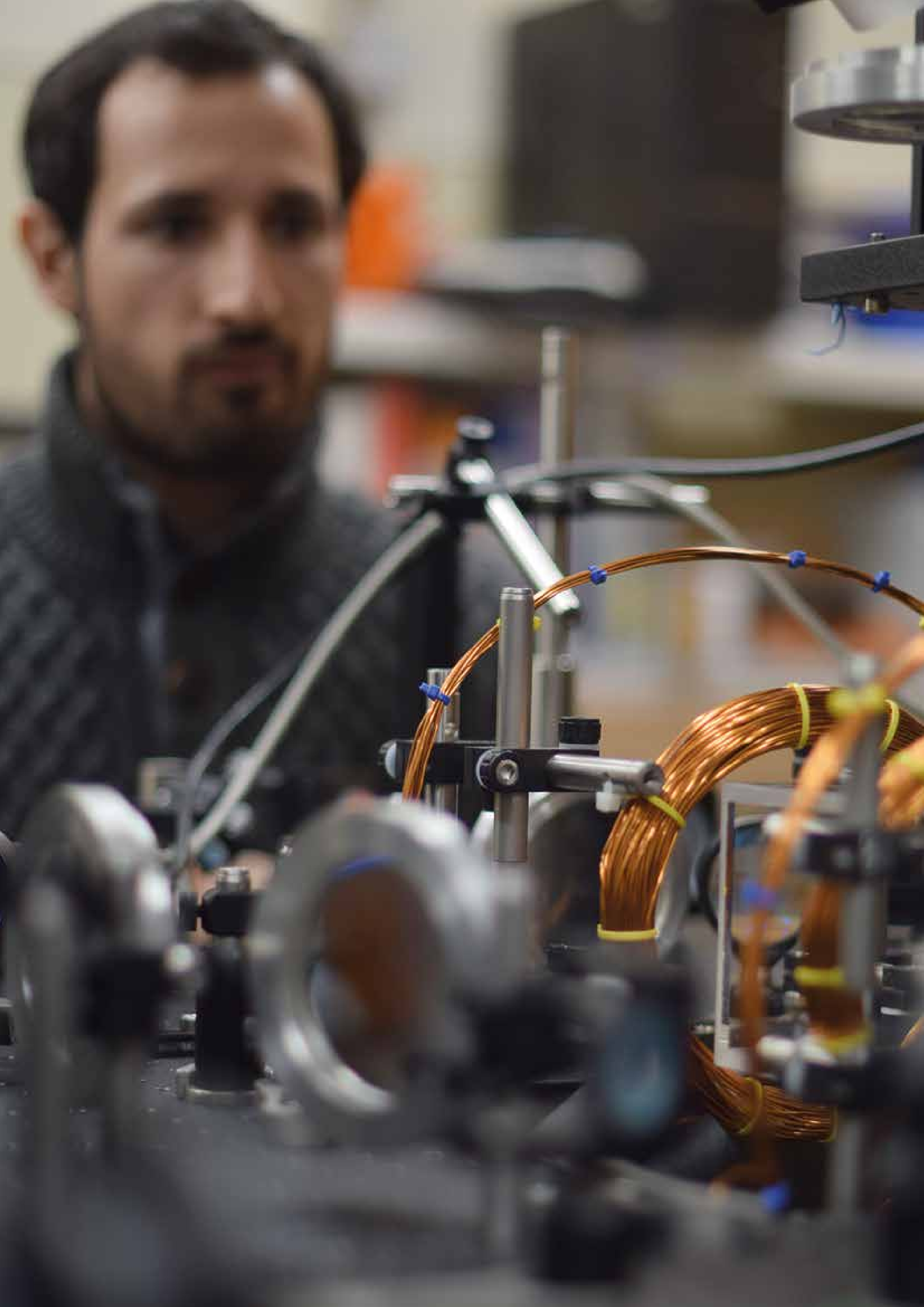
Biennial Report 2018-2019

Instituto de Plasmas e Fusão Nuclear

ipfn
INSTITUTO DE PLASMAS
E FUSÃO NUCLEAR



Biennial Report
2018-2019

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 our activities in 2018-2019. This report covers the activities carried out in the framework of the Consortium EUROfusion, the Contract of Associated Laboratory, the Contracts with the ITER International Organization (ITER IO) and the European Joint Undertaking for ITER and Fusion Energy (F4E), projects of the H2020 Programme of the European Union, projects of the European Space Agency (ESA) and projects funded by Fundação para a Ciência e a Tecnologia.

It was an outstanding period where IPFN and its researchers accomplished a number exceptional milestones and achievements.

• The most recent evaluation of Portuguese research centers by FCT (Foundation for Science and Technology), started in 2017 and concluded in 2019, has placed IPFN among the highest ranked units, with an overall classification of "Excellent". Additionally, IPFN was awarded a grade of 5/5 in the three evaluation criteria, excelling in all the metrics. Comparatively, in the area of Physics a third of the 15 national research units was ranked as excellent. But overall, only 11% of the units were awarded the triple-5-star status. We are very proud to reconfirm the level of the previous evaluation cycle, and we will continue to work together towards excellence in research, training and outreach

• IPFN hosted a second ERC Advanced Grants InPairs (awarded in 2015 and started in 2016), awarded to Luis O. Silva for a total funding in excess of 3.4 M€. This grant recognizes IPFN expertise on massively parallel kinetic plasma simulations and addresses the interaction of intense fields with plasmas and resulted in exciting scientific results, prizes and awards, invited talks and colloquia, and publications in the top multidisciplinary and physics journals.

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

• IPFN is the leading institution of VOXEL and PEGASUS, two projects funded by the highly competitive Horizon2020 programme FET (Future Emerging Technologies) Open. The VOXEL project (Volumetric medical X-ray imaging at extremely low dose), concluded in 2019, brought together a multidisciplinary research team of experts in the fields of sensors, X-rays, metrology, tomography and three-dimensional image reconstruction, with 3.99M€ funding to develop an innovative X-ray camera. The project's facility is located at IST, creating one of the new IPFN laboratorial infrastructures. PEGASUS (Plasma Enabled and Graphene Allowed Synthesis of Unique nanoStructures), with 3.99 M€ funding, has the ambitious goal of using the unique properties of plasmas for the creation of extraordinary novel materials, by controlling the energy and matter transfer processes at nanoscales through specific plasma mechanisms. During this period

PEGASUS progressed towards designing a proof-of-concept device for the large-scale production of N-graphene, resulting in 3 submitted patents.

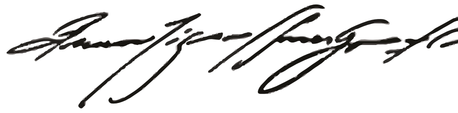
• The European Shock Tube for High Enthalpy Research (ESTHER) was inaugurated on 24 July 2019 at Campus Tecnológico e Nuclear of IST, exactly 50 years after the return to Earth of Apollo 11, the first manned Moon landing mission. This world-class research infrastructure, funded by ESA and national funds, achieved an important milestone with its inclusion in the National Roadmap for Research Infrastructures in 2019.

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

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

Participation on large-scale projects is made through long-term commitment and funding support. On behalf of IPFN, I would like to acknowledge the support of EURATOM, F4E, FCT (through project UID/FIS/50010/2013 and UID/FIS/50010/2019), and IST, for having made such commitments possible.
Science is also made through collaborations. I would like to convey my heartfelt thanks to all our partners who have contributed to make our projects a success, or to those who lead projects to which IPFN contributes.

To finalize I would like to express my deepest gratitude to the dedication and commitment of IPFN researchers, technicians, students and administrative staff. All of them together are IPFN best asset.



Bruno Soares Gonçalves
President of IPFN

About IPFN

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

IPFN ensures the Portuguese participation in EUROFusion, the European Consortium for the Development of Fusion Energy. The role of the research unit, at the national and international level, was recognised in the 2019 FCT evaluation of R&D units, where IPFN was awarded the classification **"Excellent"** with a grade of 5/5 in all evalluation criteria (awarded only to 11% of all the evaluated research units).

Research at IPFN is organised into two Thematic Areas:

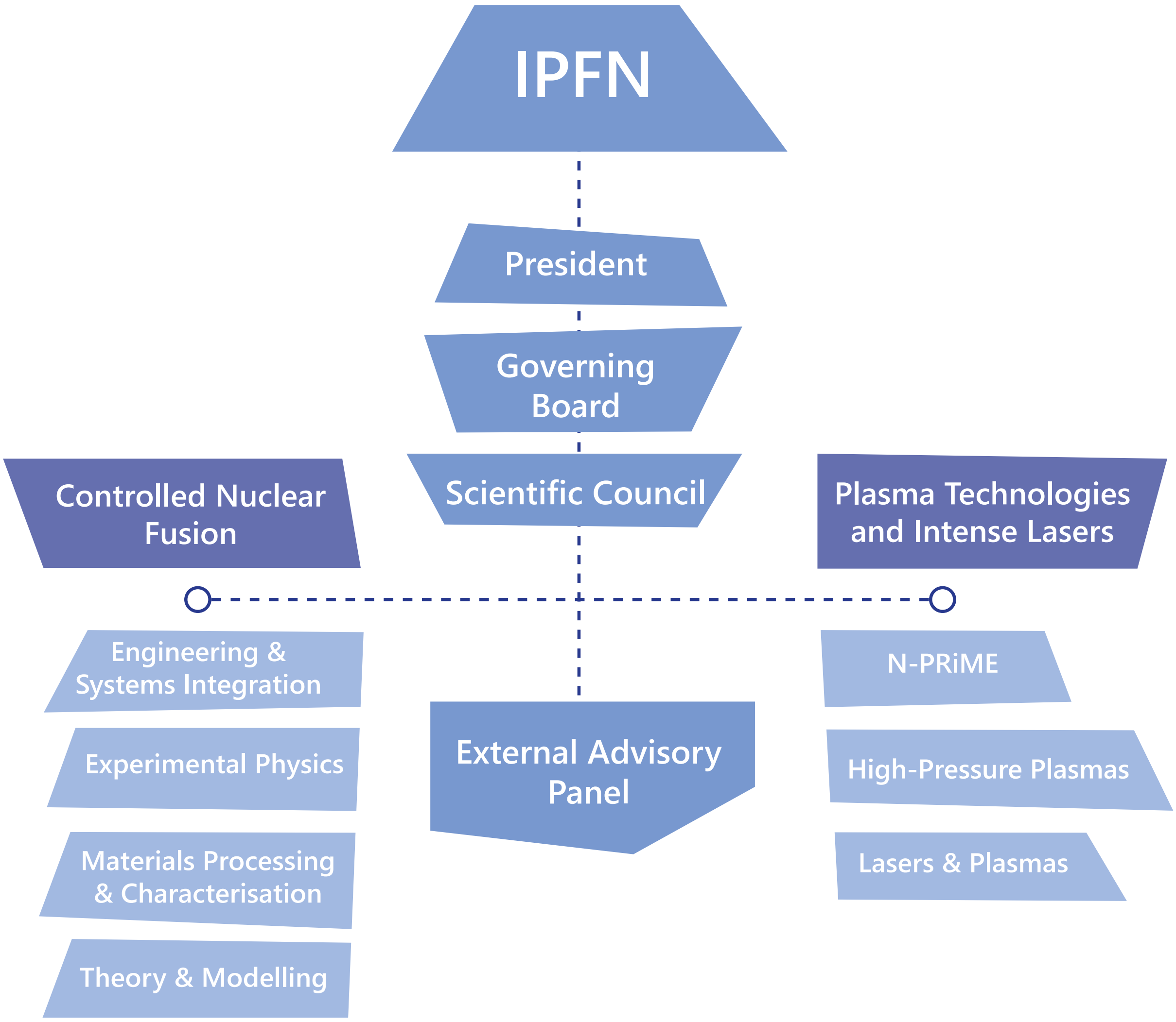
Controlled Nuclear Fusion - This research line is focused on the work programme established by the Euratom Fusion roadmap H2020, which includes activities associated with the development of systems, operation, and scientific exploitation of large and medium-sized tokamaks and stellarator, as well as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

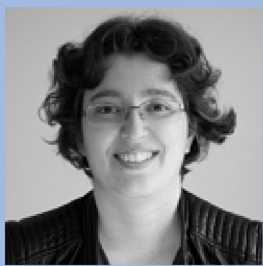
Alberto Vale
PhD representative

Bruno Gonçalves
Group of Engineering and Systems Integrations

Carlos Silva
PhD representative

Eduardo Alves
Group of Materials Processing and Characterisation

Gonçalo Figueira
PhD representative

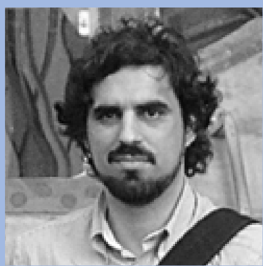


Helena Kaufmann
Group of High Pressure Plasmas

Horácio Fernandes
Group of Experimental Physics

Luís Lemos Alves
N-PRiME Group

Luís Oliveira e Silva
Group of Lasers and Plasmas



Mário Lino da Silva
PhD representative

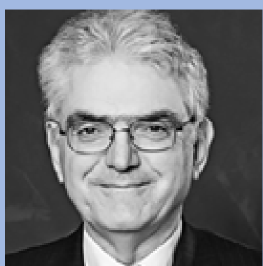
Marta Fajardo
PhD representative

Rui Coelho
Group of Theory and Modelling

External Advisory Panel

Tünde Fülöp
Chalmers University of Technology

Kunioki Mima
Osaka University



Francesco Romanelli
University of Rome

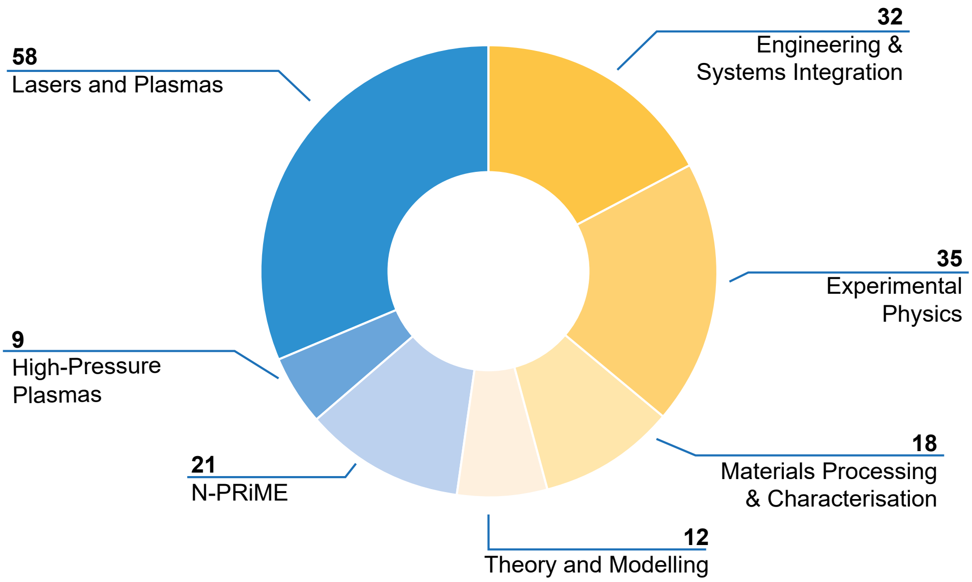
Jörg Winter
Ruhr-Universität Bochum

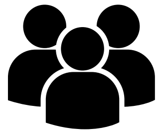
Leanne Pitchford
CNRS & Université Toulouse III

Facts and Numbers

Members per Group

at the end of 2019





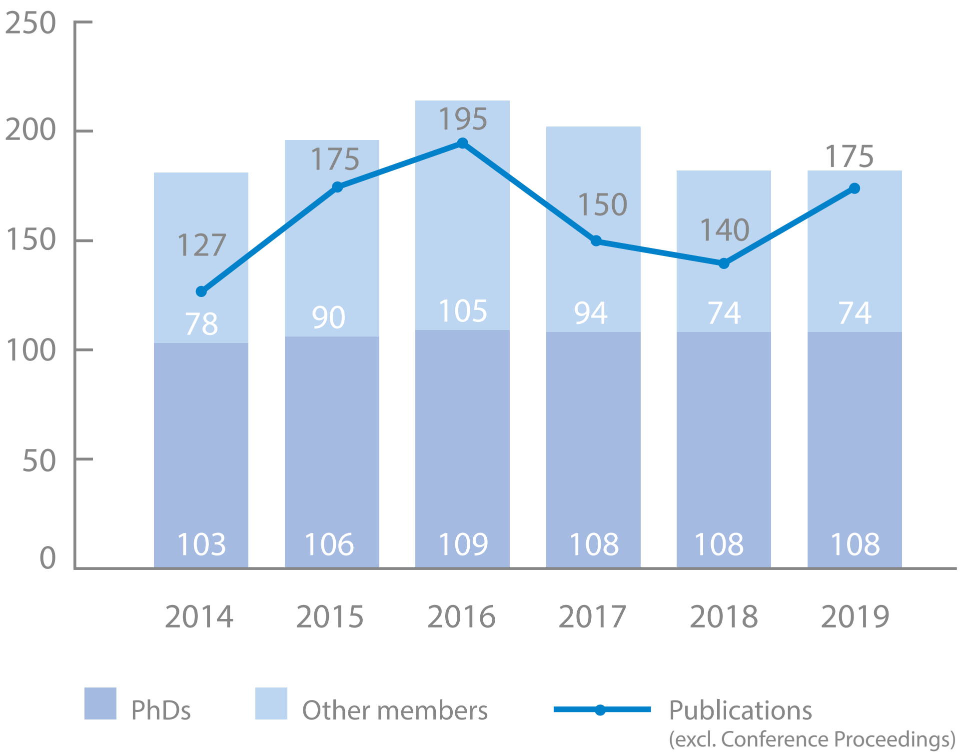
182
Collaborators
at the end of 2019

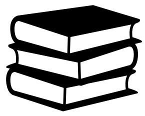
38
PhD students

108
PhDs
faculty, researchers and postdocs

Collaborators and Publications

since 2014





175
Publications per year
including Conference Proceedings

Highlights include papers published in

Nature

Nature Physics

Nature Photonics

Physical Review Letters

The Astrophysical Journal

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

Group Leader
Bruno Miguel Soares Gonçalves

Researchers

Alberto Vale	Jorge Santos
António Batista	Jorge Sousa
António Rodrigues	Luís Pinto
António Silva	Miguel Correia
Bernardo Carvalho	Nuno Cruz
Diana Baião	Paulo Varela
Filipe Silva	Pedro Carvalho
Jorge Belo	Raúl Luís

Main funding sources
Fusion for Energy, FCT, ITER Organization, EURATOM

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

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

Contributions to ITER construction

ITER Plasma position reflectometer

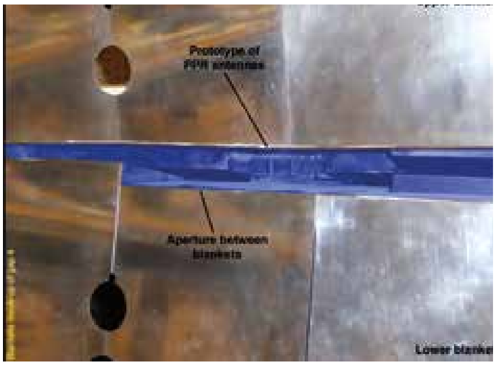
The performance of the transmission lines and antennas of the ITER Plasma Position Reflectometry (PPR) diagnostic, installed inside the vacuum vessel, is critical for the system to be able to fulfil its operational role and needed to be estimated as early as possible in the design phase to allow the effects of the design restrictions to be assessed as well as any performance bottlenecks to be identified.

