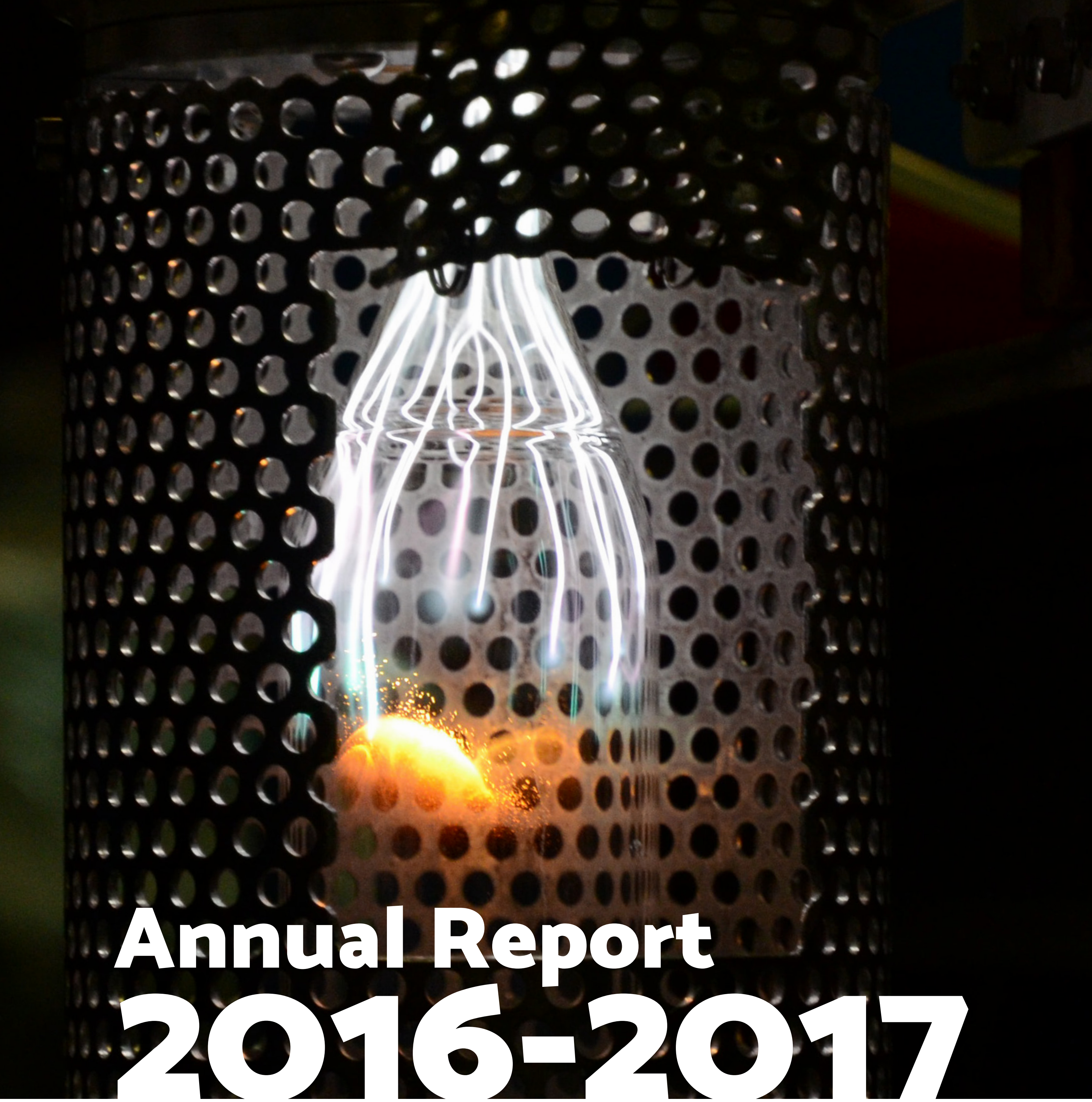

Annual Report 2016-2017

Instituto de Plasmas e Fusão Nuclear

IPFN
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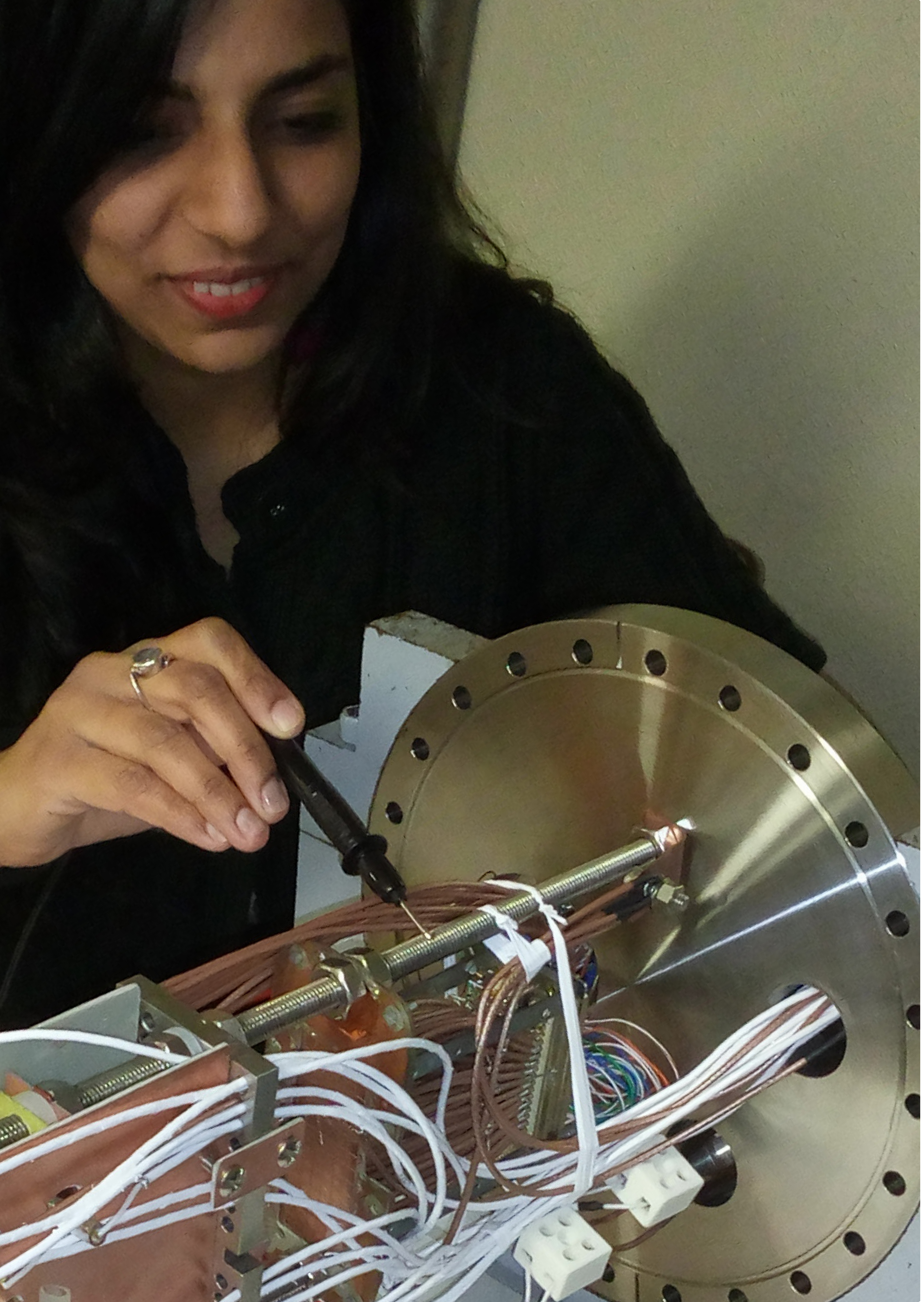
E FUSÃO NUCLEAR



Annual Report 2016-2017

Instituto de Plasmas e Fusão Nuclear

Highlights of activities

ipfn.tecnico.ulisboa.pt

Contents

President's Foreword

It is my great pleasure to present the highlights of our activities in 2016-2017. This report covers the activities carried out in the framework of the Consortium EUROfusion, the Contract of Associated Laboratory, the Contracts with the ITER International Organization (ITER IO) and the European Joint Undertaking for ITER and Fusion Energy (F4E), projects of the H2020 Programme of the European Union, projects of the European Space Agency (ESA) and projects funded by Fundação para a Ciência e a Tecnologia.

This was an outstanding period where IPFN and its researchers accomplished a number of remarkable milestones and achievements:

• IPFN hosted two ERC Advanced Grants: *Accelerates* (concluded in 2016) and *InPairs* (awarded in 2015 and started in 2016), both awarded to Luis O. Silva for a total funding in excess of 3.4 M€. This makes IPFN the only Portuguese institution to host a PI with two ERC Advanced Grants, which leverage on our expertise on massively parallel kinetic plasma simulations and address the interaction of intense fields with plasmas. Both grants have resulted in exciting scientific results, prizes and awards, invited talks and colloquia, and publications in the top multidisciplinary and physics journals.

• The nuclear fusion activities at IPFN were strongly focused on the work programme established on the Fusion Roadmap for H2020 and ITER construction: (i) Participation in several contracts with Fusion for Energy for the development of ITER diagnostics, control and data acquisition and remote handling both as leader (Plasma Position Reflectometer) and as partner with other institutions (Collective Thomson Scattering, Radial Neutron Camera, integrators for magnetic diagnostics, development of the cask transfer system); and (ii) strong and growing participation in the European Fusion Programme. IPFN researchers succeeded in securing a strong involvement in several EUROfusion tasks. Among other activities, it is worth noting the contribution to JET scientific exploitation, on JET operation – with several IST researchers working full time at JET providing support to operation and diagnostics – and management, and the contribution to medium-size tokamaks, in particular, Asdex-Upgrade, which have been an integral part of the activities.

• IPFN is the leading institution of *VOXEL* and *PEGASUS*, two projects funded by the highly competitive Horizon2020 programme FET (Future Emerging Technologies) Open. The *VOXEL* (Volumetric medical X-ray imaging at extremely low dose)[1] consortium brings together a multidisciplinary research team of experts in the fields of sensors, X-rays, metrology, tomography and three-dimensional image reconstruction, with 3.99M€ funding to develop an innovative X-ray camera. The project's facility is located at IST, in a newly created laboratory space. *PEGASUS* (Plasma Enabled and Graphene Allowed Synthesis of Unique nanoStructures),[2] with 3.99 M€ funding, has the ambitious goal of using the unique properties of plasmas for the creation of extraordinary novel materials, by controlling the energy and matter transfer processes at nanoscales through specific plasma mechanisms. *PEGASUS* will design a proof-of-concept device for the large-scale production of N-graphene, leveraging on the submitted patent for the device and the production method. The targeted outstanding electrochemical performance of the final nano-architectures will allow their use as base electrode elements in a proof-of-concept supercapacitor device.

"This was an outstanding period where IPFN and its researchers accomplished a number of remarkable milestones and achievements"

• Progress on the installation of the new laboratory infrastructure, the European Shock Tube for High Enthalpy Research (*ESTHER*). This world-class research infrastructure, funded by ESA, will enable the participation in high-level research on plasma re-entry effects as well as further synergies between IPFN research groups, namely on control and data acquisition, diagnostics development, and material characterization. *ESTHER* delivers the dream of ESA's 2017 European Space Technology Master Plan: "A new Space Renaissance has started, where a positive feedback mechanism of exploration and budget allocation could fuel development of the space economy."

1 www.ipfn.tecnico.ulisboa.pt/voxel
2 www.ipfn.tecnico.ulisboa. pt/PEGASUS

• IPFN's Laboratory for Intense Lasers (L2I) was recognized through its selection in 2014 for FCT's National Roadmap of Research Infrastructure, through a highly competitive call towards selecting facilities of strategic interest that sustain scientific and technological advancements and strengthen the scientific R&D&I community in Portugal. In the scope of this network, L2I has merged with Coimbra LaserLab, a laser facility at Coimbra University, to form the distributed infrastructure Laserlab Portugal: L2I is dedicated to very high power pulsed lasers for the study of the properties of matter at very high light intensities while CLL specializes in the use of lasers for spectroscopy, photochemistry and photomedicine. This synergistic capability covers a vast amount of laser parameters with applications in physics, chemistry, materials, biology, medicine and other fields, establishing the infrastructure as a leading hub for laser-based science and training of young researchers. Under this project, the joint facility has been awarded 2.9 M€ from FCT/ERDF for equipment renewal and human resources.

These projects nurtured innovation, promoted scientific employment, enhanced the team international projection and ability to attract additional funding and innovation through R&D activities. The impact of the research performed at IPFN has been recognized through several awards won by our researchers and through a large number of publications in prestigious journals.

High-Level Education and Outreach activities are essential in this strategy. IPFN continues actively striving towards attracting the best MSc and PhD students. The Advanced Programme on Plasma Science and Engineering (***APPLAuSE***) has been crucial to achieving this goal. Furthermore, we know that new blood is fundamental to the research unit's success and we continue motivating new generations for science through a number of initiatives such as courses on lasers and nuclear fusion for secondary school teachers, seminars at high schools and regular visits to IPFN laboratories.

Participation on large-scale projects is made through long-term commitment and funding support. On behalf of IPFN, I would like to acknowledge the support of EURATOM, F4E, FCT (through project UID/FIS/50010/2013), and IST, for having made such commitments possible.

Science is also made through collaborations. I would like to thank all our partners who have contributed to our projects, or those who lead projects to which IPFN contributes to with results.

The strength of IPFN lies in the dedication and commitment of their researchers, technicians, students and administrative staff. I am confident that together we will continue making IPFN an outstanding research unit!

Bruno Soares Gonçalves
President of IPFN

About IPFN

Instituto de Plasmas e Fusão Nuclear (IPFN, Institute for Plasmas and Nuclear Fusion) is a research unit of Instituto Superior Técnico (IST) with the status of Associated Laboratory granted by Fundação para a Ciência e a Tecnologia (FCT). IPFN holds a vast expertise in Plasma Physics, Engineering and Technologies, Controlled Nuclear Fusion, Lasers and Photonics and Advanced Computing.

IPFN ensures the Portuguese participation in EUROFusion, the European Consortium for the Development of Fusion Energy. The role of the research unit, at the national and international level, was recognised in the last FCT evaluation of R&D units, where IPFN was awarded the classification "**Exceptional**" (awarded only to 11 research units out of 300+ evaluated).

Research at IPFN is organised into two Thematic Areas:

Controlled Nuclear Fusion - This research line is focused on the work programme established by the Euratom Fusion roadmap H2020, which includes activities associated with the development of systems, operation, and scientific exploitation of large and medium-sized tokamaks and stellarator, as well as with the design and construction of the next generation fusion devices.

Plasma Technologies and Intense Lasers - This research line takes advantage of the critical mass of the groups within it to address frontier questions in gas electronics, sources of particles and radiating species, ultra-short, ultra-intense lasers and their applications, plasma accelerators and advanced radiation sources, ultra-cold plasmas, and fundamental science in space.

Organisation

IPFN is organised into two main thematic lines, with a total of seven research groups:

- **Controlled Nuclear Fusion**, organised into four research groups;
- **Plasma Technologies and Intense Lasers**, organised into three research groups.

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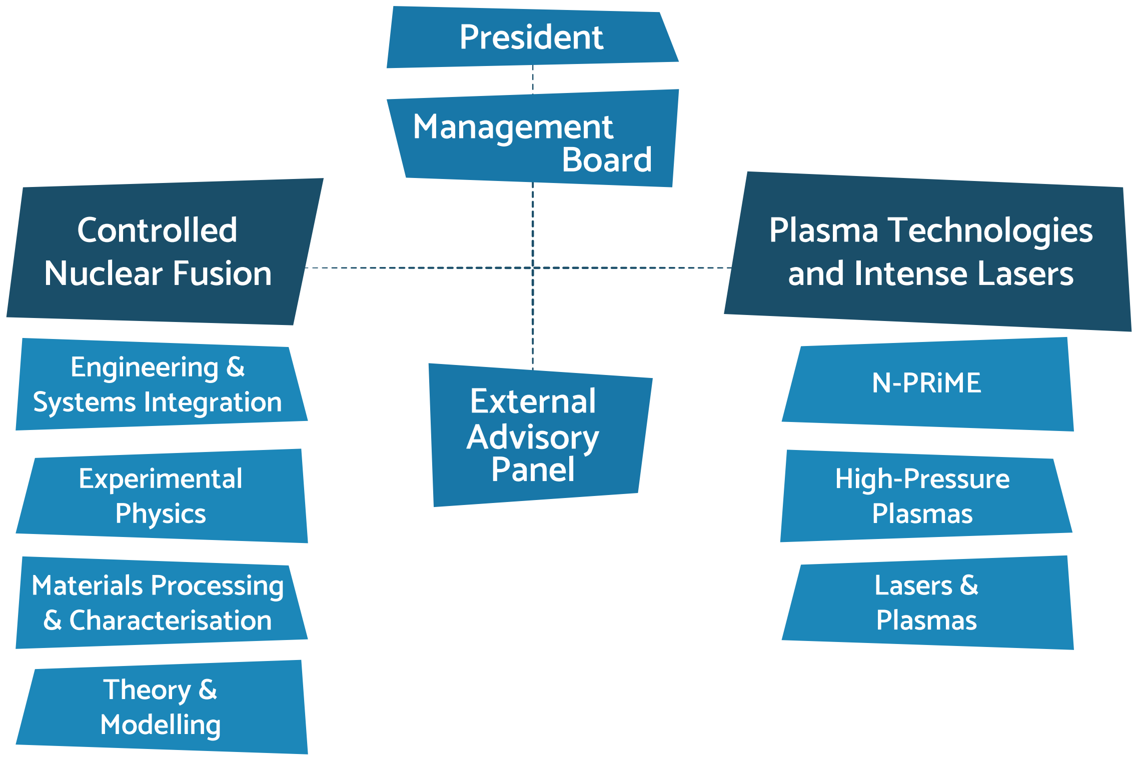


The **Management Board** is composed by the heads of each research group and by representatives of the PhD members, and carries out the global management of the research unit.

The **External Advisory Panel** monitors the activities and strategy of IPFN. This body oversees the scientific progress, graduate programmes, recruitment and overall performance, advising the Management Board on all matters related to the mission of the unit.

Management Board

Bruno Gonçalves

Group of Engineering and Systems Integration

Carlos Silva

PhD representative

Eduardo Alves

Group of Materials Processing and Characterisation

Gonçalo Figueira

PhD representative

Horácio Fernandes

Group of Experimental Physics

Luís Lemos Alves

Group of N-PRiME

Luís Oliveira e Silva

Group of Lasers and Plasmas

Marta Fajardo

PhD representative

Pedro Almeida

Group of High-Pressure Plasmas

Paulo Varela

PhD representative

Rui Coelho

Group of Theory and Modelling

Vasco Guerra

PhD representative

External Advisory Panel

Michel Chatelier

Orsay University

Kunioki Mima

Osaka University

Francesco Romanelli

University of Rome

Jörg Winter

Ruhr-Universität Bochum

Facts and Numbers

202
Collaborators
at the end of 2017

64
PhD students

108
PhDs
faculty, researchers and postdocs

+150
Publications per year
including Conference Proceedings

Highlights include papers published in

Astrophysical Journal

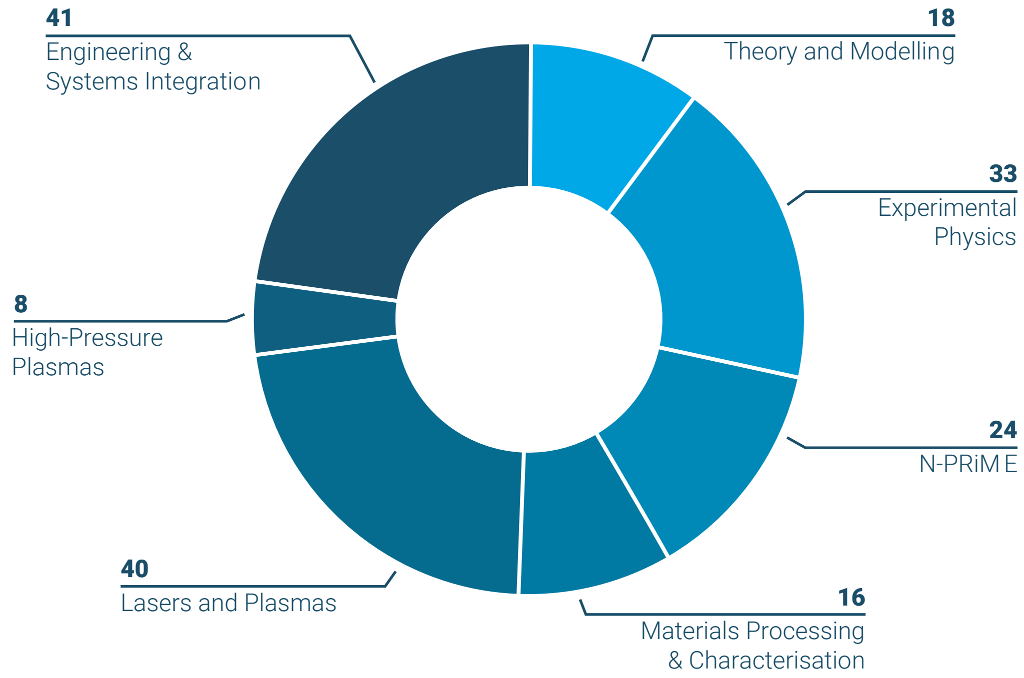
Nature Communications

Nature Physics

Physical Review Letters

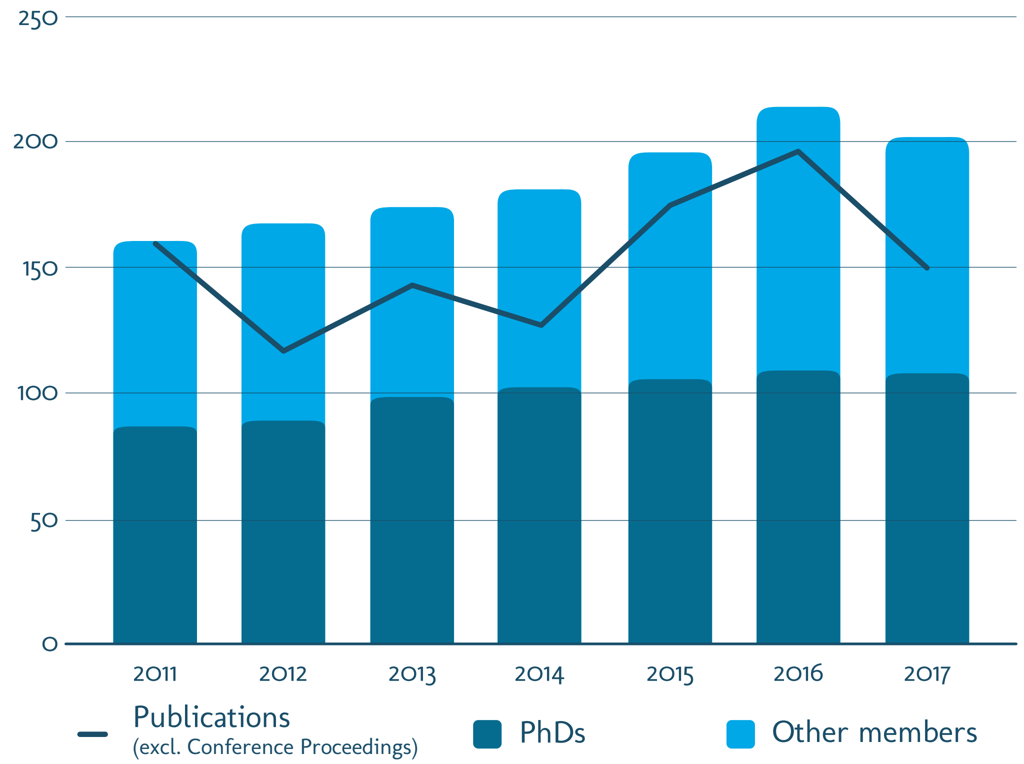
Members per Group

at the end of 2017



Collaborators and Publications

since 2011



Controlled Nuclear Fusion

Fusion is the process powering the stars, such as our sun. At their core, atomic nuclei collide and fuse together into heavier elements, releasing tremendous amounts of energy. On Earth, fusion scientists try to replicate this process in a controlled manner, by studying the physics and developing the technology of fusion reactors.

