CONSORZIO RFX
Ricerca Formazione Innovazione

2011 Activity Report

1. INTRODUCTION AND KEY OBJECTIVES

The 2011 programme of Consorzio RFX was presented and evaluated at the 25th meeting of the RFX Scientific-Technical Committee on 16 November 2010. The programme was endorsed by the Board of Directors of Consorzio RFX on 29 November 2010 and by the Steering Committee of the Euratom-ENEA Association on 14 December 2010.

Final approval of the programme, together with the associated relevant budget, was given by the Consorzio RFX Management Board on 20 December 2010.

The programme was focused upon the following main objectives:

– contributing to the magnetic fusion concept by the scientific exploitation of the RFX-mod device both at high current in RFP configuration and in tokamak configuration with experimental activities, theoretical analyses and modelling;

– to start the construction of the ITER Neutral Beam Test Facility and progress in the design and realization of its components;

– to progress on the realization of the quench protection system and the fast power supplies for JT-60 SA in the framework of the Broader Approach scheme;

– to participate in the realization of the magnetic sensors and the LIDAR diagnostic for ITER.

Relevant events which affected the activities during the year were: persistent difficulties in the budget which resulted in reduced investment capability, an unforeseen limitation for the execution of tests in tokamak configuration due to the requirements of Italian licensing rules and the very long time required to finalize the Agreement between F4E and RFX for the Neutral Beam Test Facility.

Despite these constrains, a significant advancement has been obtained in all the previous objectives.

On 13 December, at the ITER site in Cadarache, F4E Director, Dr. Briscoe, and RFX President Prof. Gnesotto signed the Agreement on the Neutral Beam Test Facility, which definitively confirmed the realization of the Facility in Padova and gave the green light to its construction. This fundamental step rewards Consorzio RFX of the great effort made in these years, with study, design and research activities qualifying Consorzio RFX as a laboratory, with integrated competencies in physics and engineering, able to drive the R&D for the ITER NBI.

In view of this result, in 2011 most of the scheduled design activities foreseen in the Grants with F4E were completed, mainly related to SPIDER, and several call for tenders for its components could be launched. Also the NBI accompanying activities have had substantial improvements with successful tests in vacuum at 300 kV, and the start of the realization of the ion source NIO1.

RFX experimental activity included 32 weeks of operation and 7 weeks for different wall conditioning. Experiments were slowed down by a fault in a saddle coil which occurred in its electrical terminal, and by subsequent time dedicated to its assessment and additional shots needed for full current operation recovery.

Nevertheless, significant advancements in all the crucial topics (high current operation, MHD control and 3D physics) have been obtained as reported in Chap. 2. They are mainly related to the optimization of the 2MA discharge setting-up in different first wall conditions, to a better experimental characterization of the dynamics of the helical states, to testing the control of m=2, n=1 mode at q(a)<2 in tokamak configuration and to a deeper comprehension of transport in helical states with a 3D physics approach.

The 2011 diagnostics development programme was significantly hindered, for the third consecutive year, due to the budget limitation, with a consequent further delay in some projects. Nevertheless some important progress in the diagnostic capability was achieved, in particular in the area of time and space resolved electron and ion temperature measurements.

MHD simulations have been the main focus of the theory and modelling programme, with first MHD simulation of the RFP in toroidal geometry: evidence of non stationary QSH states similar to the experimental one. New results were obtained on: the kinetic stabilisation of RWMs in RFP, a new technique for transport profile calculation, and other important issues, as reported in Cap. 5.

The 2011 Tokamak programme has mainly been concentrated on edge turbulence, impurity transport, 3D physics and MHD control, with a particular emphasis on topics where the RFP may give a significant contribution to the wider fusion community.

Significant advancement was obtained in the realization of the Quench Protection System for JT-60SA. The activity progressed in line with the schedule of the contractual activities: the built-to-print design was completed and the first tests on the prototypes were successful.
Finally, in September 2011 the procedure to obtain the ISO9001 certification was completed and the Certificate obtained.

2. RFX-MOD AND RFP PHYSICS

2.1 Background

In agreement with the 2011 activity program, the RFX scientific program in 2011 has been implemented through four projects:

Project 1: Exploration, understanding and improvement of RFX performance at plasma current above 1.5 MA

Project 2: Advancing feedback control of MHD stability in fusion devices

Project 3: Fusion physics in a three dimensional configuration

Project 4: Goals and directions for potential upgrades of the RFX experimental facility

Advancements have been done in all the projects, including project 1, though a fault of one of the 192 saddle coils in March has temporarily slowed the exploration of the highest current regimes, requiring a careful experimental evaluation of possible severe localized plasma wall interaction at the location of the missing coil. Since the plasma performance has not been found to be significantly influenced, discharges up to 2 MA plasma current (target value for RFX) have been performed. The exploration and optimization of the plasma confinement at high plasma current has progressed thanks to

- specific experiments dedicated to the study of the density control, an important issue for RFP plasmas
- new diagnostics allowing a better characterization of the dynamics of the helical states.

A significant part of the experimental activity has been devoted to the crucial topic of MHD control (project 2): in particular, experiments with the application of helical boundary conditions have been performed, of particular interest to understand the transition to the RFP helical equilibrium. Important results have been obtained with the operation in Tokamak configuration, where the full control of the m=2, n=1 mode at $q(a) <2$ has been demonstrated. These experiments, and the first tests to produce in RFX-mod a tokamak plasma with a double null magnetic configuration, raised wide interest in tokamak laboratories, strengthening the collaborations between RFX and the tokamak community.

The activity in 3d physics, started in the past years with a large synergy with the stellarators, has progressed in 2011, both for the magnetic equilibrium reconstructions, where the V3FIT code is being coupled to VMEC, and in the application of transport codes for a deeper comprehension of the helical states.

As to project 4, an activity has been started to identify possible modifications of the machine, aiming at assessing the potential of the RFP confinement scheme and in general at contributing to key areas of fusion science in view of ITER and DEMO.

The experimental program has been built on the basis of a public call of experimental proposals, open to internal and external researchers. More than 100 proposals have been submitted, about 20 of them in collaboration with external laboratories. The proposals have been collected and processed by two thematic Task Forces:

- physics integration for high performance RFP
- active control of RFP and Tokamak plasmas

The scientific programme produced by the elaboration of the proposals has been discussed in the RFX-mod programme workshop, held from 7th to 9th February, before the beginning of the 2011 campaigns.

The main operation schedule resulting for the 2011 experimental campaigns of RFX-mod is shown in fig. 2.1.1. It includes 20 weeks of shutdown for machine and diagnostic maintenance, while experiments have been distributed in 32 weeks of operation. Among them, 5 were in low current Tokamak configuration. The experiments in Tokamak configuration were then interrupted because the detection of a low amount of radiation with energy greater than 200 keV made necessary a licensing procedure presently in progress. The operation in Tokamak configuration will be recovered in 2012.

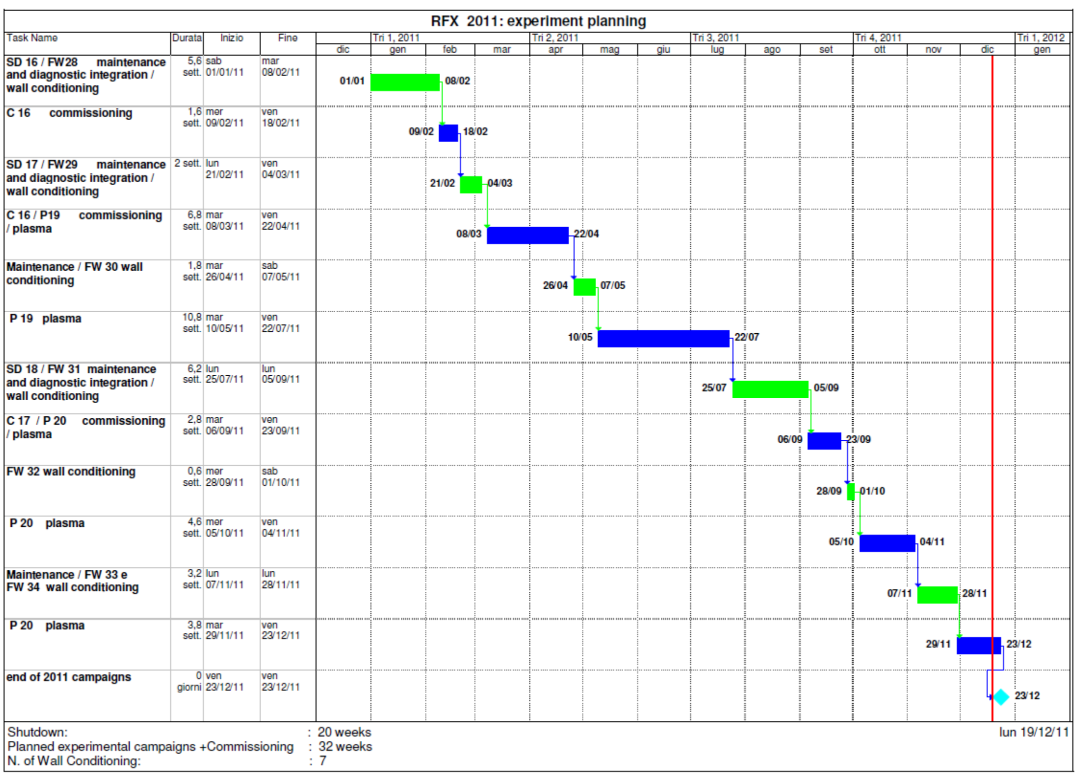

Fig.2.1.1: RFX-mod program schedule for 2011

2.2 Project 1: exploration and understanding of RFX-mod performance at plasma current above 1.5 MA

2.2.1 Density and first wall control

The issues of density and first wall control are strictly connected in RFX-mod since the plasma-facing material is graphite, which is known to store huge quantities of Hydrogen atoms and to release them during operation as a result of plasma-wall interaction. For this reason, in order to operate with plasmas at a desired electron density, it is necessary to control the status of the wall (i.e. the Hydrogen content) and the plasma-wall interaction (PWI), as well as the fuelling of the gas. In RFX the absence of limiter or divertor means that the PWI location is the whole wall and makes its control a matter of magnetic boundary control: the 2011 advances on this subject are extensively described in section 2.3.1. Actions taken in 2011 have been:

- Characterization of Glow Discharge Cleaning (GDC) wall-treatment plasmas in different conditions within the operational ranges of the GDC plant, with a set of appropriately arranged diagnostics.
- Test and characterization of GDC plasmas produced in presence of a toroidal magnetic field, in order to alter particle transport and to study the effect on the spatial uniformity of the wall treatment.
- First test of an operative procedure with a short He GDC performed between plasma shots.
- Extension of the database of discharges following different wall treatments and with different gas fuelling techniques, in order to study the impact on plasma performances. The analysis of such experiments is presently in progress.
- Supply of Lithization devices: the Lithium evaporator damaged during operation in 2010 has been repaired by the manufacturer and delivered in September of this year. A scientific collaboration with PPPL Laboratory, Princeton, USA, has been set up for the supply of a new multi-pellet launcher. More details on the latter are given in section 6.13.

Characterization of GDC plasmas

In RFX different types of GDC plasmas (process gas H_2, He or a mixture of He and B_2H_6) are used as wall treatment procedures. During 2011 a number of RFX diagnostics has been appropriately set in order to allow a characterization of these cold and weakly ionized plasmas in the different available operative conditions. The set consists in electrostatic probes, to measure ion density and voltage drop at the edge of plasma; visible/near-IR cameras, to monitor possible arcs or other macroscopic events; spectroscopic monitors at different positions, to determine the presence or appearance of species during the treatment procedure and their spatial uniformity; a manipulator for graphite sample insertion and post-mortem analysis. These new tools support the diagnostics already implemented in 2010, i.e. sample manipulators in other two positions, and the standard available measures such as anode current/voltage, gas pressure, residual gas analyzer (RGA).

The characterization has been done for GDC plasmas of H_2, He or a mixture of He and B_2H_6 gas, with cold/hot (170°C) wall, varying the number and position of the electrodes sustaining the discharge, the gas pressure, the anodes current/voltage, using or not the ionizing filaments and varying their number and position, using or not the RF power fraction that can be added to the DC power supply of the anodes. A strong toroidal non-uniformity of ion density at the edge, giving the measure of the effectiveness of the physical sputtering, i.e. the wall cleaning process during the GDC, has been measured by electrostatic probes independently from the used gas, with peaks localized at the toroidal positions of the anodes and of the filaments. A very similar pattern has been inferred from the analysis of the samples exposed to the GDC plasma and from spectroscopic monitors. The non-uniformity was mitigated by increasing the gas pressure towards the plant limit, a behavior that has been interpreted as due to the progressive transition to a regime, characteristic of glow plasmas, where the electric field produced by the electrodes is screened by the plasma itself. Anyway, within the plant limits the non-uniformity could not been avoided. A different toroidal pattern of ion density has been measured when operating with hot wall; the interpretation of these measurements is in progress.

GDC plasmas made in presence of a toroidal magnetic field

An attempt to obtain a uniform treatment of the wall has been made by GDC plasmas produced in the presence of a toroidal magnetic field. The idea was to induce a parallel transport of the ions produced at the electrodes along magnetic field lines. A magnetic field up to 7 mT has been applied; the effect on the uniformity of ion density has been opposite to what expected, with an accentuation of the localization at the anode positions. The physical reason of this behavior is under study.

Experimental campaign with GDC between shots

In 2011 a possible operative procedure, used in several fusion experiments, has been explored in RFX-mod at 1.2-1.5 MA of plasma current. Some minutes of GDC were performed at the end of each plasma discharge aiming at keeping the wall in a clean and empty state, and to control the density by gas puffing. GDC duration in the range 5-20 minutes and different waveforms for gas puffing have been explored. This first test showed that a full graphite wall makes density control difficult even with this operational approach: the non-uniform GDC likely left non-cleaned portions of the wall, occasionally producing localized PWI events with fast density growth ultimately causing the discharge termination. In addition, 5-10 minutes of inter-shot GDC were not sufficient to prevent a progressive increase of density during the experimental session, associated to the graphite saturation.

2.2.2 Scenario development

In 2011 several experimental campaigns have been dedicated to the exploitation of high plasma current operations obtaining more than 200 plasma discharges at current higher than 1.5 MA. Particular attention has been given to the optimization of the 2 MA discharge setting-up in different first wall conditions (in particular pre and after boronization, as described in the previous section 2.2.1).

Discharges with plasma current around 2 MA have been obtained with good reliability; an example is given in Fig. 2.2.1. In the last years it had been demonstrated that the best performances of RFX-mod are obtained predominantly at shallow F ($-0.05 \leq F < 0$); in 2011 an exploration of a wide range of plasma equilibria in terms of F parameter, which was made possible by the reliability of the feedback control system for the F parameter itself, allowed to clarify its role on the spontaneous generation of quasi-single helical (QSH) states, characterized by improved energy confinement properties.

In Fig. 2.2.2 the clear dependence of the normalized amplitude of the dominant m=1/n=-7 mode on the F values is shown. A maximum for the normalized amplitude of the dominant mode is actually found for plasmas with extremely shallow reversal (F≈-0.01). In this respect, the role played by the m=0, low n (≤ 2) mode numbers has been highlighted, as shown in Fig. 2.2.3, where the normalized amplitude of such modes is shown as a function of the F parameter. The decrease of the amplitude of the m=0 modes at shallow F, which induces a reduction of the non-linear coupling of m=1 modes at different n's, together with the high amplitude of the dominant m=1 mode, is believed to play an important role for the pureness of the quasi-single helical states towards the Single Helical Axis state (SHAx).

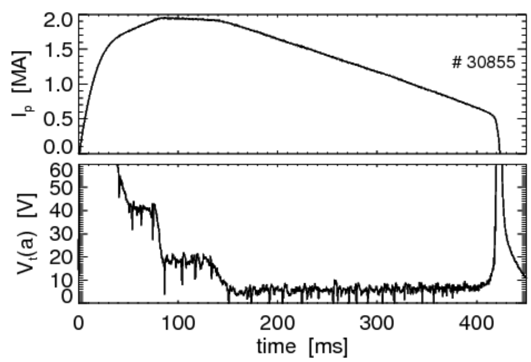

Fig.2.2.1: Typical time traces of plasma current (top) and toroidal loop voltage (bottom) for a 2MA discharge.

