle and x-ray beams. The last topic includes programs at the interface of physics and bio-medicine as well as industrial application in response to societal and military needs like non-destructive testing for example. We are developing innovative approaches for imaging healthy and pathological tissues, for the study of radiobiology at extremely high dose rate, for the development of new applications based on laser filaments like remote underwater sonar, plasma antenna, aeronautic laser spike or the control of high voltage discharge like lightning. More details on each of these topics can be found in the teams report sections. One challenge related to these developments is to provide sufficient beam time, stable beams or innovative plasma tools for reliable and long-term studies. This can be only addressed with dedicated experimental platforms that are not devoted to fundamental laser-plasma research.

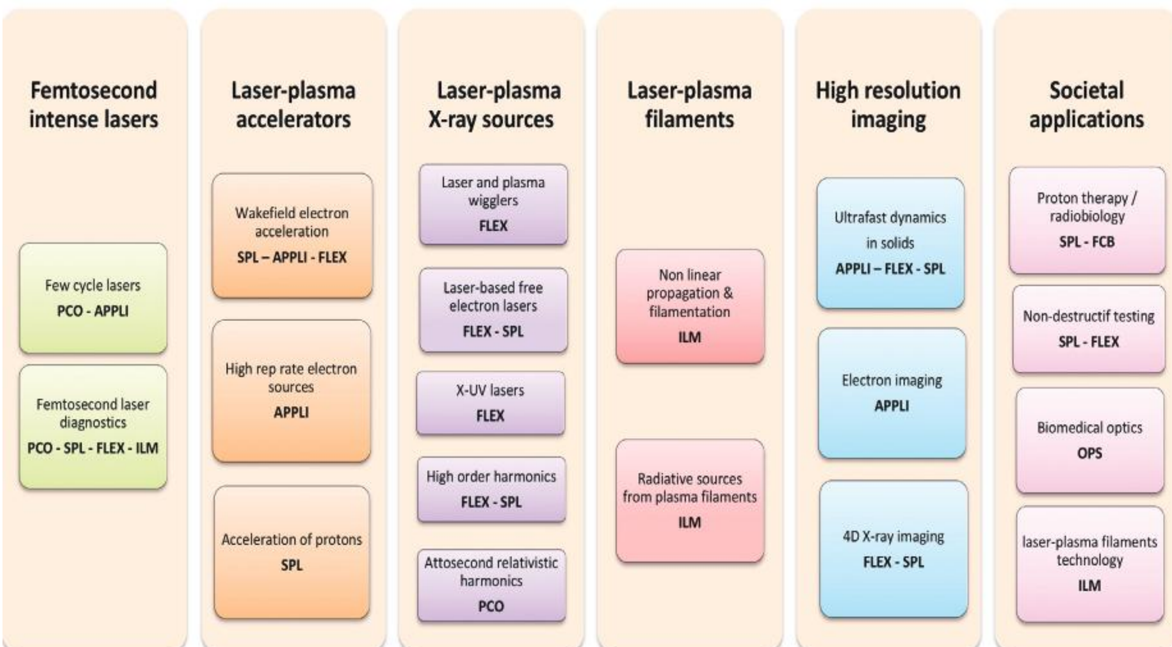


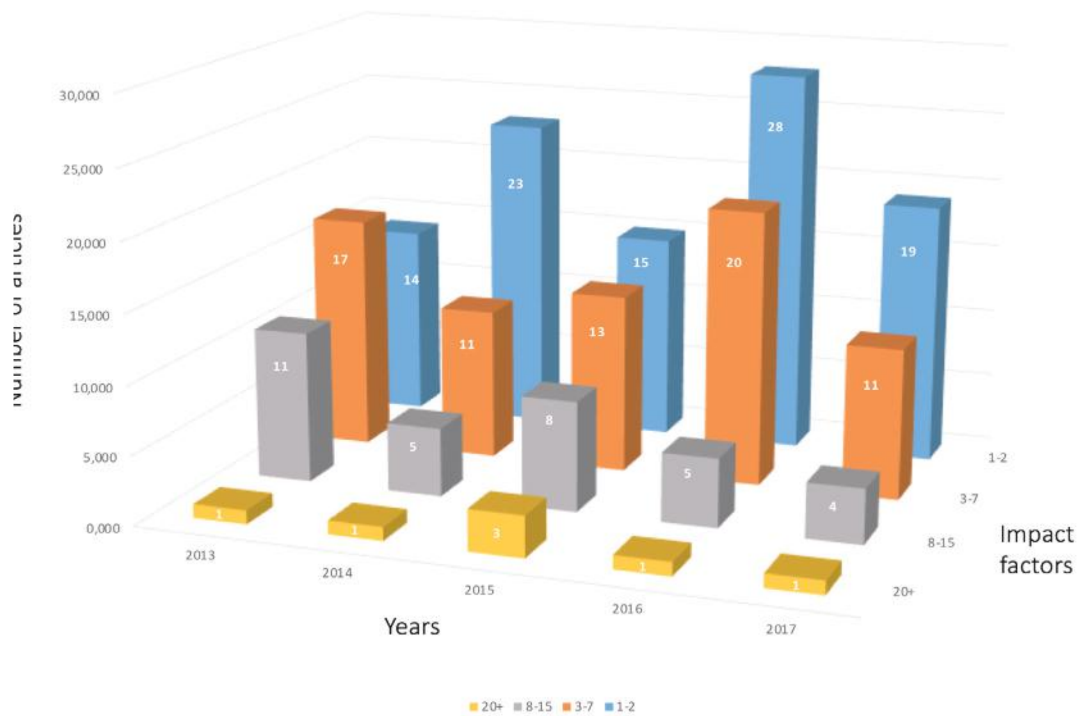
Table 1. The 6 research topics adressed by the LOA teams. Several teams join their efforts on some topics to provide the highest efficiency in research achievements.

SCIENTIFIC PRODUCTION

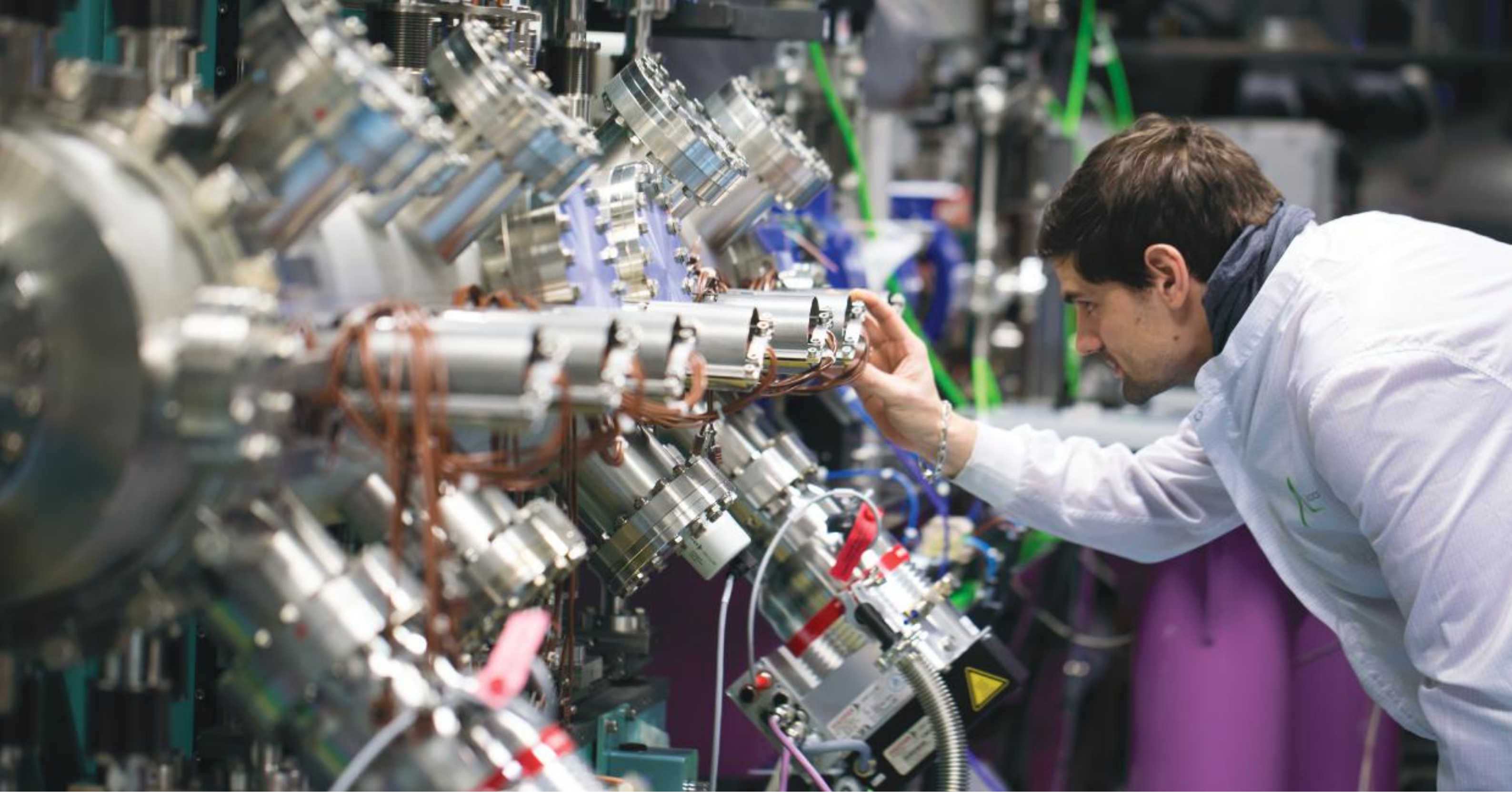
The main scientific achievements are described and highlighted in each team reports. Scientific research activity and production are presented here at the laboratory level, through the prism of bibliographic data and key parameters used to assess the laboratory recognition: impact of the publications, evolution of the number of invited conferences, national and international awards or prestigious grants.

The total number of publication (@ December 2017) since the creation of the laboratory is 1601 with a sum of time cited of 52913 according to Web Of Knowledge data analysis. Without taking into account conference proceedings, this correspond to an h-index of 111 (111 papers are cited more than 111 times) and an average citation per item of 42.

The number of publications per year has been remaining almost stable now for 15 years. This corresponds to the evolution of the research manpower at LOA that has also remained stable during this period. LOA has published 226 articles in peer-review journals in 2013-2017, which corresponds to an average of 45 articles published per year. In the top ranked journals with impact factors higher than 8, LOA teams have published 40 articles in the period 2013-2017 among which 7 are from journals with impact factors larger than 20 like Review of Modern Physics, Nature, Nature Physics, Nature Photonics. An analysis from SCImago Journal Rankings (SJR indicator) and the Scival Bibliometric data source shows that, in average and during the period of evaluation, close to 20% of LOA's articles are published in the top 1% ranked journals, 40 % within the top 5% and more than the half (60%) within the top 10%.



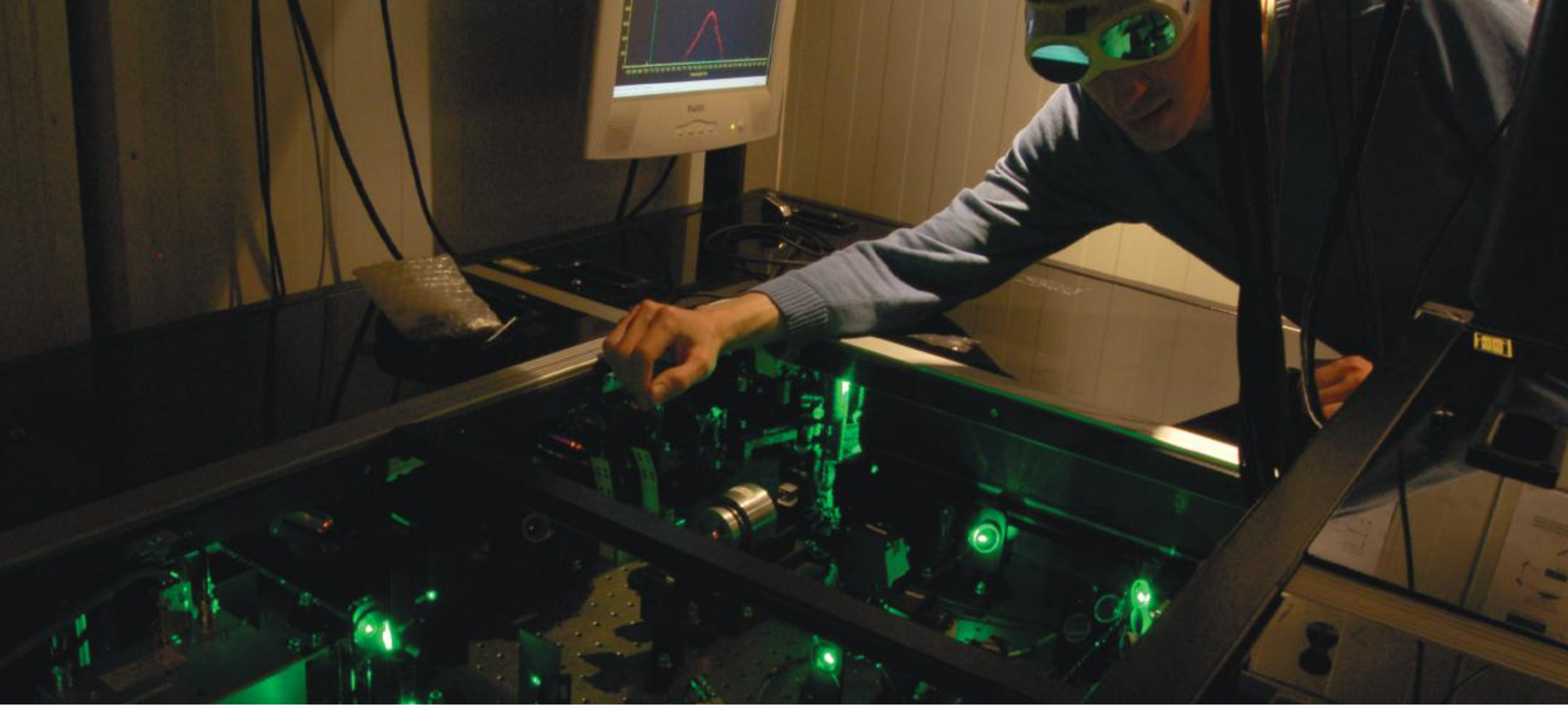
Distribution of LOA publications from 2013 (only peer-review journals without proceedings of conferences etc…) as a function of the journals impact factors(JCR 2018). "20+" includes LOA publication in RMP, Nature, Nature Physics, Nature Photonics. "8-15" includes LOA publication in Nature Communications, PRX, PRL, Light Science & Applications, Nano Letters. "3-7" includes LOA publications in Scientific reports, PRB, Optics letters, optics Express, Applied Physics Letters, New Journal of Physics, …

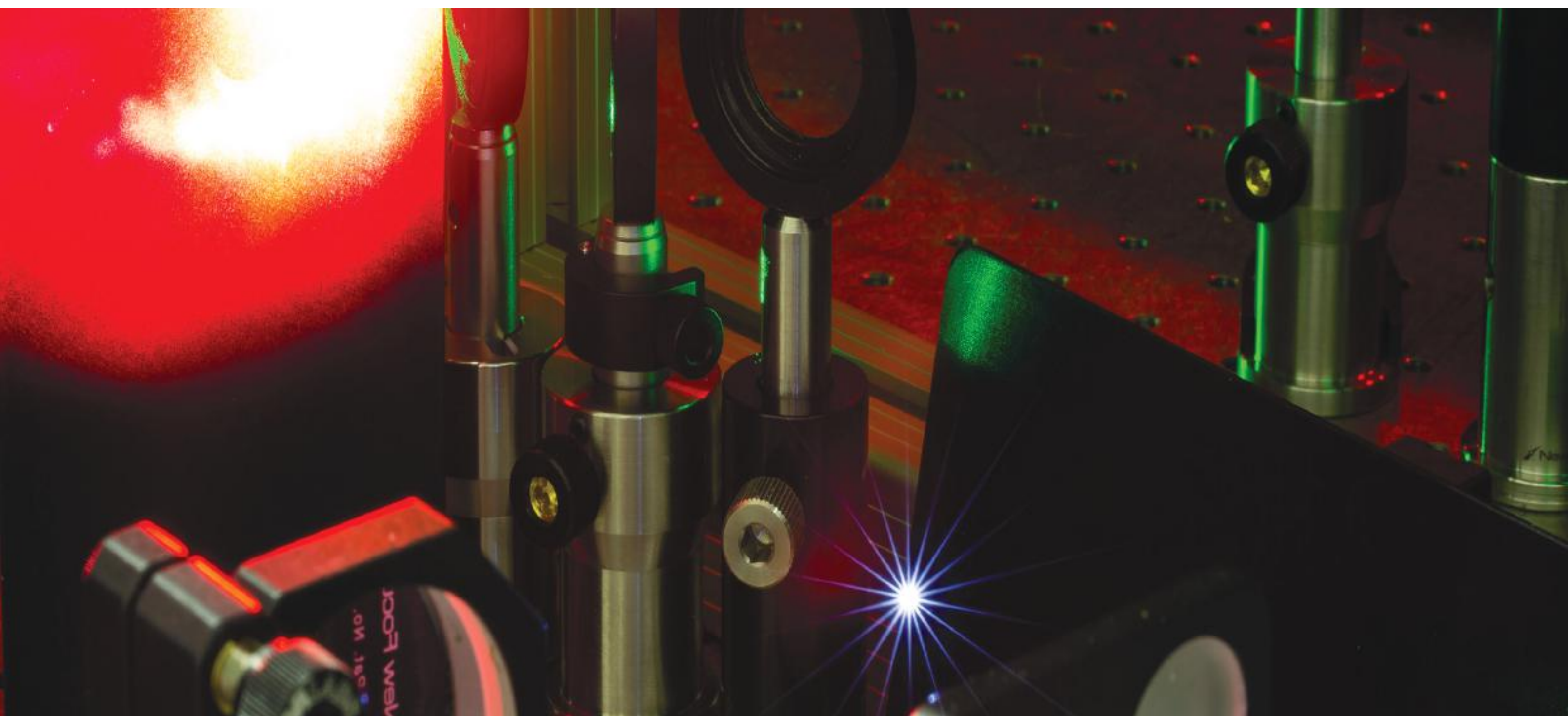


LOA has been awarded 32 prizes in the period 2013-2017. Almost 50 % of these awards are attributed to LOA students for their PhD work. 18 awards or distinctions (15 international and 3 national) have honoured 8 LOA researchers or Engineers during the period of evaluation (Officer of the Physics Division of the European Academy of Sciences, Julius Springer-Prize, European Physical Society QEOD, Fresnel Prize, Holweck prize of the Société Française de Physique and many other prizes). PhD students (24 awarded during the period of evaluation) have won 14 prizes (8 from French institution like doctoral schools or scientific funding agencies and 6 at the international level).

