CHALLENGES AND SOLUTIONS IN THE DESIGN OF RFX-MOD2, A MULTI CONFIGURATION MAGNETIC CONFINEMENT EXPERIMENTAL DEVICE

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Abstract

A number of modifications and enhancements are underway on the RFX-mod Reversed field Pinch (RFP) device. The main scientific goals motivating the modifications are the improvement of the confinement in the Reversed Field Pinch configuration and the investigation of a broad spectrum of plasma physics topics, through the exploitation of the multi configuration capability of the device, which can be operated as a RFP, ultra low q, circular and shaped tokamak. This paper describes the major challenges tackled to design technical solutions able to achieve this scientific mission.

1 INTRODUCTION

The RFX toroidal device [1] (R - major radius=2.0 m, a - plasma minor radius=0.457 m, b - shell minor radius=0.535 m; in operation 1992-1999) was designed to be operated in Reversed Field Pinch (RFP) configuration with a plasma current up to 2 MA. RFX was modified into RFX-mod (R=2.0 m, a=0.459 m, b=0.512 m; in operation 2004-2015) and then equipped with 192 independently driven saddle coils, achieving the full control of RWM modes [2] and a significant mitigation of tearing modes [3]. The mode and plasma equilibrium control innovations allowed to effectively reach the 2 MA current goal [4] and led to the experimental confirmation of the single helical axis equilibrium of the RFP [5]. RFX-mod has been operated also in ultra low-q (Ulq) pinch configuration, giving new insights on fundamental plasma properties, such as the effect of MHD on transport and the high density limit [6]. A number of experiments have been performed also in circular and shaped tokamak configurations: the highly enhanced control capability led to obtain the first active stabilization with q(a)~2 [7] and recently the H-mode has been achieved by electrode biasing [8]. Such results outlined the two future main goals of the upgrade of RFX-mod experiment to RFX-mod2 [9] (R=2.0 m, a=0.490 m, b=0.512 m): the improvement of the RFP confinement and the knowledge about a broad spectrum of plasma physics in regimes otherwise not accessible to other devices, through the extension of the operational space in terms of density control and magnetic field topology, with increased diagnostic capability, in the three above mentioned magnetic configurations.

2 NEW MACHINE LAYOUT

A key ingredient of the new design consists in the enhancement of the shell-plasma proximity from b/a=1.17 to b/a=1.04, which is expected to provide a significant reduction of the amplitude of RFP tearing modes [10]. This reduction would lead to the positive cascade effects of magnetic chaos mitigation with confinement improvement, reduced plasma-wall interaction and better mode control capability. This choice implied challenging major modifications on the components of the machine close to the plasma, while maintaining the existing magnetic coil system. The vacuum vessel of RFX-mod is being removed and the conducting shell placed in vacuum as close as possible to the plasma (Fig.1); the vacuum barrier would be then provided by the properly modified toroidal support structure [11].
Innovative solutions have been conceived to fulfil vacuum and electrical requirements of the in-vessel components, in particular to ensure their reliability during normal and abnormal operating conditions and events.

**Fig. 1:** RFX-mod2 plasma toroidal plasma complex, cross section and isometric view.

### 3 VACUUM TIGHT SUPPORT STRUCTURE

The Vacuum Tight Support Structure (VTSS) is being manufactured starting from the existing mechanical support structure composed by four quarters (Fig. 2a), which will be then bolt joined to obtain the two halves of chamber (Fig. 2b). Being the thickness of this structure (50 mm) dictated by mechanical constrains, its electrical resistivity as a continuous conductor would be too low to allow RFP operation. This requires an electrical insulating vacuum sealing, with a vacuum-tight triple joint at the crossing of the gaps. The developed solution uses standard Viton O-rings, custom PEEK gaskets and G10 fiberglass spacers, and has been successfully tested on a dedicated mock-up [12]. By avoiding component welding, this solution eases the accessibility of vacuum components for major maintenance purposes.

**Fig. 2.** The Vacuum Tight Support Structure (VTSS) is composed by four stainless steel parts (a) and acts both as mechanical support and vacuum vessel. The four parts are then bolt joined together to form the two halves of the vessel (b); the electrical insulation and the vacuum sealing is provided by PEEK half gaskets at poloidal gaps and by Viton O-rings at toroidal gaps (c).

### 4 IN-VACUUM ASSEMBLY

The in-vacuum assembly of RFX-mod2 includes the first wall graphite tiles with their supports, a thin (3 mm thick) copper shell and 72 composite clamping rings. Magnetic measurements (pick-up coils and loop probes), distributed Langmuir probes, thermocouples and strain-gauges are being embedded in the structure.
In order to place the copper shell in vacuum close to the plasma, a number of complex requirements, deriving from challenging electrical, mechanical and thermal constraints, must be fulfilled.