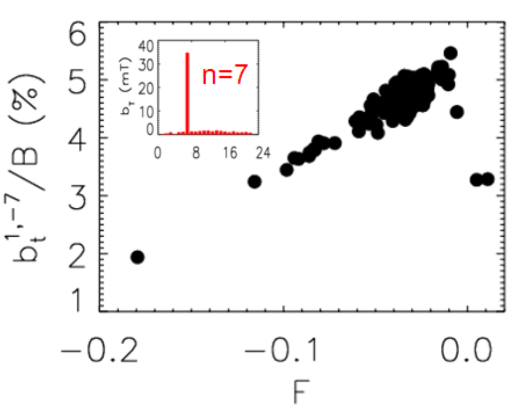

Fig.2.2.2: Normalized amplitude of the m=1, n=-7 mode (toroidal field component) vs the F parameter.

With the aim of obtaining relatively high Greenwald fractions of the electron density even at the highest plasma current values, pellet injection and impulsive gas puffing techniques have been extensively used and compared reaching transiently n/nG ≈ 0.25 in well sustained plasmas.

Pellet injection has been also used in lower plasma current regimes and deeply reversed plasmas as a particle source for the m=0 island chain resonating at the field reversal surface, in order to investigate particle confinement properties of the edge magnetic structures.

Particular attention has been dedicated to the analysis of the effect of the failure of the saddle coil for the feedback control system (located at ϕ=60°, θ=180°) on the plasma performance at the highest plasma current levels. From the point of view of the plasma quality, in terms of energy confinement, no clear effects have been observed, which is reflected in toroidal loop voltage values for plasma sustainment comparable to that measured during the operations with the feedback control system fully active.

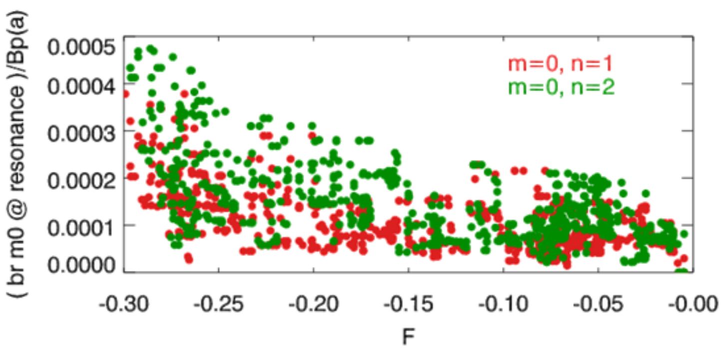

Fig.2.2.3: Normalized amplitude of m=0 n=1 (red) and n=2 (green) modes as a function of the reversal parameter F.

However, the lack of a full coverage for the MHD control is found to have an impact on the distribution of the vacuum chamber temperature, the analysis of which shows a localized heating source at a position close to that of the missing coil. It must be said that the increased temperature values measured during the experimental operations have always been comparable to those associated to other field errors, such as that due to the slight unbalance of the toroidal field system. This is shown in Fig. 2.2.4, where the distribution of the variation of the measured temperature values evaluated after few shots is plotted as a function of the toroidal position, for a given poloidal one.

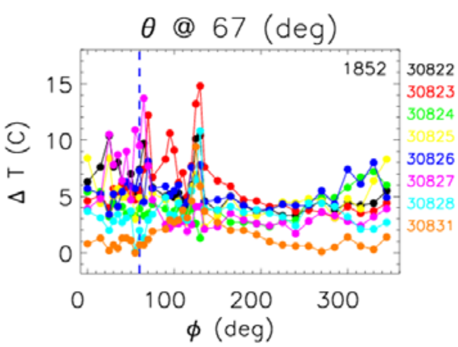

Fig.2.2.4: Variation of the vacuum chamber temperature after few shots as a function of the toroidal position evaluated at θ=67°

In summary, the experimental activity has not been negatively influenced by the fault of one saddle coil, though its position remains associated to a greater localized error field.

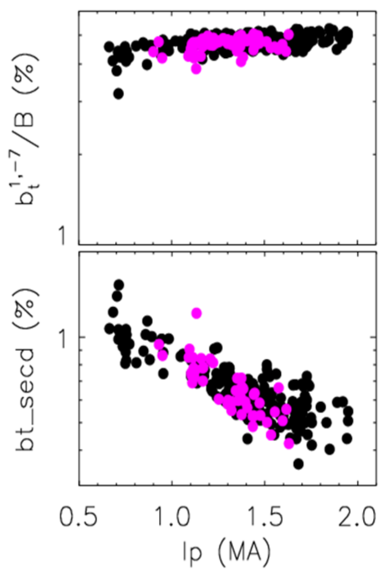

Fig.2.2.5: Saturation level of toroidal field component of the dominant (top) and secondary modes (bottom) as a function of the plasma current Ip. Black dots refer to Hydrogen plasmas, magenta dots to Helium ones.

Some experiments were dedicated during 2011 to the analysis of Helium plasmas, in order to enlarge the existing He database towards higher plasma current levels (up to 1.6 MA), with respect to the existing one, in a wide range of equilibria in terms of the reversal parameter F. An example of the results obtained, which allowed a better comparison of the energy confinement properties and of the MHD behavior of He and H RFP plasmas, is shown in figure 2.2.5. In the figure, the saturation level of the dominant *m/n*=1/-7 and of the secondary modes is plotted as a function of the plasma current, for both H and He plasmas. Despite the lower statistical value, Helium plasmas seem to be characterized by a better trend of the secondary modes with the plasma current than the Hydrogen ones. Such dependence will be checked by additional experiments at the beginning of 2012.

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2.2.3 Physics understanding: data analysis and modeling

Data analysis. The analysis of the thermal internal barriers occurring when an helical equilibrium develops has been advanced in 2011, with the new temperature diagnostics, allowing a better time resolution. As an example, a temperature profile obtained by the Thomson scattering and corresponding to a SHAx is shown in fig. 2.2.6. An effort has been done to better characterize the QSH/SHAx states dynamics; currently, such states are not stationary, and tend to completely disappear at $n/n_G>0.4$, n_G being the Greenwald density [Puiatti11]. The development of the DSX3 diagnostic, based on a multichord double-filter electron temperature measurement [Ruzzon11] has allowed to assess this point in a more quantitative way, as shown in Fig.2.2.7: showing the gradient of the temperature appears to be linked to the dynamics of the dominant and secondary modes, suggesting that within a QSH phase SHAx states correspond to the lowest values of the secondary modes [Ruzzon11,Fassina11].

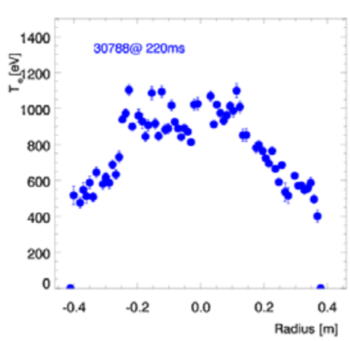

Fig.2.2.6: Example of electron temperature profilefeaturing an internal barrier in a high current discharge

A detailed investigation performed in low-current discharges [Scarin11] revealed that reconnecting events manifest with the appearance of toroidally localized poloidal current sheets. Considering the toroidal location where the MHD crash events are observed to form, it comes out that the crashes are mostly observed whenever the maximum radial shift of the dominant mode, $\Delta_{1,-7}$, is at θ=250°, namely, the bottom of the machine. Due to the phase relationship between (m=0,n=7) and (m=1,n=-7) modes [Martines10], the bottom is where the maximum shift (i.e., the source of particles) coincides with the X-point of the (0,7) islands developing at the edge. This fact underlines three main aspects in the interpretation of the SHAx duration: (a) the edge, interpreted as a complicated mixture of particle motion in a helical 3D geometry and PWI, plays an important role; (b) the stress on the importance of X-points connects the helical edge to the already known phenomenology of the density limit [Puiatti09,Puiatti11,Spizzo11]; (c) the phenomenology of the X-points underlines the importance of the flow pattern in the helical symmetry [Bonomo11,Spolaore11].

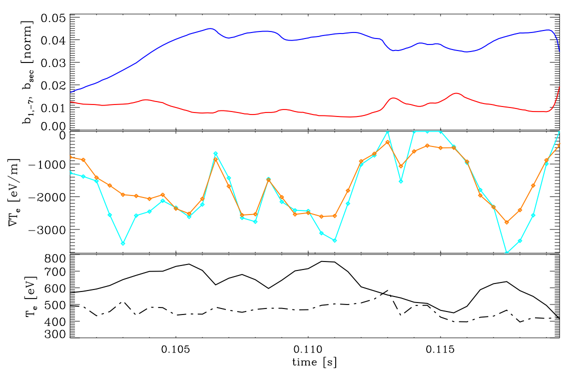

Fig.2.2.7: Time evolution of the dominant (blue) and secondary (red) mode amplitudes; time evolution of the temperature gradient in the SHAx state; time evolution of core and edge temperatures (solid and dash-dot lines respectively).

Regarding the edge, measurements show helical modulations of electron pressure, particle influx, radiation losses, and floating potential. While the only diagnostic capable of giving a complete description of the helical footprint along (θ,ϕ) at a given time is ISIS (Integrated System of Internal Sensors), the other diagnostics can be mapped onto the helix exploiting the toroidal rotation of the helical island, in particular as a function of the local magnetic shift, $\Delta_{1,-7}$.

An example of this type of analysis is shown in Fig.2.2.8, where a toroidal map of floating potential (time on the x-axis, toroidal angle ϕ on the y-axis) is shown in frame (a), together with a map of $\Delta_{1,-7}$ (frame (b)). It is evident that the floating potential exhibits a toroidal ripple closely correlated with the map of the helical flux, with the potential well (minimum of V_f) approximately matching the location of maximum deformation with a toroidal symmetry n=-7 (frame (c)). A similar analysis can be performed also on the poloidal angle, confirming the m=1 symmetry along θ [Vianello11], concluding that V_f has a dependence on the helical angle $u=\theta - 7\phi$. This matches the reconstruction of the core flow (see Figure 2.2.9) performed through radially inner (B V, H-like) and outer (C V, He-like) radiation measurements, based on passive Doppler spectroscopy and performed on a poloidal cross section at a given toroidal position [Bonomo11]. What is noteworthy is the *reversal of the flow direction* in the outer region of the plasma, which we will see later on is a distinctive signature of an ambipolar electric field working in the edge (the only caveat is that "edge" in passive spectroscopy means r/a=0.85, while ISIS measurements are at the very edge of the plasma, r/a=1). The convective cell in the edge (red arrows in Fig.2.2.9) matches the core flow (blue arrows), closing the flow circuit in the poloidal cross section. The core pattern is pretty similar to the one predicted by SpeCyl simulations (see e.g. Figure 1 in Ref. [Cappello11]). One could therefore speculate that any change in the edge flow (e.g. given by adverse edge collisionality, which affects the phase lag between the ambipolar potential and the edge magnetic ripple [Vianello11]) could have a direct impact on the dynamo mechanism that sustains the QSH.

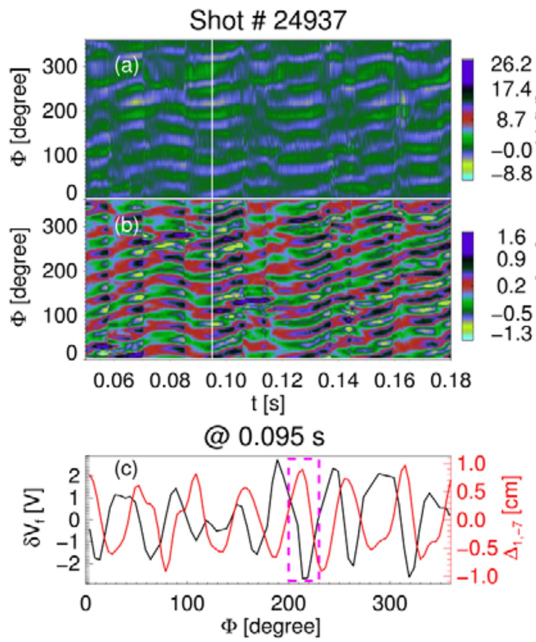

Fig.2.2.8: Map of floating potential (a), magnetic shift of the dominant mode (b). In (c) a section of the contours at t=95ms is shown, to point out the phase relationship between potential and helical ripple.

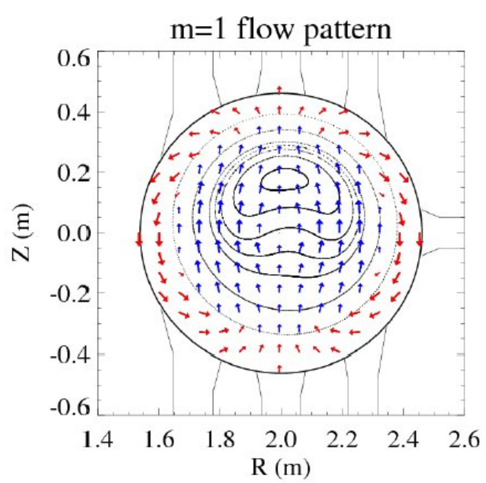

Fig.2.2.9: Flow map reconstruction on a poloidal cross-section from passive Doppler spectroscopy.

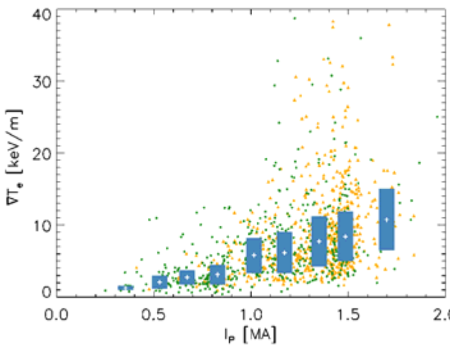

Fig.2.2.10:Electron temperature gradient as a function of plasma current for different equilibria: QSH (green dots) and SHAx (orange triangles) .

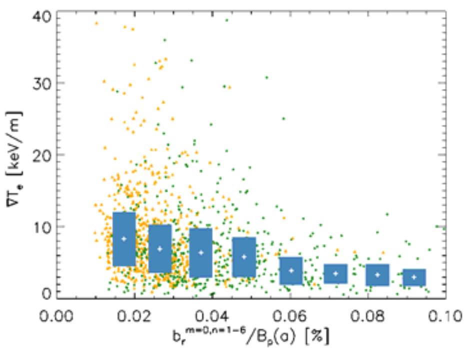

Fig.2.2.11:Electron temperature gradient as a function of m=0 secondary mode amplitudes for different equilibria:QSH (green dots) and SHAx (orange triangles) .

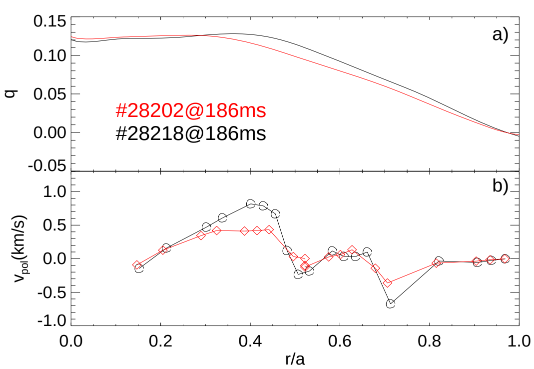

Fig.2.2.12: Average poloidal flow (b) calculated with DKES/PENTA and their respective q profile (a) for two cases with different (1,-7) amplitude (larger in the case in black).

The results on the poloidal location of the reconnection events [Scarin11] point in this direction. Obviously, one should not discard a simpler explanation in terms of a local density accumulation and enhanced radiation (a helical version of the density limit).

