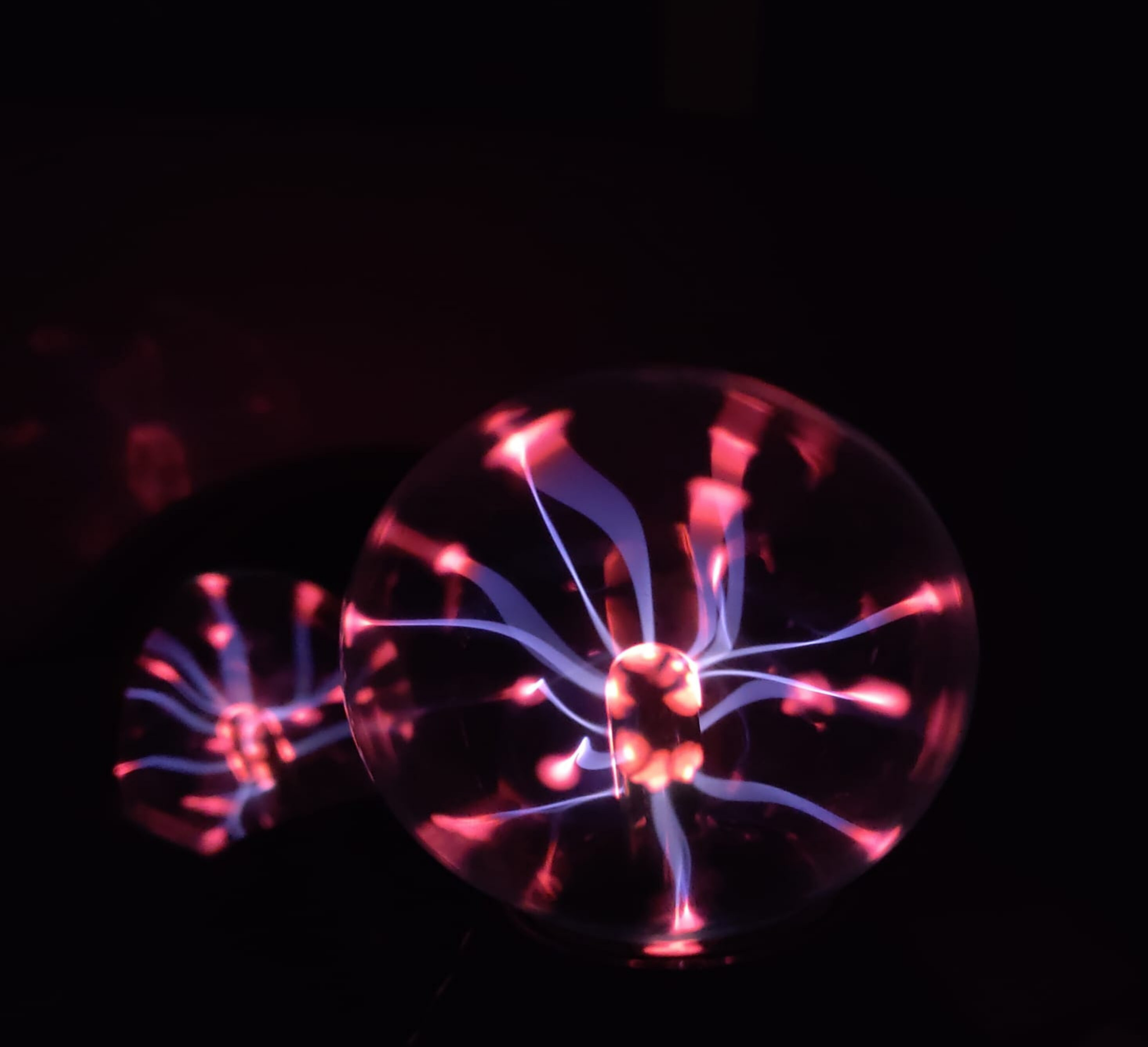


Biennial Report 2020-2021

Instituto de Plasmas e Fusão Nuclear

ipfn
INSTITUTO DE PLASMAS
E FUSÃO NUCLEAR

« Graphene produced using plasma technology with the PEL/N-PRiME machine

Biennial Report 2020-2021

Instituto de Plasmas e Fusão Nuclear

Highlights of activities

Contents

President's Foreword

I am very pleased to present the highlights of IPFN activities in 2020-2021 covering the activities 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 H2020 Programme of the European Union, projects of the European Space Agency (ESA) and projects funded by Fundação para a Ciência e a Tecnologia. These last two years were atypical, and it is undeniable the tremendous impact that COVID had on our professional and personal lives. Nevertheless, despite the difficulties, we are very proud that progress was made in our projects and research activities and, despite the difficulties, IPFN thrived:

The most recent evaluation of the Associated Laboratories by FCT (Foundation for Science and Technology), started in 2020 and concluded in 2021, has placed IPFN among the highest-ranked units, with an overall classification of "Excellent". We are very proud to reconfirm the level of the previous evaluation cycle allowing us to maintain 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 hosted a second ERC Advanced Grants InPairs (awarded in 2015 and started in 2016), awarded to Luis O. Silva for a total funding in excess of 3.4 M€. This grant recognises IPFN expertise on massively parallel kinetic plasma simulations and addresses the interaction of intense fields with plasmas and resulted in exciting scientific results, prizes and awards, invited talks and colloquia, and publications in the top multidisciplinary and physics journals.

The nuclear fusion activities at IPFN were strongly focused on the work programme established on the Fusion Roadmap for H2020 and ITER construction: (i) Participation in several contracts with Fusion for Energy for the development of ITER diagnostics, control and data acquisition and remote handling 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; and (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, on JET operation – with several IST researchers working full time at JET providing support to operation and diagnostics – and management, the contribution to medium-size tokamaks, in particular, ASDEX-Upgrade, which have been an integral part of the activities, an increasing contribution to DEMO activities (in diagnostics development and remote handling) and the award of two Enabling Research Grants to IPFN researchers.

IPFN is the leading institution of PEGASUS, funded by the highly competitive Horizon2020 programme FET (Future Emerging Technologies) Open. PEGASUS (Plasma Enabled and Graphene Allowed Synthesis of Unique nanoStructures), with 3.99 M€ funding, has the ambitious goal of using the unique properties of plasmas for the creation of extraordinary novel materials, by controlling the energy and matter transfer processes at nanoscales through specific plasma mechanisms. During this period PEGASUS progressed towards designing a proof-of-concept device for the large-scale production of N-graphene, resulting in four submitted patents of which three were already granted at the national level.

These were innovative projects that 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 through a large number of publications in prestigious journals.

High-Level Education and Outreach activities are essential in this strategy. IPFN continues actively striving towards attracting the best MSc and PhD students. The Advanced Programme on Plasma Science and Engineering (APPLAuSE) has been crucial to achieving this goal and we have decided to maintain this programme in the frame of the FCT Programmatic funding for the research units. 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.

Participation in large-scale projects is made through long-term commitment and funding support. On behalf of IPFN, I would like to acknowledge the support of Horizon2020, EURATOM, F4E, ITER Organisation, FCT (through project UUIDB/50010/2020 and UIDP/50010/2020), 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.

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

Bruno Soares Gonçalves
President of IPFN

About IPFN

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

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

Research at IPFN is organised into two Thematic Areas:

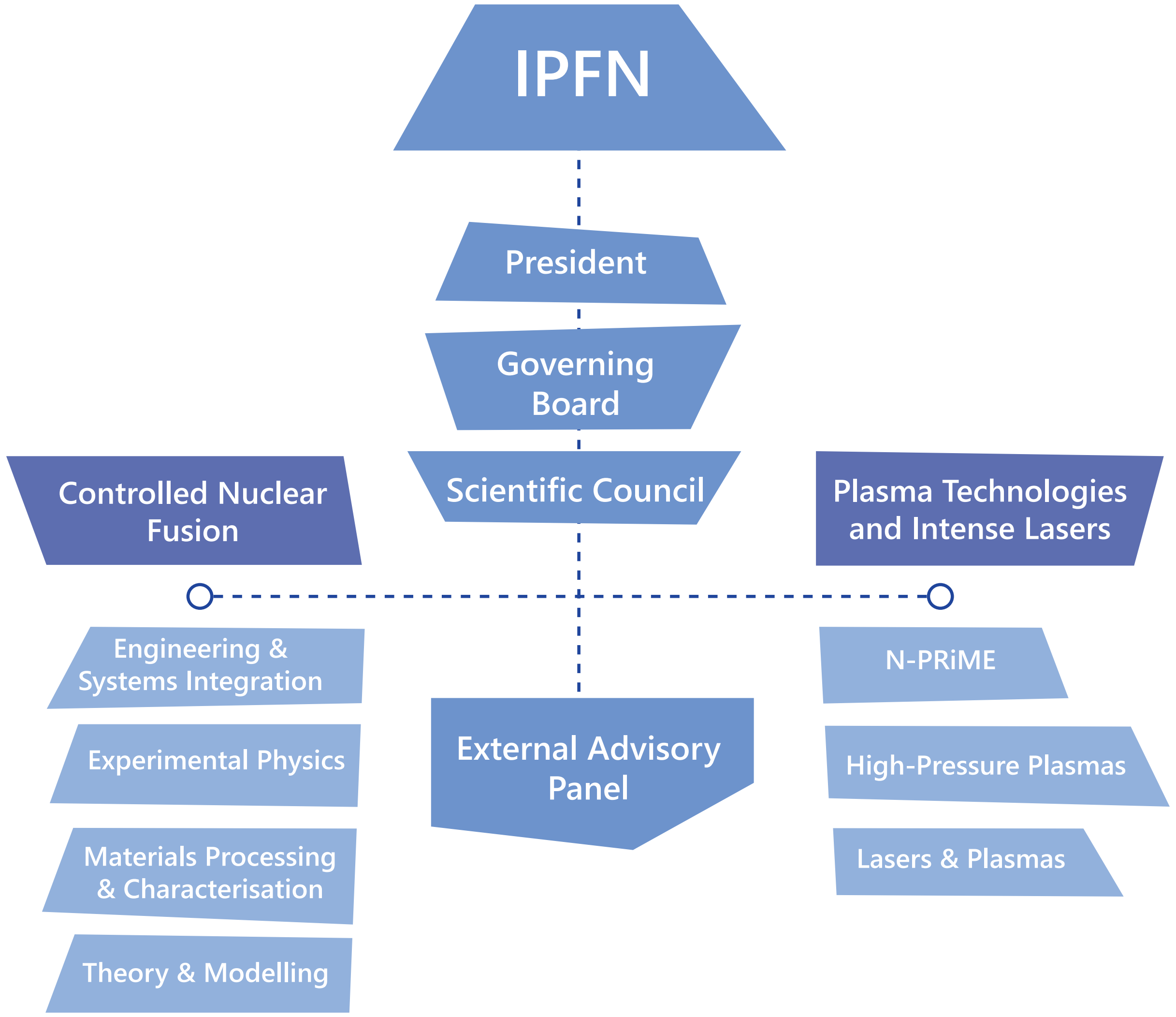
Controlled Nuclear Fusion - This research line is focused on the work programme established by the Euratom Fusion roadmap H2020, which includes activities associated with the development of systems, operation, and scientific exploitation of large and medium-sized tokamaks and stellarator, as well as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

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

Organisation

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

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



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

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

Management Board

Alberto Vale
PhD representative

Bruno Gonçalves
Group of Engineering and Systems Integrations

Carlos Silva
PhD representative

Eduardo Alves
Group of Materials Processing and Characterisation

Gonçalo Figueira
PhD representative

Helena Kaufmann
Group of High Pressure Plasmas

Horácio Fernandes
Group of Experimental Physics

Luís Lemos Alves
N-PRiME Group

Luís Oliveira e Silva
Group of Lasers and Plasmas

Mário Lino da Silva
PhD representative

Marta Fajardo
PhD representative

Rui Coelho
Group of Theory and Modelling

External Advisory Panel

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Chalmers University of Technology

Kunioki Mima
Osaka University

Francesco Romanelli
University of Rome

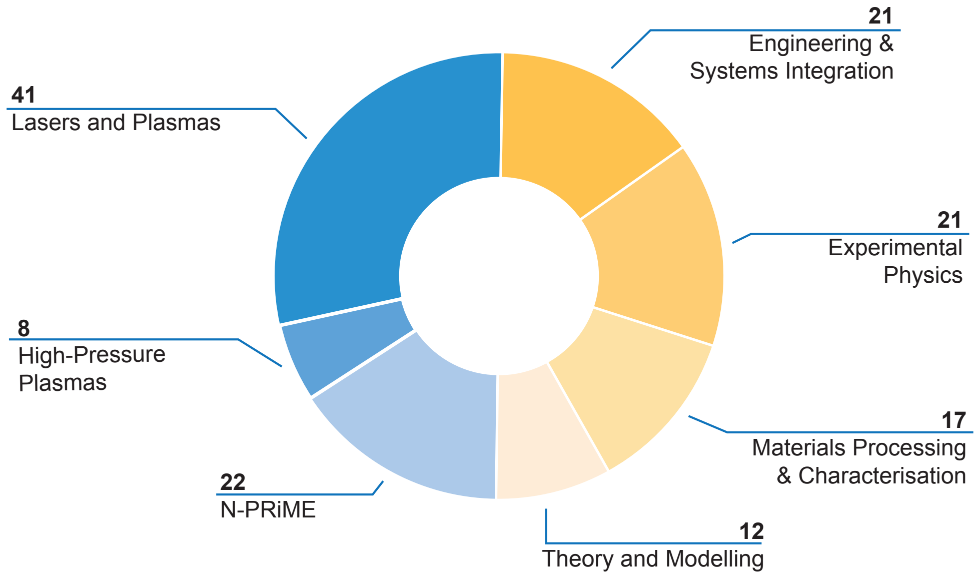
Jörg Winter
Ruhr-Universität Bochum

Leanne Pitchford
CNRS & Université Toulouse III

Facts and Numbers

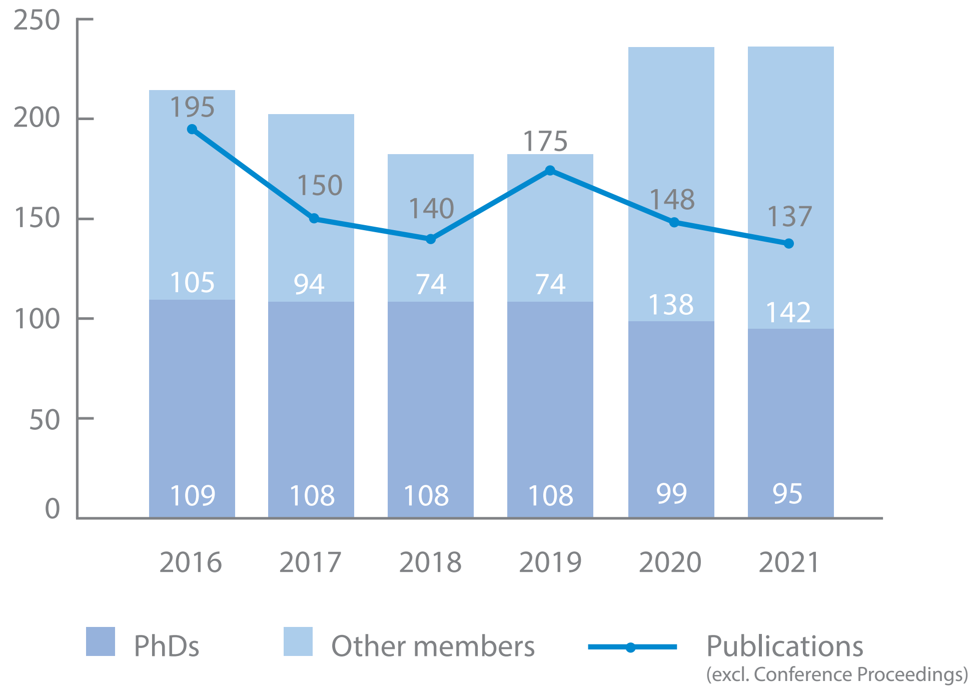
Members per Group

at the end of 2021



Collaborators and Publications

since 2016



142
Collaborators
at the end of 2021

26
PhD students

108
PhDs
faculty, researchers and postdocs

137
Publications per year
including Conference Proceedings

Highlights include papers published in

Nature

Nature Physics

Nature Photonics

Physical Review Letters

The Astrophysical Journal

Controlled Nuclear Fusion

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

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

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

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

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

Engineering and Systems Integration

Group Leader
Bruno Miguel Soares Gonçalves

Researchers

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

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

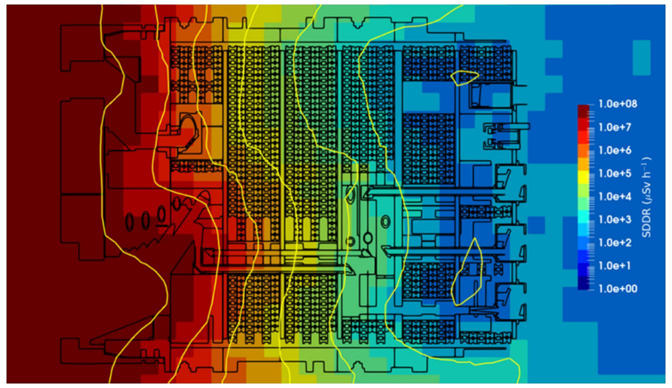
How to design reliable diagnostics for operation in nuclear fusion devices? How to design components able to cope with nuclear heating, plasma heat load, material fatigue and degradation? How to ensure high availability control and data acquisition systems? How to process the diagnostics data to ensure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

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

Contributions to ITER construction

Nuclear analyses for the ITER Collective Thomson Scattering diagnostic in-vessel system

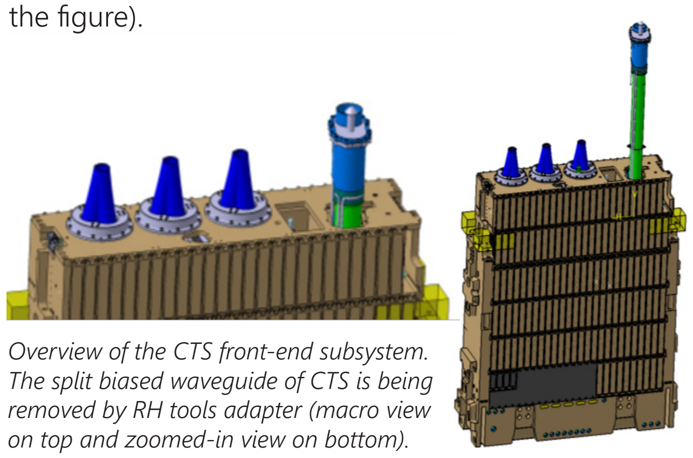
The ITER Collective Thomson Scattering (CTS) is the main diagnostic for measuring the velocity distribution of the alpha particles produced by the D-T reaction in ITER and has reached the Final Design Review Phase. The CTS system contains direct apertures to the equatorial port interspace, where maintenance is required. In order to ensure compliance with the radiation safety ALARA (As Low As Reasonably Achievable) principle, consecutive designs of the CTS system were evaluated using state-of-the art Monte Carlo simulation programs. The results show that the CTS system is not a significant contributor to the shutdown dose rates in maintenance areas, with dose rates below 1 µSv/h twelve days after shutdown in areas where the limit is 100 µSv/h. As the contribution of the CTS to the dose rates did not increase between design iterations, the final CTS design is compliant with the ALARA requirement.



Shutdown dose rates in the ITER Collective Thomson Scattering System Simulations have shown that the CTS system is not a significant contributor to the shutdown dose rates in maintenance areas and complies with the ALARA principle.

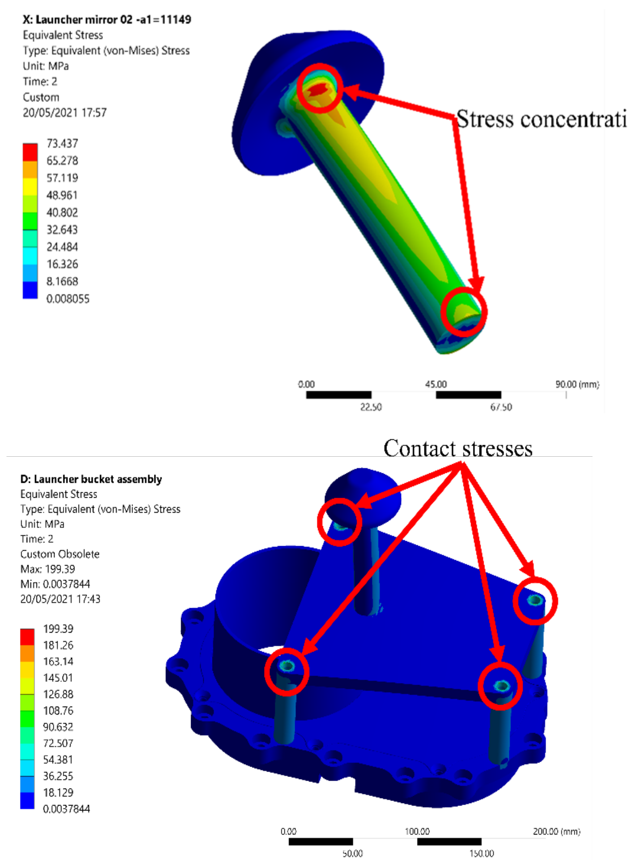
Remote Handling for ITER Collective Thomson Scattering in-vessel system

The CTS system consists of three main subsystems: the front-end (in-port plug part), the ex-vessel (atmosphere part) and the back-end. The CTS front-end subsystem, depicted in the first figure, consists of radially directed Radio Frequency launcher and receiver systems integrated inside the Diagnostic Shield Module #3 of Equatorial Port Plug #12 (EPP12). Whenever the EPP12 is taken to the Hot Cell (HC) facility, there is the opportunity to perform maintenance of the CTS front-end components, namely cleaning, inspection, refurbishment, and replacement (where the extraction is illustrated in the figure).