LOA research programs involve very high technicality of experimental instrumentations. This is developed by talented technicians and engineers in the laboratory. An LOA research engineer has been awarded in 2017 the highest recognition at the French level of CNRS institute, the Crystal Medal, for the development of innovative experimental systems in ultrafast laser-plasma and pioneering X -ray and XUV instrumentations for laser-plasma experiments. The CNRS crystal medal distinguishes engineers, technicians or administrators who, through their creativity and high level of technical expertise and innovation contribute to the advancement of knowledge and the excellence of the French research.

Laboratoire d'Optique Appliquée	**1998-2002**	**2003-2007**	**2008-2012**	**2013-2017**
publications (peer-review)	242	197	250	226
Invited conferences	77	154	207	187
Oral coonfrences	197	136	241	147
PhD Thesis	13	22	26	26
patents	-	-	10	9
prizes	1	3	20	30





SCIENTIFIC RESEARCH ACTIVITY

ILM GROUP

Created in 1994 by A. Mysyrowicz, the activity of the Laser Matter Interaction group (ILM) of LOA has been devoted to the nonlinear propagation of intense femtosecond laser pulses in transparent media (gaz, liquids and solids), and in particular to the phenomenon of laser filamentation. The group is a recognized world leader in the field of filamentation, with more than 150 publications on this subject and more than 15 000 citations. It has developed a broad expertise in the study of plasma filaments, Kerr effect, long range propagation of fs laser pulses, secondary radiation produced by filaments (conical white light emission, THz emission, acoustic wave generation, UV lasing emission from filaments in gases) and applications of the filaments such as pulse compression or control of electric discharge.

A specificity of the ILM group at LOA is the development of transportable TW femtosecond laser systems in collaboration with laser companies. The Teramobile laser from Thales was the first one in 2000, then came the ENSTAmobile from Amplitude Technologies in 2008 and the next generation is currently developed with the German company Trumpf scientific lasers in the frame of a FET OPEN project. These unique systems have allowed ILM to perform outdoor experiments (2013), test campaigns with Megavolts facilities in Toulouse (2014), and with high current SNCF facility in Vitry (2006), lightning control experiments in Singapore (2011), underwater acoustics in Marseille (2010) and supersonic flow control in ONERA Meudon (2017). The activities of the ILM group are mainly devoted to experimental physics, covering every aspects of the nonlinear propagation of ultrashort lasers from the understanding of fundamental phenomena such as the lasing effect of Nitrogen inside filaments to the demonstration of new concepts of applications based on laser filaments (remote underwater sonar, plasma antenna, aeronautic laser spike..).

Lasing effect in air and nitrogen

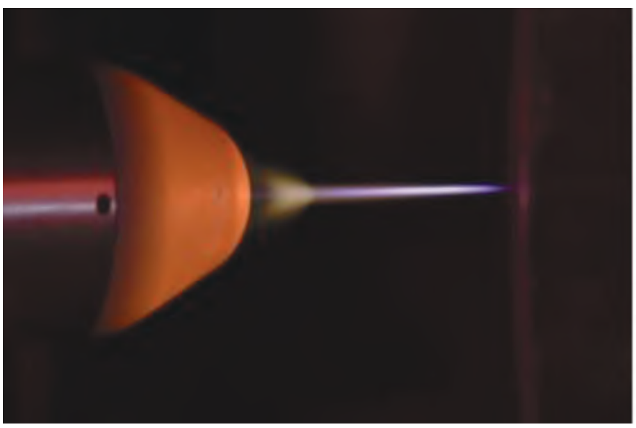
A cavity-free laser in the sky could lead to revolutionary improvements in optical remote sensing for atmospheric science. Abundant in air, nitrogen molecules are prime candidates as an active medium for such a laser. Nitrogen molecules, when pumped by an intense femtosecond laser, exhibit an important optical gain in the near UV regime. We reported intense forward emission around 391 or 428 nm with energy up to several microjoules was observed during filamentation of femtosecond laser pulses at 800 nm wavelength in atmosphere. Despite numerous works, the physical origin of this lasing is still not understood and subject to controversies. We recently proposed a consistent interpretation of all experimental facts by introducing a concept of lasing without inversion. Efforts were also made to try to obtain backward lasing emission from excited Nitrogen molecules from the filament.

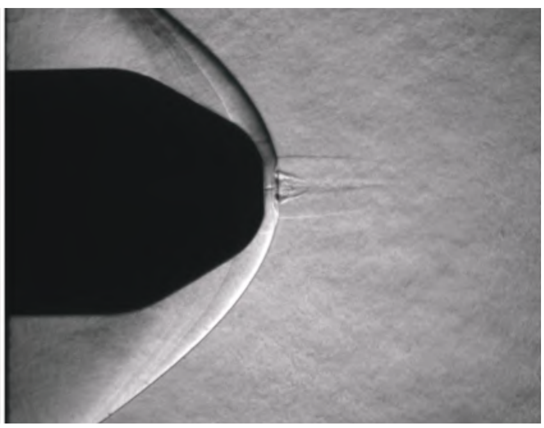
This research topic has been initiated by Yi Liu and André Mysyrowicz and is now the subject of a joint PhD between LOA and the group of Yi Liu in Shanghai. This topic has been the subject of multiple collaborations with the group of A. L'Huillier in Lund, with the PCO and SPL groups in LOA, with a group in Beijing and with Vladimir Tikhonchuk in CELIA, Eduardo Oliva in Madrid and Shihua Chen in China for the theoretical part.

The laser supersonic spike ANR and the collaboration with ONERA

When a vehicle moves in atmosphere with a supersonic velocity, a shock wave is generated, leading to a considerable increase of its drag and of its consumption of fuel. Several authors had suggested that depositing laser energy in the form of a long plasma column could decrease the drag by reducing the pressure at the nose of the object. Femtosecond filamentation appeared to be the best candidate to produce this plasma, but former estimations made in 2010 concluded that a femtosecond laser alone could not depose enough energy to produce a significant effect. However, in 2015, the results obtained during the PhD of Guillaume Point allowed us to reactivate the project with ONERA. We showed evidence of a superfilamentation regime with terawatt laser pulses, in which the intensity exceeds the clamping value of classical filaments, resulting in a very efficient energy deposition. An ANR funding has been obtained in 2016 to perform tests in the supersonic wind tunnel of ONERA Meudon with the ENSTAmobile laser, in collaboration with the company Phasics. This experiment was very successful since we demonstrated a transient reduction of the drag of a supersonic vehicle by 50 % in the presence of the filament. A manuscript detailing the results is currently in preparation for Science Advances. The next step will now consist in increasing the repetition rate of the laser to obtain a permanent effect on the drag and to test the ability of this laser spike to control the trajectory of the vehicle.

This experiment has been the occasion to establish a successful collaboration with the group of Plasma at the ONERA Palaiseau, which possess strong expertise in hydrodynamics and plasma modeling as well as plasma diagnostics, and plasma generation for aeronautic applications.





Left: Still photography of the filament produced in front of the blunt body. Right: Schlieren image showing the perturbation of the shockwave by the filament in the presence of the Mach3 airflow.

Acoustic wave generation in water

The development of laser-induced acoustic sources in water could open up new possibilities for sonar, underwater communications, high resolution imaging, tomography and fast characterization of marine environment. Since 2010, in collaboration with the Laboratoire de Mécanique et d'Acoustique in Marseille (LMA) and the DGA center for naval technologies in Toulon, we have been investigating laser-induced energy deposition and acoustic waves generation in water with ultrashort laser pulses. We have demonstrated that directive (in a plan) and broadband acoustic waves could be generated by femtosecond and picosecond filaments in water.

Numerical modelization of the phenomena by the CPHT group allowed us to show that the different acoustic shapes observed in femtosecond and picosecond regime were related to a mechanism of superfilamentation. More recently we demonstrated that the amplitude of the pressure wave generated by the plasma increases continuously with the laser pulse duration, especially in the sub-MHz frequency domain. This process is very different from the one observed by other groups in solids, where an optimum appears in the picosecond range. The results obtained received 2 PhD awards and led to a new founding from DGA in 2018 to test the source in real conditions.

We now focus on the optimization of the cavitation effect in water though optical technique, in order to increase the generated acoustic level. In parallel, laser experimentations are planned in Toulon to characterize our acoustic source in real conditions, where the plasma will be generated remotely in sea water.

Control of electric discharges and the FET-OPEN LLR project

With the help of Leonid Arantchouk, expert in high voltage electric systems, a large number of experiments have been made using femtosecond TW filamentation to control electric discharges. In 2013, we demonstrated that filament could be used to trigger high current sparks with an unprecedented low jitter (and pattent in 2013). This effect has been used in 2014 to build a multi-stage Marx generator triggered in atmospheric air by a single filament. Voltage pulses of 180 kV could be produced by this generator with a sub-nanosecond jitter.

In the frame of an important DGA contract aiming at developing a virtual plasma antenna for RF emission, a double discharge electric system including a 250 kV Tesla coil has been built at LOA. This system allowed us to increase the lifetime of the laser induced antenna by several orders of magnitude.

In parallel, in collaboration with Airbus Company who shows a strong interest in lightning protection with lasers (Patent in 2013), we demonstrated during a campaign on the campus that it is possible to trigger electric discharges between charged electrodes at distances reaching 500 m by sending a multi-terawatt laser pulse. In the center for aeronautic test of Toulouse (DGATA), we demonstrated the guiding of a 4 meter long electric discharge with filament. This result proved that the guiding effect by filament was not limited to 2 m by the short plasma lifetime, as suggested by previous work from the teramobile group. Finally, using a kHz, 200 mJ laser of Trumpf scientific, we demonstrated that the breakdown voltage could be decrease by a factor 3 using a kHz laser with respect to a 10 Hz laser.

These results motivated A. Houard and several European partners to apply for a FET OPEN grant in

2016 to develop a high-power high repetition ultrashort laser for lightning control. Started in 2017, the goal of the Laser Lightning Rod (LLR) project is to investigate and develop a new type of lightning protection based on the use of upward lightning discharges initiated through a high-repetition-rate multi-terawatt laser. The project is a collaboration between LOA, Université de Genève, EPFL, HES-SO, as well as laser company Trumpf Scientific Lasers, and aircraft manufacturer Airbus. The feasibility of the novel technique is also based on cutting-edge high-power laser technology and on the availability of the Säntis lightning measurement station in Northeastern Switzerland, located at an altitude of 2 500 meters. A low-density channel created by the 1 J, 1 kHz, 700 fs laser will operate by promoting the initiation of upward discharges to preemptively transfer cloud charges to the ground.

Y. Liu et al, Physical Review Letters 119, 203205 (2017)

G. Point et al, Scientific Reports 7, 13801 (2017)

S. Mitryukovskiy et al, Physical review Letters 114, 063003 (2015)

G. Point et al, Physical Review Letters 112, 223902 (2014)M.

Durand et al, Physical Review Letters 110, 115003 (2013)

SPL GROUP

The SPL team (Laser-Plasma accelerators) has been created in october 2001. Initially constituted by v. Malka and his phd student s. Fritzler, with the missions (i) to study the fundamental aspects of laser plasma interaction in the relativistic regime, (ii) to develop laser plasma accelerators, and (iii) to explore their pertinence for societal applications, the group has continuously attracted ms, phd, post-doc and visitors from france and from abroad (italy, usa, korea, russia, guinea, poland, sweden, germany, ukraine, bulgaria, romania, tunisia, israel, spain, portugal).

Laser-plasma acceleration of electrons

The research on laser-plasma acceleration of electrons followed two main paths, aiming at improving the beam properties, and coupling it with an undulator to generate Free-Electron-Laser (FEL) radiation, respectively.

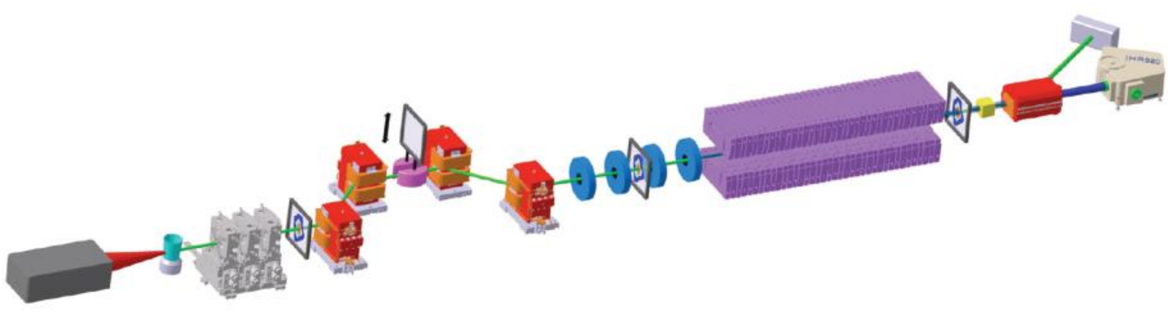
We first worked on the injection of electrons into the accelerator. This is a critical step, since most of the plasma properties of the beam are set there. We demonstrated in simulation a new injection mechanism which allows to produce electron beams combining high-charge and high beam-quality, well beyond the state of the art. On the experimental side, we studied thoroughly two injection mechanisms, density transition injection and ionization injection. We then proposed and demonstrated a new injection technique that merges the advantages of the two previous ones: a good overall beam quality and a high stability. From these experiments we also gained experience in the generation of structured sharp density profiles of the plasma. We used it to increase the electron beam energy, using the rephasing technique which consists in pushing back the electron beam to an accelerating region when it reaches a decelerating one. Our experiment was the first demonstration of this technique. It led to a 60% increase of the beam energy. Finally, we introduced the principle of the laser-plasma lens and showed that this device can be used to reduce the electron beam divergence by a factor of almost three. This last result is of particular importance for applications requiring beam transport. The divergence reduction should actually be sufficient to avoid transverse emittance growth in quadrupoles triplet (the emittance growth is due to the combination of large divergence and energy spread). Less than 3% energy spread are typically achieved. This last study was mainly driven by a groundbreaking application: the development of a FEL based on a laser-plasma accelerator. Such an achievement will allow to drastically downsize these facilities, and hence to open their access to a wider community. Since 2015, most of the electron acceleration beam time has been devoted to this application. The transport and the shaping of the electron beam was demonstrated in 2017. We then succeed in producing high quality synchrotron radiation. The generation of FEL radiation is expected in early 2019.

The main perspectives on electron acceleration experiments is also driven by the advent of the Apollon multi-PW facility in 2019. For unlocking the full potential of this facility, we are developing in Salle Jaune an all-optical plasma waveguide. It will be used to guide the laser beam over several centimeters which is mandatory to get multi-GeV electron beam energies. We will also develop new injection techniques which are compatible with wave-guiding and PW system. The implementation of these devices on the Apollon facility will open the way to well-controlled QED experiments, such as the creation of pair through photon-gamma or gamma-gamma collisions, which is a major challenge for the laser-plasma community and beyond.

Particle driven plasma wake acceleration

In a way analogous to laser-plasma accelerators (also called Laser WakeField Accelerators, LWFA), waves of electron density in the plasma can also be driven by the passage of a relativistic beam of charged particles, the "driver". For very dense electron beam drivers, the plasma wave takes the form of an ion cavity (see figure), in the so-called blow-out or bubble regime. This ion cavity has ideal properties to accelerate the main electron beam, the "trailing" electron bunch.

The UPX group is exploring the physics of particle-beam-driven Plasma WakeField Acceleration



Experimental setup for laser-plasma FEL operation: laser hutch (grey), gas jet (cyan), permanent magnet based quadrupoles (QUAPEVAs) (light grey), electro-magnet dipoles (red) with an adjustable slit placed at the center (pink), electro-magnet quadrupoles (blue), undulator (purple), dipole dump(red), UV spectrometer (light grey)

(PWFA) by following several research avenues:

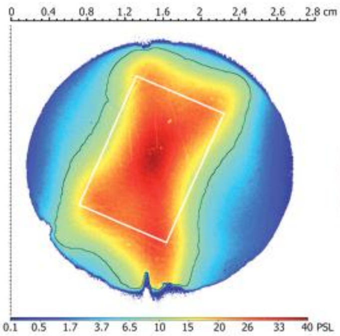
– Based on experiments conducted on the state-of-the-art conventional accelerator facilities FACET and FACET-II, the group aims at understanding the physics of beam-plasma interaction and at the experimental realization of a plasma accelerator module that would be capable of accelerating a distinct bunch of particles, with high energy gain, low energy spread, high energy efficiency, and preserved emittance. Among the many recent achievements, one can cite the 9 GeV acceleration of electron beam in a PWFA, the demonstration of high-field acceleration and electron-beam self-focusing, the multi-GeV acceleration of positrons in a self-loaded PWFA and first acceleration of a distinct bunch of positrons in a plasma, and the first measurements of transverse wakefields in hollow plasma channels. This research is conducted as part of the international E-200 collaboration, including in particular SLAC and UCLA in the US.

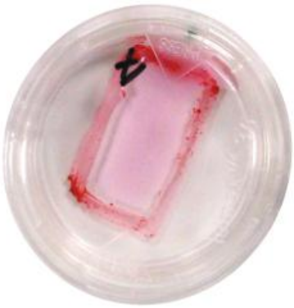
– Using a Laser WakeField Accelerator (LWFA), one can actually produce electron beams whose properties reach the very demanding requirements to drive a PWFA. Such hybrid wakefield accelerators, where a LWFA electron beam drives a PWFA section, open the opportunity to study PWFA physics using in-house compact laser facilities and to leverage the advantages of PWFA, for example for the generation of ultra-bright particle beams. Recent achievements include the observation of plasma lensing and acceleration from the PWFA section, as well as the imaging of the PWFA plasma wave. This research on hybrid LWFA-PWFA is conducted in collaboration with HZDR and LMU in Germany.

In addition to these experimental activities, the group is also contributing in the theoretical and advanced numerical modeling of beam-plasma interaction. This activity includes the topic of hybrid LWFA-PWFA, the acceleration of positrons in plasmas as well as electromagnetic plasma instabilities developing during the interaction between laser, particle beam and plasma. Recently, a new concept that leverages hybrid LWFA-PWFA for the generation of ultra-bright betatron gamma-ray radiation was demonstrated numerically. This work is conducted in collaboration with CEA in France.

Laser-plasma ion acceleration and application

Most of the activities during the past five years have been around the Salle SAPHIR infrastructure, whose laser became fully available within specs by





SAPHIR beam transport setup of the laser-produced plasma proton beam for radiobiology at high dose.

the end of 2013.

