Biennial Report

2024-2025

ipfn
INSTITUTO DE PLASMAS
E FUSÃO NUCLEAR

Instituto de Plasmas e Fusão Nuclear

Highlights of activities

2024-2025

Biennial Report

Instituto de Plasmas e Fusão Nuclear

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President's Foreword

I am delighted to present the highlights of IPFN's activities in 2024–2025, two years of scientific discovery, technological progress and collaboration. The achievements described in this report reflect the dedication of our seven research groups and the collective effort of researchers, engineers, technicians, students and administrative staff. Together, we continue to strengthen Portugal's contribution to plasma science and engineering, connecting fundamental questions with technologies that address society's needs.

Our programme brings together controlled nuclear fusion, plasma technologies and intense lasers, supported by advanced computing and specialised experimental infrastructures. This breadth is one of IPFN's greatest strengths: it enables ideas, methods and expertise to move between disciplines, linking the pursuit of sustainable energy with advances in materials, photonics, space exploration and our understanding of the universe.

Fusion remains a cornerstone of our mission. Within EUROfusion and international collaborations supporting ITER and future reactors, our teams advanced diagnostics, plasma control, engineering integration and remote handling. Progress in microwave reflectometry for DEMO and the Divertor Tokamak Test facility, together with developments in autonomous transportation of reactor components, addresses practical challenges essential to reliable fusion operation. Studies of plasma-facing materials, fuel retention and refractory high-entropy alloys further strengthened the foundations for components capable of withstanding demanding reactor environments.

Experimental and theoretical research complemented these engineering advances. Work on ASDEX Upgrade explored high-confinement regimes without damaging edge instabilities, while analysis of JET plasmas improved our understanding of confinement near operational limits.

Research on energetic particles and stellarator optimisation opened further directions for future devices. In Portugal, upgrades to ISTTOK reinforced its role as a platform for research and training. Our partnership with Next Step Fusion advanced digital-twin development, supporting the exploration of machine learning for plasma control and illustrating the value of collaboration with the emerging fusion industry.

Beyond magnetic confinement fusion, our researchers explored new frontiers in intense laser interactions, plasma acceleration and radiation generation. The demonstration of a modular discharge plasma source for CERN's AWAKE programme marked an important step towards scalable accelerators.



New concepts for coherent plasma light sources and advances in nonlinear optics opened opportunities for compact radiation technologies, while LIBScan brought laboratory expertise closer to portable elemental analysis for scientific and industrial applications.

Our astrophysical research connected theory, large-scale simulations and experiments at major international facilities. Studies of energy partition in collisionless plasmas, direct imaging of relativistic plasma instabilities and new mechanisms for coherent radio emission deepened our understanding of extreme cosmic environments. Research on axion–plasma interactions also demonstrated how plasma physics can inform the search for dark matter.



Low-temperature plasma research advanced sustainable chemical conversion, functional nanomaterials and predictive modelling. Developments in the LisbOn Kinetics tools strengthened resources available to the international community, while new studies of high-pressure discharges improved the foundations of industrial plasma technologies. A particularly significant infrastructure milestone was ESTHER’s first full dynamic test in November 2025, achieving hypersonic flow and expanding Portugal’s experimental capabilities for atmospheric-entry research.

Education and public engagement remain central to our strategy. MSc and PhD supervision, international internships and the 2024 and 2025 PlasmaSurf schools gave young researchers opportunities to learn through active participation in science. International conferences and distinguished lectures enriched our scientific community, while school visits, public demonstrations and media engagement shared the fascination and relevance of plasmas with wider audiences. Scientific and thesis awards, including Luís Silva’s Blaise Pascal Medal in Physics, recognised the quality of our community’s contributions.

I warmly thank our funding agencies, particularly FCT and the European programmes supporting our work, alongside ESA, Instituto Superior Técnico, our academic collaborators and industrial partners. Above all, I thank every member of IPFN for their commitment and creativity. Looking ahead, we will continue to advance plasma science, develop enabling technologies and train the people who will shape a sustainable future.



Bruno Soares Gonçalves,
President of IPFN

About IPFN

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

IPFN is the only Portuguese R&D institution dedicated to Plasma Science and Engineering and one of the country's leading Physics research laboratories, hosting researchers based at several Portuguese universities and building on more than 25 years of R&D experience.

IPFN pursues an ambitious research programme that balances activities motivated by contemporary scientific challenges (curiosity-driven research) with a diverse portfolio of technological applications (application-driven research).

This programme is supported by an institutional strategy centred on four main pillars:

i) internationalisation, through peer recognition of expertise in several fields and participation in high-profile projects;

ii) national reach, through the integration of researchers from several universities;

iii) a strong commitment to high-level education and advanced training;

iv) the development of state-of-the-art research infrastructures.



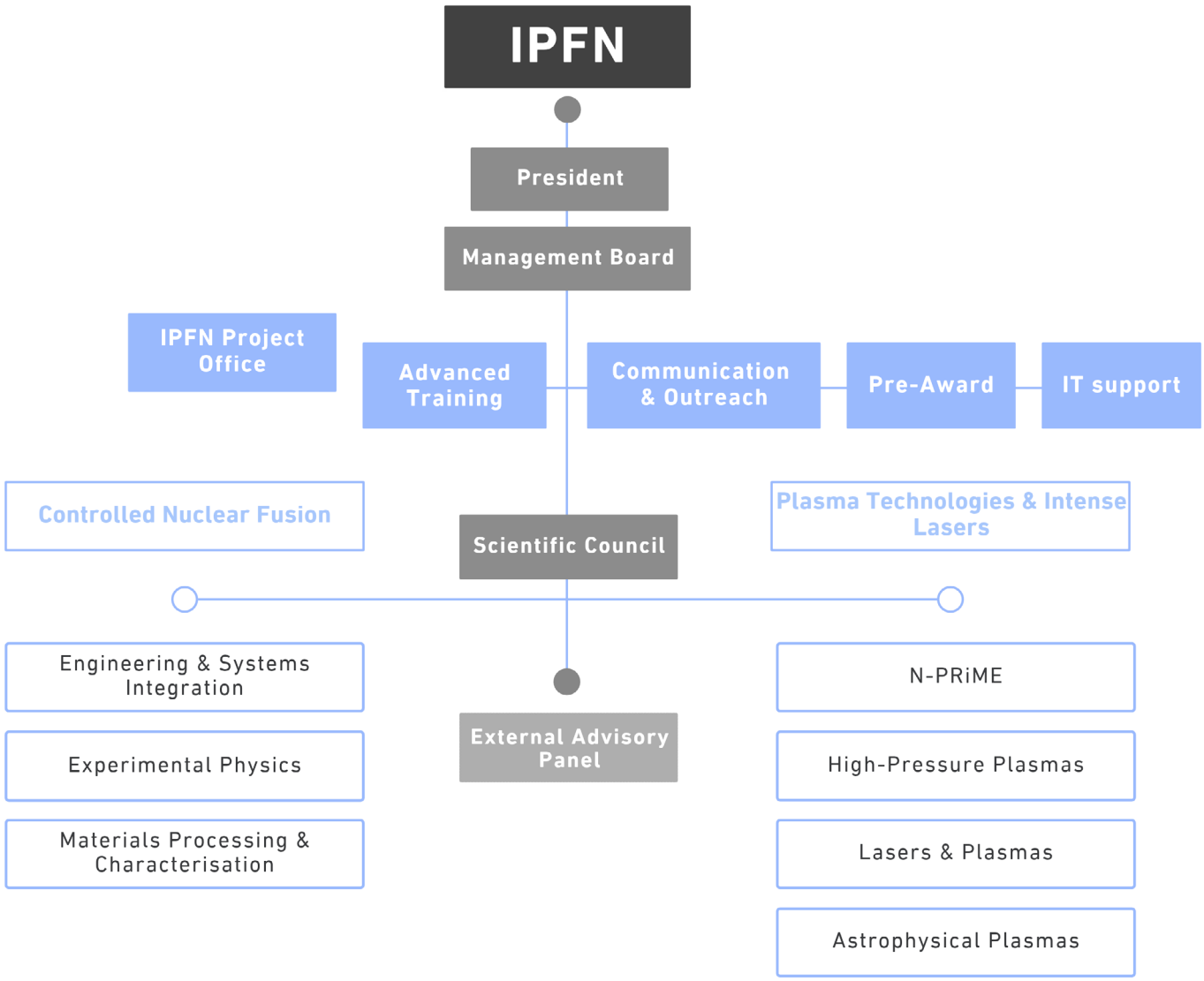


Organisation

Research at IPFN is organised into two Thematic Areas:

Controlled Nuclear Fusion - This research line is focused on the work programme established by the European Fusion Roadmap (Horizon Europe), which includes activities associated with the development of systems, operation, and scientific exploitation of large and medium-sized tokamaks and stellarators, as well as with the design and construction of the next generation fusion devices.

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



The **Management Board** is composed of the heads of each research group and representatives of members holding a PhD, and is responsible for the overall management of the research unit.

The **External Advisory Panel** monitors IPFN's activities and strategy. It oversees scientific progress, graduate programmes, recruitment, and overall performance, and advises the Management Board on all matters related to the mission of the research unit.

History of IPFN



1987

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



1990

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



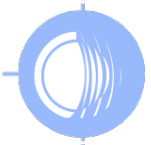
1996

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



2002

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



2008

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



2014

EUROfusion partnership agreement



2017

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



2021

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



2025

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

Management Board



Bruno Gonçalves

Group of Engineering & Systems Integration



Carlos Silva

PhD representative



Alberto Vale

PhD representative



Frederico Fiúza

Group of Astrophysical Plasmas



Gonçalo Figueira

PhD representative



Marta Dias

Group of Materials Processing & Characterisation



Horácio Fernandes

Group of Experimental Physics



Luís Lemos Alves

Group of N-PRiME



Luís Oliveira e Silva

Group of Lasers and Plasmas



Vasco Guerra

PhD representative



Marta Fajardo

PhD representative



Pedro Almeida

Group of High-Pressure Plasmas

External Advisory Panel



Alexander Schekochihin

University of Oxford



Gerrit Kroesen

Eindhoven University of Technology



Francesco Romanelli

University of Rome - Tor Vergata



Katalin Varjú

ELI ALPS



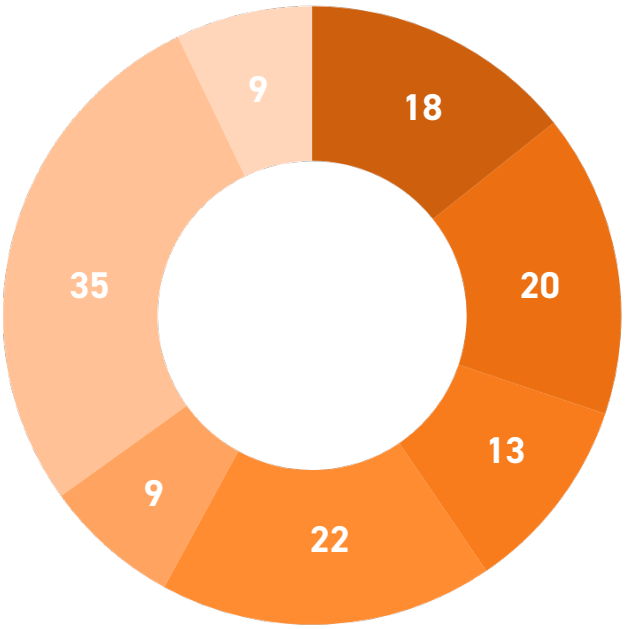
Peter Bruggeman

CNRS & Université Toulouse III - Paul Sabatier

Facts and Numbers

Members per Group

at the end of 2025



- Engineering & Systems Integration
- Experimental Physics
- Materials Processing & Characterisation
- Plasmas Reactive Modelling and Engineering (N-PRiME)
- High-Pressure Plasmas
- Lasers and Plasmas
- Astrophysical Plasmas

+110

Publications per year
inc. Conference Proceedings

155

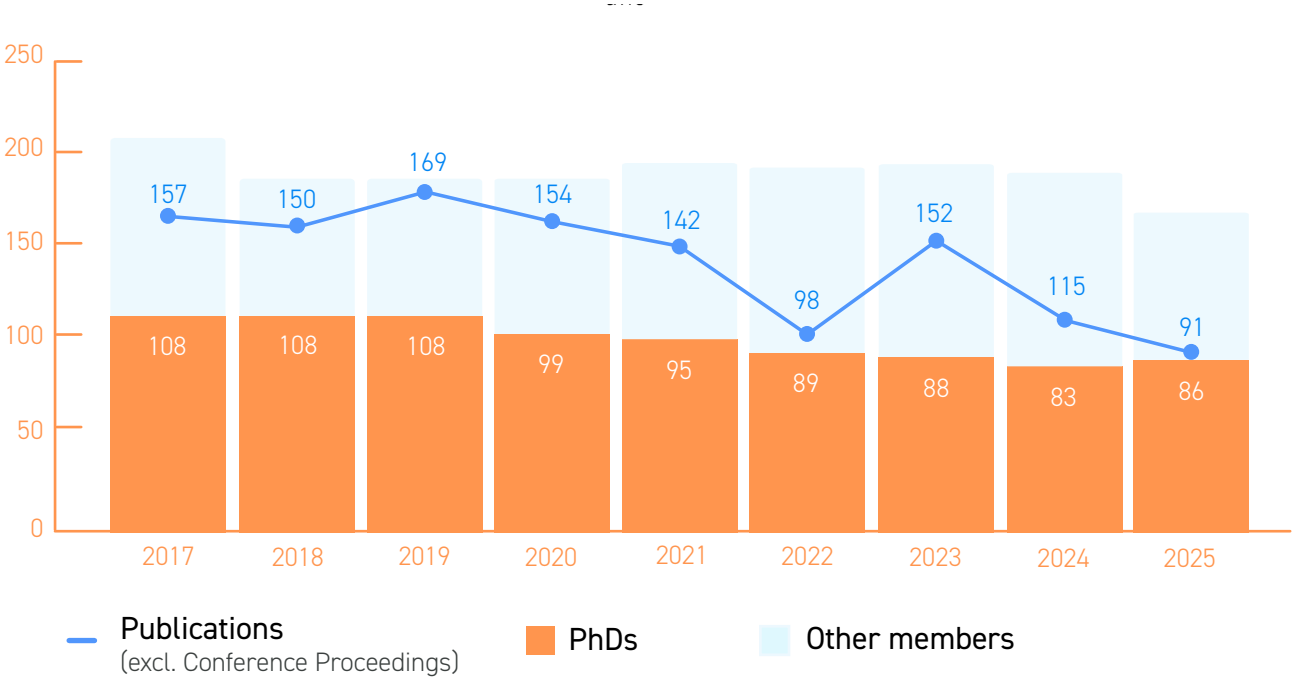
Collaborators
at the end of 2025

86

PhDs
faculty, researchers & postdocs

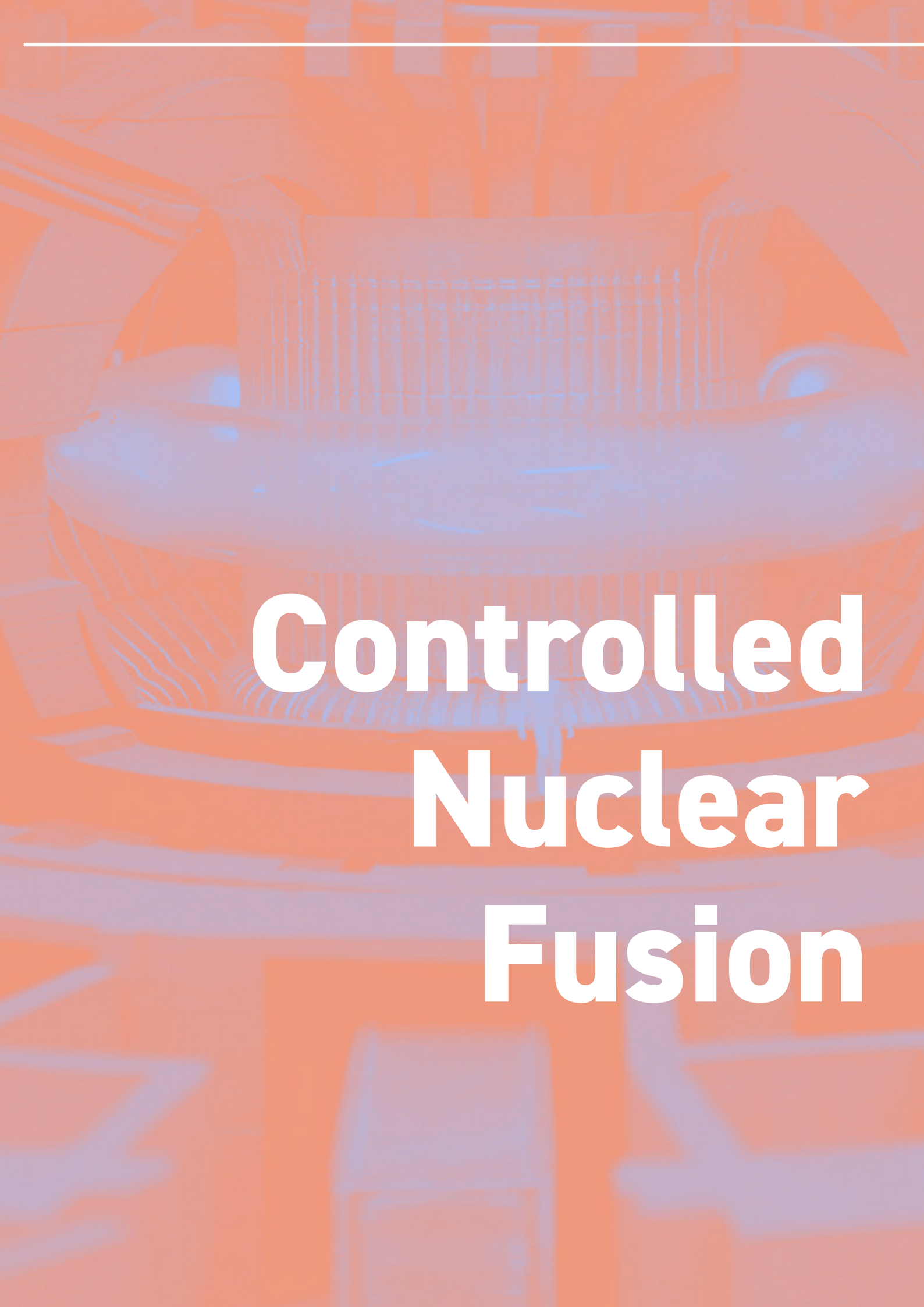
Collaborators and Publications

since 2017



Highlights include papers published in:

- *Science Advances*
- *Nature Photonics*
- *Nature Communications*
- *Physical Review Letters*



Controlled Nuclear Fusion

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

The fusion reaction most readily 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 fuels are abundant on Earth, and no greenhouse gases are produced during fusion operation. Fusion also has important advantages in terms of nuclear safety and radioactive waste. Once harnessed, fusion power could provide a nearly unlimited, safe and climate-friendly energy source.

