nuclear fusion
IAEA

PAPER • OPEN ACCESS

RFX-mod2 and the NEFERTARI project: A distributed research network for the study of magnetically confined plasmas for fusion

To cite this article: L. Marrelli *et al* 2026 *Nucl. Fusion* **66** 076032

OPEN ACCESS
IOP Publishing | International Atomic Energy Agency
Nuclear Fusion
Nucl. Fusion **66** (2026) 076032 (15pp)
https://doi.org/10.1088/1741-4326/ae6f30

RFX-mod2 and the NEFERTARI project

A distributed research network for the study of magnetically confined plasmas for fusion

L. Marrelli[1,2], M. Barbisan[1], P. Bettini[2,4], M. Brombin[1,2], L. Carraro[1,2], O. De Pascale[1], G. Dilecce[1], L. Grando[1,2], N. Marconato[2,4], S. Peruzzo[1], P. Sonato[2,4], M. Spolaore[1,2], M. Tardocchi[1], A. Uccello[1], M. Zuin[1,2,*], D. Abate[2], D. Aceto[1], P. Agostinetti[1,2], M. Agostini[1,2], P.F. Ambrico[1], D. Aprile[2], F. Auriemma[1,2], P. Barbato[1,2], A. Belpane[2], G. Berton[2], J. Bettega[10], M. Bigi[2], W. Bin[1], M. Boldrin[2], T. Bolzonella[2], D. Bonfiglio[1,2], M. Bonotto[2], G. Boschetti[4], M. Breda[2], C. Bustreo[1,2], F. Cani[1], A. Canton[2], S. Cappello[1,2], M. Carraro[1,2], F. Caruggi[6], I. Casiraghi[1], R. Cavazzana[2], A. Celora[6], L. Cinnirella[2,5], A. Cintora De La Cruz[2,5], S. Cipelli[1,5], S. Ciufo[2,5], A. Corbioli[2], L. Cordaro[2], A. Cremona[1], G. Croci[1,6], F. D'Isa[2], S. Dal Bello[2], A. Dal Molin[1], M. Dan[2], G. De Masi[1,2], M. De Nardi[2], G. De Tommasi[9,11], F. Degli Agostini[1,2], R.S. Delogu[2], G. Di Gironimo[8], G. Emma[2,5], M. Fadone[1], A. Fassina[3], F. Fellin[2], A. Ferro[2], N. Ferron[2], M. Fincato[1,2], F. Fiorenza[9,11], D. Fiorucci[3], G.A. Fontanelli[8], L. Franchin[2], P. Franz[2], S. Fusco[8], F. Galeazzi[2,5], G. Gervasini[1], M. Giacomin[2,7], S. Gitini[2], L. Giudicotti[2,7], M. Gobbin[1,2], S. Grazioso[8], G. Grosso[1], F. Guiotto[2,5], A. Hussain[1,5], A. Kryzhanovskyy[2], M. La Matina[2], A. La Rosa[2], L. Laguardia[1], B. Laterza[2], E. Lazzaro[1], R. Lorenzini[2,3], F. Lucchini[4], D. Lui[9], M. Magagna[2], A. Maistrello[2], G. Manduchi[1,2], G. Marchiori[1,2], I. Mario[2], G. Martini[2], R. Milazzo[1], P. Minelli[1], S. Molisani[2,5], F. Molon[2], B. Momo[2], M. Moresco[2], A. Muraro[1], L. Orlandi[2,5], M.T. Orlando[1,2], A. Panarese[1], E. Perelli Cippo[1], M. Pedroni[1], L. Pigatto[2], N. Pilan[2], A. Pironti[9,11], P. Porcu[2,5], N. Pomaro[1,2], I. Predebon[1,2], M.E. Puiatti[2], O. Putignano[1], M. Rebai[1], M. Recchia[1,2], D. Ricci[1], D. Rigamonti[1], A. Rigoni Garola[2], N. Rispoli[1], A. Rizzolo[2], F. Rossetto[1,2], F. Ruffini[2,5], L. Saccaro[2,5], F. Santoro[2], A. Sartore[2], F. Sattin[2], P. Scarin[2], J. Scionti[1], T. Sinico[10], A. Sofia[8], S. Spagnolo[1,2], L. Spinicci[2], G. Spizzo[1,2], A. Stagni[2], F. Taccogna[1], C. Taliercio[1,2], D. Terranova[1,2], A. Tiso[2], E. Tomasina[2,5], L. Trevisan[2], M. Ugoletti[1], M. Valente[2], M. Valisa[1,2], M. Veranda[1,2], N. Vianello[1,2], F. Villone[9,11], E. Zampiva[1,2], P. Zanca[2], B. Zaniol[2] and M. Zaupa[1]

[1] Istituto per la Scienza e Tecnologia dei Plasmi (ISTP), CNR, Italy
[2] Consorzio RFX (CNR, ENEA, INFN, Università di Padova, Acciaierie Venete S.p.A.), Padova, Italy
[3] Fusion and Nuclear Safety Department, ENEA, C. R. Frascati (Rome), Rome, Italy
[4] Department of Industrial Engineering, University of Padova, Padova, Italy
[5] CRF—University of Padova, Padova, Italy
[6] Dipartimento di Fisica 'G. Occhialini', University of Milano-Bicocca, Milano, Italy

[*] Author to whom any correspondence should be addressed.

[7] Dipartimento di Fisica e Astronomia 'Galileo Galilei', University of Padova, Padova, Italy
[8] Department of Industrial Engineering, University of Napoli Federico II, Napoli, Italy
[9] Dipartimento di Ing. Elettrica e Tecnologie dell'Informazione, University of Napoli Federico II, Napoli, Italy
[10] Department of Management and Engineering, University of Padova, Padova, Italy
[11] Consorzio CREATE, Napoli, Italy

E-mail: matteo.zuin@istp.cnr.it

Received 30 January 2026, revised 28 April 2026
Accepted for publication 18 May 2026
Published 18 June 2026

Abstract

This paper describes the status of the implementation of the upgrades for the RFX-mod2 device, the second major modification of the Reversed Field eXperiment (RFX). The machine's core update consists of a thin copper stabilizing shell placed inside the vacuum vessel to ensure long-term stability of resistive wall modes (RWM) and enable regimes with fast-rotating tearing modes. A comprehensive modernization of the facility's technological plants and diagnostics is being carried out within the NEFERTARI project (New Equipment For the Experimental Research and Technological Advancement for the RFX Infrastructure). Funded by the Italian National Recovery and Resilience Plan (NRRP) under Next Generation EU, NEFERTARI aims to strengthen the RFX infrastructure and its network of partners. Significant plant upgrades include: the refurbishment of the main vacuum system and the development of a new glow discharge cleaning (GDC) system based on eight fixed electrodes for more uniform wall conditioning; a major overhaul of the control and data acquisition system, now featuring a high-resolution multichannel acquisition system with over 1500 channels that eliminates the need for analogue integrators; the enhancement edge plasma characterization and of core diagnostics, such as the high-repetition-rate (up to 3 kHz) Thomson Scattering system and the expanded soft x-ray (SXR) tomography; the upgrade of the existing and installation of new reflectometric system; the restoration of the Diagnostic Neutral Beam Injector (DNBI) for spatially resolved ion temperature measurements. Furthermore, the paper highlights the contributions of the Italian laboratory network, including the BiGyM infrastructure for testing innovative plasma-facing components; the ROMAN remote handling facility for in-vessel maintenance development; dedicated laboratories for the development of neutron detectors and for optical diagnostics for the characterization of surfaces, and for high-voltage electrical insulation testing.

Keywords: reversed field pinch, tokamak, 3D boundary, MHD, PWI, plasma diagnostic, remote handling

(Some figures may appear in colour only in the online journal)

1. Introduction

RFX-mod2 [1] is the second upgrade of the Reversed Field eXperiment (RFX), a 2 MA reversed field pinch (RFP) device located in Padova, Italy, since the 1990 s [2], which, thanks to the extreme flexibility of the power supply system and its MHD control capabilities, can be also operated as a tokamak and in the Ultra low-q configuration.

While RFX-mod [3] provided fundamental insights into the active control of magnetohydrodynamic (MHD) stability,

the transition from RFX-mod to RFX-mod2 was primarily motivated by the need to overcome specific physics and operational limitations observed in the previous configuration. The most critical bottleneck in RFX-mod was the 'double-wall' boundary, characterized by the presence of an Inconel vacuum vessel (high-resistivity) located between the plasma and the copper stabilizing shell. This configuration introduced a significant magnetic shielding effect, which damped the penetration of fast magnetic field perturbations and introduced a phase delay in the active feedback control loop. Consequently, the system's ability to suppress resistive wall modes (RWMs) and control the dynamics of tearing modes (TMs) was intrinsically limited by the vessel's magnetic permeability and time constant [4]. This layout limited the dynamic response of the active feedback system and favoured the wall-locking of TMs [5], which in turn increased local thermal loads and limited the plasma performance at high currents [1]. To address these issues, the RFX-mod2 design features a major reconfiguration:

the vacuum vessel has been removed and the copper stabilizing shell has been brought closer to the plasma (the so-called 'thin shell' configuration), now acting as the first vacuum boundary [6]. The decrease of the plasma-shell distance, reaching a ratio of $b/a = 1.04$ (compared to 1.1 in RFX-mod) is crucial for enhancing passive stabilization and reducing error fields, which in turn facilitates the spontaneous rotation of magnetic modes even at high plasma currents (Ip $>$ 600 kA) [7].