The main goal was to evaluate the impact in the PPR measurements and how it affected the compliance of the PPR system with its requirements. To this purpose, we manufactured and tested prototypes of some in-vessel components that were deemed critical either due to their manufacturing complexity or due to their impact in the measurement performance of the PPR system, based on the technical specifications obtained from electromagnetic simulations. These prototypes were tested, and the results compared with the simulations to assess the capability of the electromagnetic modelling in predicting the final performance of the components.

Another important aspect of designing the in-vessel components of the PPR diagnostic is the need to ensure their integrity and operational capability without any maintenance for the entire lifetime of ITER. This requires the full structural analysis of the in-vessel components, in particular the antennas, which are directly exposed to the burning plasma during ITER operation.

Antenna performance

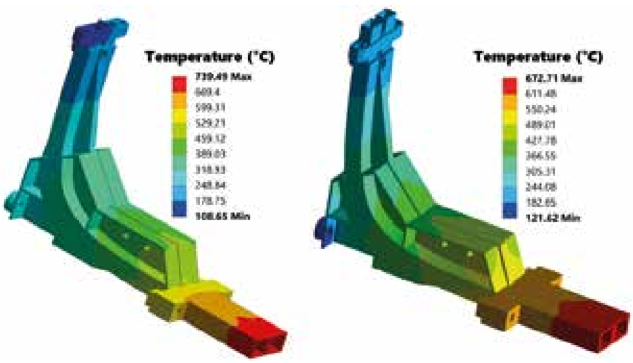
The main interest was to estimate and optimize the performance of the antennas under the imposed design restrictions, in particular to evaluate its impact in the PPR measurements and on the ability of the system to comply with its requirements. Based on the technical specifications drawn from the electromagnetic simulations we manufactured prototypes of the antennas, including mockups of the surrounding structures. Tests of these prototypes both in an anechoic chamber and with a target metallic mirror allowed us to characterize the antennas' performance and assess the influence of the blankets' structures in the antennas' radiation patterns and in the measurements. The prototype tests and the predictions obtained from the electromagnetic simulations show an excellent agreement, confirming the important role of the simulation tools in the design optimization phase before prototyping.



Electromagnetic tests of the prototype antennas, showing the mock-up of the surrounding upper and lower blanket modules. *T*

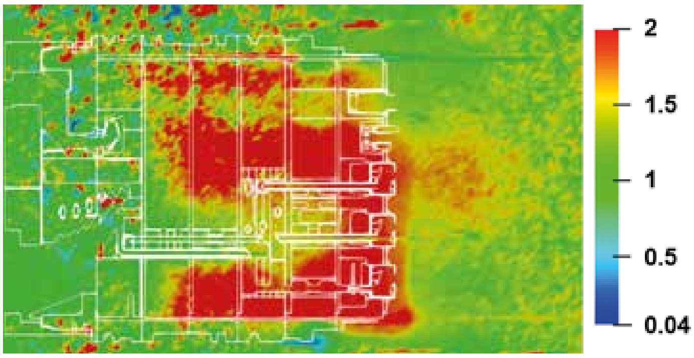
Thermal analysis

The PPR components installed inside the ITER vacuum vessel are specified to operate without maintenance for the lifetime of the ITER machine (~20 years). Thus, the design of these components shall be checked by assessing the results obtained with a full structural analysis against the standard codes for the design and construction of nuclear reactors.



Nuclear analysis of the Collective Thomson Scattering (CTS) system

The ITER Collective Thomson Scattering (CTS) will be responsible for measuring and monitoring the alpha-particle velocity distribution. The current design of the CTS was subjected to a nuclear analysis incorporating a very complex shielding system, which mirrors in detail the current design of the diagnostics shielding modules proposed for the equatorial port plugs. This shielding structure is more realistic than any other homogeneous mixture used before and the results suggest that it should be used in all nuclear analysis of the ITER equatorial port plugs. The use of this shielding in the neutronics models will lead to an increase (up to a factor 2) in the estimation of the neutron fluxes at the closure plate.

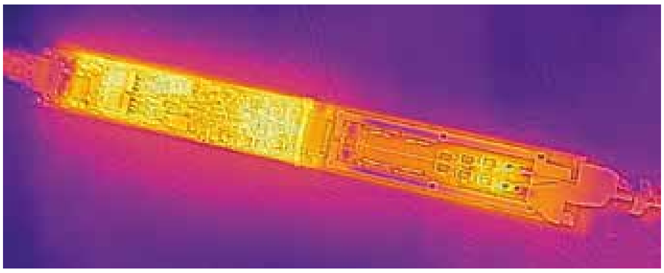


Neutron flux ratio between the neutron flux estimated with the detailed shielding structure and with a homogeneous shielding mixture.

ITER integrator final design for the magnetics diagnostic

We projected, designed and tested a prototype of this device. The integrator board contains an integral channel and a proportional channel connected to the coil signal. The integral channel is based on the chopper concept, where the input signal is inverted periodically, letting the unavoidable electronics offsets to be compensated automatically. Using this technique the integrated coil signal can achieve a

Temperature distribution in the front-end components of the two PPR in-vessel systems obtained with the transient thermal analysis. *The thermal analysis includes all the thermal loads affecting the components due to the nuclear loads and to the plasma radiation and constitutes the first step for the structural analysis of these components* drift, after one hour, below the maximum allowed by ITER specifications (500 µV.s/hour). The developed board has passed exhaustive tests to guarantee that the ITER integrator final design complies with all the required specifications, e.g. CE EMC irradiation immunity test and thermal image visualization of the board when a signal is acquired.



Thermal image of the integrator board when a 1200 Vpp signal is acquired.

ITER Radial Neutron Camera

The main role of the ITER Radial Neutron Camera (RNC) diagnostic is to measure in real-time the plasma neutron emissivity profile at high peak count rates for a duration up to 500 s. Due to the unprecedented high-performance conditions and after identification of critical problems, the work focused on the development of high-priority prototypes to address those issues before the final RNC design. Our main contribution to the project includes the design, development, and testing of a dedicated data acquisition prototype including the hardware, firmware and software to acquire, process, and store in real-time the neutron and gamma pulses from the detectors.

Participation in LIPAc-IFMIF Project

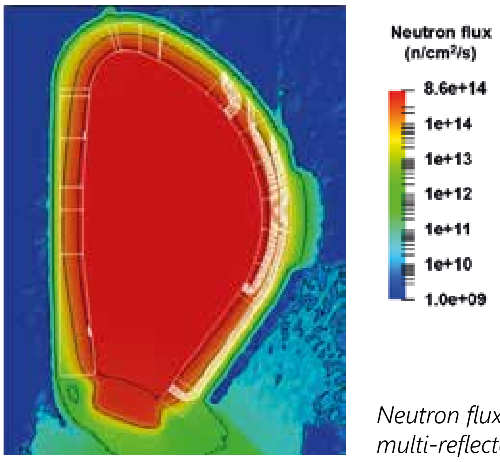
IPFN has contributed to the International Fusion Materials Irradiation Facility (IFMIF) in Japan, in the area of Instrumentation and Control (I&C). We achieved several upgrades and contributions for the beam instrumentation with relevance to the development of a new software tool that allows European scientists to visualize in real-time, from Europe, the operation and status of the Linear IFMIF Prototype Accelerator (LIPAc). The main feature of this tool is exporting all the LIPAc system control variables from Japan to Europe in real-time, under safe conditions that prevent the hacking and control of the machine remotely.

European researchers Chiara di Camillo Lalli (F4E) and Nuno Cruz (IPFN) with students from Aomori High School visiting the Rokkasho Fusion Energy Research Centre in the ITER Remote Experimentation Centre room

Contributions to DEMO design

Design of a multi-reflectometer system for DEMO

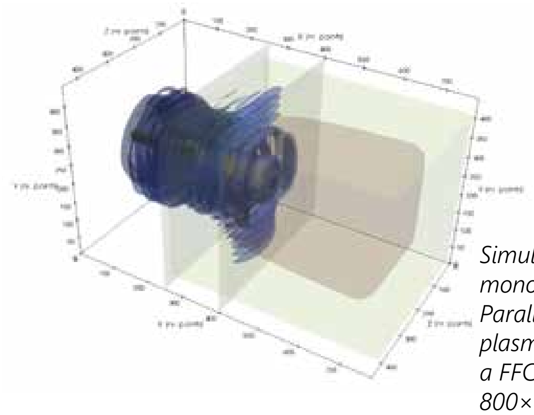
The primary integration approach for reflectometry in DEMO is based on the construction of a dedicated "dummy poloidal section" – the Slim Cassette – containing up to 100 antennas and waveguides. A 20-cm thick Slim Cassette was designed, with clusters of antennas introduced in the first wall at 16 poloidal locations. This configuration was used to perform a complete neutron shielding assessment of the Slim Cassette. The simulations showed that its introduction will not compromise the integrity of the vacuum vessel.



Neutron fluxes in the DEMO multi-reflectometer system.

Modelling reflectometry diagnostics: finite-difference time-domain simulation of reflectometry in fusion plasma

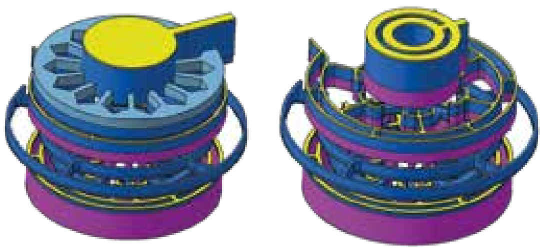
Propagation in a thermonuclear plasma is far from trivial since the plasma is an extremely complex medium. Thus the need for a numerical full-wave treatment based on a simplified model that retains the main mechanisms arises. Our main goal is to extend the capabilities of reflectometry simulation and to be able to set up improved synthetic diagnostics. To do so, we developed important work in numerical simulation of wave propagation in plasmas applied to reflectometry with two new codes (REFMULF and REFMULF3) entering a production stage.



Simulation of a FMCW monostatic reflectometer. Parallel simulation of a plasma probing using a FFCW on a volume 800×450×450.

DEMO - How much space is required for transportation in a nuclear facility?

DEMO aims to be a "first of a kind" commercial nuclear fusion power plant. Like ITER, remote handling operations of transportation are required in DEMO to exchange heavy and activated loads (e.g. the plasma-facing components) between the reactor building and the active maintenance facility. The time of shutdown that includes the transportation operations, as well as the space required to perform these operations, have a large impact on the availability and consequently the economics of the power plant. The IPFN team performed preliminary studies of the time and space required using the following types of transportation technologies: cask and hot cell concepts, radial overhead tracked-rail, radial overhead gallery crane, and ground-based track. The studies were performed taking into account the expected as well as possible rescue operations.

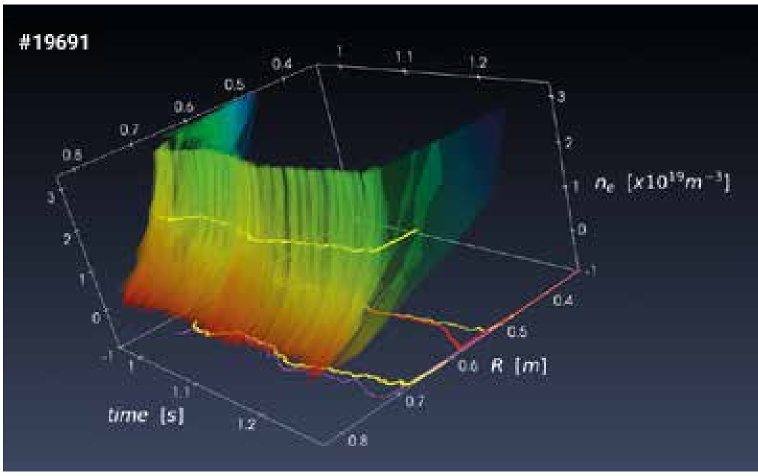


Occupied volumes for remote handling operations of transportation in all levels of the reactor building in DEMO, comparing the cask and hot cell concepts;

Contributions to European Fusion Devices

COMPASS Plasma position control experiments

To leverage IPFN's expertise in plasma position control using non-magnetic measurements of the plasma boundary position, the pioneering control experiments performed in ASDEX Upgrade using the IPFN designed and operated equatorial O-mode reflectometers have been extended to the COMPASS tokamak. The COMPASS O-mode microwave reflectometry diagnostic was equipped with an upgraded, IPFN designed ATCA acquisition system and a dedicated computational node running the Multi-Threaded Application Real-Time executor (MARTe). The first control experiments were successfully performed during the late 2019 experimental campaign in L-mode discharges, both D-shaped and circular.



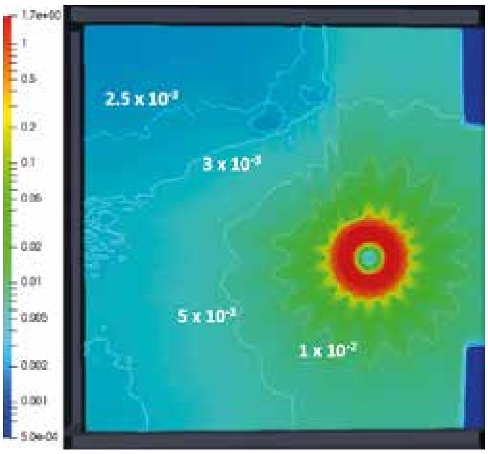
L-mode COMPASS discharge #19691. The radial control performed using only slow power supplies (500 µs control cycle) was switched between magnetic > reflectometry > magnetic controller inputs at t = 1.080 s and t = 1.220 s.

Assessment on the use of reflectometry on DTT for plasma position and shape control

The Divertor Test Tokamak (DTT) facility is a new machine proposed to study advanced exhaust solutions in conditions approaching, as much as possible, those planned for DEMO. The capabilities and access characteristics of such machine open the possibility to test and validate non-magnetic control relevant diagnostics, in reactor-like regimes, in support of DEMO diagnostic design implementations. O-mode reflectometry, due to its compatibility with a full grade reactor implementation, is being proposed as a source for real-time plasma position and shape measurements for control purposes, in replacement or complement for standard magnetic measurements. On DEMO, the foreseen position and shape feedback controller will make use of multiple (50-100), poloidally distributed, reflectometry lines-of-sight that have to be validated on present machines. We are using finite-difference time-domain codes of the REFMUL family, which implement a synthetic reflectometry diagnostic, to validate for DTT the optimal poloidal location of a number of reflectometers, capable of successfully feeding on the future non-magnetic plasma boundary reconstruction method/algorithm for plasma position and shape control.

Nuclear design of the DTT facility

We collaborated with ENEA (Italy) on the design of the DTT facility, to be built in Frascati and expected to start operation in 2025. The reactor and the building were studied in detail. For the vacuum vessel, simulations have shown that different solutions of borated water combined with inserts of 10B-enriched boron carbide can be adopted to guarantee that the nuclear heating density in the Toroidal Field Coil remains below 1 mW/cm^3. Inside the vessel, remote handling will be required for maintenance operations. With accurate planning and scheduling, it may not be needed outside of the cryostat. From the neutron shielding point of view, a building wall with 220 cm of concrete shall provide adequate protection to workers and public.



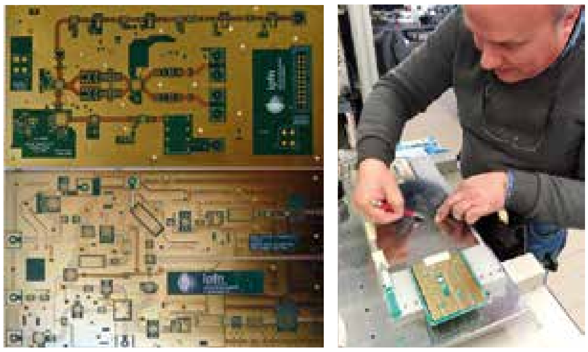
Absorbed dose rates by silicon components in the DTT facility building. Conventional electronics should be replaced periodically or placed outside the main building.