The most efficient fusion reaction reproducible in the laboratory takes place between two hydrogen (H) isotopes, deuterium (D) and tritium (T), which are heated to hundreds of millions of degrees, creating a plasma. One way to achieve a controlled fusion reaction is inside a device called a tokamak – a doughnut-shaped cage – where magnetic fields are used to contain and control the hot plasma.

Fusion ingredients are abundant on Earth, and no greenhouse gases or long-lived nuclear waste are created by fusion. Once harnessed, fusion power will be a nearly unlimited, safe and climate-friendly energy source.

Fusion research is a global effort, which is currently focused on the Fusion Roadmap, aimed at achieving power generation within 30 years. Currently, the major project is the construction of ITER in southern France. The largest tokamak ever built, ITER aims to confirm that fusion power is feasible on a commercial scale.

ISTTOK, the only fusion device in Portugal, is a tokamak with a circular cross-section, a poloidal graphite limiter and an iron core transformer. It is the only European tokamak allowing regular use of alternate discharges with a time span above 1 second. Currently, ISTTOK serves as a research infrastructure, supporting several PhD and MSc thesis projects, while also fostering the development of diagnostics, data acquisition systems and physics studies. Due to the long discharges for such a small machine, it is foreseen that its contribution to studies of compatible materials for fusion devices will increase in the near future.

Engineering and Systems Integration

Main Researchers:

Alberto Vale
Ana Fernandes
António Batista
António Rodrigues
António Silva
Bernardo Carvalho
Bruno Gonçalves
Catarina Vidal
Diana Baião
Filipe Silva
Jorge Belo
Jorge Santos
Jorge Sousa
Nuno Cruz
Paulo Varela
Pedro Carvalho
Raul Luís
Rita Pereira

How to design reliable diagnostics for operation in nuclear fusion devices? How to design components able to cope with nuclear heating, plasma heat load, material fatigue and degradation? How to ensure high availability control and data acquisition systems? How to process the diagnostic data to ensure reliable and usable measurements? How to ensure the remote maintenance of components used on fusion devices? These are among the challenges that we address in our projects.

Our main goal is to contribute to a successful operation of fusion devices by contributing to the design of several systems. We follow a cross disciplinary approach, covering modelling for simulation and optimization of diagnostic performance, engineering design of components, neutronic and thermal mechanical simulations, design of dedicated solutions on microwave high frequency components and electronics, bespoke and state-of-art Control and Data Acquisition systems for nuclear fusion and large-scale physics experiments and studies of remote handling in nuclear fusion environments and assessment of maintenance facilities.

We are strongly focused on the development of systems for nuclear fusion experiments and in particular for ITER, JET and DEMO, having already several projects in portfolio.

The H2020 fusion programme made the transition from pure research to the design, construction and operation of future facilities. The integration of all engineering activities allows a focused, timely, effective and qualified manner to opportunities for R&D and Innovation activities developed by the EU fusion program.

Group Leader: **Bruno Soares Gonçalves**

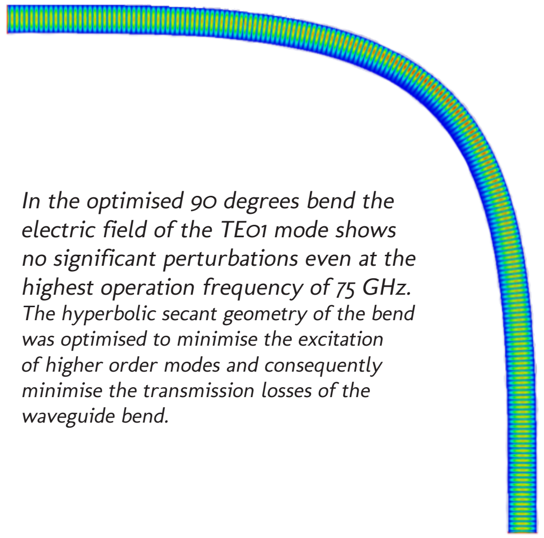
Contributions to ITER construction

DEVELOPMENT OF ITER PLASMA POSITION REFLECTOMETER DIAGNOSTIC

What is the level of performance we can expect from the in-vessel transmission lines and antennas of the ITER Plasma Position Reflectometry (PPR) diagnostic? How is the performance affected by the design restrictions? What design options are available for optimising the design of the antennas? Will the final performance be enough for the PPR system to fulfil its operational role in ITER? Addressing these critical questions as early as possible in the design phase is essential for the successful implementation of the PPR diagnostic.

We are interested in assessing the performance of the baseline design and in exploring the potential for optimisation within the allotted design and space restrictions. Our main goal is to estimate the performance of these components, how it affects the measurements and what is the impact on the capability of the PPR system to comply with its requirements.

Transmission line performance – The space available inside the ITER vacuum vessel to install diagnostic components is generally strongly restricted. Our main goal is to identify the critical components of the PPR transmission lines and to assess their expected performance before the prototyping phase. This work will allow us to pin down their technical specifications early in the design phase, minimising the number of iterations in the prototyping phase.

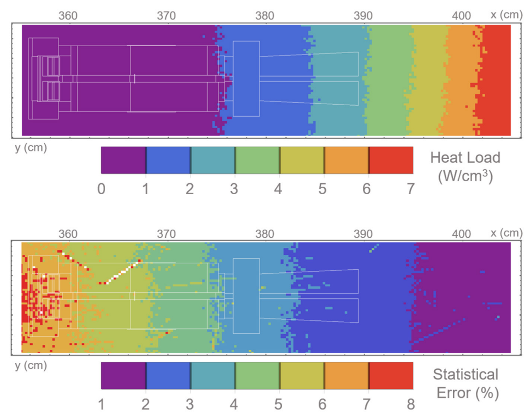


In the optimised 90 degrees bend the electric field of the TE01 mode shows no significant perturbations even at the highest operation frequency of 75 GHz. The hyperbolic secant geometry of the bend was optimised to minimise the excitation of higher order modes and consequently minimise the transmission losses of the waveguide bend.

Antenna performance – As for the transmission line components, the space available in-vessel to install the PPR antennas is restricted. Therefore, the diagnostic will use small pyramidal quasi-sectoral antennas. Our main goal is to estimate and optimise the performance of the antennas under the imposed space and design restrictions. In particular, we are interested in evaluating its impact on the measurements and on the ability of the PPR system to fulfil its requirements.

Nuclear analysis

The ITER PPR in-vessel components will be subjected to ionising radiation, both from the plasma neutrons and from gamma photons generated through nuclear reactions in the surrounding materials. The antennas and the 90º bend are directly exposed to the plasma and subjected to high neutron and photon fluxes, which will generate heat and increase their operating temperatures.



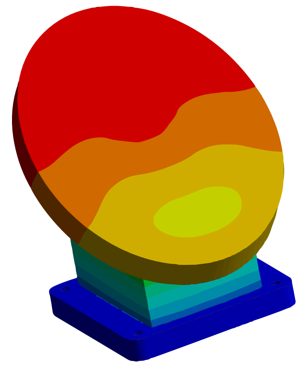
Nuclear heat loads in the ITER Plasma Position Reflectometry System.
The picture shows the nuclear heat loads in the antennas and 90° bend of the PPR system. Peak values of the order of 2.9 W/cm³ were obtained at the tips of the antennas, which translate into operation temperatures around 480C. Further design iterations are required to improve the thermal behaviour of the system.

A preliminary thermal analysis showed that these nuclear heat loads, combined with the thermal radiation coming from the plasma, translate into operation temperatures that reach 480 ºC at the tips of the antennas, slightly above the maximum temperature of operation of stainless steel for ITER in-vessel components under irradiation (450 ºC).

Calibrating an ASDEX-Up reflectometer

THERMAL STRUCTURAL ANALYSIS OF ITER'S COLLECTIVE THOMSON SCATTERING LAUNCHER MIRROR

The Low Field Side Collective Thomson Scattering system (LFS-CTS) provides a measurement of plasma parameters related to the ion velocity distribution function. The diagnostic is based on the CTS principle, where a powerful mm-wave beam (60 GHz, 1.0 MW gyrotron), scatters off electrons in the plasma. The structural integrity of the Launcher Mirror is of special importance since this is a critical component – it is under heavy thermal loading conditions for being directly facing the plasma, which provides a heat flux of 500 kW/m² and a neutron load generating 2 W/cm³ of internal heat. In addition, a fraction of the 1 MW mm-wave beam is absorbed by the material.



Temperature distribution across the CuCrZr CTS Launcher Mirror.

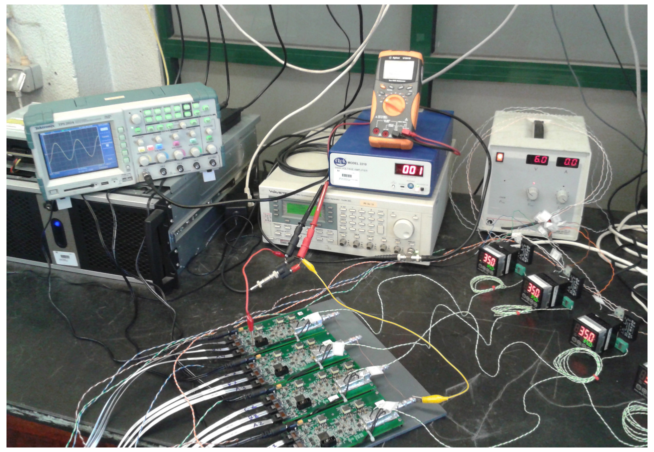
Our goals are to assess and limit the temperature distribution across the component, to evaluate the need of implementing active cooling and to compute and limit the thermal stresses and displacements through the use of finite element models.

ITER INTEGRATORS FOR THE MAGNETICS DIAGNOSTICS

The well-known drift problem of integrated signals has become very critical for fusion machines with long plasma discharges. The electronics offset integrated after a long time can no longer be ignored.

Our main goal is to demonstrate that a digital integrator based on the signal chopping concept is capable of attaining the ITER requirements.

The integrator design with best testing results complies with ITER specifications and was chosen to be the final integrator design for ITER magnetics diagnostic. The future final integrator design for ITER will be more compact and more reliable.



One of the test-benches for the chopper-based integrators.

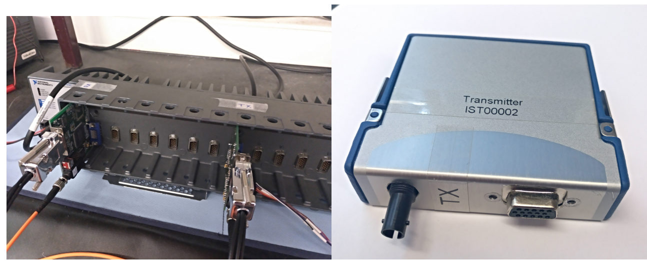
ITER RADIAL NEUTRON CAMERA & RADIAL GAMMA-RAY SPECTROMETER

The Radial Neutron Camera (RNC) & Radial Gamma-Ray Spectrometer (RGRS) for ITER is a collimated multichannel neutron detection system with 26 Lines-of-sight intended to characterise fusion plasma neutron source. The neutron emissivity profile is necessary to study the D-T fusion plasma ignition. RNC diagnostic needs a local Instrumentation and Control (I&C) unit, in charge of controlling the whole diagnostic system plant while performing Real-Time measurements of neutron flux and emissivity reconstruction in less than 10 ms.

A data acquisition prototype was developed to acquire signals provided by the different types of detectors (e.g. diamonds, scintillators and fission chambers) in order to mitigate the identified technical risks that could impact the final architecture of RNC and RGRS.

DIGITAL LINK FOR THE POWER SUPPLIES OF THE ITER GYROTRONS

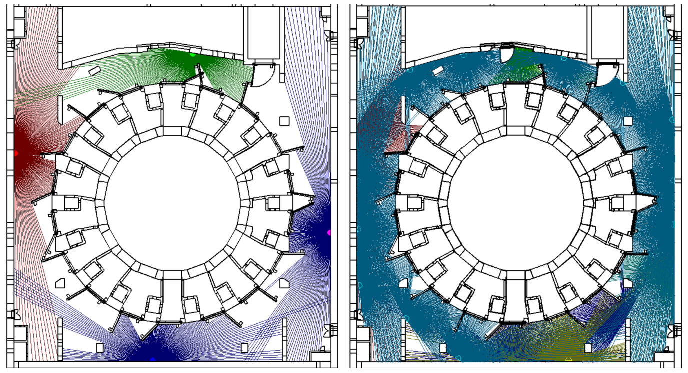
A compact RIO-based system is being developed and implemented in collaboration with F4E and GTD with the objective of monitoring the ITER gyrotron's power supplies, as part of the interlock system for ITER. During 2017, the 2nd version prototypes were produced, final firmware and software were developed and tests of the units and fibre optic link quality were performed with success. The production of 15 digital link units is in progress; these units will be supplied to the laboratories and companies involved in the power-supplies design.



Digital link test setup ad Transmitter module.

DEVELOPMENT OF REMOTE HANDLING SYSTEMS FOR ITER

Remote handling refers to the high-tech systems that will help to maintain and to repair the ITER machine. The space where the bulky and heavy equipment will operate is limited and the exposure of some of the components to radiation, prohibit any manual intervention inside the vacuum vessel.



Navigation technologies based on off-board laser rangefinders in the divertor level of Tokamak building of ITER: the best configuration of 4 (left image) and 18 (right image) laser rangefinders installed on the walls to maximise the coverage and redundancy, i.e., the AGV is always observed.

The remote handling operations of transportation are performed by automated guided vehicles (AGV). The navigation system becomes a key issue given the safety constraints of the heavy load to be transported in the complex scenarios, such as the reactor building.

We have performed an assessment of well-known and mature navigation technologies used by AGV in industry: with a physical path (e.g., wire/inductive guidance, optical line guidance and magnetic tape guidance) and with a virtual path (e.g., laser-based, motion capture, inertial, magnetic-gyro) to be followed by the AGV during the operations of transportation. We have also developed a critical assessment regarding the performance of these technologies against the operational requirements and safety demonstration in the framework of fusion facilities.

IPFN, in collaboration with the Institute for Systems and Robotics, is part of the consortium that recently won a 100 million EUR contract, considered to be one of the largest robotics contracts to date in the field of fusion energy.

Contributions to JET and ASDEX-Upgrade

ENHANCEMENT OF JET MW REFLECTOMETER DIAGNOSTIC

The effects of the different isotopic composition on the plasma turbulence and related effects (such as the modifications in the ELM behaviour) will be one of the main topics of the D-T campaigns. The installation of an additional correlation reflectometer operating at higher frequencies, F band (90-140 GHz), will allow an improved plasma density coverage, an essential ingredient during D-T operation and the measurement of density fluctuations further in the plasma. A set of 6 new Quasi-Optical Boxes (QOB) were successfully manufactured at IST workshop with very tight tolerances. The QOB were all assembled and electromagnetic tested at the IPFN laboratory using a Vector Network Analyser in the frequency range 50 to 110 GHz.

JET correlation reflectometry QOBs undergoing electromagnetic tests at IPFN facilities.

The back-end electronics was procured and should be ready for installation in January 2018, followed by the diagnostic commissioning.

JET-GAMMA RAY CAMERA UPGRADE (GCU)

JET gamma-ray camera is now equipped with the state of the art high resolution/high count rate compact gamma spectrometers. Our main goal is to combine tomography with spectroscopy information allowing the reconstruction of fast ion profiles and the energy distribution of runaway electrons during Deuterium-Tritium experiments. IST was responsible for a complete upgrade in the control and data acquisition (DAQ) system, which had also been previously developed by us.

DAQ developed by IPFN installed in GCU cubicle at JET and connected to the 19 detectors of the gamma-ray camera.

PLASMA POSITION CONTROL USING MICROWAVE REFLECTOMETRY AT ASDEX-UPGRADE

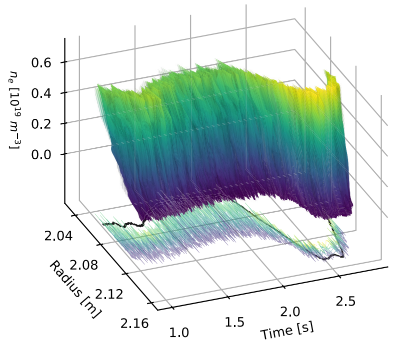
After a previous major upgrade of the diagnostic's data acquisition and processing hardware, all the reflectometry real-time software components were rewritten. A software architecture was implemented to improve the system's performance. In March 2016, the viability of using reflectometry in replacement of standard magnetic measurements for controlling the position of a fusion plasma was demonstrated for the second time on ASDEX Upgrade. In this follow-up to the breakthrough experiment performed in 2011, a second broadband O-mode reflectometer at the high-field side (HFS) of the tokamak was used in addition to the originally used low-field side (LFS) one. The joint operation of both reflectometers in the feedback control experiments allowed testing the technique at two of the four lines of sight of the future ITER plasma position reflectometer (PPR).

All developed systems and software performed flawlessly in several discharges, allowing a seamless control during the target H-Mode scenarios.

Successful Plasma position control experiment at ASDEX-Upgrade control room.

DEVELOPMENT OF ASDEX-UPGRADE ICRF REFLECTOMETER

We have successfully commissioned the new embedded multichannel reflectometry diagnostic on ASDEX Upgrade. This diagnostic measures the edge electron density profiles from three different locations, providing valuable insight on poloidal differences of the local plasma layers in

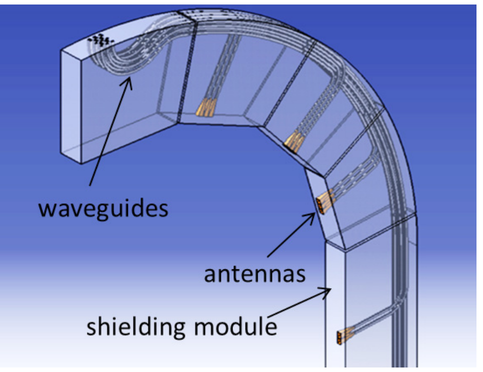


Observing plasma radial displacement. The density profiles accurately track the radial displacement of the plasma, as indicated by the separatrix position. This is the result of high diagnostic sensitivity and improved reconstruction codes.

front of the ICRF antenna. Our data has been used for ICRF power coupling studies and was able to experimentally observe the local convective transport that occurs during ICRF operation, which previously relied on remote magnetically-connected diagnostics. We have also developed sophisticated X-mode first fringe estimation algorithms that greatly improve the precision of the density profile reconstruction.

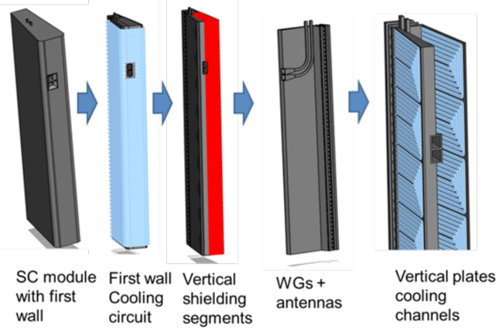
Contributions to DEMO design

ACTIVITIES ON THE INTEGRATION CONCEPT OF THE REFLECTOMETRY DIAGNOSTIC FOR THE MAIN PLASMA IN DEMO



Antennas and waveguides installed in an array of slim cassettes (total of 16 poloidal locations).
The slim cassette average width is 20-25 cm (in toroidal direction). The dummy sectors are fixed in a common frame running at the back of the structure. The radius of curvature for the antennas is kept above 12 cm following a hyperbolic curvature in order to avoid mode conversion.

