BIENNIAL REPORT

2022-2023

Instituto de Plasmas e Fusão Nuclear

IPFN INSTITUTO DE PLASMAS E FUSÃO NUCLEAR

Highlights of activities

2022-2023

Biennial Report

Instituto de Plasmas e Fusão Nuclear

ipfn.tecnico.ulisboa.pt

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President's Foreword

I am delighted to present the highlights of our research unit's activities over the past two years, a period marked by significant scientific progress, and exciting new collaborations. As we reflect on this time, I am filled with pride in the accomplishments of our six research groups and the entire community of scientists, engineers, and support teams whose dedication continues to drive innovation and excellence. IPFN is a research unit with a clear roadmap, ambitious goals and a solid scientific reputation supported by a dynamic team with a strong determination to continue at the forefront of research in the field of nuclear fusion and plasma technologies.

Over the past two years, our unit has continued to excel in scientific discovery across a wide range of areas, from advanced plasma physics to materials science and beyond. Each of our six research groups has contributed to landmark studies and pioneering technologies, which you will find detailed in this report. These efforts have been recognized through numerous grants, high-impact publications, and prestigious awards. Despite the challenges of recent years, the resilience of our teams and the support from our stakeholders have enabled us to maintain momentum and aim even higher.

In this period IPFN activities were carried out in the framework of the EUROfusion Consortium, the Contract of Associated Laboratory, the Contracts with the ITER International Organisation (ITER IO) and the European Joint Undertaking for ITER and Fusion Energy (F4E), projects of the HorizonEurope Programme of the European Union, projects of the European Space Agency (ESA) and projects funded by Fundação para a Ciência e a Tecnologia.

"We are very proud to reconfirm the status of Associated Laboratory, and we will continue to work together towards excellence in research, training and outreach while creating further conditions for the creation of scientific employment."

IPFN hosts an ERC Consolidator Grant - Xpace (third ERC at IPFN), awarded to Frederico Fiúza for a total funding of 1.8 M€. This grant recognises IPFN expertise on solving central questions of extreme plasma phenomena and open new avenues between theory, computation, laboratory experiments, and astrophysical observations. This work 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/HorizonEurope 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 as a partner with other institutions (Collective Thomson Scattering, Radial Neutron Camera, integrators for magnetic diagnostics);

(ii) a contract with the ITER organisation for the development of the Ex-Vessel Collective Thomson Scattering Diagnostics;

(iii) 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 (including the final D-T campaign), the contribution to the Tokamak Exploitation Work Package, in particular, ASDEX Upgrade, which have been an integral part of the activities, an increasing contribution to DEMO activities (in diagnostics development and remote handling).

During this period, our research unit has not only upheld its standing as a as a player in fusion energy research, but has also expanded its role in shaping the future of energy through stronger ties with both public institutions and private industry. The fusion landscape is evolving rapidly, and I am particularly pleased to highlight our growing partnerships with private companies at the forefront of developing commercial fusion energy solutions. These collaborations represent a key step in translating our scientific breakthroughs into practical applications that will ultimately help address one of the most pressing challenges of our time: securing a sustainable and clean energy future.

Our contributions to the EUROfusion program, ITER, and other international collaborations remain a cornerstone of our work, but our new engagements with private sector leaders are catalyzing innovation. By joining forces with these companies, we are accelerating the path to realizing fusion energy's potential for society. This cooperative approach, combining cutting-edge research with industrial development, promises to bring the reality of fusion energy closer than ever. Together, we are building the future of energy!

IPFN is the leading institution of the NanoXCAN projectfunded by the Pathfinder Open program of the European Innovation Council (EIC). The NanoXCAN team intends to develop a nanoscale virus imaging X-ray microscope and the €4 million funding will be crucial to achieve this purpose.

The innovative projects carried out at IPFN promoted scientific employment, enhanced the team's international projection and have contributed to attracting additional competitive funding through R&D activities.

The impact of the research performed at IPFN has been recognised through several awards won by our researchers and multiple publications in prestigious journals. High-Level Education and Outreach activities are essential to our strategy. Several IPFN researchers were strongly involved in teaching activities. IPFN's most impactful contribution is the quality of the training offered to MSc and PhD students, and early career researchers and their scientific results. IPFN is undoubtedly a training powerhouse and is shaping the future through the training of highly qualified professionals for industry, and future researchers for academia. 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 and we have decided to maintain this programme in the frame of the FCT Programmatic funding for the research units. IPFN researchers have continued to supervise more than half of the PhD concluded in the Physics Department of IST.

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 seminars at high schools and regular visits to IPFN laboratories.

As we look to the future, we remain committed to our mission of advancing fusion science while nurturing the next generation of researchers.

The support from our funding agencies, governmental partners, and the scientific community at large remains critical to this mission. Together, we will continue to drive forward, pushing the boundaries of what is possible in fusion energy and contributing to a sustainable energy future for all. On behalf of IPFN, I would like to acknowledge the support of Horizon2020, HorizonEurope, EURATOM, F4E, ITER Organisation, FCT (project UIDB/50010/2020 and DOI identifier 10.54499/UIDB/50010/2020, project reference UIDP/50010/2020 and DOI identifier DOI 10.54499/UIDP/50010/2020 and by project reference LA/P/0061/202 and DOI 10.54499/LA/P/0061/2020), and IST, for having made such commitments possible. Science is also made through collaborations. I would like to convey my heartfelt gratitude to all our partners who have contributed to making our projects a success, or to those who lead projects to which IPFN contributes.

I extend my deepest thanks to all who have supported us in this journey—researchers, technicians, students and administrative staff, industry partners, funding agencies, policymakers, and the public. Your belief in the transformative potential of plasmas and nuclear fusion fuels our work, and I am confident that the next two years will bring even greater breakthroughs.

Bruno Soares Gonçalves,
President of IPFN

About IPFN

"Instituto de Plasmas e Fusão Nuclear" (IPFN) is a Research Unit of "Instituto Superior Técnico" (IST) with expertise in Plasma Physics, Engineering and Technologies, Controlled Nuclear Fusion, Lasers and Photonics and Advanced Computing.

IPFN is the sole R&D institution in Plasma Science and Engineering and one of the top Physics laboratories in the country, IPFN boasts 25 years of R&D experience and international recognition. Its national footprint, bringing together Portuguese researchers of recognized merit and complementary expertise, expanded with the establishment of the IPFN Research Node at the University of Madeira in 2017.

With know-how spanning various plasma-related disciplines, including Plasma Diagnostics, Energy and Environment, and High-Performance Computing, IPFN cultivates scientific and technological excellence, making it a key player in large-scale physics projects and innovation.

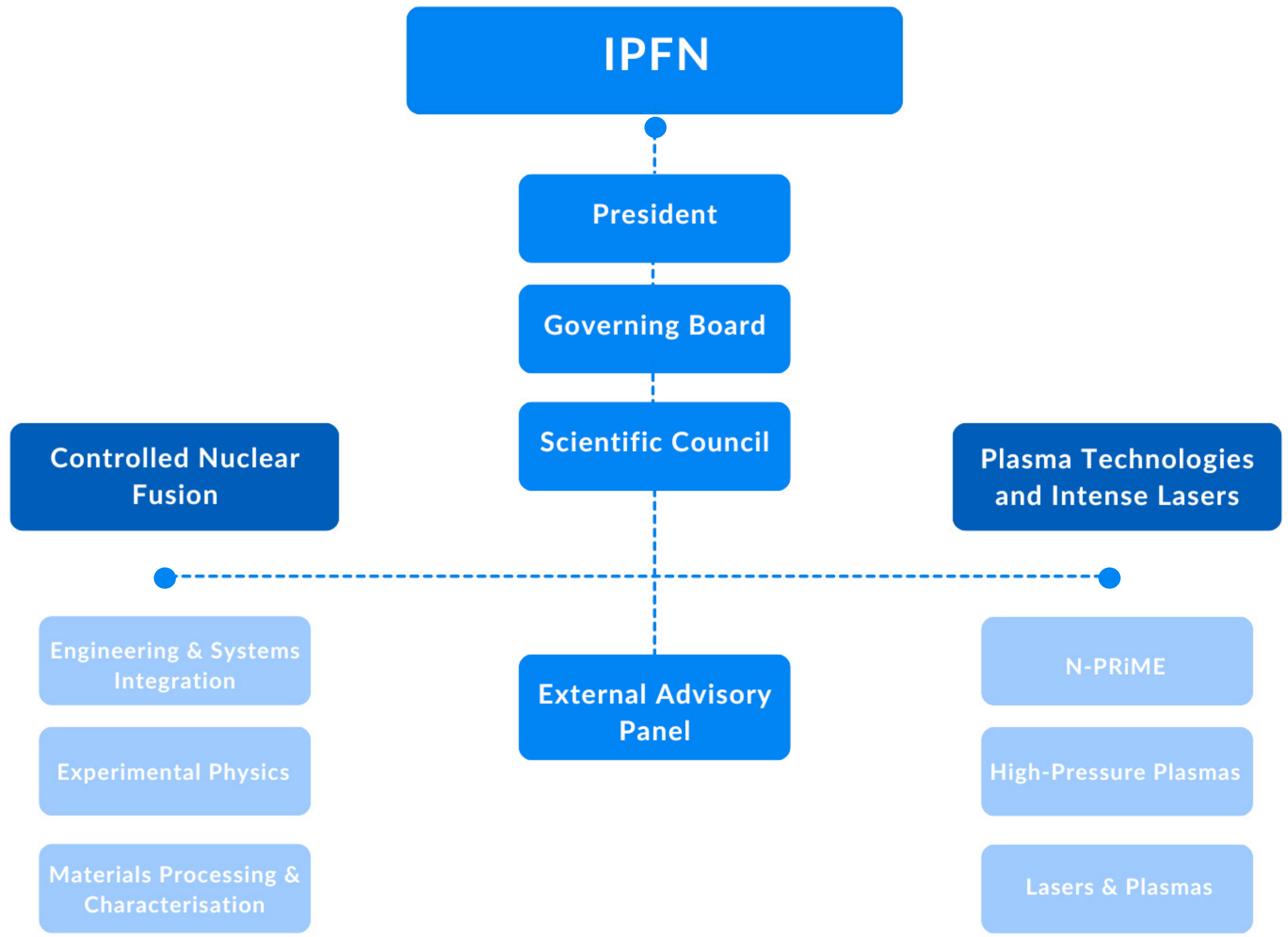
IPFN has the critical mass to foster scientific and technological excellence in an international context, providing a unique setting for world-class research, technological transfer, and advanced training. IPFN's exceptional cohesion, organizational structure and outstanding publication record granted exceptional conditions to maintain the status of Associated Laboratory in the most recent evaluation by FCT.

IPFN has an ambitious research program with a balance between activities motivated by contemporary scientific problems (curiosity-driven) and a varied portfolio of technological applications (application-driven). This program is supported by an institutional strategy with 4 main vectors:
(i) internationalization through peer recognition of competencies in several fields and participation in high-profile projects;
(ii) national reach with the integration of researchers from several universities;
(iii) strong commitment to high-level education and advanced training; and creation of reference research infrastructures.

Organisation

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.



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.

History of IPFN

1987

The Group for Nuclear Fusion is founded by Profs. Tito Mendonça and J.Costa Cabral

1990

The Contract of Association between Euratom and IST is signed, with the newly founded Center for Nuclear Fusion (CFN) in charge of the research programme

1996

The Center for Plasma Physics (CFP), dedicated to non-fusion plasma research, is established by Prof. Tito Mendonça

2002

The status os Associated Laboratory is granted to CFN, with the participation of CFP

2008

CFN and CFP merge into the unified Institute for Plasmas and Nuclear Fusion (IPFN)

2013

IPFN is awarded the classification "Exceptional" in the FCT Evaluation of R&D Units

2014

EUROfusion partnership agreement

2017

IPFN contributes to the JET (Joint European Torus) program, focusing on fusion energy research. This collaboration supports the advancement of the ITER project

2021

The final report of the External Advisory Panel (EAP) congratulates IPFN for creating a new research centre at the University of Madeira (UMa)

Historically...

>>IPFN is rooted in the former nuclear fusion research group, formed in **1987** after Portugal joined the European Union.

>>In **1990,** this same group became in charge of the Contract of Association Euratom/IST, now with the name of **Centro de Fusão Nuclear** (CFN, Center for Nuclear Fusion). Its first major assignment consisted of building the **ISTTOK tokamak,** which was successfully accomplished within time and budget.

>>Parallel to these devehlopments, in **1996** several research groups working in a range of topics in plasma physics joined to create the **Centro de Física de Plasmas** (CFP, Center for Plasma Physics).

>>The two centers joined efforts in **2001** and were successfully granted the status of **Associated Laboratory** by Fundação para a Ciência e a Tecnologia under the name CFN-LA.

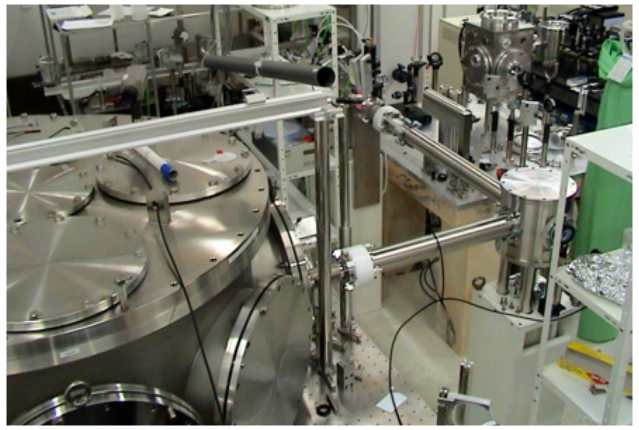
>>In **2008**, CFN and CFP merged under the common name of **Instituto de Plasmas e Fusão Nuclear (IPFN).**

>>IPFN has been until **2013** the Research Unit of the Contract of Association between the European Atomic Energy Community - Euratom - and Instituto Superior Técnico, in force since January 1st **1990.**

>>From **2014** onwards, it continues as the Portuguese representative in the Euratom co-fund action for fusion, awarded to the EUROFusion consortium of EU Fusion Laboratories, aiming at developing a joint programme of activities to implement the roadmap towards the goal of electricity production by 2050.

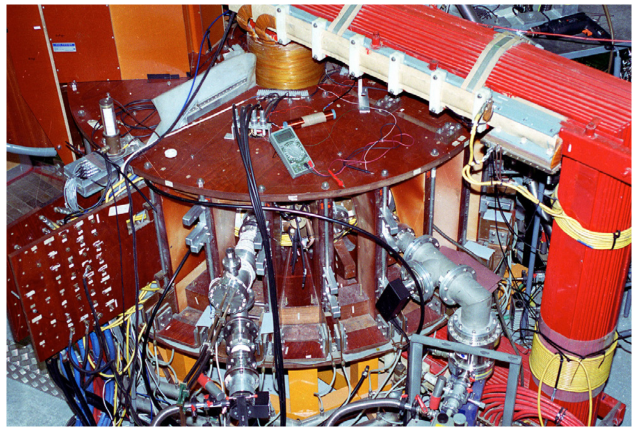
>>IPFN contributes to the **JET** (Joint European Tours) program in **2017**, focusing on fusion energy research. This collaboration supports the advancement of the ITER project.

>>The final report of External Advisory Panel (EAP) congratulates IPFN for creating a **new research centre** at the University of Madeira (UMa) - **2021**.

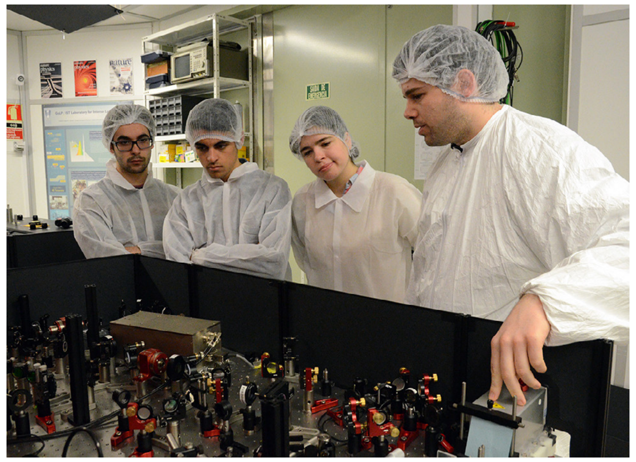


2004 - Laboratory for Intense Lasers - Interaction chamber

2005 - ISTTOK



2009 - Tokamak, ISTTOK



2015 - L2I visit

Management Board

Bruno Gonçalves

Group of Engineering and Systems Integration

Alberto Vale

PhD Representative

Carlos Silva

PhD representative

Eduardo Alves

Group of Materials Processing and Characterisation

Gonçalo Figueira

PhD representative

Horácio Fernandes

Group of Experimental Physics

Luís Lemos Alves

Group of N-PRiME

Luís Oliveira e Silva

Group of Lasers and Plasmas

Mário Lino da Silva

PhD representative

Marta Fajardo

PhD representative

Pedro Almeida

Group of High-Pressure Plasmas

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Tünde Fülöp

Chalmers University of Technology

Kunioki Mima

Osaka University

Francesco Romanelli

University of Rome

Jörg Winter

Ruhr-Universität Bochum

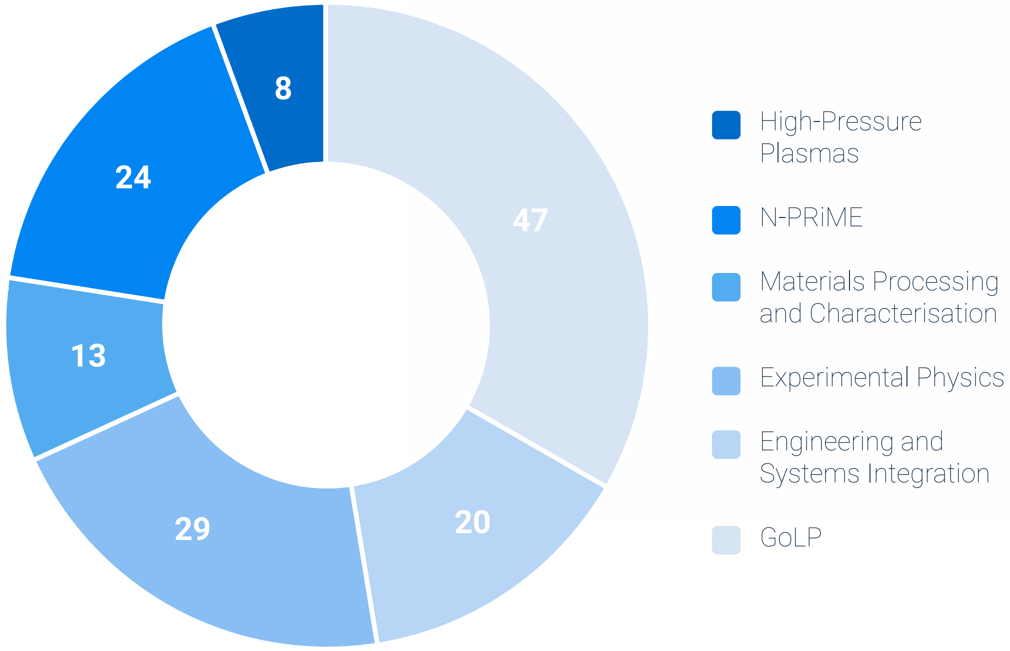
Leanne Pitchford

CNRS & Université Toulouse III

Facts and Numbers

Members per Group

at the end of 2023

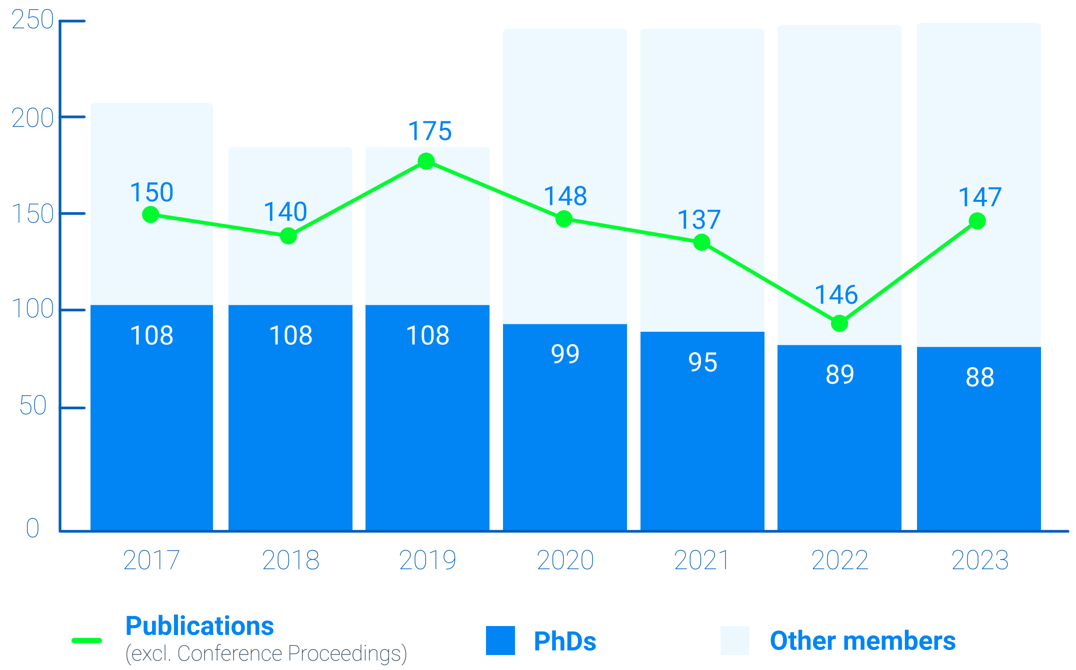


152
Collaborators
at the end of 2023

88
PhDs
faculty, researchers and postdocs

Collaborators and Publications

since 2017



+130
Publications per year
inc. Conference Proceedings

Highlights include papers published in

Nature Communications

Nature Physics

Phys. Rev. Letters

Controlled Nuclear Fusion

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

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

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

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

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

Engineering and Systems Integration

Main Researchers:

António Batista	Bernardo Carvalho	Jorge Belo	Nuno Cruz
Alberto Vale	Diogo Rechena	Jorge Santos	Paulo Varela
António Silva	Filipe da Silva	Jorge Sousa	Raúl Luís

Main funding sources:

FCT, EURATOM/Eurofusion;
ITER Organization;
General Fusion;

Summary of Research

Making nuclear fusion a reality represents a monumental challenge requiring specific expertise in engineering and systems integration, skills in short supply across Europe. To address these challenges, we are dedicated to advancing scientific and technological capabilities crucial to the fusion industry, cultivating expertise and developing cutting-edge solutions for fusion power, while nurturing young scientists and students. Our main topic is the interdisciplinary development of diagnostic systems, control and data acquisition systems, and remote handling solutions for nuclear fusion environments, following an integrated approach encompassing diagnostic development, numerical simulation of diagnostic performance, and state-of-the-art control systems. Our research is focused on projects related to ITER, DEMO, IFMIF-Dones, and other fusion industry initiatives.