Other contributions

Compact microwave reflectometer

We are developing a prototype of a compact coherent fast frequency sweeping RF back-end using commercial Monolithic Microwave Integrated Circuits (MMIC). One of the design goals for the back-end prototype centres on the flexibility of the system, so that it can easily match to the required frequency ranges. The backend alone covers the NATO J-Band (10 GHz to 20 GHz) and is designed to drive external full-band frequency multipliers resulting in an ultra-wideband coverage up to, but not limited to, 140 GHz. A full band sweep can be done in 5 μs.

The high-frequency receiver and transmitter PCBs were design to make them compatible with the CubeSat satellite platform allowing possible plasma electron density measurements during ESA vehicle Earth re-entry experiments. The PCBs are manufactured and are being populated with the high-frequency components, to be followed by electromagnetic tests to evaluate the prototype performance.



Backend high-frequency PCB's (left) and preparation of the boards for soldering the components (right).

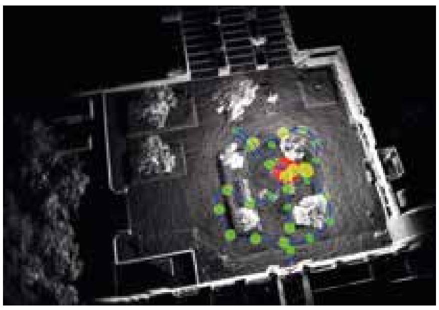
Development of microTCA instrumentation for fusion applications

The ATCA instrumentation platform for diagnostics and control developed at IST, is being extended with a MicroTCA control and data acquisition platform, still able to maintain performance characteristics in speed, channel density and availability of ATCA, at a cost suitable for smaller systems. Software and firmware have been ported to MTCA using mostly in-house developed hardware, preserving many of ATCA's benefits in performance in a smaller form-factor. The proposed platform comprises an AMC to FMC carrier module and a 500 MSPS, 14-bit, 4-channel ADC FMC module. This compact, flexible and autonomous or scalable platform may either integrate a large-experiment system infrastructure or be configured as a lower-cost, self-contained platform for smaller experiments or development and testbench purposes. Its main target applications are spectroscopy, reflectometry and LiDAR.

AMC to FMC carrier module.

Can drones be our "friends" in radiological inspection, communication and rescue?

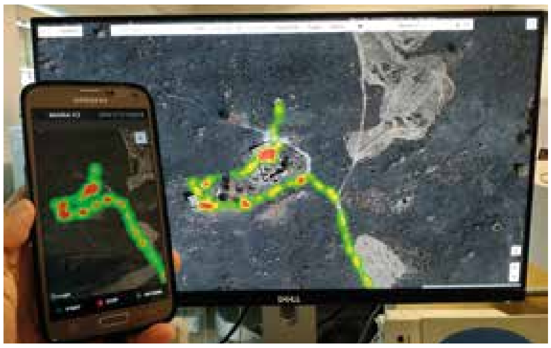
The supervision of environments with activated components, as well as search-and-rescue operations in nuclear disaster scenarios are important challenges. In most cases the scenarios become cluttered, with malfunctioning or broken communication infrastructures and missing communication with the outside. The project FRIENDS – Fleet of Drones for Radiological Inspection, Communication and Rescue, aims to design, develop and validate a fleet of drones equipped with navigation and radiological sensors for inspection and monitoring of scenarios under nuclear threats. The fleet, under a cooperative navigation system, is able to map the scenario, localize and quantify the sources of radiation and thus evaluate the level of threat. Communication is important to remotely manage and control the fleet and, at the same time, acquire the maximum information. In case of disaster, the fleet is able to support an emergency network communication channel to establish the interface between elements in the field and the outside world. The communication system will be designed to optimize the coverage, redundancy, security, range and bandwidth. The synergy of the IST research labs involved (IPFN, ISR, C2TN) and IT-Aveiro is being exploited for the success of the project, given their experience and background on nuclear science, robotics and communications.



3D reconstruction of a testing scenario using a LIDAR system, where a controlled source of radiation was installed.

MARIA and FRIENDS

MARIA is a Mobile Application for Radiation Intensity Assessment entirely developed and implemented at IPFN, which creates a real-time radiation heatmap of the surrounding area with the possibility of add-ons for chemical and biological sensors. MARIA integrates sensor data from distributed users using common mobile devices and cloud services. Unlike other solutions, MARIA doesn't require technical expertise and makes it easy for any user to record and access the information. MARIA is fully portable and compatible with any mobile Android device. It displays the colour-coded measurements on a real-time map. Tests were already performed in real scenarios with important contributions. MARIA and FRIENDS are very promising for radiological inspection in real scenarios.



Screenshots of MARIA running on an Android device and data presented by a browser in a computer with connection to the remote server.

FORMULAfusion - Mobile robots from ITER to industry

In the scope of summer internships at IPFN, students have been designing and implementing a vehicle with the same kinematics of the ITER Cask Transfer System (CTS). The vehicle is designed at a lower scale, but can transport up to 250 kg during 8 hours of operation and is able to operate in industrial facilities and warehouses. The students were excited about their participation, since they start from scratch with CAD models and reach the machining of real pieces. Some companies from Portugal and the USA became sponsors of the project providing material to build the vehicle. And the formula of the vehicle started in fusion – FORMULAfusion!

Left: Design of a rhombic like vehicle created at IPFN; right: preparation for the assembly of the first module of the rhombic like vehicle.

Experimental Physics

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Main funding sources
Fundação para a Ciência e a Tecnologia,
EUROfusion Consortium

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

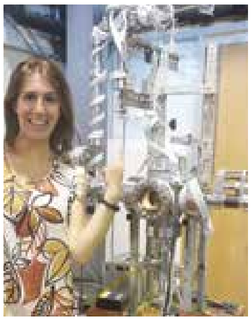
Our main goal is to provide to the community the necessary know-how and tools for the safe operation of fusion reactors in the near future. For that purpose, we maintain a continuous tracking of advanced, high-end technologies in different fields of research and industry, importing them to our community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

So far, we have succeeded in extending the nominal operation time of pulsed fusion devices from a few milliseconds up to 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 education is also provided for a considerable number of PhD students working under our supervision.

ISTTOK

Liquid metal plasma materials on ISTTOK

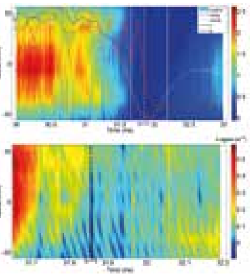
Liquid metals as plasma-facing materials have been under investigation at IPFN due to the regeneration capability of the liquid surface. Previous studies realized on ISTTOK have demonstrated that free liquid metal flows are not compatible with tokamak operations due to perturbing MHD forces. In spite of this, it is well known that liquid metal flows are required to ensure proper replenishment of liquid metal surfaces, heat exhaust or temperature control. For these reasons, a "hybrid" version of a liquid metal plasma-facing component, aimed at combining the advantages of liquid metal flows with a version of MHD resistant capillary porous system, is being implemented for testing on ISTTOK. The design of this novel component required the development of an experimental setup to investigate liquid metals wettability on stainless steel as a function of surface roughness. A procedure to effectively wet stainless steel samples by gallium, at room temperature, was established during this study.



Wettability studies on ISTTOK
Experimental setup built to investigate high purity liquid gallium wetting processes on stainless steel samples.

Investigation of plasma pressure evolution during AC transitions by HIBD

Alternating Current (AC) operation mode has been proposed as an alternative for steady-state operation of fusion devices (tokamak type). In ISTTOK, we took advantage of the fast amplifiers to use a fast beam chopping technique that allowed to obtain for the first time the pressure-like profile evolution during the AC transition, including the plasma current zero-crossing (between positive and negative cycles). This new capability is expected to help to shed light into the physics mechanisms responsible for sustaining a plasma discharge during AC transitionsThe results from ISTTOK found that the source for the existing plasma during AC transition is attributed to the non-localized overshoot of fast electrons from the decaying cycle into the opposite cycle before a close equilibrium current is formed. These electrons are responsible for the quiescent plasma that is detected during the zero plasma current phase.

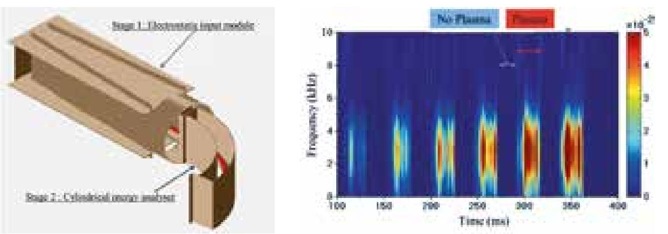


Top: evolution of a positive to negative current cycle. Bottom: zoomed view of the quiescent phase (inside white frame) taking profit of the relatively high pulse rate of HIBD. The yellowish background is the signature of a quiescent low-temperature plasma, possibly maintained by overshooting electrons around the Ip=0 instants.

Core Plasma Potential Measurements by HIBD

One of the most elusive plasma parameters to be measured directly is the plasma potential. This potential appears as a result of the plasma self-organization under competing kinetics of particles and fields. The plasma potential, or its gradient the internal electric field, plays a crucial role in plasma turbulence stabilization and transport. In ISTTOK, we are applying a typical cylindrical electrostatic energy analyzer (CEA) operated in an innovative way that allows for 5-times improved energy resolution, in what we dubbed the "de-acceleration mode of operation".

The setup was able to measure a modulating voltage of 50 V amplitude and 2.5 kHz frequency during a typical ISTTOK AC discharge. The fluctuation is clearly detected at 2.5 kHz with broadening of frequency due to the overlap with the plasma potential oscillations and some contribution from the beam finite width.

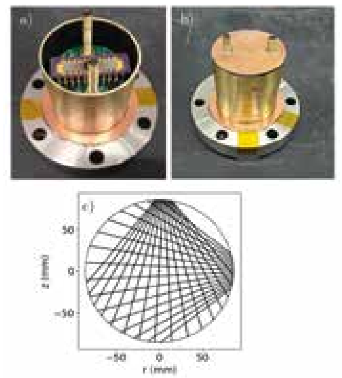


Left: model of the CEA analyser (in SIMION). Right: spectrogram of the signal on the energy analyser detector resulting from plasma potential with a superimposed 50 V modulation on the energy analyser.

ISTTOK plasma tomography using Minimum Fisher Regularization

A plasma tomography algorithm has been developed for the ISTTOK tokamak. The algorithm is an instance of the Minimum Fisher Regularization and was implemented and distributed as a Python package. Plasma tomography is an ill-conditioned inversion problem. Reconstruction algorithms try to overcome this issue by introducing some form of a priori knowledge that requires empirical tuning.

In this work, an experimental setup was developed that allows the use of physical phantoms to tune and validate the reconstruction algorithm used. This also allowed the comparison of two different implementations of the algorithm regarding the mathematical description of the spatial sampling. A possible application of the tomographic diagnostic has been demonstrated by computing the plasma position and observing the Shafranov shift.

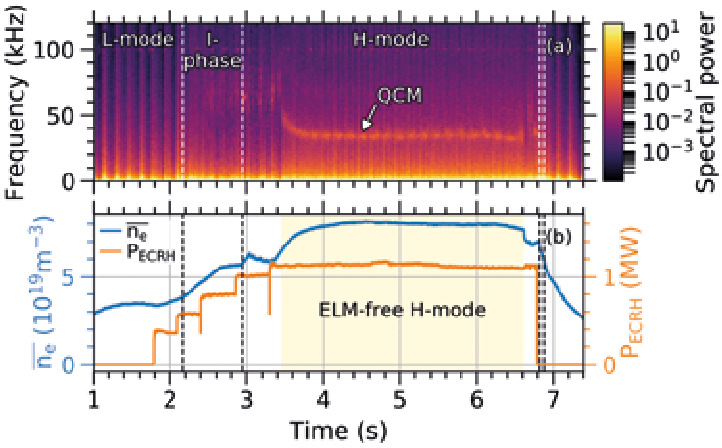


Tomography cameras installed on ISTTOK. Top: (a) camera without the pinhole lid to show the photo-diode array and b) with the pinhole lid. Bottom: lines of sight for the cameras positioned at 0 and 90 degrees.

Contributions to ASDEX program

A promising regime for a fusion reactor

A stationary H-mode without edge-localized modes (ELMs) has been recently demonstrated in ASDEX Upgrade by applying central electron cyclotron resonance heating with adequate fuelling. Besides eliminating the unacceptable heat loads posed by ELMs in future reactors, this scenario exhibits several other desirable properties, for example dominant electron heating, low input torque, compatibility with low input power, good energy confinement, high density, and no impurity accumulation. It always features an edge electromagnetic quasi-coherent mode, typically detected with reflectometry, which seems to be responsible for enhanced transport losses and may be the key to enable steady-state operation with an edge pedestal and no ELMs. This promising regime will be subject to additional experiments, with the ultimate goal of reliably assessing its compatibility with large-scale fusion devices such as ITER and DEMO.



ASDEX Upgrade discharge with a stationary ELM-free H-mode.

ICRF reflectometer

The characterization of the scrape-off layer is essential for a better understanding of the particle and heat loads on the plasma-facing components. A new multichannel X-mode reflectometer diagnostic (RIC) was recently installed in ASDEX Upgrade. It provides the electron density profiles in front of the ICRF antenna every 25 µs simultaneously in 3 different poloidal positions. The main goal of this work is to assess the measurement capabilities of the RIC diagnostic for a wide variety of plasma conditions. Although a good agreement between the different diagnostics is generally found at low discharge densities, RIC measurements often show steeper profiles at high discharge densities. Full-wave simulations are being used to understand the effect of density fluctuations on RIC profiles as well as to study the start of X-mode upper cut-off reflection.

Part of the "Reflectometry Team" in the ASDEX Upgrade control room.

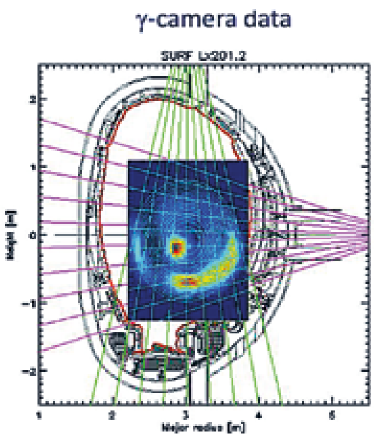
Contributions to the JET program

Role of GAMs in triggering the L-H transition on JET

Geodesic acoustic modes (GAMs) may generate strong oscillations in the radial electric field and therefore are considered as a possible trigger mechanism for the transition to improved confinement (L-H transition). Our work was focused on the characterization of GAMs in JET plasmas when approaching the L–H transition. GAMs were found to have modest amplitude at the transition except for high-density discharges where GAMs are stronger, suggesting that the GAM is not responsible for facilitating the transition as the L–H power threshold also increases with density.

Disruption and runaway electron studies in European tokamaks

Experiments on suppression of runaway electrons (RE) and mitigation of thermal loads during disruptions in support of the design of Disruption Mitigation System in ITER have been continuing in JET. Shuttered Pellet Injector and Massive Gas Injection (DMV) Systems have been used to study RE generation processes, their control and suppression. Creation of database on RE in JET including experiments with SPI and MGI – is a valuable support for the design of the ITER Data Management System. Spatial and temporal parameters of RE have been studied using different diagnostics.



Hard X-ray bremsstrahlung tomography from relativistic electron in JET.

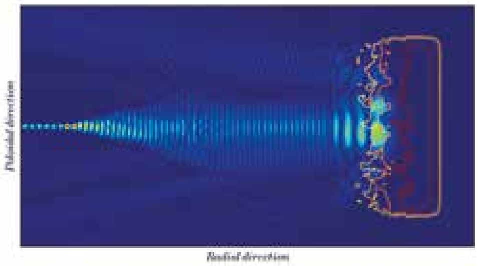
Optimisation of plasma termination

Plasma termination is of special importance for future fusion devices, where the plasma stored energy is of the order of hundreds of megajoule. It has been observed at JET that the disruptivity rate increases in pulses optimised for performance. The conditions that lead to unhealthy plasma termination have been assessed and once detected in real-time, amelioration actions can be taken allowing for a decrease of the disruptivity rate. These studies are also essential to improve the safety profile of high plasma current pulses in anticipation to the JET D-T operation.

Other contributions

Modelling of turbulence measurements with reflectometry

Richard Feynman once called turbulence "the most important unsolved problem of classical physics." In fusion devices, microwave reflectometry has shown great potential to characterise turbulence and thus address the important problems arising from the turbulent nature of fusion plasmas. Our main goal is to improve reflectometry capabilities using sophisticated models of both the microscopic properties of plasma turbulence and of the working physics behind reflectometry techniques. To achieve this goal, we have integrated numerical simulations of fusion plasmas, obtained from the gyro-fluid code GEMR, into reflectometry simulations carried out using the two-dimensional full-wave code REFMUL. This work has allowed a better understanding of the sensitivity and measuring capabilities of reflectometry instruments, for instance at different plasma turbulence levels.



Snapshot of 2D REFMUL simulation of a conventional reflectometer operating in a turbulent plasma obtained from the GEMR code.

