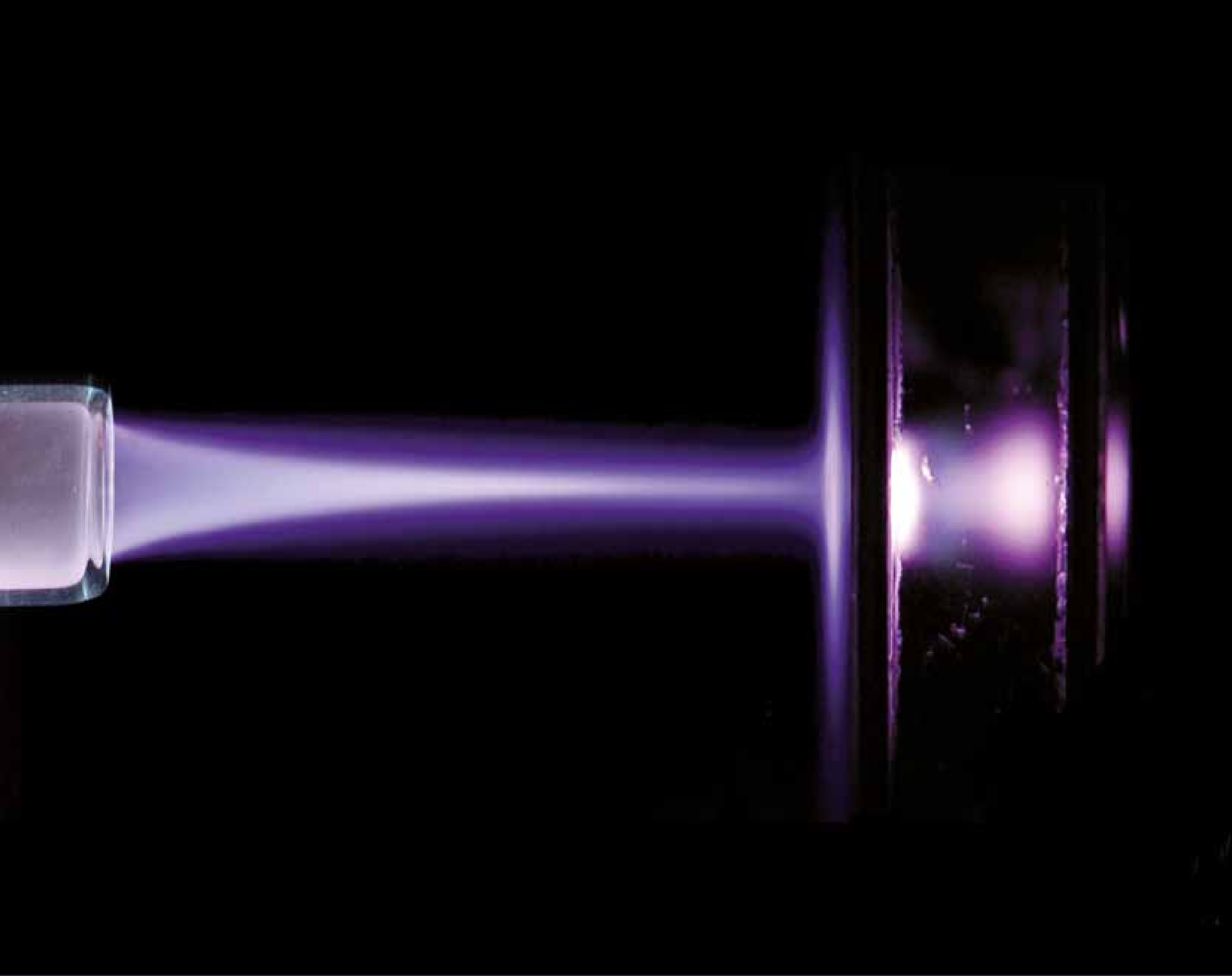


# Activity Report PLAS@PAR 2012-2019

PLAS@PAR (Plasmas in Paris, beyond the frontiers) is a Laboratory of Excellence funded by the French Governement in 2012 and aiming at federating plasma scientists of Paris area working in different disicplinary branches connected to plasma physics. This book summarizes the actions realized concerning research, education and teaching, industry, communication and outreach.

SORBONNE UNIVERSITÉ

PLAS@PAR
Plasmas à Paris

# TABLE OF CONTENTS

# EDITORIAL

From the interior of planets to solar wind, from neon signs to atmospheric lightning, from nuclear fusion reactors to electric thrusters on satellites, matter exists in the plasma state. The unique properties of plasmas enable many key technologies in the modern world, including semiconductor device manufacture, industrial surface treatment, welding, and pollution abatement. Many exciting new applications are emerging in combustion, medicine and agriculture.

**Plasma science concerns the fundamental properties of ionised matter,** its microscopic structure, dynamics, chemical reactivity and response to externally-applied and self-generated electromagnetic fields. Plasma science is a wide subject by its very nature, depending on the combination of many disciplines including electromagnetics, non-equilibrium thermodynamics and statistical mechanics, atomic and molecular physics, chemical reactivity, (magneto-) hydrodynamics, astrophysics, planetary science, engineering and mathematics.

This diversity could be seen as a disadvantage, dividing the community into independent disciplines and penalising the visibility of plasma science as a whole. However, it is also an opportunity since it allows different approaches to be combined, stimulating the emergence of innovative projects through the collaboration of scientists with diverse areas of expertise.

The PLAS@PAR (Plasmas in Paris) project was designed to tackle the various aspects of plasmas science, with the major ambition to unite all of the involved researchers working in the Paris area. It was selected by the French Government to be a "Laboratory of Excellence" over the period 2012-2019. This multi-year financial support has allowed the initiation of multiple interdisciplinary actions, the conception and development of ambitious and challenging projects, the construction of new instruments and numerical tools to be shared by the community, and the nurturing of durable links to industrial partners.

Another goal was to promote plasma science to the general public and to demonstrate its societal importance. This is a long-term and difficult objective since the students are mostly unaware of the existence of plasmas unless they have encountered them during Master level studies. To this end, PLAS@PAR has launched teaching initiatives aimed at high school teachers as well as at Bachelor's level. Moreover, the graphic beauty of plasma dynamics (both in space and in the laboratory) was linked to the arts in an innovative approach to reach a wide audience at Centre Pompidou.

**Labex PLAS@PAR** has been a wonderful common scientific enterprise developing strong links between scientists from different laboratories and horizons, giving new impetus to research through many PhDs and postdocs, and creating a strong and visible community in the Ile-de-France region. This community will continue to consolidate and grow in the future.

We are grateful to our many colleagues for the imagination, effort and commitment they have brought to PLAS@PAR to make it a successful scientific and human adventure.

We offer our warm gratitude to University Pierre and Marie Curie (now Sorbonne Université) for its strong support since the beginning of the project. We would also like to thank our trustees, as well as all of the members of the International Scientific Board, for their encouragement and advice during this 8-year period.

*Pascal Chabert, Dominique Vernhet, Alain Dubois, Chantal Stehlé*

CHAPTER 1


© Julien Labaune, ONERA

# Genesis & Objectives

- Context
- Scientific goals
- Structure
- Organization

# Key achieved goals from 2012 to 2019:

> A strong federation of scientists from different communities
> A common enthusiasm to foster new projects
> In-depth studies of fundamental plasma processes
> Innovative techniques in observations, diagnostics and simulation of plasmas
> Training & guidance for a new generation of plasma physicists
> Key technological transfers toward the industry
> Exciting and successful outreach actions for the general public

# Key figures

## 8-year project

> 150 new research projects

> 7 500 000 € from the Investments for the Future programmes of the Agence Nationale de la Recherche dedicated to research, education, transfer and outreach

## People

> 250 researchers

> 7 core & 5 associated laboratories

> 18 PhD positions & 21 Postdoctoral positions funded by PLAS@PAR

> 50 invitations of international experts

## Research

> 6 research themes

> 3 work-packages

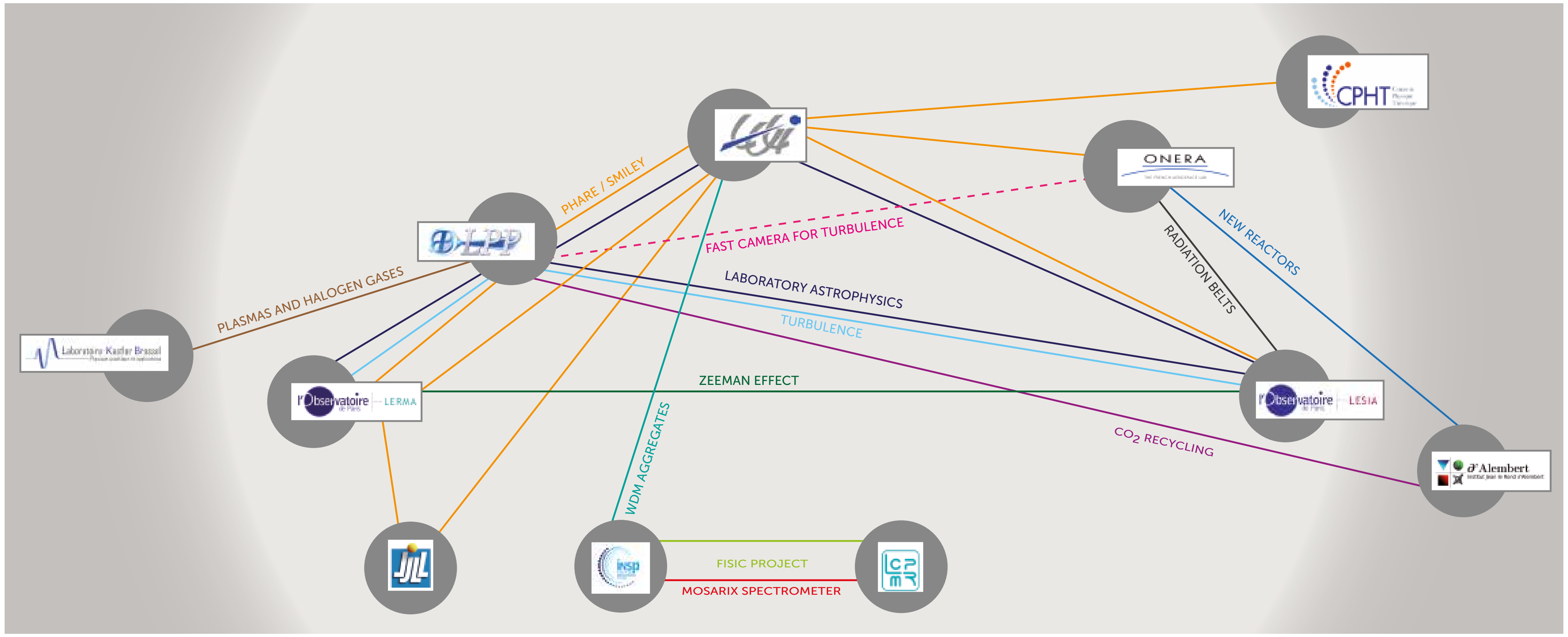
# Context

*FROM 2012 TO 2019, THE CLUSTER OF EXCELLENCE (LABEX) PLAS@PAR HAS FEDERATED ABOUT 250 PLASMA SCIENTISTS FROM ÎLE-DE-FRANCE AROUND AN INTERDISCIPLINARY PROJECT IN PHYSICS, ASTROPHYSICS, PHYSICAL CHEMISTRY AND ENGINEERING, WITH LINKS TO APPLIED MATHEMATICS AND COMPUTER SCIENCE.*
*IT IS ONE OF THE 15 MAJOR PROJECTS OF SCIENCES, ENGINEERING AND HUMANITIES RESEARCH DRIVEN BY SORBONNE UNIVERSITÉ, AWARDED IN 2011 IN THE FRAME OF THE INVESTMENT FOR THE FUTURE PROGRAM OF FRANCE (PIA).*
*IN THIS CONTEXT, PLAS@PAR RECEIVED 7.5 MILLIONS EUROS.*

Plasma science is essential to the understanding of a incredibly rich variety of phenomena occurring both in nature and in man-made devices.

Plasma science is also at the core of key industrial applications that range from nanofabrication and energy generation to air and water depollution. Furthermore, recent developments of large-scale ground-based research infrastructures and space missions are enabling unprecedented extreme plasma conditions to be created in the laboratory and unexplored phenomena to be studied. However, plasma science is a particularly broad research discipline and its study is often scattered across multiple fields. While plasma science lacks global visibility, its interdisciplinary character is also one of its advantages: PLAS@PAR has seen an exceptional opportunity to stimulate interdisciplinary and federative projects both in research and education.

**Examples of collaborations initiated by PLAS@PAR**




# Scientific goals

*CREATING NEW SYNERGIES WHILE REDUCING REDUNDANCY, PLAS@PAR STIMULATES THE EMERGENCE OF IDEAS & PROJECTS INACCESSIBLE TO INDIVIDUAL PARTNERS AND PROVIDES A UNIQUE POINT OF FOCUS TO ATTRACT YOUNG SCIENTISTS TO THE FIELD. BESIDE FUNDAMENTAL RESEARCH, THIS COMMUNITY, WHICH IS THE LARGEST AND MOST DIVERSE IN FRANCE IN PLASMA SCIENCE, PROMOTES INNOVATION FROM NANOTECHNOLOGY TO AERONAUTICS AS WELL AS ENVIRONMENT & MEDICINE.*

The project was built around 3 work packages (WP) covering 6 transverse themes: Turbulence, instabilities and energy transport, Magnetic reconnection, Shocks, Matter under extreme conditions, Plasmas in molecular gases, Interaction of plasmas with solids and liquids.

### WP1

**Fundamental processes in plasmas:** mostly theory and simulation oriented, the studies address the challenging question of particle acceleration at very high energy, the interaction of radiation at extreme intensity with matter, up to the relativistic regime, the stability of plasma devices for nuclear fusion as well as industrial processes. This theoretical work was stimulated by observations of natural plasmas and by novel experiments to explore matter in various and, sometimes, extreme conditions.

### WP2

**Developing the numerical factory:** new generation and open source simulation codes are already or will be soon available with application to laboratory and natural plasmas. Their ambition is to model plasma kinetics at particle scales and the coupling between macroscopic fluid behaviour and microscopic kinetics as well as the propagation of radiation in complex plasmas structures. Concrete example of this investigation are for instance SMILEI (PIC code), PHARE (hybrid code) and IRIS (3D radiative transfer code).

### WP3

**Innovative experiments and observations:** laboratory experiments and natural plasma observations were used to increase our knowledge and to benchmark models and simulations. Some of them were carried out on large-scale international installations (tokamaks, pulsed-power devices, lasers, heavy-ion beams) that allow matter under extreme conditions to be produced and observed. In the domain of low-temperature laboratory plasmas, new plasma sources and diagnostics have been developed to face the challenges imposed by nanotechnologies, environment, or medicine.

# Structure

## 9 TRUSTEES

- **Sorbonne Université**
- **Observatoire de Paris**
- **Centre National de la Recherche Scientifique**
- **École Polytechnique**
- **École Normale Supérieure**
- **Université Cergy Pontoise**
- **Université Paris-Sud**
- **Commissariat à l'Énergie Atomique et aux Énergies Alternatives**
- **Office National d'Études et de Recherches Aérospatiales**

A Committee of Trustees chaired by the Vice President of Sorbonne Université for research (currently Nathalie Drach-Temam and previously Véronique Atger, director of research of the COMUE Sorbonne Universités) has been meeting at least once a year to define the main strategic orientations and ensure the adequate functioning of the project at scientific and institutional levels.

**7** MEETINGS BETWEEN 2012 AND 2019

## 12 LABORATORIES

### Main Laboratories

- **INSP**, Institut des NanoSciences de Paris
- **LCPMR**, Laboratoire de Chimie Physique – Matière et Rayonnement
- **LESIA**, Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique (since 2015)
- **LERMA**, Laboratoire d'Études du Rayonnement et de la Matière en Astrophysique et Atmosphères
- **LPP**, Laboratoire de Physique des Plasmas
- **LULI**, Laboratoire d'Utilisation des Lasers Intenses
- **ONERA,** Office National d'Études et de Recherches Aérospatiales

### Associated Laboratories

- **CPhT**, Centre de Physique Théorique
- **IAS**, Institut d'Astrophysique Spatiale
- **IJLRA**, Institut Jean le Rond d'Alembert (since 2017)
- **LJLL**, Laboratoire Jacques-Louis Lions
- **LKB**, Laboratoire Kastler Brossel



# Organization

**G**eneral governance is designed together with Sorbonne Université and a global scheme validated within the Consortium Agreement in order to ensure project's best interests: (1) promoting excellence, (2) safeguarding transparency of the decision making process (3) and the independence of the reviewing procedure.

## DIRECTION TEAM

- **Chantal Stehlé,** LERMA, Director
- **Alain Dubois,** LCPMR, Vice-Director (formerly Dominique Vernhet & Pascal Chabert)
- **Xavier Fresquet,** LERMA, Project manager (formerly Dorian Zahorski - 2013-2015)
- **Charlotte Mansour,** Communication Officer (formerly Gwenaëlle Hennequin, 2013-2016 & Mélanie Venet, 2017)
- **Christophe Prigent**, INSP representative
- **Caterina Riconda**, LULI representative and WP1 coordinator
- **Philippe Savoini**, Teaching coordinator

## STEERING COMMITTEE

The Steering Committee (SC) is composed of representatives from each laboratory, the direction team (director, vice-director, project manager) and experts. They have been meeting regularly to make scientific decision, discuss organization and daily issues within the project.

### Steering Committee members:

- **Carine Briand**, LESIA representative
- **Pascal Chabert**, LPP representative
- **Andrea Ciardi**, LERMA representative and WP2 coordinator
- **Alain Dubois**, Vice-Director
- **Thierry Dufour**, WP3 coordinator
- **Paul-Quentin Elias**, ONERA representative and coordinator of actions towards industry
- **Xavier Fresquet**, Project manager
- **Maria Elena Galvez-Parruca,** IJLRA, representative of associated laboratories
- **Chantal Stehlé,** Director
- **Richard Taïeb,** LCPMR representative

### Steering Committee experts:

- **Svetlana Starikovskaya**, WP3
- **Paulo Angelo**, WP3
- **Étienne Pariat**, WP2
- **Dominique Vernhet**, "PHARE" expert

### Former members:

- Jean Larour, WP3
- Antoine Rousseau, WP3
- Julien Labaune, WP3
- Pascale Hennequin, WP3

**36** MEETINGS BETWEEN 2011 AND 2019

## INTERNATIONAL SCIENTIFIC COMMITTEE

The International Scientific Committee (ISC) is composed of both international experts and the laboratory directors. It assesses the largest projects (mostly PhDs and Postdocs projects). In order to avoid any conflict of interest, this evaluation is first done within the group of international experts and then discussed together with the lab's directors. The ISC provided the SC and the Committee of Trustees with recommendations.

### President:

- **Ambroglio Fasoli,** Swiss Plasma Center, EPFL, Lausanne, Switzerland (formerly Marina Galand, Imperial College, London, England, 2012 - 2016).

### Vice President:

- **Vladimir Tikhonchuk**, CELIA, Université de Bordeaux, France

### International experts:

- **Henri Bachau**, CELIA, Université de Bordeaux, France
- **Julien Forest**, ARTENUM, Paris, France
- **Achim Von Keudell**, Department of Physics & Astrophysics, Universität Bochum, Germany
- **Silvano Massaglia,** Department of Physics, University of Torino, Italy
- **Stefaan Poedts**, Department of Mathematics, KU Leuven, Belgique
- **Jean-Michel Pouvesle**, GREMI, Université d'Orléans, France
- **Stephane Zurbach**, plasma propulsion unit, SNECMA, France

### Former member:

- Jean-Pierre Bœuf, LAPLACE, Université de Toulouse, France

### Laboratory directors:

- **Patrick Audebert**, LULI
- **Pascal Chabert**, LPP
- **Vincent Coudé du Foresto**, LESIA
- **Richard Taïeb**, LPCMR
- **Denis Packan**, ONERA
- **Jean-Hugues Fillon**, LERMA
- **Christophe Testelin**, INSP

### Former members:

- Darek Lis, LERMA
- Bernard Perrin, INSP
- Pierre Drossart, LESIA

**7** MEETINGS BETWEEN 2011 AND 2019

## WORKING GROUP FOR PLAS@PAR NEXT CYCLE

PLAS@PAR created a working group to discuss the future of the Labex activities. Researchers met regularly to design the next roadmap: scientific goals/topics, strategy, laboratories involved, etc.

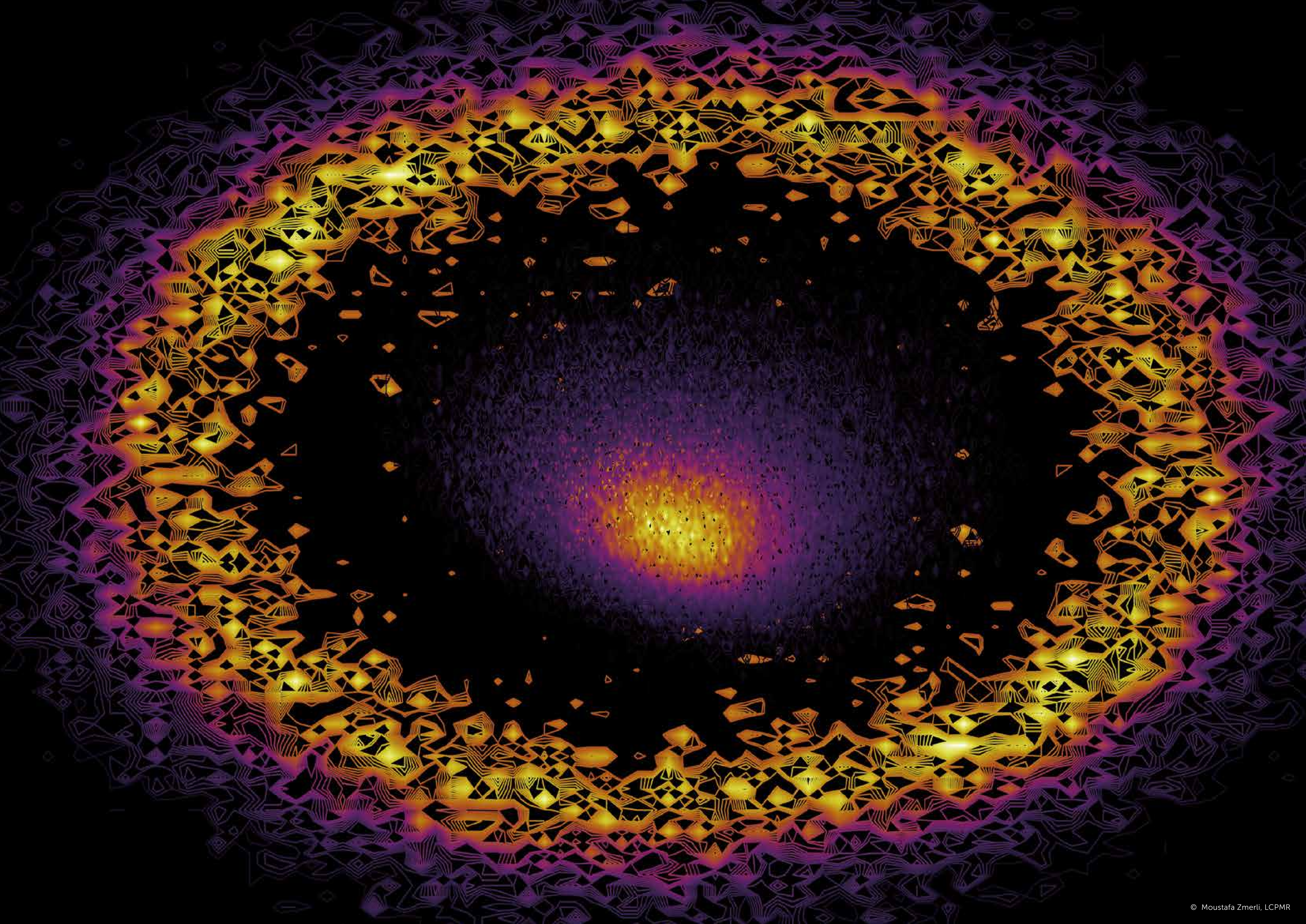
### Members:

- **Caterina Riconda**, LULI
- **Carine Briand**, LESIA
- **Anne Bourdon**, LPP
- **Fouad Sahraoui**, LPP
- **Emily Lamour**, INSP
- **Pascale Hennequin**, LPP
- **Andrea Ciardi**, LERMA
- **Denis Packan**, ONERA
- **Matthieu Berthomier**, LPP
- **Richard Taïeb**, LCPMR
- **Patrick Da Costa**, IJLRA

### Invited:

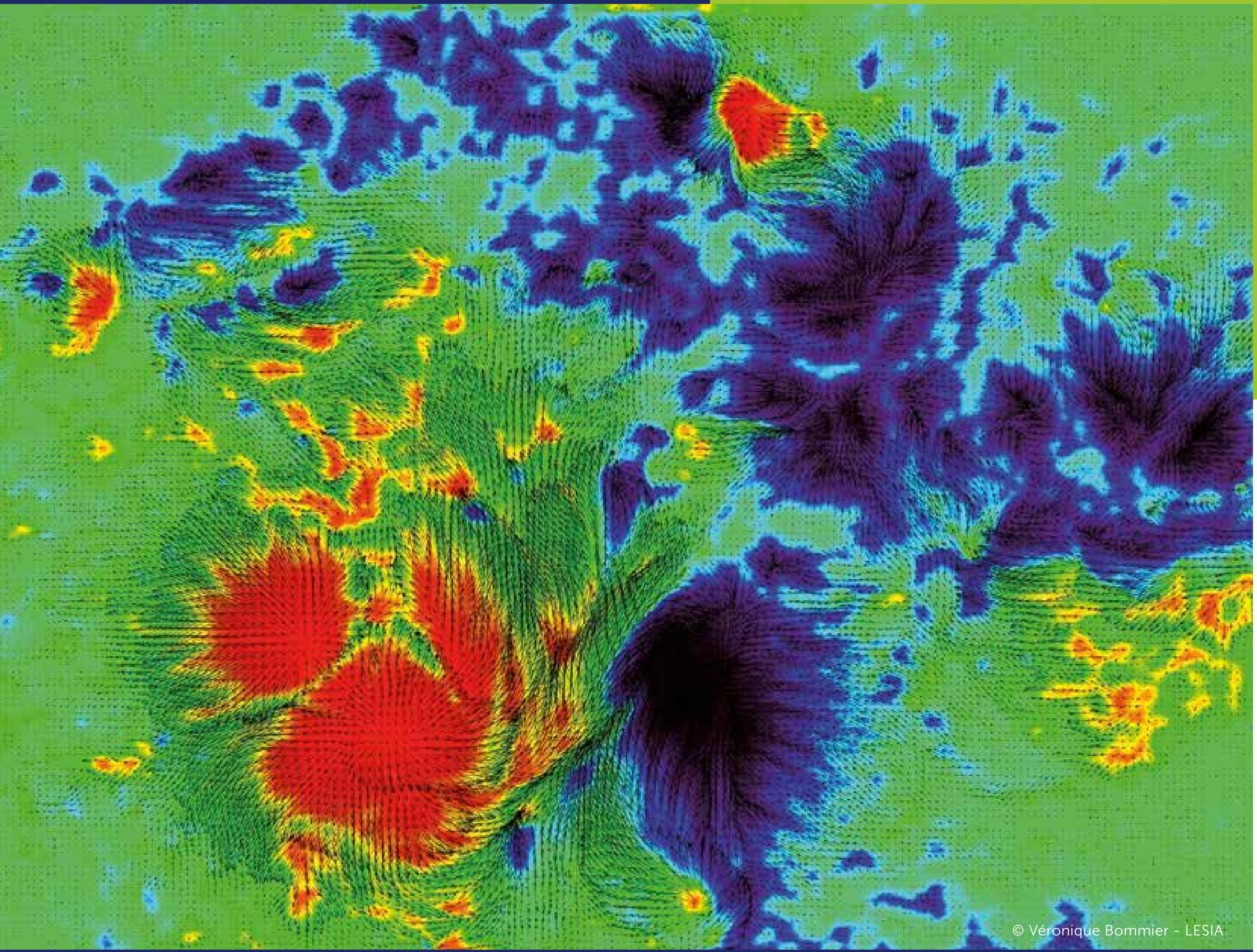
Ronan Modolo, LATMOS
Bruno Despres & Frédérique Charles, LJLL

**8** MEETINGS BETWEEN 2011 AND 2019



CHAPTER 2

# Research



© Véronique Bommier - LESIA

# ATOMIC PROCESSES IN PLASMAS

### EARLY STAGES OF INTENSE PLASMA FORMATION BY LASER

**Leaders**
Anna Levy, Richard Taieb, Dominique Vernhet

**Laboratories involved**
INSP & LCPMR

**External collaborations**
CEA - DAM (France), CELIA Laboratory (Bordeaux University, France), King's College London (UK), Institut für Kernphysik Goethe Universität (Frankfurt am Main, Germany), Institute of Physics of the Polish Academy of Sciences (Poland), Institut Lumière Matière (Lyon University, France), University of Oulu (Finland).

**Projects**
2 equipment projects, 2 innovative small projects, 1 doctoral project (Manuel De Anda Villa, INSP), 2 invitations of international experts (Robert Grisenti, Goethe University; Mathieu Gisselbrecht, Lund University).

**Budget**
180 000€

## Background & objectives

When an intense femtosecond (i.e. $10^{-15}$ second) laser pulse interacts with a system either in the gas or in condensed matter phase, lot of energy is dumped into it, resulting in a non-equilibrium regime.

For atoms or molecules in the gas phase, it leads to ionization and for a solid to its melting, both being at the origin of plasma formation. In this context, challenging time-resolved experiments – at femtosecond or attosecond ($10^{-18}$ second) scales – may help to improve the understanding of the physical processes and material properties in this very early stage of plasma formation. These findings allow to extract information on the dynamics of such systems in extreme conditions that could be obtained either at X-ray Free Electron Laser (XFEL) with very intense X-ray light or at ultra-strong laser facilities in Europe like ELI or APOLLON.

**For PLAS@PAR, this field covers two aspects:**

- Experimentally the objectives are to diagnose the excitation and relaxation of matter under these extreme laser fields by studying the temporal evolution, at the femtosecond time scale, of the electronic structure of a heated solid sample.
- On the theoretical side, and at even shorter time scales, the goal is to study atoms and molecules interacting with intense short low frequency laser pulses in the regime of high-order harmonic generation, and to capture the dynamics of electronic motion in time and space during the non-linear process leading to the generation of intense attosecond light pulses. This is done using a new approach based on the Wigner functions (Figure 2). These functions provide the quantum counterpart of the phase-space representation of a *dynamical* system, with, in addition, regions where the interferences are clearly seen as negative values (red/yellow fringes in between green-positive parts). The latter corresponds to the momenta of the electron that will be released through harmonic generation when the electron recombines with the nucleus.

## Main results

**Concerning experiments**, the temporal evolution of a solid copper sample, heated by an Infrared femtosecond laser, has been successfully measured at the CELIA lasers facilities thanks to the prior development of the required XUV beamline *[Fedorov et al., in prep]* based on High-order Harmonic Generation (HHG) *[L'Huillier A. et al., 2017]*, that delivers femtosecond pulses with the mandatory photon energy (80 – 100 eV) (Figure 1). The interpretation of the experimental data, performed in collaboration with R. Grisenti (Goethe University), indicates a valence band modification occurring in the first 10's of picoseconds following the interaction with the HHG beam. The detailed information contained in these experimental results are currently interpreted through molecular dynamics simulations performed at CEA.

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*Figure 1: XUV beamline developed at CELIA laboratory based on High-order Harmonic Generation delivering femtosecond 80-100 eV photon energy pulses.*

**Concerning the question of non-linear interaction of attosecond pulses with gases,** our theoretical study performed in partnership with A. Zair (King's college London) showed that the formalism of Wigner distribution functions to treat the wavefunction or the HHG signal gives valuable information on the physical processes that could be experimentally observed, *[Risoud, 2016]*. In particular, we could observe the signature of the different quantum electron trajectories within the laser field that lead to the emission of harmonic light *[publication in prep]*.

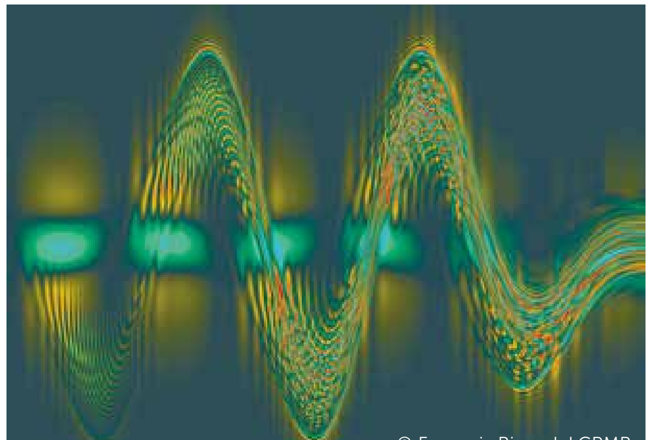

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*Figure 2: Wigner distribution at x = 0 of wave-function as a function of time (absciss) and momentum (ordinate), obtained by solving the Time Dependent Schrödinger Equation for a model system interacting with a strong ultrashort InfraRed pulse. We can clearly see the different momenta of the electron coming back to the nucleus, which will be released through the emission of a harmonic photon by rescattering (PLAS@PAR prize of the best plasma image in 2015).*

## Perspectives

These innovative experimental developments of the INSP group provides important perspectives for the study various structural phenomena on solid samples ranging from metals to semiconductors. It also opens the way for the investigation of phase transition in nanoparticles. The latter has been already initiated through synchrotron facility experiments *[de Anda Villa et al., 2019]*.
The outgoing collaboration between LCPMR's theoretical group with King's College London will allow to perform new experiments to extract directly a phase-space representation of the electronic wavefunction of an atom interacting with a strong laser field.

## Focus

After a Bachelor's degree in Mexico, **Manuel de Anda Villa** moved to the USA where he got a Master's degree in Physics before joining the team "Clusters and Surfaces under Intense Excitation" at Paris Institute of Nanosciences (INSP) for a PhD funded by PLAS@PAR: Time-resolved studies of the gold solid-liquid phase transition at the femtosecond timescale. He defended his PhD in December 2019.

## References


- *De Anda Villa, M., et al., 2019, Assessing the Surface Oxidation State of Free-Standing Gold Nanoparticles Produced by Laser Ablation, Langmuir, 39, 36, 11859-1187, https://doi.org/10.1021/acs.langmuir.9b02159*
- *L'Huillier, A., Balcou, P., 2017, High-order harmonic generation in rare gases with a 1-ps 1053-nm laser, Phys. Rev. Lett, 70, 774, https://doi.org/10.1103/PhysRevLett.70.774*
- *Risoud, F., 2016, Theoretical study of attosecond dynamics in atoms and molecules using high-order harmonic generation as a self-probe, PhD Thesis Université Pierre et Marie Curie*

## COLLISIONS & ELEMENTARY PROCESSES IN PLASMAS

**Leaders**
Christophe Blondel, Alain Dubois, Pascal Lablanquie, Émily Lamour, Jérôme Palaudoux, Francis Penent, Christophe Prigent, Marc Simon, Nicolas Sisourat, Dominique Vernhet

**Laboratories involved**
INSP & LCPMR

**External collaborations**
CIMAP laboratory (École Nationale Supérieure d'Ingénieur de Caen, France), GANIL (France), Instituto de Física Rosario and Facultad de Ciencias Exactas (Argentina), GSI and Jena University (Germany), Institute Josef Stefan (Slovenia), Institute of Applied Physics and Computational Mathematics (Beijing, China), ISMO, Niigata University, Toyama University, Photon Factory and Saga synchrotron (Japan), Université Moulay Ismail (Meknes, Morocco), University of Crete (Greece), University of Technology (Gotheborg, Sweden).

**Projects**
3 equipment projects, 4 innovative small projects, 2 doctoral projects (Mehdi Khalal and Alessandra Puglisi, LCPMR), 1 postdoctoral project (Daniel Schury, INSP), 9 invitations of international experts (Theo Tzouros, University of Crete; Abdelkader Makhoute, Université Moulay Ismail; Kouichi Soejima, Niigata University; Tatsuo Kaneyasu, Saga Light Source; Kenji Ito, Photon Factory; Alexandre Gumberidze, GSI; Maria Novella Piancastelli, Uppsala University; Alexei Grum-Grzhimailo, Lomonosov Moscow State University).

**Budget**
453 000€

# Background & objectives

During the period the study of collisions and elementary processes in plasmas has been focused on ion-ion/atom collisions and on photon-ion interactions.

**Regarding ion-ion collisions**
The development of new world class accelerators such as GANIL/SPIRAL2 (in France) and FAIR/CRYRING (in Germany) opens the door to new exploration of ion - ion collisions, in particular in a regime where the ion energy transfer is maximum. In this regime all the primary electronic processes (transfer, loss and excitation) reach their optimum probability and lead to strong effects on the projectile and/or target electrons structure and motion. A paradoxical situation has thus to be overcome since none of the theories is applicable whilst, in this energy regime, "sample" modifications are the strongest. Outcomes in different domains such as ion energy transfer in various plasmas, e.g. inertial fusion, stellar and interstellar plasmas, are therefore of prime importance. An ambitious long-term experimental program to measure the cross sections of elementary collisional processes, never attempted so far, is being carried out. This is the goal of the Fast Ion (MeV/u) - Slow Ion (keV/u) collision (FISIC) international project led by É. Lamour (INSP), with an innovative experimental crossed-beam arrangement for a wide range of projectile (fast ion) and target (slow ion) combinations, with perfect control of the experimental conditions, in order to measure absolute cross-sections. FISIC will explore the role of electrons bound to the ion target and/or to the ion projectile -one by one-, quantify several effects such as the electron-electron interactions, the importance of the multi-electron processes and the role of Coulomb forces acting on the electron cloud (entrance and exit pathways of the collision). Therefore, these studies should provide original data on quantum dynamics of N-body systems. Performing ion-ion experiments remain a real challenge in order to perform absolute cross section measurements.
To model ion-atom or ion-ion collisions, two original codes, based on a semiclassical non perturbative approach, have been developed at LCPMR. They allow the calculation of reliable cross sections for electron transfer, excitation and ionization processes involving up to three active electrons. The covered energy domain is wide, from 0.1 keV to 1 MeV/u. The objectives of our theoretical projects are two-fold, covering (i) the theory of elementary processes at the most fundamental level and (ii) producing cross sections for collision systems of relevance for astrophysics and magnetic fusion energy devices (ITER) within Coordinated Research Project organized by the International Atomic Energy Agency.

**Regarding ionic spectroscopic data**
Many detailed experimentally validated ion properties are still missing and the development of Synchrotron sources (e.g. SOLEIL in France) is an opportunity to fill the gap. As experiments on ion beams are extremely difficult and rare, they are now carried out only in France and in Denmark in the EU. Spectroscopic data on ions can also be gained indirectly by multiple-photoionization of neutral targets. Since 2005, magnetic bottle electron spectrometers allowed detailed investigations on these multiple photoionization processes, such as single and double inner shell ionization and the relaxation processes by emission of secondary electrons (Auger electrons). In this context, the objectives are to develop the photoelectron spectroscopy at the MAIA end station of the PLEIADES beam-line at SOLEIL, and to develop multi-coincidence approaches with the HERMES Magnetic Bottle experiment at LCPMR laboratory. This last approach can give access to the energy levels of multiply charged ions and to the double core ionization processes. More specifically, we wanted to develop a method discovered in 2013 by the LCPMR group *[S-M Huttula et al., 2013]* to gain information on inner shell ionization of ions and their subsequent Auger decay.

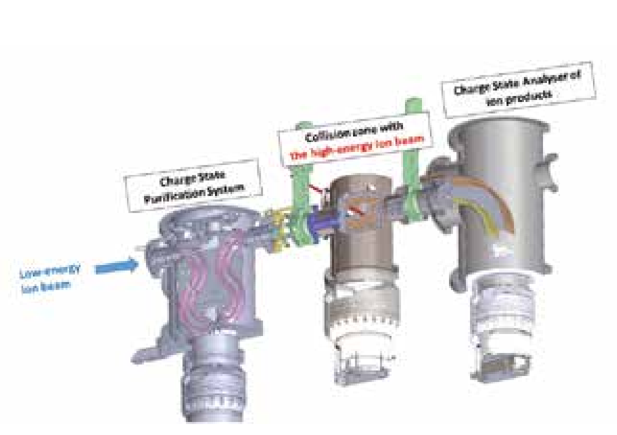
# Main results

In general, concerning ion-ion collisions the experiments on ion beams facilities request to overcome various technical issues: full control of the ion charge state upstream the collision, possibility to slightly change the energy of the low-energy ions in the interaction zone to tag the true events from the ones coming from collisions with the remaining atoms in the residual gas, difficulty to analyze in one step the collision products.

