Technological challenges for the design of the RFX-mod2 experiment

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The design of RFX-mod2 experiment implies a major change and reconfiguration of the internal components of the present machine assembly. Critical aspects of the design regard the technical solutions needed to fulfil geometrical, vacuum and electrical requirements imposed by interface with existing components and by specific operating conditions. The paper presents an overview of the design choices and the proposed implementations, assessed by means of engineering analyses and experimental tests performed on mock-ups of the new components.

Keywords: Vacuum Vessel; Vacuum Sealing; Detonation Gun Sprayed Coatings

1. Introduction

An upgrade of the RFX-mod experiment is presently in the final design phase, with the main objectives of improving the control of magnetic confinement, plasma density and plasma wall interaction in both RFP and Tokamak configuration [1].

The achievement of these aims implies a major change and reconfiguration of the internal components of the machine assembly, namely: Toroidal Support Structure (TSS), Passive Stabilizing Shell (PSS), Vacuum Vessel, First Wall and In-Vessel Sensors [2].

The machine modification is subject to stringent constraints in terms of geometrical interface with existing components (in particular external coils and diagnostic systems) and to the compliance with specified electrical insulation both along toroidal and poloidal direction, to allow suitable penetration of electromagnetic fields within the plasma chamber and to minimize the risk of arcing among in-vessel components which could occur during over-voltages induced in standard or abnormal operating conditions [3].

Critical aspects of the design regard the technical solutions needed to fulfil geometrical, vacuum and electrical requirements, in particular: the development of vacuum-tight electrical-insulated crossed joints of the new vessel, by using high-performance polymers; the implementation of specific welding procedures to control the deformation of major machine components with tight tolerances; the implementation of surface coatings of in-vessel components.

2. RFX-mod2 Vacuum Tight Support Structure

In RFX-mod the TSS (4 bolted quarters made of AISI 304L, $R_{major} = 2$ m, $r_{minor} = 553$ mm, thickness = 47 mm) provides mechanical support to the enclosed vacuum vessel and the external coils and guarantees electrical discontinuity along toroidal and poloidal direction by means of fiberglass spacers in air (Fig.1-a) [2].

In RFX-mod2 this component, renamed 'Vacuum Tight Support Structure' (VTSS), will be adapted to provide the function of vacuum vessel, still encompassing the conductive stabilizing shell. The fulfilment of this requirement implies the integration of approximately 150 ports interfaced with existing machine sub-systems (diagnostics, pumping and fueling) and the implementation of 2 vertical and 2 horizontal vacuum-tight electrical-insulated joints (Fig.1-b).

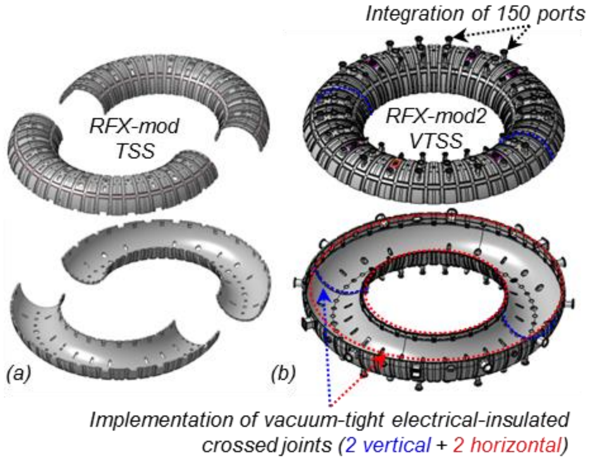

Fig. 1. Modification of the 'TSS' of RFX-mod (a) to the 'VTSS' of RFX-mod2 (b).

2.1 Integration of ports in VTSS

The integration of ports in the VTSS represents a potential issue due to the requirements of tight geometrical tolerances of the flanges (planarity and parallelism of the order of 0.2 mm) and uneven shape of the port pipe imposed by the existing interfaced components. Following the detailed structural analysis performed to assess the reliability of the design [2] [4], a specific manufacturing procedure has been specified and

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author's email: simone.peruzzo@igi.cnr.it verified with the realization of some representative prototypes, which proved the fulfilment of the requirements (Fig. 2).