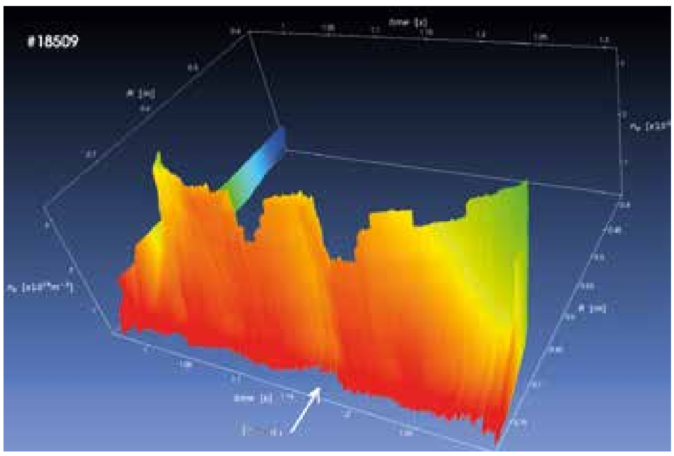
Nvidia highlights nuclear fusion research at Técnico

At the opening keynote of the GPU Technology Conference in Munich on October 10, 2018, Jensen Huang highlighted how researchers at Técnico are using deep learning to understand the inner workings of a fusion reactor. From reconstructing the plasma profile inside a tokamak to being able to predict when a disruption is about to occur, the possibilities for using deep neural networks to analyse fusion data are endless. Fusion reactors such as JET in the UK, as well as many others around the world, are collecting enormous amounts of data from every single experiment. Being able to process all this data is now becoming possible with breakthroughs in high-performance computing. In particular, deep neural networks require hardware acceleration, and Nvidia has been playing a key role in providing scientists around the world with the hardware and computational power they need to make advances in many fields.

Highlight at GTC Europe 2018. Nvidia's CEO Jensen Huang highlights research being done at IPFN as one of the prominent examples of how GPU computing is being used to shed light on some of the biggest questions in science.

Scientific exploration of COMPASS tokamak reflectometry diagnostic

We established a collaboration with IPP-CAS in Prague, Czech Republic to provide support in making the o-mode reflectometry diagnostic systematically usable by providing robust measurements during COMPASS discharges and to consequently use it in the study of ITER-relevant plasma scenarios. It was possible to tune and validate the optimal parameters for the operation of the diagnostic, being able to provide stable measurements at a rate of 10 µs, compatible with the study of plasma fluctuations and turbulence. The operation of the diagnostic in several dedicated campaigns allowed to study both ELM and ELM-free operation regimes, further contributing to the understanding of their effect in COMPASS D-shaped H-mode plasmas. Additionally, several experiments were conducted to study the possibility to use this diagnostic to monitor the plasma radial position in this device.



Density profile reconstructions using microwave o-mode reflectometry during experiments conducted on COMPASS Tokamak.

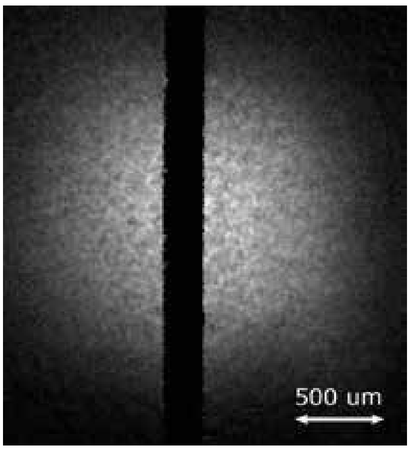
Quantum Plasmas Team

Ultra-cold wall: a cut in the dark

Probing photon turbulence in a laser-cooled Rubidium cloud should emulate interesting aspects of radiation trapping at the interior of stars. Our main goal now is to probe the two-dimensional structure of the photon turbulence, namely the formation of bubbles, and its statistical features. For that task, we make use of optical pumping techniques of a dark magneto-optical trap (MOT). This work puts in evidence a regime of plasma-like behavior that mimics the interior of some stars, as resulting from the balance between the photon-induced Coulomb repulsion (pressure) and the external trapping provided by the lasers (gravitational interaction).

Topological quantum turbulence: Advances in theory

Alongside with the experimental work on photon turbulence, we are developing ab initio tools to understand low-dimensional turbulence in quantum fluids (QF), such as Bose-Einstein condensates and plasmonic nanostructures (e.g. graphene plasmas). Strong turbulence in one-dimensional QFs is topological in nature, involving the appearance of topological objects such as dark solitons. Our hypothesis is that strong turbulence in quantum fluids is a weak turbulence phenomenon on top of a "topological gas". Our preliminary results seem to put in evidence a novel, low-energy mode (the solitonic sound) that may be underlying strong turbulence in such fluids.



An ultracold slice. A sliced dark MOT (black stripe) is employed to probe the photon turbulence structure.

Materials Character

During the last years our activities were mostly dedicated to the fusion programme developing new materials with designed properties and studying plasma material interactions to understand the physics behind these processes. The Joint European Torus (JET) has been used as test bed for plasma wall studies providing relevant information to validate the current models. We followed the changes in reference tiles from JET-ILW (ITER Like Wall) during 3 campaigns. Special designed passive diagnostics and marked tiles retrieved from JET allowed us to understand the multiple and complex processes like erosion and deposition, diffusion, implantation and fuel retention induced by the plasma interaction.

Other important issue concerning the construction of fusion reactors are the availability of materials to operate in extreme conditions of radiation and temperature. We started the study and development of new thermal barrier components based on high entropy alloys. These barriers are necessary to accommodate the thermal gradients between the plasma facing materials and the heat sink. We produced CuxCrFeTiV alloys by ball milling, followed by consolidation with spark plasma sintering. The stability studies under argon irradiation showed promising results with no significant changes observed.

Finally we kept our participation in European networks on ion beam infrastructures and technologies as a tool to model and tailor the properties of new materials with particular emphasis on wide band gap semiconductors and metallic oxides.

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Main funding sources
EUROFusion Consortium,
Fundação para a Ciência e Tecnologia,
FP7 funded projects and contracts/services.

External microbeam analysis of tile 4 after the second campaign.

Plasma Wall interactions in JET ITER Like Wall

ITER Like Wall of JET gave the possibility to study most of the plasma wall interactions relevant to establish the operating conditions for ITER. Evaluation of material migration, erosion/redeposition and fuel retention processes have been used to validate the models and provide the relevant figures to design a safe reactor. During the last two years, we measured a large number of components and passive diagnostics removed from JET to get the necessary data to model the interactions.

Moreover, we also used some mixed coatings produced in the laboratory to study fuel trapping and mixing mechanism.

JET has completed three operating periods, ILW1, ILW2 and ILW3, allowing making comparisons between tiles exposed to different plasma regimes and compare tiles exposed for all the three periods, ILW1-3 (2011-2016).

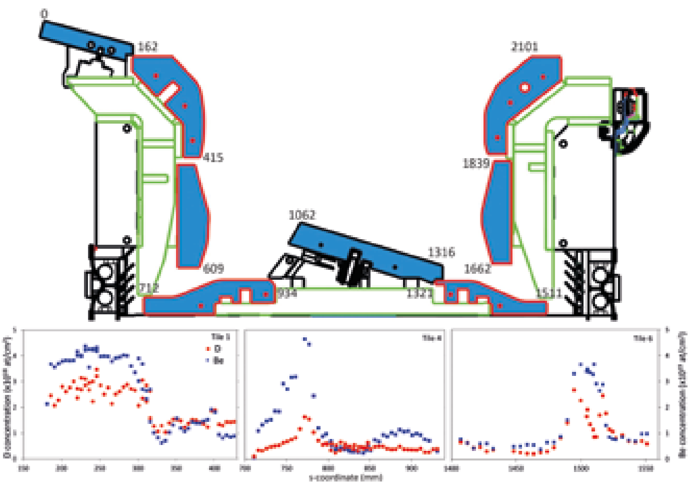
Our results give updated fuel inventories and provide comparisons of individual mid-plane limiter tiles exposed during ILW1, ILW2, ILW3 with ones exposed throughout the full operation, ILW1-3. For example, results for D concentration in deposits at the ends of the mid-plane IWGL tile are of the order of $0.1\text{-}1\times10^{18}$ D/cm^2 for tiles exposed in individual campaign, whereas results from a tile exposed for all campaigns show D concentrations at least a factor of three higher. This indicates continual accumulation of fuel in deposits, with no release due to heating. In the central eroded region, exposed to the highest heat flux, retention values remain low for all tiles analysed.

Analysis of IBA data from ILW1, ILW2, ILW3 along the inner and outer wall limiters extending poloidally show the complex fuel retention and erosion/deposition pattern from the top to the bottom of the vessel. Most interaction occurs in the central region which correlates with the heat flux patterns seen from infrared cameras.

In addition, divertor tiles also reveal similar deposition patterns after each individual campaign. The cumulative results after the 3 campaigns are shown in the figure below. The high deposition rate of Be occurs on tile 1 together with deuterium. Shadowed areas of tile 4 reveal the presence of different impurities (C and O) as well as Be and D.

A detailed overview of all the results can be found in the contributions presented at conferences and published in reference journals [1-3].

The studies on the chemical reactivity and phase formation in materials involving Be/C/N/O/W prove the impact that temperature and impurities (O, C) represent on the retention of D in the mixed deposits [4] during plasma wall interactions.



Beryllium and Deuterium distribution along tiles 1, 4 and 6 of the divertor.

In the future, studies on plasma wall interactions in different plasma configurations and tokamaks (JET, WEST.) will continue as well as the study of fuel trapping and chemical interactions in laboratory deposited materials. Collaborations with other groups to model the data will be deepened.

Contact person: Eduardo Alves (eduardo.alves@tecnico.ulisboa.pt)

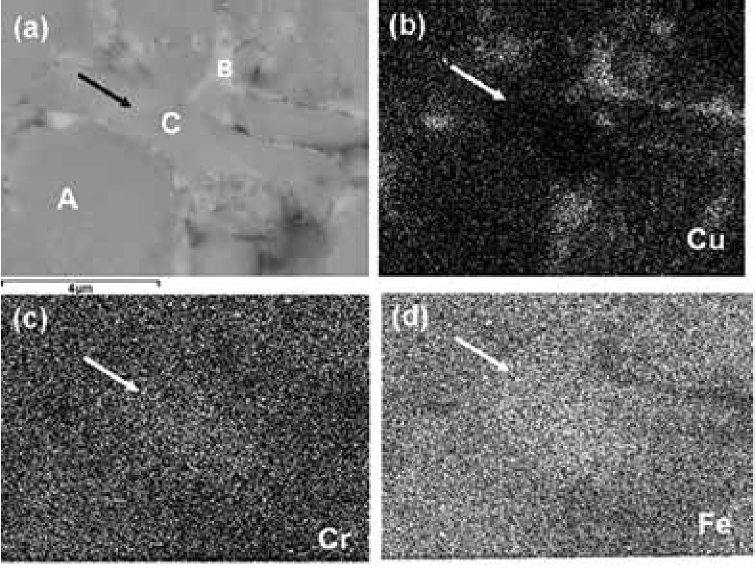
1. A. Lahtinen et al., Fusion Eng. Des. 146 (2019) 1979-82.
2. A. Widdowson et al., Nucl. Mater. Energy 19 (2019) 218-24.
3. A. Baron-Wiechec, Fusion Eng. Des. 133 (2018) 135-41.
4. R. Mateus et al., Nucl. Mater. Energy 17 (2018) 242.

Development of thermal barriers for fusion reactors

Finding the right materials for fusion reactors is a great challenge due to the extreme operating conditions of temperature and radiation. In this kind of reactors, the heat extraction in the divertor region occurs through tungstenium monoblocks bonded to CuCrZr cooling tubes. Since the optimum operating temperature windows for the two materials do not overlap, it is desirable to use an intermediate layer – capable of functioning as a thermal barrier, guaranteeing an adequate thermal transport between both materials.

In this project, a new class of materials with great potential to operate in hard conditions were investigated. High entropy alloys based on copper, CuxCrFeTiV (x = 0.21, 0.44, 1 and 1.7 molar ratio) were prepared using mechanical alloying (MA), to mix the elemental powders, followed by consolidation with spark plasma sintering (SPS) at 1178 K and 65 MPa. Equiatomic CuCrFeTiV sintered samples were irradiated at room temperature with 300 keV Ar+ beam to a fluence of 3×10^{20} at/m^2 in order to simulate the irradiation damage in the material. Structural studies were carried out prior to and after irradiation. The results showed the presence of heterogenous and multiphasic microstructures in all samples. Moreover, with the increase of the Cu content it is possible to observe the formation of Cu-rich structures [1]. The diffractogram of the CuCrFeTiV sample revealed major peaks of a BCC crystal structure and minor peaks of a FCC crystal structure. In addition, irradiation damage in the microstructure surface was only observed in samples irradiated with high fluences. A detailed X-ray profile analysis using the Williamson-Hall method was employed for estimating crystallite size and heterogenous strain after and before irradiation. The results indicated an decrease of crystallite size with the increased of Ar+ fluence compared with the as-sintered one, which can be associated to the defects accumulation. Therefore, these findings confirmed the general trend of such HEAs materials, then these CuCrFeTiV high entropy alloys will be promising to be used in future nuclear fusion reactors.

1. M. Dias et al., Fusion Eng. Des. 146 (2019), 1824-28.



Distribution of the major elements in the CuCrFeTiV alloy. Secondary electron image (a) and corresponding electron dispersive spectroscopy maps for (b) Cu-Kα, (c) Cr-Kα and (d) Fe-Kα radiation.

This research line will continue and a long.term programme to develop thermal barriers based on W high entropy alloys of type WTaCrNbV will be initiated. A PhD project started in 2019 based on this research activity.

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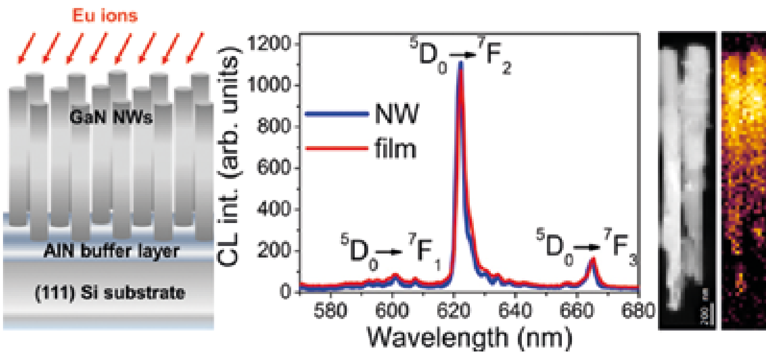
Radiation resistant wide band-gap semiconductors

Wide bandgap nitride and oxide semiconductors are promising materials for optoelectronic devices, high power electronics and sensor applications. Understanding the effects of energetic ions on the properties of these materials is essential to establish processing techniques involving ion irradiation as well as for the development of radiation-resistant devices for applications in space or nuclear facilities.

The incorporation and optical activation of implanted europium ions were achieved in Ga_2O_3 thin films and GaN nanowires (NW) (see figure above) [1]. Rare earth emissions were shown to be stable under ionizing irradiation opening the way to optical devices working in extreme environments. Furthermore, regarding Ga_2O_3, the potential to exploit optical, electrical and mechanical functionalities simultaneously in novel device designs was demonstrated [2].

The recent upgrade of the in-situ characterization capacities at the LATR microprobe enables the investigation of radiation effects on electrical and optical properties in real-time. The new set-up has been used to demonstrate the potential of Ga_2O_3 Schottky devices and GaN microwires as radiation sensors [3]. In the context of these studies, a collaboration with the NURISE company was established in order to exploit the potential of some of these radiation sensors.

Irradiation defects are not always a nuisance, in MoO_3 lamellar crystals, defect engineering by ion implantation allowed controlling the conductivity of these crystals over several orders of magnitude.



Schematics of self-assembled GaN nanowires (NWs) for Eu-implantation and comparison of cathodoluminescence (CL) spectra of the red Eu3+ emission lines in NWs and thin films. On the right a map of the nano-CL on a single NW showing Eu-emission from its tip [1].

We will continue our studies to better understand the behaviour of wide bandgap semiconductors upon ion irradiation. Nitride and oxide radiation sensors with different geometries will be developed and tested, in particular, within the context of the RADIATE project (Research And Development with Ion Beams – Advancing Technology in Europe).

Contact persons: Katharina Lorenz and Marco Peres (Lorenz@ctn.tecnico.ulisboa.pt) (marcoperes@ctn.tecnico.ulisboa.pt).

1. D. Nd. Faye et al., J. Phys. Chem. C 123 (2019) 11874-87.
2. M. Peres et al., ECS J. Solid State Sci. Technol. 8 (2019) Q3235-41
3. D. Verheij et al., J. Phys. D: Appl. Phys. 51 (2018) 175105.

Theory and Modelling

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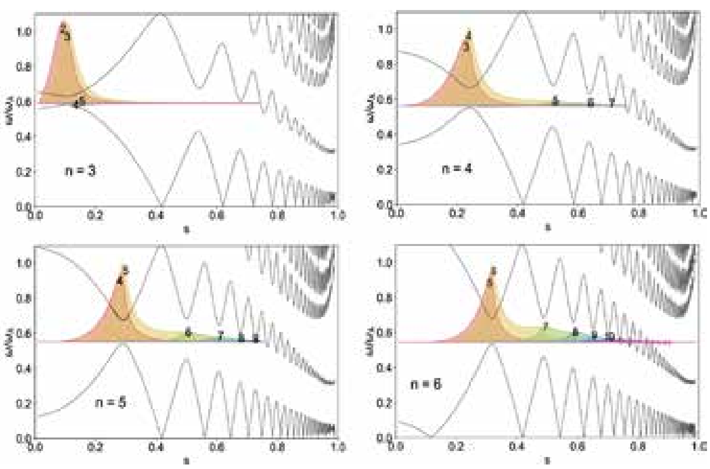
Euratom research and training programme 2014-2018 and 2019-2020, grant no. 633053

Our research is focused on key areas of plasma physics research particularly relevant for Tokamak fusion plasmas and the EU fusion program. In particular, we are interested in the pervasive ties between Alfvén Eigenmode (AE) stability and the energetic particles born from plasma heating schemes and fusion reactions in current fusion devices in view of ITER. We are also committed to exploring fundamental physical phenomena related to plasma turbulence and wave propagation in fusion plasmas and on the forging of the integrated modelling toolset lead by ITER. The group's strong commitment with the EU fusion program is evidenced by its leading representative role in the Integrated Modelling EUROfusion Work Package (MHD stability and plasma transport), a solid participation in the EUROfusion experimental campaigns of JET and AUG tokamaks and research activities for DEMO and JT60-SA devices and contract positions in the JET Exploitation Unit. The group also secured four High Performance Computing research projects and one joint running EU-Japan HPC Research project.