Fusion research is a global effort aimed at achieving power generation from fusion. Currently, the major international project is the construction of ITER in southern France. The largest tokamak ever built, ITER aims to demonstrate the scientific and technological feasibility of fusion as an energy source.

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 the regular use of alternating discharges with a duration of more than 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 its long discharges for such a small machine, it is foreseen that its contribution to studies of materials compatible with fusion devices will increase in the near future.

Engineering and Systems Integration

Summary of Research

Main Researchers:

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

Main funding sources:

Fundação para a Ciência e a Tecnologia
EURATOM/EUROfusion
ITER Organization
General Fusion

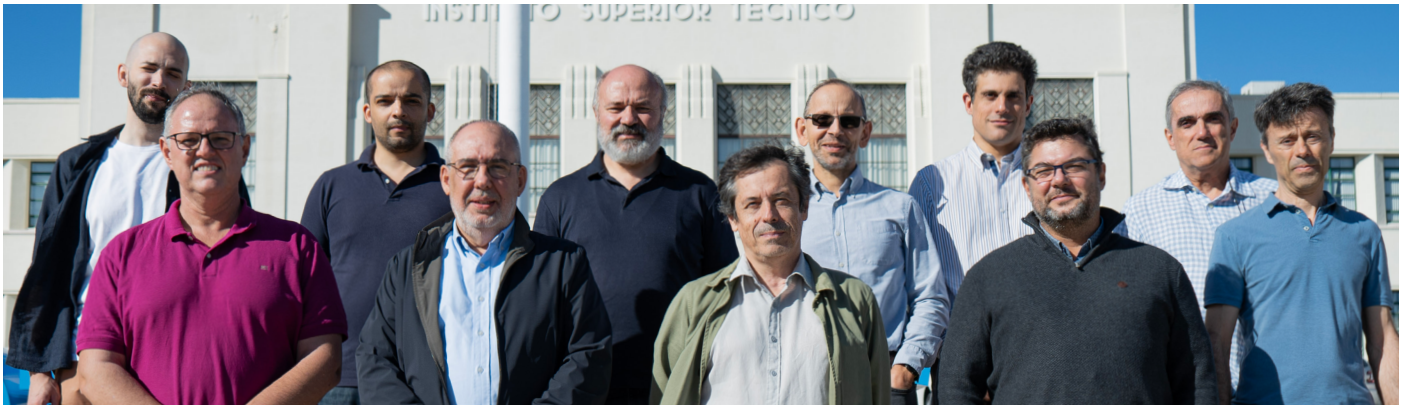
Making fusion energy a reality is one of the defining engineering challenges of our time. Europe needs specialised expertise to meet it and the Engineering and Systems Integration Group helps close this gap by developing critical technologies and training the next generation of fusion scientists and engineers.

Our work brings together diagnostics, instrumentation, control, data acquisition and remote handling for demanding fusion environments. Drawing on IPFN's expertise, we combine design, simulation and systems integration to build reliable, radiation-tolerant solutions. Our capabilities span advanced control and data platforms, diagnostic modelling, structural analysis, component design, RAMI (reliability, availability, maintainability and inspectability) and mobile robotics.

We support major programmes, including ITER, DEMO and IFMIF-DONES, and emerging fusion companies. By improving facility operation, maintenance, reliability and safety, we help lay the foundations for sustained fusion power.

Through international projects and multidisciplinary training, we strengthen Europe's fusion ecosystem, delivering the people, technologies and integrated solutions that today's programmes and tomorrow's power plants need.

Group Leader: Bruno Soares Gonçalves



CONTRIBUTIONS TO DEMO CONCEPTUAL DESIGN ACTIVITIES

WAVEGUIDE PIPES FOR LARGE THERMAL DISPLACEMENTS IN DEMO

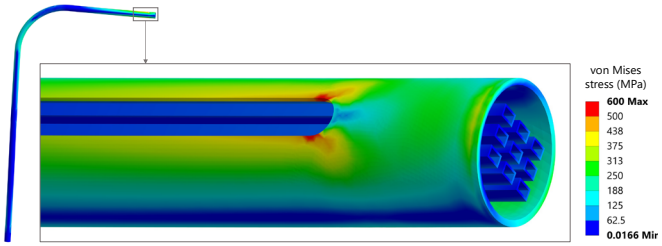
Future fusion power plants will require plasma diagnostic systems capable of surviving extreme thermal and radiation environments while remaining remotely maintainable. A key component of the reflectometry system developed for DEMO, which measures the electron density profile to determine the plasma position and shape, is a set of hollow waveguide pipes that route the microwaves from the plasma-facing antennas to the ex-vessel part of the transmission lines.

These pipes must bridge the gap between two large internal structures, the breeding blanket and the vacuum vessel, which expand and shift independently during operation, potentially moving relative to each other by several centimetres.

This project aimed to find pipe designs that can absorb these displacements without permanent deformation, which would compromise the measurements. Using finite-element simulations with conservative displacement estimates, several pipe geometries were tested and iterated, guided by the principle of removing material from the most stressed regions to improve flexibility.

The optimised design, based on elongated perforations cut into the pipe wall at critical locations, reduced peak stresses by half compared to the original concept, while the waveguides inside remained well within safe limits.

These results demonstrate a viable path for integrating the reflectometry transmission lines in DEMO and identify targeted material removal as a design strategy uniquely available to the waveguide pipes, not possible in the fluid-carrying blanket structures they share space with.



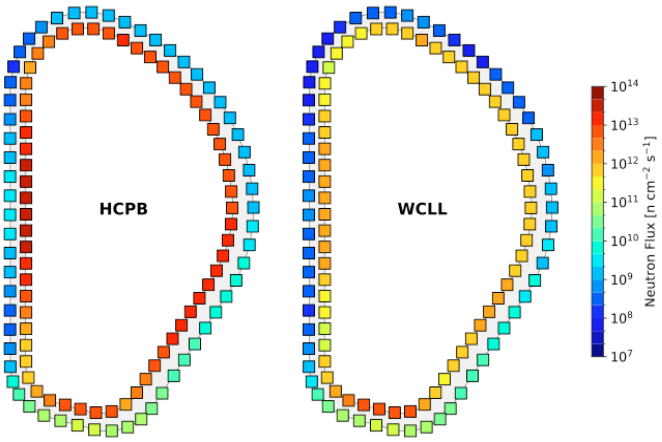
Thermomechanical stresses in the waveguide pipes. *The elongated perforations distribute the stresses away from the critical bend region, keeping the waveguides well below the material yield limit.*

MAPPING THE RADIATION ENVIRONMENT FOR MAGNETIC DIAGNOSTICS IN DEMO

Magnetic probes are the primary instruments for plasma position and shape control in fusion reactors. In DEMO, in-vessel sensors sit between the breeding blanket and the vacuum vessel, shielded from the plasma but still exposed to intense neutron and gamma radiation, expected to surpass the ITER nuclear loads by up to an order of magnitude. Knowing the radiation environment at each sensor location is essential to guide material selection and predict sensor lifetime.

Radiation transport simulations were performed for 120 sensor positions distributed around the plasma, using detailed models of the Helium-Cooled Pebble Bed (HCPB) and the Water-Cooled Lithium Lead (WCLL) breeding blanket designs. Neutron and gamma fluxes, nuclear heat loads, and atomic displacement rates were computed for a wide set of candidate sensor and insulator materials.

The two blanket designs produce dramatically different environments at the most-exposed inboard equatorial positions: HCPB yields neutron fluxes 18 times higher than WCLL at the same location, while below the divertor both configurations converge to nearly identical loads. Carving a slot into the back of the blanket to house the probes adds a modest radiation penalty in the HCPB case, but increases heat loads by up to a factor of 4 in the WCLL design. These results establish the radiation boundaries that sensor materials must satisfy, feeding directly into the qualification programme for DEMO magnetic diagnostics.



Neutron flux map around the plasma. *Poloidal distribution of the total neutron flux at 120 in-vessel and ex-vessel sensor positions. At the most exposed location, the HCPB blanket attenuates the neutron flux 18 times less effectively than WCLL.*

ENABLING RESEARCH CONTRIBUTIONS TO REAL-TIME REFLECTOMETRY FOR PLASMA TRACKING IN FUTURE FUSION REACTORS

Controlling the position and shape of a burning plasma throughout an entire discharge is critical for the safe operation of future fusion reactors. In DEMO, magnetic diagnostics may degrade under intense neutron irradiation, demanding robust alternatives. Microwave reflectometry is well suited for this role but extending it to full plasma tracking, including the start-up phase, requires advances in simulation, hardware, and signal processing.

IPFN led the EUROfusion Enabling Research project ENR-TEC.01.IST, a three-year European collaboration (2022–2024) to develop a next-generation reflectometry system for DEMO. A novel multi-mode diagnostic concept was proposed, where the same poloidally distributed hardware operates as reflectometer, interferometer, refractometer, or intensity refractometer depending on plasma conditions, enabling monitoring from the very first instants of the discharge.

The project advanced on multiple fronts: the 3D full-wave code REFMUL3 was enhanced with GPU support and a CAD import pipeline for realistic synthetic diagnostics; a compact reflectometer prototype was rebuilt; ray-tracing and full-wave studies validated the multi-mode concept for DEMO ramp-up; synchronisation of distributed reflectometers was investigated on WEST; and an integrated design workflow was applied to Plasma Position Reflectometry for DTT.

The project delivered proof of principle for the ramp-up diagnostic, a production-ready 3D simulation framework, and a working compact reflectometer. These results provide a foundation for implementing reflectometry-based plasma control in DEMO and other future machines.

Reference: F. da Silva et al., submitted to Plasma Phys. Control. Fusion (2025).

REMOTE HANDLING ACTIVITIES FOR DEMO

The maintenance and decommissioning of Nuclear Fusion Power Plants involves different types of large, heavy and activated loads. Ex-vessel transportation systems are required to transport these loads between the reactor and remote maintenance facilities.

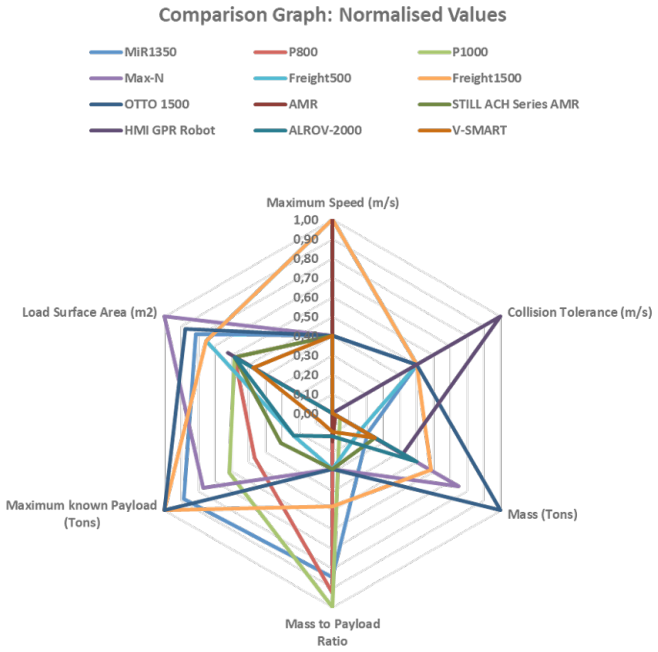
EX-VESSEL TRANSPORTATION

Various pallet transporters (a.k.a. trolleys) were assessed as possible solutions for future deployment in an EU nuclear fusion complex (EUNFC). The work highlighted the advantages and disadvantages of cooperative pallet transporters and identified gaps between current and required technologies. The main topics addressed were:

- Identification of the need and benefits of cooperative pallet transporters compared with single transporters.
- Definition of the equipment and power plant infrastructure required for transportation within the EUNFC.

- Assessment of the Equipment Readiness Levels of currently available cooperative pallet transporter technologies.
- Identification of gaps between current capabilities and requirements, and definition of an R&D plan to address them.
- Identification of risks associated with pallet transporters and cooperative scenarios.

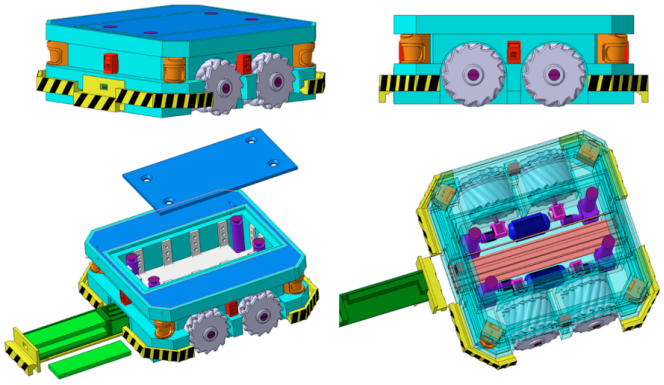
Multiple trolley-like systems were assessed and compared in terms of their capabilities, as depicted in the figure below. This comparison identified the limitations of existing technologies and which technologies could be repurposed or require further R&D. The main R&D topics identified were cooperative fleet formation and assembly, navigation in confined environments, maximum system payload and mass-to-payload ratio, optimised payload distribution and trolley placement underneath loads, and general fleet cooperation activities.



Graph comparison for multiple trolley-like systems.

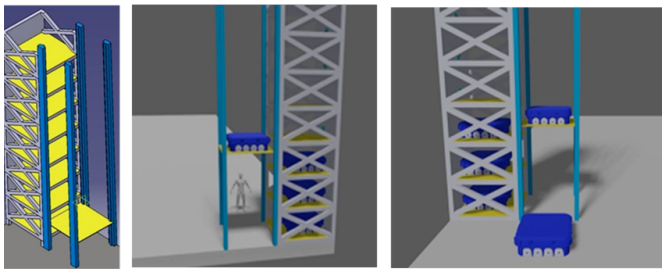
The identified gaps and risks were translated into a conceptual framework for the DEMO ex-vessel transportation system, focusing on cooperative ground transportation solutions. By defining general concepts and expected behaviours rather than final mechanical designs, the work aimed to reduce technical uncertainty and increase the Equipment Readiness Level (ERL) of autonomous systems operating in nuclear environments. ERL combines Technology, Systems and Integration Readiness Levels (TRL, SRL and IRL).

The Ground Transportation System, depicted in the figure, was centred on a "Fleet of Trolleys" (FoT) approach, moving away from conventional single-vehicle solutions. Autonomous pallet transporters work cooperatively to share loads, enhancing manoeuvrability and redundancy. Cooperative protocols ensure the autonomy and coordination required for load stability and fault tolerance, while complying with strict nuclear constraints and minimising human intervention through remote maintenance. Advanced algorithms provide the positioning accuracy required to manage uneven weight distributions.



Autonomous Omnidirectional Ground Transporter Design.

A draft Parking and Charging System, illustrated below, was also designed to provide compact storage integrated with the autonomous trolleys. Its main functions include automated energy management, with battery charging and data exchange through docking interfaces, and fleet management, providing secure vertical storage and alignment to ensure trolley readiness for transportation tasks. Together, these outputs, including technical guides for fleet assembly and smart load balancing, provide a robust foundation for subsequent design, simulation and prototyping phases of an EUNFC programme.



Charging and Parking Concept Tower with the hybrid lifting system. Two active columns on the back and two passive columns on the front shared with the tower structure.

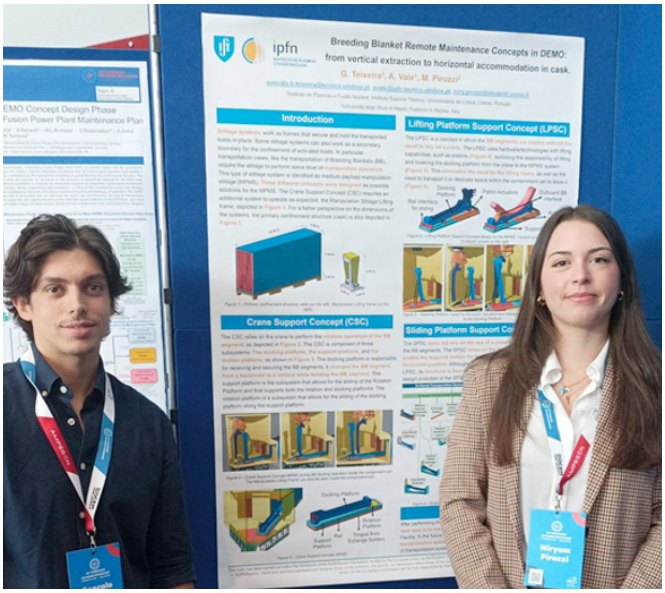
HANDLING OF BREEDING BLANKET SEGMENTS

The remote handling team has studied several approaches on how to reorient and handle Breeding Blanket segments for maintenance purposes. This reorientation and handling process is performed by a system entitled Medium Payload Manipulation Stillage (MPMS).