Our main goal is to provide critical scientific and technological support to the fusion industry. We aim to train a new generation of scientists and engineers, equip them with advanced skills, and contribute to major fusion projects. We seek to develop innovative diagnostics, control systems, and remote handling solutions that can be applied to current and future fusion reactors.

To achieve that goal, we leverage our expertise in various specialized areas. Our main tools include numerical methods for simulating diagnostic performance, the development of high availability and radiation-tolerant control systems, and advanced data acquisition systems. These activities capitalize on IPFN's competencies and foster new skills in areas like neutronics, thermomechanical and fatigue analysis, CAD-based component engineering design and simulation, systems integration,RAMI and mobile robotics.

The main application of our research is to support and enhance the operation and maintenance of nuclear fusion reactors. This will allow for more efficient and effective diagnostic and control systems, ensuring steady-state operation and safety. Our work will significantly contribute to the success of fusion projects like ITER and DEMO, and will help prime the future workforce for upcoming fusion energy challenges.

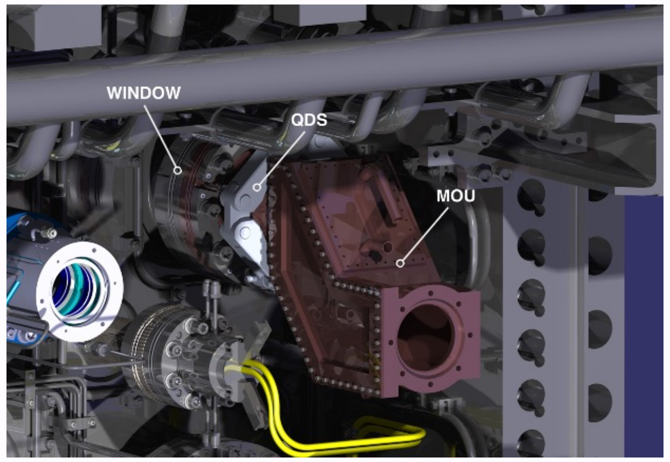
Group Leader: Bruno Soares Gonçalves

Contributions to ITER construction

DESIGN OF THE ITER COLLECTIVE THOMSON SCATTERING QUASI-OPTICAL LAUNCHER

The Collective Thomson Scattering (CTS) diagnostic is designed to measure the dynamics of fusion-born alpha particles in ITER's burning plasma by scattering a 60 GHz, 1 MW microwave beam off plasma fluctuations. The system includes a Matching Optics Unit (MOU) that aligns and maximizes the coupling between the ex-vessel transmission line and in-vessel optics.
This unit is critical for ensuring beam alignment and minimizing spill-over, and is designed to match the in-vessel optics. Space constraints near the vacuum window limit the MOU's dimensions, affecting mirror size and potentially overall performance. As a Protection Important Component , the MOU must maintain its safety role under all foreseeable conditions. With the CTS diagnostic operating during the DT phase, the MOU also needs to be easily removable to minimize radiation exposure to workers.

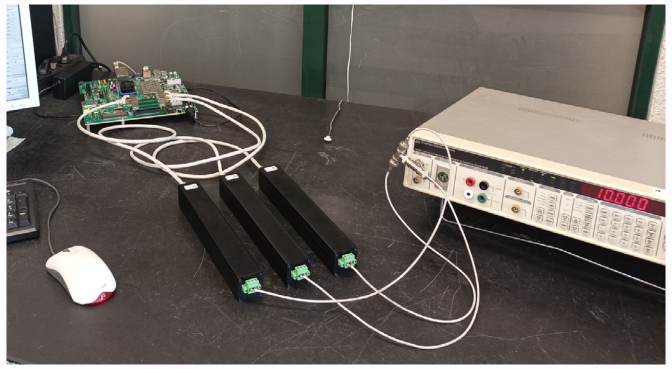
Collaborations between the CTS and ITER windows teams have led to design optimizations, such as incorporating the mirrors and cooling channels into the MOU's inner surface, now made from CuCrZr alloy. The window assembly was also compacted, and a Quick Disconnection System was introduced to simplify the MOU's attachment and removal. The design will soon undergo structural analyses to verify compliance with load requirements.



*CTS launcher's Matching Optics Unit (MOU), which contains a two-mirror setup that provides support, cooling, and maintains the vacuum boundary of the transmission line.
The Quick Disconnection System is also shown, facilitating the easy and rapid detachment of the MOU from the window.*

ITER INTEGRATOR MODULE PRODUCTION SAMPLES QUALIFICATION TESTING

The first assembled cubicles with electronics of the ITER magnetics diagnostic, of 17 to be delivered. In total, 1699 integrators will be installed in the 17 cubicles (and there are 340 spares that will be delivered separately). There are 24 integrator variants for different magnetics-sensor types.



ENOB test rig with the production samples being tested.

Production samples of the integrator module, developed previously by IPFN for tokamak ITER, were tested in 2022 by IPFN. The integrator modules have been manufactured by the company Alter Technology. The tests performed by IPFN to the integrator samples, for mass production qualification, were an ENOB test (Effective Number of Bits) and a galvanic isolation test. In the beginning of 2023 F4E conducted a test of an integrator production sample, at tokamak WEST, for assessment of the drift in a real tokamak environment. The tests on the integrated channel have shown compliance with the requirements with the integrated signal after each shot having achieved a drift below 50 uV*s/hour. The first assembled cubicles with electronics of the ITER magnetics diagnostic was already delivered to ITER with the integrator modules designed by IPFN.

NEUTRAL BEAM TEST FACILITY TOOLS FOR REMOTE COLLABORATION

At the heart of the ITER Neutral Beam Test Facility (NBTF) is the exploration of physics and technology challenges essential for implementing the neutral beam system on ITER. The facility allows for the validation of concepts where ITER's scale demands specialized expertise and collaborative efforts. The use of shared computing infrastructures and remote collaboration tools is vital, enabling the analysis of large datasets and global expert communication.

IPFN plays a major role in this collaboration, leading the design and development of operational tools using EPICS and MDSplus, alongside Grafana, Python, and nodeJS. These tools are crucial for remote participation, data visualization, and efficient operation, ensuring that scientists can conduct advanced fusion experiments and overcome the ambitious challenges posed by ITER.

ENGINEERING SUPPORT TO F4E (WITH LEONARDO)

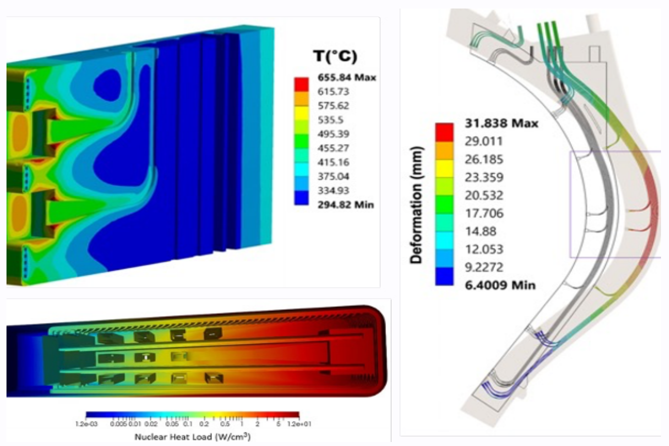
LIPAc, the Linear IFMIF Prototype Accelerator at the International Fusion Energy Research Center in Japan, is a collaborative project involving hundreds of European and Japanese experts. A significant challenge was enabling secure remote access to experimental data and QST resources for experts outside the installation. To address this, a Remote Access server was installed in F4E Barcelona, featuring high-performance machines and virtual machines (VMs) installed and maintained by IPFN. These VMs improved performance and user experience, allowing users to access LIPAc data and work in an environment similar to the LIPAc site. The success of this setup led QST to deploy their own remote access server, with IPFN assisting in testing and debugging.

In 2023, under an engineering support contract led by Leonardo, IPFN also played a key role in the installation and commissioning of a new vacuum interlock system for JT-60SA, an international fusion experiment in Naka, Japan. This system is crucial for maintaining vacuum quality in the tokamak chamber, ensuring the safety of the machine and diagnostics. IPFN developed a control system using EPICS, which included a graphical user interface for testing power supplies and began integrating the system into the JT-60SA database.

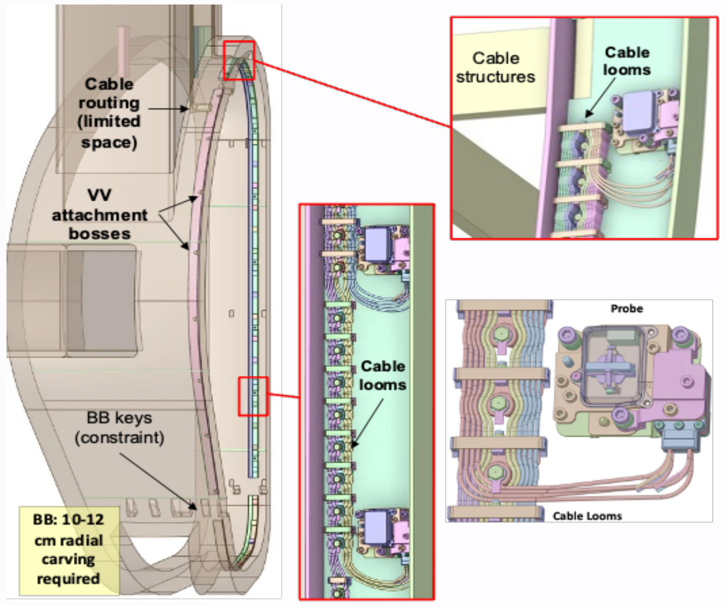
Contributions to DEMO Conceptual design activities

INTEGRATION STUDIES FOR DEMO DIAGNOSTICS

We continued the development of the Diagnostic Slim Cassette (DSC) concept for hosting reflectometry diagnostics in DEMO. Neutronics simulations and thermal analyses confirmed that with an optimized cooling system, the DSC meets the temperature requirements for DEMO materials. Structural analyses showed compliance with RCC-MR nuclear component standards, ensuring the DSC's integrity throughout the reactor's lifetime. Electromagnetic simulations indicated that while waveguide deformations have a minimal impact on measurements, adjustments are needed to account for thermo-mechanical loads, optimizing the final design. Additionally, we developed a concept for integrating magnetic sensors in DEMO using a removable structure attached behind the breeding blankets. A model of this "magnetics strip" was created, featuring space for sensors and cables, inspired by attachment methods from ITER. IPFN also designed remote handling procedures for the system, supported by CATIA simulations.



Waveguide deformation due to thermal loads - Due to the harsh radiation environment of DEMO, reflectometry waveguides will be subjected to radial deformation during operation. What is the impact on the measurements?

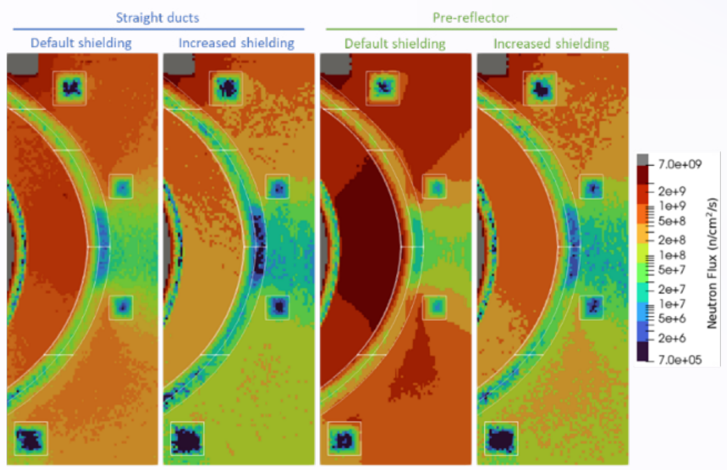


'Magnetics strip' - Will the magnetic sensors survive long-term neutron irradiation? An innovative concept has been proposed for the integration of magnetic sensors in DEMO, compatible with Remote Handling.

NEUTRONICS SIMULATIONS FOR DEMO DIAGNOSTICS

Neutronics simulations are vital for designing and optimizing nuclear components in fusion reactors and analyzing their performance in nuclear environments. IPFN has conducted simulations for all DEMO diagnostics, collaborating with European laboratories to analyze systems such as magnetic sensors, Faraday sensors, neutron and gamma cameras, and various spectroscopy systems.

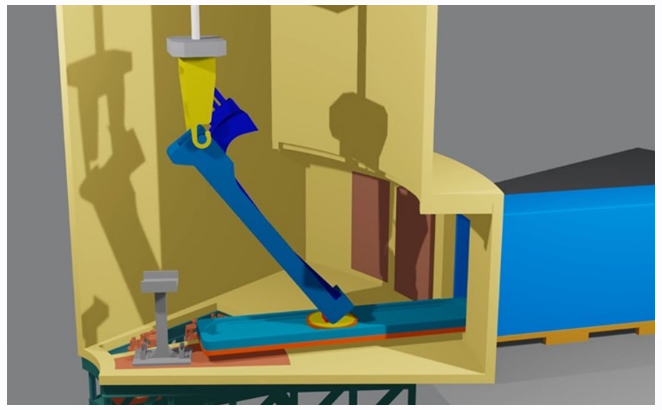
For equatorial port diagnostics, efforts have focused on reducing neutron and gamma streaming to protect the magnets and port cells, ensuring that diagnostic openings in the first wall do not exceed radiation limits. This work has helped develop critical competencies for future fusion devices.



Radiation loads in the magnets - Introducing diagnostics in the DEMO equatorial ports increases the fluxes in the toroidal and poloidal field coils. Different design and shielding configurations have been tested for the X-ray diagnostic, to ensure that the flux and load limits are not exceeded.

DESIGN CONCEPTS OF MANIPULATION STILLAGE DEVICES TO BREEDING BLANKET SEGMENTS IN DEMO

For maintenance and decommissioning in the DEMO reactor, ex-vessel transportation systems are essential for moving heavy loads to and from the active maintenance facility. The upper-level containment area is designed for interface operations between reactor component extraction and the transfer cask system. IPFN played a key role in developing design concepts for manipulation stillage devices to rotate and accommodate Breeding Blanket (BB) segments. The project also involved studying operation sequences, assessing requirements, risks, and evaluating equipment readiness. The image illustrates a concept in action, showing the handling and placement of a BB segment onto an extendable tongue from the cask.



Breeding Blanket Remote Maintenance concepts - from vertical extraction to horizontal accommodation in cask.

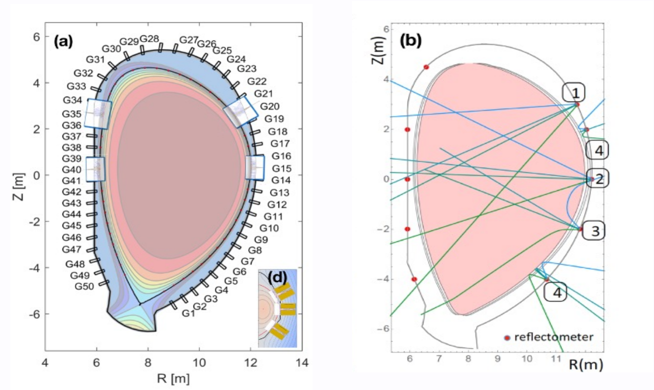
Diagnostics for fusion devices

REFLECTOMETRY PLASMA TRACKING FOR NEXT GENERATION MACHINES

IPFN is leading a EUROfusion Enabling Research Project to conceptualize a reflectometry system capable of providing control inputs during both the steady-state operation (flattop) and the initial discharge phase (ramp-up) for next-generation machines like DEMO. The project integrates various research areas, including simulation codes, synthetic diagnostics, new algorithms, synchronization between reflectometer systems, and hardware advancements. The goals are to track and monitor plasma position and shape during the start-up and ramp-down phases and to enhance steady-state operation for real-time plasma positioning, potentially replacing magnetic diagnostics.

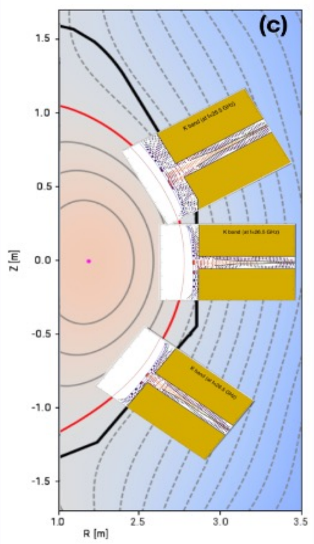
The proposed Plasma Position Reflectometry (PPR) concept for DEMO includes poloidally-distributed reflectometers, with the number of lines of sight (LOS) determined by limited waveguide accesses. The hardware will operate in different modes: a new setup for ramp-up involving interferometry, refractometry, and intensity refractometry, and standard PPR reflectometers for steady state. The project also involves deploying the REFMUL3 code, a 3D parallel simulation tool, which has been used to study DEMO's steady state. The next phase will focus on the ramp-up concept and identifying various operational scenarios.

Progress has also been made on DTT, with a comprehensive assessment of a Low Field Side Plasma Position Reflectometer (PPR) system using 2D and 3D simulations. The possibility of installing a PPR system on the High Field Side (HFS) at DTT is being explored, with significant effort directed towards antenna design and integration into the first wall, considering space constraints. Two antenna types are proposed: one for a bistatic system and another for a monostatic one.



(a) The DEMO PPR concept includes multiple reflectometry lines of sight (LOS) distributed poloidally around the machine. (d) Compares the dimensions of the DTT vessel with those of DEMO.

(b) A new diagnostic approach is being developed for the ramp-up phase, where the PPR hardware will function as an interferometer (1), refractometer (2), intensity refractometer (3), or in standard reflectometer mode (4).

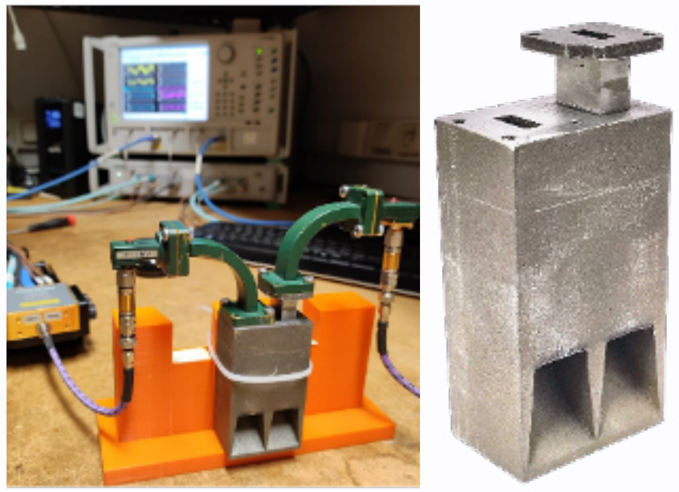


(c) Low Field Side (LFS) PPR synthetic diagnostics probing a DTT SN plasma.

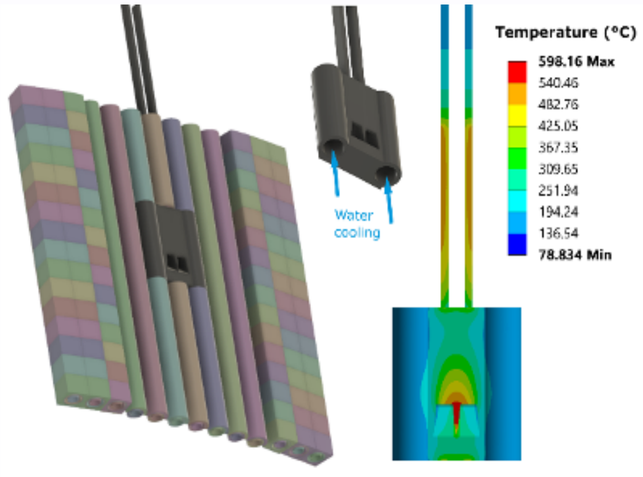
HIGH-FREQUENCY SIDE PLASMA POSITION REFLECTOMETRY (PPR) ANTENNAS FOR DTT TOKAMAK

The design of High Field Side (HFS) Plasma Position Reflectometry (PPR) antennas for the DTT tokamak offers a valuable test ground for validating advanced diagnostic design workflows in fusion devices. Leveraging IPFN's expertise, this integrated approach includes full-wave simulations in plasmas, along with structural, thermal, and neutronic analyses. The design presents unique challenges due to limited space within the tokamak's inner vessel and the evolving first wall design. Two antenna designs were proposed to meet critical requirements: operating across a wide frequency range (18-110 GHz), maintaining a small footprint, and ensuring 1 cm accuracy in separatrix localization. Hog-horn antennas with flat mirrors were selected for their ability to meet these demands.

The REFMUL3 code was instrumental in validating the microwave diagnostics, enabling realistic simulations of wave interactions with the system and plasma. To validate the bistatic antenna design and REFMUL3 simulations, a 3D-printed prototype underwent laboratory testing, showing excellent agreement between measured and simulated results. However, thermal analysis revealed that the current antenna design would exceed safety temperature limits under irradiation, highlighting the need for an improved cooling system. Future work will focus on refining the antenna design, considering non-equatorial placements and varying magnetic configurations.



Installed in the microwave laboratory for performance analysis (centre). DMSL printed bistatic antenna prototype (left).



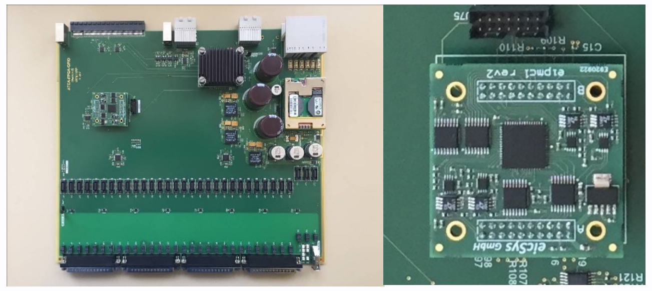
Laboratory measurements showed excellent agreement with REFMUL3 simulations, validating the accuracy of the code. (Right) thermal analysis of a cooled bistatic antenna block embedded in the current FW standard module configuration during continued DTT operation.