Regarding the confinement in helical states, though QSHs correspond to an improved regime, it has to be recalled that they are associated to the spontaneous development of an ordered structure involving a limited portion of the plasma volume (r/a< 0.4). The remaining region, from 0.4 r/a towards the Last Close Magnetic Surface, is characterized by lower temperature gradients and relatively high resistivity. To improve the understanding of the physics in this large part of the plasma volume, a statistical analysis of the electron temperature gradients extending across 0.7<r/a<0.95 has been carried out. The favorable core

confinement scaling with plasma current has been found to extend also in this region: in Fig. 2.2.10 an almost linear increase of the temperature gradient with plasma current is shown. This behavior is independent on the magnetic equilibrium. However, as recalled previously, the improved plasma performances in helical states are also related to an amelioration of the magnetic boundary, in particular affecting the m=0 modes. It has been found that such modes have a direct effect on the temperature gradient in the region 0.4<r/a<0.95, as shown in fig, 2.2.11.

Modeling: the ambipolar electric field, averaged on each helical flux surface, can be computed by DKES/PENTA codes applied to the RFP for local neoclassical transport computations [Gobbin1]:an example is shown in Fig.2.2.12. A dependence of the magnitude of the poloidal velocity on the amplitude of the dominant m=1,n=-7 mode has been found from these neoclassical computations.

Regarding the pattern of the ambipolar electric field in the edge, the interpretation takes advantage of the modeling of the simplified 2D case, which characterizes the PWI at low plasma current in multiple helicity (MH) discharges near the density-limit ($n/n_G \approx 0.8$). In this case, the dominant symmetry is (m=0, n=1), so that θ is an ignorable co-ordinate.

The distinctive feature of this type of discharges is the *reversal of the toroidal flow* along the toroidal angle, shown in Fig.2.2.13(a) (which is the MH analogue of the reversal of the poloidal flow along the poloidal angle shown in Fig. 2.2.9). The reversal of the toroidal flow is associated to a huge convective cell that carries matter from the source (first null point of the flow) to the stagnation point (second null point of the flow). The convective flux, its magnitude and role in the density limit have been assessed in detail [Puiatti09], so that this case can be a test-bed for future theories on the helical edge flow in QSH. An expression of the potential has been worked out within the ORBIT code, that balances the ion-to-electron radial diffusion rate D_e/D_i guaranteeing quasi-neutrality in a layer ~7 ion Larmor radii from the wall [Spizzo11]. This anyway happens at the expense of symmetry in the toroidal angle, such that the potential has the same (m=0,n=1) symmetry as the dominant island in the edge. If one translates this results to the QSH case, one could speculate that the m=1,n=-7 ripple in the edge could generate (through the ambipolar mechanism) a m=1,n=-7 potential of the type shown in Fig.2.2.13.

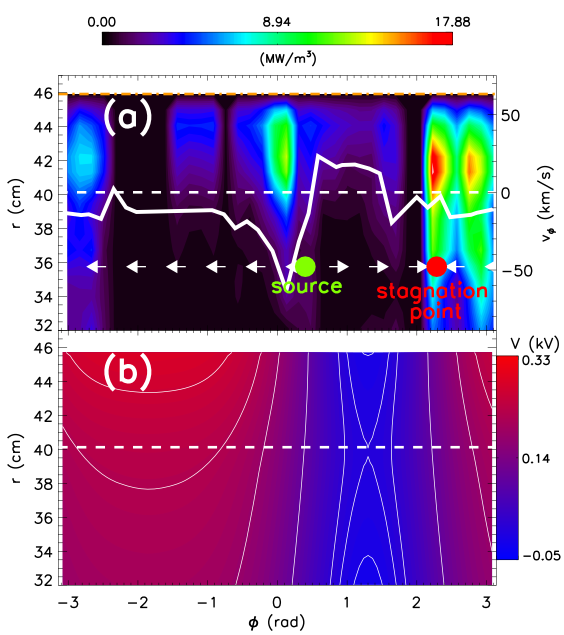

Fig.2.2.13: (a)Flow pattern along the toroidal angle (white line) and bolometric emissivity map of a high-density, low current discharge near the density limit. The stagnation point corresponds to the maximum radiation; (b) simulation of the associated ambipolar potential.

2.3 Project 2: advancing feedback control of MHD stability in fusion devices.

2.3.1 Development of MHD control in RFP configuration

Many efforts have been made during the last year to develop new MHD control approaches for the RFP configuration and to optimize the existing schemes. The main aims were to better understand and control the helical RFP state observed to emerge spontaneously at high plasma current, to characterize the MHD dynamics of the RFP, including the effect of a realistic 3D wall, and in general to optimize the feedback loop. The main results obtained are described in the following.

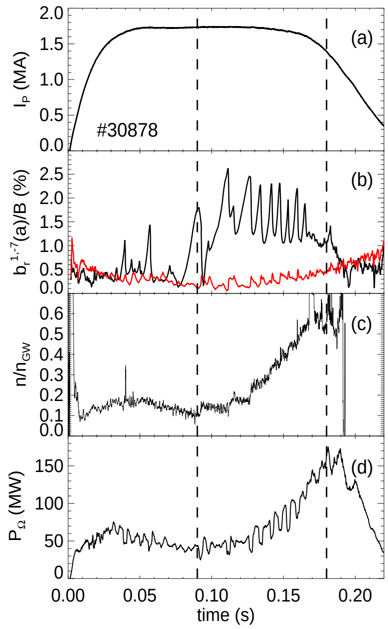

Fig.2.3.1: (a) Plasma current, (b) relative 1/-7 (black) and secondary m=1 (red) mode amplitudes, (c) Greenwald fraction, and (d) Ohmic input power for a discharge with 1/-7 helical boundary conditions applied in the period 0.09-0.18ms, as indicated with vertical dashed lines.

The study of the transition to a helical state with m=1, n=-7 has been extended to high plasma currents up to 2MA. In this high-current regime, the possibility to control the helical equilibrium by imposing 3D boundary conditions through magnetic feedback has been explored, as done previously at lower currents [Piovesan11]. The aim was to test whether this operation is compatible with high plasma current, but also whether it allows sustaining a helical state in high-density conditions, i.e. in plasmas with a Greenwald fraction $n/n_G>0.3$, where spontaneous helical states are normally inhibited. To this aim, the amplitude and frequency of the m=1, n=-7 radial magnetic field imposed at the plasma edge have been first varied in experiments with plasma current I_P=1.5MA, to identify the values that allow sustaining a helical state without excessive plasma-wall interaction, which occurs if the edge radial field is too large, and avoiding coil current saturations, which occur at large mode rotation frequency. The optimal values thus identified have been then applied at higher plasma current and density. An example of the results obtained is reported in figure 2.3.1. Here the edge m=1, n=-7 radial field amplitude is controlled at a fixed value of $b_r/B\approx2\%$ and the rotation frequency is chosen to be 15Hz. The plasma current is feedback controlled and the density is increased during the flattop by a pre-programmed waveform of the gas puffing. A sawtoothing helical state is sustained during the high-density phase up to values of the Greenwald fraction of $n/n_{GW}\approx0.5$, at which normally helical states are not observed.

The effects of helical boundary conditions on the transition to m=1, n=-7 helical states have been investigated also at low plasma current of about 400kA, where the plasma normally exhibits a multiple-helicity magnetic spectrum even at relatively low density. Also in this case, a transition to a helical state could be induced.

Simulations of the field-line tracing code NEMATO (for more details see subsection 5.2.2) suggested that a helical state with periodicity corresponding to a non-resonant harmonic, such as the m=1, n=-6 resistive-wall mode in RFX-mod, would be very resilient to magnetic chaos induced by secondary modes [Cappello11]. Following this idea, experiments with m=1, n=-6 helical boundary conditions have been performed at plasma currents of 1.2-1.5MA.

As shown in figure 2.3.2, a finite radial field amplitude for the m=1, n=-6 mode has the effect to induce a stationary helical n=-6 state and suppress the spontaneous transition to a helical state with m=1, n=-7, which normally occurs in these plasmas. The reason for this new interesting mode dynamics and the effect of a non-resonant dominant mode on the global discharge performance are being investigated.

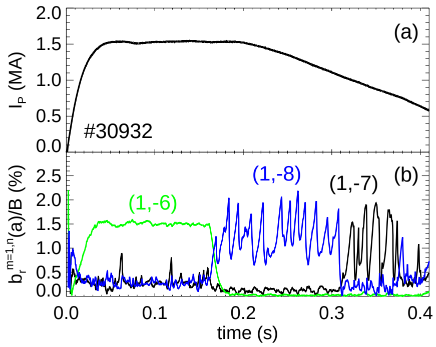

Fig.2.3.2: (a) Plasma current and (b) relative mode amplitudes for a discharge with helical boundary conditions on the m=1,n=-6 (green) and m=1,n=-8 modes (blue).

Experiments with 3D boundary conditions have been performed to explore the effect also of other harmonics, either non-resonant, for example with m=1, n=-5, or resonant, as the m=1, n=-8 mode, also shown in figure 2.3.2. In all cases, exciting a single mode has the effect to suppress the other ones that would spontaneously dominate the spectrum, normally the m=1, n=-7 mode, thus suggesting the possibility to induce helical states with different periodicity. The presence of a wall with 3D structures, such as gaps and portholes, distorts the feedback action and induces unwanted magnetic field errors in any fusion device. These error fields have been characterized in RFX-mod, in particular in experiments with rotating m=1, n=-7 boundary conditions [Piron11]. The equatorial gap was shown to introduce spurious harmonics with m=0,1,2 and n=7. The plasma can either amplify or shield them depending on the nature of each mode, hence the need to develop strategies to avoid such error fields. During the last year a dynamic decoupling algorithm that compensates for these effects has been designed, implemented in real-time, and tested with plasma [Soppelsa09, Piovesan11b]. Figure 2.3.3 shows that the dynamic decoupler reduces the error field harmonics at the edge.

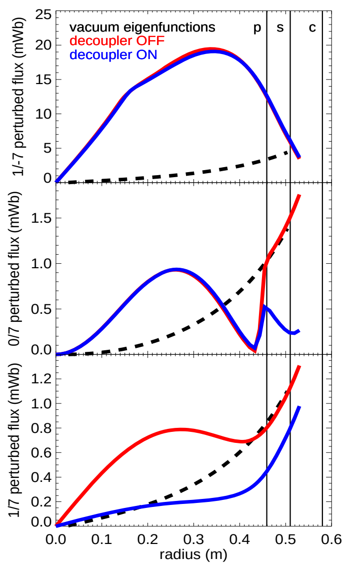

Fig.2.3.3: Radial eigenfunctions of (a) the m=1, n=-7, (b) m=0, n=7, and (c) m=1, n=7 harmonics in discharges with (red) and without (blue) the dynamic decoupler. The dashed line represents the same eigenfunctions without plasma. The vertical lines indicate the radius of the plasma edge, the radial field sensors, and the active coils.

But this can have an effect also on the plasma response, represented here by the radial eigenfunction of each harmonic computed by solving the Newcomb equation in toroidal geometry constrained by edge magnetic field measurements. The effect on the plasma response depends on the nature of the considered harmonic: the dominant m=1, n=-7 harmonic of course is not affected; the m=0, n=7 harmonic is significantly reduced at the edge, but it is not changed in the core, where most of it is due to toroidal coupling, and not to 3D wall effects; the m=1, n=7 plasma response, which corresponds to a non-resonant, stable mode is reduced over the whole radius, as expected.

Significant efforts were dedicated to the characterization of the system composed by the plasma, the 3D wall, and the set of 192 active coils and magnetic field sensors available in RFX-mod using modern system identification techniques previously developed in the Extrap-T2R experiment [Olofsson10]. A linear model of this system is being identified using these techniques, in collaboration with E. Olofsson, KTH, Stockholm. A series of vacuum and plasma discharges were performed with a small-amplitude noise in input to the active coils, the so-called dithering technique. Perturbing the system in this way allows identifying the plasma response coupled to the 3D wall under the action of feedback, including its stable and unstable modes. The identification of such a model is important also to develop new control algorithms for future experiments. Moreover the campaign carried out at RFX-mod should demonstrate the applicability of the method to large machines.

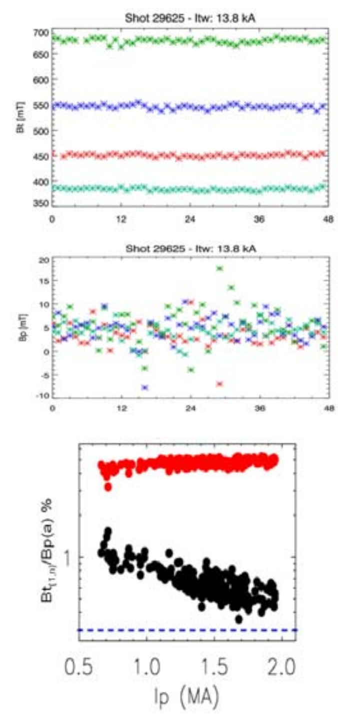

Fig.2.3.4: (a) Toroidal and (b) poloidal pick-up coil field measurements of a vacuum pulse with only toroidal field. The maximum error in the main (toroidal) component is within 2%. The slight misalignments of the sensors cause a spurious pick-up signal of up to 3% of the main field component. On the mode amplitude scaling plot (c), the cumulative error due to the pick-up is indicated with a blue dashed line.

Systematic errors in the magnetic field sensors have been investigated based on a series of calibration measurements without plasma. Small misalignments of these sensors have been shown to introduce systematic errors due to a significant pick-up of axisymmetric field components, e.g. the toroidal field, in the magnetic measurements, as illustrated in figure 2.3.4. These signals are used for real-time MHD control and thus systematic errors can affect the performance of the control system. Algorithms have been developed both to correct these errors in real-time and to analyze the data offline.

2.3.2 Experiments in circular Tokamak configuration

Given the flexibility of the power supply system, RFX-mod can also be operated as a circular cross section, high aspect ratio, ohmic tokamak. The maximum value of the toroidal field of 0.55T allows operating at plasma currents up to 160kA-170kA and pulse length up to 1s.

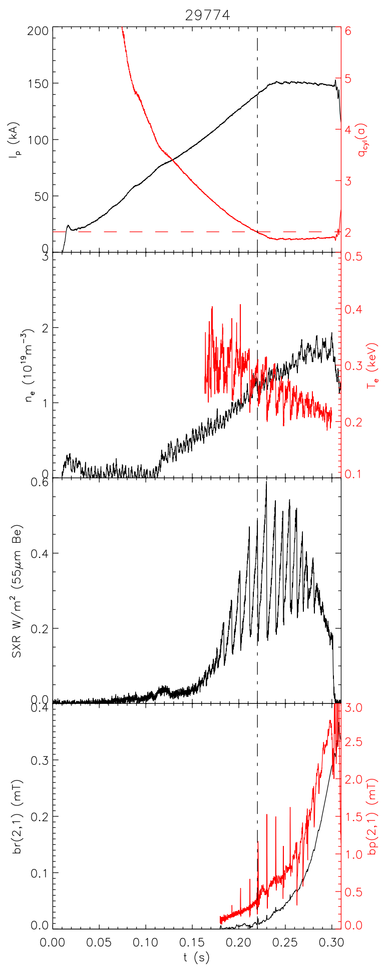

Fig.2.3.5: a) Plasma current and $q_{cyl}(a)$; b) electron density and temperature; c) SXR signals; d) radial and poloidal (2,1) harmonics

The loop voltage required to sustain a given plasma current waveform is feedback controlled. The plasma column fills the vacuum chamber (i.e. there are no limiters) and the horizontal equilibrium is feedback controlled by means of 8 couples of field shaping coils. Density is sustained through pre-programmed hydrogen puffing that needs to be adjusted shot by shot in order to compensate for graphite retention. Helium glow discharge cleaning is used to reduce wall loading and recover lower density operations. The highest plasma currents in tokamak configuration correspond to operations with $q_{cyl}(a) < 2$, a regime in which an unstable current driven m=2,n=1 external kink occurs. This mode is a Resistive Wall Mode (RWM) due to the presence of the copper shell, whose time constant is 100ms and whose distance b/a is = 1.12. The detection of the mode is performed by arrays of magnetic field probes: 48x4 radial field saddle loops are located outside the vacuum vessel (r=0.507m), each one spanning 90° in the poloidal direction and 7.5° in the toroidal one; 48x4 bi-axial pick-up probes, sensing the toroidal and poloidal field are located on the inner side of the copper shell (r=0.508m). Higher poloidal resolution is possible in 4 toroidal locations (non equally spaced) where 8 bi-axial pick-up probes are available. An example of a tokamak discharge which ends disruptively due to the spontaneous growth of the mode is shown in Fig 2.3.5. The amplitude of the (2,1) harmonic is obtained by a DFT analysis based on signals whose baseline is evaluated when the toroidal field reaches the maximum value, in order to remove pickups from the measurements. An example is shown in

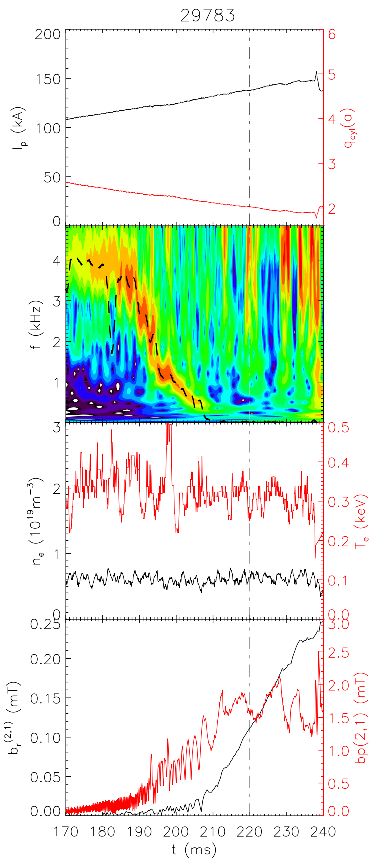

Fig.2.3.6: a) Plasma current and $q_{cyl}(a)$; b) wavelet spectrum of internal $b_p$pick-up coil; c) radial and poloidal (2,1) harmonics

Fig. 2.3.5: sawtooth activity is observed in SXR signal and a non-rotating, exponentially growing (2,1) mode appears as soon as $q_{cyl}(a)$ decreases below 2.

