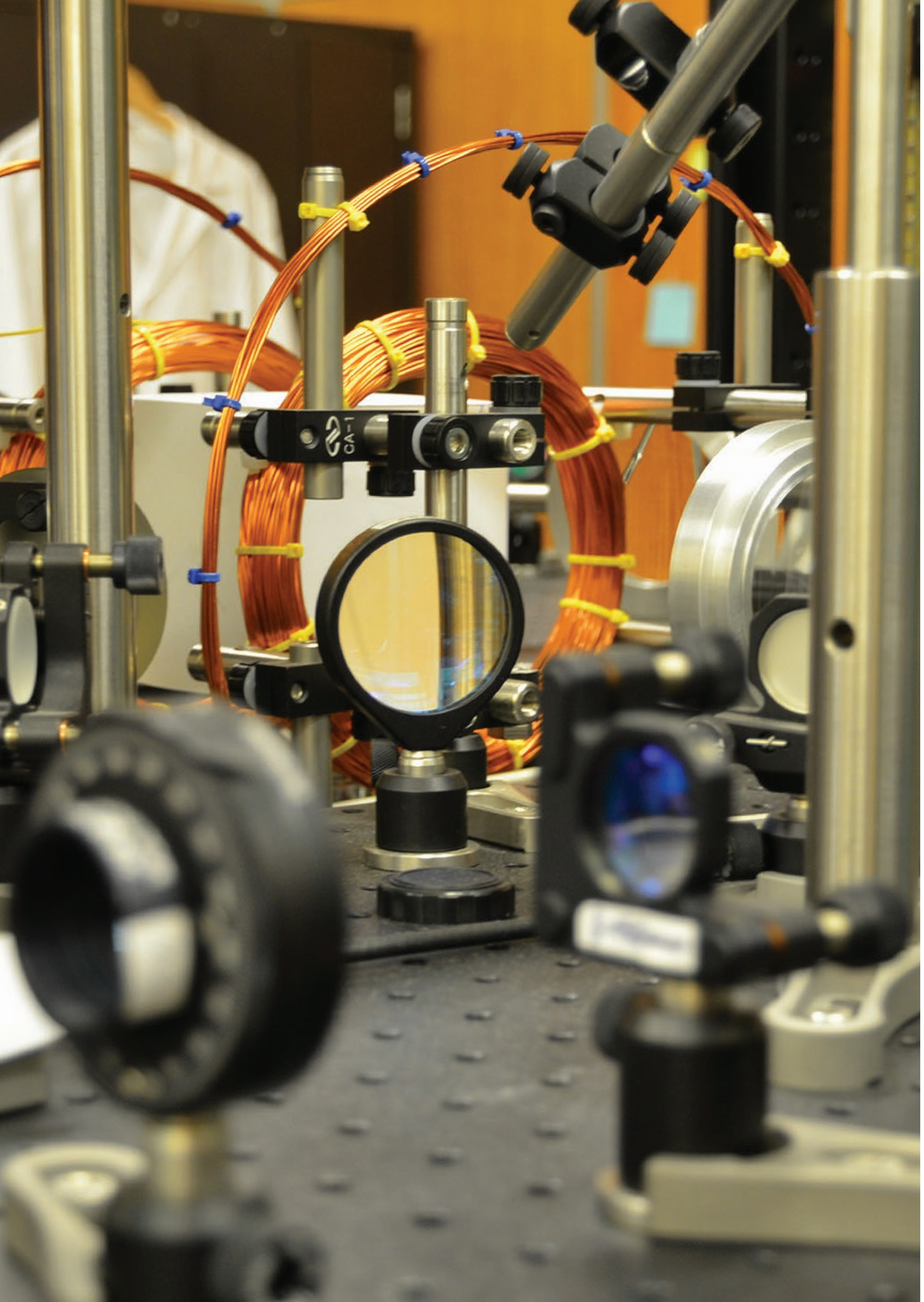
Annual Report 2014-2015

Instituto de Plasmas e Fusão Nuclear

ipfn
INSTITUTO DE PLASMAS
E FUSÃO NUCLEAR



Annual Report 2014-2015

Instituto de Plasmas e Fusão Nuclear

Highlights of activities

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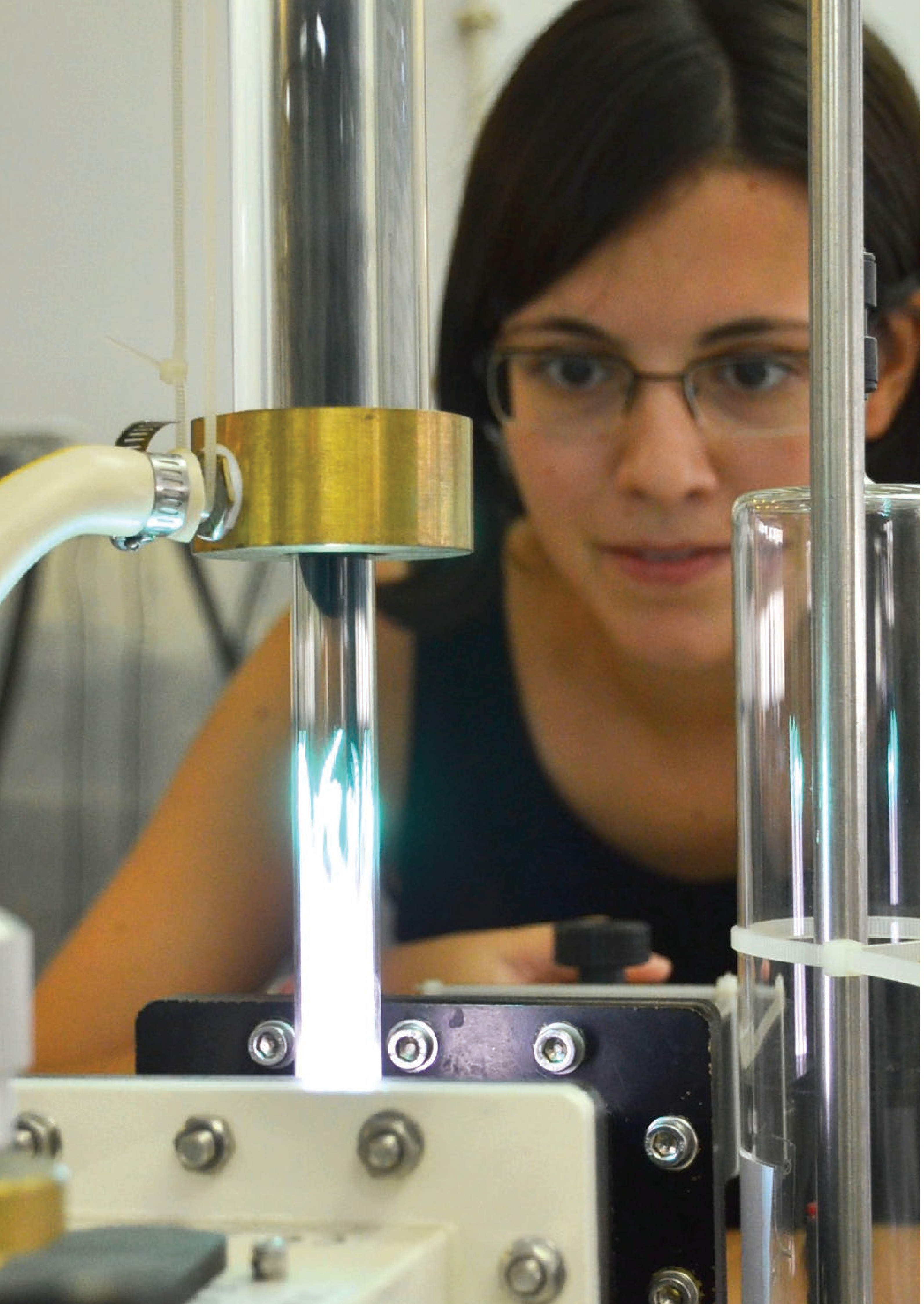


Contents

President's Foreword

I am very pleased to present the Highlights of 2014-2015 of the Instituto de Plasmas e Fusão Nuclear. This report covers the activities carried out in the scope of the EUROfusion Consortium, the Contract of Associated Laboratory, the Contracts with the ITER International Organisation (ITER IO) and the European Joint Undertaking for ITER and Fusion Energy (F4E), Projects of the Horizon2020 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 exciting period that started with the recognition of the role of the research unit, both at national and international level, by the FCT evaluation panel which awarded IPFN with the classification "Exceptional". On behalf of the IPFN Administrative Board I would like to thank our staff for the work performed and the excellent results that lead to this evaluation and that continued throughout 2014 and 2015.

" The strength of IPFN lies in the dedication and commitment of its researchers, technicians, students and administrative staff "

Furthermore, IPFN accomplished a remarkable number of milestones and achievements:

- Participation in several contracts with Fusion for Energy for the development of ITER diagnostics both as leader (Plasma Position Reflectometer) and in partnership with other institutions (Collective Thomson Scattering, Radial Neutron Camera).
- Strong participation in the European Fusion Programme. The year of 2014 also marked the start of the activities of EUROfusion consortium. The integration into the activities of the Fusion Roadmap and of the Framework Programme Horizon2020 required strategic thinking and adaptation. IPFN researchers endured and succeeded in this challenge and are strongly involved in several EUROfusion tasks. Among other activities, it is worth noting the contribution to JET scientific exploitation, on JET operation (several IST researchers work full time at JET providing support to operation and diagnostics) and on JET management, and the contribution to medium-size tokamaks, in particular ASDEX Upgrade, which have been an integral part of the activities.
- Strong progresses on the synthesis of graphene and other carbon nanostructures using microwave generated plasmas.
- 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 reentry effects as well as further synergies between IPFN research groups, namely on control and data acquisition, diagnostics development, and material characterisation.

These projects fostered innovation, created qualified employment and enhanced the team recognition and ability to attract additional funding and innovation through R&D activities. The excellence of the research performed at IPFN has been recognised through several awards won by our researchers and through a high number of publications in prestigious journals.

High-level Education and Outreach activities are essential in this strategy. At IPFN we actively strive towards attracting the best MSc and PhD students. The Advanced Programme on Plasma Science and Engineering (APPLAuSE) awarded to IPFN in 2013 is crucial to achieve this goal. Furthermore, we know that new blood is fundamental to the research unit's success and we continue motivating new generations to science through courses on Lasers and Nuclear Fusion for secondary school teachers, seminars at 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 with results.

The strength of IPFN lies in the dedication and commitment of its researchers, technicians, students and administrative staff. I am confident that together we will continue to excel!

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 on 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 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:

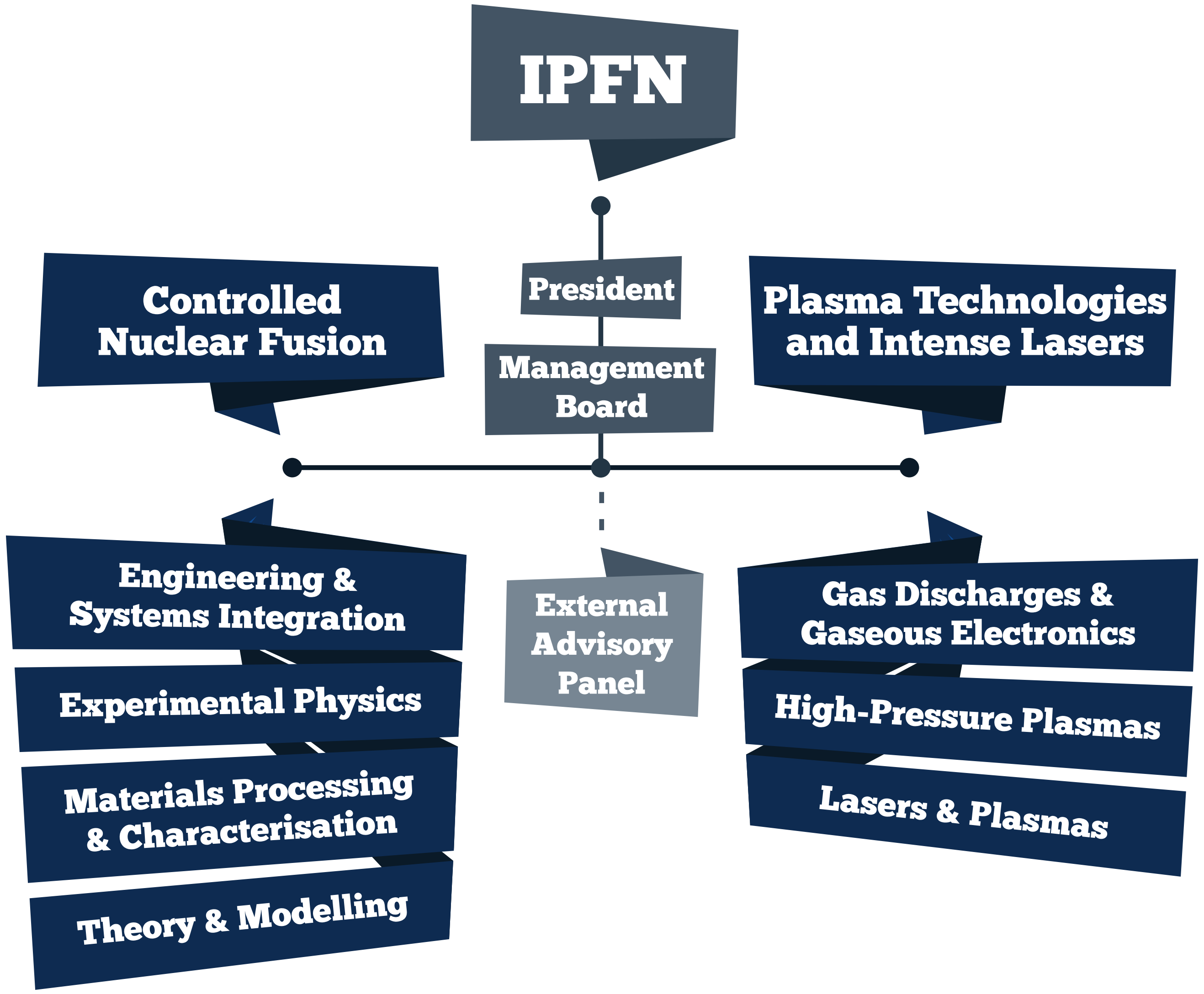
Controlled Nuclear Fusion - This research line is focused on the work programme established by the Euratom Fusion roadmap H2020, which includes activities associated with the development of systems, operation, and scientific exploitation of large and medium-sized tokamaks and stellarator, as well as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



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 Gas Discharges and Gaseous Electronics