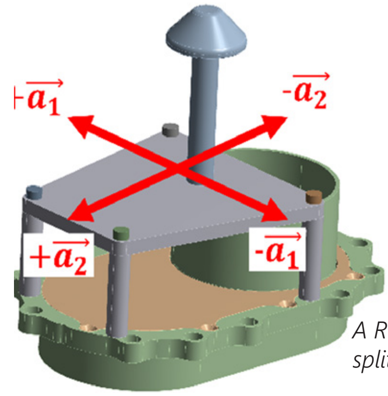


Overview of the CTS front-end subsystem. The split biased waveguide of CTS is being removed by RH tools adapter (macro view on top and zoomed-in view on bottom).

IPFN researchers defined how the maintenance requirements of the CTS front-end components are compatible with the ITER remote maintenance capabilities. It records the steps taken in the design, and the demonstration work carried out, that provide the CTS capability to achieve the required availability. Specific RH adapters (mushroom-like tools) that interface with the Hot Cell Remote Handling System tools to grasp and handle the CTS components have been designed, as illustrated in the figure. Because the RH adapters need to be able to grasp and handle the CTS front-end components without the risk of structural failure, a preliminary mechanical analysis of each adapter was performed.



Stress concentrations on the mushroom part of the RH adapter subjected to a horizontal acceleration (top) and for the launcher coupling bucket assembly considering its weight alone

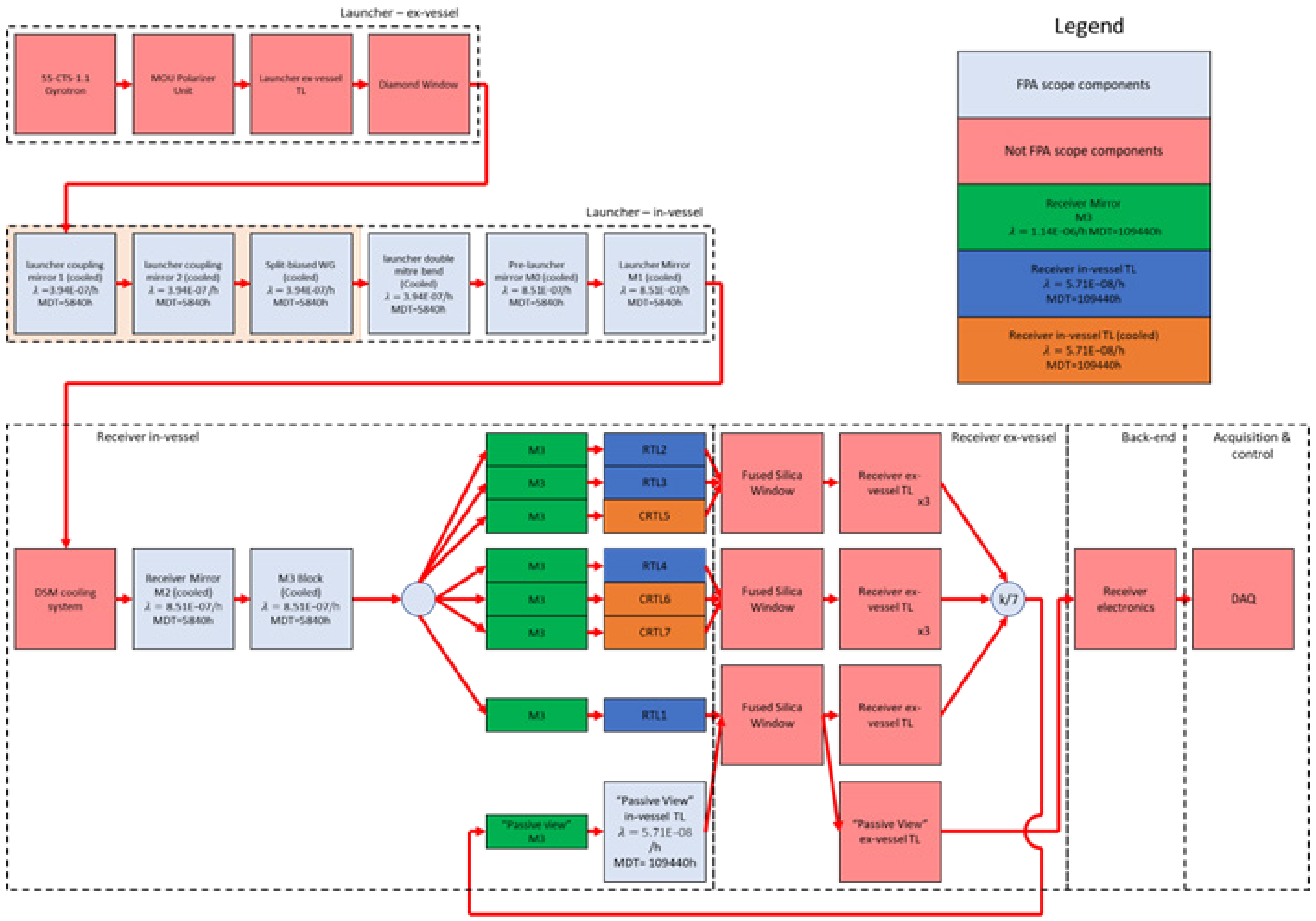


A RH adapter attached to the split biased waveguide.

RAMI for ITER Collective Thomson Scattering diagnostic

In order to operate and control the ITER fusion plasma, several diagnostic systems will be developed and installed in the tokamak. One of these diagnostic systems is the CTS. With the goal of high availability operation, it is necessary to ensure the continuity of correct operation and operational readiness of ITER's systems. The Reliability, Availability, Maintainability and Inspectability (RAMI) analysis is a set of methodologies with the purpose of managing technical risks of the operational phase during the design stages of the ITER machine. IPFN has worked towards identifying potential failure modes of the CTS front-end, their likelihood of occurrence and their consequences in terms of diagnostics downtime and their impact on ITER operations. Through the identification of risk mitigation actions, the CTS front-end design was updated, achieving a mean availability of 93%.

With the FDR of the CTS front-end having reached its conclusion, it is time to design the ex-vessel portion of the system and perform its RAMI analysis. While the ex-vessel components are not exposed to nuclear loads, they do make up a complex system with multiple interfaces such as high vacuum systems, cooling and pressurised air. IPFN is now working on the design of the ex-vessel whilst considering potential failure modes and how to deal with them from a system architecture, component design and maintenance operations standpoint.

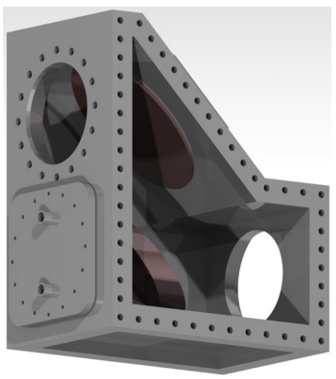


Neutron flux ratio between the neutron flux estimated with the detailed shielding structure and with a homogeneous shielding mixture.

Design of the ITER Collective Thomson Scattering quasi-optical launcher

The ITER CTS diagnostic uses a high-power (>1 MW) microwave beam to probe the plasma. A quasi-optical two-mirror arrangement located outside the vessel is used to couple the beam through a vacuum window mounted at the port closure plate; a similar arrangement, located inside the vessel, collects the beam and couples it to the front-end waveguide and mirrors. Outside the vessel, the mirrors are enclosed in a box that provides support and cooling for the mirrors and maintains the transmission line vacuum boundary. The box is attached to the vacuum window, to ensure the beam is correctly aligned. The reduced space available at the window location imposes strong restrictions on the integration and dimensions of the box. These restrictions limit the size of the mirrors and may have a negative impact on the overall coupling performance.

Our main goal with the quasi-optical box design is to achieve the best coupling with the in-vessel optics. Because we are dealing with a high-power beam, the minimisation of the beam spill-over at the mirrors and inse the transmission duct, formed by the vacuum window assembly and by the opening through the closure plate, is also a design driver. We found that the main design constraint arises from the relatively small useful diameter provided by the window assembly, which defines the aperture of the box thus restricting the maximum size of the beam. The requirement that the beam matches the already defined in-vessel optics is also an important design constraint. These issues are being actively addressed by both the CTS team and the windows ITER team. This work may lead to future changes in the design of both the quasi-optical box and the window assembly.

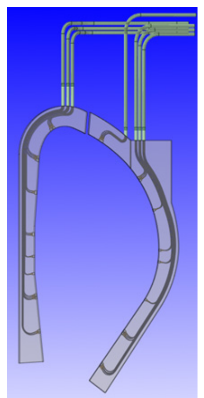


Quasi-optical launcher of the ITER CTS diagnostic. The drawing illustrates the box enclosing the two-mirror arrangement of the quasi-optical CTS launcher. The box provides support and cooling for the mirrors and maintains the vacuum boundary of the launcher transmission line.

Contributions to DEMO design

Diagnostic Slim Cassete concept for DEMO

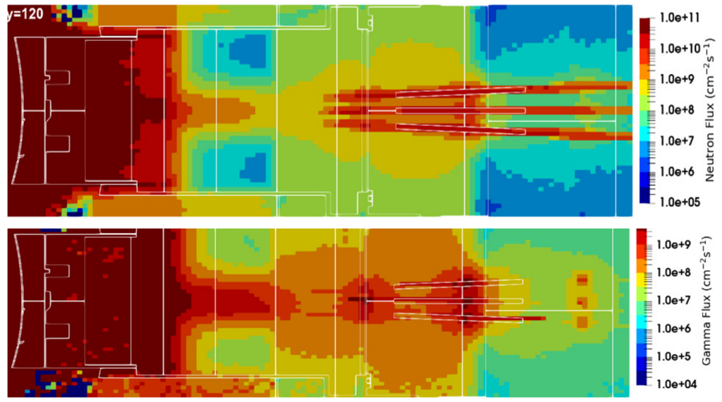
The diagnostics slim cassette (DSC) is a concept developed by IPFN for DEMO to host the microwave reflectometry diagnostic in a dedicated poloidal section, to measure the radial edge density profile at several poloidal angles and to provide feedback for plasma position and control. The DSC is expected to house up to 100 antennas and waveguides and is being designed with remote handling compatibility in mind, to facilitate a 'fast' exchange by remote maintenance. The main constraints related to the integration of the DSC in DEMO — with the breeding blankets and the upper ports — were identified, with a strong focus on the required remote maintenance operations inside the vacuum vessel. The proposed solutions can be adapted to present and future blanket and upper port designs. The current studies foresee a DSC attached to the blankets in two unaligned vertical planes (inboard and outboard), with the waveguides grouped inside pipes to be routed through the upper port and integrated with the blanket pipe modules. The sequence of procedures to manipulate the DSC were evaluated considering the existing pipe modules and the procedures for the installation and extraction of the blankets. A preliminary FMECA analysis of remote handling operations was performed for the DSC, including the identification of potential failure modes, the effects these failures may have on the system and how to avoid or mitigate them.



Diagnostics slim cassette for DEMO. The DSC, displayed partially transparent to show the antennas and waveguides, is expected to house up to 100 antennas and waveguides (WGs) distributed in clusters at 16 locations (gaps). Outside the DSC the waveguides are grouped inside pipes to be routed through the upper port.

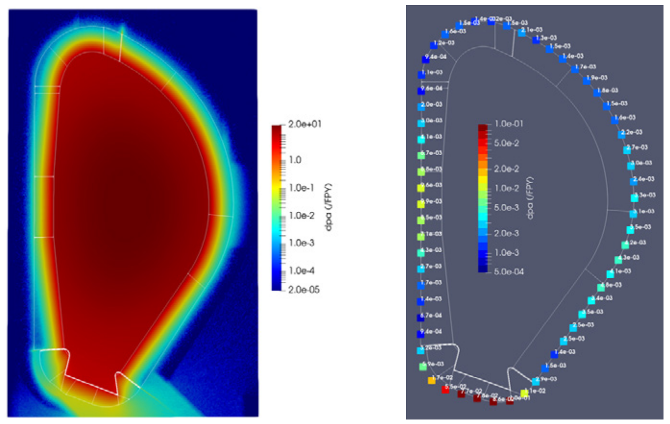
Neutronics simulations for DEMO Diagnostics

IPFN researchers collaborate with several European laboratories on the design of diagnostics systems for DEMO. Nuclear analyses have been performed for three systems proposed for the equatorial port: High-Resolution Core X-ray Spectroscopy, Near Ultraviolet, Visible and Infrared Divertor Monitoring and Pellet Monitoring. Different shielding configurations were tested, including the standard equatorial port shield block and several configurations of ITER-like boron carbide shielding trays. The results show that the usage of straight ducts in equatorial port diagnostics may increase the neutron fluxes in the Port Cell by up to four orders of magnitude when compared to the default port configuration without diagnostics. These results highlight the need to optimise the design of these systems from the neutronics point of view.



Neutron and gamma streaming through spectroscopy ducts. Straight ducts in the Equatorial Ports of DEMO used for spectroscopy diagnostics increase the particle streaming in the Port Cell by up to four orders of magnitude.

Neutronics simulations were also performed for magnetics sensors, distributed in 60 poloidal positions behind the DEMO blanket. Due to the excellent neutron shielding properties of the Water-Cooled Lithium Lead Breeding Blanket proposed for DEMO, the integrated neutron fluence behind the blanket is not expected to surpass the one foreseen for ITER. Therefore, magnetics sensors may be able to survive the extended operation periods of DEMO.

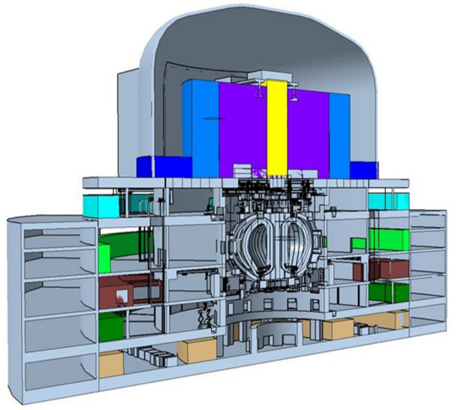


Displacements per atom (dpa) in magnetics sensors. The very low dpa values behind the breeding blanket of DEMO indicate that the magnetics sensors may be able to withstand the environment for extended operation periods without neutron-induced radiation damage

Remote Handling for DEMO

DEMO is intended to be ITER's successor, where the Remote Maintenance continues to play an important role. The ex-vessel operation of transportation inside the reactor building and between this and the Active Maintenance Facility is a culprit, mainly when the loads to be transported, such as the breeder blankets, overcome 100 tons. IPFN has provided contribution to the remote maintenance of transportation of equipment and hardware in upper port related to the design of breeding blanket transportation, single/double null divertor configuration, and in upper-equatorial, equatorial and basement levels of DEMO. Attention is given to Upper Maintenance Hall, where the Central Solenoid Magnet, Cryostat Upper Flange and Breeder Blankets are addressed. Since all Double Null concepts of Breeder Blanket fit inside the Single Null concept, a conservative approach is adopted and only the Single Null is considered to estimate the occupied volumes. Almost all occupied volumes have a ring-like shape, with exception of Upper Level for the transportation of Central Solenoid Magnet and Cryostat Upper Flange and the Lower Level, where manoeuvres are included for docking of casks. The total volumes were compared to the size of Olympic swimming pools.

Failures in ex-vessel operations may occur and IPFN also provided contribution with the proposal of strategies for recovery and rescue in all levels of the DEMO's reactor building, independently of the main ex-vessel transportation system considered in each level (overhead or ground-based), assessment of the building requirements to support the respective recovery and rescue operations. The risk of dropping loads, namely the extraction of breeder blankets from the vessel, were deeply addressed, where different solutions were considered and evaluated, as illustrated in the figure. The proposed solutions consider the stationary hoists approach, using hoists installed in the ceiling, with wire rope, sheaves and pulleys; the stationary winches approach, using winches installed in the wall (and possibly supported on the floor), with wire rope, sheaves and pulleys; the scissor lift approach using scissor lifting tables (with winches) installed on mobile platforms; the boom/lattice/telescopic crane; and the ground mobile crane, as illustrated in the figure.

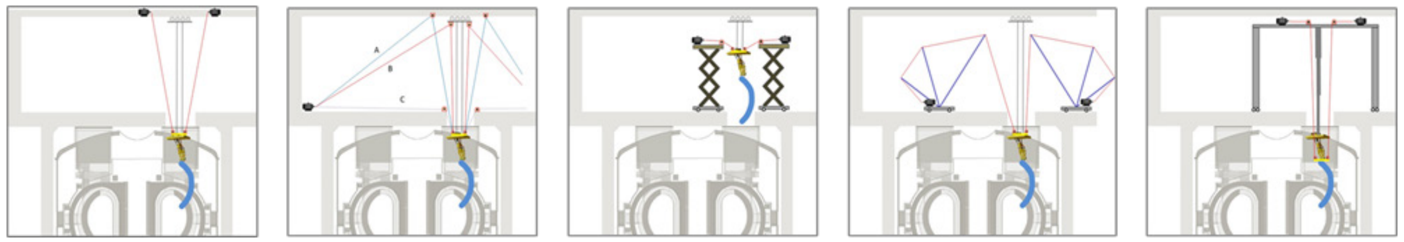


L-mode COMPASS discharge #19691. The radial control performed using only slow power supplies (500 µs control cycle) was switched between magnetic > reflectometry > magnetic controller inputs at t = 1.080 s and t = 1.220 s.

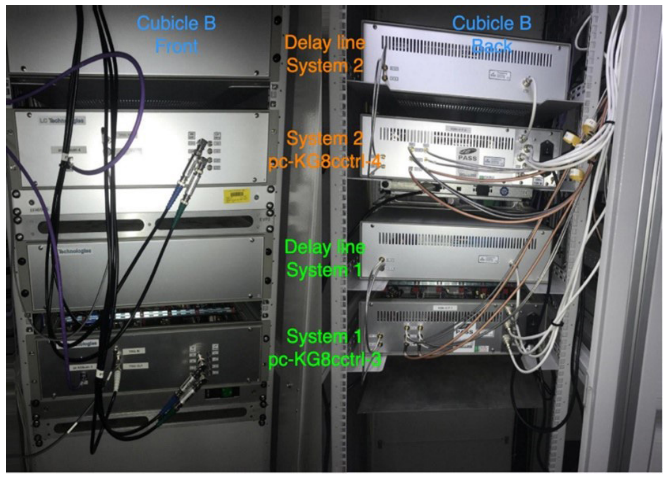
Contribution to JET enhancements

JET correlation reflectometry upgrade

IPFN led the Correlation Reflectometer Upgrade Project, a JET diagnostic enhancement implemented under the EUROfusion Consortium. The correlation reflectometer was upgraded with two new frequency bands (V and F) that extended the operational range of the system making it ready for JET D-T operation. The transmitting and receiving front-ends were installed, directly coupled to the waveguides on the quasi-optical boxes (QOB) and connected to the back-end by low loss coaxial cables operating in the frequency range 12 to 18 GHz. Each front-end, in a total of 8 units (4 transmitting and 4 receiving) are installed inside of aluminium cylinders. The four 19" back-end boxes were installed and fixed to a cubicle. All electrical connections were made, and the systems were all tested. The HTO (Hyper-abrupt Tuned Oscillator) based synthesisers can achieve very fast switching times, of the order of 20 to 40 µs. The frequency band can be operator selected and a set of coaxial relays establishes the correct combination of RF, LO, IF outputs/inputs. The system was commissioned during plasma operation. A new data acquisition system was installed with a higher sampling rate that permits the observation of higher frequency electron density fluctuations. All systems are operational although the F band shows a narrow loss of signal around 113.5 GHz, which should be corrected in the future.



Proposed solutions to mitigate the risk of drop loads in the upper port of DEMO.



Cubicle B at JD1 front (left) and back (right) with the new systems installed.

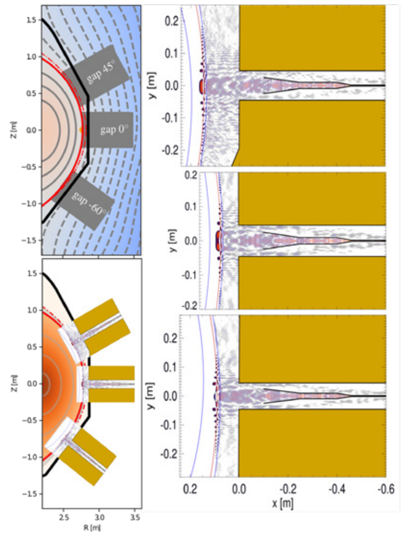
Diagnostic modelling activities

Modelling reflectometry diagnostics: finite-difference time-domain simulation of reflectometry for IDTT

The Divertor Test Tokamak (DTT) facility will study advanced exhaust solutions applicable to DEMO. This new machine opens the possibility to test and validate relevant non-magnetic control diagnostics, being one of the best candidates to implement and build a knowledge database of nonstandard reflectometry (away from the equatorial plane) that will be needed on DEMO and is currently unavailable. The performance of three Ordinary mode Plasma Position Reflectometers, placed, the first (gap 0°) on the equatorial plane, the second on the upper part of the torus (gap 45°) and the third on the lower part of the torus (gap -60°), at the Lower Field Side on DTT was assessed using the two-dimensional full-wave Finite-Difference Time-Domain, REFMULF, in two plasma scenarios.