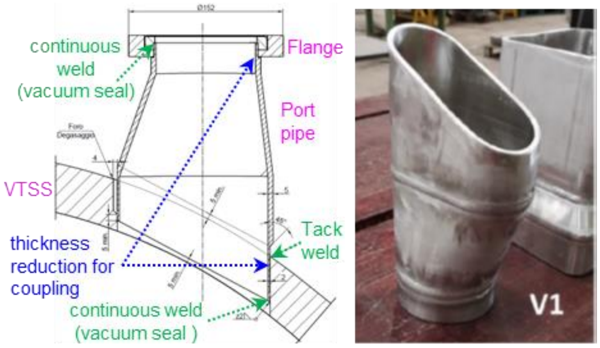

Fig. 2. VTSS port manufacturing procedure and prototype.

The integration of 22 equatorial ports, while guaranteeing the assembly of the complete in-vessel components from above, is obtained by joining a thick toroidal segment on top of the lower VTSS quarters, in order to provide enclosed apertures suitable for proper welding of the new port pipes [2].

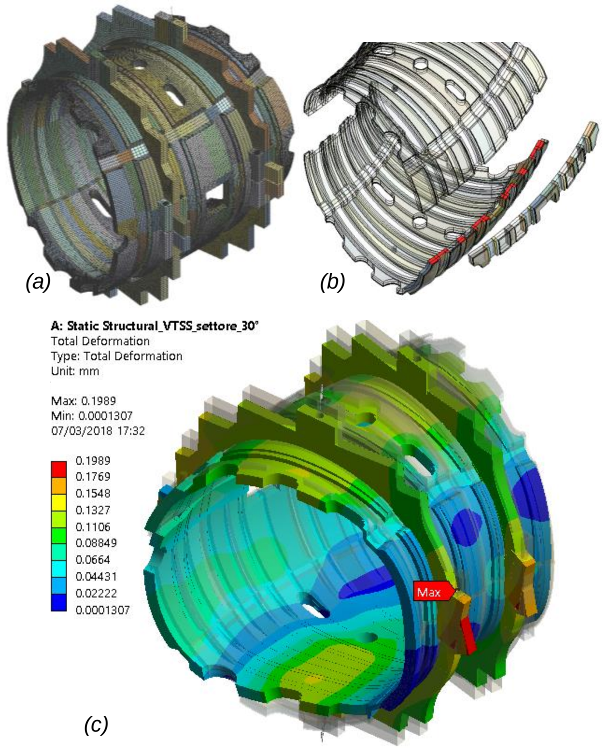

Fig. 3. Summary of VTSS FEM structural analysis: (a) mesh (1/12 of the torus); (b) definition of contact constraints (bonded/frictional); (c) total deformation

In order to minimize the deformations due to welding process, the joining of the new toroidal segments has been conceived as a combination of bolts and intermittent weld on air side (for structural function) and continuous lip weld on vacuum side (for vacuum sealing). Fig. 3 summarizes the structural analysis carried out to assess the reliability of this solution, considering the static nominal loads (dead weight of all the components, pre-load of clamping bolts, atmospheric pressure), with acceptable obtained results in terms of deformation (< 0.2 mm) and stress (< 60 MPa).

2.2 Implementation of vacuum-tight electrical-insulated crossed joints of the VTSS

One of the most critical aspects in the VTSS assembly is the requirement to guarantee vacuum tightness and electrical insulation at the present poloidal and toroidal gaps. Figures 1 and 4 show the concept of the vacuum-tight electrical-insulated crossed joints. The two lower and higher VTSS quarters are firstly horizontally tight jointed (blue seam in Fig.1), by means of the existing stud bolts, with interposed semicircular insulating spacers made of polyether–ether–ketone (PEEK) acting as “half gaskets”; vacuum tightness is provided by proper “CF knife-edge” machined in the extremely narrow room (8 mm) available on the two surfaces of the mating VTSS quarters (Fig.4). The two VTSS halves are then vertically jointed with interposed Viton O-rings (for vacuum tightness, red seam in Fig.1) and suitable PEEK and G10 fiberglass spacers (for electrical and structural functions).

The reliability of PEEK as insulating vacuum gasket has been already tested in similar applications [5]. The geometrical details of the “CF knife-edge” [6] and of the crossing of the horizontal and vertical joints have been further refined and tested in the mock-up previously used to test the concept [2], achieving satisfactory leak rates $Q_L < 1\cdot10^{-9}$ mbar·l/s.

