Progress Towards Steady State Systems For Fusion Devices

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Abstract. This paper deals with RF systems developments for steady state operation. RF systems are a key tool for high performances plasma studies. Long pulse operation at high power levels are made possible on Tore Supra tokamak, where very low or zero loop voltage can be performed. Recent experimental results are exploring the scenarios with combined RF heating, allowing both long discharges and high performances. In support to this scientific program, continuous efforts of developments of steady state RF systems are pursued. Upgrade of the LHDC system within the CIMES project –new PAM launcher and new transmitter-, test of a ITER like ICRH antenna, design proposal for a new LHCD PAM launcher for JET, or thorough study of a ICRH antenna for ITER. High power testing facilities are completing the design activities, and allow to assess the design choices.

1 Introduction

RF systems are widely used on magnetically confined fusion experiments. Developments during many years have produced RF systems which have supported the progress of plasma performances and opened up new areas of investigation. For the next step devices, long pulse operation is essential and it is a new challenge for the integration of the RF systems. They have to be highly reliable, with built-in strategies to recover from trips and breakdowns.

The Euratom-CEA association is operating the Tore Supra tokamak that can sustain long duration plasmas thanks to its superconducting toroidal field coils and full set of actively cooled plasma facing components. This device is still today a unique machine for testing any system in steady state operation. The Euratom-CEA association has developed over the years its knowledge and skill on RF systems development and integration. Three RF systems are presently operated on TS: ICRH, LHCD, and ECRH.

2 Experimental results

Active control of high power long discharges in steady-state within an environment relevant for ITER (i.e., actively cooled PFCs in the presence of fast particles) is one of main mission of Tore Supra. During the last two years substantial progress has been accomplished. Discharges lasting several resistive times with injected power exceeding 10 MW, combining ICRH (operating at various frequencies, 42 MHz/48MHZ/57MHz) and LHCD, have been achieved [1]. So far, the highest injected energy was 470 MJ: 4 MW/65 s ICRH pulse in a plasma sustained by 3 MW of LHCD (Fig. 1). These discharges have been performed at densities close to the Greenwald limit (f_G=0.7 – 0.93) and with a large fraction of non-inductive current (loop voltage ≤ 0.1 V). An example of such discharge (R=2.4m, a=0.72m,

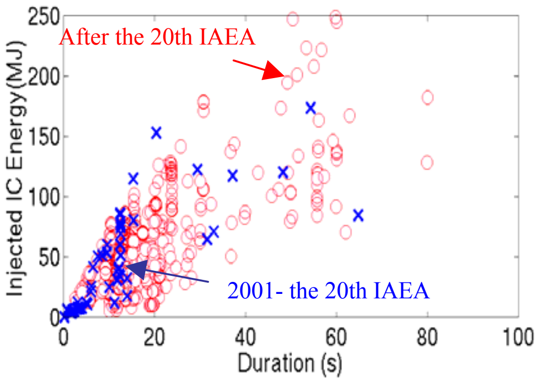

Fig. 1: Injected ICRH versus pulse duration; operations circles = during the last two years; crosses = before the 20th IAEA

Ip= 0.9MA, BT=3.7T, central line density of 6x10^{19} m^{-2}) is shown in Fig 2 . The ICRH power of 8.5 MW (at 57MHz) has been coupled into LHCD plasma using three antennas. Experiments combining ICRH with pellet injection have also been carried out. Several tens of pellets have been injected in experiments with up to 8MW of ICRH and 2 MW of LHCD. During the pellet injection, in spite of perturbed edge plasma the ICRH coupling was pretty well controlled, except the ICRF antenna located near the pellet injector [2].