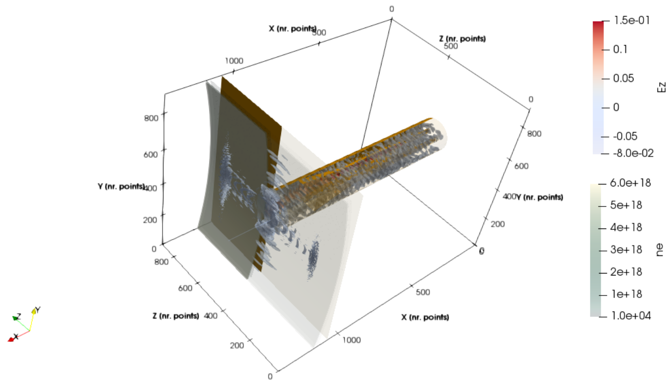
The main conclusion to take from this exercise is that the proposed positions are suitable for the placement of reflectometry systems at DTT and efforts towards an actual implementation of such systems, which would consist in one of the major advances in the last two decades, with a major impact on DEMO reflectometry plans.

FDTD simulations are computationally demanding, especially when it comes to three-dimensional (3D) simulations, which require access to High-Performance Computing facilities, making the use of 2D codes much more common. It is important to understand the compromises made when using a 2D



Left: a representation of the DTT vessel with the three locations, selected for the implementation of the synthetic reflectometers. On the top, the 2D map of the magnetic flux in machine coordinates Ψ(R,Z) and, on the bottom, the obtained 2D map of the electronic density in machine coordinates $n_e(R,Z)$. Right: snapshots of gaps 45°, 0° and -60° simulations.

model in order to decide whether it is applicable or a 3D approach is required. To appraise the differences, a comparison between the previous 2D simulations for gap 0 and a 3D case, obtained using REFMUL3, was carried through. One of the major differences between 2D and 3D simulations is the returned values for the amplitude, which are more realistic for the latter case, consistent with a decay proportional to R^{-1} for 3D and to $(\log R\sqrt{R})^{-1}$ for 2D. The phase is more resilient to the drop of the third dimension in the present simulations. Nevertheless, assessing the true values of amplitude is of major importance to have a proper signal-to-noise ratio. In an experimental setup, a low value of this ratio can impair the signal detection, especially in conditions of high turbulence. Accurate knowledge of the amplitude is also important to simulate and implement advanced methods for profile initialisation or reconstruction with hollow zones.



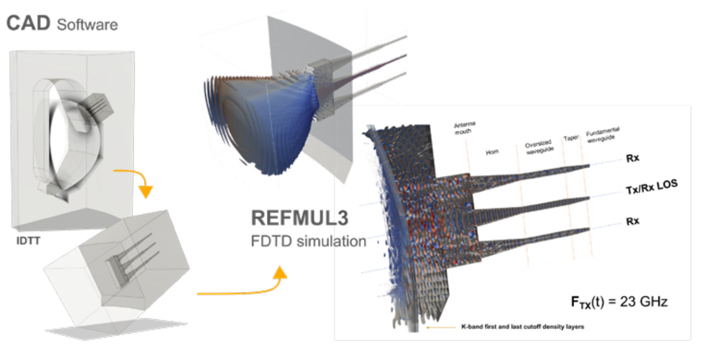
Snapshots a 3D K band simulations of IDTT gap 0°, taken at a frequency of f = 26.5 GHz. The 3D simulation volume grid size is 1348×899×899 leading to a total count of 1,089,454,948 grid points.

Developing of 3D models for simulation

Advanced simulation has become increasingly important in the planning, design, and assessment phases of future fusion plasma diagnostics, and in interpreting experimental data from existing ones. The design cycle of complex reflectometry systems, such as those being planned for next-generation machines (IDTT and DEMO), relies heavily on the results produced by synthetic diagnostics, used for system performance evaluation and prediction, both crucial in the design process decision making. These diagnostics need realistic representations of all system components, to incorporate the main effects that shape their behaviour. Some of the most important elements demanding to be well modelled and integrated into simulations are the wave launcher structures, such as the waveguides, tapers, and antennas, as well as the vessel wall structures and access to the plasma. The latter are of paramount importance and are often neglected in this type of studies. Faithfully modelling them is not an easy task, especially in 3D simulations.

Our team developed and demonstrated a software pipeline capable of producing 3D voxelised models for FDTD simulators, such as REFMUL3 (developed at IPFN), from detailed 3D models produced by standard CAD software. We proposed and validated a 3D model generation flow usable for producing highly realistic and detailed representations of tokamak vessel plasma-facing structures, emitting and receiving multi-antenna clusters and complex plasma access geometries. The adaptation of standardised STEP and STL CAD models ensures that the models used for realistic full-wave microwave simulations can be shared with neutronics, material stress and thermal analysis simulators. This add-on allowed REFMUL3 to become a full reflectometer simulator, suitable for sophisticated and integrated diagnostic design workflows.

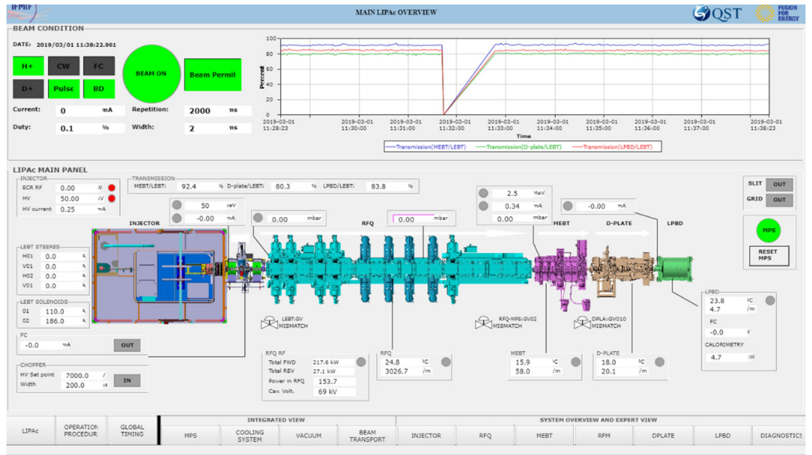
In the future, the analysis of the complex interaction between waves propagating in the plasma and the detailed antenna geometries and surrounding plasma-facing structures will be used for the test and validation of new signal processing techniques to improve reflectometry measurements made in less favourable propagation conditions, such as in probing the plasma along LOS oblique to the magnetic flux surfaces that requires the use of multi-antenna clusters.



Parameterised CAD models of an IDTT PPR antenna cluster adapted to the voxelised format required by the REFMUL3 3D full-wave FDTD simulator. Beam propagation in vacuum (top right) and snapshot (FTX(t)=23 GHz) of a K band sweep in plasma (IDTT single-null configuration).

Contributions to Broader approach

Participation in LIPAc-IFMIF Project



The LIPAc Operator Interface (OPI) can be visualised safely by the European scientific community thanks to the Data Diode software developed in collaboration with F4E and the Hardware Infrastructure designed and installed by the I&C Team at the F4E Barcelona headquarters.

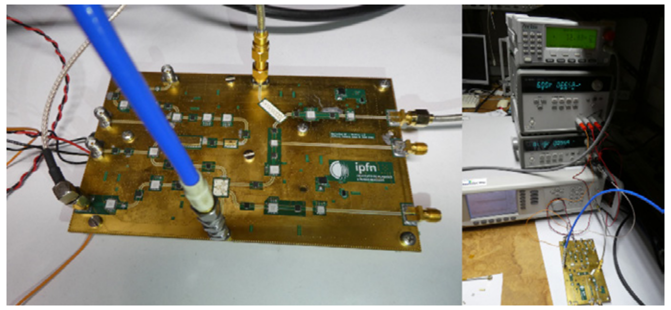
We have continued the collaboration with Fusion for Energy (F4E) in support of the International Fusion Materials Irradiation Facility (IFMIF), Japan, in the area of Instrumentation and Control through the contract for the provision of Engineering Services (led by Vitrociset). During 2020-21 the Data Diode, a software tool for Linear IFMIF Accelerator Prototype Accelerator operation and status real-time remote monitoring, has become an essential tool during the COVID-19 pandemic for remote collaboration between European and Japanese scientists. Data Diode has been developed in the framework of the

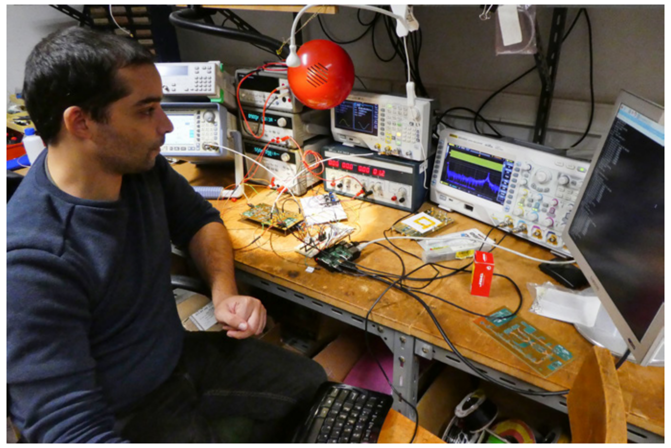
The scientific staff during the installation and tests of the new LIPAc Control Room with André Duarte (IPFN) standing at the top second from the right .

IPFN collaboration with F4E and the National Institute for Quantum Science and Technology. The LIPAc operator interface (see figure) can be monitored from European laboratories, whilst safely controlled from Rokkasho central control room. IPFN researchers participated in the successful installation and tests of the new LIPAc Control Room (second figure).

Other contributions

Compact microwave reflectometer





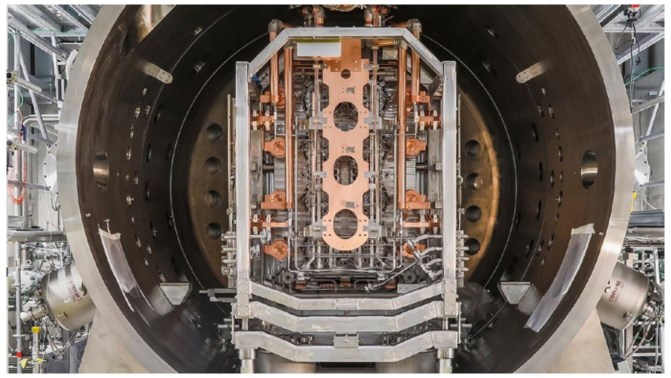
Testing of the back-end prototype.

We have been developing a prototype of a compact coherent reflectometer using commercial Monolithic Microwave Integrated circuits (MMIC). The prototype alone is capable of covering the NATO J-Band (10 GHz to 20 GHz), with a fast (5 µs) full band sweep. It is possible to extend the prototype bandwidth with external full band multipliers, up to 140 GHz, giving significant flexibility to the system depending on the application.

The project is near its conclusion with the last prototype boards in the final assembly and testing phases. The back-end and the IQ boards were designed for an easy installation on a standard 3U 19" rack. Each board will include electromagnetic shielding, now in the manufacturing process at the IST workshop. Test results show that the project goals were achieved. In the next step, the use of DDS for signal generation will allow very linear and agile frequency chirps. Direct digitalisation of the IF signals will allow the use of highly flexible data processing techniques. The DDS testing will start as soon the necessary parts are procured and purchased.

IPFN joins the EUROfusion team in ITER Neutral Beam Test Facility

A new collaboration with the ITER Neutral Beam Test Facility (NBTF) in Consorzio RFX, Padua, Italy, was started. NBTF is a joint international effort to develop the neutral beam injector prototypes for ITER. NBTF facility hosts (i) the Source for the Production of Ions of Deuterium Extracted from a Radiofrequency plasma (SPIDER), an ITER-scale negative ion source designed to achieve all ion source requirements;



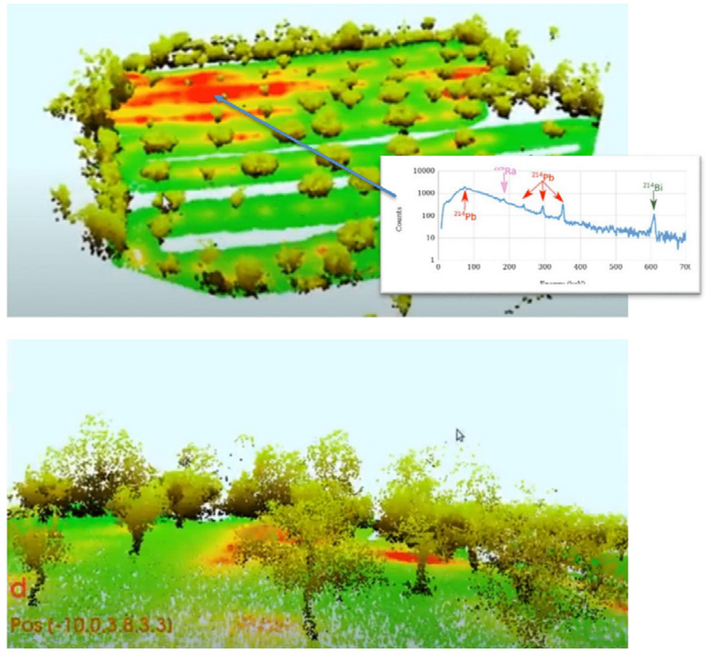
Nuno Cruz (bottom) at the entrance of the ITER Neutral Beam Test Facility where he has started his secondment as I&C expert in June 2020. Inside of the largest negative ion source in operation in the world, the SPIDER ion source (top) and the NBTF High Voltage Hall (middle).

and (ii) the Megavolt ITER Injector and Concept Advancement (MITICA), the full-size prototype of the 1 MV heating neutral beam injectors.

A new Cooperation Agreement between ITER, Consorzio RFX and EUROfusion allows European researchers to join NBTF to work on the world's largest plasma heating system. IPFN researcher Nuno Cruz was selected through an international call to join the team of researchers seconded to ITER NBTF as an Instrumentation and Control (I&C) expert, where he will be in charge of the integration, testing, operation and documentation of I&C and diagnostic systems. The researcher has been responsible for the design and development of the SPIDER Configuration Tool that sets the machine parameters for the scientific experiments, verifying the safety features of the machine and comparing them to previous successful experiments.

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

One of the hexacopter drone used in the FRIENDS project equipped with the LIDAR system and radiation sensors



3D representation achieved by the LIDAR system installed on the drone also equipped with radiological sensors, where the radiation intensity levels are represented at the ground by colours (aerial view on top and ground view on bottom).

The FRIENDS and APA team during an exercise in the open pit uranium mine.

The detection of radioactive hot-spots and the identification of the radionuclides present have been a challenge for the security sector, especially in situations involving chemical, biological, radiological, nuclear and explosive (CBRNe) threats, as well as naturally occurring radioactive materials (NORMs). The FCT-funded project FRIENDS: Fleet of dRones for radIological inspEction, commuNication anD reScue led by IPFN and in collaboration with ISR, C2TN and IT-Aveiro, aims to design, develop and validate a fleet of drones equipped with navigation and radiological sensors for inspection and monitoring of scenarios with nuclear threats.

The first experiments in the field were performed in November 2020 in i) a flooded open-pit uranium mine and, close to it, an artificial hill formed by the stacking of debris, and ii) in uranium outcrop partially disrupted by land removal and spread through an olive field. 3D representations of the scenarios are obtained during the experiments by drones equipped with LIDAR systems installed and Geiger-Müller counters. The hotspots were identified and evaluated on ground by experts equipped with gamma-ray spectrometers sensors. Goals were fully achieved and fast detection of uranium decay products (Bi-214, Pb-214, Ra-226) was possible, revealing higher count rates at the hotspots identified at the olive field. This field exercise was made under the supervision of technicians from EDM (Empresa de Desenvolvimento Mineiro) and APA (Agência Portuguesa do Ambiente).

A solution based on Machine Learning techniques, with a focus on Artificial Neural Networks (NN), has been tested to localise, quantify and identify radioactive sources, with promising results [1]. NNs have demonstrated the capability of being an emerging tool with the potential to make a difference in the nuclear field, by helping in the development of novel techniques and new solutions in order to safeguard human lives.

References

1. F. Mendes et al J. Radiol. Prot. 42, 011516 (2022).

Experimental Physics

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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, COMPASS, TCABR and more recently SMART. Our research focuses on the development of diagnostics and real-time control systems, liquid metals plasma-facing walls, participating in experimental campaigns and collaborating in the modelling, data analysis and development of numerical codes. ISTTOK serves quite often as a first-time fusion test device for new concepts due to its simplicity and reduced lead time. GFE is also responsible for the scientific exploitation of the reflectometry diagnostics developed by IPFN, with a focus on ASDEX Upgrade and JET.

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

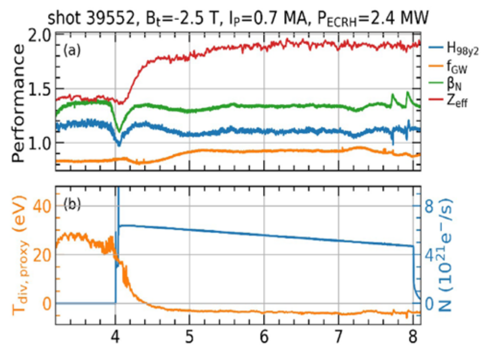
ISTTOK is the only current AC tokamak, bringing the few milliseconds of operation of similar devices up to seconds. Around it, new diagnostics systems for fusion devices are being developed such as Heavy Ion Beam probing and a continuously evolving plant operation framework for machine increased performance.

Advanced education is also provided for a considerable number of MSc and PhD students working under our team supervision and by hosting the IAEA training program in Tokamak Engineering and Operation complementary to the PlasmaSurf summer school.

Contributions to ASDEX Upgrade program

Improving the performance of the EDA H-mode

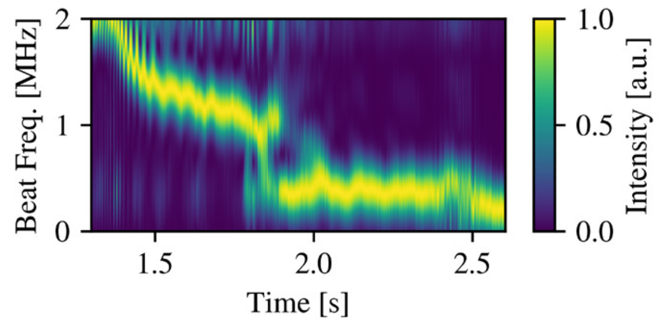
The EDA H-mode is a scenario with numerous positive features for a fusion reactor, such as high energy confinement, compatibility with tungsten walls, and low impurity content despite the absence of edge-localised modes (ELMs). We recently took different measures to enhance the performance of this regime in ASDEX Upgrade. With strong shaping, it can be accessed within a wider heating power range, allowing the achievement of higher temperatures. The higher power calls for better heat exhaust, which was successfully accomplished with nitrogen seeding. This increases divertor radiation, leading to much lower target heat fluxes without degrading confinement. In addition, argon seeding proved effective in radiatively cooling the pedestal with low impact in the core, further raising the achievable pressure without ELMs. Future experiments will focus on deeply understanding the physics of the EDA H-mode in order to improve the reliability of its extrapolation to large-scale devices.



EDA H-mode discharge in ASDEX Upgrade: (a) performance indicators; (b) divertor temperature proxy (orange) and nitrogen seeding (blue).

Impact of inverted density gradients on density profiles measured by reflectometry

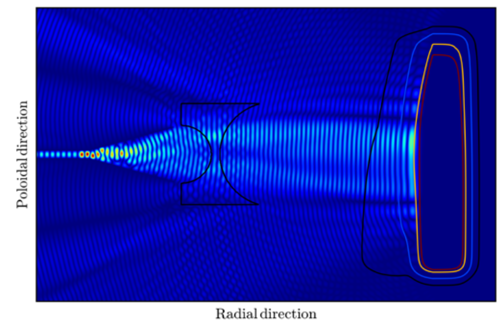
The high-field side high-density (HFSHD) region at ASDEX Upgrade is a well-documented phenomenon leading to a dense plasma in the inner divertor region that expands upwards to the midplane, resulting in poloidally asymmetric scrape-off layer density profiles. We have investigated, via simulation and experiment, whether the HFSHD at the midplane leads to hollow density profiles at the high-field side. Using the O-mode reflectometer at ASDEX Upgrade, experimental evidence has been found of reflection patterns compatible with a hollow density profile that are reproduced by 1D full-wave simulations. Furthermore, we have shown that the presence of an HFSHD may lead to an overestimation of the density in the confined region. We will explore alternative algorithms to reduce the reconstruction uncertainties using more information from the reflected signal.



Evolution of the power spectra of the beat signal showing a reduction in the beat frequency coinciding with the formation of the HFSHD.