Control and Data Acquisition

DATA ACQUISITION FOR W7-X MAGNETIC DIAGNOSTICS

A joint collaboration between IST and IPP resulted in a new data acquisition system for the W7-X magnetic diagnostics, enhancing the hardware of a previous IPFN-developed board. The redesign, driven by the obsolescence of some components, features an upgraded FPGA (Kintex 7), allowing several operational improvements for W7-X. Key enhancements include extending data processing and diamagnetic energy interlock computation from 8 to 32 input channels, incorporating an algorithm to transmit additional scientific data alongside raw ADC data, and improving data streaming to the CODAC system, minimizing the risk of data loss. The new system also features an upgraded Intelligent Platform Management Controller (IPMC) with better power management, timing, and HOT-PLUG functionality.

The new hardware was successfully commissioned during the W7-X Stellarator OP2.1 campaign. With the design approved, a new batch of boards will be produced to replace the existing ATCA acquisition boards, offering significantly improved performance.



(Left) ATCA-MIMO-ISOL-V2 data acquisition and processing board developed for W7-X Stellarator CODAC; (right) the IPMC module installed on the ATCA ATCA-MIMO-ISOL-V2.

ESTHER CODAC

The ESTHER shock tube is designed to achieve post-shock gas temperatures and shock speeds up to 14 km/s in air and 18 km/s in H2/He, with very short test times before interference waves arrive. The main diagnostic tool is a streak camera for spectroscopic measurements of plasma radiation, requiring a precise trigger system. IST-IPFN developed the streak camera trigger system using four sensors, a Kintex K7 FPGA, and a fast ADC converter. The system features digital trigger generation with 8 ns resolution, configurable thresholds, and variable delays. It supports both piezoelectric gauge sensors and optical fibers with amplified photodetectors, starting with the optical type.

The control system, developed for the ESTHER team, is based on EPICS and CS-Studio, with Linux-based EPICS I/O controllers and Siemens S7-1200 PLCs, ensuring safety and reliability in potentially explosive atmospheres.

Some of the control system panels in the Operator Console of ESTHER . The whole control system uses an architecture that follows the general trend in big experimental devices and capitalizes in the experience developing control systems for ITER.

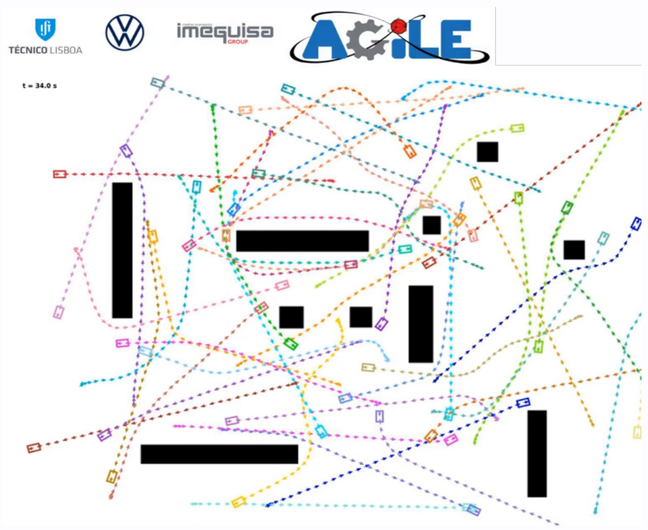
Initially implemented for the combustion chamber gas subsystem, the control system successfully operated in two campaigns with both small and full-sized combustion chambers.

During the commissioning of the ESTHER Shock Tube, the control system was expanded to manage all vacuum systems, incorporating a new cubicle, state machine, Siemens PLC, and instrumentation interfaces. Data exchange was upgraded to the OPC UA standard, aligning with trends in large experimental devices like ITER.

Remote handling and robotics

PROJECT AGILE SUCCESSFULLY CONCLUDED

Project AGILE, co-promoted by Imeguisa Portugal, Volkswagen Autoeuropa, and IST (represented bY ISR and IPFN), focused on automating intra-logistic flows in factories using a fleet of autonomous mobile robots. The project aimed to enhance resilience, optimization, and efficiency in real-time supply of assembly lines. Advanced trajectory optimization algorithms, developed from IPFN's work on the ITER project, were crucial in optimizing robot paths. Additionally, studies of navigation technologies in nuclear fusion plants, such as ITER and DEMO, played a key role in obstacle detection, avoidance, and real-time fleet location in complex environments.



The path planning algorithm is designed for transportation trolleys in dense and confined scenarios, including maintenance operations in nuclear facilities. It is particularly suited for transportation missions between reactor and hot cell buildings.

Experimental Physics

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Main funding sources:

Fundação para a Ciência e Tecnologia;

EUROfusion Consortium;

Summary of Research

We are responsible for the operation and scientific exploitation of the Portuguese tokamak – ISTTOK – and for collaborating with other fusion devices such as ITER, JET, ASDEX Upgrade, TJ-II, TCV, W7-X, and COMPASS.

GEP encompasses a diverse range of research activities, including fusion device engineering and operation, diagnostics development and interpretation, plasma modelling, data analysis and validation, numerical code development, and artificial intelligence.

For instance, ISTTOK often serves as a first-time fusion test device for new concepts due to its simplicity and reduced lead-time. Currently, ISTTOK is the only AC-current tokamak, extending the operational time from a few milliseconds, typical of similar devices, to several seconds. This allows for the development and testing of new diagnostics and systems relevant to larger fusion devices.

Our main goal is to provide the necessary know-how and tools to the community for the safe operation of fusion reactors in the near future. To achieve this, we continuously track advanced, high-end technologies across various fields of research and industry, adapting and integrating them into our community.

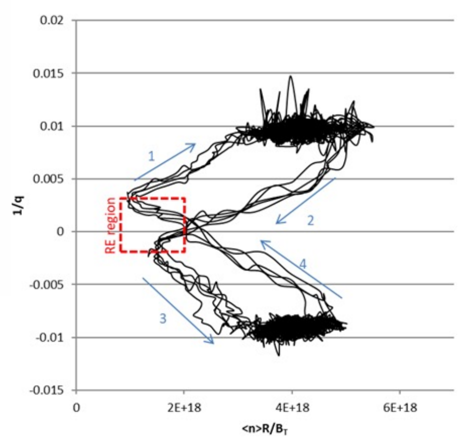
We also offer advanced education to a significant number of MSc and PhD students under our team's supervision and host students through Erasmus+ and Fusenet internships.

Group Leader: Horácio Fernandes; Deputy Leader: Carlos Silva

ISTTOK

ISTTOK ALTERNATING CURRENT OPERATION

The alternating current (AC) operation is characterised by the fast reversal of the plasma current. The plasma density maintains a steady mean value across several AC cycles except at the current transition, where it shows a residual value of about 15% of the nominal value. Understanding this quiescent plasma is fundamental to the success of AC operation. Based on the experimental observations, it has been proposed for the first time that the quiescent plasma is mostly supported by the presence of ballistic runaway electrons. The investigations are progressing in collaboration with the Australian National University for the development of numerical tools that can demonstrate the interplay between equilibria and runaway electron confinement during the current transition.



Murakami-Hugill characteristics of ISTTOK alternating discharges revealing runaway populations contributions for the plasma current (elbows in points A and B).

DIAGNOSTIC DEVELOPMENTS

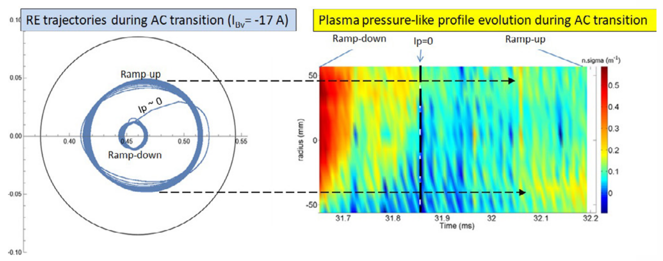
ISTTOK has expanded its diagnostic capabilities with several key upgrades:

a) Carbon Line Emission Diagnostic: This system measures ion temperatures by collecting carbon impurity emission spectra from 10 radial positions with a time resolution of up to 5 ms.

b) Retarding Field Analyzer (RFA): A novel RFA configuration was developed to address the issue of secondary electron emission (SEE), improving ion temperature fluctuation measurements. The new setup, tested successfully in ISTTOK, directly correlates backward ion current with the velocity distribution function of analyzed ions.

c) Heavy Ion Beam Diagnostic (HIBD): Using a Xe+ ion beam, this diagnostic provides 1D pressure-like profiles of the plasma. It has been crucial in determining plasma current profiles in run-away discharges and correlating increased plasma pressure with runaway beam extinction.

d) Electron Beam Line: A new electron beam line (up to 5 kV) was developed to test detector components for HIBD, enhancing detector designs by comparing experimental results with numerical simulations.



PLASMA FACING COMPONENTS TECHNOLOGY

ISTTOK is developing a liquid Gallium-based plasma facing technology aimed at continuously replenishing the elements that define the plasma boundary. A hybrid system with a free-flow channel covered by a Capillary Porous System (CPS) component has been developed to overcome the challenges posed by MHD effects on liquid metals. In ISTTOK's setup, gallium flows in a closed circuit driven by gravity, with a custom-designed MHD pump returning the liquid to the high-level tank. The system will undergo extensive testing in an external chamber for electrical insulation, thermal and flow dynamics, and vacuum compatibility before commissioning on ISTTOK. Testing is planned to start in 2024.

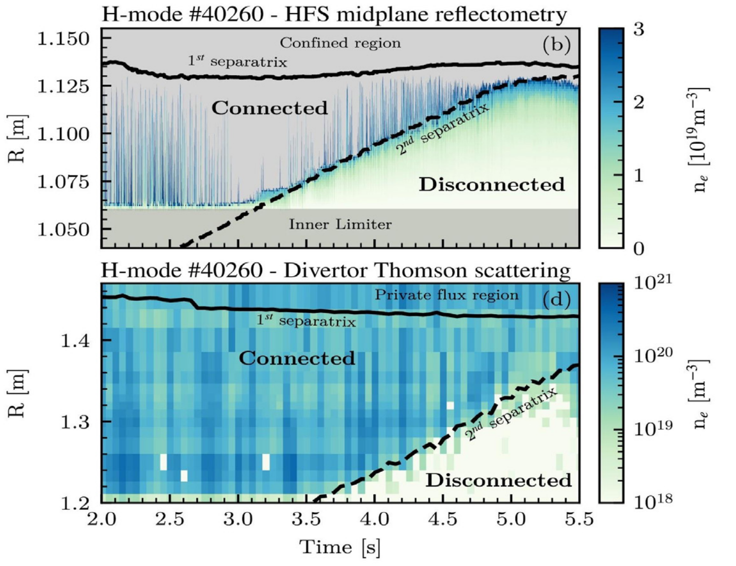
Liquid Gallium test facility.

Tokamak ISTTOK.

Contributions to the Tokamak Exploitation program

INFLUENCE OF MAGNETIC CONFIGURATION ON THE HIGH-FIELD SIDE SCRAPE-OFF LAYER AT ASDEX UPGRADE

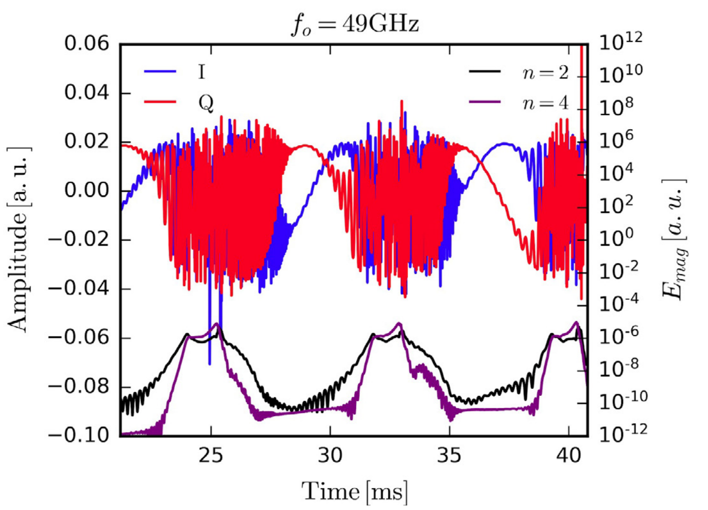
This study explores how magnetic configuration affects the high-field side (HFS) scrape-off layer in tokamaks, where radial transport is typically enhanced at the low-field side (LFS). Experiments conducted in L-mode and H-mode discharges at ASDEX Upgrade involved scanning the magnetic configuration from lower to upper single-null shapes, affecting the secondary separatrix location. The results show that the secondary separatrix determines the HFS scrape-off layer width, with lower density observed outside this separatrix. Additionally, the high density often seen in the HFS divertor decreases significantly when the separation between primary and secondary separatrices falls below a critical value, which varies between L-mode and H-mode plasmas. The study also finds that the HFS scrape-off layer density is lower in an upper single-null configuration than in a lower one, likely due to the reversal of E×B drifts. These findings offer valuable experimental data to enhance modeling and understanding of scrape-off layer physics in highly shaped plasmas.



HFS SOL density contour as a function of time and major radius at the HFS midplane using O-mode reflectometry and at the divertor using Thomson scattering from anH-mode shape scan.

SYNTHETIC MEASUREMENTS WITH MICROWAVE REFLECTOMETRY

Microwave reflectometry diagnostics rely heavily on numerical modeling to optimize instrument design and interpret plasma fluctuations. IPFN has developed a robust framework for synthetic reflectometry diagnostics using the REFMUL suite of full-wave codes. This framework, enhanced by integrating 2D REFMUL with advanced 3D plasma physics models, has been successfully used to study edge plasma turbulence and Edge Localized Modes (ELMs), particularly type-I ELMs, using the JOREK MHD code. In simulations mimicking ASDEX-Upgrade discharges, the framework effectively tracked the entire ELM cycle, including critical precursor mechanisms. Recent progress in developing the 3D REFMUL code, supported by increasing computational power, is paving the way for new research into turbulence and MHD studies.



3D simulation of Type-I ELM cycle with JOREK code and corresponding 2D synthetic reflectometry measurements with REFMUL code.

EFFECT OF THE DIVERTOR CONFIGURATION ON THE JET EDGE RADIAL ELECTRIC FIELD

The role of the divertor configuration and divertor plasma physics on the L–H transition is poorly understood, leading to large uncertainties in predicting the L–H power threshold in future devices. Edge perpendicular plasma flow measurements were performed by Doppler backscattering in JET L–H transition experiments with the outer divertor strike-point at different positions: horizontal target (HT), vertical target (VT), and in the corner configuration. The edge perpendicular flow was found to be significantly affected by changes in the divertor configuration in the region inside the separatrix.

Our results do not show evidence for the existence of a critical edge flow shear needed to achieve H-mode for different divertor configurations, with a larger shear observed for the VT configuration. No significant change in the shear flow or in the density fluctuation level was measured preceding the L–H transition in the region just inside the separatrix. The dynamics of the L–H transitions are also influenced by the divertor configuration, with divertor oscillations observed only in the HT configuration. Interestingly, divertor oscillations are associated with marked changes in the edge perpendicular flow around the separatrix.

EDA H-MODE IN ASDEX UPGRADE AND JET

The EDA H-mode allows the operation of fusion devices without edge-localized modes (ELMs), which lead to unacceptable heat loads to the divertor when extrapolated to large-scale reactors. A comprehensive set of experiments was conducted in ASDEX Upgrade to improve and better understand this no-ELM regime.

Researchers Luís Gil (IPFN), Michael Faitsch (Max Planck Institute for Plasma Physics), and Carlos Silva (IPFN) in the JET control room for EDA H-mode experiments;

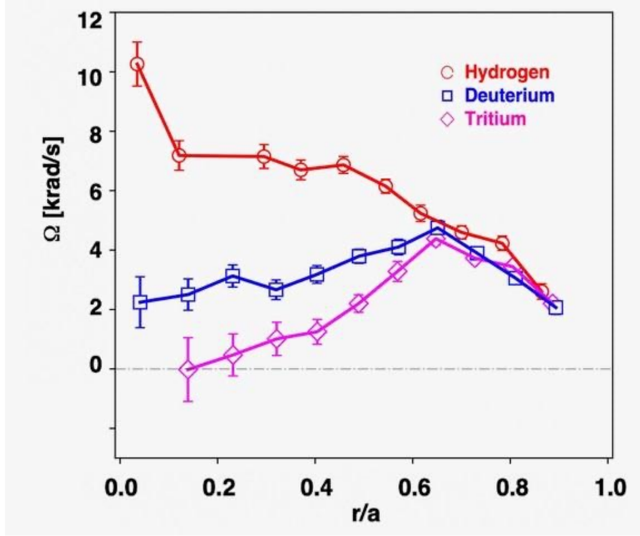
It can now be routinely obtained over a range of plasma current, magnetic field, fueling, impurity seeding, heating power, heating method, and main ion species. Furthermore, the EDA H-mode was achieved in the Joint European Torus with the beryllium-tungsten wall for the first time, extending the plasma parameters, size and number of devices that can demonstrate it. Significant advances have been made both in the experimental development and characterization of EDA plasmas and their main signature, the quasi-coherent mode, as well as in numerical simulations and theoretical interpretation. The wide operational space and numerous qualities of the EDA H-mode place it as a promising no-ELM regime for future reactors.

DISRUPTION AND RUNAWAY ELECTRON STUDIES IN EUROPEAN TOKAMAKS

The generation of runaway electrons (RE) during major disruptions in ITER poses significant risks. The Disruption Mitigation System (DMS) in ITER, which relies on massive injection of impurities through gaseous (MGI) or solid-state pellets (SPI), aims to mitigate these risks by dissipating plasma energy and suppressing RE formation. Despite progress, challenges remain in understanding the mixing and assimilation of injected impurities, the physics of RE, and their interaction with plasma and injected gases. A comprehensive analysis of the RE database from JET, WEST, TCV, and AUG tokamaks has advanced our understanding of RE behavior during disruptions. The study revealed links between pre- and post-disruption parameters, despite the challenges in measuring plasma parameters during disruptions. By comparing experimental data with known RE generation models, researchers identified how initial plasma configurations and the Disruption Mitigation Valve (DMV) positioning influence disruption dynamics and RE parameters. A key finding was the identification of a lower threshold for RE generation and a decreasing trend in the RE current conversion ratio as current quench (CQ) rates increase.

INTRINSIC ROTATION IN JET

Recent JET experiments explored the impact of hydrogen isotope mass on transport and confinement, crucial for reliable ITER predictions. In 2022-23, studies on momentum transport and confinement in Ohmic plasmas provided the first measurements of main ion toroidal intrinsic rotation in Tritium plasmas and examined isotope mass effects in Hydrogen, Deuterium, and Tritium plasmas. Density scans revealed the first clear observation of rotation reversals in a large tokamak, with two core plasma rotation reversals observed for each isotope. The first reversal occurs near the transition from electron to ion turbulence, while the second is isotope-dependent, with counter-current rotation increasing with ion mass during the Saturated Ohmic Confinement (SOC) phase. These findings also correlate stronger thermal energy confinement with Tritium.



H, D and T toroidal angular frequency profiles with the same density <Ne> ~ 2.35×10^{19} m^{-3}, for plasmas with Ip = 2.3 MA, BT = 2.7 T.

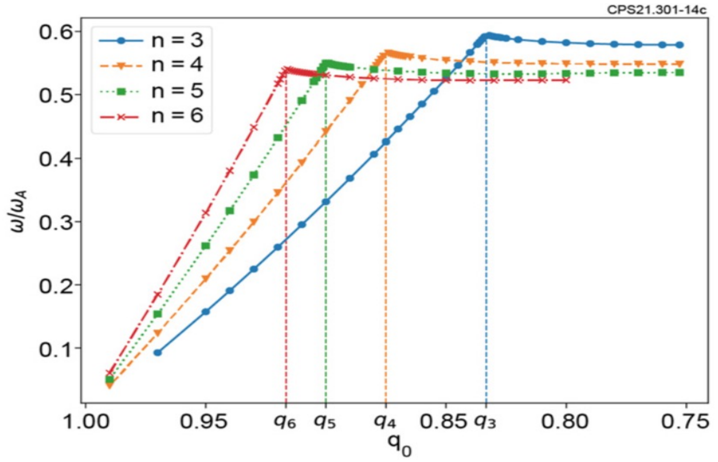
HIGH TEMPORAL RESOLUTION OF PEDESTAL DYNAMICS VIA MACHINE LEARNING ON DENSITY DIAGNOSTICS

At JET, the reference diagnostic to measure electron density is Thomson scattering. However, this diagnostic has a low sampling rate, which makes it impractical to study the temporal dynamics of fast processes, such as edge localized modes. In this work, we used machine learning to predict the density profile based on data from another diagnostic, namely reflectometry. By learning to transform reflectometry data into Thomson scattering profiles, the model was able to generate the density profile at a much higher sampling rate than Thomson scattering, and more accurately than reflectometry alone. This enables the study of pedestal dynamics, by analyzing the time evolution of the pedestal height, width, position and gradient. We also investigated the accuracy of the model when applied on experimental campaigns that are different from the ones it was trained on, particularly the transfer from DD to DT and TT.

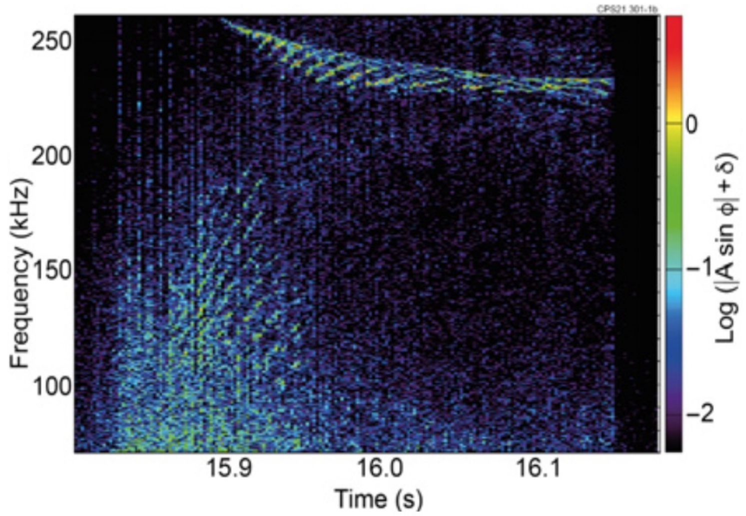
Energetic particle physics

MODELLING COUPLED ALFVEN CASCADES AND TORNADO MODES IN JET

Alfvén Cascades are a known type of MHD activity in plasmas with a non-monotonic safety factor (q) profile, typically showing upwards frequency sweeping. However, in some JET plasmas with flat q profiles, a coupling between ACs and Toroidicity Alfvén Eigenmodes (TAEs), known as tornado modes, has been observed. These TAEs, located near the magnetic axis, exhibit downwards frequency sweeping. MHD simulations were conducted to locate these eigenmodes and reproduce their frequency evolution by rescaling the q profile to mimic its decrease after a sawtooth crash.