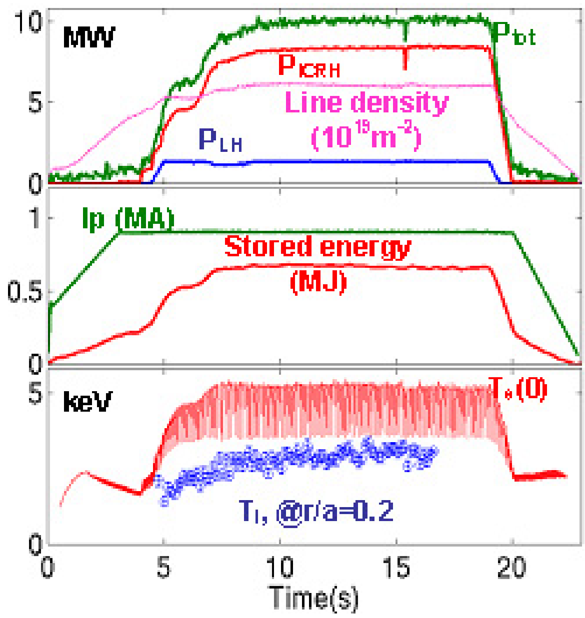

Fig. 2: shot 33612, Combination of ICRH (8.5 MW) and LHCD (1.4MW)

Controlling simultaneously plasma parameters, PFC and heating systems is necessary for high power steady-state operation. To accomplish this issue, many tools (IR cameras, hard X-ray tomography, and interfero-polarimetry/impurity diagnostics) and feedback algorithms have been developed to prevent overheating of RF antennae and PFCs, while maintaining the plasma performance in terms of MHD stability and confinement. New generation of IR cameras are used to protect the antennae in real time. Various hot spots on the antennae and associated heat sources have been identified [3]. An antenna IR picture, taken after 60 s of operation at 4MW ICRH power and 3MW LH power, is shown in Fig. 3. In this figure, different zones were identified: zone 1 (white): mainly sensitive to the total power; zone 2 (orange): mixed total ICRF power and private ICRF power; zone 3 (green): sensitive to LH power only; and zone 4 (red): predominantly private ICRF power. This study allowed to achieve the successful integration of feedback controls, including the IR system and Hard X-ray tomography. Discharges lasting one minute with 7 MW total injected RF power have been maintained in MHD stable condition, keeping the RF antennae in the safe domain [4].

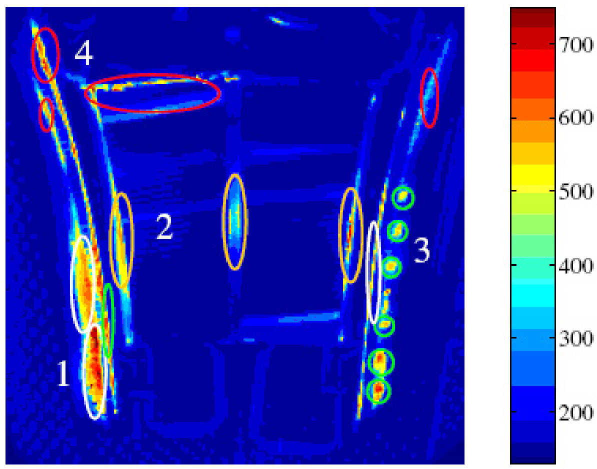

Fig. 3 : IR image of IC antenna, at t = 63.7s, in a combined ICRH (4MW)/LHCD (3MW) discharge (Unit is ◦C,

3 RF systems development

3.1 CIMES project

The major role defined for Tore Supra within the European Fusion Programme is the integration of all the various physics and technology aspects that are required to achieve and investigate high–power, long-duration plasma discharges The physics results in Tore Supra depend strongly upon RF systems development. The Tore Supra LHCD system is presently being upgraded within the CIMES project to extend the pulse duration to 1000s [5].

The new heating and refuelling systems will allow Tore Supra to explore two broad categories of discharges; one primarily aimed at testing fusion technology, the other at exploring advanced tokamak physics. Representative parameters corresponding to the operating boundaries at zero loop volts are summarised in table I.