In a first phase (2013-2015) all the efforts have been concentrated on the construction of a stable and fully characterized proton source, of sufficient quality for the application on radiation biology studies. This evolution succeeded thanks to the debugging of the laser source (mainly contrast improvement, which also demanded a precise tuning of the otherwise industrial laser source), extensive experimental campaigns for the definition of the best interaction conditions and the engineering of ad-hoc solutions for automatic production of proton bunches at high repetition rate (1 Hz). This phase also coincided the natural end of the SAPHIR project; the continuation of activities have been possible thanks to the ongoing definition of collaboration framework between the LOA and the owner of the laser system (AT).

The definition of irradiation conditions suitable for radiation biology promoted the collaboration between our group and actors from medical physics (CPO/Orsay), oncology (GR/Villejuif) and accelerator physics (LNS-INFN/Catane). These activities (2015-2016) enabled the production of a stable, characterized semi-automatic proton beam with an energy of 6 MeV. A magnetic transport line was built and configured for particle transport and energy selection in the beam. The online dosimetry protocol, validated in collaboration with the CPO, indicated a dose of 0.7 Gy per shot over a surface of 2 cm^2 and a peak dose rate (extrapolated) exceeding 10^9 Gy/s.

During a third phase (2016-2018) the SAPHIR proton beam has been extensively used for radiation biology experiments. These included survival assays and fluorescence imaging of DNA strand breakes for different cell types (HCT116 p53 and WT, U87). The resulting data enabled us to determine the relative biological efficiency of laser accelerated protons, which deliver the dose in separated bunches at extremely high dose rate, against proton beams from a medical synchro-cyclotron (CPO) and Xrays from conventional medical sources (GR).

In parallel with the experimental activities, we have been developing the design of a dedicated facility for application of laser-produced particle beam on radiation chemistry and radiation biology, in order to gain insight on the phenomena which rule the radiation toxicity at ultra-high dose rate.

HHG source developments (High Harmonics Generation) for FEL seeding activities

HHG source developments (High Harmonics Generation) for FEL seeding activities has shown great progress. A new HHG source based on the mix of two colors (fundamental laser wavelength and his second harmonic) with two linear and crossed polarizations was developed. Collaboration with Lomonossov Institute of Moscou successfully explain the main features of this new sources. The wavefront and the spatial profiles qualities were improved. The degree of polarization, the polarization axis, and the degree of ellipticity, were measured, in two different spectral ranges VUV (260 nm to 100 nm) with low harmonics orders, and in XUV (60 nm to 20 nm) with high order harmonics. The first range has been chosen to perform experiments in order to demonstrate the amplification of coherent light in a plasma-based free-electron lasers, with the collaboration of the synchrotron Soleil.

The second one was dedicated to demagnetization studies of metallic layers, rare earth and transition metals, with a strong collaboration with Paris 6 university LCPMR laboratory. Pioneer work on demagnetization through different techniques such as magnetic diffusion and circular dichroism were achieved with recently the measurement of the time evolution of magnetization state in the sub 30 fs time scale using the Faraday effect. Furthermore, an XUV polarizer/analyzer system for XUV to measure the polarization properties of the FERMi at Elletra Free electron laser in Italy has been realized. Another variation of the system was used to measure the polarization properties of a plasma-based X-ray laser at 32 nm, collaboration with the FLEX group from LOA.

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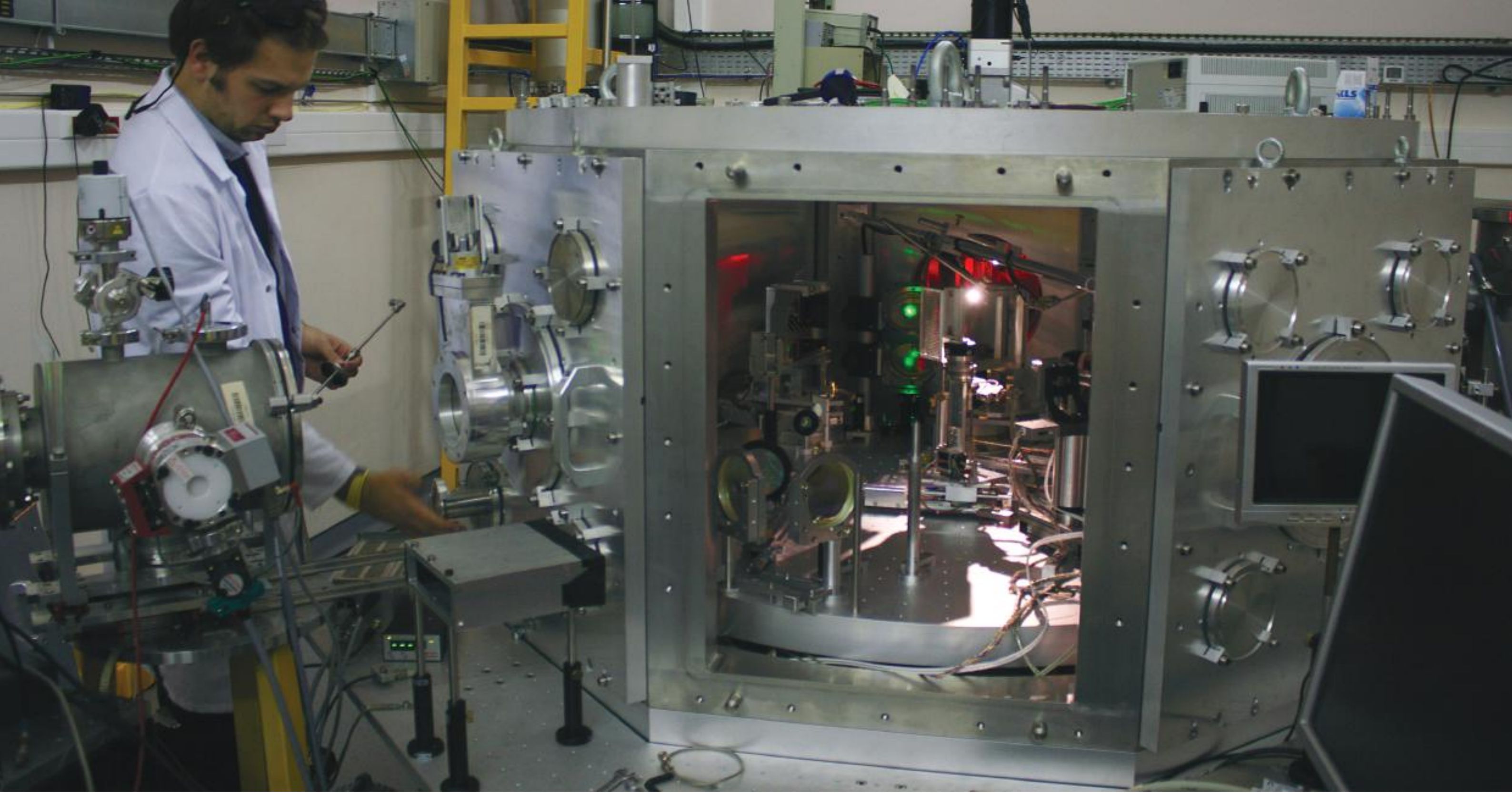
FLEX GROUP

The development of ultrafast x-ray sources from intense femtosecond lasers is a long-standing activity at LOA that has started more than 20 years ago. The activity of the FLEX group has been devoted to the nonlinear interaction of intense femtosecond laser pulses with plasmas generated from solid or gas targets, and in particular to the study and the application of femtosecond and intense radiation sources in a broad X-ray spectral range. The group is a recognized world leader in the field of ultrafast x-ray sources with many pioneering results obtained all along the years. With more than 230 publications in peer review journals on this subject and about 6 000 citations, it has developed a broad expertise in the study of High harmonic generation (HHG) sources, X-UV lasers, atomic X-ray line radiation, X-rays from laser-plasma accelerated electrons as well as the development of metrology tools and optics related to EUV and X radiation. The team has also been very involved in demonstrating the potential of these X-ray sources for application such as high-resolution imaging in time and space of the matter.

The activities of the FLEX group are mainly devoted to experimental physics, covering every aspects of the generation of ultrafast X-ray sources from the understanding of fundamental phenomena to the demonstration of new concepts of x-ray sources based on laser-produced plasmas. The main experimental infrastructures used for that purpose are located at LOA (Salle Jaune and Salle Corail/Argent) with several collaborations and experimental runs at international laboratories like KAERI in South Korea, CUOS in USA or Rutherford in England.

Relativistic X-ray Sources

The research on Femtosecond x-ray radiation sources based on laser plasma accelerators has shown considerable progresses during the past 5 years. We essentially worked on the Betatron source. Since its discovery in 2004 at LOA, the source has been widely



developed and characterized. The flux and energy of the source were improved using multi 100 TW class laser. However, the efficiency of the mechanism was never improved and, even more importantly, the source remained unstable and unreliable for applications like time-resolved studies. In the past few years, we demonstrated methods that considerably improve the stability and the efficiency of a Betatron radiation source. In addition, we performed the first femtosecond x-ray absorption experiment using Betatron radiation. In this highly competitive field of research we studied the femtosecond structural dynamic of a copper sample brought in the Warm Dense Matter regime. Recent achievements are described below.

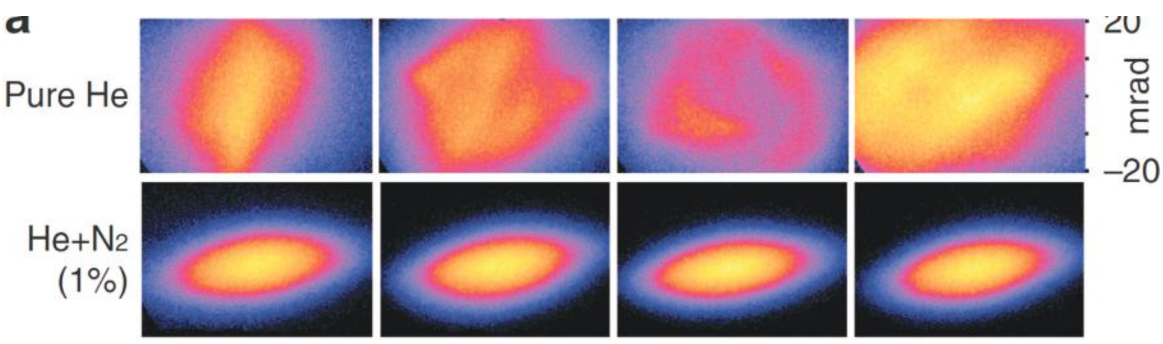
- Improvement of the stability of the Betatron source: all the features of the Betatron radiation depend on the electrons orbits. Using ionization-induced injection in a gas mixture, the orbits of the relativistic electrons emitting the radiation become reproducible and controlled. As a result we observed that both the signal and beam profile fluctuations are significantly reduced and that the beam pointing varies by less than a tenth of the beam divergence. In addition, the radiation becomes polarized. The polarization ratio reaches 80%, and its axis follows the laser polarization. The Figure below represents example of consecutive x-ray beam profiles obtained with transverse (as used so far) and ionization injection.

- Improvement of the efficiency of the Betatron source: the key for the improvement of Betatron source efficiency also relies in the control of the electron orbits. It increases if the energy of the electron is increased and if the oscillation period is decreased. However, in a laser plasma accelerator, these parameters are linked so that the electron energy increases together with the oscillation period. We explored several methods to dissociate acceleration and wiggling. We demonstrated that decoupling is possible when two gas jets are used. In the first jet, the gas density is optimized to produce energetic electrons. In the second jet, the density is much higher to produce radiation. This method allows to increase the flux by a factor up to 3. In 2018, we demonstrated that an upward density ramp is much more efficient. The Betatron radiation signal above 2 keV was increased by a factor up to 20. Theses novel results are being analyzed. We anticipate a broad impact of the source, as its remarkable performance opens the way for new applications.

- Femtosecond x-ray absorption spectroscopy: In 2017 we gathered a team of scientists with complementary expertise from LOA, CEA and CELIA and we successfully performed the first femtosecond XANES (X-ray Absorption Near-Edge Spectroscopy) experiment. We measured the femtosecond dynamic of the Copper L-edge brought to Warm Dense Matter (WDM) conditions. A clear spectral feature (pre-edge) was observed as a result of the ultrafast electron temperature increase. The temporal resolution was evaluated to 75 ± 25 fs, mainly limited by the geometry of such proof-of-principle experiment. This first experiment demonstrates the great potential of the Betatron source and open unprecedented possibilities for femtosecond X-ray absorption. Our project aims at developing this novel class of experiments.

Soft X-ray Laser beams

Overall, this scientific activity has been productive and has gone a long way on the path that began 15 years ago. At that time, a great deal of confusion was lying over the performances and possibilities offered by laser-driven SXRL: although it was a laser, the SXRL lasers at that time were not spatially coherent and therefore not efficiently focusable and usable in imaging, one of the more important application. The injection of high order harmonics, a fully coherent source, and its amplification made it possible to overcome this limit. It nevertheless took many years at the international level to be accepted as a must to operate plasma based XUV lasers. The work carried out in the FLEX team allowed to show the unique capabilities of this mechanism: production of pulses of 100 fs (against a few ps before), full coherence having an excellent wavefront and polarization tuning



Betatron X-ray profiles for different gas compositions. (a) Angular profile of the X-ray beam for four consecutive shots in pure helium and in the gas mixture (He+1% N2). The color scale is the same for all images.

(linear and circular). A final step would have been to transpose the so-called CPA technique into XUV rays as we proposed in 2012 but already excellent performances were predicted using only two amplifying plasmas. It should be noted that the technique of XUV-CPA was successfully used in a free electron laser experiment (FERMI @ ELETTRA) to which we collaborated.

Here are highlights of our latest developments.

- Efficient guiding of ultra-intense laser pulses into high density plasmas

We have successfully implemented a waveguide by focusing with an axicon lens a sequence of "ignitor" (130 mJ, 30 fs) and "heater" pulses (690 mJ, 600 ps) delayed by 600 ps. The electron density has been measured retrieving the phase change imparted by the plasma with a Mach-Zehnder interferometer. At the highest reported density, appropriate conditions for guiding in terms of size and transverse density gradient were granted for the pump pulse focused about 1.55 ns after the arrival of the "ignitor". When injecting a 5×10^{18} W.cm^{-2} laser pulse into the waveguide, the electronic density growth up to more than 10^{20} cm^{-3}. The transmitted beam is multimode and contains about 50% of the initial energy after 5 mm of propagation and decrease down to 20% after 20 mm when krypton is used. In parallel to the experimental measurements, intensive numerical calculations using hydrodynamic and particle-in-cell codes has been performed to understand and predict the creation and posterior evolution of the waveguide.

- Toward ultrashort laser driven soft x-ray lasing by collisional gain gating

We investigated the influence of electron density on the temporal properties of the 32.8 nm lasing emission. By seeding the SXRL amplifier using the 25th harmonic of the infrared driving laser we measured the temporal gain dynamic. As expected by our numerical simulations, the gain duration monotonically decreased from 7 ps to an unprecedented shortness of 450 fs FWHM as the amplification peak rose from 150 to 1200 with an increase of the plasma density from 3×10^{18} cm^{-3} up to 1.2×10^{20} cm^{-3}. From our Maxwell–Bloch modelling, the inferred SXRL pulse duration varies from about 6.4 ± 0.3 ps for $n_e = 3\times 10^{18}$ cm^{-3} down to about 120 fs for $n_e = 1.2 \times 10^{20}$ cm^{-3}, which thus breaks the decade-long picosecond barrier of plasma-based SXRL.

- Circularly Polarized Plasma-Based Soft-X-Ray Laser

In the soft x-ray range, the availability of coherent circularly polarized light has been limited so far to few large-scale facilities and more recently to high-order harmonic generation. For generating circularly polarized SXRL beams, we have converted the HHG seed polarization from linear to circular using a grazing incidence four-reflector phase shifter and a $\lambda/2$ wave plate. The polarized seed is then injected and amplified into the plasma amplifier. Using this technique, we were able to demonstrate that we are able to control the polarization of o the seeded SXRL (from linear to circular) and compensate the losses introduced by the phase shifter (1% transmission) after amplification.

- Modeling of the amplification of a high-order harmonic seed by a soft x-ray laser plasma

In collaboration with G. Maynard (LPGP-Orsay) and E. Oliva from University Politechnica de Madrid, we have performed intensive modeling of amplification of a high-order harmonic seed by a soft x-ray laser plasma. The time-dependent evolution of the x-ray signal is determined from a fully dynamic Maxwell-Bloch calculation. At high seed intensities, a simplified one-dimensional calculation leads to strong Rabi temporal oscillations of the output signal. This set of code have being recently modified to performed full 3D calculations of the amplification process. It has been used to demonstrate the concept of X-ray chirped Pulse Amplification, (that was successfully tested on FERMI free-electron laser)

X-ray Metrology and medical application of X-rays

The team worked on high-performance XUV optics: active Bender type Kirkpatrick-Baez with Imagine Optic (design and testing) and Schwarzschild (wavelength tests). Studies are still under way. These are very complex experiences in setting up. This allowed us to progress on the XUV metrology and for example to create a new wavefront sensor adapted to its high performance XUV optics. This sensor is now marketed by Imagine Optic.

We have also worked on temporal metrology and proposed a new technique only adapted to measure the amplitude and phase of an XUV laser. Finally, we are working on the X-ray transposition of the so-called plenoptic technique, which is an evolution of wavefront measurements to recreate 3-dimensional images from a single image (against thousands in tomography). This work has not been completed yet. However, we have worked a lot on X-ray tomography for the detection of nanoparticles in tumors and have advanced this theme.

Our research program on low dose X-ray imaging and high atomic number nanoparticles (NPs) to be used in innovative cancer therapies has been launched during this period of evaluation. We've been able to obtain phase-contrast tomography images at 3 µm spatial resolution of transgenic mice organs injected with gadolinium and gold-NPs have been acquired at European Synchrotron Radiation Facility (ESRF) the last 2 years. Both gold and gadolinium-based compounds are good X-ray contrast agents, due to their high X-ray attenuation coefficient with respect to tissues and are considered as promising theranostic agents. Image processing helps to emphasize several anatomical details. However, tomography requires more than 4000 projections for a good 3D rendering at the cost of an important absorbed dose. A multi-angle view technique using a microlens array in front of the x-ray detector is in development before testing to provide quasi-3D reconstruction of the scene from a single exposure.

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PCO GROUP

The PCO group was created in 2005. The original idea was to develop new areas of research, which were not present at LOA at the time: (i) the production of high-temporal contrast, high peak power few-optical-cycle pulses, (ii) the use of these pulses to drive relativistic-intensity laser-plasma interactions at high repetition rate (kHz) and (iii) the production of ultrafast secondary radiation from such interactions, such as high-brightness attosecond pulses and femtosecond electron bunches for applications. This was particularly relevant for bringing LOA back up to speed at the international level in the field of few-cycle laser development and attosecond science, which was taking off in many laboratories around the world at the time. The main impetus to this effort was given by the Chaire d'Excellence grant of Gérard Mourou, director of the LOA at the time (2005-2008).