The RWM is not always observed: in some discharges, an initially rotating (2,1) mode (very likely a tearing mode) grows when $q_{cyl}(a)>2$ and eventually locks to the wall (fig. 2.3.6). Fig 2.3.6 b) shows a wavelet spectrum of an internal non integrated poloidal field pick-up probe, whose maximum correspond to the rotation frequency inferred from the phase velocity of (2,1) harmonic of the 48x4 bp array, located outside the 3ms time constant vacuum vessel. Once the mode locks to the wall, the radial field penetrates the shell and a disruption occurs.

Closed loop operations allowed avoiding disruptions, in the experiments performed so far [Marrelli11]. Radial field saddle loops signal baselines are evaluated in real time in a short time window during the discharge, 20 ms before the start of the control phase. Simultaneously, the feedback system samples the currents flowing into the control coils and computes the aliasing of the sidebands [Zanca07] (15 sidebands are computed in real-time for each harmonic). An FFT of sensor signals (raw harmonics) is performed and the contribution of the sideband aliasing is removed giving the "clean" harmonic, to be used as the feedback variable in the Clean Mode Control (CMC) algorithm. The references (a.k.a. commands) for the 48x4 power supplies of the saddle coils are obtained by inverse FFT of the "clea A proportional and integral controller is used, with gains similar to the ones used for RWM control in the RFP [Baruzzo10]. An example of a feedback stabilized discharge is shown in Fig. 2.3.7. As long as $q_{cyl}(a)$ remains below 2 the (2,1) poloidal harmonic remains at a constant level of 0.5mT. The blue trace in panel c) describes the (2,1) harmonic of the radial field produced by the control coils at

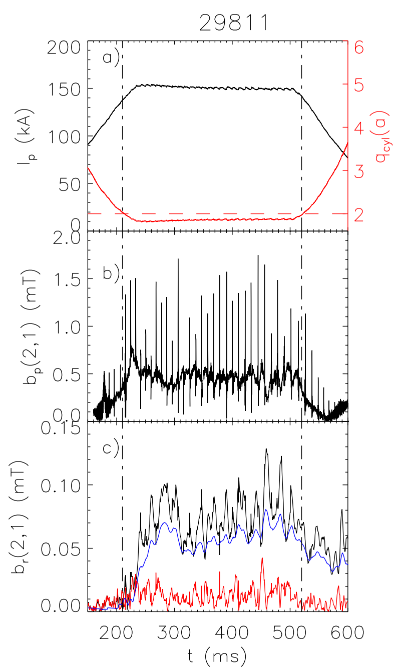

Fig.2.3.7: a) Plasma current and $q_{cyl}(a)$; b) (2,1) Poloidal field; c)(2,1) radial field. Black: "raw", red: "clean", blue: (2,1) field produced by coils

the sensors radius, taking into account the presence of the shell. The red trace in the same panel is the "clean" (2,1) radial field harmonic, which is the feedback variable in this experiment, while the black trace is the "raw" harmonic, i.e. the (2,1) harmonic polluted by the aliasing of the sidebands produced by the control coils

It is found that the choice of the feedback variable is a key issue for successful operations: in particular, it is necessary to remove from the radial field measurements the aliasing of the sideband harmonics produced by the saddle coils. Interestingly, this is not required for RWM stabilization in the RFP configuration, as foreseen theoretically [Paccagnella02] and experimentally confirmed [Paccagnella06].

n" feedback variable multiplied by the gain.

The integrated model of the control system of RWMs (CarMA) in the RFP configuration [Baruzzo10] has been successfully used to simulate the (2,1) stabilization experiments in the tokamak configuration [Marchiori11]. The plasma response is modeled by the toroidal MHD stability code MARS-F [Liu2000]. The required q profile has been determined with the 2D finite elements equilibrium code MAXFEA, which assumes the following parameterized description of the toroidal plasma current density:

$$J_{\varphi} = \left[\frac{R}{R_0}\beta + \frac{R_0}{R}(1-\beta) \right]\left(1-\overline{\psi}^{\alpha}\right)$$

where α and β are parameters related to the plasma internal inductance and pressure, respectively; $\overline{\psi}$ is the normalized poloidal flux. Since in RFX-mod no diagnostic is available to reconstruct the plasma current density profile, we validated the choice of α and β parameters matching the magnetic measures and other equilibrium macroscopic quantities such as plasma shift and poloidal field asymmetry coefficient Λ. The dependence of the unstable mode growth rate γ on q(a) and α was studied by means of MARS-F with a 2D resistive wall located at r/a=1.1 using data from two RFX-mod shots. The values of γ evaluated by MARS-F are multiplied by a correction factor to take into account 3D features of the conducting structures. The curves plotted in Fig. 2.3.8 show how sensitive is the growth rate to both α and q(a): the experimental growth rates are somewhat below the minima of the calculated ones, probably because a more refined parameterization would be necessary to fully describe the plasma current density profile. The integrated model of the control system includes a dynamic block performing the calculation of the

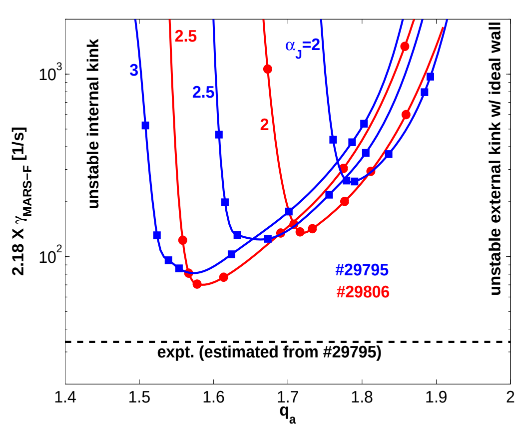

Fig.2.3.8 Growth rate dependence on q(a) and α

sidebands aliasing reproducing the behavior of the real-time controller. A gain scan was performed with and without such a model, confirming that the mode can only be stabilized with Clean Mode Control. The experimental critical gain (3000) is approximately 1/3 of the one obtained by the simulator; this has been attributed to the exceedingly high estimate of the growth rate.

2.3.3 First test of non-circular tokamak configurations

A week of experimental campaign was dedicated to assess RFX-mod capability of producing Double Null (DN) tokamak plasmas [Zanotto11]. The target of the campaign was to demonstrate the feasibility of non-circular plasmas, first with vacuum shots and then with plasmas with an open loop transition from "circular" to DN shaping.

To this end, the power supply connections to the Field Shaping (FS) coils were re-arranged to reverse the direction of some currents and new versions of the horizontal equilibrium controller were implemented and tested to produce the DN scenario with the new power supplies and FS coil configuration.

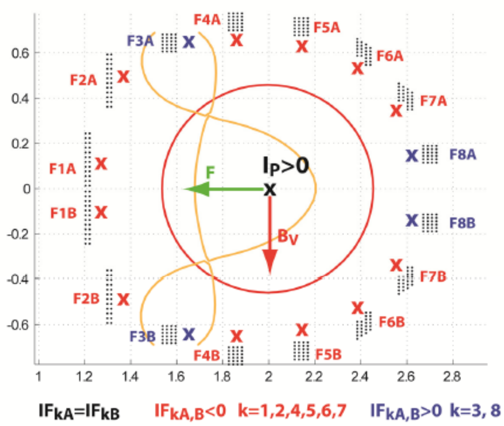

Fig.2.3.9: Current direction in the FS coils for DN plasmas.

A DN scenario can be obtained rather easily without breaking the FS coil symmetry by reversing the connections between some of them and the relative PVAT (ac-dc thyristor converters feeding the field shaping coils). More precisely, it has been decided to test a configuration where the connections of coils F3 and F8 to their PVAT are reversed, so that a DN field can be produced as sketched in Fig. 2.3.9. The reference scenario for establishing a DN has been calculated for a plasma current of 70kA, q_{95}= 2.38, β_p = 0.6, l_i = 0.72.

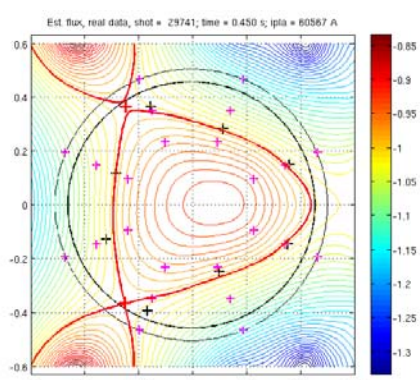

Fig.2.3.10: Equilibrium reconstruction of shot #29741 at t=0.450 s.

Some plasma shots were performed with interesting transitions to DN. In general, the plasma did not last more than some tens of milliseconds in DN before disrupting. Initially this was ascribed to the appearance of a vertical instability, but careful analyses of the magnetic signals (and of the soft x-ray tomography) seem to indicate that the plasma is not subjected to vertical shift after the DN establishment. The DN profile is showing the boundary reconstruction of Fig. 2.3.10, calculated at t=0.450 s of shot #29741. The capability of the machine of being able to produce this kind of configurations has been demonstrated without any problem in the power supply and magnet systems. Upgrades and improvements concerning both control and diagnostics aspects are planned and will be implemented for the next campaign.

2.4 Project 3: fusion physics in a three-dimensional configuration.

2.4.1 Progress in 3d equilibrium reconstruction

Equilibrium reconstruction can be addressed with different approaches. The direct problem implies the knowledge of all quantities characterizing the configuration that has to be obtained by the equilibrium solver so that no direct comparison to experimental measurements is done. On the other hand the inverse problem starts from these data and provides an equilibrium as much as possible compatible with the measurement.

The acquisition of the V3FIT code [Hanson09] and its porting to the RFX-mod experiment allowed both approaches, though the most interesting (and compelling) is the latter. V3FIT uses the VMEC code [Hirshman93] as equilibrium solver and minimizes the χ^2 obtained from modeled and experimental data by changing some parameters characterizing the equilibrium (e.g. some profiles or global quantities).

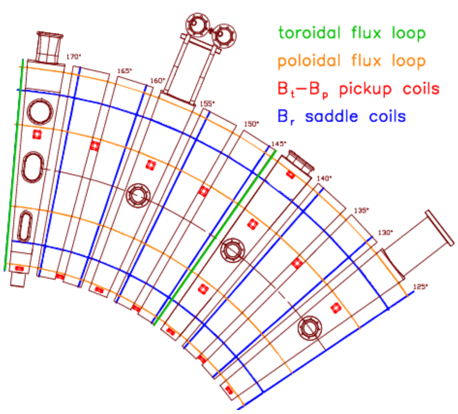

Fig.2.4.1: Diagnostics described in the V3FIT code: b_r, b_t, bp, toroidal and poloidal flux.

To this end a thorough description of the magnetic diagnostics of RFX-mod was implemented. As shown in figure 2.4.1 we implemented for V3FIT the full arrays of b_r, b_t and b_p measurements as well as the measurements of both the toroidal and poloidal flux loops. Additional internal measurements for SXR emissivity and T_e measurements were implemented but not yet tested (see section 5.6 for details). An important issue to be addressed in the near future will be the way to treat correctly the effects of passive structures that do influence the measurements and their use for equilibrium reconstruction. This is an essential piece of information for the free-boundary reconstruction. To this end most of the analyses were done as fixed-boundary reconstructions (i.e. only fields from plasma currents can be determined outside the plasma boundary) and were devoted to plasma discharges where currents in all the windings were as stationary as possible, so that passive structures could be considered fully penetrated. In these conditions the Biot-Savart law can be easily used to estimate the vacuum fields and provide the missing information from the fixed boundary solution in order to correctly compare experimental data and modeled measurements. In figure 2.4.2 we show the convergence process for V3FIT [Terranova11] using a limited number of diagnostics (the arrays of b_r and the toroidal flux loops): 5 steps were necessary to obtain a convergence. The resulting equilibrium gives a good match with the data as shown in the figure for one array of b_r measurements. In this figure one can also notice the effect of smaller modes as their phase locking (localized at about 320°) cannot be modeled with VMEC since these are not harmonics of the n=7 main helicity. For all the diagnostics suitable algorithms were conceived to determine the error bar to be used in the minimization procedure of V3FIT.

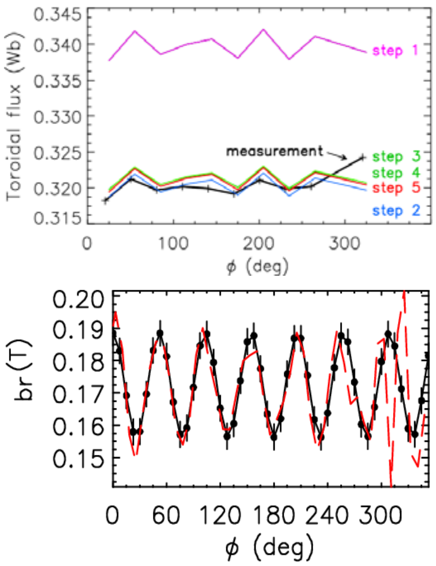

Fig.2.4.2: V3FIT convergence steps compared to experimental data (top). Comparison between experimental (red-dashed) and modelled (black) b_r data (bottom).

The inverse problem to equilibrium reconstruction is sensitive to the set of diagnostics used and in particular this set might not be sufficient to get rid of the degeneracy in the final equilibrium: using only external measurements cannot provide a univocal determination of the final equilibrium. This degeneracy is highly reduced in the helical case as we have information on the shape of the safety factor profile (i.e. its being non-monotonic) and we know the periodicity of our configuration (determined by the dominant mode toroidal number).

However important information was acquired also in the direct problem by investigating how our diagnostic set-up is sensitive to internal profile changes [Terranova11, Gobbin11]. To this end a scan in some plasma quantities was considered by changing the q profile (q on axis, maximum q and its position, etc) and the shape of the last closed flux surface in order to determine if our diagnostic set would be able to discriminate these changes.

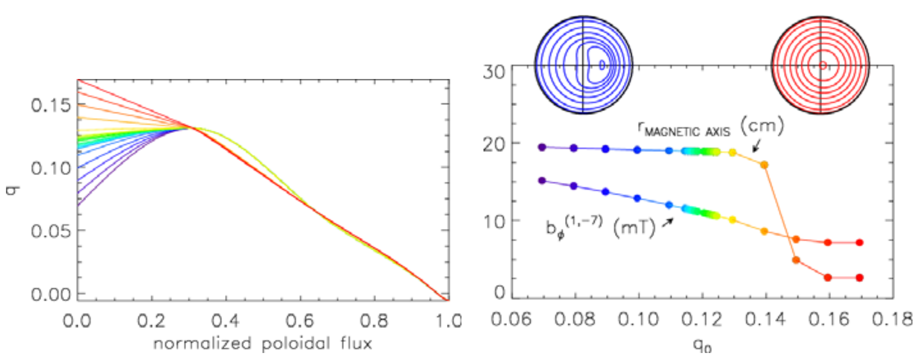

Fig.2.4.3: Effect of q_0 scan on topology and b_t measurements.