Furthermore, the increased proximity of the plasma to the stabilizing structure and the new first-wall geometry required a complete overhaul of the diagnostic systems. Furthermore, the upgrade addresses critical operational issues identified in the previous configuration. RFX-mod2 features a new boundary immediately surrounding the plasma: new tiles with increased thermal conductivity will be held in place by the suitably stiffened stabilizing shell instead of the original vessel. The Wall Conditioning system was redesigned from a 2-electrode to an 8-electrode glow discharge cleaning (GDC) setup to solve issues of spatial non-uniformity and insulator overheating, ensuring a reproducible control of the hydrogen and deuterium inventory. As discussed in [8], the new configuration demands more robust and integrated sensors (magnetic, electrostatic, and optical) to support the exploration of multiple magnetic configurations (RFP, Tokamak, Ultra-Low q) and to manage the higher power densities expected in the upgraded device.

In particular, the new layout of magnetic sensors will allow a better reconstruction and control of the plasma boundary in the RFP and to complete studies on error fields control, TM mitigation and disruption avoidance, runaway electron decorrelation by means of the active control system and the flux pumping mechanism in the tokamak.

The launch of RFX-mod2, whose plasma operations are planned to start in the first half of 2027, thus provides a unique, flexible environment to resolve lingering physics questions, complementing the move toward larger-scale reactors.

Moreover, while the core of the NEFERTARI project is centred on the RFX-mod2 machine, the infrastructure is conceived as a distributed research ecosystem aimed at addressing broader technological challenges for fusion. This holistic approach explains the inclusion of specialized facilities that, although not exclusively dedicated to RFX-mod2 operations, provide essential cross-cutting expertise.

Specifically, the BiGyM infrastructure allows for the testing of innovative plasma-facing materials under high-particle flux conditions, complementing the power exhaust studies conducted on RFX-mod2, with an extended surface characterization capabilities thanks to improved laser-based optical diagnostics. Similarly, the development of advanced nuclear and neutron detectors is crucial for future high-performance fusion devices, benefiting from the experimental environment provided by the project's network. Finally, the High Voltage Electrical Insulation Laboratory addresses critical issues in vacuum and gas insulation. These activities are strategically linked to the reliability of high-voltage components, such as those required for neutral beam injectors (NBI), which are vital both for the current RFX-mod2 diagnostic neutral beam and for the development of future heating systems in larger-scale fusion experiments.

The experimental exploitation of the RFX-mod2 improved magnetic front-end is also supported by 3D nonlinear full MHD numerical modelling with the SpeCyl code, recently upgraded to deal with realistic boundary conditions [9]. Moreover, the additional inclusion in the SpeCyl code of a second resistive shell at finite distance from the plasma allows for simulations of RWM modes dynamics in both the tokamak and RFP configurations [10].

In the last two years, the manufacturing of the new RFX-mod2 vessel complex has significantly progressed, overcoming several technical issues, as it will be reported in section 2.1.

Additionally, a substantial innovation of key RFX-mod2 technological plants and plasma diagnostics systems is being ensured by the NEFERTARI (New Equipment For the Experimental Research and Technological Advancement for the RFX Infrastructure) project [11], aimed at strengthening RFX within the framework of the Italian National Recovery and Resilience Plan (NRRP) [12], funded by Next Generation EU [13]. The project formally started in November 2022 and will end in April 2026. Plants and related procurements are briefly described in section 2.2. The complete list of the diagnostics to be upgraded was presented in [8]: we report in section 3 (core diagnostics) and section 4 (edge diagnostics) an update on the status of the implementation.

NEFERTARI brought about the opportunity to complement RFX-mod2 with developments in several other Italian laboratories: the BiGyM infrastructure for the study and test of innovative Plasma Facing components (section 5.1); a laboratory for development, construction and test of nuclear diagnostics for fusion plasmas (section 3.2); a laboratory devoted to the development, test and calibration of optical, emission and laser-aided diagnostics related to plasma exposed material measurements (section 5.2). In section 6 a brief description is given of the advanced laboratory to experimentally characterize electrical insulation issues at very high voltages; a summary follows in section 7.

2. RFX-MOD2 reassembly status

2.1. *Vessel complex reassembly*

Compared to RFX-mod, RFX-mod2 is characterized by a modified vessel complex composed by the passive stabilizing shell (PSS) and the vacuum tight support structure (VTSS). The construction of these components has been completed and the machine is now undergoing a challenging and delicate assembly phase that constantly requires the assistance of metrology tools and the application of vacuum compatible procedures [14]. The PSS is a modified version of the RFX-mod 3-mm thick Copper torus designed to be inserted in the VTSS, which is the original RFX-mod stainless steel support structure, suitably modified to become a vacuum vessel [15]. A schematic view of the torus assembly from RFX-mod to RFX-mod2, with indicated the main boundary structures, PSS and VTSS, is shown in figure 1*(b)*.

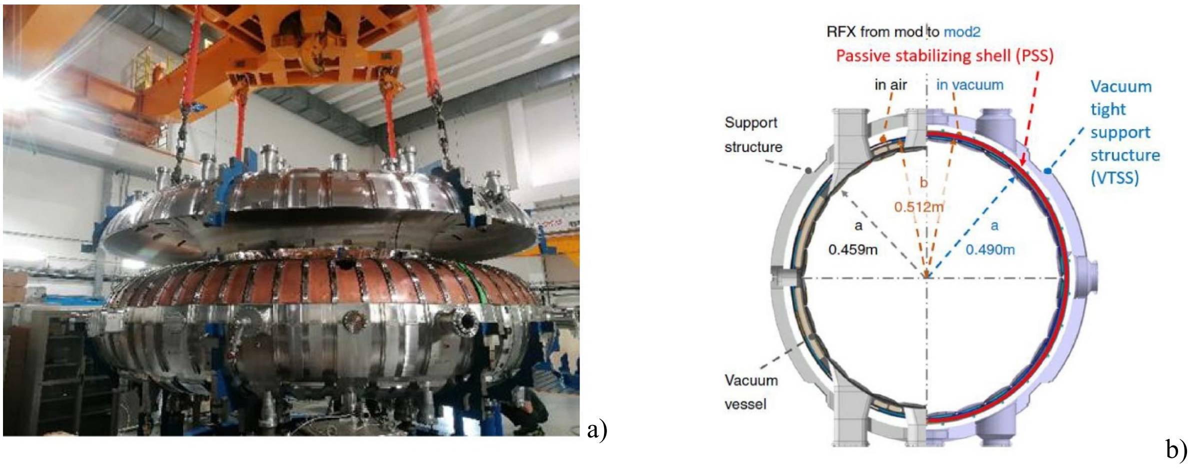


Figure 1. *(a)* closing the VTSS with the preliminary assembled PSS inside; *(b)* schematic section view of the torus assembly with magnetic front-end, vacuum confinement barrier, and first wall upgrades from RFX-mod (on the left) to RFX-mod2 (on the right).

The whole PSS surface has been finally coated with a plasma sprayed thin alumina layer ($\sim$220 μm), a ceramic insulating material, to prevent electrical discharge between gaps when high electric fields occur during plasma operations [16]. The insulation procedure required some extensive R&D to uniformly scaling up the characteristics of the alumina coating of small sample tests to the whole shell surface ($\approx$40 m^2). The final assembly, started in 2025, is on-going. It is based on the experience gained with the preliminary assembly of the non-insulated PSS -. Without installation of sensors, graphite tiles and cabling—that was successfully completed in the first half of 2024. This preliminary stage was used to develop strategies, including custom developed guide tools, with two goals: preventing damage to the ceramic insulation layer and compensating for natural deformations up to $\pm$4 mm, due to the low stiffness of the structure during assembly.

As far as the VTSS is concerned, the vacuum tightness test was completed in 2024, after correction of a leak evidenced in a welding bead, together with the electrical insulation tests of the poloidal and toroidal gaps. The achievement of the preliminary assembly of the vessel complex (shown in figure 1*(a)*) required the iterative control of a set of several hundreds of control points by means of laser tracker metrology, in order to guarantee the correct matching of the 72 supporting rings of the PSS with respect to interfaced parts of the VTSS (with required tolerance of $\pm$0.5 mm) and ultimately the proper positioning of all the plasma facing components.

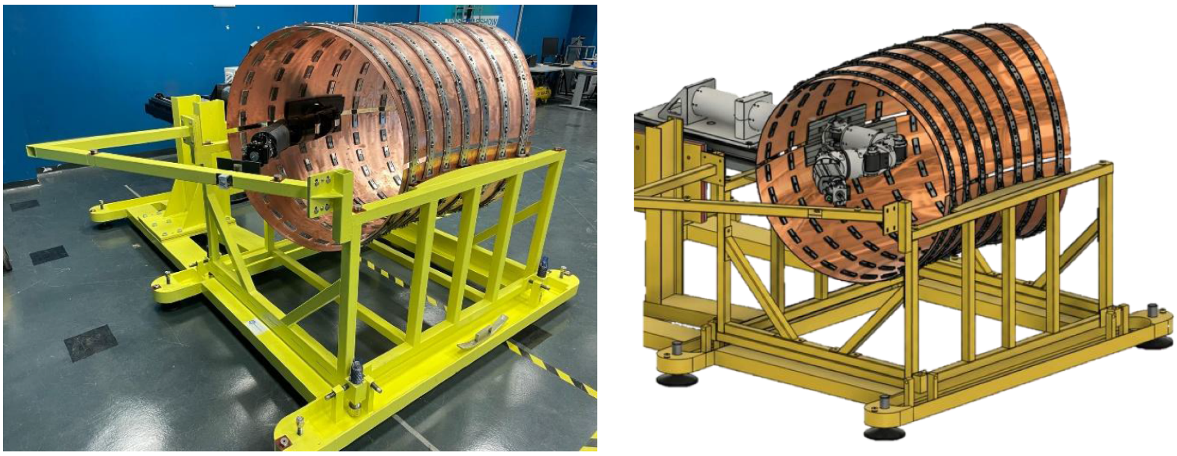
A total of approximately 1000 electric and magnetic transducers (corresponding to slightly more than 1500 signals) have been procured and calibrated on the bench [17]. Presently, they are being assembled on the PSS internal surface either embedded in the new first wall (electrostatic sensors) or located in the narrow clearance between tiles and shell (magnetic sensors).

