RFX-mod2 and the NEFERTARI project: a diffuse infrastructure for the study of magnetically confined plasmas for fusion

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The RFX-mod2 device, the upgraded version of RFX-mod, is presently under completion with a modified electromagnetic boundary, characterized by a closer in-vacuum fitting stabilizing shell for the enhancement of confinement properties, and significantly improved diagnostic set-up. The new lay-out includes the removal of the RFX-mod vacuum vessel and the realization of a new vessel [i]. The machine is designed to explore a wide variety of magnetic configurations, included the reversed-field pinch (RFP) and the tokamak, thanks to the flexibility of its power supply system and the capability of exploiting a feedback MHD active control system. In particular, 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 2MA) RFP, which makes the device an interesting environment for the investigation of, even localized, high power load effects on plasma facing components. The improved diagnostic plasma capabilities - which include, among the others, a very large number (>2200) of in-vessel magnetic and electrostatic sensors, a new detailed system for 3D characterization of edge impurity behaviour and plasma-wall interaction, a fast reciprocating manipulator for edge plasma studies, the renovated diagnostic neutral beam injector, a novel reflectometer system for both plasma position control and edge density profile reconstruction, a better time resolved Thomson scattering for the electron temperature profile, different systems for Soft X-ray energy and profile reconstruction and neutron monitors with high time and space resolutions [ii] are supported by the Italian National Recovery and Resilience Plan through the NEFERTARI project. This project aims at strengthening the technological plants and the diagnostic systems of RFX-mod2, which is the core of a distribute infrastructure for the advancement of fusion science. The plasma-wall interaction experimental activities on RFX-mod2 are indeed complemented by the GyM linear device [iii], whose upgrade to BiGyM, supported by the NEFERTARI project, is currently underway to extend the parameter space of the machine toward divertor-relevant plasma densities of 10^{18}–10^{19} m^{-3} and ion fluxes of 10^{22}–10^{23} $m^{-2}s^{-1}$, while enhancing the plasma-material interaction diagnostic capabilities. Samples of various innovative materials intended for future reactor applications will be exposed to the high heat flux of RFX-mod2 and BiGyM plasmas. The effects on surface properties will be analysed using the advanced diagnostic tools—including different laser-induced breakdown spectroscopy (LIBS) with laser sources ranging from ns to fs with multi-pulse schemes, suitable for in-situ tests in fusion machines, and to low-pressure electric discharge-assisted LIBS —and expertise of ISTP-Bari and ISTP-Milano groups within the NEFERTARI project. In more detail, the upgrade of GyM includes the installation of: (i) two 10kW helicon plasma sources [iv], (ii) a new sample exposure system capable of simulating the operating conditions of ITER divertor components, in terms of both temperature and incident particle energy, and (iii) a ps-LIBS to analyse plasma-induced modifications in material composition and hydrogen retention in situ. The interpretation of BiGyM

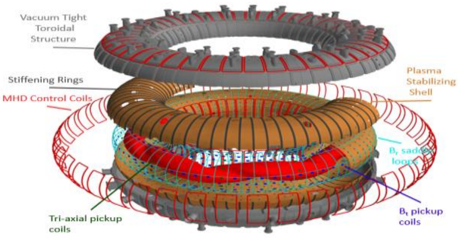

Fig. 1: Exploded layout of the RFX-mod2 assembly,.

experimental data will be fully supported by modelling activities, including the study of helicon wave propagation in the plasma using COMSOL, analysis of plasma behaviour with SOLPS-ITER, and investigation of material erosion and impurity transport with ERO2.0. Additionally, COMSOL will be also used to model the laser-material interaction process during LIBS. In the project, a new laboratory for the development and application of optical diagnostics is being established at ISTP-Bari, where the innovative LIBS analysis of surfaces will be investigated and advanced emission and laser spectroscopy will be developed, like, for example, the Laser Induced Fluorescence measurement of H (D) atoms in negative ion sources. Modelling resources are also improved, with the development of PIC models of the divertor plasma region and of negative ion sources for the neutral beam injectors. In this respect, it is worth to mention that the NEFERTARI project contributes to advanced experimental studies on the high voltage electrical insulation issues in vacuum and pressurized gases, which is a relevant aspect towards the development of the neutral beam injectors for plasma heating in ITER. NEFERTARI project aims also to investigate advanced strategies for remote handling (RH) of in vessel components using a robotic manipulator 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. A Remote Handling facility will enable the possibility to plan and test RH tasks and procedures and train operators offline without the need to access the real equipment.