### 4.1 Copper Shell and insulation requirements

To be effective for the stabilization of the plasma unstable modes, the copper shell should be as continuous as possible. At the same time a poloidal and a toroidal gap are needed to allow for the fast penetration of the applied toroidal loop voltage and magnetic toroidal field. In order to reduce the induced field errors, the shell has been built with an overlapping region at the poloidal gap (Fig. 3). The typical loop voltages during RFP operation are routinely in the range between 250 to 400 V during the start-up phase and can reach 1.5 kV during fast plasma current terminations. Since the two gaps prevent the development of net poloidal and toroidal currents, the total induced voltage develops intense electric fields at the gaps, on distances down to 2 mm. On the other hand, inside the plasma, being a continuous conductor, the applied electric field practically spreads uniformly.

![Fig.3: the thin copper shell is composed by top and bottom part; in the section highlighted in blue two coaxial layers of copper are overlapped and insulated to form an electrical gap. The top and bottom halves are then short circuited at the outer equatorial, while the inner one is left open and acts as the toroidal gap.](image)

In RFX-mod the shell was at atmospheric pressure and the overlapped gap filled by a PTFE plastic sheet. In this situation the peak electric field was well below the dielectric rigidity. On the contrary in RFX-mod2 the shell is inside the vacuum vessel and therefore exposed to low gas pressure and to the low temperature plasma of the Scrape Off Layer (SOL), a condition which can easily lead to dangerous arcing phenomena. Moreover the different distribution of the applied potential between the plasma (uniform electric field) and the shell (electric field concentrated in the gap region) does not allow the placement of the Plasma Facing (PF) components in direct electrical contact with the copper shell. In this situation they would create an electrical bridge between the main plasma and the shell itself, causing severe unbalances of currents flowing in and out of the tiles in the gap region, which would damage both the PF tiles and the shell [13]. This problem has been overcome adopting the following solutions:

- The plasma and the PF tiles, insulated from the copper shell, are maintained close to the same induced potential by connecting together all the PF tiles through a stainless steel net at controlled resistivity (about 50 mΩ total in toroidal direction, 0.8 mΩ in poloidal direction).
- The gap region of the copper shell is insulated by an alumina coating.

The feasibility of alumina coating over copper substrate by means of Detonation Gun Spray is under investigation, since it offers excellent adhesion to the substrate, together to compactness and the mechanical strength of the coating [14] required to ease the assembly of the vacuum complex.
4.2 Support and Clamping Structure

The supporting structure consists of 72 rings made up of different components, which keep in the proper position the thin copper shell. Each ring consists of a thermoplastic Torlon core, composed by 28 sectors, wedged one into the other to form a rigid chain. Each thermoplastic ring sector outside the shell is bolted to an internal stainless steel clamp, thus squeezing the copper in the middle; the clamp hosts the fixture for one PF tile and is alumina coated to provide the required electrical insulation toward the shell (Fig. 5).

Each half ring is stiffened by two lateral stainless steel ribs electrically insulated at the equatorial plane. On the top of the ring a fastening band keeps the two ring halves connected, provides the electrical continuity in poloidal direction and uniformly distributes the voltage potential of the PF tiles ring through the clamps. The band thickness (1.5 mm) and width (30 mm) result in a poloidal resistance for each ring of about 58 mΩ. From the electromagnetic point of view this resistance provides a mild filtering time constant for the inverter switching noise produced by the toroidal power supplies and some shielding toward the power supplies during internal RFP reconnection events.

Fig. 4: isometric view of the vacuum toroidal complex clamped by 72 composite rings. The shell has been rendered in transparency to allow the view of the plasma facing tiles and the internally hosted magnetic sensors.

Fig. 5: exploded view of a ring sector with the fixture for the PF tile.

Fig. 6: detailed view of the composite rings and clamping system for the copper shell.
4.3 Plasma Facing Components

The PF wall reflects the stiffening structure: the PF tiles are organized in 72 poloidal rings of 28 elements, with a total of 2016 tiles. This configuration maintains the basic layout already used in RFX and RFX-mod, and uses the same proved fitting mechanism (Fig. 7) [15]. The size of the tiles will be modified to match the increased internal dimensions and the shape smoothed to mitigate sharp wedges. The design has been optimised against the assumed loads, developing the housings for the electrostatic and thermal sensors integrated in the tiles. The new PF tiles are being manufactured using isostatically pressed graphite with high thermal conductivity (more than 140 W·m⁻¹·K⁻¹) to realise a high thermal diffusivity (1.1·10⁻⁴ m²·s⁻¹) and with acceptable flexural strength (up to 45 MPa) to cope with the assumed operating load conditions. The higher conductivity should mitigate the sudden rise of local surface temperature which is thought to be at the origin of uncontrolled local desorption of Hydrogen or Deuterium during plasma discharges, which hampered the control of the density evolution [16].