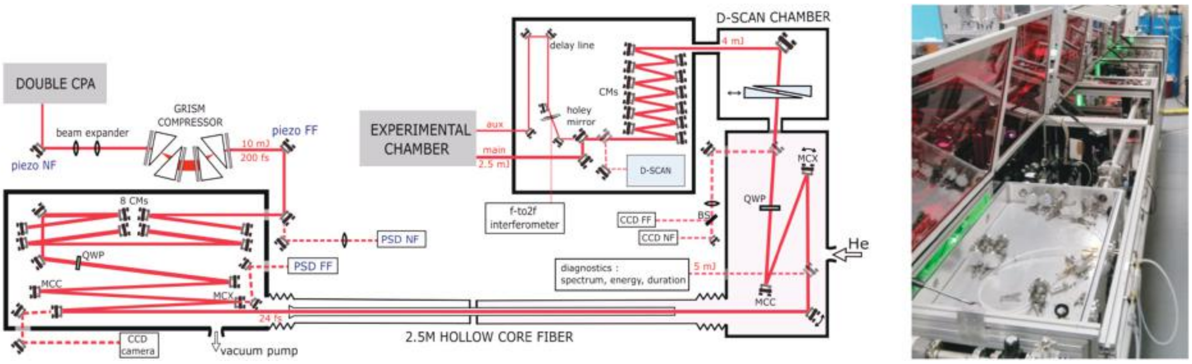
Today, the group has an internationally recognized activity on few-cycle laser development and relativistic plasma mirror interactions. Compared to other groups in the world, the specificity of PCO is that we drive attosecond pulse generation from relativistic plasma mirrors using tightly focused few-cycle pulses at high-repetition rate (kHz) with low energy (<10 mJ). Therefore, we are trying to scale attosecond pulse generation from plasma mirrors using compact kHz laser systems, better suited to applications downstream. The goal is to develop a source of intense attosecond pulses. Both aspects are important because they enable novel applications in attosecond science since high energy per pulse is a pre-requisite for performing real attosecond pump – attosecond probe experiments. The success of such experiments relies almost exclusively on the spatiotemporal fidelity of the driving laser pulses: few-cycle duration, high temporal contrast and high focusability. In this demanding context, the group also develops novel techniques to efficiently post-compress high-energy femtosecond pulses down to the near single-cycle regime with high spatiotemporal fidelity and to in order to deliver them with maximum intensity on target.

Relativistic-intensity few-cycle light source

The SN2 laser system started operating with its current parameters (1TW, 1.5 cycle, 1kHz) in 2016. These unique parameters enabled APPLI and PCO to access the relativistic regime at kHz repetition rate, exemplified by the demonstration of relativistic electron acceleration. This leap forward in capability was rendered possible by integrating stretched hollow fiber technology for compressing our laser pulses down to the few-cycle regime at high energy

Power scaling of hollow-fiber compressors had been a huge barrier worldwide for many years until then. Stretching the fiber enables arbitrary scaling of fiber length and diameter with low transmission losses due to fiber bending. After an exclusive 3-year collaboration with the inventors of this technology (Tamas Nagy & Peter Simon from Laser Laboratorium Göttingen eV), we managed to produce TW peak power near single-cycle pulses: 3.5mJ, 3.5fs at 1kHz. Stretched fiber technology also enables the compressed pulse duration on target to be continuously tuned without energy loss and therefore to follow the transition into the relativistic few-cycle regime during the laser-plasma interaction. With the shortest pulses from the fiber (1.5 cycle at 750nm central wavelength), we can reach focused intensities on target in excess of 10^{19} W/cm^2 at 1kHz.

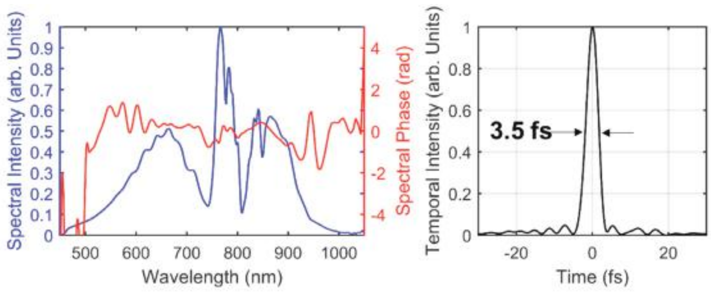
Another key feature of the few-cycle pulses delivered by SN2 is their high temporal contrast (> 10^{10} up to a few ps before the pulse peak), directly inher-



Schematic and picture of the stretched hollow-fiber compressor. The spectrally broadened pulses out of the 2.5m-long, 536μm-diameter stretched fiber are temporally compressed using broadband chirped mirrors before being sent to the plasma mirror chamber. Pulse duration is measured in-line under vacuum using the dispersion-scan technique. The fiber assembly, spatiotemporal pulse shaping optics and diagnostics are directly integrated into the vacuum beamline.

ited from the double-CPA architecture of the Ti:Sa amplifier. This high level of contrast is achieved thanks to an energy-scalable XPW-based nonlinear contrast cleaning device developed in collaboration with the Patrick Georges team at IOGS. Because of its efficiency and reliability, this technology was also integrated into the high-contrast laser front-end of the APOLLON 10PW system under construction on the Plateau de Saclay.

Until recently, we had serious issues with CEP stability (> 500mrad RMS) due primarily to laser energy instability, which meant that most few-cycle plasma mirror results obtained during this last period were performed without CEP stabilization altogether. These issues have now been solved and we can routinely achieve record-high CEP stability (sub-200 mrad RMS) thanks to the reduction of energy fluctuations out of the double-CPA seed laser to below % level and direct integration of the hollow-fiber compressor into our vacuum-integrated beamline.



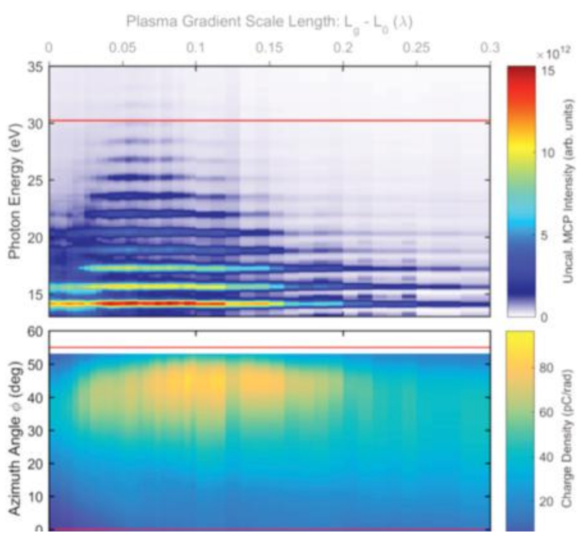
Duration (fs)	24	10	7.5	5	3.5
Intensity (10^{19} W/cm²)	0.24	0.58	0.77	1.15	1.64
Vector Potential a_0	1.1	1.6	1.9	2.3	2.8

Spectrum and spectral phase and temporal intensity profile of the TW peak power 1.5-cycle pulses produced from the hollow-fiber compressor (top); Compressed pulse duration and peak intensity of the pulses delivered on the plasma mirror target.

Relativistic plasma mirrors

The upgrade of SN2 laser parameters in 2016 were a real game changer for our plasma mirror experiments. The combination of high pulse energy (3mJ on target) near single-cycle duration (1.5-cycle) and tight focusing (spot size < 2μm FWHM) made it possible to achieve on-target intensities well into the relativistic regime ($a_0 > 2$), which opens the door to the exploration of plasma mirror interactions with spatiotemporal intensity gradients almost limited by the laser wavelength itself. We knew that conducting plasma mirror experiments under such extreme conditions would not be feasible without accurate control over the interaction parameters such as pulse duration, spatial beam profile, plasma density gradient and CEP. For this we equipped our vacuum beamline with the maximum number of online diagnostics. Accurate knowledge of the electron density gradient at the surface of the target is the key factor of success in plasma mirror experiments. This meant using a weaker time-delayed pre-pulse to trigger plasma expansion before the arrival of the main high-intensity pulse. We developed a method for direct inline monitoring of both near-field and far-field beam profiles, which ensured highly reproducible interaction conditions from shot to shot. We also introduced a new spatial interferometry technique, called SDI (spatial domain interferometer), which enables us to measure the plasma expansion velocity directly on target as a function of pump-probe delay. This method yields plasma gradient values that are in excellent agreement with those retrieved by conventional FDI (Fourier Domain Interferometry), which is far more difficult to implement. Due to its simplicity and reliability, this in-situ measurement technique has now spread to other labs working on plasma mirrors, such as CEA Saclay.

Our high degree of control over the interaction parameters enabled us to perform plasma mirror experiments under hitherto unexplored conditions. Our ability to simultaneously detect photon and electron emission from the plasma mirror enabled us to unequivocally demonstrate the correlated emission of harmonics and electrons at optimal gradient lengths around ~ λ/10 (where λ is the central laser wavelength), as predicted by the relativistic oscillating mirror model but never observed before experimentally.



Simultaneous detection of HHG and electrons as a function of the plasma density gradient for 9 fs driving laser pulses. The on target peak intensity is estimated at ~ 6.5 x 10^{18} W/cm^2 (a_0= 1.8). The top graph shows the typical harmonic emission spectrum. The red line corresponds to the plasma cut-off emission frequency of the fused silica target material. The bottom graph shows the spatially vertically integrated electron charge flux emitted between target normal (bottom red line) and target specular direction (top red line).

The results obtained for in the near single-cycle regime (3.5fs) were rather unexpected and extremely exciting results in the context of early predictions made about highly efficient attosecond pulse generation from relativistic oscillating plasma mirrors. Despite the absence of CEP stabilization, time-stamped monitoring of the laser CEP drift and harmonic emission gave us a first glimpse at potentially beneficial CEP effects in generation process. Indeed, single-shot harmonic spectra clearly show the production of quasi-continuum-like spectra, corresponding to the emission of a single, isolated attosecond pulse for specific values of the CEP. 2D PIC simulations clearly show that for there exists a range of optimal CEP values, for which the relativistic oscillating plasma surface can temporally compress the most intense the cycle of the driving laser field and produce a TW peak power few-100as pulse containing up to 30% of the driving laser energy.

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APPLI GROUP

The APPLI group was created in 2013. The original idea was to put together two distinct scientific themes that are present at LOA: (i) the field of high-intensity laser plasma interaction and the associated know-how in the production and emission of secondary sources with femtosecond durations, (ii) the field of ultrafast dynamics in condensed matter and the associated know-how in time-resolved spectroscopies via pump-probe experiments. This is particularly relevant for triggering new synergies in the laboratory and to fully exploit the laser systems, the scientific expertise and experience that exist at LOA.

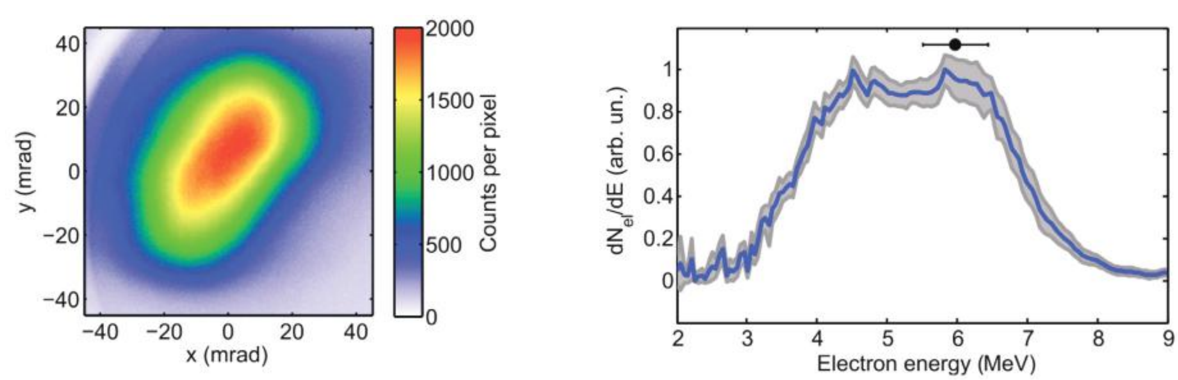
The group has an activity on laser-plasma interaction, both theoretical and experimental. Here, compared to other groups at LOA, the specificity is that we use ultrafast lasers at high-repetition rate with low energy (<10 mJ). Therefore, we are trying to scale high-intensity laser-plasma interaction using low energy, compact and kHz laser systems, better suited to applications. The goal is to develop a laser-plasma accelerator producing an electron source with unique properties: femtosecond duration, relativistic energy and high-repetition rate. The high-repetition rate it important because it enables applications in ultrafast dynamics. Indeed, data accumulation and statistics are a pre-requisite in pump-probe experiments. In this context, the group also explores the application of laser-plasma based electron sources to ultrafast electron diffraction.

In parallel, the group studies the ultrafast dynamics of various materials using more conventional and well-established techniques. We perform pump-probe experiments. In this context, the group also explores the application of laser-plasma based electron sources to ultrafast electron diffraction.

In parallel, the group studies the ultrafast dynamics of various materials using more conventional and well-established techniques. We perform pump-probe experiments using ultrafast lasers with adjustable wavelengths. These experiments monitor the ultrafast response of the optical properties of the sample under study, such as the reflectivity or the absorption. We have also developed an ultrafast electron diffractometer in order to obtain direct structural information. These techniques give valuable information on the sample, either at the electronic level or at the structural level. We are interested in a variety of problems including the dynamics of phase transitions in materials with strong electron correlation, or electron-phonon coupling in confined systems.

Electron acceleration from solid targets: theory and simulations

In close collaboration with the PCO group at LOA and the CEA group (F. Quéré), we have proposed to measure the electron beams produced when an ultra-intense laser pulse interacts with a solid density plasma with a controlled density gradient on its front surface. Our goal is to understand the physics of electron generation at the front surface in details and evaluate whether this is an interesting candidate for an electron source. We have mostly concentrated on proposing interpretations to the experimental results using theory and simulations. We have been able to identify a push-pull mechanism responsible for ejecting the electron out of the plasma. We also discovered that electrons can be further accelerated in the laser field in a process known as Vacuum Laser Acceleration . Experiments using the Salle Noire laser at kHz have shown acceleration of large amounts of charge (10-50 pC per shot) but at non relativistic energies and the accelerated beams have very large divergence angles. At the moment, using such beams for applications is not very realistic. Therefore, more recently, we have been proposing new ideas to improve the quality of the electron beams that can be generated in this manner: for example, the use of a radially polarized laser pulse can increase the efficiency of the acceleration process while producing electron beams with



kHz relativistic electron beams. Left: typical beam profile of the electron beam obtained in the interaction of a 3.5-fs laser pulse with an underdense microscale gas jet. Right: the energy distribution shows 5 MeV electron beams. The gray area represents the standard deviation of the electron distribution showing high stability. The injected charge range from 100 fC to 20 pC per shot, depending on the experimental parameters.

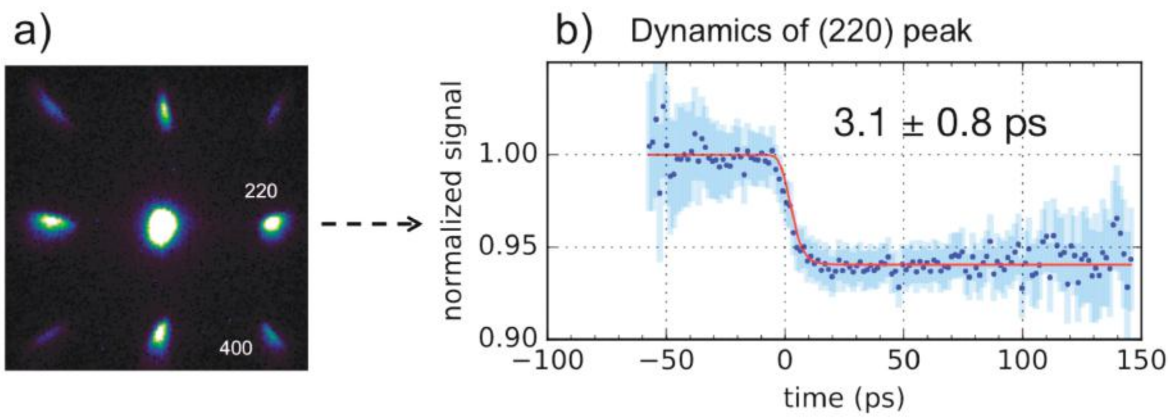
narrower divergences.

Laser-plasma accelerator at kHz and applications

Laser-plasma accelerators have the capability of producing few femtosecond electron bunches, with, in principle, perfect synchronization with the laser pulse. Therefore, such electron bunches can become very valuable tools for femtosecond probing via electron diffraction if they operate at high-repetition rate with sufficient stability and beam quality. In principle, we have shown that they have the potential to provide sub-10 fs bunches on a sample, with the beam quality required for performing electron diffraction.

In the framework of the FEMTOELEC ERC project, we have demonstrated the first laser-plasma accelerator operating at kHz, at the 100 keV level (2013-2015). In 2016, the Salle Noire laser reached new performances: the laser duration was decreased to the few cycle level, down to 3.5 fs, while keeping the energy at 3 mJ. This was a game changer for our laser-plasma accelerator as sub-5 fs pulses are needed to resonantly drive the plasma wakefields that accelerate the electrons. We were able to demonstrate a laser-plasma accelerator operating at kHz and delivering 5 MeV electron beams. Since 2016, we have been studying and optimizing the electron acceleration process in the regime of few cycle laser pulses.

Operation at kHz and increased stability of the electron beam allowed us to perform the first electron diffraction experiment using a plasma based electron source. In collaboration with the University of Michigan, we were able to demonstrate in a proof-of-principle experiment that this electron source is well suited for performing ultrafast electron diffraction. This was done using our earlier 100 keV electron source and the experiment was performed on a high-quality Si nano-membrane. The temporal resolution was limited to a few picoseconds in this first experiment, mostly because the electron source was non relativistic and had an energy spread of ~10%, causing the bunch to stretch temporally via velocity dispersion. The use of relativistic electrons, in conjunction with an appropriate transport beam line should allow us to reach sub-10 fs resolution.



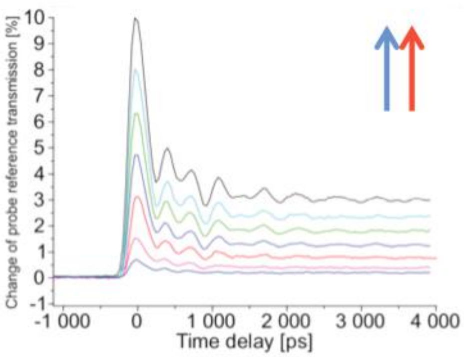
a) Typical diffraction pattern from a Silicon nano-membrane, obtained using laser accelerated electrons at 100 keV. b) Dynamics of the intensity of the (220) Bragg peak, revealing lattice heating and electron-phonon coupling on a picosecond time scale.