The MPMS is a system researched and designed by the remote handling team at IPFN, and it consists of several variations that explore different kinematic and dynamic configurations, as well as different optimisation parameters such as overall system mass, operational occupation space and system dimensions.

The different variations resulted in different impacts on the required dimensions for the upper containment cell of the EUNFC.

The MPMS was showcased in a poster session of the 33rd Symposium on Fusion Technology (SOFT 2024) by the students Gonçalo Teixeira and Miryam Pirozzi.

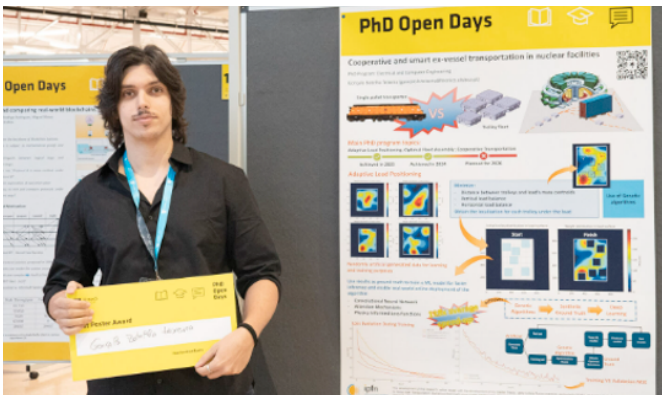


Poster presentation at SOFT2024.

COOPERATIVE AND SMART EX-VESSEL TRANSPORTATION IN NUCLEAR FACILITIES

At the 11th edition of PhD Open Days, held on 27–28 October 2025, at the Técnico Innovation Centre, IPFN student Gonçalo Teixeira was distinguished with the Best Scientific Poster Award for his work "Cooperative and Smart Ex-Vessel Transportation in Nuclear Facilities". The awarded research presented a framework for cooperative and adaptive load transportation utilising fleets of autonomous trolleys (FoT) specifically designed for nuclear fusion environments. The work focused on the development of optimisation and learning-based algorithms that determine the optimal positioning of multiple robots. This ensures the safe and stable handling of heavy, potentially activated loads within the strict constraints of a nuclear facility.

The project aimed to integrate multi-objective optimisation, deep learning, and physics-informed models into a unified system to achieve reliable autonomous transportation under safety-critical conditions. Adaptive load transportation serves as one of the three core pillars of this broader PhD research, alongside optimal fleet assembly and cooperative transportation. Beyond the confined galleries of nuclear power plants, these developments have significant potential for application in various heavy industrial settings requiring large-scale load management.



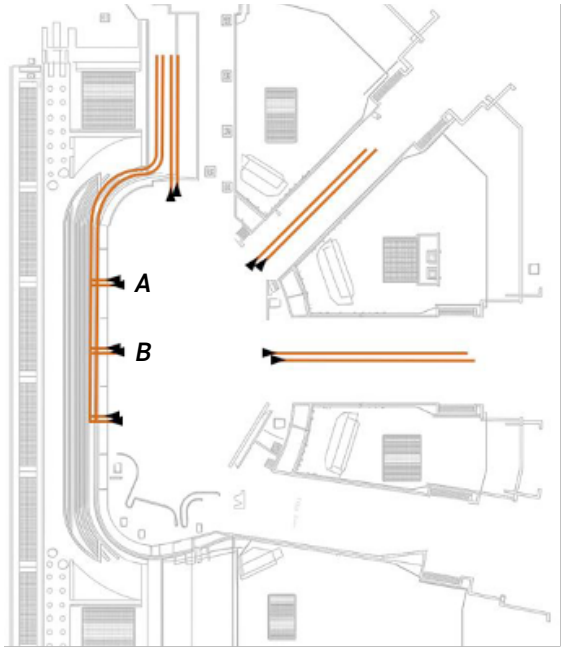
PhD Open Days 2025 Poster Award.

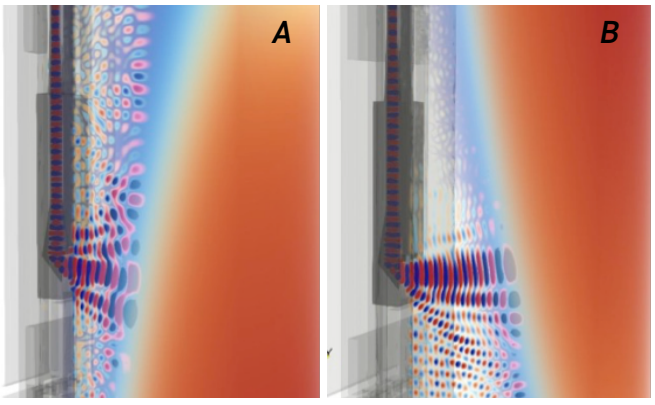
OTHER MICROWAVE DIAGNOSTIC DESIGN ACTIVITIES

DESIGNING REFLECTOMETRY DIAGNOSTICS FOR PLASMA POSITION CONTROL ON DTT

Future fusion reactors will need radiation-resistant diagnostics to control plasma position in real time. Magnetic probes, widely used today, may degrade under the intense neutron fluxes expected in machines like DEMO. Microwave reflectometry offers a complementary, neutron-insensitive solution with high spatial and temporal resolution.

Our goal is to design and validate a Plasma Position Reflectometry (PPR) system for the Divertor Tokamak Test (DTT) facility, currently under construction in Frascati, Italy. Over the past two years we consolidated the High Field Side (HFS) design through three lines-of-sight, integrated custom bistatic hog-horn antennas into a new standard First Wall module and migrated our 3D full-wave FDTD code REFMUL3 to the CINECA Leonardo and Pitagora supercomputers.





Poloidal locations of the planned DTT PPR antennas, and full-wave REFMUL3 simulations of the HFS upper (A) and lower (B) lines-of-sight in the DTT Single-Null reference scenario (I=5.5 MA, B= 6.6 T, n, = 1.6 × 10^{20} m^{-3}).

We demonstrated that, despite the severe space constraints driving the HFS antenna design, plasma density profiles can be reconstructed with position errors within the required one-centimetre tolerance in DTT Single-Null scenarios. Full-wave 3D simulations, extended for the first time ever to the W-band, confirmed profile recovery up to the pedestal, while thermal-structural validation by industrial partners proved feasibility of the redesigned cooled First Wall module.

These results establish a comprehensive blueprint for reflectometry-based position control on DTT, directly applicable to DEMO and other future fusion devices, and validate the developed integrated design workflow.

References:

J. M. Santos et al., Fusion Eng. Des. 201, 114275 (2024).

F. da Silva, J. Santos et al., JINST 20, C09004 (2025).

F. Ruffini, F. da Silva, J. Santos et al., JINST 20, C05030 (2025).

F. Ruffini et al., 67th APS DPP Annual Meeting, USA, 2025 (oral).

SYNTHETIC DIAGNOSTICS FOR THE SPEKTRE PLASMA PLATFORM

Understanding wave propagation at the plasma edge is essential for developing diagnostic techniques for next-generation fusion machines such as DEMO. A key challenge is extending microwave reflectometry beyond normal incidence to oblique and tangential injection angles, enabling new measurement capabilities such as intensity refractometry and tomographic plasma shape reconstruction.

To address this, we are contributing to the design of a new diagnostic, Variable Oblique Probing on O-mode (VOPOO), for the SPEKTRE platform, a 6-metre magnetised plasma column under construction at Université de Lorraine. VOPOO will probe the plasma edge with Ku-band microwaves at variable injection angles, using both monostatic and bistatic antenna configurations.

We developed a flexible method for constructing dynamic circular plasma descriptions on Cartesian grids, implemented within the REFMULF full-wave FDTD code. The approach uses a polar-to-Cartesian mapping through an intermediate parameter space, enabling efficient handling of plasma rotation, poloidal modes, hollow profiles, and turbulence scenarios.

This methodology underpins the synthetic diagnostic essential for interpreting VOPOO measurements and for developing advanced signal processing techniques, including machine-learning-based approaches.

This work is a first step towards building a numerical twin of VOPOO, initially in 2D and later in 3D with REFMUL3, and contributes to validating the concept of microwave tomography for DEMO plasma position tracking.

Reference: F. da Silva et al., submitted to Plasma Phys. Control. Fusion (2026).

DEVELOPMENT OF A COMPACT REFLECTOMETER

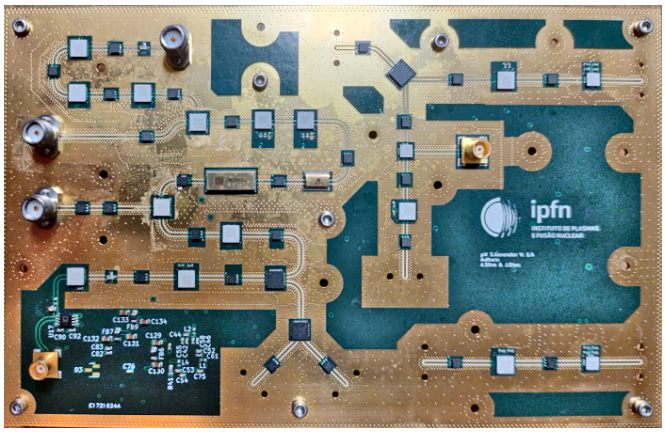
Future fusion power plants, such as DEMO, will impose severe constraints on diagnostic systems due to limited available space and harsh operational conditions.

In response to these challenges, we are developing a compact millimetre-wave reflectometer—a diagnostic system that employs microwave signals to measure plasma electron density, a key parameter for accurate plasma position and shape control.

The primary objective of this project is the design of a small, flexible, and robust back-end system capable of operating over an exceptionally wide frequency range, from 10 GHz to 160 GHz. In parallel, the new design aims to reduce overall system cost and enhance long-term reliability compared with previous generations of reflectometer electronics.

To meet these goals, the prototype electronics were completely redesigned, replacing obsolete components with commercially available integrated circuits. The resulting system architecture consists of a signal generation board, a receiver board, and a dual-synthesiser module, all of which are fully remote-controlled via software. Laboratory testing demonstrated excellent signal performance, with spurious signal levels suppressed by more than 15 dB, confirming the high quality of the generated and received signals.

The first deployment of this system will support the installation of a W-band reflectometer (75–110 GHz) on ASDEX Upgrade, a tokamak facility in Germany. This experiment will represent the first evaluation of the system in an operational fusion environment. Future work will concentrate on further miniaturisation and integration into a comprehensive diagnostic framework, ensuring suitability for next-generation fusion devices.



Signal generation board. Coherent RF probing and LO signals in the range 10 to 20 GHz are generated on a single board.

Reference: A. Silva et al., JINST 20, C10015 (2025).

OTHER REMOTE HANDLING ACTIVITIES

OPERATIONS CONCERNING THE EX-VESSEL TRANSPORTATION SYSTEM

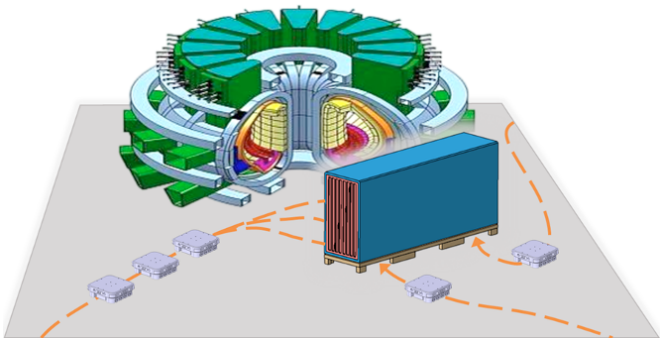
To transition from the identified operational requirements to the technical implementation, IPFN has developed a multi-layered computational algorithm designed for the operations concerning the ex-vessel transportation system.

This multi-layered algorithm for nuclear environments utilises four specialised algorithms. Navigation is driven by the CDT A algorithm*, which employs Constrained Delaunay Triangulation and A* search to discretise floor space and identify collision-free paths that respect strict clearance and bottleneck constraints.

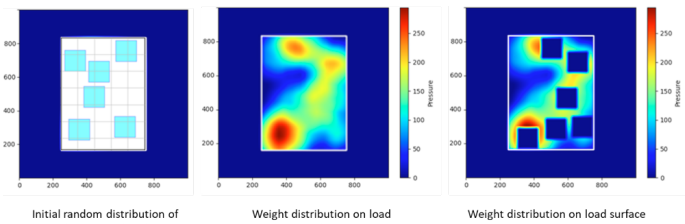
Complementing this, the Fleet Assembly Optimisation algorithm acts as a strategic decision-making tool, selecting the most operationally viable group of robots based on logistics such as battery levels, maintenance status, and proximity to the goal. Together, these systems ensure that the fleet is both spatially capable and resource-efficient before a mission begins, as depicted below.

For load management, the system employs a dual-stage Smart Payload Balancing approach. An offline evolutionary algorithm first processes weight pressure maps to predict optimal trolley positioning, as depicted in the second figure, generating a high-quality synthetic dataset to overcome the scarcity of real-world nuclear transport data, also shown in the figure. This data then trains an online Deep Learning model featuring attention mechanisms and physics-informed loss functions, enabling near-instantaneous, stable trolley placement during active operations.

By combining spatial path planning and resource allocation with predictive and real-time balancing, the architecture transforms individual transporters into a cohesive, intelligent system capable of meeting rigorous nuclear safety standards.



Cooperative trolley transportation task.



Evolutionary algorithm.

TRAINING

IPFN concluded a series of specialised research internships within the field of nuclear physics. The GESI successfully hosted several MSc students, originating from prestigious French and Italian universities.

The cohort consisted of eight students representing a diverse range of academic partners:

- Grenoble INP - Phelma – Université Grenoble Alpes
- ENSTA Paris (École Nationale Supérieure de Techniques Avancées)
- École Nationale Supérieure des Mines de Saint-Étienne
- Università degli Studi di Napoli Federico II
- ISTP ingénieurs

During their four-month programme, the interns were fully integrated into our nuclear fusion projects. Under the mentorship of IPFN researchers Alberto Vale, Raul Luís, and Diogo Rechena, as well as PhD candidate Gonçalo Teixeira, the students contributed to the design of next-generation fusion reactors. Key areas of focus included in neutronics, thermomechanical analysis, and remote handling activities

This initiative followed a successful trend of expanding our internship programme over recent years. The presence of these international students proved to be an enriching and successful experience for the group, fostering global knowledge exchange and advancing our research objectives in fusion energy. The programme reinforced IPFN's commitment to academic collaboration and its role as a hub for developing the next generation of nuclear engineering talent.



Internship programme reception.

Experimental Physics

Summary of Research

Main Researchers:

António Figueiredo
Artur Malaquias
Daniel Hachmeister
Diogo Ferreira
Duarte Borba
Fernando Nabais
Filomena Nave
Francisco Salzedas
Igor Nedzelskiy
Jorge Ferreira
José Vicente
Luís Gil
Maria E. Manso
Mário Vaz
Paulo Rodrigues
Rogério Jorge
Rui Coelho
Rui Gomes
Vladislav Plyusnin

Our mission is to advance the understanding of plasma behaviour in fusion devices through innovative diagnostics, modelling, and physics analysis, supporting the development of robust operating regimes for ITER and future fusion reactors.

Our research is carried out through multiple collaborations, particularly within EUROfusion (including experimental and modelling activities).

We are responsible for the operation and scientific exploitation of the Portuguese tokamak ISTTOK, which frequently serves as a first-test platform for new fusion concepts and for the development of diagnostics.

We also provide advanced education to MSc and PhD students and host international students through Erasmus+ and FuseNet internships.

Group Leader: Horácio Fernandes; **Deputy Leader:** Carlos Silva

Main funding sources:

Fundação para a Ciência e a Tecnologia
EUROfusion Consortium



ISTTOK

ISTTOK UPGRADES

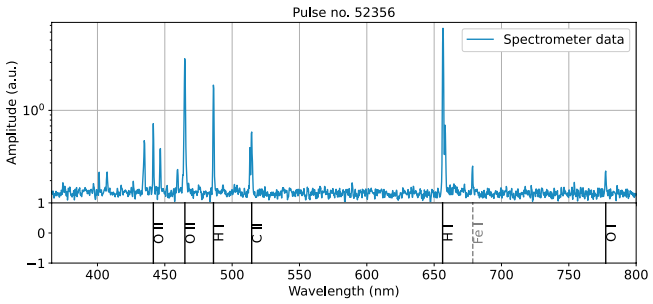
Major upgrades improved operational reliability, diagnostics, and plasma characterisation. A new movable pre-ionisation system enhanced cleaning discharges and conditioning.

Equilibrium poloidal magnetic coil supports were reinforced to reduce vibrations, while the current control system was characterised using fast ADCs, revealing new information on plasma current and loop voltage coupling. Rogowski coils were calibrated in-vessel for more accurate plasma current measurements.

A visible-emission spectrometer was installed and calibrated for impurity monitoring, initially revealing significant oxygen concentration after restart. Bolometer-like photoarray detectors for tomography reconstruction were recommissioned, improving plasma emission measurements. The hard X-ray detector was reinstalled for routine runaway electron detection, and new vacuum gauges and pumps were added.

A DC operating mode for the retarding field analyser was also developed, reducing secondary electron effects and improving ion temperature fluctuation measurements, facilitating the analysis of the experimental data.

Reference: I. S. Nedzelskiy, H. Figueiredo, C. Silva and H. Fernandes, Plasma Phys. Control. Fusion 67, 125004 (2025).