The DEMO fusion power plant demands a reliable diagnostic capability based on a minimal set of robust individual diagnostic systems. The unprecedented radiation levels and plasma-induced fluxes of particles into diagnostic components require simple and robust designs of diagnostic systems. IPFN is involved in the integration of several plasma diagnostics for DEMO (reflectometry, polarimetry and spectroscopic diagnostics). In particular, the design and integration of the reflectometry diagnostic have been developed to more detail than others, so far.



Exploded view of the SC module composition.
The antennas and waveguides are sandwiched between the cooled EUROFER (a DEMO grade of stainless steel) shield plates.

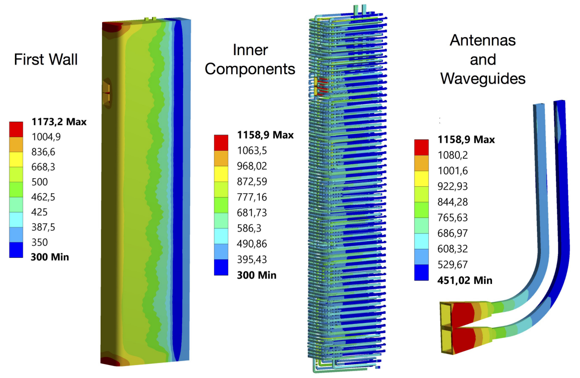
The challenges of integration are amplified by the requirements to interface with other DEMO systems. Some of the interfaces are imposed by safety requirements such as to use double barrier containments for components under or extending the main vacuum. In addition, the nuclear environment will contribute to nuclear heating of the diagnostic components and also of the slim cassette body. The figure shows an exploded view of one element of the slim cassette that contains the front antennas and a section of the waveguides. The cooling circuit of the waveguides is confined by a double vacuum compatible barrier.

NEUTRONICS CONTRIBUTION ON THE DEVELOPMENT OF AN INNOVATIVE DIAGNOSTICS CONCEPT FOR DEMO.

We developed a first design of an innovative concept for the integration of several groups of antennas and waveguides into a full poloidal section of the DEMO breading blankets, dedicated to reflectometry.

The system was studied in detail, including a preliminary design of a liquid-helium cooling system. Nuclear and thermal analyses were performed for this model, using the state-of-the-art simulation codes MCNP6 and ANSYS Mechanical.

Results show that the direct exposure to intense neutron and photon fluxes, as well as to the thermal radiation coming from the plasma, creates hotspots in regions located further away from the cooling channels, such as the antennas and some parts of the first wall. It was shown that with an adequate routing of the cooling system it is possible to lower the operating temperatures to acceptable values, even in the most exposed areas of the first wall.

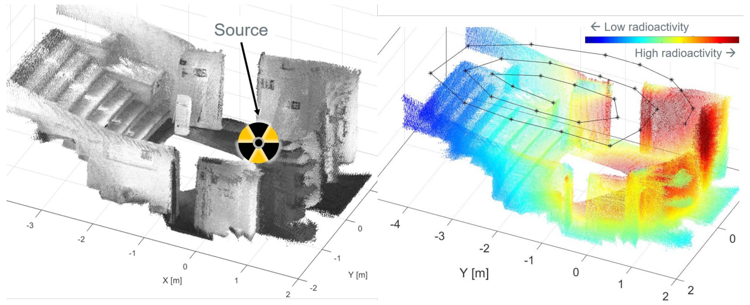


Innovative diagnostics concept developed for DEMO.
The picture shows the operation temperatures (ºC) in the antennas, waveguides, shielding components and cooling system of an integrated reflectometry diagnostics system under development for DEMO. The design of an effective liquid-helium cooling system is among the most demanding challenges faced by our engineering team.

DEVELOPMENT OF REMOTE HANDLING SYSTEMS FOR DEMO

The work done on ITER was extended to DEMO, in particular to the assessment of the cask transport system and the technical and economic impact into the building design, as the studies of occupied area in the buildings.

Are the remote handling activities circumscribed to AGV in power plants? Inspection inside fusion reactors is the most ambitious mission to achieve important information to manage the scheduled and unscheduled operations of maintenance. The aim is an insight view with a visual inspection enriched with extra information, such as radiation levels, temperature and 3D model to perform metric evaluation and comparison with the original CAD model of the reactor. This type of inspection mission is a challenge, given the hazard scenario with high levels of radiation and temperature, leading to a very short time life of any mobile robot. We are engaged to tackle the development of Unmanned Aerial Vehicles (UAV), such as drones, to perform inspection mission inside the reactors during the shutdown, without vacuum, to support the propeller system. The preliminary work was done using commercial drones and radiological sensors to test the first algorithms of estimate the radioactivity map.



3D reconstruction of a testing scenario (left image) and the radioactivity map estimation (right)

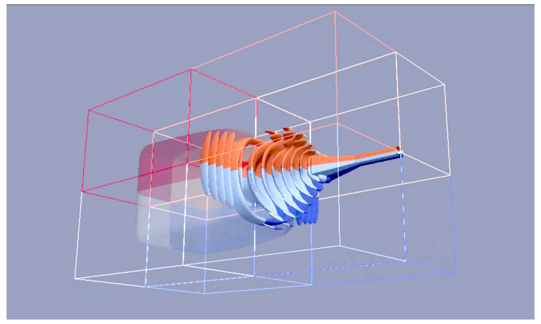
Other contributions

MODELLING FOR SIMULATION AND OPTIMISATION OF DIAGNOSTIC PERFORMANCE

Our main goal is to extend the capabilities of reflectometry simulation and to be able to set up improved synthetic diagnostics. To do so, during the period reported, we developed important work in numerical simulation of wave propagation in plasmas applied to reflectometry with the development of two new codes.

REFMULF, a novel 2D full-wave FDTD code is able to cope with full polarisation waves treating all component of the electric and magnetic fields of the wave and supports a generic external magnetic field, thus being able to describe oblique propagation, via a linear vector differential equation for the current density. This code enlarges the possibilities of simulation of microwave reflectometry offering capabilities unavailable in present-day 2D reflectometry codes and allows coping with real size problems.

REFMUL3, presently in an advanced stage of development, is a 3D full-wave code. Its 3D nature implied the usage of a parallel approach from the beginning, resulting in a parallel hybrid implementation with 3D domain decomposition and parallel input/output. Tests have shown very good scaling. REFMUL3 is of great interest to the reflectometry community as an essential tool to capture the full description of reflectometry in a synthetic diagnostic.



Parallel simulation of a plasma probing using FFCW with 800x450x450 grid points performed with REFMUL3.

DEVELOPMENT OF FAULT-TOLERANT CONTROL AND DATA ACQUISITION SYSTEMS

Recent and upcoming experimental fusion devices (e.g. ITER) are designed for steady-state operation. High-availability characteristics, required for the whole device infrastructure, are required to minimise failures that could compromise device performance.

Our main goal is to develop high-availability control and data acquisition instrumentation for critical systems in fusion devices. In particular, we developed a prototype for the ITER Fast Plant System Controller (FPSC) with instrumentation boards compliant with the AdvancedTCA (ATCA) specification, which provides the required resources for fault-tolerant, highly available systems at both hardware and software levels.

Tests for availability measurement were performed and verified the correct operation of the fault-tolerance mechanism.

IPFN FPSC prototype.
The drawings illustrate the extraction of an acquisition board from the ATCA Shelf. The developed inter-board messaging system allows to insert and remove boards with the system powered on for high-availability.

Experimental Physics

Main Researchers:

Alberto Ferro	João Figueiredo
Artur Malaquias	José Mendonça
Carlos Silva	José Rodrigues
Christophe Guillemaut	José Vicente
Diogo Ferreira	Manuel Alonso
Horácio Fernandes	Maria Emília Manso
Hugo Terças	Rui Gomes
Igor Nedzelskiy	Santiago Cortes
Isabel Nunes	Vladislav Plyusnin
Ivo Carvalho	

We are responsible for the operation and scientific exploitation of the Portuguese tokamak – ISTTOK – and for collaborating with other fusion devices like ITER, JET, TJ-II, TCV, W7-X, COMPASS, ASDEX and TCABR. Our research focuses on the development of diagnostics and real-time control systems, participating in experimental campaigns and collaborating in the modeling, data analysis and developing of numerical codes.

Our main goal is to provide to the community the necessary know-how and tools for the safe operation of fusion reactors in the near future. For that purpose, we maintain a continuous tracking of advanced, high-end technologies in different fields of research and industry, importing them to our community with suitable adaptations.

So far, we have succeeded in extending the nominal operation time of pulsed fusion devices from a few miliseconds up to seconds, creating new diagnostics systems for fusion devices such as Heavy Ion Beam probing and reflectometry, and continuously evolving a plant operation framework. Advanced education is also provided for a considerable number of PhD students working under our supervision.

Group Leader: **Horácio Fernandes**

Deputy Leader: **Carlos Silva**

ISTTOK

ISTTOK, the only fusion device in Portugal, is a tokamak with a circular cross-section, a poloidal graphite limiter and an iron core transformer. It is also the only European tokamak allowing regular use of alternate discharges with a time span longer than 1 s. Currently, ISTTOK serves as a research infrastructure, enhanced by several PhD and MSc projects developed around it. It continues being used for diagnostics and data acquisition systems developments and for physics studies, but the long discharges for such a small machine enable increasing its contribution for studying compatible materials for fusion-devices in the near future.

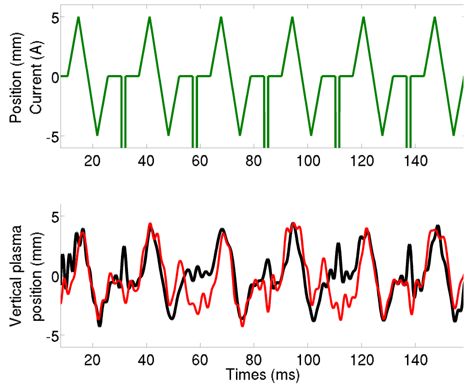
ISTTOK DIAGNOSTICS

Heavy Ion Beam Diagnostic

The development of the ISTTOK Heavy Ion Beam Diagnostic (HIBD) in the last two years has been addressing two important upgrades:

Increase of measurement bandwidth

The development of faster amplifiers enabled the measurement of relevant plasma parameters (pressure-like profiles) up to a frequency of 400 kHz. This feature allowed the implementation of efficient noise removal techniques, which resulted in a very robust reconstruction of the measured plasma parameters profiles while keeping a quite useful range of frequency information. As a consequence, the heavy ion beam diagnostic (HIBD) was able to estimate the vertical plasma position in real-time and accordingly be included in the closed-loop control of the tokamak. This constitutes the first time that the HIBD is used in such control and opens the possibility of its use in larger devices as a complementary technique.



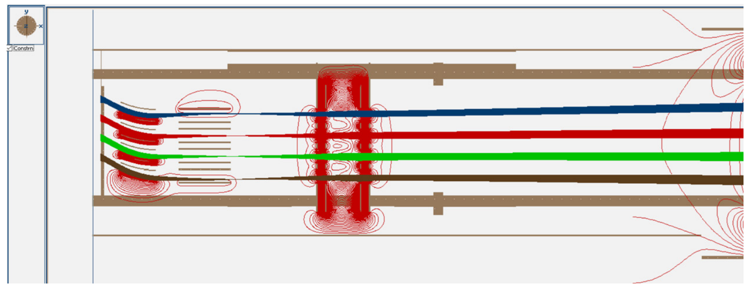
(Above) requested vertical plasma position; (below) black line: HIBD measurement; red line: ISTTOK main plasma measurement system.

Thanks to a fast combined signal processing, provided by an FPGA + MARTe real-time framework, the plasma position was estimated in every control cycle (20 kHz). The figures show the vertical plasma position control experiments in discharges using the HIBD in feedback.

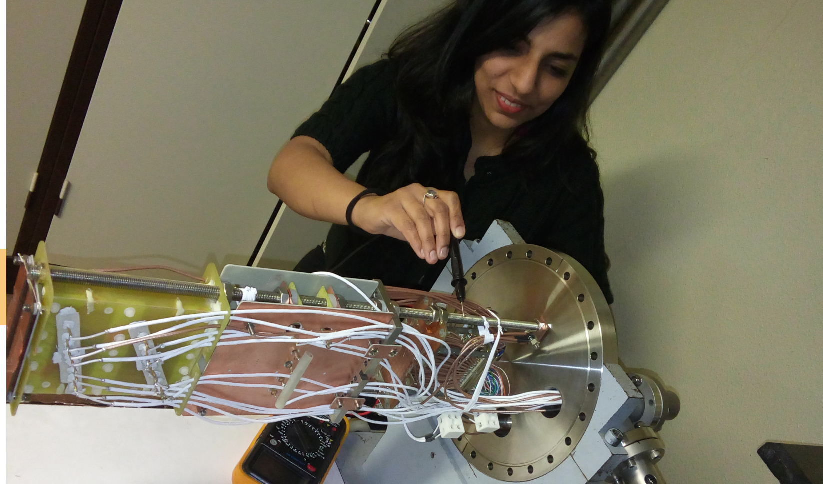
Another positive outcome of the new fast amplifier system lies in the possibility of following the evolution of the plasma pressure during the alternate current (AC) tokamak operation. The unprecedented access to this discharge phase helps to shed light on the current inversion mechanisms taking place in order to develop efficient control methods that can improve the repeatability of the AC discharges at higher plasma currents (up to 6 kA). At such current levels, more power is available to conduct material experiments for relevant time expositions (> 1 s).

Cylindrical Energy Analyser

Our goal is to design and commission a new type of detector that will allow the simultaneous measurement of plasma pressure-like profile together with the plasma potential and plasma current poloidal magnetic field. These three parameters correspond to the intrinsic electromagnetic and kinetic plasma response that underlies tokamak equilibria studies. The new detector implements an innovative design that combines electrostatic field retardation with electrostatic energy analysis, increasing 4x fold the energy resolution and about 17x fold the angular acceptance with respect to previous designs. The analyser can therefore be relatively compact. In addition, its layout enables in principle to capture all ions emerging from the HIBD probing beam, providing measurements from the full plasma diameter.



The Electrostic Input Module simulation design.



The Electrostic Input Module prototype being tested.

TURBULENCE SYUDIES ON ISTTOK

Experimental evidence of turbulence regulation by time-varying ExB flows

The interaction between zonal flows and turbulence is a self-regulating mechanism. Understanding this interaction is crucial to control plasma confinement. We aim to understand the conditions under which geodesic acoustic modes (GAMs) influence the turbulent transport. This was achieved by performing perturbative experiments where GAMs are stimulated and externally controlled. Experiments on ISTTOK revealed that increasing the GAM shear rate over its natural value leads to a reduction of the turbulent transport and to an enhancement in particle confinement. Our results indicate that the GAM shear rate is enough to regulate the ambient fluctuations without totally suppressing the turbulence.

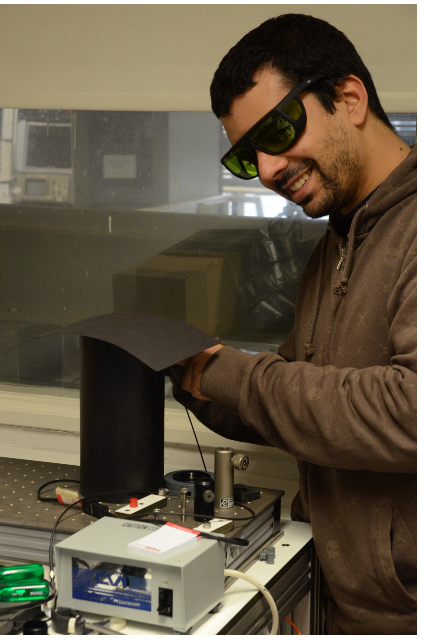
STUDY OF FUSION-RELEVANT FACING MATERIALS

Liquid metals plasma facing materials on ISTTOK

Liquid metals as plasma facing materials have been under investigation at IPFN due to their self-healing properties of the liquid surface and the vapour shielding effect. However, using these materials in fusion reactors might impact discharge performance due to impurity contamination.

Samples of pure tin and lithium-tin alloy were exposed to deuterium plasmas at the ISTTOK tokamak at the edge of the plasma column, which was characterised by spectroscopic measurements. The spectroscopy setup uses a bundle of ten optical fibres, aligned with the poloidal plane of the vessel. This 10-chord geometry allows simultaneous measurements

Solidified tin sample in its holder after exposure to ISTTOK plasmas.



PhD student performing the calibration of the high resolution spectrometer.

of the spectral emission spanning from the scrape-off layer to the inner part of the plasma core. A search for the characteristic lines from the exposed elements was done in the visible range. In particular, lithium I line (670.8 nm) and a tin II line (579.9 nm) were studied to infer the radial decay of the line intensity for these two elements present in the exposed samples. The decrease in intensity towards the core follows the increase in electron temperature, which dictates the ionisation state of the impurity populations. Simultaneously, the effective nuclear charge of the plasma was estimated and was mostly unaffected by the sample exposition. While this was observed in other pure lithium and gallium exposure experiments, it was the first time for pure tin and lithium-tin alloy.

JET

IMPACT OF ISOTOPE COMPOSITION ON PLASMA PERFORMANCE

The main objective of the dedicated experimental JET hydrogen campaign was to study the plasma dependence of plasma properties on the main ion isotope mass as well as on the isotope composition. Studies on plasma core and pedestal dependence on heat, particle, impurity and momentum transport and ELM behaviour in H, D and H-D mixtures were performed, as well as L-H transition studies, energy confinement dependence and L- and H-mode density limit and W sources on plasma isotope composition. Moreover, it is important to devise tests and strategies for isotope ratio control for future DT experiments. The L-H transition studies showed that the minimum density for the L- to H-mode transition increases with isotope mass and even a small mixture (<20%) makes a strong effect. It is also found that for most densities, the 50/50 hydrogen/deuterium mixture is equal to about the average of the threshold in pure hydrogen and deuterium.

DEVELOPMENT OF HIGH-PERFORMANCE SCENARIOS IN PREPARATION FOR DT

With high power reliably available, good H-mode confinement H98~1 was achieved at 3 MA, extending the results obtained at 2.5 MA in 2013/2014. The fusion performance reached 3×10^{16} n/s. At high input power and low gas dosing, plasmas enter a low collisionality regime with low ion-electron equipartition, excellent ion thermal transport and $T_i > T_e$ in the plasma core. The scenario makes extensive use of pacing pellets, to maintain a suitably high ELM frequency while decreasing the gas dosing to promote hotter and less dense pedestal. ICRH is essential to control the W accumulated in the plasma core. Divertor heat load control is performed by sweeping the strike points around a radius of about 5-6 cm to spread the power loads.

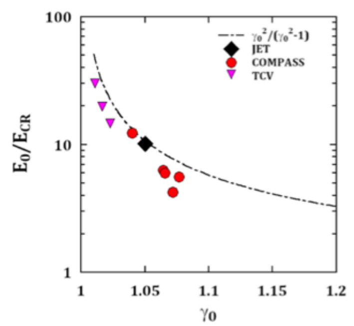
TOMOGRAPHY

Activities in JET have focused on tomographic reconstruction of the plasma radiation profile from bolometry diagnostics. A neural network has been trained using deep learning and GPU computing to produce similar results in a fraction of the time. Such neural network is now being used to produce end-to-end tomographic reconstructions for entire pulses at JET. These full-pulse reconstructions are especially useful to study the plasma behaviour during (and in the moments leading to) a disruption. There is an ongoing collaboration with JET in activities related to disruption prediction and avoidance.

RUNAWAY ELECTRON

Disruptive termination of plasma discharges is one of the most critical problems for tokamak operations. Therefore, the design of a reliable system to mitigate severe consequences of disruptions – Disruption Mitigation System – is one of the great challenges of the ITER construction. To overcome existing problems, a detailed knowledge of runaway generation physics and improved models for numerical simulations are required.

In the series of experiments on runaway electrons (RE) during 2016-2017 in small and medium-sized tokamaks – COMPASS, TCV and ASDEX-Upgrade – we aimed to study the trends in RE generation parameters and compare them to the results obtained in a large tokamak – JET with ITER-like Wall. Our main goal was to extrapolate the runaway process parameters to ITER experimental conditions for the development of Disruption Mitigation System in ITER.



Critical electric fields for different critical energies in runaway electron generating discharges in tokamaks: data from COMPASS, TCV and JET with ITER-like Wall.

New data on RE generated during disruptions in COMPASS and ASDEX-Upgrade was collected and added to the JET database. These results from small and medium-sized tokamaks have demonstrated their conformity to the RE data obtained in JET, allowing to predict runaway generation conditions at disruptions in ITER. The evaluation of runaway critical field for low-density discharges has demonstrated that the dependence of critical electric field on electron energies in sub-relativistic range is close to that predicted by theory. This critical field exceeds the relativistic runaway critical field by a factor of 4-30 in different discharges and devices.