2.2. Auxiliary plants

The main RFX ***vacuum system***, which dated back to the initial RFX construction in the '90s, has being significantly refurbished, thanks to the NEFERTARI project. Revamping of gas injection system is going to be performed next, with a separate national funding.

Due to the electrical gaps in all conducting structures of the vessel complex, high temperature baking with induced currents (routinely operated in RX-mod) will not be possible in RFX-mod2. Wall conditioning will rely instead on ***pulse discharge cleaning*** (PDC) ***and GDC***. The PDC, also named Taylor discharge cleaning, is a technique based on the repetitive generation of low current (typically in-between 20–50 kA) discharges, which can be performed both in Helium as well as Hydrogen or Deuterium (reactive PDC) for the thermal treatments of first wall components (FWC) (see for example [18] for the use of PDC in the TFTR tokamak). In RFX-mod2, it will be used to heat the graphite limiter up to 200 °C [19]. This system was commissioned but never routinely used in RFX-mod, as wall conditioning was efficiently achieved through direct inductive heating of the vessel structure. However, due to the characteristics of the new RFX-mod2 front-end, the PDC system has been restored and is planned for routine use in thermal wall treatments. The PDC system will be tested as soon as the final assembly of the vessel complex will be completed, in order to asses that proper insulation remains even after thermal expansion of the PSS.

Being RFX-mod2 first wall still composed of graphite tiles covering the entire toroidal surface, proper density control requires the GDC system to reduce the hydrogen inventory in the graphite. The RFX-mod GDC system (inherited from RFX [20]) employed two insertable electrodes composed by a radio frequency (RF) antenna with a helical design and an integrated air-cooling system. This system was found to be affected by several limitations. Firstly, a significantly uneven spatial density profile has been documented in RFX-mod [21], due to the distance between the two electrodes, compromising the hydrogen removal efficiency. Secondly, increased maintenance was necessary due to an unexpected overheating of the ceramic insulators, related to deposition of B_4C compounds occurring during GDC performed boronization. Finally, an arc discharge could occur at the base of the electrode (therefore reducing cleaning efficiency) if the entire anode support were



a) b)

Figure 2. Physical product *(a)* and virtual prototype *(b)* of Roman during the preliminary test of the maintenance operations inside the facility FaRHa-One installed in Naples.

not at floating potential. To mitigate these issues, a new GDC system, based on a set of 8 fixed air-cooled electrodes acting as FWCs has been designed [22] and manufactured. The increased number of electrodes will ensure a greater spatial uniformity: they will be utilized to perform inter-shot GDC with helium gas injection. The GDC assisted boronization will still be performed by the two mobile electrodes with a redesigned antenna.

The ***control and data acquisition system*** of RFX-mod2 has been significantly upgraded with respect to the RFX-mod one. On the one hand, it will retain the main architecture: MDSplus [23] and MARTe [24] frameworks will still be used for data acquisition and real-time control, respectively. On the other hand, the significantly increased number of real-time sensors required to design [25] a multichannel acquisition system for all magnetic and electrostatic sensors, that have been developed and procured. The system is based on novel system design based on high-resolution analogue-to digital converters (ADCs) that eliminates the need for analogue integrators [26]. The system utilizes a 1 M Samples/sec, 20-bit resolution ADC, providing a resolution comparable to that of good analogue integrators. To ensure accurate measurements, each acquisition channel is individually electrically isolated, effectively eliminating the ground loops generated by the experiment's magnetic fields, which often hamper the measurements. The digital acquisition followed by numerical integration performed directly onboard, ensures an error distribution comparable to analogue integration. The cost and the size of each channel are significantly reduced: the procurement of the overall system (more than 1500 acquisition channels) has been completed in 2025.

2.3. Remote handling facility

RFX was equipped with a state-of-the-art manipulator for maintenance of internal tiles without disassembling the whole machine. In collaboration with University of Napoli Federico II and University of Padova, RFX-mod2 will be equipped with a significantly upgraded manipulator (ROMAN), complemented with a mock-up facility for test and training (FarHa-One) [27, 28] (see figure 2). The aim is not only to ensure maintenance, but also to investigate advanced strategies for remote handling (RH) of in vessel components and a proper Virtual Reality Simulator improving the perception and awareness of the environment for the robots and the operators who must operate without the aid of exteroceptive sensors and must therefore base decisions on the system digital twin. The high accuracy digital twin, used for operator training and task simulation, replicates in real-time Roman, by including joint and link flexibility using the modelling approach proposed in [29]. The Remote Handling facility FarHa-One will enable the possibility to plan and test RH tasks and procedures and train operators offline without the need to access the real equipment. The facility will enable the integration of different robotic systems to validate multiple maintenance and inspection solutions. The facility will also support the validation of maintenance procedures on the real machine, covering the full operational workflow, from installation and calibration to inspection and tile removal inside the machine.

3. Characterizing the RFX-MOD2 core

When exploring high plasma current regimes (1 MA $<$ Ip $<$ 2 MA), RFX-mod proved the existence of transient high confinement regimes characterized by a helical topology of SXR emissivity and peaked electron temperature profiles. While RFX-mod provided a solid foundation, the investigation of these phenomena in RFX-mod2 requires a significant leap in diagnostic performance to simultaneously resolve high spatial and temporal scales. To achieve this, the core diagnostics have been upgraded focusing on three main pillars: the enhancement of electron temperature measurements through synergistic optical systems, the integration of high-speed radiation detectors for non-Maxwellian features, and the implementation of advanced neutral beam-based spectroscopy for ion and magnetic field characterization. These developments, detailed in the following sub-sections, are essential for a comprehensive understanding of the transport barriers and reconnection events that define the RFX-mod2 core physics.

3.1. Electron temperature and SXR/double filter tomograph

A major upgrade of the electron temperature (T_e) diagnostics in RFX-mod2 is currently being finalized, combining an upgrade of the existing Thomson Scattering (TS) system with an enhanced soft x-ray (SXR) tomography based on the double filter (DF) technique [30]. Together, these tools will provide improved spatial and temporal resolution for investigating the topology and dynamics of our RFP experiment, where the formation and evolution of electron transport thermal barriers strongly influence T_e gradients. For this reason, advanced T_e diagnostics are essential for understanding the physics such that will be explored by RFX-mod2.

As regarding the TS diagnostic improvement, this mainly consists in adding a new Nd:YAG laser, a Split Light Hybrid VIII by Innolas GmbH, capable of operating in burst mode at repetition rates (RR) up to 3 kHz. This laser complements the existing 100 Hz source, allowing targeted acquisition of T_e profiles synchronized with MHD activity. Indeed, the upgraded TS will rely on two coaxial Nd:YAG lasers (both at $\lambda = 1064$ nm), providing a unique combination of high spatial resolution (84 scattering volumes of $\sim$5 mm diameter across the plasma radius) and high temporal resolution (kHz bursts). Therefore, this new setup will make it possible to resolve the time evolution of key phenomena occurring during RFP discharges, providing a crucial tool for detailed studies of barrier formation, reconnection events, and QSH transitions, all accessible with sub-ms time resolution.

The delivery and the installation of this new system at the Consorzio RFX was completed. The installation included the connection of the three dedicated power supplies (Master, Slave, Hybrid) to high voltage and cooling circuits, verification of safety interlocks, and a complete inspection of the laser chain. Training sessions on operation, maintenance, and lamp replacement were also provided by Innolas GmbH technicians. Factory and acceptance tests on site confirmed compliance with specifications. Then, the laser alignment has been verified together with a coaxial red diode laser (633 nm) over a distance of at least 5 m, providing a reliable reference for further beam path adjustments towards RFX-mod2.

This novel source can operate with selectable RR either in single- or in burst-mode (0.3, 1, 2, 3 kHz). It generates bursts of up to 10 pulses (limited to 5 at 0.3 kHz), each with an overall energy of 4.11 ± 0.04 J (with a standard deviation $< 1\%$) and a pulse duration FWHM of about 20 ns for all the selectable RR, in accordance with revised specifications. For the lowest RR (namely 0.3 kHz), a burst of 5 pulses has been deemed suitable for experiments as well as for the $-13\ \mu$s jitter.

Moreover, a double-pass optical configuration, using a back-reflecting mirror instead of a dump, is also under evaluation. This aims at increasing by doubling the scattered signal without major interventions on the machine. However, preliminary tests revealed damage thresholds around 40 J cm^{-2}, highlighting the importance of hot-spot monitoring. For this reason, the TS diagnostic is equipped with an in line high-resolution beam profiler, a Beamage-4 M focus by Gentec EO, having a CMOS sensor of 4.2 MPixels. This camera can track the transverse energy distribution during operations.

The dedicated manipulator for the TS beamline has recently been assembled in all its components. Alignment procedures are ongoing, together with tests of its capability to remotely move both the final mirror and the beam dump. Once commissioning is completed, the system will be integrated into the new RFX-mod2 diagnostics-timing infrastructure. Safety procedures for remote laser operation will follow the same rules already adopted for the existing Nd:YAG source.

In parallel, the TS diagnostic has been equipped with a new acquisition system based on CAEN digitizers. It consists of four high-speed VX1742B boards (12-bit, 5 GS/s, 32 channels each) and two VX2740B boards (16-bit, 125 MS/s, 64 channels each), allowing the simultaneous readout of all photomultipliers. Characterization tests confirmed the correct operation of all channels, established reliable baseline calibration procedures, and demonstrated a linear amplitude response with a dynamic range exceeding nominal specifications. The new system ensures precise, high-rate acquisition of scattered signals, fully matching the requirements of kHz-resolved TS measurements on RFX-mod2.

The T_e profiles measured by TS will be complemented by reconstructed 2D T_e maps obtained from the expanded DF-SXR tomography diagnostic.