Luís Oliveira e Silva
Group of Lasers and Plasmas


Marta Fajardo
PhD representative


Mikhail Benilov
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

189
Collaborators
at the end of 2015

102
PhDs
faculty, researchers and postdocs

+160
Publications per year
incl. Conference Proceedings

Highlights include papers published in

Astrophysical Journal

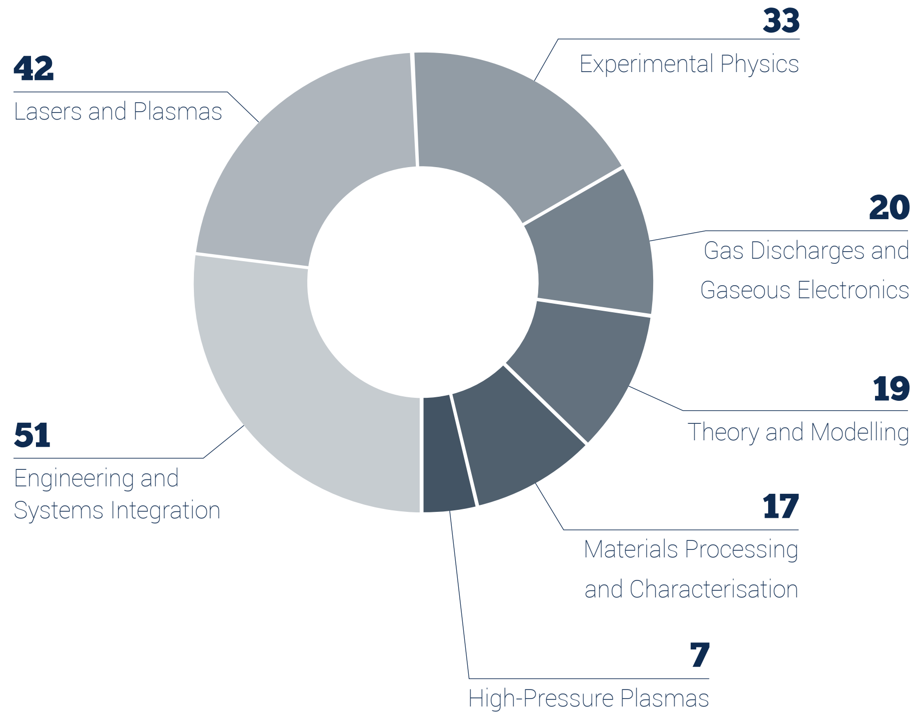
Nature Communications

Nature Physics

Phys. Rev. Letters

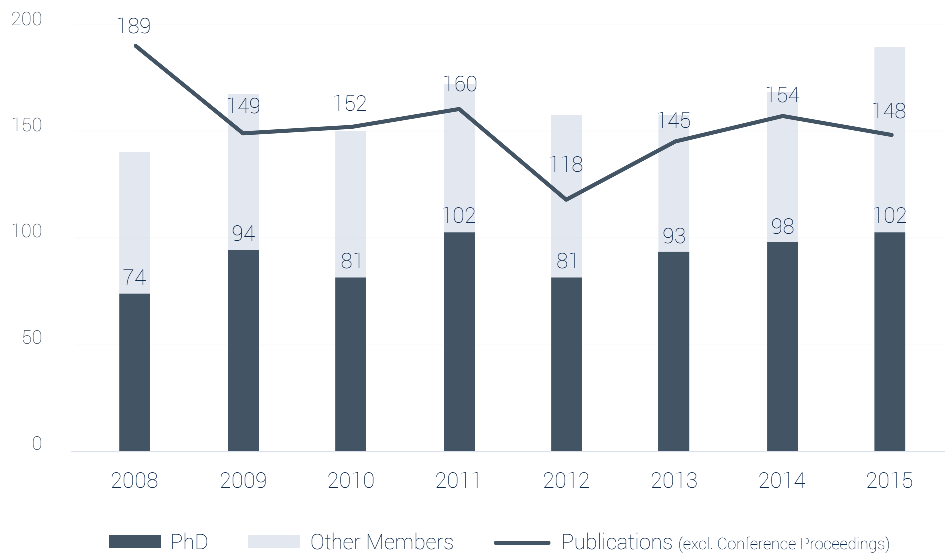
Members per Group

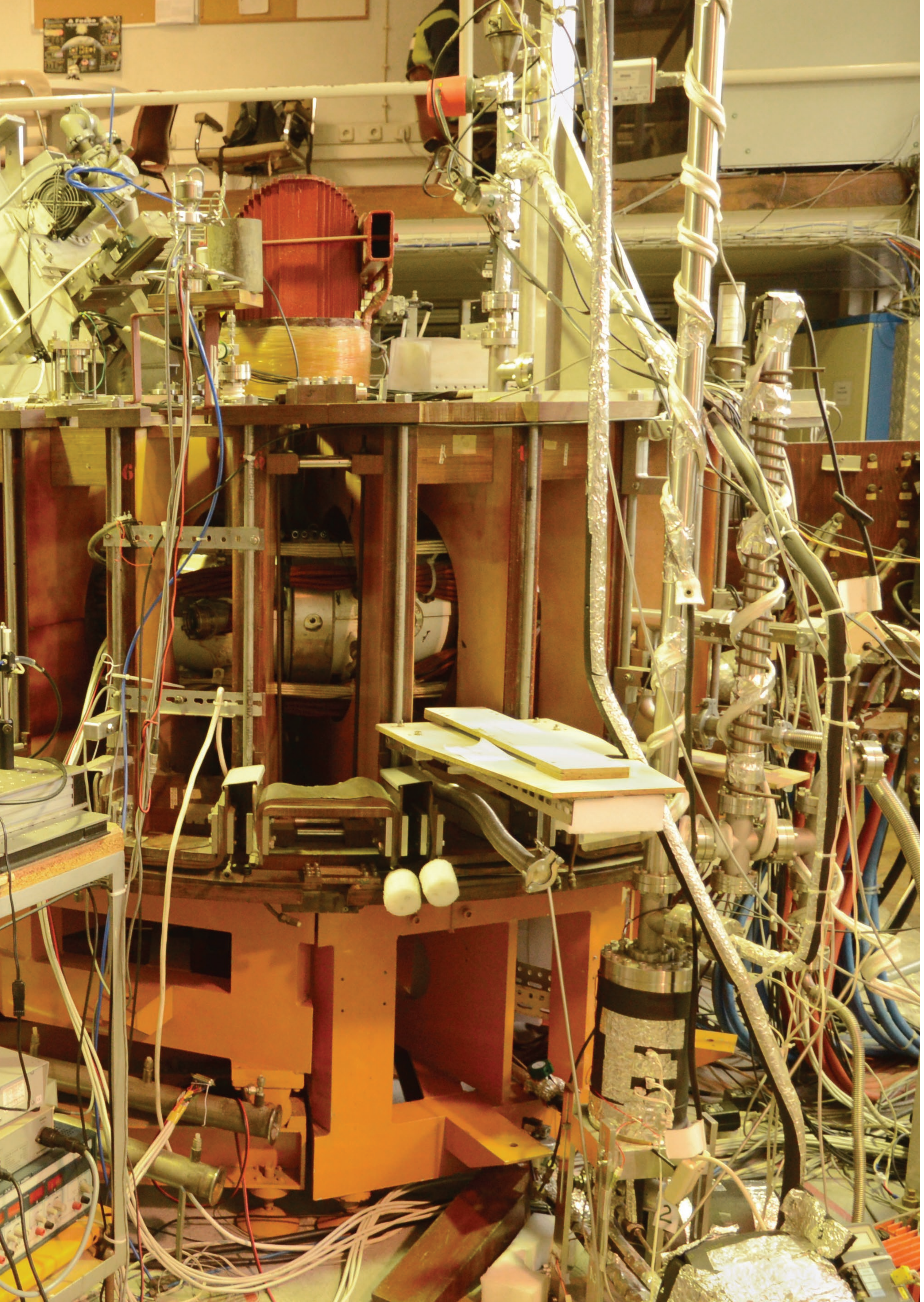
at the end of 2015



Collaborators and Publications

Since 2008





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

Principal Investigators:

Alberto Vale, Ana Fernandes, António Batista, António Rodrigues, António Silva, Artur Malaquias, Bernardo Carvalho, Bruno Gonçalves, Diana Baião, Filipe Silva, Hugo Policarpo, Jorge Belo, Jorge Santos, Jorge Sousa, Miguel Correia, Nuno Cruz, Paulo Varela, Pedro Carvalho, Raul Luís, Rita Pereira

Summary of Research

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 our portfolio in the areas of Control and Data Acquisition, Microwave Diagnostics and Remote Handling.

H2020 fusion programme will make a transition from pure research to design, construction and operation of future facilities like ITER and DEMO, increasing the focus on engineering and integration activities. To enhance the participation in this effort, the available engineering resources were strengthened. Our group results from the merging of the former Microwave Diagnostics and Control & Data Acquisition groups and from integrating the Remote Handling (RH) activities previously carried out by the Experimental Physics Group. The integration of all engineering activities enables answering in a focused, timely, effective and qualified manner to F4E and ITER calls and other contract opportunities for R&D and Innovation activities developed by the EU fusion programme. The group has well equipped microwave (MW) and instrumentation laboratories with capability for fast production of prototypes.

Group Leader: **Bruno Soares Gonçalves**

Contributions to ITER construction

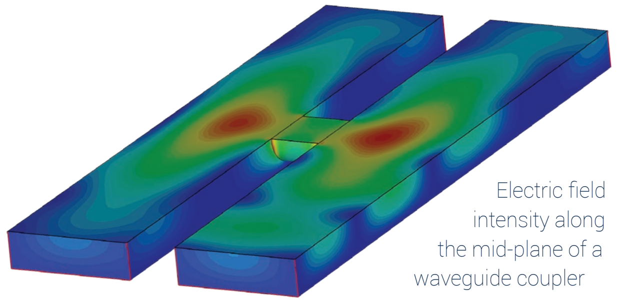
How do we diagnose and control a nuclear fusion experiment? IPFN has been actively participating in several projects related to ITER construction, having several contracts for the development of plasma diagnostics (e.g. Plasma Position Reflectometer, ITER Collective Thomson Scattering), control and data acquisition (e.g. development of magnetics integrators, Provision of System & Instrumentation Engineering support to F4E) and Remote Handling.

ITER Plasma Position Reflectometer

Measurement of thermal-induced changes in the total length of the PPR transmission lines

Our goal is to design ITER in-vessel components able to sustain the harsh ITER environment. The ITER Plasma position reflectometer system uses long oversized transmission lines to connect the front-ends located inside the ITER vessel and port-plugs to the back-ends located in the Diagnostic and Assembly Hall buildings. The transmission lines cross several areas and are subject to thermal gradients, which will modify their overall length from standby to operation.

Our goal is to be able to correct the changes in the detected signals due to these length variations, preserving the accuracy of the measurements. With this purpose, we have designed a passive wave-coupling device able to sustain the harsh ITER environment that can be installed in-vessel just before the antennas. In order to assess and optimise performance, we modelled the device using CST Microwave Studio, a software for 3D Electromagnetic simulation of high- frequency components.



Electric field intensity along the mid-plane of a waveguide coupler

Structural integrity analysis of the in-vessel components of the PPR diagnostic

We need to understand how the high levels of mechanical and thermal loads (mainly due to plasma disruption events, plasma radiation and neutrons) affect the antennas and waveguides of the in-vessel systems. In particular, no maintenance of these components is expected during ITER lifetime. It is, therefore, critical that a very detailed structural integrity analysis is performed to ensure these components remain fully operational under all load cases, including accidents like seismic events. For this goal, we bring together a multidisciplinary team to perform a comprehensive engineering analysis, ranging from the creation of finite-element models and implementation of simplified CAD representations of the PPR components to the final application of loads.

Neutronics analysis of the PPR in-vessel components

Part of the thermal load that the PPR in-vessel components will have to endure during operation is due to neutrons. In order to evaluate this contribution, the PPR components have been modelled. The results will provide both insights about the neutron flux on the location where the components are installed and help in the risk assessment involved in the decision to perform specific irradiation testing.

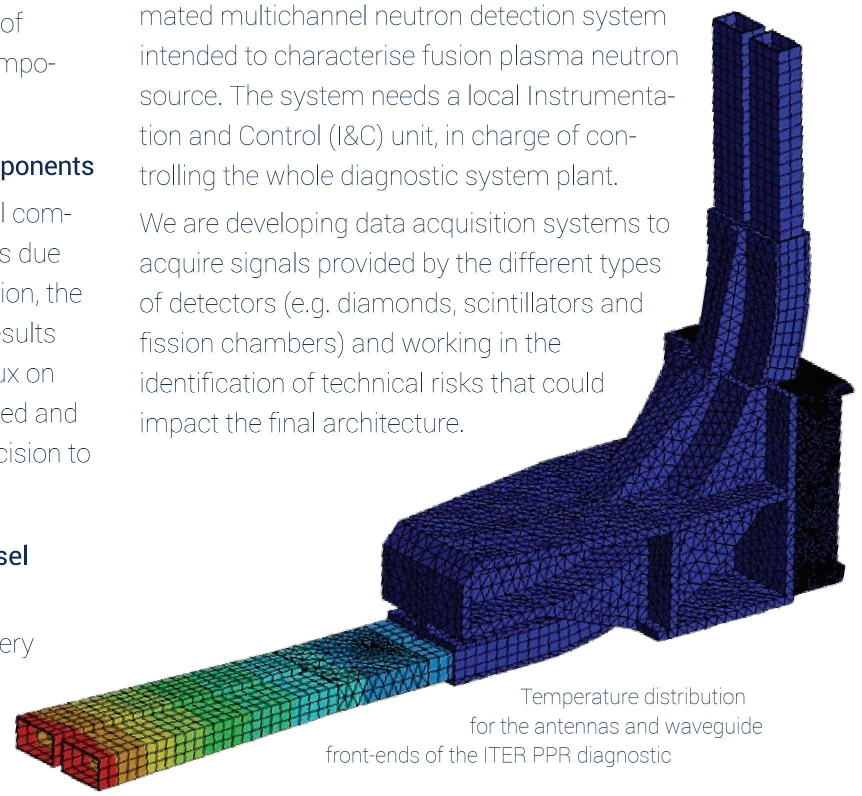
Electromagnetic analysis of the PPR in-vessel systems antenna setup

The space inside the ITER vacuum vessel is very restricted. Additionally, access to the plasma is limited by stainless steel blocks, known as blanket shield modules, which cover the vessel to provide shield from the high neutron flux and reduce activation of the adjacent areas outside the vessel. For the PPR in-vessel systems, these restrictions result in very small, low directivity antennas that view the plasma through narrow cut-outs between two conse- cutive blanket modules, making the design of the antenna a difficult challenge. To assess and optimise performance, we modelled the antenna and surrounding blanket modules.

ITER Radial Neutron Camera & Radial Gamma-Ray Spectrometer

The Radial Neutron Camera (RNC) for ITER is a collimated multichannel neutron detection system intended to characterise fusion plasma neutron source. The system needs a local Instrumentation and Control (I&C) unit, in charge of controlling the whole diagnostic system plant.

We are developing data acquisition systems to acquire signals provided by the different types of detectors (e.g. diamonds, scintillators and fission chambers) and working in the identification of technical risks that could impact the final architecture.



Temperature distribution for the antennas and waveguide front-ends of the ITER PPR diagnostic

Remote Handling activities for ITER

The Remote Handling (RH) activities of ex-vessel transportation in ITER and DEMO are performed by autonomous guided vehicles under remote supervision. The navigation system presents a significant technical challenge, mainly due to the requirements to demonstrate safety in a nuclear environment. We developed a benchmark of the technologies commonly used in industry and a critical assessment regarding their performance against the specific operational requirements of ITER. As a result, we proposed the navigation methodologies that manage the predicted conditions of the ITER buildings.

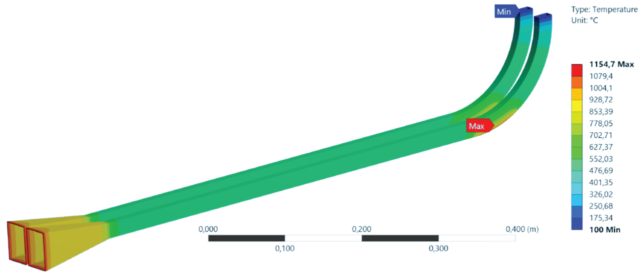
In case of failure, the vehicles engaged in the ex-vessel transportation have to be manually guided. We proposed a human machine interface specially designed to manual drive rhombic-like vehicles, the kinematic model used in the cask transfer system of ITER. In case of recovery or rescue operations, the intervention of a multi-purpose rescue vehicle (MPRV) may be required. We proposed a design of an MPRV equipped with different sensors, two manipulators with different sets of end-effectors, holonomic capabilities and an omnidirectional camera mounted on the top of an articulated neck. A human-machine interface equipped with a head mounted display is used to carry out the rescue and recovery operations.

Contributions to DEMO design activities

How to design a fusion reactor where operation conditions will be so harsh that almost no diagnostics can survive? DEMO activities are focused on developing such a power plant and addressing the engineering challenge of creating a device to harvest the fusion energy.

Participation in diagnostic design for DEMO

The current diagnostic integration activities for DEMO build upon the experience on current devices (for establishing the measurement concept) and on ITER (for engineering and integration concepts). As a power plant demonstrator, DEMO will operate based on robust burning plasma scenarios and only a selection of diagnostic systems (mostly passive and the least intrusive) will be installed. From the availability point of view, such diagnostic system and its components must operate and survive the lifetime of the tokamak components in which they are installed. In addition, the diagnostic access to plasma via penetrations must have minimal impact on the overall first wall area (e.g. blanket), on the shielding of the machine components (e.g. coils), and must comply with the DEMO auxiliary systems (e.g. remote handling, cooling, vacuum barriers, etc.). Given the relatively high neutron and radiation fluxes in DEMO, the lifetime of diagnostic components becomes the key design drive for the geometry and plasma coverage of the diagnostics. We are strongly focused on three main integrated areas of expertise: diagnostic design, diagnostic integration



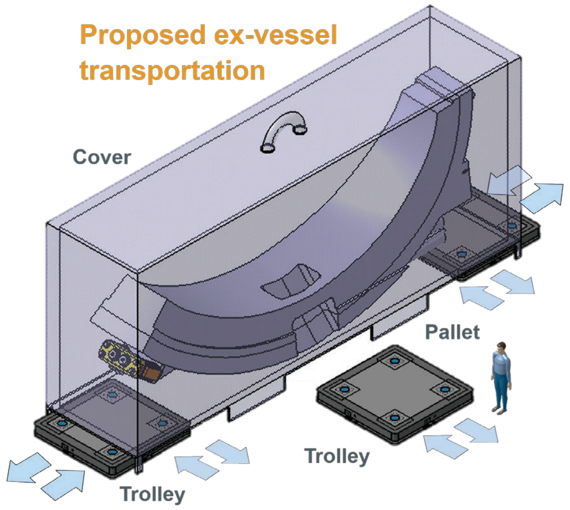
Temperature distribution for the antennas and waveguides front section of a microwave diagnostic in DEMO

engineering (CATIA and ANSYS) and neutronic analysis.

We are contributing to the modelling and feasibility studies, the analysis of lifetime and properties of diagnostic components localised in critical areas (antennas and waveguides) subjected to intense plasma radiation and neutron fluxes, and the engineering solutions for integration of the diagnostic within the vacuum, safety and remote handling requirements. To do so, we have developed a preliminary CAD model of one reflectometry antenna pair and respective waveguides taking into account the geometrical constraints inherent to its integration in the blanket modules, and performed studies on the impact of radiation on the components.

Remote Handling activities for DEMO

In DEMO, a new design of the ex-vessel transfer cask was proposed taking into account the best outcomes achieved with the design used in ITER, with upgrades in some features, such as the single typology of trolleys, the kinematic model that provides the ability to move in any direction and beneath the pallet in the front/rear or sideways, and the improvement of the safety margin to the closest obstacles.



Participation in JET Enhancements

JET-Gamma Ray Camera Upgrade (GCU) & JET Gamma-Ray Spectrometer Upgrade (GSU)

We developed data acquisition cards that were successfully tested with new fast detectors to be used for the JET Deuterium-Tritium campaign. The system was able to successfully detect alpha particles.