**Here are the main results obtained recently:**

- Selection of the desired charge state for the fast ions: the interaction of a MeV/u ion with a solid thin foil permits to efficiently change its initial charge state. Our ETACHA code recently extended *[Lamour et al., 2015]* is able to predict the evolution of the ion charge state distribution as a function of the solid foil thickness. Thus, we can determine the most appropriate foil nature and thickness to optimize the production of the desired ion charge state for the collision.

- Design of the FISIC charge state purification system (i.e. the interaction zone and the product analyzer for the low energy ion): thanks to ion trajectory simulations and on-line tests, great progress has been recently performed for the preparation, control and analysis of the slow ions. A schematic view of the final design is shown in figure 1. A newly built omega-type electrostatic analyzer, designed to act as an in-line charge state purification system for ions in the keV/u energy range, has been successfully tested at the ARIBE beam-line at GANIL in 2017 and 2018 *[D. Schury, 2019]*.




© FISIC project

*Figure 1: Sketch of the Low-energy Channel of the FISIC project.*

**Concerning the theoretical study of ion-atom or ion-molecules collisions**, during the last 8 years, an important effort to develop, optimize and extend the use of our codes was done to be able to cover more complex collision systems than 1-active electron ones of importance for application in plasmas physics. More than 6 articles have been published, including one in 2019 for general collision purposes *[W. Gao et al., 2019]* and one in 2018 *[A. Taoutioui et al., 2018]* with focus on fusion plasma collision systems.

**As photoelectron spectroscopy on ion beams is extremely challenging**, only 4 papers were published in the 1990's up to recently. The LCPMR team re-launched such studies at Soleil synchrotron in collaboration with local teams. The detection of the photoelectron in coincidence with the resulting ion has been demonstrated in the observation of 4d inner shell ionization of $Xe^+$ ions *[Khalal et al., 2017]*. Based on this achievement, we upgraded the detection of the photoelectron using a position sensitive detector, instead of simple chaneltrons.

**Here are the main results from the HERMES experiment linked to plasma physics:**

- The double core holes in molecules: although they have a low probability ($\sim 10^{-3}$) to be formed by single photon absorption, the sensitivity of our coincidence technique allows a detailed study of their properties. Recent focus has been on the path in which a core electron is ionized, while a second core electron is excited *[Carniato et al., 2015]*.

- The decay of transient ionic states with an inner shell hole: this decay takes place through the emission of one or several Auger electrons. One of our major results concerns the study of the mechanism of 3 Auger electrons emission in Argon and the selectivity of the decay of oriented 3d holes in HBr molecule *[Palaudoux et al., 2018]*.

- The inner shell ionization of $Xe^{+}$ ions: we used the method of core - valence double ionization proposed in 2013 *[S-M Huttula et al., 2013]*, which is sensitive enough to reveal the detailed subsequent Auger decay *[Khalal et al., 2017]*, (Figure 2).

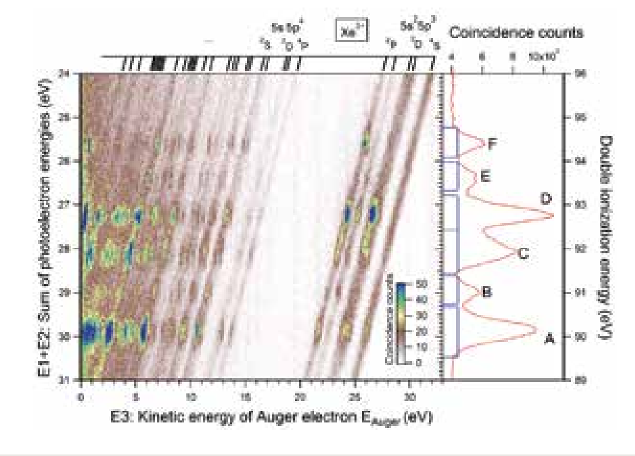



*Figure 2: Results on 4d innershell ionization of $Xe^{+}$ ions, in a simulation experiment [Khalal et al., 2017] performed on neutral Xe and with the HERMES Magnetic Bottle experiment. The 2-dimensional map displays energy correlations between the sum of two photoelectron's energies E1 + E2 (y-axis) and that of a third electron (x-axis), all detected in coincidence. Projection on the y-axis reveals the $Xe^{2+}$ $4d^{-1}$ $5p^{-1}$ levels, while intensity along the associated horizontal lines show their Auger decay. [From Khalal et al., 2017]*

# Perspectives

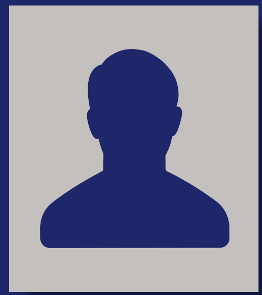
The first ion-ion experiments should be carried out on the CRYRING ion storage ring since the commissioning of the facility is in time. In 2019 the low-energy purification system has been mounted with our new beam line. The ensemble will be then tested with the SIMPA ion source located at the INSP laboratory.

On the theoretical standpoint, the LCPMR team is aiming to continue the dual approach, i.e. fundamental atomic and molecular collision physics and cross sections productions for plasma physics. Two relevant directions to develop will be the low impact energy domain (cold plasmas) and ion-ion collisions in relevance for the new experimental facilities.

Regarding photoelectron spectroscopy, increased sensitivity of the new equipment on ion beams was demonstrated in 2018 on $Xe^{5+}$ ion beams *[J-M Bizau et al., 2016]*. Experiments on $SiH_n^{+}$ ions are planned in 2019. The HERMES experiment campaigns on SOLEIL synchrotron have given a wealth of results which are being analyzed now. Among the interesting points: the decay of asymmetric double core holes (with holes in different shells). Additionally, we are now able to launch our new long-term project for a new spectrometer giving access to high resolution filtered Auger spectroscopy, for fundamental and applied research.

We note also the starting experiment at LPP on the photodetachement of $D^{-}$ in the presence of a magnetic field, which could eventually provide an alternative scheme for the injection of neutral deuterium atoms in Tokamak fusion reactors.

# Focus



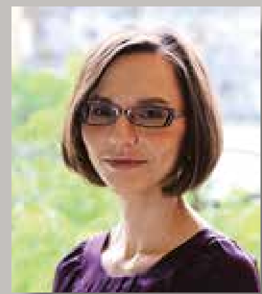
**Mehdi Khalal** got a Bachelor's degree in Algeria and a Master in "Optics, Matter and Plasmas" at Sorbonne Université before joining the HERMES team "High Energy Resolution Multi Electron Spectrometer" at LCPMR for a PhD funded by PLAS@PAR. He defended his thesis "Multiple Photoionization of metallic vapours" on September 17, 2018.

After a PhD in Germany, **Daniel Schury** came in 2018 in Paris for a postdoctoral position at INSP with the team ASUR "Agrégats et Surfaces sous excitations intenses (ASUR)". He actively works on the FISIC project, to study of ion-ion collisions when the energy transfer is at its maximum.

**Alessandra Puglisi** got her Master degree at the University of Palermo in Italy before joining the LCPMR for a PhD in "Physical and Analytical Chemistry on the Spectroscopic study of silicon hydride molecular ions", which she defended in September 2017. In 2016, she obtained the **poster prize at PCPMS** (Physical and Chemical Principles in Materials Science). In 2017, she worked at Scuola Normale Superiore in Pisa on the Study of spectroscopic properties of systems in complex environments; now she's in the industry sector.

# Awards

**Nicolas Sisourat**, associate professor at LCPMR (Sorbonne Université), has been awarded in 2019 by the **prize Aimé Cotton** from French Physics Society (SFP) for his contribution to the development of theoretical and numerical methods to describe the ultra-fast electronic and nuclear processes occurring during the interactions of atoms or molecules with radiation or with ions.



**Tatiana Marchenko**, LCPMR, **bronze medal at CNRS in 2018**, is a specialist in atomic, molecular and optical physics, with a particular focus on ultrafast dynamics studies in molecules and atoms in the gas phase. Her experimental activities mainly concern different X-ray spectroscopy techniques performed on large instruments, mainly synchrotron and more recently XFEL (X-ray Free Electron Laser). One of the latest highlights of Tatiana Marchenko and her collaborators (international and LCPMR colleagues) deals with an original spectroscopy technique based on double-core-hole formation to probe nuclear and electron dynamics in molecules.

**Oksana Travnikova, LCPMR, bronze medal at CNRS in 2019**, works on ultrafast dynamics of electron relaxation and nuclear motion induced by hard X-rays. She is the PI of the ANR JCJC MUSTACHE and the first author of two Physical Review Letters in 2016 and 2017. She is also involved in the development of the MOSARIX X-ray emission spectrometer funded by PLAS@PAR. She participates in several experiments on XFEL and synchrotron light sources and particularly with the LCPMR's HAXPES and CELIMENE instruments in France.

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# OPACITY AND EMISSIVITY OF HOT LABORATORY AND ASTROPHYSICAL PLASMAS

**Leaders**
Franck Delahaye, Frank Rosmej, Sylvie Sahal-Bréchot, Lydia Tchang-Brillet

**Laboratories involved**
LERMA & LULI

**External collaborations**
Ohio State University (Columbus, USA), Astronomical Observatory (Belgrade, Serbia), National Research Center Kurchatov (Moscow, Russia), Russian Academy of Sciences (Troitsk, Russia), University of Fudan (Shanghai, China), Lund University (Sweden), LCLS, National Accelerator Laboratory (Stanford University, California, USA), LPCQ (University Mouloud Mammeri, Tizi-Ouzou, Algeria).

**Projects**
3 equipment projects, 1 doctoral project (Florian Condamine, LULI), 7 invitations of international experts (Marc Pinsonneault, Ohio State University; V. S. Lisitsa & A. V. Demura, National Research Center Kurchatov; Milan S. Dimitrijevic, Astronomical Observatory, Belgrade; Alexander Nikolaevich Ryabtsev, Russian Academy of Sciences, Troitsk).

**Budget**
176 000€

## Background & objectives

Atomic data and derived quantities like opacities and radiative accelerations are crucial building blocks in many domains of research in general and in plasma physics in particular. From the analysis of astronomical spectra to the modelling of our Sun and other stars, from Active Galactic Nuclei (AGN) studies to the simulation of magnetized plasmas, whenever radiative transfer plays a role, the atomic data are of prime importance. In order to provide the quality required depending on applications, we approach the determination of such atomic coefficients using 3 points of view: Theory – Experiments – Applications. Hence, we can take into account the feedback from any approach to ascertain uncertainties attached to our data, define the regime/physical conditions of validity and improve the theory and codes used.

These long-term projects aim at calculating and measuring fundamental atomic parameter and opacities and at using them in applications to estimate the effect of their uncertainties. Here, we focus our studies on Fe-group elements and lanthanide atoms, where the calculation is particularly challenging due to the large number of bound electrons.

This topic is particularly important for stellar applications and in the case of W (tungsten) for nuclear fusion in the context of ITER's divertor *[Ryabtsev et al., 2013]*.

## Main results

Using high voltage vacuum discharges, we have investigated complex spectra of atomic ions using the 10.7 m high resolution vacuum normal incidence spectrograph of Paris Observatory.

The emission spectra of moderately ionized heavy elements, such as transition metals and rare earths, have been analyzed to provide identified lines, energy levels, semi-empirical transition probabilities and Landé factors, which are fundamental for modeling fusion and astrophysical plasmas.

**The results concern in particular:**

- VUV spectra of $W^{7+}$ and $W^{8+}$ and neighbouring isoelectronic ions (Hf, Ta and Re) *[Ryabtsev et al., 2014 and 2015]*, those of lanthanide ions ($Tm^{3+}$, $Yb^{4+}$, $Er^{3+}$ and $Nd^{3+}$), and other heavy ions ($U^{+}$ and $Os^{2+}$) *[Meftah et al., 2017]*, and also M1 and E2 transitions for the lanthanide ions *[Tchang-Brillet et al., 2018]*. Most of the data are available online (molat.obspm.fr).
- High resolution vacuum spark emission of Mn, Fe and Ni ions have been recorded and measured. The analysis of $Mn^{3+}$ has been completed and is at the drafting stage.

Beside emission spectra we also work on absorption. A new experimental setup to measure Fe group element opacities at $T_{sample}$~ 50 eV and $N_{e-}$ ~ $10^{21}$ cm$^{-3}$ is planned in 2019-2020 on the Gekko XII laser (Japan) in the framework of a collaboration between LERMA, LULI and ILE (Japan). This will pave the way to adapt onto Laser MégaJoule (France) in the future, to reach temperatures and densities ($T_{sample}$= 180 eV and $N_{e-}$ = $10^{21}$ cm$^{-3}$) found in our Sun and other stars. These experiments are useful to solve the Solar composition problem. Theoretical work is already underway *[Delahaye et al., 2019 to be submitted]*.

Still at high temperature (~ 700 eV) and high density ($10^{21-22}$ cm$^{-3}$), Florian Condamine (PhD at LULI) showed for the first time, as part of an experiment at SLAC, the fundamental importance of frequency and population redistribution mechanisms in the case of resonant pumping by XFEL radiation of He-like transitions at different excitation levels of a vanadium plasma generated by a sub nanosecond optical laser. This result is particularly important In order to correctly interpret the X-radiation emitted by dense and hot laboratory and astrophysical plasmas and to understand the population mechanism of the different ions of the element considered.

On the theoretical side, a new standard for stellar codes is being developed: started in October 2018, the collaboration between Paris Observatory and Ohio State University will provide a new stellar code including on the fly opacity calculation and micro-diffusion processes. The parallelization of the opacity subroutines is underway (collaboration with IDRIS HPC center) and a new set of opacity is already tested on the existing stellar evolution codes like YREC, CESAM end TGEC.

Accurate spectroscopic diagnostics and modeling require also the knowledge of numerous collisional line profiles, among them Stark profiles. With the help of a Paris Observatory code extended within a collaboration between LERMA and Belgrade Observatory, numerous calculations for a wide range of densities and temperatures have been carried for Isolated lines of neutral and ionized atoms broadened and shifted by collisions by electrons and ions in the conditions of warm experimental and astrophysical plasmas *[Dimitrijevic et al., 2015; Sahal-Brechot et al., 2018; Hamdi et al., 2019]*. The results are published in refereed journals and integrated in the STARK-B database (http://stark-b.obspm.fr), which is a node of the European consortium VAMDC (Virtual Atomic and Molecular Data Centre, http://www.vamdc.org/) aiming to provide and use of interoperable atomic and molecular data.

## Perspectives

A compact source EBIT, in collaboration with Y. Yang, R. Hutton (Shanghai) and T. Brage, combined with the VUV spectrograph of the Paris Observatory (Meudon) will allow to reach higher ionic states of Fe. The goal is to measure precisely the $3p^4 3d\ 4D_{5/2} - 3p^4 3d\ 4D_{7/2}$ fine structure energy interval in $Fe^{9+}$ ion. This is crucial for the determination of the Solar Corona magnetic field using magnetic induced transitions (0 - 0.2 T).

The new YREC stellar code will define the new standard of Stellar code and will allow us to provide grid of models to the space missions TESS and the future PLATO.

A new set of more precise opacities will be provided for stellar codes by the Opacity project (http://cdsweb.u-strasbg.fr/topbase/testop/home.html), including the contributions of more astrophysical elements). This Opacity project is the only project providing the raw atomic data, monochromatic opacities, mean opacity and radiative acceleration tables derived from atomic data. *[New Opacity tables from The Opacity Project, Delahaye, Cerfolli, Pinsonneault to be submitted, 2019]*

## Focus

**Florian Condamine** did all his university studies at Sorbonne Université. During his PhD he worked on X-ray spectroscopy on dense plasmas produced by 4th generation Light Sources at LULI. He's now working at ELI Beamlines (Czech Republic) as a postdoctoral fellow.

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# PLASMA DYNAMICS

## TURBULENCE FROM SOLAR WIND TO TOKAMAKS

**Leaders**
Olga Alexandrova, Dominique Fontaine, Roland Grappin, Ozgur Gurcan, Pascale Hennequin, Jean-François Panis, Filippo Pantellini, Fouad Sahraoui

**Laboratories involved**
LESIA, LPP, LERMA

**External collaborations**
University Wuhan (China), University Buenos Aires (Argentina), University Florence (Italie), Seoul National University (Korea), University of California San Diego (USA).

**Projects**
1 equipment project, 1 small innovative project, 5 postdoctoral projects (Katy Ganthous, LPP; Nahuel Andrés, LPP; Shiyong Huang, LPP; Andrea Verdini, LPP & LESIA; Denis Kuzzay, LESIA), 4 invitations of international experts (Emilia Kilpua, University of Helsinski; Taik Soo Hahm, Seoul National University; Simone Landi, Universita degli Study di Firenze; Daniel Osvaldo Gómez, University of Buenos Aires).

**Budget**
372 000€

## Background & objectives

Turbulence in magnetized plasmas is a very active area of research because of the role that it plays in different astrophysical objects and experimental devices. Turbulence manifests itself in the form of non-linear, dynamical interactions among different kinds of structures (eddies, vortex sheets, current filaments, zonal flows etc).

**In the heliosphere,** turbulence is thought to be responsible for contributing to the heating of the solar corona and the acceleration of the Solar Wind. In the interstellar medium, turbulence generated by supernovae explosions plays a role in star formation by preventing the collapse of self-gravitating molecular clouds. In accretion disks of black holes or neutron stars, turbulence is thought to be generated by the Magneto-Rotational Instability (MRI) that allows converting the gravitational potential energy of the inflowing mass into MHD turbulence at the outer scale (i.e., scale size of the disk height), which then cascades to smaller scales (following the classical picture of MHD cascade), where it is converted into heat. This heating is observable through the energetic X-rays and radio emissions emitted by these disks.

**On Earth, in tokamaks,** turbulence that can be generated by different plasma instabilities due to strong density and temperature gradients (e.g., Ion or Electron Temperature Gradient, ITG and ETG) is the major obstacle that prevents long-time plasma confinement.

In all these media, unraveling the turbulence properties is crucial to better understand how it affects processes such as mass transport, particle heating and/or acceleration. PLAS@PAR supported different research programs that have been undertaken in the past in different groups. These works include theoretical, numerical and observational studies of turbulence and energy dissipation in the near-Earth space (the magnetosphere and the solar wind) and in fusion plasmas.

**The projects funded by PLAS@PAR aimed at investigating different facets of plasma turbulence:**

- For space plasmas, this concerns its scaling laws and spatial anisotropy, the global and local energy transfer rates, the kinetic scale turbulence and the processes of particle energization. The works were done using theoretical models, numerical simulations and *in situ* spacecraft observations in the solar wind and the terrestrial magnetosheath.
- The development of numerical tools which are adaptable to both magnetic fusion plasmas (i.e. for drift waves) and solar wind plasmas (Hall / MHD turbulence). The goal is to inspect the link between the different types of structures using simple hierarchical tree models which are expected to represent both spectra and its spatio-temporal dynamics reasonably well. The results can form the basis of a comparison with global gyrokinetic simulations and correlation reflectometry measurements in fusion plasmas and the data from the STAFF/FGM detectors of the CLUSTER space mission in solar wind turbulence.
- The experimental detection of the presence and dynamical evolution of turbulent structures, like blobs and filaments, at the boundary of magnetic plasmas like TORIX at LPP. To catch images of such dynamical structures, a fast camera (Photron Fastcam SAZ) has been acquired (up to 1 Mf/s or 20 kf/s in full resolution 1024x1024, with a Memory – 64 GB- adapted for duration ~1 to 5 s). This camera is shared with the propulsion teams at LPP and ONERA, for imaging of thruster's plasmas.

## Main results

**For space plasmas**

**Important results on turbulence were obtained and published in peer-reviewed journals. This includes:**

- The determination of the role of the non-linearities and the wind expansion in controlling 3D spatial anisotropy of the turbulence and structures (tubes vs. ribbons) *[Verdini et al, ApJ, 2019]*.
- The development and application of a new method that allows obtaining and estimating the local energy transfer rate in incompressible MHD turbulence *[Kuzzay et al., Physical Review E, 2019]*.
- The derivation of various exact laws of compressible isothermal turbulence in MHD and Hall-MHD in view of using to estimate the global energy cascade rate in space plasmas *[Andrés et al., PRE, 2018]*.
- The first statistical characterization of the nature and scaling laws of plasma turbulence at MHD and kinetic scales in the magnetosheath *[Huang et al., ApJL, 2014; Huang et al., ApJL, 2017a]*.
- The evidence of new electron-size coherent structures (electron vortex, electron holes) and their role in energizing the plasma particles using *in situ* data from the new NASA/MMS mission in the magnetosheath (Figure 1) [*Huang et al., GRL, 2016; Huang et al., ApJL, 2017b*].

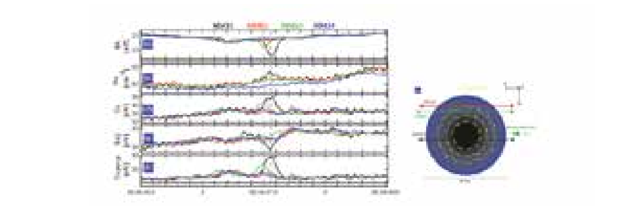


*Figure 1: First evidence of an electron-scale vortex (~ a few km) in the Earth's magnetosheath by the four satellites of the NASA Magnetospheric Multiscale Mission (MMS) mission (right) and the different signatures associated to it (dips in the magnetic field, pick in density, electron heating in the perpendicular direction and cooling in the parallel one). Adapted from [Huang et al. 2017].*

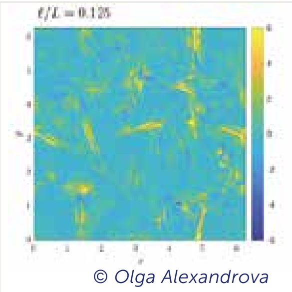



*Figure 3: Local energy transfer rate in incompressible MHD turbulence. The cascade can go in both directions (direct and inverse positive and negative sign) at the same time and the maximum transfer is located in the structures.*

The visit of Pr. Gomez (Univ. Buenos Aires, UBA) to LPP allowed for initiating strong collaboration between the two groups (e.g., link between turbulence reconnection, exploiting the code GHOST developed at UBA in turbulence studies at LPP) *[Andrés et al., PRE 2018, PoP, 2017]*. These collaborations continue within the CNRS-CONICET LIA (Laboratoire International Associé) MAGNETO (2017-2021) in which LPP is an active member.

After they left LPP, S. Huang and N. Andrés were hired as permanent staff members at Wuhan Univ. and UBA, reinforcing the existing collaboration between LPP and their institution.

**For magnetic fusion plasmas**

**The principal results include:**

- The identification of a transition scale for dissipative drift wave turbulence *[Ghantous & Gurcan, 2015]* as "the scale at which the nonlinear eddy turnover rate is balanced by parallel streaming rate of the electrons".
- The development of a shell model *[Ghantous & Gurcan 2015]* and then a hierarchical tree model *[https://github.com/katazmic/tree]* for plasma turbulence and standard 2D fluid turbulence in rotating fluids and able to address various fundamental physics issues in plasma fusion devices, such as turbulence spreading, and formation of small-scale turbulence spectrum via interactions with zonal flows, etc.
- Pr. Hahm (one of the founding fathers of non-linear gyrokinetic theory), visited LPP many times, gave 3 different pedagogical seminars on gyrokinetics, zonal flows, and on the isotope effect, in addition to informal talks and discussion which lead to numerous ongoing studies and collaborations (including a thesis at the LPP funded by the Chinese Scholarship Council).
- A new collaboration was established on bounced averaged gyrokinetics between IJL-Univ. Lorraine, Seoul National University and LPP.
- In terms of experiments, the fast camera allowed the study of the turbulence flow interaction and predator prey dynamics (Figure 2). The experimental results on TORIX were cross validated with other of turbulence diagnostics: Langmuir probes, light scattering.

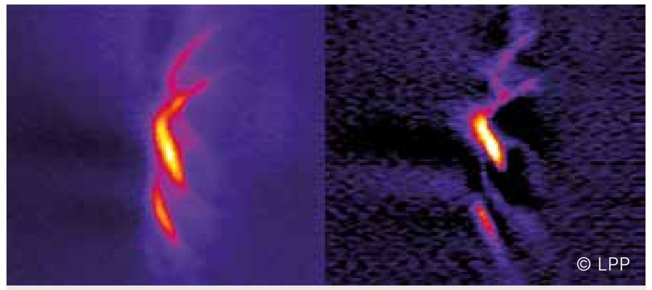



*Figure 2: Fast Imaging of ToriX plasmas, showing a poloidal section along a toroidal view: (left) plasma in a helical configuration (small vertical field compared to the toroidal field) (right) fluctuations of the light intensity showing filamentary structures.*

# Perspectives

There is a clear trend in space plasmas toward exploring the kinetic scales of the turbulence (sub-ion and electron scales) where the energy dissipation becomes important using the MMS that yields will be unprecedented high time resolution of the plasma and kinetic (hybrid, PIC or Vlasov codes). On the other hand, the Parker Solar Probe (PSP) mission explores the very inner heliosphere, a region of space never explored before, where the solar wind is accelerated (~10 solar radii). This mission will bring strong constraints on the solar wind generation/acceleration models and on the evolution of the turbulence dynamics as a function of the radial distance.

Concerning the link between magnetic fusion and space plasmas, the tree model can be extended rather easily to 3D Magnetohydrodynamic (MHD) turbulence (i.e. the tree model would still be 1D, but it would be tailored to represent 3D MHD turbulence, paying attention to the details of the geometry).

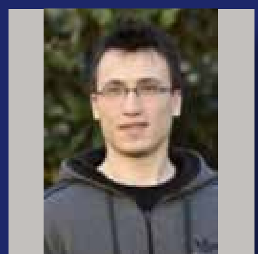
The results obtained at TORIX with the fast camera will be confronted to similar measurements in larger magnetic fusion devices where LPP instruments are installed.

# Focus

**Nahuel Andrés** obtained his PhD in Space Physics from the University of Buenos Aires (UBA) in 2016. He joined LPP in 2016 to work on theoretical, numerical and observational aspects of space plasma turbulence, and was supported by École Polytechnique Fellowship, PLAS@PAR, then DIM-ACAV grants. As a postdoc, Nahuel Andrés co-authored about 10 papers (7 of which as 1st author). Since February 2019, he obtained a permanent position at the Institute of Astronomy and Space Physics at Buenos Aires (UBA-CONICET) and a teaching assistant at the Physics Department (UBA) at Argentina. He still collaborates closely with the LPP turbulence team.

After a PhD (2007-2013) in Plasma Physics at Princeton University, in the Princeton Plasma Physics Laboratory, **Katy Ganthous** joined LPP to work with Ozgur Gurcan in October 2013 on the development of models for studying turbulence in the Hasegawa-Wakatani (HW) model. In October 2014, she obtained a 1 year postdoctoral position from PLAS@PAR to work on a hierarchical tree model approach to plasma turbulence in magnetised fusion and space plasmas. She is now Senior Data Scientist at Applecart.

**Shiyong Huang** received his PhD on 2012 in space physics at Wuhan University. He joined LPP space plasma physics group in 2013 for a 2 year postdoctoral project on "Turbulent cascade, intermittency and heating in the solar wind from MHD to kinetic scales" with Fouad Sahraoui together with Jean-François Panis (LERMA). S. Huang holds now a Full Professor position at the University of Wuhan.



**Denis Kuzzay** received his PhD on 2016 at Service de Physique de l'Etat Condensé, CEA Saclay, France "Investigations on the relevance of Onsager's conjecture in real incompressible turbulence", supervised by Dr. Bérengère Dubrulle. After a year in ENS-Lyon, he joined LESIA plasma physics group in 2017 for a 1.5 year postdoctoral project on "Study of local energy transfers in the MHD turbulent". He is now creating his start-up on "Performant numerical solutions in aeroacoustics".

**Andrea Verdini** defended his PhD entitled "Magneto-hydrodynamic turbulence sustained by Alfvén wave reflection in the solar atmosphere and solar wind" in February 2007 at Florence University. After different postdoctoral positions in Europe, he joined in 2016 PLAS@PAR to work on the anisotropy of the turbulence in the solar wind with Olga Alexandrova (LESIA) and Roland Grappin (LPP). He got a researcher position at the University of Fiorenze in November 2016.

# Awards

In 2017, **Pascale Hennequin,** Research Director CNRS (LPP), was honored by the Helmholtz Association with the **Helmholtz International Fellow Award**. She is a specialist in the fields of plasma diagnostics and nonlinear plasma dynamics. Using microwave diagnostic systems, she has studied the dynamics and statistical properties of plasma turbulence in various conditions in different magnetic fusion devices, under challenging conditions of large-scale experiments (Tore Supra in France, TCV in Switzerland, and, since 2013 under the auspices of a Virtual Helmholtz Institute on ASDEX Upgrade).

**Shiyong Huang** received **several national and international awards** thanks to his outstanding research in the field of space physics, in particular on magnetic reconnection and plasma turbulence. This includes the National Youth Talent Support Program in China (2019), the URSI Young Scientists Award (2018), the EGU Planetary and Solar System Sciences Division Outstanding Young Scientists Award (2016) and the ESA award for Outstanding Contribution to the Cluster and Double Stars Missions (2015).

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## PLASMA WAVES

**Leaders**
Carine Briand, Catherine Krafft, Caterina Riconda

**Laboratories involved**
LESIA, LPP, LULI

**External collaborations**
School of Physics and Astronomy (Queen Mary University of London, UK), Space Research Institute (Russia).

**Projects**
1 equipment project, 1 postdoctoral project (Andrea Sgattoni, LULI/LESIA), 5 invitations of international experts (Alexander Volokitin, Space Research Institute of Russian Academy of Sciences; Tatyana M. Zaboronkova, Polytechnical University Nizhny Novgorod).

**Budget**
134 000€

# Background & objectives

**Electron beams originated from the Sun during solar eruptions are the source of energy of instabilities for the interplanetary plasma. Characterizing these electron beams enables to test the mechanisms of eruption launch and enters in the frame of space weather to forecast the potential impact of these electrons in the Earth's environment.**

One way to characterize the beams is to exploit the instabilities that they generate. These instabilities lead to radio emissions that are routinely observed on Earth and by space instruments. A better understanding of the physical processes leading to these emissions, due to a non-linear multi-step coupling process between the beam and the ambient plasma, will lead to a better estimate of several properties of these beams (velocity, density).

**Several questions are still under investigation:**

- How density inhomogeneities affect the formation of electron plasma waves and the subsequent formation of electromagnetic radiation?
- How cascade of wave-decay can accelerate electrons?
- What is the emission pattern of the fundamental wave coupling processes in an inhomogeneous medium?
- What is the efficiency of each step of the radio emission (electron beam to electron plasma waves, and electron plasma wave to electromagnetic waves)?
- How does the magnetic field affects the wave-coupling?

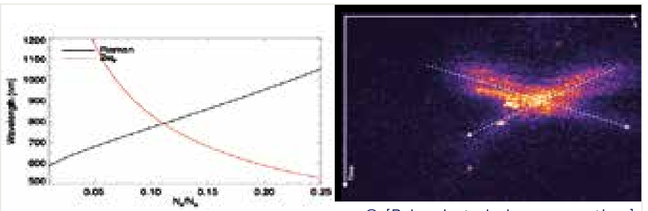
# Main results

The works performed by C. Krafft et al. concern the electromagnetic emissions by solar plasmas presenting randomly varying density inhomogeneities and well developed Langmuir or upper-hybrid wave turbulence *[Volokitin and Krafft, 2018; Krafft and Volokitin, 2019a, 2019b]*.
The processes generating these emissions at the fundamental and the harmonic plasma frequencies have been investigated. A novel approach allowed developing a self-consistent theoretical model based on modified Zakharov equations and building hybrid 1D and 2D codes.

The studies performed by P. Henri are complementary as they are based on the Particle-In-Cell kinetic approach and use a 3D-electromagnetic PIC code *[Henri et al., 2019]*, without including however density fluctuations in the background plasma. Moreover, the simulations performed using the approach developed by C. Krafft have led to various results illustrating the crucial role of plasma inhomogeneities on the Langmuir wave turbulence, the beam's dynamics, the statistics of waves' amplitudes, the wave-wave interactions, the transformation and scattering of waves on the inhomogeneities, the diffusion of waves and particles, as well as the acceleration of beam particles [*Krafft et al., 2013, 2014, 2015; Krafft and Volokitin 2016c, 2017, 2019a*].

The LPP team also investigated the influence of small-scale density inhomogeneities on Whistler waves' propagation, transport and parametric coupling in the Earth magnetosphere *[Zudin et al., 2019; Zaboronkova et al., 2019]* and of random plasma density and magnetic field fluctuations on Whistler envelope solitons in inhomogeneous solar and magnetospheric plasmas *[Krafft and Volokitin, 2018a, 2018b]*.

The very new approach developed by the LESIA-LULI collaboration was to conduct a lab-experiment of wave coupling. Based on the simulations *[Henri et al., 2019]*, an experiment was set-up to check the directivity of the emission pattern and the efficiency of the conversion mechanism. These experiments were successfully performed on the LULI-2000 infrastructure, in September 2018 (Figure 2).



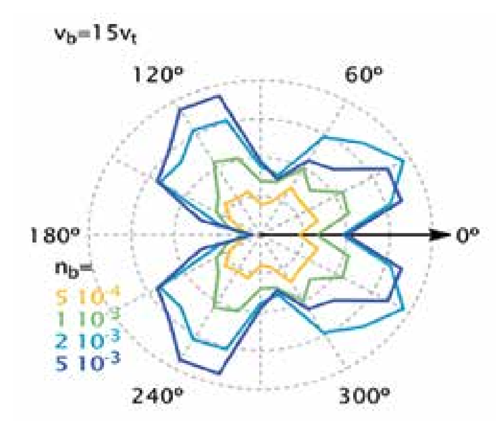
© [Briand et al., in preparation]

*Figure 1: Left panel: theoretical evolution of the Raman and $2\omega_p$ emissions as a function of the electron density (which mimics time increase from right to left).*
*Right Panel: Wavelength (ordinate) vs. time (absciss) of the emission observed during the laser experiments of September 2018. The emission showing a decrease of the wavelength with time is the Raman emission, while the $2\omega_p$ emission presents an increase of λ with time.*

# Perspectives

The works on the role of density inhomogeneities will continue based on the same approach (theory and simulations).

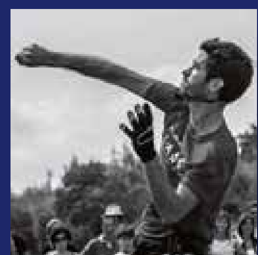
As a follow up of our experiment at LULI, a new campaign of laser experiment is scheduled in June 2020. Indeed, according to the simulations, there exist privileged directions for the emission of electromagnetic radiation from the fundamental process (Figure 2). A broader observed-pattern could be the signature of the diffusion of electromagnetic radiation by the interplanetary medium. This will be further study with the Parker Solar Probe and Solar Orbiter missions that orbit the Sun at a very short distance from it (limiting the effect of the interplanetary medium).




© [Henri et al., 2019, JGR]

*Figure 2: Directivity of the emission at $2\omega_p$ resulting from the propagation of an electron-beam in a homogeneous, non magnetic plasma (where $\omega_p$ is the plasma frequency).*

# Focus



**Andrea Sgattoni** defended his PhD entitled "Theoretical and numerical studies of the laser plasma ion acceleration," in June 2001, at the University of Bologna. He joined the LULI and LESIA plasma teams in December 2016. He was in charge of the numerical studies to prepare the lab-experiments. He first studied the role of inhomogeneities in the development of Electron Plasma Waves from 1D simulation *[Sgattoni et al., PoP]* and lead 3D-electromagnetic simulations of wave-coupling (which results were published in *[Henri et al., 2019]*. He is now recruited at EDF. Apart of his interest for plasma physics he is also a boomerang thrower, world class athlete (twice first place at the World Boomerang Team Cup - Brazil 2012, Australia 2014 - among other amazing achievements).

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# ROTATING ASTROPHYSICAL PLASMAS

**Leaders**
Sébastien Galtier, Ludovic Petitdemange

**Laboratories involved**
LERMA, LPP

**External collaborations**
School of Physics and Astronomy (Queen Mary University of London, UK), Space Research Institute (Russia).

**Project**
1 doctoral project (Mélissa Menu, LPP/LERMA)

**Budget**
100 000€

## Background & objectives

How do cosmic magnetic fields arise? Why does the Sun's magnetic field experience periodic reversals whereas for the Earth it is erratic? How does turbulence amplify, sustain and shape magnetic fields? What is the role of rotation in the dynamo mechanism? What are the spectral and structural properties of MHD turbulence under moderate or fast rotation? How do waves and coherent structures interact in MHD turbulence? Despite several major research advances over the past half-century, the current understanding of turbulent dynamos cannot satisfactorily answer these fundamental questions. This stimulated a PLAS@PAR's collaborative project about the dynamo problem, based on three-dimensional direct numerical simulations of rotating MHD turbulence.

Although rotation plays an important role in the dynamo process there is still a lack of theory quantitatively describing the different possible dynamo regimes. The aim of this project is to put a theoretical basis on the behaviour of magnetic fields generated by rotating turbulent MHD flows. The old study involves mainly computational works with 3D direct numerical simulations (TURBO/LPP and PaRoDy/LERMA codes) in massively parallel computers.

## Main results

We investigate in a cubic geometry (TURBO code) the impact of a solid-body rotation $\Omega$ on the large-scale dynamics of an MHD flow in the presence of a background magnetic field $B_0$. A unit magnetic Prandtl is chosen with a polarized forcing at intermediate wavenumber. When $\Omega$ is parallel to $B_0$, (angle $\theta$=0) an inverse transfer is found at large-scale. This transfer is stronger when the forcing excites preferentially right-handed fluctuations; it decreases when $\theta$>0 (Figure 1). These properties are understood as the consequence of an inverse cascade of hybrid helicity. *[Menu, Galtier & Petitdemange, 2019]*.

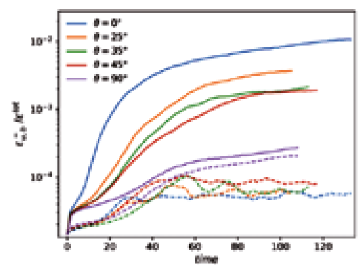


*Figure 1: time evolution (in linear-logarithmic scale) of the normalized large-scale dissipation rate of kinetic energy **u** (dashed lines), and magnetic energy **b** (solid lines) for different angles $\theta$ between the rotation axis and the magnetic field. $\epsilon_{tot}$ is the total dissipation rate. For $\theta$ = 0 the large scale dissipation rate is dominated by the magnetic contribution, while for $\theta$ = 90°, the contribution of each field is similar [Menu et al., 2019].*

In order to apply these results to planetary dynamos, we have also performed an extensive parameter study with geodynamo simulations. By using the PaRoDy code which solves the MHD equations in a rotating spherical shell, we have shown that dipolar dynamos (large-scale fields) can be maintained in a turbulent regime if the initial field strength is sufficiently strong. In this case, the combination of rotation and magnetism promotes dipolar dynamos as observed for the geomagnetic field or rapidly-rotating low-mass stars *[Menu, Petitdemange & Galtier, in preparation]*.

## Perspectives

Our fundamental simulations have confirmed that turbulence promotes large-scale magnetic structures when rotation and magnetism play a significant role. These encouraging results require additional work in order to apply them to astrophysical objects. More realistic numerical models could be considered to study the effects of thermal and mechanical boundaries, the effects of density stratification etc. Such effects are also known to play a role in planetary and stellar dynamos. They could affect the efficiency of the observed inverse cascade that we have highlighted.