The upgraded SXR tomography in RFX-mod2 is based on four measurement heads designed to reconstruct the 3D emissivity distribution and 2D electron temperature (T_e) profiles using the DF technique. To enhance the spatial coverage requested for detailed tomographic inversion, the system has been expanded to a total of 194 photodiodes. The diagnostic utilizes a distributed geometry to view the plasma from multiple angles, which is essential for accurate tomographic reconstruction. Three newly redesigned heads (SXR1, SXR2, SXR3, green lines in figure 3) are installed in vertical top ports at a toroidal angle of 202.5○. These heads provide 129 LOS (43 per head) viewing the plasma from above. A fourth existing head (SXR4, blue lines in figure 3) is positioned in a horizontal port, contributing 65 additional LOS from the plasma edge. Each line of sight (LoSs) is defined by the combination of a rectangular photodiode (1.1×5.9 mm) and a corresponding pinhole. This setup creates pyramid-shaped 'cones of view' that maximize the plasma region involved in the measurement. To ensure geometric precision, all components were machined with high precision (tolerances $<$0.1 mm) and verified during Site Acceptance Tests. The 'double-filter' technique estimates T_e by calculating the ratio of signals from the same plasma volume viewed through two different Beryllium (Be) thicknesses. The filter configuration has been optimized

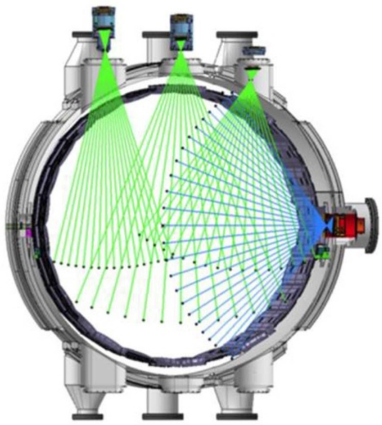


Figure 3. RFX-mod2 poloidal section with indicated the lines of sight of the new double filter SXR diagnostic system (in green). The lines of sight of the original system already present in RFX-mod are shown in blue.

as follows: Beryllium filters are used to select the SXR energy range while excluding unwanted UV and visible light; two specific thicknesses were chosen for all probes: 50 μm and 100 μm (achieved by stacking two 50 μm foils). In each head, one array uses the 50 μm filter for emissivity reconstruction, while the other arrays use the 100 μm filter. The choice to make the thicker foil exactly twice the thickness of the thin one is based on maximizing the sensitivity of the ratio $R(T_e) = SXR(Be1)/SXR(Be2)$ for the expected temperature range. To prevent filter breakage or deformation due to heat, the filters in the heads closest to the plasma (SXR1 and SXR2) are shielded inside the casing behind steel or graphite protection disks.

In addition, remote-controlled amplifiers have been implemented, allowing flexible gain adjustment and improved signal-to-noise performance.

This expanded coverage, combined with the optimized filter configurations, will enable accurate reconstructions of SXR emissivity maps with improved sensitivity to asymmetries and localized structures, providing complementary information to the point-wise TS measurements.

This will provide unprecedented insights into the T_e topology and dynamics of RFX-mod2 plasmas. While TS measurements typically ensure accurate spatial resolution along the equatorial plane, their temporal resolution is being expanded for RFX-mod2. At the same time, the distinctive high temporal resolution of the SXR tomography is being accompanied so to extend the coverage to 2D maps with higher spatial resolution. This synergy will make it possible to track the formation, sustainment, and collapse of electron transport barriers, to correlate T_e profiles with magnetic reconnection events, and, last but not least, to carry out detailed analyses of QSH transitions in high-current RFP plasmas, and the potentiality of new helical regimes suggested by 3D nonlinear MHD studies [31]. Moreover, the comprehensive dataset obtained from these complementary diagnostics will enable robust benchmarking of transport models in regimes approaching improved confinement, and the validation of a newly developed advanced tool for the detection of hidden structures in weakly chaotic regimes (Lagrangian Coherent Structures [32]).

3.2. Neutron, SXR and gamma diagnostics

Double Filter estimates of electron temperature depend on the assumption of a Maxwellian distribution of SXR emissivity [33], which may not be completely applicable to the SXR emission by particles accelerated during fast magnetic reconnection events occurring during RFP operations. Moreover, SXR signals have been observed during Runaway Electrons control experiments by Resonant Magnetic Perturbation in RFX-mod $q(a) < 2$ ohmic tokamak plasmas [34]. On the other hand, during RFX-mod2 deuterium operations neutron emission is expected. It is therefore interesting to diagnose both SXR and neutron emission, with simultaneous energy, time and spatial resolution.

To this end, both neutron diagnostics and gas electron multipliers (GEM) pixelated detectors [35], are being developed, constructed and tested in the neutron and gamma-ray detector development laboratory of CNR ISTP-MI, thanks to the upgrades funded by the NEFERTARI project. The laboratory essentially consists of two facilities, the detector assembly unit (DAU) and the test irradiation area (TIA). The DAU is essentially an integrated facility for the design and fabrication of non-sensitive detector components, such as frames, covers, supports, as well as other parts required to mount the detectors onto the RFX-mod2 structure.

The TIA is a laboratory equipped for the use of x-ray sources up to 100 kV and its main goal is to test large-dimension detectors. It was developed from the former *Laboratorio Cuspide* at the ISTP Laboratory in Milan and is, in essence, a shielded room (approx. dimensions 3 m $\times$ 5 m) lined with 3 mm of lead on each side and 6 mm on the front. The TIA will be equipped with a primary x-ray source—specifically, a 100 kV, 200 uA Hamamatsu L10101 unit—along with two auxiliary 40 kV sources. Because of safety procedures, these sources can only be operated one at a time; however, this configuration nevertheless provides a high degree of flexibility. The sources will be mounted on a pneumatic optical table and positioned on 90 cm long *XYZ* stages, enabling 2D characterization of the detectors (especially important for 2D resolved detectors like GEMs).

The development of the GEM diagnostic for SXR measurements on the RFX-mod2 experiment has advanced significantly with respect to its state described in [8]. Under the current design (a schematic of the installation configuration in RFX-mod2 is shown in figure 4), the GEM diagnostic system should be able to provide simultaneous spatial, temporal, and energy-resolved measurements of the RFX-mod2 plasma emissivity. While the full details of the diagnostic development can be found in [36], below we summarize the main results achieved so far.

The current diagnostic setup comprises two GEM detectors placed in the upper part of a poloidal sector of the RFX-mod2 device, with two vertical lines of sight, allowing to cover more than half of the plasma poloidal section. Each detector is built using a triple-GEM foil configuration [37]. This arrangement

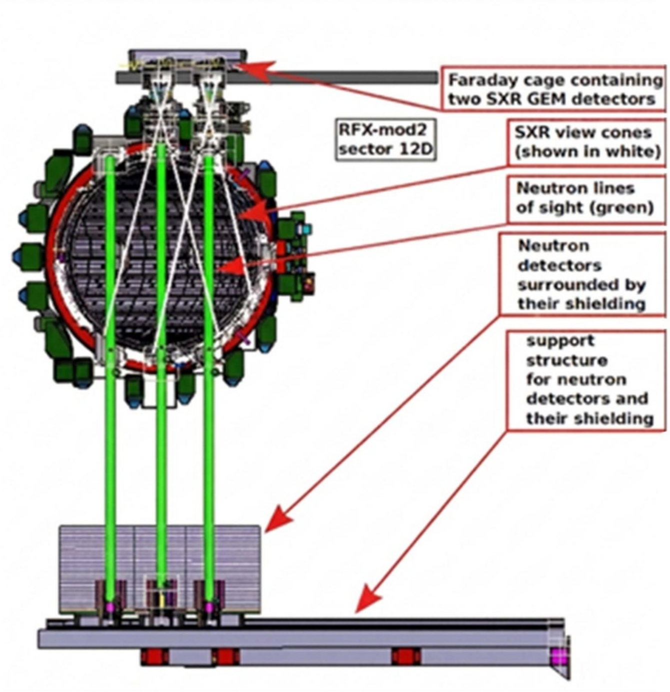


Figure 4. CAD model of the RFX-mod2 poloidal section housing the GEM (installed on the top of the machine, with view cones indicated with white lines) and the Neutron diagnostics (lines of sights indicated with green vertical lines).

achieves photon-counting operation with a temporal resolution of ∼10 μs, an energy resolution of ∼30% at 8 keV, a count-rate capability of ∼1 MHz mm^{-2}, and has already been tested under thermonuclear plasma emissivity at the MAST-Upgrade experiment [38].

Two motorized pinholes and helium buffers have been included in the diagnostic design for RFX-mod2. Each motorized pinhole is capable of precise aperture adjustments (resolution of 2.6 μm), while the Helium buffers allow to control the x-ray attenuation (Helium attenuates x-rays significantly less than air in the energy range of interest for this application). These features should make the diagnostic flexible, allowing it to work in presence of different plasma scenarios (difference of a few orders of magnitude in x-ray fluxes at the detector). Studies based on synthetic data obtained using the dedicated software tool REVOLT-Upgrade [39] have demonstrated the diagnostic's capability to reconstruct plasma emissivity profiles. Tests indicate robust performance even under complex emissivity shapes, such as those measured in past experiments at RFX-mod during Quasi Single Helicity phases. Radial average residuals between the reconstructed and true emissivity profiles were found to be around 2% and 4% at simulated noise levels of 10% and 40%, respectively. Moreover, an algorithm for energy-resolved tomographic reconstruction was developed and allowed the discrimination between the thermal and suprathermal emissivity components of the simulated plasma.

This particular feature could offer crucial insights into plasma dynamics during magnetic reconnection events at RFX-mod2. Future work involves the calibration and commissioning of the diagnostic system on RFX-mod2, along with experimental benchmarking to validate the simulations and data analysis algorithms.