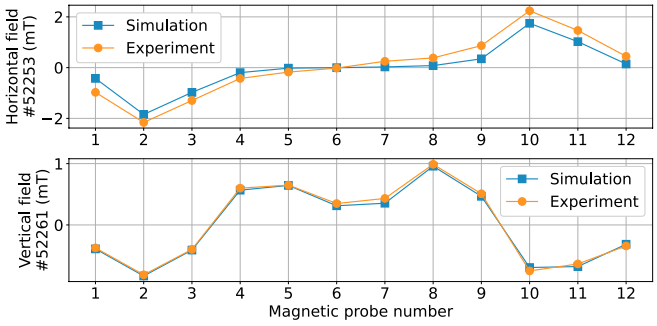
Spectrometer data for a typical pulse soon after restarting the machine showing significant oxygen concentration.

PARTNERSHIPS WITH THE PRIVATE SECTOR

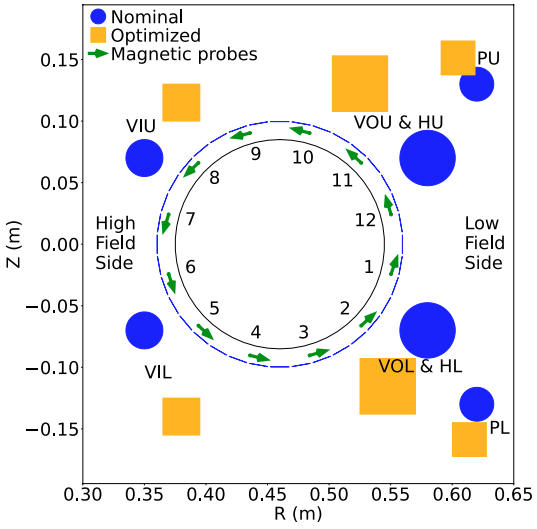
A partnership between IPFN and Next Step Fusion (NSF) advanced the use of machine learning and reinforcement learning for autonomous plasma control. NSF previously demonstrated these methods on the DIII-D tokamak and collaborated with ISTTOK to create a digital twin using the NSFSim Grad–Shafranov and transport solver. ISTTOK presented unique challenges due to its iron-core transformer, conductive copper shell, alternating current (AC) operational regime, and limited diagnostics.

The first milestone reproduced experimental magnetic fields. Agreement between simulations and experiments was only obtained when actuator coil positions were slightly shifted from their nominal locations, suggesting that coil positioning tolerances and non-planar conductor routing may contribute to anomalous transport and reduced AC efficiency.

Reference: R. Henriques et al., 51st EPS Conference on Plasma Physics (2025).



Comparison of the magnetic pickup coils' experimental and simulated data during dry runs.



ISTTOK magnetic system (in blue) and "twin" magnetic system (in orange).

ALTERNATING CURRENT DISCHARGE CHARACTERISATION AND CONTROL

ISTTOK continued investigating AC plasma discharges as a route toward continuous tokamak operation. Unlike conventional models assuming two counter plasma currents during current reversal, ISTTOK results suggest that a quiescent plasma may instead be sustained by ballistic runaway electrons during the transition phase. Efficient AC operation therefore requires precise control of runaway electron dynamics through external magnetic coils, closely linked to the reinforced learning control strategies developed with NSF.

In collaboration with the Australian National University, theoretical models describing equilibrium evolution during AC transitions in the presence of runaway electrons are being developed. A runaway electron trajectory model was extended to include relativistic effects and plasma drag forces, enabling identification of the energy ranges that remain confined during AC transitions. A PhD project planned for 2027 aims to develop a detector for confined runaway electrons.

Reference: A. Malaquias et al., 50th EPS Conference on Plasma Physics (2024).

CONTRIBUTIONS TO THE TOKAMAK EXPLOITATION PROGRAMME

REFLECTOLAB: GUI FOR PROFILE REFLECTOMETRY IN ASDEX UPGRADE

IPFN leads the operation and exploitation of a reflectometry diagnostic in the ASDEX Upgrade tokamak in Garching, Germany. This diagnostic allows researchers to measure the electron density profile, an important plasma parameter. IPFN has recently completed the refactoring of its toolchain to analyse data from the ASDEX Upgrade reflectometry diagnostic.

The migration from the previously used IDL to Python 3 brings the toolchain to an open-source language that is widely used across the scientific landscape. This refactoring was undertaken by several IPFN students leveraging existing Python libraries in the IPFN software ecosystem and is already being used to fulfil data analysis requests by the broader ASDEX Upgrade community.



From left to right: Filipe Hachmeister, Daniel Hachmeister, and Mário Vaz discussing the development of the ReflectoLab software toolchain.

EDA H-MODE IN ASDEX UPGRADE: SCANS OF HEATING POWER, FUELLING, AND PLASMA CURRENT

Achieving high-confinement plasma scenarios without damaging edge-localised modes (ELMs) is essential for fusion reactors. We investigated such a regime on ASDEX Upgrade, the EDA H-mode, to define its operational limits and performance. By systematically varying heating power, fuelling, and plasma current, we were able to characterise the plasma dynamics over a wide range of conditions.

This led to the development of a novel method to identify phases with ELMs, allowing the derivation of scaling laws for no-ELM boundaries and key plasma parameters. The results show that EDA H-mode sustains high energy confinement and density over the entire input power range. This work reinforces the EDA H-mode as a promising no-ELM scenario for future devices, while providing a robust testbed for validating theoretical models and guiding new experiments.

Reference: L. Gil, T. Pütterich, C. Silva, D. Hachmeister et al., Nucl. Fusion 65, 046002 (2025).



Luís Gil (left) and Mário Vaz (right) next to the reflectometer acquisition system in the ASDEX Upgrade control room during an experimental campaign.

EXPLORING EDGE RADIAL ELECTRIC FIELDS IN JET L-MODE PLASMAS FROM LOW RECYCLING TO THE DENSITY LIMIT

Understanding edge electric fields in fusion plasmas is crucial because they control plasma confinement and stability. In this study, we aimed to investigate how plasma density affects the radial electric field in JET L-mode plasmas. To do this, we analysed density ramp discharges up to the density limit using Doppler backscattering measurements.

Our results show that as density increases, the scrape-off layer radial electric field peak diminishes quickly while its well deepens until a Greenwald fraction of approximately 0.8. Our findings indicate that no collapse of edge flow shear occurs prior to the density limit onset, within a time scale of 10 ms. The edge radial electric field overall maintains sufficient shear to preserve steep density gradients even near the density limit. We also found that the density limit is not caused by a collapse of flow shear or by oscillating flows.

These findings provide important insights into the mechanisms controlling plasma edge stability, which is essential for predicting and avoiding disruptions in fusion devices. Moving forward, we will investigate how approaching the density limit affects edge flow shear during high-performance operation.

Reference: C. Silva et al., Nucl. Fusion 65, 036042 (2025).

ENERGETIC PARTICLE PHYSICS

D–^{3}HE PLASMAS AS A PLATFORM FOR ALPHA-PARTICLE STUDIES

Future fusion power plants will rely on self-heating from alpha particles produced in DT reactions. Understanding how these particles are created and confined is therefore a key challenge, especially in view of the experimental reactor ITER, where such conditions will be tested. With the end of the JET tokamak after 40 years of successful operation, no current large device can use DT fuel due to strict safety limits linked to neutron production. This also applies to JT-60SA in Japan, now the largest operating tokamak. As a result, alternative ways to generate alpha particles are needed.

In this work, we investigated one such option based on helium-3 (^{3}He) and neutral beam injection (NBI). JT-60SA is particularly well suited for this approach thanks to its high-energy (500 keV) beams, which can drive stronger fusion reactions than those achieved in earlier devices like JET, where beam energy was limited to ~100 keV. Using the ASCOT5 simulation suite, we studied alpha particle production and confinement in both low- and high-power scenarios.

The results show clearly higher alpha and neutron production than in comparable JET cases. By optimising plasma conditions, we also found that alpha production could be increased by up to 60%.

These findings open the way for continued studies of alpha particle physics in JT-60SA. While the yields remain below those of DT plasmas, they are sufficient to explore key processes and help prepare for future fusion reactors.

Reference: R. Coelho et al., Proc. of the 30th IAEA Fusion Energy Conference IAEA-CN-316/3269 (2025).

STELLARATOR DESIGN

EVALUATING GYROMOTION EFFECTS ON STELLARATOR OPTIMISATION

A stellarator reactor must have its 3D magnetic field accurately optimised to confine charged particles and achieve sustainable fusion reactions. To save computational resources, present-day optimisations simplify particle orbits to their guiding-centre (GC) motion only, ignoring their fast gyromotion around field lines. While the GC approach is valid for the fuel ions (~10 keV), fusion-born alpha particles (~3.5 MeV) are more challenging because their larger gyro-radius may compare with localised features of the field being optimised.

In this work, we tested a handful of stellarator magnetic fields that were optimised following different strategies to ensure particle confinement, all rooted in the GC approximation. The simulations tracked two large populations of alpha particles for 10 ms, one under GC motion and the other resolving their full gyromotion, an effort similar to tracking the Earth's position around the Sun for 150,000 years.

We found that some configurations are able to keep the alpha particles confined, with minimal differences between losses predicted by each approach. However, for some others, the number of lost particles increases by one order of magnitude when their full gyromotion is taken into account. These results show that a GC approach is not always adequate, paving the way for more sophisticated optimisation procedures. Indeed, gyromotion effects are expected to become more relevant for the smaller and more compact designs of future stellarators.

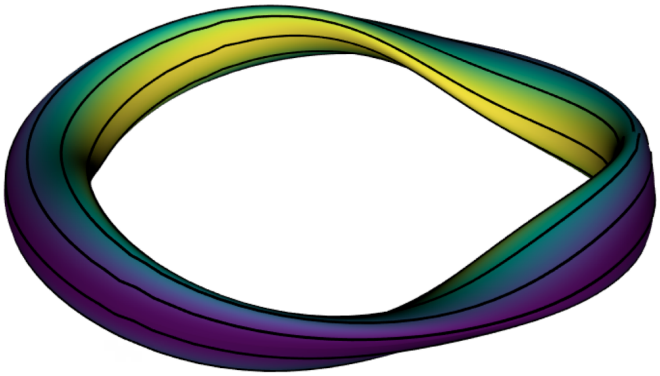
Reference: P. Rodrigues et al., 50th EPS Conference on Plasma Physics (2024).

STELLARATOR DESIGN WITH DEEP LEARNING AND MIXTURE DENSITY NETWORKS

The design of stellarator devices usually requires heavy computer simulations. For a given set of design parameters, a simulation must be run to check whether the resulting configuration has the desired properties, such as good plasma confinement, stability, and compact geometry. It is often necessary to run many such simulations in order to find good design parameters. To make this process more efficient, we trained a deep learning model that receives the desired properties as input and produces a set of design parameters as output.

Because very similar properties can be achieved with quite different parameter values, the model is probabilistic: it is a Mixture Density Network that draws samples from regions of parameter space that are likely to yield the desired properties. With the parameter values proposed by the model, it becomes much easier to discover new stellarator designs with good confinement properties.

Reference: P. Curvo, D. R. Ferreira, and R. Jorge, J. Plasma Phys. 91, E38 (2025).



Plasma boundary of an optimised quasisymmetric stellarator with three field periods. The colours represent the magnetic field strength at the boundary, and a magnetic field line is shown in black.

Materials Processing and Characterisation

Summary of Research

Main Researchers:

Bernardo Monteiro
Katharina Lorenz (20%)
Luís C. Alves (20%)
Marco Peres (20%)
Marta Dias
Norberto Catarino
Nuno Barradas (20%)
Rodrigo Mateus
Rui Silva
Sérgio Magalhães

Main funding sources:

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

Selecting suitable materials for nuclear reactors is critical for efficient and safe energy production. One of the main challenges is managing the extreme heat generated during operation, without compromising structural integrity of the materials for nuclear fusion reactors. In this framework, materials development and its irradiation becomes a central pillar of fusion technology.

During this period, we focused on tiles from WEST and on Li-based materials, analysed through elemental depth profiling by Ion Beam Analysis (IBA) to follow the erosion/deposition behaviour and the irradiation damage. Despite the overlap between the deuterium signal and reaction products originating from lithium, we demonstrated that reliable deuterium quantification is possible with optimised Nuclear Reaction Analysis (NRA).

The development and characterisation of the thermal barriers for the divertor is an ongoing project, now extended to other compositions and elements. The influence of chromium addition on the microstructure, mechanical properties, thermal transport and irradiation behaviour of refractory high-entropy alloys was evaluated and compared with related alloy compositions.

Group Leader: Marta Dias



RESEARCH HIGHLIGHTS

PLASMA-WALL INTERACTIONS IN THE DIVERTOR TEST SECTOR OF WEST

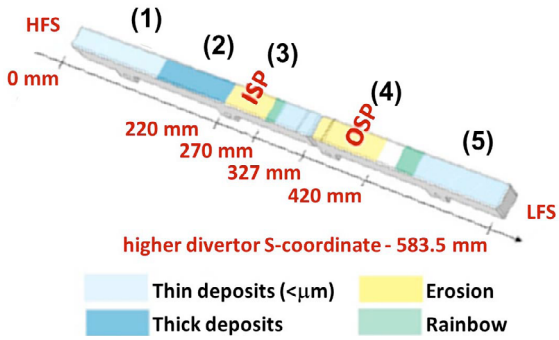
The divertor is one of the most demanding components of a fusion reactor, continuously exposed to intense heat and particle fluxes. Understanding how plasma-facing materials erode, redeposit and retain hydrogen isotopes is essential for predicting component lifetime and optimising the design of future fusion reactors such as ITER and DEMO.

We analysed tungsten-coated divertor marker tiles removed from the WEST tokamak after its first operational phase (2018–2020). Ion Beam Analysis, performed at IST, was combined with Secondary Ion Mass Spectrometry (SIMS) measurements from VTT to determine elemental depth profiles at representative locations across the divertor.

The two complementary techniques produced consistent elemental depth profiles, confirming the location of erosion- and deposition-dominated regions across the divertor. The measurements identified strong erosion at the plasma strike points (zones 3 and 4), thick material deposits in neighbouring regions (zone 2), and thin deposits nearby the inner and outer divertor limits (zones 1 and 5), providing a comprehensive picture of material migration during reactor operation.

These results provide essential experimental data for validating plasma-wall interaction models and support the development of more durable plasma-facing components for next-generation fusion power plants.

Reference: R. Mateus et al., Nucl. Mater. Energy 46, 102050 (2026).



Erosion/deposition zones identified from the EM tiles along the lower divertor of WEST after the C3 campaign; figure adapted from R. Mateus et al. (2026).

DEUTERIUM QUANTIFICATION IN LI-BASED MATERIALS BY NUCLEAR REACTION ANALYSIS

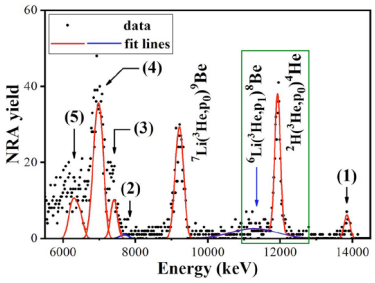
Lithium-based materials are attracting growing interest for fusion applications, including plasma-facing components and breeder blanket technologies. A key challenge is to accurately measure the amount of retained deuterium fuel, as NRA is complicated by competing nuclear reactions occurring in lithium. Particularly, there is an overlap between the deuterium signal and a nuclear reaction product originating from lithium (lithium-6 isotope).

We investigated the limits and optimisation of NRA for lithium-containing materials by measuring the relevant nuclear reaction cross-sections and analysing their influence on deuterium detection. The methodology was validated using lithium-tin alloys produced and irradiated at IST, and later applied to lithium-based plasma-facing materials exposed in the COMPASS tokamak.

We demonstrated that reliable deuterium quantification is possible with optimised NRA. The achieved detection limits are suitable for fusion applications, and two-dimensional elemental maps successfully resolved the distributions of both lithium and deuterium in irradiated samples.

This work extends the capabilities of ion beam analysis for lithium-based materials and provides an important diagnostic tool for studying fuel retention in next-generation fusion devices and future reactor technologies.

Reference: R. Mateus et al., Fusion Engineering and Design 217, 115140 (2025).



NRA spectrum collected from a Li-Sn alloy irradiated by D ions; yield fit lines achieved using the nuclear reaction cross-section data measured at IST.

HIGH-ENTROPY ALLOYS FOR ENERGY APPLICATIONS

The extreme temperatures, heat loads and particle bombardment inside fusion reactors demand structural materials with exceptional mechanical strength, thermal stability and radiation resistance. High entropy alloys (HEAs), which combine five or more metallic elements, have emerged as promising candidates for these challenging environments.

We investigated a new family of refractory HEAs by combining alloy synthesis, advanced materials characterisation, atomistic simulations and experimental irradiations. The influence of chromium or vanadium addition to an FeTaTiW alloy was evaluated concerning the microstructure, mechanical properties, thermal transport and irradiation behaviour and compared with related alloy compositions.

Chromium significantly improved the alloy's high-temperature performance. At 1000 °C, the new $(CrFeTaTi)_{70}W_{30}$ alloy exhibited nearly twice the mechanical strength of the reference FeTaTiW alloy while maintaining ductile behaviour. The VFeTaTiW alloy also showed excellent thermal stability after prolonged heat treatment, whereas irradiation experiments revealed distinct deuterium retention mechanisms, indicating that both new alloys are good candidates for fusion applications but identifying the V-containing alloy as the most promising alloy.

This work provides valuable guidelines for designing next-generation plasma-facing and structural materials for fusion reactors, demonstrating how the combination of modelling and experiments can accelerate the development of materials capable of operating under extreme conditions.

Reference: R. Martins et al., J. Mater. Sci.: Mater. Eng. 20, 52 (2025).

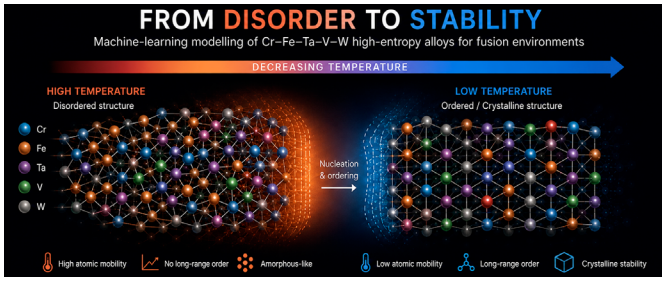


Preparation of the ball milling equipment.