Synthetic turbulence and MHD measurements with microwave reflectometry

The performance of a nuclear fusion reactor will strongly depend on the characteristics of turbulence and magnetohydrodynamic (MHD) instabilities. To understand and ultimately control these phenomena, we have successfully applied microwave reflectometry techniques have, with strong support from modelling and simulations, where a full-wave treatment is required to properly study wave propagation. Complete chains, integrating a two-dimensional full-wave code (REFMUL) simulating reflectometry in realistic plasma descriptions obtained from three-dimensional gyro-kinetic and non-linear MHD simulations have been implemented (using the GEMR and JOREK codes, respectively). This allows modelling real experiments such as the ASDEX Upgrade with an unprecedented capability, as well as predicting with greater confidence the behaviour of reflectometry in future machines such as ITER or DEMO. It is expected that the next generation of simulations of microwave reflectometry will combine the outputs of the 3D gyro-kinetic codes with a 3D full-wave treatment, allowing the interpretation of problems such as the cross-polarisation scattering by plasma fluctuations.



Synthetic diagnostic implementation. 2D REFMUL simulation run during an H-mode Type-I ELM crash in the ASDEX Upgrade tokamak, as obtained from the 3D JOREK code.

Contributions to the JET program

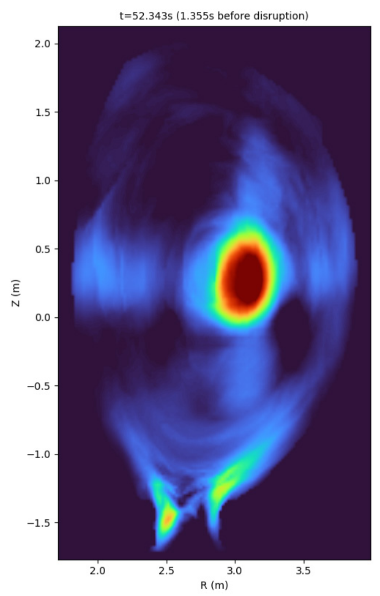
Structure of the JET edge radial electric field in He and D plasmas

The existence of a strong shear in the plasma flow perpendicular to the magnetic field is thought to be fundamental for the edge turbulence suppression, explaining the transition to the improved confinement regime (H-mode). However, the origin of the perpendicular flow is still not fully understood. We performed detailed plasma flow measurements by Doppler backscattering in JET experiments designed to determine the effect of the main ion species mass in the L-H transition physics. We found that the perpendicular flow profile at low density has a modest or even no well and a marked peak near the separatrix. As the density increases, the

SOL peak decreases, while the well becomes deeper. Contrary to observations in other devices, we found no evidence for the existence of a critical value in the perpendicular flow at the transition. This may be explained by the existence of an edge toroidal flow relevant mainly at low density, where the power threshold is high. Surprisingly, no significant change in the edge perpendicular flow was measured preceding the L-H transition. Our results indicate that the trigger for the L–H transition is not solely defined by the mean perpendicular flow profile at the plasma edge.

Real-time bolometer tomography at JET

The use of real-time tomography at JET opens up new possibilities for monitoring the plasma radiation profile and for taking preventive or mitigating actions against impending disruptions. By monitoring the radiated power in different plasma regions, such as core, edge and divertor, it is possible to set up multiple alarms for the radiative phenomena that usually precede major disruptions. The approach is based on the signals provided by the bolometer diagnostic. Reconstructing the plasma radiation profile from these signals is a computationally intensive task, which is typically performed during post-pulse analysis. To reconstruct the radiation profile in real-time, we use machine learning to train a surrogate model that performs matrix multiplication over the bolometer signals. The model is trained on a large number of sample reconstructions, and is able to compute the plasma radiation profile within a few milliseconds in real-time. Experimental results

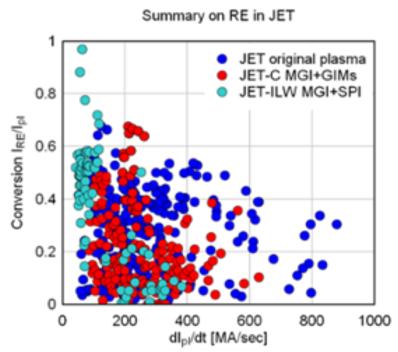


Tomographic reconstruction of the plasma profile showing a peak in core radiation.

show that, during uncontrolled termination, there is an impurity accumulation at the plasma core, which eventually leads to a disruption. A threshold-based alarm on core radiation, among other options, is able to anticipate a significant fraction of such disruptions.

Disruption and Runaway electron studies in JET in support of the design of ITER-DMS

The development of ITER DMS requires an understanding of the generation of relativistic electron beams and their interaction with the massive quantities of matter. As the evolution of the plasma parameters during the thermal and plasma current quench stages of the disruptions is poorly known, numerical simulations of RE generation often use model functions. We aim at formulating input data for simulations based on key experimental physical processes capable of determining the suppression/avoidance of disruption generated RE in ITER. An experimental database on RE generated during JET disruptions has been collected and analysed to establish its trend depending on disruption parameters. The experimental data were processed taking into account the differences and similarities (phenomenological and numerical) in spontaneous or triggered by GIMs, Massive Gas Injections and Shuttered Pellet Injections disruptions.



Surprisingly decreasing dependence of conversion ratio IRE/Ipl vs. plasma current time derivative (new data), which may represent a possible critical issue for RE data extrapolation to ITER parameters.

ISTTOK

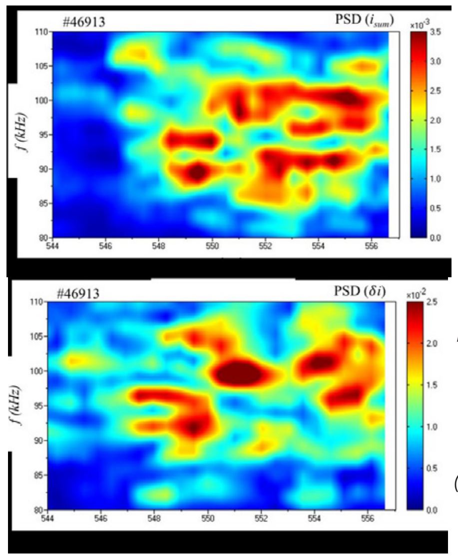
Commissioning of the 90° Cylindrical Electrostatic Energy analyser in ISTTOK

The measurements of probing beam energy of the Heavy Ion Beam Diagnostic allow the local measurement of plasma potential. The innovative proposed Cylindrical Energy Analyser (CEA) detector operation is based on the deceleration mode which takes advantage of probing beam retardation in order to perform plasma potential measurements with improved resolution. SIMION simulations have indicated that the deceleration mode has significant improvements in the beam energy measurements resolution and angle aberration characteristics as compared to conventional CEA operation. An additional intermediate unit, the electrostatic input module (EIM), responsible for focusing and deflecting the secondary beams from ISTTOK plasma output to CEA detector input was also designed and optimised in SIMION. Both systems were installed in the ISTTOK tokamak. The single-channel 90° CEA prototype operating in two-times deceleration mode was successfully commissioned and demonstrated the capability to measure the plasma potential and its fluctuations.

ISTTOK overall control assessment

The ISTTOK tokamak operates in AC mode allowing it to have consecutive positive and negative plasma current cycles, being the unique tokamak featuring this type of operation. This fact requires a very demanding and regularly developed control system in order to test several control strategies. Benchmarking those strategies allows one to determine not only the best control algorithms but as well estimators for the plasma centroid position.

Furthermore, the recent implementation of numerical integrators in the real-time ATCA based data acquisition system substantially improved the real-time conditioning of the measurements of the magnetic signals. First results demonstrate that this approach, using state-space models obtained through retrieved experimental data for the designing of Kalman filters and MIMO-LQR optimal controllers, delivers a more reliable estimation of the plasma current centroid position with a noticeable improvement in control performance, which is paramount to the success ratio of the AC plasma current switching.

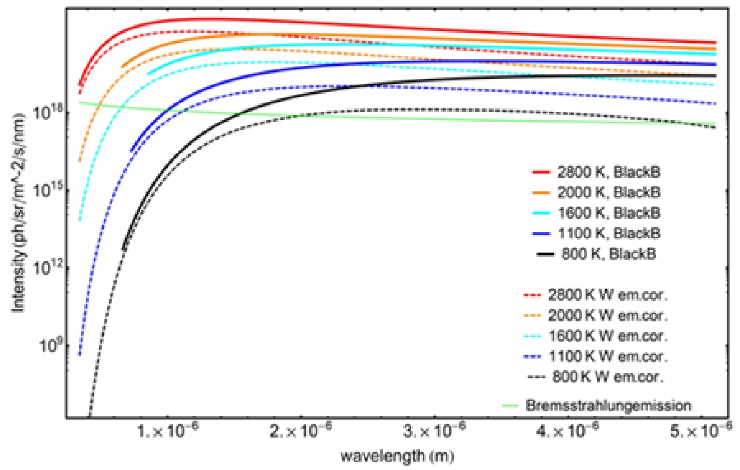


Power spectra density of plasma potential (top) and plasma density (bottom) as a function of time (ms) for the frequency range (80-110 kHz).

Other contributions

Optical analysis for DEMO divertor view diagnostic in the UV to IR spectral region

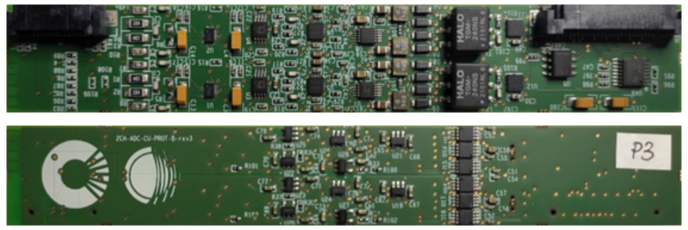
The optimisation of the optical system with a ZEMAX© model for DEMO's divertor view diagnostic was conducted. The full coverage of the divertor will be achieved by five different lines of sight, each based on a set of six mirrors imaging the region of interest through a 30 mm diameter pupil. This configuration with three "dog-legs" is deemed to provide suitable attenuation for neutron dose at the bio-shield exit. The optimisation process on ZEMAX© resulted in a 46 mm diameter image with a 1/17 imaging ratio and less than 70 µm rms spot size. The mentioned diagnostic is aimed at assessing two control parameters: divertor detachment state and divertor tiles temperature. For detachment analysis purposes, the assessment of density profiles time evolution at the X-point vicinity is achieved by performing Stark spectroscopy of Balmer and/or Paschen series. A value of $1.34X10^9$ ph/nm/s has been evaluated to reach the coupling fibre at the exit port for the D10-2 Balmer line, taking into account system geometry (throughput), overall mirror/window transmittance (rhodium mirrors, quartz window) and similar plasma emission intensity as measured on JET divertor. The most suitable wavelength range for the tiles temperature measurement has been assessed, comparing evaluated tiles emissivity corrected emission with calculated line integrated bremsstrahlung radiation. Results show that measurements around 800 ºK can only be achieved in the 3 to 4 µm wavelength range.



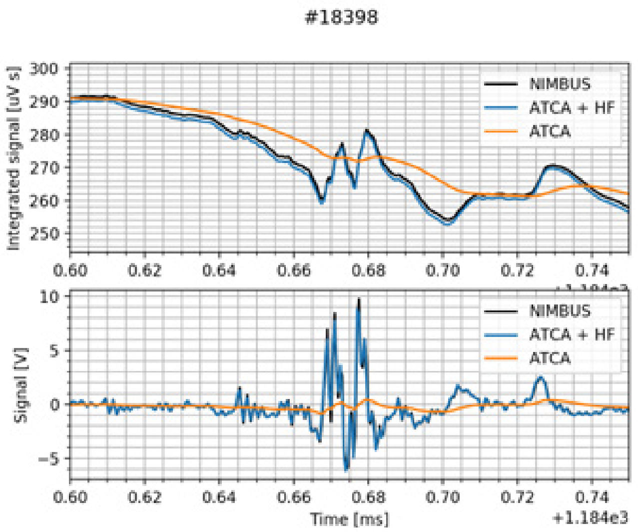
Line integrated Bremsstrahlung emission compared to W tiles emissivity, at several temperatures, for DEMO's divertor view diagnostic.

COMPASS-U

The collaboration with IPP.cz has a long track on the development and installation of new facilities in Prague starting with COMPASS commissioning and currently with the new design and construction of COMPASS-U. At the moment we are involved in the development of MHD signal coils which face the challenge of operating at very high temperatures (>500ºC) maintaining the necessary frequency response desired not only for machine control but also for MHD studies. For that end, an algorithm to recover high-frequency components of magnetic signals acquired with low bandwidth is being tested using ISTTOK data capture modules installed previously in COMPASS. The new face-lift prototypes for the data capture modules for COMPASS-U include more recent and recommended components addressing some of the problems used in previous versions as for the new data acquisition and control hardware.



COMPASS-U Magnetics data acquisition modules prototype.



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

Materials Characterization and Processing

The major goal of our activities is to unveil the physics behind plasma-wall interactions. Processes like fuel retention and material transport and deposition are key factors in fusion reactor technology. Several projects addressing these problems, funded by EUROfusion contracts, were executed during the reporting period. We analysed the changes in reference tiles retrieved from JET to study the multiple and complex interactions, namely, erosion and deposition, diffusion, implantation and fuel retention induced by the plasma. A great finding of these studies supports the long term stability of fuel retention in the reactor tiles. In addition, the low fuel retention and dust production was confirmed, a crucial result for ITER construction and operation.

Another important topic concerning the construction of fusion reactors is the availability of materials to operate in extreme conditions of radiation and temperature. We started the study and development of new 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. We sintered CuxCrFeTiV alloys with different stoichiometry by ball milling, followed by consolidation with spark plasma sintering. These newly designed alloys display very promising properties for fusion applications.

Finally, we kept our participation in European networks on ion beam technologies as a tool to model and tailor the properties of new materials with particular emphasis on wide bandgap semiconductors and advanced materials.

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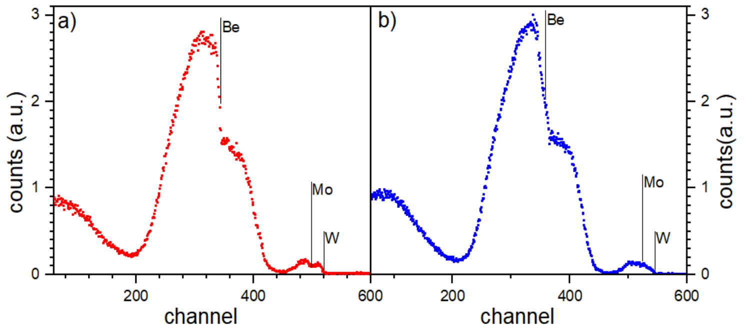
Plasma-wall interactions in JET ITER-like wall

The ITER-like wall of JET gave the possibility to study most of the relevant plasma-wall interactions expected to happen in ITER and DEMO fusion reactors. In parallel, we also used some mixed coatings produced in the laboratory to study the fuel trapping and mixing mechanism.

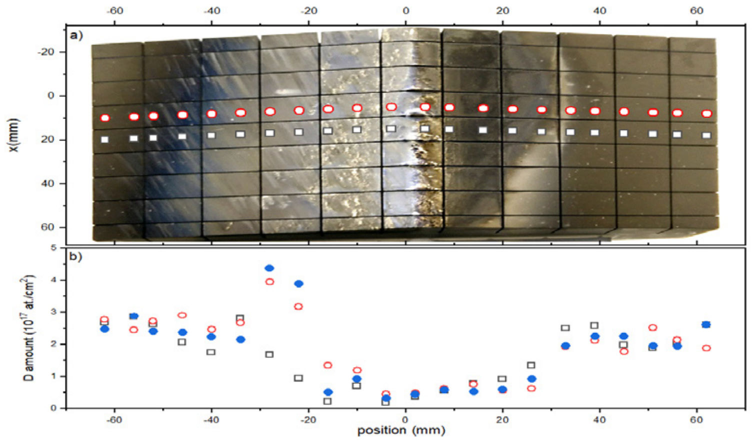
Our main goals are the evaluation of material migration, erosion/redeposition and fuel retention in plasma-wall interactions in JET and West tokamaks. Ion beam techniques were used to measure reference tiles and other diagnostic components to obtain the profiles and quantify 2H and Be deposited on the tiles.

Several tiles and diagnostic components were studied in a dedicated experimental chamber. Special marker tiles were used to measure the erosion process. The fuel retention mechanisms in mixed layers were also investigated in Be and W-based co-deposited layers produced in-situ with different compositions, bulk temperatures and surface morphologies in order to mimic the structures and compositions found at JET and investigate fuel retention mechanisms [1].

Our results gave updated fuel inventories and provided comparisons of individual mid-plane limiter and divertor tiles exposed during the three irradiation campaigns, ILW1, ILW2 and ILW3. The results indicate a continuous accumulation of fuel in deposits, with no release during operation. In addition, divertor tiles also reveal similar deposition patterns after each individual campaign. A major finding indicates that fuel retention remains stable after long term storage of the tiles (see figure). The results were fundamental to validate the theoretical models and provide relevant figures to design a safe reactor. Studies on plasma-wall interactions in different plasma configurations in WEST and linear devices will continue as well as the study of fuel trapping and chemical interactions in laboratory deposited materials.



Comparison of Elastic Backscattering Spectrometry (EBS) spectra measured in a) 2016 and b) 2020 in the same spot of Dump tile 2BC4.

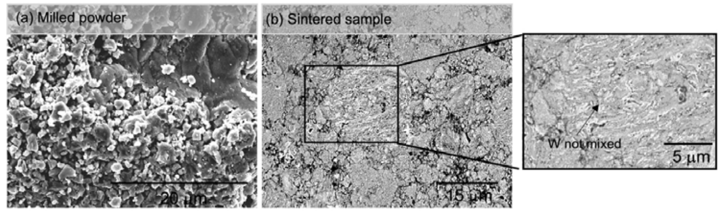


D concentration along the toroidal direction for 2016 scan in open symbols and 2020 in closed symbols.The upper panel show the scans along the dump tile 2BC4.

Development of thermal barriers for fusion reactors

Structural and functional materials to build fusion reactors are a major issue. Finding the right materials to operate in extreme conditions of temperature and radiation is a challenge. In particular, heat extraction requires a complex structure of materials with different thermal properties such as W and CuCrZr. To obtain a match between the materials it is necessary to introduce an interlayer with a gradient composition to accommodate the thermal and structural differences. In this research line, a new class of materials with great potential to operate in hard conditions were investigated. High entropy alloys (HEA) based on copper, CuFeTaTiW with different molar ratios, were prepared using mechanical alloying to mix the elemental powders, followed by consolidation with spark plasma sintering (see figure). The results indicate that a solid solution started to be formed, however without full incorporation of W. The work hardening of W during the milling process makes the mixture difficult and a new strategy to produce these materials will be considered in the future.

The results achieved gave the team a clue on how to proceed and the thermal conductivity and radiation resistance of the new alloys will be the major goal for the next steps. A PhD project started in 2021 will be fully dedicated to this research activity.



SEM image of the (a) milled powder of Cu, Fe, Ta, Ti and W and (b) sintered sample showing some porosity and W not mixed.

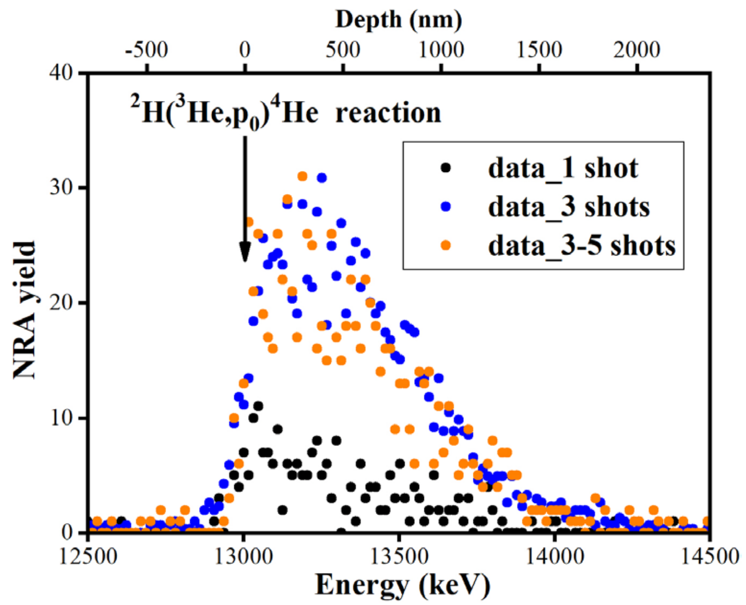
Plasma focus applications in fusion materials

Irradiation of relevant fusion materials in high flux plasma environments is mandatory to investigate their stability under extreme and accidental scenarios. Plasma Focus (PF) facilities present a simple way to create such scenarios, where the structural modifications imposed by PF discharges are highlighted by X-ray diffraction, optical, atomic force or electron microscopy investigations. The elemental depth distributions were measured using ion beam analysis (IBA), particularly the deuterium distribution.

High Entropy Alloys (HEA, $W_2TaCrNbV$ and $W_30TaCrNbV$) developed under the EUROfusion materials work package, were irradiated with 1, 3 and 5 shots of deuterium plasma at the PF-1000U device at IPPLM in Warsow and analysed at IST by secondary electron microscopy (SEM) and IBA techniques.