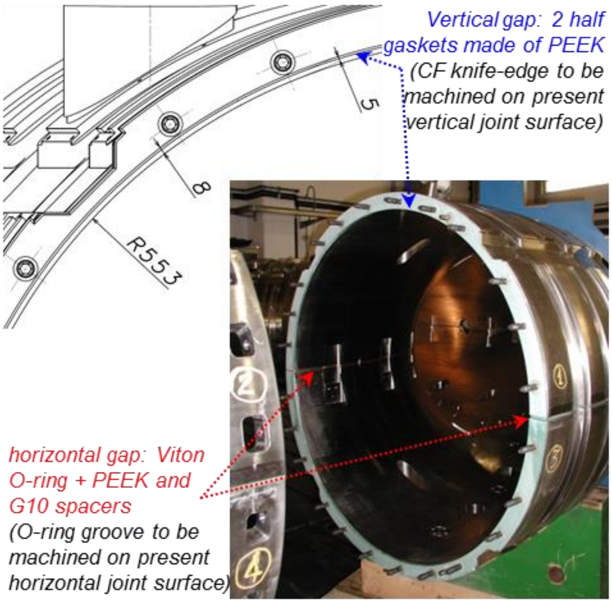

Fig. 4. Concept of the vacuum-tight electrical-insulated crossed joints at the horizontal/vertical gaps of the VTSS.

3. RFX-mod2 Passive Stabilizing Shell

In RFX-mod the PSS (2 toroidal halves made of copper, $R_{major} = 2$ m, $r_{minor} = 514$ mm, thickness = 3 mm) provides magnetic stabilization to the plasma, being wrapped and fastened around the external surface of the vacuum vessel (Fig.5-a). In order to allow the penetration of electromagnetic fields in the plasma region, the conductive shell is provided with one electrical discontinuity in both poloidal and toroidal direction, namely a 5 mm gap along the internal equator and an overlap of 30° along the toroidal direction of 2 edges of the shell, with interposed 2 mm thick insulating spacer made of PTFE.

In RFX-mod2, due to the removal of the vessel, the PSS (Fig.5-b) will be deeply modified in order to sustain the new first wall (2016 graphite tiles) and a wide system of in-vessel diagnostics (more than 1000 electro-magnetic and thermo-mechanical sensors) and to operate in vacuum conditions. To fulfil the new requirements, a new support structure and suitable electrical insulations must be provided.

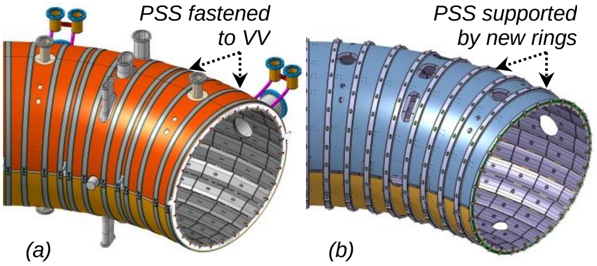

Fig. 5. Modification of the 'PSS' from RFX-mod (a) to RFX-mod2 (b).

3.1 Design of new support structure for the PSS assembly

The new support structure for the PSS is composed of a set of 72 poloidal rings made of thermoplastic material (Torlon 5030® PAI) bolted to the shell by means of 72x28 clamps which, on the internal surface of the shell, provide also the fastening of the first wall tiles (Fig.6). Torlon was selected for the good mechanical and electrical characteristics and also for its thermal expansion coefficient ($16\cdot10^{-6}$ K^{-1}) very close to that of copper, which guarantees no significant differential expansions and consequent stress even at the maximum operating temperature expected for baking (180 °C).

