Detailed design of the RFX-mod2 machine load assembly

Simone Peruzzo[a], Marco Bernardi[a], Roberto Cavazzana[a], Samuele Dal Bello[a], Mauro Dalla Palma[a], Luca Grando[a], Eleonora Perin[b], Roberto Piovan[a], Andrea Rizzolo[a], Federico Rossetto[a], Diego Ruaro[b], Marco Siragusa[a], Piergiorgio Sonato[a], Lauro Trevisan[a]

[a]*Consorzio RFX, Corso Stati Uniti 4, 35127 Padova, Italy*
[a]*De Pretto Industrie S.r.l., Via A. Fogazzaro 5, 36015 Schio (VI), Italy*

An upgrade of the RFX-mod experiment is presently in the final design phase, aimed at widening the explored operational scenarios both in RFP and Tokamak configuration. The main design driver for this machine upgrade is the enhancement of the ‘shell-plasma proximity’, which is expected to provide a significant improvement in the plasma magnetic confinement. The achievement of this aim implies a major change of the internal components of the machine such as the removal of the present vacuum vessel, transferring the function of vacuum barrier to the duly modified toroidal support structure, and the integration of a new in-vessel support system to sustain the conductive stabilizing shell and the whole first wall. The paper presents an overview of the design choices and the proposed implementations, assessed on the base of engineering analyses and results of experimental tests performed on mock-ups of the new components. The solutions conceived to fulfill vacuum and electrical requirements of the in-vessel components, to guarantee their reliability during normal and abnormal operating conditions events, and interface compatibility with existing components and torus assembly sequence are finally highlighted.

Keywords: Vacuum Vessel, Plasma-Facing High Heat Flux Components, First Wall Technology.

1. Introduction

After 10 years of operation since its major modification [1], a design study for an upgrade of the RFX-mod experiment has been launched, aimed at widening the explored operational scenarios both in RFP and Tokamak configuration [2].

The upgrade implies a major reconfiguration of the internal components of the machine devised to set up the ‘Passive magnetic Stabilizing Shell’ (PSS) closer to the plasma boundary, by removing the present ‘Vacuum Vessel’ (VV) and transferring the function of vacuum barrier to the ‘Toroidal mechanical Support Structure’ (TSS). The main modifications are therefore addressed to the adaptation of the present TSS (R_{maj}=2m, r_{min}=0.5 m, made of stainless steel), to provide the function of vacuum vessel (now renamed ‘Vacuum vessel & Toroidal Support Structure’, VTSS), the change of the support system of the magnetic PSS, encompassed by the new vessel, and the replacement of the whole graphite ‘First Wall’ (FW), attached to the inner surface of the shell and facing the plasma (Fig.1).

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 resistance both along toroidal and poloidal direction, to allow suitable penetration of electro-magnetic fields within the plasma chamber [3].

During the conceptual design phase the integration of the 22 equatorial ports on the outer boundary of the VTSS was considered compatible only with the pre-assembly of two halves of the toroidal complex and the final welding of the two poloidal gaps of the VTSS [3]. This assembly sequence would have excluded the possibility of overlapping the insulated gaps of the PSS, as adopted in the present RFX-mod configuration to minimize radial magnetic field errors with respect to the ‘butt-joint’ configuration. This issue in principle could be compensated with the use of a dedicated active control system of local magnetic field at the PSS and VTSS poloidal gaps [4]; nevertheless the implementation of such a system, together with the realization of welded VTSS joints based on metal-ceramic brazed structures, were considered too risky both for technical and economical reasons. Therefore the final design, described in the following Sections, was focused on a solution compatible with the original assembly sequence of RFX machine, in which the PSS can be fully assembled with overlapped joints and then vertically inserted between the bottom and top halves of the VTSS, finally bolted at the equatorial gaps.

2. Vacuum Toroidal Support Structure

The present RFX-mod TSS is a stainless steel (AISI 304L) toroidal structure made up of 4 segments, each extending 180° in both poloidal and toroidal direction, separated by 2 poloidal and 2 toroidal insulated gaps made of G10 fiberglass spacers [1]. The implementation of a vacuum barrier requires the vacuum tight sealing of the above mentioned gaps and the closure of approximately 150 apertures, which in the present configuration (Fig. 1) are wide enough to allow the outlet of the VV ports connected to the machine sub-systems (diagnostics, pumping and fuelling), which must be kept as unchanged constraints.