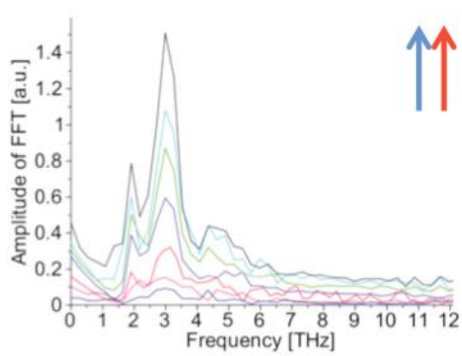
Ultrafast electron diffraction with conventional electron gun

We decided early on that the group needed to gain expertise in "conventional" ultrafast electron diffraction in order to be able to be reactive when our plasma source is ready and to propose relevant experiments. Therefore we built a state-of-the-art ultrafast diffractometer based on a DC gun, delivering up to 60 keV electrons with bunch durations >300 fs and few fC of charge. We quickly realized that the biggest problem for these experiments comes from the sample: it has to be extremely thin (<100 nm) because the electrons probe the sample in transmission, and large transversely (100 micron scale) because the electron beam is weakly focused. As it is extremely difficult to obtain such samples, we started multiple collaborations with LPS (Orsay), LSI (Polytechnique) and University of Wisconsin. It took us more than three years to debug the experiment, increase the signal to noise ratio and test different samples, until we finally obtained the first publishable results. We used a near perfect Silicon crystal and discovered that the dynamics of the Bragg peaks in a pump-probe experiment can be dominated by multi-scattering of the electrons in the sample. This effect is well known in microscopy, but it is the first time that it was clearly measured in an ultrafast electron diffraction experiment. This has important consequences for the interpretation of the diffraction peaks and their related dynamics in these kinds of experiments.

Ultrafast dynamics in solid by optical methods

The major fact of the last five years has been the move from the old experimental setup to the new platform. We have widely used the capability of changing independently the wavelengths of the pump and probe pulses. We have investigated several materials, focusing our attention primarily on bi-dimensional systems and strongly correlated materials. After studying graphene, the prototype for 2D systems, we have started the investigation of layered incommensurate system, in particular the chalcogenure (LaS)1.196VS2, which exhibits an intriguing change of the resistivity of several orders of magnitude when submitted to an external electric field. We were able to discriminate a preferential coupling between the photo-excited electrons and three coherent phonon modes, and we





Time resolved pump-probe experiment on (LaS)1.196VS2 for several fluences and parallel polarization configuration (left), together with the fast Fourier transform (right), where three coherent optical phonons can be detected.

did point out the dynamics of electrons trapping in the vanadium site, relied to the incommensurability of the system. As for the strongly correlated material, we have been working on the Mott isolator prototype V_2O_3, which exhibits a counterintuitive phonon hardening when excited in the mid infrared. We have investigated the sample not only by infrared optic, but also by femtosecond X-ray diffraction, using the X-FEL beam at SLAC in Stanford. It is worth saying that we have a strong collaboration with Stanford University on this subject.

N. Zaïm, M. Thévenet, A. Lifschitz and J. Faure, Phys. Rev. Lett. 119, 094801 (2017)

D. Guénot et al, Nature Photonics 11, 293 (2017)

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M. Thévenet et al, Nature Physics 12, 355 (2016)

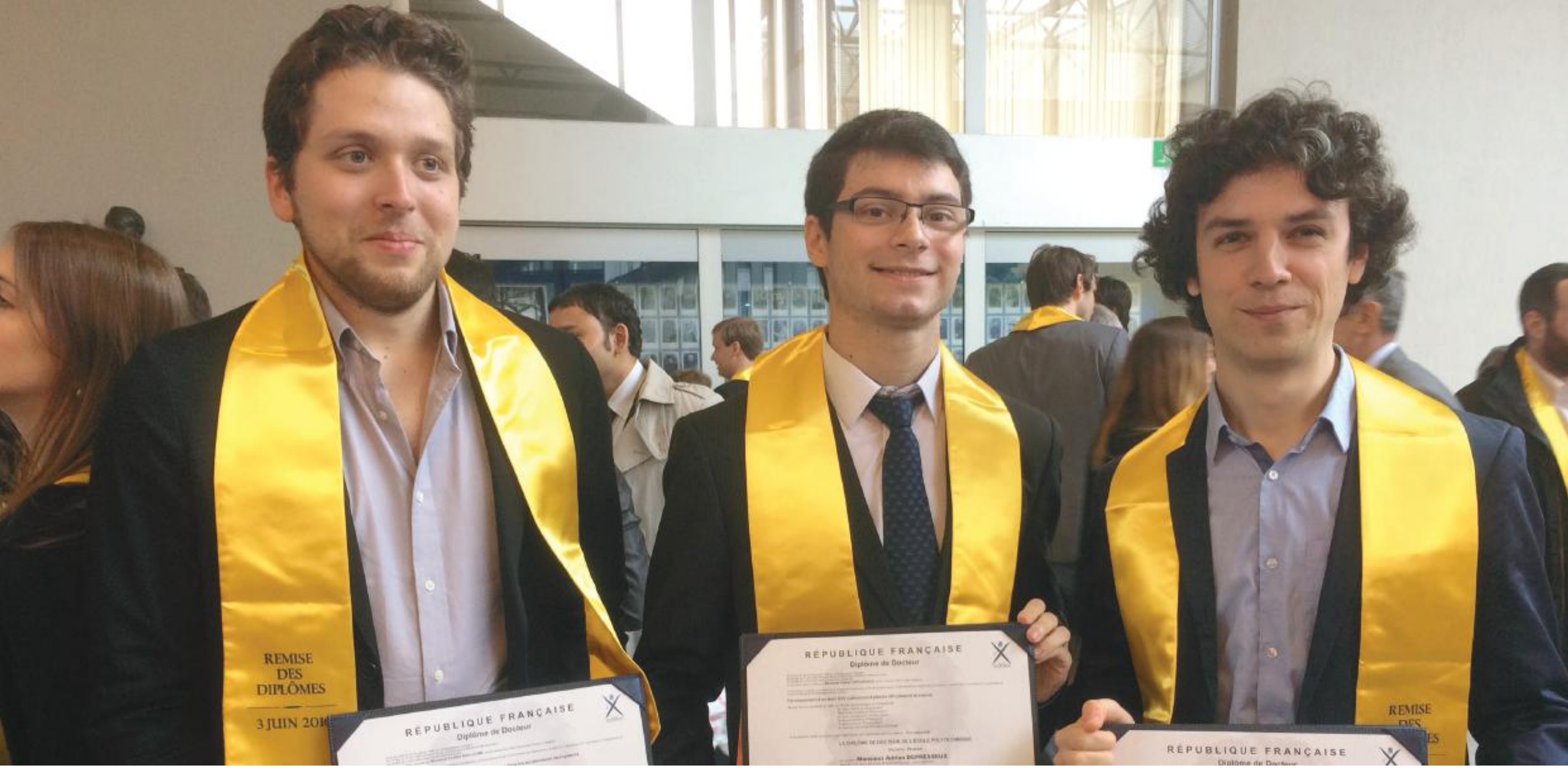
D. Boschetto et al, Nano Letters 13, 4620 (2013)

OPS GROUP

By the mid-noughties LOA activities in the field of eye surgery assisted by ultrashort pulse lasers, notably keratoplasty (corneal grafting). In close collaboration with a partner team at Hôtel-Dieu hospital in Paris and with Laboratoire d'Optique et Biosciences (LOB; École polytechnique – INSERM – CNRS), the group focused on the study of secondary effects of the surgery and notably on the optimisation of the procedure with respect to the optical properties of healthy and pathological cornea. The latter field became the key competence of the group and its worldwide recognised speciality.

Wavelength Optimization in Femtosecond Laser Corneal Surgery

The study published in Crotti et al, IOVS, 2013 aimed to evaluate the influence of wavelength on penetration depth and quality of femtosecond laser corneal incisions in view of optimizing procedures in corneal surgery assisted by ultrashort pulse lasers. Based on a diode-pumped solid state laser comparable to sources used in clinical systems we performed penetrating and lamellar incisions on eye bank corneas using several ultrashort pulse laser sources. Several wavelengths within the near-infrared and shortwave-infrared wavelength rane were used and the pulse energy was varied. The corneas were subsequently analyzed using light microscopy as well as transmission and scanning electron microscopy. We found higher penetration depths and improved incision quality when using wavelengths close to $\lambda = 1650$ nm rather than the wavelength of $\lambda = 1030$ nm typical in current clinical systems. Optical micrographs show an improvement of the penetration depth by a factor of 2 to 3 while maintaining a good incision quality when using the longer wavelength. These results were confirmed with micrographs obtained with transmission and scanning electron microscopy. We concluded that a wavelength change from the standard 1030 nm to 1650 nm in corneal surgery assisted by ultrashort pulse laser considerably reduces light scattering within the tissue. This results in a better preservation of the laser beam quality in the volume of the tissue, particularly when working at depths required for deep lamellar or penetrating keratoplasty. Using this wavelength



yields improved penetration depths into the tissue; it permits use of lower energies for any given depth and thus reduces unwanted side effects as thermal effects. This study concludes our studies in laser-tissue interaction and summarises our findings concerning the wavelength-dependent tissue optics and the choice of optimal laser wavelengths.

Cell viability and shock wave amplitudes in the endothelium of porcine cornea exposed to ultrashort laser pulses

In parallel to our studies on the laser-tissue interaction physics we performed experiments examining the biological effects induced in the tissue under laser exposure.

Some forms of keratoplasty (corneal grafting) assisted by ultrashort-pulse lasers require performing laser cuts close to the endothelium, which requires the knowledge of “safe” values concerning incision depth and pulse energy preserving endothelial cell viability. Our study published in Graefe’s Archives, (2017) aimed to determine the thresholds for cell death in porcine corneas exposed to ultrashort laser pulses, in terms of laser pulse energy and nearness of the impacts to the endothelium. Using the aforementioned laboratory laser set-up, lamellar cuts were induced while varying pulse energies and distances from the endothelium. A fluorescent staining protocol was used to determine the percentage of surviving endothelial cells. Numerical simulations of the Euler equations for compressible fluids,performed by our partners at the Centre of Theoretical Physics of the École polytechnique provided pressure level and axial and radial pressure gradient estimates at the endothelium. Ninety percent of the endothelial cells survived when using 16.5 µJ pulses no closer than 200 µm to the endothelium, or pulses not exceeding 2 µJ at a distance of 50 µm. The comparison of the observed percentage of surviving cells with the estimates of the shock wave amplitudes and gradients generated by the laser pulses yielded cell death thresholds at amplitudes in the megapascal range, or gradients of the order of 10^8 Pa/m. Our results provide limits in terms of pulse energy and distance of the incision from the endothelium within which endothelial cell viability is preserved. Current forms of corneal laser surgery are compatible with these limits. However, these limits will need to be considered for the development of future laser routines working in close proximity to the endothelium.

Stromal striae: a new insight into corneal physiology and mechanics

The study published in Scientific Reports (2017) and coordinated by our colleague Kate Grieve at CIC permitted the identification of the significance of a previously unappreciated structural feature in corneal stroma, important to its biomechanics. We were able to contribute images obtained by scanning electron microscopy recorded during our studies concerning microstructural alterations of the tissue by laser exposure clearly showing those features.

The so-called Vogt striae are a known clinical indicator of keratoconus which is a disease associated with a biomechanical alteration of the cornea and loss of eyesight. Vogt striae consist of dark, vertical lines crossing the corneal depth. However we detected stromal striae in most corneas, not only keratoconus. We observed striae with multiple imaging modalities in 82% of 118 human corneas, with pathology-specific differences. Striae generally depart from anchor points at Descemet's membrane in the posterior stroma obliquely in a V-shape, whereas in keratoconus, striae depart vertically from posterior toward anterior stroma. Optical coherence tomography shear wave elastography showed discontinuity of rigidity, and second harmonic generation and scanning electron microscopies showed undulation of lamellae at striae locations. Striae visibility decreased beyond physiological pressure and increased beyond physiological hydration. Immunohistology revealed striae to predominantly contain collagen VI, lumican and keratocan. The role of these regions of collagen VI linking sets of lamellae may be to absorb increases in intraocular pressure and external shocks.

Recent and ongoing work

Since the completion of our studies on laser eye surgery we have shifted the focus of our activities to the quantitative assessment of corneal transparency in the laboratory and in clinical practice. Lack of anterior segment transparency is the leading cause of blindness worldwide, with corneal blindness alone affecting over 10 million people. Early diagnosis and quantitative follow-up could improve clinical outcome and hence prevent blindness. There is thus a critical need for reliable and easy-to-use clinical tools for objective and quantitative characterisation, including monitoring ability, of corneal transparency.

Our recent and ongoing work addresses three main topics:

- We perform highly resolved and wavelength dependent measurements of the tissue optics using full field optical coherence tomography (at CIC) and digital holography (at LOA, now at LOB) on ex vivo animal and human corneas;

- In collaboration with our partners at Institut Langevin we develop a few-parameter physical model which takes into account the impact of the tissular structural order of the tissue at nanometric and micrometric levels on macroscopic light transmission and scattering properties;

- At CIC we perform clinical measurements on standard (or little modified) clinical diagnostic devices and confront the data to predictions of the physical model.

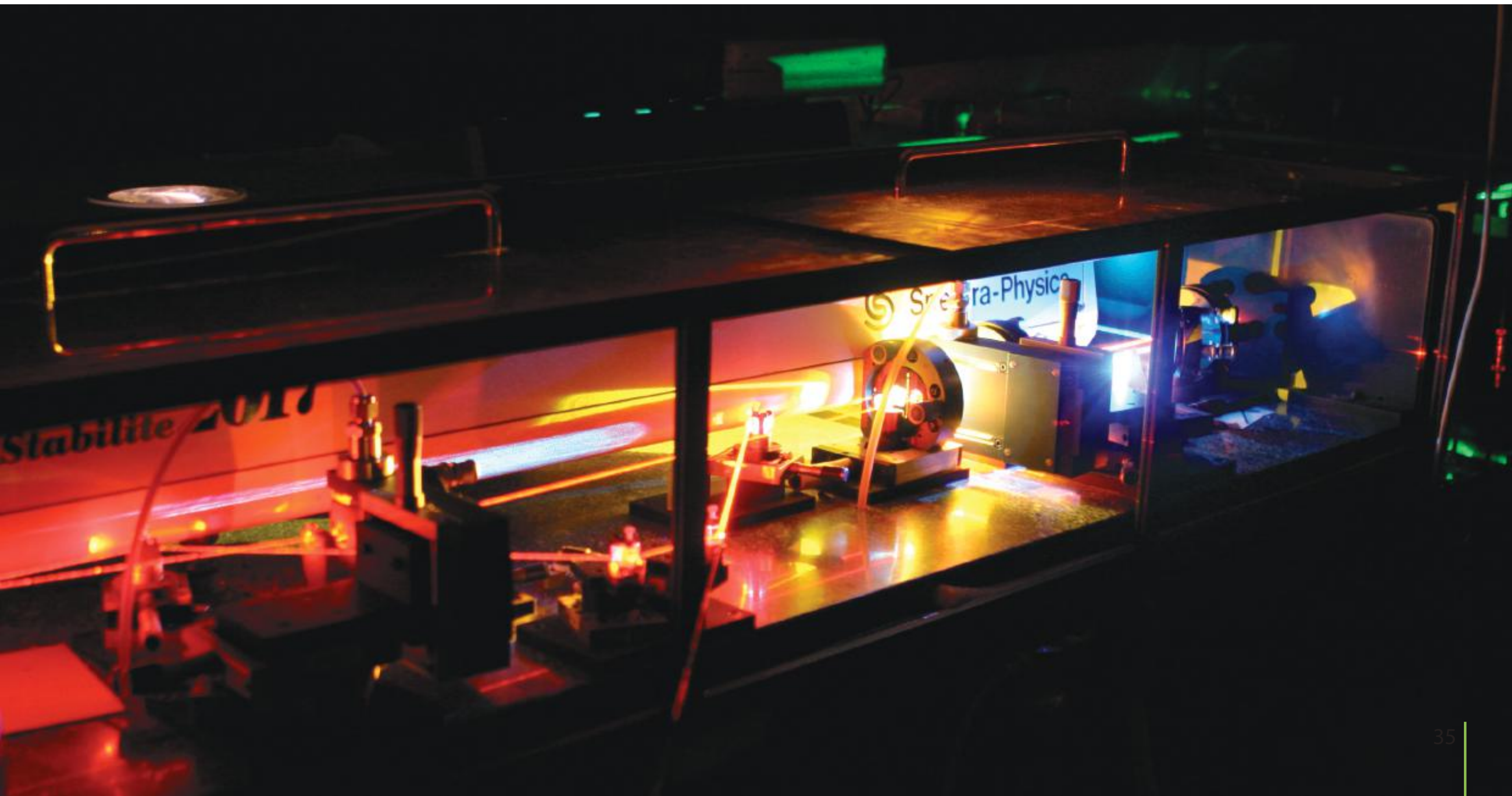
We are presently able to express tissular properties in terms of their impact on the coherence of the transmitted wavefront. We are capable of measuring the mean free pathlength of photons in healthy and pathological tissue and we have shown the tissular optical properties to be strongly wavelength dependent. We have also shown that our method is applicable in vivo with comparable precision.

Given that our approach permits quantitative diagnostics of corneal transparency, provides additional information about the nature and distribution of the scattering structures, and may be implemented as a data analysis algorithm in existing devices it may represent a considerable economic potential. Our characterisation measurements associated with the mathematical-physical model provide data on macroscopic properties like pressure, volume and transparency in connection with microscopic properties like the interaction potential of the tissular components and their structural order (which may be expressed in terms of entropy). Unexpectedly, we may state that we are close to a full description of the tissue in terms of its thermodynamic properties. Our future projects will also address this more fundamental aspect of our research.

S.A. Hussain et al, Clinical and Experimental Ophthalmology, 255(5), 45-953 (2017)

K. Grieve et al, Scientific Reports, 7(1), p.13584 (2017) (3)

K. Plamann, Ophthalmologe 111(6), 514-22 (2014)



FCB GROUP

Since its creation in the 90s, the FCB Bioradical FemtoChemistry team has contributed to bring together different scientific communities, more particularly in the physical and medicine domains. FCB contributes to the valorization of pulsed and ultra-short irradiation sources resulting from advanced laser-plasma technologies. This implies a strong synergy between FCB and the SPL group at LOA. For several years, this synergy has demonstrated its effectiveness in running pioneering research: the Bioradical High-Energy Femtochemistry.