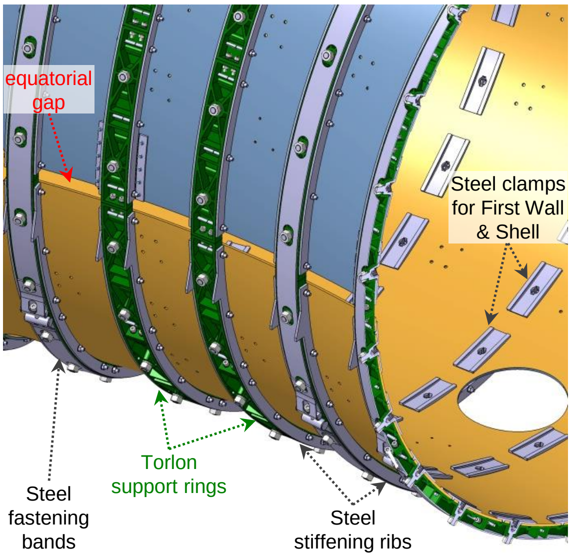

Fig. 6. Detail of the components of the PSS assembly.

With respect to the previous design phase [2] the thermoplastic rings have been reinforced with additional fastening bands and stiffening ribs, which still provide the suitable electrical discontinuity of the shell along the poloidal direction (Fig.6). This solution has been implemented in order to withstand the electromagnetic loads evaluated in the worst operating condition expected (2 MA plasma current quench in approximately $3\cdot10^{-3}$ s, with a maximum dIp/dt = $1\cdot10^{9}$ A·s^{-1}). The forces acting on the components have been calculated with the same model used for the RFX-mod design [7], suitably adapted to take into account the new configuration of the passive stabilizing structures. Fig. 7 summarizes the structural analysis carried out to assess the reliability of this solution taking into account, besides the above mentioned electromagnetic loads due to eddy current in the shell, also the dead weight of all the components, the pre-load of clamping bolts and the loads on first wall tiles due to circulation of halo current with similar assumptions adopted for the design of RFX-mod (3 kA per tile) [8], considered a conservative threshold since the enhancement of the 'shell-plasma proximity' is expected to reduce the deformation of the last close magnetic surface and ultimately the plasma wall interaction phenomena [1]. The results reported in Fig. 7 show the acceptable safety margin in terms of maximum stress in Stainless Steel parts (< 125 MPa), Torlon parts (< 50 MPa) and Copper shell (< 25 MPa).

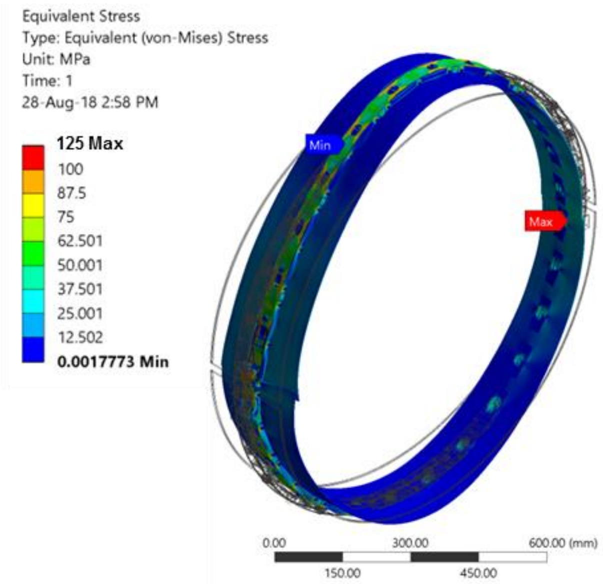

Fig. 7. Equivalent stress in the PSS assembly in the worst expected condition (1/72 model of the torus).

3.2 Electrical insulation of in-vessel components at plasma boundary

The overlapped gap of the PSS spanning 30° along the toroidal direction, necessary to minimize magnetic error fields, represents a potential risk of arching between facing edges of the shell which could be exposed to overvoltage of the order of 1 kV during plasma operation [3]. The possibility to guarantee a proper electrical insulation by means of solid spacers is considered difficult, due to the presence of several imperfections and interstices in the shell which, in presence of the weakly ionized gas at the plasma boundary, could determine the conditions of a discharge.

As an alternative to solid insulation, a feasibility study to obtain an insulating Al_2O_3 coating on a wide surface of the Cu shell (of the order of some square meters) has been started up. Among different thermal spray coating processes, Detonation Gun Spraying (DGS) [9] has been selected, for its potential excellent bond strength, low porosity and cost effectiveness, and it was tested with a facility available at ENEA Brasimone (Fig. 8).