Corresponding author’s email: simone.peruzzo@igi.cnr.it

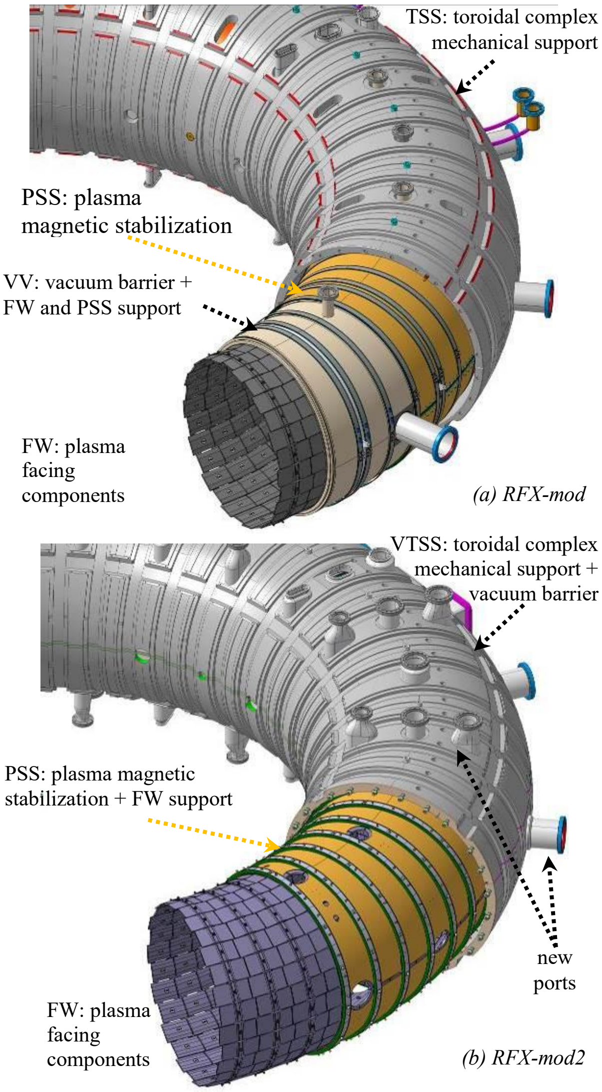

Fig. 1. Comparison between RFXmod (a) and RFXmod2 (b) components of the machine assembly (R_{maj}=2 m; r_{min}=0.5 m) and relative modified functions

2.1 Port integration and assembly sequence

Fig.2 describes the solution adopted to fulfill the requirement to integrate the equatorial ports at the outer boundary of the VTSS, while guaranteeing the possibility to insert the complete PSS from above: a thick toroidal segment is welded on top of the lower VTSS in order to provide an enclosed window suitable for proper welding of the new port pipes (Fig. 3). This solution requires a stringent control of deformations of the new welded parts to guarantee correct interface with existing components (coils and diagnostics) and to allow the assembly sequence of the PSS within the VTSS with a tolerance in the coaxiality of less than 10mm over a maximum diameter of 5 m (Fig. 2).