As an example in Figure 2.4.3 we show the effect of a q_0 scan on the topology of the configuration and the measurements. On the left panel the different considered q profiles are plotted with different colors, while on the right panel we show the resulting position of the magnetic axis and the amplitude of the m=1,n=-7 mode of the toroidal magnetic field. As the q profile becomes monotonic, the configuration goes from having a helical axis (blue surfaces) to having an axi-symmetric axis (red surfaces) characterized by the Shafranov shift. Note that the increase of the non-axisymmetric shift (that can be experimentally obtained by means of an external helical perturbation) produces an increase in the shift of the helical axis with respect to the vacuum vessel centre as long as the q profile is non-monotonic.

As stated above the possibility of using V3FIT in free-boundary mode or in more general conditions will require a better knowledge of the effect of passive structure as well as a careful determination of the diagnostics that are actually useful to the equilibrium determination as presented in section 5.6.

2.4.2 3d tools for transport analysis

The understanding of energy and particle transport mechanisms acting in the RFX-mod plasma during the helical SHAx state is a topic of strong interest in the RFP community. The helically nested flux surfaces, which change the topology around the helical (m=1,n=-7) axis, deeply affect particle trajectories, their transport, and heat fluxes. The analysis of the experimental observations must be carried out considering the actual geometry of the flux surfaces on which the kinetic gradients develop. In particular, during 2011, an effort has been dedicated to the study of the particle transport, exploiting the experiences gained in the past years on the thermal transport studies. The main question to be answered is whether the transport barriers observed in SHAx plasmas as strong temperature gradients affect also the particle confinement. The main tool used for such study is the Automatic System for TRansport Analysis ASTRA [Pereversev2002] that has been adapted to the RFP topology.

ASTRA is a transport code that combines the 3D toroidal geometry with a mono-dimensional description of transport. It solves a set of transport equations (temperature, density, current density, impurities, etc.) considering the shape of the magnetic surfaces: the internal Grad-Shafranov solver gives the equilibrium for tokamak discharges, whereas an external input file feeds ASTRA with the geometry for other configurations (Stellarator or RFP). The 1D transport equations are written by averaging out all quantities on the flux surfaces defined by the magnetic equilibrium.

Initial conditions to the code are the experimental temperature and density profiles as well as the source term profiles, averaged on the flux surfaces. Furthermore, for the equilibrium computation, an external file provides to ASTRA the radial profile of the specific volume $V'=dV/d\rho$ and of the first element of the metric tensor.

For SHAx states these quantities have been calculated by the SHEq code [Martines2011] using the description of the equilibrium based on the calculation of tearing mode eigenfunction in toroidal geometry for RFP plasmas [Zanca2004]. The helical equilibrium is expanded in a perturbative approach as a dominant, saturated tearing mode summed with an axisymmetric equilibrium. In this description the effective radial coordinate ρ is the square root of the helical flux.

This approach has been already used in 2010 to study the energy confinement properties; for particle transport studies further developments have been recently implemented. It is important to notice that since all the tools have been prepared to deal with stationary simulations, in the following the time evolution will not be considered; additional work is going on to analyze also the temporal evolution of the kinetic quantities.

The SHEq code has been modified in order to compute the flux surface average of new quantities, defined by the formula:

$$< F > = \frac{\iint_0^{2\pi} \mathrm{d}\beta \, \mathrm{d}\varphi \sqrt{g}\, F}{\iint_0^{2\pi} \mathrm{d}\beta \, \mathrm{d}\varphi \sqrt{g}}$$

This has been applied to the electron temperature and density, the ExB inward pinch and the particle source, computed by the NENE 2D code as described in the following.

In a SHAx plasma, neglecting recombination processes, the particle source term S can be described by the equation:

$$S(x,y,z) = R_I(x,y,z) n_e(x,y,z) n_n(x,y,z) \qquad (2.4.1)$$

where R_I is the neutral ionization rate for electron impact (function of the electron temperature), n_e is the electron density and n_n is the neutral density. Since the neutral penetration is not affected by the geometry of the flux surfaces, it is mandatory to describe the quantities in equation 2.4.1 in a general three dimensional geometry.

In the MonteCarlo code for the neutral density computation, named NENE 2D and based on [Hughes1978], the plasma is assumed to be infinite and symmetrical in the toroidal direction. This symmetry can be assumed in RFX-mod SHAx plasma because the diffusion of neutral particles is shorter than the minor radius, whereas the gradients in toroidal direction have longer characteristic length. The electron density and electron and ion temperature are then described on a poloidal grid, allowing radial and poloidal gradients, according to the experimental data. NENE 2D takes into account charge-exchange reactions, electron impact ionization and reflection of neutral on the first wall. An example of output of the code is shown in figure 2.4.4, for shot #29328. It can be observed that the resulting neutral density and the particle source are poloidally and radially distorted due to the shape of the density and temperature distributions. Once the neutral density $n_n(x,y,z)$ has been computed by NENE 2D, the SHEq code provides to ASTRA its flux average. Some very preliminary transport analysis with ASTRA have been run: the shot #29328 is a very good test bed for this study because at different times presents, for similar density and plasma current, both a well developed SHAx state, featuring a thermal transport barrier, and a multiple helicity state. The comparison of the particle diffusivity in the two cases gives a first hint on the effect of the helical equilibrium on particle transport. The results of the analysis are shown in figure 2.4.5: the electron density and temperature are shown in the upper part of the figure. The radial coordinate is the root square of the helical flux. The colors represent 2 different cases: the multiple helicity profiles are in blue and the red is referred to the SHAx state.

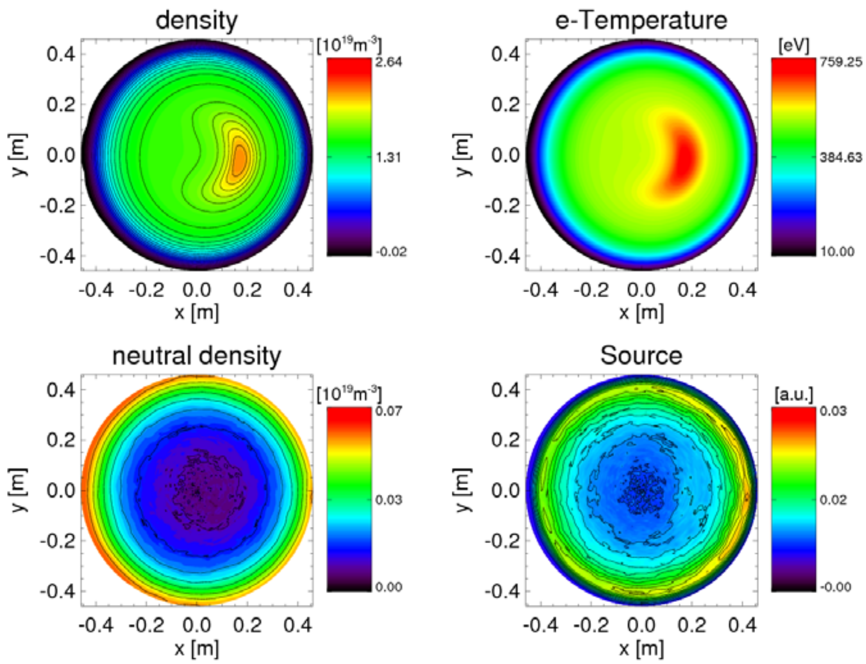

Fig. 2.4.4: example of output of NENE 2D: input electron density and temperature are shown in the upper part of the figure. The two bottom plots represent the output of the code: the poloidal map of the neutral density and the related particle source, according with equation 1

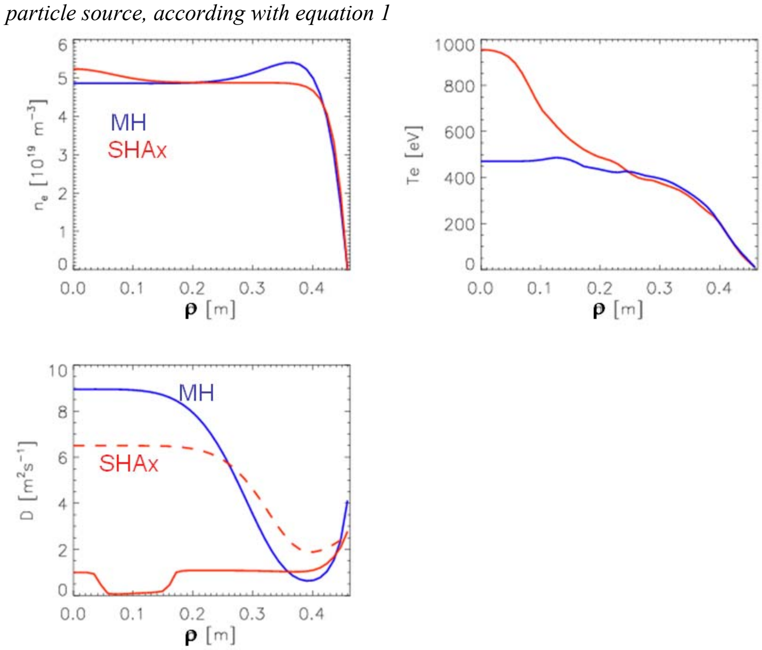

Figure 2.4.5: comparison of particle transport properties for a multiple helicity (MH) plasma in blue and a SHAx plasma in red. The radial coordinate ρ is the root square of the helical flux. The electron density, temperature and particle diffusivity are shown. The dashed line in the diffusivity plot represents the upper limit for the particle diffusion in SHAx

The diffusivity profile is shown in the lower part of the figure: in the multiple helicity case D is well consistent with with past results. For the SHAx case two calculations are shown: the first one (red solid line) corresponds to a strong reduction, in particular in the radial region of the strong temperature gradient., However, this estimate is not realistic, since relies on the assumption of a stochastic relation between diffusion coefficient and convective velocity, probably not well suited for a SHAx equilibrium, especially in the gradient region. If in the convective velocity only the E X B term is included, the resulting D is higher (dashed red line), but remains anyway lower than the multiple helicity case.

The comparison of the 3D tools among different machines is important to cover a larger parameters space, and allows more detailed analyses in different experimental conditions to gain a deeper understanding of the confinement properties of the RFP plasma. With this aim, some of the 3D transport tools of RFX (SHEq, the Zanca and Terranova's code for the eigenfunction reconstruction [Zanca2004] and NENE) have been shared with the MST group, in Madison (WI), in the framework of a long lasting collaboration between the two laboratories.

2.5 Project 4: goals and directions for potential upgrades of the RFX experimental facility.

Following the positive results obtained in the previous years, in 2011 a project to examine goals and directions for potential upgrades of the RFX experimental facility has been launched, including both improvements to be implemented already in 2012, and medium-long term upgrades, requiring a longer preliminary activity of feasibility assessment and design.

2.5.1 Improvement of the active MHD control system

An activity to upgrade the active control system has started in 2011 and will be completed in the first part of 2012: actually, the main financial investment at the end of 2011 regards the upgrade of the RFX-mod active MHD control system. A first step of such improvement consists in an increase of the computing power and in a change of the software architecture, to be based on MarTe. A significant reduction of the system latency is expected; in addition, the possibility of feedback control algorithm developments is expanded.

The upgrade will be completed with a second step, in collaboration with the IST Portuguese Association, including a complete revision of the present system.

2.5.2 Deuterium operation

The licensing procedure necessary to allow the operation with deuterium as filling gas instead of hydrogen has started in 2011 and is presently in progress. The interest in using deuterium is associated both to the RFP and Tokamak operation: in fact, an isotopic effect on confinement favoring deuterium plasmas has been documented in Tokamaks [Bessenrodt-Weberplas93] and also reported by the MST Reversed Field Pinch (for example in [Chapman04] for momentum confinement time).

2.5.3 Medium-long term upgrades

A specific activity dedicated to the study of possible medium-long term upgrades of the RFX-mod device has been launched. The possible upgrades are based on the analysis of confinement and main plasma parameter scaling laws, according to present experimental data.

Four main areas have been identified, with two coordinators for each of them:

a) - current drive and heating

b) - MHD stability control

c) - operation beyond 2MA and innovative scenarios

d) - plasma-wall interaction and density control.

As a first action, a web page for internal access has been established, to stimulate proposals and comments from all the physicists and engineers in Consorzio RFX.

After this phase of collective discussion, that is continuing up to the end of 2011, the proposals will be evaluated in terms of scientific interest, technical feasibility and compatibility with the financial situation, to allow for the selection of some of them which will be advanced with detailed designs.

For example, a good number of contributions have already been collected about the point d), PWI and density control, in particular with the proposal of changing the PFC, substituting the graphite tiles with a metallic wall, tungsten or molybdenum. The aim is to improve the density control (see section 2.2.1) and the neutral penetration. In RFX-mod, the impurity transport studies both for intrinsic impurities (C and O) and injected Nickel have shown an outward convection velocity, indicating that the core effective charge should not be affected significantly by a metallic wall.

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3. ITER

3.1 Background

Consorzio RFX is strongly committed in the international programme aimed to the realization of ITER. The main related activity is the design, realization, test and optimization of the first prototype of Neutral Beam Injector for ITER in the related Test Facility. During 2011 the design of the system has been almost completed and the call for tender for several components has been initiated. The call for tender for the buildings of the Test Facility is expected to be completed at the beginning of 2012 and the construction will start soon as the agreements between Consorzio RFX, F4E and ITER have been signed.

Several important agreements have been already signed during 2011 among which the recent approval by F4E ExCo of the agreement for the NBI Test Facility and the signature of the Procurement Arrangement between the Japanese Domestic Agency JADA and ITER (IO-JA-PA-09) The latter joins the other Procurement Arrangements already signed by ITER with F4E (IO-EU-PA-06 e 09) and with the Indian Domestic Agency INDA (IO-IN-PA-09) all together ensuring the procurement and delivery to the Test Facility of the NBI components.

These agreements and the recent signature of the memorandum of understanding between ITER and F4E, have strengthened the international commitments of Consorzio RFX so that nowadays the NBI development has become an important long term activity.

During 2011 the accompanying programme to the NBI development has gained momentum. Two facilities (ICE and the High Voltage facility) are routinely in operation at Consorzio RFX and a third one (the NI01 facility) is in the procurement phase.

These local facilities together with the participation to operation in existing facilities abroad and activities in modeling, are supporting the preparation of the operation team in time for the start of SPIDER.

Consorzio RFX is also continuing its activity in the development of magnetic sensors and LIDAR system for ITER making available its well recognized experience on these subjects.

3.2 NBI development background

During 2011 the activity for the development of the Neutral Beam injectors has been carried out under four Grant Agreements between Fusion for Energy and Consorzio RFX.

In April 2011, GRANT-032 initiated in March 2009 has been closed with the complete acceptance of all the deliverables without exception.

For the continuation of the design work for PRIMA-MITICA-SPIDER and the support to F4E to the procurement contracts of PRIMA plant, SPIDER and MITICA, three new GRANTS have been stipulated:

1. GRANT-303: this GRANT foresees the completion of the design activities of the Cryogenic pump for the HNB and for MITICA. This Grant entered into force on 13 May 2011 and will be closed on 13 March 2012.
2. GRANT-306: in this GRANT are included all the activities (design and procurement follow up, depending on the different stages of the work) concerning the PRIMA-MITICA-SPIDER plant systems and the Residual Magnetic Field Coils design work. The plant systems included are the following: cooling plant, vacuum-gas injection/storage plant, cryogenic plant, control/interlock/safety systems, all the power supplies in charge to Europe and the high voltage decks for SPIDER and MITICA, the Transmission Line for SPIDER and the High Voltage bushing between the high voltage deck of MITICA and the SF6 insulated transmission line.
3. GRANT-313: in this GRANT are included all the design activities for SPIDER (limited to the Neutron Diagnostics and the Short Pulse Calorimeter design and the follow up fo the procurement contract for the Beam source and the vessel) and MITICA (almost all the mechanical components) and all the Physics and R&D activities in support to the design and in preparation of the exploitation phase of the injectors.