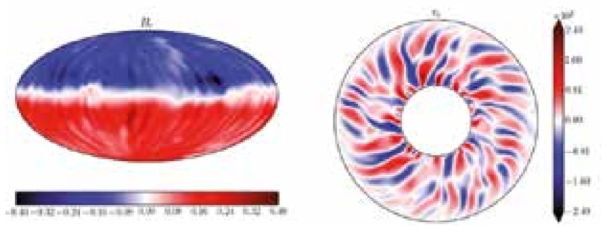

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*Figure 2: Typical radial magnetic field (on the left) and radial velocity field (on the right) corresponding to a dipolar solution. Global rotation plays an important role by making the flow almost constant on coaxial cylinders (geostrophic). Such patterns promote large-scale magnetic field in which the dipolar component is dominant as it is the case for the geomagnetic field.*

## Focus

In 2016, **Mélissa Menu** completed her master studies in astrophysics at Observatoire de Paris. After a 3 months internship "Competing mechanisms of ionization in molecular clouds near a supernova remnant" performed at APC laboratory in Paris Diderot University, she started a PhD project in October 2016 entitled "turbulent rotating dynamos" together with Ludovic PetitDemange (LERMA) and Sébastien Galtier (LPP). She defended her thesis in December 4, 2019.

## Award

**Sébastien Galtier**, Professor at Paris Sud University and a member of the Space plasmas team of LPP was **nominated at Institut Universitaire de France** for 5 years (starting on 1st October 2018) as a senior member. His research work covers turbulence in various astrophysical plasmas (solar wind, stellar and planetary dynamo, interstellar medium up to turbulence in gravitational waves).

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## MAGNETIC RECONNECTION

**Leaders**
Andrea Ciardi, Julien Fuchs, Alessandro Retino, Roch Smets

**Laboratories involved**
LERMA, LPP, LULI

**External collaborations**
CEA-DIF (France), Laboratory for Atmospheric and Space Physics - University of Colorado (USA), Massachusetts Institute of Technology (USA), Swedish Institute of Space Physics (Sweden), Saint Petersburg State University (Russia), Imperial College London (UK).

**Projects**
1 postdoctoral project (Alexandra Alexandrova, LPP), 1 doctoral project (Simon Bolanos, LPP/LULI), 4 invitations of international experts (Nuno Loureiro, MIT; Sergey Lebedev, Imperial College London; David Sundkvist, California University).

**Budget**
227 000€

# Background & objectives

**Magnetized plasma dynamics, either in laboratory or in space, involves the formation of regions of strong currents, the so-called current sheets, where magnetic energy is stored and later released in an explosive fashion through magnetic reconnection.**

Reconnection leads to the plasma bulk acceleration and energization of charged particles. Kinetic effects operating at small scales, comparable to particle gyroradii, lead to global reconfiguration of fields and plasmas mixing on much larger scales. Reconnection in near-Earth plasma occurs mostly in the absence of particle collisions and is the most important mechanism to transfer energy, momentum and mass from the solar wind into the terrestrial magnetosphere. On the other hand, collisions can play an important role during reconnection in laboratory devices such as high-power lasers and pulsed-power devices. A number of key open questions of reconnection physics can be addressed through laboratory and spacecraft measurements and numerical simulations. The role of collisions on reconnection dynamics, e.g. on plasmoid formation, and the transition from collisionless to collisional regime are not yet fully understood. Another open issue is how reconnection is initiated in current sheets (the so-called onset), both in terms of large-scale current sheet conditions prior to reconnection and in terms of local kinetic processes responsible for the disruption of the current. Another debate concerns the spatial structure of reconnection sites, namely if reconnection occurs at one isolated site or rather over a chain of plasmoids embedded in between multiple reconnection sites, which may also evolve into a turbulent structure. Finally, another key open question which is also relevant for astrophysical plasmas is what are the mechanisms leading to plasma heating and acceleration of particles to high energies.

**To understand the dynamics of reconnecting current sheets we have used a combination of spacecraft observations, experiments on high-power lasers and pulsed-power devices and numerical simulations:**

- We have studied the Earth's magnetotail current sheet by using spacecraft observations from Cluster and Magnetospheric MultiScale (MMS) missions. One case of plasmoid-chain reconnection observed by Cluster was investigated in order to help understand the energy exchange between fields and plasma in such a complex configuration. We have analysed ion acceleration, wave activity and plasma stability conditions to verify whether kinetic-scale instabilities may affect reconnection. In addition, the problem of the reconnection onset has been addressed to the MMS observations. MMS provides long monitoring of the current sheet in the Earth's magnetotail. Observations of fields and particles prior and during the activity in the current sheet are aimed to shed light on the onset of reconnection.
- We have also resorted to investigate reconnection in scaled-down experiments using high-power lasers and pulsed-power devices. The latter are specifically interesting for investigating reconnection events in high-energy-density plasmas, like the ones taking place in the context of inertial confinement fusion.

# Main results

With respect to spacecraft observations, we could provide, for the first time, an evidence of the proton firehose instability developing during plasmoids formation in a collisionless regime, by using Cluster data in the Earth's magnetotail *[A. Alexandrova et al., to be submitted]*. The current sheet was observed to disrupt in multiple reconnection sites alternating with plasmoid structures (Figure 1a).

**The analysis revealed that at the periphery of the plasmoid, protons are strongly accelerated in the direction parallel and anti-parallel to the background magnetic field.**
Typically, such acceleration sets off the firehose instability ones the centrifugal force of particles moving along the magnetic field overcomes the magnetic tension force. The instability induces the electromagnetic fluctuations, thereby converting the excess of plasma energy of the proton anisotropy to the magnetic fields. Indeed, the firehose-associated fluctuations were observed (Figure 1a). In this regard, the firehose instability which converts the plasma energy to the magnetic energy between the reconnection sites, counteracts with the conversion of magnetic energy to the energy of plasma in the reconnection sites. Observational results were also supported by the 2.5D Particle-In-Cell (PIC) simulations (Figure 1b). Our results suggest that magnetic energy conversion in the current sheets disrupted to several reconnection sites might be limited by the kinetic instability mechanism. Motivated by these results, we have used the novel high-resolution Magnetospheric MultiScale (MMS/NASA) data in the Earth's magnetotail to investigate the role of different instabilities on reconnection. The detailed study of a reconnection event revealed the electron firehose instability operating in the vicinity of the reconnection site *[A. Alexandrova et al., in preparation]*. There, the instability might be responsible for the patchy energy conversion unexpectedly detected in the electron diffusion region. In summary, our results

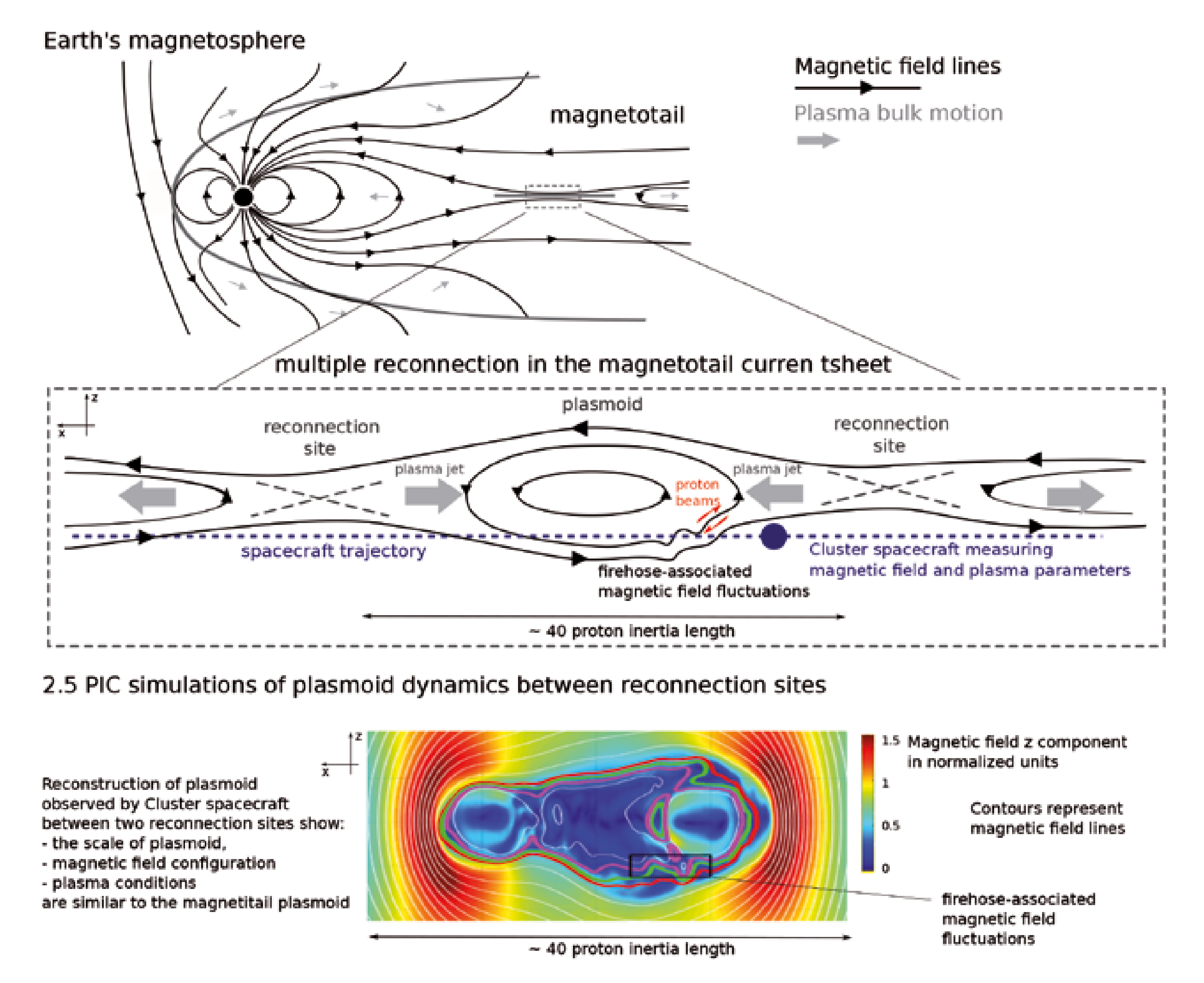


*Figure 1: (a) Schematic view of the Earth's magnetotail with the zoom in the plasmoid forming between two adjacent reconnection sites, with the marked proton beams parallel to the magnetic field and the magnetic field fluctuations associated with the firehose instability as they observed in situ by the Cluster spacecraft; (b) reconstruction of observations with the 2.5D PIC simulations [A. Alexandrova et al., to be submitted].*

suggest that the kinetic instabilities on electron and ion scales play a fundamental role in the energy redistribution during the reconnection process. To support the results, the quantitative estimates on a large statistical basis would be highly valuable. We have developed a tool to browse the MMS database and automatically select the crossings of the magnetotail current sheet during the reconnection activity. Currently, we analyse the resulting reconnection database in order to understand the role of kinetic plasma instabilities on reconnection onset and the energy redistribution.

**Concerning experiments,** several investigations were performed at the GSI (Germany), LULI and LMJ (France) laser facilities, in the framework of a collaboration between LULI, CEA and LPP, showing very interesting results: in these experiments the magnetic field is self-generated on the surface of a solid target following the high-power laser interaction (100 J to several kJ, 1 to 5 ns duration, intensity $1e^{13}$ to $1e^{14}$ W/cm$^2$). We then showed that this magnetic field is strongly compressed on this surface due to the Nernst effect. It has the shape of a thin (a few microns thick) disk with a high strength field (of the order of 100s of T) in a dense ($1e^{21}$ cm$^{-3}$) plasma. This makes the topology very suitable for reconnection studies as the magnetic field due to the two-dimensional geometry of the magnetic field.

Then, two such magnetic field structures were juxtaposed to investigate reconnection between the two neighbor magnetized plasmas (Figure 2). We looked in detail at three topics: 1) the influence of a guide-field (i.e. a magnetic field normal to the two-dimensional plane of canonical reconnection), 2) the influence of an enhanced quadrupolar magnetic structure, and 3) the influence of having more than two neighbouring magnetized plasmas trying to reconnect.

- For #1, we could clearly show that even a weak guide field strongly delays reconnection *[S. Bolanos et al., 2019]*.
- For #2, we could show that an enhanced quadrupolar magnetic structure prior to reconnection accelerates reconnection.
- For #3, we could show that having more than two neighbouring plasmas frustrates reconnection.
- For #2 and #3, the experimental measurements are being presently compared to numerical simulations *[S. Bolanos, in preparation]*.

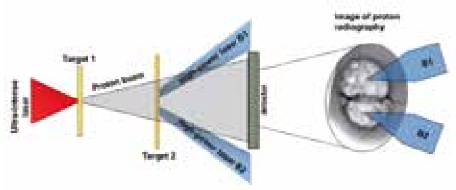


*Figure 2: Schematic of laboratory measurements of magnetic reconnection: an ultra-intense laser beam irradiates a target (target 1) from which a laminar beam of MeV protons is generated. These protons propagate through a second target (target 2) which is irradiated by two nanosecond high-power (10 GW) lasers, each generating a toroidal magnetic field loop compressed onto the target surface by the Nernst effect. These two loops collide as each hot plasma expands along the target surface. The protons propagating through the target are deflected by the Lorentz force induced by the magnetic field patterns on the target surface. The protons are collected afterwards on a film detector, allowing to obtain a time-resolved, spatially resolved image of the magnetic field pattern on the surface of target 2 and of the changes induced by the reconnection [from Bolanos et al., 2019].*

Other experiments were performed at MAGPIE pulsed power device at Imperial College. In these experiments, reconnection occurs in a semi-collisional regime, and we showed for the first time the development of plasmoids in this regime. In particular, the measurements demonstrate the presence of an anomalous heating of ions and electrons in the reconnection layer whose origin remains unknown *[Suttle et al., 2018; Hare et al., 2016, 2017, 2018]*.

To understand the origin of anomalous ion heating and to work on the theoretical interpretation of the experiments Nuno Loureiro from MIT and Sergey Lebedev from Imperial College London, were invited to Paris on several occasions. The possible development of lower hybrid micro instabilities in the current layer as a source of enhanced resistivity and heating is being explored.

# Perspectives

Studying the development of different plasma instabilities in current sheets, in particular during plasmoid formation and evolution, is of pivotal importance to understand reconnection onset and evolution in time.

This requires studying the different stages of the reconnection process. *In situ* spacecraft measurements, in particular the recent ones from MMS, are ideal for this purpose and will be further used to improve our understanding of the physics of reconnection onset. Regarding laboratory experiments, the next step will be to evaluate how the knowledge acquired could be used to optimize the design of controlled fusion experiments in order to maximize the energy invested in heating the plasmas.

# Focus

**Alexandra Alexandrova** did her master studies at St. Petersburg State University, Russia, with a focus on a theoretical approach to magnetic reconnection process in space plasma.
Then she was working in the Space Research Institute of Austrian Academy of Sciences (IWF), Graz, Austria, on spacecraft observations of magnetic reconnection in the Earth's magnetosphere. She finished her PhD at the University of Graz, Austria, with a thesis entitled "Magnetic reconnection in the Earth's magnetotail: temporal evolution and spatial characteristics", in November 2016. She joined LPP laboratory in January 2017 as a PLAS@PAR postdoc to work with Alessandro Retinò on the microphysics of magnetic reconnection. Currently she continues working in LPP as a postdoc of École Polytechnique, started on November 2018.

In 2015, **Simon Bolanos** did an internship during 6 months at LULI in École Polytechnique, whose subject was "Laser-amplification via Brillouin scattering in the strongly coupled regime". This internship completed his engineering diploma and master degree in optics/ photonics at Telecom Bretagne, renamed IMT Atlantique. Then in October 2016, he started his PhD investigation into the dynamic of the magnetic reconnection driven by high-power lasers under the supervision of Julien Fuchs (LULI) and Roch Smets (LPP). He defended his thesis in december 2019.

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# ACCRETION, EJECTION AND SHOCKS IN ASTROPHYSICS AND IN THE LABORATORY

**Leaders**
Sylvie Cabrit, Andrea Ciardi, Bruno Desprès, Julien Fuchs, Laurent Ibgui, Jean Larour, Philippe Savoini, Chantal Stehlé, Tommaso Vinci

**Laboratories involved**
LERMA, LPP, LULI, LJLL

**External collaborations**
Imperial College London (UK), INAF - Osservatorio Astronomico di Palermo (Italy), Palermo University (Italy), Universidad de Las Palmas de Gran Canaria (Spain), University of Arizona (USA), ELI and PALS centers (Czech Republic), Institute Applied Physics (Russia). In France: Paris Diderot University, Observatoire de la Côte d'Azur, Laboratoire National des Champs Magnétiques Intenses.

**Projects**
3 equipment projects, 5 innovative small projects, 2 doctoral projects (Salvatore Colombo, LERMA / Palermo University; Raj Laxmi Singh, LERMA), 1 postdoctoral project (Adrian Stan, LERMA), 6 invitations of international experts (Alejandro C. Raga, Universidad Nacional Autonoma de Mexico; Petros Tzeferacos, University of Chicago; Sergey Lebedev, Imperial College; Rafael Rodriguez-Perez, University of Las Palmas de Gran Canaria; Ivan Hubeny, University of Arizona; Francisco Suzuki-Vidal, Imperial College).

**Budget**
387 000€

## Background & objectives

Stars are born out of dense gas in magnetized molecular clouds under the action of gravity.

It is an observational fact that the accretion of matter onto the newly forming stars is invariably accompanied by the ejection of matter at super-Alfvenic speeds in the form of collimated jets. It is also widely accepted that it is magnetic fields which tightly couple matter accretion and matter ejection in these systems. Furthermore, the collimation and stability of protostellar jets largely depends on the spatial distribution of the magnetic field, and its associated currents, with current-driven kink-instabilities possibly disrupting the flow. The accretion-ejection paradigm has been observed from giant planets to supermassive black holes and the basic underlying mechanisms, at least for non-relativistic jets, are thought to be universal.

Mass accretion in solar-mass sized, pre-main sequence stars is mediated by the star's magnetosphere, which essentially carves out a hole in the central region of the accretion disk. Material from the disk is then forced along the magnetic field and guided towards the stellar chromosphere where it generates a strong accretion shock. Similarly, accretion onto magnetized white-dwarfs with Mega-Gauss magnetic fields is mediated by a single accretion channel of matter and shock with temperatures of several million Kelvins.

Shockwaves are ubiquitous in space and in laboratory plasmas and they are generated when a supersonic plasma (jet, star wind, supernova remnants, laser-produced plasmas...) propagate through an ambient medium, such as the interstellar medium. Shocks are boundaries where the bulk kinetic energy of the flow is converted irreversibly into thermal energy (entropy increase). In general, shocks are structured by radiation, thermal, fluid and kinetic instabilities. Importantly, shocks are also the site where energetic (suprathermal) particles are accelerated.

Within the context of accretion-ejection in astrophysics, our research combines numerical modelling, observations and high-energy density plasma experiments to understand the fundamental physical processes that link magnetic fields and radiation to the dynamics and stability of accreting flows, jets and shocks.

## Main results

### Interaction of protostellar jet bowshocks with a surrounding disk wind

Protostellar jets are highly variable in ejection speed; internal shocks thus form where overpressured jet material is pushed sideways into the surrounding medium, and sweeps a large bowshock. During a 2-month visit of A. Raga (UNAM), funded by the PLAS@PAR visiting program, we investigated for the first time the interaction between such a time-variable axial jet and a surrounding slower disk wind, by means of both analytical models and 2D numerical hydrodynamical simulations *[Tabone, Raga et al., 2018]*. We demonstrated that the disk wind is able to partially refill the cavity swept out by the last bowshocks, allowing pristine disk wind properties (eg., molecules) to be preserved up to a certain distance from the source. We also showed that the long-term evolution of the jet – wind interaction creates a steady conical cavity. This appears as a very promising scenario to explain the slow conical molecular flows newly discovered by the ALMA interferometer towards several young stars, such as HH30 *[Louvet et al., 2018]*.

### Magnetized laser-plasma experiments: accretion and jets

We have developed the first laboratory study of the collimation of jets by a large-scale poloidal magnetic field. Results from the experiments, which coupled a laser-produced plasmas to a 20 T magnetic field, and numerical simulations have shown that an x-ray emitting, stationary shock forms at the base of the jet. This could help explain the observations of such shocks in certain young stars *[Albertazzi et al., 2014]*.
Extending this work to magnetized accretion flows, we have confirmed the role of the magnetic field in creating a dense shell of absorbing plasma around the accretion shock, and we have highlighted the development of a magnetized Rayleigh-Taylor instability *[Revet et al., 2017; Khiar, PhD 2017]* (Figure 1). For the accretion on magnetized white dwarfs we have shown that multi-dimensional modelling is required to explain the quasi-periodic oscillations observed in theses systems.
We have also developed a technique to generate unsteady flow jets and accretion flows in the laboratory *[Higginson et al., 2017]*.

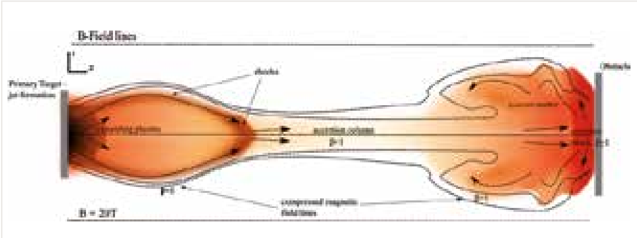



*Figure 1: Schematic of the experimental set-up to study magnetized accretion columns in the laboratory. The laser irradiates the target on the left-hand side of the image. The plasma is collimated by the magnetic field into a rapidly moving (several 100 km/s) flow that collides with an obstacle (right-hand side) generating a shock [Revet et al., 2017].*

### Radiative shocks and plasma focus experiments

In many astrophysical phenomena radiation couples strongly with the fluid dynamics, examples include supernovae explosions, jets and accretion flows. This complex interplay has been studied in dedicated laser experiment. Of particular relevance is the first study of the interaction of two radiative shocks at different velocities propagating in noble gases, which show strong developed radiative precursors in a regime close to the supercritical limit. The experiments were performed at PALS, ORION and on SGII laser facilities *[Singh PhD 2017; Singh et al., 2017; Suzuki-Vidal et al., 2017, and 2019 in prep]*. To study slower, but still radiatively cooled shocks, under conditions similar to jet shocks, a 1 kJ pulse power device (plasma gun) was developed by J. Larour (LPP) *[Larour et al., 2015]*. In this context, but on the larger pulsed-power installation MAGPIE, we have demonstrated the fragmentation of bow shocks driven by thermal instability in laboratory-astrophysics experiments *[Suzuki-Vidal et al., 2015]*.

### The effects of radiative transfer in accretion streams

By extending to full non-LTE the previous work of de Sá *[de Sá et al., 2019]*, we have demonstrated the existence of a radiative precursor in the upstream region of a column accreting onto the surface of a Classical T Tauri Star (CTTS) *[Colombo et al., 2019]*. The precursor reaches temperatures of up to 105 K and our model predicts that a significant fraction (70%) of X-ray emission from post-shock plasma is reprocessed by the absorbing upstream flow (Figure 2). This may explain the reason why mass accretion rates inferred from UV observations are always found to be larger than the rates inferred from X-ray observations.

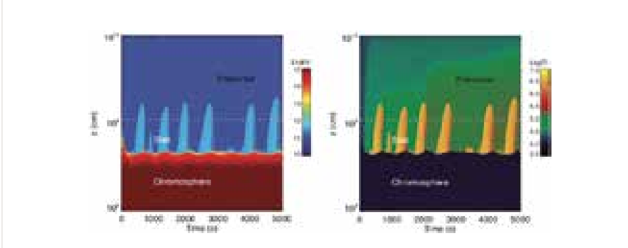


*Figure 2: Time-space maps of the density (left) and temperature (right) of a 1D simulation of accretion shocks on CTTS. The spatial extent of the shock is along z-axis. The x-axis indicates the time. The dashed grey lines indicate the initial position of the chromosphere. The precursor at $10^5$ K, clearly visible in green in the temperature map and should be observable in the UV range [Colombo et al., 2019].*

### The effects of flares on accretion in CTTS

We have demonstrated, from a 3D MHD model with PLUTO, that flaring activity can be an efficient mechanism to trigger accretion onto a CTTS. We simulated the formation of several loops that link the star to the circumstellar disk, and that build up a hot X-ray emitting extended corona. Accretion funnels can form with a significant contribution to the mass accretion rate of the star *[Colombo et al., A&A 2019]*.

### Studies of ion and electron foreshocks

The Earth's bow shock is a characteristic collisionless shock wave which allows the conversion of solar wind directed energy (slowdown) into thermal energy through wave-particle interaction. One of the consequences of such energy conversion is the formation of regions populated by back streaming particles observed in front of the shock wave, namely the Foreshock region. Two-dimensional, full PIC numerical simulations have demonstrated that the ion foreshock formation is not a continuous process but have evidenced "burst" acceleration mechanisms *[Savoini and Lembège, 2019]*. Furthermore simulations with the SMILEI code on the GENCI supercomputers has allowed for the first time to follow self-consistently the simultaneous formation of electron and ion foreshocks at low Mach number (MA~2). This opens up the possibility to study the interactions of these two distinct populations and their effects on the shock wave behavior.

### Code developments

We have expanded a radiation module in the PLUTO code, initially implemented within the Local Thermodynamic Equilibrium (LTE) approximation, to allow it to handle a non-LTE regime. PLUTO can now model non-LTE 3D radiation Magnetohydrodynamics flows, under the flux-limited diffusion approximation *[Colombo et al., 2019b]*. Code development was also carried out for our code GORGON to include anisotropic thermal conduction with super-time-stepping to model strongly magnetized laser generated plasmas *[Higginson et al., 2017]* and to implement the basis of an implicit solver for radiation transport.

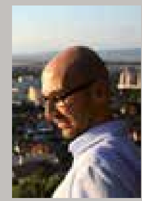
## Perspectives

In the future, multi-dimensional, multi-physics modelling of accretion columns will be crucial to improve our understanding of observations. In particular we will carry out the modelling of accretion flows in 2D and 3D including radiation transport and perform direct comparison to observations through the generation of synthetic spectra with the non-LTE version of the 3D IRIS radiative transfer code *[Ibgui et al., in prep.]*. In addition, the stability of magnetized accretion flows and shocks will be investigated in 3D through new experiments on large-scale laser facilities and state-of-the-art MHD simulations.

## Focus

**Salvatore Colombo** performed his master studies in astrophysics at the Università degli Studi di Palermo. In November 2016, he joined LERMA as a PhD on a project linked to stellar accretion in the framework of a collaboration with University of Palermo, under the supervision of Laurent Ibgui and Chantal Stehlé from LERMA and Salvatore Orlando from Osservatorio Astronomico di Palermo. He defended his thesis, entitled "Radiation dynamic and magnetohydrodynamic models of plasma flows accreting onto Classical T Tauri stars" in October 2019.

**Raj Laxmi Singh** did her master studies at the University of Allahabad in India with a specialization on X-rays and Beam physics. She then was working as Project Associate in the national programme "Isotope Fingerprinting of Waters of India" at Physical Research Laboratory (a unit of Department of Space, Govt. of India). She joined LPP in November 2013, to work with Jean Larour in collaboration with Chantal Stehlé (LERMA). She defended her thesis, entitled Strong radiative shocks relevant for stellar environments: experimental study and numerical approach" in March 2017. She works as a postdoc at the Queen's University Belfast in the field of Laboratory Plasma Astrophysics.



**Adrian Stan** got his PhD in 2008 at the University of Groningen before joining École Polytechnique for two postdoctoral projects, in the theoretical spectroscopy group of École Polytechnique Palaiseau, on subjects in link with correlated quantum many particle systems and non-linear equations. In November 2014, he joined LERMA for a 3-year project, co-funded by PLAS@PAR and Institut du Calcul et de la Simulation on radiation Magnetohydrodynamics in collaboration with Laboratoire Jacques Louis Lyons. He works today as senior scientist Systems Toxicology at Philip Morris International in Neuchatel area.

## Award

**Bruno Albertazzi** performed his PhD at École Polytechnique and INRS-EMT, Canada. He defended his thesis "Laser plasmas and magnetic fields" in 2014. Then, he joined Osaka University as a Specially Appointed Researcher. He is now working at LULI. His work has been awarded several times: in 2015 he received the **European Physical Society plasma physics PhD and the INRS International Outreach prizes.**

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# OBSERVATIONS OF SOLAR SYSTEM PLASMAS

**Leaders**
Guillaume Aulanier, Nicolas Aunai, Matthieu Berthomier, Laurent Lamy, Christophe Verdeil, Philippe Zarka

**Laboratories involved**
LESIA, LPP

**External collaborations**
FUN (Japan), INPE (Brazil), ONERA (France), IRAP (France), University Sydney (Australia), IAS (France), NASA's IRIS team (USA).

**Projects**
3 equipment projects, 1 innovative small project, 1 doctoral project (Corentin Louis, LESIA), 2 postdoctoral projects (Christof Barczynski, LESIA; Fabiola Magalhaes, LESIA), 2 invitations of international experts (Vladimir Ryabov, Future University-Hakodate; Ulrich Taubenschuss, The Czech Academy of Sciences).

**Budget**
372 000€

## Background & objectives

**Natural plasmas are found through the solar system, from the solar corona, up to the solar wind, in the planetary magnetospheres including Earth. Their intrinsic properties are very different from one region to the other, but they remain interconnected through the solar wind.**

This section presents observational and numerical aspects relative to the solar eruptions and on the magnetospheres of Jupiter and Saturn, and the effort to improve *in situ* diagnostics of these very dynamical plasmas.

**Solar eruptions** are the most energetic events of the whole solar system. They involve a flare that heats the plasma to several million Kelvin, and a coronal mass-ejection (CME) which is a macro-plasmoid that launches several billion tons of highly-magnetized plasma into the heliosphere. Recent space-observations have shown unexpected magnetic feedback of eruptions on the Sun's surface. Evidence for increasing downward Lorentz-forces, in particular, have triggered a major debate about how to include all these feedbacks in the standard flare model. State-of-the-art numerical tools available at PLAS@PAR, and a new participation to the NASA's IRIS satellite operations made possible thanks to PLAS@PAR, altogether offered a unique chance to study this issue.

Using their magneto-hydrodynamics parallel code Observationally-driven High-order Magneto-hydrodynamics (OHM), researchers from PLAS@PAR have addressed the puzzle of eruption-driven magnetic-feedbacks at the Sun's surface. Their goal was to develop the right theory that accounts for existing observations, and to predict yet-unobserved behaviors.

**Jupiter** is the strongest known planetary natural radio emitter, seconded by Saturn. Most of these radiations emanate from the auroral regions surrounding the magnetic poles, from a supposedly universal cyclotron plasma instability driven by energetic electrons accelerated in the planetary magnetic environment (the magnetosphere) by various energization processes. Understanding in detail the production of such radio waves informs on (i) the dynamics and the structure of the magnetosphere of Jupiter and Saturn and (ii) the possibility to extrapolate this knowledge to the remote search for exoplanets and more massive objects (brown dwarfs, young/variable stars) at radio wavelengths. To tackle these questions, our research team at LESIA has reanalyzed large data sets from ground- (Nançay Decameter Array or NDA, UTR-2) and space-based (Cassini/RPWS, Voyager/PRA) radio instruments and compared them with physical simulations of the jovian produced emissions through the PhD project of C. Louis at LESIA and the invitation of Pr V. Ryabov (Hakodate Univ.) supported by PLAS@PAR.

**Saturn** also hosts bright auroral radio emissions, which display ununderstood Faraday rotation observed at some limited occasions so far. We started to investigate them in a statistical manner with the Cassini/RPWS radio dataset through the PLAS@PAR invitation of Dr U. Taubenschuss (Univ. Graz). Finally, the Saturn's magnetosphere hosts the second example known so far of planet-satellite interactions which can be tracked by searching for the auroral footprint of Enceladus moon at UV wavelengths. To investigate this interaction in detail, we built a Cassini/UVIS processed database covering the full mission through to the PLAS@PAR (ongoing) post-doc research project of F. Magalhaes at LESIA.

**Understanding solar system plasmas requires state-of-the-art *in situ* diagnostics** that will be correlated with remote observations. As an example, auroral radiation processes depend on the exact shape of the charged particles distribution function which needs to be captured at high-time resolution. It is meaningful to analyze the angular spectrum of charged particles relative to the main magnetic field direction. However this direction is often highly variable. The field-of-view of plasma spectrometers must cover the widest solid angle possible in order to constantly track the magnetic field. However, measuring both energy and 3D particles spectra at high-time resolution is a tremendous challenge.

## Main results

**The solar simulations** with the OHM code recover the horizontal magnetic-fields increase at the Sun's surface, as observed. Detailed analyses unveiled that this occurs within the area that grows between pairs of spreading flare ribbons. Their connection to the flare-related reconnection region at higher altitudes in the Sun's corona demonstrated for the first time that the ideal contraction of previously-reconnected coronal flare-loops naturally increase both their shear-field component and the magnetic energy-density. Using typical data-analysis methods, synthetic Lorentz force-density maps were generated. They showed the same increase in their downward component at the source region of the eruption, as in the observations. The first-ever analyses of this feature with numerical simulations revealed a flaw in observational methodologies. This major finding questions some previous theoretical conjectures, and it provides a new solid theory for eruption-driven magnetic-feedbacks at the Sun's surface. This is now incorporated in the standard flare model in three-dimensions *[Barczynski et al., 2019]*. This modelling approach also led to predict yet-unobserved electric feedback related to the CME. Unprecedented methods for data analysis are currently being developed and used to test the model predictions on solar observations with the SDO and IRIS satellites *[Barczynski K. et al., in prep]* (Figure 1).

© NASA; [Spacecraft:] the Solar Orbiter mission (ESA)

*Figure 1: Solar eruption model and observation. [Colored field lines:] three-dimensional MHD simulation of the unstable eruption of twisted field-lines, as calculated with the OHM code (credit: Observatoire de Paris / LESIA); [Pink image:] space observation of a solar eruption, as recorded by SDO / AIA in the EUV in 211A.*

Thanks to high-resolution UTR-2 **observations of Jupiter** *[Ryabov, V. B. et al., 2014]*, we investigated the characteristics of Io-Jupiter decametric millisecond bursts (Figure 2). The analysis of 26 years of NDA observations of Jupiter yielded the identification of new radio components *[Marques et al., 2017]*, including decametric emissions induced by the moon Ganymede which has implications for the detection of exoplanets *[Zarka et al., 2018]*. Decametric emissions induced by both Ganymede and Europa were also detected from the comparison of Cassini/RPWS and Voyager/PRA space-based observations with simulations performed with the ExPRES code *[Louis et al., 2017 a, b]*. Jupiter/Io decametric emissions then started to be analyzed from data acquired from the Juno spacecraft in polar orbit around Jupiter since mid-2016 *[Louis et al., 2017; Louis PhD, 2018]* (Figure 3).

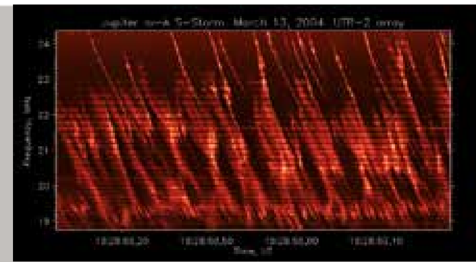

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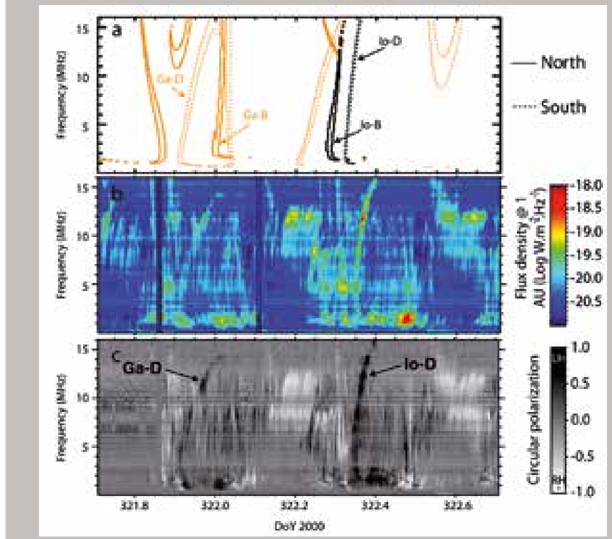
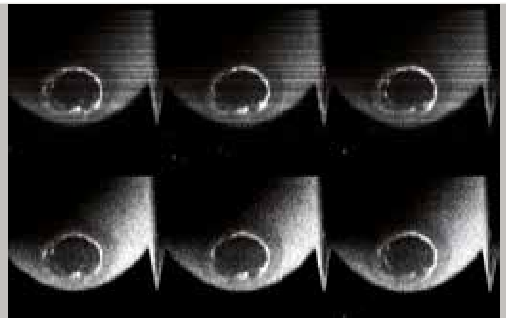
*Figure 2: Temporal and spectral complexity of Jovian magnetospheric radio emissions: this 1s-long dynamic spectrum (intensity versus time and frequency) shows radio emissions produced by the Io/Jupiter interaction. These appear as drifting bursts with variable drift rates and repetition rates, horizontal stripes due to Faraday rotation of the linearly polarized emission traversing Io's plasma torus, extreme variations of intensity from intense bursts to the background level in extremely short times. Observation was carried at the Ukrainian radio telescope UTR-2 using a waveform capture receiver. These fine structures are not yet explained, but hints are given in [Ryabov et al., 2014].*




© C. Louis

*Figure 3: Time-frequency radio observations from Cassini (middle, bottom) and simulations (top) of Jupiter's decametric emissions induced by the moons Io and Ganymede [Louis et al., J. Geophys. Res., 2017].*

**As for Saturn,** we started the construction of a catalog of all know Faraday rotation events within Saturn's kilometric radiation spanning the full Cassini mission. We selected some case studies and attempted to model the observed wave Stokes parameters with realistic simulations (using the latest density and magnetic field models). To investigate the Saturn's UV aurora, we constructed a processed Cassini/UVIS database which was released mid-2019 through the CNRS/INSU APIS service https://apis.obspm.fr and whose analysis is now under progress *[Magalhaes et al., in prep]* (Figure 4).



© F. Magalhaes

*Figure 4: Cassini/UVIS observations of Saturn's UV aurora.*

**Two instrumental projects** benefited from the PLAS@PAR support. Firstly, the Ion Mass Spectrometer developed by LPP for the ESA THOR project was tested with the new ion source control system. This instrument included an electrostatic analyzer that was coupled to an electrostatic deflector to increase the field-of-view of the instrument. A set of 4 identical sensors would provide the full distribution of mass-resolved ions in a few 100's msec, an order of magnitude faster than on previous space missions *[cf Thor assessment study report, ESA/SCI(2017)3, 2017]*. Functional tests showed the performances of the optics was in line with numerical simulations. These measurements allowed increasing the Technological Readiness Level of this high-time resolution ion mass spectrometer. Secondly, a 3D vacuum manipulator and a magnetic field attenuation system were installed in the LPP clean room facility to test 3DCAM, an innovative electron plasma spectrometer. 3DCAM has an instantaneous 3D field-of-view and 2 sensors provide the full 3D distribution *[Morel et al., 2017]*. The 3D manipulator has been successfully installed. A dedicated software has been developed to operate the manipulator. This allowed us to test our innovative plasma spectrometer at high energy (Figure 5). Low energy electrons are deflected by the ambient field and the compensation system will allow low energy tests.

© LPP

*Figure 5: Overview of the 3D vacuum manipulator with the plasma spectrometer on top.*

# Perspectives

The theory-driven discoveries regarding the magnetic and electric feedback of solar eruptions provide new and original predictions regarding the connection between the Sun's surface and interplanetary large-scale plasmoids. Those will have to be tested with the upcoming Solar Orbiter spacecraft, which will couple solar remote-sensing and heliospheric *in situ* observations for the first time.

The above-mentioned ongoing studies of Jupiter and Saturn will help to perform a long-term comparative monitoring of planet/satellite electrodynamic interactions at two different planets, will serve to prepare a review book focusing on the rich variety of Jupiter's radio emissions and the underlying wave emission mechanisms and will complement a reference frame necessary to search for/analyze radio emissions produced by exoplanets.

LPP will pursue the development of high-time resolution ion mass spectrometers and of its innovative 3DCAM plasma spectrometer. In July 2019, 3DCAM was selected by an industrial consortium led by Thalès Alenia Space for the DAEDALUS ESA Phase 0/A study, DAEDALUS being an Earth Explorer 10 mission candidate to study low altitude ionospheric plasmas. The PLAS@PAR funded equipment is a key asset of this development strategy.

In addition, dedicated innovative softwares (SciQLOP) based on machine learning techniques, are currently developed at LPP to analyze the large amount of data of the future space missions.