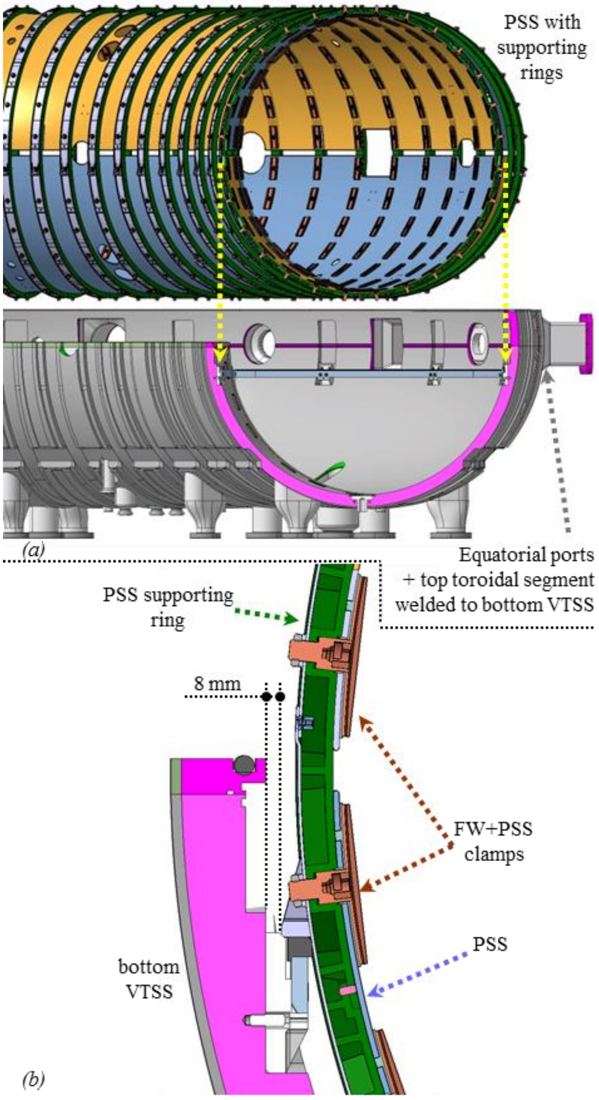

Fig. 2. (a) top-down assembly sequence of PSS into VTSS; (b) tolerance analysis for installation

To complete the structural verification of the VTSS in the new foreseen operating conditions performed during the conceptual design phase [5], a detailed structural analysis of the new ports has been carried out, in order to assess the reliability of the uneven geometry of the ports imposed by interfaces with existing components. Fig. 4 reports the results of the analysis for the worst case representative port type, calculated considering the expected loads: atmospheric pressure on the external surfaces; deadweight of the port; distributed mass at the flange (up to 150 kg) representing possible

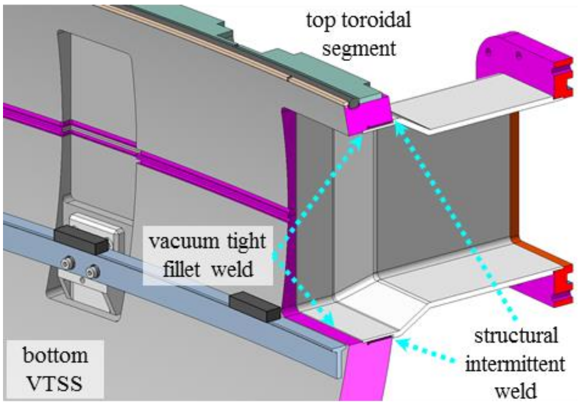

Fig. 3. Welding concept of equatorial ports

equipment attached to the flange. The results obtained are satisfactory, with acceptable deformations and stresses even with the conservative assumption of fixed joint limited to the vacuum tight fillet weld and neglecting the structural intermittent weld, which will be actually performed.

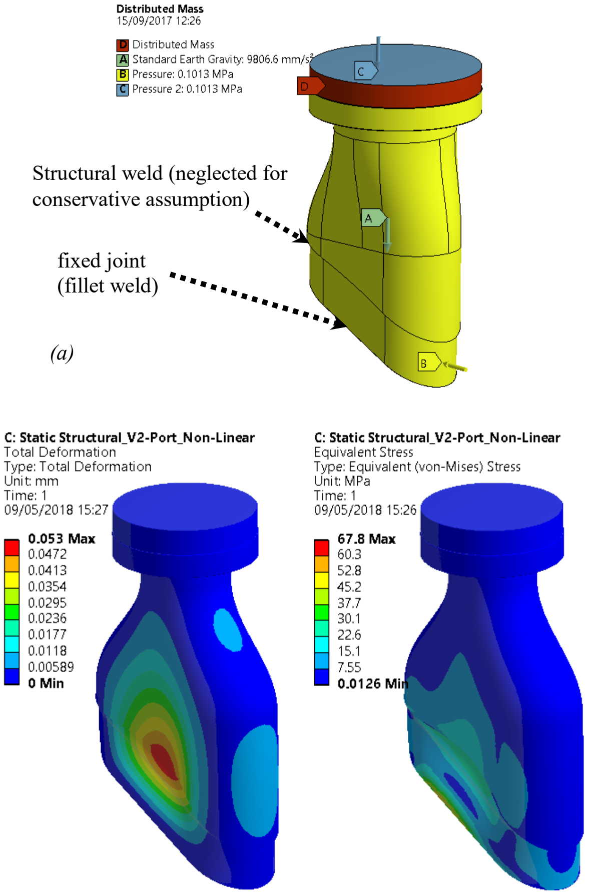

Fig. 4. Results of structural analysis of the worst case VTSS port (vertical port for in-vessel sensors cabling feedthrough DN63CF)
(a) loads and boundary conditions
(b) total deformation and equivalent stress