Simulated evolution of the frequency with the on-axis safety factor value q0 for the toroidal mode numbers n = 3, 4, 5, and 6.



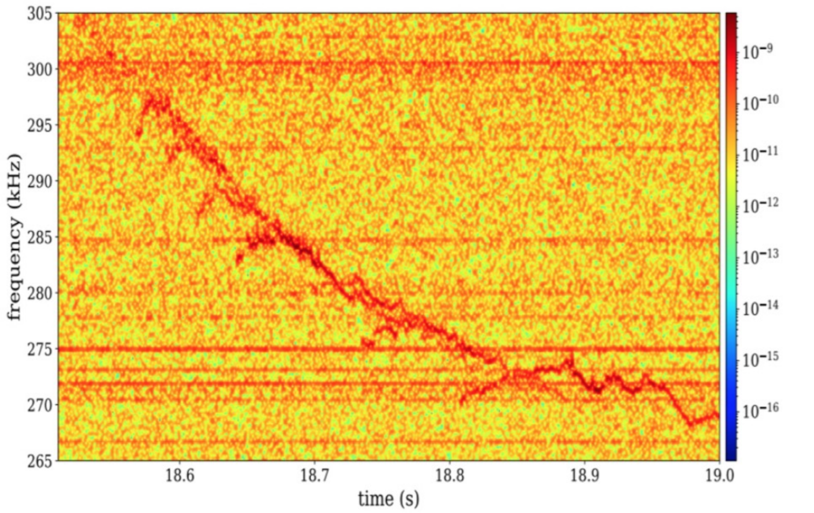
Spectrogram of density perturbations from O-mode interferometry on JET discharge #66203, with tornado modes visible around 225-250 kHz while AC sweep the frequency range 100-225 kHz.

It was found that as q decreases, cascade modes sweep upwards in frequency until they transition to tornado modes when the q value at the magnetic axis crosses (n − 1/2)/n, where n is the toroidal mode number. This transition provides a basis for a novel MHD spectroscopy technique to track the time evolution of q at the magnetic axis. Observing tornado mode transitions in magnetic diagnostics allows for the determination of the safety factor value at the magnetic axis, making MHD spectroscopy a valuable tool for modeling and data analysis in tokamak experiments.

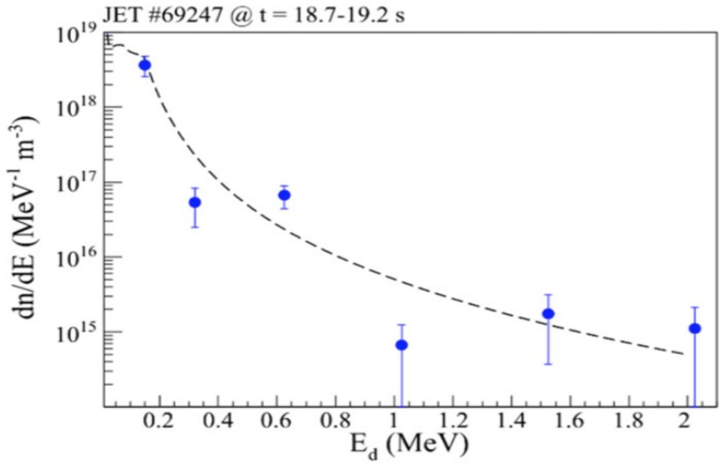
INTERPRETING ENERGETIC-ION REDISTRIBUTION MEASUREMENTS IN JET

A series of experiments was performed in the JET tokamak in order to study the characteristics and eventual effects of further accelerating a beam-injected ion population via 2nd harmonic ion-cyclotron heating. It was found that the presence of such accelerated ions could not only affect sawtooth stability but also drive unstable TAEs in the core of the plasma (figure W, top). More interestingly, measurements obtained by the TOFOR spectrometer of the neutrons produced in Deuterium-Deuterium (D-D) collisions, i.e. between beam-accelerated and plasma ions, show evidence that these modes caused local bump-on-tail distributions in energy.

Indeed, measurements at particular energies (near 0.4MeV and 1MeV) show a clear deficit of energetic ions when compared with model predictions obtained by the heating code PION, which does not take MHD activity into account (figure W, bottom). Numerical simulations performed with the linear hybrid MHD/drift-kinetic code CASTOR-K successfully explained a strong resonant interaction between the core-localized TAEs identified previously and accelerated ions with energies matching the measured local minima in the energy distribution. Mechanisms leading to the existence of bump-on-tail distributions are of great importance in energetic particle physics as they may cause the further excitation of a variety of MHD modes through the produced gradient in energy.



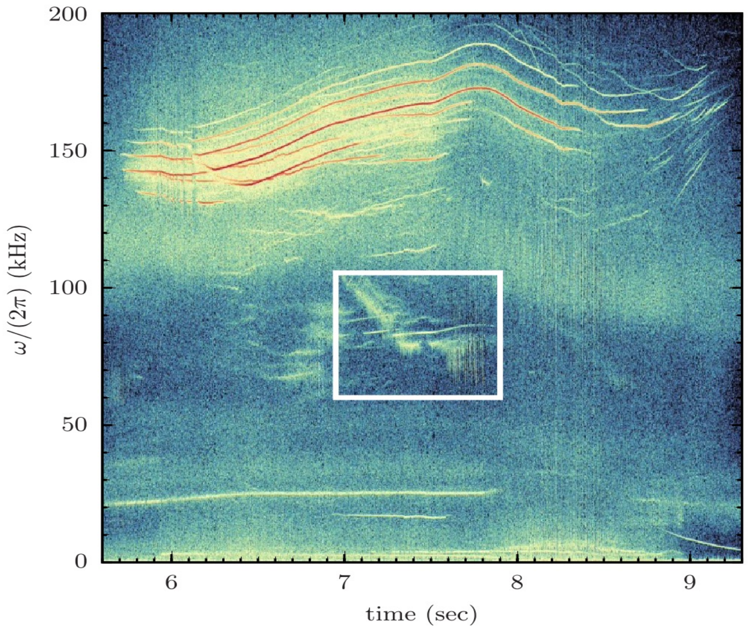
Spectrogram of MHD activity from interferometry diagnostic in the TAE range of frequencies for JET pulse #69247.



Distribution in energy of the energetic D population as deduced from the spectrum of D-D produced neutrons measured by TOFOR in pulse #69247 (blue dots) compared to prediction from PION code (black dashed line, bottom).

UNDERSTANDING SHEAR-ACOUSTIC MHD ACTIVITY OBSERVED IN JET

A recent model coupling shear-Alfvén and acoustic continua, which is highly dependent on plasma shaping and elongation, was used to explain Alfvénic activity observed in JET plasmas at frequencies slightly below those of typical Toroidicity Alfvén Eigenmodes (TAEs). The model predicts frequency gaps resulting from high-order harmonics of geodesic field-line curvature due to plasma shaping, leading to the identification of high-order geodesic acoustic eigenmodes (HOGAEs). These modes were found to have frequencies around half that of TAEs. Theoretical predictions of HOGAE frequency and radial location were in good agreement with experimental data from various JET diagnostics, including magnetic, reflectometry, and soft x-ray systems. Stability analyses using the CASTOR-K code showed that HOGAEs were destabilized by energetic ions from neutral beam injection and ion cyclotron resonance heating, particularly ions around 340 keV. The validated shear-acoustic coupling model could significantly impact predictions of Alfvénic activity in future experiments like JT60-SA and ITER, where plasma beta is much higher than in JET.

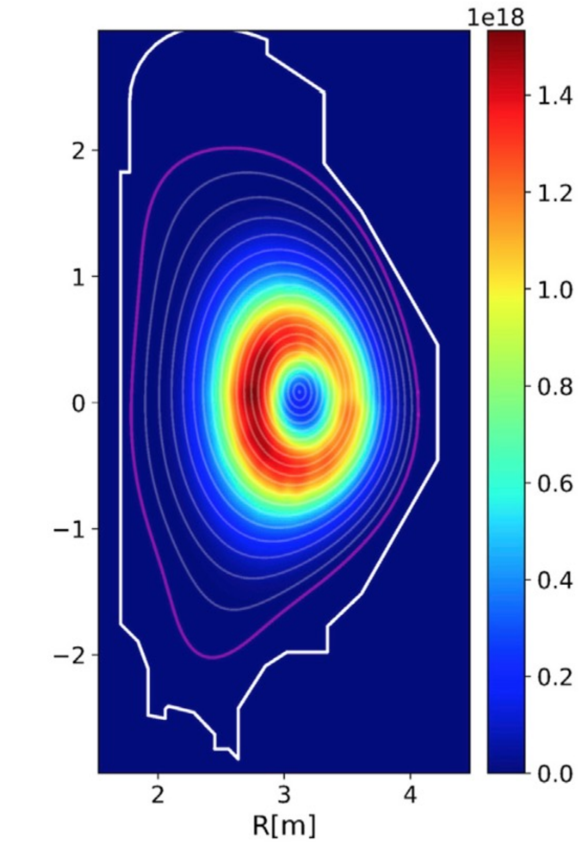


Magnetic-coil power spectra for JET pulse #90199: ICRH-driven Alfvénic activity, with TAEs around 150 kHz and lower frequency AEs in the range between 60 and 100 kHz (inside the white box), evidencing the bursty frequency bands surrounding sharp frequency lines.

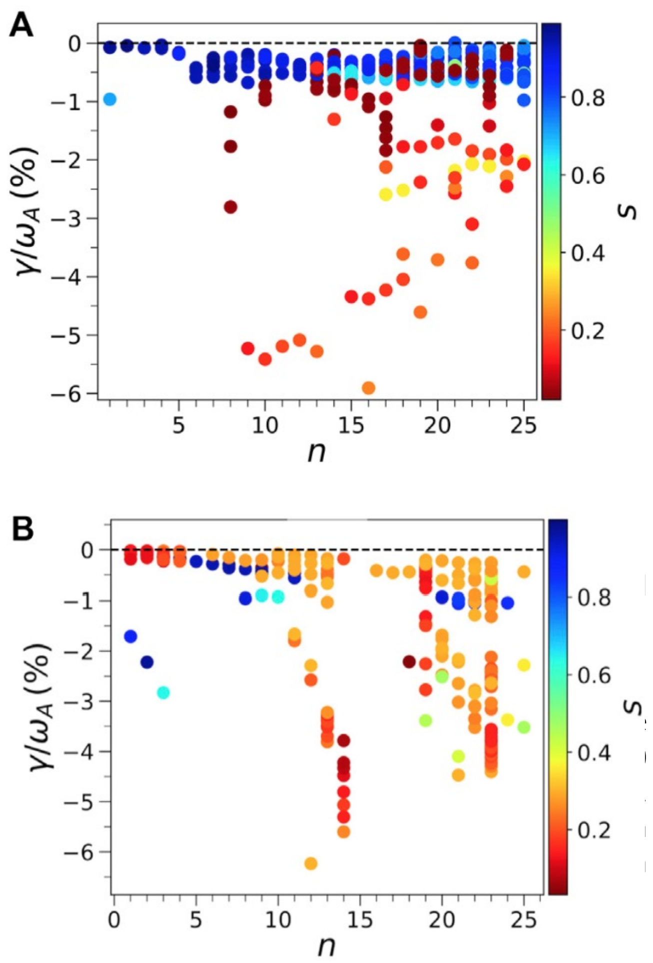
PREDICTING THE ALFVENIC ACTIVITY EXPECTED FOR THE JT60-SA TOKAMAK

As JT60-SA nears its scientific operation, stability analyses of two key scenarios—an inductive scenario with 5.48MA toroidal plasma current and high density, and an advanced scenario with an ion energy transport barrier (ITB) and 3.5MA plasma current—were conducted. The workflow involved using the CRONOS code for scenario establishment, the ASCOT code for calculating energetic particle distributions from the neutral beam, and the MISHKA/CASTOR-K suite for assessing Alfvén eigenmodes (AEs) and their drive/damping contributions.

The analysis revealed that while the supra-Alfvénic particles from the negative ion source neutral beam (500 keV) could drive AEs in both scenarios, this drive was insufficient to overcome thermal ion Landau damping. Consequently, all predicted AEs were stable, indicating favorable conditions for sustaining plasma performance and the ITB during JT60-SA operation.



Spatial distribution of energetic particles from the negative beam source as calculated by ASCOT.

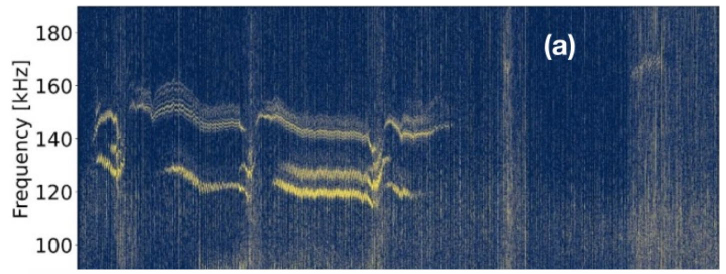


Normalized growth rate of the AEs with toroidal mode numbers n=1-25 for the two scenarios considered, colored by their radial location.

EXPLAINING CURRENT-DRIVE EFFECTS ON ALFVEN EIGENMODES IN ASDEX-UPGRADE

The effect of Electron Cyclotron Current Drive (ECCD) on Toroidicity Alfvén Eigenmodes (TAEs) in ASDEX-Upgrade was studied numerically. Plasma profiles were modeled using the European Transport Solver (ETS), with TAE excitation by ion cyclotron resonance heating-accelerated H-minority ions assessed via the PION code. TAE drive and damping were analyzed using CASTOR and CASTOR-K codes.

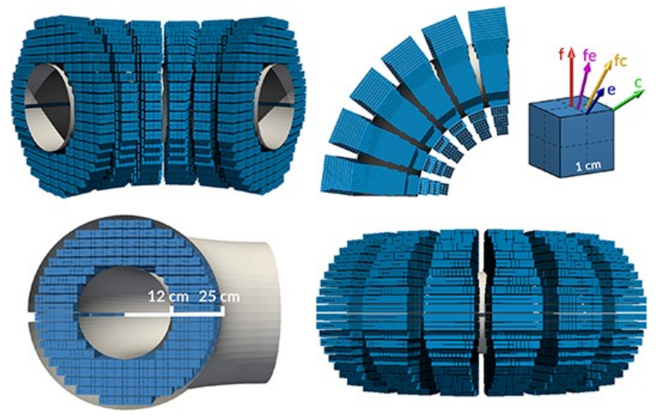
Experiments revealed two TAE groups differing in frequency and location when no ECCD was applied. Counter-ECCD suppressed higher-frequency modes (~150 kHz) while amplifying lower-frequency ones (~125 kHz). Co-ECCD had the opposite effect, suppressing lower-frequency modes. Numerical analyses showed that neither energetic particle drive nor thermal plasma damping alone could account for these observations. The experimental results were best explained by considering the combined effects of drive, radiative damping, and continuum damping.



Spectrograms in the TAE range of frequencies corresponding to ASDEX-UPGRADE discharge #38012 (no ECCD).

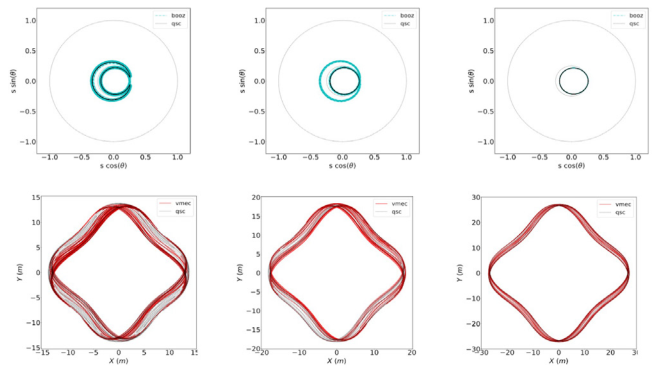
Stellarator design

The group has played a key role in the recent global stellarator optimization efforts, supported by an Enabling Research grant (~100 kEur) and an FCT researcher grant, as part of the Hidden Symmetries Collaboration funded by the Simons Foundation. This research focused on optimizing stellarators for alpha particle confinement, and several Master's students contributed by designing new configurations, including converting tokamaks into stellarators using permanent magnets, and applying analytical magnetic fields to understand alpha particle dynamics. The permanent magnets project resulted in a publication [1] showcasing the conversion of tokamaks into quasisymmetric stellarators using SIMSOPT for magnetic field optimization.



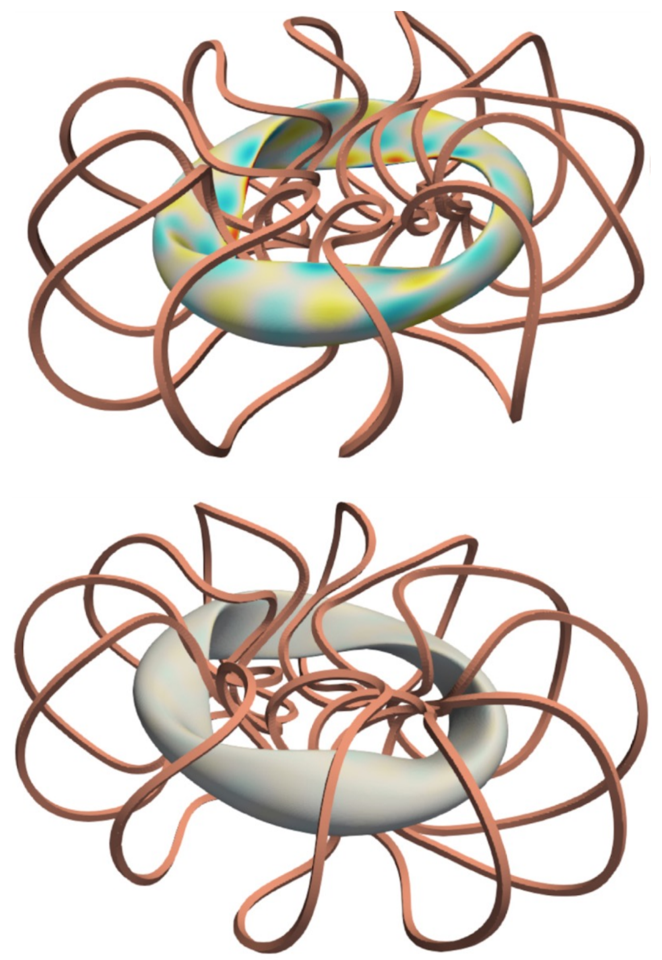
Design of ISTELL - a non-axisymmetric version of ISTTOK using permanent magnets [1].

The particle dynamics project led to a publication [2] demonstrating that near-axis expansion can model energetic particle trajectories in quasisymmetric stellarators much faster than traditional methods, applicable to both trapped and passing particles. Additionally, the group developed a new method to optimize both stellarator coils and the magnetic plasma surface simultaneously, resulting in more precise quasisymmetric configurations, enabling a reduction in coil complexity and a better reproduction of target fields [3].



Orbits of fast particles in quasi-helically symmetric stellarators [2].

The group was involved in the stellarator optimization effort that has re-started in the worldwide fusion community in the last five years thanks to the Hidden Symmetries Collaboration funded by the Simons Foundation. Here, we explored the synergy between the energetic particle physics effort at GFE and the need to optimize stellarators for good alpha particle confinement. During this time, the group hosted several Master's students who: designed new configurations, namely the conversion of tokamaks into stellarators using permanent magnets; and the use of analytical magnetic fields to gain new insights into the physics of alpha particle dynamics in stellarators.



The simplification of coils of a 3 field period quasi-axisymmetric device with a lower coil ripple [3].

References:

1. M. Madeira and R. Jorge, Plasma Phys. Control. Fusion 66, 085008 (2024).
2. P. A. Figueiredo et al., J. Plasma Phys 90, 905900207 (2024).
3. R Jorge et al, Plasma Phys. Control. Fusion 65, 074003 (2023).

Materials Characterisation and Processing

Main Researchers:

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Main funding sources:

EUROfusion Consortium;
Fundação para a Ciência e Tecnologia;
IAEA projects;
H2020 Infrastructures (RADIATE);
Contracts/services;

Summary of Research

Plasma-wall interaction control and development of advanced materials are among the research priorities to reach the ultimate goal to build a fusion reactor. Processes like fuel retention and material transport and deposition are key factors on fusion reactor technology and have been intensely studied during the last decades. During the reporting period we focused our activities on the study of reference tiles retrieved from JET to get information on aging effects of fuel retention and promote an intercomparison exercise of different techniques to quantify hydrogen isotopes in fusion reactors. We prove the long term stability of fuel retention in the reactor tiles. In addition the low level of fuel and dust production in metallic walls was confirmed, a crucial result for future designs of reactors.

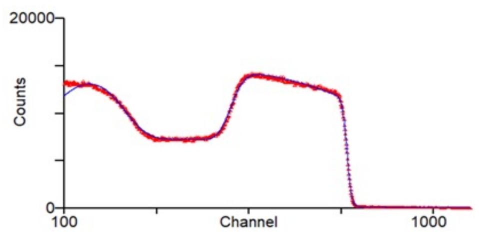
Another important topic concerning the construction of fusion reactors is the availability of materials to operate in extreme conditions of radiation and temperature. With this in mind we expanded our studies of multifunctional thermal barrier components based on high entropy alloys. These barriers are crucial to accommodate thermal and mechanical mismatch between the plasma-facing materials and the heat sink.

Finally, we continue our participation within European Accelerator networks on the use of ion beam technologies (RADIATE and ReMade) and participate in projects using these techniques to model the properties of new materials with particular emphasis on wide bandgap semiconductors.