# Focus

**Corentin Louis** did a Bachelor's degree in Fundamental Physics in Nantes, then he continued with a Master 1 in fundamental physics in Toulouse and did a Master 2 in Astrophysics with an internship at the Paris Observatory. In 2015, he joined Laurent Lamy (LESIA) as a PhD to work on Comparative study of auroral processes of Saturn and Jupiter sampled *in situ* by Cassini and Juno missions. His study confirmed the existence of radio emissions associated with the interaction between the Galilean moons of Jupiter and Jupiter itself. Now, he is working at IRAP (Toulouse, France) as a postdoctoral researcher.

**Fabiola Magalhaes** obtained her PhD in space Geophysics at National Institute of Space Research in 2016 on the following topic "Temporal variability of the Io plasma torus inferred from ground-based [SII] emission observations". Then she joined Laurent Lamy at LESIA for a 18 months post-doctoral position to work building a high-level database of Cassini/UVIS auroral observations of Saturn in the frame of the APIS service (apis.obspm.fr). Now, with the development of the database it is possible to take advantage of the multi-platform measurements to characterize the different components of kronian aurorae, e.g., energy budget, dynamics from short-term scales to solar/seasonal variations.

**Krzysztof Barczynski** defended his doctoral thesis "Small-scale structures in the upper atmosphere of the Sun" in 2017 at the International Max Planck Research School for Solar System Science from the University of Göttingen. He then obtained a postdoctoral position for a few months in the same group before to join the solar group of LESIA in 2019 to work with Sophie Masson and Guillaume Aulanier on postdoctoral project relative to the formation, structure and feedback of 3D solar eruptions.

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# PLASMAS IN EXTREME CONDITIONS

## UHI LASER-PLASMA INTERACTION and RELATIVISTIC PLASMAS

**Leaders**
Paulo Angelo, Elisabeth Dalimier, Mickaël Grech, Caterina Riconda

**Laboratories involved**
LULI

**External collaborations**
Heidelberg University (Germany), University of Pisa INP/CNRS (Italy), Auburn University (USA), Laboratoire Surfaces irradiés (CEA, École Polytechnique, France).

**Projects**
1 innovative small project, 1 postdoctoral project (Samuel Marini, LULI), 1 doctoral project (Anna Grassi, LULI), 2 invitations of international experts (Eugene Oks, Auburn University; Andrea Macchi, University of Pisa).

**Budget**
217 000€

## Background & objectives

New theoretical and experimental challenges are proposed to researchers by the new generation of Ultra High Intensity (UHI), High–Power (multi-PW) lasers, that will allow the interaction of particles with extremely strong fields.

This interaction will lead to ground-breaking ultra-short synchronized light and electron sources, high energy electrons and ions sources, as also intense hard X-ray and Gamma radiation with many possible applications. UHI lasers will also allow fundamental studies of matter and physics in the presence of extremely high electromagnetic fields, that cannot be obtained on earth by any other means.

In order to anticipate future experiments on the forthcoming high-power lasers, like APOLLON or ELI in Europe, a large effort has to be put in the theoretical and numerical modelling of the new regime of laser-plasma interaction associated with these ultra-high laser intensities (I >~ $10^{23}$ W/cm$^2$). Various ideas are developed in this respect in the projects presented in this section:

- **Exploring the generation** of fast electrons beams in relativistic laser-solid interaction by using adequate structured targets, and exploiting schemes of ultra-relativistic plasmonic physics, such as excitation of surface plasma waves with ultra-relativistic lasers (I >= $10^{20}$ W/cm$^2$);
- **Generating X-ray and Gamma ray sources** with unique characteristics, and also abundant electron and positron pairs (through laser pulses carrying orbital angular momentum). This last point includes the design for the future multi-PW lasers an optimal scheme for the generation of electron-positron pairs plasmas of astrophysical interest;
- **Developing adequate diagnostics** such as for instance X-ray spectroscopic methods for measuring ultra-strong magnetic fields arising during relativistic laser-plasma interactions;
- **Using laser-plasma interaction** as an experimental platform for studying astrophysical phenomena in the laboratory.

## Main results

### Excitation of surface plasma waves with UHI lasers

We have investigated the impact of the angle between the direction of propagation of the laser and the surface on the excitation of surface plasma waves. Attention was also paid to the ultra-relativistic effects which are important since the laser intensities are very high. We derived the interval in these incidence angles that allow excitation of these surface plasma (Figure 1). Among the results obtained, it was shown that above a critical laser intensity, which depends on the plasma density, the laser radiation pressure starts to play an important role and influence the electron energy distribution *[Marini et al., 2019]*.

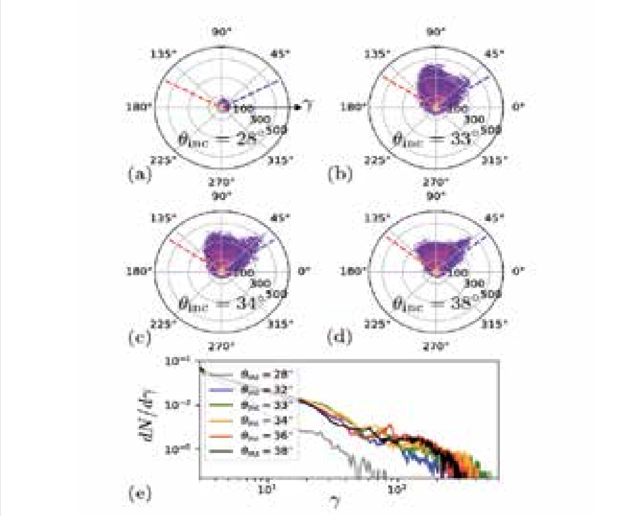
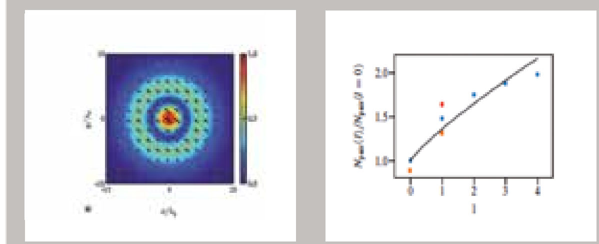


*Figure 1: Energy and angular distribution of electrons generated on a dense structured plasma by a laser at intensity of $10^{20}$ W/cm$^2$, for different incident angles $\theta_{inc}$ between the laser and the normal to the surface. The optimal conditions to generate fast electrons at relativistic gamma correspond to 32° and 36°. In these conditions, the gamma Lorentz factor is 500, which corresponds to 250 MeV. [S. Marini 2019 et al., submitted].*

### Creation of abundant electron and positron pairs

Among other possible applications of fast electron beams, we notice that they will radiate and generate X and Gamma rays. The interaction of these energetic photons beam with an intense laser can lead to abundant pairs creation, as described by the Breit-Wheeler process. For a given laser energy we studied the role of the laser peak intensity versus the size of the focal spot. In particular we studied lasers with a focal spot that is not a standard Gaussian. Indeed, focal spots described by Laguerre Gauss (LG) polynomials are accessible today with interesting characteristics. An example is shown in Figure 2 where we see that the focal spot has the form of a central spot plus a concentric ring. This is a Laguerre Gauss polynomial with radial index l=2. We thus explored the influence of the order of the LG laser beams, see Figure 2 on pairs creation.



*© F. Niel, PhD thesis*

*Figure 2:*
*Left image: laser electric field (arrows) and transverse intensity distribution at focus when the intensity distribution is described by a Laguerre-Gauss polynomial with radial index l=2 (notice that l=0 correspond to a standard laser with gaussian intensity distribution). Right image: number of pairs created in the interaction of Laguerre polynomials with Gamma rays as a function of the radial index l.*

By theory and self-consistent PIC simulations we obtained the counter-intuitive result that, above a given threshold, a larger spot size (or a higher l number in the case of LG laser beams) is more favorable than the highest peak intensity, as shown in Figure 2 right, *[Niel et al., 2018,]*.

### Developpement of a diagnostic to measure extreme magnetic fields

A new spectroscopic method for measuring Giga Gauss magnetic fields is proposed, based on the phenomenon of Langmuir wave- caused dips in X-ray line profiles. This phenomenon is due to the resonance between the Stark splitting of the levels and the frequency of the Langmuir wave at the critical density. The ultra-strong magnetic fields affect the separation of the dips from one another. This relative shift can be used to measure such fields. This method is more efficient for Balmer-alpha and beta lines, than for the Lyman lines. However, the half-width of the Langmuir dips measured for Lyman lines can be relevant *[Dalimier et al., 2019; Oks et al., 2019]*.

### Relativistic collisionless laboratory astrophysics

The work aims both at developing theoretical models and numerical simulation capabilities to understand basic processes of interest for laser-plasma interaction (LPI) and collisionless astrophysics, and at designing future experimental campaigns to recreate, in the laboratory, conditions relevant to various astrophysical scenarii. On the theoretical side, the effects of a flow-aligned external magnetic field on the linear and nonlinear phases of the Weibel instability driven in counterstreaming electron beam were investigated *[Grassi et al., 2017]*. This work relies on analytical modeling supported by kinetic (PIC) simulations and sheds light on the saturation mechanisms of an instability that is of utmost importance for both LPI and collisionless astrophysics. The Weibel instability is indeed one of the major mediators of astrophysical collisionless shocks, which are identified as the most likely source of high-energy radiation and particles (cosmic rays) in the universe. Today, the LPI community is thus strongly involved into recreating in the lab such collisionless structures using moderate intensity, high energy, laser pulses such as NIF or LMJ. In contrast, we propose a new experimental scheme *[Grassi et al., 2017]* involving ultra-high intensity, kJ, laser systems to investigate the first phase of shock formation by making use of the strong radiation pressure of such laser systems to drive high-velocity collisionless flows (Figure 3). This works, based on massively parallel PIC simulations (section 5.2), has also interesting implications for LPI as it demonstrates how some laser-target configurations allow to mitigate electron heating, providing a more effective particle acceleration by the laser radiation pressure.

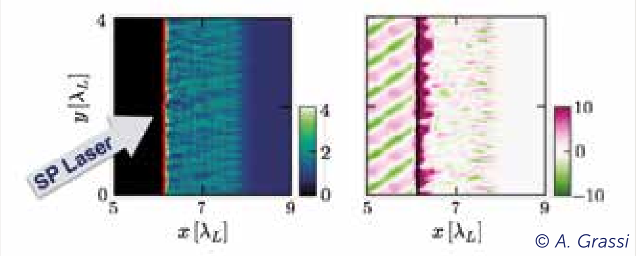



*Figure 3: A scheme to induce large turbulent magnetic fields from radiation-pressure-driven flows in a 3D PIC simulation with realistic ion mass. A quasi-neutral plasma flow is pushed inside the target (toward positive x) by the strong laser radiation pressure. Distances are in units of the laser wavelength $\lambda_L$. The electron density (in units of initial density) is shown on the left and the magnetic field (in units of $m_e c \omega_L /e$, where $\omega_L$ is the laser angular frequency) on the right.*

# Perspectives

Concerning the electron acceleration by surface plasma waves, it will be interesting to control other characteristics of the electron beams generated by the interaction of ultra-intense laser and structured targets, and their secondary radiation. In particular ideas from plasmonics can be extended to intense fields plasma interaction: for example the possibility of obtaining ultrashort and fast electron beams using a laser with a rotating wavefront (i.e. such that the front and the back of the pulse do not have the same incident angle). The corresponding radiation can have also interesting characteristics and needs to be studied.
Currently there is in the community special interest in the generation of abundant electron-positron pairs (up to a plasma of pairs), that is still an important experimental challenge. An analogous challenge applies to laboratory astrophysics and to the generation of collisionless shocks. The main perspective of our work in this respect is to use our understanding to dimension experiments in multiPW laser facilities that are now starting to be operational.

# Focus

**Samuel Marini** received his PhD in 2016 from Universidade Federal do Rio Grande du Sul (Brazil) on the topic "A fully kinetic model for the electron flow in a crossed field device" under the supervision of Renato Pakter and Felipe Barbedo Rizzato. He received in 2017 a PLAS@PAR fellowship to pursue the study of electron acceleration via excitation of surface plasma wave by intense laser in collaboration with the Laboratoire des Solides Irradiés.

# Awards

**Anna Grassi** received in 2014 M.Sc. degree in Physics from the Università di Pisa, Italy. She received a PLAS@PAR fellowship to do her PhD in Plasma Physics under the supervision of Caterina Riconda, LULI and Andrea Macchi, UNIPI. Her thesis on "Relativistic shocks in magnetized plasmas in the context of laboratory astrophysics" was defended in October 2017. Right after she joined Stanford University (California) for a postdoctoral position.
Anna was the recipient of the 2018 **René Pellat Prize** from the Société Française de Physique, plasma division; she was also was **awarded by the University of Pisa for the best doctoral thesis - year 2018 - sector "Mathematics, Informatics, Physics and Earth Sciences".**

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## COSMIC RAYS AND PLASMAS

**Leaders**
Andrea Ciardi, Pascal Démoulin, Julien Fuchs, Miho Janvier, Roch Smets

**Laboratories involved**
LERMA, LESIA, LULI, IAS, LPP

**External collaborations**
Christian-Albrechts-Universität, Kiel, Germany.

**Projects**
1 equipment project, 1 innovative small project, 1 doctoral project (Loïc Nicolas, LPP-LERMA), 1 invitation of international expert (Jingnan Guo, Christian-Albrechts-Universität, Kiel, Germany).

**Budget**
117 000€

# Background & objectives

**The acceleration of cosmic rays is attributed to various mechanisms in astrophysical environments. In supernova remnants, the galactic cosmic rays are supposed to be produced by diffusive shock acceleration.**

The stream of these charged particles in the cold galactic magnetized plasma is associated with instabilities leading to the growth of magnetic fluctuations in the interstellar medium. These magnetic fluctuations can then perturbate the dynamics of the cosmic rays in a non-linear way.

In the heliosphere, irregularities of the solar wind can also perturb the propagation of cosmic rays and modulate their intensity. Forbush decreases are identified as a temporary and rapid depression in cosmic ray intensities, followed by a comparatively slower recovery phase that typically lasts for a few days. Due to the diversity of solar sources (e.g. fast streams interacting with a slow solar wind, or magnetic structures such as coronal mass ejections), and their dynamic interactions throughout the heliosphere, the properties of Forbush decreases can be very diverse. While most studies have been conducted on Earth (e.g. via neutron monitors), recent space missions also offer multiple viewpoints of the interaction between the heliosphere and cosmic rays at different distances from the Sun. This is the case, for example, with the Mars Science Laboratory (MSL) RAD experiment that offers a study of Forbush decrease on the surface of Mars. These multiple points offer the possibility to study the diverse origins of Forbush decreases at different heliospheric location.

While mainly studied by *in situ* or remote sensing measurements, laboratory experiments can provide a fruitful alternative way to investigate the dynamics of charged particles in magnetized plasmas.

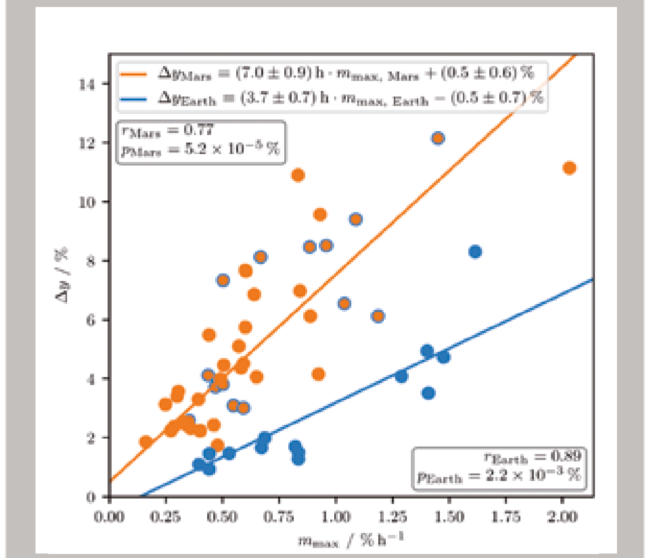
**The projects funded by PLAS@PAR aimed at investigating the interaction of these ultra-high energy particles with an ambient medium by numerical simulation, remote observations and experiments :**

- **Using a kinetic PIC code**, we aimed at following the nonlinear dynamics of charged particle at energy of 1-10 Mev in a cold magnetized plasmas in order to investigate the kind of instability at play, and its nonlinear evolution not described by linear or quasilinear theories.
- **The weaker magnetic** shielding of cosmic rays due to the Martian atmosphere, combined with measurements of the Forbush decrease at another location such as Earth (with traditional measurements) provides an opportunity to better constrain the physics involved in the interaction of high energy particles with heliospheric magnetic fields.
- **Experiment performed with lasers at LULI of LULI facilities**, allowed the first study of the effect of a magnetic field on the propagation of ion beams (E ~ 10 Mev). This work takes benefit of a high-strength (up to 40 T) magnetic field coil on the laser facility, realized by LNCMI.

# Main results

The investigation of the streaming instability for both astrophysical and laboratory plasmas started through a collaboration between LULI/ LPP and LERMA, and the PhD work of Loïc Nicolas with a dual approach: theory and simulation with a PIC code and first applied to the interstellar magnetized plasma and experiments performed at LULI.
The first part of the work was dedicated to a theoretical analysis to determine which kind of mode can grow - depending on the plasmas parameters - among the three possible modes predicted by linear theory.
The numerical investigation of this instability shows a slow-down the streaming cosmic rays, resulting in a local enhancement of their density. Such confinement is the most favorable scenario to explain the birth of protostar when these enhanced fluxes of cosmic rays interact with dense molecular clouds. For practical applications, it was necessary to include the effect of the collisions.
Then, Loïc Nicolas investigated how the small collisionality of the interstellar medium can reduce this confinement. Among other results, he put forward that collisions can unexpectedly decrease the confinement by reducing the anisotropy of the plasma, which inhibits the instability in some cases.

The continuous measurement of cosmic ray fluxes by the Radiation Assessment Detector on the surface of Mars since August 2012 together with the plasma and magnetic field measurement by MAVEN since its arrival at Mars in September 2014 have just opened up a new window for case as well as statistical studies of Forbush decreases at Mars.
Following our recent statistical study *[Guo et al., 2017; Papaioannou et al., 2019]*, where a list of Forbush decreases have been obtained at Mars, we investigate how interplanetary coronal mass ejections are affecting Martian Forbush decrease. Due to a larger screening of energetic particles by the Earth magnetosphere than by Mars one, Forbush decreases at Mars have a larger magnitude. However, analyzing and comparing the Forbush decreases at different heliospheric locations cannot directly give information on the physics involved.
A deeper analysis is needed, for example by plotting the amount of decrease (Δy) versus the maximum decrease rate ($m_{max}$) as shown in Figure 1. The fitted slopes represent the time information of the passage of the ICME. As the maximum decrease rate of the Forbush decreases typically occurs right after the shock arrival in front of the coronal mass ejection, it indicates that the sheath region at Mars is generally larger than that at Earth.




© [Freiherr von Forstner et al., 2019, JGR, soumis]

*Figure 1: Forbush decrease amplitudes, Δy in percentage, versus the maximum decrease rate, $m_{max}$, in percentage per hour, at Mars (in orange) and at Earth (in blue). The orange dots with a surrounding blue circle are events that first passed Earth and later arrived at Mars. The straight lines are least square fits of the data.*

On the laboratory side, a preliminary experiment was done at the ELFIE ps/ns laser installation at LULI in 2016 using a gas jet as an ambient medium. This one could be ionised by a ns laser beam. The ions were independently generated after the interaction of a ps beam with a metallic foil. We observed a substantial modification of the ion energy spectrum of the streaming ions after the interaction with B (Figure 2). The results of the experiments are still under investigation and should be published in the near future.
The PLAS@PAR's funded engineering studies at LNCMI resulted in a design of this magnetic coil that is now on its way to be installed on Apollon, which will allow to study the effect of a magnetic field on various plasmas, with exciting applications for cosmic rays streaming instability.

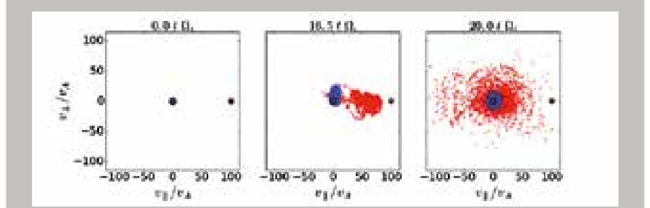



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*Figure 2: Effect of the magnetic field B on the velocity distributions of both the high density ambient plasma and the lower density ion beam. Velocity distribution functions, at 3 times, of the cold ions (blue) and of the cosmic rays (red, velocity parallel to B) in the plane parallel/perpendicular to the magnetic field: left panel is prior the initial state (initial condition), middle panel is during the linear growth phase and right panel is during the non-linear phase (from PIC simulations). The time is in units of $1/\Omega_i$, where $\Omega_i$ is the initial gyrofrequency and $v_A$ is the Alfven velocity.*

# Perspectives

The work on streaming instability requires further theoretical investigations, especially concerning the importance of the velocity distribution of the streaming ions, and is one of the topics of the PhD thesis of Alexis Marret.

On the experimental point of view, thanks to the implementation of the magnetic field coil on Apollon laser facility, we plan to increase the density of the ion beam, which will facilitate the development of the instability up to its non linear stage. The extension to higher velocities and the possibility to access to a reduced width of their energy spectrum would be of great interest.

Further investigation of Forbush decreases at Mars is ongoing using more statistics as well as theoretical calculations. The pass-by of streaming interaction regions at a heliospheric location can also cause *in situ* modulation of cosmic rays. Using a cross-correlation method, we found the *in situ* solar wind peak speed at Earth being delayed by about 3.5 days while this delay is about 5.5 days at Mars after the passage of the solar source of the fast wind at the origin of the streaming interaction region. This is consistent with the heliospheric distance of the planets and the travel speed of the solar wind. We are still working on refining the results to quantify the correlations in order to better understand the radial evolution of the streaming interaction regions.

# Focus

Former student at the Sorbonne Université, **Loïc Nicolas** did a Master degree in Plasma Physics. Then as a PhD, he joined Andrea Ciardi (LERMA) and Roch Smets (LPP) in 2014 to work on Streaming instability in low-energy cosmic rays. On 28 September, 2017, he defended his thesis, entitled "Effects of collisions on the magnetic streaming instability". He is now working in the private sector at Texeï.

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# PLASMA AMPLIFICATION

**Leaders**
Julien Fuchs, Caterina Riconda

**Laboratories involved**
LULI

**External collaborations**
Livermore National Laboratory (USA), Heine University (Germany), Eli-Beamlines (Czech Republic).

**Projects**
1 equipment project, 1 doctoral project (Marco Chiaramello, LULI).

**Budget**
110 000€

## Background & objectives

**The generation of short and high intensity laser pulses has become important in many technical applications such as in alternative schemes for laser-driven nuclear fusion or high energy particles and radiation sources generation.**

Current solid-state technology allows to generate laser pulses of a few femtosecond duration with up to a Petawatt peak power ($10^{15}$ W), leading to intensities of $10^{22}$ W/cm$^2$ in the laser focal spot. The limitation in terms of maximum achievable intensity is due to the damage thresholds of the optical components. The use of plasma as an amplification medium or more generally as an optical medium (plasma mirrors) can be considered because of the absence of such damages.

This amplification can be obtained through the coupling of a long laser pulse (pump) and the short laser pulse (seed). Various schemes to implement this technique have been proposed, and proof-of-principle experiments of plasma based amplification have been conducted confirming the interest of this technique over the last ten years. LULI's team is one of the leaders of the field since the past ten years *[Weber et al., 2013; Lancia et al., 2010; Chiamarello et al., 2016; Chiamarello et al., 2017]*.

The main objective of the project was to improve the efficiency of the plasma based laser amplification process and acquire a better theoretical understanding of the coupling mechanisms between pump and seed in the so-called strong Stimulated Brillouin Scattering (sc-SBS) scheme. An important goal was thus to identify the parameters to control the amplification process in a realistic experimental configuration. To reach this objective we participated in the development of the Particle In Cell code SMILEI (see section 5.2) in order to have a robust numerical support for dimensioning the experiments of the amplification process.

## Main results

The PhD thesis of Marco Chiamarello was devoted to the analytical and numerical description of the different stages of the sc-SBS amplification of the laser pulse seed. It allowed to clearly understand the role of important parameters influencing the amplification process, namely: the duration and temporal shape of both the pump and the seed pulses, the laser chirp, the profile of the plasma density, the pump and seed relative intensities.

The optimal parameters for experimental conditions have then been identified, and the experimental setup was prepared with the support of both very large two dimensional simulation of sc-SBS amplification, and analytical predictions. The joint theoretical and experimental expertise of the team allowed to obtain new record results in terms of energy exchange between pump and seed and amplification. These results have been granted publication in Physical Review X *[Marques et al., 2019]*.

For the first time, laser-plasma amplification of subpicosecond pulses above the Joule level is demonstrated with a large energy transfer and a very high efficiency, up to 20%. This is a major milestone for this scheme, which could become a solution for the next generation of ultra-high-intensity lasers.

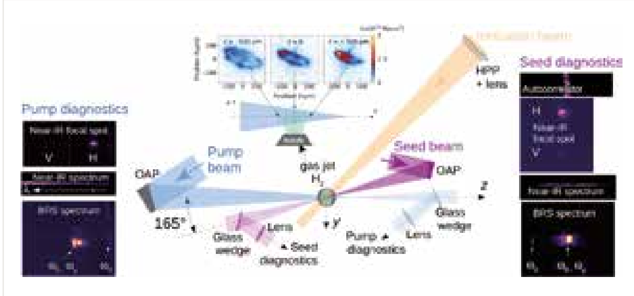

*Figure 1: Experimental arrangement, showing pump and seed beams focused on target, the ionization beam creating the plasma in a gas jet at the beam intersection and the different diagnostics used in the experiment. Inserts also shown transverse profiles of the pump [Marques et al., 2019]*

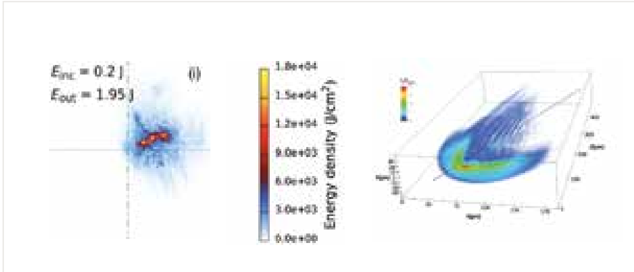

*Figure 2:*
*Left: experimental signal of the amplified seed.*
*Right: 3D simulations showing a 3D view of the amplified seed signal [Marques et al., 2019].*

*© M. Chiaramello, PhD thesis*

*Figure 3: 2D simulations of a typical experimental situation showing the pump and seed crossing in the plasma at different times (5.8, 7.6 and 9.6 ps). The seed is amplified while the pump is depleted.*

## Perspectives

After this successful experiment, the technique will be extended to more energetic lasers: this should allow to improve the homogeneity and extent of the interaction volume, reduce beam losses from competing instabilities with the use of a plasma with a density ramp and a much higher temperature. The main goal is to obtain an amplification of very large focal spot that, coupled to a plasma mirror, will allow to reach extremely high intensities and give an alternative to the chirped pulse amplification (CPA) technique.

## Focus

**Marco Chiamarello** studied nuclear engineering at École Polytechnique in Turin (Italy). He discovered plasma physics research during an internship in the USA at "Los Alamos National Laboratory". Then, he decided to start a PhD at LULI to work on "Study of short pulse amplification by Brillouin Backscattering in the strong coupling regime". Right after his thesis defense in 2016, Marco Chiamarello has been recruited at RTE, where he is in charge of R&D studies.

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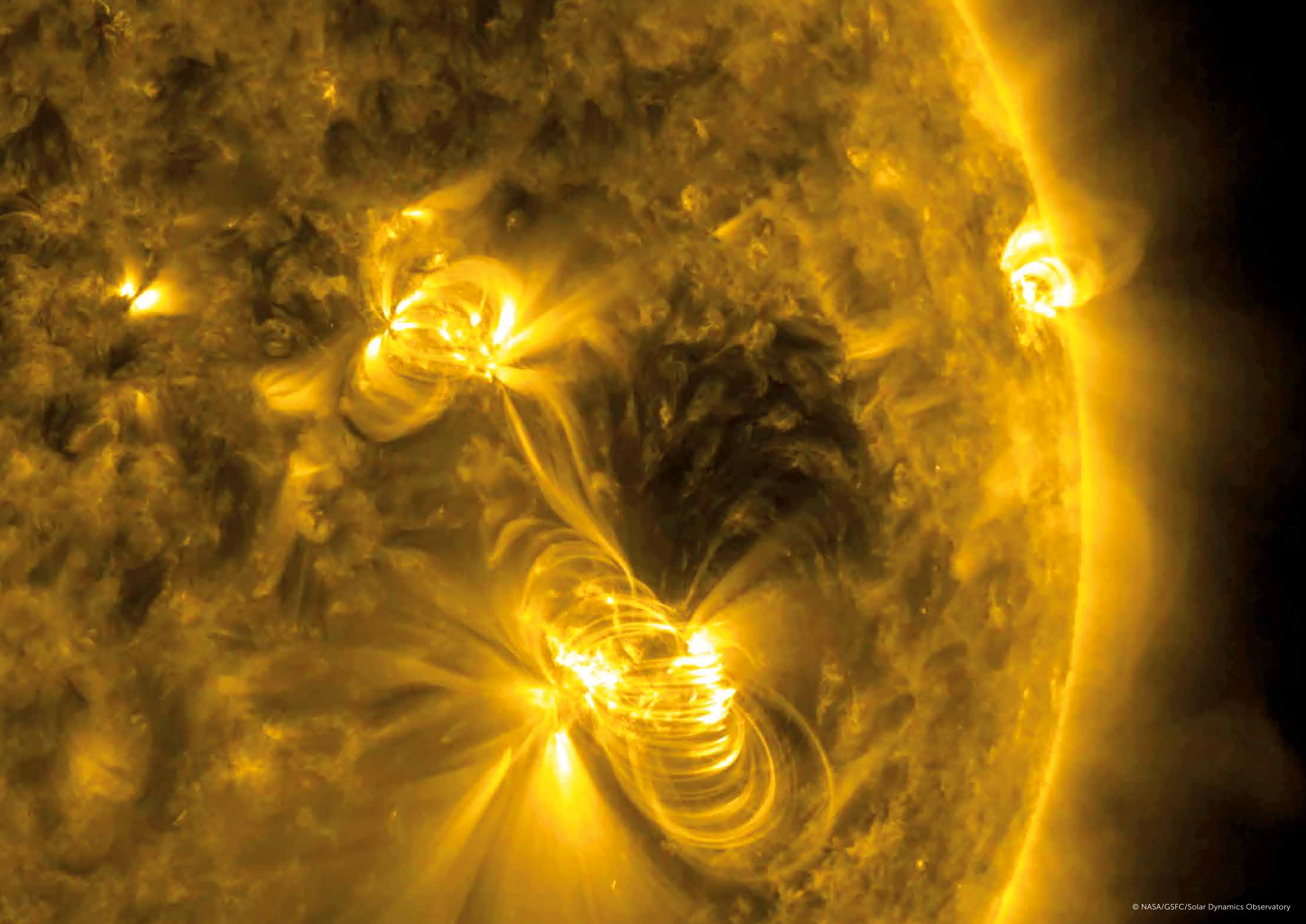

# PHYSICO-CHEMISTRY OF PLASMAS AND APPLICATIONS

## PLASMA PROPULSION

**Leaders**
Ane Aanesland, Anne Bourdon, Pascal Chabert, Paul-Quentin Élias, Julien Jarrige, Denis Packan

**Laboratories involved**
LPP & ONERA (Lightning, plasmas and application - FPA)

**External collaborations**
Department of Physics, University of York (UK), Department of Physical Electronics, Masaryk University (Czech republic), Istituto di Metodologie Inorganiche e dei Plasmi (Monterotondo, Italy), V.N. Karazin Kharkiv National University (Ukraine).

**Projects**
6 equipment projects, 3 innovative small projects, 1 doctoral project (Pascaline Grondein, LPP), 1 postdoctoral project (Trévor Lafleur, LPP & ONERA), 4 invitations of international experts (Stanislav Dudin, V.N. Karazin Kharkiv National University; James Dedrick, University of York; Zdenek Bonaventura, Masaryk University; Francesco Taccogna, Istituto di metodologie inorganiche e dei plasmi).

**Budget**
311 000€

## Background & objectives

**In a few decades, space missions have taken a tremendous importance in society. The development of satellites orbiting Earth has greatly aided everyday life, from those used for communication, broadcasting and navigation (GPS) to satellites that orbit our planet for surveillance, remote sensing and observation.**

According, to the Union of Concerned Scientists (UCS) Satellite Database, 1 168 active satellites were either in geostationary or low orbits around Earth in 2013. Among them, 236 were equipped with Electric Propulsion systems for satellite motion in outer space, such as orbit transfer, station-keeping and attitude control. Space propulsion includes the propulsion technologies required to leave the Earth's atmosphere, as well as the ones to perform maneuvers in space.

Four types of electric thrusters are found on these satellites (65% of arcjets and resistojets, 16% of Hall-effect thrusters, 16% of ion thrusters and 3% of pulsed plasma thrusters). Although, these technologies differ, they are all based on the same principle, namely creating a force on the object by changing its momentum by expelling mass. This thrust is given by the product of the rate of change of the spacecraft mass by the velocity of the ejected mass. Electric Propulsion makes use of electrical power to ionize and accelerate a propellant to velocities up to twenty times larger than those used for of chemical thrusters.

The higher exhaust velocity of these electric thrusters reduces the mass needed to provide a given impulse, and thus allows substantial cost savings. For example, to maintain a 3 ton satellite on a geostationary orbit for 15 years, a propellant mass consumption of about 100 kg is needed with an exhaust velocity of 20 km/s for an electric thruster, while nearly 1000 kg would be required with an exhaust velocity of 2 km/s for a chemical thruster. The thrust of electric thrusters is lower than that of chemical thrusters but a combination of low thrust and high specific impulse (defined as impulse per propellant mass unit) is sought for orbit insertion, attitude control and drag compensation.

The research on plasma thrusters concerns basic scientific and technological issues and is thus extremely developed both in industry and academic institutions (see for instance http://erps.spacegrant.org/). In the last years, the field of electric propulsion has evolved significantly with, in particular, a growing need for low power (1-700W) electric propulsion systems for the expanding and disruptive market of small satellites (divided into small-, micro- and CubeSat nano-satellites), with a thrust level of the order of micro-Newtons. This technology represents an extreme cost reduction and the possibility for mass production via for example the use of the standardized CubeSat technology.

Some electric thruster concepts, such as the Hall effect thruster, have been invented in the 60s and have been extensively studied since then as their physics is very complex. Recently, new concepts have been invented, for example the gridded thrusters PEGASES and NEPTUNE and the magnetic nozzle thruster ECRA. The goal of the research activities carried out at LPP and ONERA and their collaborators is to improve understanding of the key physical processes such as anomalous electron transport, plasma surface interactions and wall erosion in electric magnetized thrusters, such as the Hall-effect thruster, ion-ion thruster (as PEGASES at LPP) and Electron Cyclotron Resonance (ECR) thruster (at ONERA), and develop new reliable diagnostic tools to improve the experimental validation of the thruster physics.

Another question concerns the choice of the propulsive gas (in particular the study of electronegative molecular gases like iodine) for future industrial applications.

## Main results

### PEGASES

The research on the PEGASES thruster (Plasma propulsion with electronegative gases) started at LPP in 2006. Its main interest is to use both positive and negative ions produced in an electronegative gas to generate thrust. Since 2006, experimental prototypes were built at LPP, and analysed with the help of theoretical models and simulations. Their recent improvement required the setup of new experimental test benches and the development of dedicated diagnostics.

**In this context, the research work focused on three main aspects:** i) the plasma generation using inductively coupled plasmas with electronegative gases such as $SF_6$ and Iodine, ii) the generation of ion-ion plasmas downstream magnetic filters, in which the transport of electrons and ions in the magnetic field plays a key role and iii) the acceleration of positive and negative ions to generate thrust without the need for a separate electron neutralizer. PLAS@PAR provided support for this research mainly on two fronts:

- To study this innovative acceleration of positive and negative ions: a new and unique square waveform generator allowed the first proof-of-concept of this type of acceleration *[Aanesland et al., 2015]*.
- To develop an experimental prototype for the research on iodine plasmas and also new global models, where iodine collision cross sections and reaction sets are included. This work paved the way to improve the understanding of the physics of iodine plasmas and the technological challenges of using iodine for propulsion applications, putting LPP on the map as one of the pioneers in this field *[Grondrein et al., 2016]*.
- To improve the quality of the modeling of iodine plasma kinetics with a new collaboration between LPP and LCPMR on the calculation of a set of key cross sections for the modeling of iodine plasma chemistry.

### NEPTUNE

NEPTUNE is a new concept for gridded ion thrusters, where a novel RF acceleration technique is applied to allow the extraction of both ions and electrons from the thruster, and thus to remove the need for a separate neutraliser as in Hall effect thrusters.

The concept was patented by researchers at LPP in 2012/2015. The first prototypes were developed over the years of 2012-2015 that showed the significant potential of this technology. PLAS@PAR supported this work by funding new equipment to investigate this novel acceleration method, and research visitors that contributed with their expertise to increase the understanding of the physics of the electrons' acceleration.

The research supported by PLAS@PAR demonstrated that this concept of RF acceleration results in the formation of a neutralizing electrons beam, showing that contrary to classical thruster beams where plasma plume is composed of an anisotropic ion beam with a neutralizing isotropic electron cloud, the beam in this new case is composed of both accelerated ions and electron anisotropic populations *[Dedrick et al., 2017]*.

### ECRA

**Electron Cyclotron Resonance (ECR) plasma thruster**

Laser Induced Fluorescence (LIF) has been shown to provide a wealth of information on the ion velocity distribution function (IVDF). Recently, ONERA has demonstrated an innovative diagnostic to retrieve the full IVDF in the plume of electric thrusters, based on 3D LIF tomography in the phase space. The technique has been successfully applied to a miniature Hall-effect thruster. It can be improved through the capability to perform time resolved measurements. For this purpose, PLAS@PAR has funded the purchase of a laser amplifier, a boxcar average, and an acousto-optic modulator. The material is currently being tested and will enable to significantly reduce the experiment duration, and to gate the fluorescence signal with a good time resolution.
The ECRA thruster uses electron cyclotron resonance as the heating mechanism in the discharge chamber. This resonance is obtained using microwaves at 2.45 GHz. The design and investigation of the thruster requires a careful characterization of the microwave circuit. PLAS@PAR has contributed to the purchase of a 20 GHz two-channel vector network analyzer to perform this type of microwave characterization. This equipment has been used by 3 PhD students (Cannat, Vialis and Peterschmitt) working on ECRA since 2015 *[Cannat, 2015; Vialis, 2018]*.

**Diagnostics of low-pressure magnetized plasmas for electric propulsion**

Electrostatic (or Langmuir) probes are widely used to measure dynamic plasma parameters. In the context of the postdoctoral project of Trevor Lafleur, they were applied to the plasma beam of quasi-neutral electric thrusters, like PEGASES and ECRA. Both thruster beams present challenges in terms of analysis using the classical theories for Langmuir probes. For PEGASES, the ion-ion plasma requires a careful reexamination of the classical ion collisions laws used for Langmuir probes measurements. For ECRA, the presence of high energy magnetized electrons requires careful procedures in the

Langmuir scans, but the analysis led to the first measurement of the electron temperature, and to its interpretation through a semi-analytical model *[Cannat et al., 2015]*. In addition, the dynamics of the expanding beam has also been analyzed, in particular the electron cooling in the thruster magnetized beam *[Lafleur et al., 2015]*. These results have been an important step in the understanding of the ECRA thruster physics.

At the LPP, we also started a new project to couple optical emission spectroscopy, collisional radiative models and PIC simulations to extract the spatially and temporally resolved electron temperature inside the channel of Hall thrusters. The optical set-up has been partially funded by PLAS@PAR in 2018. The equipment has been bought and experiments are underway. The extraction of the electron temperature (or electron energy distribution functions), with this complementary approach coupling experiments and simulations, in new generation Hall effect thrusters, will be a real breakthrough for electric propulsion applications.