2.2 Implementation of poloidal and toroidal vacuum-tight electrical-insulated junctions

One of the most critical aspects in the new VTSS assembly is the requirement to guarantee vacuum tightness and electrical insulation at the present poloidal and toroidal gaps. In the conceptual design a solution for this issue was conceived with the use of a composite ceramic-metal brazed ring to be welded at the poloidal gap and a thin metal plate (with high electrical resistance) to be welded at the toroidal gap [3]. In the final design phase a different approach was adopted in order to allow the change of machine assembly sequence. Fig. 5 shows the concept of the vacuum-tight electrical-insulated crossed joints. Two VTSS quarters (lower and higher) are firstly horizontally tight joined by means of the existing stud bolts with interposed insulating spacers made of polyether–ether–ketone (PEEK) acting as “half gaskets”; vacuum tightness is provided by proper “CF knife-edge” manufactured on the two surfaces of the mating VTSS quarters. The two VTSS halves are then vertically joined (after insertion of the PSS as indicated in Fig.2) with interposed standard Viton O-rings (for vacuum tightness) and suitable PEEK and G10 fiberglass spacers (for electrical and structural function). This solution requires a precise machining of the two VTSS mating surfaces, to attain a maximum planarity error within 1mm. Possible errors are conceived to be compensated by the deformation of the O-rings (Ø 10 mm compressed with a squeeze of 30%).

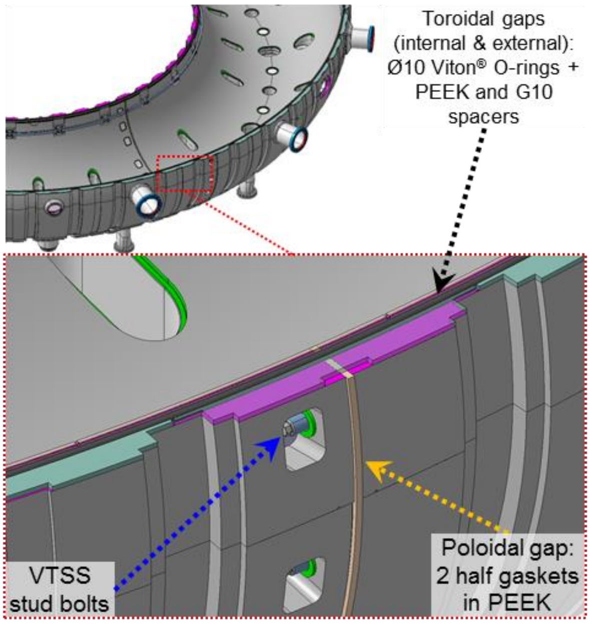

Fig. 5. Concept of the vacuum-tight electrical-insulated crossed joints of the VTSS

The crossing of the horizontal and vertical joints, which could be source of potential leakage, has been designed with a novel concept combining a particular geometrical shape and a selection of compatible

Fig. 6. Mock-up realized to test the VTSS vacuum-tight electrical-insulated crossed joints

materials; the patentability of this concept is presently under evaluation. To verify the reliability of the VTSS crossed joints a mock-up vacuum chamber has been manufactured and tested. Fig.6 shows the bottom part of the mock-up cylindrical chamber (Ø 0.5 m, $\ell = 0.8$ m) made of 4 segments, joined at the mid vertical and horizontal planes by means of spacers equivalent to those designed for the VTSS. The mock-up was successfully tested with helium leak detector that revealed maximum leak rate $Q_L<5\cdot10^{-9}$ mbar·l/s, which is considered acceptable for the operation of the RFX-mod2 vessel.

3. Passive Stabilizing Shell and First Wall

The RFXmod PSS is a copper toroidal structure, 3 mm thick, surrounding the VV and providing MHD stabilization of RFP plasma in short time length. This conductive shell must provide at least one electrical discontinuity in both toroidal and poloidal direction to allow the penetration of electromagnetic fields in the plasma region. In RFXmod2 the PSS is supported by a new set of 72 poloidal rings made of thermoplastic material (Torlon® PAI) and reinforced with steel plates, which are interfaced to a new set of rails on the VTSS, to guarantee support during operation. Each ring supports also the poloidal array of 28 FW tiles by means of a new set of stainless steel bushing which provide simultaneously the clamping of the PSS and the tiles [3].