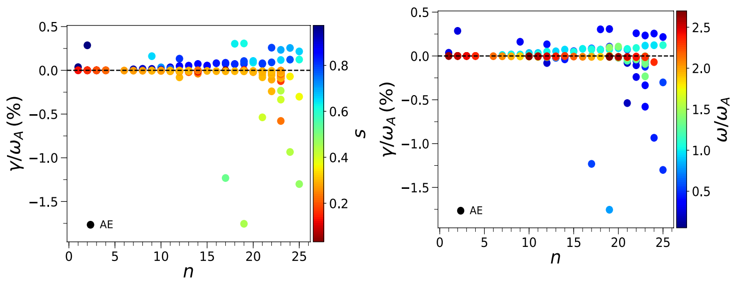
Energetic particle physics in Tokamak plasmas

With the start of operation of the new Alfven Eigenmode Active Diagnostic (AEAD) antenna system installed at JET tokamak, experimental measurements of the damping rates of Toroidal AE (TAE) modes in JET plasmas have been finally resumed. Such an antenna is an essential tool to probe the linear stability of Alfven wave modes in fusion-relevant plasmas and we aim to promote and push for a detailed validation of modelling estimates of damping and growth rates in support of the interpretation of the experimental findings. To achieve that goal, we performed a detailed modelling study using a toolset of MHD equilibrium and stability analysis codes on a dedicated JET pulse (discharge #92416). The numerical calculations aimed at an assessment of all relevant sources of damping/drive to Alfven waves, namely the collisional damping, radiative damping, continuum damping, Landau damping on thermal species and resonant interaction with the ICRH accelerated population. As envisaged, our analysis yielded a good agreement with experimental data namely on the frequency of the modes excited by the antenna and the radial structure/location of the modes calculated with the MISHKA code. To calculate the damping rates, we used the hybrid MHD kinetic code CASTOR-K and resistive MHD code CASTOR which showed that the radiative damping was largely dominant over all other sources of damping.



Radial structure of the n = 3 to n = 6 TAE calculated with MISHKA using data from LIDAR diagnostic and the equilibrium reconstructed by EFIT code. Top left: n = 3, top right: n = 4, bottom left: n = 5, bottom right: n = 6.

We planned to discover how Neutral Beam Injection on working plasma scenarios of JT-60SA Tokamak could affect AE stability. With foreseen high plasma current operation (~5 MA) and modest toroidal magnetic field (~2 T), a non-negligible fraction of supra-Alfvenic particles slightly below the MeV range with normalised drift orbit widths comparable to fusion alphas in ITER is expected in JT-60SA plasmas, raising its relevance for ITER studies. To achieve such a goal we used realistic distribution functions of energetic ions from NBI sources on a first systematic scan of Alfven mode stability. This pilot study used the ASPACK code suite, with CASTOR-K code used to compute the energy exchange between ideal incompressible MHD modes and computed energetic particle distribution functions by state-of-the-art Neutral Beam particle following codes. We confirmed that the Negative Neutral Beam Injection system, with a maximum power of 10 MW and injecting 500 keV deuterium neutral atoms, can destabilise some Alfven Eigenmode (mostly TAEs and EAEs) in vicinity of the largest radial gradients of the distribution function.

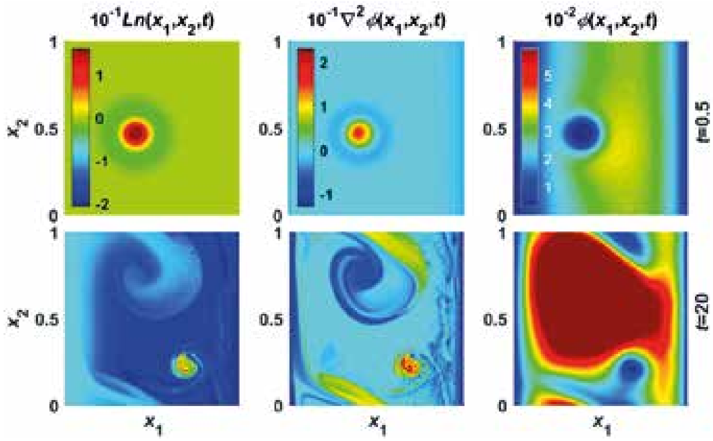


Normalised growth rate of AEs from negative NBI beams only coloured by radial location of the modes (left) and normalized frequency (right)

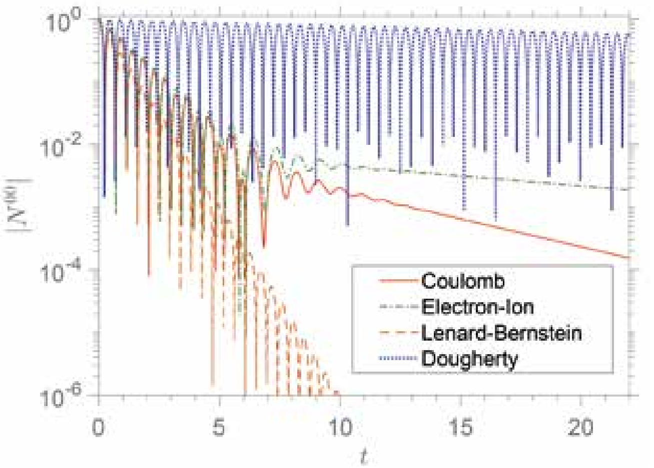
Turbulence studies in confined plasmas

For decades, the inherent complexity of the Coulomb collision operator has undermined our ability to develop a model that allows for efficient and reliable investigations of the plasma dynamics at arbitrary collisionalities. In a work recently developed at IST, Lisbon and EPFL, Lausanne, we have been able to overcome this long-standing issue. To achieve that goal we developed a theoretical framework to carry out kinetic calculations that involve the full Coulomb collision operator. We developed a formulation of the full Coulomb (or Landau) collision operator, based on suitable projections of the Boltzmann equations and the collision operator, which allows for an efficient numerical implementation, both in unmagnetized and magnetized plasmas. With an appropriate numerical code, we have described for the first time the dynamics of electron-plasma waves at arbitrary collisionality by considering the full Coulomb collision operator. We also investigated and showcased the need for retaining the Coulomb collision operator on linear regime of drift-waves, especially at the intermediate levels of collisionality relevant for present and future magnetic confinement fusion devices.

Focusing on the fundamental understanding of plasma turbulence on the scrape-off layer (SOL) of fusion devices, we have developed a new, exact, analytical solution for the conservative part of a standard two-fluid (density plus vorticity) model of the SOL. We confirmed the travelling-wave type of the solutions that describe the transport of large, machine-scale structures across a plasma cross-section. These conservative solutions, some extended throughout space, others much more localized, are conjectured to be the ancestors of propagating coherent structures, known as blobs, often seen in experiments and numerical simulations of SOL turbulence.

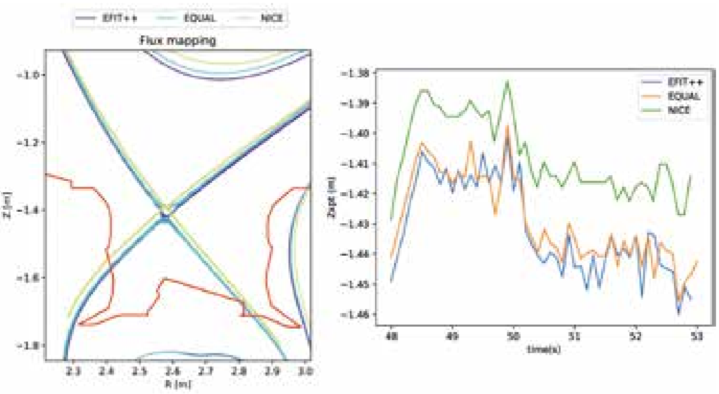


Snapshots with contour plots of the analytical logarithmic density , vorticity and electrostatic potential for the non-conservative SOL turbulence model with faint traces of the conservative solutions at later stages of the evolution.



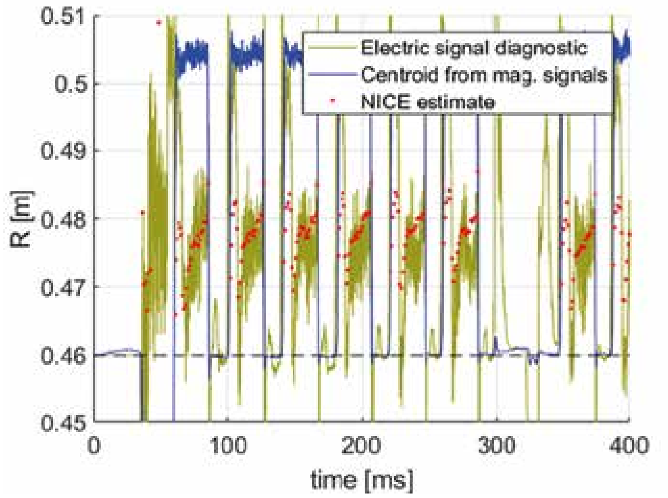
Time evolution of the absolute value of the density for the case of electron-plasma waves. While at initial times, there is a clear damping of the initial perturbations due to Landau damping, a purely damped mode appears at later times only in the presence of an accurate collision operator, such as the full-Coulomb one or the electron-ion pitch-angle scattering operator, as opposed to simplified ones such as the Lenard-Bernstein or the Dougherty ones.

Integrated Tokamak modelling and workflow development



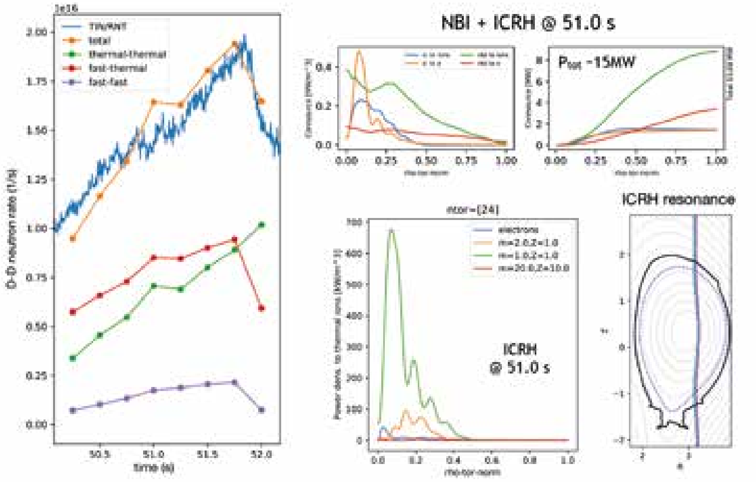
Details on divertor region for equilibrium reconstruction at t=50.0 s for #84600 with magnetic only (left) and time evolution of the lower X-point Z-coordinate (right).

We are strongly committed and prominent contributors to the EU modelling effort in support of ITER and current devices. We aim to establish a solid experience in the verification and validation of integrated modelling suites and codes as well as on the development of modelling workflows for key targets in Tokamak modelling. In track with the design and development of the Integrated Modelling Analysis Suite (IMAS) by the ITER Internal Organization, we have contributed to the verification and validation of an extensive pool of plasma simulation codes covering, among others, the topics of free boundary plasma equilibrium reconstruction, high resolution equilibrium calculation, linear MHD stability, particle and energy transport models and neutral beam deposition. Showcasing the application of IMAS, we developed prototype Kepler workflows for the reconstruction of Tokamak plasma equilibrium and MHD linear stability, demonstrating the modular workflow approach when applying it to a JET tokamak discharge by running the same KEPLER workflow in two different HPC clusters running IMAS. A pilot study on the plasma boundary reconstruction of ISTTOK tokamak plasma discharges was also completed using NICE code in IMAS.



Comparison of plasma radial center position estimations from electrostatic probes, magnetic probes (centroid from magnetic signals) and NICE (centroid of reconstructed plasma boundary).

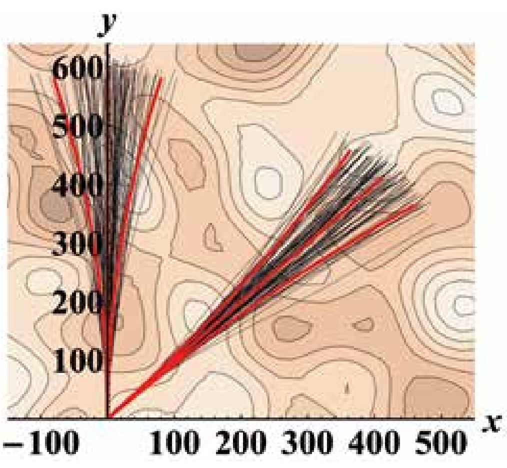
We are supportive of how multi-tokamak analysis of transport and confinement in a wide range of plasma regimes and engineering parameters can strengthen Tokamak physics awareness. Leveraging on the deep understanding of Tokamak system integration and data accessing and integration, the group increased its competence on the development of a set of mapping tools to translate local database formats into the Interface Data Structure (IDS), the basis of IMAS. The effort firstly enables swift access to experimental and simulated data such as thermal and non-thermal profiles, equilibrium, heating and current drive sources, as well as machine descriptions for the auxiliary systems such as NBI, ICRH, ECRH, from any Tokamak with compliant data mapping e.g. ASDEX-Upgrade, JET, MAST, TCV, and WEST. This is crucial to provide input to the European Transport Simulator (ETS) and its exploitation for predictive and interpretative modelling activities by EUROfusion users. We gave important steps in ETS validation with an interpretative analysis of fusion power production on dedicated JET discharges in view of the next DT campaign. The neutron rate as calculated by ETS, as well as the calculated power transferred to the plasma bulk by the heating and current drive auxiliary systems available at JET, offer a clear indicator of the quality of ETS as a plasma simulator.



Interpretative modelling of a JET baseline scenario with ETS. Left: the computed D-D fusion neutrons calculated by ETS are shown; total rate (orange), neutron rate (red) from thermonuclear fusion reactions, and the neutron rates between the NBI fast ions and themselves (violet) and with the thermal plasma bulk (green). The agreement is quite remarkable, but further investigations are needed. Right: power transfer to the plasma by the auxiliary heating and current drive systems, NBI and ICRH, are shown as computed by ETS at a given time.

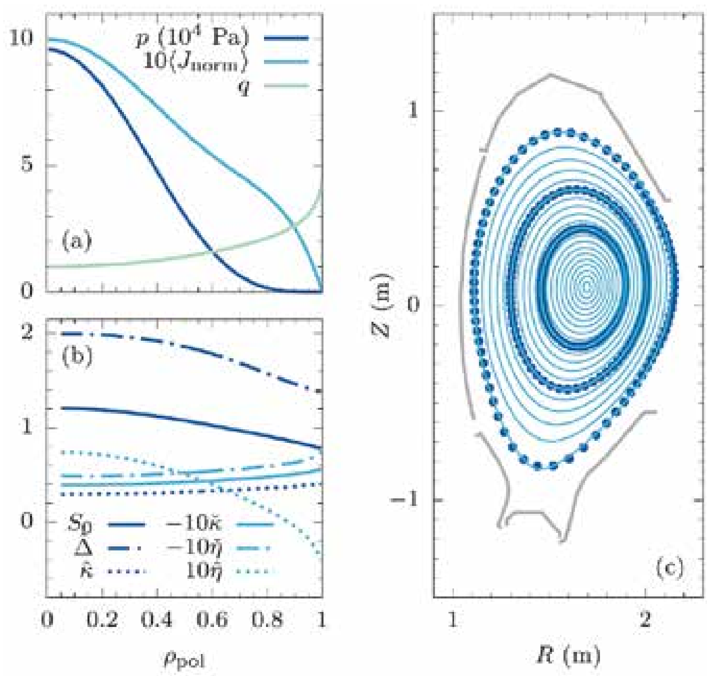
Fundamental plasma phenomena

We are interested in the intricate ties between wave propagation in plasmas and plasma turbulence. For this, we have developed a quasilinear (QL) approach for ray propagation in weakly turbulent media in which the dispersion relation and the ray equations are expanded up to, and including, second-order terms in the medium and ray fluctuations. We derived equations for the ensemble-averaged ray and its root-mean-square (rms) spreading, showing that the average ray does not coincide with unperturbed ray but may exhibit a drift with respect to the latter that is governed by the mean squared fluctuations. When choosing 4% both for the level of fluctuations and for the maximum ratio between the wavelengths of the propagating ray and of the turbulent modes, we have shown that the overall agreement between QL and an equivalent Monte Carlo is fairly good, particularly for quantities such as the distance travelled by the average ray, its perpendicular rms spread, and the averages of the wave-vector components.