4.4 Conditioning of in-Vacuum Components

The conditioning system will exploit Pulse Discharge Cleaning (PDC) and Glow Discharge Cleaning (GDC). The PDC plant [17] will provide a sequence of low q discharges at about 50 kA lasting few ms. Its use is mainly planned for PF wall treatments after machine venting. Due to the lack of enough space to accommodate a baking system, the PDC itself will be used to heat the PF tiles up to 180 °C, by adjusting the pulse repetition rate. The heating will produce the outgassing from the vacuum components, while the plasma treatment is expected to remove impurities from the exposed graphite surfaces. The existing GDC plant used for RFX-mod, based on two RF capable electrodes mounted on long stroke manipulators, will be also applied [16]. A new system composed by eight additional short stroke electrodes will be added and used mainly for short duration and uniform inter-shot glow discharge[18].

Beside the aforementioned systems for PF components cleaning, which are the standard methods applied on fusion research devices, on RFX-mod2 additional procedures to avoid the formation of undesired arcing during plasma operation are needed. As explained in section 4.1, during plasma experiments, intense electric field between the PF tiles and the copper shell, and at the gap of the copper shell will develop. It has been experimentally demonstrated that in presence of two facing electrodes immersed in a low temperature plasma, in a condition similar to the scrape-off layer behind the PF tiles, arcing is likely to occur even with modest potential difference applied, in the range of 50V-100V, whereas the expected vacuum or gas breakdown voltage is in the range of several kV. This phenomenon can be ascribed to the formation of the plasma sheath, which intensifies the electric field in proximity of the electrode surface. Indeed the behaviour of the arc formation closely resembles that of arc formation on very high voltage systems in vacuum. The voltage holding of these systems can be improved by a conditioning procedure where the voltage is gradually increased and the arc energy is kept low, by limiting the arc current. Dedicated experiments have been done proving that a similar procedure performed in presence of low temperature plasma is effective in obtaining a voltage holding level which satisfies the requirements for RFX-mod2 (Fig. 8)[13].

A system devoted to check the voltage holding of the shell gap will be also needed. The shell is a continuous conductor, so that the gap insulation cannot be verified by DC methods. As an alternative a high frequency AC
system can be used by exploiting the shell self-inductance in order to create an LC resonator which can be driven at high voltage [19].

4.5 Internal sensors

The study for the detailed final arrangement of the in vessel magnetic probes [20][21] is still underway. The current baseline design [21] is summarized in Tab. 1 and shown in Fig. 10. The toroidal arrays for toroidal and radial field measurements are designed to improve the reconstruction capability of the time evolving helical structure peculiar of the RFP configuration. The aim is a mode resolution with n number up to 36, with the capability to estimate the amplitude and phase for low m components (0, ±1,±2) at each n. The improved resolution will provide more precise field reconstructions [22] and Poincare maps [23][24]. The increased mode amplitude and phase resolution will improve the accuracy of the MHD real time control system, with further enhance the mode control capability.

The 12 poloidal arrays of three-axes probes (Fig.9) are placed in a checker-board configuration, so that the expected equivalent resolution is roughly equivalent to 6 arrays of 28 sensors, allowing the measurement of the total plasma current and for resolving modes and structures in the range n=1,2; m=−14..+13. This latter feature is in particular crucial to the reconstruction of the LCFS in shaped tokamak configuration, where the toroidal periodicity is of low order. The pick-up coils are designed with a reference area of 0.025 m², which ensure a signal level high enough for good signal integration, and a bandwidth at the transmission line end of 200 kHz. These features open the door to the detailed study of the spatio-temporal evolution of a broad range of magnetic modes and fluctuations, such as free rotating tearing modes, sawtooth crashes and reconnection events.

**TABLE 1. Basic magnetic measurements**

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Probe type</th>
<th>Layout</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local magnetic field (Br, Bt, Bp), plasma current</td>
<td>Three axes pick-up coil</td>
<td>12 poloidal arrays of 14 probes</td>
</tr>
<tr>
<td>Local toroidal field (Bt)</td>
<td>Single axis pick-up coil</td>
<td>6 toroidal array of 72 probes</td>
</tr>
<tr>
<td>Average radial field (Br)</td>
<td>Saddle loop</td>
<td>8 toroidal array of 72 probes</td>
</tr>
<tr>
<td>Toroidal loop voltage and poloidal flux</td>
<td>Single loop</td>
<td>8 + 8 loops</td>
</tr>
<tr>
<td>Poloidal loop voltage and toroidal flux</td>
<td>Single loop</td>
<td>12 loops</td>
</tr>
</tbody>
</table>