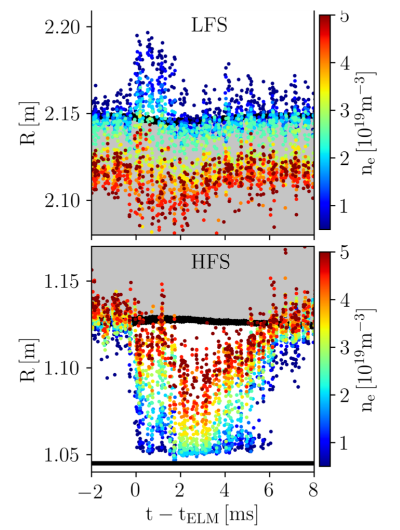
MICROWAVE REFLECTOMETRY

Edge turbulence in ASDEX Upgrade

Transport in the scrape-off layer (SOL) depends on the state of divertor detachment. Knowledge is derived mainly from data at the low field side (LFS) while at the high field side (HFS) data is scarce. To improve the global understanding of the SOL transport, density fluctuations were measured simultaneously at the LFS and the HFS with reflectometry in plasmas where the state of divertor detachment was varied. At the LFS SOL, low-frequency components are found to be responsible for the increase of density fluctuations along the discharge, which is in agreement with an enhanced convection of filaments. At the HFS with a much lower level of fluctuations in agreement with ballooning transport, a strong increase is seen at the far SOL suggesting that faster filaments originated at the LFS may propagate to the HFS.

Influence of the high-field side density front on midplane density profiles in ASDEX Upgrade

The separatrix density and the SOL conditions have a significant impact on the pedestal stability and hence in confinement. However, the physics mechanisms responsible for the changes in confinement with fuelling, input power and seeding have not yet been identified. Our main goal is to clarify the impact of the region of high density in the inner divertor (HFSHD) on the H-mode midplane profiles using mainly HFS/LFS measurements from reflectometry. A good correlation was observed between the HFSHD formation and the evolution of the LFS midplane density with respect to changes in fuelling and seeding. However, the HFSHD was observed to respond strongly to the heating power contrary to the LFS midplane density and plasma confinement, indicating that other mechanisms are at play. Pronounced HFS/LFS asymmetries were also found in the evolution of the density profiles during the ELM cycle associated with the evolution of the HFSHD.



Evolution of the density layers at the LFS and HFS during an ELM

Scaling of GAM amplitude on JET

The practical relevance of fluctuating sheared *E x B* flows in controlling turbulence and confinement is not yet fully established. Our work aims at establishing the parameter space for the existence of GAMs on JET as well as investigating their driving and damping mechanisms predicted by different theoretical models.

This was achieved using an experimental dataset based on GAM measurements by reflectometry with variations mainly on plasma current and line-averaged density. We found clear experimental evidence for the different mechanics determining the GAM amplitude predicted by theory: turbulence drive and collisional and collisionless damping. Although the observed GAM suppression at high plasma current is in good agreement with the collisionless models, the estimated damping rates appear to be too small to explain our measurements.

Commissioning of the reflectometry system on ASDEX Upgrade

Materials Processing and Characterisation

Main Researchers:

Carlos Cruz
Eduardo Alves
Hélio Luís
Katharina Lorenz
Marco Peres
Marta Dias
Rodrigo Mateus
Rui Martins
Rui Silva
Sérgio Magalhães
Victoria Corregidor

Ion beam technologies play a relevant role on the fundamental studies to unveil the behaviour of materials operating under extreme radiation conditions. Particle solid interactions in the universe are governed by the fundamental laws of physics and most of these phenomena can be mimic in laboratory. Our group is responsible for the operation of the Ion Beam Laboratory of IST and use the installed capabilities to explore medium-low energy interactions of charged particles with matter. Furthermore the enormous potential of ion beam techniques allowed us to establish a multidisciplinary programme of collaborations with national and international research groups in multiple research fields.

The research activities carried by the group addresses the challenges related with plasma interaction with materials in fusion devices. The outcome of these studies are fundamental to understand the characteristics of the dominant erosion, deposition and fuel retention patterns and validate the theoretical models available. It is expected that the results will contribute for the success of the Fusion Programme making this controllable source of energy available for the human kind.

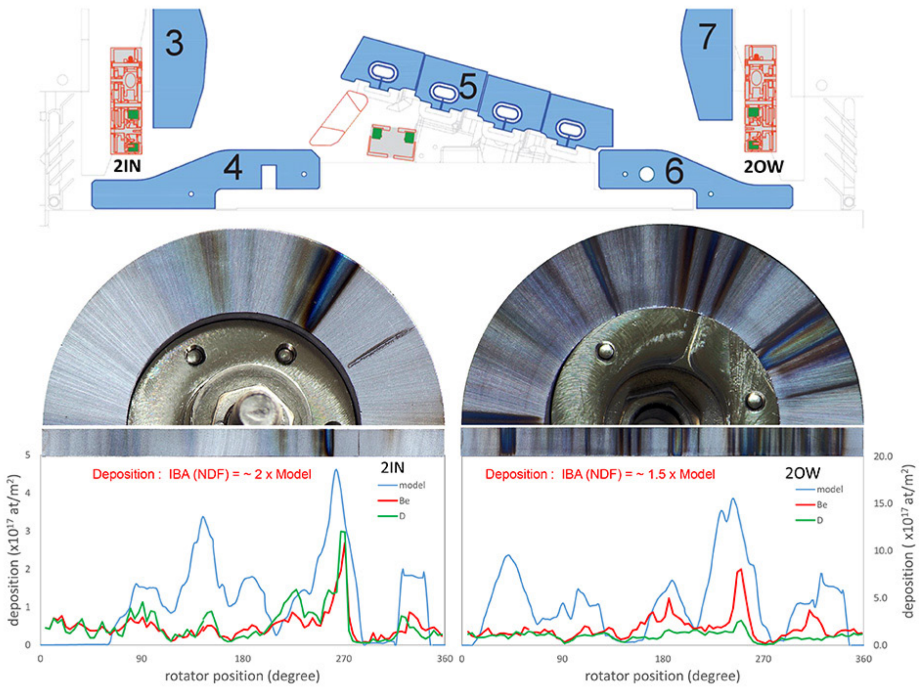
The participation of the ion beam laboratory in the European network on ion beam infrastructures supports other important research activities on modelling and tailor the properties of low dimensional material structures and new materials with particular emphasis on wide band gap semiconductors and metallic oxides, where a major step will be the development of new optoelectronic devices to support future technologies.

Group Leader: **Eduardo Alves**

Research highlights

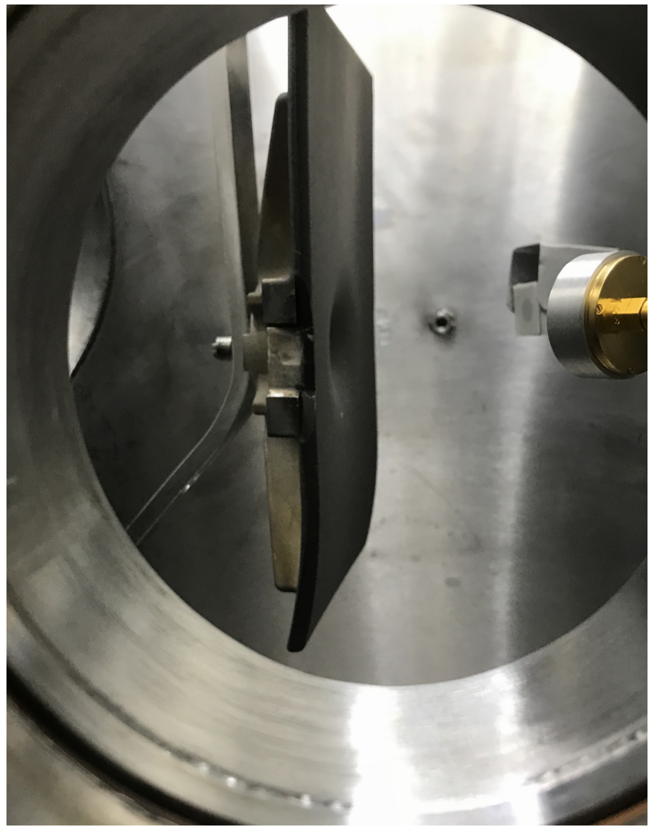
PLASMA WALL INTERACTIONS IN JET ITER-LIKE WALL

ITER-Like Wall (ILW) of JET offers the possibility to study most of the plasma wall interactions relevant to establishing the operating conditions for ITER. Evaluation of material migration, erosion/redeposition and fuel retention processes are crucial to validate the models and provide the relevant figures to design a safe reactor. During the last two years, we have been measuring a large number of components and passive diagnostics removed from JET after the last two D-D campaigns.



Beryllium and Deuterium deposition on the inner (2IN) and outer (2OW) collectors for ILW 2 campaign. The blue line represents the model for the Be deposition.

Most of the samples studied belong to the second JET-ILW campaign (2013-2014), ILW-2. A combined set of ion beam techniques (NRA, EBS and PIXE) were used to study the erosion/redeposition, impurity migration and fuel retention

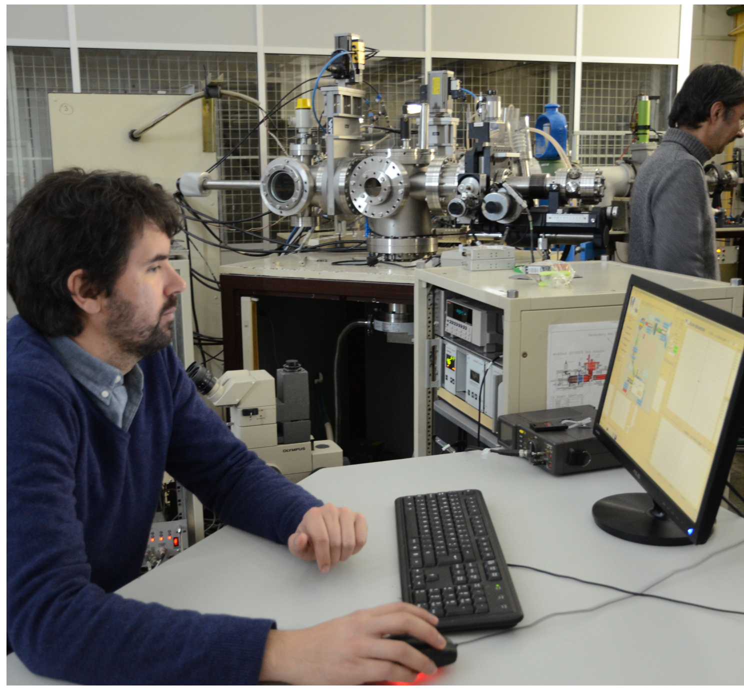


Inside view of JET Chamber, showing tile IWC403 ready for analysis.

in selected components from the main chamber and divertor. The results obtained confirm the overall migration pattern established from the previous ILW-1 (2011-2012) campaign and point out for the correlation between deposition and retention. Plasma configuration has an important role in the erosion and transport of impurities influencing the final distribution of the deposits and fuel retention. ILW-2 campaign had about 10% of the pulses with hydrogen (at the end of the campaign) and a strong concentration of the striking points on tile 6 and tile 4, which correlates well with the higher deposition and retention found in the hide regions of the divertor corners. Inside the main chamber, deposition and retention were observed mostly in the limiters, recessed tiles and top region of the castellation gaps. A noticeable difference at the outer divertor corner tile is increased Be deposition, 3×10^{19} at./cm^2, in a band outboard of the plasma accessible region, which correlates with an increase in the outer strike point time in this region compared with ILW-1, like seen in the figure.

A new aspect of JET-ILW tile analysis was the evaluation of tungsten coating on CFC tiles. First results from ILW-1 showed erosion of coatings at the central region of the inner divertor vertical surface. Cross-sectional micrographs of a tile exposed for both ILW-1 plus ILW-2 campaigns shows that erosion in this same region is highly non-uniform with some areas eroding up to 4 µm, whilst others show no erosion.

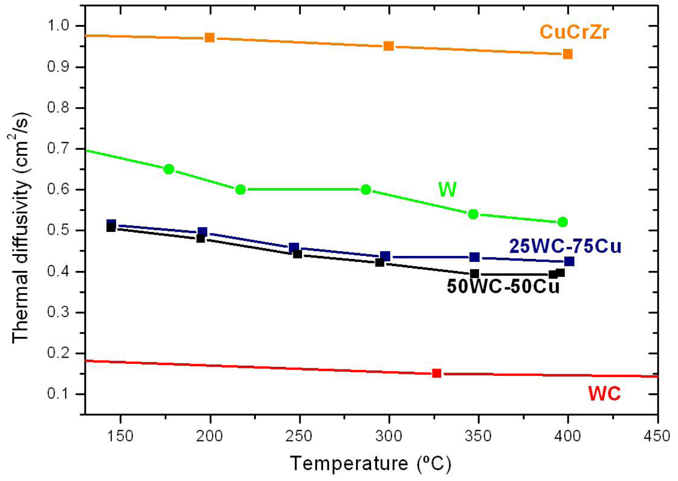
We will continue the studies of JET diagnostics and tiles to fill the gaps in the information available in close cooperation with the researchers working on the models. In addition, we will use laboratory samples produced to mimic the mixed materials formed by redeposition in the reactor walls and study their retention properties.



Tuning the AMS line to measure the 3H profile in plasma facing components.

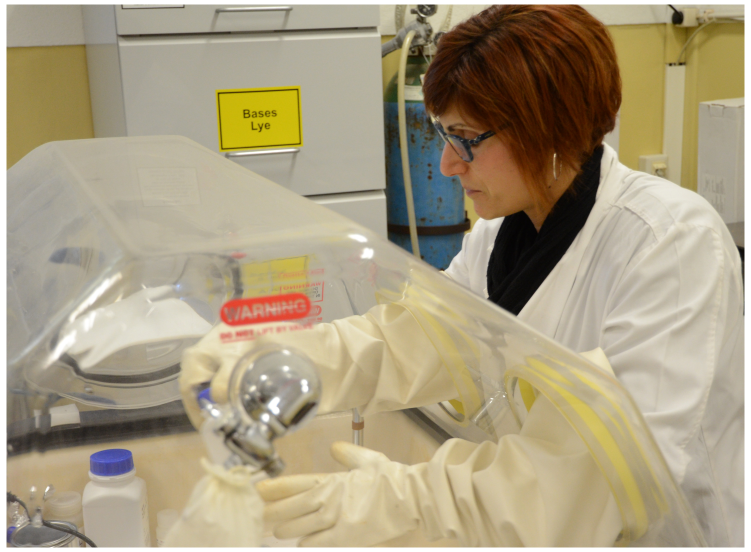
DEVELOPMENT OF THERMAL BARRIERS FOR FUSION REACTORS

The operation of the fusion reactors at high temperatures (500 °C) imposes the need to use thermal barriers between the wall material (tungsten in most of the cases) and the heat sink, the CuCrZr alloy. A potential candidate is the WC-Cu alloy and a series of compositions were produced and studied. In addition, we started the study of a new and promising composite, Cu reinforced by Y_2O_3 particles.



Thermal diffusivity of samples 25WC-75Cu and 50WC-50Cu cermets. For comparison the curves for CuCrZr, W and WC are also presented.

The WC-Cu cermet composition series were produced using commercially pure WC powder (diameter of 12 µm) with 99.9% nominal purity and Cu powder (size < 37 µm) with 99.99% nominal purity for variable volume fraction of Cu (25%, 50% and 75%). The WC-Cu powders were consolidated by hot pressing varying the temperature between 900°C to 1150°C and using loads of 22, 37 to 47 MPa. The 50WC-50Cu and 25WC-75Cu samples were consolidated using WC covered particles and high densifications were obtained (95-98%), in figure (a). The thermal diffusivity behaviour for the 50WC-50Cu sample is similar to the 25WC-75Cu and is shown in figure (b). The measured cermet thermal diffusivity is lower than that of copper or tungsten, as desirable for thermal barrier materials; however, more studies are necessary to optimise the material. Results reveal a strong dependence of the performance on temperature and on the volume fraction of copper and a slight percent of Cu (25 vol. %) can effectively reduce the large difference in thermal expansion between tungsten and copper alloy.

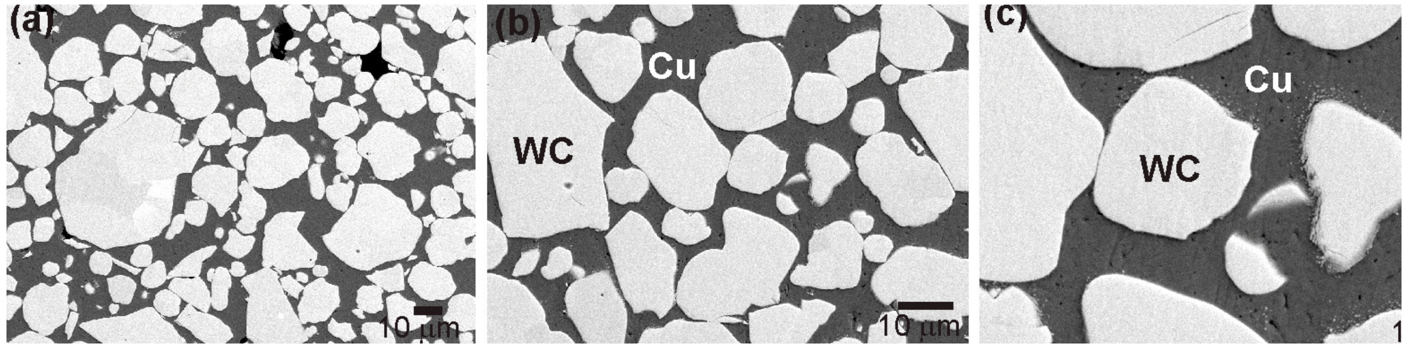


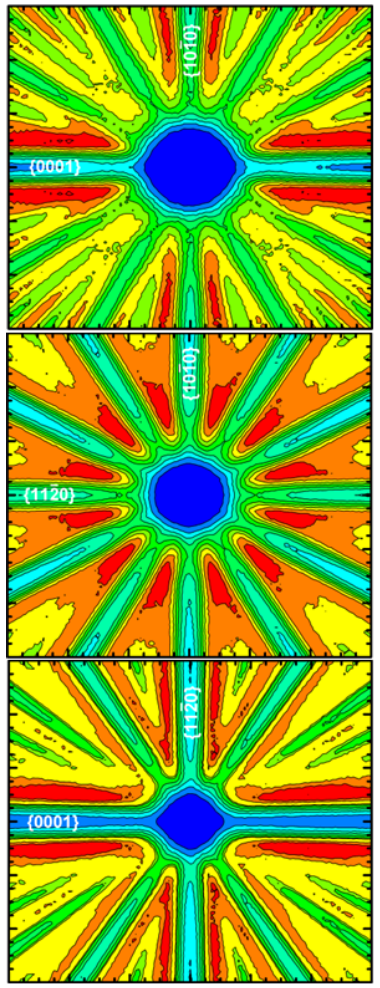
Selection and preparation of metallic powders for consolidation of new thermal barrier compounds.

Moreover, series of Cu-Y_2O_3 composites were produced by hot pressing and a densification around 98% was obtained. The microstructures evidence a dispersion of agglomerates of Y_2O_3 in the copper matrix.

We will continue the studies to find the best conditions to produce thermal barriers based on yttria dispersed in copper matrices with the desirable thermal properties to operate in fusion reactors. A long-term programme to develop thermal barriers based on high entropy alloys of type $Cu_xCrFeMoTi$ (x = 0.21, 0.44, 1) will be initiated.

Microstructure of sample 50WC-50Cu with WC particles covered by Cu consolidated by hot pressing at 1060ºC, 37.5 MPa during 5 min.



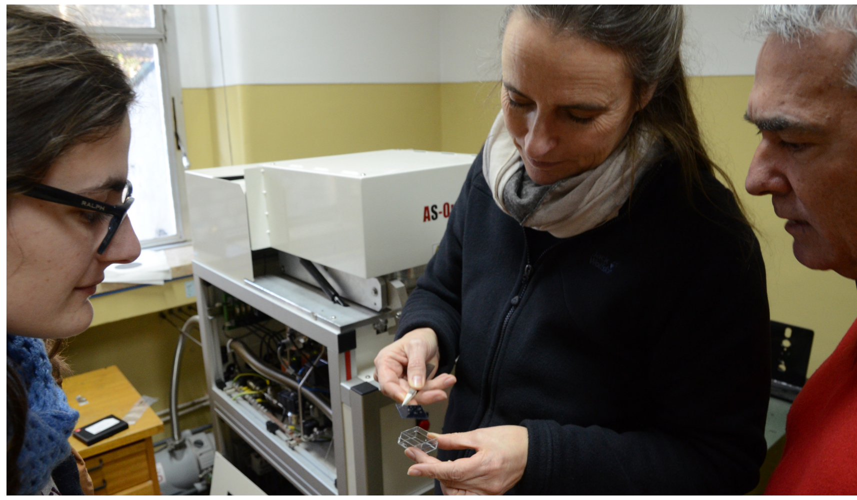


Two-dimensional ion channelling patterns along a-, c- and m- axes in GaN.

RADIATION RESISTANT WIDE BAND-GAP SEMICONDUCTORS

The necessity of robust electronics and sensors working in extreme conditions is driving the research on finding alternatives to the ubiquitous silicon-based semiconductor devices. In particular, the development of radiation resistant semiconductors for radiation detectors and electronic circuits is of utmost importance for applications in space, accelerators (for research and health sector) or nuclear facilities.