Transdisciplinary research project NANOBIODOS

The research developed in the framework of the NANOBIODOS project since 2014 focused on the innovative laser-plasma sciences for designing ultra-short sources of relativistic particles (electron, proton) of high energy (15 to 150 MeV). These new sources are likely to deliver 1 Gy in 50 fs. These unique technical characteristics are obtained thanks to the know-how of the SPL group.

At the frontier of knowledge on the spatio-temporal effects of ionizing radiation, NANOBIODOS is characterized by a very transdisciplinary approach based on the synergy between the Femto-biophysics of Low Energy Radiations (FRBE) and the emerging field of Femto -biophysics of High Energy Radiations (FRHE).

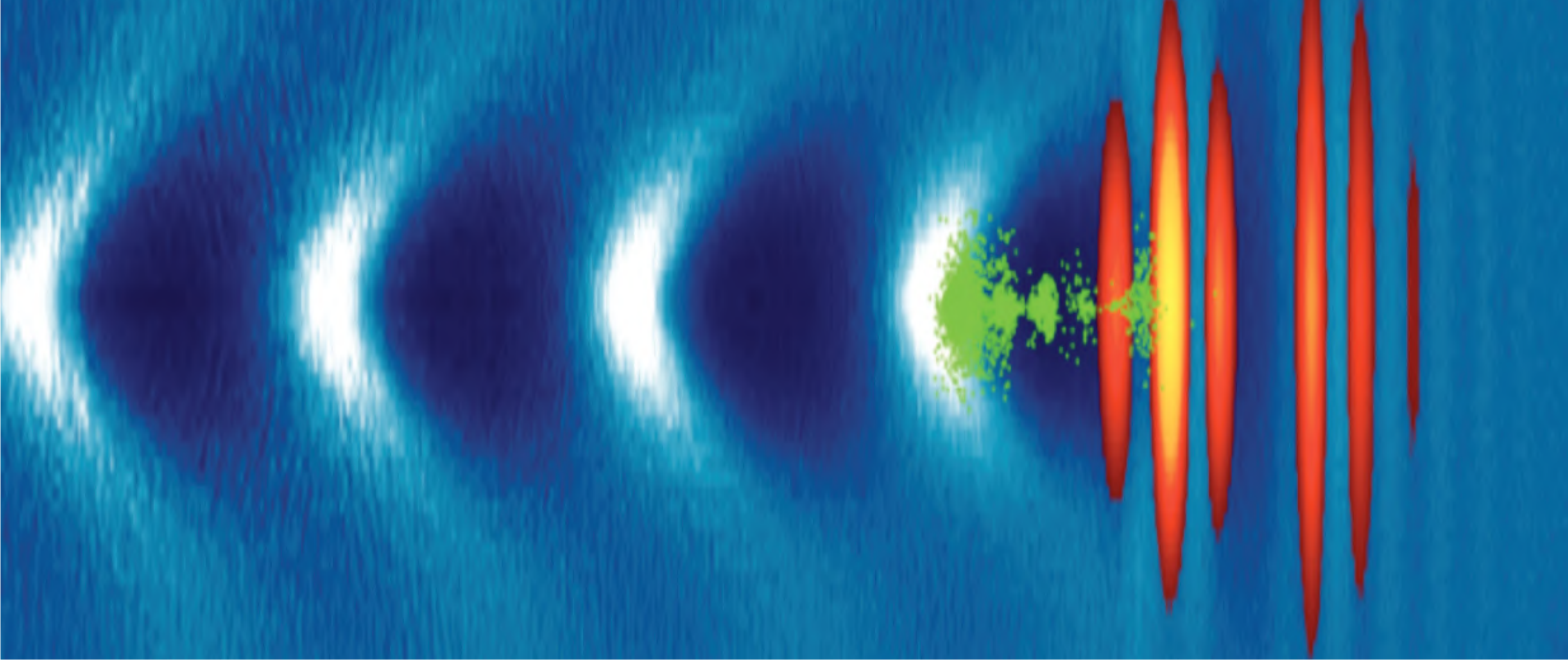
The project uses complex techniques of investigation of quantum phenomena at both experimental and theoretical levels to study real-time nano-biodosimetry or relative biological efficiency at the molecular level. Major scientific advances have been presented and discussed at numerous symposia. The Molecular Approach to the Relative Biological Efficiency of Pulsed Radiation in Relation to Quality Factors (Nature of Electromagnetic or Particulate Radiation, Energy, Fluence, Density, and Nanoscale Dose Rate) should allow the selective treatment of tumor zones, depending on the tumor's genetic profile and the pharmaceutical molecules used during protocols combining pulsed radiotherapy and targeted chemotherapy.

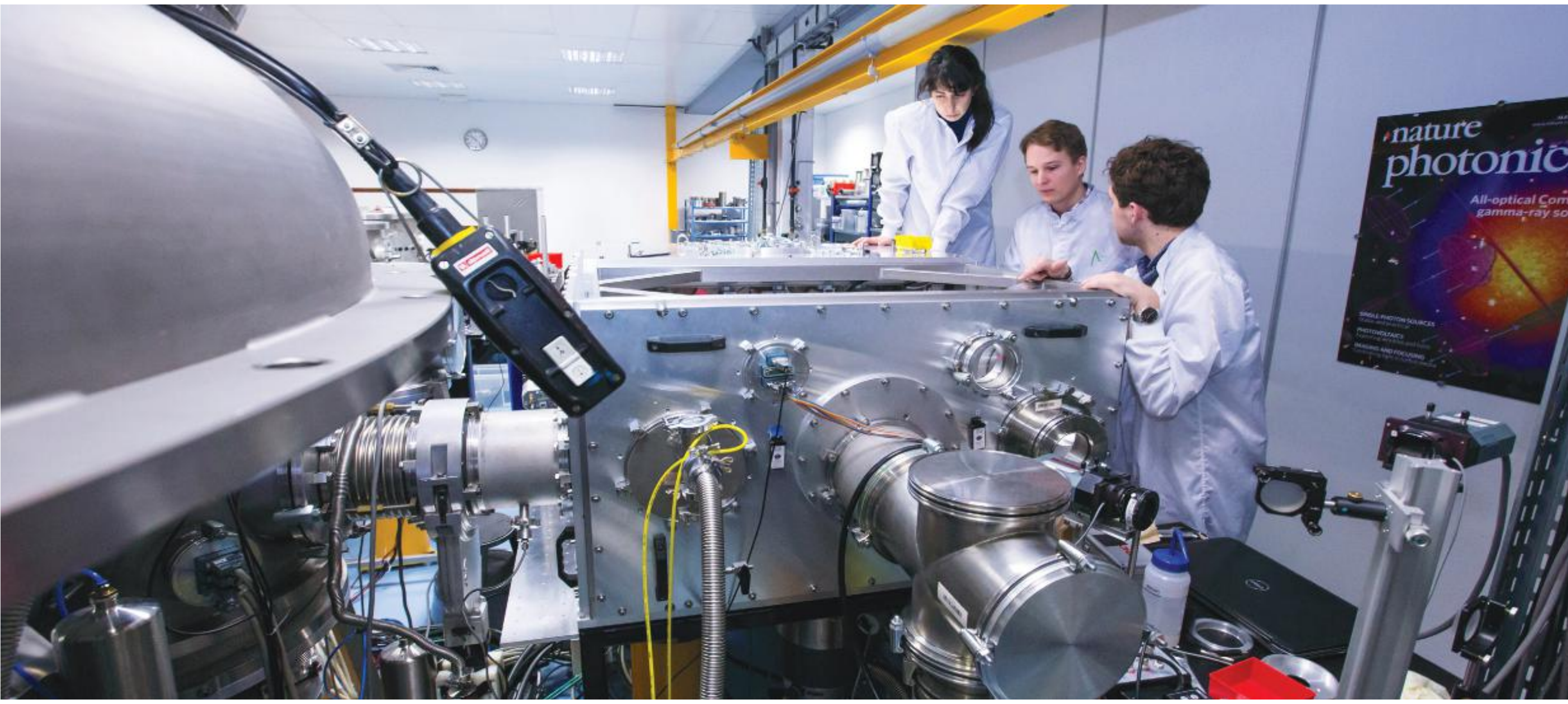
Transdisciplinary research structuring and governance activities for oncology

During the 2014-2017 period, within the MELUSYN Radiation Biology Network, FCB has strongly contributed to the pooling of knowledge and skills in the field of living radiation-matter interactions for cancer, notably by organizing thematic days focused on latest advances in therapeutic treatments for cancers. Thus, in the context of the preparation of the 3rd national cancer plan 2014-2019, the FCB team also contributed very actively to the elaboration of a document on the national strategy for cancer research.

At the European level, the member of FCB has been a member for France of the Management Committee of COST Action MP1002 Nano-scale insights into beam cancer therapy (Nano-IBCT).

FCB joined the International Scientific Council of the National Cancer Institute and the Steering Committee of the HTE consortium (Tumor Heterogeneity and Ecosystem Program) under AVIESAN and INCa. This fundamental, translational and clinical research is focused on understanding, diagnosing and treating the heterogeneity of cancerous tumors.

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SZÉCHENYI PLAN
REME LIGHT
ASTRUCTURE
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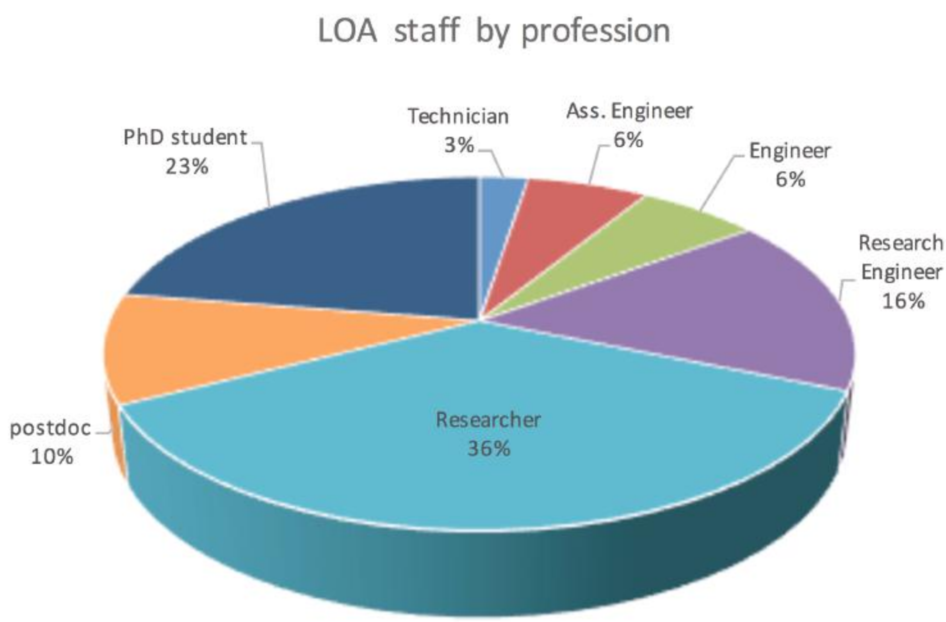
loa

STAFF

The average number of permanent staff has slightly decreased compared to the last period of reporting (5%). Permanent researchers, non-permanent researchers (Ph.D and Postdocs) and support staff are homogeneously spread, each of them representing 1/3 of the total laboratory staff. The average annual turnover of employees is 7 %. During the evaluation period, 13 people left the lab and 9 have been hired. At LOA, 45 % of our researchers are junior scientists (up to 10-12 years after the Ph. D) and 55 % confirmed ones. The pool of researchers has decreased by 17 % (@ 2018). Two researchers have been hired (CNRS and EP) while 3 moved to the industry and another 3 moved to other research laboratories. Departures appeared to be related to living conditions in the Paris area, the lack of promotion, and the impressive attractiveness in terms of salary and financial opportunities to pursue research activities offered by private companies or international labs. This decrease of research manpower was partially compensated by a 37 % increase of non-permanent researchers (37%, 8 to 11 people), which reaches 33 % of the total research manpower (@2018). Furthermore, we have appointed 3 associate researchers.

32 % of the research staff have been promoted during the evaluation period (3 changements de corps and 4 changements de grade - Ecole Poytechnique and CNRS -), which corresponds to an average of 1.4 per year. The number of permanent technicians and engineers have been kept constant over the years. The need of additional support to run the experiments is nevertheless very high, and non-permanent staff has doubled since 2013. Some of them have been upgraded to permanent positions recently in 2018. We've been able to recruit 4 engineers for



LOA staff (81) @ july 2018. Non-permanent staff in Researcher, Technician & Engineers categories are included. If permanent staff are only considered (still with postdoc and PhD students), the percentages do not change significantly (2%). Researcher category includes also Research Engineers doing a research activity instead of technical support of the research.

technical support at Ecole Polytechnique and CNRS to compensate retiring staff or staff transfer to other labs or administrative departments. LOA has to face since 2008 a strong turnover of its support staff, which has significantly rejuvenated LOA's employee population for technical support.

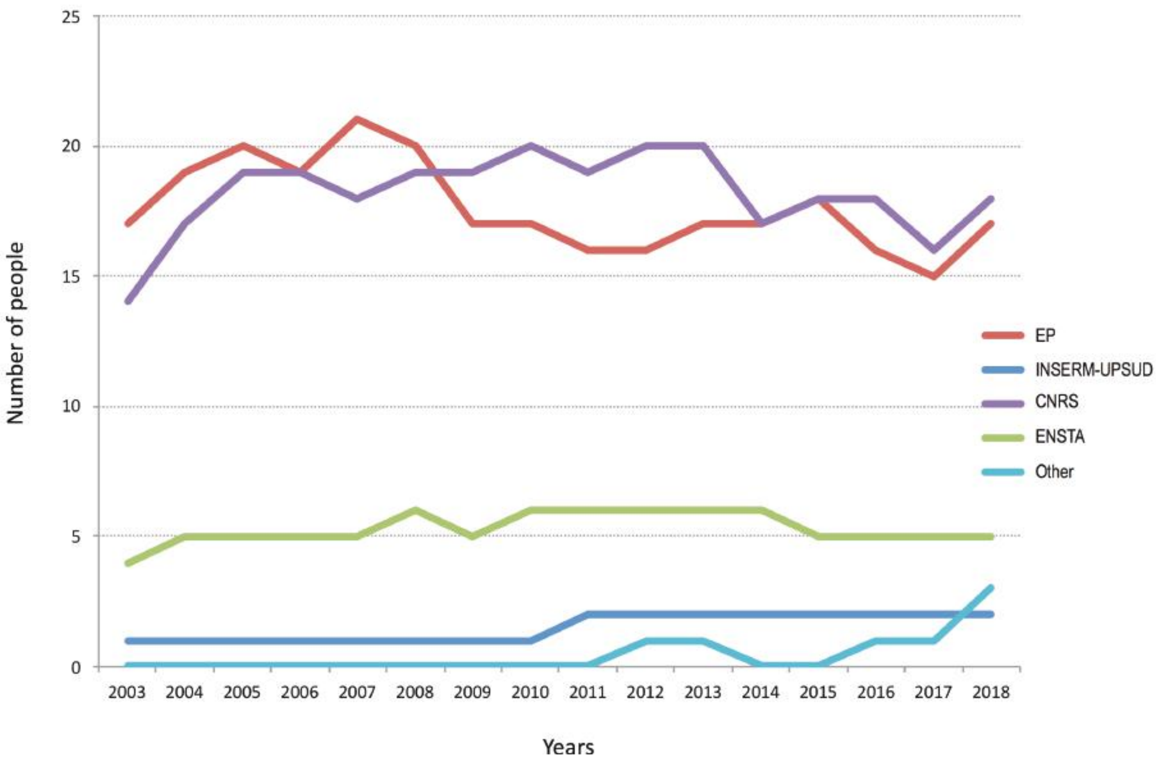
Three promotions have been awarded to the support teams (18 % of the staff) during the evaluation period (2 changements de corps and 1 changement de grade), which corresponds to an average of 0.6 per year.

The average number of PhD students is constant (16) with a yearly turnover slightly higher than 30%. Funding grants come from the Ministry of Research through the doctoral School EDOM (Ecole Doctorale Onde et Matière) that gathers all laboratories dealing with optics and diluted matter (quantum physics, optics, atomic and molecular physics, plasma physics, nanophotonics as well as the interface domains of these topics, such as biomedical imaging or physics of biomaterials, lasers). In this process, two PhD grants per year are opened for 5 laboratories belonging to the department of Physics at Ecole Polytechnique and ENSTA, with an additional very few from the own Ecole Polytechnique funds (average of 5 per year for all the departments of Ecole Polytechnique). Despite the strong competition, LOA teams succeeded in getting an average of almost 2 grants per year through these channels, which represents 40 % of the total grants used to finance LOA PhD students. The other grants come from specific programs (CIFRE) and specific contracts with European or French institutions (Ministry of Defence, collaboration, …).