Concerning the neutron diagnostic, in the same cross section of the GEM detectors, a system of EJ-276D scintillators is being procured to be installed to monitor neutron counts, complemented with LaCl3 detectors to measure the neutron energy spectrum when the count rate is sufficiently high (e.g. possibly during magnetic reconnection events). Several centimetres of polyethylene and stacked lead rings will be employed to block scattered neutrons, to reduce the gamma rays background and to define the lines of sight (green lines in figure 4). This should be useful to study the ion and electron acceleration processes with spatial, temporal and energy resolved SXR and neutron measurements.

3.3. Ion temperature and internal magnetic field

Spatially resolved ion temperature measurements will be available in RFX-mod2, thanks to Charge eXchange Recombination Spectroscopy (CXRS). This well-established diagnostic technique derives ion temperature from the Doppler-broadened emission lines of impurities in the plasma. This is made possible by injecting a neutral beam in the plasma: the fully ionized impurity atoms can emit because they receive an electron from beam atoms through charge exchange processes [40, 41]. In RFX-mod, a ***Diagnostic NBI (DNBI)*** was installed to provide a beam of hydrogen atoms at 50 keV, for an equivalent current of 2 A. The beam duration could reach 50 ms, with the possibility to modulate the beam current at max. 250 Hz to separate the beam-induced emissions from the passive ones [42]. Whereas simulations proved the CXRS technique to be feasible in RFX-mod [43], several technical difficulties however prevented to get stable and reliable measurements. In particular, the gas flowing from the torus back to the DNBI caused beam reionization and consequent beam losses, leading to too weak CXRS emissions at the plasma core. Thanks to NEFERTARI project, the beam duct and its pumping system have been redesigned to minimize beam losses [44]. The cryopump system of the DNBI is being replaced with closed-cycle pumps, to avoid He expensive consumption. Moreover, the High Voltage Deck (together with the associated insulation transformer and CAMAC control system), hosting the ion-source-related devices at 50 kV potential, is being upgraded for better safety and reliability; the insulation transformer serving the High Voltage Deck will be replaced and simplified. The whole CAMAC control system is going to be replaced with state-of-the-art instrumentation [45].

On the detection side, CXRS will make use of a Czerny-Turner spectrograph of 750 mm focal length (F/# 9.7) and 1200 gr mm^{-1} diffraction grating, coupled to a new electron multiplying CCD of 512 × 512 pixel (16 μm pixel size) for improved sensitivity. For further sensitivity, a new ISOPLANE SCT-320 spectrograph (focal length 320 mm, 1800 and 2400 gr mm^{-1} gratings) with F/# down to 4.6 will be available. The instrumentation will also be used to observe the H_α emission of the beam in the plasma core, to measure the magnetic field intensity and magnetic field direction thanks to the Motional Stark Effect. Considering that the magnetic field will be typically less than 2 T, the Stark splitting will be relatively low [43]. The standard techniques, as for example the one adopted for JET plasmas [46], involving interference filters and photoelastic modulators, is thus expected to be unfeasible. Instead, the diagnostic technique for RFX-mod2 will involve the measurement of emission spectra in four polarization planes for each LoS, as similarly successfully done in the W7-X stellarator [47].

The ion temperature measurement from the DNBI will be complemented by the passive reconstruction of the distribution function of the neutrals produced by charge-exchange processes exiting the plasma and detected by the ***upgraded Neutral particle Analyzer (NPA).*** With respect to the existing one, this will be equipped with a larger number of detectors (from 11 to 15 channeltrons for each atomic species, *H* and *D*) for a wider energy scan and a faster (500 MHz) signal digitalization and acquisition system.

4. Characterizing the RFX-MOD2 edge

The transition from the core to the plasma edge in RFX-mod2 involves dealing with complex 3D plasma-wall interactions and steep gradient regions that govern the overall particle and energy exhaust. Characterizing this boundary layer requires a multi-faceted approach, combining high-coverage stationary sensors with mobile systems capable of deep radial plunges. This section describes the suite of edge diagnostics—ranging from distributed electrostatic probes and fast reciprocating manipulators to advanced reflectometry and impurity tomography—designed to resolve the turbulent structures and asymmetries that emerge in both RFP and tokamak configurations.

4.1. Distributed electrostatic sensors

In order to characterize the 3D properties of plasma-wall interaction in the variety of accessible magnetic configurations (included the shaped tokamak [48]), RFX-mod2 is equipped with a complex system of electrostatic probes, measuring plasma density and temperature, plasma potential, particle and energy fluxes and floating potential fluctuations on the first wall. The probes, distributed over two toroidal arrays of 71 probes each on the high and low field sides, along with four poloidal arrays (made of 28, 36 and 2 × 17 elements) are presently under installation on dedicated graphite tiles.

The acquisition system for the electrostatic sensors has been specifically designed and procured, along with the whole set of power-supplies equipped with arc-protection systems to avoid probes overheating.

4.2. Fast reciprocating manipulator for edge plasma

A ***fast-reciprocating manipulator (FaRM)*** for insertable probes (with insertion and extraction times of 50 ms) has been realized and is ready for the installation on RFX-mod2 from the bottom side of the machine [49] (a schematic of the overall and main components: fast and slow movement systems, and head support, along with a picture of the system during testing phase are presented in figures 5*(a)* and *(b)*, respectively).

The main purpose of the system is to host insertable probes in all the accessible plasma regimes, here included the *X*-point region of tokamak plasmas and the flat-top phase of the 2 MA RFP discharges, characterized by an ohmic input power up to 60 MW. In addition to standard probes the manipulator will host a novel diagnostic, named DIVO (diagnostic for ion velocity observation) [50] for the determination of the ion distribution function, by resolving both the parallel and the perpendicular (with respect to the local magnetic field) velocity components, thanks to a combination of an applied discriminating *E* and the local *B* fields. The aim is to investigate the relationship among turbulence, magnetic reconnection phenomena and ion acceleration/heating processes, mainly in the RFP plasmas.

4.3. High frequency phenomena characterization

A multi-channel very high frequency (up to 3 GHz) acquisition system has been procured for the signals from the ***single-loop antennas*** devoted to the detection of electromagnetic plasma emission to be installed at the edge of the plasma along three poloidal positions and devoted to the analysis of fast and transient phenomena (such as run-away electron induced whistler waves and ion cyclotron emission harmonics for the

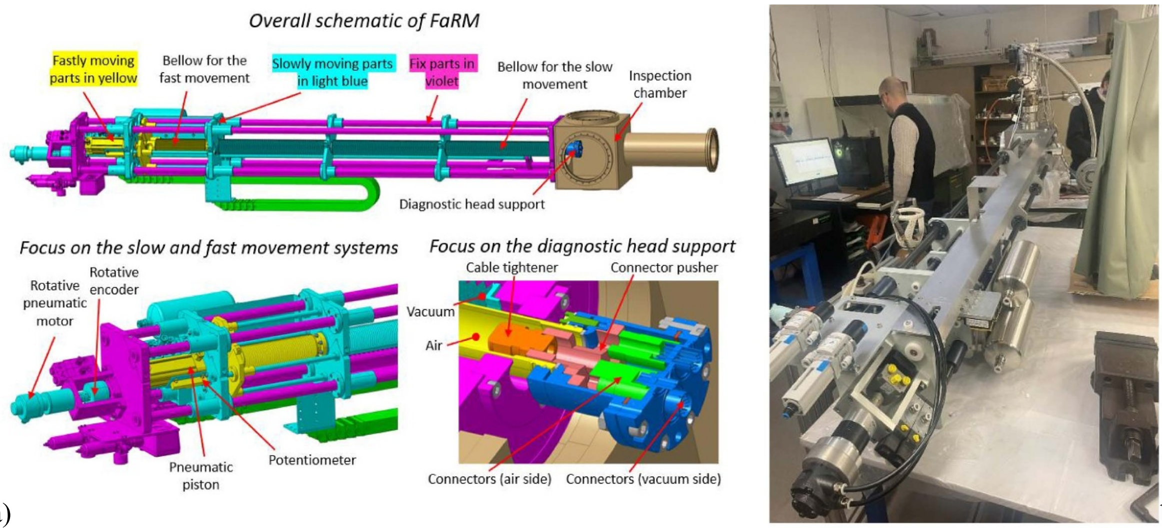


Figure 5. *(a)* Schematic of the Fast reciprocating Manipulator (FaRM), overall and main components: fast and slow movement systems, and head support; *(b)* picture of FaRM during mechanical testing and validation phase.

investigation of ion acceleration processes). The system has already been successfully tested in a small-scale plasma device for the characterization of beam-plasma induced Langmuir waves [51].

4.4. Reflectometric diagnostics

A ***new reflectometric diagnostic*** for real-time determination of tokamak plasma position is presently under development with the aim of testing the technique also proposed for DEMO [52]. This includes four ultrafast K band units (18–26 GHz) coupled to two antennas on the equatorial plane (from inner High Field Side and outer Low Field Side respectively) and two at the vertical top/bottom ports at the same toroidal position. The diagnostic complements the ***existing reflectometer*** devoted to the analysis of the RFP edge plasma density profile, which is under upgrades for a high time resolved (5 μs) measurements, with a new full Ka band (26–40 GHz) microwave source driven by an innovated control circuit will replace. The acquisition systems have been procured, while part of the antennas, of the waveguides and the microwave units are under realization.

4.5. Light impurity tomography (LIT)

RFX and RFX-mod RFP plasma wall interaction (PWI) did show marked poloidal and toroidal asymmetries, mainly due to the LCMS deformation generated by phase locked TM. In RFX-mod2, given the expected change of TMs (reduction in amplitude and fast rotation regimes) significant changes of PWI is likely to occur. A series of diagnostics in RFX-mod2 is dedicated to characterize such an interaction. Among these, the ***LIT*** is a spectroscopic diagnostic designed for the characterization of the 2D structure of the emissivity of the edge plasma on a poloidal section, which will make possible to study how the 3D magnetic field modifies the plasma edge, and the coupling between the $m = 0{,}1$ magnetic modes and the plasma itself.