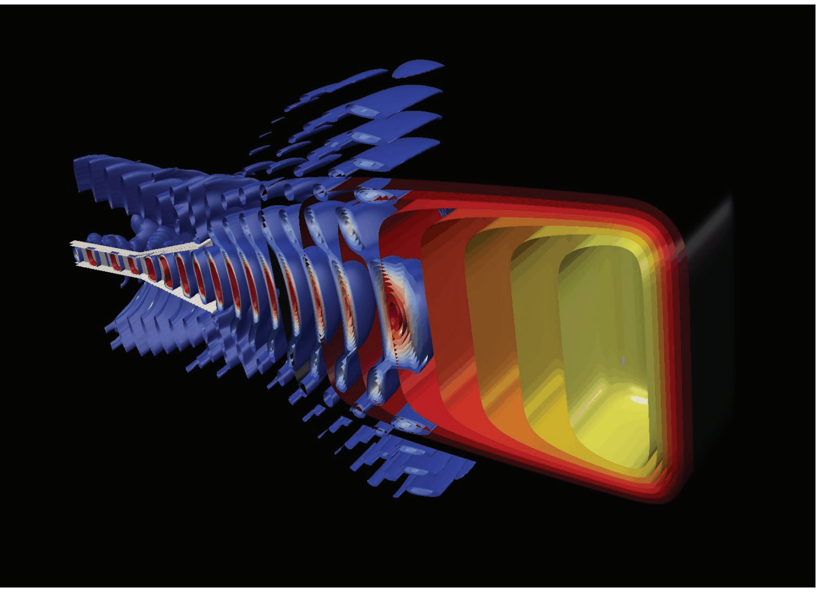
Other contributions in MW diagnostics development

A Multichannel Reflectometer for edge Density Profile Measurements at the ICRF Antenna in ASDEX Upgrade

We developed a new fully coherent reflectometer and corresponding data acquisition system for the ASDEX Upgrade tokamak. The device will be used to study the plasma properties in front of the new ICRF antennas. First plasma data was collected showing a very good signal-to-noise ratio, and the first fringe is clearly identified. Data analysis and profile inversion software are under development.

Numerical simulation of reflectometry

We performed important work in the area of numerical reflectometry simulation, namely in the advancement of numerical techniques and development of new codes for simulation (REFMUL) using the Finite-Difference Time-Domain (FDTD) method, in collaboration with Institut Jean Lamour from the University of Lorraine and the Laboratoire Jacques-Louis Lions. These codes are important to understand the coupling of probing microwave beams with the plasma in order to optimise microwave diagnostics performance. The knowledge gained allowed us to write a first prototype of a three-dimensional code. Its development will be carried out during the next years and upon completion it will greatly enhance the scope of reflectometry simulations.



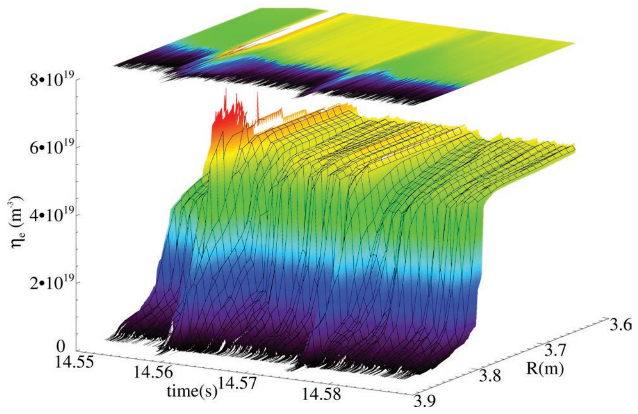
Reflectometry simulation showing the probing wave reflected on a plasma (simulated with REFMUL3, a 3D FDTD - full wave code)

These codes were applied to several physical and engineering problems. In ASDEX Upgrade, REFMUL was used to support reflectometry studies of the measurements of plasma filaments with radial and poloidal velocity components. Although aimed for reflectometry, REFMUL was also adopted in an Electron Cyclotron Resonance Heating study of beam broadening in the edge of turbulent plasma in collaboration with the Ioffe Institute.

For DEMO microwave diagnostics, a first assessment of the Low Field Side plasma position reflectometer behavior was performed using REFMUL. These simulations helped not only to get a first assessment of the DEMO environment from the point of view of microwave reflectometry but also helped to detect in an early stage some inconsistencies between the CAD model and equilibrium available.

Improvement of JET MW reflectometry profile determination

A new code has been implemented to process JET's reflectometry data and produce electron density profiles. By employing the spectrogram approach, it intrinsically provides a good definition of the pedestal and scrape-off layer. Robustness against contaminated data is achieved by resorting to image analysis techniques. It was also possible to obtain the time evolution of the electron density profile of an H-mode JET plasma, with Edge Localised Mode instabilities.



Temporal evolution of the electron density profile showing an ELM induced by a pellet (t~14.56s) and a spontaneous ELM (t~14.575s)

Other contributions on control and data acquisition

Control and Data acquisition system for the European Shock-Tube for High Enthalpy Research (ESTHER)

The control system for gas injection, ignition and diagnostic for the European Shock-Tube for High Enthalpy Research (ESTHER) was developed and installed entirely by the team. The software used is similar to that used for ITER CODAC Instrumentation and Control architectures and software technologies for slow control. The control system is in charge of handling the gas purge and injection, preparation for ignition, and exhaust burned or unburned mixtures ensuring a safe, reliable and reproducible shock tube operation. This system allowed a successful operation of ESTHER during the preparation phase, completing already more than 80 deflagration pulses using a reduced volume, 3-litre combustion chamber ("bombe") with filling pressures close to final ESTHER specifications. The Project is a successful collaboration between our group and the Group of Gas Discharges and Gaseous Electronics.

Development of high availability control systems

Nuclear Fusion experiments having a large number of components operating for long periods require high-availability on its critical systems. High availability features enable the whole facility to perform seamlessly in case of component failure, ensuring safety of equipment, people, environment and investment. We developed a high-availability control and data acquisition system, based on Advanced Telecommunication Computing Architecture (ATCA) instrumentation modules. The system was designed for hardware monitoring and management by providing hot-swap capabilities to implement component fail-over substitution and a redundancy schemes.

SEU detection and mitigation in neutron irradiated FPGAs

The effects of neutron radiation and respective mitigation in Field Programmable Gate Arrays (FPGAs) must be evaluated, should those devices need to be located in nuclear hazard environments. Data acquisition boards and their respective FPGAs were tested in the Portuguese Research Nuclear Reactor (RPI) with neutron radiation levels above those expected in ITER port cells. The test results show that most of the logical errors induced by neutrons (Single Event Upsets – SEU) can be detected and repaired in real- time, allowing the use of non-space grade FPGAs in harsh neutron radiation environments.

Advanced Mezzanine Card (AMC) Fast Digitiser

We designed a full-size Advanced Mezzanine Card suitable to meet the processing needs of high-performance applications in demanding nuclear fusion data acquisition applications. The module is intended for high-performance, high-bandwidth, and low-latency processing applications.

Preparation of exploitation of JT-60SA - Contribution to the Magnetic Control Tools

The European Union participates in the preparation of the exploitation of the JT-60SA tokamak located in Japan, in support to ITER and complementary activities regarding key issues for DEMO. In collaboration with the CREATE Consortium (Italy), we participated in the development and validation of the magnetic control tools needed for the exploitation of JT-60SA. The design of a near optimal controller of the plasma vertical stability was used to validate the developed model as well as to analyse the controllability of the JT-60SA plasmas.

The developed control algorithm was considered robust at different operational scenarios, showing that the magnetic configuration of the tokamak design is capable of effectively controlling vertical displacement events.

Experimental Physics

Principal Investigators:

Artur Malaquias
Carlos Silva
Horácio Fernandes
Igor Nedzelskiy
Isabel Nunes
Ivo Carvalho
João Figueiredo
José Vicente
José Tito Mendonça
Maria Emília Manso
Patrícia Carvalho
Rui Gomes
Santiago Cortes
Vladislav Plyusnin

Summary of Research

The Group of Experimental Physics is responsible for the operation and scientific exploitation of ISTTOK - the Portuguese tokamak, as well as collaborating with other fusion devices such as ITER, JET, TJ-II, TCV, W7-X, COMPASS, ASDEX and TCABR. Our research is focused on the development of diagnostics and real-time control systems, participating in experimental campaigns, collaborating in the modelling, data analysis and development of numerical codes.

Our main goal is to provide the community with 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.

Examples of our success include extending the ISTTOK nominal operation time from a few milliseconds into seconds, creating new diagnostics systems for fusion devices such as Heavy Ion Beam probing, and continuously evolving a plant operation framework for machine performance. Advanced training is provided for a large number of PhD students working under our supervision.

Group Leader: **Horácio Fernandes** and **Carlos Silva**

Tokamak ISTTOK

Study of fusion-relevant facing materials

Deuterium retention in liquid metals

The use of liquid metals as plasma-facing material has been suggested as a possible alternative to solid walls, in order to cope with the high power loads impinging on the first wall of fusion reactors. Materials such as tin and an alloy of tin and lithium (particularly Sn with 20-30% Li) have been exposed in ISTTOK to access the discharge performance degradation induced by the enhanced impurity contamination and on their affinity to retain hydrogenic isotopes.

An experimental setup has been developed to produce and expose LM samples in both liquid and solid states to ISTTOK plasmas.

Real time control and data acquisition

In tokamaks, the plasma configuration is created and controlled by magnetic fields generated by external coils. Similarly, plasma macroscopic parameters are determined by using sensors to measure the magnetic field or magnetic flux. With all this information a feedback control system can be devised and in ISTTOK, due to its flexibility in reprogramming such algorithms, several methods could be tested and implemented. Examples of proxies for control based on tomography or using the heavy ion beam were successfully accomplished.

Machine control and operation

ISTTOK was upgraded with a plasma control system based on ATCA, designed with the goal of improving the discharge stability and extending the operational space to the alternate plasma current (AC) discharges. All diagnostics and actuators relevant for real-time operation were integrated in the control system.

To extend the duration of the AC discharges and the plasma stability, a new magnetising field power supply was commissioned and the horizontal and vertical field power supplies were also upgraded. The AC current discharges duration increased to more than 1 s, corresponding to 40 semi-cycles, without apparent degradation of the plasma parameters. This enables ISTTOK to be used as a low-cost, long-duration (comparable to medium size tokamaks) material testing facility with long time exposures for nuclear fusion relevant plasmas.

Diagnostics

Heavy Ion Beam

This is one of the few plasma diagnostics allowing an inside-view of the plasma properties, thanks to the injected ions operating as probes to diagnose the local density and temperature. Our current goals are the modelling of MHD rotating islands and the development of extended retrieving algorithms for determining the radial profile of plasma structures and their temporal evolution.

We have conducted edge biasing experiments aiming at studying the interplay between turbulence and MHD activity on the edge and plasma core. For the first time a strong correlation between pressure-like fluctuations and MHD activity was found located spatially. A new detector is being designed for characterising the full radial electric field inside the plasma, enabling the simultaneous measurement of the pressure-like profile and plasma potential profiles along the full plasma diameter.

Retarding field analyser

This diagnostic has been employed for ion and electron temperature measurements in the scrape-off-layer of ISTTOK and for ion temperature measurements on the TJ-II stellarator.

Its DC operation has been applied for the direct instantaneous measurements of the electron temperature. The results are in good agreement with the RFA conventional swept measurements.

Edge turbulence

Multi-scale study of isotope effect in ISTTOK

Understanding the mechanism of plasma confinement scaling with isotope mass has been a long-standing open issue in fusion. Recently, a multi-scale mechanism has been proposed to explain the isotope effect. Our research focuses on the impact of isotope mass on multi-scale mechanisms, including the characterisation of radial correlation lengths (L_r) and long-range correlations (LRC) of plasma fluctuations using a multi-array Langmuir probe system in hydrogen and deuterium plasmas. We found that when changing plasma composition from H to D, the LRC amplitude increased clearly (10-30 %) and the L_r increased slightly (~10 %), while the particle confinement improved around 50 %, sharing the impact of the isotope effect on both the largest scales and the characteristic radial scale of plasma fluctuations.

Comparison of fluctuations properties measured by Langmuir and ball-pen probes

A complete estimate of the particle and heat transport requires knowledge of the fluctuations in density, temperature and electric field. However temperature fluctuations are generally difficult to measure and then often ignored. To address this problem, we compared the fluctuation properties measured by Langmuir and ball-pen probes at ISTTOK. We found a considerable difference in the amplitude of the floating potential fluctuations measured by both types of probes, but not in statistical properties such as skewness. Because ball-pen and emissive probe also have limitations and may underestimate the amplitude of the plasma potential fluctuations, we conclude that probe measurements must be carefully validated.

The IPFN team at the JET control room

Plasma performance

Plasma Confinement at JET

We investigated two key areas as a possible explanation for the differences observed in the pedestal between JET-C (carbon wall) and JET-ILW (ITER-like wall): the effect of W in the core plasma and the interaction of the plasma with the edge through the increase of neutral pressure and recycling. ICRH heating can control W accumulation in the plasma core by reducing the neo-classical inward pinch of W. However, keeping W concentration in the core below the critical level to achieve stationary plasmas requires a sufficient level of gas injection rate. The pedestal temperature decreases and with it the core confinement. An improvement in confinement with decreasing collisionality is also observed.

Studies of Runaway Electrons in Tokamaks

The database on runaway electrons has been updated by including results on disruptions and RE generation in JET with full-metal ITER-like wall, ASDEX-Upgrade with W-wall and COMPASS (carbon limiter). In these experiments the disruptions with RE generation were triggered using MGI. These studies allowed the mapping of runaway processes in a wide range of device operational parameters and provided new results on RE generation trends and disruption physics.

Physics studies based on microwave reflectometry

LFS/HFS edge density profile dynamics on ASDEX-Upgrade

Next-generation fusion devices are required to operate in regimes with high energy confinement and high density in order to achieve large fusion power. In these regimes the development of a High Field Side Density Front (HFSHD) associated with the inner divertor detachment has been reported, exhibiting a complex dynamic yet to be understood. Our research focuses on the study of the edge density profiles on ASDEX-Upgrade taking advantage of the high-resolution high/low-field side measurement capabilities provided by the reflectometry system. Studies reveal that with increasing input power the HFSHD extends all the way up to the machine midplane, leading to strong poloidal asymmetries in the edge density profiles.

Measurements of H-mode filaments in the vicinity of the separatrix

Understanding plasma filament dynamics is crucial to better predict their impact in the lifetime of future fusion devices such as ITER. Experimental results were acquired at both ASDEX-Upgrade and JET using reflectometry. Numerical studies were performed employing a 2D finite-difference time-domain full-wave code. Results revealed its high sensitivity (to filaments of small radial width) and how the phase signals behave as predicted by 1D geometric optics, under reasonable assumptions. For small poloidal widths and/or certain combinations of radial and poloidal velocity components, nonlinear regimes of the phase response were observed, bringing complexity to the interpretation of the reflectometry signatures.

Edge turbulence

Magnetic configurations (upper, lower and double null) seem to influence many fusion plasma processes, such as transport driven flows and the L-H power threshold. Our goal is to obtain information about underlying plasma turbulence for different magnetic topologies in ASDEX-Upgrade by measuring the poloidal asymmetries of turbulence with reflectometry. We have established a method to extract the level of plasma turbulence from FM-CW O-mode reflectometry and studied the dependence of turbulence spectrum and radial profile of plasma density fluctuations on the magnetic configuration (HFS/LHS). We found a drop in density fluctuations in the region of strong radial electric field shear for all magnetic topologies.

Effect of divertor geometry on the L-H transition

Divertor geometry can vary the L-H power threshold by up to a factor of two, having a large impact on the cost and viability of future devices. The effect of divertor geometry on the L-H transition was investigated at ASDEX-Upgrade, using three magnetic configurations with different X-point positions. The power threshold to access H-mode was found to be sensitive to the divertor configuration only at high densities, where it exhibits an inverse correlation with the X-point height. Microwave reflectometry diagnostics were used to measure edge electron density profiles and fluctuations, showing that the density gradient is not the critical parameter to explain the observed differences.

Experimental investigation of geodesic acoustic modes on JET using Doppler backscattering

Spontaneously generated, large-scale sheared flows such as geodesic acoustic modes (GAMs) regulate the turbulent transport and can be important in the process leading to the transition to improved confinement regimes (L-H transition). We have investigated GAMs in the JET edge plasma for ohmic discharges using mainly Doppler backscattering. Radially-resolved measurements indicate that GAMs are located in a narrow layer at the edge density gradient region with amplitude up to 50 % of the mean local perpendicular velocity. The GAM shearing rate is ~1.3×10^5 s^{-1}, which is comparable to that of the mean flow confirming the relevance of GAMs for turbulence control.

Quantum Plasmas

This team operates a state-of-the-art magneto-optical trap (MOT), where rubidium atoms are collected from a background atomic vapor and laser-cooled to microkelvin temperatures. The high number of particles in these experiments induces multiple photon exchanges between the atoms, giving rise to a collec-

tive interaction mediated by light. This is equivalent to assigning an effective electrical charge to the atoms, allowing for the exploration of plasma physics analogies.

By measuring the atomic equilibrium density profiles, we were able to infer the details of the equation of state of the laser-cooled gas. This analysis is reminiscent of the Lane-Emden formalism in astrophysics and a polytropic exponent determines the deviation from the ideal gas case, which results from the correlations induced by the effective charge of the atoms.

Materials Processing and Characterisation

Principal Investigators:

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

Summary of Research

Plasma wall interactions together with fuel retention mechanisms are among the most relevant processes which must be properly understood and modelled in order to get the operation conditions to maintain the plasma stable during long runs. The new ITER-like wall (ILW) of JET is being used to assess these processes in order to improve and validate the existing models and allow a robust design of the future fusion devices.