SEM images of the irradiated $W_20TaCrNbV$ batch show blisters, most of them detached from a fully cracked surface after 1 and 3 discharges. After 5 discharges the $W_20TaCrNbV$ target collapsed. The $W_30TaCrNbV$ surfaces present blistering and superficial swelling after 1 discharge with additional fracture and zoned melting afterwards. RBS-NRA quantifications evidenced similar and extremely low deuterium retention in both irradiated surfaces (lower than $9.0X10^{15}$ at/cm^2 for both alloys along a depth range close to 1.5 µm.

The results point to a low retention behaviour in the bulk of the HEA alloys under extreme deuterium plasma exposure and a correlation with irradiations with similar plasma conditions in tokamaks are underway.



NRA spectra showing the D profile in W after 1, 3 and 3 plus 5 shots. The results point out saturation after 3 shots.

Nanoengineering of wide bandgap semiconductors using ion beams (NASIB)

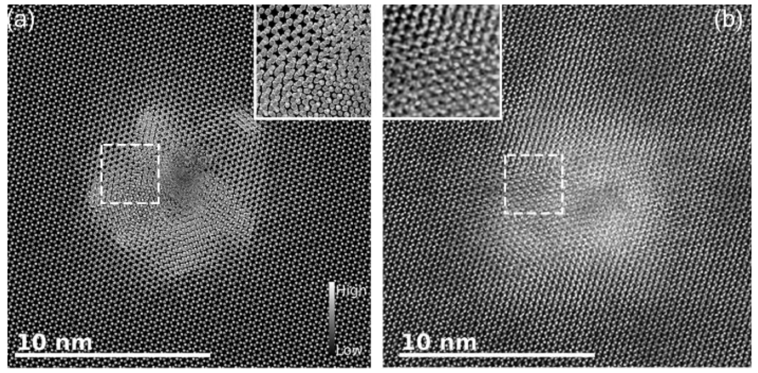
Wide bandgap semiconductors are expected to replace the ubiquitous silicon devices in key technologies such as power electronics and radiation-resistant electronics for space and nuclear applications.

The NASIB project aims at understanding radiation effects in these emerging semiconductors. Furthermore, we use ion beams to tailor the properties of these materials for their use in light-emitting and sensor devices.

We have studied the effect of ion irradiation on GaN combining structural, electrical and optical characterisation with Molecular Dynamics and Monte Carlo simulation tools. The impressive radiation resistance of GaN upon swift heavy ion irradiation was attributed to an efficient regrowth of the GaN crystal within the molten ion track [2] (see figure).

As a demonstration of the excellent radiation resistance of GaN devices, we have fabricated particle detectors based on single p-n junction GaN core-shell microwires [3]. The devices detect ultraviolet and proton radiation in self-powered mode, i.e. they are working without any external power supply. Their small size and weight together with their high radiation resistance make these sensors interesting for space and medical applications.

In the future, we want to explore other wide bandgap semiconductors. The first promising results on optical detection of ionising radiation using Cr-doped Ga_2O_3 have been already achieved.



Extraordinary agreement between the simulated (a: Molecular Dynamics result) and measured (b: Transmission Electron Microscopy result) ion track caused by the passage of a 185 MeV Au swift heavy ion in GaN.

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Theory and Modelling

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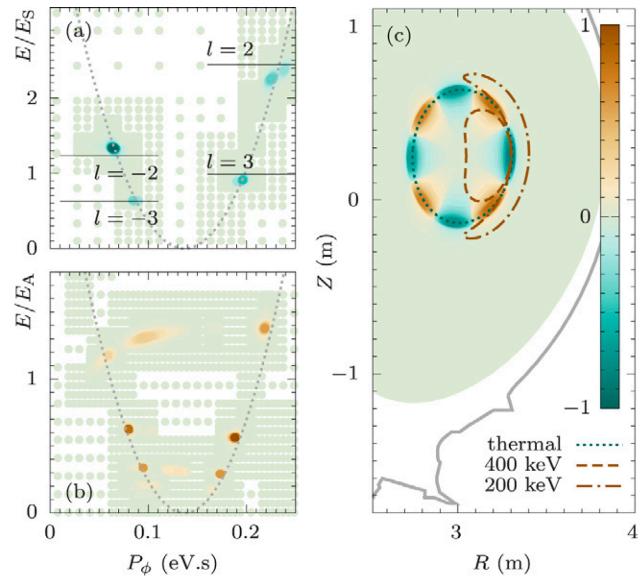
Our research is focused on key areas of plasma physics research particularly relevant for Tokamak fusion plasmas and the EU fusion programme. In particular, we are interested in the pervasive ties between Alfvén Eigenmode (AE) stability and the energetic particles born from plasma heating schemes and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

Energetic particle physics in Tokamak plasmas

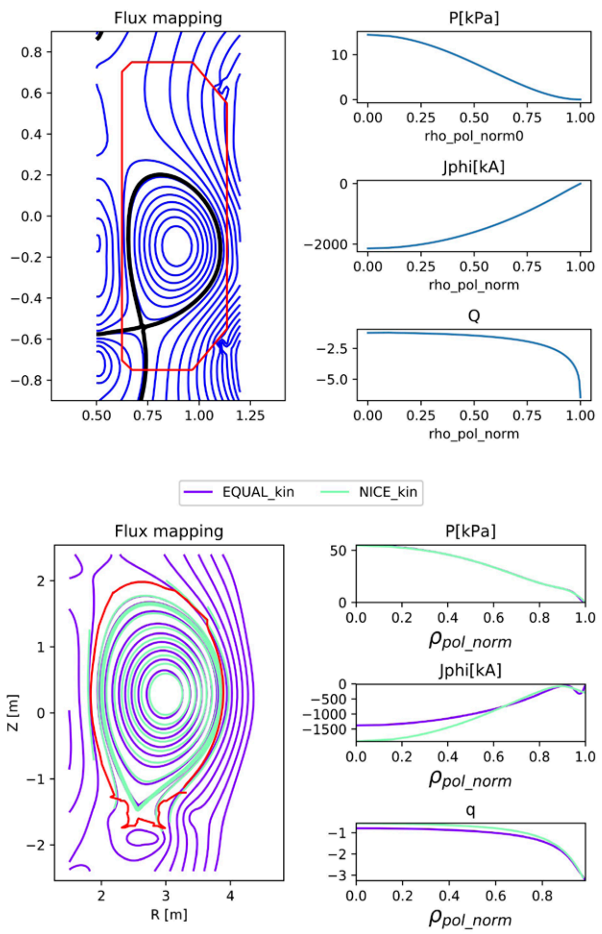
High-order plasma shaping (i.e., shift, elongation, triangularity, etc) were shown, under certain conditions, to open gaps in the coupled shear-Alfvén and acoustic continua at frequencies significantly above the values predicted by previous theories. Global eigenmodes in these gaps, which lie between the frequencies of geodesic acoustic modes and toroidicity-induced Alfvén eigenmodes, were found to be destabilised by hot-ion populations typical of tokamak operation. Along with more conventional Alfvénic plasma perturbations, these eigenmodes may therefore play a significant and still unexplored role in the stability of fusion reactors like ITER [1].



Energy exchange (shading code, a.u.) due to passing thermal (a) and trapped ICRH ions with T=200 keV (b), along with the gap radial location (dotted line); Eigenmode poloidal structure and orbits with largest energy transfer (c).

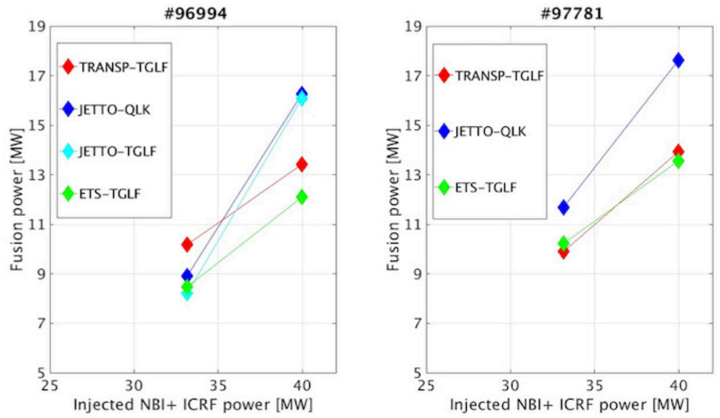
Integrated Tokamak modelling and workflow development

In a collaboration towards the design and development of the Integrated Modelling Analysis Suite (IMAS) by the ITER Internal Organisation, we have contributed to the verification and validation of an extensive pool of plasma simulation codes covering, among others, the topics of free boundary plasma equilibrium reconstruction, linear MHD stability, particle and energy transport models and neutral beam deposition [2]. Showcasing the application of IMAS, the developed Kepler workflows for the reconstruction of Tokamak plasma equilibrium were applied on several devices including JET, AUG and TCV, evidencing the modular workflow approach allowed by IMAS using different codes on the same input data.

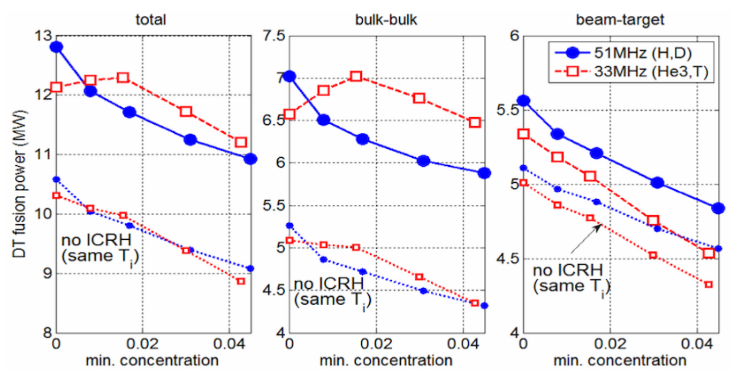


Left: R,Z [m] map of EQUAL equilibrium reconstruction at t = 0.75 s from UDA mapping for discharge #51262 of TCV. Right: (b) EQUAL and NICE reconstruction at t = 51 s from UDA mapping with pressure constraint for JET discharge #84600.

We have also been involved in the development and maintenance of the European Transport Simulator, with the responsibility to enable and support the use of ETS for interpretative and predictive transport analysis for ASDEX, TCV, WEST and JET, and in particular for the later, on modelling and interpretation of DT plasmas scenarios. Other tokamaks like JT60SA and DIII-D were also integrated and tested, in view of much broader use of ETS by the international fusion community. The ETS was updated to account for the computation of anomalous transport, alpha heating and impurity radiation. The successful implementation of self-consistent predictive simulation of combined RF+NBI heating schemes was demonstrated, in which the majority, minority and beam ions are simultaneously heated, through validation against JET ILW baseline and hybrid scenarios. The first DT consistent extrapolations from a DD baseline discharge were performed and, in a coordinated effort, ETS was benchmarked against other state-of-the-art transport codes, such as JINTRAC and TRANSP. The fusion power estimate is in line with other integrated modelling tools, as shown in the first figure below [3]. Another important outcome from a work coordinated by CEA and LPP-ERM/KMS was a clear demonstration, through predictive modelling, of whether H minority or 3He minority ICRH scheme is better for boosting the D-T fusion performance (second figure) which gave a definitive answer to an important issue raised during the preparation of the 2021 JET D-T campaign [4].



Extrapolated DT fusion power from the DD JET discharges #96994 and #97781



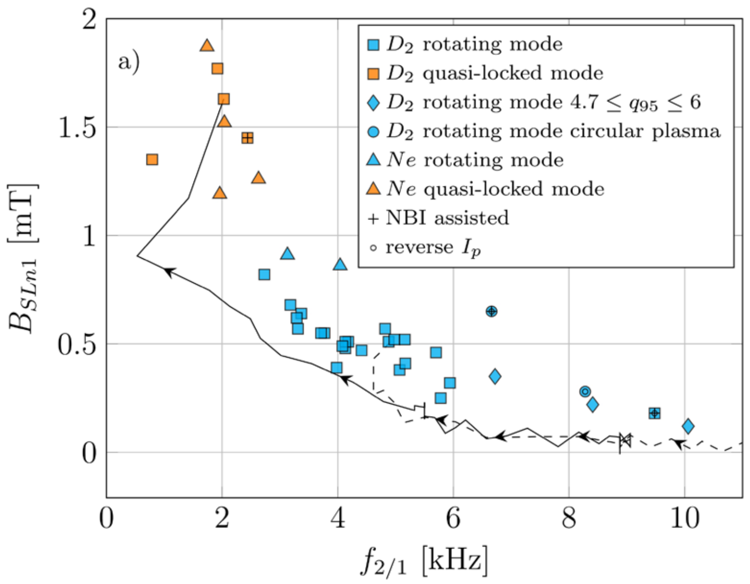
Fusion Power scan on H or 3He minority concentration for a JET baseline scenario

Magnetic islands and destruction of energy confinement in density limit disruptions

To achieve the triple product of ion density, temperature and energy confinement time for D-T reactions, high yield fusion reactors will have to operate at densities that are prone to the occurrence of plasma energy confinement disruption. It is crucial to understand the dynamics of such disruptions, in order to safely operate larger reactors like ITER under those regimes. One feature that is well known in fusion plasmas is that at such high densities, magnetic islands can develop in the plasma that if left free to evolve, energy confinement is suddenly destroyed, in an event called density limit disruption (DLD).

It was observed for the first time in JET plasmas that the onset of the energy confinement destruction in DLDs is marked by a secondary instability (SI) of this magnetic island. The SI is observed when the island growth rate is fast and the rotation sharply decreases. To better understand this SI, a systematic study [5] was carried out in COMPASS tokamak which, as JET, has ITER-like configuration, but its smaller size renders disruptions harmless and allows for large parameters exploration. Several plasmas were studied such as with limiter or separatrix boundary, D or circular shaped Last Closed Flux Surface, Neutral Beam Injection auxiliary heating, reversed toroidal plasma current, and DLD provoked with Ne or just D gas puff. An important result was the observation of the SI at the onset of the DLD energy confinement erosion. At this time the magnetic island amplitude and its rotation frequency showed to be inversely related to each other. It was also observed that erosion of energy confinement can start at different values of precursor island amplitude, depending on the value of its rotation frequency as shown in the figure. DLDs occur either with a precursor, a smaller island rotating faster, or a larger island rotating slower (quasi-locked).

Since the occurrence and behaviour of disruptions in Tokamaks is still poorly understood, a major effort was carried out at JET with a detailed analysis of disruptions occurring during JET ITER-like wall (ILW). On account of the privileged position as JET Chain1-RO, a contribution to the study of disruptions in JET ILW was done [6]. A special set of high time-resolution magnetic data and equilibrium reconstruction were created around the disruption time to resolve the



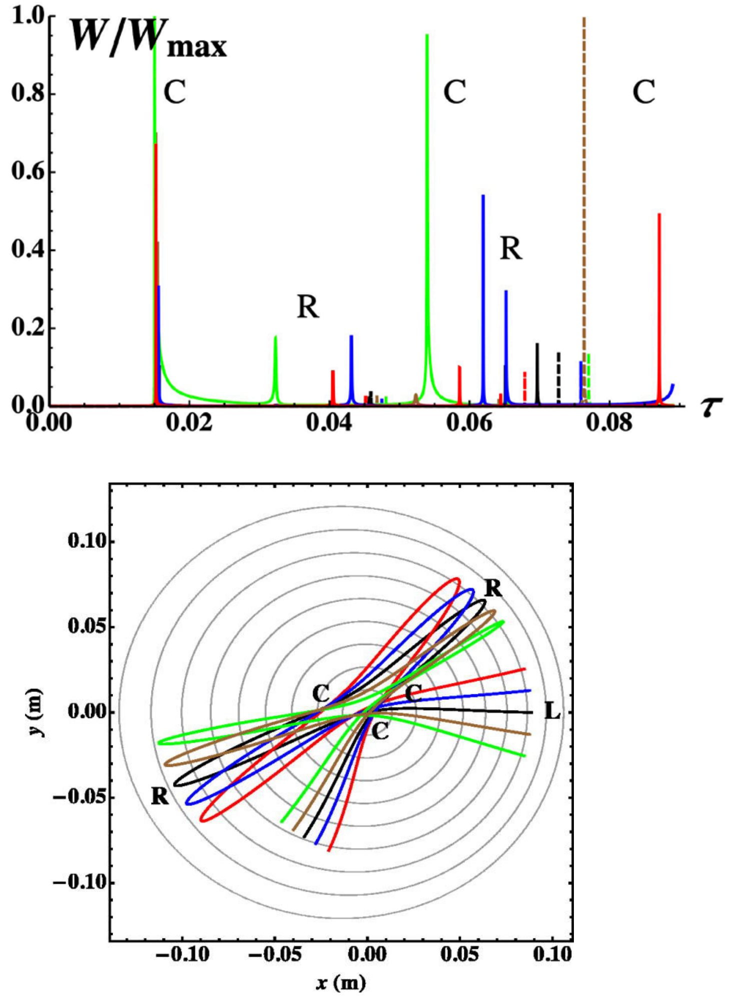
Dependence of the amplitude of the (m=2,n=1) island on its frequency at the onset of the secondary instability (SI). Different symbols indicate different gas puffed (deuterium or neon) or plasma/mode characteristics.

features to be studied. A total of 1951 JET disruption shots were thus processed, considering EFC coils status (off, n=1 or n=2), the correct magnetic diagnostic (in JET abbreviations, KC1D, KC1Z), and the correct equilibrium code to be used (efit_90 or jec2020).

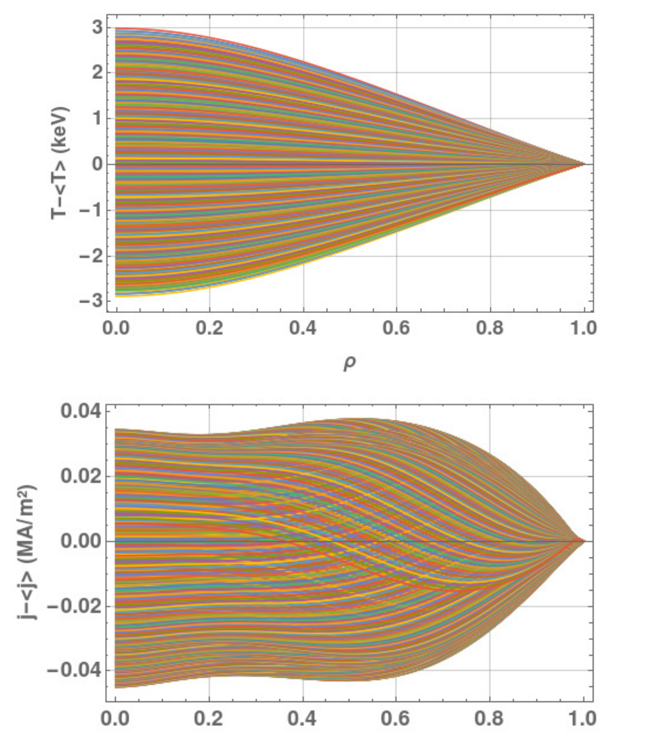
Fundamental plasma phenomena

A most persistent limitation of the geometrical-optics (GO) approximation is the difficulty in integrating the focusing/defocusing term in the equation for the wave amplitude when rays go through singularities (i.e., caustics and cutoffs), points where GO fails and wavelengths and other wave field-related quantities (e.g., the wave amplitude and energy density) become arbitrarily large. A new asymptotic matching (AM) technique was presented that allows one to recover the wave amplitude of rays crossing singularities and which improves on previous approaches, going higher in the order of the asymptotic expansion about the singular point and eventually leads to a less critical violation of the GO ordering when a ray approaches and crosses a caustic or a cutoff. The implementation of this new AM technique was illustrated with numerical examples of LH wave propagation in a tokamak plasma, using parameters characteristic of a LH current drive experiment [7].

Stationary regimes and limit cycle oscillations have been investigated on the time evolution of the electron temperature T and current density j in tokamaks [8]. Using a 0-D model for the time evolution derived from the cylindrical 1-D electron heat transport and current density diffusion equations, the stationary regimes (stable fixed points) of the deduced dynamical system were analysed. It was shown that the model reproduced well the cases of total diffusion (no sources), of a pure Ohmic (OH) discharge and of a constant external heating scenario. As the fraction of externally-driven, non-inductive current applied off-axis is increased, the system moves from an OH regime into an internal transport barrier (ITB) regime, where j is reversed and the negative magnetic shear reduces the heat diffusivity, thus increasing T at the core. Limit-cycle oscillations were found when the external power deposition is made proportional to both T and j, resemble those of the O-regime at Tore Supra tokamak. An ITB oscillatory regime with features similar to the experiments (e.g. a period of oscillation that is of the order of the resistive timescale) was also found when solving the 1-D transport equations numerically.



up: Ray trajectories in the tokamak plasma poloidal cross-section; bottom: normalised energy densities for rays traced across caustics (C) and cutoff reflections ®.



Temperature (up) and current density (bottom) envelopes during ITB oscillations.