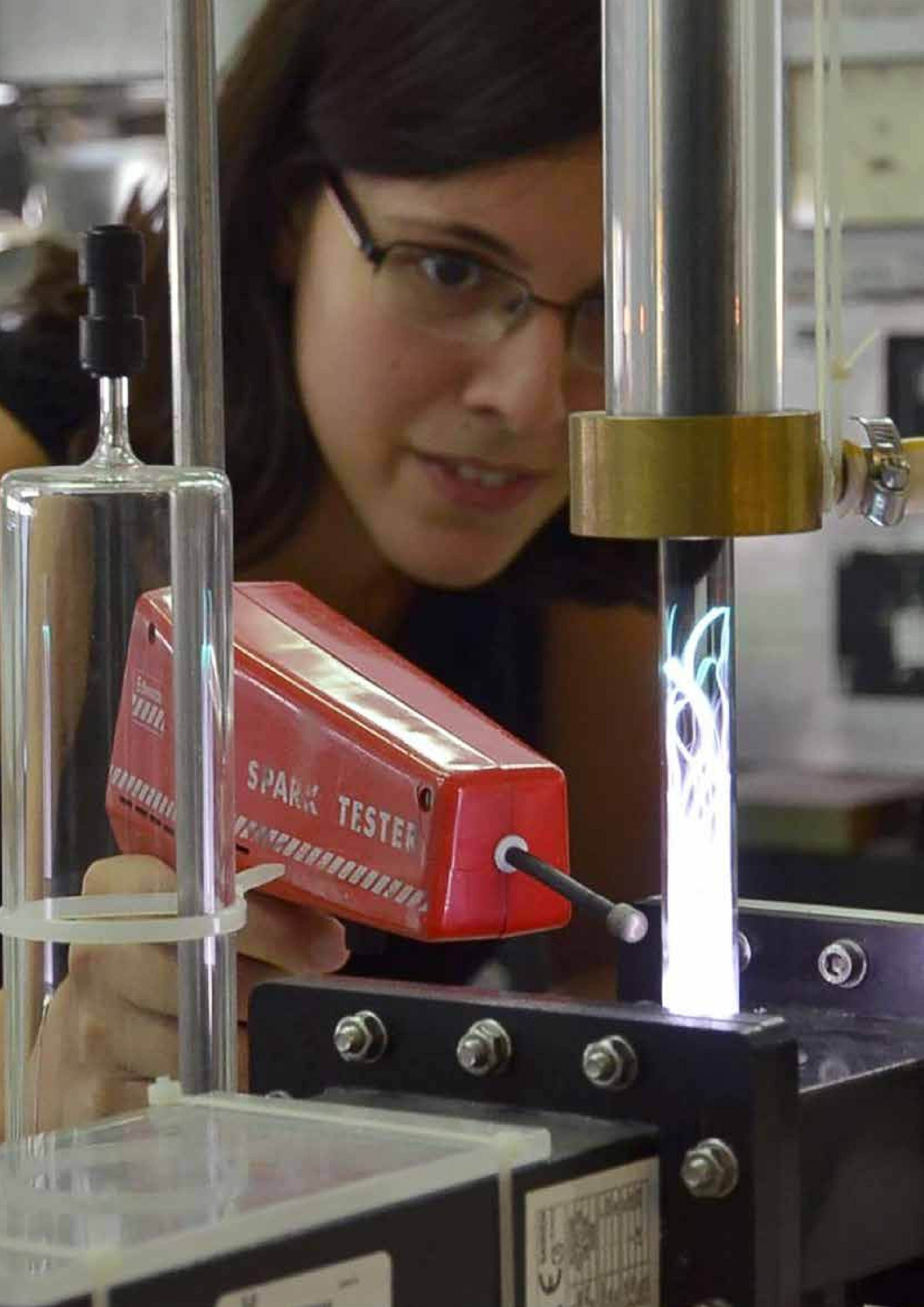


Average (x,y) ray trajectories and their perpendicular rms spreadings σ⊥ from the QL formalism (red lines) vs. MC calculation with N = 100 rays (black lines).

We are interested in exploring simple yet accurate representations of the magnetohydrodynamic equilibrium of tokamak confined plasmas. We have established a local magnetic equilibrium model with up–down asymmetric cross-section, where the poloidal-field flux is expanded as a series of Solovev solutions with radially changing coefficients. The model, accurate to fourth-order terms in the inverse aspect ratio and depending on eight free parameters, is devised to produce analytically tractable expressions for the magnetic-field components. Using the transformation to straight-field coordinates as an example, terms up to first-order in the inverse aspect ratio and in the normalised magnetic shear were used. This allowed us to interpret how the wave vector values k// and k⊥ of a MHD perturbation depend on equilibrium geometry, namely on the equilibrium-shaping effects (see figure). This breakthrough is expected to afford useful analytical insight into a wide variety of tokamak plasma phenomena.



Top left: pressure p, normalized surface-average toroidal current density, and safety factor q. Bottom left: fitted coefficients in model expansion . Right: numerical magnetic surfaces (solid lines) and analytical ones (dots).


SPARK TESTER

Plasma Technologies and Intense Lasers

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

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

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

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

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

N-PRiME

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Main funding sources
EU/H2020-FETOPEN, European Space Agency, Fundação para a Ciência e a Tecnologia, Portugal

The N - Plasmas Reactive: Modelling and Engineering (N-PRiME) group explores the potential of Nonequilibrium low-temperature plasmas for tailoring energy and matter at Nanoscale level and for reaching New Horizons in Space exploration. We intertwine experimental, theoretical and model-based predictive capabilities, providing answers to fundamental scientific challenges and developing novel plasma technologies with societal benefits.

N-PRiME multidisciplinary activities articulate three research axes: the Plasma Engineering Laboratory (PEL), the Hypersonic Plasmas Laboratory (HPL) and Plasma Modelling and Simulation (M&S), under the strong leadership of internationally recognized principal investigators.

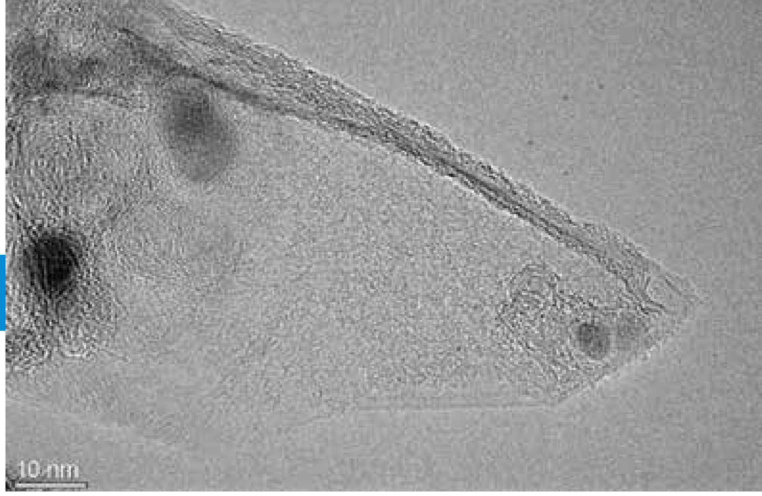
At PEL (E Tatarova and J Henriques, PIs) we exploit the flexibility of microwave-driven plasmas to tailor matter and energy at the nanoscale level. This impressive know-how is used to conceive, design and operate innovative experimental setups for synthetizing bi-dimensional nanostructured materials, and to extend the amazing properties of graphene to the third dimension. The outcome of this applied research contributes to consolidate the technological portfolio of IPFN.

Our M&S activities (V Guerra and ML Silva, PIs) focus on the study of non-equilibrium reactive plasmas created from different gas mixtures, adopting state-of-the-art volume/surface kinetic schemes, and considering the multi-dimensional transport of species and radiation, also under hydrodynamic flow regimes. This goal is achieved by developing, verifying and validating predictive numerical tools, for a large variety of systems and conditions.

The research at HPL (ML Silva, PI) pays tribute to the Portuguese heritage on the exploration of new worlds, now with new horizons. HPL hosts the European Shock-Tube for High Enthalpy Research (ESTHER), commissioned by the European Space Agency (ESA) and inaugurated in July 2019. ESTHER is the sole Portuguese Space facility for the planning of planetary exploration missions.

Plasma Engineering Laboratory

Using microwaves for exploring Plasma Nanoscience



Few-layer NG sheets and MnO nanoparticles present in the nanocomposites

Research activities at PEL are related to the emerging cutting-edge field of Plasma Nanoscience. They are focused on exploring microwave plasmas as a powerful tool for the synthesis of 2D nanostructures (e.g. graphene, N-graphene, graphene-based nanocomposites) and for extending the extraordinary properties of graphene to the third dimension, by assembling unique architectures of vertical graphene.

We have produced free-standing high-quality N-graphene (NG) sheets, with low content of oxygen (~1%) and small amount of sp3 carbon, via a single-step, environmentally friendly plasma-based method at atmospheric pressure conditions. Selecting the type of the precursors and adjusting the injection position of the nitrogen precursor in the plasma medium leads to selectivity in terms of doping level (up to 8% N), nitrogen configuration and production yield (~1.3 mg/min). Depending on the level of nitrogen doping, the synthetised NG can be considered as a prospective low secondary electron emission material, with sub unitary (< 1) yields. Our NG has demonstrated superior quality at a lower price (5-6 times cheaper), as compared with that produced by a reference supplier.

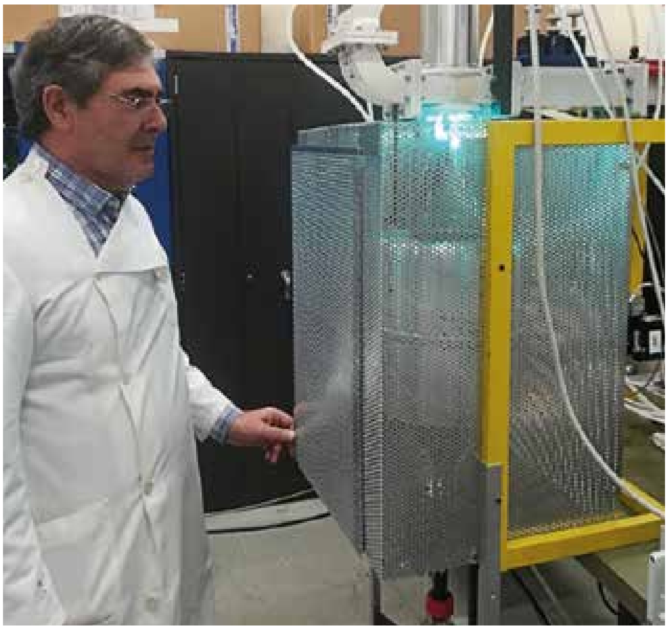
We have accomplished a novel single-step microwave plasma-driven method for assembling free-standing NG sheets decorated with metal oxide (MO) at atmospheric pressure. The NG/MO nanocomposites were assembled using methane, methylamine and MnO_2, with a relatively high amount of nitrogen doping (~4.6% N). The MO nanoparticles of several manganese oxide phases are dispersed or encapsulated by the NG sheets, via weak van der Waals forces or π-π* interactions.

This line of research is pursued within the project "Plasma Enabled and Graphene Allowed Unique Nanostructures" (766894-PEGASUS-H2020-FETOPEN-2016-2017; 3,99M€ funding)[1], where other highlights include:

• tailoring of graphene plasmons performance, demonstrating the potential of graphene as plasmonic material;

• plasma-based growth of vertical graphene on nickel foam;

• synthesis of the first carbon-based nanostructures using the new reactor for large-scale production of graphene/N-graphene.



Operation of the new PEGASUS reactor for large-scale synthesis of graphene and its derivatives

[1]*https://www.ipfn.tecnico.ulisboa.pt/PEGASUS/*

Plasmas Modeling & Simulation

The leading role the N-PRiME M&S activities was recognised with two important review papers recently published, on the foundations of modelling of nonequilibrium plasmas and on the modelling of N_2-O_2 plasmas.

Release of the LisbOn KInetics (LoKI) tool

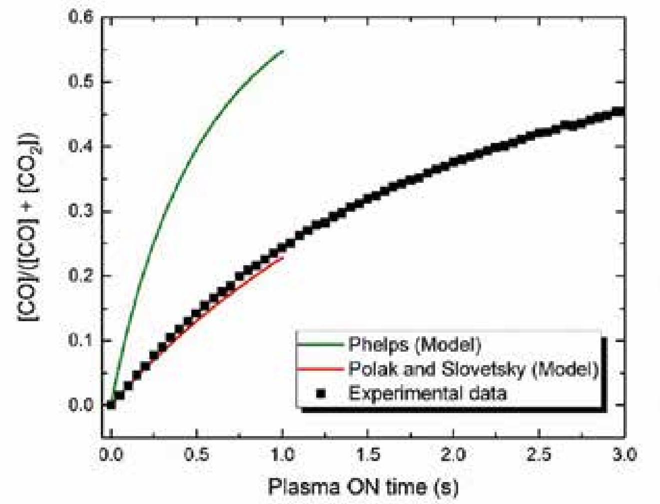
The Lisbon KInetics (LoKI)[1] is a simulation tool that couples two main calculation blocks: an electron Boltzmann solver (LoKI-B) and a Chemical solver (LoKI-C). LoKI-B, released in 2019 as open-source code licensed under the GNU general public license, describes the electron kinetics in any complex gas mixture. LoKI-C solves the global kinetic model(s) of pure gases or gaseous mixtures, receiving as input data the kinetic schemes KIT(s) for the gas/plasma system under study, via an intuitive parser-file.

The LoKI tools and data leverage on the scientific heritage in the field of non-equilibrium plasma kinetics of N-PRiME and were developed / consolidated resorting to well-grounded scientific foundations established years ago.

CO2 plasmas for a sustainable-energy transition

The continuous increase in utilisation of renewable sources calls for large-scale seasonal energy storage. A very promising and environmentally friendly solution relies on the storage of energy in chemical fuels produced from recycling CO_2. Our main goal is to investigate the potential of non-thermal plasmas to activate CO_2, while producing value-added products for energy storage.

We performed theoretical and simulation studies in close collaboration with the Laboratoire de Physique des Plasmas in Paris, targeted at investigating the role of electron- and vibrational- driven excitation for an efficient molecular dissociation. We have shown the importance of vibrational transfers from N_2 to the asymmetric mode of CO_2, suggesting the possible use of N_2 to help up-pumping the vibrational ladder of the CO_2. We have also validated the electron impact dissociation cross-section of CO_2 calculated by Polak and Slovetsky, which has eliminated previous discrepancies found in the literature.



Dissociation of CO_2 in a pulsed glow discharge at 4 Torr pressure and 40 mA current. The points are experimental data and the lines are modelling calculations using cross sections of Polak and Slovetsky (red) and Phelps (green).

Kinetic mechanisms in air plasmas

Gas discharges in N_2-O_2 have a significant number of applications, such as sterilisation, combustion, the study of sprites, space re-entry of spacecraft, air breakdown and pollution control. Fundamental knowledge of the elementary processes of these plasmas is essential to achieve their control and optimization.

We have continued to develop our self-consistent kinetic model devoted to the study of air and N_2–O_2 plasmas in different regimes. We have unveiled the formation of a highly excited oxygen vibrational distribution function, whose origin lays on electron impact collisions, contrary to all other molecular gases known to date. The calculation of gas heating in pulsed air plasmas and the heterogeneous formation of ozone in an oxygen afterglow are other major new results.

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[1] *https://nprime.tecnico.ulisboa.pt/loki/*

[2] *http://esther.ist.utl.pt/*

Hypersonic Plasmas Laboratory

Inauguration of ESTHER shock-tube

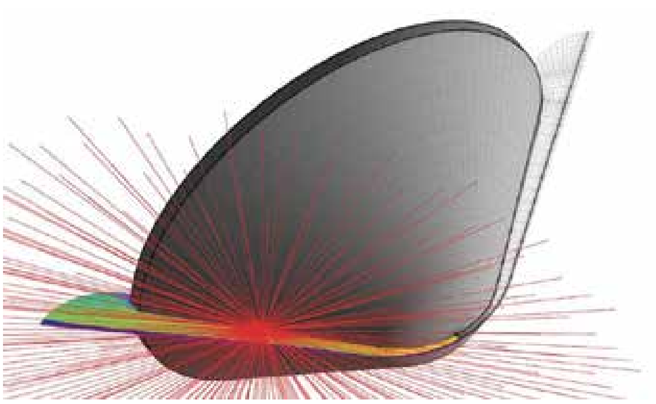
On 24th July 1969, the Apollo 11 Mission returned to Earth. 50 years later, another important step was achieved in the history of space exploration: the European Shock-Tube for High-Enthalpy Research (ESTHER)[2] was inaugurated at the Técnico CTN campus in the presence of several distinguished personalities: the Minister for Science, Technology and Higher Education, Manuel Heitor, the Representative of the European Space Agency (ESA-ESTEC), Victor Villace, the President of Portugal Space, Chiara Manfletti, the President of Loures City Hall, Bernardino Soares, the Vice-rector of Universidade de Lisboa, José Manuel Pinto Paixão and the President of Técnico, Arlindo Oliveira.

The inauguration ceremony marks the conclusion of a long development phase during the past decade, leading to the assembly of a new generation shock-tube capable of reaching superorbital velocities in excess of 10 km/s. This facility will contribute to maintaining European independence in access to space, through the faithful reproduction of the aerothermodynamic conditions of the flow surrounding a spacecraft entering a planetary atmosphere. ESTHER is equipped with an innovative vacuum ultraviolet (VUV) fast-spectroscopy setup, comprising an Aberration Corrected Seya-Namioka VUV spectrograph from McPherson, capable of measuring spectra in the ~100-400 nm range, and a VUV streak camera from Hamamatsu. The facility will now undergo field test-trials before becoming fully operational in the first quarter of 2020. Afterwards, it will start producing science and engineering to the benefit of the European community.

Analysis of Galileo's Jupiter entry probe reveals gaps in heatshield modelling

In 1995, the Galileo mission to Jupiter launched a probe that descended from Mach 50 to Mach 1 during its entry, generating enough heat to cause plasma reactions on the surface. The data on the probe's heatshield burning differed from the effects predicted in fluid dynamics models.

In collaboration with the University of Illinois at Urbana-Champaign, we examined what might have caused such a discrepancy, applying new computational techniques to fluid radiative dynamic models and using data transmitted from Galileo's 30-second entry. We recalculated features of the hydrogen-helium mixture the probe passed through, such as viscosity, thermal conductivity and mass diffusion, and found that the Wilke/Blottner/Eucken transport model fails to accurately predict the interactions between hydrogen and helium molecules. The work helps improve future spacecraft design, including upcoming projects to explore Neptune.