Our major goals in the framework of these activities are to establish the global erosion and deposition patterns in JET-ILW together with the retention mechanism of fuel in the main chamber. We are interested in identifying the places where the plasma produces strong changes in surface composition and topography of the plasma-facing components. This work will help to elaborate more reliable models that can be incorporated in the design of future power plants.

In addition, we are developing new materials able to stand the extreme working conditions of a fusion reactor using novel approaches. New W-Ta composites were produced from W powder and 10 at.% Ta fibres and consolidated by pulse plasma sintering in order to improve the mechanical properties. The structural properties reveal some weakness due to the formation of TaO at the internal interfaces. In parallel dense high entropy alloys of CuxABZD composition with A, B, Z, D = Cr, Fe, Mo, Ti, V and x corresponding to 5, 10, 20 and 35 at.% are being studied for potential applications as thermal barriers in nuclear fusion technology.

There is also a strong involvement in developing ion beam technologies as a tool to model and tailor the properties of nanomaterials with particular emphasis on wide band gap semiconductors like the III-nitride compounds.

Group Leader: Eduardo Alves

Global erosion, deposition and retention patterns in JET with the ITER-like Wall

Plasma wall interaction is a very complex process with multiple chemical species interacting and changing continuously the shape and composition of the surfaces. Erosion, deposition and retention of the plasma fuel in the vessel first wall materials play a key role in the operation of a fusion reactor. The limit on the hazardous hydrogen isotope tritium (T) inventory in the wall material for ITER in-vessel is limited to 1 kg of T (in an easily mobilised form). The JET ITER-Like Wall (JET-ILW) project allowed us to investigate the plasma-surface interactions which are expected to take place during ITER operation.

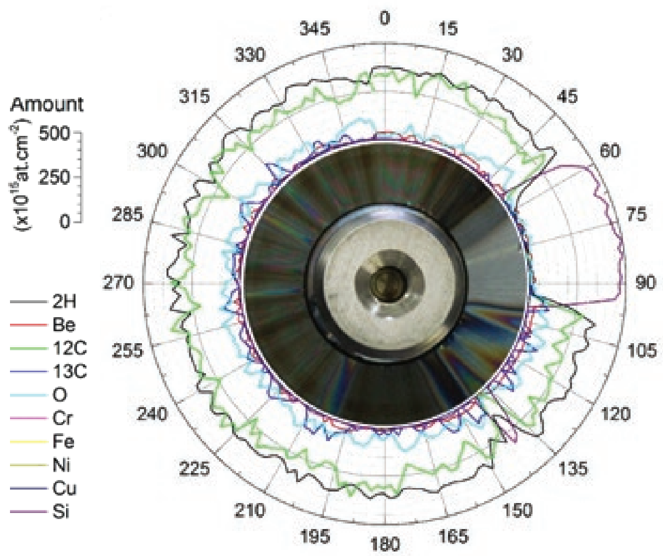
Post-mortem analysis of marker tiles removed from the first wall components allows us to scrutinise the net effects of plasma-surface interactions. During the JET-ILW campaign 2011-2012 the deuterium (D) and tile erosion/deposition was accurately measured after the first JET-ILW campaign using total Ion Beam

Analysis. The table on the right summarises the results on global D retention of JET-ILW as measured from the first wall and recessed wall areas. Results are obtained by analysing a poloidal selection of first wall tiles, and probes from selected wall areas as indicated in the figure on the right. Global values are calculated by assuming a toroidal symmetry in JET vessel. In the JET-ILW, the D retention process takes place via implantation and co-deposition in JET-ILW and the highest retention values were measured from regions with the highest deposition.

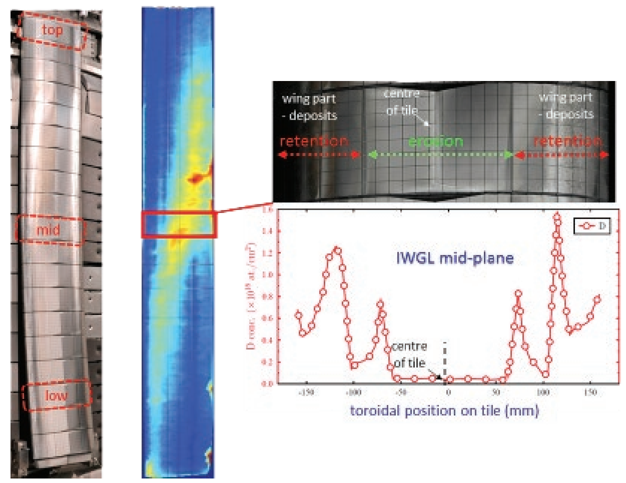
Currently, we are performing a similar study for components retrieved after the 2013-2014 campaign.

Fuel inventory for different surfaces of the JET-ILW divertor and main chamber. Shading = remote/recessed surface

Divertor Tungsten	Inventory (10^{22} D atoms)	Main chamber Beryllium	Inventory (10^{22} D atoms)
Inner divertor	17	Inner limiters	1.4
Outer divertor	3.9	Outer limiters	5.2
Bulk tungsten	0.5	Dump plate	2.1
Inner corner	2.0	Inner wall	2.8
Outer corner	2.2	Outer wall	0.9
		Castellation gaps	0.9



Composition results from a rotating collector retrieved from JET



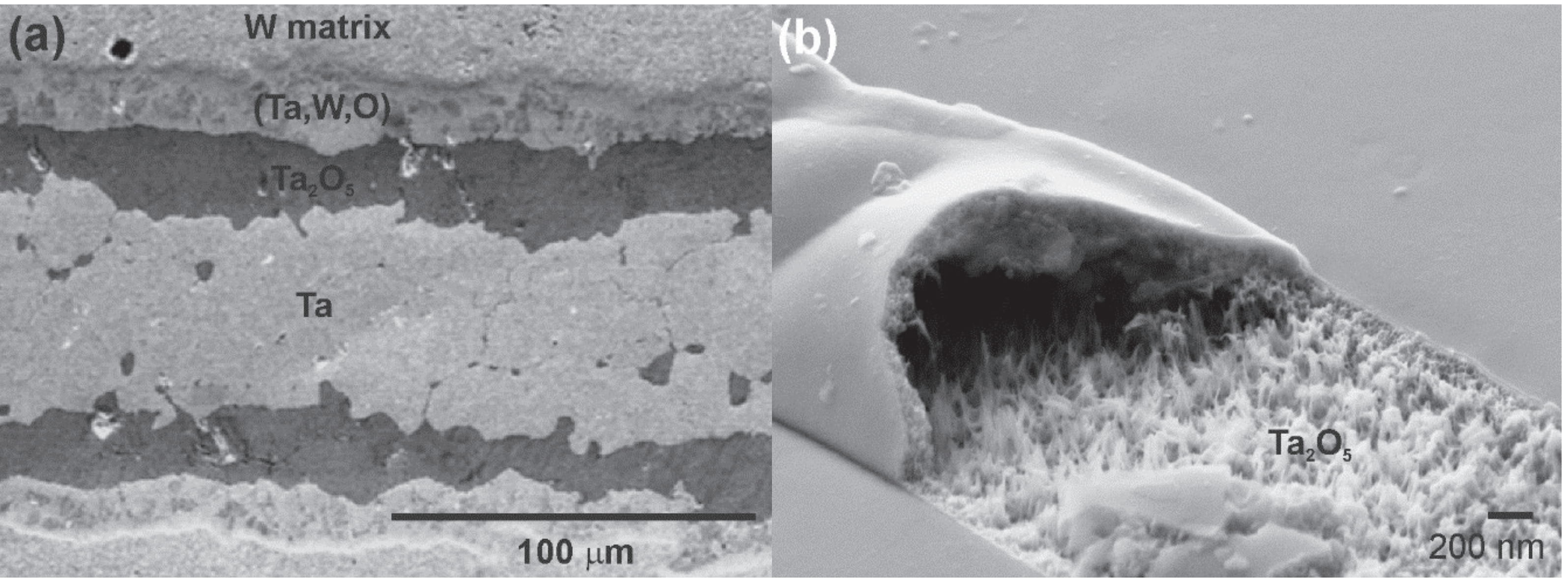
Thermal load on the JET Inner Wall Guarder Limiter during a discharge. A full tile from the mid-plane of the chamber where the different interaction regions are identified.
The 2H distribution shows that the retention occurs mostly in the junction regions of the various parts of the tile.

W-Ta composites consolidated by pulse plasma sintering

Tungsten is a promising candidate to produce plasma facing components since it has high melting point, good thermal conductivity and low sputtering yield, which minimises the impurity generation. However, there is one main disadvantage in the tungsten use, which is very hard to overcome: the ductile-to-brittle transition temperature (DBTT) is too high. Since tantalum enhances low neutron activation and high radiation resistance, ductility and toughness relative to W can be used in the W-Ta composites production. Therefore, dispersions of ductile Ta fibres in a W matrix have been proposed as a novel approach for the development of suitable plasma facing materials.

W-Ta composites were produced from W powder and 10 at.% Ta fibres and consolidated by pulse plasma sintering. The radiation behaviour of the new material was tested through the Implantation at room temperature of He^+ or D^+ or sequentially with He^+ and D^+ using ion beams with fluences in the 10^{20}-10^{21} at/m^2 range.

The composite materials consisted of a nanostructured W matrix with dispersed Ta fibres presenting Ta_2O_5 at the interfacial regions. Blistering was observed after He^+ implantation with a stronger effect in Ta_2O_5 than in Ta or W and was worsened with prior D^+ implantation. The blister cavities in Ta_2O_5 exhibited a nanometer-sized fuzz structure. Nuclear reaction analysis showed that D retention increased with He^+ pre-implantation, which justifies the shifts of the tungsten X-ray diffraction peaks after He^+ implantation and reflect the strain associated with the presence of interstitial atoms in the W lattice. Transmission electron microscopy observations revealed the presence of dislocations in the W and Ta metallic phases after the sequential implantation with He^+ and D^+ ions, while a lower density of defects was detected in Ta_2O_5 due to an apparent shielding effect of the blisters.



TaO forms at the boundaries (a) and He coalesce in a separate gas phase within the material just below the surface leaving walls of initial bubbles (b)

Bandgap engineering of III-nitride quantum wells for efficient green light emitting diodes (LEDs) using ion beams

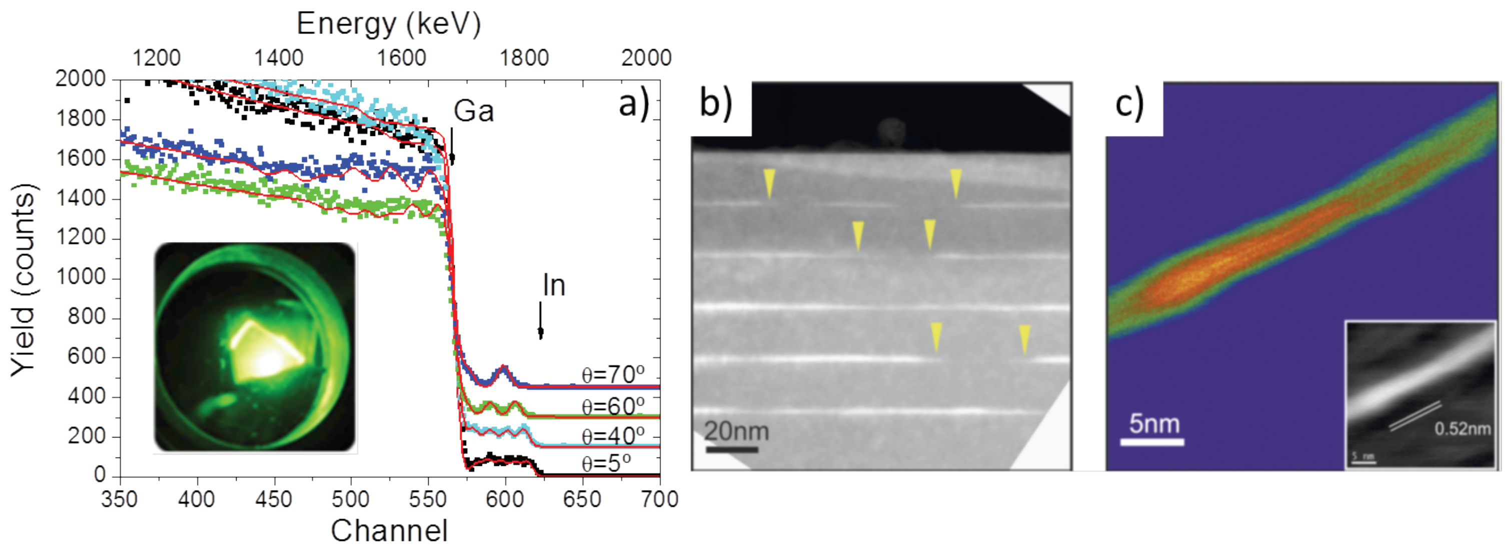
Blue-emitting InGaN LEDs are currently used for highly energy efficient solid state lighting. However, the internal quantum efficiency (IQE) for nitride-based LEDs decreases dramatically in the green and red spectral region. Theoretical work suggests that InGaN/GaN quantum wells (QWs) with graded compositional profiles may increase IQE and mitigate Auger losses when compared to conventional, abrupt QWs.

Our goal is to use ion beams to investigate the possibility of quantum well intermixing (QWI) to achieve such graded layers.

A set of InGaN/GaN QW structures, emitting from blue to green, were used and the RBS spectra, photograph of the green emission during PL measurements and TEM high angle annular dark field (HAADF) images of a 5 multi QWs of InGaN sample are shown in the figures below. TEM HAADF mapping of the In distribution inside the QWs revealed lateral interruptions of the QWs and strong compositional fluctuations. This inhomogeneity explains the long emission wavelength (green) despite relatively low average InN contents measured by RBS of ~14%.

Although simple in concept, the implementation of QWI by conventional post-growth ion implantation along with annealing turned out to be difficult. The novel approach presented here consists in using Swift Heavy Ion (SHI) irradiation to induce QWI. A green emitting InGaN QWs, as well as GaN reference samples, were irradiated with 185 MeV Au ions to different fluences. X-Ray Diffraction and Reflectometry reveal an efficient intermixing. Luminescence studies further confirm that QWI does indeed occur, resulting in a blue shift of the QW emission.

Currently, we are establishing the experimental conditions to tune and control the mixing mechanism to get a clear insight into the physics underlying this process.



(a) RBS/C spectra of the 5-period InGaN/GaN multi-QW structure taken with different beam incidence angles allowing to separate the signal of the individual InGaN QWs. The channels corresponding to the signal from Ga and In at the surface are marked by arrows. The inset shows a photograph of the green QW emission during the PL measurement

(b) TEM HAADF image of the QW region showing lateral interruptions of the QWs (marked by yellow triangles).

(c) High magnification Z-contrast image of a QW in colour scale where In fluctuations can be noticed, the inset shows the original image in grey scale

Theory and Modelling

Principal Investigators:

António Figueiredo, Duarte Borba, Fernando Nabais, Francisco Salzedas, João Bernardo, João P. Bizarro, Jorge Ferreira, Luís Fazendeiro, Maria F. Nave, Nuno Loureiro, Paulo Abreu, Paulo Rodrigues, Rogério Jorge, Rui Coelho, Rui V. Mendes

Summary of Research

Theoretical and numerical research play an essential role in the interpretation of current magnetic confinement fusion plasma discharges and extrapolation to ITER, demonstration reactors such as DEMO and future fusion power plants. The group's research focuses on the understanding of the key physics of magnetically confined plasmas, namely on energetic particle driven instabilities, plasma momentum transport and intrinsic rotation, and on turbulence and magnetic reconnection.

The group is also committed to a solid effort on Integrated Tokamak modelling. Breakthrough studies on Alfvén Eigenmode (AE) stability in JET and ITER scenarios have shed new insight into the complex interplay between energetic suprathermal particles and AEs. A novel interpretation of bifurcations in core plasma rotation in Tore Supra plasmas, induced by turbulent momentum transport, was proposed. Experimental measurements and trends in intrinsic rotation in JET Ohmic plasmas were successfully interpreted by way of gyrokinetic modelling.

The group's competencies and output are evidenced by the 31 papers in scientific journals, 7 invited talks in conferences, a task coordinator role in an EUROfusion Work Package, 2 positions in the JET Exploitation Unit, a solid participation in the EUROfusion task agreements and experimental campaigns of JET and AUG, including scientific coordination of 3 experiments.

Group Leader: Rui Coelho

Energetic particle physics in Tokamak plasmas

Understanding the complex interplay between energetic particles and AEs is a key goal in the fusion research effort, encompassing not only the interpretation of current experiments but also, and most importantly, the planning and preparation of future DT experiments like the JET-DT campaign and burning plasmas during ITER operation.