Goal	Fusion Technology	Advanced tokamak physics
Heating power	12 MW 1000 s	19 MW 30 s
Density	~ 1.5×10^{19} m^{-3}	~ 3.8×10^{19} m^{-3}
Edge q	~3	~5.5
Current at 4 T	1.4 MA	0.8 MA
Bootstrap fraction	~ 20 %	~ 50 %
Profile control	None	Essential
H factor	H~1	H~2

Table I: summary of operating limits for CIMES-1

The higher-current, long-pulse discharges, with currents up to about 1.4 MA will be used primarily for fusion technology testing. Higher-density, lower-current discharges will be used to study advanced confinement modes. In such cases, the fully non-inductive plasma current would consist of approximately equal amounts of LH and bootstrap currents, the latter mainly sustained by the strong plasma pressure (βN would exceed 2). Gas puffing, supersonic jets and pellet injection will be used. An example of operational domain is shown in Fig. 4.

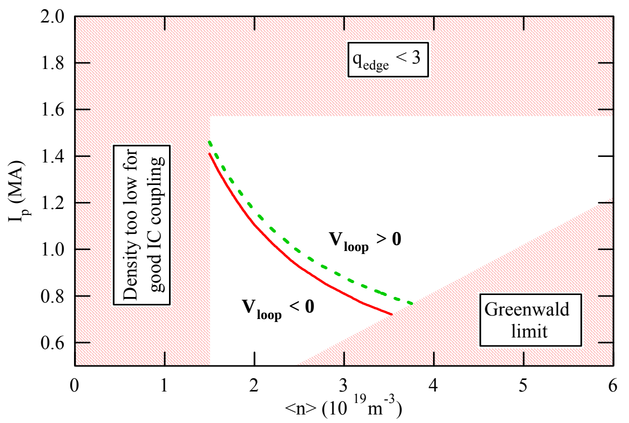

Fig. 4: plasma current vs. mean plasma density for the 30 s pulsed (green dashed curve) and steady state (red solid curve) scenarios.

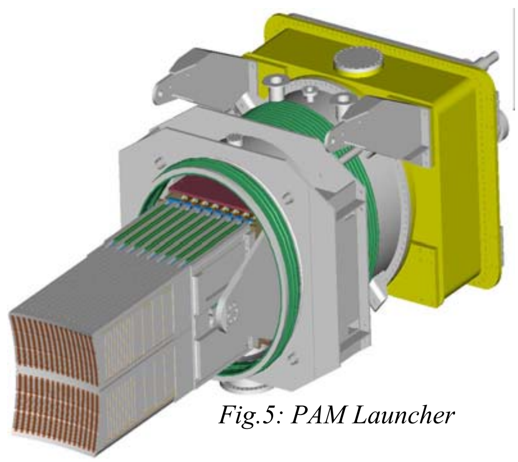

Fig.5: PAM Launcher

The CIMES targets to inject 8 MW of LH power to be coupled steady-state into Tore Supra. This requires a new LHCD antenna [6], which will be an opportunity to test the PAM concept on long discharges. The present Mk I launcher will be replaced with a new launcher (Fig.5) based on the PAM concept : it allows to bring the cooling channels in the walls between the active guides at the back of the passive waveguides, thus providing neutron shielding and cooling where necessary. The concept has been briefly tested on FTU, in collaboration with CEA. The new PAM LH launcher has been studied, designed and is presently under realisation. It should be completed in the end of 2007 and operational for TS experiments in spring 2008.

The amplifier chains also will be upgraded with new, higher-power klystrons to deliver about 5.6 MW per launcher to allow for transmission losses, reflected power and to provide a margin for reliable operation under steady-state conditions. An in-depth transformation of the transmitter will use new CW klystrons specially developed to deliver 700 kW on a load presenting a VSWR up to 1.4, any phase. The prototype tube is under tests at the factory : it has delivered more than 700 kW on matched load during hours, and the nominal power of 750 kW has been demonstrated. On VSWR= 1.4, the power has reached 680 kW on the most unfavourable phase, where the output power is limited by thermal limits. Beam instabilities have however been observed when the power or the cathode voltage are scanned : further studies are needed to cure the problem. It is planned to upgrade the first part of the transmitter for the 2008 experimental campaign. The integration of this klystron includes a specific on/off solid-state high voltage switch (100kV, 25A) using an array of MOSFET transistors for protection with a recovery scheme [7]. The transmitter's control system will be able to switch back on any klystron that has shown transient alarm or default.