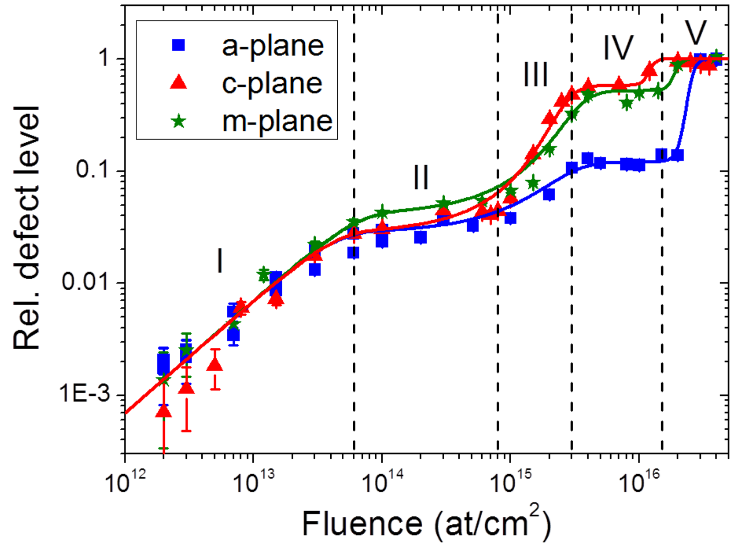
Wide bandgap group-III nitrides and metal oxides such as (Al)GaN, Ga_2O_3 and MoO_3 have been investigated in order to understand the damage build-up processes during ion irradiation and to test their performance as radiation detectors. GaN and AlGaN show strong dynamic annealing leading to efficient defect recombination during the irradiation. This extraordinary resistance to radiation damage was evidenced by experiments as well as Molecular Dynamics simulations. The figure shows the sigmoidal damage build-up curves upon ion implantation of GaN grown along different crystallographic directions evidencing strong radiation resistance, in particular, for a-plane material. GaN microwires were furthermore processed into sensor devices and first tests revealed their good performance as detectors for UV radiation and protons. Ga_2O_3 and MoO_3 are emerging semiconductors with promising characteristics for high power and sensor applications. The modification of these materials by ion beams allows the tailoring of their electrical and optical properties.



Observation of a nitride semiconductor structure after irradiation.

As a sign of international recognition, several invited talks were given and two students received awards at international conferences.

We will continue the studies to fully understand the behaviour of these new oxides and real-time measurements will be performed under irradiation conditions envisioning their application for radiation detectors.



Implantation damage build-up curves measured along these crystal directions revealing strong radiation resistance.

Theory and Modelling

Main Researchers:

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António Figueiredo
Duarte Borba
Fernando Nabais
Francisco Salzedas
Hugo Hugon
João Bernardo
João Pedro Bizarro
Jorge Ferreira
Luís Pereira
Maria Filomena Nave
Paulo Abreu
Paulo Rodrigues
Rogério Jorge
Rui Coelho
Rui Vilela Mendes

Our research is focused on forefront areas in plasma physics, particularly relevant for tokamak fusion plasmas and the EU fusion program. In particular, we are interested in the pervasive ties between Alfvén Eigenmode (AE) stability and the energetic particles born from plasma heating schemes and fusion reactions in current fusion devices and also in ITER, and in understanding the complex mechanisms ruling intrinsic plasma rotation and plasma momentum transport. We also investigate the dynamics of Scrape-Off Layer turbulence and are strongly involved on Integrated Tokamak modelling, including the development and use of state-of-the-art scientific workflows for tokamak physics applications. The group also addresses more fundamental plasma research connected to magnetic reconnection, wave propagation in plasmas and mathematical methods for plasma physics.

Our strong commitment with the EU fusion program is evidenced by our leading representative role in the Integrated Modelling EUROfusion Work Package, a solid participation in the EUROfusion experimental campaigns of JET and AUG tokamaks and research activities for DEMO and JT60-SA devices and contract positions in the JET Exploitation Unit.

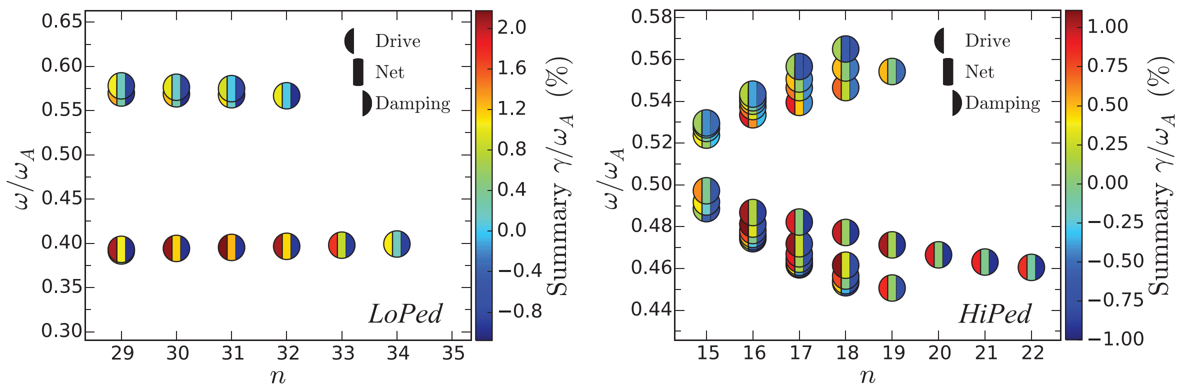
Group Leader: **Rui Coelho**

Research highlights

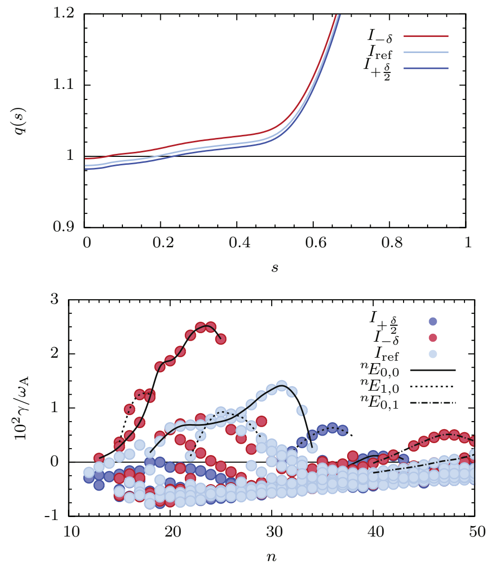
ENERGETIC PARTICLE PHYSICS IN TOKAMAK PLASMAS

We have made a thorough analysis of two variants of an ITER baseline scenario, differing in their core and pedestal temperatures, using a specialised workflow that profits from the performance of the hybrid MHD drift-kinetic code CASTOR-K. The largest growth-rates occur in the scenario variant with higher core temperatures, which has the highest alpha-particle density and density gradient, for eigenmodes with toroidal mode numbers n ≈ 30 (LoPed scenario – low pedestal temperature). Although these eigenmodes suffer significant radiative damping, which is also evaluated, their growth rates remain larger than those of the most unstable eigenmodes found in the variant of the ITER baseline scenario with lower core temperatures, which have n ≈ 15 (HiPed scenario – high pedestal temperature) and are not affected by radiative damping.

Using the same code workflow suite, a sensitivity scan was performed on the low-temperature pedestal Ip = 15 MA baseline scenario (LoPed), having a very low and broad core magnetic shear. Slight variations (of the order of 1%) of the safety-factor value on axis were seen to cause large changes in the growth rate, toroidal mode number, and radial location of the most unstable eigenmodes found. The observed sensitivity was shown to proceed from the very low magnetic shear values attained throughout the plasma core, raising issues about reliable predictions of alpha-particle transport in burning plasmas.



Summary of growth-rates for even and odd LSTAEs in both scenario variants, showing their net value γ (middle part of the circular markers), drive γα (left marker part), and damping $\gamma_{DT} + \gamma_e + \gamma_{He}$ (right marker part). Only modes with positive net growth-rates are shown. In LoPed the most driven modes are the even LSTAEs, which are also the most unstable. That is not the case in HiPed because although even modes are the most driven, they also have the highest damping, whereby the most unstable HiPed modes are odd LSTAEs.

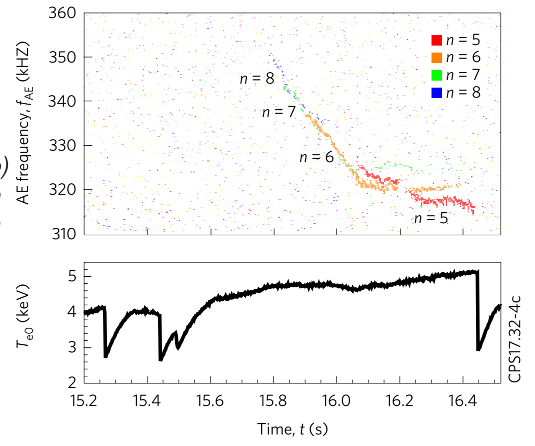


Safety-factor profiles for the reference plasma current and two slightly different Ip values (top). Distribution of the normalised growth rate γ/ω_A by toroidal mode number n for the three plasma-current values, with indication of three TAE families (bottom).

We have explored the implications of the recently developed "three-ion" Radio Frequency plasma heating scenarios. These scenarios rely on matching the cyclotron layer of the third ions party with the mode conversion layer, which carries the increased left-hand polarised RF electric field favourable for RF absorption by the ions. This new "three-ion" method is rather flexible and allows the use of various resonant ion species and plasma mixtures particularly relevant for future D-T plasmas foreseen as a fuel mix in a fusion reactor. The small concentration of minority ions used are accelerated to much higher energies, typically to the MeV range and can potentially destabilise Alfven Eigenmodes that then redistribute the fast ion population. We have shown using our code suite that core-localised n=5-7 modes with frequencies around 285 to 295 kHz can be destabilised by the ^{3}He energetic ions population with energies in range 1.5 to 2.5 MeV, in agreement with experimental observations.

"Fast particle Team" at work, analysing novel CASTOR-K results.

Mode analysis (top) and electron temperature (bottom) in JET pulse #90758



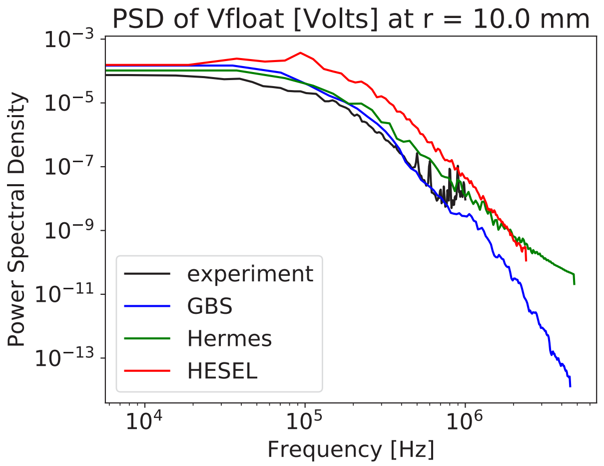
PLASMA MOMENTUM AND INTRINSIC ROTATION IN CONFINED PLASMAS

Intrinsic rotation is expected to play a key role in the performance of future tokamak power plants where the momentum input will be small. Increasing rotation shear in the core is valuable for increasing thermal confinement. Our research provided great insight on the mechanisms determining the shape of the rotation profile in JET plasmas without momentum input from neutral beam injection. The effect of magnetic shear on core rotation was investigated in plasmas with Lower Hybrid Current Drive (LH) and we found that LH-waves can induce changes in core rotation that can be either in the co- or counter-current directions. A change from co- to counter-rotation as the q-profile evolves from above unity to below unity, suggests that processes associated with magnetic shear could be important. For pulses with monotonic q profiles, with q_0<1, a power scan at fixed density, shows a power threshold around P_{LH}~3MW.

For smaller LH powers, counter rotation increases with power, while for larger powers a trend towards co-rotation is found. An observed correlation with a decrease in the internal inductance indicates that the co-rotation trend is related to an increase in non-inductive current.

TURBULENCE STUDIES IN CONFINED PLASMAS

Significant progress was made during recent years in the study of plasma dynamics in the outermost plasma region, commonly known as scrape-off layer (SOL), of magnetic confinement devices. This region plays a substantial role in many physical processes of such devices, such as the exhaust of power, plasma fuelling, and impurity dynamics. It also sets the overall boundary conditions to the plasma. We are finalising a validation effort between several SOL turbulence codes, analysing turbulent profiles from each code and comparing with the experiments at ISTTOK.

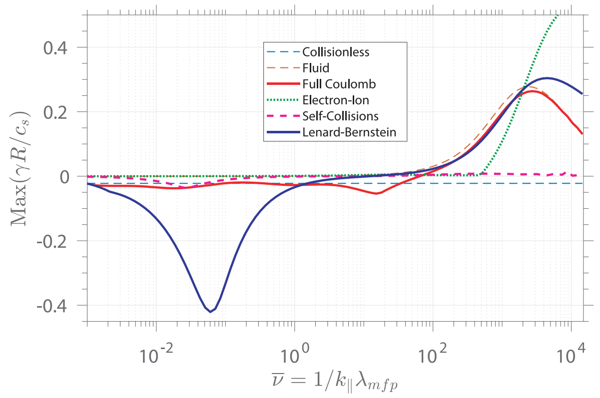


Validating turbulence floating potential spectra obtained from GBS, HESEL and Hermes codes on experimental ISTTOK probe data.

Through a numerical implementation of the linearized version of the moment model, the growth rate of the drift-wave instability as a function of the normalized electron collision frequency was computed. A comparison is made between the collisionless drift-wave instability (dashed blue), the fluid case (dashed orange), the use of the full Coulomb collision operator (red), only electron-ion collisions (dashed green) and like-species collisions (dashed pink). Both the fluid and the collisionless limits are retrieved using the moment formalism.

Following previous studies using simplified collision operators such as the Lenard-Bernstein (LB) one, it was also compared the growth rate of the drift-wave instability obtained using a LB operator and the full Coulomb one, showing significant differences in the low-to-intermediate collisionality regime. A similar study was also made for the case of electron-plasma waves, where important collisional effects absent in simplified operators that are used in moment models (e.g. LB operator) can be accurately modeled using a small number of moments. The fluid (collisional damping) and the collisionless (Landau damping) limits are also retrieved using such formalism.

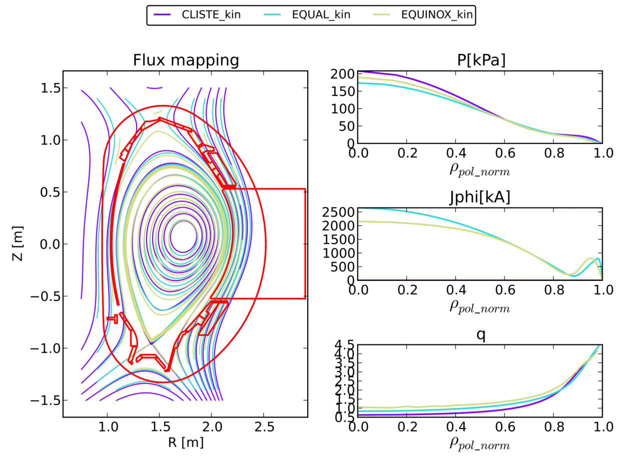
We have explored analytically the transport, turbulence, and generation of large-scale, collective structures (so-called blobs) in the SOL of tokamaks using a reduced two-dimensional two-field (density plus vorticity) model of the SOL. The model is built around a conservative system describing transport perpendicular to the magnetic field in a slab geometry, to which terms are added to account for diffusion and parallel losses (both for particles and current) and to mimic plasma flow from the core (in the form of a source). Nonlinear estimates for the growth rates were derived, evidencing that the growth in the density gradient is bounded above by the vorticity gradient, and vice-versa, therefore suggesting a nonlinear instability in the model. The possibility of controlling fluctuations by means of a biasing potential is confirmed (negative polarisations being shown to be more effective in doing so, thus providing an explanation for what is seen in experiments), as well as the advantage in reducing the inhomogeneity of the magnetic field in the SOL to decrease the plasma turbulence there. Focusing on the conservative part of the equations, we have obtained exact solutions in the form of travelling waves that might be the conservative ancestors of the blobs that are observed in experiments and in numerical simulations.



Growth rate of the drift-wave instability as a function of the normalized electron collision frequency.

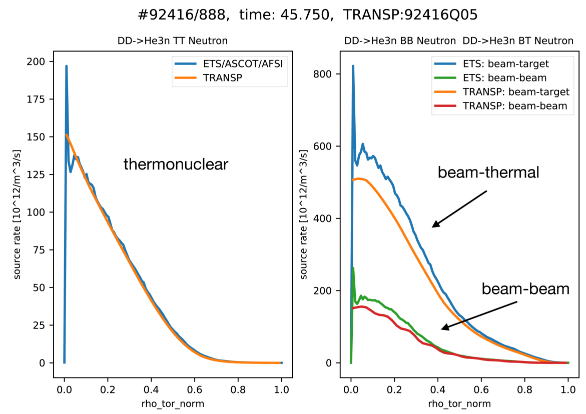
INTEGRATED TOKAMAK MODELLING AND WORKFLOW DEVELOPMENT

The main goal of our activity was on the development and exploitation of scientific workflows in the EU Integrated Modelling Infrastructure, including the verification and validation of the physics modules included. As a pilot project in EUROfusion work package on Code Development, an extensive verification of the plasma equilibrium reconstruction codes EQUAL and EQUINOX was made, integrated into a Kepler workflow for the reconstruction of plasma equilibria from JET, ASDEX Upgrade and TCV tokamaks. Using only magnetics data (all devices) but also with additional Motional Stark Effect (JET) or thermal pedestal pressure (AUG) constraints, a good agreement with the local reconstructions tools and with some experimental observations, under the same model assumptions and data usage, was obtained (see figure, AUG equilibrium reconstruction assisted with thermal pressure is shown).



Code Benchmarking of EQUAL and EQUINOX reconstruction codes against CLISTE code of an AUG plasma using additional pedestal plasma pressure constrain.

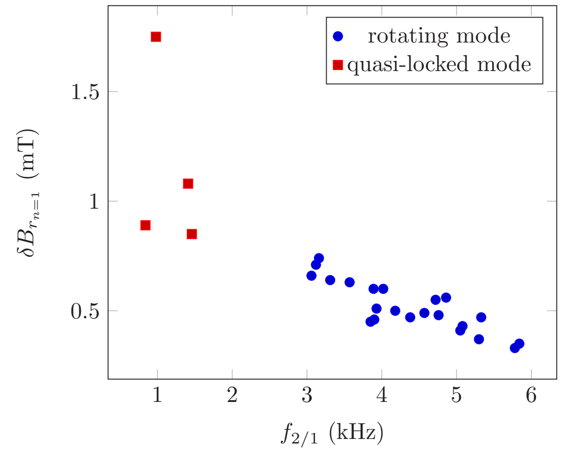
The team also contributed vigorously to the development, verification and deployment of the ETS plasma transport simulator on the JET cluster facility. The effort involved the development of synthetic diagnostic modules (interferometry), stabilisation schemes for the transport solvers, assembly of the starting plasma scenario of the ETS from TRANSP simulations and an extensive verification of the Neutral Beam Injection heating and current drive codes. We have successfully benchmarked the NBI beam deposition and Fokker Planck code ASCOT included in the ETS against NUBEAM included in TRANSP, focusing also on the neutron production rate from the fusion reactions either thermonuclear or beam-thermal and beam-beam using the neutron source AFSI module included in the ETS and the TRANSP suite equivalent internal module.



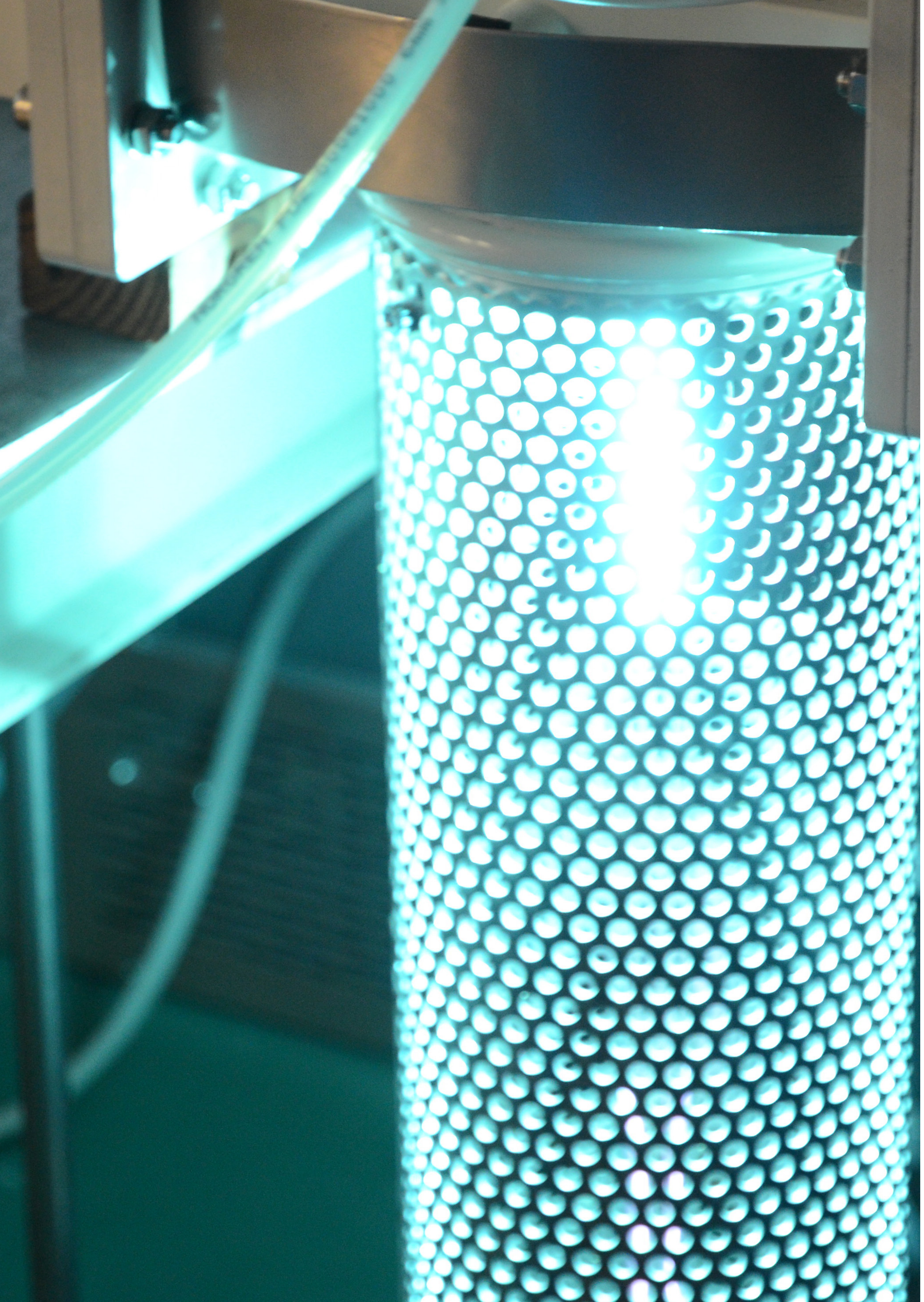
Benchmarking ETS against TRANSP simulation suites, showing neutron production rates from thermonuclear fusion reactions (left) and beam-thermal / beam-beam reaction using the Neutral Beam Injection modules included in both suites (right).