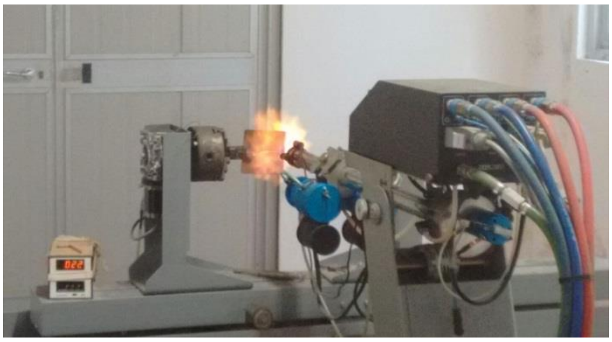

Fig. 8. Detonation Gun Spray facility in operation at ENEA Centro Ricerche Brasimone.

Being information on DGS alumina coating on copper substrate rather scarce in literature, a preliminary test has been carried out to tune the various parameters affecting the process, i.e.: surface pre-treatment, gun-target distance, detonation frequency, overlapping sequence. Fig. 9 shows the results obtained on a set of samples in terms of n. of layers deposited and coating thickness measured with optical microscope. From visual inspection the coatings appear uniform and well bonded, except for the 15 layers sample (thickness > 200 µm) which exhibited a spontaneous detachment of a wide fraction of the coating. The electrical resistance of the 3-12 layers coatings was measured with a digital Megohmmeter with satisfactory results > 10 GΩ.

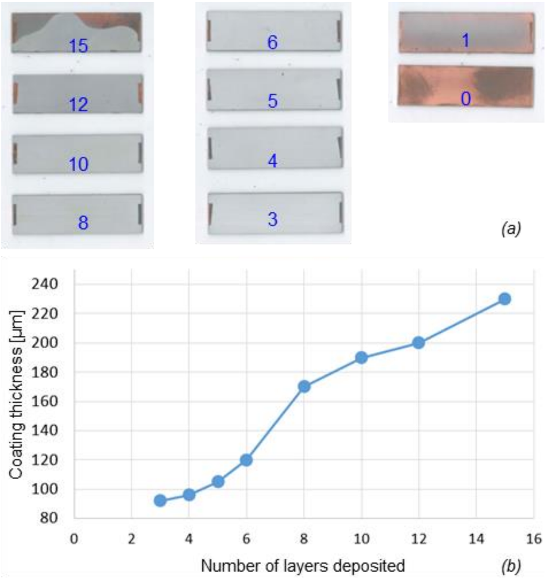

Fig. 9. (a) Cu samples (100 x 30 x 3 mm) with different number of coating layers deposited; (b) coating thickness as a function of number of layers.

The 6 layer coating sample has then been tested in an experimental set-up available at Consorzio RFX able to reproduce the operating conditions expected at plasma boundary during RFX-mod2 operation. It consists of a vacuum chamber with a hot cathode plasma source and movable supports for samples and electrodes fed with high voltage supply. Fig. 10 shows the satisfactory results of the test which demonstrate the capability to withstand overvoltage up to 2 kV. To assess the actual reliability of the process, further tests have been planned, consisting in thermal cycles and mechanical stress.

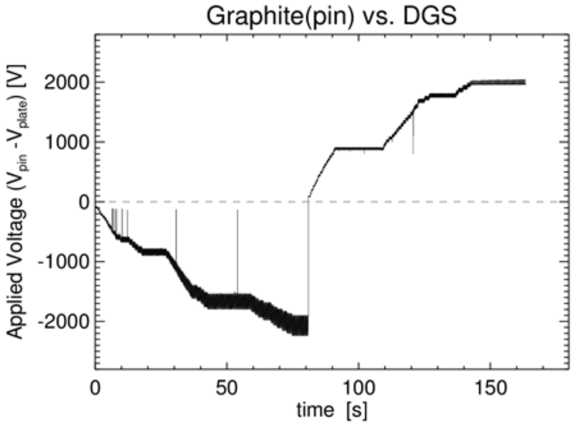

Fig. 10. Results of electrical insulation withstand test of Al_2O_3 coated Cu samples in weakly ionized plasma.

Conclusions

The critical aspects of the RFX-mod2 design, related to peculiar geometrical, vacuum and electrical requirements, have been faced. Solutions to main technical issues have been identified and are going to be implemented in the forthcoming manufacturing phase.

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