**Simulations of low-pressure magnetized plasmas for electric propulsion**

Since 2014, a 2D massively parallel PIC code (LPPic2D) is under development at the LPP to simulate low-pressure plasmas in gridded and Hall-effect thrusters *[Croes et al., 2017]* and has benefited from PLAS@PAR's support. A significant effort has been devoted to the verification of the code and its optimization. In particular, in collaboration with Zdenek Bonaventura we have worked on the implementation of different parallel libraries for Poisson solvers in LPPic2D to test their performances on test-cases of increasing complexity. The small size test-cases have been performed on local machines and have allowed to carry out more challenging test-cases and to demonstrate the scalability of the code LPPic2D on national supercomputers of GENCI (Figure 1).

During the visit of Francesco Taccogna, we discussed more in detail the benchmarking of PIC codes on test-cases relevant for electric propulsion applications. LPP is now at the forefront of an international benchmarking activity named LANDMARK for (Low temperature magnetized plasma benchmarks)

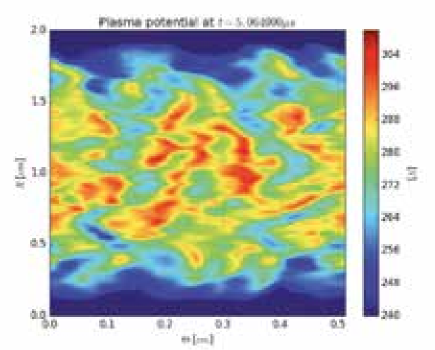

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*Figure 1: 2D PIC simulation of the radial-azimuthal plane at the exit of a Hall-effect thruster [V. Croes, PhD Thesis, 2017]. The figure shows a snapshot of the plasma potential in the r-theta plane. It demonstrates the propagation of a strong instability in the azimuthal direction.*

# Perspectives

On the plasma simulations for electric propulsion applications, we expect to develop interactions between researchers working on plasma simulations and to promote the sharing of validated numerical tools.

The diagnostics for Electric Propulsion developed with the support of PLAS@PAR seek to improve the quality and accuracy of the measurements. These ongoing developments are readily usable for other thruster technologies (HET), and could be used for the development of other new technologies (e.g. Vacuum Arc Thrusters or neutralizer-free gridded ion thrusters) or for the validation of models.
Since January 2017, the start-up ThrustMe has been created by Ane Aanesland and Dmytro Rafalskyi on electric propulsion for the next generation satellites (See Chapter "Industry").

A "Chaire ANR industrielle" POSEIDON (2016-2020) has been independently obtained at LPP. This project is co-funded by Safran Aircraft Engines and the ANR to work on future plasma thrusters for low earth orbit satellite propulsion systems.
At the European level, LPP was one of the contributors of the WP6 on alternative propellants in the H2020 CHEOPS (Consortium for Hall Effect Orbital Propulsion System, 2016-2020), whereas ONERA was coordinator of H2020 MINOTOR (MagnetIc NOzzle thruster with elecTron cyclOtron Resonance, 2017-2019).

# Focus

**Pascaline Grondein** did several internships at LPP, GAP Optique and IAP before joining the LPP to carry out a PhD on electric propulsion, on the study of iodine as a propellant for electric gridded thrusters, that she defended in September 2016. Then she moved to the UK for a postdoctoral position at the University of York and at the University of Surrey. Since 2018, she works as Propulsion Engineer at Thales Alenia Space, UK.



# Awards

**Trévor Lafleur** studied aeronautical engineering at the University of the Witwatersrand in Johannesburg (South Africa) and obtained his PhD in plasma physics from the Australian National University in 2011. In 2012, he joined the LPP as a postdoctoral researcher, and was involved in several projects with different groups within LPP and also with ONERA. He worked for instance on tailored voltage waveform RF capacitive plasmas, their influence on ion velocity flux distributions and electron heating mechanisms, as well as the development of two new plasma propulsion concepts. From 2015 to 2017, he has been involved in research supported by CNES to investigate Hall effect plasma thrusters. Since September 2017, he is the owner and physics consultant at PlasmaPotential in Canberra. In 2016, he received the **Noah Hershkowitz Early Career** for his work in the field of cold plasmas.

**Pascal Chabert,** Director of the LPP and former Vice-director of PLAS@PAR received in 2014 the **William Crooke's prize** for his major contributions to the physics of radio frequency plasmas and space propulsion. The prize was co-sponsored by the European Physical Society and Institute of Physics Publishing through Plasma Sources Science and Technology (PSST).

**Ane Aanesland** and **Dmytro Rafalskyi**, founders of ThrustMe, a start-up on space propulsion systems, received the **grand prize** of the 19th edition of the national competition for the creation of innovative technology companies (I-LAB 2017 competition). In 2019, Ane Aanesland has been awarded by the **2019 CNRS Innovation Medal.**

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## PLASMAS IN MOLECULAR GASES

**Leaders**
Jean-Paul Booth, Paul Indelicato, Julien Labaune, Svetlana Starikovskaia, Fabien Tholin

**Laboratories involved**
LCPMR, LPP, ONERA

**External collaborations**
IST Lisbon (Portugal), Ruhr University (Germany), University of York (UK), Michigan (USA), Bristol (UK), Oxford (UK), Synchrotron Soleil (France), Paris-Sud University (France), Princeton University (USA), Ohio State University (USA), Moscow State University (Russia), Joint Institute for High Temperatures RAS (Russia), The French-Russian Laboratory KaPPA (Laboratoire International Associé from CNRS), Lille University (France), Institut Gustave Roussy (France), PHASICS Paris (France).

**Projects**
3 equipment projects, 1 innovative small project, 3 doctoral projects (Mickaël Foucher, LPP/LKB; Abhyuday Chatterjee, LPP/SOLEIL; Jean Baptiste Layly, ONERA/LPP), 3 postdoctoral projects (Andrew Gibson, LPP/York Plasma Institute; Sébastien Rassou, ONERA; Tat Loon Chng, LPP/York Plasma Institute), 1 invitation of international expert (Mark J. Kushner, University of Michigan).

**Budget**
566 000€

# Background & objectives

**Low temperature plasmas enable many applications with high societal and industrial impact, for instance: materials processing (enabling the microelectronics revolution), polymer surface modification, plasma assisted combustion, and emerging medical treatments. In all of these the plasma is used to convert electrical energy into chemical energy in unique and very controlled ways.**

**One specificity of this field is the interaction of charged particles with molecules, which breaks them into highly-reactive fragments** (atoms, free radicals and ions, collectively known as "reactive species") which enable the different applications. In order to control these complex systems, in addition to "standard" plasma physics it is necessary to understand:

- the creation of reactive species by charged-neutral collisions,
- how these reactive species interact with each other in the gas phase, ultimately leading to stable molecular products,
- how charged particles lose energy in their collisions with molecules (feeding back into the plasma physics),
- how reactive species interact with surfaces (such as a processed substrate or biological tissue, and with the walls of the chamber containing the plasma).

Such complex systems can only be understood by building large models which take into account plasma physics, charged-particle collisions with neutral molecules and atoms, neutral chemistry, and the transport of both matter and heat. However, often the data necessary to build these models (especially for collisional processes) is incomplete or often unreliable.

One approach is to determine the missing collisions data case-by-case, either through theoretical models (which may be still immature) or to develop painstaking dedicated experiments (which are often not feasible, and even when they are, are time-consuming and complex). Another approach, valid when the chemical system is not too complex, is to compare the available models to comprehensive *in-situ* diagnostic measurements, so that the models can be tested, improved and ultimately validated. Such experiments measure the absolute densities of the reactive species (ideally time and space resolved) and their energy distribution functions. However, as existing measurement techniques are often inadequate, the community invests a considerable effort into developing new diagnostic techniques, or improving and extending existing ones. This is aided by the context of continually improving light sources (lasers, synchrotrons, broadband plasma sources) and better (faster, and/or multichannel) detectors.

A range of different feed gases ($O_2$, $N_2$, $H_2$, halogens, alkanes, etc) are used in various applications, and the collision processes occurring in each gas (both individually and in mixtures) must be studied in detail. Furthermore, the different applications operate at widely different pressures (from $10^{-5}$ atmosphere to above atmospheric pressure) and are excited by different electrical schemes (including continuous voltage (DC), alternating current (AC) from 50Hz through to radio frequency and microwaves, and nanosecond pulsed power). While some of the collision processes for a given gas will be common to the different discharge regimes, the differing collision frequencies (for instance allowing third-body collisional recombination reactions at high pressure only) and widely-differing reduced electric fields, timescales and particle collision energies impose specific experimental and theoretical approaches for each case.

Plasmas generated at low pressures inside vacuum chambers can be uniform over large volumes and stable in time. As a result, they have been widely applied to high-value-added surface processing of technological materials, most notably in integrated circuit manufacturing, where plasmas have been essential in allowing the information revolution. Although one might assume that applications are now mature (being in operation since the 1980's), they are still the object of intense investment in process and reactor improvement to enable enhanced product performance and lower cost. Their uniformity and stability also make these systems easier to study experimentally, and as such they are the best test-bed for plasma chemico-physical models. Nevertheless, many major gaps in the models exist, motivating the study of both inductively-coupled plasmas (as used for microelectronics) and DC plasmas (as an optimal system for model validation) at LPP.

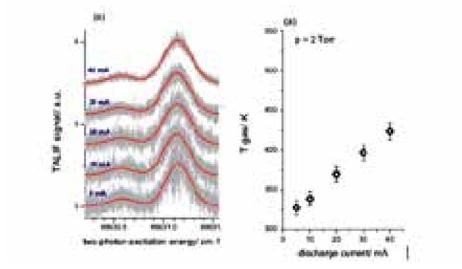
More recently much interest has focused on atmospheric pressure plasma applications, in areas as diverse as combustion, medicine, and agriculture. Several excitation schemes have been developed to inhibit the transition to plasma arcs (which otherwise cause highly non-local power deposition and gas heating), notably the use of extremely short (nanosecond) high-voltage (10's of kV) pulses. The small spatial scales (mm) and short times involved, as well as rapid collisional quenching, make diagnostics of these systems more challenging, but this has nevertheless been addressed by innovative techniques by the team at LPP.

Finally, precise ab-initio calculations, such as performed at LCPMR, of collision processes offer a complementary way to complete the data gaps in the models.

# Main results

**Inductively-coupled plasmas in low-pressure diatomic gases**
This study includes both numerical and experimental aspects:

- A 2-dimensional fluid model (HPEM) of plasmas in $O_2$ and $Cl_2$ was developed and tested against *in-situ* measurements in an industrial-scale inductively-coupled plasma at LPP *[Gibson et al., 2017]*.
- A High-Resolution Two-photon Absorption Laser Induced Fluorescence (HR-TALIF) diagnostic was developed to measure the translational temperature of atoms by the Doppler effect as well as their absolute densities *[Booth et al., 2015; Marinov et al., 2016; Marinov et al., 2017]* (Figure 1), ultra-broadband high-sensitivity absorption spectroscopy was developed to measure the densities and vibrational energy distributions of molecules *[Foucher et al., 2015; Marinov et al., 2016]*. This study showed that a major source of errors in the models is the failure to correctly model gas heating and thermal transfer to surfaces *[Gibson et al., 2017]*, as well as the role of vibrational excitation and energy transfer processes *[Annušová et al., 2018; Kemaneci et al., 2018]*. We also revealed and thoroughly investigated several issues with the TALIF calibration scheme that is widely used to determine absolute densities of reactive atoms *[Morillo-Candas et al., 2019]*.



© [Booth, J.P., Marinov, D., 2015]

*Figure 1: (a) HR-TALIF Two-photon excitation line profiles of oxygen atoms measured at different discharge currents in a DC discharge ($O_2$, 2 Torr, I = 5–40 mA). (b) Temperature determined from the Gaussian FWHM of fitted spectra as a function of the discharge current.*

**DC discharges in $O_2$**
In order to improve and then validate plasma kinetic models of this key gas, we undertook a comprehensive study of this highly-controlled, spatially and temporally uniform discharge. Experiments carried out at the Vacuum Ultraviolet (VUV) beamline (DESIRS) of Synchrotron Soleil provided new high-resolution vacuum-ultraviolet absorption spectra of $O_2$ molecules in the ground (X) and metastable excited ($a^1\Delta_g$ and $b^1\Sigma^+_g$) states, allowing their absolute densities to be measured, as well as their kinetics in partially and fully modulated discharges. Cavity ringdown spectroscopy (CRDS) using a tunable diode laser at 630nm was developed to measure the absolute density and kinetics of both ground-state oxygen atoms and $O^-$ negative ions. We made a systematic study of oxygen atom recombination on the Pyrex surface of the discharge tube *[Booth et al., 2019]*, demonstrating for the first time the effect of atom kinetic energy on the recombination probability, and proposed a full Eley-Rideal model for this plasma-surface interaction process.

**Nanosecond discharges at high electric field and high delivered energy**
The technology of generation using solid state diodes of the nanosecond short voltage pulses at few tens of kilovolts tens came onto the scene about 20 years ago. The field is today very active thanks to the development of high-current electronics and the miniaturisation of the high-voltage generators. Fast rise of the voltage on the discharge gap, to the amplitudes much higher than the breakdown voltage, allow developing a uniform discharge up to tens and hundreds of mbar. At atmospheric pressure and higher, nanosecond high voltage pulses produce highly nonequilibrium plasmas. Recently, nanosecond plasmas have been widely used for fundamental study of strongly nonequilibrium plasmas, surface treatment at various pressures (units and tens of mbar), plasma

flow control, plasma-assisted combustion, plasma medicine, etc. The LPP team is a world leader in studying physics and kinetics of such nanosecond discharges.

One of the most challenging aspects of characterization of kinetic processes in these plasmas, which occur on ns or even sub-ns time scales, is accurate diagnostics of electric field, electron density and temperature, and species number densities. Development of non-intrusive, field vector sensitive, high spatio-temporal resolution diagnostics is essential for quantitative understanding of ionization kinetics in the wave, charge transport and species generation in the plasma behind the wave front, and wave propagation and attenuation. A new diagnostic, electric field induced second harmonic (E-FISH) generation, was for the first time used in Europe to measure E-field in the nanosecond discharge, the picosecond laser was borrowed from Orsay laser centre. PLAS@PAR supported this project with the postdoctoral fellowship of T. Chng (PhD Princeton University, 2017) and I. Adamovich (Award Gaspard Monge École Polytechnique, 2018) helped in transferring this technique developed in 2017 in Princeton and Ohio Universities. For the first time, the E-field in the front of nanosecond discharge was measured with 100 ps resolution and the absolute peak value of the E-field 2000 Td in a nanosecond discharge in nitrogen has been obtained (Figure 2 right) *[Chng et al., 2019]*.

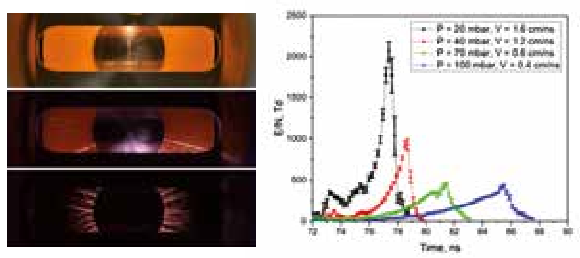



*Figure 2:*
*Left: High Pressure High Temperature experiments, nanosecond filamentary discharge developing at high pressure in air, the diameter of the high voltage electrode disk is 20 mm. Credit: P. Lavialle, École Polytechnique*
*Right: measured reduced electric field in a nanosecond discharge in nitrogen at P=20-100 mbar in the long tube 2 cm in diameter. Electric field in plasma is the most important parameter of the gas discharge allowing to predict the mean electron energy and so, the efficiency of plasma as a chemical reactor [Chng et al., 2019].*

### Nanosecond surface barrier discharges at high pressure

In the last few decades, the concept of Plasma-Assisted Combustion (PAC) has been developed. The interest of nonequilibrium plasmas for combustion initiation is that it provides together a significant density of atomic species and an increase of the gas temperature, allowing shortening the ignition delay time by a few orders of magnitude. The range of potential applications is wide: ignition of fuel-air mixture at moderate gas densities and high velocity gas flows, including ignition in supersonic flows, combustion sustaining or enhancement by plasma at atmospheric pressure, stimulation of combustion of lean mixtures, development of detonation engines and Homogeneously Compressed Charge Ignition engines (HCCI) engines. The experimental study of nanosecond surface dielectric barrier discharge (nSDBD) for plasma-assisted combustion was previously performed in Rapid Compression Machine (Lille University). It showed that nanosecond Surface Dielectric Barrier Discharge (nSDBD) allow to ignite extremely lean mixtures (with 50% or 33% of fuel relative to the stoichiometric mixture) based on $CH_4$. Stable ignition of n-$C_4H_{10}$ and n-$C_7H_{16}$ - based mixtures was obtained up to 15 bar pressure *[Boumehdi et al., 2015]*.

To get the understanding of plasma processes proceeding the ignition, it was decided to study the discharge and initiation of combustion in a single shot experiment. As a result, the high-pressure high-temperature discharge cell was developed at LPP with financial support of PLAS@PAR. Experimental study of ignition of $H_2$-based lean mixtures was performed and shown the efficiency of the nanosecond discharges. A new form of the discharge was observed: filamentary nSDBD at high pressures (2-15 bar) and high voltage amplitudes (>30 kV). When transforming to the filamentary form, the discharge appeared in the form of multiply filaments synchronously propagating along the surface of the dielectric. Up to 40-50 plasma filaments 10 mm in length were simultaneously observed in the discharge system. The discharge provided stable and efficient ignition of combustible mixtures with a minimum ignition energy around a few microjoules by streamer/filament *[Shcherbanev et al., 2017]* (Figure 2 left).

To support the interpretation of these experiments, a newly developed two-dimensional parallel code PASSKEy coupling plasma with hydrodynamics has been developed *[Zhu et al., 2017]*.

# Perspectives

Inductively-coupled plasmas in low-pressure diatomic gases
We are currently using the HR-TALIF technique with spatial resolution to measure the temperature gradients for Inductively Coupled Plasma (ICP). These devices are widely used for chemical analysis. The goal is to perform the first experimental determination of O and Cl atom surface thermal accommodation coefficients and to extend it, if industrial funding is received, to studying the dynamics of pulsed ICP discharges in these gases, which is currently a hot topic for industrial materials processing.

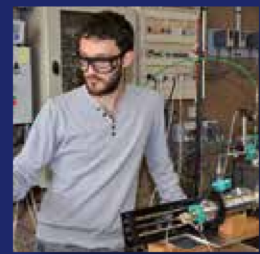
### DC discharges

We are currently developing the CRDS technique to allow time-resolved measurements of absolute O atom densities in pulsed discharges. We are extending the methodology developed for the systematic study of oxygen DC discharges to nitrogen. In particular, we are developing a new CRDS scheme to measure nitrogen atoms, and will use the VUV beamline at Synchrotron Soleil to measure nitrogen metastable atom and molecule densities and kinetics.

### Nanosecond discharges

The capillary nanosecond discharge will be used for the study of dissociation of other molecules than $O_2$, for instance $CO_2$; The E-FISH diagnostics will be further developed thanks to a picosecond laser (supports of DGA, École Polytechnique and PLAS@PAR); the parameters of plasma of filamentary surface barrier discharge and physics of streamer-to-filament transition and the interaction of plasma of nanosecond discharges with detonation wave in combustible mixtures will be studied.

# Focus



**Mickaël Foucher** obtained his Master degree in Plasma Physics at the Sorbonne Université in 2013 before starting for a PhD at LPP/LKB on the Dynamics of pulsed radiofrequency plasmas in halogen gases, which he defended in October 2016. In 2014 he was awarded the **"Best Poster" Prize at the PESM workshop** (Plasma Etch and Strip for Microelectronics workshop) for a poster entitled "Inductively-coupled plasmas of $Cl_2/O_2$: measurements of atoms, $Cl_xO_y$ and electron densities".

After a Master degree of IISER Kolkata (India), **Abhyuday Chatterjee** arrived in France in 2016 where he started a joint PhD between LPP and Synchrotron Soleil. During his PhD work, he applied various different diagnostics to study DC discharges in pure molecular oxygen. including Vacuum Ultraviolet absorption spectroscopy, HR-TALIF, time-resolved actinometry and CRDS. He will defend his thesis, "Electric field characterization of atmospheric pressure Helium plasma jets through numerical simulations and comparisons with experiments" in the fall 2019.

**Jean-Baptiste Layly** graduated at École Centrale Nantes in 2015. Then, he joined ITER Organization in Cadarache to perform thermal analysis on the super-conducting magnets. In 2016, he joined the physics department (DPHY) of ONERA to start a PhD in the FPA unit. This PhD, co-funded by ONERA and PLAS@PAR, is dedicated to the modeling of the damages and plasma discharge phenomena that may occur during a lightning stroke to an aircraft. More precisely, the main goal was to develop a numerical model to predict the complex dynamics of an electric contact subject to lightning currents (~100 kA) and estimate the discharge ignition risk in fuel tanks (Figure 4). He received his PhD in April 2019, and is now working at Akka Technologies as an engineer for the ATMOSTAT company on the design and qualification of thermal metallic parts for the ITER project.

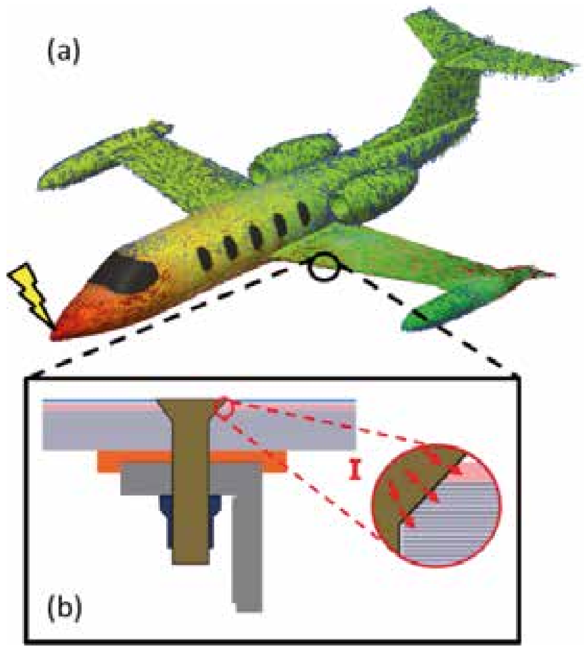



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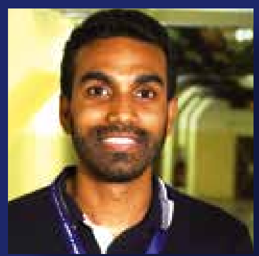
*Figure 4: (a): EM simulation of a lightning current distribution in a Learjet 35A; (b) Zoom on the current flowing through a mechanical assembly in fuel tanks; (c) Screw-skin electric contact at the microscopic scale: concentration of the current density in the a-spots, and illustration of the cylindrical a-spot model developed during the PhD; (d) Plasma discharge phenomena experimentally observed in assemblies due to lightning currents.*

**Andrew Gibson** obtained a PhD jointly between Queen's University Belfast and York Plasma Institute. He then worked as a postdoctoral fellow (between LPP and YPI) on "Hybrid simulations of inductively-coupled plasmas in diatomic gases with vibrational state kinetics". His work highlighted the high impact of (poorly-known) surface processes of atom recombination and thermal accommodation. He also worked on power coupling mode transitions induced by tailored voltage waveforms in capacitive oxygen discharges and on the calculation of electron impact dissociation cross sections for molecular chlorine, and modelling and diagnostics of atmospheric pressure radiofrequency plasma jets. He was awarded a **prize for his poster at the international symposium on Gas Kinetics.** Since October 2018, he currently has a 5-year junior professor position at Ruhr University - Bochum.

**Tat Loon Chng** received his PhD from Princeton University in 2017 on the experimental development of radar resonance enhanced multi-photons ionization (REMPI) for combustion and magnetometry applications. Radar REMPI combines the excellent sensitivity of microwave (radar) scattering from free electrons with the high target specificity of REMPI spectroscopy. Modelling the kinetics of the free electron evolution along with measurements of important species such as atomic oxygen, atomic nitrogen, xenon and nitric oxide have been successfully demonstrated and addressed in the thesis. At LPP, Tat Loon is a PostDoc financially supported by PLAS@PAR and partially by York Plasma Institute. He has developed Electric Field Induced Second Harmonic (E-FISH) diagnostics of electric field amplitude and direction with picosecond resolution; he is currently working on N-TALIF diagnostics for nanosecond capillary discharges and discharges in large volumes.



After his Master degree in Plasma Physics at University Paris Sud, **Sébastien Rassou** joined CEA (Service de Physique des Plasmas et Électromagnétisme) for a PhD on electron acceleration in laser induced wake fields. He defended his PhD in 2016, and benefit from a PLAS@PAR funding to join ONERA in FPA unit as a postdoctoral researcher. His work was dedicated to the numerical simulation of plasmas for high velocity flow control [1] (Figure 3) and nanosecond repetitively pulsed discharges in air [2]. Since April 2018, he's back at CEA as an Engineer/researcher, working on microwave plasmas and optical emission spectroscopy diagnostics.

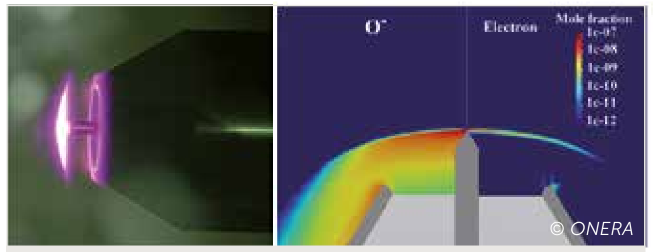



*Figure 3:*
*Left: Negative glow discharge for supersonic flow control;*
*Right: Numerical simulation of a glow discharge in the same configuration, showing respectively the moles fractions of O⁻ and electrons.*

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## PLASMA AND ENVIRONMENT

**Leaders**
Patrick Da Costa, Paul-Quentin Élias, Elena Galvez-Parruca, Olivier Guaitella, Antoine Rousseau

**Laboratories involved**
LPP, IJLRA, ONERA

**External collaborations**
Instituto Superior Técnico IST, (Portugal), Eindhoven University of Technology (Netherlands), Synchrotron Soleil (France), Paris-Sud University (France), Moscow State University MSU (Russia), LPICM (École Polytechnique, France).

**Projects**
3 equipment projects, 1 innovative small projects, 1 doctoral project (Ana Sofia Morillo Candas, LPP), 2 postdoctoral project (Zixian Jia, LPP; Radoslaw Debek, IJLRA/ONERA), 4 invitations of international experts (Ana Sobota, Eindhoven University of Technology; Carlos Pintassilgo, University of Porto; Vasco Guerra, IST Lisbon; Richard Engeln, Eindhoven University of Technology).

**Budget**
337 000€

# Background & objectives

**For a long time, the use of cold plasmas for environmental applications mainly consisted in generating ozone to clean up the water in drinking water networks.**

Since the 1980s, the reduction of NOx emissions from engines has led to the use of plasmas coupled with catalysts, which were subsequently studied first for indoor air treatment and then for $CO_2$ recycling. These last two applications are the subject of intense research activities worldwide and have been at the heart of PLAS@PAR's "plasma environment" operation projects. The study of air, or $CO_2$ plasma kinetics and the fundamental mechanisms of plasma/catalyst interaction have benefited from major advances through these actions.

About $CO_2$ recycling, with the support of PLAS@PAR, the LPP has developed a close collaboration on modeling with the IST Lisbon and diagnostics with the TU/e Eindhoven placing these three groups as leaders in the field. Advanced diagnostics tools such as Mueller polarimetry have also been developed in collaboration between LPP and LPICM at École Polytechnique, which were then used within joint work with IJLRA on plasma/catalysis. These fundamental works have later allowed the development of an innovative reactor design on microfluidic between ONERA and IJLRA, as well as the continuation of industrial partnerships between LPP and Al-Ko Therm Gmbh and Air-Serenity on indoor air treatment.

The coupling of a plasma with a catalytic material constitutes a complex system combining a poorly understood out-of-equilibrium chemistry in the gas phase, with surface processes for which only very few measurement methods exist. The first objective of this action was therefore to develop new time resolved surface diagnostics under direct plasma exposure. The determination of species adsorbed on catalysts under plasma exposure was a first step in understanding surface reactivity. This reactivity differs from what is known in conventional catalysis, in particular due to the high gradients of the electric field induced by the plasma on the surfaces. Another objective of the action was therefore to determine these field gradients on complex surfaces.

The chemical kinetics in the gas phase (and on surfaces exposed to the plasma) of $CO_2$ plasma is in itself a very complex system, particularly because of the importance of the vibrational kinetics of $CO_2$. A major effort has focused on the fundamental study of the kinetics of $CO_2$ plasma with the development of systems dedicated to effectively constrain self-consistent 0D kinetic models of $CO_2$ plasmas.

Finally, the goal of gaining these fundamental understanding was to conceive, design and develop efficient $CO_2$ conversion reactors for clean energy production (high value chemicals, fuels, etc).

# Main results

**Development of in situ, time resolved, surface diagnostics**
Infrared absorption spectroscopy is a very efficient tool for studying species in the gas phase (as will be developed below) but it can also be used to study species adsorbed on surfaces (bio-purity and oilseed projects). Dielectric barrier discharge reactors have been developed specifically to perform these measurements by allowing the IR beam from a Fourier Transform Spectrometer (FTIR) to pass through catalyst pellets directly into contact with plasma filaments at atmospheric pressure. This innovative technique makes it possible to monitor the reaction intermediates adsorbed on catalysts for both air treatment and $CO_2$ recycling. But perhaps the most significant result was the development in collaboration with Ana Sobota from Eindhoven University of Technology and Enric Garcia-Caurel from École Polytechnique with a brand-new Mueller polarimetric imaging technique *[Slikboer et al., 2018 a, b]*.

This last technique allows images to be taken of all the optical properties (diattenuation, birefringence and depolarization) of a dielectric target exposed to a plasma. Thus, for the first time the three electric field components induced in a target exposed to a plasma jet were obtained resolved in time. These results, complementary to techniques like E-FISH or Stark polarization spectroscopy that have also been performed in similar plasmas *[Klarenaar et al., 2018]*, have shown the large difference between values of field obtained in the gas phase above the surface compared to the one obtained inside the material. This result of particular importance has allowed the first quantitative comparison of measurement in a target with a fluid model developed by the group of Anne Bourdon (LPP) *[Viegas et al., 2018; Slikboer et al., 2019]*. It was also possible to deduce the temperature gradients generated inside the dielectric material exposed to atmospheric pressure plasma. Most importantly, it has been proven that this new measurement technique can be applied to complex surfaces (e. g. catalysts) to derive surface electric field values without the depolarization of light due to surface roughness. This is essential to study the impact of surface electric fields on adsorption/desorption and surface reactivity processes and to optimize chemical conversion processes.

**Characterization and understanding of $CO_2$ vibrational kinetics**
A large programme in close collaboration with the University of Eindhoven and IST Lisbon has been set up to study the kinetics of pure $CO_2$ plasma (or in mixture with $N_2$, $CH_4$ for instance) in homogeneous low-pressure landfills in order to develop and constrain a relevant kinetic model of $CO_2$ plasmas. A detailed understanding of this kinetics is crucial for predicting the most favourable configuration for an efficient conversion of $CO_2$ by plasma. The vibrational excitation of the three vibrational modes of $CO_2$ and CO was measured time resolved in such pulsed plasmas, which improved the accuracy of the energy transfer coefficients between vibration levels *[Klarenaar et al., 2017; Klarenaar et al., 2019; Klarenaar et al., 2018]*. The essential role of oxygen atoms as a quencher for $CO_2$ vibrations has been highlighted by Two Photons Laser Induced Fluorescence (TALIF) measurements (Figure 1) *[Morillo-Candas et al., 2019]*. The considerable importance of the role of the back reaction with CO reforming $CO_2$ has been evidenced by isotopic measurements. Gas heating mechanisms that are

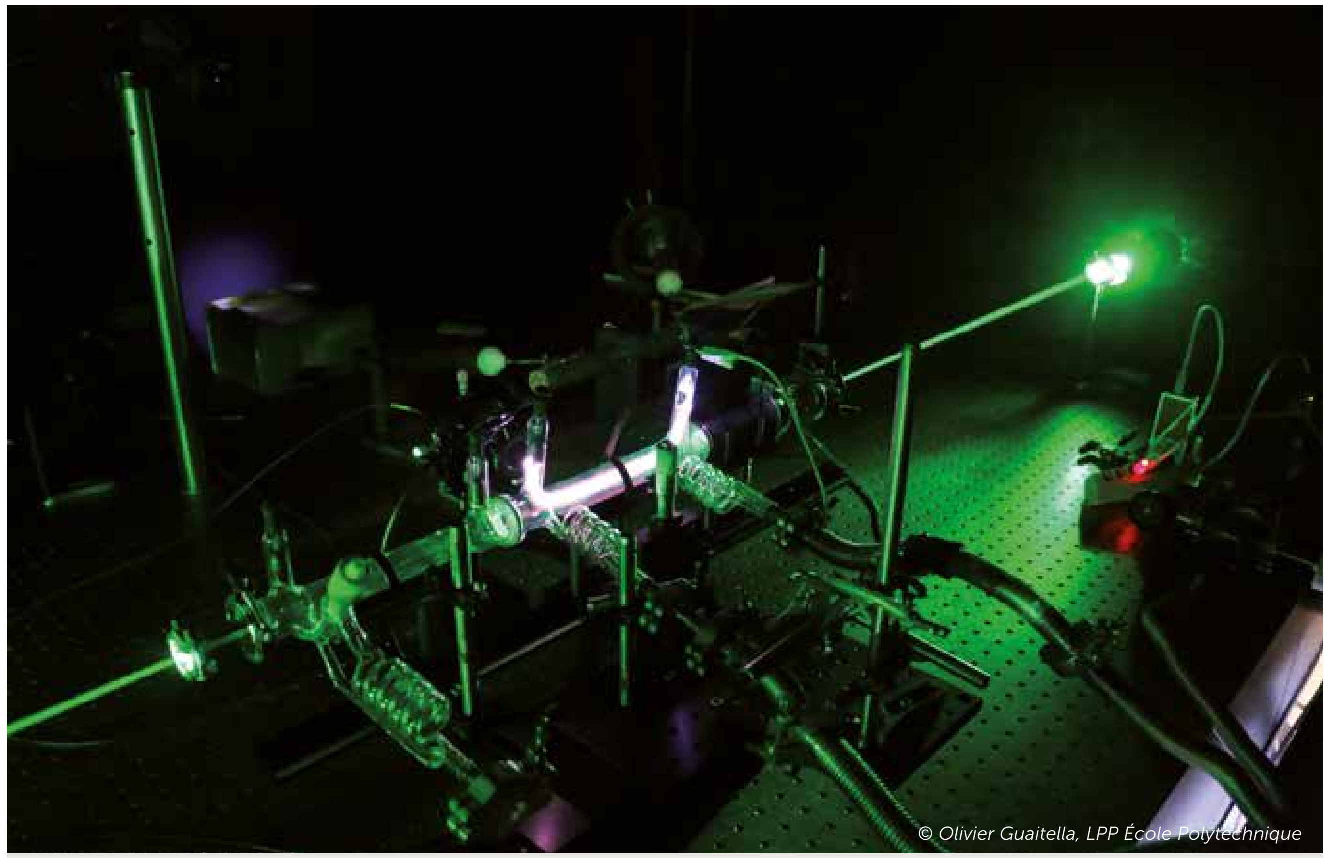


*Figure 1: Laser scattering measurement to determine both the gas temperature and $CO_2$ vibrational temperature in a pulsed DC discharge which is here used for comparing with kinetic model of $CO_2$ recycling plasmas.*

detrimental to the energy efficiency of $CO_2$ conversion could also be highlighted in order to better control them. All these data have made it possible to develop the most predictive models for $CO_2$, $CO_2/N_2$, and $CO_2/Ar$ plasma kinetics to date *[Silva et al., 2018; Grofulović et al., 2018]*. This work is still ongoing, particularly through the recent ITN-H2020 PIONEER (www.co2pioneer.eu) project launched in January 2019 coordinated by IJLRA and LPP.

**Micro-structured plasma-catalytic reactor**

Among the possibilities to enhance plasma/catalytic efficiency, Micro Structured Catalytic Reactors (MSCR) are particularly attractive since they allow considerably higher overall chemical and energetic efficiencies, through the accurate control of heat and mass transfer phenomena, which is a new approach for coupling a plasma with a catalyst. However, a key factor for the optimization of these MSCR is the control of the power deposition and topology of the discharge used to activate the reactive species. Guided pulsed surface discharge can be generated directly in the micro-channels of the MSCR. The properties of this discharge in terms of topology, control of the energy deposition rate make it a very promising candidate for developing efficient chemical conversion processes. The results of this project could:

- enable a better understanding of the fundamental processes in plasma-catalytic reactors,
- lead to significant improvement of plasma catalytic processes with promising applications in energy valorization and pollution control.

In addition to their important advantages for the accurate control of heat and mass transfer phenomena, MSCR have also the advantage to be easy to scale up allowing for adapting to various gas sources in terms of concentration and flux. They also allow relatively straightforward characterization of the plasma discharge, through direct visualization, optical measurements and spectroscopy allowing for scientific studies and process optimization.

# Perspectives

The development of truly predictive tools to optimize the energy efficiency of $CO_2$ to plasma conversion will continue, in particular but not only, through the ITN. The innovative diagnostics developed for the study of plasma/catalyst interaction will finally make it possible to design materials truly dedicated to coupling with plasma, i.e. capable of making the most of the short-lived species generated in a plasma discharge instead of using only commercial catalysts intrinsically designed to use only stable molecules. This is the heart of the ITN PIONEER project, which, in addition to the internal collaboration promoted by PLAS@PAR (LPP, IJLRA, ONERA), will strengthen the external collaborations already initiated (Eindhoven University of Technology, IST) and emerging within the consortium with the 15 academic partners and the 6 industrial partners throughout Europe. In addition, since 2018, the start-up Energo has been created by Maria Elena Galvez and Patrick Da Costa to build a new generation reactor able to convert $CO_2$ into biofuel (See Chapter 3 "Industry").

# Focus

**Radosław Debek** performed a PhD thesis between AGH University of Science and Technology (Krakow) and University Pierre and Marie Curie (Paris) on novel catalysts for chemical $CO_2$ utilization, which he defended in 2014. After a postdoctoral position on plasma catalysis at the LCS laboratory in Caen, he joined in 2019 PLAS@PAR within a collaboration between M. E. galvez (IJLRA) and P.Q. Élias (ONERA) on "the Controlled surface discharges for the miniaturization of plasma-catalytic reactors".

After a PhD on Plasma catalysis for environmental applications defended in December 2013 in Paris Nord University, **Zixian Jia** joined PLAS@PAR in 2014 to work on the PLASMA PURE project with Antoine Rousseau at LPP. The project, performed in partnership with AL-KO THERM company aimed at understanding the mechanisms of adsorption and oxidation of Volatile Organic Compounds at the surface of a catalyst exposed to short life and long-life species produced by a Non Thermal Plasma. He is now research engineer at Paris 13-Nord University.

**Ana-Sofia Morillo-Candas** got her Master degree at Complutense University of Madrid in Spain before joining in 2016 the LPP to do a PhD in Plasma Physics entitled SYCAMORE (Surface reactivitY of moleCular plAsMas for $CO_2$ REcycling). She developed numerous optical diagnostics that allowed for the detailed characterization of $CO_2$ containing plasmas. Her work allowed the development and validation of kinetic models of $CO_2$ plasma. She also developed a Monte Carlo model of surface processes to account for the surface reaction she evidenced experimentally. She defended her thesis in November 2019.

# Award

**Ana-Sofia Morillo-Candas** got the **Poster pitch award** of 24th International Symposium on Plasma Chemistry (ISPC, Napoli, Italy, June 9-14, 2019) on the following topic: "Time-evolution of the $CO_2$ conversion studied by *in situ* FTIR absorption and isotopic exchange".

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## PLASMA AND LIFE

**Leaders**
Thierry Dufour, Antoine Rousseau, Svetlana Starikovskaia

**Laboratories involved**
LPP

**External collaborations**
Centre Régional Gustave Roussy, PHASICS S.A, Espace Technologique de Saint-Aubin; Centre d'Immunologie et des Maladies Infectieuses - CIMI, Hôpital Saint-Antoine; Hôpital des Armées, Institut Pasteur; Institut de Biologie Paris-Seine - IBPS; Laboratoire d'imagerie Biomédicale - LIB (France).