The diagnostic consists of 7 cameras, installed in 7 different portholes around the poloidal direction at a fixed toroidal angle, with changeable interferential filters (H_α at 656 nm, He I at 668 nm, and C III at 465 nm).

The 7 cameras observe line-integrated signals, and the 2D map of the emissivity of the specific ion species selected by the interferential filter is obtained with a tomographic inversion. The global layout and the optical setup of a single camera are shown in figure 6. Each camera has a series of 3 objectives: a first lens with $f = 24$ mm collects the light from the plasma; a $f = 85$ mm lens collimates the light beam, ensuring it impinges perpendicularly on the filter; a third $f = 85$ mm lens focuses the image on the camera. For having more fans and increasing the spatial resolution, one or two mirrors can be installed in vacuum in front of the first objective. The resulting LoSs are outlined in the left panel of figure 6.

In order to characterize the spatial resolution of the diagnostic, different simulations of the plasma edge emission of ions $\varepsilon_{\text{simu}}$ have been performed, resulting from a superposition of $m = 0{,}1{,}2$ modes. The tomographic algorithm developed is based on the pixels method [53]: the poloidal region is divided into 50 pixels, with a radial dimension Δr, and constant emissivity. The emissivity of each pixels ${\varepsilon_i}^k$ at iteration k is obtained by using the maximum likelihood expectation maximization (ML-EM) iterative algorithm [54], according the formula:

$$\epsilon_i^{k+1} = \frac{\epsilon_i^k}{\sum_{j=1}^{nlos} a_{i,j}} \cdot \sum_{j=1}^{nlos} \frac{I_j}{\sum_{i=1}^{npix} \epsilon_i^k a_{i,j}} a_{i,j}$$

where a_{ij} is the length of the LoS j inside the pixel i, I_j is the integrated signal of the LoS j, $nlos$ is the number of LoSs and $npix$ the number of pixels. Figure 7 shows the result of the tomographic inversion for a simulation: the simulated emissivity on the left side, and its tomographic reconstruction on

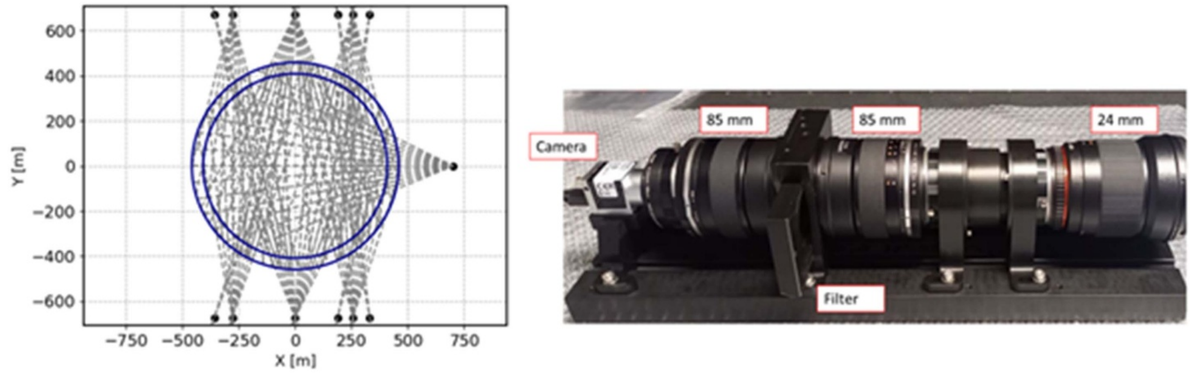


Figure 6. Poloidal section of RFX-mod2 with the layout of the 7 cameras and lines of sight (left), and the optical setup of the single camera.

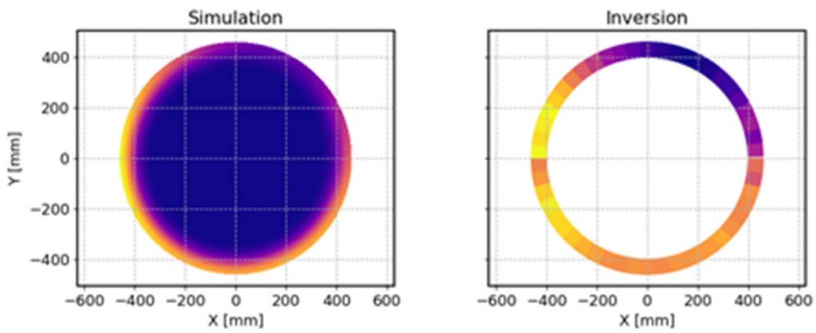


Figure 7. Simulated LIT emissivity (left) and its tomographic reconstruction (right).

the right. The reconstruction well reproduces the simulation, with a minimum emissivity at about $\theta = 45^\circ$, and a large maximum at about $\theta = 180^\circ$. The poloidal resolution of 50 pixels (7.2°) is a compromise between a good angular resolution and a good tomographic inversion, and it is sufficient to detect the poloidal variation of the edge plasma emissivity, in presence of $m = 0$, 1, 2 magnetic modes.

4.6. Edge turbulence simulations

The experimental analysis will be complemented by the first ***global boundary turbulence simulations*** of RFX-mod2 plasmas in both tokamak and RFP configurations. In particular, the GBS code [55] is being used to simulate plasma turbulence in a tokamak discharge in the presence of edge voltage biasing [48, 56], with particular focus on turbulence suppression from the induced $E \times B$ flow shear and the subsequent steepening of the edge pressure profile [57]. GBS will also be extended thanks to the NEFERTARI project to allow for global boundary turbulence simulations of a RFP plasma, which will be the first-of-their kind.

5. Plasma wall/materials interaction studies

In the RFX-mod2 plasmas, ohmic power levels up to 60 MW can be coupled to the plasma when operated as a high current (up to 2 MA) RFP, which makes the device an interesting environment for the investigation of, possibly localized, high power load effects on plasma facing components.

5.1. The BiGyM experiment

The laboratory hosting the linear plasma device GyM [58] of ISTP-Milan is one of the research facilities supporting the RFX-mod2 infrastructure within the framework of the NEFERTARI project. In this context, GyM is being upgraded to BiGyM, with the objective of extending its operational parameters toward conditions relevant for plasma–material interaction (PMI) studies in tokamak divertor environments. The main upgrade activities include:

- Installation of two 10 kW RF sources at 13.56 MHz, enabling the generation of helicon plasmas. This configuration is expected to enhance the plasma density (10^{18}–10^{19} m^{-3}) and particle flux (10^{22}–10^{23} m^{-2} s^{-1}), supporting PMI studies under divertor-relevant conditions.
- Integration of a new sample exposure system, capable of reproducing the operating conditions of ITER divertor components, in terms of temperature (up to 1500 K) and incident particle energy (300 eV).
- Implementation of a picosecond laser-induced breakdown spectroscopy (ps-LIBS), designed for surface compositional analysis of plasma-exposed materials and hydrogen isotope retention studies. This system complements nanosecond (ns-) and femtosecond (fs-) LIBS diagnostics of ISTP-Bari (see the details below).

A schematic representation of the BiGyM experiment and set-up is presented in figure 8.

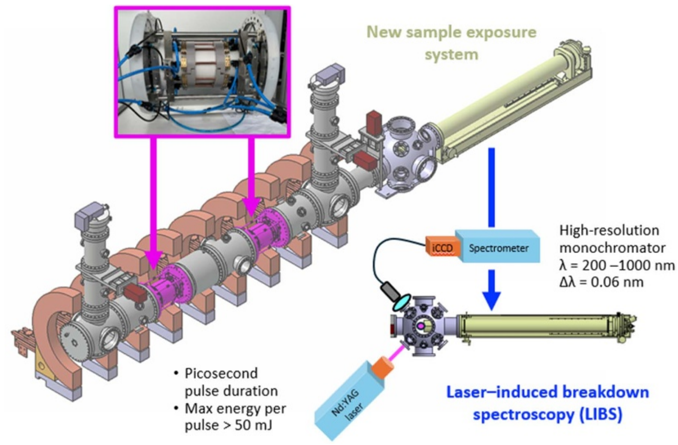


Figure 8. Schematic representation of the BiGyM experiment and set-up, including a picture of one of the 10 kW RF sources and the layout of the sample exposure system and of the LIBS diagnostics.

In parallel with the hardware upgrade, numerical modelling activities are being conducted to predict the behaviour of BiGyM plasmas and support future experimental interpretation. Current modelling efforts include: (i) modelling of helicon wave propagation with COMSOL Multiphysics, (ii) prediction of plasma density, temperature, and particle flux profiles via the tokamak edge SOLPS-ITER package, (iii) investigation of sputtering and material migration using the ERO2.0 code, and (iv) modelling of laser–material interaction processes, in support of the LIBS diagnostic system, also conducted with COMSOL-based frameworks.

The BiGyM upgrade will enhance the experimental capabilities of the ISTP research infrastructure in the field of magnetic confinement fusion, serving as a versatile platform for diagnostic development and validation, and contribute to training activities in preparation for future large-scale devices such as DTT. In particular, while, as mentioned, BiGyM is motivated by the need to test Plasma-Facing Components (PFCs) for tokamak environments, its role within the NEFERTARI project is intrinsically linked to RFX-mod2. The high Ohmic power discharges in RFX-mod2 (reaching up to 60 MW) generate power fluxes that are among the highest in the fusion community. BiGyM provides a dedicated environment to make preliminary erosion test under controlled high-particle flux conditions on innovative materials and components to be exposed in future experiments to RFX-mod2 plasma—whether during RFP or tokamak operations. Furthermore, the upgraded facility is expected to foster cross-sectoral applications in advanced technology domains including aerospace, solar thermal energy, and plasma-assisted catalysis.