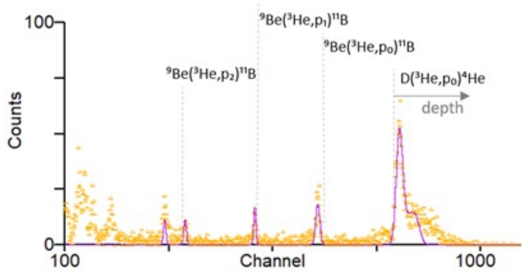
Group Leader: Eduardo Alves

Fuel retention studies in JET ITER-like wall

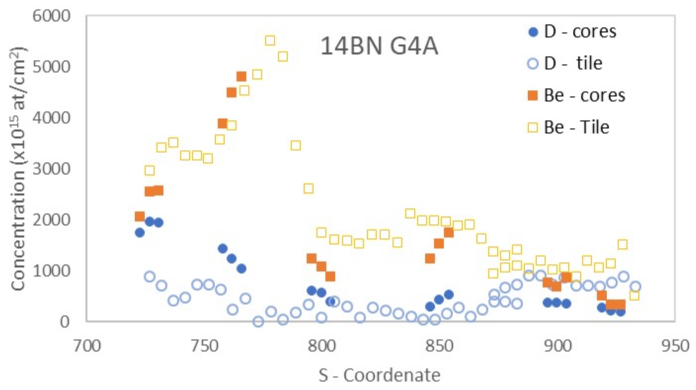
The work focuses on comparison of hydrogenic retention quantification by different techniques and fuel removal assessment. At JET main deposition occurs at the top part of the inner divertor, i.e. on tiles 0 and 1 with the highest fuel content. The scope of this task is the completion of the studies of divertor tiles exposed over an extended period (ILW1-ILW3) using various surface analysis techniques. The results will be used as input to predict the behaviour of JET deuterium tritium campaign and get information on fuel removal. In the first figure we show the data obtained from a reference tile of the divertor using ion beam analysis (IBA). After cutting the samples into cores, so that they could be processed using different techniques, the samples were measured by NRA, and the results of the deuterium retention compared with the measurements previously made on the tiles before cutting (see second figure). These values will serve as a reference for the other techniques like laser induced desorption.



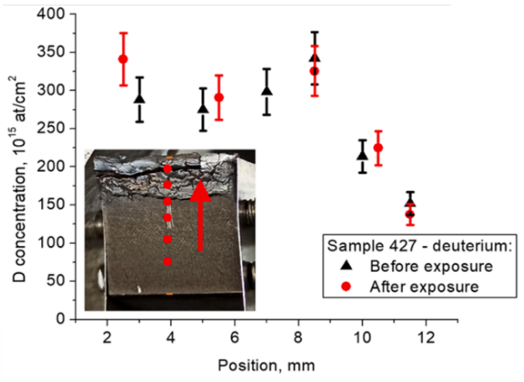
IBA spectra for tile 14BN G4A.
EBS Spectra of protons with 2300keV in Tile: 14BN G4A.



NRA Spectra of ^{3}He.



2300keV in Tile: 14BN G4A
Comparison of fuel retention on the cores and full tile.



Results of the IBA measurements across samples. Deuterium in Sample 427 (with melt damage and crack network).

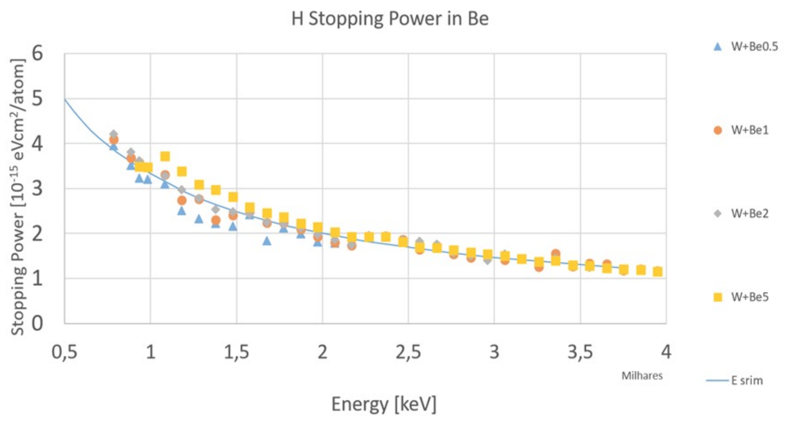
Impact of water ingress on oxidation and dust generation in beryllium plasma-facing components

The possibility of the water leaking into the vacuum vessel is a major safety concern for ITER and future fusion reactors. This work focuses on investigating the effects of hot water interaction with damaged beryllium plasma-facing components (PFCs) and co-deposited layers to assess the consequences of water in the tokamak vessel, particularly in the context of nuclear safety during reactor operation, such as in ITER.

Beryllium samples from the JET ITER-like wall limiter tiles were immersed in boiling water to simulate the impact of coolant water ingress into a tokamak (see figure, right). Rutherford backscattering (RBS) and nuclear reaction analysis (NRA) were performed to determine deuterium (D) and oxygen (O) concentrations in the samples. The results indicated that no thermomechanical damage, surface modification, enhanced beryllium oxidation, or dust generation occurred during the exposure. Additionally, there was negligible deuterium release into the water, suggesting limited tritium release from beryllium components during reactor operation. The findings provided positive insights for ITER operation, indicating that water ingress may not lead to significant permanent deterioration of beryllium components, potentially eliminating the need for their replacement.

Stopping power of hydrogen ions in beryllium in the range 0.5–2.35 MeV

Stopping power is a crucial quantity to analyse the results obtained with ion beam techniques. The precise knowledge of the stopping power determines the accuracy of the results measured on irradiation studies, retained number of ions and depth profile of impurities in different materials. The goal of this IAEA project is to obtain the stopping power values for various ions, as H and He, in typical materials used in fusion as Be and W, starting with H in Be. The values of the stopping power of H+ ions, with energy ranging from 600 keV to 4000 keV, in a Be substrate were measured (figure 1) and were included as part of a more extended set of stopping power data.

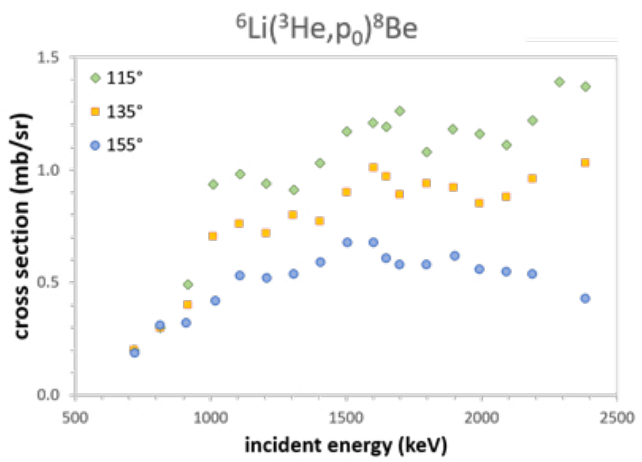


Stopping power of H ions in Be as function of incident energy.

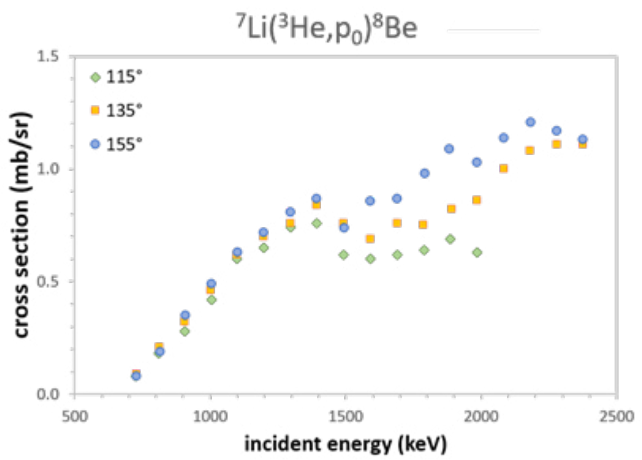
Nuclear reaction cross-sections of lithium with ^{3}He in the range 0.5–2.5 MeV

The determination of the excitation functions for nuclear reactions induced by ^{3}He in ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, ^{11}B, ^{12}C and ^{13}C was set as a IAEA project priority due to lack of data and poor agreement between already existing datasets. The present work is a contribution to the goals of the project through the measurements of the excitation functions of ^{6}Li(^{3}He,p$_0$)^{8}Be, ^{7}Li(^{3}He,pi)^{9}Be (i=0,2,3,4) and ^{7}Li(^{3}He,d$_0$)^{8}Be reactions. The spectra were acquired using two thin lithium films (one of ^{6}Li and another of ^{7}Li) in the energy range between 800 keV and 2500 keV (the typical energy range for ion beam techniques) and scattering angles between 115° and 165° with a 10° step.

Additionally, in this work, differential cross sections were determined for the elastic scattering of protons in ^{6}Li, ^{7}Li and ^{19}F in the energy range between 620 keV and 2050 keV and for a scattering angle of 165°.



Excitation functions for nuclear reactions induced by ^{3}He in lithium.

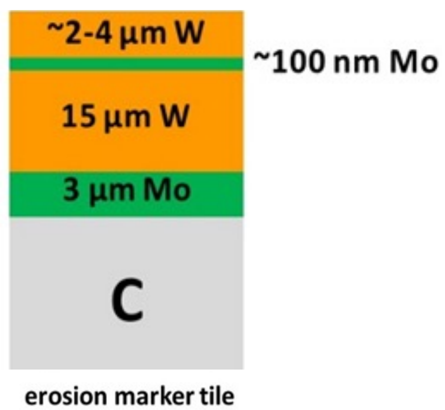


Excitation functions for nuclear reactions induced by ^{3}He in lithium.

Plasma wall interaction in the WEST divertor during the C3, C4 and C5 campaigns

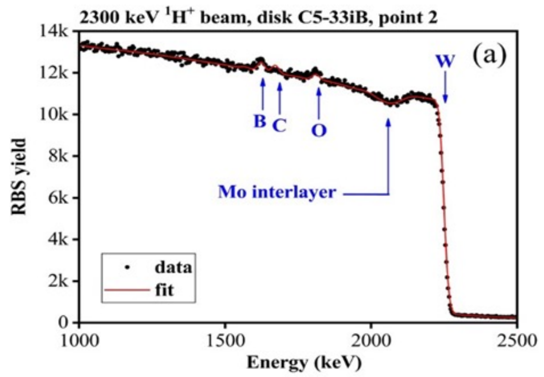
Erosion marker tiles composed by a W surface layer (2-4 mm) and a deeper thick W layer (15 mm separated by a thin Mo interlayer were positioned at the divertor test sector of the WEST tokamak to localize the erosion and redeposition dominated areas at the divertor during the C3, C4 and C5 operation campaigns. After irradiation, different sets of samples were cut from the entire erosion marker tiles and sent to distinct laboratories for complementary analysis (optical and electron microscopy, ion beam analysis, ion mass spectroscopy).

Ion beam analytical techniques are suitable tools to assure if the individual exposed samples were located within erosion or redeposition dominated areas. The analysis follows the near surface (first 3-5 mm) of the depth profile of the W yield in the Rutherford Backscattering Spectrometry (RBS) spectra (see Figure 2a) where the presence of small peaks indicate the presence of other elements. The light elements and heavy trace impurities are commonly quantified by Nuclear Reaction Analysis (NRA) following the emitted particle yields, and by Proton Induced X-ray Emission (PIXE), respectively (see figures below). The RBS, NRA and PIXE analyses of the samples studied revealed the location of dominated erosion and deposition areas in the WEST divertor, the contents of light impurities as ^{2}H, B, C and O and of the main heavier impurities as Cr, Fe and Cu. The figure presents the RBS, NRA and PIXE spectra collected from a specific zone of a marker tile and the corresponding fit lines achieved from the elemental analysis.

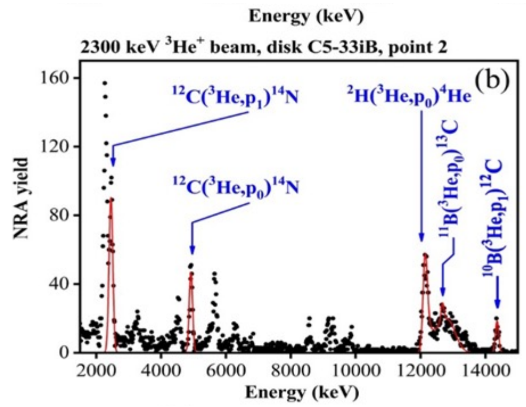


Erosion marker tile as-deposited on a carbon fibre composite.

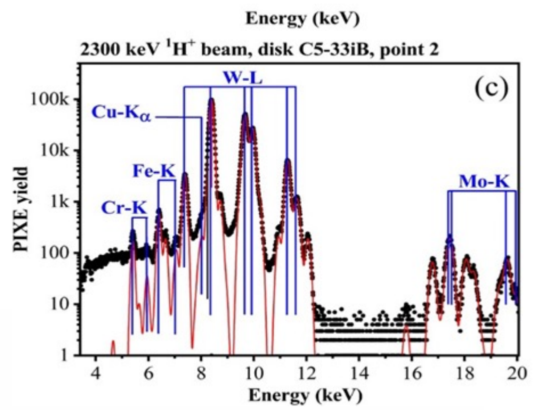
Example of the IBA analysis performed to the C5-33iB sample:



RBS (a)



NRA (b)



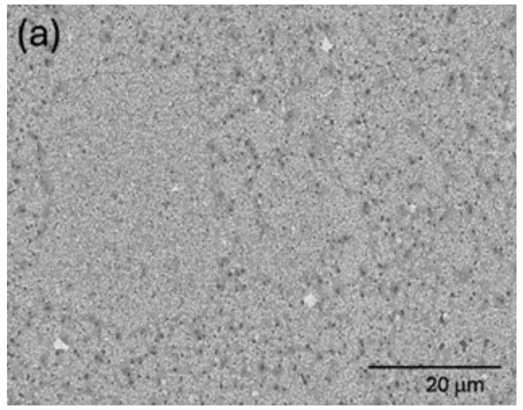
PIXE (c) spectra with corresponding fit lines achieved from the elemental analysis.

Development of thermal barriers for fusion reactors

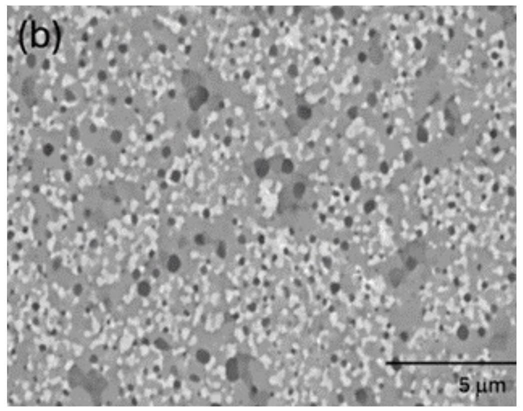
Tungsten is considered the best candidate for plasma facing tiles due to its endurance for high temperature –due to its high melting point, high sputtering resistance and low tritium retention [1]. However, the presently available grades are brittle for temperatures below 623 K, due to the occurrence of a ductile-to-brittle transition [2]. Based on this, the necessity for new materials to improve the mechanical properties of tungsten is an opportunity and a challenge for the future of fusion, suggesting an open door for new materials.

The goal of this work is the development of the W-based high entropy alloys to be applied as functional gradient material (FGM) to improve mechanical properties of W. Therefore, two systems ((CuFeTaTi)$_{70}$W$_{30}$ and FeTaTiVW) of high entropy alloys were explored. The production of the FeTaTiVW and (CrFeTiTa)$_{70}$W$_{30}$ high entropy alloys was optimised using ball milling and consolidated by changing the parameters in spark plasma sintering in order to allow the solid-state consolidation.

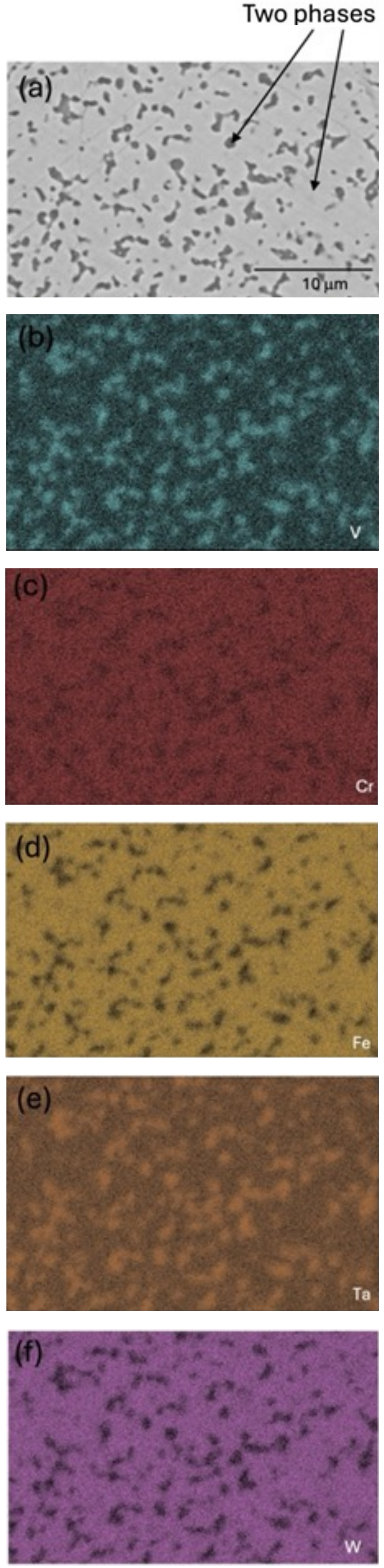
In the in FeTaTiVW and (CrFeTiTa)$_{70}$W$_{30}$ samples a complex eutectic mixture was observed, indicating the presence of liquid in the material. Moreover, two new different systems were started: (CrTaW)$_{90}$Fe$_5$Ti$_5$ and CrFeTaVW. The (CrTaW)$_{90}$Fe$_5$Ti$_5$ and CrFeTaVW were consolidated, however more simple microstructure was only observed for CrFeTaVW as can be seen in the first figure. This sample evidence three different phases and a complex X-ray diffraction with non-identified peaks. A heat treatment was performed as shown in the second figure and it was observed the presence of two phases which requires more investigation.



(a) Low



(b) high magnification of the microstructure of the consolidated (CrTaW)$_{90}$Fe$_5$Ti$_5$ sample.

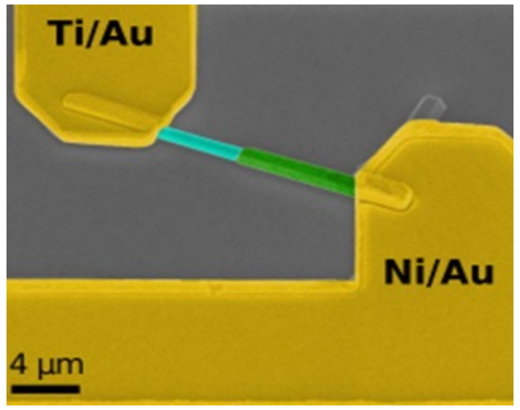


EDS map of the (a) consolidated CrFeTaVW for (b) V-Kα, (c) Cr-Kα, (d) Fe-Kα, (e) T-Lα and (f) W- Lα lines.

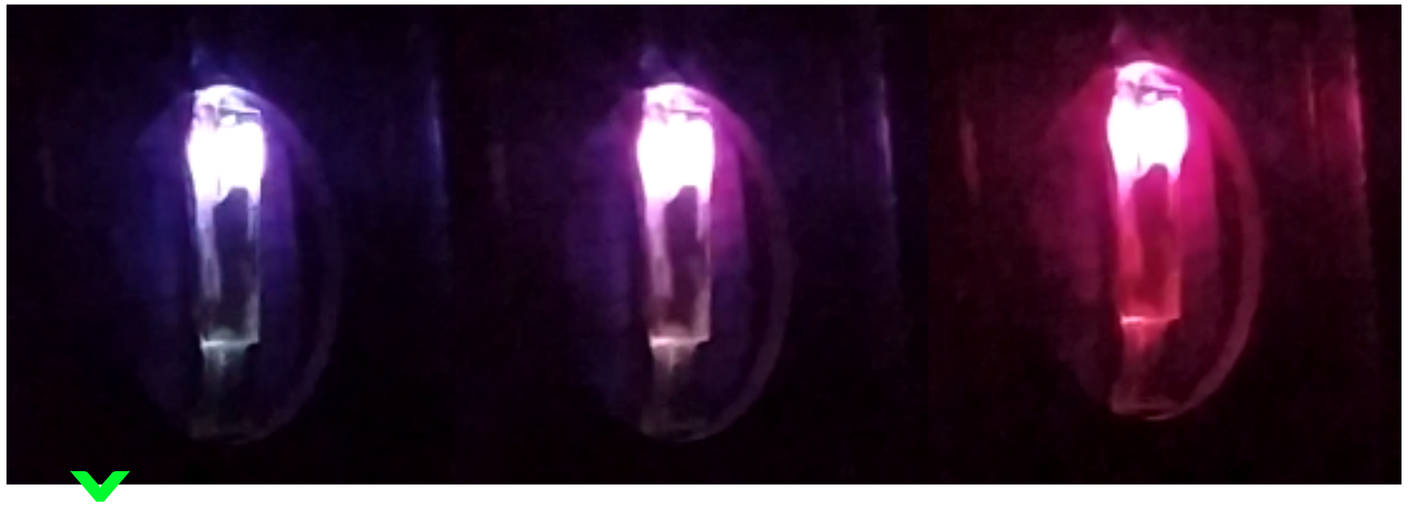
Radiation-induced properties in wide band gap semiconductors

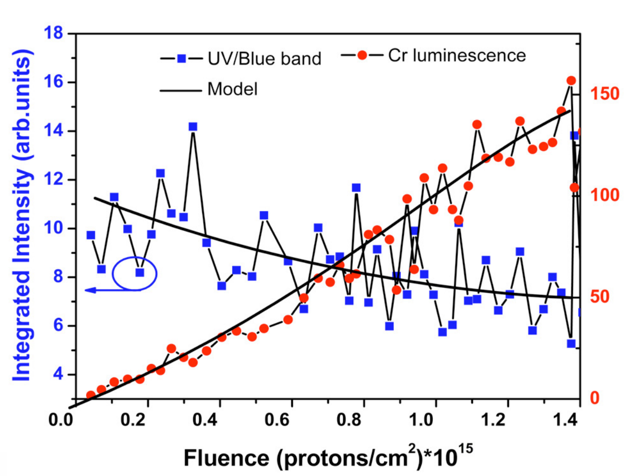
Wide band gap semiconductors like Ga_2O_3 and GaN, known for their high thermal stability and unique electrical and optical properties, show great potential for applications in extreme environments, including radiation-resistant technologies and radiation detectors. In the projects Ion beam processing of Ga_2O_3 (IonProGo) and Defect Engineered 2D Oxide Field Effect Transistors for efficient biosensing (DEOFET), innovative results have recently been obtained demonstrating the potential of Ga_2O_3 for developing optical radiation detectors with potential applications where precise detection and measurement of ionising radiation levels are necessary such as medical imaging, environmental monitoring, and scientific research.