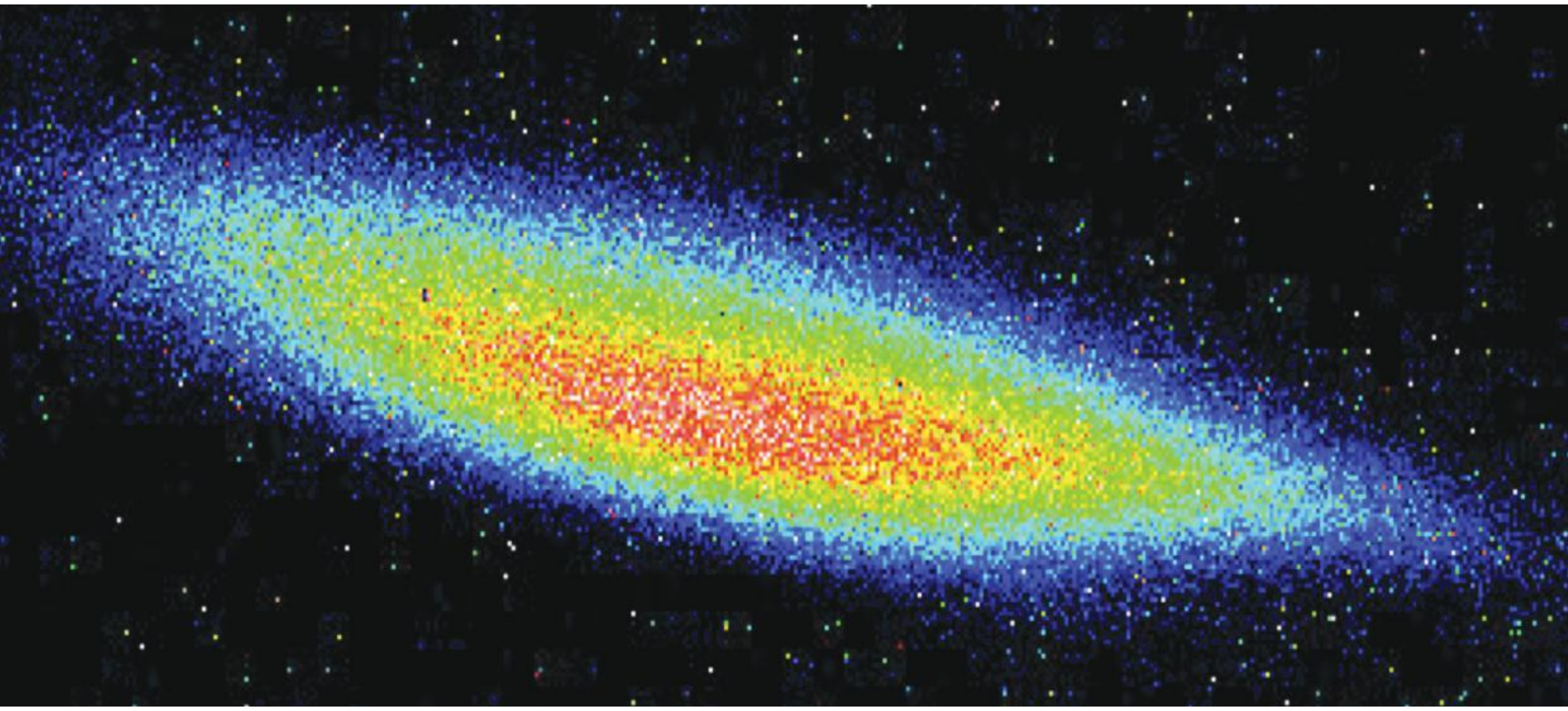
Gender considerations

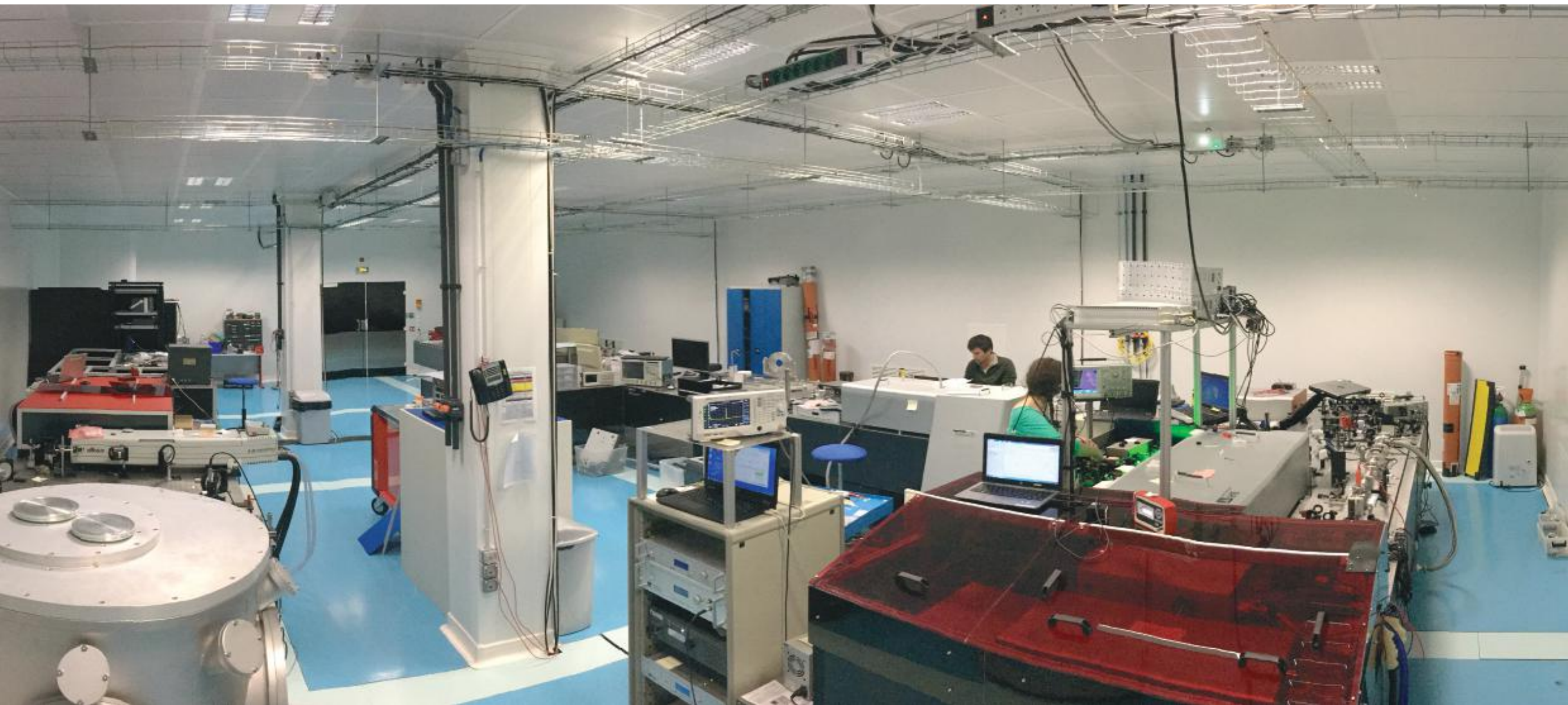
The LOA staff guarantees equality between men and women on its best effort basis. Women and men are considered equally in each level of LOA daily operation (hiring, career progression, etc…).

The gender balance remains almost constant over the years. There are 20 % of women among the permanent staff @ July 2018 (25 % for the whole laboratory staff). This ratio remains almost the same (23 %) for PhD students.



Number of LOA permanent staff from each funding agencies as a function of the years. “Other” includes LOA associate researchers from CEA, University of Shanghai and University of Paris VI.





Funding

The consolidated running budget of LOA averaged over the last 5 years is 6 M€ (22% CNRS, 21% ENSTA, 14% EP, 43% research contracts). CNRS and EP contribute more in the personnel costs, 56% and 32 % (@ 2017), while the hosting institute, ENSTA, supplies 56 % of the research costs (@ 2017) provided by the 3 funding agencies. It reaches up to 72 % if the operating cost of the infrastructure is included.

Research contracts

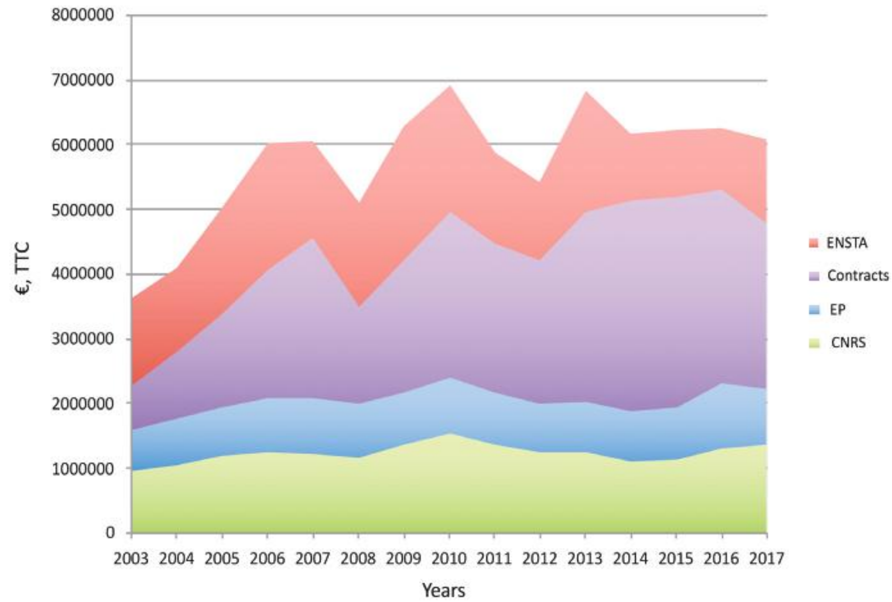
An average of 45 contracts are running each year. This represents between 2.5 M€ and 3 M€ per year averaged over each contract duration. This is higher (20%) compared to the last reporting period (AERES 2009-2013) for which the level of annual research contracts was lying between 2 M€ to 2. 5 M€.

50 % of these resources arises from European grants. In 2018, we are running 18 European contracts, 8 ANR-Ministry of Research contracts, 6 from the "Investissement d'Avenir – PIA" program, 5 from the DGA-Ministry of Defence to name a few. Year to year variations are directly linked to the success rate in the different calls. Spreading these funds over the whole duration of each contract to better match an annual research facility operation provides a nearly constant full cost running budget. The highest financial supports come from 4 ERC (6 since the start of the program in 2009) and 2 FET-OPEN European projects as well as from 2 DGA (Rapid and PEA) projects.

During the reporting period we've succeeded in getting an average of 2 ANR grants per year with a success rate of 28 %. It is less than during the last period (2008-2012) for which 13 ANR projects were accepted. This may certainly be due to the reduction of the overall funds available from the Ministry of Research and the averaged increase of the number of projects submitted (15%) at the national level. The number of projects supported by this program in France has actually decreased from a success rate of more than 20 % in 2012 down to 10 % in 2014 and 13 % in 2017. Keeping the funds from research contracts at our current level is an important goal to support all the activities of the research groups.

Due to the very high dependency of our research development on contracts, LOA teams have always been very concerned to diversify the sources of funding. We regularly apply to calls open at the regional level, like the "Sesame", which are devoted to developing new major research projects and to implement original experimental research devices to make the region of Paris a world reference in science and technology. This is again the case in 2018 with our proposal to develop the first national platform, based on laser-plasma technology, fully devoted to medical applications. The technical and scientific expertise of our teams has also been used for obtening contracts to design and construct beamlines for new large-scale infrastructures in construction in Europe like the ELIs. Another example is the high-level programs from the Ministry of Defence (former PEA, "Plan d'Etude Amont") that operate on specific topics supported by the DGA, Direction Générale de l'Armement. We also take benefit of the mobility of a few LOA researchers who are launching new labs in foreign countries (Shangai University in China and Weizmann Institute in Israel). We are developing strong collaboration like an international joint laboratory with the goal to apply to new programs only accessible with such federative structures.

Improving our partnership with the industry is certainly one of the additional directions to follow. We already get funds from several laser companies for



Consolidated LOA annual budget (euros TTC) cumulated over the funding agencies (permanent staff & annual funding) and the research contracts as a function of the years.

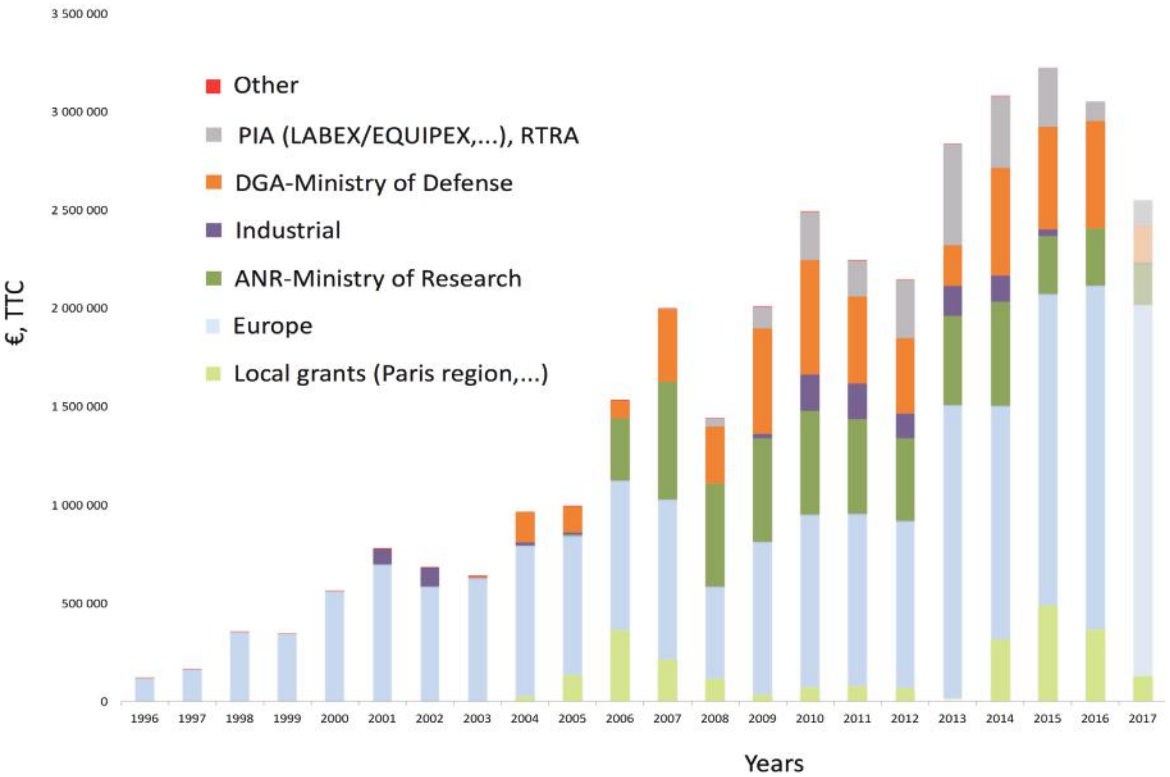
specific developments. However, the amount of the funds remains quite limited as they mainly come through CIFRE grants (5 during the period of evaluation) or instrumentation sharing. The collaboration with our SpinOff SourceLab to promote and transfer laser-plasma technology to the industry is one step to this end. This is quite a success since several joined contracts have been already obtained as well as the launch of technological projects like the NDT (X-ray Non Destructive Testing) platform that may, in the near future, generate additional incomes once positioned into the market.

LOA teams apply and succeed in obtening grants providing high financial support in accordance with the needs. The number of permanent researchers at LOA is stable over the years and does not increase. This constrains what can be realistically achievable in terms of resources from contracts due to already overcharged activities (close to saturation) that each researcher can sustain while still running experimental research.

Funding from the supervising agencies

While the resources coming from contracts have continuously increased over all the years since 1996 to reach 80 % of the annual research costs in 2014-2015, one can observe that the financial support from funding agencies has decreased since 2010. It has remained constant since 2014 following a 40% drop in 5 years, due to a reduction of ENSTA-ParisTech's investments which has, at the same time, chosen to secure the LOA operating cost during these years.

ENSTA-Paristech provides more than 50 % of the annual research budget of the laboratory and supports the infrastructure costs at an average of 300 k€ per year since 2003. CNRS and Ecole Polytechnique subsidize the LOA with very close overall contributions. About 10 % of the whole support is devoted to annual funding, which is seen to remain unchanged for almost 20 years. Personnel costs represents the main participation of EP and CNRS with 80 % of the investment for LOA. The overall payroll expenditures



Annual LOA research contracts (euros, TTC) cumulated over the different categories of programs (national and European) @ July 31st, 2017. Each contracts amount is spread homogenously over its whole duration. Values for years 2018 to 2021 corresponds to the contracts already granted @ July 31st, 2017.

are almost stable over the years (about 2.5 M€) with a CNRS, EP and ENSTA contributions of about 56%, 30 % and 14 % respectively. The number of permanent staff from CNRS and Ecole Polytechnique is nevertheless almost the same. The payroll difference comes from the salary taxes for CNRS employees which are 40% higher than the ones for employees funded by Ecole Polytechnique.

The development of new research programs or the increase of our activity as well as the yearly operation of LOA facilities is then strongly relying on research contracts. Annual funds coming from our funding agencies participate mainly to fund part of the maintenance of the experimental beamlines and instrumentation.

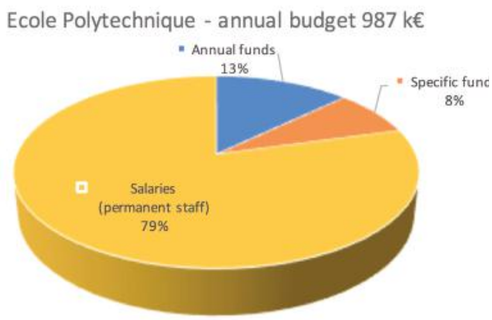
More than 80 % of the funds are used for transverse activities. They are not allocated to research groups and are appointed to each experimental site which are actually shared and managed in efficient synergy between research teams. This prevents spreading of resources and strengthens coordination in managing the sites.

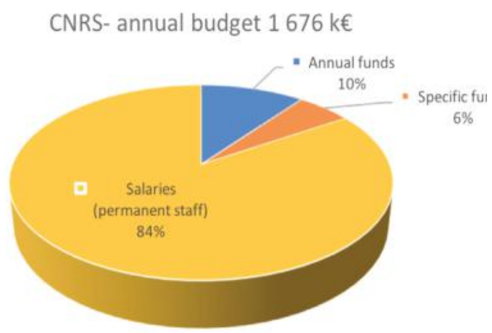
Specific funds from the supervising agencies

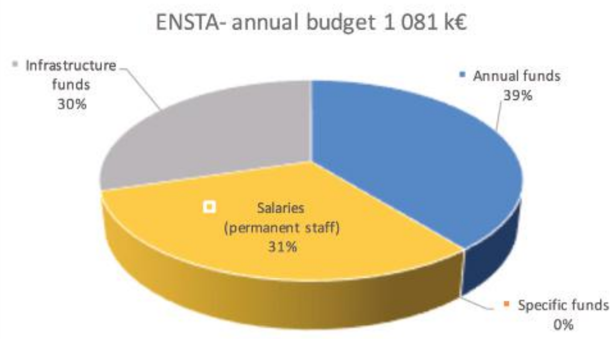
Each year, 1 or 2 specific programs, discussed within the laboratory councils, are submitted to the funding agencies during the board of directors' assembly. It mainly concerns laboratory-size equipment to be installed at LOA, especially for the implementation of laser-plasma diagnostics that may also serve the community in a more general way. This represents typically 5 % to 8 % of the total contribution of Ecole Polytechnique or CNRS. In addition, the LOA policy is to use about 10 % of the annual funds from the funding agencies to finance a specific group, researcher or experimental site. This is important to smooth the impact of a temporary lack of contracts for some researchers, to help in starting or finalizing the developments of in-house instrumentation or to replace costly materials that cannot be handled alone by the research team(s). Last but not least, Ecole Polytechnique has launched since 2008 two significant fundraising campaigns to finance projects with a high societal impact. In the frame of these specific funds, Ecole Polytechnique participates with ENSTA-ParisTech to the development of the LOA medical platform for the study of bio-medical processes at extremely high irradiation dose-rate.