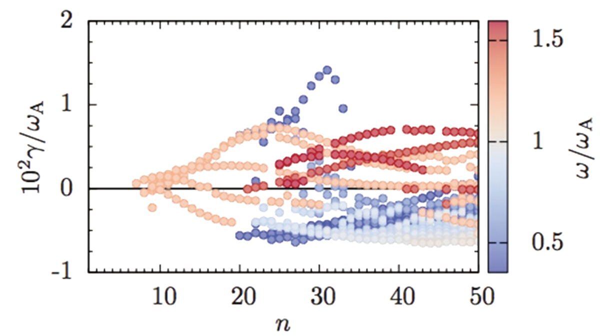
JET experiments addressing the loss of energetic ions in the presence of AEs have shown that the majority of the losses were associated with the presence of core-localised modes in the plasma. To explain this, it was suggested the fast ions losses triggered by core-localised modes did not correspond to barely confined ions, as previously thought, but instead corresponded to ions which travelled all the way from the plasma core to the edge of the plasma transported by a chain of modes at different radial locations (channelling effect). Measuring the pitch angle of the lost ions with a scintillator probe, we have proved the correctness of this explanation, by evidencing losses associated with outer Toroidal Alfvén Eigenmode (TAE) modes, centred close from Λ=1 and subdominant when compared to core localised tornado modes, centred at a pitch angle close from 70 degrees, corresponding to Λ=1.1.

We have made a systematic assessment of AE stability on ITER's I_p=15 MA baseline scenario using the drift-kinetic CASTOR-K code, a hybrid magnetohydrodynamic (MHD)-drift kinetic code developed for the study of MHD modes in the presence of energetic ion populations. We found that most AEs with low toroidal mode number (n < 10) interact with the Alfvén continuum whereas most-unstable modes occur for 20 < n < 30.

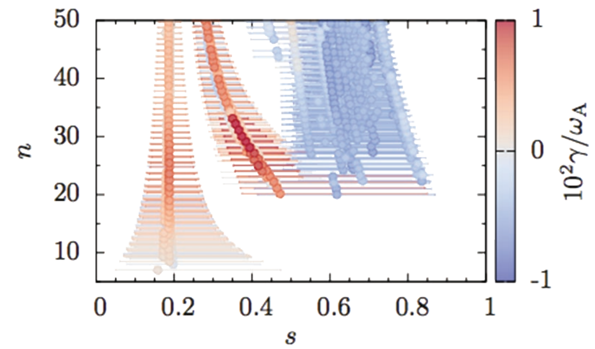
While broad-width TAEs located outside the core were seen to be either stable, close to marginal stability, or to interact with the Alfvén continuum, short-width TAEs located around the maximum of the alpha-particle density gradient (at r/a~0.4) and within a low magnetic-shear region (0 < r/a < 0.5) were found to be the most unstable (as the charts on the right show).

We also initiated a linear-stability assessment of AEs for future JET-DT scenarios. A high fusion performance JET hot-ion DD pulse was selected and used as a reference for a predictive TRANSP analysis to extrapolate that discharge to a mixed DT scenario and estimate the α content.

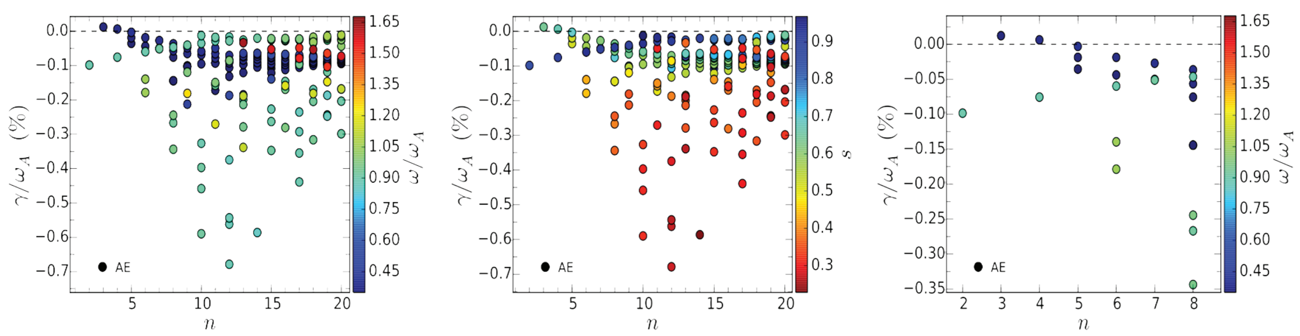
This preliminary assessment found that the outer radial low-n TAEs, localised in a lower ion-damping region, are easier destabilised although driven by fewer α-particles. The high ion Landau damping in the very hot inner half of the plasma may overcome the α-drive (as shown below).



Normalised growth rate versus n for 700 AEs found in three frequency gaps: TAEs (ω/ω_A~0.5), EAEs (ω/ω_A~1), and NAEs (ω/ω_A~1.5); Each AE is coloured by its normalised frequency



AEs radial localisation (circles) and width (horizontal bars) distribution by toroidal number n; Each AE is coloured by its normalised growth rate



Total growth rates for all the AEs found for n up to 20 coloured as a function of frequency (left and right – unstable region of interest) and of peak mode amplitude radial location (middle). A careful analysis shows that modes closer to the unstable threshold are localised in the outer half of the plasma, where the ion damping is significantly lower than in the very hot inner core.

Plasma momentum and intrinsic rotation in confined plasmas

Driving plasma rotation in ITER with external momentum injection is expected to be challenging. This has driven a worldwide research effort to predict its intrinsic rotation levels, since rotation influences plasma stability and how far turbulent transport is suppressed.

Intrinsic rotation in JET Ohmic plasmas was investigated and the typical rotation profile is observed to change sign from co-current rotation in the edge to

counter-current rotation in the core. A comparison of a JET Ohmic rotation profile and detailed simulations using a new version of the gyrokinetic code GS2 has been performed (in collaboration with F. Parra and M. Barnes, Oxford University) The results of the simulation matched the profile in the region where the change of direction happens.

We also investigated the density impact on toroidal rotation during density ramps in Tore Supra ohmically heated plasmas and observed bifurcations in the plasma core ($r/a < 0.5$) for a threshold density $n_l \sim 3\times10^{19}$ m^{-2}, where the plasma accelerates, to break again at $n_l \sim 3.5\times10^{19}$ m^{-2}. Core rotation changes are not reproduced by neoclassical predictions and are uncorrelated to sawtooth activity. Turbulence-driven momentum flux is thus the possible candidate to explain the deviation from neoclassical predictions. Quasi-linear gyrokinetic simulations with the QuaLiKiz code evidenced a change in the dominant linear microinstability (from ITG-TEM to pure ITG) at $n_l \sim 3\times10^{19}$ m^{-2} in the core. We conjecture that, although Tore Supra high magnetic ripple makes the neoclassical toroidal viscosity the dominant player in setting the toroidal rotation profile, turbulent momentum transport modifications arising from the stabilisation of the TEM can explain the change in rotation. A modification in the residual stress contribution can explain the bifurcation of the core rotation around this density.

Turbulence studies in confined plasmas

In order to ensure ITER's success, a solid theory on the fusion fuel behaviour in the outermost plasma region of magnetic confinement devices is needed. This scrape-off layer (SOL) region determines the boundary conditions for the core plasma, controls the plasma refuelling, heat losses and impurity dynamics and regulates the interaction of the plasma with the wall. As ions and electrons freely flow along the SOL field lines, the energy flux to the vessel can be very large, potentially exceeding the limits of the plasma facing materials. In this region, turbulent phenomena occur on a wide range of spatiotemporal scales, and some approximations typically used to study the plasma core (such as small-amplitude fluctuations) are not valid.

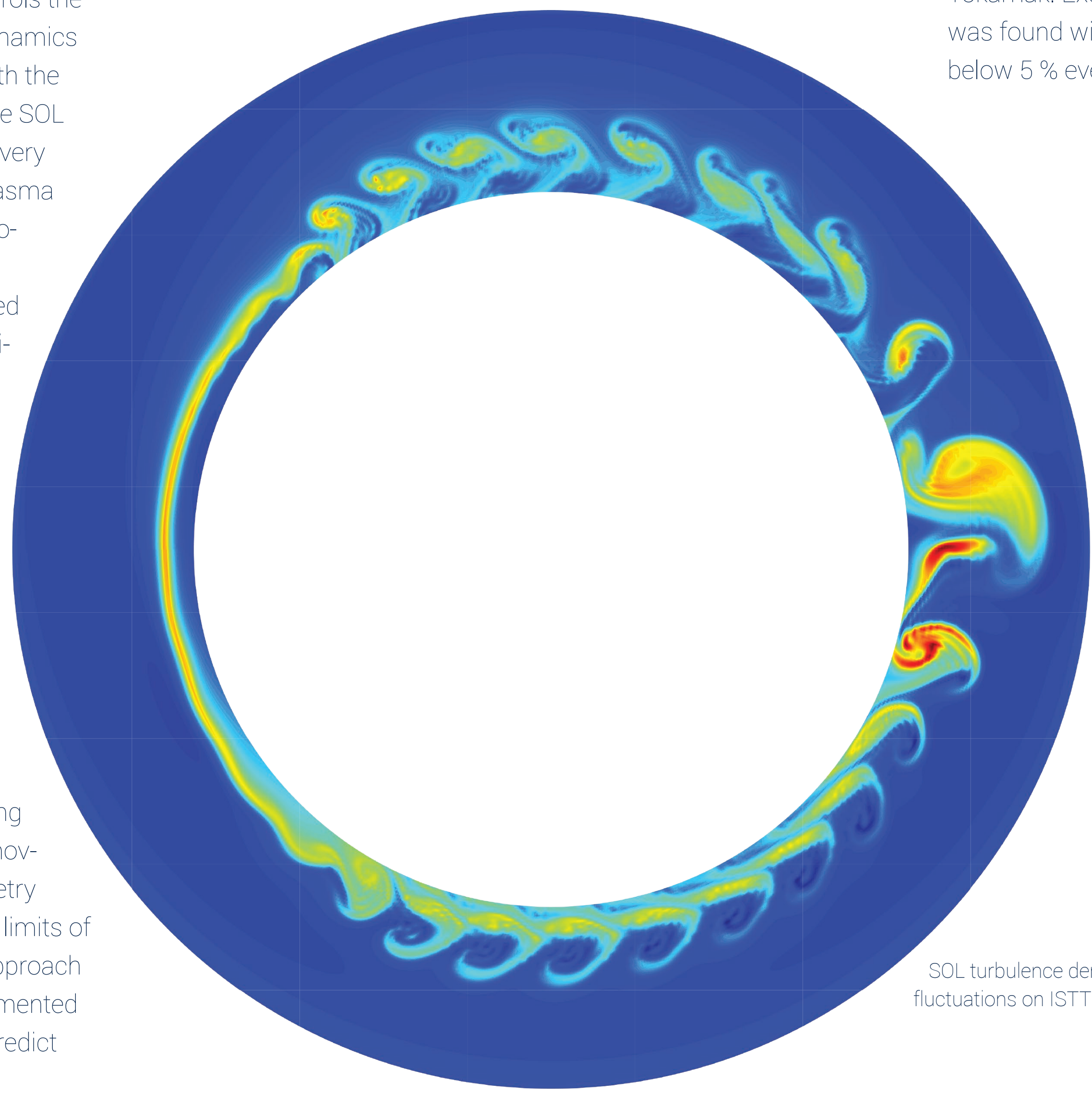
We have established a collaboration with the Swiss Plasma Center group in Lausanne where the SOL is modelled numerically with the GBS code. The GBS was successfully applied to the ISTTOK geometry where the turbulent regimes and the SOL width scaling were identified. Furthermore, we have shown not only for ISTTOK but also for magnetic fusion devices with a poloidal limiter that turbulence is driven mainly by the drift-wave instability and the SOL width is set by ballooning modes. The nonlinear saturation "gradient removal" mechanism has been applied to this geometry and validated. Currently, we are expanding the limits of our model, considering a hybrid kinetic-fluid approach based on a gyrofluid model. This will be implemented numerically in order to better reproduce and predict the behaviour of the SOL plasma.

Integrated Tokamak modelling and workflow development

Integrated modelling towards a "numerical tokamak" requires a large coordinated effort between model generation, integration and validation of modular sets of codes in modelling infrastructures. Our main goals in this topic are the development and maintenance of scientific workflows in the EU Integrated Modelling Infrastructure, the verification and validation of the physics modules included and ultimately the scientific exploitation for interpretive or predictive modelling in present and future tokamak devices.

In the scope of the Work Package on Code Development, we developed and released a Kepler scientific workflow for the MHD equilibrium and stability analysis of tokamak plasmas. The workflow includes state-of-the-art equilibrium codes CHEASE, HELENA and CAXE and linear MHD codes MARS, MARS-F, ILSA and KINX. A modular approach allows equilibrium and stability codes to be fully interchangeable for compatible equilibrium metrics e.g. ILSA/MARS/MARS-F, compatible with the jacobian $J\alpha R^2$ straight field line coordinate system provided by CHEASE/HELENA.

A thorough benchmark of the integrated MHD stability codes was performed using both synthetically generated equilibrium and reconstructed equilibrium from JET (#77877) and AUG (#29100) Tokamaks. Convergence studies were conducted for the dependence of the growth rate of kink instabilities with poloidal harmonic spectra, radial/poloidal mesh size and radial position of the perfect conducting metallic wall of the Tokamak. Excellent agreement between the codes was found with relative deviation in growth rates below 5 % even close to marginal stability.



SOL turbulence density fluctuations on ISTTOK

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 health care.

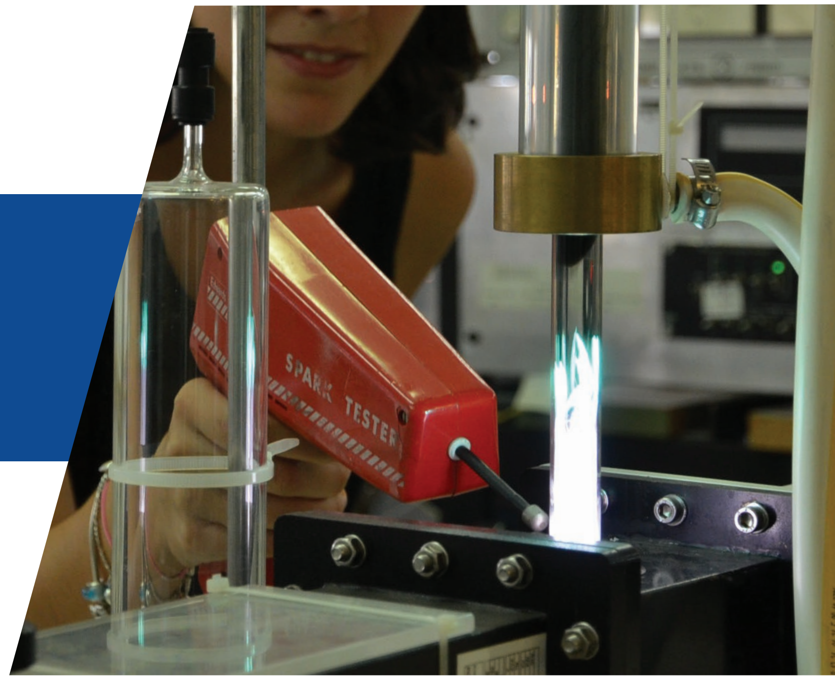
Laser-produced plasmas are test beds for extreme regimes of nature, where electrons can oscillate at relativistic velocities – and, for instance, become accelerated to GeV energies in a few millimetres, thanks to the overwhelming electric fields associated with electron plasma waves.

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.

Gas Discharges and Gaseous Electronics

Principal Investigators:

Adriana Annusová, Dmitry Tsyhanov, Júlio Henriques, Neli Bundaleska, Bruno Lopez, Elena Tatatova, Luís L. Alves, Nuno Pinhão, Carlos D. Pintassilgo, Francisco M. Dias, Luís Marques, Philippe Coche, Carlos M. Ferreira, Jorge Loureiro, Mário Lino da Silva, Vasco Guerra



Summary of Research

Low-temperature collisional plasmas (LTPs) are constituted by electrons, ions, photons, and also by neutral atoms, molecules and radicals often in excited states, exhibiting high physical-chemical reactivity that depends on the working conditions adopted. These complex non-linear features are at the heart of the research interests and goals of the Gas Discharges and Gaseous Electronics group (GEDG): to tailor matter and energy at nanoscale level, using experimental, theoretical and model-based predictive capabilities, developing novel plasma technologies with societal benefits. GEDG multidisciplinary activities bridge fundamental studies to very-applied research, and the synergies between both perspectives are important to advance knowledge in LTPs.

At the **Plasma Engineering Laboratory** (PEL) we master the production of LTPs and their interaction with matter, both in volume and in surface phases. This know-how is used to conceive, design and operate innovative experimental setups for plasma-based applications. The impressive outcome of our applied research contributes to consolidate the technological portfolio of IPFN.

Our **Plasma Modelling and Simulation** (P-M&S) activities focus on the construction and/or optimisation of predictive tools: complex numerical codes, describing the dynamics of plasma (production, transport, and non-equilibrium reactive chemistry, in volume and in surface interaction) in 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 in other planets. HPL hosts the European Shock-Tube for High Enthalpy Research (ESTHER), the sole Portuguese space facility for the planning of planetary exploration missions.

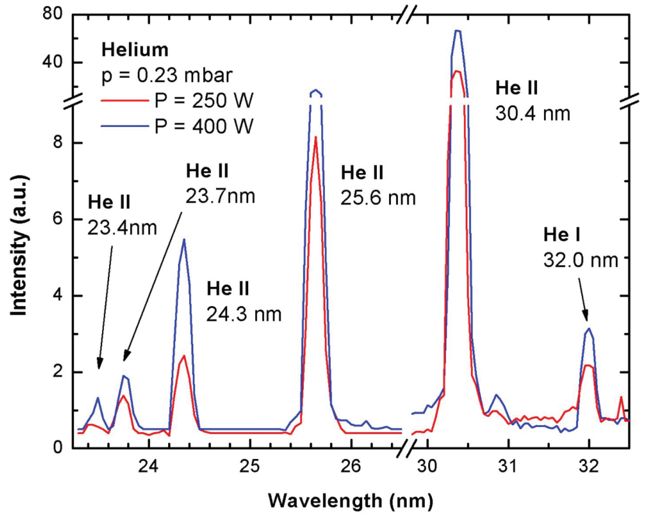
Group Leader: **Luís Lemos Alves**

Plasma Engineering Laboratory

PEL follows an experimental approach, including state-of-the-art plasma diagnostics and complementary complex modelling, to exploit the flexibility of microwave plasmas for tailoring matter and energy at the nanoscale level.