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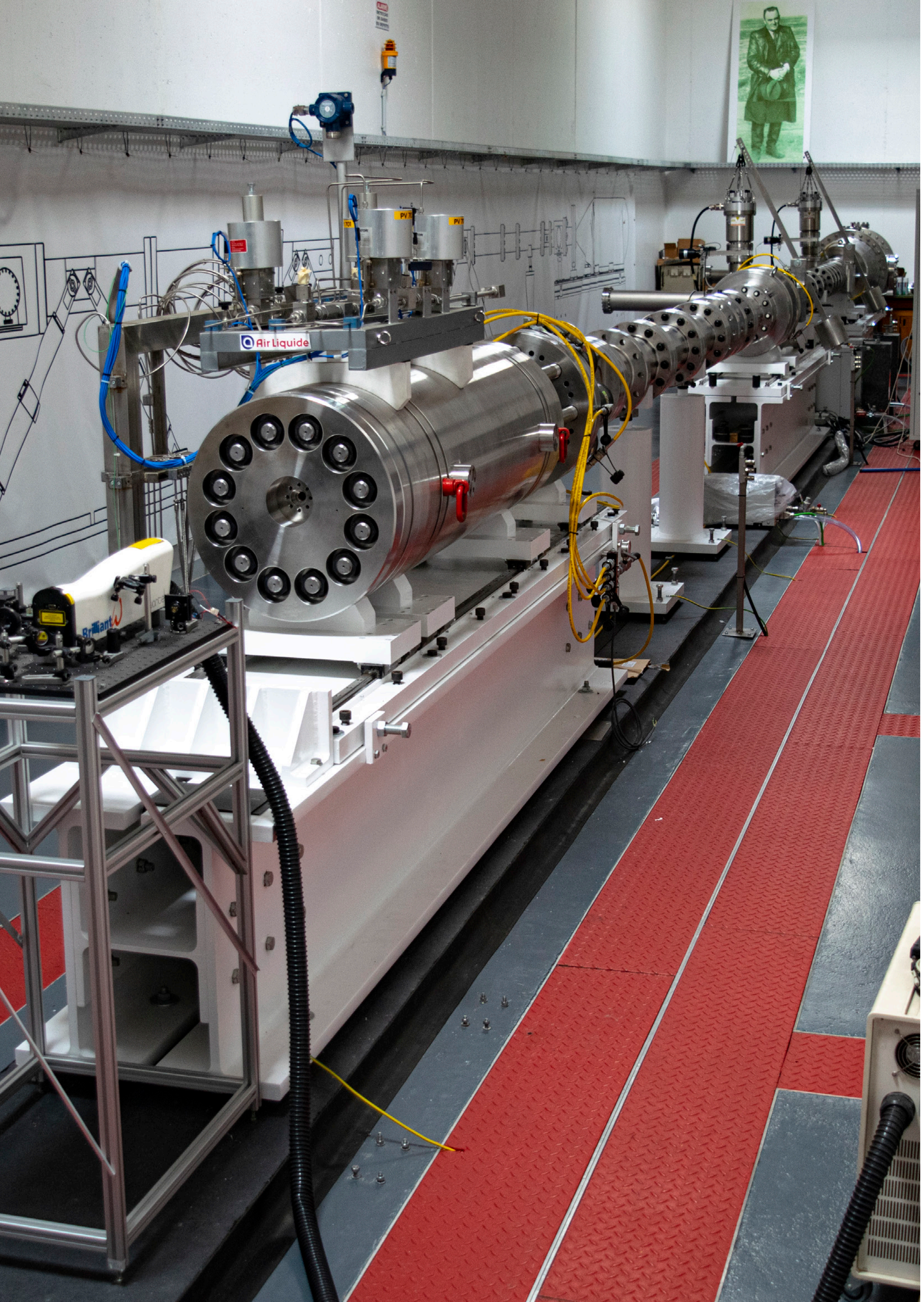

« The European Shock-Tube for High Enthalpy Research (ESTHER)
N-PRiME

Plasma Technologies and Intense Lasers

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

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

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

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

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

N-PRiME

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The N-Plasmas Reactive: Modelling and Engineering (N-PRiME) group explores the potential of *Nonequilibrium* low-temperature plasmas (LTPs) for tailoring energy and matter at the *Nanoscale* level and for reaching *New Horizons* in Space exploration. Our multidisciplinary activities bridge fundamental studies to very-applied research, and the synergies between both perspectives are paramount to advancing knowledge in LTPs, providing answers to fundamental scientific challenges and developing novel plasma technologies with societal benefits.

N-PRiME is organised in three research axes, the Plasma Engineering Laboratory (PEL), the Hypersonic Plasmas Laboratory (HPL) and Plasma Modelling and Simulation (M&S), coordinated by internationally recognised principal investigators.

At PEL (E. Tatarova and J. Henriques, PIs) we exploit microwave-driven plasmas to tailor matter and energy at the nanoscale level. This impressive know-how is used to develop plasma-based technologies, and to conceive, design and operate innovative experimental setups for synthesising bi-dimensional nanostructured materials. The outcome of this applied research contributes to consolidating the technological portfolio of IPFN.

Our activities in M&S (V. Guerra and M.L. Silva, PIs) aim at describing the dynamics of non-equilibrium LTPs, proposing state-of-the-art kinetic schemes, both in volume and in interaction with surfaces, and considering the multi-dimensional transport of species and radiation, also under hydrodynamic flow regimes. These activities also involve the development, verification and validation of predictive numerical tools and computational platforms, for a large variety of systems and conditions.

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

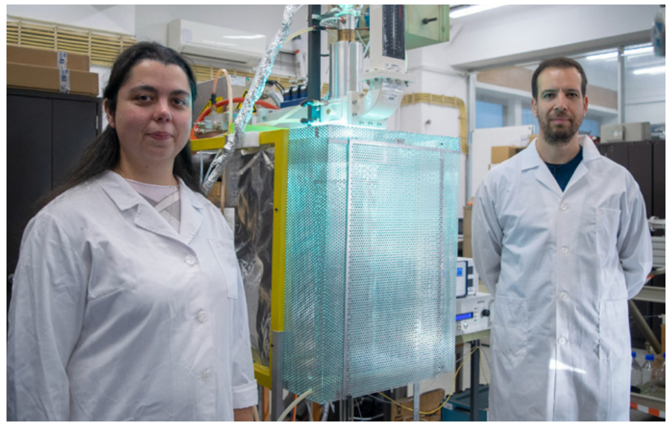
Plasma Engineering Laboratory

Working in the cutting-edge field of Plasma Nanoscience

The R&D activities of PEL are related with the cutting-edge field of Plasma Nanoscience. Our ambitious purpose is to translate the unique properties of plasmas into extraordinary material characteristics and to create novel forms of matter by using a multitude of specific plasma mechanisms to control the energy and matter transfer processes at nanoscales.

Plasma machine for versatile large-scale fabrication of graphene and derivatives

In the framework of the project PEGASUS, "Plasma Enabled and Graphene Allowed Unique Nanostructures" (Horizon2020 FET-OPEN), we have developed a versatile plasma-based prototype machine for the gram-scale fabrication of high-quality graphene and derivatives with high-level of customisation (see figure). PEL's disruptive technology for the synthesis-by-design of advanced 2D materials allows a single-step, continuous and cost-effective fabrication at atmospheric-pressure conditions. A patent portfolio protecting both the process and machine was submitted and is currently under examination.



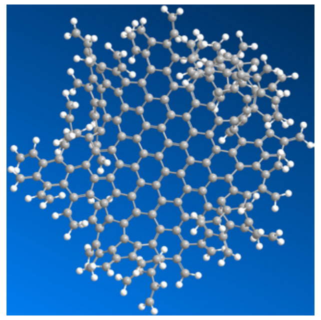
Prototype of the plasma machine for the large-scale fabrication of graphene and derivatives (PEL researchers in the photo: A Dias, left and E Felizardo, right).

The plasma machine uses cheap starting materials (e.g., ethanol, methane) to provide the controlled and repeatable fabrication / customisation of graphene and N-graphene, by applying distinctive protocols fostering high selectivity (~50% single atomic layers; ~0.5 μm sheets size), high quality (graphene: C/O > 50, sp2 carbons ~ 70%; N-graphene: C/O > 40; sp2 > 60%), and high yield (~40 mg/min). Nanocomposite materials can also be fabricated at a large scale under atmospheric conditions, using graphene/N-graphene as a highly conductive matrix to incorporate metal oxide/sulfide nanoparticles (e.g., MnOx/MnSx with ~10-30 nm). Advanced spectroscopic techniques have revealed a high structural quality and a wide distribution of the metal nanostructures on the N-graphene sheets. This technology is one of the fastest approaches to design a large amount of high-quality graphene-metal hybrid nanostructures, with potential to be used as electrode materials in energy storage devices for sustainable energy development (e.g. supercapacitors with specific capacitances reaching ~273 F/g at 0.5 A/g). Work is in progress to bring the machine up to a TRL of 6-8.

Deterministic simulations to unveil the formation of free-standing carbon nanostructures

A deterministic approach, fostering synergistic experimental and theoretical efforts, was adopted to master the fundamentals of the plasma-enabled synthesis process. Numerical simulations, based on the principles of the Grand Canonical Monte Carlo method, have demonstrated the role of different radicals in the formation of free-standing carbon nanostructures via σ-electronic free bonds in the 3D plasma afterglow. The conditions for assembling planar free-standing 2D graphene sheets have been unveiled by considering C_2, C and H radicals as main "building units", and the results were compared with experimental data (see figure). Further work, linking the outputs of plasma models and molecular dynamics simulations, will unveil the plasma-driven carbon nucleation processes and elucidate the role of different nitrogen-containing radicals in the formation of N-graphene.

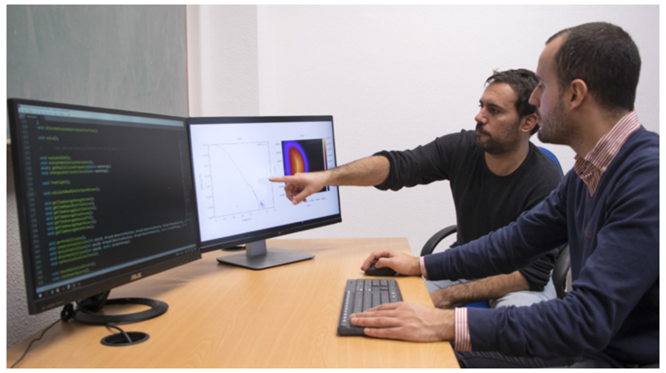
Numerical simulations showing the growth of graphene flakes in 3D space



N-graphene as promising plasmonic material

Considering the relative low loss, high confinement, flexibility and long relaxation time of electrons, N-graphene can be considered as a promising alternative plasmonic material to noble metals. Experimental investigations have demonstrated the ability of this plasma-based technology to also tailor the performance of graphene plasmons. Increasing pyridinic/pyrrolic nitrogen functional groups on graphene scaffold yields the strong suppression of graphene π-plasmons in the 4-10 eV energy range, and the excitation of low-energy 2D plasmons in the near-infrared spectral range (0.4 – 1 eV). Further work will lead to the design of a metamaterial unit-cell based on N-graphene.

Plasmas Modelling & Simulation



Plasma M&S activities at N-PRiME (M&S researchers in the photo: T. Dias, front and T. Silva, back).

Activities fully funded by competitive projects

The international recognition of our M&S activities is demonstrated by the level of competitive funding secured, in FCT projects ("PlAsma RoAD to Solar fuEls" – PARADiSE and "Reaching Oxygen-Accumulated production through non-thermal Discharges on MARS" – ROADMARS), a Seed proposal MITPortugal ("Inverse design and Modelling of Plasma-Assisted CO_2-conversion Technologies" – IMPACT) and an ESA's Initial Support for Innovation ("ISRU on Mars: Plasma conversion of CO_2 from the Martian atmosphere"), corresponding to more than 500 k€.

CO_2 plasmas for sustainability

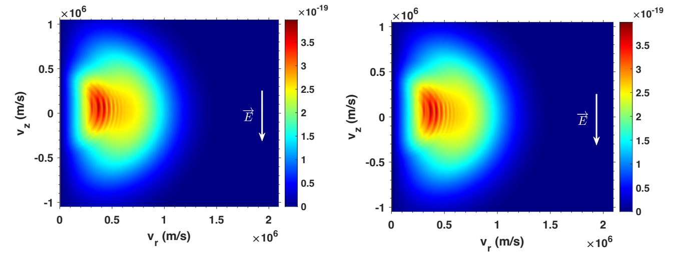
Recent years saw intense research on CO_2 plasmas, associated to environmental concerns due to CO_2 emissions. Our modelling work, developed in collaboration with experimental teams at Laboratoire de Physique des Plasmas (LPP), Ecole Polytechnique, France, and Eindhoven University of Technology (TUe), The Netherlands, has provided a validated set of reactions and rate coefficients for vibrationally cold plasmas, and has shown that electronically excited states play a key role in CO_2 dissociation and that pulsing can influence the concentration of O_2 (and hence of CO_2 and CO) by favouring or limiting oxygen atomic recombination during the afterglow.

Mars in situ oxygen and propellant production

In-situ resource utilisation (ISRU) is a key concept in space exploration, corresponding to the harnessing of resources on the exploration site that would have to be brought from Earth otherwise. We studied the conversion of CO_2 in a DC glow discharge operating at Martian conditions, in a joint modelling and experimental investigation with LPP and TUe, and confirmed the potential of plasma technologies for oxygen and fuel production on Mars.

Development of the LisbOn KInetics (LoKI) tool

New releases of the LoKI simulation tool included (i) LoKI_v2.0.0, coupling the chemistry model to a thermal model for the neutral gas, and simulating post-discharges; (ii) the open-source Boltzmann solver LoKI-B_v2.0.0, describing the kinetics of electrons excited by time-dependent (non-oscillatory) electric fields; (iii) the release candidate LoKI-MC, that solves the electron kinetics using the Monte Carlo (MC) technique.



Electron velocity distribution function in oxygen, obtained with LoKI-MC at E/N = 10 Td (left) and 500 Td (right).

Kinetic Monte Carlo simulations of plasma chemistry

A Kinetic Monte Carlo (KMC) algorithm to solve gas-phase chemistry was implemented and validated, as a first step to achieve the unified description of the electron and heavy-species kinetics. The strategy enables accounting for the time-dependent mutual influence between chemical species and electrons, at unrestricted *E/N* values. To circumvent the fluctuations on the minority species, two novel variance-reduction methods were proposed.

Electron impact cross-sections in carbon monoxide

A complete and consistent set of cross-sections for electron impact collisions with carbon monoxide (CO) was developed and published in the IST-Lisbon database with LXCat. The role of anisotropic scattering in rotational collisions with CO was also investigated, and a novel anisotropic scattering model was derived, improving the agreement between calculated and measured swarm parameters. New electron swarm data in CO was obtained, at very-high *E/N*, and fitted to the latest cross-sections using a density gradients expansion model.

Improving state-to-state and radiative models

We developed new models for vibration-specific N_2 dissociation in high-speed shockwaves, accounting for 1250 molecular vibronic levels and 212 atomic levels, and for high-temperature CO_2 dissociation using the Forced Harmonic Oscillator method and including vibration-to-electronic transitions. We released a vibration-specific radiation database based on CDSD, allowing fast modelling of high-temperature CO_2 radiation, and reinvestigated the concept of vibrational temperature in non-equilibrium conditions and its impact in plasma modelling.

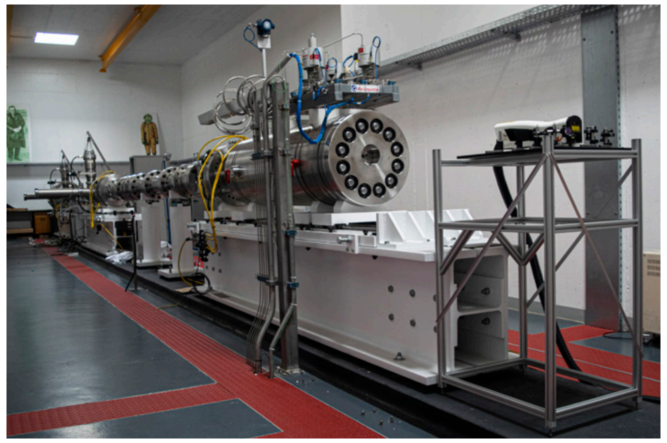
Hydrodynamic and state-to-state kinetics in Atmospheric Pressure Plasma Jets

The Software Package for Aerothermodynamics, Radiation and Kinetics (SPARK) was extended to subsonic conditions, allowing the study of Atmospheric Pressure Plasma Jets (APPJs). The updates included (i) solver improvement for faster simulations of subsonic jets: SLAU solver, WENO reconstruction, development of preconditioners, parallelisation with OpenMP; (ii) modelling fast discharge effects using a streamer model loosely coupled to the fluid solver; (iii) the development of Reduced-Order State-to-State (ROSS) models, accounting for the state-to-state kinetics in argon-air discharges.

Hypersonic Plasmas Laboratory

The ESTHER shock-tube

The ESTHER shock-tube (see figure below) has initiated its step-by-step qualification process, and despite the restrictions due to the Covid19 crisis, the facility is expected to become fully operational in early 2022.



The European Shock-Tube for High Enthalpy Research (ESTHER)

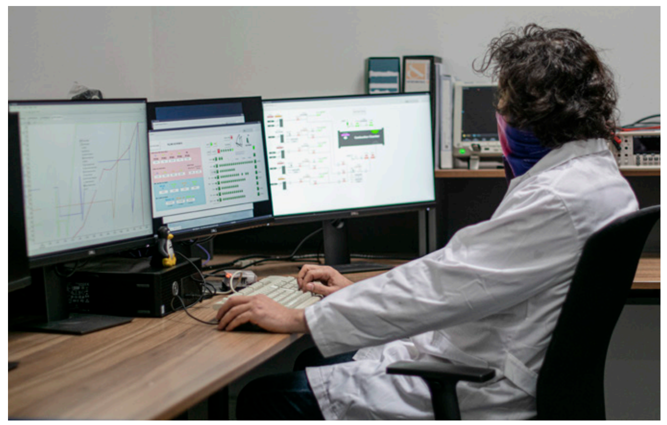
Qualification of the combustion driver

The combustion driver has been qualified, firstly through a 1,500 bar proof pressure test using water, then through a qualification campaign of 99 shots (second figure below) using a diaphragm blank.

The shots were carried out for H_2/O_2 mixtures using He or N_2 as a dilutant, up to 100 bar filling pressure. Dilution by a heavier gas, such as nitrogen, will allow for ESTHER to reproduce slow entry speeds (e.g. Mars and Titan entries at $v \leq 5$ km/s), something previously not possible for nominal dilutions ($H_2/He/O_2$).

An innovative ignition method was adopted, using an Nd:YAG laser source focused inside the vessel through a thick sapphire window. This ignition system, outside of the combustion chamber, allows for a clean combustion setup. A steady combustion (deflagration) has been achieved for post-combustion pressures up to 660 bar, above the requirements of the facility (600 bar).

Investigations have allowed us to better understand the dynamics of combustion at very high pressures (5-100 bar filling pressure) in large vessels (50 litres), and the key influence of the filling pressure, stoichiometry, and dilution ratios on the flammability and detonability of the mixture.



Control room of ESTHER at HPL (researcher in the photo: Mário Lino da Silva)

Lasers and Plasmas

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EUROFusion Consortium
Fundação La Caixa

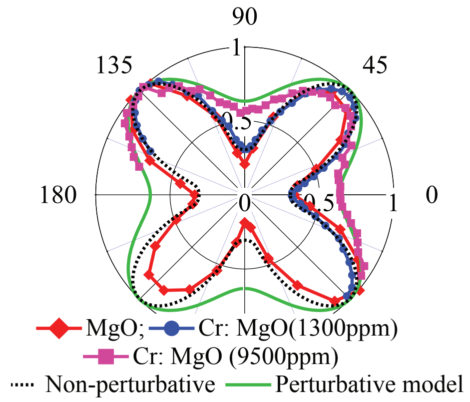
How does matter behave in extreme electromagnetic fields, either at ultra-relativistic intensities, ultra-short timescales or at extremely short wavelengths? What are the conditions for the creation of pair plasmas in the laboratory under the action of ultra-intense fields and what is the role of the 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, and plasma-based accelerator projects combined with the exploration of Tier-0 supercomputers.

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



Polarisation response of third-harmonic generation in MgO (red diamond), analytical perturbative (green line) and non-perturbative (black dotted line) models, Cr: MgO for 1300 ppm (blue circles), and 9500 ppm (pink squares). The lines connecting the markers are used to guide the eye.

High harmonic generation from solids

In the past two years we started to explore a new technology: high harmonic generation (HHG) from solids. This process yields an ultrashort pulse in the deep ultraviolet (DUV) to soft X-ray region, employed for attosecond imaging of molecular orbitals or real-time observation of electron tunnelling. It provides a new tool for ultrafast physics, such as electron or molecular dynamics in metal oxide semiconductors and two-dimensional materials.

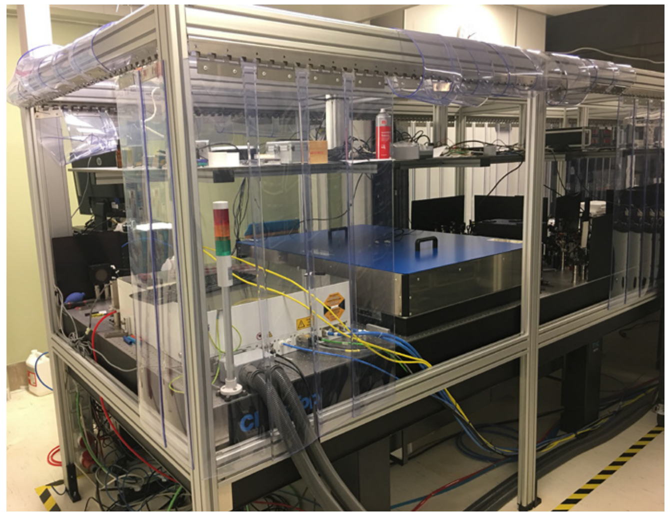
HHG can be perturbative and non-perturbative, depending on the driving field strength and the material properties. The surge in interest towards non-perturbative HHG in solids has been driven by the appeal of compact solid-state extreme ultraviolet (XUV) sources and the prospect of untangling the material properties through the intimate interplay of strong fields and solids.