RFX-mod2, as mentioned, can be also operated as a low current tokamak, even in very low-q condition (edge safety factor $q(a)<2$) with the possibility to explore shaped X-point plasmas, here included the negatively triangular ones, and to induce the transition to H-mode thanks to a polarized electrode, which actively modifies the edge electric field and the associated ExB flow shear, which is believed to play a key role in suppressing turbulence. Consistently with experimental measurements performed in RFX-mod, recent dedicated simulations with the GBS code show a strong and clear suppression of turbulent transport caused by the flow shear generated by the biasing electrode, with the formation of an edge transport barrier and the transition to a high confinement regime. Turbulence suppression with edge voltage biasing is also predicted to occur in the proximity of the density limit crossing, suggesting that active biasing may allow for larger maximum achievable density values in future RFX-mod2 experiments [v]. The presence of the close-fitting stabilizing shell, which should make the RFX-mod2 tokamak plasma stable to tearing modes, will also provide the ideal condition to perform error field penetration studies [vi]. The large number of magnetic diagnostic signals available in real-time will also allow to test complex magnetic control algorithms which potentiality can be exported to the ITER Plasma Control System. Moreover, RFX-mod2 offers unprecedented capabilities, thanks to this new wall structure and dedicated diagnostics, in the analysis of the disentanglement of the different current components (Hiro, halo, ATEC) which have been proposed to be induced on the electromagnetic wall boundary during kink development and plasma disruptions. This variety of terms reflects the complexity of plasma-wall interaction during disruptions and the absence of a universally accepted theory. The uncertainty in the magnitude and distribution of wall currents results in a 25-fold variation in predictions for the sideways force on the tokamak wall (the magnitude of the sideways force for ITER still remains highly uncertain, with an upper estimate exceeding the design margin of 48 MN).

The RFP plasmas in RFX-mod2 allow the possibility to deeply investigate magnetic reconnection phenomena, which are ubiquitous processes in many spaces, astrophysical, and laboratory systems. Magnetic reconnection, which in the RFP is associated with a global rearrangement of the equilibrium and spontaneous generation of magnetic flux, is responsible in high current condition for the breaking of the quasi-helical symmetry associated to the improved confinement regimes [vii]. 3D nonlinear visco-resistive MHD modelling shows how reconnection in the RFP exhibits the classical features of conversion of magnetic energy into kinetic energy, and the generation of waves, turbulence, and energization of particles [viii]. The associated bursty enhancement of neutron generation from fusion reactions is of interest for future exploitation of an RFP device as a compact neutron source [ix]. For a deeper understanding of these phenomena, RFX-mod2 is equipped with new dedicated diagnostics, which include an insertable edge probe for the determination of the time and space resolved ion energy distribution function [x] and a set of novel neutron and soft X-ray diagnostics, which have been designed and developed by the CNR-ISTP in Milan. In particular, a Gas Electron Multiplier based detector will be installed on RFX-mod2 to provide temporal, positional, and spectral information on X-ray emission for the study of electron acceleration and temperature dynamics. The novel design of the RFX-mod2 neutron monitors enables the operation of a multi-line-of-sight system, maintaining the capability to distinguish 2.5 MeV neutrons from the gamma ray background even in high magnetic stray fields of up to hundreds of mT. The system was designed to investigate fast ion processes during magnetic reconnections in RFX-mod2 but could easily be adapted to other magnetic confinement devices with deuterium fuel mixtures, extending the benefits of this project to a wider range of applications.

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