**Projects**
1 equipment project, 3 innovative small projects,
1 doctoral project (Bruno Honnorat, LPP),
3 postdoctoral projects (Javier Vaquero, LPP; Shiqiang Zhang, LPP; Ilya Marinov, LPP),
1 invitation of international expert (S. Loganathan, SRM Institute of Science and Technology, India).

**Budget**
495 000€

# Background & objectives

**Cold plasmas appear as a new and promising research avenue in answering modern stakes of life sciences.**

The interaction of cold plasmas with cells, tissues and tumors is studied for a decade to address medical issues such as blood clotting, wound healing, dentistry, repair surgery, cosmetics, infectious/inflammatory diseases and oncology. Owing to the emerging and highly multidisciplinary aspects of "cold plasma oncology", only 5% of the studies published so far deal with *in vivo* experiments. The common purpose to all these works is to induce antitumor effects without damaging adjacent healthy tissues (e.g. hematoma, burns, necrosis, ablation) that may result from the plasma exposure. Following the direct approach, tumor volume reductions have been demonstrated on murine subcutaneous tumor models of pancreatic cancer, melanoma, ovary, breast and colon cancer *[Hattori, 2015; Utsumi, 2013]*. Following the indirect approach, *in vivo* experiments have shown for instance that the plasma activation of Ringer's lactate solution generates acetyl and pyruvic acid-like groups which induce antitumor effects in the case of the ovarian cancer cell line SKOV-3. Whatever the approach, plasma can trigger apoptosis in cancer cell, primarily by supplying reactive oxygen and nitrogen species (ROS, RNS) with the ability to deliver them a few millimeters into tissues *[Szilli, 2018]*. However, one of the most important challenges remains the induction of antitumor effects without damaging adjacent healthy tissue.

So far, all the research has been performed thanks to the proximity of the Faculty of Science and the Faculty of Medicine. Physicists, biologists and physicians have the privilege of collaborating in a dynamic and balanced interdisciplinary context impulsed by Sorbonne Université. Besides, PLAS@PAR played a determinant role in flagshiping the "plasma medicine" topic, rising its visibility beyond the national landscape. Thus, in 2019, the LPP has received three grants, including one from Cancéropôle and another from SIRIC CURAMUS (Emergence program of Sorbonne Université) and the last one from Alliance Sorbonne Université.

The exploration of cold plasma technology to agriculture stakes has started at the early 2010 and is an unprecedented research avenue at Sorbonne Université. The success of germination in non-optimal conditions, especially under water and heat stress, is one of the major challenges of tomorrow's agriculture in a context where global warming is likely to significantly alter the productivity of certain agrosystems *[Challinor, 2014]*. Therefore, it is mandatory to better understand the cellular and molecular bases of seed responses to environmental constraints while designing new technological levers allowing seeds to better tolerate environmental stresses. This problem is crucial at a time when agriculture is undergoing profound paradigm shifts and where it is moving towards sustainable and reasoned management (abandonment of synthetic pesticides, management of water resources). Through the PF2 ABIOMEDE platform, LPP and IBPS (Institut de Biologie Paris Seine) have started a partnership in order to answer these issues.

**Objectives:**

- **Engineering plasma processes (sources & protocols)** that meet with the specifications and issues of oncology. The laboratories of the Labex have innovated processes that are: (i) safe, ie that do not induce deleterious effects on the tissues on the long term and that do not present electrical hazards for the patients as for the operators (ii) robust, ie producing same biological effects with strong repeatability, (iii) efficient, ie likely to induce antitumor effects.
- **Engineering plasma processes for agriculture applications.** One of the flagship approaches is to plasma-activate water subsequently utilized to irrigate seeds and plants so as to increase their bio-parameters, e.g. germination rate, vigor rate, stems growth, etc.
- **Understanding the mechanisms** at the interface between plasma and life sciences issues like plasma-triggered signalization pathways in oncology or in agriculture.

# Main results

In the context of plasma-life sciences interactions, two flagship research works have been funded by the Labex: in oncology, the treatment of oral squamous cell carcinomas and cholangiocarcinomas, and in agriculture the promotion of seedlings growth using plasma wet processes.

### Plasmas applied to oncology

**Engineering plasma sources for squamous cell carcinoma and modeling of plasma-tissues interaction.**

In collaboration with Hôpital Pitié Salpêtrière and Laboratoire d'Imagerie Biomédicale, oral squamous cell carcinoma (OSCCs) have been treated by plasma jets upon *in vivo* and *in vitro* experiments. Plasma Jets (PJ) are powered by a high voltage electrode and propagated in helium gas flowing to be directly applied onto the target (Petri dish, biological tissues, small animal, etc). Two PJ devices have been designed and engineered in the laboratory by 3D printing: a low power (0.1 mW) and a high power (3 W) multi-jet plasma sources (Figure 2). Such method guarantees the design of fashionable and versatile plasma sources to meet the diversity of the pathologies (Figure 1).

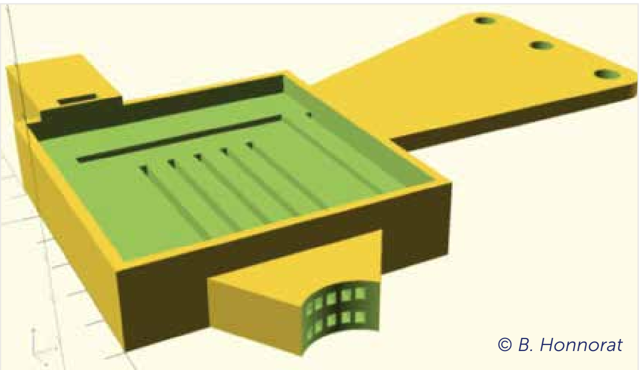

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*Figure 1: Left, view of a multi-channel plasma jet 3D-printed using PLA material. The gas circulates in five rectangular channels.*

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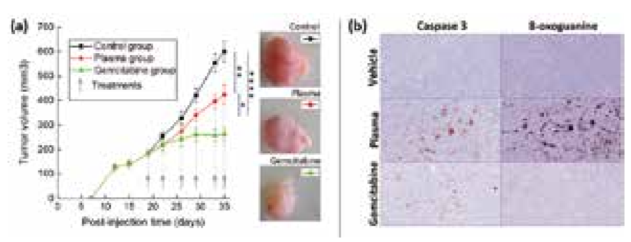
*Figure 2: Phase images with a numerical high pass filter for detail enhancement, at magnification x150 and NA=1.3, of Htori cells at the indicated time period subsequent to the plasma treatment [Ohene et al., 2015].*

Based on experimental results obtained on murine models, we have developed an original numerical simulation modeling the heat transfers of tumors and tissues under plasmas exposure. It quantifies and predicts the increase of tissues temperature under plasma exposure and related hyperthermia and/or lesions. In the present work, the tissues damages are modeled with the denaturation reaction of collagen, the major component of skin. Our model mimics the kinetics of heating and cooling of the tumor's surface. The sensitivity of the cooling rate to various parameters has also been studied and it turns out that the thermal conductivity (and not the convection) is the main factor of tissues cooling. The potential of the simulation is strong and promising as it takes into account the specificity of mouse skin compared to human skin.

**Treatment of cholangiocarcinoma**

In parallel to research works performed on OSCCs, plasma experiments have been carried out on cholangiocarcinoma (CCA) to assess the potential of plasma strategy on several cancer lines. CCAs correspond a heterogeneous group of malignancies that can emerge at every point of the biliary tree. This cancer has a poor prognosis, rapid progression, propensity for early metastasis and high recurrence. PLAS@PAR post-doctoral researchers (LPP & Saint Antoine Hospital) have investigated plasma as a new therapeutic option to demonstrate antitumor effects and compared them with conventional chemotherapy. For these 3 groups of mice showing ectopic CCA tumor models have been realized: control group, gemcitabine group (drug delivery in IP) and plasma group (APPJ supplied in helium *[Judée, 2019a])*. The follow-up of the tumor volumes is represented vs time in Figure 3.a *[Judée, 2019b]*.



© F. Judée

*Figure 3: (a) Temporal follow-up of CCA tumor volumes for the 3 groups of mice (n=9) corresponding to control, plasma group and gemcitabine group (b) Immunohistochemistry slices of CCA cell tumors. Cleaved caspase-3 is an indicator of apoptosis while 8-Oxoguanine) is an indicator of oxidative stress.*

Even if chemotherapy seems the most effective option, the plasma approach stands for much stronger assets: (i) plasma induces a local treatment while gemcitabine has long term deleterious effects on the whole organism (ii) each tumor from the plasma group is exposed only 90s per treatment while tumors in the gemcitabine group remain exposed to this drug a much longer time (its half-life is at least 200 times longer than a 90s plasma exposure). Furthermore, the plasma approach appears more interesting since plasma does not induce hepatotoxic effect, in contrast to gemcitabine, as attested by the plasma level of transaminases and LDH in mice that is similar to control mice. In addition, plasma induces cell death and oxidative stress (Figure 3.b). The method as well as dedicated technological incrementation of the plasma source are currently the subject of a patent processed by INSERM TRANSFERT.

### Quadriwave Lateral Shearing Interferometry applied on plasma-treated cells

The method of Quadriwave Lateral Shearing Interferometry (QWLSI) was for the first time used to follow the morphological changes in the cells under the action of low-temperature plasma.The QWLSI technique produces, at high resolution, phase images of the cells having been exposed to a plasma treatment and enables the quantitative analysis of the changes in the surface area of the cells over time. Morphological changes in the HTori normal thyroid cells were demonstrated using this method *[Ohene, 2015]* (Figure 2). There was a comparison of the cell behaviour between control cells, cells treated by plasma of a nanosecond dielectric barrier discharge, including cells pre-treated by catalase, and cells treated with an equivalent amount of $H_2O_2$. The major changes in the cell membrane morphology were observed at only 5 min after the plasma treatment. The primary role of reactive oxygen species (ROS) in this degradation is suggested. Deformation and condensation of the cell nucleus were observed 2–3 h after the treatment and are supposedly related to apoptosis induction. The coupling of the phase QWLSI with immunofluorescence imaging will provide a deeper insight into the mechanisms of plasma induced cell death. It could be applied to the two experimented cell lines, i.e. OSCCs and CCAs, hence clustering all the forces and partners involved in this research axis.

### Plasmas applied to agriculture

Cold atmospheric plasma processes have been engineered so as to activate liquids such as tap water, i.e. changing its chemical composition and properties. 16 long lifetime chemical species have been characterized in PATW (Plasma-Activated Tap Water). We have shown that the chemical composition of PATW has no impact on pH but a major one on electrical conductivity. Reactions between gas phase species and tap water lead to the formation of aqueous reactive species like hydrogen peroxide, nitrite, nitrate or ammonia. Conversely this interaction activates the consumption of bicarbonate ions.
Due to acid/base equilibria and to the increase of water temperature during plasma activation, a redistribution of chemical species has been observed from their basic to acid form. We have also demonstrated that variations of electrical conductivity during activation are thoroughly described by the variation of two predominant ions: nitrate and bicarbonates ions. Besides, placing the plasma device in a confined enclosure modified the chemical reactions in the gas phase and therefore in the liquid. Initially filled with air, the plasma activation increased relative humidity and ozone concentrations in the enclosure. The increase of relative humidity favors the production of hydroxyl radical and consequently of aqueous hydrogen peroxide. These reactions result in a quadratic and non-linear increase in the concentration of hydrogen peroxide in PATW as a function of the activation time. A higher concentration of ozone combined with a decrease of molecular oxygen in the reactor enclosure lead to a lower production of nitric oxide over time and finally of nitrites and nitrates in the PATW.

A proof of concept has been demonstrated in which plasma-activated tap water for 15 min has shown significant and positive effects on the growth of coral lentils with increase in plant length after 6 days of PATW activation (+128%). From the state of the art on chemical treatment of seeds, we have been able to demonstrate the possible contribution of five chemical species on the growth of plants by DBD activations. Formation of aqueous nitrite, nitrate, ammonium ions and hydrogen peroxide during treatment reaches concentrations such that each one can induce an increase in growth. Conversely, the consumption of bicarbonate ions during plasma activation can also promote the seedlings growth.
Today, these research works are the subject of an "invention declaration" processed by the SATT LUTECH.

# Perspectives

For cancer applications, further works will be performed to enhance the selectivity of the plasma treatments, i.e. targeting tumor cells by plasma without inducing any deleterious effects on the adjacent healthy cells. It will be also a mandatory to work on plasma treatments that are likely to drive to permanent antitumor effects, i.e. tumor volumes that remained reduced a long time after their last plasma exposure. The new developed diagnostics will be also utilized and incremented.
For agriculture applications, new insights include the treatment of seeds before their sowing to the soil to release their dormancy and increase their vigor. Such approach will find a particular interest on the point of economical view although it remains a strong challenge. Finally, the understanding of the interface mechanisms between plasma and seeds systems will be a subject of interest for the forthcoming years, in particular identifying which signaling pathways are plasma-activated or prohibited.





# Focus

**Bruno Honnorat** followed the first year of the PHYTEM master's degree at the École Normale Supérieure of Cachan and then specialized in plasma physics by following the second year of the Master's degree in Optics Plasma Matter Research at Sorbonne Université and École Polytechnique. He joined the LPP in 2014 for a PhD dealing with Non thermal plasma applied to medicine issues, which he defended in November 2017. before joining a postdoctoral position at the University of Greifswald.

**Javier Vaquero** is a biologist, specialist in liver cancer. In 2013, he obtained his PhD at the University of Salamanca (Spain) before coming to France for a postdoctoral position at Saint Antoine Research Center. Thanks to the support of PLAS@PAR, he has been recruited in 2017 at LPP to work on an interdisciplinary project (physics and biology) focused on the treatment of cholangiocarcinoma. Now, Javier has a postdoctoral position In Barcelona at "L'Hospitallet de Llobregat" (TGF-Beta and Cancer Group, Oncobell Program, IDIBELL).

**Shiqiang Zhang** obtained a Master in Power Machinery and Engineering in 2011 at Harbin Institute of Technology (China) and then a PhD at the University of Technology (TU/e) of Eindhoven (Netherlands) in 2015. Then, Shiqiang joined the LPP as a PLAS@PAR post-doctoral researcher to work in the field of plasmas applied to life sciences, and more specifically in the framework of the CAP4CARE project dealing with the treatment of carcinomas using cold atmospheric plasmas. Today, he works as a postdoctoral researcher at the University of Maryland.

# Award

**Ilya Marinov** obtained a Master of Science at École Polytechnique before starting a PhD in 2010 at LPP. Ilya was the recipient of the **2014 René Pellat Prize** from the Société Française de Physique, plasma division. After his PhD, he worked as a postdoctoral researcher within a collaboration between LPP and Gustave Roussy. His project was focused on Plasma-Cell Interactions: Efficiency of Nanosecond Plasma in Melanoma Cells Treatment and kinetics of Reactive Oxygen Species. Today, Ilya works for a private company in Russia.

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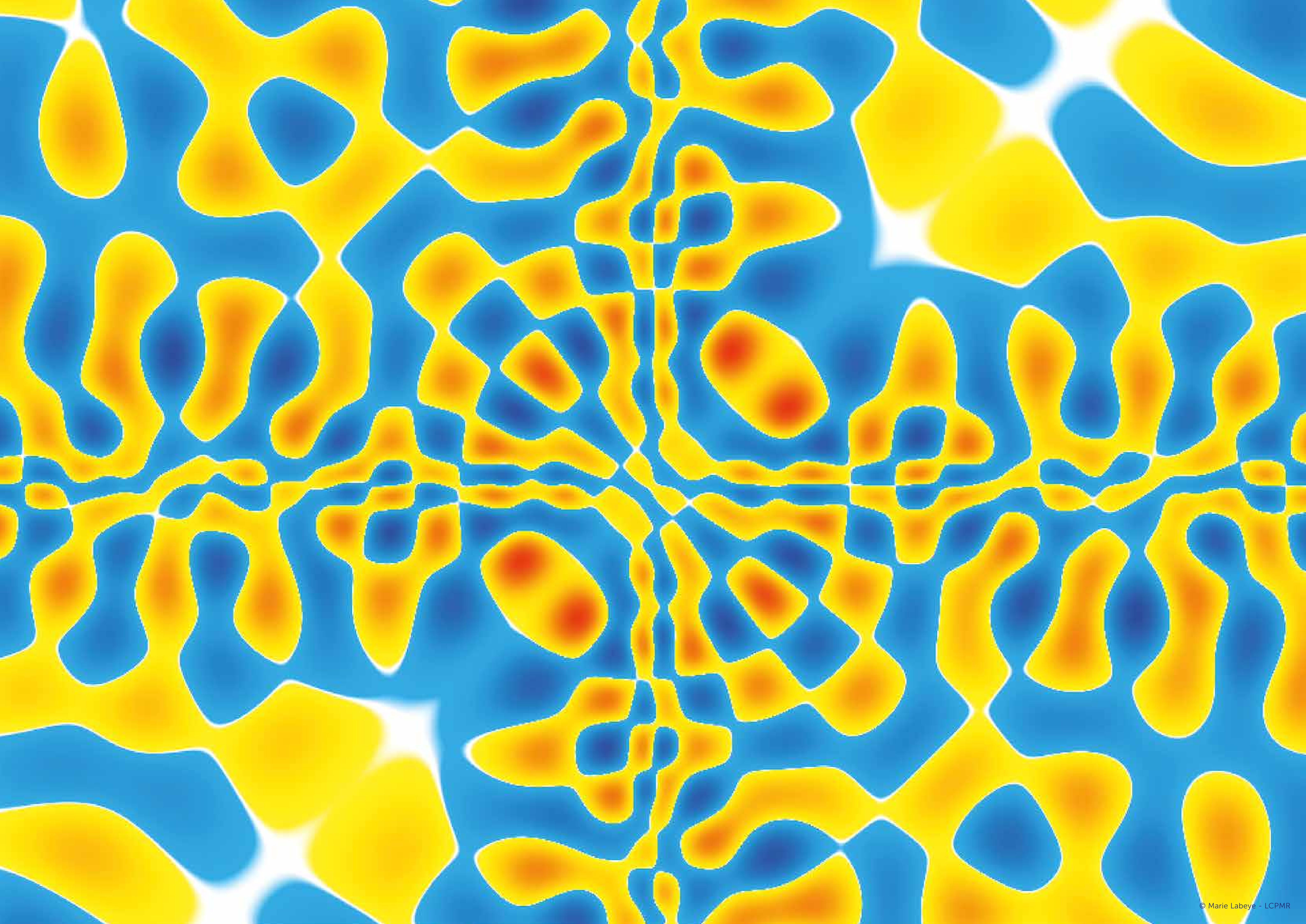


# NUMERICAL & EXPERIMENTAL TRANSVERSE PROJECTS

## PHARE

**Leaders**
Nicolas Aunai, Andrea Ciardi, Roch Smets

**Laboratories involved**
LPP, LERMA

**Projects**
1 innovative small project, 3 engineers
(Mathieu Drouin; Thibault Payet; Philip Deegan)

**Budget**
310 000€

## Background & objectives

**Most of the space and astrophysical plasmas contain a large range of scales associated to different kinds of physical processes: large scales are associated to MHD processes, while small scales are associated to kinetic effects, such as Finite Larmor Radius effects or wave-particle interaction. In many cases, all these scales have to be considered: solar flares, acceleration of cosmic rays by diffusive shock acceleration in SuperNovae Remnants, etc.**
From a numerical point of view, this is a fundamental problem. On one hand, fluid codes are well designed for large system but do not treat properly the microphysics as the dissipative terms are reduced to a finite resistivity which can hardly be justified in most cases. On the other hand, kinetic codes (whether Particle-In-Cell -PIC- codes or Vlasov codes) need a lot of RAM memory and CPU time, and mostly use unrealistic electron to ion mass ratio or Alfven to light speed in order to treat meso-scales systems.

Since twenty years, some efforts have been dedicated in code coupling. The idea is as simple as exciting: treat a large scale system in a fluid way, and manage the appropriate interface with a kinetic treatment of the small regions where a kinetic approach is mandatory. The main problem in doing so is that there is much less information in a finite number of fluid moments than in a distribution function. Hence, such a coupling is necessarily associated to physical assumptions, which decrease the reliability of such an approach.

A promising alternative is to use Adaptive Mesh Refinement in a PIC code. As in all PIC codes, the kinetic effects are correctly treated (Landau damping, cyclotron resonances, etc), but the size of the mesh is locally adapted (increased or decreased) in order to correctly treat the smallest scale at play at each grid point. Such an approach allows to save computational resources without compromising the microphysics. While widely used in fluid codes, AMR techniques is seldom used in kinetic codes, essentially because the finite size of the particles is given by the mesh size. Some mathematical and numerical works have already been done on this topic, and outlined the need to develop some adapted techniques.

The objective of PHARE is here to develop a state-of-the-art PIC code using AMR technique. As in many cases for space, astrophysical or laboratory plasmas, the kinetic effects on the electrons can be neglected, this code is hybrid, meaning that the ions are treated as macro-particles and the electrons are treated as a fluid. This is an elegant way to get rid of the electrons scales.

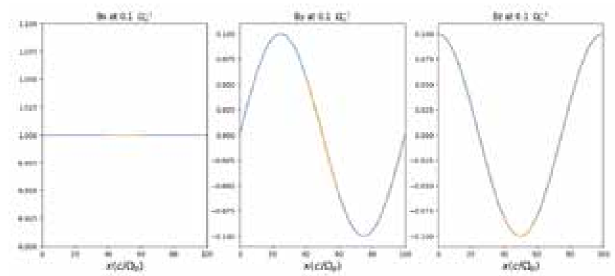
**There are two main aspects behind "state-of-the-art", physical and numerical:**
- it has to be versatile, manage all kind of initialisation and boundary conditions;
- it has to be highly scalable, meaning that it will run on tens of thousand of cores without loss of performance.

PHARE is intended to be shared by a large community and it is designed in such a way to be easily modifiable or extendable without a full knowledge of its whole structure. In addition, for code validation and reliability, the goal is to include unitary and integration tests for all objects and methods. As an example, PHARE should be able to address the three-dimensional reconnection process at the Earth magnetopause, including the bending of this boundary because of the solar wind pressure. Such a simulation is yet not reachable by any hybrid code.

## Main results

**There have been several steps in this operation which we can detail by their chronological order:**
- We started this operation in January 2016 with an extensive bibliographical study of all the aspects of the project. We then selected a "Predictor-Predictor-Corrector" scheme *[Kunz et al., 2014]* as it has a very high accuracy at a moderate numerical cost. We also selected a "Multi-Level-Multi-Domain" technique *[Innocenti et al., 2013]* to manage the grids of different resolutions. With such technique, in regions where we need a fine grid, a coarse one is also kept. For numerical reasons, a particle has to be split when traveling from a coarse grid to a fine one. While few papers have been dedicated to this problem, none were satisfying. We then started a work to find the most appropriate way to split a particle. A paper on this topic has been written and is about to be submitted for publication *[Smets et al., 2019]*.
- In order to test these concepts in a AMR-PIC code, we started to develop a test code, called "miniPhare". It only includes 2 levels with a refinement factor equal 2 (ratio between coarse grid and fine grid mesh). The development started in August 2016 with the help of M. Drouin. The code is written in C++17, mainly using Test-Driven-Development, meaning that unitary test were designed before writing the code, in order to be sure for each object/method to do what they are expected to. This development has been achieved in March 2018. We had several tests, one among them being the propagation of an Alfven wave illustrated in Figure 1, and clearly showing that the cosine profile is not altered by the refinement or coarsening of the grid size.
- While in "miniPhare" the AMR technique were "handmade" (for simplicity), we had to select which library will manage the AMR aspect. In 2016, there were essentially 3 of them: LibBox, Chumbo and SAMRAI. The choice of SAMRAI was quite obvious, because it is an Object Oriented library, already containing a huge amount of functions to manage the meshing, and having to date the best numerical performances. In order to get familiar with this library and test the built-in functions, we then developed a test-code, in which we integrate the advection of a step function, so a fine grid is needed in the large gradient regions. This code has been achieved in August 2018, but will be used beginning 2020 to implement the output files using the HDF5 format.
- We started to work on "phare1D", the one-dimensional version of the code in August 2018. To simplify the presentation, there are essentially three parts in interactions: (i) the "core" part contains all the objects and functions associated to the hybrid model, (ii) the "interface" part is intended to manage the communication with all the SAMRAI objects and functions and (iii) the "SAMRAI" part containing all the derived classes to manage our data in a SAMRAI way (considering that fields already have a lot of them, but particles are not existing).

In September 2019, "phare1D" is on its way, but is not yet fully operational. All the objects of "core" are developed, but some more efforts are needed in both "interface" and "SAMRAI". We should also emphasize that a significant amount of the objects have been developed (meaning tested) in 1, 2 and 3 dimensions. Furthermore, as the parallelization is managed through SAMRAI, the code is already parallel (using both shared and distributed memory).



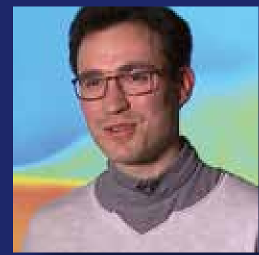
© PHARE team.

*Figure 1: From left to right, components of the magnetic field in a two-grid domain. The blue part corresponds to the coarse grid and the orange one the fine grid. This simulation has been performed with "miniPHARE".*

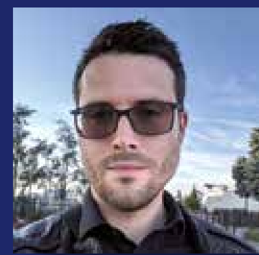
## Perspectives

With the help of Philip Deegan, who joined the project in September 2019 as a C++ HPC developer, we shall finalise the implementation of the components needed first in PHARE 1D (SAMRAI interface, diagnostic and input modules), and then in PHARE 2D and PHARE 3D.

## Focus



**Mathieu Drouin** did a PhD thesis at Bruyères-Le-Châtel CEA, on "the Conception of an implicit Particle-In-Cell method extended to the relativistic case applied to laser plasma interaction", which he defended in 2009. He was then hired on a permanent position at CEA to work on the development of a code solving the neutron transport equation in multi-dimensional geometry. He joined PLAS@PAR from 2015 to 2018, to work at LERMA as PHARE's technical project manager and developer. He works now as R&D engineer in the industry.



After a bachelor at the institute of technology Dublin obtained in 2009, **Philip Deegan** worked at different places on software development, and in particular at École Polytechnique Paris since September 2017 at Applied Math department on Machine Learning projects. He joined PLAS@PAR in 2019 and works now at LPP as HPC PHARE's developer.

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## SMILEI

**Leaders**
Mickaël Grech, Tommaso Vinci

**Laboratories involved**
LULI

**External collaborations**
Maison de la Simulation (Saclay, France), Laboratoire Leprince Ringuet (Palaiseau, France), Laboratoire Interaction Dynamique Laser (Saclay, France), Institut du Développement des Ressources en Informatique Scientifique (Orsay, France), Intel Corp. (Meudon, France).

**Budget**
See Chapter 3 (PhD M. Chiamarello and A. Grassi and postdoc S. Marini) and Chapter 1 (postdoc A. Sgattoni).

# Background & objectives

**Introduced in the late 1950's, the Particle-In-Cell (PIC) method is today a central tool for the kinetic simulation of plasmas.**

PIC codes model the self-consistent evolution of the charged particles in a plasma and of the electromagnetic fields through which they interact, and which they in turn modify. To provide the required level of accuracy, a single PIC simulation involves computing the dynamics of an extremely large number (billions) of particles in self-consistently evolving fields. This comes with a cost and thus requires the use of massively parallel super-computers and high-performance computing (HPC).

The SMILEI project started at the same time as the construction of the Apollon laser in Saint Aubin (France). Hence, new physics processes needed to be included in the existing PIC codes for UHI applications. At the same time, recent evolutions in the HPC landscape made it necessary to develop a new HPC-relevant simulation tool in close collaboration with HPC specialists.

SMILEI aims at providing the scientific community with an open-source, collaborative and HPC-relevant PIC code that can address a wide range of physics studies, from laser-plasma interaction at extreme intensities to space plasmas and astrophysics.

# Main results

Initiated in early 2013, SMILEI *[Derouillat et al., 2018]* is today an outstanding simulation tool, completely open to the scientific community. It is distributed under a CeCILL-B free-software license, and the code, output analysis & visualization tools as well as documentation are available online (www.maisondelasimulation.fr/smilei).

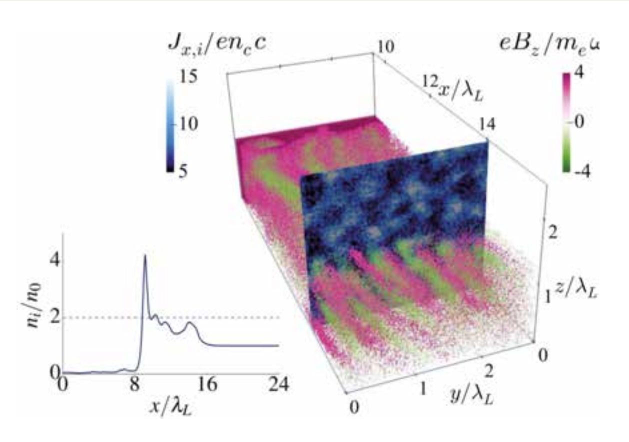

*Figure 1: First 3D simulation performed with SMILEI demonstrating the possibility to drive the ion-Weibel instability into a dense target by irradiating it with a UHI laser beam. This instability is the first step in obtaining a collisionless shock of utmost interest for astrophysics and cosmic-ray physics in particular [Grassi et al., 2017].*

On the physics side, SMILEI operates in various geometries (1D, 2D and 3D Cartesian, as well as quasi-cylindrical); it includes additional physics modules like field ionization, particle collisions and collisional ionization, radiation reaction and QED processes related to high-energy photons and electron-positron pairs production *[Niel et al., 2018]*.

On the HPC side, the code benefits from an innovative, hybrid MPI-OpenMP parallelization strategy that allows for dynamic load balancing; as well as an adaptive vectorization strategy that was successfully tested on the latest super-computers in France *[see Figure 2 and Beck et al., 2019]*.

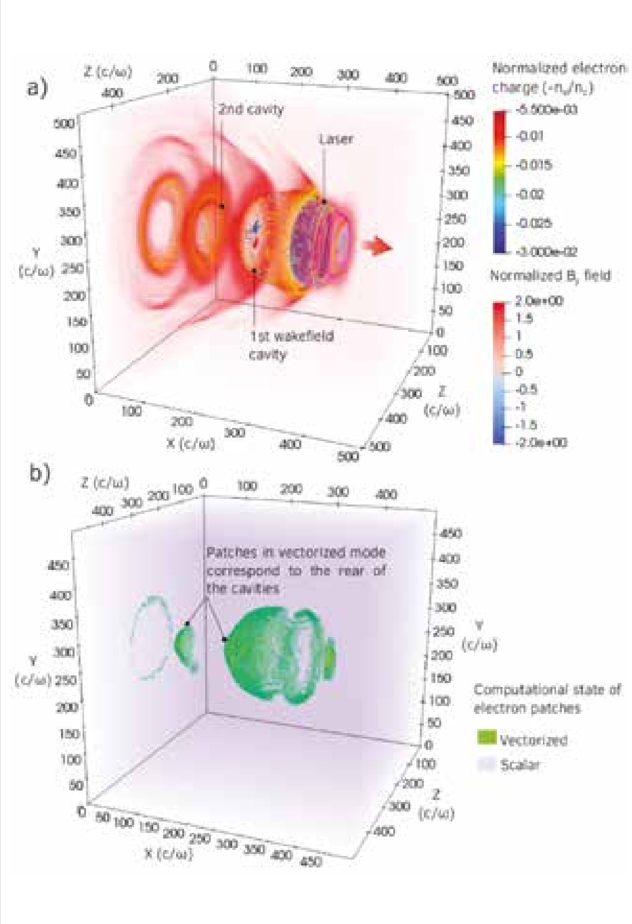


*Figure 2:*
*Panel a: Simulation of laser wakefield acceleration of electrons showing the creation of the so-called bubble in the electron density in the wake of a UHI laser.*
*Panel b: adaptive vectorization strategy developed in SMILEI selects region in space where the electron density is high enough for the code to run in vectorized mode, while region of lower density function best if treated using a scalar mode [Beck et al., 2019].*

Applied to a broad range of physics studies, from astrophysics *[Plotnikov et al., 2018]*, laboratory astrophysics *[see Figure 1 and Grassi et al., 2017]* or ultra-high intensity laser-plasma interaction *[Niel et al., 2018]*, SMILEI has been central to 8 PhD thesis (among them, two funded by PLAS@PAR, M. Chiamarello and A. Grassi); 3 postdocs (2 from PLAS@PAR, A. Sgattoni and S. Marini), and over 20 publications in peer-reviewed journals (11 of which have been supported by PLAS@PAR).
Last, two training workshops (1 of which was partially funded by PLAS@PAR) have been held, bringing in over 70 new users from across Europe.

# Perspectives

SMILEI already allows to simulate plasmas relevant to space physics, astrophysics and laser-plasma interaction from inertial fusion studies to extreme light. Some new physics developments are still going on, in particular to include more extreme light or high-energy density physics-related processes. More numerical-oriented developments, such as advanced Maxwell solvers or adaptive mesh refinement will also be undertaken.

In addition, for the next few years, a strong effort will be done to bring together the scientific community around this collaborative project, for instance by proposing plasma physics lectures supported by PIC simulations.

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## MOSARIX

**Leaders**
Marc Simon

**Laboratories involved**
LCPMR, INSP

**External collaborations**
IMSOX group (LCPMR), GALAXIES beamline (SOLEIL, France).

**Projects**
1 equipment project, 1 innovative small project, 2 engineers (Iyas Ismail; Thomas Trivellato), 1 invitation of international expert (Alexei Grum-Grzhimailo, Lomonosov Moscow State University, Russia).

**Budget**
640 000€

# Background & objectives

**Owing to the availability of high-resolution x-ray position-sensitive detectors, there has been a fast recent development of Von Hamos x-ray emission spectrometers worldwide, providing excellent compromise between resolution and efficiency.**

Several methods have been used in the photon energy range 5-10 keV in order to increase the efficiency by using large crystal solid angle or by employing multi-crystal. The used crystals are not appropriate for the 2-5 keV energy range. In order to maximize the efficiency of the spectrometer, we chose mosaic crystals having high reflectivity. Recent implementation of graphite mosaic crystals in von Hamos geometry spectrometer to measure X-ray in the range 4.5-10 keV and 8-60 keV with a resolution power < 2000 have been described *[Zastrau, U., et al., 2013; Gerlach, M., et al., 2015]*.

The groups involved in this project have a strong interest in the 2-5 keV photon energy range because it covers the Kα emission lines of sulphur, chlorine and argon as well as the L emission lines of iodine and xenon. The 2-5 keV photon energy range is challenging because conventional silicon crystals cannot be used and because there is a strong absorption in air in this energy domain.

For the design of MOSARIX, multi-crystal geometry with mosaic HAPG (highly annealed pyrolytic graphite) crystals have been selected in order to gain one order of magnitude in the efficiency compared to HOPG (highly oriented pyrolytic graphite).

The project MOSARIX aims to develop a new generation x-ray spectrometer in the tender x-ray domain (2-5 keV) with high efficiency, allowing performing x-ray emission and coincidences (or covariance mapping) experiments using synchrotron radiation and XFEL. It involves 2 groups at LCPMR (F. Penent and M. Simon) and one group at INSP (D. Vernhet). The coincidences/covariance measurements will be between x-ray photons and ions or electrons. It would be the first time for such coincidences with energy-resolved photons. The spectrometer will be portable and will be used at different large-scale facilities (Synchrotrons, XFEL sources).

MOSARIX is a multi-crystal HAPG von Hamos spectrometer optimized for the 2-5 keV photon energy range. Its resolving power E/ΔE will be 4000. It will be equipped with a fast time and position sensitive detection system, allowing performing coincidences, or with a Pilatus detector more adapted for measurement requiring higher efficiency.

# Main results

Ray-tracing simulation have been performed to evaluate the possibility of using curved mosaic crystals in von Hamos geometry. The mosaic graphite crystals HAPG have been selected as our best choice of crystals because of their high integrated reflectivity. Furthermore, it allows working at the first order of reflection in the energy range 2-5 keV. We have developed a new micro-channel-plates (MCPs) based detector for keV (patent application and publication) *[Ismail, I. et al., 2018]* energy photons operating under ultra-high-vacuum. This detector has been employed with success to construct a prototype version of the spectrometer with one HAPG crystal. This spectrometer, working under high vacuum, was commissioned initially at our laboratory and then during two beamtimes (May and September 2017) at GALAXIES beamline of SOLEIL synchrotron. The results obtained with this spectrometer were very encouraging. A resolving power of E/ΔE=4000 was obtained by measuring the elastic peak and was also verified by measuring potassium Kα emission spectrum.

The successful operation of the one-crystal spectrometer allowed to go toward the multi-crystal version of the spectrometer. Several designs (in-vacuum and in-air) of the spectrometer have been studied and discussed with the PLAS@PAR experts committee (02/2019). Following the experts recommendations, we are currently constructing the final version of the spectrometer operating at 1 bar Helium with 8 crystals, Pilatus detector and a time resolved detector (TPX3) since the MCPs detector cannot operate at 1 bar Helium.

The first commissioning of the spectrometer is expected to be carried out for July 2020 at GALAXIES beamline (SOLEIL). After a full characterisation of the spectrometer, the first experiment using high-energy resolution off-resonant spectroscopy (HEROS *[Kavcic, M., et al., 2013]*) in gas phase is expected to reveal the electronic dynamics on an attosecond timescale in $CS_2$ molecule as a showcase.




*Figure 1: photography of the one-crystal version of MOSARIX installed at GALAXIES beamline at SOLEIL Synchrotron.*

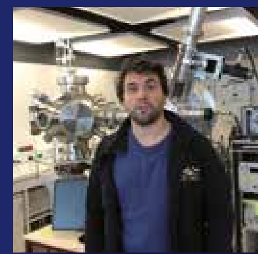
# Perspectives

MOSARIX will be used in the different projects of the three groups involved in the development. These projects require the measurement of photons with high efficiency, high resolution and even sometimes in coincidence mode. Particularly, we are aiming to revisit the Resonance-Enhanced X-ray Multiple Ionization (REXMI) using MOSARIX at XFEL light source and to perform Resonant Inelastic X-ray Scattering measurements at the sulphur edge in gas and liquid phases at synchrotron facilities.
In addition to the three groups initially involved, two "external" groups have expressed their interest on MOSARIX to study the chemical depth profile of nano-multi-layers structures (IMSOX group) and the sulphur chemistry becoming very attractive for the development of new type of batteries (GALAXIES SOLEIL and RS2E).


*Figure 2: design of the final multi-crystal MOSARIX.*

# Focus

**Iyas Ismail** obtained a PhD in physics in 2005 from Université Paris-Sud (Orsay). Then he worked as a researcher and senior researcher (2014) at the IBA laboratory - atomic energy commission of Syria. He developed a large international expertise in various fields ranging from electronics, multi-detection, spectroscopy, which he applied to various experimental R&D projects. In 2015 he moved back to France to join PLAS@PAR as MOSARIX project manager at LCPMR. Since 2018, he has a CNRS permanent position in the same laboratory and spends part of his time to the MOSARIX project.



**Thomas Trivelatto** obtained in 2016 the Master Outils et Systèmes de l'Astronomie et de l'Espace, Université Paris-Saclay. He then worked as Engineer at "Laboratoire d'Optiques Atmosphériques" in charge of different instruments and at "Institut de Géophysique du Globe" in charge of instruments used in marine campaigns. He joined PLAS@PAR in 2019 to work on the development of MOSARIX spectrometer.