These developments are supported by a corresponding development of the test facilities. A dedicated LH test bed has been upgraded and used to check individual components such as RF 4-port switch, window, power combiner, flange cooling, and even an intermediate tube prototype which delivers 500KW CW at 3.7GHz [8].

3.2 ITER-like ICRH antenna

A prototype ICRF antenna has been built for Tore Supra using the conjugate-T concept proposed for ITER (Fig.6). It has been already tested in 2004 in moderate power and pulse length (600kW/6s). Improved diagnostic and control systems have been implemented for the automatic control loops and the matching experiments which are in progress. These experiments complement the JET-EP antenna experience on JET, and help to document choices for the ITER ICRF antennas.

The automatic matching scheme on present antennas is only compatible with load variations slower than its characteristic response time (100ms). To cope with fast transients expected on ITER, such as Edge Localized Modes (ELMs) or pellet injection (see below), a new electrical circuit intrinsically resilient to load variations was proposed [9]. A Tore Supra prototype 2×2 strap array featuring this “ITER-like” scheme (also called “conjugate-T”) is outlined on figure 3 : on each side of the antenna it consists of two straps separated by a horizontal septum, short circuited on one end and connected to a variable capacitor at the other end. The two capacitors are connected side by side by a bridge, fed by a 2-stage impedance transformer from the standard 30 Ω transmission line. The capacitances are feedback controlled by dielectric rods.

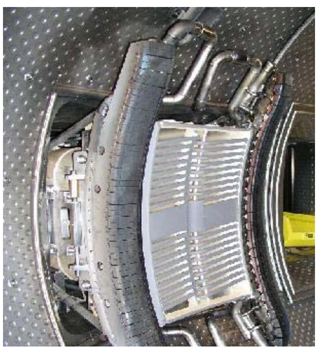

Fig.6: ITER-Like antenna in Tore Supra

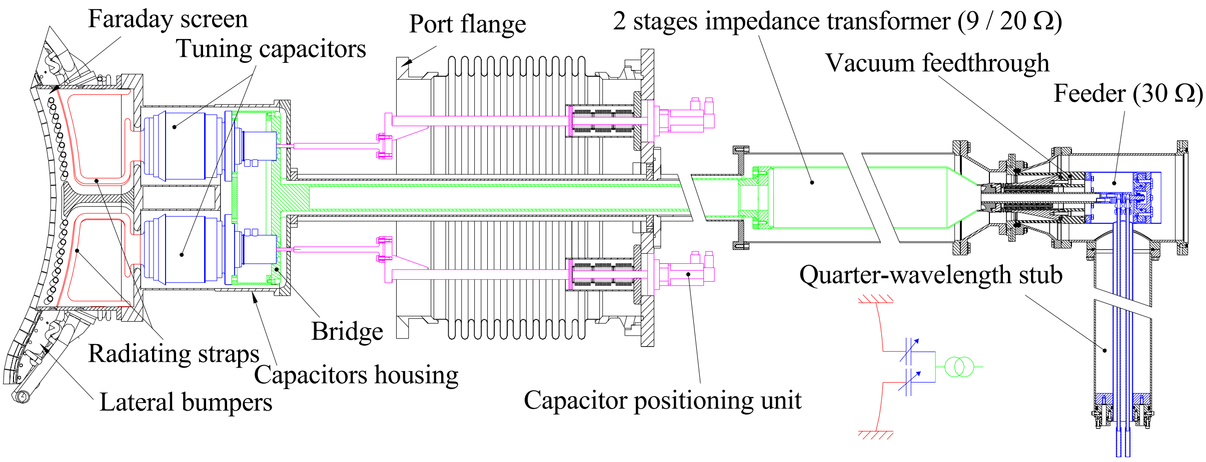

***FIG. 7 :** Layout of the ITER-like antenna prototype tested in 2004, featuring in color the different subsystems. red : radiating straps; green : vacuum feed (9Ω) and 2-stage impedance transformer (9/20Ω); blue : tuning capacitors ; dark blue : quarter wavelength stub ; magenta : capacitor positioning units.*