Langmuir probes will be integrated in the PF tiles, with the aim of providing a full set of internal sensors to monitor plasma electrostatic quantities and their fluctuations along both toroidal and poloidal directions. In particular two toroidal arrays on high field side and on low field side respectively are foreseen and three poloidal arrays, the latter in the proximity of the insertable probe manipulator toroidal location. This choice is due to the need of having complementary information from the insertable and wall-integrated diagnostics. The toroidal arrays are composed of 72
elements, while the poloidal one of 24 elements, with a total amount of about 400 electrostatic sensors. Different kind of electrostatic sensors are planned to be installed in order to monitor plasma density, particle and energy fluxes, plasma potential, electron temperature and other related quantities. In particular two of the poloidal arrays are constituted by cluster of 5-pins sensors, to be configured as five pin balanced triple probe (Fig. 11). The pin arrangement of the latter has been laid out to allow effective measurements of the particle flux in both the RFP configuration, where the field is mainly in the poloidal direction, and the tokamak one with the main field directed on toroidal direction.

A set of 6 toroidal arrays of 36 thermocouples are finally foreseen to continuously monitor the shell and the thermoplastic rings temperature, during plasma operation and conditioning procedures.

5 DIAGNOSTIC AND CONTROL SYSTEM IMPROVEMENT

By taking advantage of the modifications to be carried out on the support structure, new and modified accesses have been designed. Nineteen new diagnostic ports are being added to include new systems: D2 emission tomography, position and shape reflectometry, reciprocating manipulators, high frequency magnetic probes, D-recycling diagnostic. Eight of the new ports will be used for the fast insertion GDC electrodes and four more for pre-ionization and gas injection from the high field side. Three equatorial access ports will be enlarged with a square shape and will allow the installation of a neutral beam injection [27], pumped limiter or RF antenna. The possible RF heating schemes considered are the ordinary to Bernstein wave conversion [28]in RFP configuration and the 2nd harmonic ECRH for tokamak configuration[29].

Fifty ports are being reserved to host electrical signal feedthroughs necessary for the foreseen 2500 signals coming from the sensors installed on the vacuum toroidal assembly. In particular the magnetic signals, which account for more than 1500 channel, will be directly acquired by means of high resolution ADCs and numerically integrated [30] by an FPGA architecture which allow simultaneous signal transient recording and real-time data collection, pre-processing and dispatch [31]. This solution avoids the complexities deriving by the use of analog integrators and makes such a signal count manageable. The availability of all magnetic signals (B and $\dot{B}$) in the MArTe framework [32], will allow the implementation and test of advanced real-time algorithms for feedback control of unstable modes, plasma equilibrium and disruption avoidance [33].

Finally the more flexible electrical connection scheme for the existing 16 field shaping coils will allow quickly switching between different tokamak shaping, namely single/double null, internal or external X point position, with negative or positive triangularity (Fig.12).

![Fig.12. Right: layout of the Field Shaping coils (FS, highlighted in blue) of RFX-mod which will be maintained in RFX-mod2. Left: examples of two possible double null and single null configurations attainable.]

6 UPGRADE OF THE TOROIDAL CIRCUIT POWER SUPPLY

During the operation of RFX-mod the existing toroidal circuit power supply [35] has shown two main limitations. It presents a relatively high latency time (2.5 ms), which prevented a correct closed loop control of the toroidal field during transient phases (e.g. the RFP start-up) and low plasma current experiments. In addition an unbalance on toroidal current circuit during field transients appears randomly, being induced by a slight difference in timing operation of the inverter controllers; this imbalance translates into a seed for $m=0$ modes which deteriorate the plasma confinement. These limitations motivate the upgrade of the toroidal power supply control system in order to reduce the latency below 1 ms and to precisely synchronize the inverter units. Being the MHD equilibrium of RFP and ultra low-q highly sensitive to the variation of the applied external toroidal

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magnetic field, these new features will be exploited in experiments aimed at the exploration of transient current profile shaping [36], reconnection mitigation and low plasma current operation.

7 CONCLUSIONS

The upgrade to RFX-mod2 issued a number of technical challenges, which have been successfully faced through innovative solutions and technical R&D. The whole project, presently in the implementation phase, is expected to bring a powerful and flexible experimental device for the extension of the RFP scaling laws and the advancement of the high current performance, better clarifying the fusion potentialities of such magnetic configuration. At the same time, RFX-mod2 will contribute to the study of specific topics of tokamak physics, such as for example ELM mitigation by magnetic perturbations, and to cross-configuration issues, such as density limit, magnetic self-organization and edge turbulence.

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