These recently published results have contributed to a better understanding of the optical properties of this Cr-doped semiconductor, particularly how the processes of excitation and optical recombination associated with the Cr centre in Ga_2O_3 vary with the concentration of intrinsic defects induced by ionising radiation [3,4]. The graphs below show an enhancement of optical emission in the red region associated with intraionic emission of Cr^{3+} ions incorporated into Ga_2O_3 crystals was observed with increasing ionising radiation fluence. This process is particularly relevant and has potential applications due to its reversibility with thermal treatment. This irradiation-induced modification of optical and electrical properties in Ga_2O_3 is also being explored in other materials by our research group, such as in GaN nanowires (figure, right), and in GaN multi-quantum wells [5], for potential applications in the fields of dosimetry, photonics, and electronics.

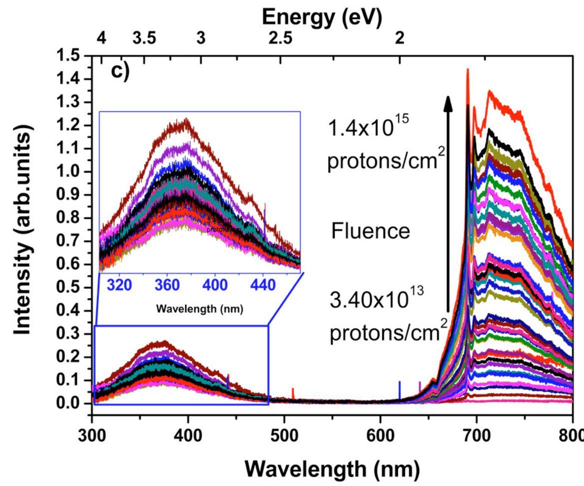


SEM image of a core-shell GaN nanowire device.





SEM image of a core-shell GaN nanowire device.



Lonoluminescence evolution of a single crystal of Cr-doped Ga^2O^3 as a function of protons irradiation fluence;

References:

1. N. Baluc et al., Nucl. Fusion 47, S696–S717 (2007).
2. P. Gumbsch, J. Nucl. Mater. 323, 304-312 (2003).
3. D. M. Esteves, et al., ACS Omega 8, 47874–47882 (2023).
4. D. M. Esteves, et al., Scientific Reports 13, 4882 (2023).
5. D. Verheij et al., ACS Appl. Electron. Mater. 6, 1682–1692 (2024).

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.

Lasers and Plasmas

Main Researchers:

- Anthony Baron (last quarter of 2023)
- Frederico Fiúza
- Gareth Williams
- Gonçalo Figueira
- Hugo Pires
- Hugo Terças
- João Dias
- Jorge Vieira
- José Rodrigues
- José T. Mendonça
- Lucas Gamiz (last quarter of 2023)
- Marija Vranic
- Marta Fajardo
- Nelson Lopes
- Pablo Claveria
- Ricardo Fonseca
- Susana Muiños
- Thales Silva
- Thomas Grismayer

Main funding sources:

- European Research Council;
- European Innovation Council;
- H2020;
- Horizon Europe;
- Eurofusion;
- Fundação para a Ciência e Tecnologia;
- ANI;

Summary of Research

How does matter behave in extreme electromagnetic fields, either at ultra-relativistic intensities, ultra-short timescales or at extremely short 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, relativistic beams, and plasma-based accelerator projects combined with the exploration of Tier-0 supercomputers.

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

Group Leader: Luís O. Silva

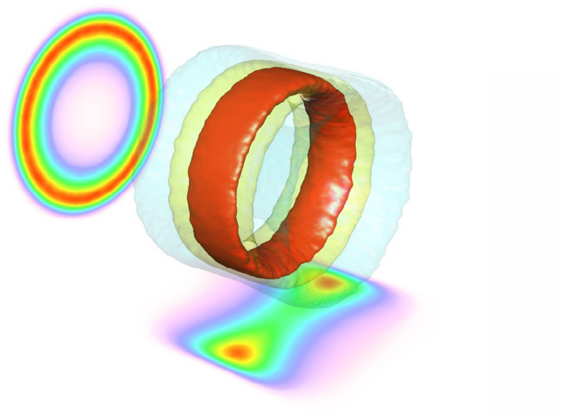
Radiation reaction cooling as a source of strongly anisotropic momentum distributions

A team of GoLP researchers has discovered a previously unknown effect in plasma physics that alters the behaviour of plasmas under strong electromagnetic fields, potentially causing intense coherent radiation. The research focuses on plasmas around neutron stars, and other compact objects with ultra-high magnetic fields.

In classical electrodynamics, charged particles accelerated in powerful electromagnetic fields radiate.

In strong fields, this radiation, known as synchrotron radiation, significantly modifies particle motion due to radiation damping. This phenomenon has been studied since the 1890s. This process is important in plasmas near pulsars and magnetars, where magnetic fields exceed 100,000 Teslas. Recent ultra-high intensity laser experiments enable the creation of relativistic plasmas in the laboratory, making the study of radiation reaction effects increasingly relevant also in lab conditions.

Radiation reaction force differs from the Lorentz force; it is a damping force that cools relativistic particles non-linearly, leading to momentum space bunching and ring formation. Previous works missed this aspect. The work's key finding is that plasmas with relativistic temperatures under extremely strong magnetic fields will cool and develop ring-shaped momentum distributions, which are unstable and can emit coherent radiation through the maser process [1]. This discovery could explain coherent radiation from astrophysical objects like Fast Radio Bursts and suggests similar physics in other setups, paving the way for further research in extreme plasma physics.

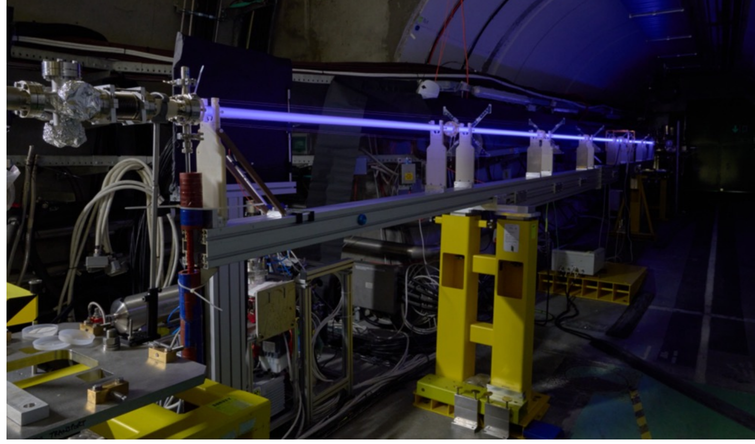


Simulation of the momentum distribution of a plasma undergoing synchrotron cooling. The initial momentum distribution is Gaussian in shape, but as the plasma undergoes cooling, it evolves into a ring-shaped momentum distribution. The simulation was performed OSIRIS, a particle-in-cell (PIC) code that incorporates the effects of synchrotron radiation.

Double-pulse DC disharge plasma source for the AWAKE experiment

Xenon, argon and helium plasmas with length up to 10 m and controlled electron density in the range 0.1-2 x 1015 cm-3 were used in a 3-week beam-time AWAKE experiment at CERN. This was a readiness test for possible future use of this type of plasma source in the AWAKE subsequent phases where highly uniform and reproducible plasmas are required with lengths up to 100m. In this experiment, high-energy (400 GeV) proton bunches delivered by the CERN Super Proton Synchrotron (SPS) were self-modulated into periodic sequences of micro-bunches. The observation of this self-modulation was the experiment's main objective and confirmed the plasma source readiness.

The parameter flexibility of these plasmas enabled an extended experimental program including the verification of the ion mass effect on the beam-plasma interaction, studies of beam filamentation for the highest plasma densities and the study of the plasma light emission due to the beam-plasma interaction. The experiment confirmed the discharge plasma source as a possible enabling technology for proton-driven electron acceleration to energies



Discharge Plasma Source mounted in the AWAKE facility at CERN in April 2023, producing a 10 m long argon plasma.

relevant for high-energy physics. Future experiments will require even higher precision in controlling the plasma parameters to achieve stringent (~0.1%) plasma density control necessary for acceleration experiments.

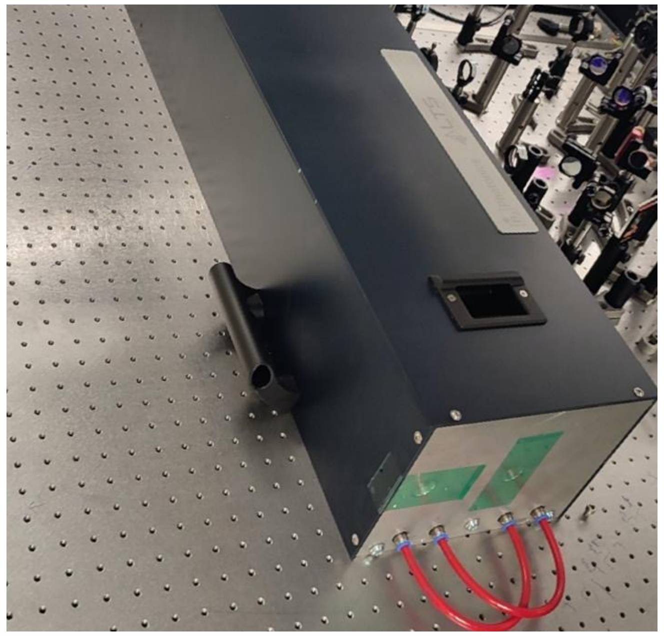
Multipass cell for compression of high power laser pulses

Multipass cells (MPC) are advanced optical devices designed to enhance the nonlinear media interaction length of laser pulses within a confined space, significantly increasing their spectral bandwidth and enabling shorter, more powerful pulses. The traditional method consists of a Herriott-type geometry using two identical, parallel concave mirrors. By multiplexing the number of passes, the optical path inside a nonlinear medium is increased, resulting in spectral broadening.

Our main goal was the development of a compact, efficient and reliable MPC for compressing the picosecond output of a commercial laser to sub-100 fs in order to extend the range of experiments. This project was performed through an industrial collaboration with n2-Photonics, Germany. Our facility at IPFN/IST is equipped with a commercial Yb-based laser, delivering 1 mJ, ~1 ps, 1030 nm, pulses at 100 kHz. The cell is 1.4 m long by 0.25 m wide and is capable of withstanding pressures up to 20 bar. The mirror configuration allows a total of 26 passes, with a total optical path of ~32 m.

By using krypton at 3 bar, the nonlinearly broadened output spectrum spans from 1010 to 1050 nm, with an effectively measured pulse duration of 89 fs, achieved using multiple bounces on chirped mirrors. The output energy of the system is 0.82 mJ representing an impressive efficiency of ~82%. This corresponds to a 7.7x increase in peak power.

The broadened spectrum was accurately predicted using the 1D simulations for the nonlinear propagation in Herriott cell systems. The demonstrated system, whose pioneering version was installed in Lisbon, is now commercially available from n2 Photonics.



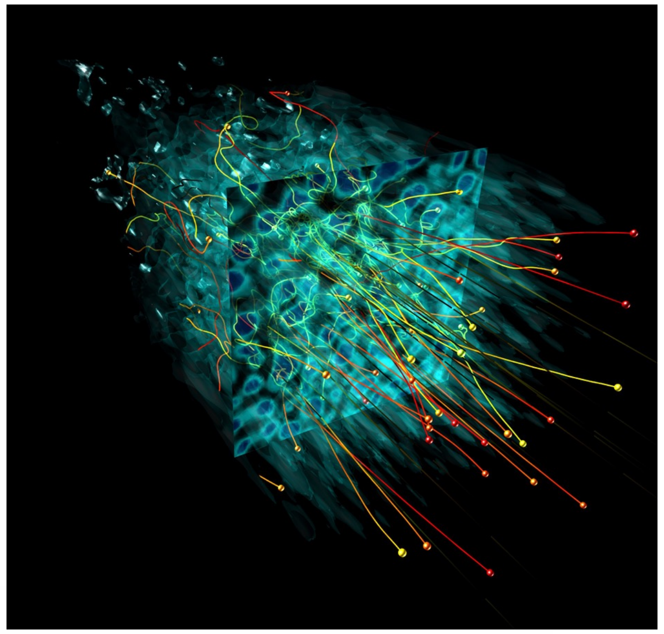
Multipass cell system installed at L2I.

Electron injection in collisionless shocks

Astrophysical collisionless shocks, such as those associated with the violent interaction of the remnants of exploding stars (supernova) with the interstellar medium, are amongst the most powerful particle accelerators in the Universe. One of the most important long-standing questions in astrophysical shocks is how electrons manage to be injected from the thermal distribution into the nonthermal energy tail that produces the observed radiation–this is known as the injection puzzle and is critical for our understanding of what controls the acceleration efficiency in these systems. By performing large scale kinetic plasma simulations and comparing them with the results of recent laboratory astrophysics experiments at the National Ignition Facility, we have proposed a new model for the injection of electrons in high-Mach number shock waves [2].

We show that small-scale magnetic turbulence produced at the shock transition is key in enabling diffusion/scattering of electrons and allowing them to be energised via a first-order Fermi process akin to diffusive shock acceleration (DSA).

This work provides a description of electron injection as a natural extension of DSA in astrophysical shocks, such as those associated with young supernova remnants and accretion shocks in galaxy clusters.



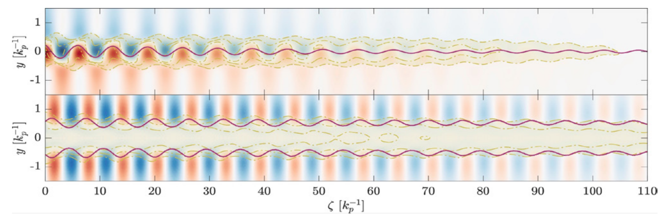
OSIRIS fully kinetic simulation of the acceleration of electrons by repeated scattering in magnetic turbulence produced in a collisionless shock.

Direct laser acceleration of positrons

Relativistic positron beams are required for fundamental research in nonlinear strong field QED, plasma physics, and laboratory astrophysics. Positrons are difficult to create and manipulate due to their short lifetime, and their energy gain is limited by the accelerator size in conventional facilities. Alternative compact accelerator concepts in plasmas are available for electrons, but positron generation and acceleration remains an outstanding challenge. Our team has proposed a new setup to generate, inject, and accelerate positrons in a single stage during a propagation of an intense laser in a plasma channel. Breit-Wheeler pair creation serves as a source of these particles, where the injection and guiding are ensured by electron beam loading, which reverses the polarity of the self-created plasma fields within the channel. Our recent simulation campaign has demonstrated that GeV-class positrons can be injected and accelerated within 0.5 mm of plasma [3]. This study has laid the groundwork for further, more detailed exploration of positron plasma accelerators in the future.

De-hose a long proton bunch in AWAKE at CERN

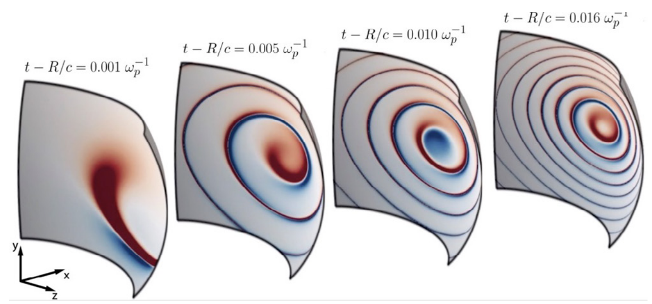
The Advanced Wakefield Experiment (or AWAKE) at CERN uses proton bunches to drive plasma-based accelerators. Proton bunches at AWAKE carry more energy than any laser pulse or electron bunch currently available. Thus, the AWAKE experiment promises to accelerate electrons beyond the energy frontier, and in a shorter distance than conventional particle accelerators. One of the essential ingredients to reach this goal is to stabilize the propagation of the proton bunch in the plasma against deleterious processes. A process that can destabilize proton bunch propagation is the so-called beam break-up instability. Our main goal was to devise a concept to attenuate or even suppress the growth of this instability, by considering a suitably structured plasma density profile. To this end, we performed theoretical and numerical calculations with the PIC code Osiris. Our calculations demonstrate that a sequence of plasma density steps can dampen the instability. Thanks to the simplicity of the approach, this concept can be tested experimentally shortly at AWAKE. Our theoretical approach applies to other beam-plasma instabilities in AWAKE, namely the so-called self-modulation instability. We aim to develop this generalization in the future. More details can be found in [4].



Field structure and beam-plasma instabilities at AWAKE. Up: onset of the beam-breakup (or hosing) instability, which consists of an exponential increase of the proton bunch centroid displacements (purple line). Bottom: onset of the self-modulation instability, which consists of an exponential amplification of the proton bunch transverse size (purple line).

Radiation Diagnostic for Osiris (RaDiO): efficient radiation calculations for PIC codes

Light sources are essential for scientific and technological progress and play a major societal role. New scientific discoveries depend on the availability of ultra-short-wavelength light sources, such as x-rays and gamma-rays, that can probe ultra-fast processes at the molecular and atomic scales. Making these sources more compact and affordable, leveraging intense lasers and plasmas, can amplify scientific progress, being a main goal. This is the cornerstone of the EuPRAXIA project, for example. In parallel to experiments, modelling these sources numerically is necessary to understand how they work, to make them more efficient, and to predict the outcomes of experiments. To achieve this goal, we developed a novel and computationally efficient tool to retrieve the radiation emitted by charged particles - Radiation Diagnostic for Osiris (RaDiO). RaDiO is fully integrated into the Osiris framework, has built-in spatial and temporal coherence effects, and retains the spatiotemporal structure of the radiation. Our numerical approach captures the radiation from a large number of particles in the simulation, and provides a full spatiotemporal characterisation of the radiation emitted by charged particles. RaDiO was instrumental in developing the concept of generalised superradiance, for example (see e.g. [5]) . Our new tool applies to the study of radiation in any plasma phenomena, from plasma-based accelerators and light sources, to plasma instabilities relevant in laboratory and astrophysical scenarios, to name but a few examples. Next, we plan to develop a GPU-compatible version of RaDiO, to capture the radiation from all particles in Osiris simulations. More details can be found in [6].



Synchrotron radiation emitted by a relativistic electron: the birth of electromagnetic radiation. The image shows the temporal history of the radiation emitted by an electron performing a synchrotron trajectory starting from the initial moments where its radiation reaches the detector.
Simulation results obtained with RaDiO show the electric field captured in a virtual detector as a function of detector time.

References:

1. P. J. Bilbao, and L. O. Silva, Phys. Rev. Lett. 130, 165101 (2023).
2. A. Grassi et al., Astrophysical J. Lett. 958, L32 (2023).
3. B. Martinez, B. Barbosa and M. Vranic, Phys. Rev. Acc. Beams 26, 011301 (2023).
4. M. Moreira, P. Muggli, J. Vieira, Phys. Rev. Lett. 130, 115001 (2023).
5. J. Vieira et al., Nat. Phys. 17, 99–104 (2021).
6. M. Pardal et al., Computer Phys. Communications 285, 108634 (2023).

N-PRiME

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Main funding sources:

Fundação para a Ciência e a Tecnologia;
European Space Agency;
Massachusetts Institute of Technology;
Fulbright programme;

Summary of Research

Low-temperature plasmas (LTPs) are essential for advanced technologies with societal benefits in areas like the environment, energy, agriculture, defence, and Space exploration. The N-Plasmas Reactive: Modelling and Engineering (N-PRiME) group investigates the potential of Nonequilibrium LTPs to tailor energy and matter at the Nanoscale and to reach New Horizons in Space exploration. Our multidisciplinary approach combines fundamental research with applied science, creating synergies that drive progress in LTPs.

Our research is organised into three main axes.

1. The Plasma Engineering Laboratory (PEL, E. Tatarova PI) exploits microwave-driven plasmas to develop new plasma-based technologies. We design and operate innovative experimental setups to synthesise two-dimensional nanostructured materials.
2. The Hypersonic Plasmas Laboratory (HPL, M.L. Silva PI) is home to the European Shock-Tube for High Enthalpy Research (ESTHER), which was commissioned by the European Space Agency (ESA) and inaugurated in July 2019. ESTHER is the sole Space facility in Portugal dedicated to planning planetary exploration missions.
3. Plasma Modelling and Simulation (M&S, V. Guerra PI) focuses on understanding the dynamics of non-equilibrium LTPs. We develop state-of-the-art kinetic schemes for volume and surface interactions, considering the multidimensional transport of species and radiation, also under hydrodynamic flow regimes. Our work involves creating, verifying, and validating predictive numerical tools.

Our comprehensive approach bridges theoretical studies with practical applications, advancing knowledge and capabilities in the field of LTPs.

Group Leader: Luís Lemos Alves

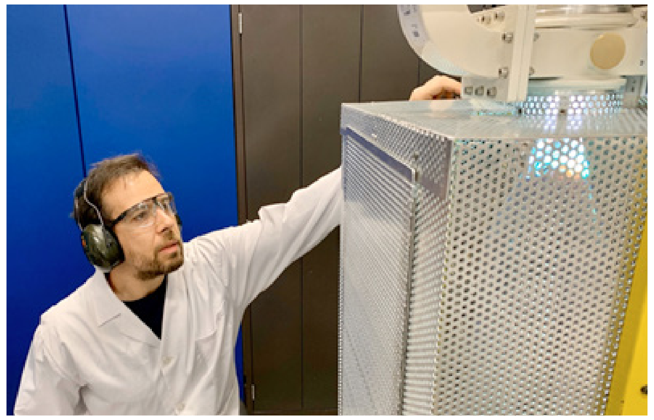
Plasma Engineering Laboratory

WORKING IN THE CUTTING-EDGE FIELD OF PLASMA NANOSCIENCE

The R&D activities at PEL focus on Plasma Nanoscience, aiming to utilise the unique properties of plasmas to develop advanced nanomaterials by precisely controlling energy and matter transfer processes at the nanoscale.

MULTIFUNCTIONAL PLATFORM FOR THE CONTINUOUS PRODUCTION OF GRAPHENE AND DERIVATIVES AT THE GRAM SCALE

We have exploited our multifunctional platform capable of self-assembling free-standing graphene and N-graphene nanosheets, as well as hybrid nanostructures, in a continuous one-step process in seconds, under atmospheric pressure conditions without the need for post-treatment. Diverse protocols of industrial interest have been established, each tailored to distinct carbon and nitrogen precursors. These protocols were used as structured methodologies, to achieve reproducible outcomes in terms of production rate, structural quality (including the presence of sp3 carbons, lateral dimensions, etc.), and chemical composition (e.g. the presence of oxygen). The method enables the conversion of a wide range of low-cost feedstock (e.g. ethanol, acetonitrile, etc.) into graphene and derivatives at a rate up to 50 mg/min. Both the process and the device are protected by a patent portfolio: 7 patents granted (4 PT, 1 EP, 1 US, 1 JP); 2 patents pending (1 EP, 1 US).