The design is detailed in [10]. This ITER-like prototype was tested at low power and commissioned at high power on Tore Supra in 2004 [11]. On test bed a significant interaction between the two toroidal resonant sections of the array was found, and on plasma pulses an increased sensitivity to power balance was observed, compared to standard TS antennas. The best performance achieved was 500kW during 6s with a power reflection coefficient lower than 10%. The settings of the capacitors for most of the successful shots were very close to vacuum match settings, which is a first hint of load tolerance properties. This indication could not yet be confirmed by varying for example the plasma-antenna gap or the plasma density.

These preliminary results motivated an assessment of load resilience properties of IC ITER-like structures (ILS) in presence of coupling terms and asymmetries in the array input impedance matrix [12]. Load resilience of one ILS is obtained by the conjugate symmetry between half sections currents, which can be maintained by a suitable control system in each branch. When this is done, the input impedance of the ILS writes $Z_{in}=R_0+ik_pX_s$ where R_0 is the characteristic impedance to be matched, k_p is the coupling coefficient between half sections and X_s the average reactance of the two half sections. The reactive part of Z_{in} causes a mismatch, and the amplitude of VSWR depends on the ratio $|k_pX_s|/R_0$. Increased sensitivity of the Tore Supra prototype comes from the low value of R_0 (4 Ω *vs* 30 Ω in standard TS antennae). For low $|k_pX_s|/R_0$, the mismatch can be accepted by the power source. Otherwise, the reactive term can be cancelled by the addition of a small reactance in the impedance transformation. Due to toroidal coupling terms in the input impedance matrix, an accurate vectorial control at a toroidal symmetry condition ("monopole" or "dipole") of the array currents is also needed in order to prevent power circulation between adjacent ILSs and to control array instability.

The antenna has been modified with a new toroidal septum to reduce toroidal coupling between ILSs. RF current measurements in the resonant part of the RF circuit have also been implemented for strap current control. Associated with a dedicated feedback control scheme [13] they should allow to find automatically the 2×2 array match point in dipole or monopole toroidal phasing. The new RF measurements will also be more sensitive to the presence of arcs than previous ones located in the feeding lines, which proved inefficient to detect breakdowns in the prototype [11]. The present prototype is a small evolution of present Tore Supra antennas only intended to validate the ITER-like electric scheme during short RF pulses.

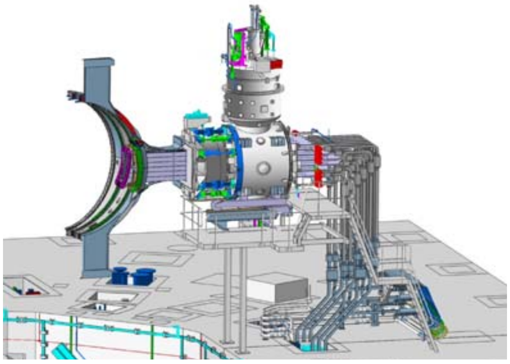

Fig.8: PAM launcher as inserted in JET port, fed by its 36 waveguides transmission line

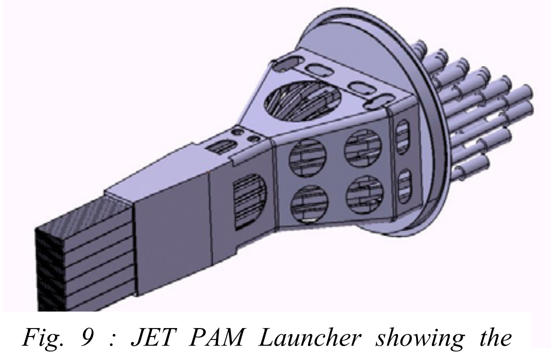

Fig. 9 : JET PAM Launcher showing the mechanical structure which holds the wave guide array from the back flange

If these tests are conclusive, the prototype could be upgraded to allow operation of the ICRF system in the range 9MW-1000s. [14].