5.2. Optical diagnostics laboratory

The optical diagnostics of election for surface analysis is LIBS. It involves two processes: laser ablation, to vaporize the material, and optical emission spectroscopy to inspect the composition of the vapour, which expands in the form of a hot plasma, assumed to reflect the chemical composition of the material. To preserve the possibility of depth profiling of the fuel retention on the wall surfaces, the ablation process must be sufficiently 'gentle' and geometrically well defined as to drill regular craters in the material avoiding its melting. Femtosecond laser pulse duration is the best choice to this end [59]. Using relatively small pulse energies is also mandatory to avoid vaporize the retained fuel in few laser shots, preventing an accurate depth profiling. On the other hand, the Balmer lines of H, D and T have a large Stark broadening. Therefore, spectral isolation of these lines requires measuring the emission spectra in conditions of small plasma density. All these requirements have a heavy influence on the magnitude of the spectroscopic signal. We are studying strategies to maximize the signal in conditions of minimal laser energy and plasma density, with the aid of a laser with variable pulse duration from 400 fs to 10 ps and maximum pulse energy of 4 mJ (Light Conversion Pharos). Beyond the choice of the optimum pulse duration and delay of the measurement after the laser shot, we are studying further methods to enhance the LIBS signal, like glow-discharge assisted LIBS [60] and TALIF assisted LIBS. The latter consists in applying Two-Photon Absorption Laser Induced Fluorescence to measure the D atoms in the ablation plume.

The other face of Plasma-Wall interaction is the plasma itself, that needs thorough characterization. To this end, the NEFERTARI laboratory for research and development of plasma optical diagnostics is also equipped with tuneable lasers for the laser spectroscopy of the gas phase.

6. High voltage electrical insulation laboratory

Within the framework of the NEFERTARI project, and in collaboration with the University of Padova, the High Voltage Padova Test Facility (HVPTF) [61] has been upgraded and extended through the implementation of a new experimental setup. The HVPTF was originally established in 2010 as a dedicated facility for investigating high-voltage holding in high-vacuum conditions, with particular reference to the testing of

Figure 9. Picture of the external (left) and internal (right) view of the new experimental device for HVDC-GIS testing.

components and configurations relevant to the development of NBIs for ITER.

The original facility is based on a cylindrical stainless-steel vacuum vessel with an inner diameter of 1.2 m and a length of 2.4 m, allowing the testing of a wide range of electrode configurations under vacuum conditions in the pressure range 10^{-4}–10^{-1} Pa. The system is equipped with two electrodes, whose separation can be continuously adjusted between 5 and 250 mm. Each electrode is powered by a Cockcroft–Walton DC power supply rated at $\pm$400 kV, enabling the application of a maximum voltage difference of up to 800 kV between the two. Several components of the facility have been refurbished and upgraded using NEFERTARI funding.

In addition to the refurbishment of the original setup, a new experimental device (see figure 9) has been designed and installed to extend the laboratory capabilities toward the investigation of gas-insulated systems (GIS) under DC high-voltage stress, up to a maximum voltage of 500 kV. This facility is specifically intended to support research activities related to the development and optimization of next-generation, high-efficiency negative-ion-based NBIs (NNBIs), such as the one for the DTT project [62, 63].

The new experimental setup is equipped with dedicated diagnostic systems enabling, among others, the implementation of measurement techniques for the investigation of electric charge accumulation on insulating surfaces. The study of surface charge deposition represents a key issue in the characterization of high-voltage insulation behaviour in pressurized gas environments. Furthermore, the design of the pressurized chamber allows operation under vacuum conditions, thereby enabling the extension of surface charge studies to vacuum insulation regimes, although not at ultra-high-vacuum levels.

Overall, these upgrades significantly extend the laboratory capabilities, enabling a broad spectrum of high-voltage DC experimental investigations relevant to the development of NNBIs.

7. Summary

The RFX-mod2 upgrade represents a major step forward in the evolution of the RFX, providing a substantially renewed experimental platform for the investigation of magnetically confined plasmas in both RFP and tokamak configurations. The introduction of a thin copper PSS inside the vacuum vessel, coupled with a fully integrated active control system, is expected to significantly improve MHD stability, mitigate resistive wall and TMs, and enable access to regimes characterized by faster mode rotation and reduced error fields. Together with the redesigned first wall and the reduced plasma–wall distance, these features open new perspectives for improved equilibrium control, confinement studies and plasma–wall interaction research. The upcoming start of RFX-mod2 operations offers a vital, agile platform, providing a complementary approach and a crucial counterpart to larger machines to untangling core physics uncertainties, ensuring a robust knowledge base before transitioning to the DEMO project.

The NEFERTARI project has played a central role in this transformation by enabling a comprehensive modernization of the RFX-mod2 technological plants, diagnostics and supporting infrastructures. Funded within the framework of the Italian NRRP, NEFERTARI has fostered a coordinated network of Italian laboratories, effectively extending RFX-mod2 into a distributed research network of infrastructures. This approach has allowed the parallel development of advanced diagnostic systems, auxiliary facilities and modelling capabilities, significantly enhancing the overall scientific reach of the experiment.

A broad suite of upgraded core diagnostics will provide unprecedented access to the spatial and temporal dynamics of RFX-mod2 plasmas. In particular, the combination of high-resolution, high-repetition-rate TS with extended double-filter SXR tomography will enable detailed investigations of electron temperature topology, transport barriers and magnetic reconnection phenomena with sub-millisecond resolution. Complementary measurements of ion temperature and internal magnetic fields will be achieved through a refurbished diagnostic neutral beam and charge-exchange recombination spectroscopy, while advanced neutron, gamma-ray and energy-resolved SXR diagnostics based on GEM detectors will allow the study of fast particles and suprathermal populations during reconnection events.

At the plasma edge, an extensive system of electrostatic probes, fast insertable diagnostics and high-frequency electromagnetic sensors will support detailed characterization of turbulence, transport and plasma–wall interaction across a wide range of magnetic configurations. These experimental activities will be tightly integrated with first-principles global boundary turbulence simulations, extending for the first time to RFP plasmas, and with magnetic field-line and particle-orbit modelling during reconnection phases.

Beyond the tokamak and RFP experiment itself, NEFERTARI has enabled the development of dedicated laboratories for plasma-facing component testing, optical and nuclear diagnostics, and RH technologies. Facilities such as the upgraded BiGyM linear plasma device and advanced LIBS laboratories provide essential support for PMI studies under divertor-relevant conditions and contribute to diagnostic validation and operator training in view of future fusion devices.

Overall, the RFX-mod2 and NEFERTARI program establishes a highly flexible and integrated experimental environment, capable of addressing key physics issues in magnetic confinement fusion, from stability and transport to plasma–wall interaction and diagnostic innovation. The upgraded infrastructure is expected to play a significant role in supporting the Italian and European fusion roadmap, while offering a versatile testbed for concepts and technologies relevant to next-generation devices such as DTT and DEMO.

Acknowledgment

This work has been carried out within the framework of Italian National Recovery and Resilience Plan (NRRP), funded by the European Union—NextGenerationEU (Mission 4, Component 2, Investment 3.1—Area ESFRI Energy—Call for tender No. 3264 of 28-12-2021 of Italian University and Research Ministry (MUR), Project ID IR0000007, MUR Concession Decree No. 243 of 04/08/2022, CUP B53C22003070006, 'NEFERTARI—.

New Equipment for Fusion Experimental Research and Technological Advancements with Rfx Infrastructure'). Views and opinions expressed are however those of the author(s) only and do not. necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

The authors would like to acknowledge C. Allocchio, E. Ballarano, V. Barassi, A. Barbugian, A. Barzon, L. Baseggio, M. Basso, M. Battistella, A. Bazzan, M. Bernardi, A. Berti, A. Berto, M. Bevilacqua, N. Biasutti, M. Bonora F. Bordin, S. Boscolo, L. Bozza, C. Caloi, M. Caon, R. Capobianco, N. Ceccato, P. Cinetto, A. De Lorenzi, R. Di Grazia, D. Fasolo, M. Fiorenzato, D. Friso, G. Gittini, R. Ghirardelli, M. T. Giordano, E. Girotto, A. Grava, A. Guercio, P. Gusella, P. Izzinoso, F. Lanza, G. Lazzaro, D. Longo, L. Lotto, G Manduchi, M. Maniero, M. Minicuci, A. Molisso, M. Morandin, M. Moressa, G. Moro, S. Munari, A. Nardone, G. Palazzo, G. Passalacqua, M. Patanè, K. Peloso, C. Procacci, D. Ravarotto, M. Realini, F. Ripamonti, L. Romanato, S. Santarsiero, M. Santi, E. Sanvito, P. Simionato, E. Sole, R. Spolaore, M. Tollin, M. Vanzetto, E. Vassallo, M. Vignando, V. Yanovskiy, L. Zanaga, L. Zanotto, P. Zava, D. Zella, E. Zerbetto, S. Zucchetti, E. Zuin for their invaluable support.