MACHINE-LEARNING POTENTIALS FOR FUSION ALLOYS

Understanding materials under extreme conditions is essential for fusion energy systems. Refractory high-entropy alloys based on CrFeTaVW are promising candidates due to their potential resistance to high temperature, radiation damage and mechanical stress. This work aims to develop a computational framework combining density functional theory (Quantum ESPRESSO) and machine-learning interatomic potentials to study these alloys with different tungsten contents.

A key highlight in 2024–2025 was the implementation of a robust DFT workflow for multi-component systems, enabling the generation of consistent datasets of energies and atomic forces. Another highlight was the initial identification of structural ordering and temperature-dependent stability trends. These results provide a basis for predicting diffusion, segregation and mechanical behaviour under fusion-relevant conditions. This work is currently being prepared for publication and contributes to ongoing MSc research within the group.



Workflow illustrating the development of machine-learning interatomic potentials for Cr–Fe–Ta–V–W refractory high-entropy alloys, combining density functional theory calculations and atomistic modelling to investigate structural stability, energetic trends, and materials behaviour under fusion-relevant conditions.

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 flames, lightning and aurora boreales; and artificial plasmas such as fluorescent lamps, welding arcs and plasma cutters.

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 now employed across a broad range of fields, such as materials processing, with applications in microelectronics and nanotechnology; environmental control, including waste treatment and plasma reforming; and biotechnology, spanning applications from agriculture to 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 addresses a broad range of topics, encompassing theoretical, simulation, and experimental studies. It is conducted in a strongly international environment, through several important collaborations with world-leading institutions. Research outcomes with potential for market application are identified and, where appropriate, pursued towards technology transfer in response to societal needs.

Lasers and Plasmas

Summary of Research

Main Researchers:

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

Main funding sources:

European Research Council
European Innovation Council
H2020
Horizon Europe
EUROfusion
Fundação para a Ciência e a Tecnologia
Agência Nacional de Inovação (ANI)
EuroHPC

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

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

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

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

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

Group Leader: Luís O. Silva



RESEARCH HIGHLIGHTS

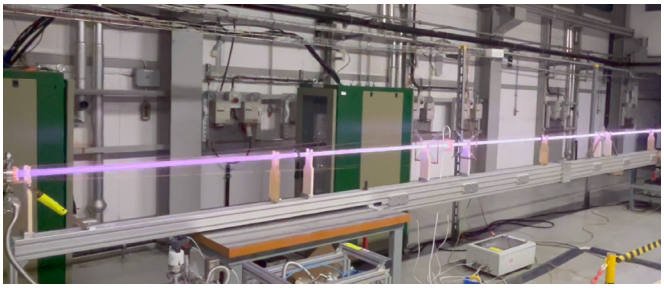
SCALABLE PLASMA SOURCES FOR FUTURE ACCELERATORS

Particle accelerators are essential tools for science, medicine and industry, but conventional technologies require increasingly large and costly facilities. Plasma-based acceleration offers a promising alternative by producing extremely strong accelerating fields over much shorter distances.

A major challenge, however, is the development of plasma sources that can be extended to the tens or even hundreds of metres required for future accelerator stages.

Within the AWAKE experiment at CERN, our goal is to develop a scalable plasma source architecture compatible with next-generation plasma accelerators. Over the past two years, we demonstrated for the first time the operation of a modular discharge plasma system composed of multiple independently controlled plasma sections operating together as a single source.

The experiment validated the key principles required for scalability, including current balancing, stable operation and reproducible plasma formation across all modules. This demonstration represents an important step towards the long plasma sources required for the AWAKE Run 2-D programme and future plasma accelerator facilities, where plasma sections may eventually need to extend over hundreds of metres or more.



Modular discharge plasma source developed for the AWAKE experiment at CERN, demonstrating a scalable approach towards the long plasma sources required for future plasma accelerators.

HOW COOLING PLASMAS IN STRONG MAGNETIC FIELDS GENERATE COHERENT RADIO BURSTS

Extreme cosmic environments — neutron stars, pulsars, active galactic nuclei — host plasmas so hot and so strongly magnetised that particles radiate away their energy as light. These relativistic plasmas are thought to power some of the most enigmatic signals in the universe, including pulsar emission and fast radio bursts, yet how they generate the bright, coherent radiation we detect remains an open question.

We set out to understand how radiative energy losses reshape the collective behaviour of magnetised relativistic plasmas, and whether this could naturally produce the coherent emission seen in astrophysical sources.

Using first-principles, high-resolution kinetic simulations, we followed the self-consistent evolution of magnetised electron populations as they cooled by emitting synchrotron radiation, capturing both the particle dynamics and the electromagnetic fields they generate.

We discovered that radiative cooling drives the plasma into a state that spontaneously amplifies coherent, linearly polarised radiation via the electron cyclotron maser instability, and that this amplification persists much longer than in non-cooling plasmas because radiative losses alter the usual saturation mechanism.

Published in Science Advances, these findings identify a new mechanism for coherent radio emission in extreme magnetised environments, offering a natural explanation for pulsar signatures and fast radio bursts and a path to interpret upcoming radio-astronomy observations.

Future work will extend the simulations to broader astrophysical regimes and explore signatures that can be tested directly against pulsar and fast-radio-burst observations.

Reference: P. Bilbao, T. Silva, L. O. Silva, Science Advances 11, eadt8912 (2025).

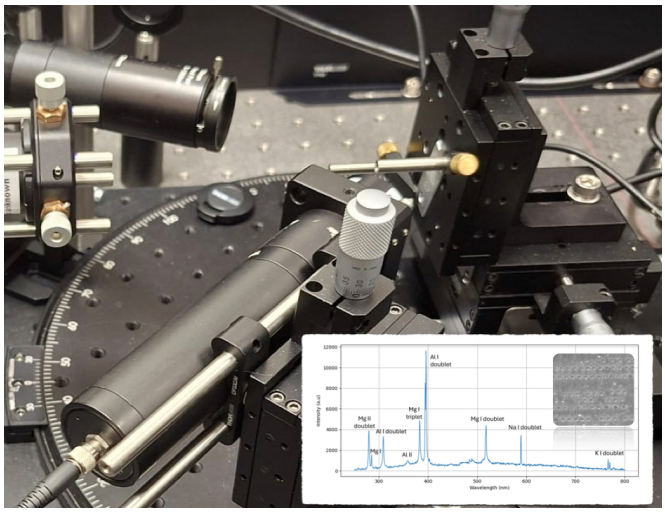
LIBSCAN: A PORTABLE LIBS SYSTEM FOR RAPID ELEMENTAL MAPPING

Rapid, non-destructive mapping of elemental composition across large surfaces is a key challenge in geology, environmental monitoring, and industrial quality control. Current LIBS mapping systems are large, expensive, and slow, taking hours to cover a 10 cm × 10 cm area.

LIBScan, approved by Agência Nacional de Inovação under COMPETE2030/FEDER (€1.3 M total; €818 k co-funded), was launched in 2024 by Sarspec, IST-ID/IPFN, and INESC TEC to develop a compact portable LIBS instrument producing 100 µm-resolution elemental maps in minutes. GoLP leads several tasks in the project. One of them is creating and operating a LIBS test bench at the L2I laser laboratory, and another main contribution is through ray-tracing simulations (ZEMAX®) and CMOS readout electronics design.

We systematically characterised plasma emission as a function of laser energy, focus, and collection geometry, demonstrating linear signal response below 22 J/cm² for 0.9 ps laser pulses, two plasma generation maxima, quasi-isotropic emission and significant chromatic and geometrical optical aberration.

An optimised multi-lens collection architecture is being designed by simulation, and the first CMOS signal-conditioning PCB prototype was completed. These results establish the experimental and design foundations for the LIBScan prototype, advancing portable in-situ elemental analysis for science and industry.



LIBS test bench at the L2I laser laboratory (IST/IPFN). The rotational breadboard allows the collection angle to be varied systematically. Inset: optical emission spectrum from an aluminium target showing the main elemental lines (Al I, Al II, Mg, Na, K), and ablation craters on the target surface (top right).

UNCOVERING HIGHER-ORDER NONLINEARITIES IN SILICON

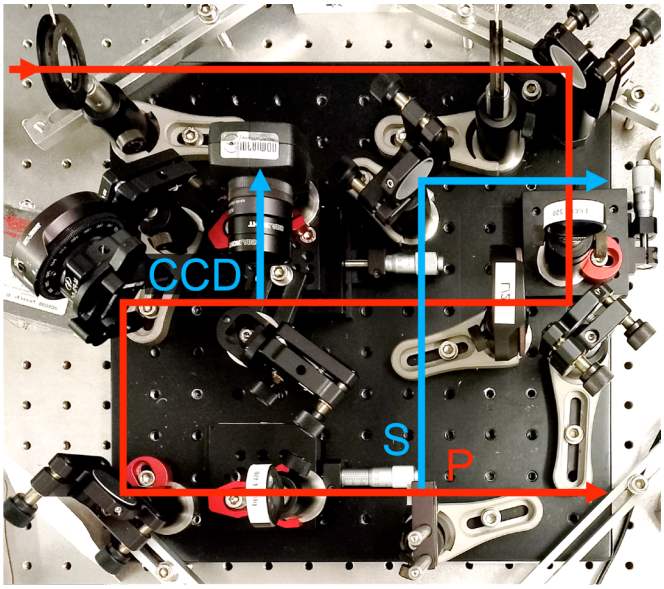
When intense laser pulses interact with a material, they can generate light at new colours (harmonics). These nonlinear optical effects are widely used to probe the properties of semiconductor surfaces and are becoming increasingly important for advanced optical technologies. Understanding the physical mechanisms behind these signals is therefore essential.

We investigated harmonic generation from silicon surfaces using an automated ultrafast laser system. By measuring how the emitted light changed with laser intensity, sample orientation and polarisation, we searched for nonlinear effects beyond those predicted by the standard theory. We found the first experimental evidence that the observed second-harmonic signal contains not only the expected

second-order $\chi^{(2)}$ contribution, but also a previously unreported fourth-order $\chi^{(4)}$ contribution. The characteristic angular dependence of this signal allowed us to distinguish it from experimental artefacts and conventional harmonic generation.

These findings improve our understanding of how intense laser light interacts with silicon and may enable more sensitive optical methods for characterising semiconductor surfaces and interfaces.

Reference: H. Pires, H. Gomes, C. Priebe, G. Figueira, A. G. Silva, Sci. Reports (accepted, 2026).



Ultrafast laser setup at L2I for measuring second-harmonic generation from silicon as a function of intensity, crystal orientation and polarisation.

PLASMA QUASIPARTICLES AS COMPACT SOURCES OF COHERENT LIGHT

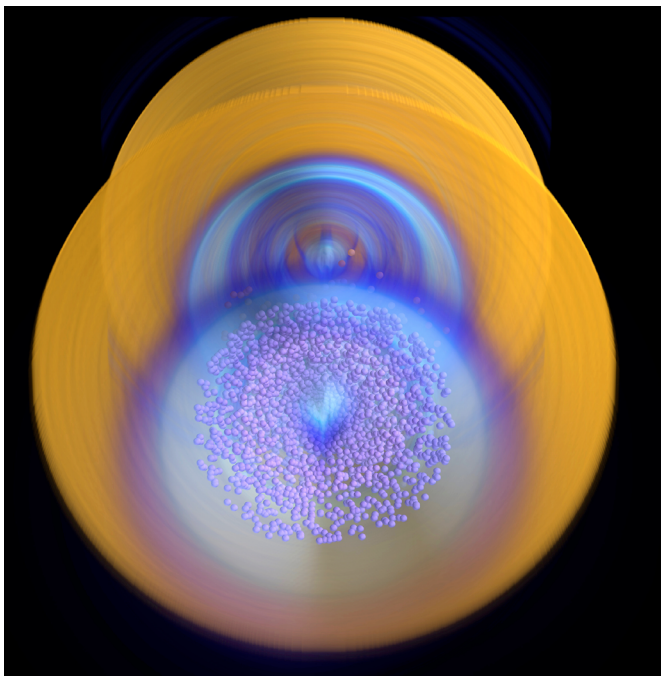
Powerful coherent light sources, such as free-electron lasers, have transformed science and technology, but they are large, costly instruments available only at a few facilities. Our work asks whether plasma accelerators, which can be only centimetres long, can produce similarly bright and ordered light.

We introduced a new concept: a plasma-based quasiparticle light source, where many electrons in a plasma organise into a dense moving structure that behaves like one controllable finite-sized radiation emitter. By shaping the plasma, this collective emitter can be guided so that light from many electrons arrives in sync, producing coherent emission and superradiance – a rapid increase in brightness caused by collective radiation.

Theory and 3D simulations show that this approach can generate both ultrashort broadband bursts and narrowband radiation, with clear signatures from the terahertz range to the extreme ultraviolet. In some regimes, the predicted peak brightness is comparable to that of extreme-ultraviolet free-electron lasers.

The result changes the design principle for compact light sources: instead of requiring perfectly prepared electron beams, it exploits the self-organised motion of the plasma itself. This opens a path toward affordable, laboratory-scale sources of bright coherent light for materials science, biology, medical imaging, nanolithography, and fundamental physics.

Reference: B. Malaca et al., Nat. Photon. 18, 39 (2024).



3D simulation of a plasma-based quasiparticle light source. Electrons in the plasma (purple spheres) organise into a moving collective structure that behaves as a single finite-sized emitter; the radiation they emit (orange wavefronts) adds up coherently, producing superradiant emission.

REVEALING NEW PATHWAYS TO DETECT DARK MATTER AXIONS

Dark matter remains one of the greatest mysteries in modern physics. Among the leading candidates are axions, hypothetical particles that could be detected through their interaction with electromagnetic fields in the extreme plasma environments surrounding neutron stars and magnetars.

Our research has developed new theoretical frameworks describing how axions interact with magnetised astrophysical plasmas. In particular, we demonstrated that resonant axion-plasmon conversion can significantly modify the electromagnetic signals expected from neutron star magnetospheres, reducing the observable photon flux and altering the regions of parameter space accessible to current experiments.

We also showed that magnetic reconnection, a fundamental plasma process in which magnetic field lines break and reconnect, can generate transient bursts of axion radiation. This reveals a previously unexplored mechanism for axion production in astrophysical environments and provides new opportunities for observational searches.

Together, these results establish plasma physics as a key ingredient in the interpretation of axion signals and open new avenues for discovering dark matter using next-generation radio telescopes and future astrophysical observations.

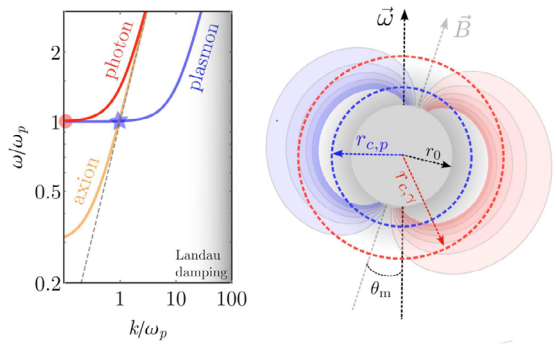


Illustration of axion-plasma interactions in the magnetosphere of a neutron star, highlighting new mechanisms for axion production and conversion relevant for dark matter searches.

DIRECT LASER ACCELERATION AS A RADIATION SOURCE

Compact, tuneable radiation sources hold transformative potential for medicine and industry. They are used both for imaging (medical diagnostics, industrial non-invasive quality control) and for direct cancer treatment. In this setup, the emitters are very energetic electrons, which are accelerated in a plasma channel by an intense laser pulse.

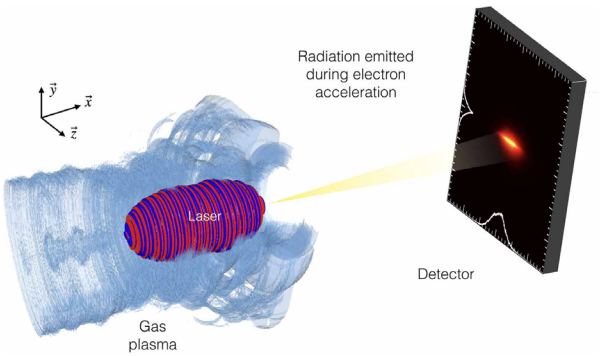
While they accelerate, these electrons wiggle due to the plasma background, which makes them act as a million miniature antennas working together to emit light. This light may not be visible – it is a similar source to a traditional synchrotron but is much smaller and allows for dynamic control of the target photon energies.

The goal of this project was to predict the properties of this radiation as a function of plasma and laser parameters, such that we can tune the output radiation according to the needs of a particular application.

The energy of the emitted light is sensitive to the energy of the accelerating electrons, so the acceleration process is studied in detail. After that, all we know about the electron trajectories was used to characterise the emitted light.

This work was done by combining analytical models and high-fidelity simulations performed on supercomputers. This research has shown that one can obtain a very bright source, which can be tuned from the X-ray to the gamma-ray range (up to several GeV). This is particularly interesting for imaging, because different radiation wavelengths allow looking at objects of different sizes.

Reference: R. Babjak and M. Vranic, Plasma Phys. Control. Fusion 67, 085019 (2025).



Radiation emission from direct laser acceleration in a gaseous plasma.