The final design of the PSS for RFXmod2 was focused on the careful definition of the electrical topology of the in-vessel components, to minimize the risk of arcing which could occur during over-voltages induced in standard or abnormal operating conditions (plasma start-up or fast termination) [6].

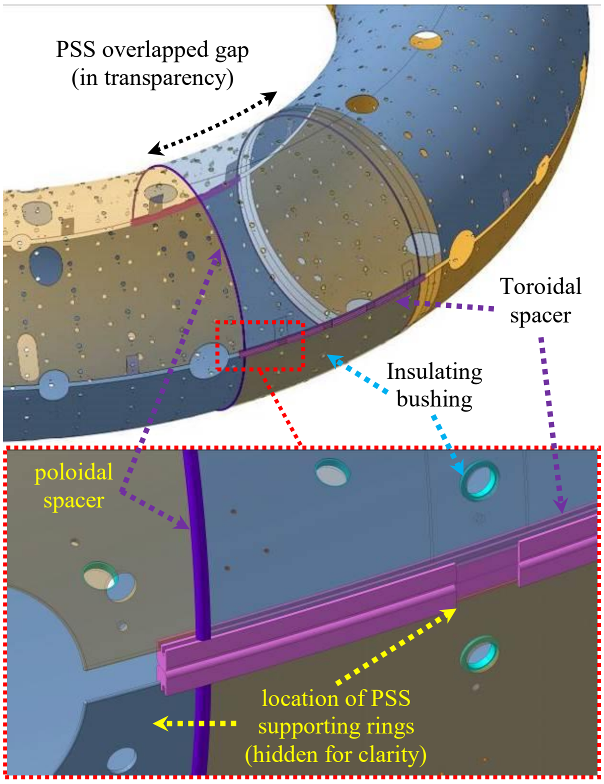

Fig. 7. Implementation of the overlapped poloidal gap of the PSS

3.1 Implementation of overlapped poloidal gap

The requirement to maintain an overlapped gap of the PSS spanning 30° along the toroidal direction, necessary to minimize radial error fields, entails the interposition of suitable insulating spacers at the critical points of the overlapped region, kept in position by compression exerted by 4 supporting rings (out of the total 72) suitably reduced in thickness. Fig.7 shows the insulating elements made of Torlon implementing the overlapped gap: bushing at each tile clamping (to keep the 2 overlapped surfaces at the nominal distance of 2 mm) and spacers along the edges of the overlapped surfaces (to avoid the penetration of ionized gas in proximity of sharp edges of the shell, where the increase of the electrical field could initiate a discharge). The use of Torlon for both supporting rings and insulating spacers was selected for its thermal expansion coefficient ($16\cdot10^{-6}$ K^{-1}) very close to the one of copper. For this reason no significant differential expansions and consequent stresses are expected to occur during operation.

3.2 Arrangement of the electrical grounding of invessel components

A further requirement was imposed on the electrical insulation of the FW with respect to the PSS and simultaneously the electrical connection of all the FW tiles to a resistive grounding grid in order to smooth and distribute evenly the electrical potential of the plasma facing components [6]. Fig.8 shows the solution implemented to fulfill the requirement of insulation between tiles and PSS, obtained with an insulating pad made of Torlon interposed between the tile locking bushing and the PSS. Fig.9 shows the resistive grounding grid connecting all the tiles, realized with stainless steel thin sheets which provide the prescribed global electrical resistances > 700 μΩ and > 50 mΩ along the poloidal and toroidal direction respectively.

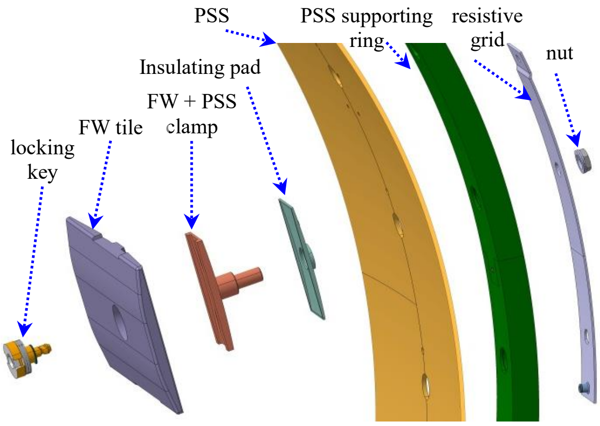

Fig. 8. Exploded view of FW + PSS clamping system.