3.3 PAM LHCD launcher

In parallel with this kind of in-house developments, projects are designed for other laboratories, as JET, FTU, and EAST for example or for the future ITER.

A fully documented study of a PAM launcher for JET (Fig.8) has been proposed in February 2005, with scientific and technical evaluation on any aspects of this new antenna : coupling, thermo mechanical, thermal, disruption induced stresses, technological choices, diagnostics, testing techniques, vacuum techniques, as well as costing and schedule. This project was a coordinated effort from many contributors in Europe, driven by the Euratom-CEA association [15]. The project was finally put on hold for financial reasons.

Similarly to the present JET launcher, this PAM version (Fig.9) is composed of 6 horizontal rows of modules. For a N// peak value of 1.83, there is be 6 modules per row. Therefore that leads to 36 modules fed by 18 klystrons. The power is divided by two, using hybrid junctions inserted in the transmission line. Each module as on present JET launcher is made of a double disk BeO pillbox type RF window followed by a hybrid junction. The two output waveguides are then split in the E plane. Geometric phase shifters will be included in order to obtain the correct launched spectrum, taking into account the front face curvature matching the single null plasma edge. The target coupled power is ~6MW at a mean power density of 25MW/m² in the active waveguides.

A proposal for the ITER LHCD launcher has also been proposed in [16]. It is a PAM launcher array with more than 1100 waveguides arranged in a port plug to deliver 20 MW to the plasma.

3.4 ITER and ICRH antenna

Euratom-CEA association has been long contributing to the design of ITER RF systems.

Studies are progressing in the detailed definition of an ITER ICRF antenna that would deliver 20 MW to the ITER plasma. This design is based on the conjugate-T concept that allows to minimize the loading perturbations due to the ELMs [17]. It is a compact design in which the tuning elements are located in a private vacuum within the port so that high voltage areas are limited to a small volume, giving thus a noticeable margin for low coupling.

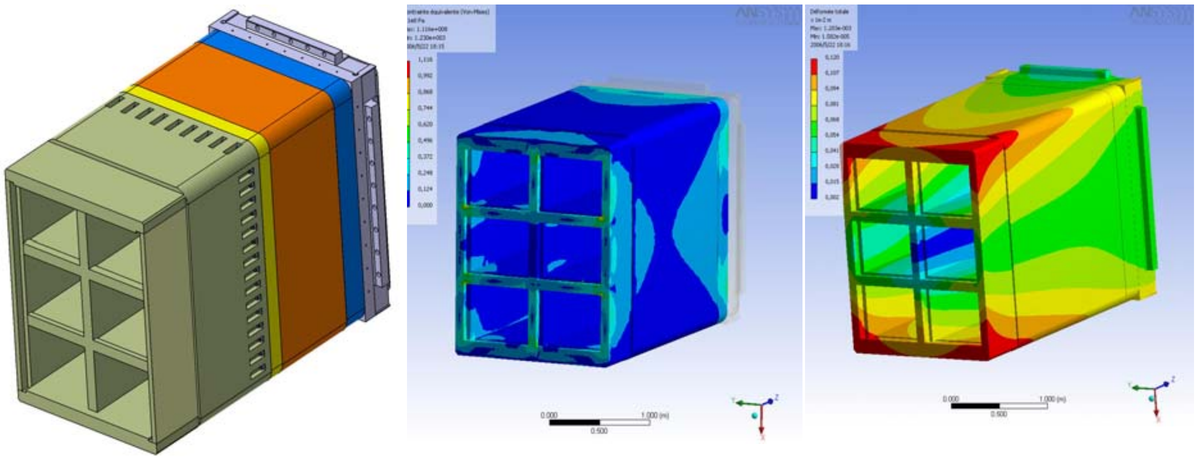

Fig.10 : a) Plug overview,   b) Stress distribution Von Mises Max=116 MPa   c) deformation (Max= 1.2mm)

Two antenna designs are presently in a conceptual study phase in Europe. They differ by the position where the matching elements are implemented in the system. An external match is using conventional components located outside the cryostat envelop, while an in-port design is incorporating variable impedances close to the resonant loops. A brief description of this second option is given hereafter.