FUNDAMENTAL PLASMA PHENOMENA

In order to get a deeper understanding of the physics of density limit disruptions (DLD) in future nuclear fusion reactors with high-density plasmas, we have investigated the phenomena of secondary instability (SI) observed on typical rotating (2,1) MHD mode prior to the thermal quench (TQ) of a DLD in the COMPASS Tokamak. The SI is observed when the amplitude of the MHD mode is large and its rotation frequency is low and is characterised by small amplitude perturbations, with no poloidal or toroidal mode numbers, superimposed on the perturbations of the precursor mode. The frequency of the SI is higher than the rotating frequency of the mode itself. Focusing on a short period, where the secondary instability develops and covering the TQ, we have found that in the majority (~85%) of DLDs, the mode is still rotating at ≈5 kHz when the TQ occurs while in the remaining DLDs, the mode is quasi-locked to the wall at the TQ. The duration of the high-frequency phase of the SI for quasi-locked modes can be up to four times shorter than for rotating modes, consistent with a faster destruction of energy confinement in DLDs with quasi-locked modes. A general decrease of B_r with the rotation frequency of the mode $f_{2/1}$ was observed. We found that the SI occurs at lower B_r amplitude and higher $f_{2/1}$ for DLDs with rotating modes than with quasi-locked modes. The TQ is triggered only when the SI develops and not at a particular amplitude of the 2/1 mode.



(2,1) mode perturbed B_r vs rotation frequency measured at the beginning of Δt_{sr}



Plasma Technologies and Intense Lasers

The plasma state is commonly called the fourth state of matter. It is generated when energy is provided to a solid, liquid or gas such that a fraction of its atoms is ionised.

The plasma state is the most abundant state of visible matter in the universe, comprising the stars and the interstellar space. On Earth, we are used to natural plasmas, in the form of lightning and flames; and artificial plasmas such as plasma TV displays and fluorescent lamps.

Plasmas come in an amazing variety of parameters, making plasma science a fascinating subject, both at the fundamental and application levels. Plasma-based technologies are used today in a variety of fields spanning from microelectronics and materials processing to waste treatment and environmental control, biotechnology and healthcare.

Laser-produced plasmas are test beds for extreme regimes of nature, where electrons can oscillate at relativistic velocities – and, for instance, become accelerated to GeV energies in a few millimetres, thanks to the overwhelming electric fields associated with electron plasma waves.

Research at IPFN in plasma technologies and intense lasers is dedicated to investigating a multitude of topics in these areas, encompassing theory, simulation and experimental research, in a strongly international environment, and in the framework of several important collaborations with world-leading institutions.

N-PRiME

Main Researchers:

Antonio Tejero-Del-Caz
Carlos D. Pintassilgo
Elena Tatarova
Francisco M. Dias
Jorge Loureiro
Júlio Henriques
Luís Lemos Alves
Luís Marques
Maria Castela
Mário Lino da Silva
Neli Bundaleska
Nuno Pinhão
Rafael Rodrigues
Tiago Silva
Vasco Guerra

Our multidisciplinary activities bridge fundamental studies to very-applied research, and the synergies between both perspectives are paramount to advance knowledge in low-temperature plasmas (LTPs).

At the Plasma Engineering Laboratory (PEL) we use microwave-driven plasmas to tailor matter and energy at the nanoscale level. This impressive know-how is used to conceive, design and operate innovative experimental setups for producing extreme ultraviolet radiation and synthetizing bi-dimensional nanostructured materials.

Our activities in Modelling and Simulation (M&S) aim at describing the dynamics of nonequilibrium LTPs, including its reactive chemistry both in volume and in surface phases. This goal is achieved by developing, verifying and validating predictive numerical tools, for a large variety of systems and conditions.

The research at the Hypersonic Plasmas Laboratory (HPL) pays tribute to the Portuguese heritage on the exploration of new worlds, now with new horizons. HPL hosts the ESTHER shock-tube, the sole Portuguese space facility for the planning of planetary exploration missions.

At the end of 2017, the group entered a totally new stage of development, with the above three research axes operating within targeted projects, funded by various sources. To mark this milestone, the group designation has now become N- Plasmas Reactive: Modelling and Engineering (N-PRiME), where the "N" embeds the goals we seek in our studies: Nonequilibrium, Nanoscale and New horizons in space exploration.

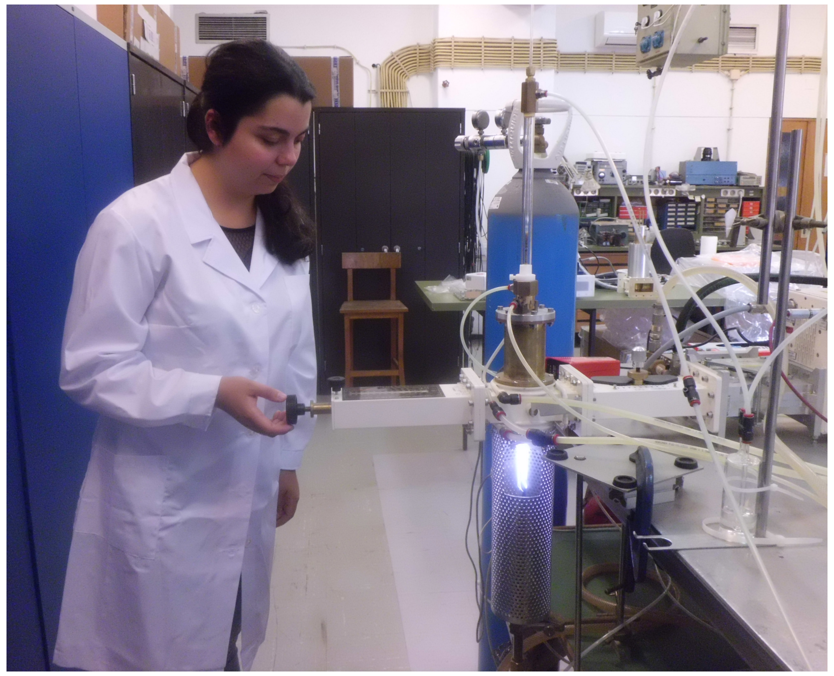
Group Leader: **Luís Lemos Alves**

Plasma Engineering Laboratory

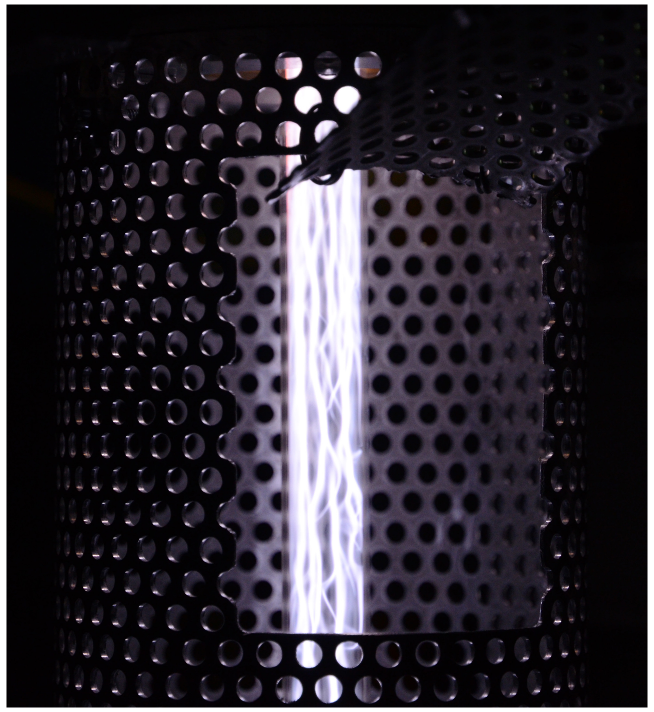
USING MICROWAVES FOR EXPLORING PLASMA NANOSCIENCE

Research activities at the Plasma Engineering Laboratory (PEL) are related to the recently emerging cutting-edge field of Plasma Nanoscience. They are focused on exploring microwave plasmas as a source of Extreme Ultraviolet (EUV) radiation and a powerful tool for assembling 2D nanostructures.

EUV spectra emitted by microwave-driven Ar/He/H_2 plasmas have been investigated at low-pressure conditions. The spectral lines observed correspond mainly to transitions from excited He^+ ions (e.g. the well-known 30.4 nm line and four other lines in the region 25.6-23.4 nm). The most intense lines of the Ar plasma spectrum correspond to the atomic resonance transitions (104.8-106.7 nm) and to the ion lines (92.0 and 93.2 nm). Emissions at lower wavelengths were also detected, including uncharted lines for which no information is available in radiation databases.

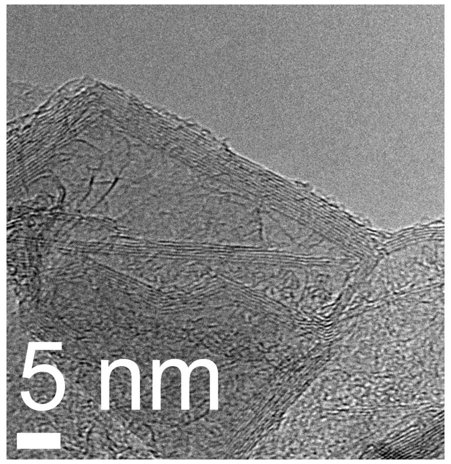


Operation of microwave-driven plasma setup for the synthesis of 2D materials



Micro-wave plasma.

One of the greatest challenges in the commercialization of nanostructured materials (such as graphene and its derivatives) is the reproducible production of high-quality material, in bulk quantities at a low price. The very-limited control over the synthesis process is one of the main problems of conventional production approaches. We provided substantial evidence that microwave plasma technologies, and in particular those based on wave-driven plasmas, can be used as a competitive and disruptive alternative to chemical methods in the controllable fabrication of 2D nanostructures.



HRTEM image of freely suspended graphene

We have developed a microwave plasma-enabled scalable route for continuous, large-scale fabrication of free-standing graphene and nitrogen doped graphene sheets (see previous figure). The method's crucial advantage relies on harnessing unique plasma mechanisms to control the material and energy fluxes of the main building units at the atomic scale. By tailoring the high-energy-density plasma environment and complementarily applying *in situ* IR and soft-UV radiation, a controllable selective synthesis of high-quality graphene sheets at 2 mg/min yield with prescribed structural qualities was achieved (see figure). The method has also the potential for producing other graphene derivatives (e.g. graphene-metal nanocomposites with well-designed nano-architecture), diamond-like nanostructures, and other 2D materials (e.g. boron-doped graphene, hBN, stanene etc). This line of research will be pursued within the recently funded project *Plasma Enabled and Graphene Allowed Unique Nanostructures*, awarded 3.99 M€ in funding.[1]

Plasmas Modelling & Simulation

IN-SITU RESOURCE UTILISATION FOR OXYGEN PRODUCTION ON MARS

Sending a manned mission to Mars is one of the next major steps in our exploration of space. Creating a breathable environment, however, is a substantial challenge. We have shown that Low-temperature Plasmas (LTPs) can hold the key to solve this problem, as Mars has nearly ideal conditions for CO_2 decomposition by plasmas. In particular, the pressure and temperature ranges in the ~96% CO_2 Martian atmosphere favour the vibrational excitation and subsequent up-pumping of the asymmetric stretching mode, at the expense of the excitation of the other modes. The LTP decomposition method offers a twofold solution for a manned mission to Mars: it would

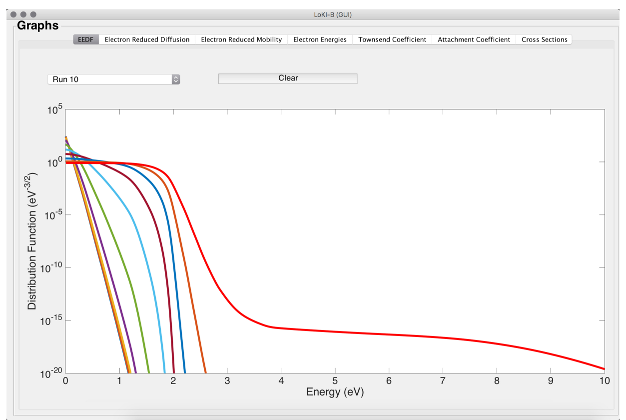
1 766894-PEGASUS-H2020-FETOPEN-2016-2017

provide a stable, reliable supply of oxygen, as well as a source of fuel, since carbon monoxide has been proposed as to be used as a propellant mixture in rocket vehicles.

Image from NASA - National Aeronautics and Space Administration from the United States federal government.

NEW COMPUTATIONAL PLATFORMS TO SIMULATE NON-EQUILIBRIUM REACTIVE PLASMAS

Increasing the ability to quantitatively predict the behaviour of LTPs can leverage scientific understanding issues and limit the time, cost and risk associated with the development of novel plasma-based technologies. The KInetic Testbed for PLASMa Environmental and Biological Applications (KIT-PLASMEBA) started in 2016, aiming to develop a web-platform (KIT) with state-of-the-art kinetic schemes, and a MATLAB® kinetic code (LisbOn KInetics, LoKI) embedding a Boltzmann solver (LoKI-B, to become open-source) and a Chemistry solver (LoKI-C) for N_2-O_2 mixtures in the presence of rare gases. At present, LoKI-B was internally released, along with the first version of KITs for O_2/O and N_2/N mixtures. The next steps will focus on the development of LoKI-C and of other KITs, also consolidating the research outcomes through verification and validation procedures.



Graphical user interface of LoKI-B, displaying the electron energy distribution function for N_2.

DEGRADATION OF PHARMACEUTICAL COMPOUNDS IN EFFLUENTS USING NON-THERMAL PLASMA

The use of plasmas in interaction with liquids is one of the emerging advanced oxidation processes for water treatment and for the elimination of pharmaceutical products. Our goal was to study the degradation of clofibric acid using a corona discharge in contact with the liquid and compare with a gamma radiation treatment. We found that both technologies are effective, the degradation following similar but not identical paths, for which a new degradation law was obtained.

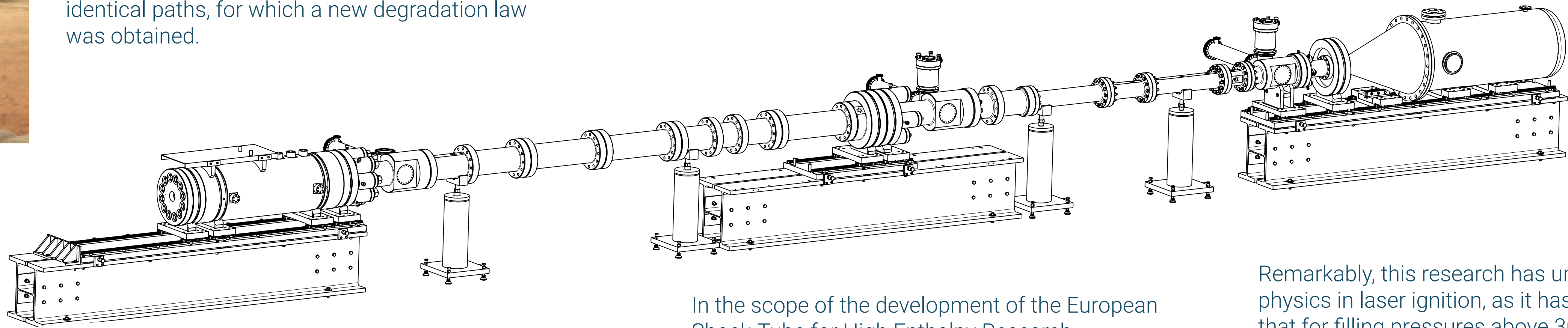
CO_2 PLASMAS: MIMICKING THE BIOGEOCHEMICAL CYCLE OF EARTH

Achieving CO_2 dissociation at low energetic cost is the key for various energy storage strategies and for the viability of new organic synthesis. LTPs are very promising for activating the CO_2 molecule due to their ability to spend most of the energy on vibrational excitation of molecules, a key factor for an efficient plasma dissociation. The goal of project PREMiERE (CO_2 Plasmas: a fRiEndly Medium for Renewable Energy), started in 2016 is to conduct a thorough theoretical and simulation investigation of all the steps involved in plasma decomposition of CO_2. We have developed a detailed kinetic model describing the kinetics of the lowest vibrational levels and established a *reaction mechanism* for the vibrational kinetics of these CO_2 levels. Moreover, we demonstrated the need for further improvement of the electron impact cross sections.

Hypersonic Plasmas Laboratory

ULTRA-HIGH-PRESSURE IGNITION OF H_2/HE/O_2 MIXTURES USING A LASER SOURCE

High-intensity pulsed lasers have recently been introduced as viable alternatives to spark ignition systems, with several advantages such as cleanliness and the possibility of having the overall ignition source setup outside of the combustion chamber.



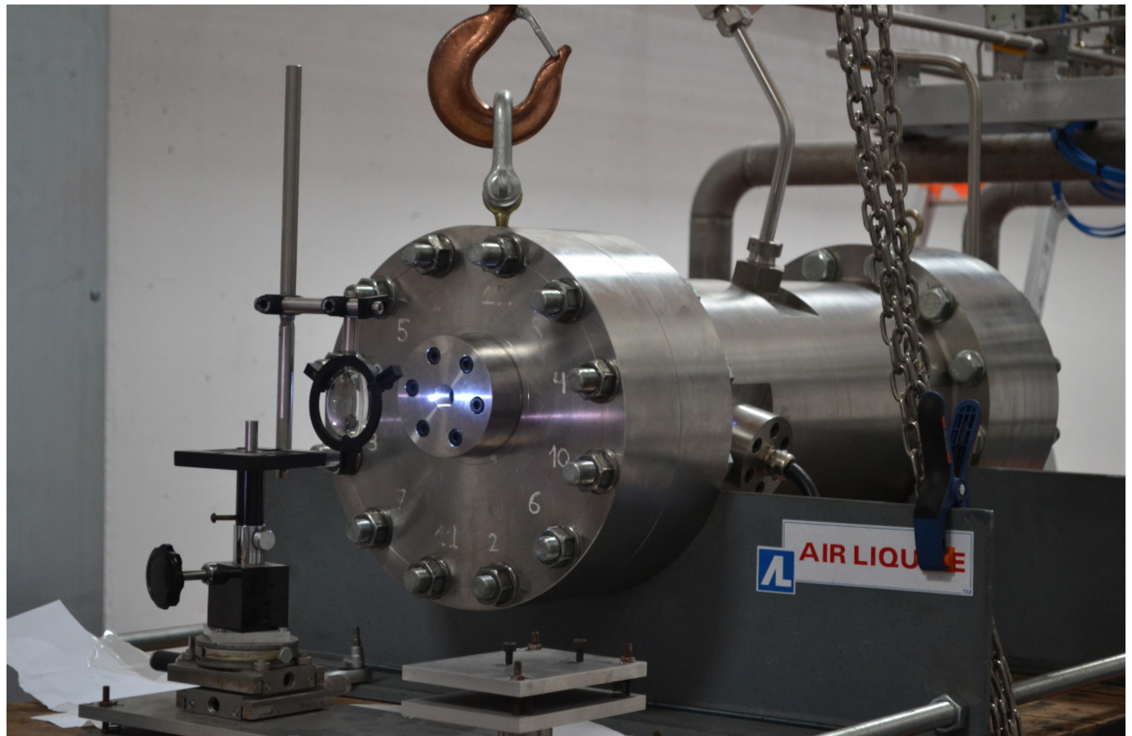
3D view of the ESTHER shock-tube.

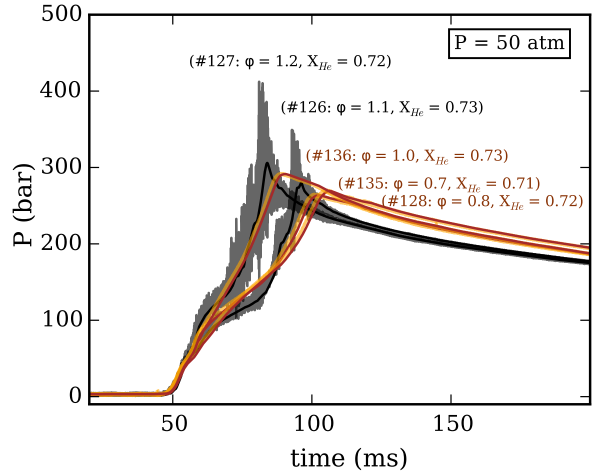
In the scope of the development of the European Shock-Tube for High Enthalpy Research (ESTHER), we have demonstrated laser ignition to be a promising alternative for the ignition of the shock-tube driver, a technology breakthrough that will solve issues common in combustion-driven shock-tubes, such as pollution from spark systems and the necessity to have robust, detonation-resistant ignition components inside the combustion chamber.