TURNING INFRARED LASER LIGHT INTO NEW COLOURS IN GALLIUM OXIDE

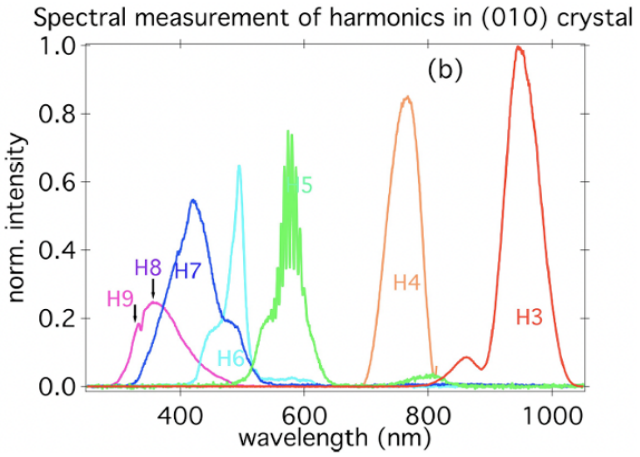
Modern photonics needs compact ways to make short-wavelength light. Harmonic generation in crystals is a leading candidate and is intrinsically linked to electron motion in these crystals. Beta-gallium oxide is a strong, transparent semiconductor that is already important for power electronics, but its response to very intense laser light is still not fully understood.

Our goal was to test whether this material can act as a solid-state source of new light frequencies, and whether the emitted light can reveal information about the crystal structure. Using ultrafast mid-infrared laser pulses, we generated new colours of light in two differently cut gallium oxide crystals.

We demonstrated harmonic generation up to the ninth order, including both odd and even harmonics, in air. The signal changed strongly when the crystal was rotated, showing that the light emission is sensitive to the direction of the laser field relative to the atoms in the crystal. We also observed interference fringes, caused by light generated at different parts of the crystal travelling at different speeds.

These results show that gallium oxide is a promising material for compact ultraviolet light sources and for optical methods that probe crystal and electronic structure.

Reference: M. Hussain et al., Opt. Express 32, 47296 (2024).



The spectrum of harmonics emitted from the interaction of a 3-micron laser pulse with gallium oxide.

N-Plasmas Reactive Modelling and Engineering (N-PRiME)

Summary of Research

Main Researchers:

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Main funding sources:

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

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

Our research is organised into three main axes:

1. The Plasma Engineering Laboratory (PEL, PI: E. Tatarova) conducts cutting-edge research in plasma nanoscience, leveraging microwave-driven plasmas for the scalable synthesis of advanced functional nanomaterials. The laboratory develops and operates innovative experimental platforms that enable precise control of energy and matter transfer at the nanoscale, paving the way to produce two-dimensional nanostructured materials at commercially relevant scales and supporting their transition towards industrial applications.

2. The Hypersonic Plasmas Laboratory (HPL, M.L. Silva PI) is home to the European Shock-Tube for High Enthalpy Research (ESTHER), which was commissioned by the European Space Agency (ESA) and inaugurated in July 2019. ESTHER is the only space facility in Portugal dedicated to planning planetary exploration missions.

3. Plasma Modelling and Simulation (M&S, V. Guerra PI) focuses on understanding the dynamics of non-equilibrium LTPs. We develop state-of-the-art kinetic schemes for volume and surface interactions, considering the multidimensional transport of species and radiation, also under hydrodynamic flow regimes. Our work involves also creating, verifying, and validating predictive numerical tools.

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

Group Leader: Luís L. Alves



PLASMA ENGINEERING LABORATORY

ADVANCED ELECTROMAGNETIC N-GRAPHENE-BASED SHIELDS VIA PLASMA INDUCED SYNTHESIS

Electromagnetic (EM) pollution has emerged as a growing global concern due to the rapid proliferation of electronic and wireless communication devices. The widespread adoption of portable electronics and the deployment of 5G, with the future introduction of 6G technologies, are leading to an increasing density of EM radiation across a broad range of frequencies.

This EM environment can cause electromagnetic interference (EMI), resulting in system malfunctions, data loss, signal degradation, and reduced communication reliability. Consequently, the development of EM functional materials has become increasingly important for mitigating EM pollution in both civilian and military applications.

Such materials are finding widespread use in commercial and scientific electronics, antenna systems, aerospace and Space exploration, satellite communications, advanced driver-assistance systems, millimetre-wave wireless networks, and medical devices.

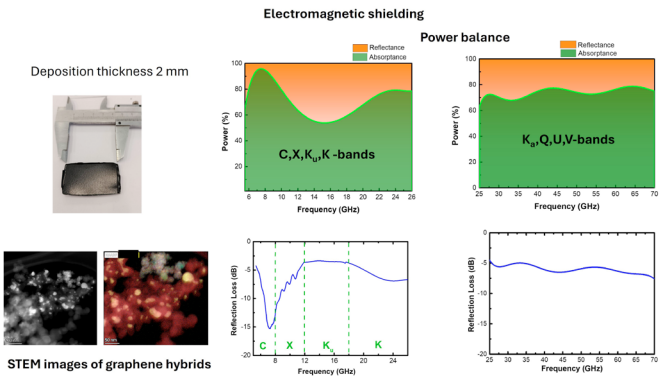
To address these challenges, there is a growing demand for materials with tunable EM properties capable of providing efficient EMI shielding. However, carbon-based absorbers synthesised through conventional multistep chemical routes often exhibit limited tunability due to the complex and non-linear interplay among numerous synthesis parameters.

Although significant advances have been made in EMI shielding materials over recent years, major challenges remain in achieving broadband absorption while simultaneously minimising shield thickness. Moreover, the commercialisation of these materials is constrained by complex multistep batch-processing techniques, which result in high production costs and limited scalability.

To overcome these limitations, we developed a plasma-enabled synthesis process for the controllable fabrication of ultralight nanocomposites exhibiting absorption-dominated EMI shielding, providing a scalable route towards next-generation EM protection materials.

The developed process enables the efficient conversion of low-cost precursors - including acetonitrile and micron-sized metal oxide particles - into N-doped graphene hybrid nanostructures at production rates of up to 50 mg min^{-1}, facilitating rapid synthesis and subsequent composite fabrication.

The resulting advanced functional nanocomposites exhibit outstanding EM absorption performance, absorbing more than 70% of the incident microwave power over the broad 5–70 GHz frequency range, spanning the C, X, Ku, K, Ka, Q, U, and V microwave bands.



High-angle-annular dark-field (HAADF) STEM images of the nanocomposites reveal graphene-like sheets decorated with nanoparticles of varying sizes. The power balance demonstrates absorption dominated performance.

Advanced N-graphene-based EM functional nanocomposites produced via plasma-enabled synthesis demonstrate strong potential for applications in wearable electronics, wireless communication systems, and radar stealth technologies.

Their excellent EMI shielding performance can effectively protect sensors and communication modules from external EM disturbances, thereby enhancing their accuracy, reliability, and operational stability.

Future work will focus on the development of next-generation graphene-based hybrid EM functional materials. Emphasis will be placed on optimising engineered nanocomposites through the synergistic integration of dielectric and magnetic components with precise nanoscale structural control, paving the way towards thin, lightweight, broadband, and high-performance EM shielding materials.

PLASMA MODELLING AND SIMULATION

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

N-PRiME develops numerical tools for plasma simulation under the LisbOn Kinetics (LoKI) brand, several of which are available as open-source codes. A major recent update includes the release of v25.10 LoKI-B (MATLAB) and LoKI-B++, its C++ counterpart, which essentially replicates all the features of the original code. Both tools are part of the LoKI tool suite and are freely available at https://github.com/LoKI-suite.

They are designed to support electron kinetics calculations, while also enabling modellers and developers to test, validate, and further extend the software. In addition, LoKI-B++ has been integrated into the plasma simulation platform PLASIMO, developed by Plasma Matters B.V.

We also contribute to the generation and curation of elementary data, through the IST-Lisbon database available on LXCat. This database has been enhanced with updates on the complete and consistent cross-section set for CO_2, including explicit data for electron-impact dissociation. The IST-Lisbon database has been expanded through its migration to the new LXCat platform, to be available soon for the benefit of the Low-Temperature Plasmas community.

LisbOn Kinetics

Plasma Matters.

Official logos of the LisbOn Kinetics tool and Plasma Matters.

HIERARCHICAL OPTIMISATION FOR PREDICTIVE PLASMA CHEMISTRY

The predictive modelling of natural systems often relies on multiphysics simulations constrained by numerous free parameters. However, many of these complex systems are inherently sloppy, since their physical behaviour is governed by a small handful of stiff parameters, while most parameters have a negligible effect.

Taking advantage of this structure, we developed a stochastic hierarchical optimisation framework that efficiently calibrates physical models without the heavy computational burden of exhaustive sampling.

Our approach explicitly identifies and targets the stiff parameter directions using minimal simulator queries and can be applied to any sloppy physical system. It was used to develop a mesoscopic surface kinetics model in O_2 and CO_2 discharges, which describes atomic oxygen recombination on Pyrex walls.

Optimal kinetic parameters were found for surface recombination, leading to model validation and predictiveness, and to further insights into the reaction mechanisms. The hierarchical data-driven optimisation provides a scalable, general-purpose tool for optimising complex reaction networks widely used in plasma chemistry.

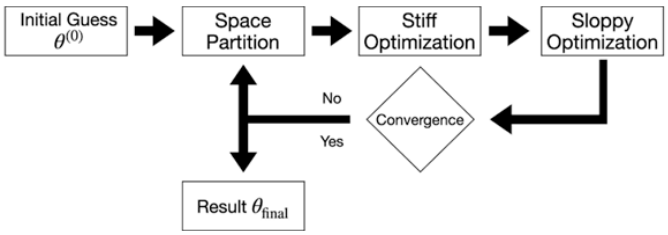
PLASMA-ASSISTED CONVERSION FOR SUSTAINABLE CHEMICALS

The transition toward sustainable chemical manufacturing requires new approaches capable of converting stable molecules such as CO_2, N_2, and CH_4 using renewable electricity. However, achieving competitive conversion rates and energy efficiencies remains challenging.

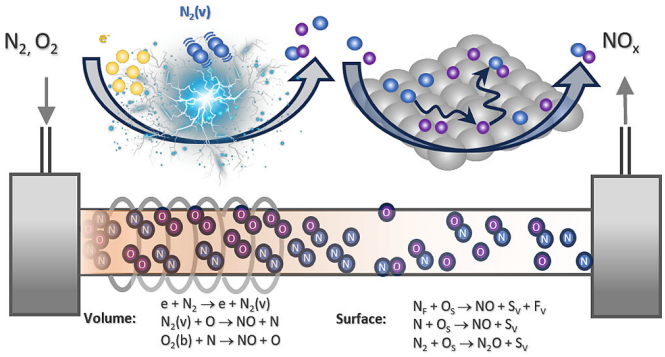
We explore the unique opportunities for electrified chemistry offered by non-equilibrium plasmas, which transfer their energy into molecular excitation while operating far from thermodynamic equilibrium.

We investigated the mechanisms governing NO_x synthesis for nitrogen-based fertilisers and plasma-assisted CO_2 conversion for carbon valorisation and sustainable fuels. Combined experimental and modelling studies identified the dominant reaction pathways and revealed the critical role of plasma-surface interactions, excited species and post-discharge chemistry.

These advances support the broader transition towards low-carbon chemical manufacturing and establish the foundations for future energy-efficient plasma-catalytic reactor technologies.



Schematic overview of the hierarchical algorithm, illustrating the iterative process guided by a geometric heuristic space partition.



Plasma assisted formation of NOx from air (N_2–O_2) plasmas.

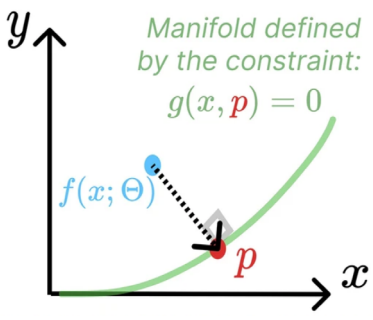
PHYSICS-CONSISTENT MACHINE LEARNING FOR PHYSICAL MODELS

Data-driven machine learning models often require extensive datasets, which can be costly or inaccessible, and their predictions may fail to comply with established physical laws. Current approaches either do not guarantee compliance with physical constraints for unseen inputs or lack flexibility and generality.

We proposed a physics-consistent machine learning method that directly enforces compliance with physical principles by projecting model outputs onto the manifold defined by these laws. Our method was demonstrated in a low-pressure oxygen plasma enforcing quasi-neutrality, charge conservation and the ideal gas law.

Compared to purely data-driven models, our approach reduces errors in physical law compliance, enhances predictive accuracy of physical quantities, and outperforms alternatives when working with simpler models or limited datasets.

The proposed projection-based technique is versatile, offering an interpretable, general and scalable solution for developing fast and reliable surrogate models of complex physical systems, particularly in resource-constrained scenarios.



Projection of the prediction f(x;Θ) into the manifold g(x,p) defined by the physical constraints. p is the final prediction.

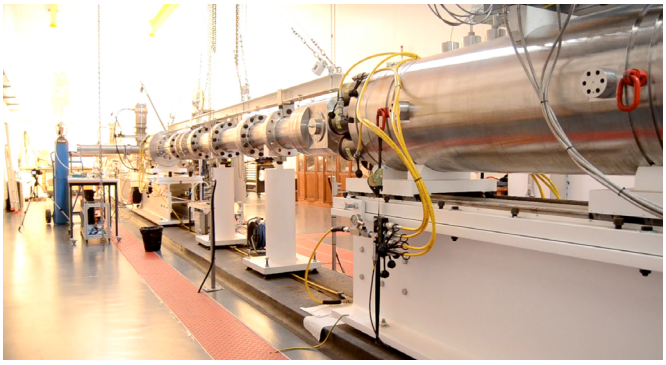
HYPERSONIC PLASMAS LABORATORY

EXPERIMENT - FIRST HYPERSONIC FLOW ACHIEVED IN THE ESTHER SHOCK TUBE

The qualification of the European Shock Tube for High Enthalpy Research (ESTHER) reached another major milestone with the successful completion of its first full dynamic test on 19 November 2025.

An estimated flow velocity of about 8 km s^{-1} was achieved in the test section. Pressure sensors distributed along the shock tube provided valuable data on the propagation of the shock and expansion waves, enabling the characterisation of the facility's dynamic performance.

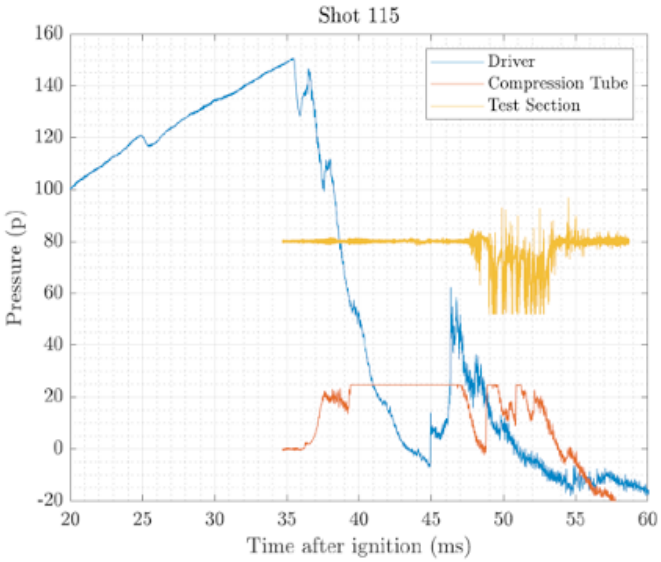
This achievement represents a landmark for fluid dynamics research in Portugal, marking the first time that a national experimental facility has generated hypersonic flow conditions (Mach numbers above 5).



Still from the first hypersonic shot for the ESTHER facility. The shockwave light is seen bleeding through the dump tank walls.

The various subsystems were successfully validated under operational conditions, including:

- Stable operation of the combustion chamber in deflagration mode was demonstrated through ignition by a focused Nd:YAG laser at the centre of the chamber. This approach limited the combustion length and prevented the onset of deflagration-to-detonation transition (DDT). Furthermore, the research programme conducted over the past several years enabled the achievement of the target post-combustion driver pressures.
- The control system for vacuum operation and test-gas filling was further enhanced, enabling fully automated remote control of the entire shot sequence.
- The data acquisition system was configured to provide a single synchronized time base for all shock tube sensors. This enabled continuous, time-resolved monitoring of the complete test sequence, from laser ignition, combustion, and diaphragm rupture in the driver section, through shock-wave propagation in the compression tube and test section, to gas collection and venting in the dump tank. The resulting measurements provide a comprehensive characterisation of the facility's dynamic behaviour throughout each test.



Signal from the pressure sensors located at the driver section, the compression tube and the test section.

Work is now focused on resolving the minor issues identified during facility operation, including enhancing the resilience of the plug insulators, the diaphragm sealing system, and the optical plug.

MODELLING – FUNDAMENTALS OF NON-EQUILIBRIUM KINETIC AND RADIATIVE PROCESSES

We have investigated the impact of trace amounts of carbon in the freestream composition of Ice Giant atmospheres on the post-shock radiative environment, as part of preparatory studies supporting a potential joint NASA–ESA mission to Uranus that would include an atmospheric entry probe.

We have revised, updated, and extended the STELLAR-X database of high-temperature multi-quantum transition rates to include hydrogen-bearing species (H_2, OH, NH, and H), enabling more accurate modelling of thermodynamic nonequilibrium in detonation flows. This work is being carried out in collaboration with Maastricht University and Zhejiang University.

High-Pressure Plasmas

Summary of Research

Main Researchers:

Diego Santos

Mário Cunha

Mikhail Benilov

Nelson Almeida

Nuno Ferreira

Pedro Almeida

Rui Almeida

Main funding sources:

European Regional Development Fund

Siemens AG Corporate Technology

Siemens Energy Global, GmbH & Co. KG

Schneider Electric Industries SAS

Fundação para a Ciência e a Tecnologia

Our research focuses on the physics and modelling of low-temperature plasmas at high pressure, with particular emphasis on plasma-surface interaction, near-electrode regions, corona discharges, arc ignition, and discharge stability.