We have found signatures for this transition between perturbative to non-perturbative HHG in several crystals by studying the generation dependence on the degree of impurities, polarisation, focus position and angle with respect to the crystals. In parallel, we developed a semi-classical model for the electron trajectories that reproduces qualitatively our observations. This research, performed mainly on the 800 nm VOXEL laser and a 2 μm, MHz laser at CEA, has recently been extended to the new 3 μm laser at L2I, where we will perform a systematic study of novel materials and applications in the future.

Successful upgrade of the laser capability at L2I

With the conclusion of the first edition of the National Roadmap of Research Infrastructures, promoted by the Portuguese Foundation for Science and Technology, we successfully upgraded its laser capability of the Laboratory for Intense Lasers (L2I) according to the established plan. In mid-2020 the two main new laser systems were delivered and installed: a 100 W, 100 kHz, 1 ps pump laser operating at 1030 nm (Amphos GmbH) coupled to a mid-infrared (3.2 μm) parametric amplifier delivering 40 fs, 65 μJ, phase-stable pulses (Fastlite). A new suite of optical pulse and beam diagnostics was also acquired for the characterisation of the output laser pulses. Further energy scaling of the mid-infrared laser system to the mJ has been studied [1], is underway, and will broaden the scope of experiments available to L2I's users.

The first experiments using the mid-infrared laser took place during the spring of 2021 and consisted in the investigation of supercontinuum generation in a range of optical materials. In a second set of experiments, L2I and VOXEL researchers joined efforts to investigate high-harmonic generation in solid media, namely calcium fluoride, fused silica, lithium fluoride, sapphire, MgO and Cr-doped MgO. Following the goals of the National Roadmap and



Laboratory for Intense Lasers. View of the upgraded laser system and optical table.

Laboratory for Intense Lasers. View of the upgraded laser system and optical table.

within the Laserlab-Portugal consortium, the new laser system will be made available to the national community of researchers through periodic calls for experiments [2].

Final prototype construction of compact Raman spectrometers

The goal of the RamSERS project was the development of two portable Raman spectrometers, using laser lines at 785 nm and at 1064nm, for general industrial and medical applications. As a conclusion of the project, our work was devoted to the final integration process of optics, electronics and mechanics for the final prototypes of the two spectrometers.

After the design phase and lab tests for validation and characterisation of the instrument, the following step was going from the lab to the construction of a prototype close to the commercial product. These tasks were led by the company of the consortium in close collaboration with the optics and electronics development teams under our responsibility. As a result of the performed work, the two prototypes were produced and tested in the lab and in the field, achieving the targeted specifications.

Raman spectrometer prototype. Final integration and lab tests for the construction of a tablet-sized Raman spectrometer prototype

Although this project is now finished, we foresee in the near future to maintain this type of collaboration with the industry on the development of optical instrumentation in the framework of new projects or contracts.

Plasma source for the AWAKE experiment

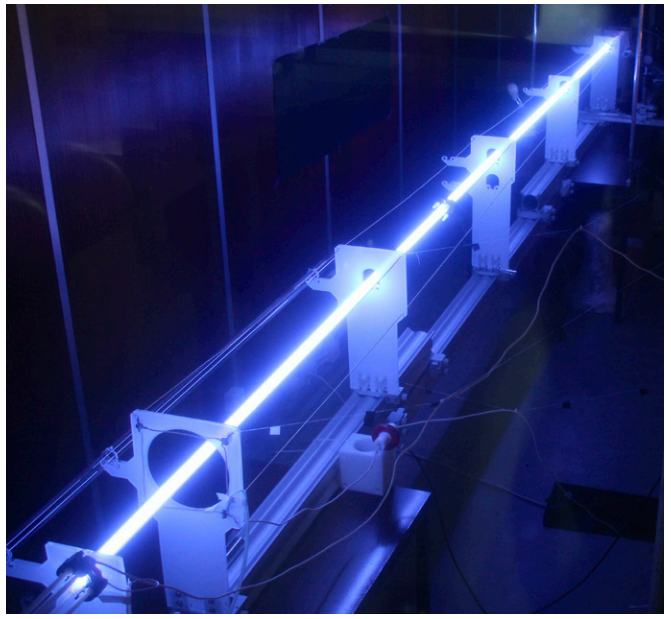
The AWAKE experiment at CERN demonstrated the feasibility of using proton beams, accelerated to high energy in ring accelerators, to drive relativistic waves in linear plasmas that are used to accelerate externally injected electron bunches. Future developments include the demonstration of the energy gain scalability in long plasmas. At IPFN we are developing a scalable modular plasma source for unlimited extension of the AWAKE acceleration length.

Plasmas with lengths beyond 5 m are created by an electrical discharge in low pressure with heavy noble gases contained in a glass tube. The stringent requirements for the density precision and uniformity, about 0.2%, force the long plasma to be ignited and heated to the correct temperature in a few tens of microseconds to avoid the development of density modulation instabilities before the use of the plasma.

We are using a high-voltage electrical circuit with a flyback topology to produce the fast and low-jitter ignition of the plasmas into a low current arc. This is followed by a second high-current pulse used to increase further the plasma temperature and reach the desired plasma density.

We have built a test facility with a 5 m long plasma tube to support the development of the electrical modules. Both the ignition and heating circuits were optimised to produce the plasmas required in the AWAKE experiment using 25 mm diameter glass tubes with lengths beyond 10 m, although so far only up to 5 m were demonstrated due to space limitations. The figure shows a long integration photograph of a plasma discharge produced by a 120 kV pulse used to ignite the plasma to an arc with a current of approximately 10 A to which a 10 µs, 10 kV capacitive discharge was added, generating a peak of approximately 400 A in the tube. The high ionisation fraction (close to 1) of the gas (argon at 10 Pa), results in the emission of strong blue radiation.

The test tube and the electric circuits can now be used in plasma wakefield experiments in the AWAKE facility, to support the development of the diagnostics to characterise the plasmas, and to prepare a future modular plasma source to extend the AWAKE acceleration length to 50 m and beyond.



Plasma discharge in the IPFN Discharge Plasma Source Test Facility.

Superradiance with less than a particle per wavelength

Superradiance, a classical concept first introduced by Robert Dicke in 1954, is the anomalous radiance describing coherent photon emission from a collection of light-emitting particles. Initially proposed in the context of atomic physics, superradiance now provides valuable insights into the fields of quantum electrodynamics, quantum communications and astrophysics. Superradiant emission is also highly desirable in light sources, as it leads to peak radiation

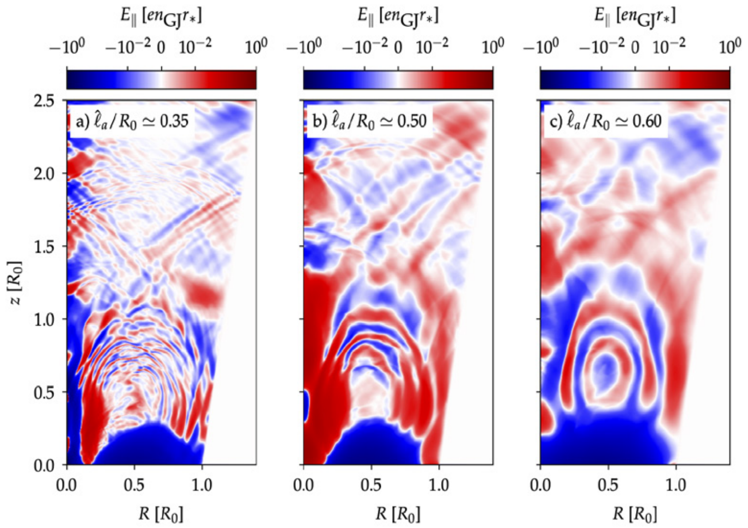
Helical optical shock in generalised superradiance. Superradiant radiated electric field recorded in a virtual detector as a function of time (vertical direction) and transverse position. Blue/red refers to negative/positive electric field values. The optical shock forms a helix.

intensities that scale with the number of particles squared. It is therefore a key element underlying the design and construction of advanced light sources such as free-electron lasers. Superradiance is intuitively expected when the distance between light-emitting particles is much smaller than the photon wavelength.

This superradiance condition, which was first proposed by Dicke, has far-reaching implications. It is a central element, for instance, in free-electron lasers where it imposes strict requirements on the quality and structure of radiating electron ensembles. We have reconsidered this question by predicting a previously unexplored form of superradiance. Our work breaks a long-standing tenet in this field, by demonstrating that superradiance can occur even with less than a particle per radiation wavelength [3]. This finding can have deep implications ranging from the physics of free-electron lasers and advanced plasma-based light sources to nonlinear Thomson scattering and plasmonics.

Modelisation of the magnetospheres of neutron stars

Since pulsars were discovered over 50 years ago, it has been clear that their bright and short-pulsed radio emission is produced by a coherent process over small distances. However, no consensual model exists for the origin of pulsar radio emission. We performed massively-parallel simulations of pair cascades including the relevant QED processes from first-principles and the realistic field geometry of pulsar polar caps. These simulations allowed us to show that



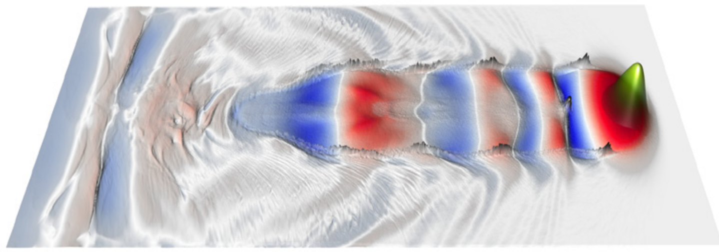
Coherent plasma waves generated during pulsar pair cascades. Electric field oscillations self-consistently excited during pair cascades with different aspect ratios. Flatter pair production bursts (left) generate a stronger flux of electromagnetic radiation in the vertical direction, whereas rounder bursts (right) produce more pronounced drifting waves across the polar cap.

pair cascades develop non-uniformly across pulsar polar caps and trigger coherent plasma waves that couple to electromagnetic modes. The frequency, polarisation and power profile of the coherent waves produced in this process are consistent with the properties of radio emission. Our significant progress [4,5], leveraged on the high-performance particle-in-cell code OSIRIS, demonstrated that the observed radio emission from pulsars has direct imprints of the coupling between QED and plasma kinetic processes.

Interaction of hard photons with plasmas

The description of plasmas as a dielectric media breaks down at scales where the notion of averaged fields loses its meaning — this scale being typically the inter-particle distance. Photons with a wavelength smaller than the plasma inter-particle distance are not dressed and only interact with the electrons of the plasma through incoherent quantum processes such as Compton scattering (dominant for low photon energy). A photon burst can exert a Compton force (which has for classical analogy the classical radiation reaction force) on the electron of the plasma and therefore drive plasma wakes [6].

We investigate this fundamental process for different photon frequencies, photon flux, and plasma magnetization. The analytical findings are in very good agreement with the simulations performed with our particle-in-cell codes OSIRIS coupled to a Compton scattering module [7]. Our results show that Langmuir and extraordinary modes are driven efficiently when the photon energy density lies above a certain threshold. The interaction of photon bursts with magnetized plasmas is of distinguished interest as the generated extraordinary modes can convert into pure electromagnetic waves at the plasma/vacuum boundary. This could possibly be a mechanism for the generation of radio waves in astrophysical scenarios in the presence of intense sources of high energy photons.



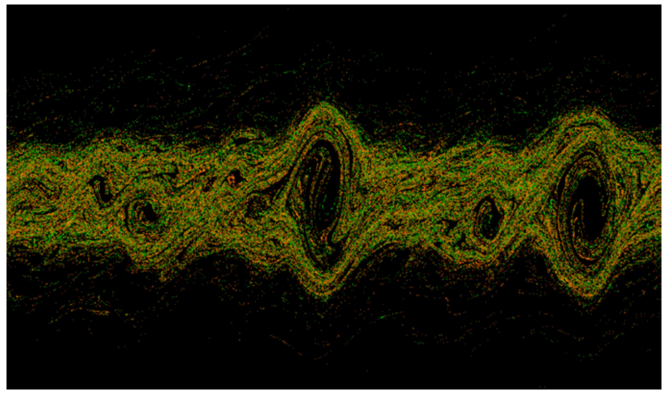
Formation of a plasma wake driven by a photon burst. The figure illustrates the electrostatic field associated with the plasma wake (the colour plot indicates the amplitude and polarity of the field, red being positive and blue negative). The driven photon burst is depicted in green.

Kinetic plasma simulations in research and education

The complexity of the phenomena involved in several relevant plasma physics scenarios, where highly nonlinear and kinetic processes dominate, makes purely theoretical descriptions impossible, and numerical simulations must play a key role in the scientific process. As such, particle-in-cell (PIC) codes have established themselves as the leading simulation in several areas of plasma physics.

The workhorse behind our simulation efforts is the OSIRIS code that we develop. Work has focused on the implementation of new particle pushers and field solvers that improve the accuracy of the PIC algorithm, especially for high-field/high-momenta situations and studying the evolution of particle spin and dealing with curvilinear coordinate systems. Extensive work was also devoted to the new linear (particle-particle) Compton scattering and nuclear fusion modules, as well as improved boundary conditions for overdense plasmas. We also worked on the development of a general relativity module for modelling neutron star and black hole magnetospheres including strong gravitational fields.

The use of these codes is not limited to high-level research but is also of fundamental importance for plasma physics education. To this end, we develop the ZPIC educational code suite, which is aimed primarily at education and training in plasma physics using computer simulations. Recent work on this suite focused on the support for Jupyter (Python) notebooks to control and analyse ZPIC simulations. Leveraging on this work, we have prepared a set of well-documented notebooks, with example problems of textbook and advanced plasma mechanisms, as well as reproduced and extended the work done in seminal plasma physics papers.



Simulation of the Two-Stream instability. Particle phase-space (momentum versus position) for two interpenetrating particle species showing the development of the so-called Two-stream instability. The simulation was performed using the ZPIC educational code on a standard laptop in under one minute.

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High Pressure Plasmas

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Main funding sources
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Schneider Electric Industries SAS, Grenoble, France.
European Regional Development Fund through the Operational Programme of the Autonomous Region of Madeira 2014–2020.
Fundação para a Ciência e a Tecnologia, Portugal.

What is the state-of-the-art of models of interaction of high-pressure arcs with their electrodes? Can stationary solvers be used to study the time-averaged characteristics of DC corona discharges? Can the enhanced ionisation of air molecules in regions of amplified electric field near microprotrusions explain deviations from the similarity law observed in the experiment? What is the role of different mechanisms of current transfer to non-thermionic arc cathodes?

Apart from searching answers to these questions, the group has also focused on developing a practical tool for modelling low-current quasi-stationary gas discharges, as well as a numerical model of vacuum arcs in transverse magnetic fields, in the framework of an industry-sponsored project with Siemens AG started in April 2020.

The search for answers to these questions has been facilitated by the creation and installation of a high-performance computing lab, thus having significantly expanded the scope of predictive simulation capabilities of the group.

Our main goals are: to develop numerical models of the plasma-electrode interaction for different types of discharges; to develop accurate and robust tools for modelling the whole range of existence of quasi-stationary discharges, as well as the characteristics of DC corona discharges; to clarify the mechanisms of current transfer to non-thermionic arc cathodes; among others.

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

Inauguration of the Zarco supercomputer at the Research Node of IPFN at UMa.

Creation and installation of a high-performance computing lab

The creation of the IPFN Research Node at the University of Madeira (UMa) in 2017 opened access to regional funding for the High-Pressure Plasmas Group, an opportunity that the group has successfully used by submitting an application for a large-scale research project through the Operational Programme of the Autonomous Region of Madeira 2014–2020 for research and development in the field of Energy, Mobility and Climate Change. The large-scale research project PlasMa: Theory and advanced simulation of plasmas relevant to energy applications, M1420-01-0145-FEDER-000016, was awarded to the group in 2019. The project is funded with more than 1.4 M€, for four years, by the European Union (85% of funding) through the European Regional Development Fund, and by UMa. Project PlasMa capitalises on HPPG's acquired experience and significantly enhances the potential for knowledge transfer to the high-tech electrical industry.

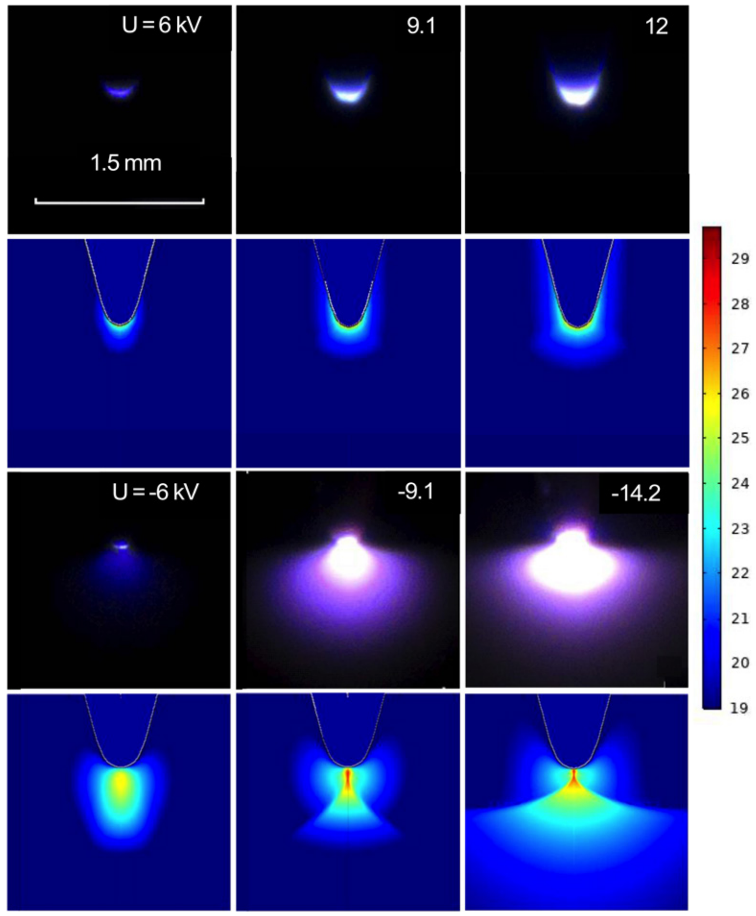
Funding from the project PlasMa resulted in the creation and installation of a high-performance computing lab, which has significantly expanded the scope of predictive simulation capabilities of the group. On October 28, 2020, the Research Node of IPFN at UMa was visited by the President of the Regional Government of Madeira, Dr Miguel Albuquerque, the Regional Secretary for Education and the President of the Board of Directors of the Regional Development Institute, being also present among others, UMa's rector, Prof José Carmo. The President of the Government was introduced to the investigation carried out at the Node and inaugurated the Zarco supercomputer.

State-of-the-art on the modelling of the interaction of high-pressure arcs with their electrodes

A review of the state-of-the-art of modelling of the interaction of high-pressure arcs with their electrodes was written. The review was invited by the Editors of the Special Issue of Journal of Physics D: Applied Physics, dedicated to thermal-plasma–material interactions and was published as a Topical Review [2]. The importance of the topic stems from the fact that the incorporation of realistic models of plasma-electrode interaction remains a bottleneck in the development of predictive models of devices with high-pressure arcs. The most important aspects of the underlying physics have already been understood, so no fundamentally new physical mechanisms have been described in the recent publications (which are many); the aim was rather to develop practical numerical models that adequately describe known mechanisms. Unfortunately, no universally accepted numerical models have emerged: the developed models are in many cases incompatible with each other, and it is not easy to identify the place of each model in the global picture. The aim of the review was to summarise physically justified descriptions of the interaction of high-pressure arcs with their electrodes and to survey from this point of view the recent works, thus bringing them into a kind of system insofar as possible. The relevant aspects of the conventional LTE arc models were discussed and outstanding challenges for future work were identified.