ORCID iDs

L. Marrelli 0000-0001-5370-080X
M. Barbisan 0000-0002-4065-3861
L. Carraro 0000-0001-9400-0092
G. Dilecce 0000-0001-5808-1868
M. Spolaore 0000-0002-2350-2033
A. Uccello 0000-0003-3044-1715
M. Zuin 0000-0002-0282-2978
D. Abate 0000-0002-0331-3454
D. Aceto 0000-0002-5748-8962
P. Agostinetti 0000-0003-2103-7630
M. Agostini 0000-0002-3823-1002
F. Auriemma 0000-0002-1043-1563
A. Belpane 0009-0009-9054-1364
W. Bin 0000-0002-2050-4885
T. Bolzonella 0000-0003-1128-964X
D. Bonfiglio 0000-0003-2638-317X
M. Bonotto 0000-0001-9147-7506
S. Cappello 0000-0002-2022-1113
F. Caruggi 0000-0002-5480-1327
R. Cavazzana 0000-0002-1651-1070
A. Celora 0009-0006-0160-2195
L. Cordaro 0000-0002-8068-5307
A. Cremona 0000-0001-8207-8597
G. Croci 0000-0001-9720-7232
A. Dal Molin 0000-0003-0471-1718
G. De Masi 0000-0002-5283-5478
G. De Tommasi 0000-0002-8509-7176
G. Emma 0009-0002-7252-8210
P. Franz 0000-0002-4369-2348
G. Gervasini 0000-0002-6732-7337
M. Giacomin 0000-0003-2821-2008
L. Giudicotti 0000-0002-2115-7491
M. Gobbin 0000-0001-5261-3683
F. Guiotto 0000-0001-6014-918X
A. Hussain 0009-0002-8763-928X
A. Kryzhanovskyy 0000-0002-4343-0807
M. La Matina 0009-0002-2629-5698
E. Lazzaro 0000-0002-3291-8890
R. Lorenzini 0000-0001-8353-4857
F. Lucchini 0000-0002-6791-9340
G. Marchiori 0000-0001-9369-5486

References

[1] Peruzzo S. *et al* 2023 *Fusion Eng. Des.* **194** 113890
[2] Rostagni G. 1995 *Fusion Eng. Des.* **25** 301–13
[3] Sonato P. *et al* 2003 Fusion Eng *Design* **66–68** 161–8
[4] Zanca P., Marchiori G., Marrelli L. and Piron L. 2012 *Plasma Phys. Control. Fusion* **54** 124018
[5] Marrelli L. *et al* 2007 *Plasma Phys. Control. Fusion* **49** B359–69
[6] Terranova D. *et al* 2024 *Nucl. Fusion* **64** 076003
[7] Marrelli L. *et al* 2019 10.1088/1741-4326/ab1c6a *Nucl. Fusion* **59** 076027
[8] Carraro L. *et al* 2024 *Nucl. Fusion* **64** 076032
[9] Spinicci L., Bonfiglio D., Cappello S. and Veranda M. 2024 *J. Plasma Phys.* **90** 995900601
[10] Galeazzi F. *MSc Thesis* (available at: www.politesi.polimi.it/handle/10589/243356)
[11] (available at: www.istp.cnr.it/nefertari/)
[12] (available at: www.italiadomani.gov.it/content/sogei-ng/it/en/home.html)
[13] (available at: https://next-generation-eu.europa.eu/index_en)
[14] Aprile D. *et al* 2026 *Fusion Eng. Design* **227** 115734
[15] Peruzzo S. *et al* 2019 *Fusion Eng. Des.* **146** 692–6
[16] Cordaro L., Zuin M., Peruzzo L., Abate D., Cavazzana R., Laterza B., Lotto L. and Peruzzo S. 2024 *Fusion Eng. Des.* **207** 114638
[17] Abate D. and Cavazzana R. 2022 *Sensors* **22** 9767
[18] Mueller D. *et al* 1991 *J.Vac. Sci. Technol. A* **9** 2713–5
[19] Palma M.D., Cavazzana R., Erculiani A., Gambetta G. and Peruzzo S. 2020 *J. Therm. Anal. Calorim.* **142** 2061–75
[20] Gnesotto F., Sonato P., Baker W.R., Doria A., Elio F., Fauri M., Fiorentin P., Marchiori G. and Zollino G. 1995 *Fusion Eng. Des.* **25** 335–72
[21] Canton A., Dal Bello S., Agostini M., Carraro L., Cavazzana R., Fiameni S., Grando L., Rais B., Spolaore M. and Zuin M. 2013 *J. Nucl. Mater.* **438** S1164–S1167
[22] Fadone M., Cavazzana R., Ciufo S., Grando L., Peruzzo S., Rizzolo A. and Zuin M. 2025 *Fusion Eng. Des.* **219** 115228
[23] Fredian T., Stillerman J. and Manduchi G. 2008 *Fusion Eng. Des.* **83** 317–20
[24] Neto A.C. *et al* 2010 *IEEE Trans. On Nucl. Sci.* **57** 479–86
[25] Manduchi G. *et al* 2021 *Fusion Eng. Des.* **167** 112329
[26] Cavazzana R. *et al* 2025 Implementation of a high resolution two-thousand signal acquisition and preprocessing system *IEEE Symp. on Fusion Engineering* (*23–26 June*) (available at: www.mit.edu/~wallaceg/SOFE_abstracts_final.pdf)
[27] Fontanelli G.A., Sofia A., Fusco S., Grazioso S. and Di Gironimo G. 2024 *Fusion Eng. Des.* **206** 114586
[28] Fusco S., Sofia A., Fontanelli G.A., Grazioso S. and Di Gironimo G. 2025 *Lecture Notes in Mechanical Engineering* (Springer) (https://doi.org/10.1007/978-3-031-76597-1_17)
[29] Grazioso S., Di Gironimo G. and B. Siciliano 2019 *Soft Robot.* **6** 2169–5172
[30] Franz P., Gobbin M., Marrelli L., Ruzzon A., Bonomo F., Fassina A., Martines E. and Spizzo G. 2013 *Nucl. Fusion* **53** 053011
[31] Veranda M. *et al* 2017 *Nucl. Fusion* **57** 116029
[32] Di Giannatale G., Bonfiglio D., Cappello S., Chacón L. and Veranda M. 2021 *Nucl. Fusion* **61** 076013
[33] Murari A., Franz P., Zabeo L., Bartiromo R., Carraro L., Gadani G., Marrelli L., Martin P., Pasqualotto R. and Valisa M. 1999 *Rev. Sci. Instrum.* **70** 581–5
[34] Gobbin M., Valisa M., White R.B., Cester D., Marrelli L., Nocente M., Piovesan P., Stevanato L., Puiatti M.E. and Zuin M. 2016 *Nucl. Fusion* **57** 016014
[35] Muraro A. *et al* 2019 *J. Instrum.* **14** C08012
[36] Guiotto F. *et al* 2025 *Plasma Phys. Control. Fusion* **67** 125013
[37] Caruggi F. *et al* 2023 *Nucl. Instrum. Methods Phys. Res. A* **1047** 167855
[38] Celora A. *et al* 2025 *Meas. Sci. Technol.* **36** 016019
[39] Guiotto F. *et al* 2025 *Meas. Sci. Technol.* **36** 07550
[40] Carolan P.G. *et al* 1987 *Phys. Rev. A* **35** 3454–71
[41] Isler R.C. 1994 *Plasma Phys. Control. Fusion* **36** 171
[42] Korepanov S.A. *et al* 2004 *Rev. Sci. Instrum.* **75** 1829–31
[43] Carraro L., Puiatti M.E., Sattin F., Scarin P. and Valisa M. 1999 *Rev. Sci. Inst.* **70** 861–4
[44] Cinnirella L. *et al* 2025 *51st EPS Conf on Plas Phys* (*Vilnius, 7–11 July*) (https://doi.org/10.5281/zenodo.15834331)
[45] Barbisan M. *et al* 2025 *Fusion Eng. Des.* **220** 115320
[46] Alves D., Stephen A., Hawkes N., Dalley S., Goodyear A., Felton R., Joffrin E. and Fernandes H. 2004 *Fusion Eng. Des.* **71** 175–81
[47] Zanini M., Ford O., Bannmann S., Kügler J., Poloskei P.Z., Romba T. and Wolf R. 2024 *J. Instrum.* **19** 12010
[48] Spolaore M. *et al* 2017 *Nucl. Fusion* **57** 116039
[49] Agostinetti P. *et al* 2026 *IEEE Trans. Plasma Sci.* 1–7
[50] Molisani S. *et al* 2025 submitted to *Plasma Phys. Control. Fusion* Special Issue ECPD 2025
[51] Zuin M. *et al* 2025 *6th Eur Conf on Plas Diag, Prague, (ECPD)* (*Prague 7–10 April 2025*) p O13 (available at: https://indico.ipp.cas.cz/event/30/overview)
[52] De Masi G. *et al* 2024 *Fusion Eng. Des.* **201** 114257
[53] Agostini M. *et al* 2025 *51st EPS Conf. on Plas. Phys* (*Vilnius, 7–11 July 2025*) (available at: https://epsplasma2025.com/)
[54] Shepp L.A. and Vardi Y. 1982 *IEEE Trans. Med. Imaging* **1** 113
[55] Giacomin M., Ricci P., Coroado A., Fourestey G., Galassi D., Lanti E., Mancini D., Richart N., Stenger L.N. and Varini N. 2022 *J. Comp. Phys.* **463** 1112942
[56] Grenfell G. *et al* 2020 *Nucl. Fusion* **60** 126006
[57] Giacomin M., Vianello N., Cavazzana R., Molisani S., Spolaore M. and Zuin M. 2025 *Nucl. Fusion* **65** 036013
[58] Uccello A. *et al* 2023 *Front. Phys.* **11** 1108175
[59] Chichkov B.N., Momma C., Nolte S., Alvensleben F. and Tünnermann A. 1996 *Appl. Phys. A* **63** 109–15
[60] Hussain A. *et al* 2025 *Proc. 6th Eur Conf on Plas, Diag, (ECPD)* (*Prague, 7–10 April 2025*) (available at: https://indico.ipp.cas.cz/event/30/overview)
[61] De Lorenzi A., Pilan N., Lotto L., Fincato M., Pesavento G. and Gobbo R. 2011 *Fusion Eng. Des.* **86** 742–5
[62] Lucchini F. and Marconato N. 2023 *IEEE Access* **11** 9731–41
[63] Lucchini F., Frescura A., Urazaki Junior K., Marconato N. and Bettini P. 2024 *Appl. Sci.* **14** 11666