We aim to understand the fundamental mechanisms governing ionisation processes, plasma-sheath transitions, current transfer near electrodes, and the onset of steady or pulsed discharge regimes. To achieve these goals, we combine analytical theory, bifurcation and linear stability analysis, time-dependent numerical simulations, and fluid and kinetic plasma models.

During the 2024-2025 period, the group developed a hybrid fluid-kinetic description of ionisation layers with collision-free neutral atoms, advanced models of non-equilibrium near-cathode plasma layers for arc ignition on cold refractory cathodes, clarified theoretical issues in the plasma-sheath transition and the Bohm criterion, and investigated the inception, stability, and transition to pulsed regimes of negative corona discharges in atmospheric-pressure air.

These results strengthen the theoretical foundations of high-pressure gas discharge physics and support the development of more reliable models for high-pressure arcs, plasma sources, corona devices, and related plasma-based technologies.

Group Leader: Pedro G. C. Almeida



RESEARCH HIGHLIGHTS

IONISATION LAYERS IN PARTIALLY IONISED PLASMAS

The interaction between ions and neutral atoms near cathode surfaces plays a key role in the ignition and operation of high-pressure arc discharges. The group developed a new theoretical description of ionisation layers in conditions where neutral atoms move almost collision-free. A hybrid fluid–kinetic model was introduced, combining fluid treatment of ions with kinetic treatment of neutral atoms.

The resulting analytical solution enabled the derivation of new formulas for evaluating ion currents over a broad range of plasma conditions. These results improve the physical description of glow-to-arc transitions and provide more accurate tools for modelling arc ignition on cold cathodes. The work contributes to the development of predictive models for industrial arc systems and plasma-based technologies operating at high pressures.

Reference: M. S. Benilov, Plasma Sources Sci. Technol. 33, 055002 (2024).

MODEL OF NON-EQUILIBRIUM NEAR-CATHODE PLASMA LAYERS FOR SIMULATION OF IGNITION OF ARCS ON CATHODES

The ignition of high-current arcs on cold refractory cathodes is a technologically important process in switching devices, plasma torches, and industrial arc systems. The group extended existing models of non-equilibrium near-cathode plasma layers by including secondary ion-electron emission mechanisms, allowing the models to remain valid even for low cathode temperatures. The improved model successfully described both glow-like discharges on cold cathodes and thermionic arc discharges on hot cathodes within a unified framework.

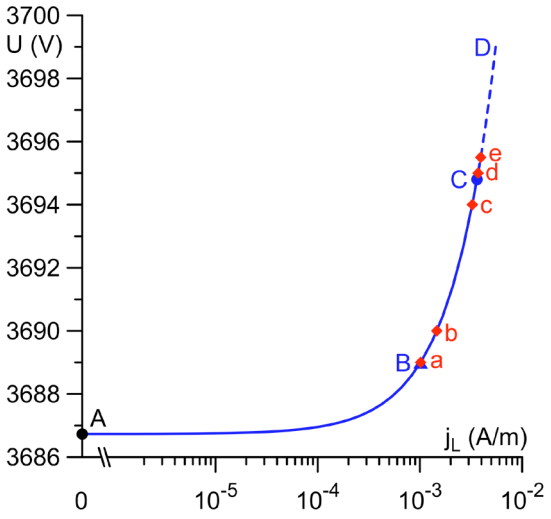
A new method for evaluating ion current under conditions of weak ion–atom coupling was implemented and tested. The resulting model can be used in multidimensional simulations of arc ignition and contributes to more reliable numerical tools for the design of high-pressure plasma systems.

Reference: D. F. N. Santos, N. A. Almeida, L. G. Benilova, and M. S. Benilov, J. Phys. D: Appl. Phys. 57, 405202 (2024).

THEORY OF STABILITY OF SELF-SUSTAINING DC DISCHARGES AT INCEPTION

The ignition of self-sustaining DC discharges is a fundamental problem in plasma science and electrical engineering. During the reporting period, the group developed a theoretical framework describing discharge inception using bifurcation theory. The work demonstrated that the transition to self-sustained corona discharges can be interpreted as a transcritical bifurcation and showed that negative coronas are expected to be stable immediately after ignition. This prediction was validated through numerical simulations and linear stability analysis.

The study also showed that the loss of stability occurs through the growth of harmonic perturbations that later evolve into Trichel pulses. These results provide a unified theoretical interpretation of corona ignition and help explain contradictory observations reported in previous experimental studies.



Stability of the self-sustaining negative corona discharge near inception. The discharge is stable immediately after ignition: perturbations decay monotonically on branch AB and with damped oscillations on branch BC. Stability is lost at point C; beyond this point, oscillatory perturbations grow and evolve into Trichel pulses. Adapted from Fig. 4 of Almeida, Naidis and Benilov, Phys. Rev. E 110, 045201 (2024).

Reference: P. G. C. Almeida, G. V. Naidis, and M. S. Benilov, Phys. Rev. E 110, 045201 (2024).

CLARIFYING THE PLASMA–SHEATH TRANSITION

Understanding how a quasi-neutral plasma changes into a charged sheath near a surface is a long-standing challenge in plasma physics. Despite decades of research, there is still no universally accepted theory describing this transition and the associated Bohm criterion. During this period, the group published a comprehensive review analysing why this problem remains unresolved and identifying the mathematical and physical requirements for a theory to be accepted by the plasma community. The work critically compared fluid, kinetic, and asymptotic approaches and highlighted the importance of presenting complex mathematical results in a physically transparent way.

The study also clarified limitations of several modern formulations of the Bohm criterion for collisional sheaths. This contribution provides an important reference for future theoretical developments in plasma–surface interaction and helps bridge the gap between mathematical plasma theory and practical gas discharge physics.

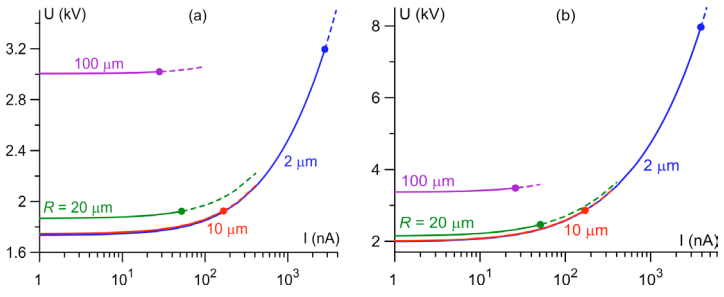
Reference: M. S. Benilov and N. A. Almeida, Phys. Plasmas 32, 030501 (2025).

STABLE AND PULSED NEGATIVE CORONA DISCHARGES

Negative corona discharges in air are widely used in environmental, industrial, and electrostatic applications, yet their transition from steady operation to self-pulsing Trichel regimes remains poorly understood. The group carried out advanced numerical simulations of low-current needle-to-plane negative corona discharges in atmospheric-pressure air.

The study identified conditions under which the discharge remains stable immediately after ignition and analysed the mechanisms responsible for the later appearance of oscillations, in particular, the well-known Trichel pulses.

The simulation results revealed how harmonic oscillations evolve into regular pulsing regimes and provided new insight into experimentally observed stochastic pulses. Modelling results were found to agree well with available experimental current–voltage data. These findings improve the understanding of corona discharge stability and are relevant for the optimisation of plasma reactors and electrohydrodynamic devices.



Effect of the tip radius on the stability limit of the negative corona. (a) Configurations 1,3,5 and 7, discharge gap of 10 mm. (b) Configurations 2,4,6 and 8, discharge gap of 50 mm. Solid lines: stable regions. Dashed lines: unstable regions.

Reference: N. G. C. Ferreira, P. G. C. Almeida, A. E. Taher, G. V. Naidis, and M. S. Benilov, Plasma Sources Sci. Technol. 34, 085002 (2025).

Astrophysical Plasmas

Summary of Research

Main Researchers:

Frederico Fiúza

Kaushik Satapathy

Pablo San Miguel

Philipp Kempski

Tej Chand

Main funding sources:

European Research Council (ERC)

Marie Skłodowska-Curie Actions

The vast majority of visible matter in the universe exists as plasma. Understanding the microphysical processes that govern these astrophysical plasmas is one of the grand challenges of modern physics.

Our main goal is to advance the fundamental understanding of how cosmic plasmas accelerate particles, impact their transport and produce high-energy emission in extreme conditions such as supernovae, neutron star magnetospheres and relativistic jets.

Our primary tools are kinetic and multi-scale numerical simulations, theoretical modelling, and laboratory astrophysics experiments at major international facilities. We develop novel computational methods, including machine learning-based reduced models, to bridge microscopic plasma processes and macroscopic astrophysical scales.

This research deepens our understanding of cosmic-ray origin and high-energy plasma astrophysical phenomena, while also informing plasma physics applications in fusion energy and laser-plasma science.

Group Leader: Frederico Fiúza



RESEARCH HIGHLIGHTS

ADDRESSING THE PUZZLE OF ENERGY PARTITION IN ASTROPHYSICAL PLASMAS

The universe is full of powerful streams of matter launched by violent events such as exploding stars, black hole jets, and stellar winds. When these plasma flows slam into surrounding space at enormous speeds, they generate shock waves that light up the cosmos and shape how galaxies evolve. Yet for decades, scientists have struggled with a deceptively simple question: how is the energy of these extreme flows converted into heat when particles almost never collide?

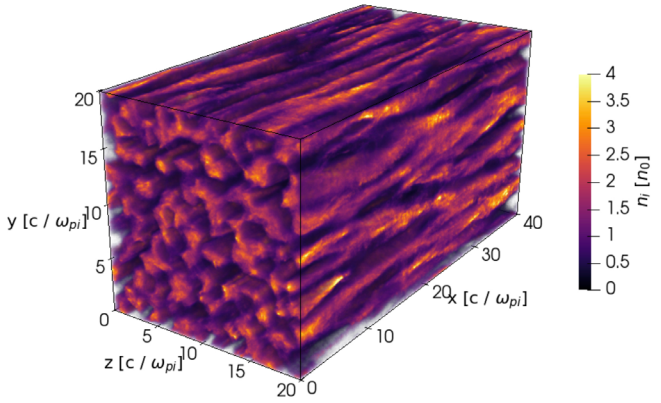
In this project, we have used large-scale, three-dimensional kinetic simulations to peer inside these collisionless plasmas and track how energy is redistributed between particles and fields. Our results reveal that most of the heating occurs later than previously assumed, driven by the twisting and kinking of filament-like electric currents.

These structures act like tiny cosmic dynamos, amplifying magnetic fields and transferring energy to particles in a fundamentally three-dimensional process.

Crucially, the study shows that electrons — the particles responsible for much of the radiation astronomers observe — receive only a small fraction of the available energy, while heavier ions carry most of the heat. For realistic plasmas like those found in supernova remnants, electrons end up with only a few per cent of the original energy of the flow.

This finding helps resolve long-standing puzzles in astronomical observations, where electron temperatures appeared surprisingly low compared to theoretical expectations.

By uncovering the hidden mechanisms that govern energy flow in violent cosmic plasmas, this research brings scientists closer to a unified picture of how the universe's most energetic events heat and transform their surroundings. It also arrives at a timely moment, as new laboratory plasma experiments and high-resolution simulations are beginning to probe these extreme conditions directly.



As energetic counter-streaming plasmas collide they transfer energy between electrons, ions and fields through plasma instabilities. New fully kinetic 3D simulation reveal the resulting plasma structure and dominant mechanisms.

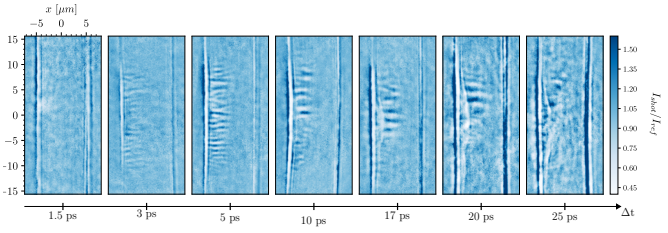
DIRECT IMAGING OF FUNDAMENTAL RELATIVISTIC PLASMA INSTABILITY IN THE LABORATORY

When energetic charged particle beams stream through a plasma — as occurs in supernova explosions, gamma-ray bursts, and relativistic jets — they are thought to drive an instability that spontaneously generates magnetic filaments and dramatically affects how energy and radiation are transported.

This so-called current filamentation instability is thought to seed the formation of astrophysical shock waves, yet directly observing its development in controlled laboratory experiments has been a significant challenge.

We have directly imaged this instability in a laboratory plasma by combining for the first time a high-intensity optical laser — used to drive fast electron beams through a solid-density plasma — with the world's brightest X-ray free-electron laser (LCLS at SLAC) as a probe, achieving 200 nm spatial and 50 femtosecond temporal resolution simultaneously.

Our experimental results, combined with advanced kinetic simulations and analytic theory, demonstrate the formation and nonlinear evolution of micron-scale magnetic filaments, directly revealing — for the first time — the combined critical role of space-charge effects, ion motion and collisions in governing the instability's evolution, and confirming the production of magnetic fields reaching tens of megagauss.



X-ray images of the plasma density in the interaction of a high-intensity optical laser with a 10 micron copper wire. The micron-scale filamentary modulations are associated with the current-filamentation instability driven by relativistic electrons in the solid-density plasma.

These findings provide the first direct experimental benchmark for models of a process central to magnetic field generation and particle transport in some of the most energetic phenomena in the universe, and open a new avenue for laboratory astrophysics using X-ray free-electron lasers.

Community & Outreach



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

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

OUTREACH EVENTS AND INITIATIVES

EUROPEAN RESEARCHERS' NIGHT

The European Researchers' Night returned to Lisbon on 26 September 2025, at the National Museum of Natural History and Science (MUHNAC-ULisboa), under the theme `Science for Global Challenges´. IPFN was part of the programme with two activities, CANMILK (Carbon Neutral MILK) and "The magical world of lasers and plasmas", giving visitors the opportunity to explore leading research and practical demonstrations.

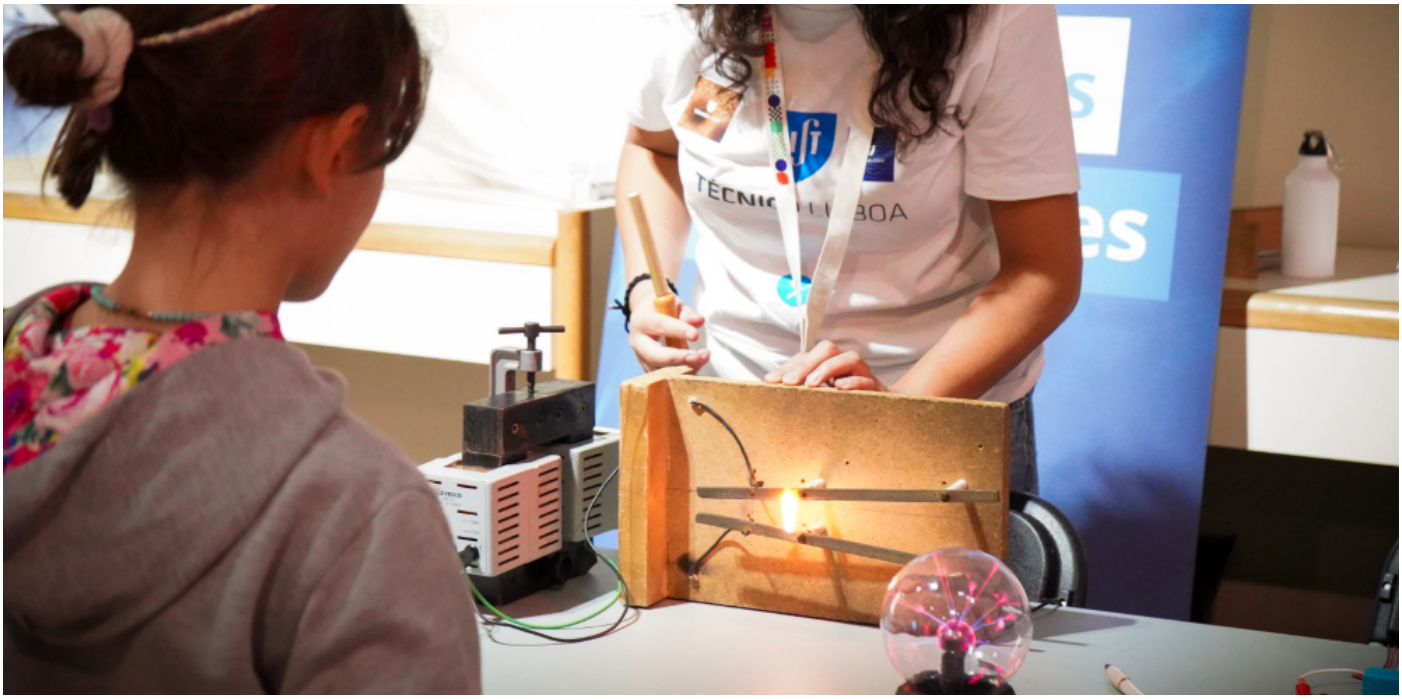
In the activity "CANMILK: Sustainable innovation in milk production", the European project Carbon Neutral MILK was presented. The initiative focuses on reducing methane emissions in the agricultural sector by converting them into less harmful compounds, such as carbon dioxide, through the combined use of catalysis and plasmas.

Centro de Química Estrutural (CQE), a research unit of the University of Lisbon, and IPFN, through Instituto Superior Técnico (IST), are contributing to the project by developing a kinetic model that will provide valuable insights into the mechanisms behind the reaction under study.

At the stand, researchers Farzaneh Ostovarpoor (IPFN), Mariana Pereira (CQE) and Rita de Jesus (CQE) introduced visitors to the idea of heterogeneous catalysis, using real catalysts, including one from a car, to show how plasma can make these reactions more efficient. They also used a children's puzzle game to illustrate how molecular modelling can help identify catalysts with potentially favourable properties for different reactions, in a way that is both fast and cost-effective.