Wave-driven plasma as effective tools for hydrogen production via reforming of alcohols and pretreatment of biomass

The interest in hydrogen producing technologies has increased significantly in recent years with the implementation of fuel cells, i.e. electric power sources with high efficiency and low-level emission of pollutants. Plasma-assisted reforming is a promising alternative technique for producing H_2 from the conversion of hydrocarbons or the pyrolysis of biomass. Our research has identified the mechanisms of ethanol and water decomposition in microwave Ar plasma, suggesting and validating the corresponding integral reaction scheme. We have also demonstrated that the air-water highly reactive plasma environment provides a number of long-lived active species that are able to destroy the cellulosic wrapping of biomass and accelerate its pretreatment process.



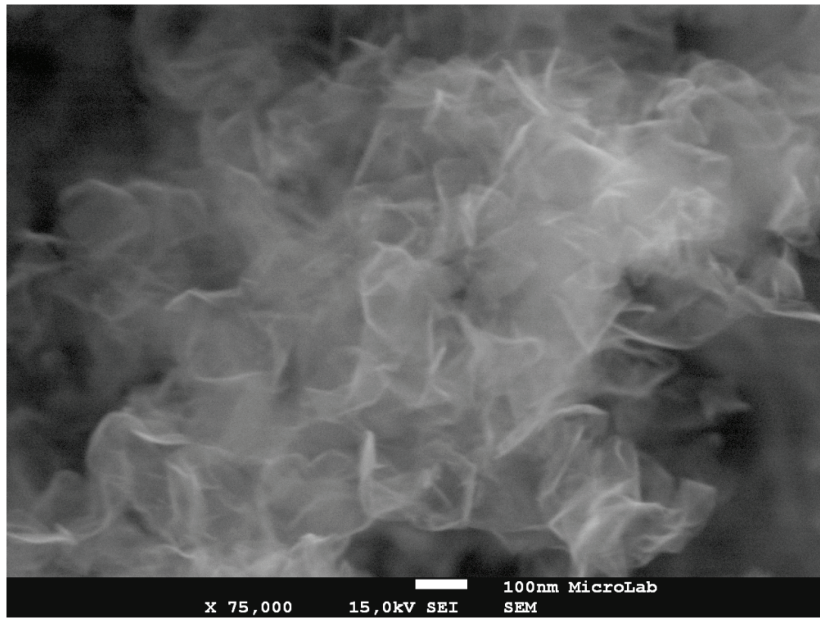
Extreme UV radiation emitted by He microwave plasma

Study of microwave plasmas as VUV/EUV radiation sources

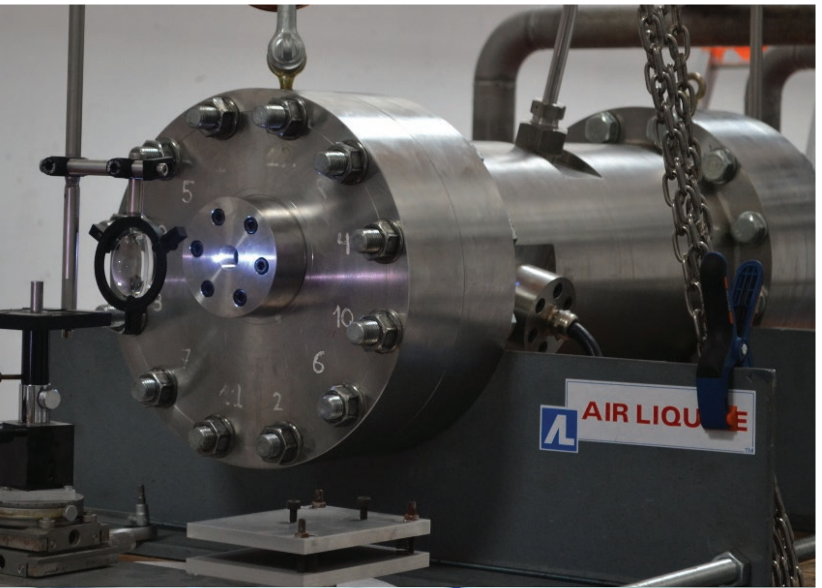
VUV radiation is extremely attractive for developing ultraviolet light sources for sterilisation and decontamination, plasma-based lithography, surface cleaning and modification, etc. Microwave-driven Ar, He and H_2 plasmas are rich environments in VUV radiation, but the experimental research of EUV radiation below 110 nm is quite scarce. Our study has covered this uncharted spectral region, demonstrating that the increase of power input per unit volume triggers stepwise processes and enhances the intensity of VUV/EUV radiation.

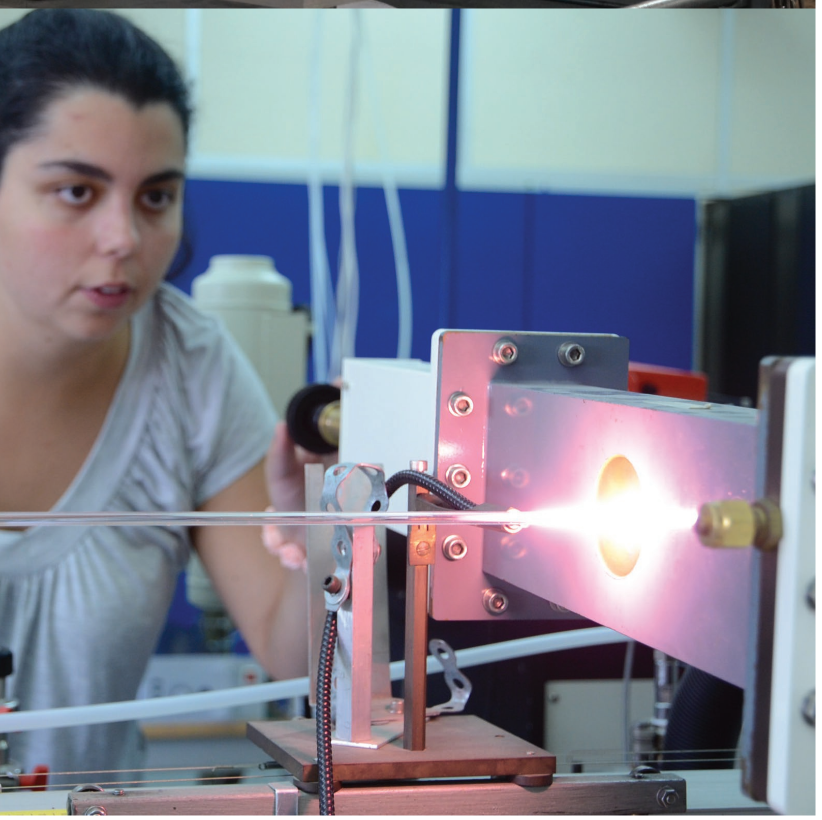
Microwave plasma-based methods for synthesis and engineering of advanced carbon nanostructures

Carbon-based nanostructures, such as graphene and byproducts, have outstanding electrical, thermal and mechanical properties, with a wide number of potential applications in energy conversion and storage. Plasma-based techniques allow an effective control over the supply of particles and energy for the synthesis of these nanostructures. We have engineered an original method for producing free-standing graphene sheets with high structural quality (the presence of sp^3-carbons is below 10%), via a synergistic tailoring of the intense microwave plasma environment (used to decompose hydrocarbons) and the thermodynamic



SEM image of graphene sheets synthesised by the novel plasma reactor conditions in the downstream assembly zone of a reactor. A novel plasma reactor was designed and implemented, providing high yields of graphene of about 0.3 mg/min. We have also achieved the successful doping of graphene sheets with nitrogen (denominated as N-graphene), by exposing graphene sheets to a low-pressure N_2-Ar plasma environment (0.1-1 Torr). By controlling the plasma exposure time or the percentage of nitrogen atoms in the plasma mixture, the doping can be easily tuned and optimised. We have attained typical doping levels of 6%. Diamond-like nanostructures (35-55 nm) have also been synthesised, using Ar-CH_4 plasmas.





Plasma Modelling and Simulation

Predictability in plasma science and engineering based on fundamental modelling has been considered a requirement for the progress in the field. Our M&S activities address exciting research topics involving reactive gas mixtures and include the development of sophisticated numerical codes and computational platforms.

Non-equilibrium plasma chemistry in reactive gases

Micro-plasma sources have enormous potential for applications in various fields. We developed a model describing N_2-O_2 plasmas produced in capillaries at low pressure, meeting the challenges associated with the extreme working conditions adopted. Results revealed a significant influence of negative ions and very efficient production of O and O_2(a) active species.

Understanding gas heating mechanisms in low-temperature plasmas is essential for optimising applications. Gas heating in N_2-O_2 occurs at short times from O_2 dissociation and quenching of N_2 by O_2, and at longer times from NO kinetics, V-T N_2-O collisions and wall recombination of O-atoms.

Plasma-surface interaction is a prevalent subject in various areas of PST. Various dynamical Monte Carlo algorithms were developed, evaluated and successfully compared with a deterministic approach based on reaction-rate equations, for silica and Pyrex surfaces.

High-energy-density plasmas may be sustained at low electric fields. The influence of rotational mechanisms in these plasmas was investigated by solving the electron Boltzmann equation, using a new version of the continuous rotational collision operator that bridges the gap between descriptions at low/intermediate fields.

Conversion of CH_4 and CO_2 is an alternative route for the production of Syngas and HCs. We have modelled the energy efficiency of an atmospheric DBD with CO_2 as an oxidant, for three routes: fast rising power pulses; EEDF shift through dilution with rare gas; increase of gas temperature.

Development of computational platforms

Substantial research work is still needed in plasma-based environmental and biological applications involving N_2-O_2 plasmas often in combination with a non-reactive gas. To address this need we put forward a proposal for delivering a "KInetic Testbed for PLASMa Environmental and Biological Applications" (KIT-PLASMEBA). At the heart of the project is the LisbOn KInetics (LoKI) numerical code that passed successfully several verification and validation procedures. Future steps include the revision of the Boltzmann-solver (to be released as open-source), and the Chemistry-solver (namely of its kinetic and transport schemes).

The SPARK code, a Software Package for Aerothermodynamics, Radiation and Kinetic, integrates several physical models for the simulation of high-speed, non-equilibrium plasmas. The code is capable of simulating different physical systems such as the 0D time-evolution of a thermodynamic system or a post-discharge, the 1D spatial relaxation behind a normal shockwave or the full multi-dimensional description of reentry flows around generic spacecraft geometries. The code is structured as a collection of independent modules (some using the STELLAR database), sharing a common data structure.

Hypersonic Plasmas Laboratory

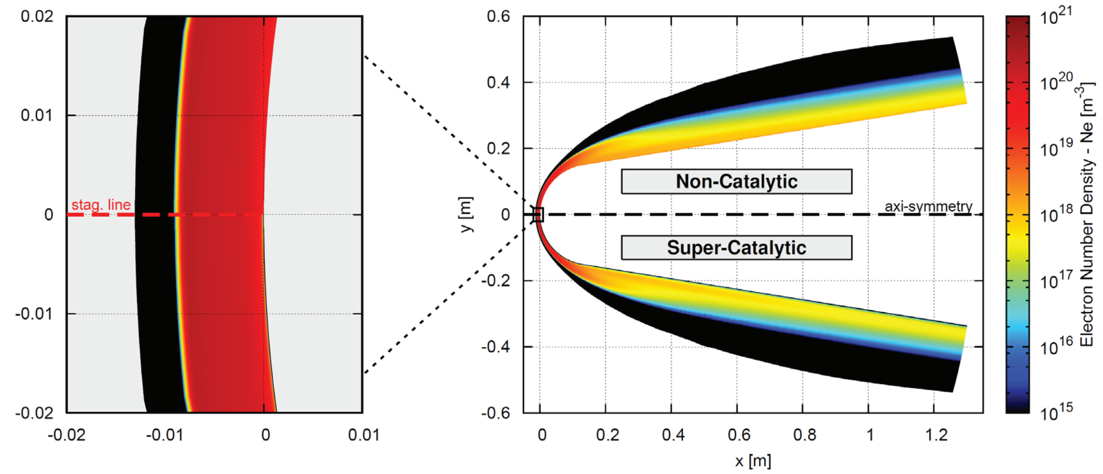
The prediction of non-equilibrium heat transfer processes in atmospheric entry plasmas is an enabling technology for ensuring access to space. HPL hosts ESTHER, funded by ESA and currently in commissioning phase. This piston-free combustion-driven shock-tube is capable of reaching shock speeds in excess of 10 km/s, and will support future European planetary exploration missions.

Experiment (with ESI group)

HPL has been commissioned an experiment for high-pressure (up to 100 bar) deflagration / detonation of H_2/He/O_2 mixtures, comprising a prototype combustion chamber, a remotely handled gas-filling system and a hot wire ignition system. Reliable and repeatable ignition and detonation conditions have been achieved, reaching detonation overpressures of up to 550 bar. This test campaign gave new insights on very-high-pressure hydrogen combustion processes, also validating solutions for safety and remote handling of HPL equipment and finalising the geometrical design of ESTHER's main combustion chamber.

Modelling

The SPARK code has been tailored for predicting the radiation production from shock-tube experiments, using the STELLAR (State-to-State Elementary Rates) and the GASPAR (Gas and Plasma Radiation) databases, including high-fidelity vibration-electronic specific rates. Work is in progress to deploy complex quantum models of high-temperature heavy-impact collisions, as a means to improve the predictability of SPARK for describing high-speed, shock-induced plasmas, supporting ESTHER operation.



Sample simulation of the RAM-C reentry spacecraft at 7.6 km/s.
Electron densities for a non-catalytic and a fully catalytic wall

High-Pressure Plasmas

Principal Investigators:

Gabriel Gomes
Pedro Almeida
Mário Cunha
Mikhail Benilov
Nelson Almeida

Summary of Research

The concentration of electrical current onto the surface of 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 surprising the observer. In addition to being of high scientific interest, understanding and modelling of the current spots are of importance to many industrial devices.

Our goals in 2014-2015 were as follows: to develop a general theory of spots and patterns on cathodes of DC discharges; to facilitate, by means of numerical modelling, the first experimental observations of spot patterns on cathodes of glow discharges in gases other than xenon; to study stability of stationary spots on cathodes of arcs in vacuum and ambient gas; to investigate the physics of spots on composite contacts of vacuum arcs; to identify the mechanism of spotless arc attachment to cathodes of vacuum arcs; and to develop an asymptotic theory of collisionless plasma generated by UV illumination. Methods used to achieve those goals range from numerical modelling to the theory of self-organisation in bistable nonlinear dissipative systems to the method of matched asymptotic expansions 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 an industry-sponsored project and helped to establish a scientific basis for another industry-sponsored project, which started in 2015.

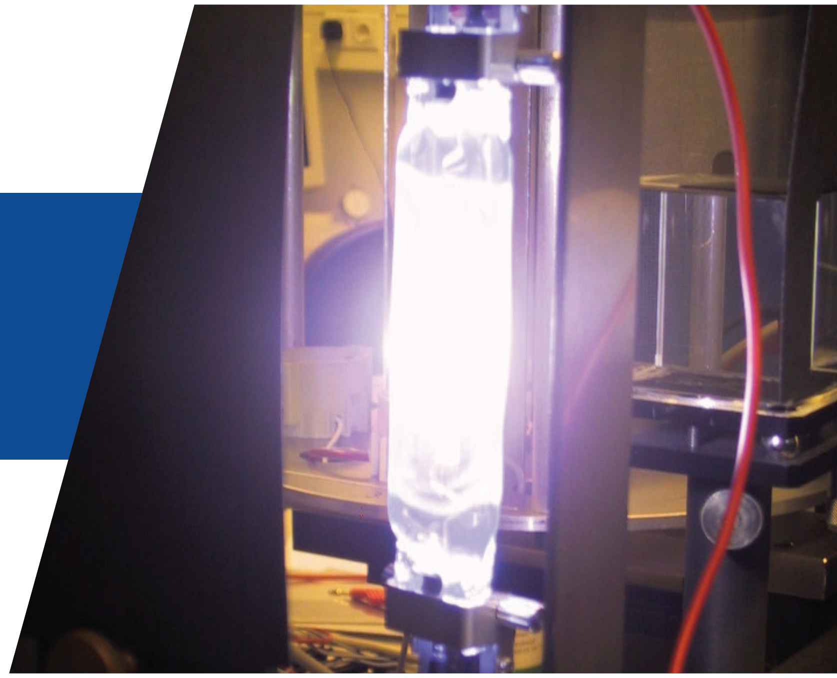
Group Leader: Mikhail Benilov

Spots and patterns on electrodes of DC discharges

One of our main goals in 2014 was to develop a general theory of spots and patterns on cathodes of DC discharges. The theory is based on a new class of stationary solutions in the theory of glow discharges and plasma-cathode interaction in ambient-gas arc discharges, which have been computed over the past 15 years. These solutions exist simultaneously with the solution given in textbooks, which describes a discharge mode with a uniform or smooth distribution of current over the cathode surface, and describe modes with various configurations of cathode spots: normal spots on glow cathodes, patterns of multiple spots recently observed on cathodes of glow microdischarges, spots on arc cathodes. We have reviewed the multiple solutions computed to date with the aim to systematise these solutions and analyse their properties and physical meaning.