Computational and experimental study of time-averaged characteristics of positive and negative DC corona discharges in point-plane gaps in atmospheric air

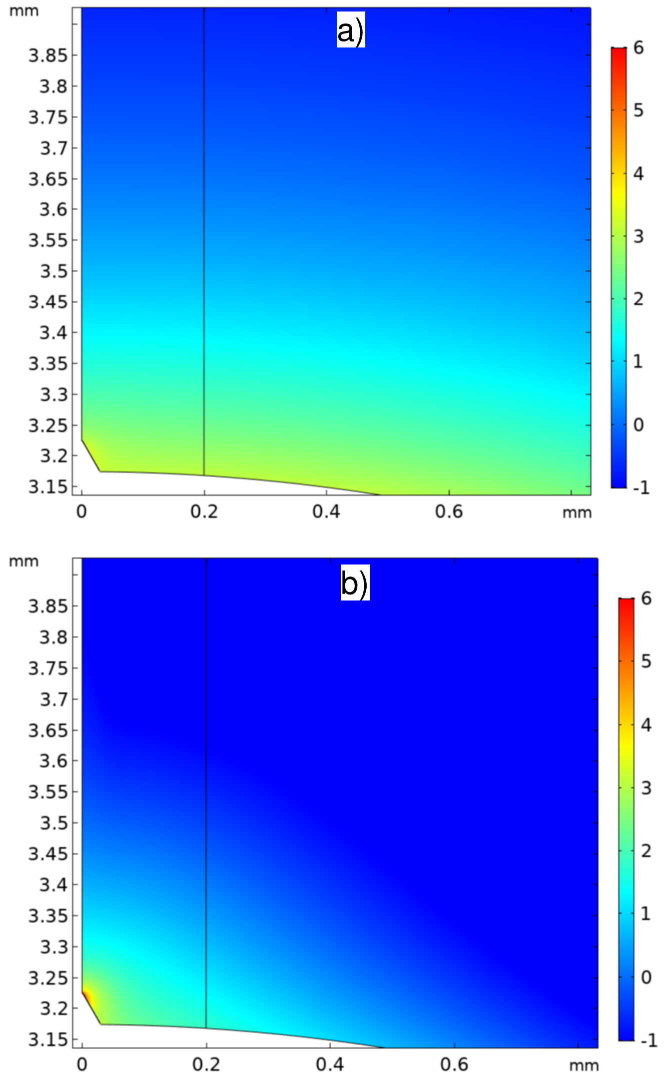
The use of stationary solvers – instead of approximate solution methods or time-dependent solvers, which are standard tools in gas discharge modelling–allows one to develop a very fast and robust numerical model for studying the time-averaged characteristics of DC corona discharges. Such an approach has been applied to DC corona discharges in point-plane gaps in ambient air. A wide range of currents of both voltage polarities and various gap lengths were investigated, and the simulation results were validated by comparing the computed current-voltage characteristics and spatial distributions of the radiation intensity with experimental results.



Images of positive and negative corona discharges and simulation results of distributions of excitation rate of radiating N2 states for various applied voltages in atmospheric-pressure air.
Computed distributions in $m^{-3}s^{-1}$ on a logarithmic scale. Applied voltage U for positive (upper two rows) and negative (bottom two rows) polarity. Gap width d=14 mm.

Simulation of pre-breakdown discharges in high-pressure air

There is vast interest in obtaining information about microprotrusions on the surface of the electrodes of discharges. We have compared the results of simulations with experiments on discharge ignition and breakdown in corona-like configurations; 2D numerical modelling with conical or cylindrical protrusions on the surface of the inner electrode was performed. The enhancement of the field electron emission from the surface of the negative electrode due to the amplification of the electric field on the microprotrusion was estimated and found insignificant in the range of values of the protrusion aspect ratio where the enhanced ionization in the gas phase is already appreciable. It is shown that the deviations from the similarity law, observed in the experiment, may indeed be attributed to enhanced ionization of air molecules in regions of amplified electric field near the microprotrusions.



Distribution of negative ions O^{-2} (densities in m^{-3} on a logarithmic scale) in the vicinity of a conical protrusion (height = 50 μm) at the surface of a positive electrode (sphere radius = 3.18 mm). Air at (a) p = 1 atm. (b) p = 5 atm.

A practical guide to modelling low-current quasi-stationary gas discharges

We published a tutorial concerning the modelling of low-current quasi-stationary discharges, including the Townsend and corona discharges [3]. The aim is to develop an integrated approach suitable for the computation of the whole range of existence of a quasi-stationary discharge from its inception to a non-stationary transition to another discharge form, such as a transition from the Townsend discharge to a normal glow discharge or the corona-to-streamer transition. This task includes three steps: (i) modelling of the ignition of a self-sustaining discharge, (ii) modelling of the quasi-stationary evolution of the discharge with increasing current, and (iii) the determination of the current range where the quasi-stationary discharge becomes unstable and the non-stationary transition to another discharge form begins. Each of these three steps is considered in some detail with a number of examples, referring mostly to discharges in high-pressure air.

Numerical investigation of AC arc ignition on cold electrodes in atmospheric-pressure argon

The mechanism of current transfer to non-thermionic arc cathodes cannot be clarified or studied in detail in experiments. As an alternative, we attempted to study the mechanism by means of a numerical model based on first principles and not based on a priori assumptions. Our goal was to investigate the ignition of AC arc on cold electrodes in atmospheric-pressure argon. The approach used is so-called unified modelling, where a single set of differential equations, comprising conservation and transport equations for all plasma species, the electron and heavy-particle energy equations, and the Poisson equation, is solved in the whole interelectrode gap up to the electrode surfaces. This approach allows us to describe, in a natural way, the whole process of an AC arc development, including the switching of polarity, until the periodic regime has been reached. The dominant mechanisms of current transfer to (non-thermionic) cathodes during AC arc ignition between cold electrodes are the displacement current, the ion current, and thermionic emission current. We also determined that electron emission from the impact of excited atoms can hardly be a dominant mechanism, and that the introduction of a so-called field enhancement factor predicts appreciably lower cathode surface temperatures, which are in contradiction with experimental findings.

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Community and Outreach

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

Workshops, training and outreach events

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

IPFN Science Summer Camp

In 2021 we held the first edition of a new training event targeted at undergraduate students. During five weeks in early September, the students had the opportunity to join a research group at IPFN, becoming immersed in the environment and developing a short term project. Additionally they received training on topics such as ethics on science, technology transfer, scientific infrastructures, scientific writing and scientific presentation. Nine students took part in the school, supported by FCT Summer with Science 2021 scholarships.

To know more:
https://www.ipfn.tecnico.ulisboa.pt/summercamp/

European Researcher's Night 2021

IPFN president Bruno Gonçalves took part in the debate "Which is the best alternative energy?"

International Day of Light 2021 – Photography Competition

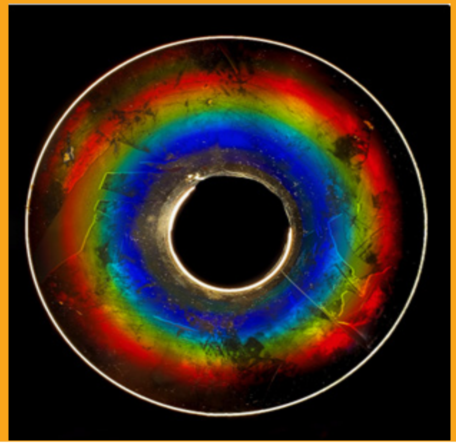
Celebrating the International Day of Light 2021, and with the collaboration of the IST Physics Department of Physics and IST's Center for Photographic Art (NAF), we promoted a photographic competition on the subject of "Light", also supported by by IST's media and outreach team.

Approximately 70 photographs of 45 participants were submitted – each participant could submit up to 3 photographs. The images were evaluated by a jury representing each of the organizers, chaired by Carlos M. Fernandes (NAF), and joined by Prof. João Mendanha Dias (Phys. Dept.) and Diana Amado (IPFN).

The winners were the following:

- **Higher education students:** Ana Trigo, *Plasma Ball 1* (highlighted on this report's cover)
- **Secondary school students:** Margarida Kalinichenko, *Decomposition of light from an LED lamp*
- **General public:** Andreia Barroso, *Propagation of light*

The winners in each of the categories received a copy of the book Haja Luz! by Professor Jorge Calado, offered by IST Press.



Margarida Kalinichenko, Decomposition of light from an LED light

Explain to me like I'm five years old

IPFN researchers Bruno Gonçalves and Gonçalo Figueira participated in the new IST initiative geared towards disseminating science to young children, talking about nuclear fusion and lasers, respectively

School visits and talks

Every year, IPFN facilities such as ISTTOK, L2I and VOXEL receive many tens of school visits, from basic to secondary school students. During the tours, the students have the opportunity to contact with undergraduate students and researchers and have a first contact with the research developed at IPFN, the technologies involved and perspectives of future careers. Our researchers are also frequently invited to give talks at schools, workshops, training sessions and public events. Unfortunately, this type of events was greatly affected by the 2020-21 pandemic, but has already been resumed in 2022.

Press Releases

Superradiance, but not as we know it – September 2020

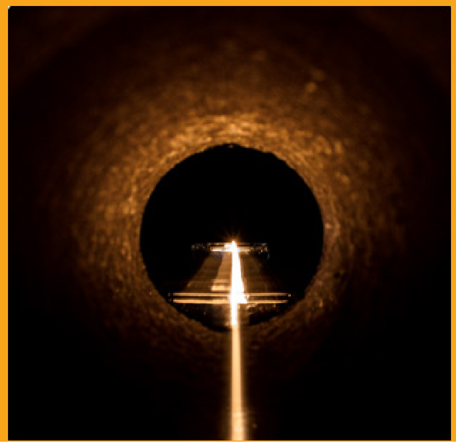
ESTHER successfully launches qualification test campaign – Oct. 2020

Zarco sets sail at IPFN – University of Madeira – Nov. 2020

New mechanism converts x-rays into radio waves in a plasma – Jan. 2021

"Research meets Industry" event – May 2021

Marta Fajardo leads project funded by the European Innovation Council – Nov. 2021



Andreia Barroso, Propagation of light

Web and media

The main communication channels used by IPFN are online based. Our online presence of IPFN is now extended over six different channels:

Webpage – ipfn.tecnico.ulisboa.pt

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

Facebook – fb.com/IPFNLA

Launched in 2010, the IPFN page has gathered more than 1600 followers

Instagram – instagram.com/ipfnmedia/

Almost 150 pictures about what's going on at IPFN!

YouTube – youtube.com/IPFNmedia

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

LinkedIn – linked.in/ipfn

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

Flickr – flickr.com/ipfn

Database of high-quality photos, graphics and scientific images, with more than 280 pictures

Twitter – twitter.com/IPFN_Lisbon

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

Education

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

Participants in the 2021 Plasmasurf Summer School engaged in the afternoon group activities.

PlasmaSurf

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

The programme includes lectures, visits to laboratories and plenty of outdoor activities and water sports. Bringing together science and seaside adventure, PlasmaSurf has emerged to become one of Europe's most popular summer schools in these fields. Due to the pandemic, the 2020 edition was cancelled, but we were able to organize the 8th edition in 2021, with 23 international participants, during a period where travelling and meeting restrictions eased.

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

ATHENS course on Plasma Science and Technology

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

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

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

APPLAuSE doctoral programme

APPLAuSE is IPFN's flagship international doctoral programme in Plasma Science and Engineering. Funded by FCT and hosted by IPFN, the degree is awarded by the University of Lisbon, Portugal. During 2020-2021, the 7th cohort joined the programme, adding 3 new students. As with every other activity, student mobility was severely affected by the pandemic during this period. Up to now, more than 50 students have been enrolled in APPLAuSE, originating from 11 countries in 4 continents.

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

PhD completed in 2020-21

André Lopes, *Collective Thomson Scattering and Plasma Position Reflectometry systems for ITER and DEMO: Neutronics performance assessment and optimisation*

Anton Helm, *Ultra-fast plasma based acceleration modelling: on reduced algorithms to predict the future generation of particle accelerators*

Egor Seliunin, *Validation of the density profiles from the ICRF antenna X-mode reflectometer on ASDEX Upgrade*

Fábio Cruz, *Multiscale modeling of pulsar magneto-spheres*

Fabrizio Del Gaudio, *Analytical and in silico modelling of collective plasma dynamics driven by QED phenomena*

Giannandrea Inchingolo, *Kinetic-scale effects in collisionless accretion disk dynamics*

Hugo Hugon, *Beyond standard geometrical optics: Paraxial WKB treatment of lower-hybrid wave propagation in tokamaks*

João Vargas, *High-temperature non-equilibrium CO2 kinetic and radiation processes*

Doménica Corona, *Tokamak magnetic control simulation: applications for JT-60SA and ISTTOK operation.*

Loann Terraz, *Kinetic mechanisms in non-equilibrium plasmas: influence of N2 on CO2 dissociation and sensitivity analysis of computational models*

Luís Gil, *Stationary ELM-free H-mode in ASDEX Upgrade*

Mario Galletti, *High contrast front-end for a petawatt laser system designed for electron acceleration & high intensity laser-matter applications towards advanced compact particle accelerators*

Muhammad Khan, *Dissipative quantum dynamics of hybrid mechanical systems*

Mukhtar Hussain, *Controlling the microscopic and macroscopic aspects of high harmonic generation in solids*

Pedro Lourenço, *Real-time plasma position reflec-tometry on COMPASS tokamak*

Polina Ogloblina, *In situ resource utilization on Mars using non-equilibrium plasmas*

Ridhima Sharma, *Cylindrical energy analyzer for heavy ion beam diagnostics*

Rolandio Salinas, *Molecular dynamics simulations of Rydberg and strongly correlated plasmas*

Thomas Wodzinski, *XUV metrology: focusing and optimization of the wave front*

Awards and distinctions

Scientific prizes

Thomas Grismayer, awarded an Assistant Researcher contract by Fundação para a Ciência e a Tecnologia

Lígia Diana Amorim and Rogério Jorge, awarded Junior Researcher contracts by Fundação para a Ciência e a Tecnologia

Óscar Amaro, awarded a scholarship "New Talents in Quantum Technologies" by Fundação Calouste Gulbenkian.

Marija Vranic, selected by the Lisbon Academy of Sciences to join the Young Scientists Seminar

Horácio Fernandes and Marta Fajardo, nominated for the International Union of Pure and Applied Physics Commissions on Physics for Development (C13) and on Plasma Physics (C16), respectively.

Luís Gil, awarded EUROfusion Researcher Grant

Thomas Grismayer, Lígia Diana Amorim and Rogério Jorge, three new FCT researchers at IPFN

Conferences Awards

Chloé Fromentin and Duarte Gonçalves, 'Michel Cantarel' students awards of the conference Plasma Thin Film International Union Meeting (PLATHINIUM).

Óscar Amaro, Outstanding Undergraduate Poster award at 2020 APS Division of Plasma Physics Conference

Camilla Willim [▶], PhD Poster Prize at the 2021 EPS Plasma Physics and Controlled Fusion Conference

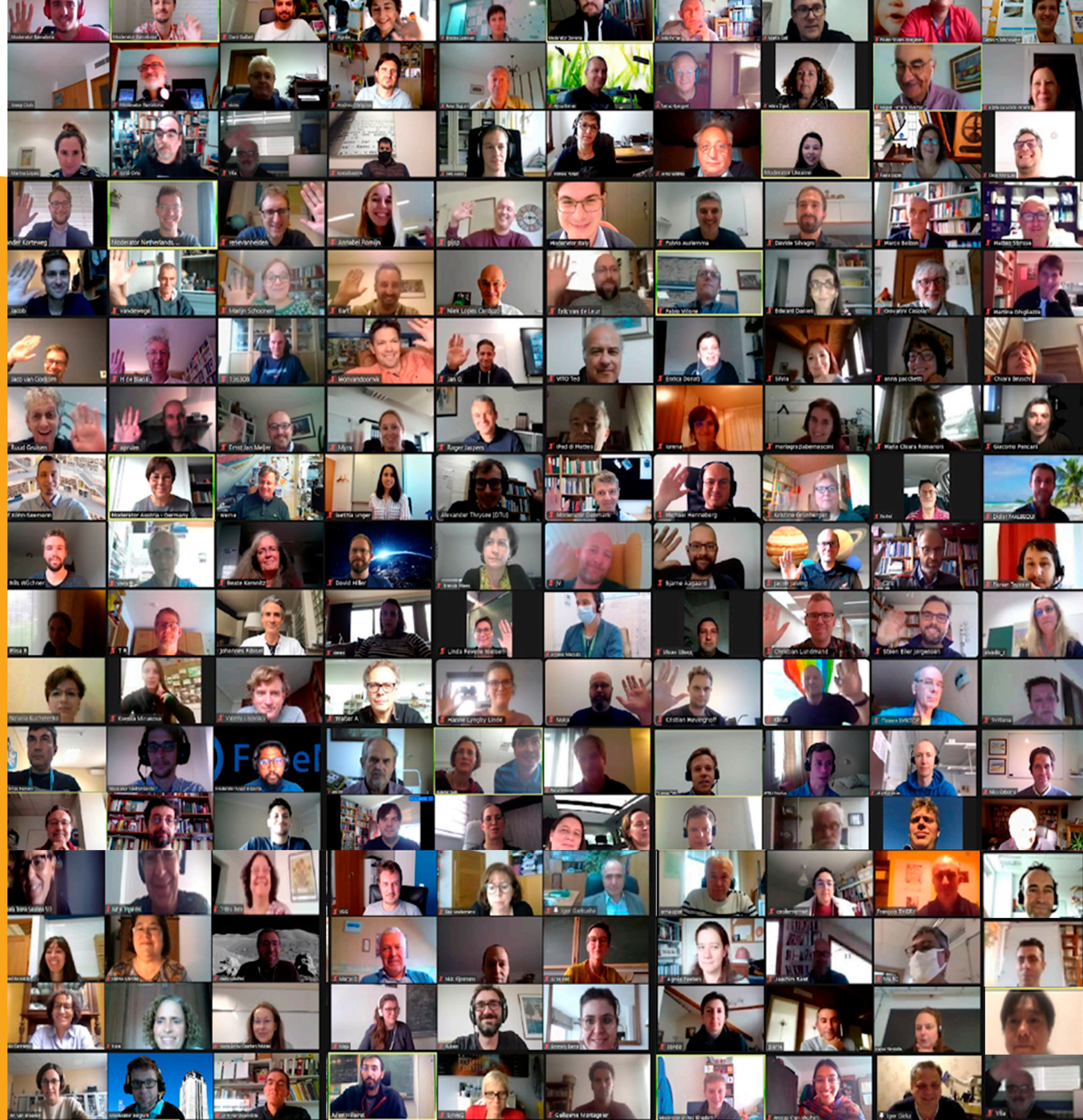
▶ 

Thesis prizes

Mario Galletti [▶], Best PhD thesis award by the Portuguese Society for Optics and Photonics, 2020

Mario Galletti [▶], PhD Research Award from the Plasma Physics Division of the European Physical Society**, 2021**

▶ 



2020 European Fusion Teacher Day

On October 2nd, 2020, eighty-six high-school teachers from Portuguese schools participated in the European Fusion Teacher Day. The event gathered 650 teachers from all around Europe on a first-of-its-kind online seminar to promote nuclear fusion education at the high school level.

A total of 17 seminars took place simultaneously across 13 countries, given by local experts to the local group of teachers. This was followed by an international webinar live from ITER, JET, and GOLEM, arguably some of the most iconic nuclear fusion reactors.

The organizer of this event, FuseNet, relied on a number of European institutions to put together the local sessions, such as IPFN, where PhD student Daniel Hachmeister coordinated the Portuguese session. The latter unfolded in a morning and an afternoon talk, both given by IPFN's President Bruno Gonçalves. The subjects ranged from nuclear fusion basics to the current development of the world's experimental reactors.

Despite the relatively small population, the number of Portuguese participants was only second to Italy's (98 registrations), accounting for around 13% of the total participants – a clear sign that our high-school teachers have a strong interest in nuclear fusion!

In Memoriam

João Pedro Bizarro
1963-2022

Professor João Pedro Saraiva Bizarro passed away prematurely on January 2022 in Lisbon. He was Associate Professor of the Department of Physics and Researcher of the Instituto de Plasmas e Fusão Nuclear (IPFN) with Instituto Superior Técnico (IST). He was former Head of the Theory and Modelling Group of IPFN and former Director of the Advanced Programme in Plasma Science and Engineering (APPLAuSE) with IPFN/IST.

João Pedro Bizarro graduated in Engineering Physics at IST (1987), received the doctorate in *Rayonnement et Plasmas* from Université de Provence Aix-Marseille I (1993), with the grade *Très Honorable,* and obtained the title of *Agregado* in Physics at IST (2010).

His scientific work was in the field of theory and modelling of magnetic fusion plasmas (non-inductive current drive, plasma transport and kinetics, Grad-Shafranov equilibria, time-frequency analysis of diagnostic signals, simulation of tokamak experiments), covering a broad and eclectic spectrum of knowledge, ranging from fundamental theoretical physics (quantum formalism, thermodynamics of irreversible processes, waves in plasmas) to engineering (RF antennas, system analysis).

He authored or co-authored over 100 papers published in leading scientific journals of the field, he supervised 12 research programs of undergraduate and graduate students, and he was actively involved in modelling activities for JET, in the Integrated Tokamak Modelling Task Force (ITM-TF), in the ITER Scenario Modelling (ISM) activity, and was one of the proponents of the Goal Oriented Training Programme on Lower-Hybrid and Ion Cyclotron Technology (LITE).

His teaching duties, often as coordinator, spanned different topics and courses, from Basic Physics (Electromagnetism and Optics, Thermodynamics and Structure of Matter) for various engineering degrees, to Advanced Physics (Plasma Kinetic Theory, Nuclear Fusion, Statistical Physics) for Engineering Physics.

João Pedro was enthusiastic when teaching students, insightful and thorough when discussing science, and very active when looking for fair solutions to any human relations problem. His colleagues will remember his eclectic knowledge of Physics and the strength of his convictions.

He will be greatly missed by us all.

Luís L. Alves
Senior researcher IPFN/IST

Biennial Report 2020 - 2021

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