In March 2016, we concluded an exploratory programme leading to the safe ignition of H_2/He/O_2 mixtures with filling pressures capping at 100 bar. This represents a world record compared to past experiments that only demonstrated the feasibility of this ignition technique up to 60 bar. The prototype combustion chamber operated at HPL has been filled with a lean 8:2:1.3 He/H_2/O_2 mixture with initial pressures ranging between 5 and 100 bar. Ignition of the mixture has been achieved through the focusing of a ms-pulse from an Nd:YAG laser. A post-combustion pressure of up to 620 atmospheres has been recorded.

Remarkably, this research has uncovered new physics in laser ignition, as it has been found that for filling pressures above 30 bar ignition may be reached using an unfocused laser, with an irradiance of about 10^8 Wm^{-2}, i.e. three orders of magnitude below the accepted limits of 10^{11} Wm^{-2} cited in the literature for reliable ignition of such mixtures. This scientific breakthrough opens new avenues for understanding the physics of laser-ignition combustion, to be further pursued in ESTHER, the first laser-ignited facility of its kind in the world.

Laser ignition setup for the prototype combustion chamber at HPL.





Pressure vs. time in the combustion chamber, ignited with both focused and non-focused laser beam.

High-Pressure Plasmas

Main Researchers:

Mário Dionísio Cunha

Mikhail Benilov

Pedro Almeida

What are the mechanisms of operation of cathodic spots of vacuum arc discharges? What is the role of explosive electron emission? Apart from searching answers to these questions, our group has continued to advance theory and modelling of current spots, and patterns of spots, on electrodes of gas discharges.

Our main goals are: to develop a numerical model of cathodic spots of vacuum arcs, accounting for all the potentially relevant mechanisms; to develop physically justified and practicable methods of modelling of interaction of high-pressure arcs with refractory electrodes; to analyse observations of transitions between modes with different spot configurations in glow microdischarges with the aim to identify eventual bifurcations; and to compute self-organized patterns of spots on a flat metallic anode of a glow discharge.

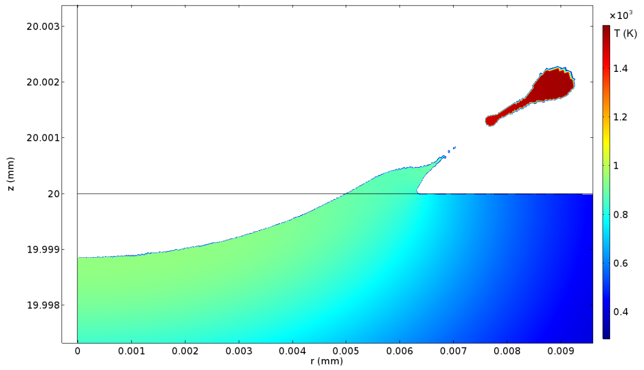
Methods used to achieve those goals range from numerical modelling, to the theory of self-organization in bistable nonlinear dissipative systems, to order-of-magnitude estimates and qualitative considerations. The obtained results, in particular, proved useful for the investigation of physics of high-power circuit breakers, which is conducted in the framework of two industry-sponsored projects.

Group Leader: **Mikhail Benilov**

Research highlights

PHYSICS OF CATHODE SPOTS IN VACUUM ARCS

Understanding of mechanisms of operation of cathodic spots of vacuum arc discharges, including the role of explosive electron emission, is a challenging topic of high scientific interest and importance for applications. We conducted this research on the suggestion of, and in collaboration with, colleagues from Siemens Corporate Technology (Erlangen, Germany), one of the aims being the application of results to contacts of high-power vacuum circuit breakers. Our main goal was to develop a comprehensive numerical model of cathodic spots of vacuum arcs, accounting for all the potentially relevant mechanisms: the bombardment of the cathode surface by ions coming from a pre-existing plasma cloud; vaporisation of the cathode material in the spot, its ionisation and the interaction of the produced plasma with the cathode; the Joule heat generation in the cathode body; melting of the cathode material and motion of the melt under the effect of the plasma pressure and the Lorentz force and related phenomena.



Droplet detachment from a Cu cathode of a vacuum arc. The bar is in K. The maximum temperature of copper is about 1500 K.

All phases of the life of a spot have been investigated, from ignition to extinction. The latter is accompanied by emission of a droplet. No explosions have been observed, which disproves the reigning paradigm of ectons (explosive electron emission centres). The modelling results conform to experimental data on the net and ion erosion of copper cathodes of vacuum arcs. One of our papers on this topic was selected by the editors for promotion through AIP's *Scilights* project.[1]

1 H. T. C. Kaufmann et al., J. Appl. Phys. 122, 163303 (2017)

In the future, the developed model will be used for investigation of unipolar arcs in fusion devices and of cathode erosion in other types of gas discharges.

Mikhail Benilov, group leader.

MODELLING OF PLASMA-ELECTRODE INTERACTION IN HIGH-PRESSURE ARC DISCHARGES

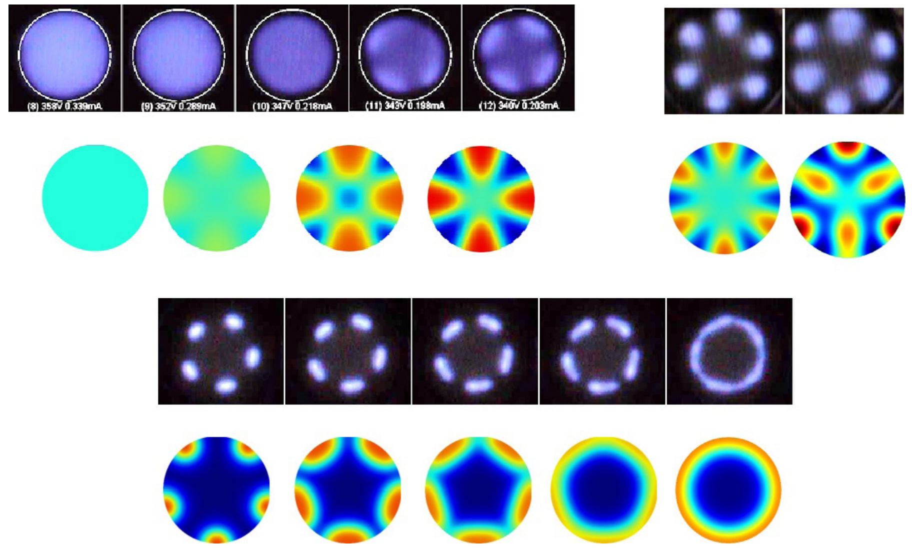
Efficient methods of modelling of electric arcs in a high-pressure environment are of high importance for many technical devices, and the interaction of arc plasmas with electrodes, in the first place, the cathode, is currently a bottleneck. This explains a surge of interest in plasma-electrode interaction in high-pressure arc discharges in the scientific community that has occurred over the past couple of years.

Our main goal was to develop physically justified and practicable methods of modelling the interaction of high-pressure arc plasmas with refractory electrodes. This research was started on the suggestions of, and conducted in collaboration with, colleagues from Leibniz Institute for Plasma Science and Technology (Greifswald, Germany) and GREMI (CNRS/Université d'Orléans, Orléans, France).

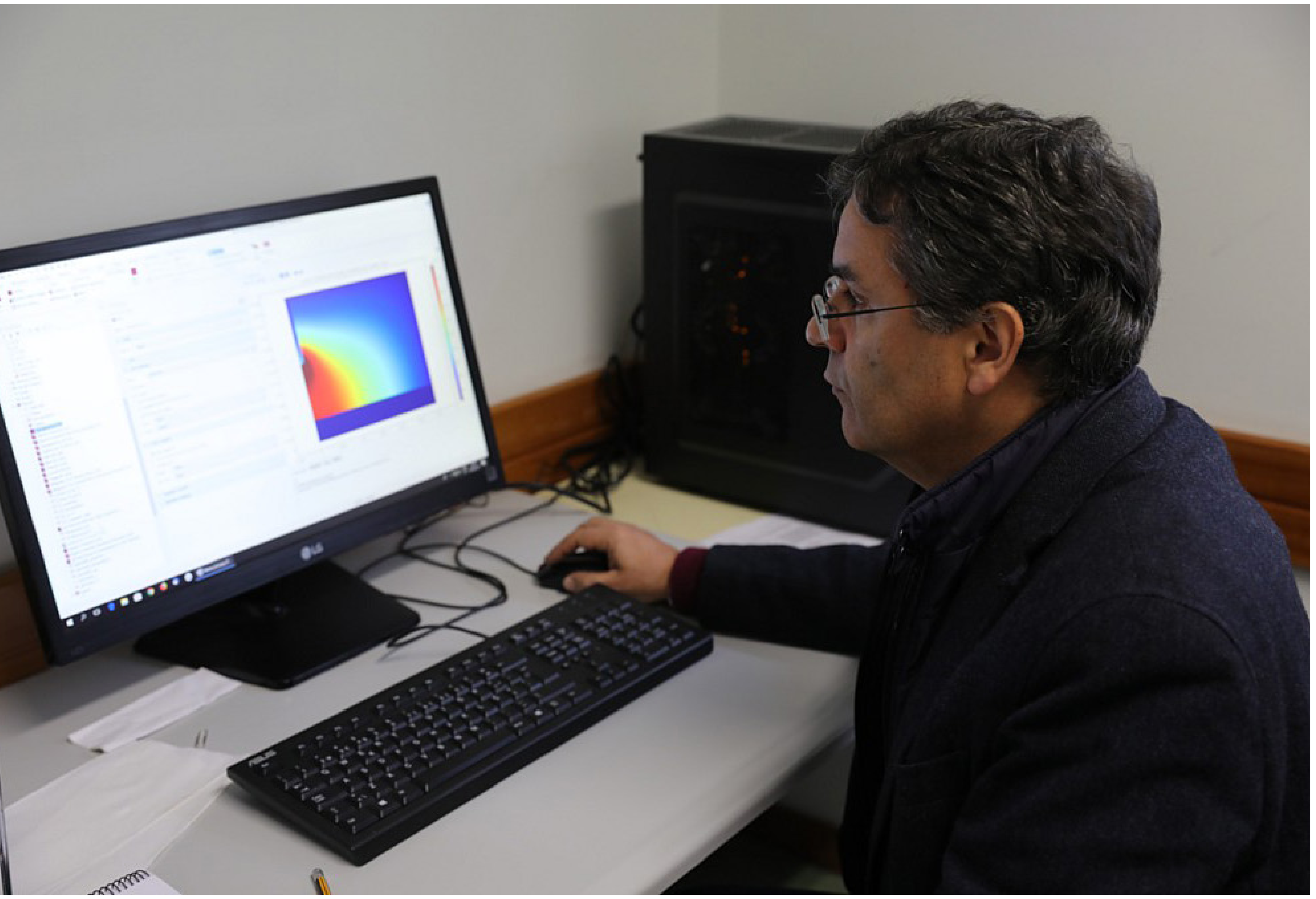
We have developed two models of plasma-cathode interaction, relying on different descriptions of the arc bulk plasma: a description based on the assumption of local thermodynamic equilibrium (LTE) in the bulk and a fully non-equilibrium (non-LTE) description. The two models give results that are in good agreement with each other and with the experiment. Also developed was a model of plasma-anode interaction. The model employing the assumption of LTE in the bulk plasma has significant potential and may serve as a basis for the development of industrial modelling tools.

BIFURCATIONS IN THE THEORY OF CURRENT TRANSFER TO CATHODES OF DC DISCHARGES AND TRANSITIONS BETWEEN DIFFERENT MODES

The concentration of electrical current onto the surface of the electrodes of gas discharges in well-defined regions, or current spots, is often the rule rather than the exception. These spots occur on otherwise uniform electrode surfaces, a regime where one might expect a uniform distribution of current over the surface. In many cases, multiple spots may appear, forming beautiful patterns and



Experimentally observed and computed transitions between different modes in glow microdischarges in xenon.



Mário Cunha working on simulations of plasma-electrode interaction.

surprising the observer. The theory of the different modes of current transfer to electrodes of gas discharges is an important part of gas discharge theory in general and is needed for applications.

Modern theoretical description of spots and spot patterns on electrodes of dc glow and arc discharges is based on the multiplicity of solutions: an adequate theoretical model must in some cases allow multiple steady-state solutions to exist for the same conditions (in particular, for the same discharge current I), with different solutions describing the spotless (diffuse) mode of current transfer and modes with different spot configurations. The cornerstone of the theory is the existence of bifurcations of steady-state solutions. Unfortunately, this question has not been addressed in experimental publications on observations of transitions between spotless mode and modes with different spot configurations.

Our goal was to analyse these observations with the aim to identify eventual bifurcations. We have employed a basic numerical model of glow microdischarges, which includes a single ionisation channel and a single ion species, and a detailed model, which accounts for different ionisation channels, different ion and excited species, and nonlocality of electron transport and kinetics.

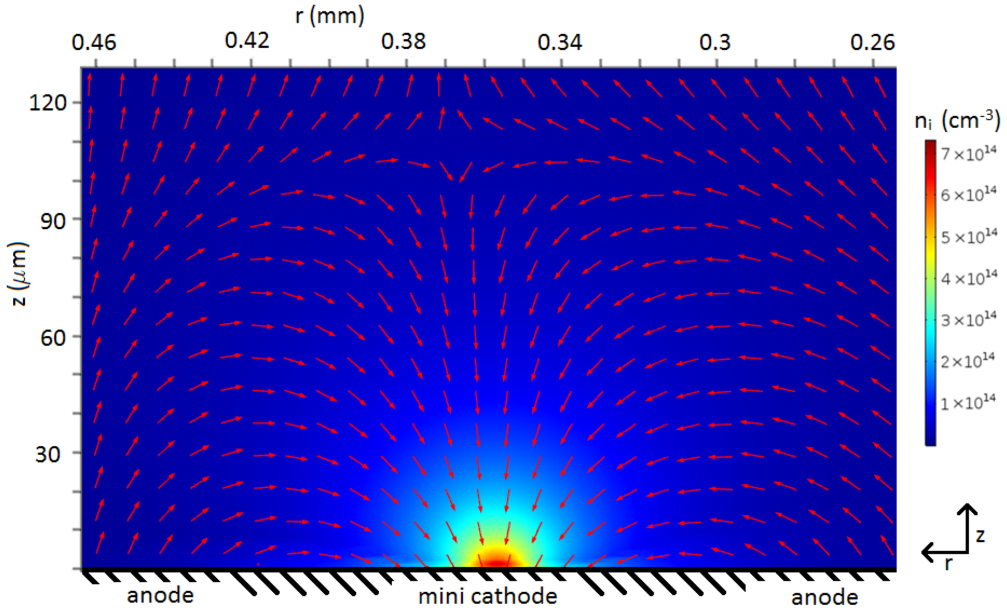
We have computed the relevant bifurcations and spot patterns and found that the latter conform to spot patterns observed in the course of the corresponding transitions in the experiment. While the comparison between the theory and the experiment still remains qualitative, the agreement is convincing and lends further support to the theory.

MODELLING ANODE SPOTS IN A DC GLOW DISCHARGE

Beautiful patterns on anodes of DC glow discharges have been observed for over a century. In addition to being of significant theoretical interest by themselves, self-organised patterns on liquid anodes of atmospheric pressure glow microdischarges reveal a non-trivial cancer-inhibiting capability.

Our goal was to compute self-organised patterns of spots on a flat metallic anode of a glow discharge. We have employed a standard model of a glow discharge in a computational domain comprising the near-anode region.

We have computed multiple solutions existing in the same range of discharge current and describing the spotless mode and modes with patterns of anode spots. In contrast to dc glow and arc discharges, multiple steady-state solutions describing different modes of current transfer do not reveal bifurcations. We found that the existence of multiple solutions, in this case, is a consequence of the change of sign of the anode sheath voltage. The computed spots exhibit a double layer-type structure and a reversal of electric field and current density.



Density of ions in cross section through the centre of an anode spot. Red arrows: direction of current density. Reversal of current density is apparent.

PhD student Nuno Ferreira simulating a streamer discharge.

Lasers and Plasmas

Main Researchers:

Gonçalo Figueira
João M.Dias
Jorge Vieira
Luís Oliveira e Silva
Marta Fajardo
Nelson Lopes
Ricardo Fonseca
Thomas Grismayer

How does matter behave in extreme electromagnetic fields, either at ultra-relativistic intensities, ultra-short timescales or at extremely hard wavelengths? What are the conditions for the creation of pair plasmas in the laboratory under the action of ultra intense fields and what is the role of the self-consistent collective dynamics of such plasmas, in laboratory and in astrophysics?

Can one use plasma acceleration to develop compact accelerators for use at the energy frontier, in medicine, in probing materials, and in novel light sources for bioimaging? What are the mechanisms for particle acceleration in relativistic shocks and what can we learn about these cosmic accelerators in a laboratory experiment?

Can advanced ignition concepts be used to develop inertial fusion energy? What are the enabling technologies to construct a laser with a peak power of over 1 Exawatt that would allow us to study matter subject to unprecedented forces?

These are some of the most challenging science questions in our field, being propelled by new ultra high intensity lasers and light sources, and plasma-based accelerator projects combined with the exploration of Tier-0 supercomputers.

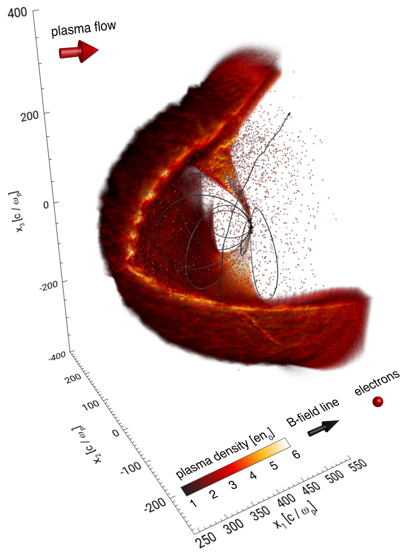
The overarching research topic is the behaviour of matter in extreme electromagnetic fields, with an emphasis on particle acceleration and radiation generation. Answering these questions holds the promise not only of advances on the fundamental scientific questions but also of significant societal impact in secondary sources for bioimaging, photonics, medical therapy, or fusion energy.

Group Leader: **Luís Oliveira e Silva**

Research highlights

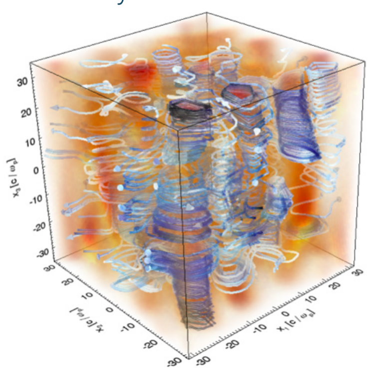
EXTREME ASTROPHYSICAL CONDITIONS IN THE LABORATORY

The key open challenges in astrophysics involve the acceleration of particles to extremely high energies (up to 10^{20} eV) and the mechanisms by which these particles can emit extreme radiation bursts measured on Earth. Our work combines theory, simulations and experiments that reproduce astrophysical conditions in the laboratory, in order to address critical components associated with these puzzles. In a collaboration with scientists from the UK, we have mimicked in the laboratory sub-relativistic astrophysical shocks as a source of energetic particles, both experimentally and through detailed PIC simulations using our code, Osiris. This work constitutes an important step towards the validation of particle acceleration models used to explain the high-energy electrons observed at strong astrophysical shocks.[1]



Formation of a collisionless bow shock in the interaction between a plasma flow and a magnetic obstacle: a candidate mechanism to explain energetic electron populations in astrophysical scenarios.

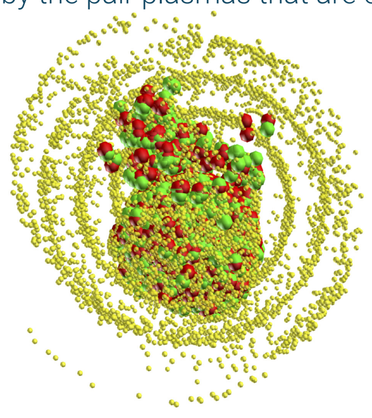
In another collaboration with the Tata Institute of Fundamental Research, India, we investigated magnetic turbulence measured in a laser-solid interaction experiment. Our research is critical to understand the origin of magnetic fields in astrophysics, which is the first step to understand and explain the origin of gamma-ray bursts. The laboratory model employed intense laser-plasma interactions to create initial magnetic fields that were measured and compared with our simulations.[2]



Magnetic field lines associated with an intense laser-plasma interaction experiment to explore the origin of magnetic fields in astrophysical settings.

QUANTUM ELECTRODYNAMICS IN PLASMA PHYSICS: PAIR PLASMA PRODUCTION

Is there a limit for the maximum intensity that a beam of light can reach? Can lasers boil the vacuum? These are two outstanding questions in the study of strong field quantum- electrodynamics (QED). Motivated by these longstanding challenges, our recent research focuses on the pair plasma production via QED cascades, and how light is absorbed by the pair plasmas that are created. With the overarching goal of maximising the pair plasma production with soon to be available laser pulses in the laboratory, we developed a new theoretical framework confirmed by Osiris-QED simulations to explore electron-positron pair production in ultra-high-intensity optical lattices resulting from two[3] and four[4] colliding laser pulses. Our work sets the stage for the experiments aimed at producing pair-plasmas in purely all-optical setups, and to understand the nonlinear processes that determine light absorption in self-generated electron-positron plasmas colliding laser pulses. Our work sets the stage for the experiments aimed at producing pair-plasmas in purely all-optical setups, and to understand the nonlinear processes that determine light absorption in self- generated electron-positron plasmas.[5]



Electron-positron cascade in a standing wave produced by two circularly polarised laser pulses. The photons propagate through the intense background field and decay to create new particles.