High temperature flow-field around Galileo spacecraft upon entry to Jupiter, visualized with ray-tracing algorithm distribution

Inauguration of ESTHER shock-tube

Lasers and Plasmas

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Main funding sources
EU/H2020, Fundação para a Ciência e a Tecnologia

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

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

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

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

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

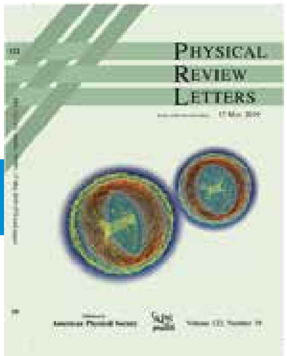
OSIRIS: Committed to open-science

The backbone of our simulation effort is the OSIRIS framework, which is a massively parallel, fully relativistic particle-in-cell code, with demonstrated scalability to over 1 million computing cores, that includes explicit support for advanced hardware features, ranging from vector units on high-performance CPUs to GPUs using CUDA. The code is used by more than 40 research groups worldwide, leveraging on a large developer and user community, whose work has led to over 300 publications in leading scientific journals.

Recent improvements focused on the development of a new OSIRIS module named RaDiO, that enables the calculation of shorter than cell size radiation in our simulation via the Liénard-Wiechert potentials using the particle's trajectories, thus removing the need for a finer grid. This allows us to obtain short-wave radiation in the spatiotemporal domain with built-in coherence, collected by virtual detectors in the simulation, that can be placed inside or outside of the simulation domain.

We also widened the scope of our simulation capabilities through the addition of linear Compton scattering into QED-OSIRIS. Compton scattering was always conceived as a thermalization process in plasmas. Given the intrinsic difficulty of the problem, the radiation scattering within a plasma was always addressed considering a gas of free electrons and neglecting the collective plasma fields. Our implementation of this new scattering module in the framework of a PIC code allows for a self-consistent analysis of both radiation scattering and collective plasma fields.

Contact person: Ricardo Fonseca



Cover of Physical Review Letters with OSIRIS simulation result. *Collision of ultra-relativistic, counter-propagating lepton bunches leading to pair creation and extreme photon emission in nonlinear QED.*

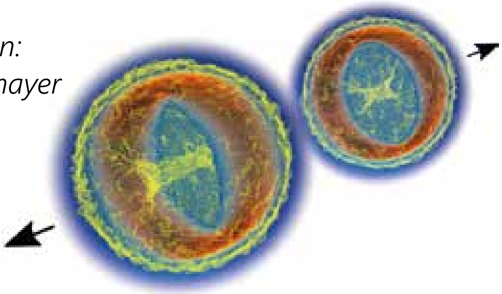
Collision of dense particle beams: gamma rays, electron-positron pairs and non-perturbative QED

The collision of ultra-short, high-density electron or electron and electron-positron beams at few GeV to be available at the FACET II and in laser wake-field accelerator experiments, can produce highly collimated γ rays with peak brilliance of 10^{27} photons/s/mm^2 mrad^2 0.1%BW and up to 10^5 nonlinear Breit-Wheeler pairs.

Our theoretical analysis is found to be an excellent agreement with full-scale 3D self-consistent particle-in-cell simulations that include quantum electrodynamics effects. Our results show that beam-beam collisions can be exploited as secondary sources of γ rays and provide an alternative to beam-laser setups to probe quantum electrodynamics effects at the Schwinger limit.

When the energy of the electron beams is increased up to 100 GeV and that the beam is compressed to 10's nm, the beamstrahlung radiation loss can be mitigated, allowing the particle to experience extreme electromagnetic fields. This experimental forefront envisaged has the potential to establish a novel research field and to stimulate the development of a new theoretical methodology for the unexplored regime of fully non-perturbative QED.

Contact person:
Thomas Grismayer



Beam-beam collider for probing nonperturbative QED. *3D OSIRIS-QED simulation of the collision of two electron beams with 125 GeV energy (blue) shows particles experiencing the fully nonperturbative QED regime (red). The interaction produces two dense gamma-ray beams (yellow).*

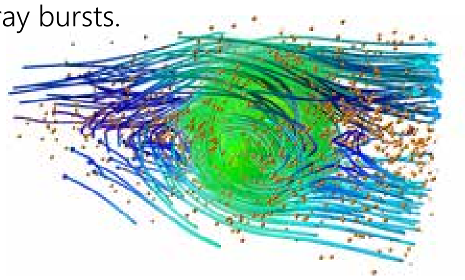
Compression of magnetic fields and enhanced quantum effects

Bright gamma-ray flares are observed in the vicinity of neutron stars and magnetars, but identifying the source of the intense radiation emitted in these violent eruptions remains a great challenge to the astrophysics community. Extremely strong magnetic fields are found around these objects, and a mechanism known as magnetic reconnection is a strong candidate to explain the flares. Our main goal is to clarify when quantum effects play a role in magnetic reconnection, and how to identify them. In particular, we are interested in exploring where gamma ray photons, and pair production occur.

We performed simulations investigating reconnection over various magnetic field strengths ranging from the classical case to the fully quantum case. We have made progress calculating radiation spectra for each of these cases and finding that the spectral index depends on the level of magnetic field strength. This has allowed us to identify signatures that distinguish reconnection where quantum effects play a role from classical reconnection.

We found that even for moderate magnetic field strengths, a process of magnetic compression leads stronger fields and in turn quantum effects. We found that the compression occurs in regions in the centre of magnetic islands, and this is where quantum effects such as gamma-ray emission and pair production occur. We hope to gain insight as to what strengths of magnetic fields would be required to see quantum effects that may play an important role in gamma-ray bursts.

Contact person:
Kevin Schoeffler

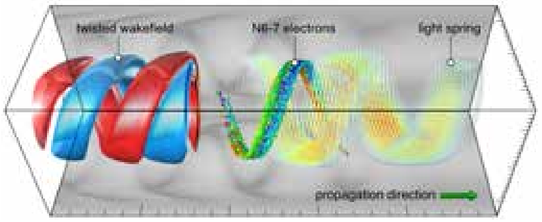


Quantum effects enhanced due to magnetic compression. *Magnetic field lines (blue) undergoing reconnection. Quantum emission of photons (orange) occurs throughout the simulation especially near magnetic islands where the magnetic energy density (green) is compressed.*

Topological plasma-based accelerators

A crucial feature of the plasma is the tremendous flexibility on its topology. Although nearly unexplored, obtaining control over the topology of plasma accelerators could have profound implications in the acceleration and radiation emission processes. Thanks to the recent advances on ultrafast laser technology, current lasers can deliver high power laser beams with advanced spatiotemporal features that promise to control the relativistic motion of electrons in completely new ways. This is a crucial step to achieve control over the plasma topology. With this motivation, and using theory and simulations, we have thus demonstrated that a special class of laser pulses characterized by spiralling wavefronts, often referred to as twisted light, can effectively control the topology of the plasma. Our work shows that these laser pulses can impart orbital angular momentum to the acceleration structures in the plasma. This new type of plasma accelerator can produce relativistic vortex electron bunches, with quantized levels of angular momentum. The emergence of such quantization rule could open new paths to produce coherent x-rays and to probe magnetic materials.

Contact person: Jorge Vieira



Vortex plasma accelerator.
An intense twisted laser pulse (light spring, green-yellow-orange) drives a plasma accelerator with a twisted plasma wakefield (blue-red), which can accelerate relativistic vortex electrons (coloured spheres).

Are we ready to convert optical light to gamma-rays?

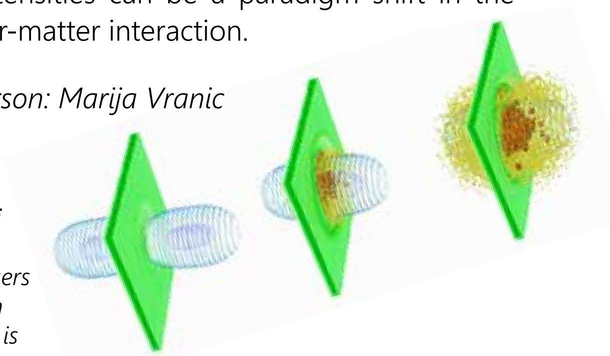
Intense lasers of tomorrow will be able to accelerate electrons close to the speed of light in a matter of femtoseconds. The electrons can then radiate high-frequency photons. These photons are immersed in the extreme electromagnetic environment where they decay into electron-positron pairs. The new electrons and positrons can repeat the cycle of acceleration and photon emission until the energy of the background laser becomes depleted. Our main goal is to probe this in the laboratory with the next generation of lasers.

J. Vieira, J.T. Mendonça, F. Quéré, Phys. Rev. Lett. 121, 054801 (2018)

The most promising configuration to observe this process known as the QED cascade is using two intense lasers counter-propagating towards one another. They create a standing wave that allows particles to be in good conditions for re-acceleration even after being created at low energy. The question is, how much plasma do we need to fully convert the laser energy to high-frequency gamma-rays? Can we use a few electrons as a seed, or we need a solid target? How does energy conversion depend on laser intensity?

We explored these ideas using analytical theory and massively parallel simulations using supercomputers all around Europe . Currently, we are working on establishing other configurations where access to extreme intensities can be a paradigm shift in the field of laser-matter interaction.

Contact person: Marija Vranic



QED cascade in the field of two colliding lasers. *The lasers hit a hydrogen ice target that is transparent for the lasers because of the extremely high intensity. Emitted photons are shown in yellow, and the created positrons are displayed in red.*

Upgraded laser capability at L2I

Five years ago, the Laboratory for Intense Lasers (L2I) was selected as strategic research infrastructure in the scope of FCT's National Roadmap programme. In this context, L2I merged efforts with Coimbra LaserLab, a laser facility at the University of Coimbra, to create a new distributed infrastructure: Laserlab-Portugal. The joint laboratory successfully applied for funding, being awarded 2.6 M€ for upgrading its facilities over the period 2017-2020.

The L2I team will upgrade the laboratory space and the laser capability, with the goal of preparing it to host external users. A state-of-the-art 3 µm, 100 kHz, few-cycle, carrier-envelope phase-stable laser system will enable to perform a range of new experiments in at very high repetition rates in different physical regimes, ranging from nonlinear optics and spectroscopy to harmonic generation.

During this period, the laboratory underwent the first phase of the project, including some major changes

M. Vranic et al., Phys. Plasmas 26, 053103 (2019)

to host the new laser system. The previous Nd:glass amplifiers were disassembled and stored and most of the optical setups were temporarily removed. A new integrated optical table was installed and the laser sub-systems were reassembled with improved stability and interconnection. The upgraded L2I laser capability was defined, as well as plans for future energy upgrades to allow experiments in plasma physics. The new laser will be installed in mid-2020, inaugurating a new era of research at this facility.

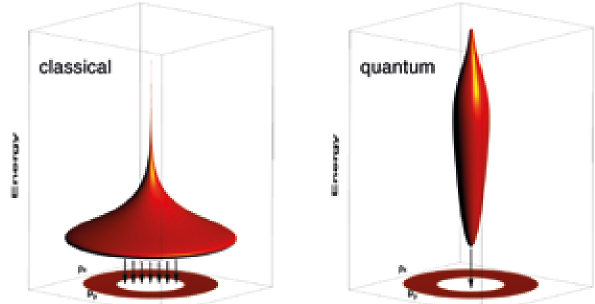
Contact person: Gonçalo Figueira

Ready for an upgrade. *The new integrated optical table at L2I just after installation.*

Quantum rules slow down collisions

Quantum laws forbid two electrons from occupying the same state. This limits the available states an electron can occupy, or scatter to. This phenomenon, known as degeneracy, occurs when electrons are tightly packed and cold, and is all too familiar to scientists working with solids. Conversely, plasmas, being generally hot and gas-like, do not exhibit any degeneracy. However, there exists a range of plasmas in nature and on Earth that have densities and temperatures that make them strongly degenerate. For example, current laser technology can squash matter into plasmas one thousand times the density of solids, making a strongly degenerate plasma. How degeneracy affects the electron-electron collisions that define the plasma properties has only been theorised recently, yet experimental evidence is so far lacking.

Here, we use the most brilliant source of x-rays on Earth, x-ray free-electron lasers (XFELs), to simultaneously create and diagnose a degenerate plasma. We use the XFEL to create a monoenergetic group of high energy electrons that ionise the atoms inside a foil of solid aluminium. Free states without electrons are created during ionisation and can be filled by a transition from the free electrons. These transitions, now coming from a degenerate distribution where states are limited, are drastically reduced.



Electron distribution functions vs. electron energy and momentum for classical and quantum systems. The classical distribution (left) allows electrons to occupy many more states at lower energies. The states are restricted in the quantum treatment (right). Recombination favours the lower energy electrons, and the rate is slowed due to degeneracy.

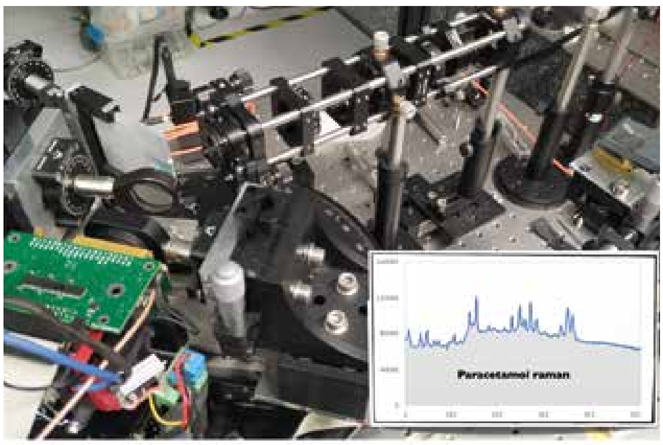
We have shown experimentally that the rate of collisional processes in degenerate plasmas is orders of magnitude lower than predicted by classical theory. We include the degeneracy effects in a current atomic physics code that reproduces the results. This work is the first experimental evidence of collisional rates in degenerate plasmas

Contact person: Gareth Williams

Lab testing and construction of compact Raman spectrometers

The work on RamSERS project, which aims the development of two portable Raman spectrometers (using laser lines @785 nwm and @1064nm) for general industry applications and more specifically for the detection of breast cancer biomarkers using of SERS substrates, was devoted to the tasks of lab testing and construction of the instrument optical and electronic circuits.

After the design phase of the optical circuits, the need for lab tests is essential for completely validating and characterising the specifications of the instrument. Also, very important was the lab testing the integration of the optical and the electronics circuits for the determination detectability and noise characterisation. The insight given by this lab test was also crucial for the construction of the prototype carried out by the company at the consortium.



Raman spectrometer.
Optical Test Bench and tested Raman signal of a paracetamol pill.

In this collaboration with the industry, our task in the consortium was to develop and test the optical circuits of the compact spectrometers in the project.

Contact person: João Mendanha Dias

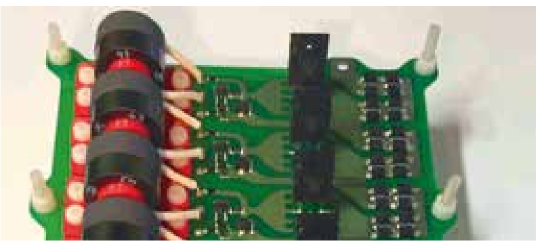
High precision DC discharge plasma densities for plasma accelerators

The AWAKE experiment, in CERN, demonstrated self-phase modulation and acceleration of externally injected electrons and prepares for its second phase where energy gain and beam quality will be the main goals. A DC discharge over a rarefied gas can be used to extend the plasma beyond the current 10-metre length. At IPFN we are developing the modules of a DC discharge plasma source for AWAKE, in collaboration with CERN and Imperial College.

The plasma source will use a double plasma discharge with a common cathode in the middle of the tube and grounded anodes at the tube extremities. The discharge duration is limited to less than 10 microseconds to preserve the plasma uniformity. Several plasma sources can be added to extend further the acceleration length. A critical aspect is a sub 1% plasma density fluctuation requirement both in time and space. This will require real-time control of the high-voltage discharge during the plasma formation based on the density measurement provided by interferometry.

For each plasma, the electric circuit uses a high-voltage short pulse to ignite the plasma between the tube cold electrodes and to bring it to a low current arc. This is followed by two new currents (of lower voltage and higher current) to heat the plasma to the correct temperature/density and keep it stable before the accelerator shot respectively. We have developed new high voltage and current solid-state switches that will allow full control of the plasma discharge in experiments planned for 2020.

Contact person: Nelson Lopes



Example of a high-voltage switch prototype developed for the AWAKE experiment (16 kV and up to 3kA).

E. Adli et al., Nature 561, 363 (2018)

High Pressure Plasr

What are the mechanisms of unipolar arcs in fusion devices? How can the motion of cathode spots on vacuum arc cathodes be described? Is the assumption of local thermodynamic equilibrium (LTE) in the whole arc plasma up to the electrode surfaces justified in the modeling of current transfer from high-pressure arc plasmas to thermionic cathodes? Apart from searching answers to these questions, the group has also focused on the development of a numerical model to compute low-current quasi-stationary discharges in high-pressure air, and the development of a fast, robust, and accurate tool for modelling of high-pressure arc discharges.

Our main goals are: to develop numerical models of the plasma-electrode interaction for different types of discharges; to perform simulations of the spot motion in vacuum arcs and compare the results to experiments; to develop an accurate tool for modelling of high-pressure arc discharges that will rely on an LTE model for the arc bulk coupled with the electrodes by means of interfaces describing non-equilibrium plasma layers; and to compute low-current quasi-stationary discharges in high-pressure air based on the use of stationary solvers.