The GRANT 306 and 313 entered into force on 1 May 2011 and were closed on 31 December 2011.

This year was also crucial for the final establishment of the agreements between ITER Organization, the three Domestic Agencies, Japan, India and Europe (F4E), involved in the establishment of the PRIMA-MITICA-SPIDER experimental facility and the agreement between Fusion for Energy (F4E) and Consorzio RFX to establish a long term (8 years) partnerships sharing the commitments of Europe and Italy towards ITER Organization to develop the ITER Neutral Beam Test facility at the Consorzio RFX premises.

It is recalled here that in 2009 and 2010 Europe (F4E) and India signed their Procurement Arrangements for the in-kind contribution of the agreed sharing of the component/plant systems for PRIMA-MITICA-SPIDER. Within the three signed PAs approximately 70% of the hardware procurements are included.

On December 2011 the Procurement Arrangement between ITER Organization and the Japanese Domestic Agency for the in-kind contribution of Japan to the components/plant systems for PRIMA-MITICA-SPIDER has been signed.

In December 2011 have been approved by ITER, F4E and Consorzio RFX the bilateral agreements establishing the mutual commitments and responsibilities of the parties in establishing and operating the Neutral Beam Test Facility.

The first bilateral agreement is called Memo of Understanding and is established between ITER Organization and Fusion for Energy to identify the role/responsibilities of the two parties. It foresees the role/responsibility of Consorzio RFX that is contractually defined in the second bilateral agreement between Fusion for Energy and Consorzio RFX.

This second bilateral agreement foresees also the sharing of the costs for the establishment/operation of the Neutral Beam Test Facility in the period 2012-2019 (8 years).

3.2.1 PRIMA (Padova Research on Iter Megavolt Accelerator)

In this section all the activities performed in 2011 and concerning the building construction to host the test beds and all the plant systems, excluding the electrical ones, are described.

Buildings

In Q2-2011 the final phase of the Call for Tender to a selected number of civil construction companies has been issued. The offers have been presented during Q3-2011 and in Q4-2011 the awards process is on-going. The awards process is expected to be completed by early 2012.

Fig.3.2.1: PRIMA buildings

Cooling plant for SPIDER and MITICA

In Q1-2011 the Call for Tender has been closed, but the offers exceeded the estimated budget by an excessive amount due to overspecification of some requirements. Therefore in Q2-2011 the requirements have been revised and agreed again with IO and F4E and in Q2-Q3-2011 the Technical Specification have been revised completely including all the revision steps foreseen by F4E and IO. The new Call for Tender is scheduled to be issued before the end of the year 2011.

Vacuum, gas storage/injection for SPIDER and MITICA

During 2011 the work has been dedicated to revise the Technical Specification and to support F4E in the preparation of the documentation for the issue of the Call for Tender that is expected by the end of this year.

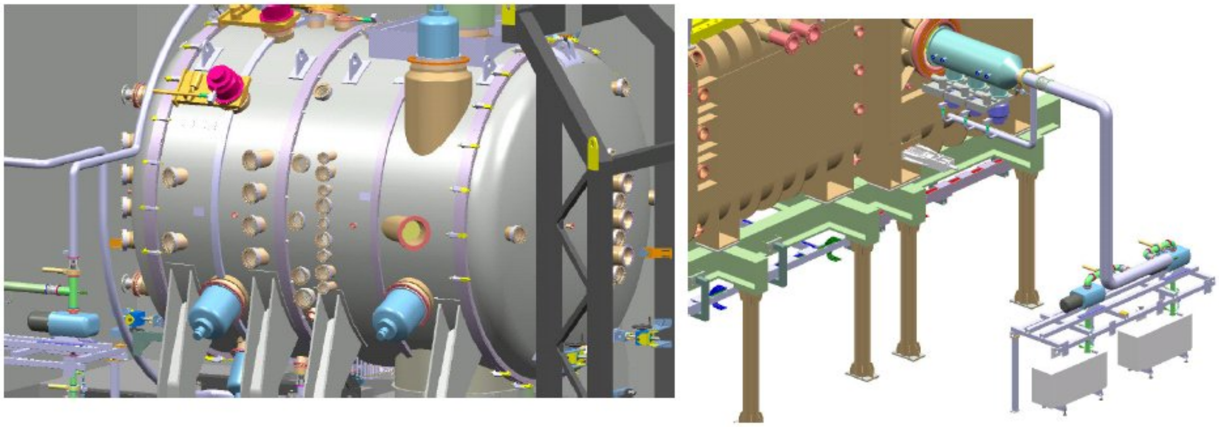


Fig.3.2.2: SPIDER vacuum system and MITICA vacuum system

Cryogenic Plant for MITICA

In 2011 the Cryogenic plant design (Fig. 3.2.3) has been revised and additional options have been analysed and implemented in the Technical Specification to allow a minimization of the overall plant costs during the call for tender phase. The final documentation ready for the call for tender has been prepared within the year. The call for tender phase, due to the restructure of the planning of the facility in consequence to the earthquake in Japan has been reallocated to start on Q4-2012.

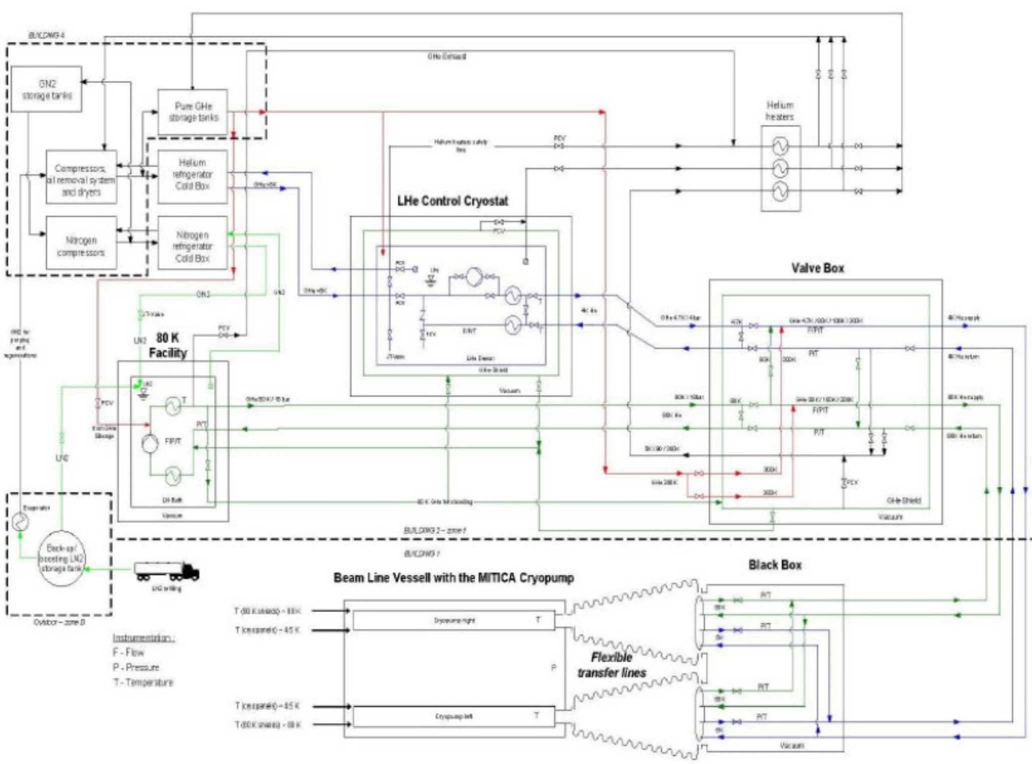


Fig.3.2.3: MITICA cryogenic plant scheme

3.2.2 SPIDER

The design activities for SPIDER mechanical components within EU responsibility were completed during 2010. The unified call for tender comprising Beam Source, Vacuum Vessel and Handling Tool was launched during 2011, offers were received and the evaluation is ongoing. During this year RFX contributed to the preparation of tender documents, official feedback to the tenders during tender stages, and is currently involved in the evaluation of the offers (both technical and financial documents) as external experts.

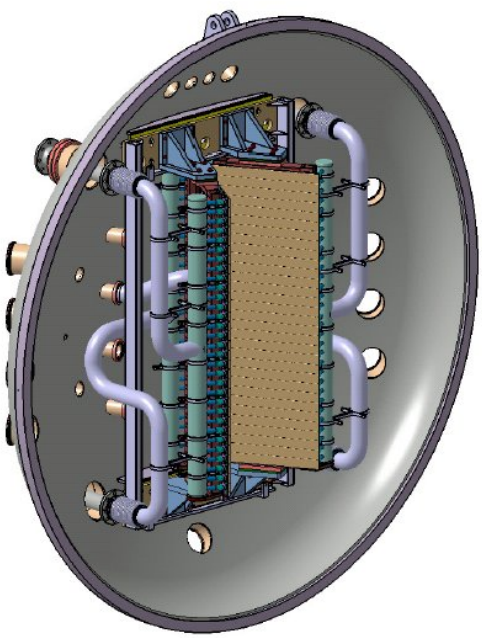


Fig. 3.2.4: SPIDER beam dump integrated in the SPIDER vessel lid

The Beam Dump, the component that intercepts the full beam of H_2 or D_2 negative ions exiting from the SPIDER Beam Source, is instead within ITER India responsibility, in terms of design and procurement of the component.

The ITER India's thermo-mechanical analyses have been followed by RFX considering the main load combinations: maximum thermal power and power density, coolant temperature and pressure, static and cyclic loads including thermal fatigue loading, drying and baking conditions, seismic events; pressure and leak testing conditions, material processing and manufacturing have been also verified.

The integration inside the SPIDER experiment (Fig.3.2.4) has been verified by RFX considering the interfaces with the supporting structure at the Vessel, the cooling lines, the sensor connectors, the installation and the operation of the neutron diagnostic, the lines of sight for other diagnostics (infrared cameras, spectroscopy, visual inspection).

Satisfying all the verifications and integrations, the final design review of the Beam Dump is planned at the end of the 2011.

3.2.3 MITICA

Further progress on MITICA Injector design has been achieved during 2011, mainly regarding the Beam Source, the Vessel, the Neutralizer and the Residual Magnetic Field Coils, all in charge of RFX according to F4E Grant313 specification. Further management activities have been carried out at RFX to follow up and check proper integration and coordination of works and deliverables foreseen by F4E Grant313 for CCFE (design development of Electrostatic Residual Ion Dump and Calorimeter) and by F4E Grant303 for KIT (design of ITER HNB and MITICA cryopumps).

Beam Source: design of the MITICA Beam Source was deeply revised in 2011, taking into account all relevant requirements discussed and agreed with the other stakeholders.

In Fig.3.2.5 the state-of-art of the MITICA BS design can be seen, together with the integration within the Beam Source Vessel.

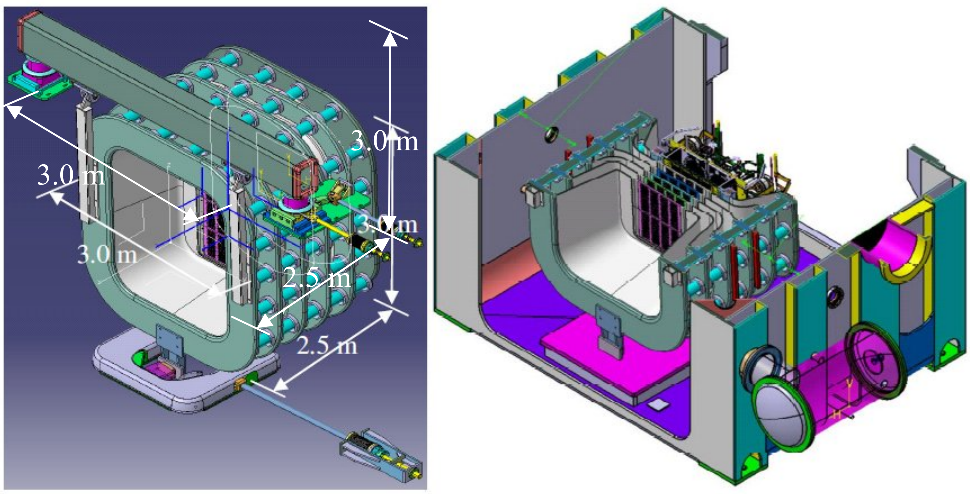


Fig. 3.2.5: MITICA Beam Source

In particular, the design was developed and updated with regard to the following aspects [Zaccaria11]:

- Extractor and accelerator grids: the definition of the grid segments was kept updated to the development of the physics and magnetic optimization, and thermo-mechanical verifications were carried out based on latest estimated power deposition, showing promising indications for future detailed mechanical optimizations.

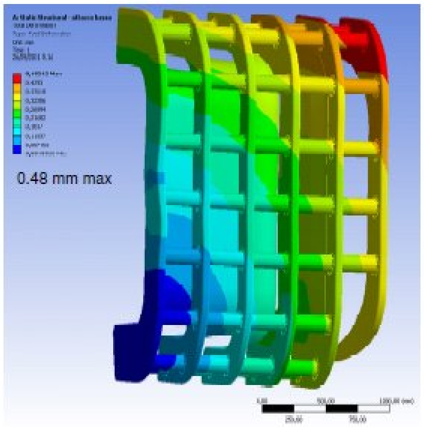


Fig.3.2.6: Mechanical verification of the accelerator structure under dead weight; global deformation [mm].

- Accelerator supporting structure: the shape of frames and flanges was optimized towards a more "squarish" profile, with several simultaneous advantages, such as enhancement of profile matching with rectangular grids and vessel section, maximization of distances between parts at different voltage, improvement of lateral conductance for stripping minimization and reduction of heat loads on grids. The result of the first mechanical verifications of the new shape (deformation under static loading shown in Fig.3.2.6) indicates that the choice of the configuration is correct; finalization is planned for 2012. A preliminary assessment of manufacturing/assembly procedures was carried out in support of the design definition. The addition of lateral magnets proposed in the latest magneto-physics configuration was successfully included in the design.
- The activity on the RF source involved a thorough revision of the cooling circuit scheme, the design of a new support structure integrated with the revised accelerator frames and the revision of the SPIDER PG bus bar routing inside MITICA environment.
- Support and tilting systems were revised in order to comply with RH requirements and interfaces: new source supports and related (dis)assembly procedures were drafted in collaboration with CCFE team developing the RH equipment and IO NB team managing the interfaces within ITER NB cell.
- A new rear electrostatic shield was drafted to comply with all source modifications; electrostatic verifications were carried out in parallel to support the design, in order to assess the breakdown probability between source parts at different voltage and between source envelope and the grounded vessel.
- Embedded diagnostics, signal cables and the connections with HV Bushing were discussed at length with JADA, IO and F4E. A final agreement on the interfaces between EU and JA procurement was not reached; nevertheless a design proposal for all services within the source was developed and modeled, in order to speed up the interface finalization.

The activity design on the Beam Source is expected to continue throughout 2012 and to be completed in 2013, including the build-to-print technical specification for the tender.

Vacuum Vessel: most of the activities in 2011 have been dedicated to revise the design following changes of requirements by IO and further definition of interfaces under development or review during the year. All these design activities and related structural analyses have been carried out by RFX in strong collaboration with the design teams from different parties involved in the design (IO, F4E, RFX and CCFE (in charge for ITER HNB Vessel)). Design revisions of some interfaces were due to newly identified remote handling requirements for in-vessel components and to the progressive review of several diagnostic accesses to be agreed with IO and F4E.

Most of requirements for MITICA Vessel have been finally fixed and agreed among RFX, F4E and IO in 12-14 October 2011 progress meeting of Grant GRT313. Some interfaces still suffer from lack of information or not yet detailed definition, since the design of in-vessel components is still on-going. However, in agreement with F4E, any further activity related to changes of requirements or interfaces revision have been temporarily stopped to allow RFX to complete the foreseen detailed design and structural analyses of MITICA vessel within the end of Grant 313.