Coordinated by IST Professor and IPFN researcher Marija Vranic, with support from NFIST students, the activity "The magical world of lasers and plasmas" offered experiments for visitors to try. Children placed their hands on a plasma ball to trace the electric filaments, watched the current rise along the electrodes of a Jacob's Ladder and handled an educational "lightsaber".





"ENGENHARIA E CIÊNCIA VÃO À ESCOLA (ENGINEERING AND SCIENCE GO TO SCHOOL)"

As part of the first edition of "Engenharia e Ciência vão à Escola", an initiative by Instituto Superior Técnico, during the Science and Technology Week, students from Lisbon, Loures, and Oeiras had the opportunity to engage with researchers across interactive sessions.

Throughout the week, these activities inspired pupils in years 1 to 9 to explore scientific concepts and innovations, with IPFN researchers contributing to this initiative by sharing their knowledge and fostering curiosity in science and technology.



2024 Edition.



2025 Edition.

TÉCNICO OPEN DAY

Técnico opened its doors to more than 2,700 visitors at Open Day 2025. The School offered the public lab visits, experimental activities, course presentations and other initiatives organised by the school community.

God Plays Dice!, developed by researchers at Técnico including IPFN members, was unveiled during Técnico's 2025 Open Day. The game was facilitated on-site by PhD students, who guided participants through the gameplay and its connection to real quantum effects.



IPFN FEATURED ON CNN INOVAÇÃO

IPFN was featured on the programme 'CNN Inovação' in August 2025. The episode presented its research in nuclear fusion as well as practical plasma applications in medicine, environmental protection, and aerospace technology, including oxygen generation on other planets and atmospheric re-entry testing using a shock tube.

The programme also underscored IPFN's pioneering work in large-scale computational plasma simulations and the development of intense lasers for radiotherapy and 3D medical imaging. In addition to its strong international presence, the institute's commitment to top-tier advanced training was emphasised, marked by the graduation of over 65 PhD students in the past six years.



SCHOOL VISITS AND TALKS

Every year, IPFN facilities such as ISTTOK, L2I, VOXEL and MOTLab receive many visits from undergraduates and from primary and secondary school pupils.

During the guided tours, the pupils have the opportunity to meet undergraduate students and staff, having a first contact with the research developed at IPFN, the technologies involved and perspectives of future careers. Our researchers are also frequently invited to give talks at schools, workshops, training sessions and public events.

PRESS RELEASES

JET's final tritium experiments yield new energy record
Feb. 2024

IST and Next Step Fusion sign collaboration agreement
Jul. 2024

First experimental observation of nonlinear Compton scattering
Nov. 2024

Paving the way for portable laser-induced breakdown spectroscopy
Dec. 2024

IPFN researchers challenge classical laws of statistical physics
Apr. 2025

Axion–plasmon conversion found in neutron stars
Sep. 2025

LoKI-B++ released as part of PLASIMO
Oct. 2025

WEB AND MEDIA

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

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

FACEBOOK – FB.COM/IPFNLA
Launched in 2010, the IPFN page has gathered more than 1,700 followers

INSTAGRAM – INSTAGRAM.COM/IPFNMEDIA
More than 200 posts about what's going on at IPFN

LINKEDIN – LINKEDIN.COM/COMPANY/IPFN
Connecting current, previous and prospective employees, while also disseminating career opportunities - more than 1,800 followers

WEBPAGE – IPFN.TECNICO.ULISBOA.PT
The central hub of all our websites, with news, events and detailed information about activities and scientific results

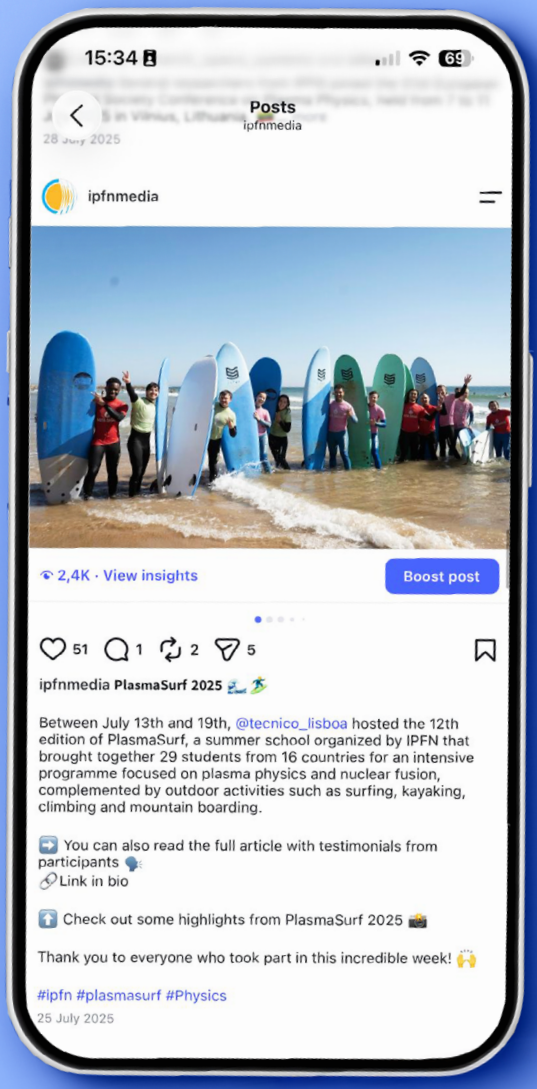
YOUTUBE – YOUTUBE.COM/IPFNMEDIA
It serves as a video repository, either for dissemination purposes or events taking place at IPFN











Education



EVENTS

PLASMASURF SUMMER SCHOOL

PlasmaSurf is IPFN's summer school on plasma physics, intense lasers and nuclear fusion, aimed at BSc/MSc engineering and physics students. The 11th and 12th editions, held in July 2024 and July 2025, respectively, brought together 44 and 29 students from diverse international backgrounds.

The programme combined lectures and hands-on sessions delivered by IPFN researchers and faculty with visits to experimental facilities, including ISTTOK, VOXEL and L2I, as well as outdoor activities such as surfing, kayaking, climbing and mountain boarding.



TRAINING AND INTERNSHIPS AT THE INTERNATIONAL LEVEL

IPFN welcomed eight European Master's students in Nuclear Engineering from five French and Italian institutions for four-month research internships at the Engineering and Systems Integration Group.

There, they worked on projects related to future reactors such as ITER and DEMO by focusing on the integration of diagnostic systems and robotic manipulation in high-radiation environments. This allowed them to gain practical experience in computational tools, finite-element analysis, Monte Carlo modelling, and scientific report interpretation.



IST ATHENS COURSE

The course, organised by IPFN, was attended by 15 students coming from 8 different higher education institutions in France, the Czech Republic, Belgium, Turkey, and other countries. They were exposed to the fundamentals of plasma physics and its technological applications through theoretical classes, hands-on experiments, and laboratory visits.

The ATHENS Network is made up of 15 leading European technological universities. It organises intensive short-duration courses at each member institution, offering a platform for students to deepen their knowledge in specialised fields and build connections across Europe.



STUDENTS VISIT TO IPFN

IPFN welcomed a group of 24 visitors from École Nationale Supérieure des Arts et Métiers (ENSAM), in France. The group was composed of 20 students and 4 accompanying staff, and their visit was part of a study trip to Lisbon.



SPECIAL GUEST LECTURES

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

Uwe Czarnetzki

Kinetic effects in low-temperature plasmas

13 March 2024

Anne L'Huillier

The route to attosecond pulses

27 May 2024

Richard Morgan

Shock and expansion tunnels for the study of hypervelocity flows

6 June 2024

Satoshi Hamaguchi

Future manufacturing technologies for semiconductor devices with physics-based models, data, and AI

3 July 2024

INTERNATIONAL CONFERENCES

IPFN hosted the following conferences:

Laserlab-Europe Conference, 27-29 May 2024



ECLIM 2024 - 37th European Conference on Laser Interaction with Matter, 16-20 September 2024



THESES AT IPFN

MSC THESES, 2023/2024

Alexandre Gil Gouveia Maia Barbosa
Bell correlations and optical quantum memory for noble-gas nuclear spins
Supervised by Hugo Terças and Emmanuel Cruzeiro

Alexandre Valente Pargana Advinculo Sequeira
Learning reduced nonlinear plasma models from data
Supervised by Frederico Fiúza

Blandine Berdugo
Surface recombination on Pyrex in CO_2 glow discharges
Supervised by Pedro Viegas and Vasco Guerra

David Matias Cristino
Nonlinear optics for Ultrashort High Intensity Pulse Amplification
Supervised by Hugo Pires and Gonçalo Figueira

Diana Filipa Prata e Cunha
Kinetic theory of vortex gases in low-dimensional superfluids
Supervised by Hugo Terças

Diogo Borges Soares
Spin glass phenomenology in frustrated magnetic spinners
Supervised by Hugo Terças

Gonçalo Amadeu Mendes Cardoso
Monte Carlo study of charged-particle collisions in low-temperature plasmas
Supervised by Tiago Dias and Vasco Guerra

Henrique Miguel Álvares Pereira Lima Gonçalves
Axion dynamics in spin -1/2 quantum plasmas
Supervised by Hugo Terças

João Francisco Portugal da Silveira Marques
Ultrafast lasers towards TRIR spectroscopy
Supervised by Gonçalo Figueira and Hugo Pires

Mariana Azevedo Ferreira
GarbageSat: Demonstration Mission for Debris Removal in LEOs
Supervised by Mário Lino da Silva

Mariana Da Silva Ribeiro
A framework for studying CO_2 microwave plasmas
Supervised by Tiago Silva and Vasco Guerra

Mário António Geraldes Vaz
Exploring the role of sheared flows in the L-H transition
Supervised by Luís Gil and Carlos Silva

Miguel Francisco Paixão Mendes
Second-order couplings in ultrashort pulses with cylindrical symmetry
Supervised by Gonçalo Figueira

Rafael Ferreira Valente da Silva
Calibration of the hopping reflectometer and study of the quasi-coherent mode at ASDEX Upgrade
Supervised by Carlos Silva and Luís Gil

Rui Manuel Pires Martins
Modeling of atomic oxygen in the effluent of CO_2 microwave discharges
Supervised by Vasco Guerra and Tiago Silva

MSC THESES, 2024/2025

André Rodrigues
Study of the properties of CrFeTaVW high entropy alloys for nuclear fusion
Supervised by Marta Dias

André Sampaio
Production and characterisation of W-based high entropy alloys as thermal barriers
Supervised by Marta Dias and Bernardo Monteiro

Armando Rafael Pires Gonçalves
The plasma way to ammonia: modelling and understanding plasma-derived NH3
Supervised by Luís Lemos Alves

Diogo Miguel dos Santos Simões
Kinetic instabilities in bidimensional Dirac materials
Supervised by Hugo Terças and Jorge Ferreira

Diogo Sampaio Pereira
Enhancing Tungsten's Nitride Formation with Ion Implantation Technique
Supervised by Norberto Catarino and Rodrigo Mateus

Diogo Tovar Nogueira de Lemos
Development of a LWFA target for fine electron injection control
Supervised by Thales da Silva and Nelson Lopes

Eduarda Álvaro Martins
Study of the FeCrTiVW and FeTaTiVW high entropy alloys (HEAs) for hydrogen storage applications
Supervised by Marta Dias and Bernardo Monteiro

Francisco Maria Gaspar de Assunção
Particle drifts and radiation reaction in astrophysics
Supervised by Luís Silva

Francisco Valério Raposo
Numerical Integration of Nonlinear Dynamics in a Magneto-Optical Trap
Supervised by Hugo Terças

Gonçalo Pina de Almeida
Plasma optical emission signal characterisation in Laser-Induced Breakdown Spectroscopy
Supervised by João Mendanha Dias

Inês Robalo Dias Martins dos Santos
Design and modeling of a plasma reactor for the production of O2 from the conversion of CO_2
Supervised by Pedro Viegas and Nuno Pinhão

Joana Bárbara Cerqueira Araújo
Multidimensional fluid modelling of reactor coupling plasma and oxygen separation membrane
Supervised by Pedro Viegas and Nuno Pinhão

João Alexandre Garcia Cândido
Kinetic simulations of highly magnetized plasmas
Supervised by Frederico Fiúza and Luís Silva

João Bernardo Figueiredo Rodrigues
Descriptive and predictive modeling of chaos in cold atom physics using explainable deep learning
Supervised by Rui Henriques and Hugo Terças

João Maria dos S. Leitão dos Santos Joaquim
General-relativistic radiation reaction cooling in pulsar magnetospheres
Supervised by Luís Silva

João Pedro Ferreira Biu
Data-driven methods for anomalous resistivity in collisionless shocks
Supervised by Frederico Fiúza

Manuel Afonso dos Santos Ratola
Plasma instabilities in the fireball experiments at CERN and INFN
Supervised by Thales da Silva and Luís Silva

Marco Pereira Costa
Whole-organism 3D maps reveal parallel self-similar vascular and neural networks with divergent Murray-like exponents
Supervised by Gonçalo Figueira

Margarida Melo Pereira
Reduced models for plasmas: integration of "particle-in-cell" simulations and machine learning
Supervised by Luís Silva and Frederico Fiúza

Matilde Lopes Fernandes
Incoherent Diffraction Imaging with hard X-rays: Single-shot characterisation of 2D spatial coherence of a focused X-ray beam
Supervised by Pablo Claveria and Marta Fajardo

Matthieu Cuffaro
Preparation and full characterisation of high entropy alloys
Supervised by Bernardo Monteiro

Miguel José Mendes Pereira
Where is the quasi-coherent mode?
Supervised by Luís Gil and Carlos Silva

Rodrigo Semedo
Feasibility Study of Passive Aerocapture for Mars Orbital Insertion
Supervised by Mário Lino da Silva

Sofia Lara Jardim
CuCrTaVA (Ti or Fe) as termal barrier for nuclear fusion
Supervised by Marta Dias

Tiago Nascimento
Advancing Nuclear Fusion Reactors: Investigating the Irradiation Effects on ITER-grade Tungsten Plasma facing Components
Supervised by Marta Dias and Norberto Catarino

Vasco Castanheira da Silva Ramos dos Santos
Topological modes in bidimensional Dirac materials
Supervised by Hugo Terças

PHD THESES, 2024

Bernardo Farinha Malaca
Superradiant and coherent radiation emission in plasma accelerator light sources
Supervised by Jorge Vieira and Ricardo Fonseca

Duarte Nuno Barreto Gonçalves
Aerodynamic study of atmospheric-pressure plasma jets
Supervised by Luís L. Alves and Stéphane Pasquiers

Pedro Afonso Cosme e Silva
Plasmonic instabilities in bidimensional materials
Supervised by Hugo Terças and José Tito Mendonça

Ricardo João Grosso Marques Ferreira
Development and Qualification of the European Shock Tube for High Enthalpy Research
Supervised by Mário Lino da Silva

Rui Pedro Tourinho Torres
Dynamics of magnetospheres of rotating compact objects with general relativity
Supervised by Luís Silva and Thomas Grismayer

PHD THESES, 2025

Camilla Willim
Structured Laser-Plasma Interactions at Ultra-High Intensities
Supervised by Jorge Vieira and Luís Silva

Duarte Rogado Nina
Understanding the link between scrape-off layer and pedestal conditions at JET using density profile measurements by reflectometry
Supervised by Carlos Silva

João António Silva Oliveira
A data acquisition system for the magnetic diagnostic of COMPASS-U
Supervised by Horácio Fernandes

Luís Miguel Cabeça Marques
Development of a radiation detection system coupled to an unmanned aerial vehicle for security and defence applications
Supervised by José Vaz and Alberto Vale

Pablo Jaime Bilbao Santiago
Kinetic Instabilities in Extreme Plasma Physics: Laboratory and astrophysical dynamics
Supervised by Luís Silva

Awards and distinctions



SCIENTIFIC PRIZES AND APPOINTMENTS

Hugo Terças
2024 APS Outstanding Referee Distinction

The award distinguishes exceptional contributions to peer- reviewing



Frederico Fiúza and Hugo Terças
Selected for Young Scientists Seminar

Lisbon Academy of Sciences



Luís Silva
Blaise Pascal Medal for Physics 2024,

European Academy of Sciences



Frederico Fiúza
Lev D. Landau and Lyman Spitzer Jr. Award

American Physical Society and European Physical Society



Marco Piccardo
ERC Starting Grant

Researcher collaborates with IPFN laser laboratories



Filipe Cruz
Awarded a Fulbright Portugal scholarship for UCLA

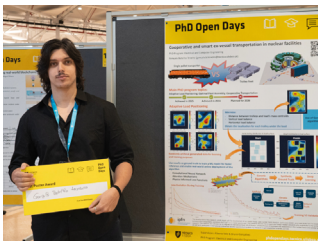
This support allowed him to spend 6 months at the Plasma Simulation Group of the University of California



CONFERENCE AWARDS

Gonçalo B. Teixeira
Best PhD Poster

2025 PhD Open Days



Filipe da Silva
ANACOM-URSI Portugal 2025 Award



ACADEMIC DISTINCTIONS

Luís Silva
Elected Socio Efectivo (Chair 8C) of the Lisbon Academy of Sciences



THESIS AWARDS

Bernardo Malaca,
Best PhD Thesis Award 2024, Sociedade Portuguesa de Óptica e Fotónica

Prize awarded for the best thesis in optics and photonics in Portugal



Central Administrative Team



Acknowledgements

The IPFN extends its sincere gratitude to all those who have been part of the Institute and moved on during this reporting period.

We gratefully acknowledge their contributions to the Institute's scientific achievements and community.

Biennial Report 2024-2025

Coordination and Chapter Editors
Gonçalo Figueira and Bruno Gonçalves

Section Editors
Bruno Gonçalves, Marta Dias,
Horácio Fernandes, Luís Lemos Alves,
Luís Oliveira e Silva, Pedro Almeida, Frederico Fiúza

Layout and Design
Alexandra Franco

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