Fig.10 describes the interface between VTSS and PSS obtained with 72 pairs of sliding and insulating supports (one pair at each PSS supporting ring) laying on 2 stainless steel rails attached to the VTSS. This solution guarantees the centering of the structures during installation and allows a maximum radial deformation of approximately 5mm of the PSS with respect to VTSS, expected for thermal expansion during baking of the FW at 180°C.

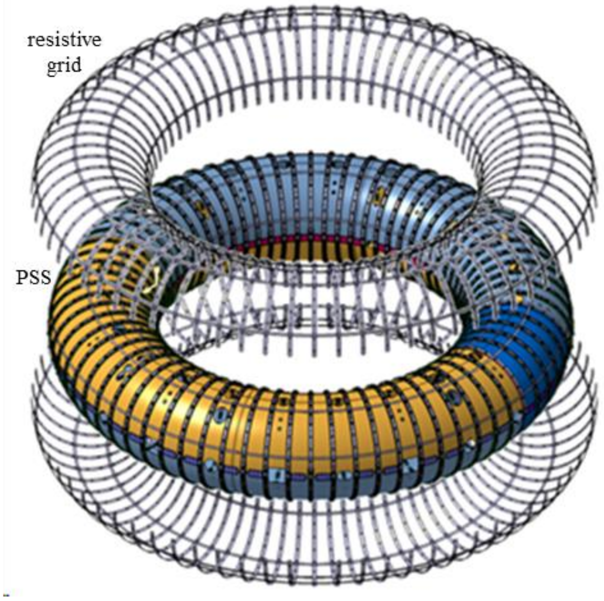

Fig. 9. Exploded view of the resistive grounding grid connecting the array of 72x28 FW tiles

Conclusions

The design of the RFXmod2 machine load assembly has been completed with substantial modifications with respect to the conceptual design phase, driven in particular by the revised top-bottom assembly sequence of the main components (PSS and VTSS).

Novel concepts have been developed to implement the vacuum tight electrical-insulated crossed joints at the present mechanical structure and to control the electrical topology of the plasma facing components, with proper insulation of FW tiles with respect to PSS and the inclusion of a grounding grid to distribute evenly the electrical potential of the tiles.

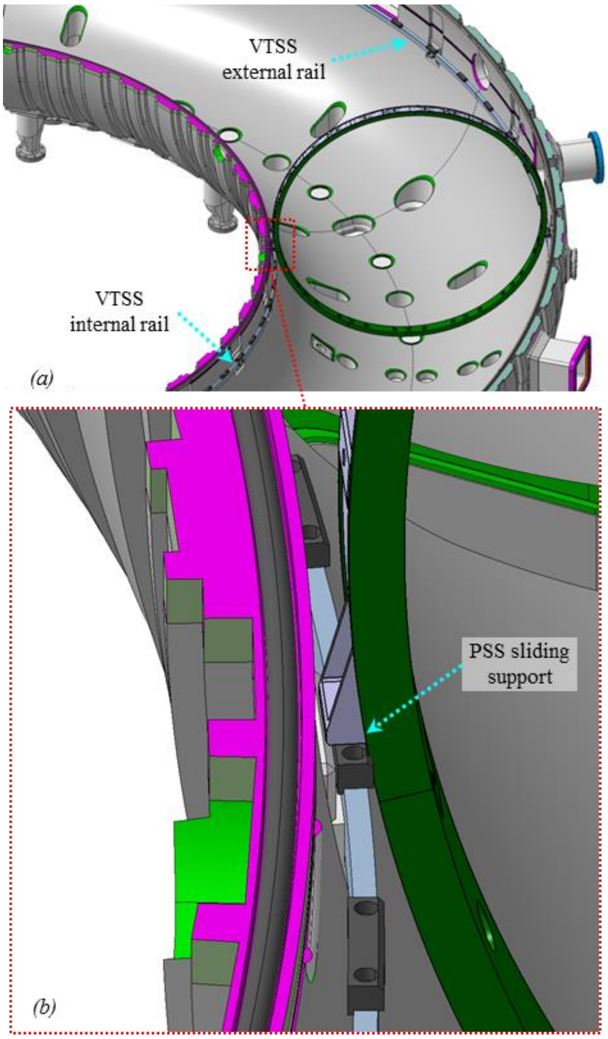

Fig. 10. Sliding and insulating interface between PSS and VTSS: (a) representative ring within VTSS; (b) detail of inner equatorial region

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