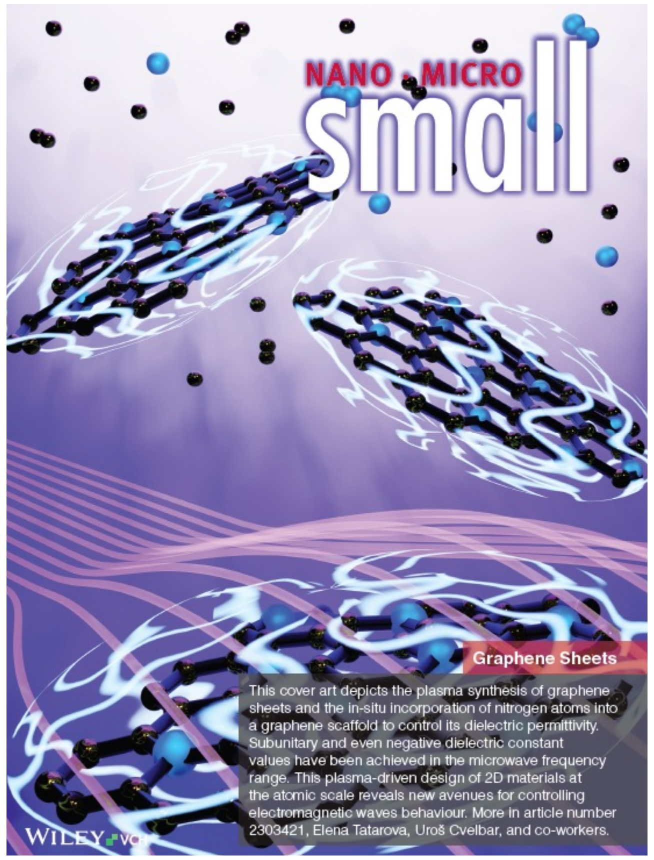
Researcher Edgar Felizardo operating the Multifunctional platform for the synthesis of graphene and derivatives.

EXCEPTIONAL PROPERTIES. BREAKTHROUGH APPLICATIONS

The implications of our research are vast, impacting areas like energy storage and conversion devices, conductive inks, metamaterials, and more. Plasma-synthesised metal oxide/sulfide anchored N-graphene composites, tested as supercapacitor electrodes, have shown promising specific capacitances of up to 273 F g^{-1} at 0.5 A g^{-1}. The plasma's intrinsic thermal and chemical functionalities induce the reduction of micron-sized particles to nanoparticles, and the conversion into distinct chemical phases. Additionally, we have demonstrated the ability of the plasma method to enhance graphene plasmons' performance.

By increasing pyridinic/pyrrolic nitrogen functional groups on the graphene scaffold, we suppress graphene π-plasmons (4-10 eV) and excite low-energy 2D plasmons in the near-infrared range (0.4-1 eV).

These synergy effects due to nitrogen doping also suppress secondary electron emission, resulting in sub-unitary secondary electron yields. Furthermore, plasma-synthesised N-graphene exhibits tunable dielectric permittivity (e.g. sub-unitary and negative) over a wide frequency range (1-40 GHz), paving the way for the next generation of 2D metamaterials.



Cover of journal Small based on a paper by E. Tatatova et al., illustrating the incorporation of nitrogen functional groups on the graphene scaffold to obtain exceptional material properties.

Plasmas Modelling & Simulation

ACTIVITIES FULLY FUNDED BY COMPETITIVE PROJECTS

The international recognition of our M&S activities is demonstrated by the level of competitive funding secured, corresponding to more than 400,000 Eur.

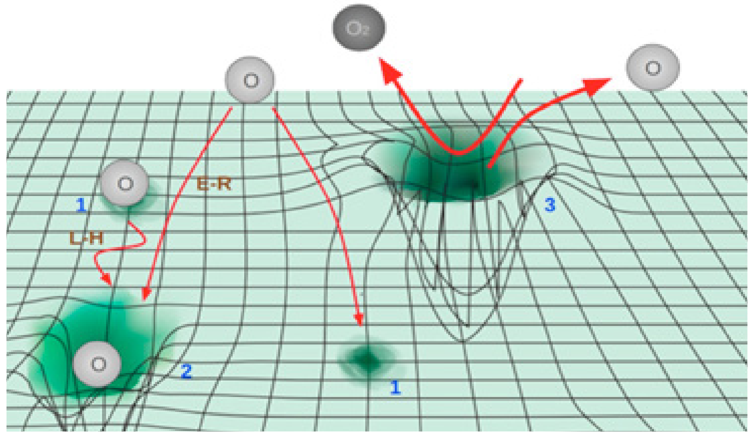
THE LISBON KINETICS (LOKI) SIMULATION TOOLS AND IST-LISBON ELEMENTARY DATA

N-PRiME develops numerical plasma simulation tools under the LisbOn Kinetics (LoKI) brand, some already available as open-source codes. Currently, the LoKI simulation tools include: (i) LoKI-C_v2.2.0, which combines a chemistry model with a thermal model for neutral gas, incorporating coupled volume and surface kinetics, and simulating post-discharges; (ii) the open-source Boltzmann solver LoKI-B_v2.2.0, which describes the kinetics of electrons excited by time-dependent (non-oscillatory) electric fields; and (iii) the open-source LoKI-MC_v1.1.1, which uses the Monte Carlo (MC) technique to solve the electron kinetics.

We also contribute to the generation and curation of elementary data, through the IST-Lisbon database at LXCat. Our database was expanded with complete and consistent cross section sets for CO and H_2O, where the role of anisotropic scattering in rotational collisions was investigated, improving the agreement between calculated and measured swarm parameters.

DEVELOPMENT AND VALIDATION OF PLASMA CHEMISTRY KINETIC SCHEMES

One of the pillars of LTP modelling are kinetic schemes describing the interactions between heavy species and electrons. Therefore, the definition of a reaction mechanism, i.e., a set of reactions and corresponding rate coefficients that are validated against benchmark experiments, is mandatory to make meaningful modelling predictions. N-PRiME is pioneering the systematic development of reaction mechanisms, in collaboration with the experimental team of Dr. Olivier Guaitella from the Laboratoire de Physique des Plasmas, Ecole Polytechnique, France, and has already published mechanisms for O_2, N_2-O_2, CO_2, CO_2-N_2 and CO_2-CH_4 plasmas. The definition of reaction mechanisms involves also validating electron-impact cross sections (a novel proposal for the CO_2 dissociation cross section is to be highlighted), and studying the influence of plasma-surface interactions on molecule conversion and selectivity (a novel model for atomic oxygen surface kinetics in silica-like walls, including plasma-induced reversible surface modifications, is to be highlighted).



Graphical representation of plasma-surface interactions, involving physisorption (1), stable chemisorption (2) and metastable chemisorption (3) sites.

STATE-TO-STATE MODELLING OF CO_2 DISSOCIATION PROCESSES

Dissociation of CO_2 in heavy-particle collisions is poorly understood to date, owing to the complexity of the internal structure of this linear triatomic molecule. We have developed a physically consistent model that extends the theory of the Forced Harmonic Oscillator for linear triatomic molecules, by recalculating with potential reconstruction methods the so-called "extreme states" of CO_2 up to the dissociation limit. The new model supports over 200 vibration levels, and we have demonstrated reasonable agreement with high-temperature shock-tube CO_2 dissociation measurements.

Hypersonic Plasmas Laboratory

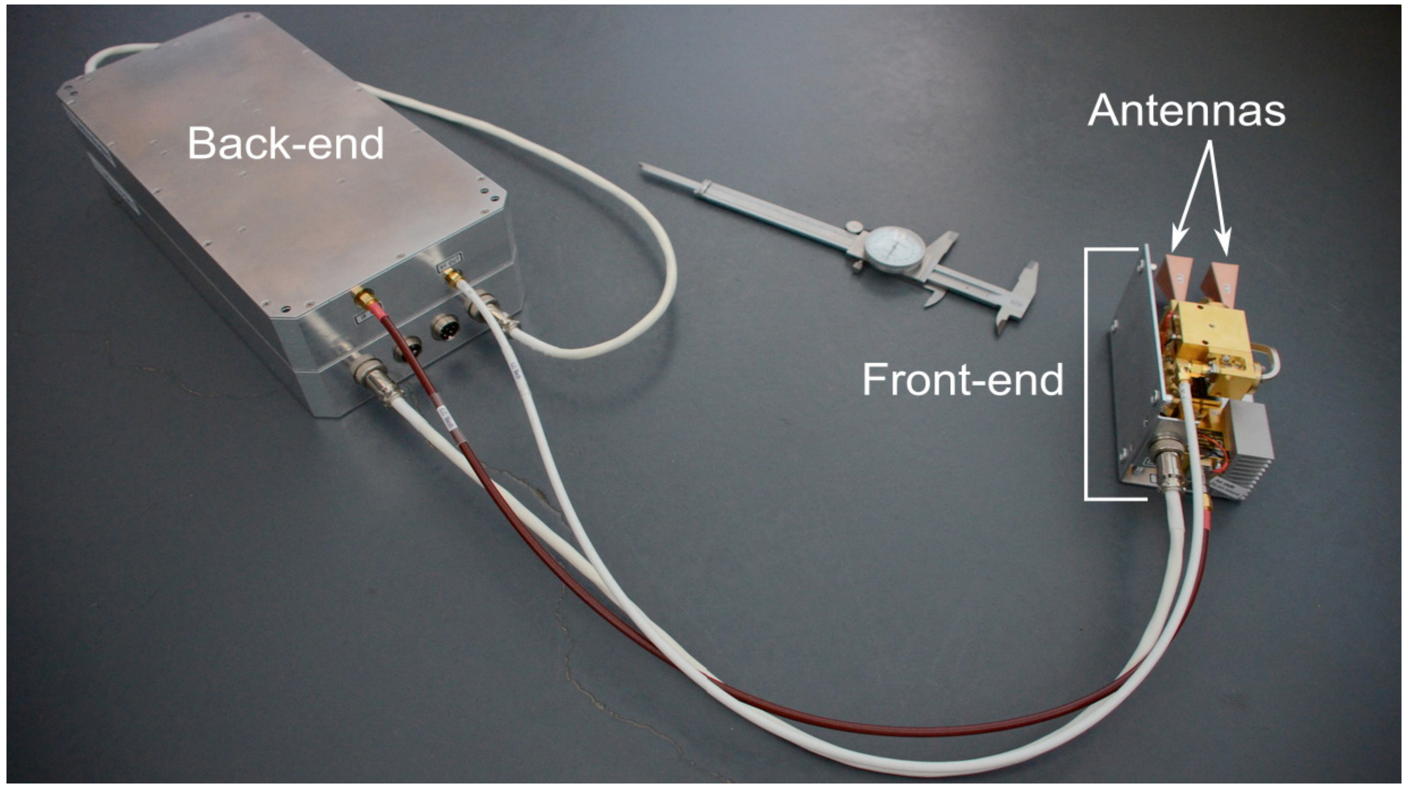
THE ESTHER SHOCK-TUBE - FINAL COMMISSIONING TESTS

After the acceptance of the driver section, following a series of 99 shots of the combustion chamber using an unique laser-ignition setup, the compression tube, test-section, dump-tank and their associated vacuum systems also underwent extensive testing. An ultimate vacuum of 10^{-6} mbar was achieved, adequate to ensure the stringent criteria of cleanliness for the facility.

The facility is expected to become fully operational in 2024. The VUV spectrometer-streak-camera assembly was delivered and its acceptance testing was successfully carried out. A 75-100 GHz microwave interferometer prototype was commissioned and successfully tested with a steady-state plasma source.

This innovative diagnostic shows great promise not only for time-resolved shock-tube electron density measurements, but also for other steady-state plasma sources. Successful measurements have already been achieved in an ICP mini-torch of the Von-Karman Institute.

Researcher M. Lino da Silva preparing the commissioning of ESTHER.



Microwave interferometer prototype.

High Pressure Plasmas

Main Researchers:

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Nelson A. Almeida
Nuno G. C. Ferreira

Main funding sources:

European Regional Development Fund;
Siemens AG Corporate Technology;
Schneider Electric Industries SAS;
Fundação para a Ciência e a Tecnologia;

Summary of Research

Main areas of research of the HPPG have been plasma-electrode interaction in high-pressure arc discharges, DC low-current discharges on cold electrodes, and high-voltage vacuum breakdown.

The focus of research of the group has been on the interaction of high-pressure plasmas with electrodes, in particular, near-electrode phenomena in arc plasmas, sheath physics, and self-organisation on electrodes of discharges of different types, where the group is a recognized international authority. The group, while continuing active research in these fields, has expanded its research to DC low-current discharges, including corona discharges, and their inception.

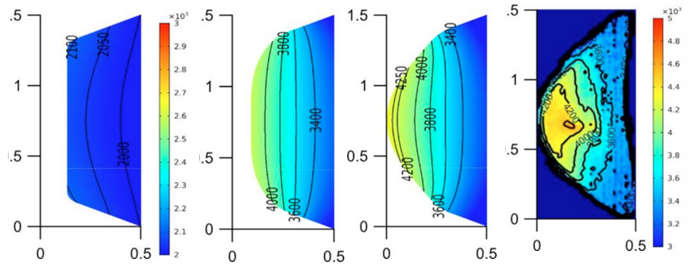
Plasma-electrode interaction is a multi-scale phenomenon and processes occurring on different scales are governed by mechanisms of different nature. Therefore, the approach of the group is necessarily multidisciplinary and relies on theoretical methods of plasma physics and chemistry, fluid dynamics, nonlinear physics, kinetic theory, asymptotic methods, numerical modelling, and experiments performed in partner laboratories abroad and also in the plasma laboratory operated by the group.

The principal tools used by the group are theoretical methods and numerical simulation.

Group Leader: Pedro G. C. Almeida

Plasma-electrode interaction in 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. HPPG undertook an effort towards the simulation of 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 the models of cathode spots of vacuum and unipolar arcs developed by the group previously, and was applied to thermionic cathodes of high-current arc plasma torches, consisting of cylindrical inserts with conical tips, made of pure tungsten or tungsten doped with thorium, or yttrium, or lanthanum, surrounded by a massive water-cooled copper holder. The work was performed in collaboration with colleagues from the Joint Institute for High Temperatures of the Russian Academy of Sciences, where the experiments have been conducted.



The cathode tip shape and the temperature distribution in the tip. (a)-(c): Modelling, t=295 ms (a), 331 ms (b), 1 s (c). (d): Experiment, stable mode. The spatial dimensions are in millimetres and the temperature bars in kelvin. Temperature bars for frames (b) and (c) are the same as for frame (d).

As an example, the computed evolution of the shape of the tip of the pure-tungsten insert and of the temperature distribution in the tip is shown in figures 1a–1c. The torches were operated at a DC current of 200 A in atmospheric-pressure argon. The computed maximum tip temperature for t=1 s approximately equals 4300 K, which is close to the maximum temperature measured in the stable mode of the cathode operation, which is approximately 4200 K. There is also a good agreement between the modelling (figure 1c) and the experiment (figure 1d) in what concerns the shape of the cathode tip during the stable mode operation.

AC arc ignition on cold electrodes in atmospheric-pressure argon

Many works have focused on the theory and modelling of thermionic cathodes, with many published recently. However, understanding of anodes and non-thermionic cathodes is still limited. The HPPG studied arc ignition and re-ignition on cold electrodes in atmospheric pressure argon, and current transfer to anodes. This research was part of an industry-sponsored project, suggested and collaborated on by Schneider Electric Industries SAS (Grenoble, France) and Université d'Orléans (Orléans, France). The project aimed to apply these results to low-voltage circuit breaker contacts.

The model was developed on the unified modelling developed by the group previously and was applied to study the AC arc ignition and re-ignition on cold electrodes in atmospheric pressure argon. The comprehensive numerical modelling has clarified how current transfers to non-thermionic arc cathodes, the understanding of different regimes in the anodes and allows to describe the entire process of arc development from low to high current density, including polarity switching. The modelling results match experimental data on contactor opening.

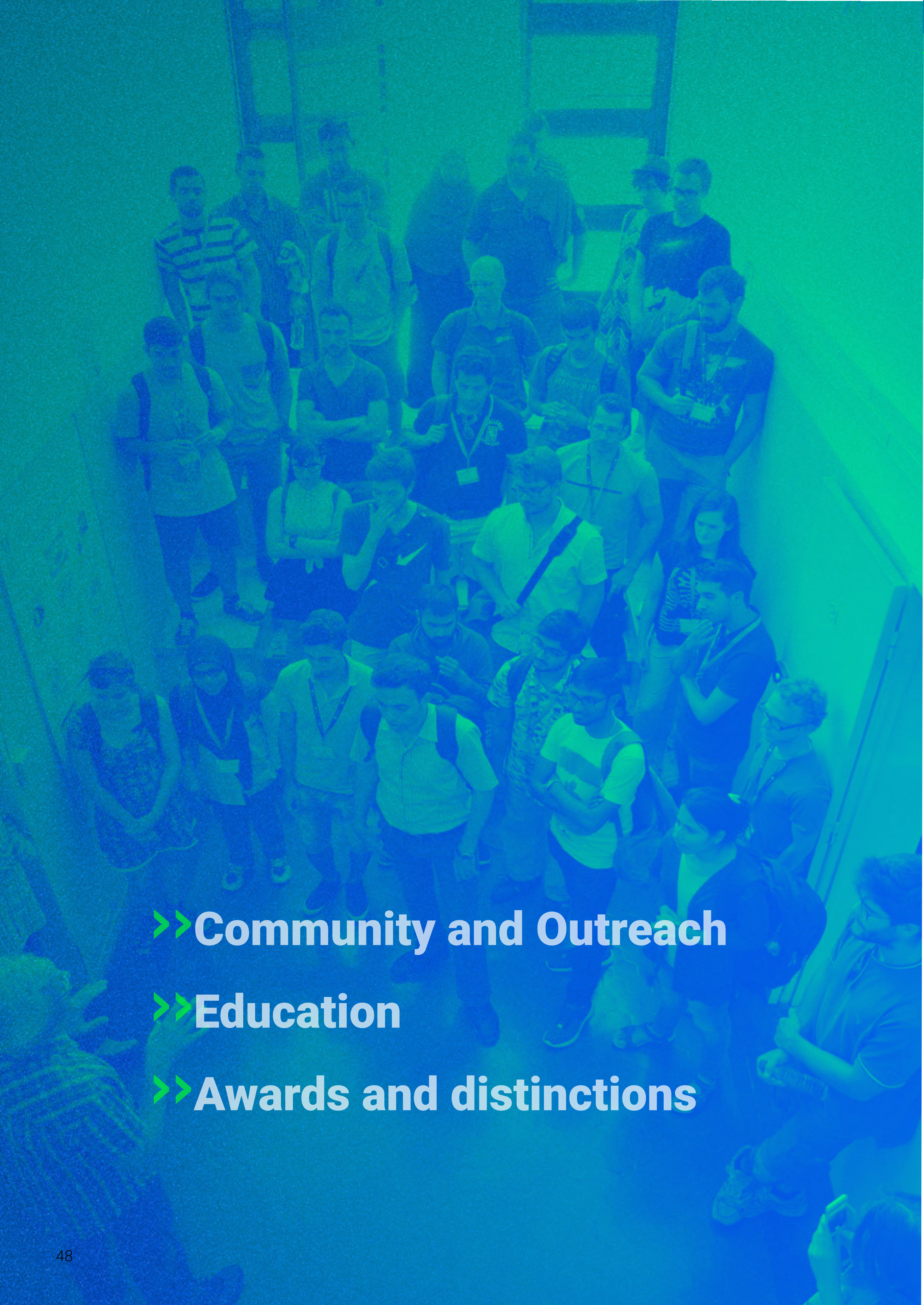
DC low-current discharges on cold electrodes

A simplified version of the eigenvalue problem governing ignition of volume discharges has been formulated neglecting the diffusion of the charged particles, or, in other words, in the drift approximation. A general form of the Townsend ignition (self-sustainment) criterion is deduced by partial integration of this eigenvalue problem neglecting the photoionization, and, in the case of electronegative gases, also the detachment. The comparison of the results obtained from different forms of the Townsend criterion with those given by the accurate numerical solution of the full eigenvalue problem shows that the neglect of the diffusion of the charged particles produces an error in the ignition voltage of the order of 1% or less. The lower and upper estimates of the effect of negative ions over the ignition voltage are obtained from different forms of the Townsend criterion. A form of the Townsend criterion, which employs an effective attachment coefficient in air and takes into account, in an approximate way, also the detachment, gives a virtually exact value of the inception voltage in all the cases considered.

High-voltage vacuum breakdown

A phenomenological description of the field electron emission is used in practice: experimental current-voltage characteristics of field emission from cold electrodes in vacuum are fitted by the Fowler-Nordheim formula with the applied electric field being multiplied by the so-called field enhancement factor, which has to be of the order of 10^2 or higher. A correlation of the vacuum breakdown field with the field enhancement factor, determined by means of analysis of the measured field emission currents, has been reported in the literature. On the basis of this correlation, it was proposed by HPPG to explore the possibility to describe the initial stage of vacuum breakdown within the framework of the same phenomenological approach, without invoking any special mechanism for the breakdown apart from the mechanism responsible for the enhancement of field emission.

First modelling results confirmed this possibility, thus opening the way to complete simulations of high-voltage vacuum breakdown from the initial, high-voltage, phase, where the cathode surface is cold, to the cathode arc spot phase, where transition occurs from the field to thermo-field to thermionic electron emission, vaporisation of the cathode material comes into play with subsequent ionisation of the metal vapour, cathode surface is melted and a crater is formed with eventual droplet detachment. In addition to being of high scientific interest and relevant to particle accelerators, this approach is applicable to modelling high-voltage breakdown in high-power circuit breakers. Results of this work constitute the starting point of a new collaboration with Siemens Energy, Berlin.



>>Community and Outreach

>>Education

>>Awards and distinctions

Community and Outreach

IPFN is strongly dedicated to actively engaging in science communication and sharing its scientific, technological, and educational advancements with society.