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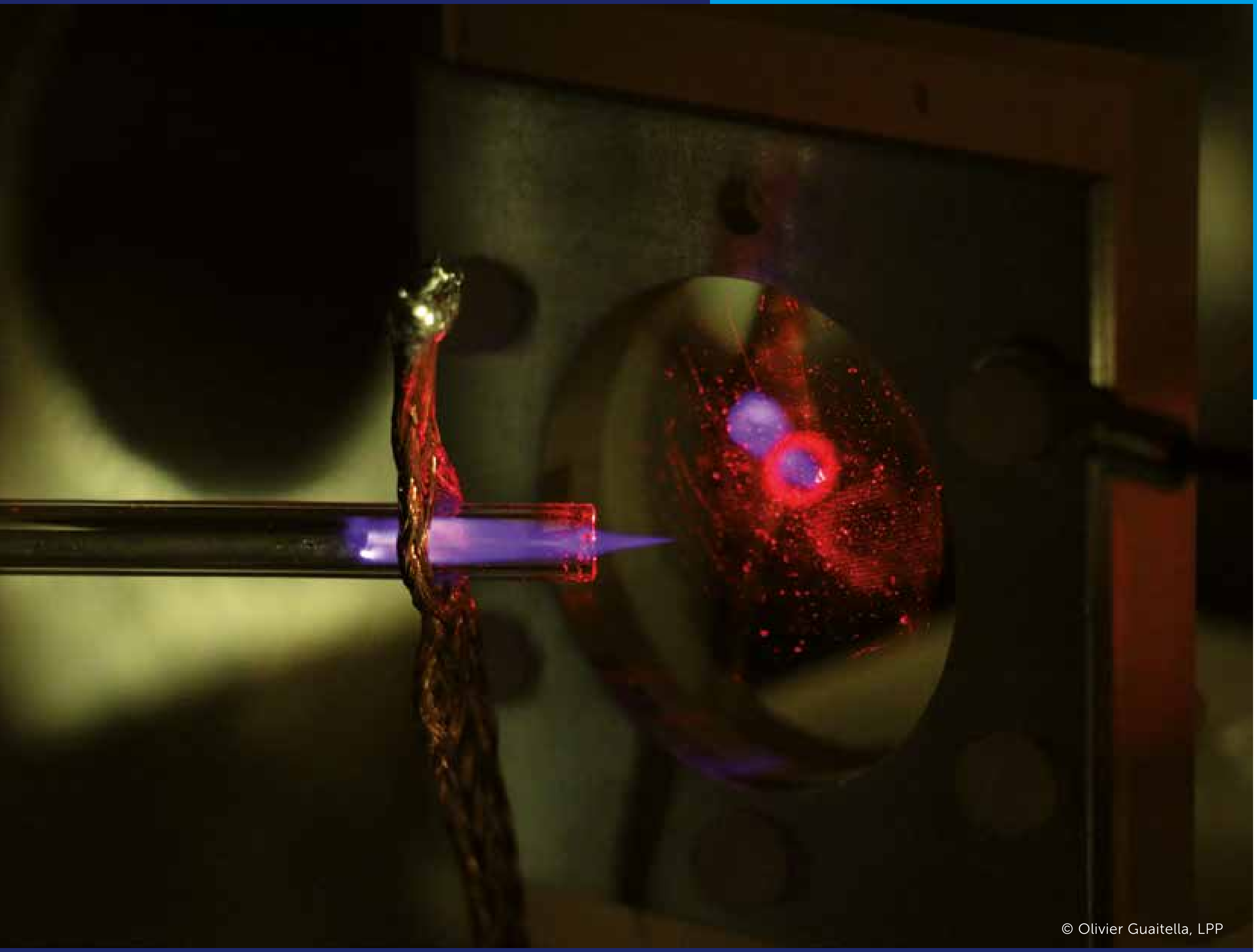
CHAPTER 3

# Industry


© Olivier Guaitella, LPP

- Industrial projects supported by PLAS@PAR
- International network
- Industrial partners involved

## PLAS@PAR SEEKS TO PROMOTE AND FOSTER A CULTURE OF COLLABORATION BETWEEN THE RESEARCH COMMUNITY AND THE INDUSTRY

First, PLAS@PAR encourages co-funded projects with industrial partners and strenghtens collaborations between academic research groups and applied research teams from industry.

This was achieved since 2012 by developing its international network and by organizing a one-day meeting that provided an opportunity for companies to meet with plasma physics researchers and students.

Second, PLAS@PAR encourages Master students in Plasma Physics to get involved in Industry-oriented training and conferences.

Since 2016, students have been attending a workshop organized by SATT Lutech (Technology transfer accelerator) at Sorbonne Université specifically designed to introduce the topic of patent protection, intellectual property management and technology transfer strategies.

For Bachelor students, industrial applications are also part of the curriculum taught during the PLAS@PAR annual summer school.

**400000€**
INVESTED SINCE 2013

V

**11**
PhD AND POSTDOCTORAL RESEARCHERS FROM THE COMMUNITY CURRENTLY WORK IN THE INDUSTRIAL SECTOR

# 4 main projects linked to industry received support from PLAS@PAR

*(see Chapter 2 Research , p. 61 & 68).*

*2 START-UPS SUCCESSFULLY EMERGED: THRUSTME BENEFITED FROM SUPPORT TO INITIAL SCIENTIFIC INVESTIGATIONS AT LPP JUST BEFORE ITS LAUNCH IN 2017 AND ENERGO, CREATED IN 2018 BY RESEARCHERS FROM PLAS@PAR, IS LINKED TO ONE EQUIPMENT DEVELOPED BY THE LPP AND IJLRA.*

## ThrustMe

Founders: Ane Aanesland and Dmytro Rafalskyi
Theme: space propulsion
Laboratory initially involved: LPP
Budget allocated by PLAS@PAR: about 300k€ (for initial scientific investigations)
Website: https://thrustme.fr


© ThrustMe

Project:
Constellations of miniaturized satellites in low Earth orbit are the future of global connectivity and real-time Earth monitoring.
ThrustMe, founded in 2017, and created to enable an economically and environmentally sustainable space industry. ThrustMe's core activity is the development, production and commercialization of unique standalone, fully integrated space propulsion systems for next generation satellites.

Their products vary from cold gas thrusters operating with solid propellant to innovative stand-alone electric propulsion systems at low and medium power, where the core technology is based on plasma physics and ion thrusters.


© ThrustMe

Their products are supported and backed up by high-end engineering services for space and ground applications. ThrustMe recruited a highly qualified and multidisciplinary team with expertise in plasma physics, electric propulsion, fluid dynamics, thermal management, digital and power electronics and chemistry in addition to aerospace engineering.
The creation of ThrustMe leverages more than 10 years of applied and fundamental research at LPP, where the two founders of ThrustMe carried out research on iodine plasmas and innovative acceleration concepts for space propulsion and semiconductor applications.

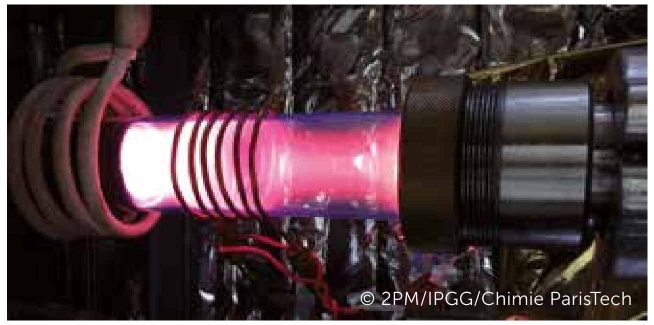
This research was actively supported by PLAS@PAR through direct support for equipment, PhD, postdoc and research grants. The important support can be illustrated by for example the success of the postdoc recruitment funded by PLAS@PAR, Dr Trevor Lafleur (see p. 61).

PLAS@PAR has contributed up to 300 000 € in funding for the research and technology development that is a baseline for ThrustMe's products today.


© ThrustMe

## Energo

Founders: Maria Elena Galvez and Patrick Da Costa
Theme: $CO_2$ valorization
Laboratories initially involved: IJLRA & 2PM/IPGG/Chimie ParisTech
Budget allocated by PLAS@PAR: 40k€
Website: https://energo-biogas.eu


© 2PM/IPGG/Chimie ParisTech

Project:
Founded in 2018, Energo is a small industrial company which designs and builds an innovative generation of reactor to convert $CO_2$ into biofuel. Energo aims at producing innovative catalytic methanation reactors to control $CO_2$ emissions or to store electricity from renewable energy sources. For biogas production sites, the startup develops EnergoBox, a device that can be integrated to existing or future gas cleaning process systems.

The degradation and replacement of the catalyst greatly increases the cost of conventional thermo-catalytic methanation systems. Using the plasma technology, the catalyst can be regenerated *in situ* without regular replacement.

The startup will benefit from the plasma-catalysis research on surface reactivity of molecular plasmas for $CO_2$ recycling financed by the Labex (see Chapter 2 Research - Plasma & environment, p. 68 - 71).

# Developing our international network

*IN NOVEMBER 2016, PLAS@PAR JOINED BALTICNET-PLASMATEC, AN INTERNATIONAL CLUSTER – LOCATED IN GREIFSWALD, GERMANY – AIMING AT REINFORCING A TECHNOLOGY AND MARKET-ORIENTED COOPERATION OF SCIENCE, RESEARCH AND ECONOMICS IN THE FIELD OF PLASMA TECHNOLOGY.*

BalticNet-PlasmaTec has currently 71 members in 15 different countries (including 44 companies).
PLAS@PAR and BalticNet-PlasmaTec aim at increasing cooperation with industry, for instance in jointly organized events and future European projects.

A first joint event has been organized in November 15, 2017 with a series of conferences of PLAS@PAR researchers and various industrial partners of this network such as Innovent, the Lithuanian Energy Institute, Envisolve - RAFFLENBEUL ANLAGENBAU GMBH and Impreglon.

**Paving the way towards industry by training future leaders**

Each year, PLAS@PAR's Industry days welcomed about 50 people (researchers, post-doctoral fellows, doctoral and master students) to promote technology transfer and research in the industrial sector.

Indeed, Industry days facilitate interaction and professional integration of junior staff, in order for them to find employment or internships commensurate with their training.

In addition, each year since 2016, 25 Master students (M2) in plasma physics have been invited to participate in the workshop « Boost your ideas and innovative technologies onto the market! Transfer to industry and startup: issues & methodology » co-organized with SATT Lutech coaches. In this event, students groups perform a technology transfer case study with a patent from a PLAS@PAR researcher. Students have to develop a credible business plan for a start-up, the pitch is in front of a jury composed of PLAS@PAR's researchers and SATT coaches.

The student feedback for this interactive training is very positive. Students appreciate the teamwork, the hands-on approach and the friendly competitive atmosphere of the event.



# Industrial partners involved in PLAS@PAR industry days since 2012

Global groups
- ABB (electronics)
- EADS (aerospace)
- SAFRAN (aerospace)
- SODERN (aerospace)
- THALES (aerospace and defense)

Small and medium sized entreprises (SMEs)
- AL-KO (air treatment)
- ARTENUM PARIS (computer simulation)
- ENVISOLVE (air treatment)
- EXCICO (semi conductors)
- IMPREGLON (plasma coatings)
- INNOVENT (thin films)
- IVEA SOLUTION (LIBS technology)
- PANTECHNIK (instrumentation for nuclear research)
- PHASICS (optical beam quality instrumentation)
- PLASMA BIOTICS (medicine)
- SCITECH PRECISION (target manufacturing)

Startups
- THRUSTME (space propulsion)
- SOLAYL (RF power and metrology)
- AIR SERENITY (air treatment)

Clusters
- OPTICS VALLEY (optics)
- BALTICNET-PLASMATECH (plasma technologies)
- SATT LUTECH

CHAPTER 4

# Teaching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- Bachelor to Master: improving the visibility of plasma related topics in the curriculum
- Online teaching
- International Summer school
- Master to PhD: attracting the best students & training future teachers
- Training future teachers to use plasmas in middle and high schools
- Middle and high school student supervision
- Specific PhD trainings

## EDUCATION IN ONE OF THE MOST IMPORTANT PILLARS OF PLAS@PAR

Since 2012, PLAS@PAR trains a new generation of plasma scientists thanks to the active support from researchers, professors and associate professors involved in teaching activities from Bachelor to PhD level.

This outstanding work helped to:
- Increase the quality and quantity of students in plasma sciences in the Paris region
- Increase the visibility of plasma sciences within Sorbonne Université and its partners
- Attract the best students to the PLAS@PAR laboratories
- Train middle and high school teachers
- Shape the future of plasma sciences

ABOUT
**500 000€**
INVESTED SINCE 2012 IN ACTIONS & ACTIVITIES RELATED TO EDUCATION

**18 PhD**
POSITIONS FUNDED AND COFUNDED BY PLAS@PAR

ABOUT
**130 PhD**
STUDENTS TRAINED IN THE COMMUNITY BETWEEN 2012 AND 2019

# Training a new generation of plasma scientists

## Bachelor to Master: improving the visibility of plasma related topics in the curriculum

PLAS@PAR encourages new innovative initiatives by giving financial support to hands-on experiments at the L3 and M1 level.

The first one, developed in 2016 by Dr Christophe Prigent (INSP) in collaboration with the experimental platform of the Physics Faculty (Sorbonne Université), was a great success. About 150 students learned about fundamental concepts of Plasma physics through practical work using the Langmuir probe diagnostic to measure the local conditions of a plasma discharge. In addition, the spectroscopic studies are carried out using several commercial portable plasma discharges of rare gas and molecules as examples. Since September 2019, more than 50 students performed these experiments.

Another hands-on experiments built under the supervision of Christophe Prigent and that received the support of PLAS@PAR concerns fundamental aspects in atomic physics related to the effect of a magnetic field on the light emitted by the plasma (the so-called Hanle effect). It is expected that more than 50 students at the Master level will carry out experiments on this new platform.

All the experimental devices developed for teaching purpose are also used for various outreach actions such as the National Science Day and "Prof en fac", increasing the visibility of plasma science at all levels of society.

ABOUT
**35000€**
INVESTED IN STATE OF THE ART HANDS-ON EXPERIMENTS SINCE 2013

### What about the plasma discharge experiment?

"We focus here on discharge tubes commonly (and inacurrately) called "neon". These glass tubes are filled by air at very low pressure. By plugging a high-voltage supply to the metal electrodes of the tube, we create a very high electrical potential (around a few hundred volts DC). From a "disruptive" value, a breakdown can be observed: the gas becomes conductive and releases a large number of electrons. Then, a plasma appears between the electrodes."

Objectives:
- Students have to **quantitatively** measure the breakdown voltage of a tube under a given residual gas pressure; Then, they are able to verify the Paschen law.
- Students **qualitatively** study the light emitted by the plasma's glow discharge (by image analysis) and highlight that inelastic electron/ion collisions are the source of this light emission.
- Students measure the floating electrostatic potential within the plasma and highlight the inhomogeneity of the electric field inside discharge (screening effects).
- The Langmuir probe allows them to measure the temperature and density of electrons in the plasma.
- A spectroscopic study helps identify more precisely the ions and their excited states formed in the glow discharge and to estimate the collisional temperature of the cold plasma.

PLAS@PAR's instructors:
Christophe Prigent (Sorbonne Université - INSP)
Carine Briand (Paris Observatory - LESIA)
Gaëtan Gautier (Sorbonne Université - LPP)
Julien Aublin (Sorbonne Université - LPNHE)
Sylvain Beaumont (Sorbonne Université - LPNHE)
Louis d'Eramo (Sorbonne Université - LPNHE)
Mathieu Guigue (Sorbonne Université - LPNHE)

### What about the Hanle Effect?

The Hanle effect is the modification of polarization of scattered radiation in presence of magnetic field. Most fusion relevant high temperature plasma device, such as Tokamaks, operates at high magnetic field. Hence, a typical magnetic diagnostic developed for these plasmas (Zeeman effect, Faraday rotation, etc.) measures high magnetic field (above 1 kG). In contrast, the Hanle effect allow to measure the low magnetic field (< 10 G) and is widely used to measure the magnetic field on the sun corona.

Objectives:
- Students have to **quantitatively** measure the degree of polarization of scattered light as function of the strength of the magnetic field.
- Different configurations (with linear or circular polarized light) can be performed to measure the lifetime of the atomic excited states.
- The experiment can be upgraded with a radio-frequency field to realize double resonance experiments (Brossel experiments, the historical experiments of nuclear magnetic resonance and optical pumping at the beginning of the laser development).

This experiment will be inaugurated for the autumn semester 2019.

# Online teaching

**Distance learning by Sorbonne Université**

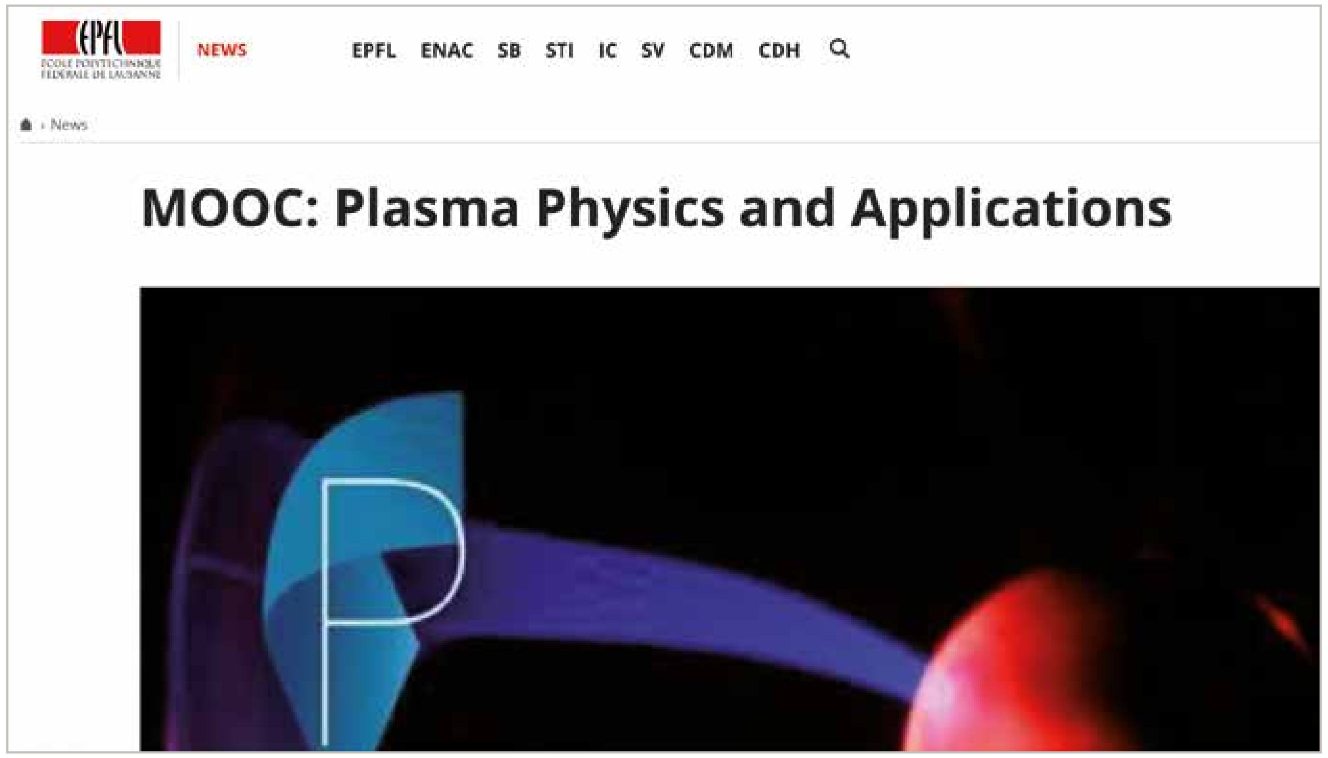
Researchers of PLAS@PAR actively participates in the development of distance learning courses (SPOC) at the Master 1 level of Physics and Applications at Sorbonne Université. The lectures, in French, aim at allowing students holding the distance learning Bachelor's degree in physics (L3 PAD – Physique à distance) from Sorbonne Université to continue their studies, and also to reach a new public. In this context, this training offers an introduction to plasma physics.

PLAS@PAR's instructors:
Laurence Rezeau: Physics professor at Sorbonne Université
Caterina Riconda: Physics professor at Sorbonne Université

**MOOC (massive open online course) by Sorbonne Université and EPFL**

PLAS@PAR was also highly involved in the creation and funding of the new "MOOC Plasma Physics: Applications", a joint production of SU-EPFL, online since January 1, 2018. The aim is to learn about plasma applications from nuclear fusion powering the sun, to making integrated circuits and to generating electricity. In this course, PLAS@PAR provides lectures on laser plasma interaction as well as plasma applications in medicine.

Length: 6 weeks
Effort: 5-6 hours per week, lectures in english
Level: Bachelor
Price: Free (Verified Certificate available for $49 USD)
Institutions: EPFLx and SorbonneX on edX platform




2580
STUDENTS REGISTERED FOR THE MOOC & MORE THAN 20 STUDENTS EACH YEAR FOR THE SPOC COURSE

Program:
- Applications of plasma
- Understanding of the fusion energy challenge, and acquisition of the basis for developing an overall vision of the different R&D elements
- Understanding of the main plasma societal applications and relevant tools
- Vision and appreciation of the importance of plasmas in space and astrophysics
- Acquiring some basic knowledges of MATLAB programming by solving problems in course content

PLAS@PAR's instructors:
François Amiranoff: Research director at CNRS
Caterina Riconda: Physics professor at Sorbonne Université
Thierry Dufour: Associate professor at Sorbonne Université



# International Summer school

Each year since 2013, PLAS@PAR organizes a summer school entitled, "From the laboratory to the distant universe, the World of Plasmas". The school, which takes place usually during one week in August in Roscoff (Brittany) or Banyuls (Languedoc-Roussillon), is targeting students entering the master level, but can also be appreciated by master students to broaden their horizon or PhD students that are seeking to change research topics.

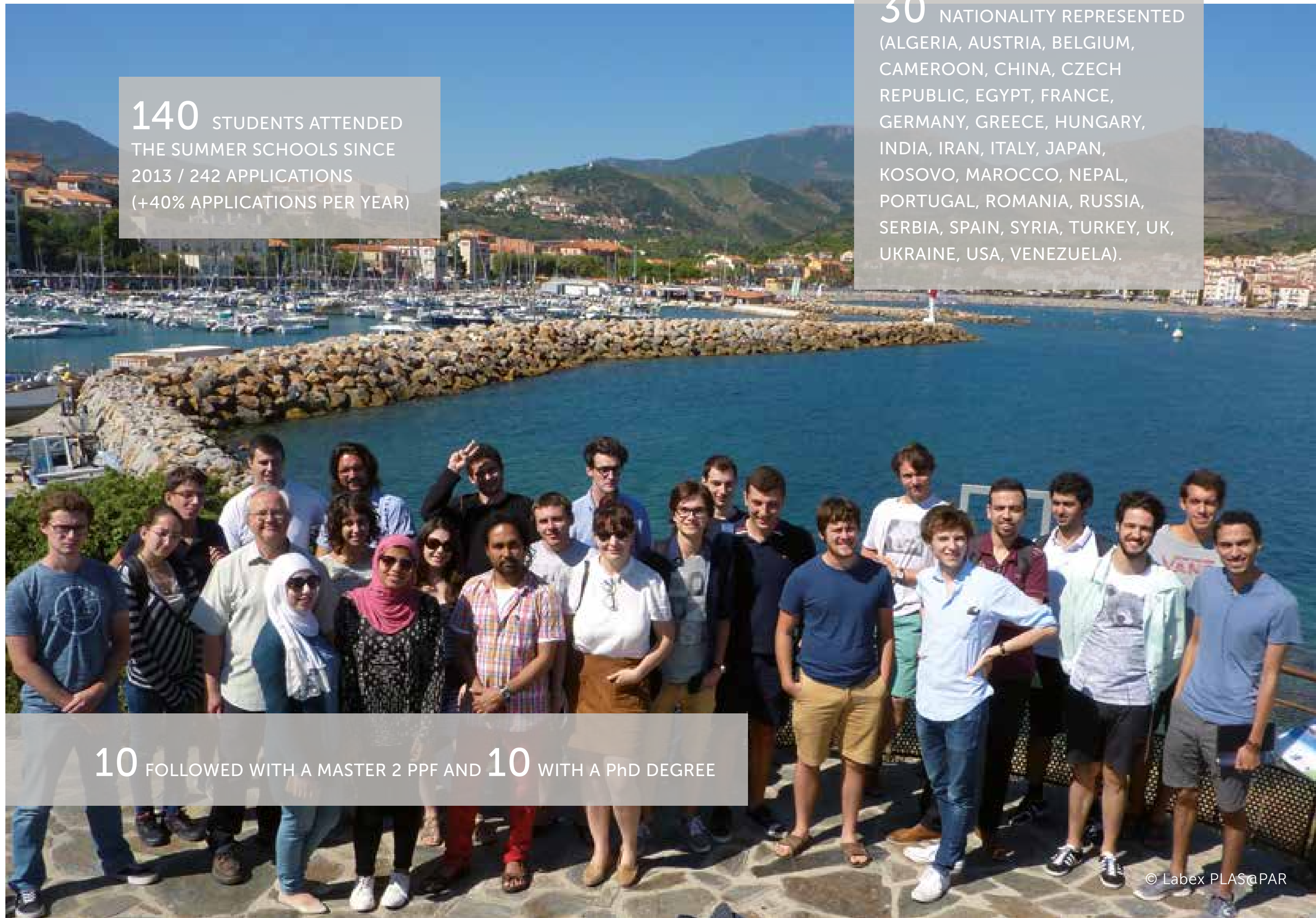
The school, free of charge and taught in English, is a unique opportunity to introduce students to plasma physics.
The formation covers various aspects of plasmas: astrophysical and natural plasmas, laboratory plasmas generated by lasers, electrical devices, ion beams, and also cold plasmas for industrial applications, etc. Students with a good background in physics or applied mathematics are ranked by PLAS@PAR on academic merit.

**One of the important characteristic of this summer school is that it is devoted mainly to the students at the end of the Bachelor degrees or at the beginning of the Master degrees. As such, the school is not specialized on one topic but presents instead a complete panorama of all plasmas research present in the PLAS@PAR network.**
In 2019, PLAS@PAR decided to broaden the summer school and lead a new international Summer school in Vietnam organised within the XVth Rencontres du Vietnam at The International Center for Interdisciplinary Science and Education (ICISE): a unique science and education institution located in the coastal city of Quy Nhon, Vietnam. It welcomes worldwide students holding a Bachelor's degree, studying to complete a Master's degree or a PhD.

Program director: Philippe Savoini, Physics professor at Sorbonne Université

Plenary lectures and hands-on sessions on:
- Introduction to plasma physics
- Astrophysical plasmas
- Spectroscopy: foundations and applications for diagnostic
- Symbiosis between plasmas and technologies
- Plasmas for energy and fusion (Tokamaks and other devices)
- Plasma for environment
- Laser generated plasmas
- Plasma physics as an innovative opportunity for space propulsion

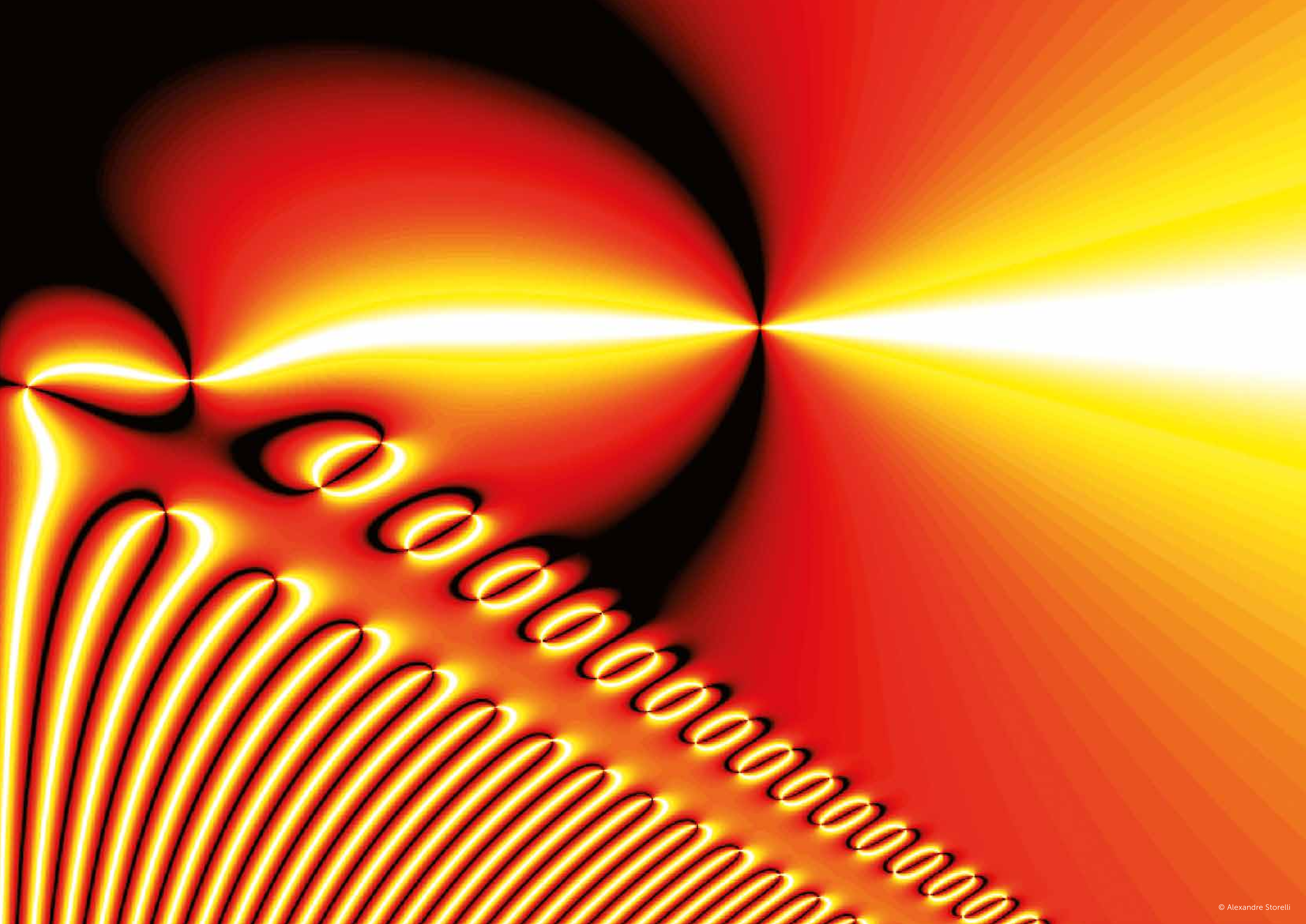
Instructors involved since 2013:
Mhedine Ali Chérif (LPP), Jean-Paul Booth (LPP), Stéphane Carniato (LCPMR), Gaëtan Gauthier (LPP), Olivier Guaitella (LPP), Mickaël Grech (LULI), Pierre Henri (LPC2E), Jean Larour (LPP), Pierre Morel (LPP), Loïc Nicolas (LPP/LERMA), Laurence Rezeau (LPP), Philippe Savoini (LPP), Pedro Viegas (LPP), Stéphan Zurbach (SAFRAN).



30 NATIONALITY REPRESENTED (ALGERIA, AUSTRIA, BELGIUM, CAMEROON, CHINA, CZECH REPUBLIC, EGYPT, FRANCE, GERMANY, GREECE, HUNGARY, INDIA, IRAN, ITALY, JAPAN, KOSOVO, MAROCCO, NEPAL, PORTUGAL, ROMANIA, RUSSIA, SERBIA, SPAIN, SYRIA, TURKEY, UK, UKRAINE, USA, VENEZUELA).

140 STUDENTS ATTENDED THE SUMMER SCHOOLS SINCE 2013 / 242 APPLICATIONS (+40% APPLICATIONS PER YEAR)

10 FOLLOWED WITH A MASTER 2 PPF AND 10 WITH A PhD DEGREE



# Master to PhD: attracting the best students & training future teachers

### Grants and scholarships

International internship

The Master 1 Physics and Application at Sorbonne Université offers a range of courses in physics within all its diversity and it encourages internship for:

- Implementation in a research laboratory (to prepare a thesis)
- Experience within the industry (career path)
- Practice in teaching and education

In order to open the doors to plasma physics and encourage students to broaden their international horizon, PLAS@PAR offered grants for international internship to M1 and M2 students.

Outgoing mobility

PLAS@PAR supported grants for international internships to students at the M1 master level, registered at Sorbonne Université. The projects were carried out in foreign laboratories with a close collaboration with PLAS@PAR such as UC Berkeley, ELI Prague, Las Palmas. About 5 grants since 2013.

Incoming mobility

Grants were also available to help students come to the Paris area to do an internship (M1 or M2) within one of PLAS@PAR's labs. These grants could cover travelling expenses as well as a part of the living expenses. About 5 grants since 2013.

Master 2 International internships

PLAS@PAR is highly involved in the Master 2 Plasma & Fusion Physics (M2 PPF).

Since 2016, PLAS@PAR offered one-year scholarships to international students to study plasma physics at the Master 2 level at Sorbonne Université: an opportunity to the top-class students with a solid background in physics and applied mathematics to study a wide scope of topics within plasma physics, in order to work in plasma research programs, whether natural or artificial, cold or hot, diluted or dense. Amount of the scholarship: 1000€ per month and 500€ for installation expenses.

PLAS@PAR also offered a part (50%) of the one-year scholarships for French students who want to study plasmas in Italy at Pise University (Laurea Magistrale in Fisica) and obtain the Sorbonne Université & UNIPI double master degree.

OVER 100 CANDIDATES FOR THE MASTER 2 IN PLASMA PHYSICS IN 2017 AGAINST ONLY 40 IN 2014, THANKS TO PLAS@PAR INCREASED VISIBILITY.

10 GRANTS FOR INTERNATIONAL INTERNSHIPS

15 MASTER 2 ONE-YEAR SCHOLARSHIP

© Raj Laxmi Singh, LERMA

# Training future teachers to use plasmas in middle and high schools

Given that plasmas are everywhere, from the sun to the stars, as well as in lightnings, fire and even in neon lights, the PLAS@PAR community is convinced that concepts related to plasmas should be taught earlier, to school audiences. To reach this goal PLAS@PAR was part of the program « Prof en fac » and is offering, yearly since 2016, a 2-day training at Sorbonne Université to future professors from the «Master des Métiers de l'Enseignement, de l'Éducation et de la Formation (MEEF), parcours physique-chimie ». This training (in French) entitled « Les plasmas dans tous les leurs états ! » is accessible with a basic knowledge of physics and is a great occasion to give some simple key information and tips to allow teachers to talk about the 4$^{th}$ state of matter to their future students.

The training was focused on 3 main activities:

- Discussion & presentations about all types of plasmas
- Hands-on experiments
- Visits of facilities and experiments (in particular the SIMPA ion source of INSP, the plasma medicine and plasma clean room at LPP).

Teachers involved since 2017:

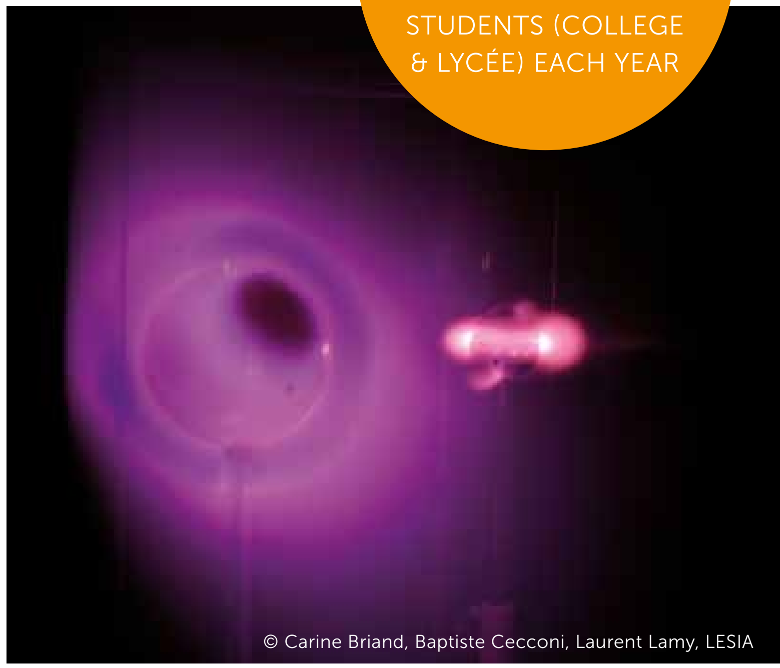
Andrea Ciardi (LERMA), Lionel de Sá (LERMA), Thierry Dufour (LPP), Gaëtan Gauthier (LPP), Julien Guyot (LPP/LERMA), Benjamin Khiar (LERMA), Frédéric Leblanc (LPP), Loïc Nicolas (LPP/LERMA), Christophe Prigent (INSP), Philippe Savoini (LPP), Christophe Verdeil (LPP).

© Gaëtan Gauthier, LPP

OVER 50 TEACHERS TRAINED EACH YEAR

# Middle and high school student supervision:

OVER 20 STUDENTS (COLLEGE & LYCÉE) EACH YEAR



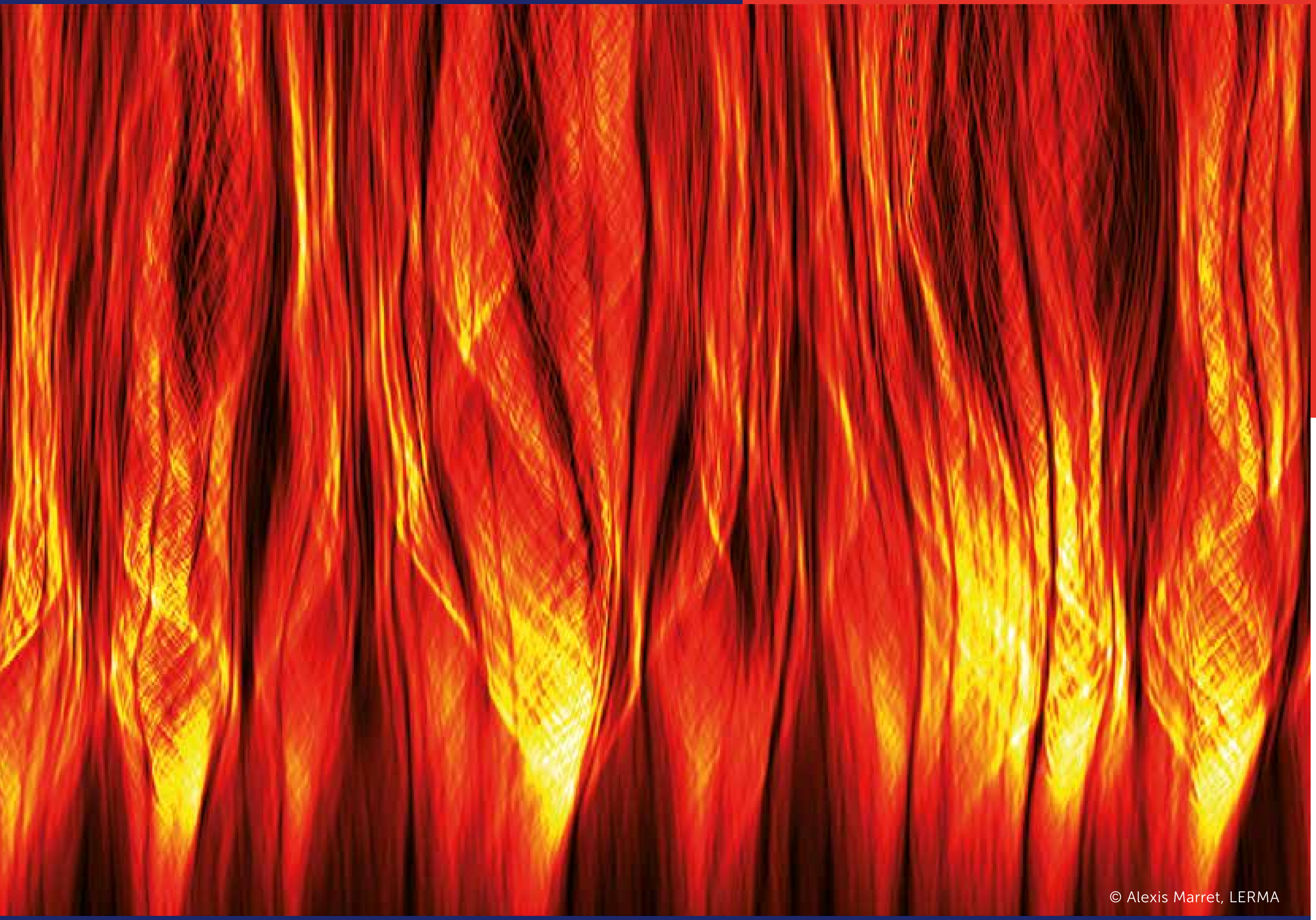
© Carine Briand, Baptiste Cecconi, Laurent Lamy, LESIA

Plasma teachers from the Sorbonne Université welcome each year students from "college" and "lycée" for one day to help them for their work of personnel interest (TIPE in French for « Travaux d'Intérêt Personnel Encadrés »).
The fascinating interest for one the most mysterious show on earth related with the plasma (polar aurora) is illustrated with the planeterrella experiments from the « Collection de Physique » of the Physics department of Sorbonne Université. With the help of an electron gun within Helmhotz coils, students can learn the circular motion of charged particle along a magnetic field, phenomena at the origin of aurora. The planeterrella experiments allow to mimic different astrophysical phenomena such as the Aurora Borealis or Aurora Australis, the Van Allen radiation belts, stellar jets, coronal holes, and stellar ring currents.