This antenna is located in a horizontal port (Fig.10). It has to deliver 20MW to the plasma on the whole range of IC frequencies. It is built inside a port plug similar to the one used for any RF heating system. This plug has to withstand the electromagnetic forces that could appear during a plasma disruption. A modular construction is chosen in order to prepare and tests 6 modules subassemblies which are inserted in the plug. The modular approach will also ease the handling, maintenance and qualification to reduce cost/time of all technical intervention foreseen on the antenna [18].

A module is a double resonant loop structure with integrated variable impedances to perform the matching to the generator impedance. Each module consist of a front part (Fig.11) in the torus vacuum, which is separated from the rear part (Fig.12) by a vacuum boundary. The matching components are located in the rear part, in a private –and controlled- vacuum. A second vacuum boundary isolates the coaxial lines from the main transmission lines running in the building to the generators.

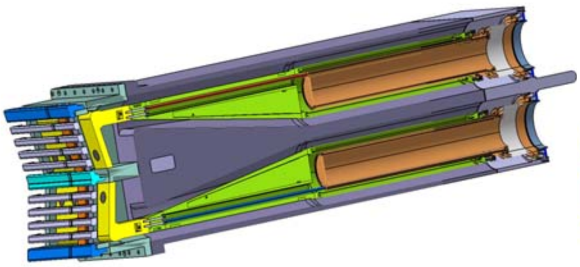

Fig.11: front part of module

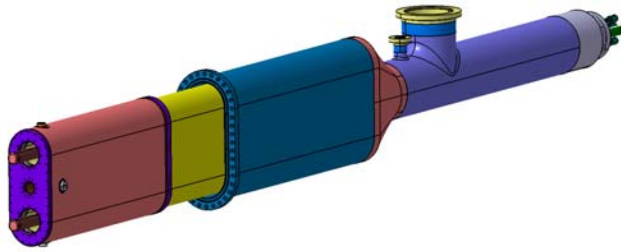

Fig.12: rear part of module

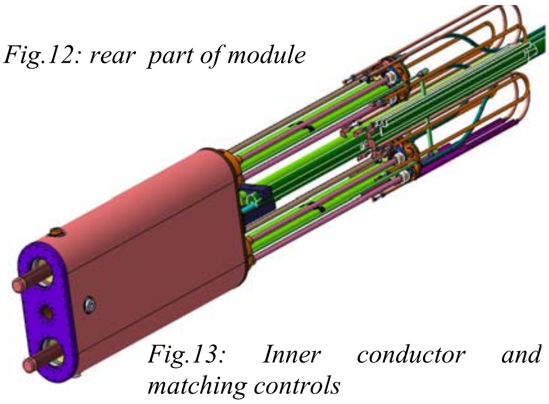

Fig.13: Inner conductor and matching controls

The rear part inner conductor (Fig.13) has a vacuum section containing the adjustable impedances, and a section vented to atmosphere where driving and guiding mechanism are located. The mechanical control and cooling circuits are run to the inside of the inner conductor through a quarter wavelength service stub.

The antenna design is still evolving, and supported by a R&D program under EFDA contracts. The detailed design should start early in 2008, in order to implement the heating system for the first plasma operation of ITER.

4 Conclusion

The Euratom-CEA association has built a solid experience in the design, fabrication and experimentation of steady state RF heating systems. First level results are obtained on Tore Supra, where advanced scenarios can be studied on long lasting discharges. The know how and the experience are presently used to prepare the detailed design and procurement of ITER RF systems, together with experiments supporting the R&D steps on Tore Supra or dedicated test beds.

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