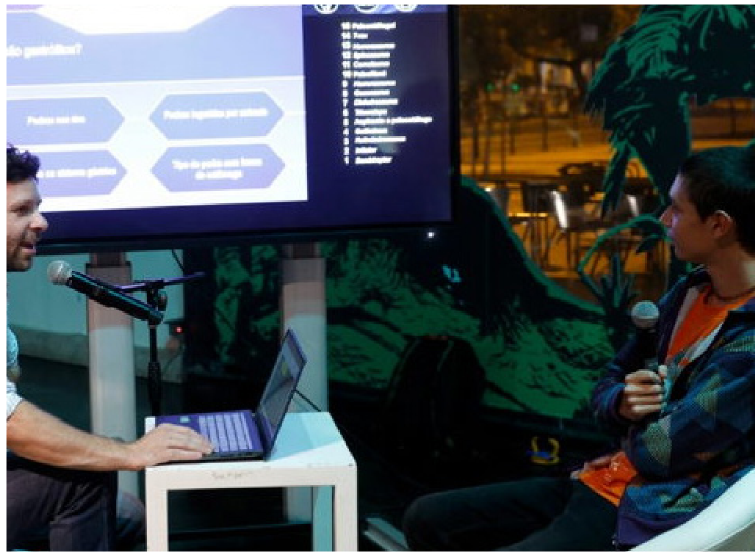
We use a wide range of communication channels tailored to diverse audiences, including primary and secondary school students and teachers, university undergraduates and graduates, as well as the media, industry professionals, and the broader scientific community.

Outreach events and initiatives

European Researchers Night

A large number of IPFN researchers participated in the 2023 edition of European Researchers' Night. At the Museu Nacional de História Natural e da Ciência, one of the featured activities showcased IPFN's research in reflectometry modelling and simulations.

The event highlighted the propagation of electromagnetic waves in plasma through numerical simulations, with applications to nuclear fusion plasmas, using both 2D and 3D visualizations. Meanwhile, at the Centro Ciência Viva - Pavilhão do Conhecimento, another activity introduced visitors to the fascinating world of lasers and plasmas. The event presented extreme plasma physics research through simulations of astrophysical plasmas and plasmas under extreme conditions. Several hands-on experiments were available, including the Plasma Ball, Optical Cable, Radiometer, Tesla Coil, and Jacob's Ladder, providing engaging, interactive experiences for the visitors.



In addition to these, other initiatives included a scientific quiz titled 'Who Wants to Be a Palaeontologist?', where children had the opportunity to test their knowledge about dinosaurs and other extinct creatures, making the event both educational and fun for younger participants.

School visits and talks

Every year, IPFN facilities such as ISTTOK, L2I, VOXEL and MOTLab receive a large number of school visits, from undergraduate students, basic to secondary school students. During the guided tours, the pupils have the opportunity to contact undergraduate students and staff, having 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.

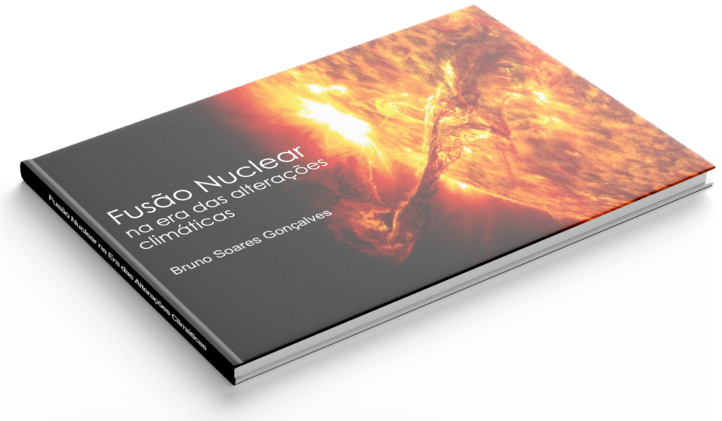
PaleoMoz project documentary

The PaleoMoz Project seeks to advance the scientific development of Mozambique by preserving and enhancing its paleontological heritage, while also training the first generation of Mozambican paleontologists. PaleoMoz was initiated by scientists from various Portuguese institutions, including IPFN, in collaboration with the National Geology Museum of Mozambique.

In 2023, a documentary about the PaleoMoz Project was produced, funded by Aga Khan/FCT and National Geographic Society grants. The film offers an unprecedented look at the challenges of conducting fieldwork in remote areas of Africa, highlights the extraordinary discoveries—ranging from mammal ancestors to fossilized forests—and follows the daily lives of the international team of palaeontologists during the 2019 PaleoMoz expedition.

New book on nuclear fusion

IPFN President Bruno Gonçalves has authored a new book titled "Fusão na era das alterações climáticas" (in Portuguese), which explains the fundamentals of nuclear fission and fusion in clear, accessible language. The book delves into the future of energy production, exploring how nuclear fusion is generated, its potential benefits, and the associated risks. It offers an insightful look at fusion's role in addressing the global energy challenge in the context of climate change.
The book is available for free download on the IPFN website.



Press releases

European researchers achieve fusion energy record- Feb. 2022

Nature paper sheds light on the origin of warm-bloodedness in mammals - Jul. 2022

Major boost to European plasma accelerator facility- Nov. 2022

Historical milestone in nuclear fusion: world's largest laser achieves ignition- Dec. 2022

Proxima Fusion and IST collaborate on stellarator optimisation- May. 2023

Ultrashort light pulses shaped like a spring toy bring a new twist in photonics- Jun. 2023

First observation at JET of how fusion keeps itself hot- Oct. 2023

Generating ultra-bright radiation with faster-than-light "particles"- Oct. 2023

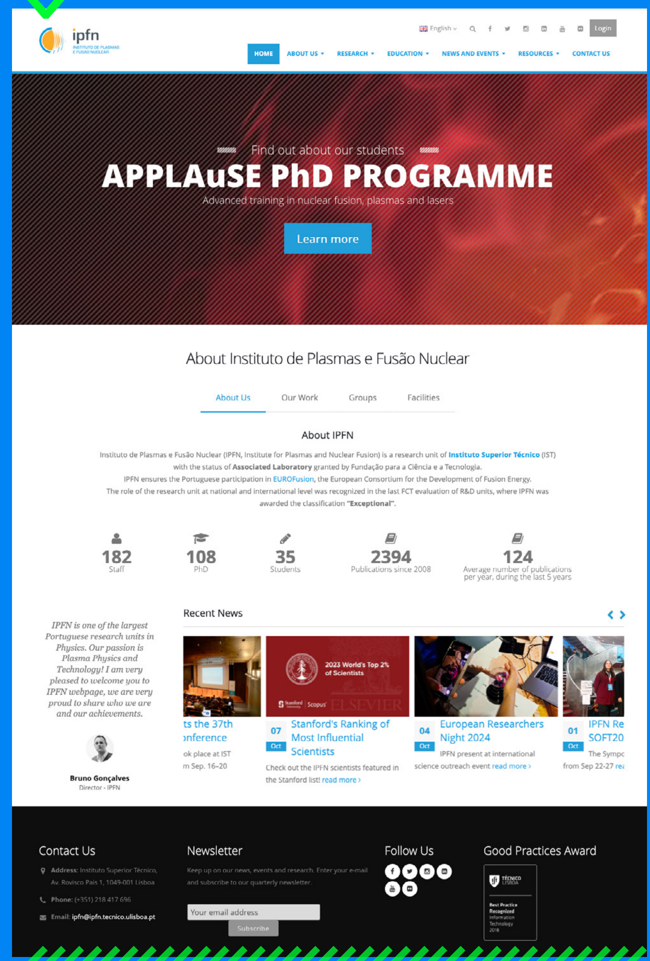
IPFN and General Fusion collaborate on new diagnostic for fusion device- Dec. 2023

Web and media

During this period we increased our social media presence both through the number of contents and the diversity of channels. IPFN is now active on Facebook, Twitter, Instagram, YouTube and LinkedIn.

Through these platforms, we share the latest news, research highlights, educational initiatives, and recruitment opportunities.

- **Facebook – fb.com/IPFNLA**
  Launched in 2010, the IPFN page has gathered more than 1600 followers;
- **Flickr – flickr.com/ipfn**
  Database of high-quality photos, graphics and scientific images, with more than 280 pictures;
- **Instagram – instagram.com/ipfnmedia/**
  More than 150 pictures about what's going on at IPFN!
- **LinkedIn – linked.in/ipfn**
  Connecting current, previous and prospective employees, while also disseminating career opportunities;
- **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.
- **Webpage – ipfn.tecnico.ulisboa.pt**
  The central hub of all our websites, with news, events and detailed information about activities and scientific results;
- **YouTube – youtube.com/IPFNmedia**
  It serves as a video repository, either for dissemination purposes or events taking place at IPFN;



Education

Events

PlasmaSurf summer school

PlasmaSurf is IPFN's summer school on plasma physics, intense lasers and nuclear fusion, tailored for BSc/MSc engineering and physics students. It is a great opportunity to get an insight into these topics with a view to a future career or to complement the student's curricular training by broadening your knowledge in an exciting and forefront area of physics.

The teaching component and laboratory sessions are ensured by IPFN faculty and researchers. With growing popularity, the 9th (July 2022) and 10th (July 2023) editions of PlasmaSurf attracted 17 and 24 participants respectively. The participants also had the opportunity to try out the remote-controlled experiments, in particular performing the Langmuir Probe and the Microwave Plasma Cavity experiments. These experiments were partially funded by Fusenet are available online. Additionally, PlasmaSurf provides a unique opportunity to try a range of outdoor activities, from kayaking and surfing to climbing and mountain boarding sessions.

FuseNet European Fusion Teacher Day 2022 and 2023

IPFN/Técnico is the national partner of European Fusion Teacher Day, an outreach event on nuclear fusion aimed at secondary school teachers, taking place in early October. IPFN researchers coordinate a session in Portuguese aimed at secondary school teachers. Participants learn about the fundamentals of nuclear fusion, present research into fusion carried out in Portugal and how it contributes to the European fusion program. The international session consists of a live stream with talks by researchers from the international nuclear fusion community, providing a privileged view of one of the most extensive scientific collaborations in the world.

Training and internships at the international level

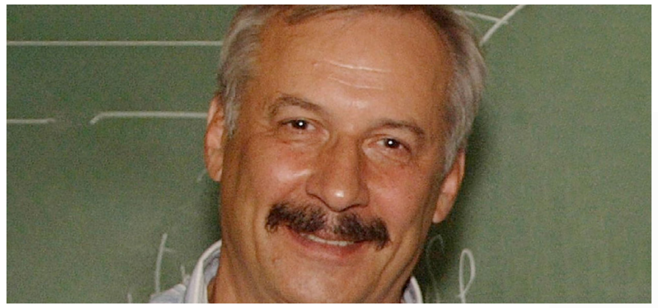
IPFN hosts a large number of BSc, MSc, and PhD students for training and internships, welcoming participants from IST, other Portuguese universities, and institutions abroad. In particular, two Master's students from the University of Naples Federico II and an intern from UKAEA, under the EUROfusion Engineering Grant, were involved in remote handling activities. Additionally, students from national (FCUL) and French universities (INSA Lyon, ENSTA Paris, Grenoble INP) contributed to research on neutronics and diagnostic development for DEMO. The group also hosted a PhD student from the University of Padova, focused on designing and developing the Plasma Position Reflectometry system for DTT.

Special guest lectures

IST Distinguished Lectures are special events that consist of lectures given by guest researchers of exceptional prestige and are awarded this special distinction by the IST Scientific Council. During this period IPFN proposed and hosted the following lectures:

>>*Chan Joshi, Perspectives on beam-driven plasma-based acceleration,* March 13, 2022

>>*Sergei Bulanov, Extreme light-matter interaction through the lenses of the relativistic flying mirror concept",* November 10, 2022



>>*Gerrit Kroesen, Plasmas in the semiconductor industry: modern trends, opportunities and diversity,* December 15, 2023

The Physics Department Colloquium takes place weekly and attracts a large number of faculty and students. IPFN hosted Mark Kushner (University of Michigan, USA) for his lecture 'Plasmas for Microelectronics Fabrication: A Modeling Perspective'.

Internship for secondary school students

Through a protocol between IPFN and António Damásio Secondary School school, our unit welcomed two students in 2022 and three in 2023 for two-month-long internships in activities related to plasmas and nuclear fusion.

The internships involve workplace context training and comprise specific projects for each student.

Theses at IPFN

MSc Theses, 2021/2022

Alexandru Ciobanu, ***Topological waves in two-dimensional plasmas.*** Supervised by Hugo Terças.

Ana Sofia Ramalhete, ***Coupling of multiple proton-driven wakefield accelerator stages.*** Supervised by Jorge Vieira.

Bernardo Barbosa, ***Phase Control of Nonlinear Breit-Wheeler Pair Creation.*** Supervised by Marija Vranic.

Carlo Alfisi, ***Towards the detection of ultra-low energetic neutrinos with plasma metamaterials.*** Supervised by Ilídio Lopes and Hugo Terças.

Filipe Cruz, ***Mini magnetospheres in the laboratory.*** Supervised by Luís O. Silva.

Gabriela Gomes, ***An improved aerothermal database for hypervelocity air flows up to 25 km/s.*** Supervised by Mário Lino da Silva.

Girolamo Musso, ***Concurrent design study: Venus Atmosphere Sample Analysis mission.*** Supervised by Lionel Marraffa and Mário Lino da Silva.

João Pedro Ornelas, ***Dashboard Development for a Solar Electric Auto Rickshaw.*** Supervised by Horácio Fernandes and Paulo Branco.

José Carlos Veiga, ***Optimization and Evaluation of Solar Powered Electric Rickshaw.*** Supervised by Horácio Fernandes and Paulo Branco.

Luís Miguel Pereira, ***Applications of the Wigner function to quantum problems involving angle variables.*** Supervised by Hugo Terças and João Pedro Bizarro.

Mariana da Cunha e Silva, ***Production of single-cycle laser pulses through nonlinear pulse compression***. Supervised by Marta Fajardo.

Sebastião Antunes, ***Time-resolved studies of Warm Dense Titanium: A Bayesian search of coupling parameters.*** Supervised by Marta Fajardo and Gareth Williams.

Vasco Pinhão, ***Two-fluid models in solid state plasmas.*** Supervised by Hugo Terças.

Vladislav Frunza, ***Aerothermal Modeling of a CubeSat-based Biconic Reentry Vehicle.*** Supervised by Mário Lino da Silva.

MSc Theses, 2022/2023

André Antunes, ***Modelling solid-state High Harmonic Generation.*** Supervised by Marta Fajardo and Gareth Williams.

André Luís, ***Risk Analysis and Maintenance in Nuclear Facilities.*** Supervised by Alberto Vale and Virgínia Infante.

Daniel Batista, ***Routing problem optimization for mobile robots including the number and location of charging points.*** Supervised by Alberto Vale.

Francisco Madeira, ***Nonlinear Model Predictive Control for trajectory tracking and obstacle avoidance of industrial mobile robots.*** Supervised by Rodrigo Ventura and Alberto Vale.

Gonçalo Teixeira, ***Optioneering of transportation systems in nuclear facilities.*** Supervised by Alberto Vale.

Hélder Pereira, ***Radar in UAV obstacle detection and height navigation.*** Supervised by Alberto Vale and Rodrigo Ventura.

Inês Silva, ***Decentralized trajectory optimization for a fleet of industrial mobile robots.*** Supervised by Alberto Vale and Rodrigo Ventura.

Joaquim Nogueira, ***Design and Optimization of a SHCRAMJET Engine.*** Supervised by Mário Lino da Silva.

João Miguel Palma, ***Resonant interaction of fusion alphas and shear-acoustic Alfvén eigenmodes in burning plasmas.*** Supervised by Paulo Rodrigues.

João Silva, ***RAMI of the ITER CTS and Effects of Maintenance Plans on a System's Availability.*** Supervised by Diogo Rechena and Virgínia Infante.

João Tavares, ***Decentralized Market-Based Task Allocation for a Fleet of Industrial Mobile Robots.*** Supervised by Alberto Vale and Rodrigo Ventura.

Jorge Silveira, ***Plasma-surface interactions in plasmas for CO2 conversion.*** Supervised by Pedro Viegas and Vasco Guerra.

Manuel Maria Assunção, ***Integration algorithms for charged-particle dynamics in magnetised plasmas.*** Supervised by Paulo Rodrigues.

Marcelo Rodrigues Gonçalves, ***Machine learning for optimizing plasma resource utilization on Mars.*** Supervised by Vasco Guerra and Rodrigo Ventura.

Miguel Madeira, ***Permanent Magnet Optimization for Nuclear Fusion Reactors.*** Supervised by Rogério Jorge.

Miguel Mauritti, ***Assessment of the security of energy supply in Portugal in 2035-2040 and analysis of possible alternatives.*** Supervised by Bruno S. Gonçalves.

Miguel Roldão, ***Quantum Fluids of Light and Brownian Dynamics on Bose-Einstein Condensates.*** Supervised by Hugo Terças and José Tito Mendonça.

Nuno Veiga, ***Safe Landing Site Selection and Autonomous Landing of a UAV in Unstructured Environments.*** Supervised by Alberto Vale and Rodrigo Ventura.

Paulo Figueiredo, ***Transport of particles in nuclear fusion devices.*** Supervised by Rogério Jorge.

Pedro Rossa, ***Deployment of a microwave cavity experiment using the Framework for Remote Experiments in Education.*** Supervised by Horácio Fernandes and João Nuno Silva.

Rafael Almeida, ***Arbitrarily non-paraxial electromagnetic wave-packets in particle-in-cell codes.*** Supervised by Jorge Vieira.

Tiago Saraiva, ***Developing a systematic approach to enhance visualization and performance of a fleet of industrial mobile robots through Process Mining.*** Supervised by Rodrigo Ventura and Alberto Vale.

PhD Theses, 2022

Emanuel Ricardo, ***Assessment of reflectometry diagnostics for DEMO.*** Supervised by Filipe Manuel da Silva, Stéphane Heuraux (Univ. Lorraine) and Bruno Gonçalves.

Ruggero Giampaoli, ***Astrophysics in cold atoms: photon bubble turbulence.*** Supervised by José Tito Mendonça and João Rodrigues.

Yohanes Nietiadi, ***Nuclear technology and engineering studies on reflectometry systems for ITER and DEMO.*** Supervised by Raul Luís, Catarina Vidal (FCT/UNL) and Bruno Gonçalves.

PhD Theses, 2023

André Torres, ***Design and commissioning of the magnetic diagnostics system for COMPASS-U.*** Supervised by Horácio Fernandes, Bernardo Carvalho and Aleš Havránek (IPP Prague).

Chloé Fromentin, ***Reaction mechanism for CO2-N2 low-temperature plasmas: the role played by O2 and N2 on the CO2 vibrational kinetics and dissociation.*** Supervised by Vasco Guerra, Tiago Silva and Timo Gans (Dublin City Univ.).

Joana Alves, ***Ultrafast mid-infrared tunable laser sources.*** Supervised by Gonçalo Figueira, Jens Biegert (ICFO) and Hugo Pires.

João Braz, ***Vortices in two-dimensional condensates: towards a novel platform for quantum technologies.*** Supervised by Hugo Terças and Pedro Ribeiro.

Rui Calado, ***Modelling of Alfvén modes and their stability in the presence of ICRH-accelerated energetic ion populations in tokamak devices.*** Supervised by Fernando Nabais and João Pedro Bizarro.

Tiago Dias, ***Monte Carlo Algorithms for Low Temperature Plasmas.*** Supervised by Vasco Guerra, Milan Simek (IPP Prague) and Olivier Guaitella (LPP France).

Victor Hariton, ***Nonlinear spectral broadening and pulse compression in multipass cells.*** Supervised by Gonçalo Figueira and Celso João.

Awards and distinctions

Scientific prizes and appointments

>>Artur Malaquias, *member of the Technical Advisory Panel of Fusion for Energy for the term 2022-2023*

>>Bruno Soares Gonçalves, *ANACOM-URSI Portugal 2022 Prize*

>>Carlos Matos Ferreira†, Eduardo Alves, João Loureiro, José T. Mendonça, Luís O. Silva, Mikhail Benilov, and Vasco Guerra, *Stanford University World's Top 2% most influential scientists 2022 ranking*

>>Eduardo Alves, Luís Lemos Alves, Mikhail Benilov and Vasco Guerra, *Stanford University World's Top 2% Scientists 2022 ranking*

>>Frederico Fiúza, *Fellow of the American Physical Society (2023)*

>>Frederico Fiúza, *ERC Consolidator Grant for the project XPACE: Extreme Particle Acceleration in Shocks: from the laboratory to astrophysics*

>>FRIENDS project, *honourable mention at the 2023 Pedro Oliveira Innovation Award*

>>Jorge Vieira and Vasco Guerra, *ULisboa/CGD Scientific Prizes 2022*

>>Luís Marques, *Scientific Research Award in Military Sciences 2023*

>>Luís Marques and team, *Innovation Award in the Armed Forces 2022*

>>Marija Vranic, *2022 IUPAP Young Scientist Prize in Plasma Physics*

>>Marija Vranic, *2022 PRACE Ada Lovelace Award*

>>Marta Fajardo, *Tremplin Mariano Gago award for NanoXIMAGES project*

>>Pedro Viegas, *Outstanding Reviewer for Plasma Sources Science and Technology and Plasma Science and Technology (2022)*

>>Rui Coelho, *Outstanding Reviewer for Nuclear Fusion (2021 and 2022)*

Conference awards

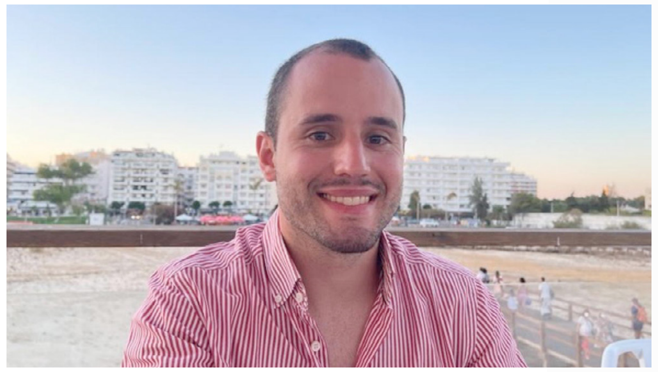
>>André Antunes, *2nd Prize student poster, ELI Summer School 2022, Szeged*

>>Carolina Amoedo, *poster prize at the AAC24 Advanced Accelerator Concepts Workshop*

>>Patrícia Estrela, *2nd Prize student poster, UltraFast Optics UFO XIII, 2023, Bariloche*

>>Sebastião Antunes, *1st Prize student poster, ELI Summer School 2022, Szeged*

>>Tiago C Dias, *poster prize at the XXXVth International Conference on Phenomena in Ionized Gases*



>>Tiago C Dias, *76th Gaseous Electronics Conference Student Award for Excellence*

Thesis awards

>>Luís Gil, *European Physical Society / Plasma Physics Division PhD Research Award 2023*

Academic distinctions

>>Luís O. Silva, *IST Distinguished Professor (2023)*

Biennial Report 2022-2023

Coordination and Chapter Editors
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Section Editors
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Horácio Fernandes, Luís Lemos Alves,
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