Although the physical mechanisms of plasma-cathode interaction in dc glow and arc discharges are very different, the overall patterns of different modes of current transfer turned out to be remarkably similar. Of course, this is not surprising: in terms of general theoretical physics, cathodic parts of both discharges represent bistable nonlinear dissipative systems; cathode spots represent self-organisation phenomena; hence, solutions describing the spots must conform to general trends of self-organisation in bistable systems. Therefore, the treatment of this work is based on the theory of self-organisation in bistable nonlinear dissipative systems.

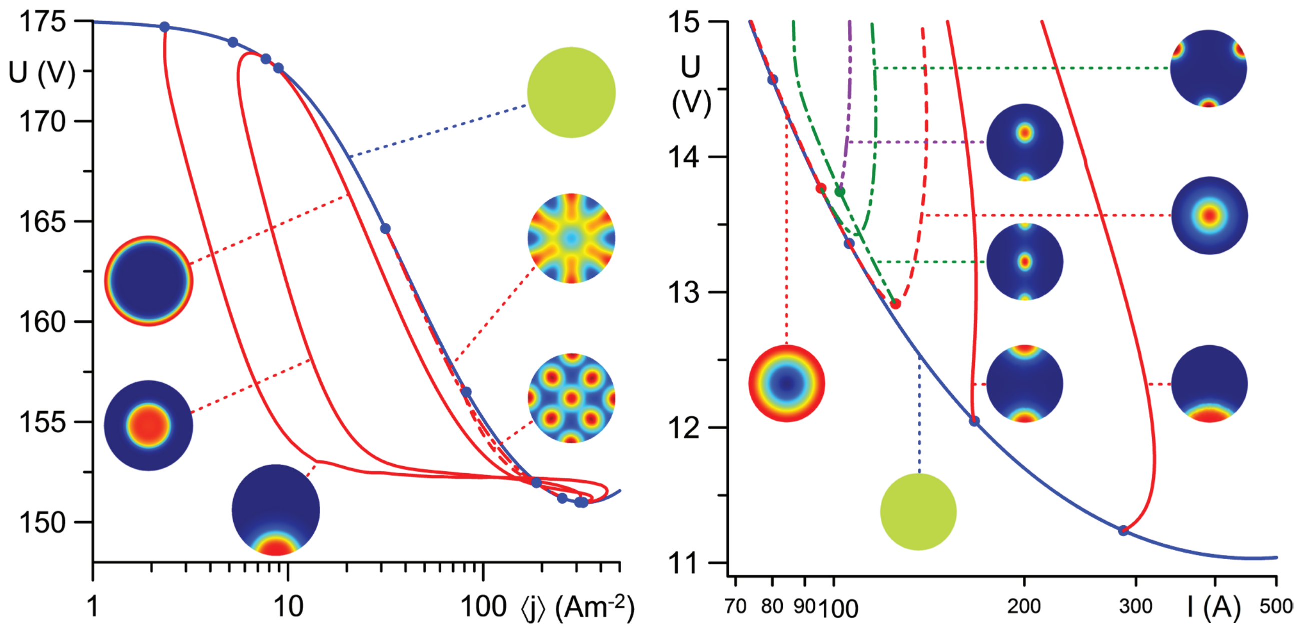
The developed theory describes general properties of spots and patterns on cathodes of glow and arc discharges within a single physically transparent framework. It also offers a possibility of systematic computation of the multiple solutions. In particular, it is shown that cathode spots in DC discharges represent a manifestation of self-organisation caused by the well-known basic mechanisms of the near-cathode space-charge sheath; no special mechanisms favoring self-organisation need to be invoked.



This theory was presented in a review article in the Cluster Issue on Spots and Patterns on Electrodes of Gas Discharges, published in 2014 by the journal Plasma Sources Science and Technology and guest-edited by the group leader jointly with Prof. U. Kogelschatz (Switzerland).

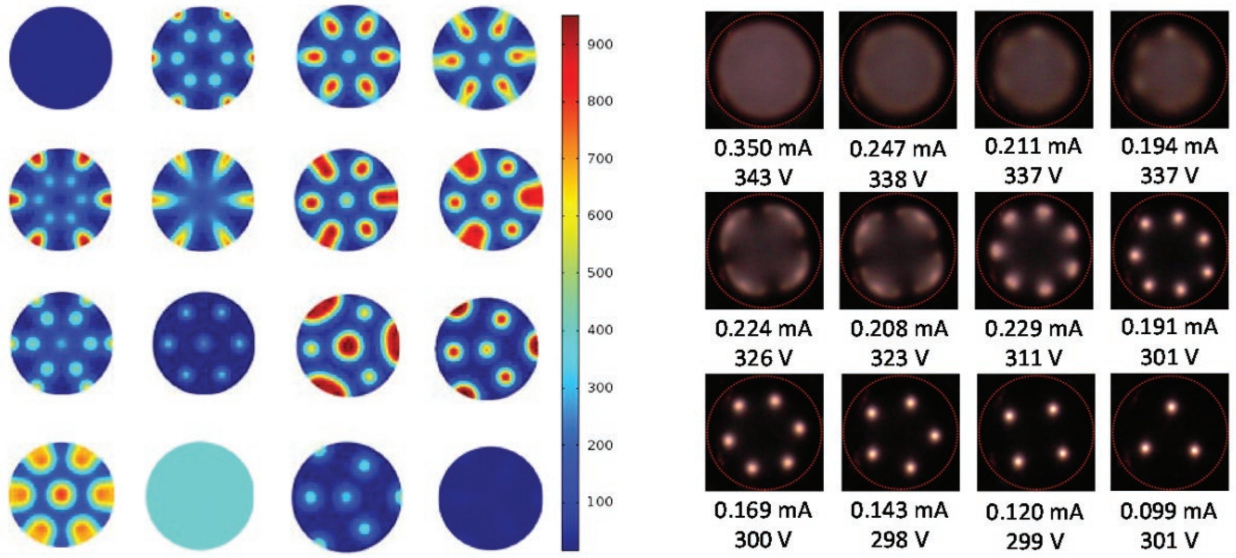
Self-organised patterns of cathodic spots have been observed previously in glow microdischarges operated in xenon, but not in other gases. Modelling has indicated that it is, in principle, possible to observe the spot patterns in discharges operated in other gases,

Computed current-voltage characteristics and schematics of current density distribution over the cathode surface described by different steady-state solutions



Glow discharge: Xe plasma, p=30 torr, discharge tube of a radius and height of 0.5 mm with a reflecting wall

Cathode of an arc discharge: Ar plasma, p=1 bar, W cathode of a radius of 2 mm and height 10 mm with an insulated lateral surface



Computed and experimentally observed self-organised spot patterns in Kr

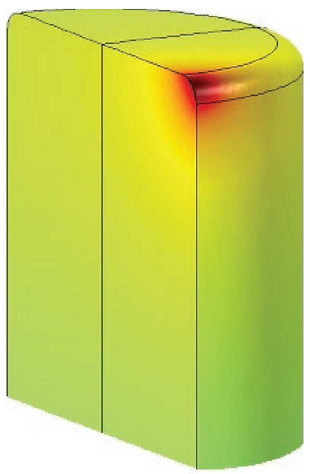
provided that the experimental conditions, in particular, pressure, are right. This conclusion has been confirmed by special experiments, conducted by a partner team in New Jersey.

Stability of stationary spots on cathodes of arcs in vacuum and ambient gas has been investigated by means of simulation of development in time of perturbations imposed over steady-state solutions. It is shown, in particular, that if the ballast resistance in a small-scale laboratory experiments is insufficient, potential consequence may be a thermal explosion of a spot, if the arc burns in vacuum, and massive melting of the cathode surface, if the arc burns in ambient gas. This conclusion conforms to trends observed in the experiment.

The physics of spots on composite CuCr cathodes of vacuum arcs was investigated by means of a self-consistent space-resolved numerical model of cathode spots in vacuum arcs. The attention is focused on spots attached to Cr grains in the Cu matrix in a wide range of values of the ratio of the grain radius to the radius of the spot. In the case where this ratio is close to unity, parameters of spot are strongly different from those operating on both pure-Cu and pure-Cr cathodes; in particular, the spot is maintained by Joule heat generation in the cathode body and the net energy flux is directed from the cathode to the plasma and not the other way round. An investigation of stability has shown that stationary spots are stable if current-controlled. However, under

Computed stationary spots on cathodes of arcs in vacuum and ambient gas

Axially symmetric spot on a Cu cathode of vacuum arc. Arc current 47 A.

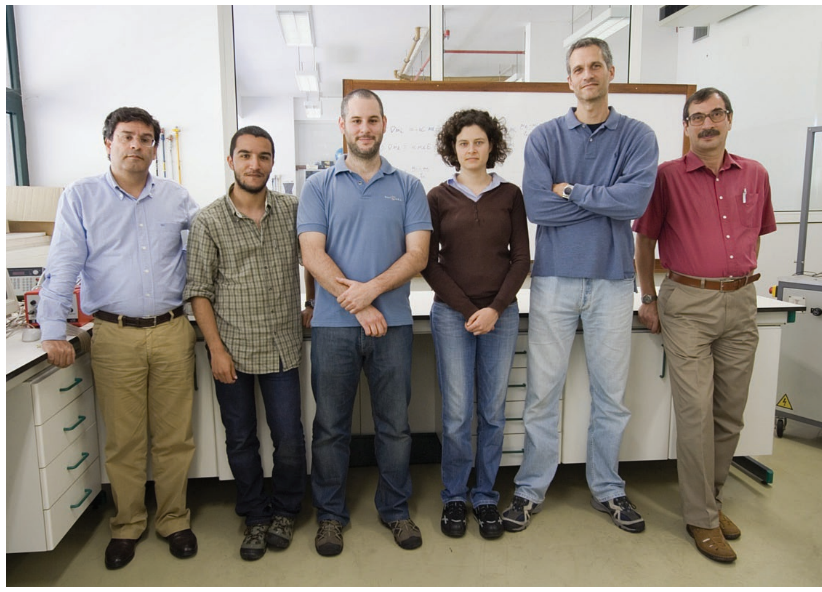


3D spot on a W cathode of 1 bar Ar arc. Arc current 6 A.

conditions of very high current, where the near-cathode voltage is not affected by ignition or extinction of individual spots, the spots are unstable and end up in either explosive-like behaviour or destruction by thermal conduction. On the other hand, spots live significantly longer – up to one order of magnitude – if the spot and grain sizes are close; else, typical spot lifetimes are of the order of 10 μs. This result is consistent with the experimental fact that after several switching events the size of Cr grains is reduced down to values of the order of 10 μm.

The spotless mode on cathodes of vacuum arcs occurs in cases where the average temperature of the cathode surface is high enough, in similarity with the diffuse mode on cathodes of ambient-gas arcs. The spotless mode on cathodes of vacuum arcs has been observed for several decades by now. However, its understanding remains elusive: none of the known mechanisms of the electron emission is capable of producing the current densities observed in the experiment (except for cathodes made of Gd, which is characterised by a very low work function). We have made a fresh attempt to elucidate basic mechanisms of the spotless vacuum arc attachment to cathodes. It was shown that in the case of chromium cathode the usual mechanism of current transfer to arc cathodes cannot sustain current densities observed in the experiment, the reason being that the electrical power deposited into electron gas in the near-cathode space-charge sheath is insufficient. It is hypothesised that the electrical power is supplied to the electron gas primarily in the bulk plasma, rather than in the sheath, and a high level of electron energy in the vicinity of the sheath edge is sustained by electron heat conduction from the bulk plasma. Estimates of the current of ions diffusing to the sheath edge from the quasi-neutral plasma gave values comparable to the experimental current density, which supports the above hypothesis. On the contrary, the spotless attachment of vacuum arcs to gadolinium cathodes may be interpreted as a manifestation of the usual mechanism of current transfer to arc cathodes. Results given for gadolinium cathodes by a model of near-cathode layers in vacuum arcs conform to available experimental information.

The method of matched asymptotic expansions was applied to the problem of a collisionless plasma generated by UV illumination localised in a central part of the plasma in the limiting case of small Debye length. A second-approximation asymptotic solution is found for the double layer positioned at the boundary of the illuminated region and for the un-illuminated plasma for the plane geometry. Numerical calculations for different values of Debye length are reported and found to confirm the asymptotic results. The net integral space charge of the double layer is asymptotically small, although in the plane geometry it is just sufficient to shield the ambipolar electric field existing in the illuminated region and thus to prevent it from penetrating into the un-illuminated region. The double layer has the same mathematical nature as the intermediate transition layer separating an active



plasma and a collisionless sheath, and the underlying physics is the same as well. In essence, the two layers represent the same physical object: a transonic layer.

The described results on spots and patterns on electrodes of DC discharges, in particular, proved useful for the investigation of physics of high-power circuit breakers, which is conducted in the framework of an industry-sponsored project, and helped to establish a scientific basis for another industry-sponsored project, which started in 2015.

Lasers and Plasmas

Principal Investigators:

Gonçalo Figueira
João M. Dias
Jorge Vieira
Luis O. Silva
Marta Fajardo
Nelson Lopes
Ricardo Fonseca
Thomas Grismayer

Summary of Research

The research programme at GoLP is focused on a few of the most challenging science questions in our field:

- How does matter behave in extreme electromagnetic fields, either at ultra-relativistic intensities, ultra-short timescales or at extremely hard wavelengths?
- 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?
- 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 a laboratory and in astrophysics?

These directions are propelled by new ultra high-intensity lasers (e.g. ELI), light sources (e.g. LCLS, XFEL) 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 hold 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

High-resolution and high-speed compact spectrometer

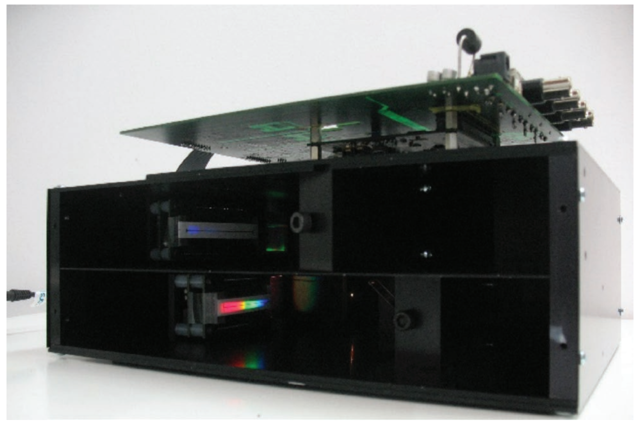
This research line took place in the frame of the INScan project, developed by an IST-SARSPEC Consortium. It involves different aspects of instrumentation challenges to develop a spectrometer for advancing the state of the art in optical resolution, for both UV and visible bandwidths, and in high-scanning speed, for compact commercial spectrometers.

Being responsible for the optical design and test of the developed spectrometers our aim was to obtain a compact optical circuit for the spectrometer with a resolution below the 0.2 nm, covering simultaneously UV and visible bands.

First, we have designed and tested an optical circuit for a very compact, configuration-flexible, low-cost and low-speed spectrometer. With a resolution just below 1 nm it covers the ultraviolet, visible and infrared regions up to 1 μm. From this step of the project, SARSPEC was able to already market a spectrometer line.

With the acquired knowledge, the high-resolution and high-speed spectrometer was designed, prototyped and tested, achieving the optical specification goals.

The project was successfully concluded with a good evaluation by the funding agency. There are plans to start a new project with the same company for developing a Raman Scattering Spectroscopy Instrument.



Inner structure of the spectrometer prototype developed for the INScan project

Positrons ride on a twisted plasma wake

Plasma based accelerators have the potential to greatly reduce the size and cost of particle accelerators. Experiments operate in conditions that are ideally suited to accelerate electrons to high energies, but are not adequate for positron acceleration. Positron acceleration in plasmas then remains a grand-challenge for the field. To answer this outstanding question, we have explored the plasma wakefields driven by intense twisted light with orbital angular momentum.

To investigate high gradient positron acceleration we developed a theoretical model and confirmed theoretical predictions with the aid of computer simulations.

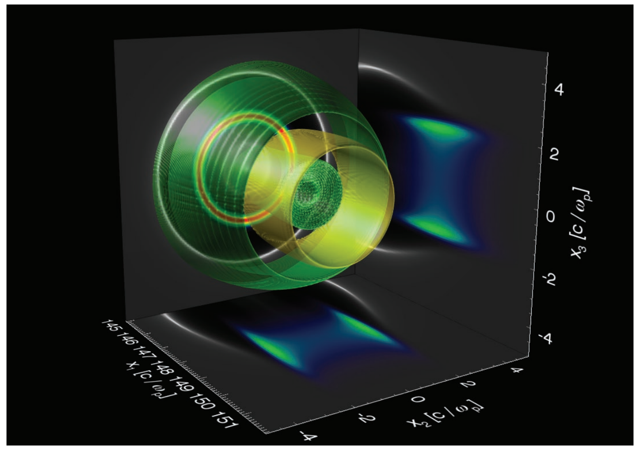
Simulations were performed in SuperMUC, a TIER-0 supercomputer in Munich, Germany. For the numerical calculations, we used Osiris, a massively parallel, fully relativistic particle-in-cell code, developed in collaboration with the University of California, Los Angeles.

We have demonstrated that the plasma wakefields driven by intense twisted light have a series of novel properties due to its exotic spatial field structure. These properties make these wakes ideally suited for positron acceleration.