Methods used to achieve those goals range from numerical modelling to experiments performed by our industrial partners. The obtained results, in particular, proved useful for the investigation of physics of high-power circuit breakers conducted in the framework of two industry-sponsored projects.

Group Leader
Mikhail Benilov

Researchers
Diego Santos
Helena Kaufmann
Mário Cunha
Nelson Almeida
Nuno Ferreira
Pedro Almeida

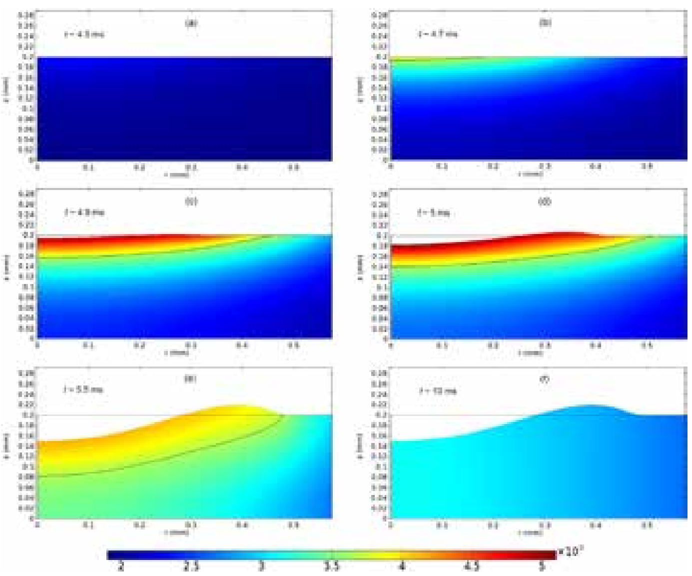
Main funding sources
Fundação para a Ciência e a Tecnologia,
Siemens AG, Schneider Electric
Industries SAS,
European Regional Development Fund

Numerical simulation of unipolar arcing in fusion-relevant conditions

Unipolar arcing between the plasma and the wall, triggered by plasma instabilities which deliver high energy and particle losses to the walls, is thought to be one of the mechanisms of the erosion in fusion devices. A possible mechanism of unipolar arcing is similar to the mechanism of formation of cathode spots in vacuum arcs, which was modeled previously. Our goal was to therefore apply a similar model for unipolar arcing in fusion devices. This research was started on the suggestions of, and conducted in collaboration with, colleagues from the Experimental Physics Group at IPFN.

The developed model was used for simulation of the interaction of an external energy load (laser beam) with a tungsten plate immersed in a helium background plasma. The results revealed the formation of a crater, but no jet formation or droplet detachment. The peak temperature attained varied with the size of the plate, and in the case of a small plate the potential of the plate surpasses the plasma potential. In the future, the developed model will be used for investigation of the plasma-cathode interaction and cathode erosion in other types of gas discharges and for investigation of the vacuum breakdown in conditions of accelerators (this research was started on the suggestions of, and is being conducted in collaboration with, colleagues from CERN, Geneva, and other institutions).

Contact persons: Helena Kaufmann, Mikhail Benilov



Simulation results obtained with the model of unipolar arcing in fusion relevant conditions.
The temporal evolution of the temperature distribution in the tungsten plate and the deformation of the plate surface are shown for the case of a large plate (radius R=100 mm).

Account of diffusion in LTE and two-temperature plasma models

A commonly used approach in models of high-pressure arc discharges is that of LTE for the arc bulk, however conventional LTE approaches do not take into account the diffusion currents in thermal plasmas (it is known that the latter are important in certain situations, e.g., they are responsible for the negative potential drop and the electric field reversal in front of arc anodes). Our goal was to develop a self-consistent description of diffusion currents in the framework of LTE. This amounts to introducing into Ohm's law in LTE, in addition to the conventional term proportional to the electric field (conduction current) and thermal-diffusion terms, also terms proportional to the temperature gradient. Representative modelling results show that this form of Ohm's law, when introduced into standard LTE, has the potential of describing the electric field reversal in front of arc anodes. This research was started on the suggestions of, and is conducted in collaboration with, colleagues from Schneider Electric.

A publicly available online tool for evaluation of the relevant coefficients (thermal-diffusion terms, also terms proportional to the temperature gradient) for argon, xenon, and mercury plasmas has been released on the internet.

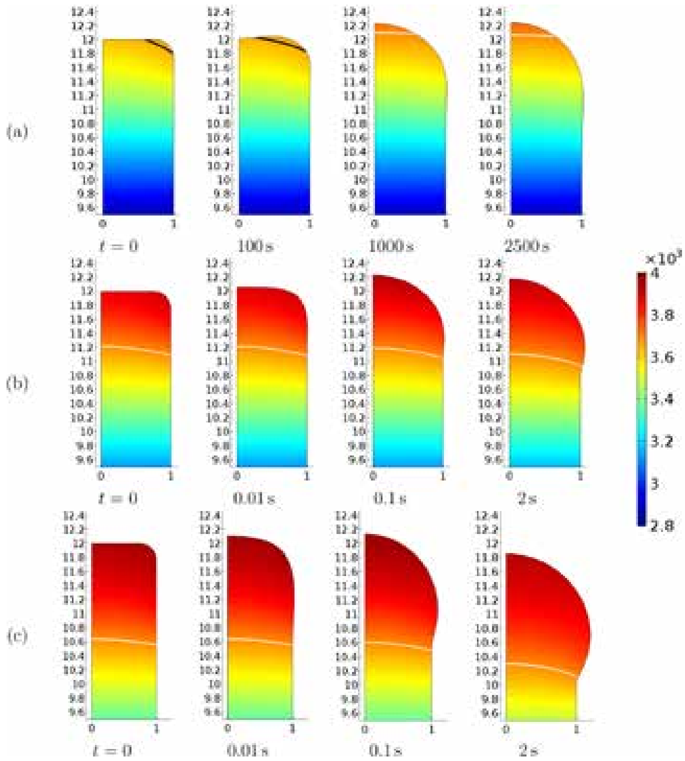
Contact persons: Diego Santos, Mikhail Benilov

Simulating changes in shape of thermionic cathodes during operation of high-pressure arc discharges

In studies of gas metal arc welding and plasma cutting, state-of-the-art arc plasma simulations, coupled with simulations of melting of electrodes and motion of the melt, rely on the assumption of LTE in the whole arc plasma computation domain up to the electrode surfaces; deviations from LTE occurring in the near-electrode regions are not considered. Our goal was to try to simulate current transfer from high-pressure arc plasmas to thermionic cathodes, including motion of the molten metal and the change in shape of the cathode, with a physically justified account of deviations from LTE occurring in the near-cathode space-charge sheath.

The model was developed on the basis of models developed previously by our group. Computation results were obtained for conditions of experiments with atmospheric-pressure argon arc with a tungsten cathode. The computed time scales conform to those observed in the experiment, indicating that the model of non-equilibrium near-cathode layers in high-pressure arc discharges predicts the cathode temperature for a given arc current with adequate accuracy. In contrast, modelling based on the assumption of LTE in the whole arc plasma computation domain up to the cathode surface does not produce a similar agreement.

Contact persons: Mário Cunha, Mikhail Benilov

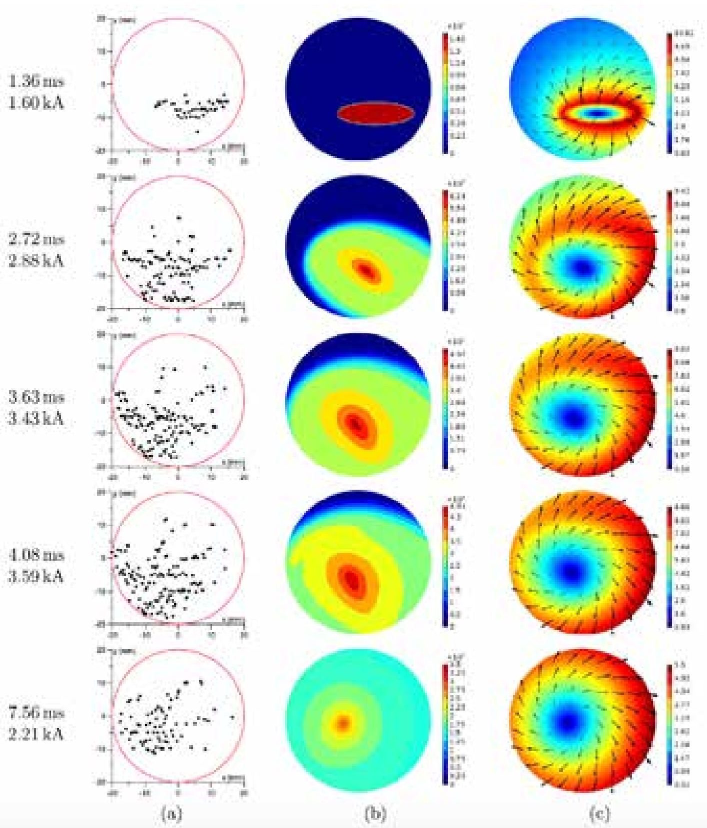


Simulation results of the evolution of the cathode shape of a thermionic (tungsten cathode) in an atmospheric-pressure argon arc.
Distances in mm, temperature bar in K. (a) I=60 A. (b) 140 A. (c) 200 A. White lines: isotherm of the melting temperature (3695 K). Black lines in the first and second images in figure (a): isotherm T=3650 K.

The motion of cathode spots of vacuum arcs

Several hundreds of spots operate simultaneously on cathodes of vacuum arcs in high-power vacuum circuit breakers. At the macroscopic level, and in the absence of a magnetic field, the motion of a cathode spot can be described as a random walk along the cathode surface. When an external magnetic field is applied, parallel to the cathode surface, an ordered motion, directed in the opposite direction of the Amperian force exerted by the magnetic field, is superimposed over the random walk, i.e., retrograde motion. Our goal was two-fold: to simulate the spot distribution along the contact surface by means of an approach that is based on the concept of surface density of spots and represents a natural alternative to tracing individual spots; and to propose a fresh attempt to develop a self-consistent description of the retrograde motion of cathode spots. We conducted this research on the suggestion of, and in collaboration with, colleagues from Siemens Corporate Technology, one of the aims being application of results to contacts of high-power vacuum circuit breakers.

In the first case, the proposed model is simple and physically transparent and correctly reproduces the trends observed in the experiments under conditions where the cathode arc attachment is diffuse. The distribution of the macroscopic current density on the cathode, given by the model, represents the boundary condition that is required for existing numerical models of vacuum arcs in high-power vacuum circuit breakers.



Macroscopic motion of cathode spots during arcing.
(a) Distributions of cathode spots observed at different arcing times in the experiment. (b) Computed distributions of macroscopic (averaged over individual spots) current density on the cathode; bars in Am^{-2}*. (c) Computed distributions of spot drift velocities; bars in* ms^{-1}*.*

In the second case, three potential mechanisms of effect of transversal magnetic field on the distribution of parameters in the spot were studied: the effect of magnetic field on hydrodynamics processes in the spot, and the effect of transversal magnetic field over the motion of ions and emitted electrons in the near-cathode space-charge sheath. It was found that for typical conditions all three mechanisms are either negligible or only have a marginal effect. A phenomenological description of the retrograde motion was developed as an alternative, employing general considerations without relying on specific assumptions and the (only) unknown parameter can be determined from comparison with the experiment.

Contact persons: Mário Cunha, Mikhail Benilov

Simulation of pre-breakdown discharges in high-pressure air

High-pressure air is commonly used nowadays in high-voltage insulating switchgear. The physics of low-current gas discharges (corona, Townsend, and streamer discharges) in high-pressure gases has been understood reasonably well by now. Time-dependent solvers are virtually universally employed in gas discharge modelling but can be too heavy to be routinely used in engineering practice. Our goal was to develop a numerical model to compute low-current quasi-stationary discharges in high-pressure air based on the use of stationary solvers, which offer important advantages in simulations of steady-state discharges when compared to standard approaches that rely on time-dependent solvers. We conducted this research as a part of an applied-physics project sponsored by Siemens Corporate Technology, one of the aims being application of results to high-power vacuum circuit breakers.

A ‘minimal’ kinetic model of plasmachemical processes in low-current gas discharges has been employed, which takes into account electrons, an effective species of positive ions, and three species of negative ions. The model was validated by comparison of the computed inception voltage of corona discharges with several sets of experimental data on glow coronas. A good agreement with the experiment has been obtained for positive coronas between concentric cylinders in a wide range of pressures and diameters of the cylinders. Inception voltages of negative coronas, computed using the values of the secondary electron emission coefficient of 10^{-4} to 10^{-3}, agree well with the experimental data.

Contact persons: Nuno Ferreira, Mikhail Benilov

Community and Outreach

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

Conferences and Seminars

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

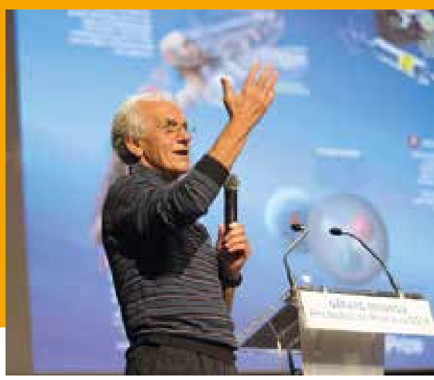
- Laserlab JRA LEPP Meeting, IST, 22 June 2018
- Laserlab Workshop on Data Handling and Open Data, IST, 7 December 2018
- CERN Accelerator School on plasma acceleration, 11-22 March 2019
- European Conference on Plasma Diagnostics 2019, IST, 6-9 May 2019

School visits and talks

Every year, IPFN facilities such as ISTTOK, L2I and VOXEL receive many tens of school visits, from basic to secondary school students. During the tours, the students have the opportunity to contact with undergraduate students and researchers and have a first contact with the research developed at IPFN, the technologies involved and perspectives of future careers. Our researchers are also frequently invited to give talks at schools, workshops, training sessions and public events.

Following the attribution of the Nobel Prize in Physics in 2018, we co-organized a public lecture by laureate Gérard Mourou at Pavilhão do Conhecimento, Lisbon, followed by another one at IST.

ECPD 2019



Nobel laureate Gérard Mourou

School visit to ISTTOK

Workshops, training and outreach events

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

- **H2020 PEGASUS - First International Workshop, June 2018**
- **Joint IPFN-CeFEMA Mini Workshop in Strong Field Physics: from lasers to QCD, June 2018**
- **Mini-course: An introduction to turbulence in magnetized plasmas, July 2018**
- **Lasers workshop for secondary school teachers, September 2018**
- **GoLP Virtual Reality Lab at Ciência 2019 meeting, July 2019**
- **Mini-workshop: topological light-matter states, October 2019**

Web and media

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

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

Webpage – ipfn.tecnico.ulisboa.pt

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

Facebook – fb.com/IPFNLA

Launched in 2010, the IPFN page has gathered more than 1500 followers.

YouTube – youtube.com/IPFNmedia

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

LinkedIn – linked.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 280 pictures

Twitter – twitter.com/IPFN_Lisbon

The growing popularity of this platform led IPFN to add it to its media portfolio at the beginning of 2020

Lasers – workshop for secondary school teachers

Bringing light to Príncipe

Ciência 2019

Education

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

APPLAuSE C6 students: the most recent cohort to join the programme!

APPLAuSE doctoral programme

APPLAuSE is IPFN's flagship international doctoral programme in Plasma Science and Engineering. Funded by FCT and hosted by IPFN, the degree is awarded by the University of Lisbon, Portugal. During 2018-2019, the 5th and 6th cohorts joined the programme, adding 14 new students.

Simultaneously, this period saw the first PhD thesis defences, with several former APPLAuSE students successfully completing the programme and moving on in their careers, either in academy or industry. Up to now, almost 50 students have been enrolled in APPLAuSE, originating from 11 countries in 4 continents.

For more information:

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

ATHENS course on Plasma Science and Technology

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

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

For more information:
http://athensnetwork.eu/

Participants in the 2019 ATHENS course

Participants in the Plasmasurf Summer School of 2019

PlasmaSurf

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

The programme includes lectures, visits to laboratories and plenty of outdoor activities and water sports. Bringing together science and seaside adventure, PlasmaSurf has emerged to become one of Europe's most popular summer schools in these fields. A total of 51 students from all over the world participated in the latest two editions.

For more information:
http://plasmasurf.tecnico.ulisboa.pt/

Ciência Viva no Verão

IPFN 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.

For more information:
https://www.ipfn.tecnico.ulisboa.pt/education

Awards and distinctions

Community Awards

Luís O. Silva, Member of the European Academy of Sciences; Corresponding Member of the Lisbon Academy of Sciences

Scientific prizes

Marija Vranic, IBM Scientific Prize 2018

José Luís Figueiredo, 2019 Young Researchers Incentive Programme, Calouste Gulbenkian Foundation

Camilla Willim, 2019 Doctoral INPhINIT Fellowships Programme - Incoming, La Caixa

Fabio Cruz, 2019 best talk Journal of Plasma Physics prize, Les Houches Plasma Physics School

Conferences

Giannandrea Inchingolo, Best Video in Plasma Physics award, 45th EPS Conference on Plasma Physics, 2018

Luís Gil, high commendation for his poster, 45th EPS Conference on Plasma Physics, 2018

Mariana Moreira, PPCF/EPS/IUPAP PhD Poster Prize, 46th EPS Conference on Plasma Physics, 2019

Thesis prizes

Rogério Jorge, EPFL Doctoral Thesis Award 2019

Rogério Jorge, European Physical Society Division of Plasma Physics PhD Award 2019

Miguel Pardal, Best MSc Thesis in Plasma Physics, Lasers and Nuclear Fusion in 2017/2018

Biennial Report 2018 - 2019

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

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Diana Amado

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Researcher Catarina Praefke at the VOXEL Laser Laboratory

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