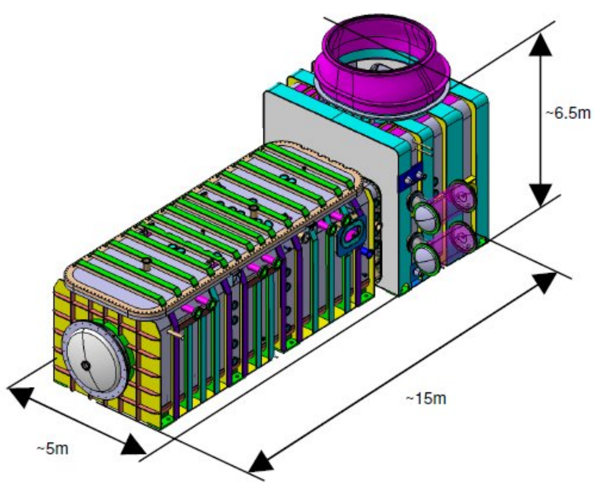
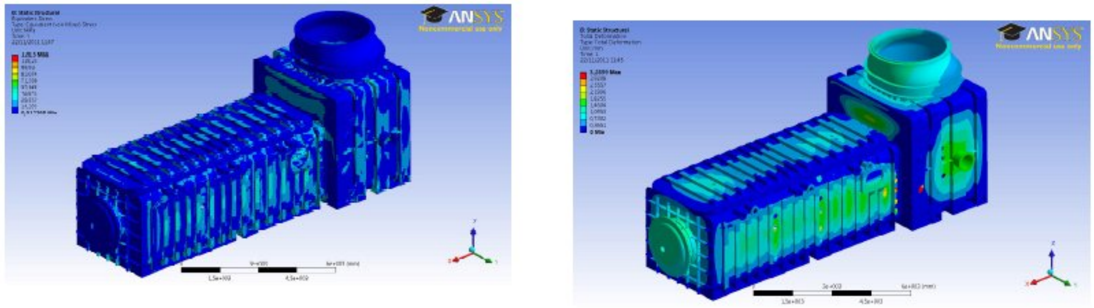


Fig.3.2.7: MITICA Vacuum Vessel 2011 design

A thorough design review has been also carried out by RFX to reduce the manufacturing complexity and then the future procurement cost. The present design of MITICA Vessel is shown in figure 3.2.7.

Overall and detailed structural analyses have been carried out during 2011 to compare different design solutions, also as regards the complex connection flange of Vessel Top Lid and the new definition of Dome geometry from IO.

Further structural analyses are planned by RFX within December 2011 to support the updated vessel design with proper verifications referring to the main and most critical load cases. The most recent results show acceptable stress distribution and well reduced displacements with respect to the previous design (see Figure 3.2.8). Analyses and verifications for all the different load cases are foreseen in 2012 in parallel with writing of Technical Specifications for MITICA Vessel procurement.



(a) (b
Fig.3.2.8: Von Mises stress distribution [MPa] (a) and displacements [mm] (b) of MITICA Vacuum Vessel under dead weight and vacuum load condition

In the framework of Grant 313, activities have been also carried out on integrated MITICA design, aiming to fully identify forces at Vessel interface with HV Bushing and to design a new structure for HV Bushing support inside MITICA bio-shield.

The CAD integrated model is shown in Figure 3.2.9 and the correspondent finite element model in Figure 3.2.10.

Final results of analyses will be delivered to F4E by the end of the year and will be the basis for HVB support structure design and verifications.

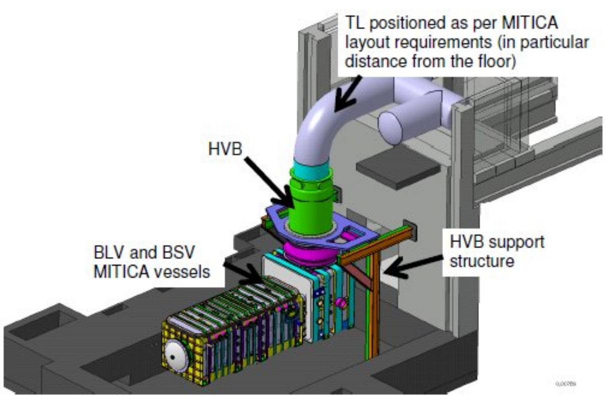


Fig.3.2.9: MITICA Injector integrated CAD model

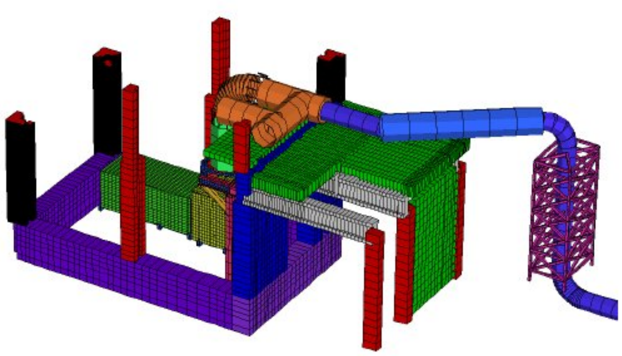


Fig.3.2.10: MITICA Injector integrated FEM model 2011

Neutralizer and Electron Dump: a big effort during 2011 has been dedicated to optimize the Neutralizer design and to develop a first design proposal for the Electron dump, fully integrated with the Neutralizer.

The design of the Neutraliser and Electron Dump has been developed considering the requirements for the operation in MITICA and in ITER HNBs.

The thermo-mechanical analyses have been carried out considering the main load combinations: maximum thermal power and power density, coolant temperature and pressure, static and cyclic loads including thermal fatigue loading, drying and baking conditions, seismic events; pressure and leak testing conditions, material processing and manufacturing have been also verified.

The updated design of Neutralizer and electron dump is shown in Figure 3.2.11.

The main aspects considered for 2011 design improvements have been:

- updating of interfaces according to further RH requirements from IO;
- design development and improvement of pipework for water cooling including flexible joints, aiming to simplify manufacturing and reduce production costs, still keeping reliability and IO requirement compatibility;
- design development and analyses of the pipework constraints considering: free expansions under static loads, stiffness under dynamic response;
- development of some design details to improve manufacturability and access of welds for non destructive tests;
- preliminary seismic analyses and verifications;
- calculation of thermal loads on the electron dump panels;
- preliminary thermal and structural analyses of electron dump panels;
- preliminary evaluations of changes of gas pressure distribution along the beam line due to electron dump panels;
- further progress in design of embedded diagnostics sensors (layout, fixing, cables, connectors);
- procurement of CuCrZr alloy tubes and R&D program for activities to be developed during the 2012.

The integration of Neutralizer and Electron Dump inside the injector has been verified considering the interfaces with the supporting pads at the Vessel, the cooling lines, the gas lines, the sensor connectors, the lines of sight for MITICA diagnostics (beam emission spectroscopy, tomography, visual inspection).

Requirements and interfaces documents have been prepared by RFX, submitted to F4E and IO and finally approved by F4E and IO in ITER IDM.

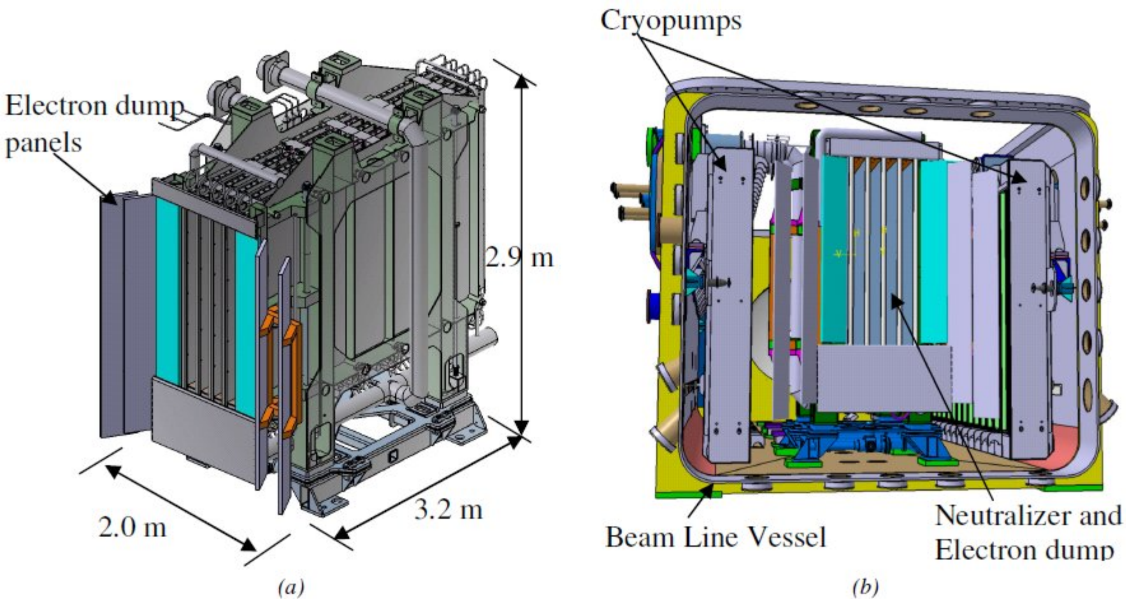


Fig.3.2.11: Neutralizer and electron dump updated model 2011: isometric view (a) and front view inside the vessel (b)

Residual Magnetic Field Coils:

The purpose of the RMFC system in the MITICA test facility is primarily:

- to simulate the "residual" magnetic field existing in the ITER HNB inside the HNB Magnetic Field Reduction System (MFRS), which is constituted by the Active Correction and Compensation Coils (ACCC) and by a Passive Magnetic Shield (PMS).
- to allow the experimental evaluation of the impact of such residual magnetic field on beam aiming, beam efficiency and heat loads on the beamline components.

Therefore the requirements for the MITICA RMFC are logically related to those of the ITER HNB MFRS. Indeed, the RMFC shall produce a (vertical) field Bz exceeding the expected residual field inside the HNB MFRS, increased by a "flexibility" factor.

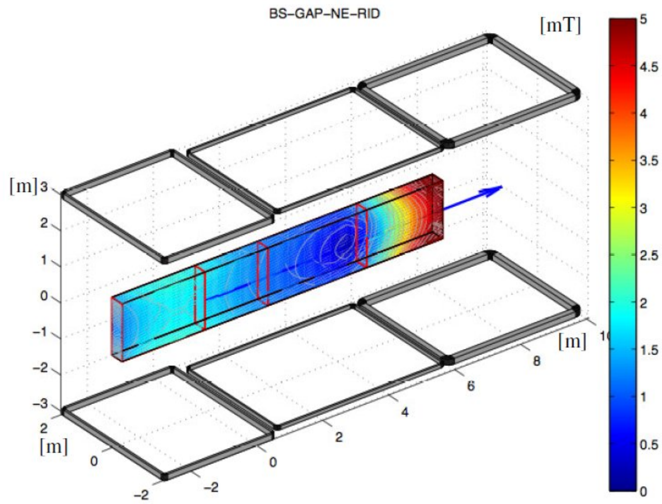


Fig.3.2.12: space distribution of the magnetic field strength produced by 3 pairs of RMFC coils in a control volume representing the Beam Source, the Neutralizer and the RID. (the current is 15 kA turns in the BS coils, 6.5 kA turns in the Neutralizer coils and 50 kA turn in the RID coils).

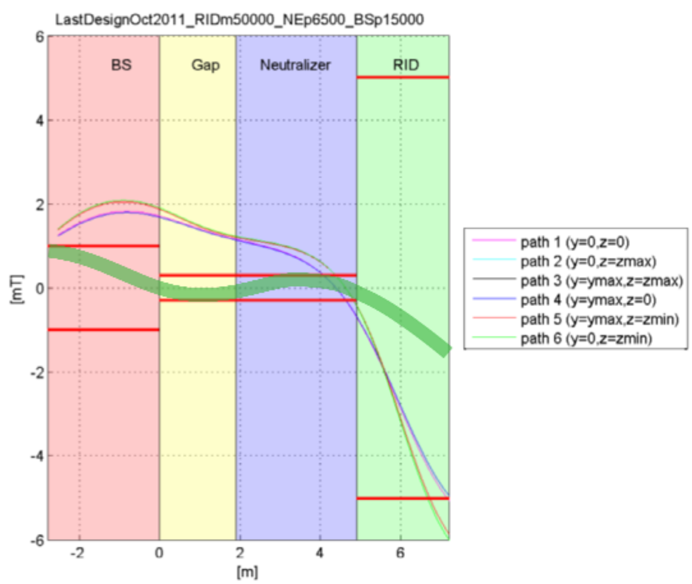


Fig.3.2.13: distribution of the magnetic field produced by the RMFC coils along the axis and the edges of the control volume. The thick green line represents the expected residual magnetic field strength inside the ITER HNB passive and active reduction system. The straight red lines represent the HNB magnetic field limits according to DDD5.3 (2001). The space distribution of the RMFC field is similar to that expected in the HNB and can reach a larger strength.

A preliminary design and several performance analyses have been carried out by RFX in order to evaluate the possibility of substantially simplifying the size and complexity of the RMFC system. In parallel, a detailed discussion on the essential requirements of the MITICA RMFC with ITER IO was stimulated, which led to the conclusion that the original DDD 5.3 (2001) requirements were correct, but some of the requirements considered later on were actually unnecessary. In addition, requirements in terms of field uniformity were necessary. In the end, this process has led to the definition of the final requirements of the MITICA RMFC system in agreement with F4E and ITER IO.

A 3x2 coil configuration is proposed for the MITICA RMFC. The preliminary performance analysis has shown that the configuration is capable of producing a magnetic field in fairly good compliance with that expected inside the ITER HNB active and passive magnetic field reduction system (see Figg. 3.2.12 and 13).

3.2.4 Power supply systems and related components

The activities to carry out during 2011 corresponded to the natural prosecution of those performed in 2010. For SPIDER, the most advanced project in terms of schedule, the management of the ISPES contract, signed in 2010, and the activities of CfT and follow-up of the HVD and Transmission Line procurement. Regarding MITICA power supplies, the completion of the conceptual design, including technical specification preparation of the main power supply systems, with the aim of launching the CfT procedures of the main procurements during 2012.

In practice, as described in the following, the work planned for SPIDER power supplies was not respected due to external causes, and as a consequence also the work plan of the RFX personnel had to be adjusted accordingly.

SPIDER Power supplies

At the start of the year the follow up of the Ion Source and Extraction Power Supply (ISEPS) contract, in support to F4E, involved RFX in the technical review of the OCEM First Design Report. This was subsequently approved by F4E and by the IO. However, at the end of May OCEM went bankrupt, stopping virtually all the RFX activities in this area. In July F4E made official the interruption of the ISEPS contract and the future course of this procurement will not be known before 2012.

An open call for tender for the procurement of SPIDER High Voltage Deck (HVD) and Transmission Line (TL) [Boldrin11] closed at the end of January with no valid offer received. In the subsequent months, RFX carried out further work on the technical specifications also in response to comments raised by an F4E's consultant and had some contacts with potential suppliers, in view of a new call for tender. This was eventually launched by F4E in July as a negotiated procedure and closed at the end of September, with a result identical to the first attempt. As a result RFX, in agreement with F4E, has resumed contacts with industry in view of a new procurement possibly based on a negotiated procedure.

Over 2011 much effort was devoted by RFX to support, interface and integration activities with the Indian procurement for SPIDER Acceleration Grid Power Supply (SP-AGPS). Two interfaces meetings were held with the participation of RFX, ITER India, F4E and the IO. RFX contributions covered signal exchange, interlock architecture, safety design prescriptions and site layout, both indoor (switched power modules) and outdoor (multisecondary transformers) and with clear implications on building design.

Partly related to the activity described above was the implementation of an integrated SPIDER circuit model, on the basis of the information available from OCEM (at a good level of maturity) and ITER India (still at a preliminary level) [Zamengo11]. RFX undertook this task with the objective of confirming or defining the passive protection components necessary to ensure protection of the power supply system, in particular to limit the adverse effects of the transients resulting from grid breakdowns.