The main results, published in Physical Review Letters, are the demonstration of a new mechanism for high gradient positron acceleration in plasmas.

This work makes a significant step towards a future plasma-based linear collider.

In the future, we want to explore the potential of these plasma waves for radiation generation.



Osiris simulation of a plasma accelerator driven by an exotic doughnut shaped electron beam (yellow), with the plasma wake (green) forming a toroidal wakefield.

Laser absorption via multiple laser-driven QED cascades

It is extremely desirable to study dense pair plasmas in the laboratory, both for fundamental purposes and astrophysical applications. Producing pair plasmas in ultrastrong fields may demonstrate that we can mimic the conditions of these extreme astrophysical environments in terrestrial laboratories. As pulsars efficiently convert the large-scale Poynting flux to gamma rays, the laboratory analogue of a pulsar is expected to efficiently convert optical light into gamma rays.

Our exploration relies on a QED module, part of our particle-in-cell code OSIRIS 3.0, which includes real photon emission from an electron or a positron, and decay of photons into pairs, known as the Breit- Wheeler process. The prolific number of pairs/photons that may be generated can be sorted out with the use of particle merging algorithm, which allows resampling the 6D phase space with different weighted macro-particles.

We have studied laser absorption in self-produced critical pair plasmas resulting from the saturation of QED cascades for intensities relevant for near-future laser facilities. We also demonstrated the conditions to achieve substantial laser absorption, extending the pioneer results of previous works. We have shown that if significant laser absorption was occurring, most of the initial laser energy was converted into gamma ray.

The main result is that the degree of absorption depends on the laser intensity and the pulse duration and that absorption above 80% can be reached for 100 PW class lasers.

This work has resulted in qualitative signatures of absorption in QED cascades that can serve as a guide for future experiments.

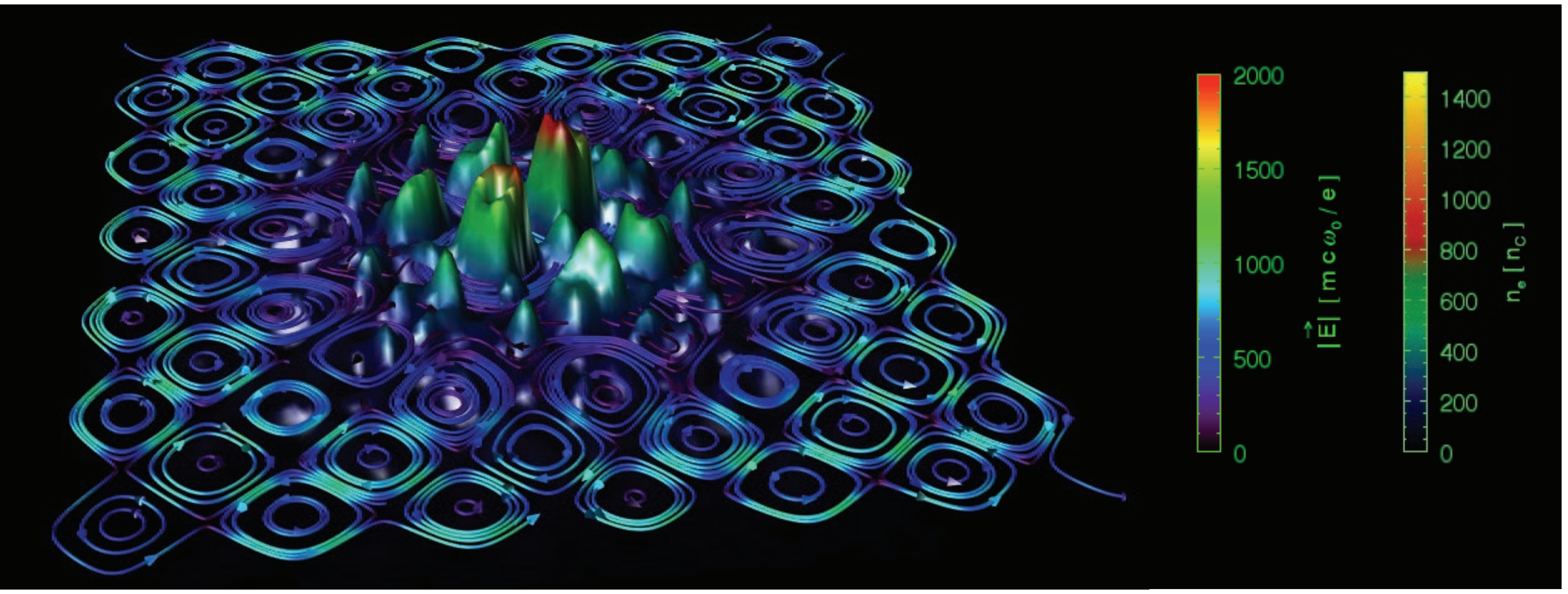
We will now use our findings to establish whether the gamma ray spectra occurring during these cascades are compatible with the photon spectra measured in the context of extreme astrophysical objects observations.

Fourier holography

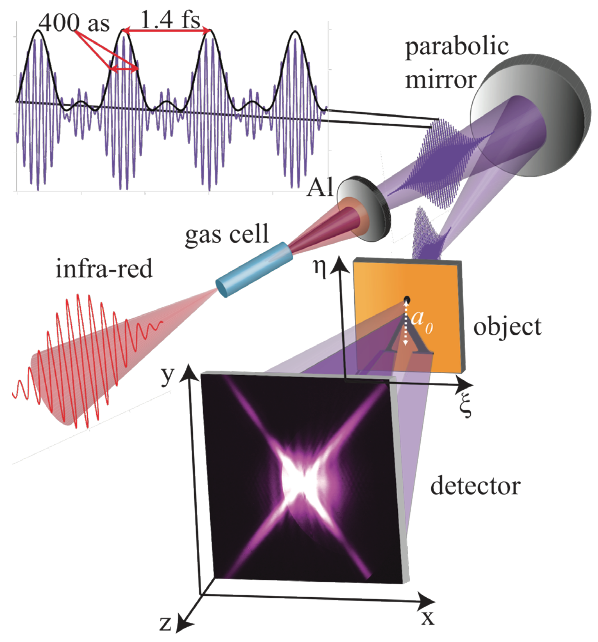
Soft x-rays from High Harmonic Generation are the fastest source on record, down to the attosecond range. Imaging with soft X-rays not only allows for nm range imaging resolution, but also allow to capture events at world-record short pulse durations. However, when the image is captured, the colour spectrum of the source needs to be preserved, otherwise the temporal information is lost. Multicolour imaging with x-rays is now being explored.

Our main goal is to be able to capture an image of an object with attosecond resolution. To do so, we use a high harmonic backlighter source and use digital Fourier holography to record the image.

We have studied the best configuration in Fourier holography that allows to capture and reconstruct multicoloured holograms.



Simulation of an electron-positron QED cascade in a four-laser optical trap. The field lines show the electric field structure in a standing wave produced by 4 lasers. Surface plot shows the density of the self-created e+e- plasma.



Method of ultrafast holography: a high intensity infrared (IR) laser is focussed on a low-density gas to produce soft x-rays through high-harmonic-generation

We successfully recorded 3-colour holograms of microscopic objects, which we could reconstruct with ~100 nm resolution.

A triple image at each wavelength could be reconstructed with nm resolution: our device is a single-shot imaging spectrometer with unprecedented spatiotemporal resolution.

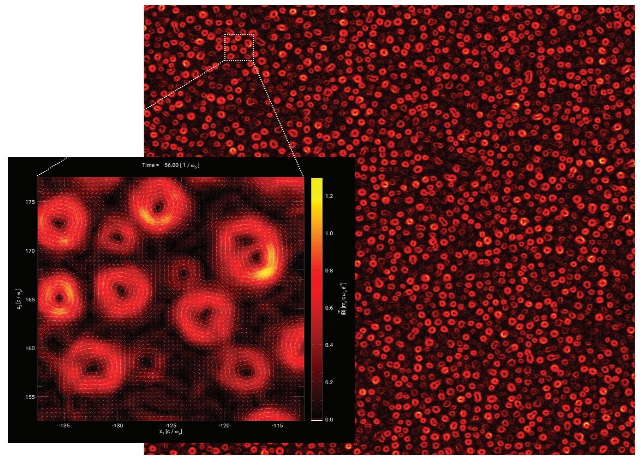
We now need to extend the technique to single-attosecond pulses. In this case, the spectrum has the same bandwidth but is not discrete, making the reconstruction a bit harder to achieve.

OSIRIS: Setting the gold standard for kinetic plasma simulations

The highly non-linear and kinetic processes that occur in many relevant plasma scenarios require accurate modelling with computer codes to capture the underlying physical mechanisms. We develop the OSIRIS framework, one of the most advanced simulation infrastructures for kinetic plasma simulations, which is widely used by many research groups in Europe and the US for scientific research in astrophysics, beam-plasma interaction studies, particle acceleration, nuclear fusion, radiation generation, and nanoplasmas among others. Our recent work focused mainly in two broad areas: development for exascale architectures, and extending the simulation infrastructure.

The quest towards exascale computing has lead to the development of hybrid systems with add-on accelerator cards such as the Xeon Phi accelerators powering, for example, the Tianhe-2 system in China (currently the #1 system in the world) and the SuperMIC at LZR in Germany. We successfully deployed the OSIRIS code on the latter system, achieving performances of ~ 600 (2D) | 300 (3D) million particle pushes per second on a single board, and very good parallel scalability up to 32 boards, with above 74% (strong)/ 94% (weak) scaling efficiency. The approach used combined the existing MPI parallelisation for multiple board use with specific vector code to improve single board performance.

The continuous improvement of the OSIRIS framework, which added new features and algorithms, support for different computing hardware, and additional physics models, resulted in a large and complex code base with the inherent difficulties in maintenance and development. To address this, we have developed a new version of the OSIRIS framework, that leverages on the object-oriented features of Fortran 2003, which are now widely supported by available compilers. The new object-oriented structure allows for the encapsulation of specific features, and better collaboration between the development team while allowing for a gradual transition from the existing Fortran 95 code base. The new version also implements a new strategy for run-time selection of simulation mode, that allows for a single binary to be used with all code features.



Plasma cloud collision modelled on a Xeon Phi cluster: the collision of two neutral electron-positron plasma clouds leads to the generation of magnetic field through the Weibel instability

Community & Outreach

IPFN is deeply committed to taking an active role in the communication of science and dissemination of its scientific and technological achievements to the 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, both specialised and broad-scope. The highlights of this period are the following:

- International Congress on Plasma Physics (ICPP 2014) – IST, Lisbon, September 15-19, 2014
- Advancements in Nuclear Instrumentation Measurement Methods and Their Applications (ANIMMA 2015) – Lisbon Congress Centre, April 20-24, 2015 (400+ participants)
- 42nd European Physical Society Conference on Plasma Physics – Centro Cultural de Belém, Lisbon, July 22-26, 2015 (800+ participants)

School visits and talks

ISTTOK and L2I together receive more than 80 group visits per year from 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.

IPFN researchers are frequently invited to present their activities at secondary schools. The celebrations of the International Year of Light (IYL 2015) offered an extremely fruitful opportunity to strengthen this method of dissemination, with a large number of talks at basic (3rd cycle) and secondary schools.

Web and social media

The online presence of IPFN is extended over five different channels:

Webpage – ipfn.tecnico.ulisboa.pt
For 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 25% in 2014/15

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 240 pictures

Workshops and training

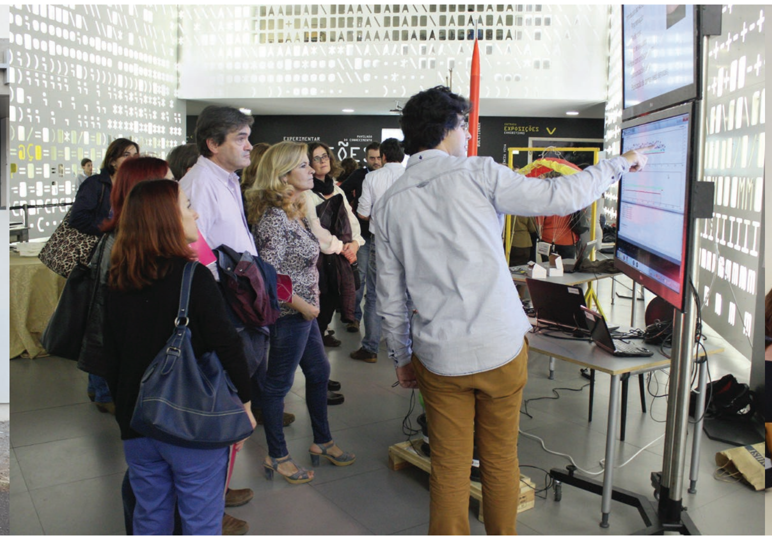
Since 2011 IPFN has been organising an annual 5-day workshop in nuclear fusion for secondary school teachers, with a similar 5-day workshop in lasers starting in 2012. More than 150 teachers have had the opportunity to participate in these workshops and incorporate the contents into their classrooms.

The 2015 Workshop on Lasers brought inspiration from the IYL 2015 celebrations and provided the participants with a one-day training in using an educational kit of experiments in optics. The kits, which were offered to each participant, were partially supported by the Photonics Explorer intracurricular educational programme, of which IPFN is a partner for Portugal.

Every year IPFN also hosts groups of secondary school students in the scope of the Ciência Viva summer project. The participants interact with the researchers and join a number of laboratory activities.

The European Fusion Theory Conference was organised by IPFN members and held in Instituto Superior Técnico

Official visit by the Astronaut Jean-Jacques Favier and Eric Jurado at ESTHER facilities



IPFN's participation on "Noite dos Professores", an initiative of Ciência Viva

One of the classes during the 2015 workshop on lasers for secondary school teachers

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.

The APPLAuSE External Supervisory Committee during their official visit (Nov. 2015) together with the 1st and 2nd cohort students

APPLAuSE Programme: lecture on plasma physics

Surf and science: an out-of-the-box seminar organised by the Group of Lasers and Plasmas

The third edition of PlasmaSurf (2015) proved again a huge success

APPLAuSE doctoral programme

APPLAuSE is an FCT-funded international doctoral programme in Plasma Science and Engineering. It consists of a student-centred and highly modular PhD programme designed to enhance each student's capabilities and maximise their potential. IPFN hosts the PhD programme and the degree is awarded by the University of Lisbon, Portugal. During 2014-2015, seventeen students from nine different nationalities joined the programme in its first two editions.

MSc and PhD programmes

Many IPFN researchers are involved with undergraduate and graduate training at the Physics Department of IST, ensuring teaching in basic and specialised courses of the MSc in Physics Engineering. A large number of MSc and PhD thesis are carried out every year at IPFN.

Colloquia and seminars

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.

Summer School

PlasmaSurf is IPFN's flagship 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.

In Memoriam

Carlos Matos Ferreira (1948-2014)

Professor Carlos Matos Ferreira passed away unexpectedly on 27 December 2014 in Lisbon. He was a Full Professor at the Department of Physics of Instituto Superior Técnico (IST) since 1979. He was President of IST from 2001-2009, founder of the Gas Discharges and Gaseous Electronics group of IPFN at IST, and Director of the Doctoral Programme APPLAuSE (in Plasma Science and Engineering) with IPFN/IST. He was a member of the Academia Europaea (elected in 2002), and Grand Officer of the Order of Prince Henry, a decoration awarded by the President of the Portuguese Republic in 2005. He was awarded a Stimulus for Excellence in Research prize by FCT in 2004.

He graduated in Electrical Engineering at IST (1971), received a doctorate in physics at the University of Paris XI – Orsay (1976), with the grade *Très Honorable*, and earned the title of *Agregado* in Physics at IST (1979).

His scientific work was in field of low-temperature plasmas (LTP), mainly on Discharges and Electronics in Gases, Kinetic Theory and Atomic and Molecular Physics in plasmas. He devoted many years of his research career to the study of the electron Boltzmann equation and to the theoretical formulation describing the structure of surface-wave-sustained plasmas.

He was an internationally well-known plasma physicist. He authored two books and published more than 400 papers in international journals, as book-chapters published by international publishers and as articles in the proceedings of international conferences with refereeing. He supervised more than 20 research programmes of undergraduate and graduate students (post-doctoral, doctoral and master), national and international. His work will continue to have an important impact in the LTP community (presently, about 3000 citations).

Professor Matos Ferreira was, for many years, in charge of lecturing the MSc course on Plasma Physics and Technology, in the scope of the Master in Engineering Physics. His faculty colleagues, and particularly those with the Area of Plasma Physics, Lasers and Nuclear Fusion, will remember and perpetuate the values that guided his activity as an academic, a scientist and a mentor.

He will be greatly missed by us all.

Annual Report 2014-2015

Coordination and Chapter Editors

Gonçalo Figueira and Bruno Gonçalves

Section Editors

Bruno Gonçalves, Eduardo Alves, Horácio Fernandes, Luís Lemos Alves, Luís Oliveira e Silva, Mikhail Benilov and Rui Coelho

Layout and Design

Joana Cabral

TÉCNICO LISBOA

ipfn
INSTITUTO DE PLASMAS
E FUSÃO NUCLEAR

Instituto de Plasmas e Fusão Nuclear
Instituto Superior Técnico
Av. Rovisco Pais,
1049-001 Lisbon, Portugal

ipfn@ipfn.tecnico.ulisboa.pt
(+351) 218 417 696

ipfn.tecnico.ulisboa.pt
facebook.com/IPFNLA