# Specific PhD trainings

On top of training Bachelor and Master students, PLAS@PAR also provided support to PhD students through initiation to technology transfer (see Chapter Industry), participation in many scientific and public events (see Chapter Communication and Outreach), as well as the classroom teaching activities mentioned above.

CHAPTER 5



© Alexis Marret, LERMA

# Communication & Outreach

- Internal communication
- External communication
- Outreach

ABOUT

**200 000€**

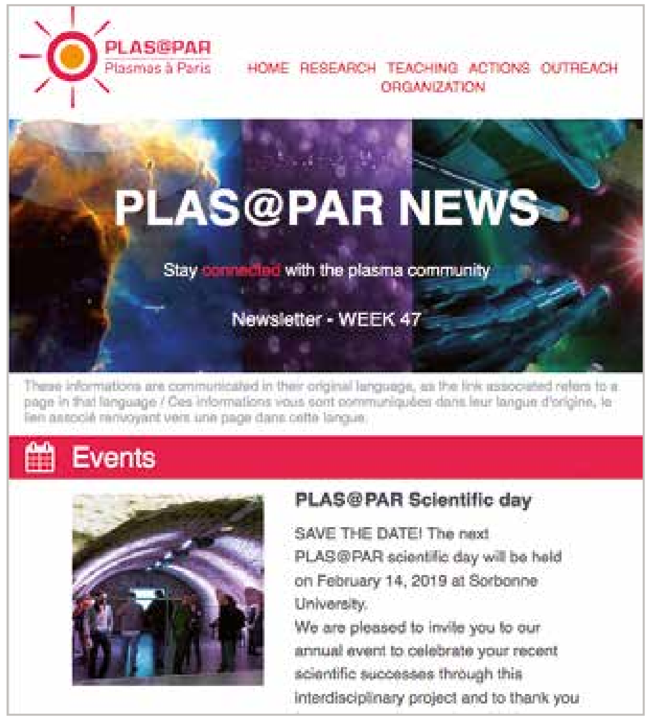
INVESTED SINCE 2012 IN ACTIONS RELATED TO COMMUNICATION & OUTREACH

# Internal communication: improving information, sharing within the community

Public: members of the Plasma physics community, which includes researchers, engineers, teachers, PhD students, postdoctoral fellows.

Goals: to foster collaborations between laboratories, to create a sense of community, to provide key and efficient information.

*BECAUSE OUR COMMUNITY IS BROAD, INTERNAL COMMUNICATION IS ESSENTIAL TO STRENGTHEN COLLABORATIONS. DIGITAL TOOLS HAVE BEEN SPECIFICALLY CREATED TO REACH THIS GOAL: WEBSITE, SOCIAL MEDIA, FILMS, PHOTO-VIDEO COMPETITION.*





© Sorbonne Université - P. Kitmacher

Dedicated meetings have also been regularly organized. In the past years: 7 annual Industry Days, 7 annual Scientific Days, 4 Young Researcher Days and 7 specialized workshops.

Moreover, community members receive a weekly newsletter to keep them informed about all important news related to plasma: calls, events, highlights, positions, awards, education, trainings, etc.

Finally, an institutional video "PLAS@PAR from inside" has been produced in 2017, it aims at showing to the plasma community (but also the institutional partners), some great interdisciplinary projects, collaborations and successes.

# External communication: reaching students, laboratories & industry

Public: academic institutions, medias, students, scientific community (institutions, laboratories, researchers & industrial partners).

Goals: to promote research towards a wider audience in line with the communication strategy of Sorbonne Université and other trustees.

*TO INCREASE THE IMPACT AND VISIBILITY OF PLAS@PAR'S ACTIONS TOWARDS A GENERAL AUDIENCE, THE COMMUNICATION OF NEWS AND UPDATES HAS BEEN DONE THROUGH SORBONNE UNIVERSITÉ AND PLAS@PAR'S WEBSITES, SOCIAL MEDIA (TWITTER/FACEBOOK).*

The Labex works in close collaboration with the Communication Department of Sorbonne Université in order to highlight important news with either a press releases (ITN Pioneer, Arts and Plasma sciences: an experience of ionized matter) or articles on Sorbonne Université's home page (recently about the BepiColombo mission).

To advertise PLAS@PAR to students in France and abroad, communication campaigns targeting students, through supports like promotional posters and leaflets or web advertising, have been set for different actions such as summer schools, internships, international Plasma Physics Master SU-UNIPI, PhD recruitments, etc. Releases are regularly sent by PLAS@PAR partners, professors of the PLAS@PAR community and their network (Embassies, partner universities, Campus France, social media, etc).


**1 600**

VIEWS IN 2019

To promote young researcher projects and highlight what PLAS@PAR has to offer, a series entitled « Meet with... » has been produced (since 2015). 13 episodes are currently published on PLAS@PAR Youtube channel. These short videos aim at promoting thesis and post-doc projects, with information on the project, scientific objectives, results, added value of the Labex, future professional projects, etc. They were broadcasted on PLAS@PAR Youtube channel, on the website and by email to the research community. It totalizes 1 600 views in 2019.

# Outreach efforts: explaining the beauty and wonder of science & plasmas

Public: schools, teachers, general public

*THANKS TO THE STRONG MOBILIZATION OF SEVERAL RESEARCHERS, PLAS@PAR HAS BEEN ABLE TO SET UP VARIOUS OUTREACH ACTIVITIES AIMED AT SCHOOLS AND THE GENERAL PUBLIC.*

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**PLAS@PAR participates each year in the National Science festival at Sorbonne Université (Village des Sciences – Pierre et Marie Campus) which is a growing success every year. In 2019, PLAS@PAR welcomed over 1400 visitors during this three-day event with the help of 23 scientists (engineers, researchers, professors, students, postdocs, technicians). Each year, PLAS@PAR offers a playful and creative experience to discover the ionized matter!**

One full day is dedicated to students generally between 12 and 18 years old, using different tools and activities, such as posters, Planeterrella experiment (scaled-down aurora experiment), laboratory visits (LPP, LCPMR, INSP), and a dedicated workshop to build a homemade spectroscope out of a cardboard box and a CD, which is then used to identify the spectral lines of the elements contained in different plasma lamps.

Two days are then open to the general public. Multiple experiments are available: spectral lamps, plasma discharge experiment, Planeterrella, plasma bowls, *Plasma Reflection* created by Danny Rose, agronomy experiment, plasma thruster model, etc. In addition, general public conferences on plasma physics are given by members of the Labex.
At the INSP laboratory, visits of the electron cyclotron resonance ions source (SIMPA) have also been usually organized and in 2019, an Escape Game called "Mission EvaZ'ionS" has been created at SIMPA; the game was a real success. In 2018 and 2019, the Institut des Sciences du Calcul et des Données (ISCD) hosted 3D aurora projections thanks to auroras hunters from Institut d'Astrophysique de Paris (IAP).

**Arts and Sciences of plasmas: an experience of ionized matter**

In 2016, PLAS@PAR started to think about going further and reaching a broader public with one main goal: bring to light the fourth state of matter with a new original approach.
To reach this goal, PLAS@PAR developed in 2017-2018 an interdisciplinary program resulting from an unprecedented collaboration with Centre Pompidou. A project bringing together science, engineering and humanities at Sorbonne Université, sponsored by multiple partners: Centre Pompidou, Labex PLAS@PAR, Sorbonne Université, CNRS, Observatoire de Paris, École polytechnique, ONERA, Université Paris Sud, CEA, École normale supérieure, Université de Cergy-Pontoise, Région Ile-de-France, Ville de Paris, ITER, Collegium Musicae, European Physical Society.

## Goals

- Discover or rediscover the 4$^{th}$ state of matter.
- Decompartmentalize the scientific, artistic and cultural worlds.
- Transcending scientific content into works of art.
- Initiate bridges between scientists and artists.
- Interrogate the notion of transversal and interdisciplinary transmission.

## Acts

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**Act 1 / Crossroads arts and sciences of plasmas**
300 secondary and high schools students participated at the Institut des NanoSciences de Paris (INSP), the Observatoire de Paris and the Centre Pompidou

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**Act 2 / Teaching and transmission workshops**
66 teachers and future teachers in physics-chemistry and plastic arts at the Centre Pompidou

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**Act 3 / Micro-residency artists and scientists**
4 artists and 3 scientists immersed 3 days at the Radioastronomy station of Nançay (Observatoire de Paris)
Artists: Agathe Rosa (Marseille), Aurélie Pertusot (Nancy), Cyrille Courte (Tours), Olivier Leroi (Nançay).
Scientists: Ludwig Klein, Philippe Zarka and Laurent Denis

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**Act 4 / Plasma Reflection: a workshop at the heart of ionized matter**
Elaboration of a collective work at the crossroads of arts and sciences of plasmas and immersion within the process of creation.
Students and staff of Sorbonne Université at Pierre et Marie Curie Campus and at Clignancourt Campus.

© Danny Rose

**Act 5 / Campus - Arts and Science of plasmas: an experience of ionized matter**
General public
Visit of collections and musical moments in the National Museum of Modern Art, conferences and debates, exhibition of *Inside Plasma and Plasma reflection*, both created by Danny Rose, live scientific experiments, virtual and augmented reality applied to solar plasmas by scientists from IAS.
At the Centre Pompidou - April 7th and 8th 2018.


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**Plasmas in library**

As the *Plasma Reflection* met a great success during the previous projects, PLAS@PAR decided to create a new exhibition to keep going the outreach actions about plasmas. A new partnership has been initiated with 2 libraries of Sorbonne Université, on the Pierre et Marie Curie Campus (from November 26 to December 21, 2018) to reach sciences students (bachelor level) and on the Clignancourt Campus (from March 18 to April 12, 2019) to meet students in the humanities (bachelor level).
The *Plasma Reflection* surprised students who came to study in the library because it only works when students pass in front of it. Both exhibitions were illustrated with several books from the library collections and with beautiful plasma images and explanations.

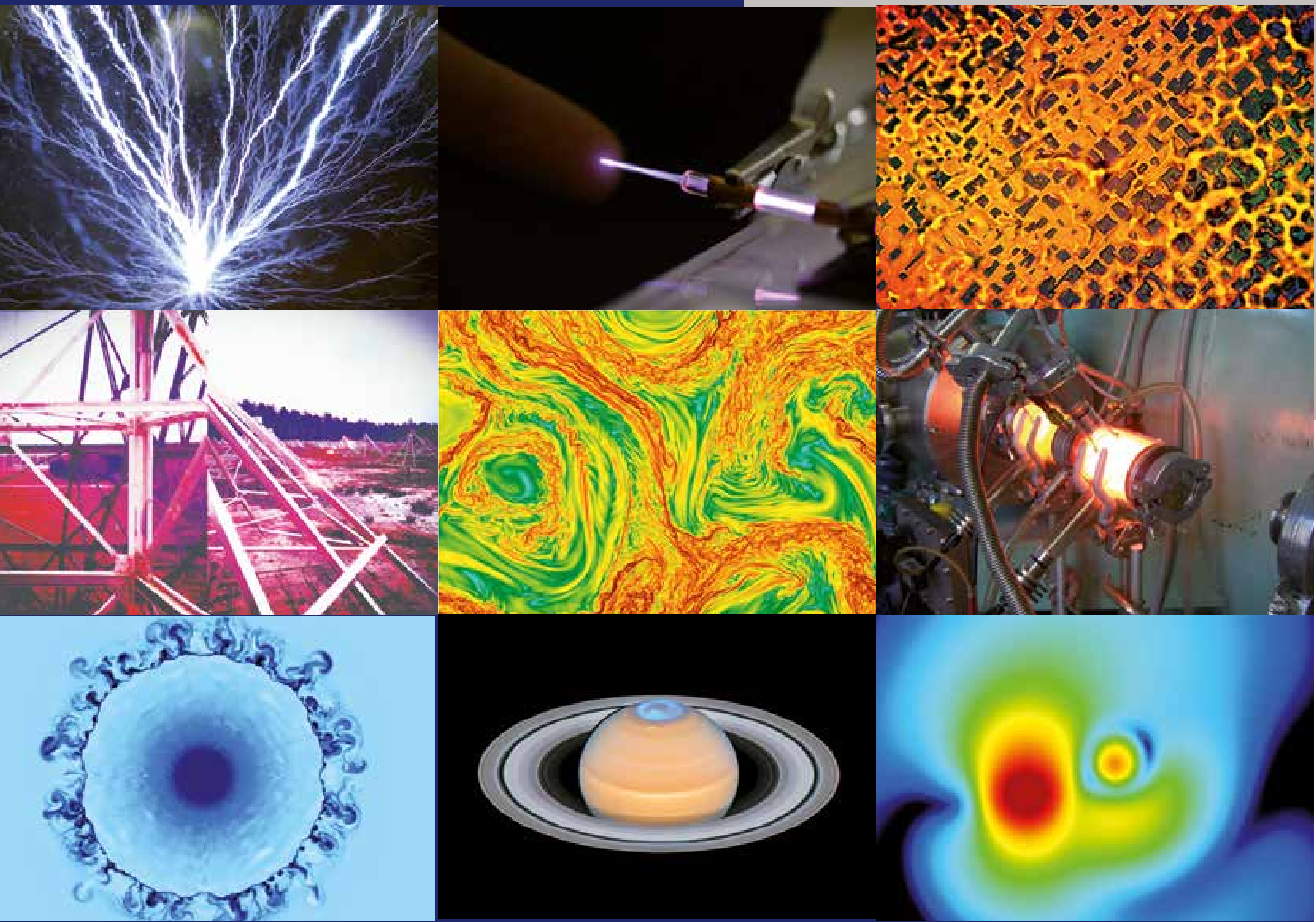
At Clignancourt library some reproduction of work of art linked to plasmas have been printed and a reflection about the link between arts and plasma sciences around three common themes "light, color and matter" (a work done in collaboration with Sylvie Cabrit, Observatoire de Paris and Arnauld Pierre, Sorbonne Université) has been exhibited. Concomitantly, the exhibition hosted concerts:

- Trio of electroacoustic improvisation by Pierre Couprie, Hugues Genevois & Vincent Goudard.
- Medieval works by the undergraduate students of the Music Department of Sorbonne Université. Teacher: Katarina Livljanić.


DannyRose

CHAPTER 6

# Appendices



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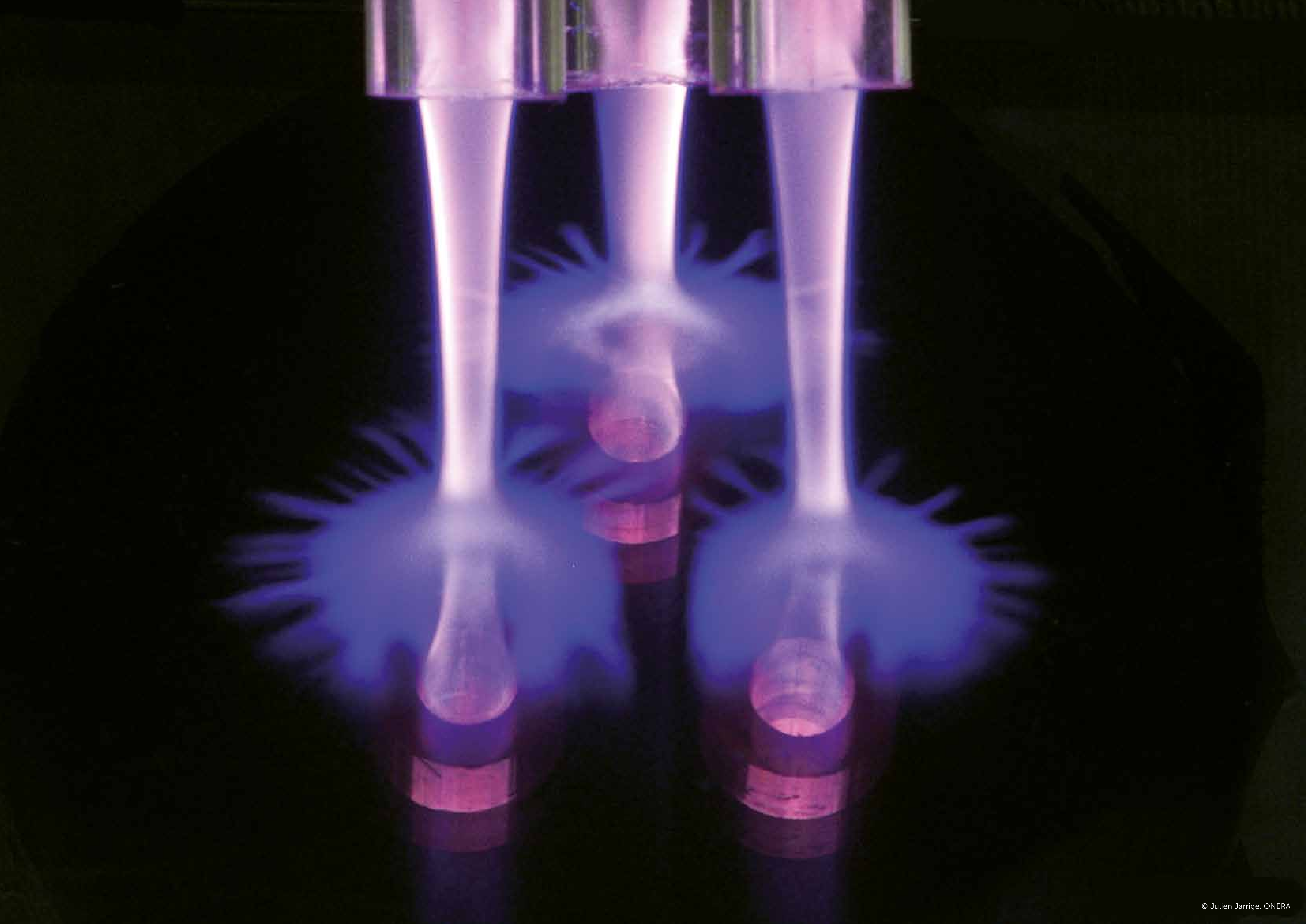

# Funded actions

## PhD

2013
- Pascaline Grondein, Alternate acceleration of positive and negative ions for application in space propulsion, with Ane Aanesland (LPP)
- Mickaël Foucher, Dynamics of pulsed radiofrequency plasmas in simple halogen gases, with Jean-Paul Booth (LPP) and Paul Indelicato (LKB)
- Raj Laxmi Singh, Electromagnetically-launched strong shocks relevant for accretion shocks in astrophysics: experimental study and numerical approach, with Jean Larour (LPP) and Chantal Stehlé (LERMA)
- Marco Chiaramello, Study of short pulse amplification by Brillouin Backscattering in the strong coupling regime, with Caterina Riconda (LULI)

2014
- Alessandra Puglisi, Spectroscopic study of silicon hydride molecular ions, with Stéphane Carniato (LPCMR)
- Anna Grassi, Relativistic shocks in magnetized plasmas in the context of laboratory astrophysics, with Caterina Riconda (LULI), Mickael Grech (LULI) and Andrea Macchi (UNIPI)
- Bruno Honnorat, Non thermal plasma for medical applications, with Antoine Rousseau (LPP), Anne Janin (Hôpital Saint-Louis) and Corinne Dupuy, Institut Gustave Roussy.
- Loïc Nicolas, Streaming instability in low-energy cosmic rays, with Roch Smets (LPP) and Andrea Ciardi (LERMA)

2015
- Mehdi Khalal, Multiple Photoionization of metallic vapors: Auger decays in ions, with Pascal Lablanquie and Francis Penent (LCPMR)
- Corentin Louis, Comparative study of auroral processes of Saturn and Jupiter sampled in situ by Cassini and Juno missions, with Laurent Lamy (LESIA)
- Florian Condamine, X-ray spectroscopy on dense plasmas produced by 4th generation Light Sources, with Frank Rosmej (LULI) and Siegfried Glenzer (SLAC National Accelerator Laboratory)

2016
- Abhyuday Chatterjee, Vacuum Ultraviolet Diagnostics of Discharges in $O_2$, with Jean-Paul Booth (LPP) and Laurent Nahon (SOLEIL)
- Jean-Baptiste Layly, Micro-discharged in confined media, with Fabien Tholin (ONERA) and Anne Bourdon (LPP)
- Ana-Sofia Morillo-Candas, Surface reactivitY of moleCular plAsMas for $CO_2$ REcycling, with Olivier Guaitella (LPP) and Vasco Guerra (IST Lisbon)
- Salvatore Colombo, Radiation models and spectral signatures, with Laurent Ibgui and Chantal Stehlé (LERMA) and Salvatore Orlando (Palermo University)
- Mélissa Menu, Rotating turbulent dynamos, with Sébastien Galtier (LPP) and Ludovic Petitdemange (LERMA)
- Manuel de Anda Villa, Time-resolved studies of the gold solid-liquid phase transition at the femtosecond timescale, with Anna Levy (INSP) and Dominique Vernhet (INSP)
- Simon Bolanos, Study of magnetic reconnection dynamics, with Julien Fuchs (LULI) and Roch Smets (LPP)

## Post-doctoral contracts

2013
- Trevor Lafleur, Electrostatic probes in beam plasmas for space propulsion, with Ane Aanesland (LPP) and Paul-Quentin Elias (ONERA)
- Ilya Marinov, Plasma-Cell Interactions: Efficiency of Nanosecond Plasma in Melanoma Cells Treatment and kinetics of Reactive Oxygen Species, with Svetlana Starikovskaia (LPP), Antoine Rousseau (LPP) and Corine Dupuy (Institut Gustave Roussy)
- Shiyong Huang, Turbulence cascade, intermittency and heating in the Solar Wind, with Fouad Sahraoui (LPP) and Jean-François Panis (LERMA)

2014
- Adrian Stan, Towards a multi-group radiation magnetohydrodynamics code for high energy density plasmas, with Andrea Ciardi
- Katy Ganthous, Hierarchical three model approach to plasma turbulence in magnetized fusion and space plasmas, with Özgür Gürcan (LPP) and Roland Grappin (LPP)

2015
- Andrew Gibson, Hybrid simulations of inductively coupled plasmas in diatomic gases with vibrational state kinetics, with Jean-Paul Booth (LPP) and Timo Gans (York Plasma Institute, UK)
- Andrea Sgattoni, Density fluctuations and their role in the instability development: from laser to heliophysics, with Carine Briand (LESIA) and Caterina Riconda (LULI)
- Sébastien Rassou, Numerical simulations of nanosecond discharges in air, with Julien Labaune (ONERA)
- Zixian Jia, Plasma pure, with Antoine Rousseau (LPP)

2016
- Shiqiang Zhang, CAP4CARE, with Thierry Dufour (LPP)
- Alexandra Alexandrova, The physics of magnetic reconnection, with Alessandro Retino (LPP)
- Andrea Verdini, Turbulent structures in the solar wind, with Roland Grappin (LPP) and Olga Alexandrova (LESIA)

2017
- Samuel Marini, Plasmonics in ultra relativistic regime, with Caterina Riconda (LULI) and Michèle Raynaud (LSI)
- Christof Barzsinski, Formation, structure and feedback of 3D plasmoids in solar eruption, with Sophie Masson (and Guillaume Aulanier (LESIA)
- Javier Vaquero, Cold Atmospheric Plasmas Applied to the Treatment Of Cholangiocarcinoma (CAPATOCHOL), with Thierry Dufour (LPP) and Laura Fouassier (INSERM)
- Tat Loon Chng, Physics and chemistry of high pressure pulsed discharges for triggering of chemically active systems, with Svetlana Starikovskaia (LPP) and Deborah O'Connell (York Plasma Institute, UK)
- Nahuel Andres, Role of the compressible fluctuations at MHD and sub-ion scale turbulence in the terrestrial magnetosheath, with Fouad Sarahoui (LPP)

2018
- Daniel Schury, Towards the study of ion-ion collisions when the energy transfer is at its maximum, with Emily Lamour (INSP)
- Fabiola Magalhaes, Saturn's magnetosphere with auroral observations of Cassini and Hubble, with Laurent Lamy, Renée Prangé (LESIA) and Wayne Pryor (University of Arizona, USA)
- NN, Controlled discharges for the miniaturization of plasma-catalytic reactors, with Paul-Quentin Élias (ONERA) and Maria Elena Galvez (IJLRA)

## Equipments and innovative projects

2012-2013

*Equipments / Projects*
- Ane Aanesland (LPP), Realization of NEPTUNE acceleration System
- Olivier Guaitella (LPP), Bio-PURITY
- Laurent Ibgui (LERMA), Spectra and data analysis of simulations of accretion shocks and jets from Young Stars
- Julien Jarrige (ONERA), Vector Network Analyzer for RF measurements applied to electric propulsion
- Nicolas Sisourat, Gabriel Labaigt and Alain Dubois (LCPMR), Study of X ray emission from collision induced highly excited states of ions
- Roch Smets (LPP) and Andrea Ciardi (LERMA), Streaming instability in low energy cosmic rays
- Svetlana Starikovskaia (LPP), Study of gas discharges at high gas pressures and high gas temperatures. Development of High Pressure High Temperature Chamber for study of Gas Discharges
- Christophe Verdeil (LPP), Ion beam source dedicated to ion composition spectrometers for space instrumentation

2013-2014

*Equipments*
- Ane Aanesland (LPP), Innovative iodine experiment for the development of the PEGASES thruster
- Jean Larour (LPP) and Chantal Stehlé (LERMA), Visualisation and spectroscopy of radiative shocks

*Projects*
- Anne Bourdon (LPP), Efficient numerical methods for Poisson's equation and the derivation of the electric field: a challenge for low-temperature plasma group
- Chantal Stehlé (LERMA), Laser produced radiative shock waves
- Richard Taïeb (LCPMR) and Amelle Zair (Imperial College, UK), Harmonic generation and Wigner function: diagnosis for ionization dynamics

2014-2015

*Equipments*
- Jean-Paul Booth (LPP) and Louis Cabaret (LAC), Gas Temperature Measurements by High-Resolution TALIF
- Olivier Guaitella (LPP), O.I.L.S.E.E.D., $CO_2$ recyclIng by pLaSma couplEd with fluidizEd beD reactor
- Philippe Savoini (LPP), Self consistent 2D Full Particle Simulations of the collisionless shock
- Lydia Tchang-Brillet (LERMA), High-resolution VUV emission spectra of multiply charged ions

*Projects*
- Paul-Quentin Élias (ONERA), A massively parallel Monte-Carlo Collision module for PLAS@PAR's codes
- Anna Levy (INSP), Jérome Gaudin, Patrick Martin, Nikita Fedorov and Irene Papgiannouli (CELIA), Laser-induced ultrafast melting of gold investigated by X-rays

2015-2016

*Equipments*
- Thierry Dufour (LPP), Lori Bridal (LIB), François Lemoine (Hôpital Pitié Salpêtrière) PF2ABIOMÈDE (Plateforme Francilienne des Plasmas Froids Appliqués à la Biologie et la Médecine)
- Ane Aanesland (LPP) and Denis Packan (ONERA), Upgrade of space simulation chamber and diagnostic park for iodine propelled electric propulsion systems
- Olivier Guaitella (LPP), Étincelles
- Katerine Krafft (LPP) and Alexander Volotikin (Space Research Institute of Russian Academy of Sciences, Russia), Nonlinear processes in solar wind
- Christophe Prigent (INSP), Ion charge state distribution analysis
- Lydia Tchang-Brillet (LERMA), High-resolution VUV emission spectra

*Projects*
- Nicolas Aunai (LPP), SciQLOP
- Andrea Ciardi (LERMA), PLAS@PAR hybrid code
- Alain Dubois (LCPMR), Electronic processes in laser
- Chantal Stehlé (LERMA) and Jean Larour (LPP), Radiative shock waves at PALS – follow-up campaign
- Julien Fuchs (LULI), and Oswald Willi (Dusseldorf University, Germany), SBS_laser_plasma_amplifier
- Svetlana Starikovskaia (LPP), Nanosecond pulsed spatially uniform discharge

2016-2017

*Equipments*

- Matthieu Berthomier (LPP), 3D vacuum manipulator for the tests of an innovative plasma spectrometer
- Francis Penent (LCPMR) and Jean-Marc Bizau (ISMO), Study of SiHn+ ions photoionization by electron spectroscopy
- Anna Levy and ASUR Team (INSP), Jérôme Gaudin, Nikita Fedorov and Patrick Martin (CELIA), Laser-induced ultrafast melting of solids and nanoparticles investigated by X-rays
- Julien Fuchs (LULI), Magnetizing high energy density, high-velocity plasmas on the Apollon facility
- Julien Jarrige (ONERA), Periodic evolution of ion velocity
- Roch Smets (LPP), New storage and post-processing machines for the Labex
- Olivier Guaitella (LPP) and Patrick Da Costa (IJLRA) Sycamore (Surface reactivitY of moleCular plAsMas for $CO_2$ REcycling)
- Franck Delahaye (LERMA), Patrick Renaudin (DAM-DIF), Michel Koenig and Bruno Albertazzi (LULI), MUMEO (MUltiple MEasurements of Opacities)

*Projects*

- Thierry Dufour (LPP) and Christophe Bailly (LBD), CAPGREEN (Cold Atmospheric Plasmas for seeds GeRmination and Early growth ENhancement)
- Laurent Ibgui (LERMA) and Salvatore Orlando (Obs. Palermo), New insights into the Physics of accretion processes onto classcial T Tauri stars: 3D MHD models, and inclusion of radiative transfer
- Anna Levy and ASUR Team (INSP), Jérôme Gaudin, Nikita Fedorov and Patrick Martin (CELIA), Laser-induced ultrafast melting of solids and nanoparticles investigated by X-rays
- Nicolas Aunai, Dominique Fontaine, Alexis Jandet (LPP) and Erwan Le Pennec (CMAP), SciQLOP
- Caterina Riconda (LULI) and Antonino Di Piazza (Max Planck Institute for Nuclear Physics, Germany), First-order QED processes in the ultra-relativistic regime with intense Laguerre-Gaussian light beams
- Lydia Tchang (LERMA) and Véronique Bommier (LESIA), Measurement of the 3p43d4D5/2 – 3p43d4D7/2 fine structure energy in Fe X

2017-2018

*Equipments*

- Matthieu Berthomier (LPP), Magnetic field compensation system for the plasma spectrometer test facility
- Svetlana Starikovskaia (LPP), Picosecond laser diagnostics of the electric field resolved in time and space in moderate and high pressure plasmas
- Jérôme Palaudoux (LCPMR), HRAPECS

*Projects*

- Thierry Dufour (LPP) and Laura Fouassier (Hôpital Saint Antoine), IDOMIGUTRE (Innovation of an enDOscopic MIcro-plasma GUn for solid Tumors Regression)
- Anna Levy and ASUR team (INSP), Jérôme Gaudin, et col. (CELIA), Robert Grisenti (Institut für Kernphysik, Frankfurt University, Germany), Laurent Videau et col. (CEA- DIF), Ryszard Sobierajski (Institute of Physics PAS, Varsovie), Laser-induced ultrafast melting of solids and nanoparticles investigated by X-rays
- Pascal Chabert (LPP), Optical Emission Spectroscopy (OES) coupled to Particle-In-Cell (PIC) simulations as a new method to measure the electron temperature inside the channel of Hall Thrusters
- Paul-Quentin Elias (ONERA) and Maria Elena Galvez (IJLRA), Development of a Micro-structured plasma-catalytic reactor

2018-2019

*Projects*

- Christophe Blondel, Cyril Drag and Philippe Auvray (LPP), Enhanced photodetachment
- Andrea Ciardi (LERMA), Roch Smets (LPP) and Julien Fuchs (LULI), Non-resonant cosmic ray instability
- Thierry Dufour (LPP) and Maria Kitsara (IBPS), PEBOSACT - Plasma-Engineering of Biocompatible porous pOlymer Scaffolds – Application to Cardiac Tissues scars and complications
- Özgür Gurcan (LPP) and Alessandro Biancalani (IPP), Nonlinear dynamics of zonal flows in tokamak plasmas investigated with gyrokinetic and reduced models
- Nicolas Sisourat, Alain Dubois, Tsveta Miteva (LCPMR), Anne Bourdon, Pascal Chabert, Jean-Paul Booth, Cyril Drag (LPP), Modeling iodine plasma for electric propulsion
- Chantal Stehle (LERMA) and Véronique Cayatte (LUTH), The magnetosphere of Young Stars: an experimental point of view

## Invitations of international experts

2013

- Inner-shell ionisation of positive ions
  Visitor: Kenji Ito (Photon Factory, Japan) / Grant holder: Pascal Lablanquie (LCPMR)
- Spectroscopy properties of moderately charged ions of tungsten
  Visitor: Alexander N. Ryabtsev (ISAN / Troisk) / Grant Holder: Lydia Tchang-Brillet (LERMA)
- Radiation friction studies and energetic particle acceleration
  Visitor: Andrea Macchi (Pisa University, Italy) / Grant Holder: Caterina Riconda (LULI)
- "Stark" spectral line broadening in warm plasmas: Stark-b database in the VAMDC node
  Visitor: Milan S. Dimitrijevic (Astronomical Observatory, Belgrade) / Grant Holder: Sylvie Sahal-Bréchot (LERMA)
- Electromagnetically-driven strong shocks: optical diagnostics and application to laboratory astrophysics
  Visitor: Francisco Suzuki-Vidal (Imperial College, London) / Grant Holder: Jean Larour (LPP)

2014

- ICE-CREAM
  Visitor: Mark J. Kushner (University of Michigan, USA) / Grant Holder: Jean-Paul Booth (LPP)
- Magnetic reconnection and dissipation in the turbulent solar wind
  Visitor: David Sundkvist (University of California, Berkeley, USA) / Grant Holder: Alessandro Retino (LPP)
- Interaction of Langmuir waves with electron beams in strongly inhomogeneous solar wind plasmas
  Visitor: Alexander Volokitin (Space Research Institute of Russian Academy of Sciences, Moscow, Russia) / Grant Holder: Caterine Krafft (LPP)
- A 3D Spectroscopic analysis of the signatures of Accretion in Young Stellar Objects
  Visitor: Ivan Hubeny (University of Arizona, USA) / Grant holder: Chantal Stehlé (LERMA)
- Interplay of radiative and nonradiative decay in multistep relaxation processes
  Visitor: Maria Novella Piancastelli (Uppsala University, Sweden) / Grant Holder: Marc Simon (LCPMR)
- Towards atomic physics of Fast Ion – Slow Ion Collisions
  Visitor: Alexandre Gumberidze (EMMI-GSI Darmstadt, Germany) / Grant Holder: Emily Lamour (INSP)
- Differential rotation in experiments with magnetized plasma flows
  Visitor: Sergey Lebedev (Imperial College, London, UK) / Grant Holder: Andrea Ciardi (LERMA)

2015

- Beam kinetics in neutraliser-free plasma thrusters using advanced spectroscopic techniques
  Visitor: James Dedrick (University York, UK) / Grant Holder: Ane Aanesland (LPP)
- Energy storage by plasma recycling of $CO_2$
  Visitor: Richard Engeln (Technical University Eindhoven, Netherlands) / Grant Holder: Olivier Guaitella (LPP)
- Studies of anisotropic plasma turbulence and nonlocal transport: Theoretical approaches in k-space and configuration space
  Visitor: Taik Soo Hahm (Seoul National University) / Grant Holder: Özgür Gurcan (LPP)
- Are solar wind electrons heated by turbulence?
  Visitor: Simone Landi (Universita degli Study di Firenze, Italy) / Grant Holder: Filippo Pantellini, LESIA
- Langmuir turbulence generated by electron beams in solar wind plasmas with random density fluctuations: particle diffusion and acceleration processes
  Visitor: Aleksander Volokitin (Space Research Institute of Russian Academy of Sciences, Moscow, Russia) / Grant Holder: Caterine Krafft (LPP)
- Energy levels in Iron group ions: Mn IV and Ni VII
  Visitor: Alexander Ryabtsev (USSR Academy of Sciences, Russia) / Grant Holder: Lydia Tchang Brillet (LERMA)
- Jupiter decameter radio emissions studies at ultrahigh temporal and spectral resolutions, preparation of a book and of supporting ground-based observations for the mission Juno
  Visitor: Vladimir Riabov (Future University Hakodate, Japan) / Grant Holder: Philippe Zarka (LESIA)
- Opacities for shock experiments
  Visitor: Rafael Rodriguez-Perez (University of Las Palmas de Gran Canaria) / Grant Holder: Chantal Stehlé (LERMA)
- Using FLASH to model magnetized laser experiments
  Visitor: Petros Tzeferacos (University of Chicago, USA) / Grant Holder: Tommaso Vinci (LULI)

2016

- RIRE - Radio-frequency Ion and electron acceleRation using self-bias Effects
  Visitor: Stanislav Dudin (Karazin Kharkiv National University, Ukraine) / Grant Holder: Ane Aanesland (LPP)
- Kinetic turbulence and magnetic reconnection in space plasmas
  Visitor: Daniel Osvaldo Gómez (University of Buenos Aires, Argentina) / Grant Holder: Fouad Sahraoui (LPP)
- Cold plasmas: PIC simulation for electric propulsion
  Visitor: Francesco Taccogna (Istituto di Nanotecnologia, Italy) / Grant Holder: Anne Bourdon (LPP)
- Observational predictions of shocks
  Visitor: Alejandro C. Raga (Universidad Nacional Autonoma de Mexico) / Grant Holder: Sylvie Cabrit (LERMA)
- Atomic collisions in extreme conditions
  Visitor: Abdelkader Makhoute (Université Moulay Ismail, Morocco) / Grant Holder: Alain Dubois (LCPMR)
- VIOLINIST: Vibrationnal Kinetics in Molecular Plasma for an efficient green chemistry
  Visitor: Vasco Guerra (Universidade de Lisboa, Portugal) / Grant Holder: Olivier Guaitella (LPP)

2017

- Ultrafast laser-induced structural transformations
  Visitor: Robert E. Grisenti (Goethe University, Darmstadt, Germany) / Grant Holder: Dominique Vernhet (INSP)
- Inner shell holes
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## Image caption

- Cover: An atmospheric plasma jet pointed towards a dielectric surface. An intriguing formation of a secondary plasma is visible on the other side of the dielectric. Credit: Olivier Guaitella, LPP.
- P.4: Plasma plume from the new ECR acceleration thruster developed at ONERA. Credit: Julien Labaune, ONERA
- P.12-13: Momentum distribution of three ions, Hydrogen, Carbon and Iodine, after photodissociation of Methyle Iodide using Tender X-ray photons. Credit: Moustafa Zmerli, LCPMR
- P.14: Two sunspots surrounded by their active region observed by the American-Japanese satellite HINODE. Credit: Véronique Bommier, LESIA
- P.24-25: Turbulent dissipation in a pseudo-spectral simulation of non-ideal magneto-hydrodynamical turbulence. Credit: Pierre Lesaffre, LERMA
- P.46-47: Boreal aurora images in Norway. Credit: Thierry Legault
- P.56-57: Sun observed by Nasa Solar Dynamics Observatory. Credit: NASA/GSFC/Solar Dynamics Observatory
- P.76-77: This is the bielectronic wave-function of a doubly ionized state of a one-dimensional system modeling Helium. This wave-function was calculated by inverse iteration performed on the Hamiltonian in a simulation box for an energy of 2.2 eV. Credit: Marie Labeye, LCPMR
- P.84: Experimental setup showing the propagation of plasma bullets and their interaction with surfaces. Credit: Olivier Guaitella, LPP
- P.96-97: The plot illustrates a non-linear equation of the so called geodesic acoustic mode, a rapidly oscillating zonal flow in tokamak plasmas. Credit: Alexandre Storelli
- P. 100: Perturbed magnetic field intensity resulting from the non-resonant streaming instability growth. This 1D simulation shows asymmetric space-time structures which are a signature of the instability mechanism. Credit: Alexis Marret, LERMA
- P.126-127: Atmospheric pressure plasma bullets impacting a dielectric surface. Credit: Julien Jarrige, ONERA



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