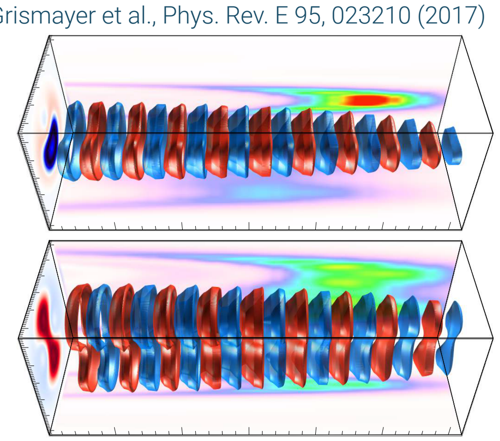
1 A. Rigby, F. Cruz et al., subm. Nat. Phys. (2017)

2 G. Chatterjee et al., Nat. Commun.8, 15970, (2017)

PHYSICS AT ULTRA-HIGH INTENSITIES DRIVEN BY STRUCTURED LIGHT

Twisted lasers with orbital angular momentum (OAM) provide a transformative set of tools and research directions in a growing range of fields and applications, from super-resolution microscopy and ultrafast optical communications to quantum computing and astrophysics. Although actively explored at intensities below damage thresholds, the physics at ultra-high intensities has been unexplored. Our work pioneers the use of twisted light as a driver for compact plasma. We showed that twisted

3 T. Grismayer et al., Phys. Rev. E 95, 023210 (2017)



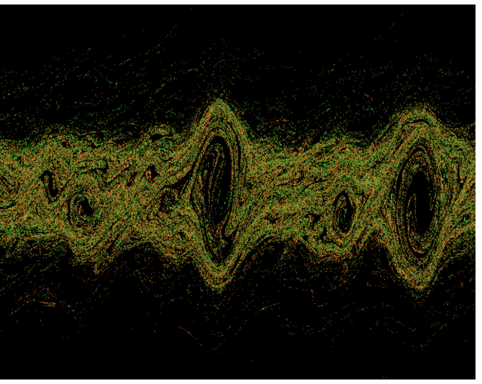
Seed pulse electron field containing high OAM harmonics while it is still in the plasma. (Above) seed pulse with odd OAM harmonics; (bottom) seed pulse with even harmonics.

4 M. Vranic et al., Plasma Phys. Contr. F. 59, 014040 (2017)
5 T. Grismayer et al., Phys. Plasmas 23 (2016)

light can provide a solution to a longstanding challenge in plasma-based accelerators, which is high gradient positron acceleration.[6] We have also explored several plasma processes capable of generating and amplifying twisted light and twisted harmonics beyond the intensity frontier.[7] Our theoretical and computational work is paving the pathways towards the experimental study of ultra-intense twisted lasers with matter in strongly nonlinear regimes.

OSIRIS PARTICLE-IN-CELL FRAMEWORK

Osiris is our fundamental work-tool for simulations in extreme plasma physics team. It was developed from scratch to be used in Tier-0 computational resources. It now also contains advanced hardware support, allowing the code to efficiently use SIMD units on modern CPUs, the new Intel Knights Corner/Landing architectures, and GPGPUs using CUDA. These features allow OSIRIS to be efficiently used on 9 out of the top 10 computing systems in the world.[8] The code has a demonstrated parallel strong scalability of 75% from 4096 to 1.6 million cores on the Sequoia system at LLNL, and reached floating point performances in excess of 2 PFlop/s, corresponding to over 30% of peak theoretical performance of the CPU partition of the BlueWaters system at NSCA. OSIRIS supports additional physics models that extend the application of the PIC algorithm, namely tunnel ionisation, radiation cooling, and binary collisions for applications involving highly collisional plasmas. Furthermore, we added a hybrid high-density model that allows us to explore scenarios ranging from vacuum to solid densities, and a QED module for modelling problems involving extreme fields. OSIRIS was also extended to include the possibility of using reduced models, for faster parameter space exploration.

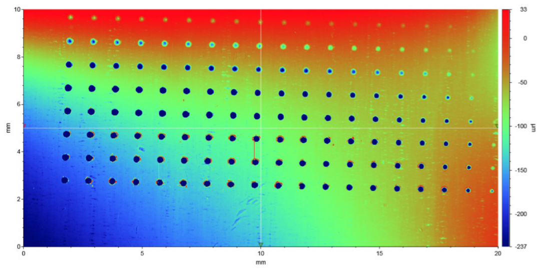


Two-stream instability simulation performed on the educational PIC code ZPIC, illustrating particle trapping and phase-space vortex formation during the nonlinear stage of the instability.

6 J. Vieira et al., Nat. Comms. 7 10371 (2016)
7 J. Vieira et al., Phys. Rev. Lett. 117, 265001 (2016)
8 Top 500 list, June 2017

FEMTOSECOND ABLATION WITH SHAPED LASER PULSES

Femtosecond laser pulses, with durations approaching the timescales of fundamental atomic and molecular processes, have revolutionised a wide range of scientific domains, giving rise to new ultrafast processes and observation techniques.



Two-dimensional map of the depth profile (in μm) of holes in copper. The colour scale shows depths in micrometres. Number of shots ranging from 10 to 5000 (top to bottom) and from 25 μJ to 116 μJ (from right to left).

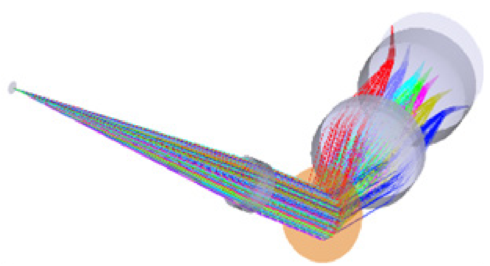
We are interested in investigating the effect of simultaneous pulse spatial and temporal shaping on the dynamics of femtosecond laser ablation. This technique holds the potential to significantly improve the efficiency of the process, contributing to a better understanding of the material processing methods at such extreme timescales.

Our main goal is to apply this technique for materials processing and biological applications. We have developed a new automated ultrafast ablation setup allowing the systematic study over a range of parameters, including beam shaping. This has allowed us to determine the thermal threshold fluence, the depth profiles and the conditions for micro-cracking formation and strong damage, for media such as copper and dentine. The next steps are the implementation of temporal shaping and the acquisition of further measurements in more diverse media.

This work is supported by Fundação Calouste Gulbenkian in the scope of the *Stimulus to Research Prize*.

OPTICAL DESIGN OF COMPACT SPECTROMETERS FOR THE RAMAN SPECTROSCOPY IN RAMSERS PROJECT

The RamSERS project proposes the development of a portable Raman instrument combined with the use of SERS substrates capable of detecting breast cancer biomarkers. In collaboration with the industry, our aim is to develop and test the optical circuits of the compact spectrometers in the project.



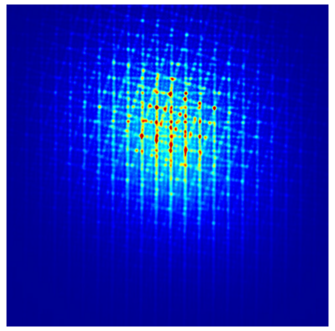
Ray-tracing simulation of compact spectrometer design.

In order to find the best design, an extensive review of the market solutions and possible strategies were studied and a design method was developed. Using a ray-tracing design software, the circuits were simulated and optimised to achieve the proposed specifications.

Two compact spectrometers optical circuits, based on off-the-shelf components, for excitation laser wavelengths of 785 and 1064 nm were obtained for future lab tests.

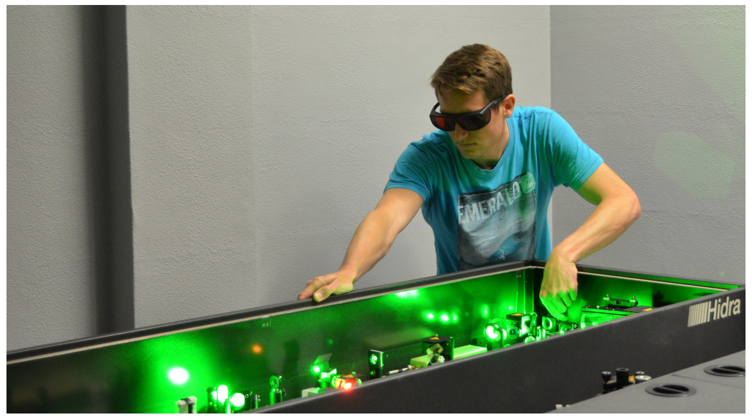
VOLUMETRIC MEDICAL X-RAY IMAGING AT EXTREMELY LOW DOSE (VOXEL)

The ultimate goal of VOXEL, a H2020 FET Project led by IST, is to provide an alternative to tomography with a disruptive technology enabling 3D X-ray imaging at very low dose. We aim to transpose plenoptic imaging to X-rays, enabling single-view 3D reconstruction. A prototype in the soft X-rays will enable microscopic 3D imaging at the sub-micron scale, while demonstration of the concept for hard X-rays will lay out the path toward medical imaging.



Thanks to the high spatiotemporal coherence of XUV the harmonics, a strong Talbot pattern from the periodic grating of a gridded aluminium filter is generated.

Given the wide range of wavelengths (from the visible to the X-rays), a dedicated station for the production of radiation sources, their calibration, and testing of optics and detectors is necessary. The new VOXEL metrology station at IST has the capability to produce short bursts of soft X-ray radiation from High Harmonic Generation, whose coherence makes them ideal to study optical aberrations at or close to target wavelength. The 35 fs, kHz driving laser also provides high flux K-alpha radiation in a very flexible setup.



Working at VOXEL

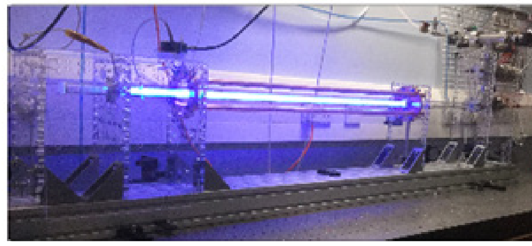
VOXEL achieved first light in the XUV in April 2017. We have since calibrated several X-ray detectors from the VUV to the X-ray range. This allows us to test several components of the VOXEL camera individually, to guide the choice of the final design based on optimal performance.

In the near future, we will characterise soft X-ray focusing optics wavefront and efficiency. Soft X-ray microscopy will be possible with the VOXEL prototype, allowing for 3D information to be captured in a single acquisition.

LONG PLASMAS FOR FUTURE ACCELERATORS

Plasmas can accelerate electron beams to high energy in very short distances, up to 1000x shorter than radiofrequency-based accelerators. The accelerating plasma waves can be driven by high-energy particle beams. Plasma accelerators were successfully demonstrated using electron beams, but now the experiment AWAKE at CERN is dedicated to demonstrating the use of existing high-energy proton beams in compact high-energy accelerators. A key component for these accelerators is a modular and cost-effective plasma source able to produce a pre-formed plasma. We have proposed to use a pulsed electric discharge in an argon-filled glass tube and started a program to develop this technology.

Our main goal is to develop a robust prototype that can reliably produce adequate plasmas for AWAKE. The plasma source consists of a long glass tube containing a controlled pressure, rarefied gas with electrodes in the ends that also interface with the adjacent accelerator sections. The electric discharge circuit uses a very high voltage pulse to ignite the plasma and a high current pulse that heats it and increases the ionisation level to close to 100%.



Plasma source for the AWAKE experiment.

We have built prototypes of lengths up to 3 meters that demonstrate the formation of the adequate plasma using the igniter-heater circuit. The plasma density was measured confirming a high ionisation level. The next steps are the development of longer prototypes to be integrated into the AWAKE experiment.

Community and Outreach

IPFN is deeply committed to taking an active role in the communication of science and the dissemination of its scientific, technological and educational achievements to society. We explore a vast number of communication channels targeted at different audiences, from basic school children through secondary school students and teachers, undergraduate and graduate students, to the media, industry representatives and fellow researchers.

Conferences

IPFN regularly hosts international conferences and meetings, both specialised and broad-scope. The highlights of this period are the following:

- EUROfusion Joint Working Session on Integrated Plasma-Wall Modelling, 8-11 March 2016
- EUROfusion General Assembly, IST, 11-12 April 2016
- EUROfusion Goal Oriented Training on Project & Quality Management, IST, 21-23 June 2016
- XXXIII ICPIG – International Conference on Phenomena in Ionized Gases, Estoril, Portugal, July 9 to 14, 2017
- ExHILP 2017 - Extremely High-Intensity Laser Physics, IST, 5-8 September 2017
- 2nd EUPRAXIA Yearly Meeting, IST, 20-24 November 2017

School visits and talks

Every year, the IPFN facilities such as ISTTOK and L2I receive many tens of school visits, from basic to secondary school students. During the tours, the students have the opportunity to contact with undergraduate students and researchers and have a first contact with the research developed at IPFN, the technologies involved and perspectives of future careers.

Our researchers are also frequently invited to give talks at schools, workshops, training sessions and public events.

Workshops, training and outreach events

We have organised a number of events targeted to different audiences, for education, for training and for sheer scientific fun!

Plants on Mars workshop for high school teachers

Young people with energy workshop for high school students

Ciência Viva summer course for pre-university students

European Researchers Night at Pavilhão do Conhecimento

Light and Art workshop for middle school students

Web and media

The main communication channels used by IPFN are online based. The main highlight of this period goes to our new website, which was launched in July 2016 after a major redesign and content definition. Apart from this, we also create about ten press releases per year for Portuguese and international media.

Our online presence of IPFN is now extended over five different channels:

Webpage – ipfn.tecnico.ulisboa.pt

The central hub of all our websites, with news, events and detailed information about activities and scientific results.

Facebook – fb.com/IPFNLA

Launched in 2010, the IPFN page has gathered more than 1000 followers, with a growth of 20% in 2016/17.

YouTube – youtube.com/IPFNmedia

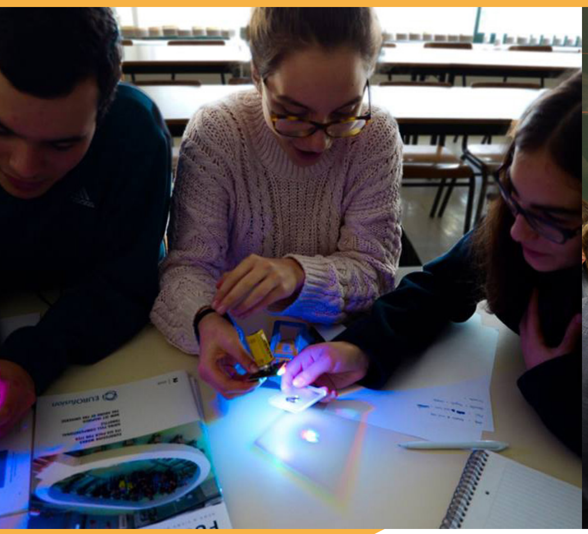
It serves as a video repository, either for dissemination purposes or events taking place at IPFN.

LinkedIn – lnked.in/ipfn

Connecting current, previous and prospective employees, while also disseminating career opportunities.

Flickr – flickr.com/ipfn

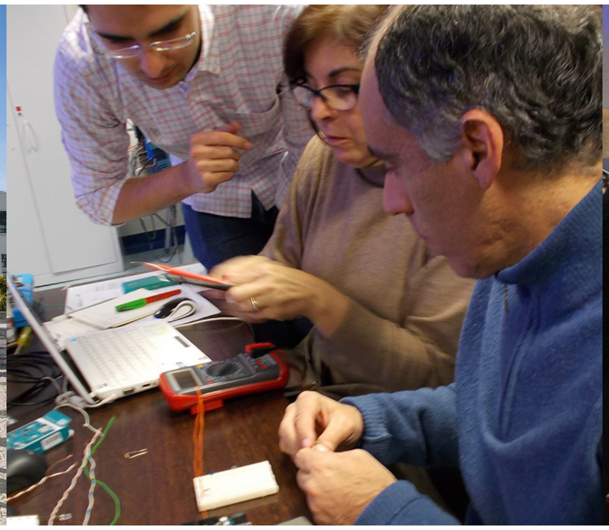
Database of high-quality photos, graphics and scientific images, with more than 200 pictures.



Light and Art workshop for middle school students.

Ciência Viva summer course for pre-university students.

2nd EUPRAXIA Yearly Meeting.



Plants on Mars - workshop for high school teachers.

European Researchers Night at Pavilhão do Conhecimento.

Education

IPFN is strongly involved in academic teaching, with many of its researchers belonging to the faculty of the Physics Department at IST. IPFN ensures teaching, student training and supervision in the broad scientific area of Plasma Physics, Lasers and Nuclear Fusion of this department. The 2nd (MSc) and 3rd (PhD) cycles have a number of specialised courses in these topics. Additionally, IPFN develops a number of dissemination and outreach activities targeting both undergraduate and graduate students and prospective candidates.

APPLAuSE students at the Doors Open Day 2016

APPLAuSE C2 students at Técnico PhD Open Days 2016

Participants in the ATHENS courses of 2017

Participants in the Plasmasurf Summer School of 2017

APPLAuSE doctoral programme

APPLAuSE is IPFN's flagship international doctoral programme in Plasma Science and Engineering. Funded by FCT and hosted by IPFN, the degree is awarded by the University of Lisbon, Portugal. During 2016-2017, the 3rd and 4th cohorts joined the programme, adding 17 new students.

A total of 34 students are currently enrolled in APPLAuSE, distributed over its 4 years, and originating from 11 countries in 4 continents.

For more information:

https://www.ipfn.tecnico.ulisboa.pt/education/applause

ATHENS course on Plasma Science and Technology

This biannual course is targeted at students attending European technological universities within the ATHENS network. For a week, the students are exposed to the fundamentals of plasma physics and its technological applications through lectures and hands-on modules.

The programme included topics such as plasmas in nature, fluid and kinetic theories, plasma applications, plasma probes, workshops and a visit to the ISTTOK tokamak. Students are evaluated through homework and a final written exam.

For more information:

http://www.athensprogramme.com/catalog/show/2004

IPFN Colloquium

The groups at IPFN promote a large number of regular seminars with specialised talks by local and guest speakers. Starting in 2015, the high-profile IPFN Colloquium series aims to bring renowned researchers from world-leading institutions to give talks for a wider audience.

PlasmaSurf 2017

PlasmaSurf is IPFN's established summer school on plasma physics and related topics. It is specifically tailored for engineering and physics students aiming at complementing their education with a PhD in plasma physics, high power lasers or nuclear fusion.

The programme includes lectures, visits to laboratories and plenty of outdoor activities and water sports. Bringing together science and seaside adventure, PlasmaSurf has emerged to become one of Europe's most popular summer schools in these fields.

For more information:

http://plasmasurf.tecnico.ulisboa.pt/

Awards and Distinctions

European Grants

Luís O. Silva, Advanced Grant, European Research Council (2016)

Public Awards

Luís O. Silva, Grand Officer, Order of Public Instruction (Portugal)

Carlos Varandas, Medal of Scientific Merit by the Ministry of Science, Technology and Higher Education (Portugal)

Vasco Guerra, winner of the 2016 William Crookes Prize

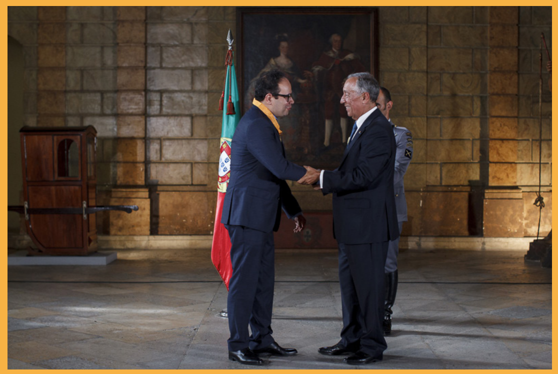
Thesis Prizes

Paulo Alves, Honourable Mention of Abreu Faro Prize for the best PhD thesis in Electrical Engineering, Informatics, Mathematics and Physics

Celso João, Best PhD in Optics and Photonics 2017, awarded by the Portuguese Society for Optics and Photonics

Mariana Moreira, Best MSc Thesis in Plasma Physics, Lasers and Nuclear Fusion in 2016/2017, Physics Dept., IST

Marija Vranic, John Dawson PhD Thesis Prize, for the best PhD thesis in the area of plasma accelerators driven by ultra-intense laser pulses



Luís O. Silva receiving the Order of Public Instruction from Portugal's President

Community Awards

Luís O. Silva, fellow of the European Physical Society (2016)

Vasco Guerra, 2016 William Crookes Prize, awarded by EPS/PSST

Scientific Prizes

Fábio Cruz and ***Victor Hariton***, 2016 Young Researchers Incentive Programme, Calouste Gulbenkian Foundation

Jorge Vieira, Honorable mention, University of Lisbon Science Prizes 2016

Conferences

Dirkjan Verheij and ***Maria Isabel Fialho,*** Best Poster Presentation Award, International Conference on Surface Modification of Materials by Ion Beams - SMMIB-2017

Miguel Sequeira, Best Oral Presentation Award, 19th International Conference on Radiation Effects in Insulators - REI19

Ana Dias, EPS Poster Prize, 27th Symposium on Plasma Physics and Technology 2016

Diana Amorim, Best Student Poster Prize, Advanced Accelerator Concepts Workshop 2016

Giannandrea Inchingolo, PPCF/EPS/IUPAP Poster Prize, 44th EPS Conference on Plasma Physics

Marija Vranic, winner of the John Dawson PhD Thesis Prize

Annual Report 2016 - 2017

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