Funding from LOA European Facility

The LOA is part of the consortium LASERLAB-EUROPE (LLB), a group of leading European laboratories working on the development of femtosecond laser systems and the use of ultrashort laser pulses in various scientific fields: physics, chemistry, biology, medicine. It is an interdisciplinary European network of laboratories and competitive national lasers with the goal to strengthen Europe's leadership in laser research and applications through the development of joint research activities, to propose a program of transnational access facilities to various partner laboratories, and to assist national laboratories in developping their research infrastructures at national and European level. Some laboratories like LOA participating in the consortium are funded through a program of transnational access to research infrastructure and laser applications for researchers or







Consolidated annual budget of each of the 3 funding agencies for year 2017.

research teams belonging to the EU member states and the associated states. A set of laser equipment and experimental site are available at LOA to perform experiments of laser-matter interaction in a wide range of power, wavelengths or pulse durations. Access is fully supported by LASERLAB-EUROPE and provides additional funds for our hosting institute. These funds are directly proportional to the number of days provided to users. It is granted after selecting experiment proposals by a panel of outside scientific experts. European teams selected to run an experiment in any of LOA experimental infrastructures are assisted by our LOA scientist. During the reporting period, LOA has welcomed 23 projects of international users under the LLB III and LLB IV programs from 16 European institutions like FSU-Jena, Max Born Institute, IST Lisbon, Queen's University Belfast, University of Bern or Institute of Physics FZU to name a few. The funds obtained through this channel are allocated to LOA teams that have been involved in this program and are used to operate and to upgrade the experimental sites and to develop new instrumentations.

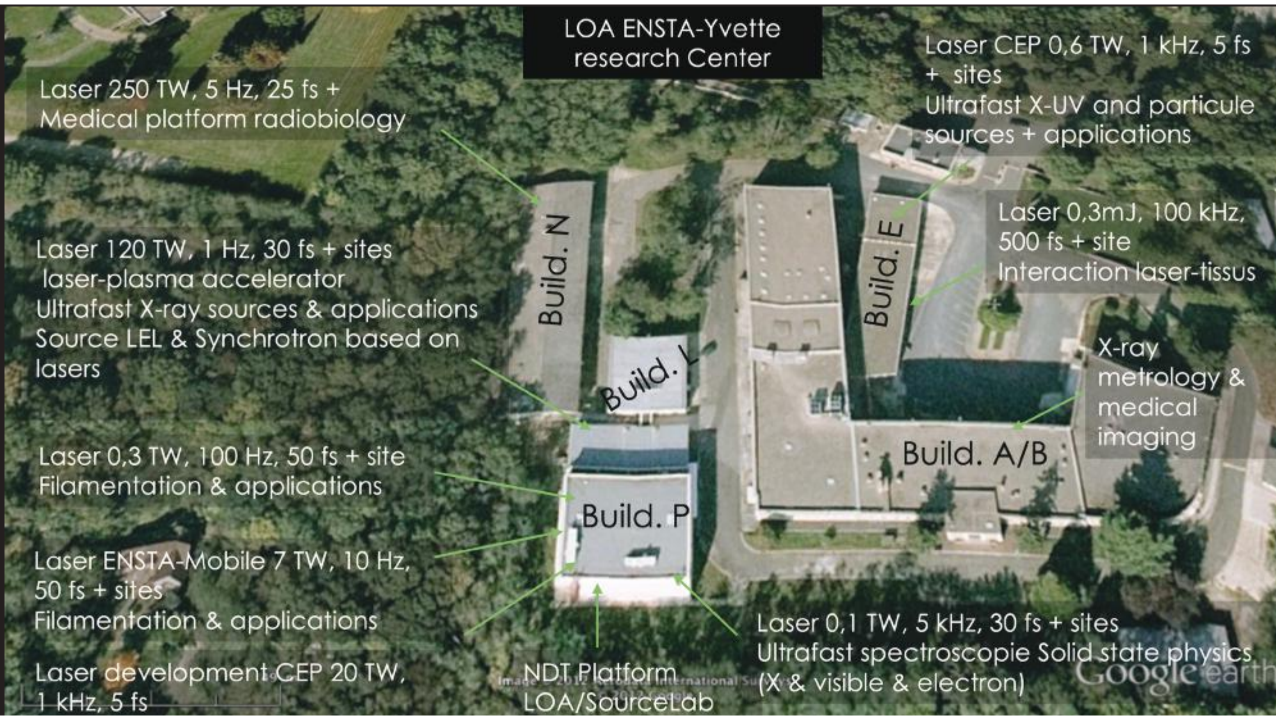
Data sheets

Staff @ july 2018	total	Permanent researcher	Engineer (permanent)	Non-permanent researcher	Engineer (non permanent)	Ph.D	Visitors
ILM	10	1	2	-	1	3	3
SPL	22	6	2	3	1	8	2
FCB	1	1	-	-	-	-	
FLEX	15	5	3	2	1	1	3
PCO	10	4	3	-	-	2	1
OPS	3	1	-	-	-	2	-
APPLI	9	3	1	1	-	3	1
Transverse support	11	-	9	-	2	-	-

Scientific production @ july 2018	ILM	SPL	FCB	FLEX	PCO	OPS	APPLI
Publications (peer-review journals)	53	114	2	49	28	5	28
Conference prooc.	1	13	1	13	11	10	4
Book chapters	4	6	1	2	4	-	1
Invited conferences	41	82	10	33	21	1	28
Oral conferences	17	32	2	24	52	11	19
Ph.D defended	4	5	-	5	6	1	2
HDR defended	2	-	-	-	-	-	-
Prizes	3	14	-	11	1	-	3
patents	2	6	-	1	2	-	-

running contracts 2013-july 2018	Number	M€ TTC	Europe	ANR	Industry	Investissement d'Avenir - PIA	Local grants	DGA	others
ILM	11	2,9	2	2	1	-	-	6	-
SPL	18	8,13	9	4	2	-	2	-	1
FCB	1	0,24	-	-	-	1	-	-	-
FLEX	23	4,3	6	5	1	5	1	1	4
PCO	18	3,73	6	2	2	6	2	-	-
OPS	1	0,51	-	-	-	-	-	-	1
APPLI	8	2,1	2	1	-	1	3	-	1


1000 kg
ZITA

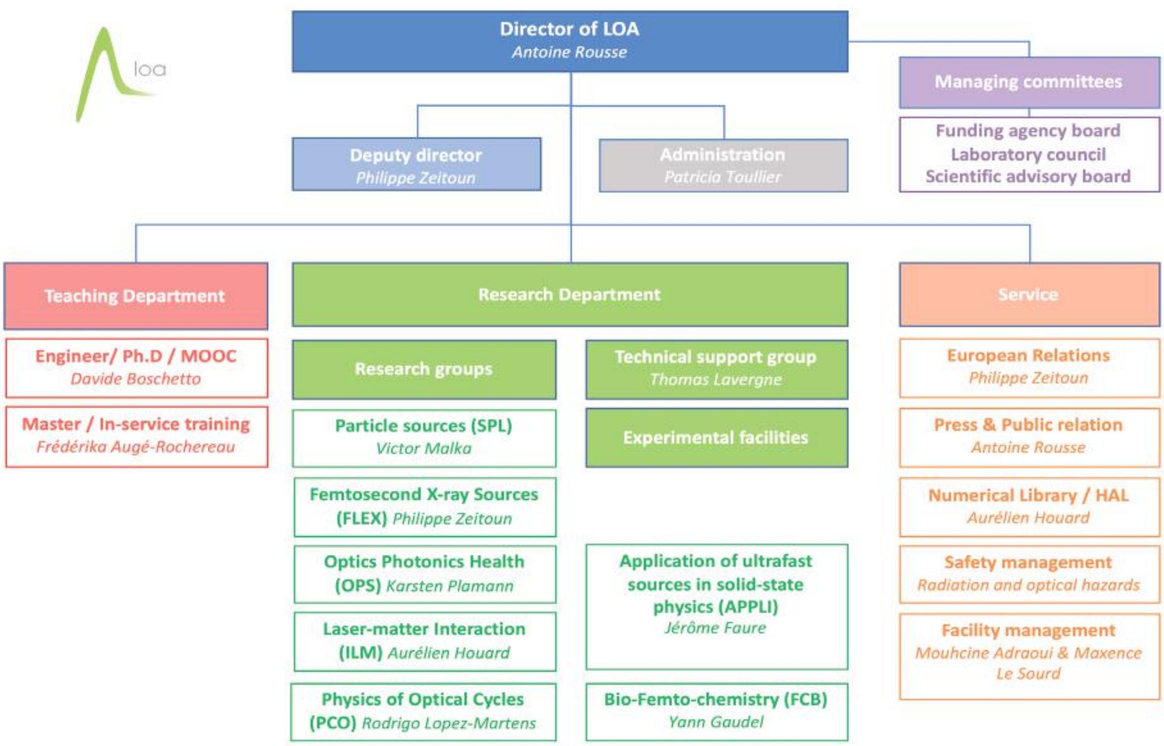

LOA ENSTA-Yvette
research Center
Laser 250 TW, 5 Hz, 25 fs +
Medical platform radiobiology
Laser CEP 0,6 TW, 1 kHz, 5 fs
+ sites
Ultrafast X-UV and particule
sources + applications
Laser 0,3mJ, 100 kHz,
500 fs + site
Interaction laser-tissus
Laser 120 TW, 1 Hz, 30 fs + sites
laser-plasma accelerator
Ultrafast X-ray sources & applications
Source LEL & Synchrotron based on
lasers
Build. N
Build. E
Build. L
X-ray
metrology &
medical
imaging
Build. A/B
Laser 0,3 TW, 100 Hz, 50 fs + site
Filamentation & applications
Build. P
Laser ENSTA-Mobile 7 TW, 10 Hz,
50 fs + sites
Filamentation & applications
Laser 0,1 TW, 5 kHz, 30 fs + sites
Ultrafast spectroscopie Solid state physics
(X & visible & electron)
Laser development CEP 20 TW,
1 kHz, 5 fs
NDT Platform
LOA/SourceLab
Google earth


REID

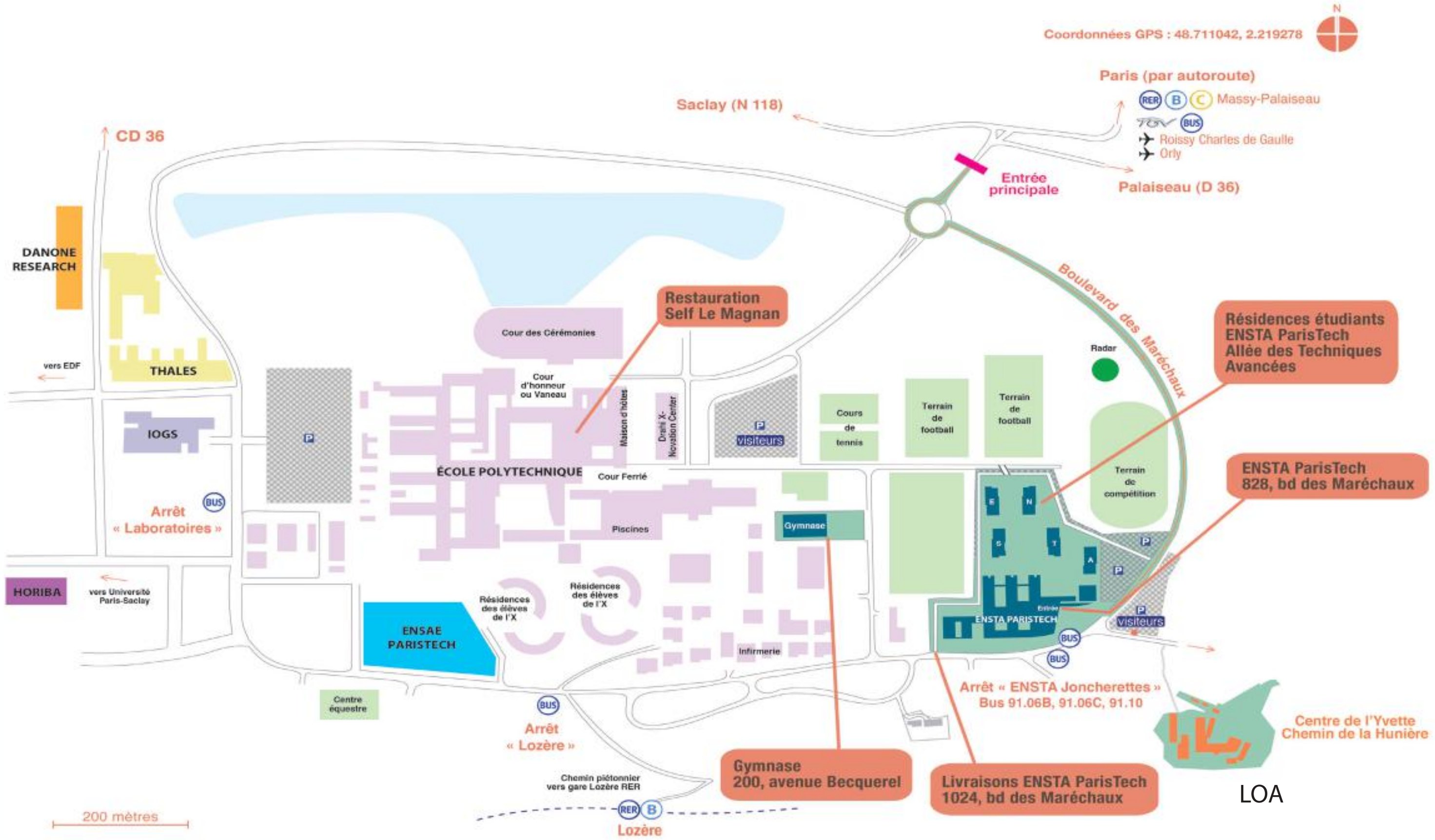
INFRASTRUCTURES

Name	Laser system	Laser-matter interaction beamlines	Topics
Salle Jaune	800 nm; 1 Hz, 120 TW: 2 x 60 TW @ 30 fs; 6 synchronized laser beams; 1 laser beam 500 ps @ 0.5 J	3	laser-plasma studies, Electrons acceleration, ultrafast Relativistic X-ray beams, Soft X-ray lasers, application of X-rays and particle sources
Salle Saphir (Radio-bio Platform)	800 nm, 5 Hz, 26 fs, 4 J	1	Radio biology, radio therapy, with electrons, X-rays and protons at ultra-high dose (10^9 Gy/s, multi pulses)
Salle Corail/ Argent	800 nm, 3 mJ, 40 fs, 5 kHz	5	High Harmonics from gas targets, X-ray metrology, femtosecond visible and electron spectroscopy, Ultrafast solid state physics, THz time domain spectroscopy
Salle Indigo	OPG (1-3 μm,100 kHz to 1 kHz, 600 fs to 1 ps, 1 mJ /10 uJ)	1	Eye surgery assisted by ultrashort pulse lasers. Optical properties of healthy and pathological cornea
Salle Noire 3.0	few optical cycle, kHz & mJ	-	Laser development
Salle Violette 1	800 nm, 100 Hz, 50 fs, 15 mJ	1	Filamentation (fondamental physics and applications) - Lasing, THz and acoustic generation experiments
Salle Violette 2	ENSTA-Mobile 800 nm, 10 Hz, 50 fs and 0.3 J (mobile TW laser facility)	1	Filamentation and high-voltage experimental platform
NDT Platform	LOA-SourceLab laser: 800 nm, 0.4 J to 0.8 J, 40 fs, 10 Hz	1	Non destructive testing with laser-plasma γ-rays
Salle Noire 2.0	4 mJ, < 4 fs, 1 kHz, 1 TW, CEP	2	Attosecond plasma physics, High Harmonics from solid targets, Acceleration of electron beams, Non-linear optics

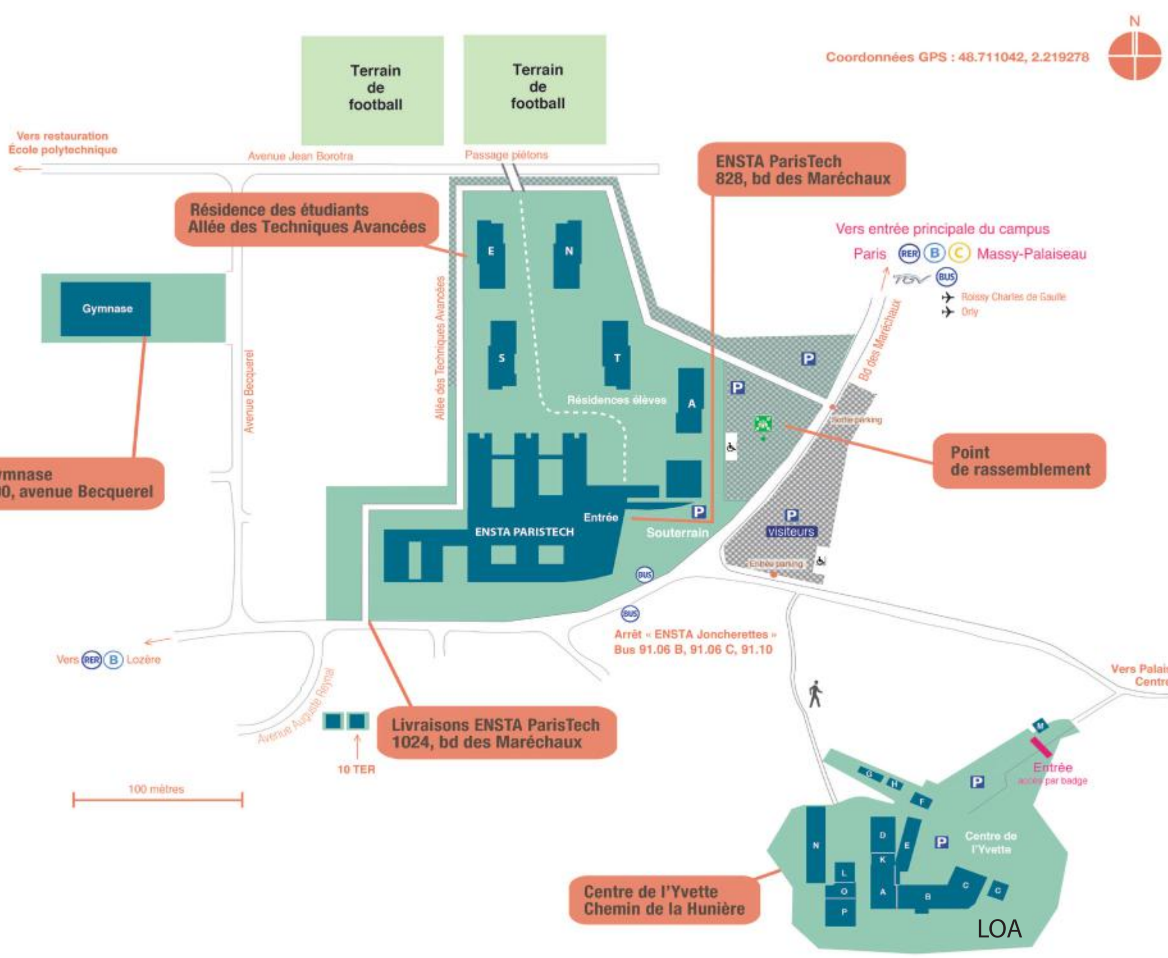
ORGANISATIONAL CHART



Ecole Polytechnique Campus



ENSTA-ParisTech Campus



PROGRESS REPORT 2013-2018

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