MITICA Power supply systems

During 2011, many efforts have been made to complete the conceptual design of the AGPS-CS and GRPS control system [Ferro11, Barp11] and to define a complete and detailed list of tests to be performed both at the factory and on site to accept the AGPS-CS and GRPS procurement. Moreover, many discussions among the IO, JAEA, F4E and RFX personnel have been organized and supported by RFX documents in order to define and agree about the electrical parameters of the power interfaces between AGPS-CS (EUDA procurement) and associated AGPS-DCG load (JADA procurement).

Two technical specification issues, relevant for the procurement of three sets of AGPS-CS and GRPS systems, have been released during 2011 and revised both internally to RFX (with reviewers other than the authors) and externally by F4E staff and consultants. By the end of 2011 the technical specifications have not been completely consolidated, due to a lack of information on the definition of the ITER site conditions (information expected from the IO) and on the signal interfaces with the AGPS_DCG system (information expected from JAEA). Moreover, a recent request from IO to modify the performance of the Active Correction Coils in ITER stopped the definition of the relevant power supply, part of the GRPS, awaiting for the new parameters to be defined. A consolidated version of the technical specifications is expected in the spring of 2012, followed by the launch of the CfT procedure.

Analyses to evaluate the impact of the AGPS “load” on the 400kV Italian grid have been performed and finalized during 2011. As result, it has been demonstrated the low impact of the MITICA and SPIDER experiments on the 400kV network both in terms of voltage drop and harmonics injected in the HV grid. At the same time, the need has been confirmed of coordinating the RFX and NBI experiments in order to avoid the time overlap of the two experiments thus avoiding exceeding the limits of voltage drop on the medium voltage network fixed as design parameters of the power systems.

Support activities to the JADA procurement have been performed during 2011, in particular during the first part of 2011. Then, in the second part of the year the activity has been progressively reduced, as required by the IO, in order to avoid the risk of opening up new issues that could lead to further postponement of the signature of the JADA PA, expected at the end of 2011. The support activity mainly concerned the definition of the conductors internal to the Transmission Line and relevant electrical parameters and the interface electrical parameters between AGPS-CS and AGPS-DCG. Many other interfaces remain to be defined and agreed in detail, in particular electromechanical interfaces between the TL (JADA procurement) and HVD1-TL Bushing (EUDA procurement). These interfaces will be discussed and defined during 2012, after negotiations have resumed following the signature of the PA of JADA.

During 2011, the MITICA Gas Handling and Storage System (GHSS) conceptual design has been completed including the integration with the PRIMA buildings, as activities included in the F4E Grant 32. No further activities have been performed, not being foreseen in the following F4E Grants carried out in 2011.

The most critical component of the NB Injectors power supplies to be procured by F4E is the HV Bushing connecting HVD1 to the HV Transmission Line. For this reason F4E had initiated a procedure, known as Competitive Dialogue, which foresees the set up of the technical specifications on the basis of technical discussions with industry personnels, expert in the specific field. During 2011, RFX supported F4E in this activity participating to discussions with competitive dialoguers, preparing technical documents, revising industry technical proposals, suggesting solutions for specific open issues, i.e. HVD1 access system, a new ISEPS layout inside HVD1 compatible with the new position of the HV Bushing, etc. In this regard RFX has proposed new layouts of HVD1 and HV Bushing for both MITICA and ITER sites to achieve a single common design. RFX has also produced a first version of the Technical Specifications, issued in October 2011, then reviewed by F4E with the help of external experts, and is preparing a second version that will be issued later in 2011. All these activities, performed in agreement with the F4E procurement schedule, will be concluded in spring 2012, immediately followed by the CfT phase.

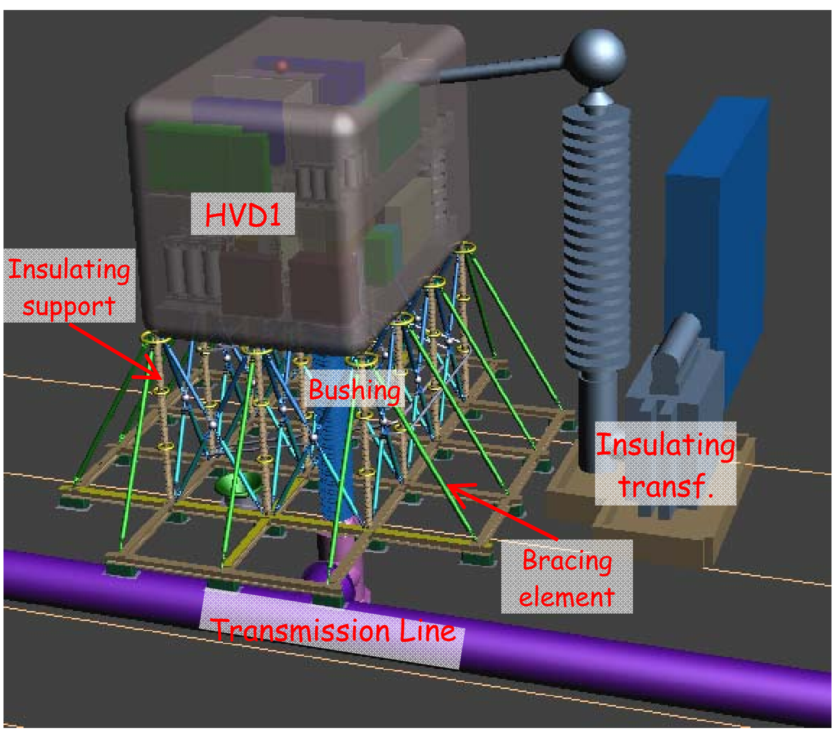


Fig.3.2.14: 3D cad view of the MITICA HV components inside the High Voltage Hall

Grid Break Downs (BD) will be frequent events during the normal operation of the neutral beams. When a BD event occurs, high frequency overvoltages are generated that stress the insulation materials and induce stray current circulation through grounded structures, producing EMI and damage to the equipment connected to it. During 2011, a high frequency model of the power supply system was developed, including the beam source and the insulated gas Transmission Line, able of simulating these phenomena by helping the development of appropriate measures to mitigate potentially adverse consequences. The model, derived from an earlier one developed in 2007 and 2008, has been improved in particular with respect to the beam source, the power conversion system, the internal conductors of the Transmission Line and the feedthroughs of the HV Bushing which represent one of the most critical issues of the overall system. First results were obtained in which it was shown that during the BD phenomenon, overvoltages in the range of tens to hundreds of kilovolt will be induced between conductors that normally operate at a few hundred thousands volts, if no action is taken. The positive effects were also verified of the inclusion of appropriate protection systems, i.e. capacitors. These preliminary results will be refined through further analysis during 2012 and will be used to test the efficiency of passive protection systems that will be adopted.

PRIMA Medium Voltage Distribution Grid

The PRIMA Medium Voltage Distribution Grid, including SPIDER and MITICA Distribution Boards and all the required upgrades of the 400kV substation to feed the new experiments, will be supplied by Consorzio RFX, the Host of the experiments, as part of the PRIMA building procurement. As a consequence, all activities necessary to tender for the procurement, including preliminary design activities will not be supported by any F4E Grant and will be performed directly by RFX staff without any external coordination. During 2011, the Medium Voltage distribution grid conceptual scheme has been completed, also supported by the results of market surveys to assess the new available technologies. Moreover, a first draft was prepared of the technical specifications for the procurement of this plant, specifications that will be upgraded during 2012 on the basis of the procurement strategy now under discussion.

3.2.5 Control and Data Acquisition

The activity on control and data acquisition has been pursued in 2011 under F4E-Grant-032 and -306, covering the periods before and after end of April 2011, respectively.

The finalization of the F4E framework contract for the development of the control, interlock and safety systems in the Test Facility that was expected for early 2011 has been delayed to 2012, in view of more general agreements on the Test Facility by ITER, F4E and Consorzio RFX.

In 2011 progress has been achieved in the development of the SPIDER control and data acquisition system (CODAS) and of the SPIDER interlock system. Limited resources have been also devoted to sketch the conceptual architecture of MITICA control and data acquisition.

As for SPIDER, efforts have been addressed to define in details the system architecture and derive the specific requirements of the plant systems to be integrated with SPIDER CODAS [Luchetta11]. Figure 3.2.15 shows the SPIDER CODAS system architecture that consists of three main blocks: Central CODAS, Networks and Plant System CODAS. Central CODAS provides high-level functions such as data storage, control of experimental activity (run-time control) and data analysis. Networks and Plant System CODAS implement data communication and plant system interface, respectively. The software components and their interaction have been defined in detail. The SPIDER countdown program has been specified and implemented. It consists of a tree-like structure of finite state machines that allow integrating progressively plant systems into a single beam pulse sequence. This approach provides high flexibility in building a commissioning sequence capable to integrate progressively the operation of plant systems when ready.

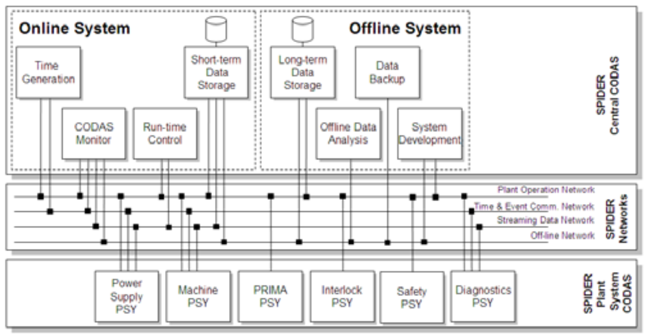


Fig.3.2.15: SPIDER CODAS system architecture.

Real-time control implementation has also been addressed in details [Barbalace11]. The hardware components have been also defined in detail, including the data storage systems, the communication networks and the data acquisition specific equipment. To decouple pulse-dependent and independent activities, data storage will be split into short-term and long-term. The former will sustain the incoming data streaming during experimental activity and will be, thus, optimized for data writing. Storage capacity will be limited to about a day of experimental data. The latter will be dimensioned to have a storage capacity sufficient to maintain the whole SPIDER data archive and data will be moved overnight from short-term to long-term data volumes. The networks and short-term data storage have been design to sustain up to 200 MB/s of incoming data during experimental activity. Long-term data storage capacity has been fixed at 50 TB, amount that is evaluated sufficient for a few years of operation.

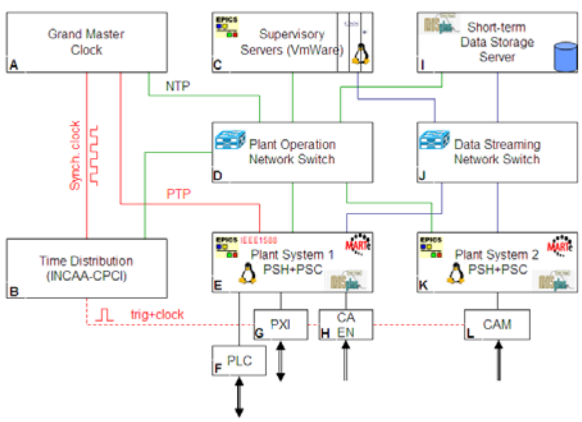


Fig.3.2.16: SPIDER CODAS prototype.

Interface sheets have been produced for most plant systems to be integrated with SPIDER CODAS to freeze interface information and point out possible issues. A comprehensive prototype of SPIDER CODAS has been developed to test component interaction and system performance during operation (Figure 3.2.16). It implements most SPIDER CODAS functions, such as the short-term data archiving, run-time control, time generation, communication (plant operation, streaming data and time & event communication networks). Two plant systems simulate data flow from/to the SPIDER plant including slow control data (PLC), continuous acquisition data and reference generation (PXI), event-driven fast data (CAEN) and images (CAM).

In parallel, the architecture of the SPIDER interlock system has been progressively defined, including the interface to plant units (Figure 3.2.17). The system requirements of the SPIDER Interlock System have been derived and, consequently, a suitable architecture has been designed. The Interlock System will be required to implement protection actions on two different timescales: μs and tens of ms in case of fast and slow protection, respectively. Slow and fast protection functions will be realized by different technologies. The slow interlock will be implemented by reliable commercial equipment (Siemens programmable controllers), whereas the fast interlock will rely on custom-developed electronics.

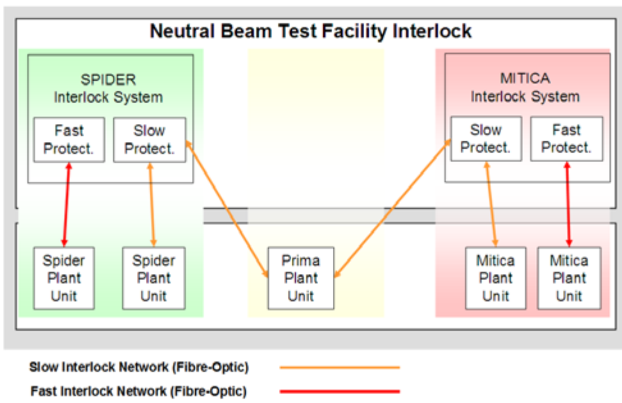


Fig.3.2.17: SPIDER interlock system architecture

3.2.6 Diagnostics

After agreement with IO and F4E in November 2010 on the set of diagnostics to be installed on SPIDER and MITICA, in 2011 the design of SPIDER diagnostics has been completed to the functional specification level, supported by an extensive market survey leading to a global cost estimate and to prototype tests of some critical items, while the conceptual design of MITICA diagnostics has started, mainly to define requirements, interfaces with other systems, a tentative layout and lines of sight of optical diagnostics.

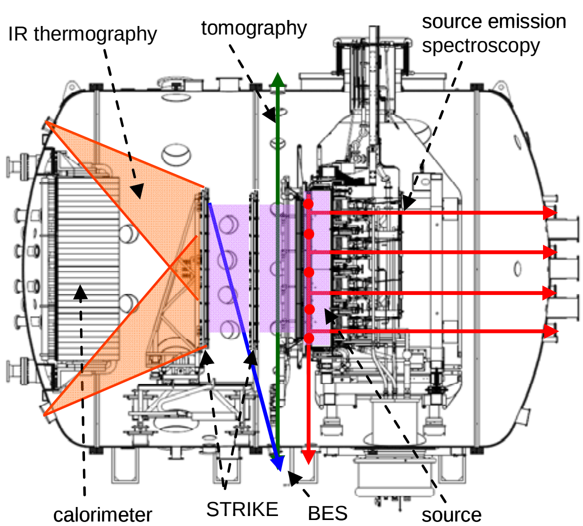


Fig.3.2.18: Vertical section of SPIDER along the beam, with internal components and diagnostics LOSs. STRIKE is represented in the two possible operational positions at 1.1m and 0.5m from the GG. Source emission spectroscopy has LOSs along three directions: circles represent those perpendicular to this section.

The suite of diagnostics for SPIDER and MITICA [Pasqualotto11a] comprises some sensors required mainly for operation of specific plants (power supplies, vacuum and gas injection, cesium oven, cooling plant of ion source, beam dump and other beam line components) and other measurements dedicated to characterize the plasma in the source and the beam. Fig.3.2.18 shows the main lines of sight of optical diagnostics in SPIDER. Thermocouples are used for calorimetry in water cooling circuits, to measure the dissipated power [Agostinetti11], and are also installed on heat exposed components of source and beam line components (BLCs) to characterize the distribution of the power load. An optical transmission system has been developed for those sensors that would be otherwise susceptible of high voltage breakdowns [Brombin11]. The source plasma will be investigated also with electrostatic probes, absorption spectroscopy for cesium density, cavity ring down spectroscopy (CRDS) for negative ion density [Pasqualotto11b], and especially emission spectroscopy for electron temperature, density of electrons, negative ions, cesium, neutral hydrogen and to monitor the amount of impurities. The beam will be measured mainly in terms of uniformity and divergence. On SPIDER a short pulse calorimeter (STRIKE) observed by IR thermocameras will provide a high resolution map of the beam intensity and thus its uniformity and divergence (Figure 3.2.19) [DallaPalma11, Serianni11, DeMuri11]. It will be complemented, as illustrated in Fig.3.2.18, by beam emission spectroscopy (BES), visible tomography [Agostini11] and neutron imaging on the beam dump [Rebai11]: they are not limited to short pulses and the last one is only operational with deuterium.

MITICA will have the same set of operational diagnostics as on SPIDER, with a large number of thermocouples on BLCs, including and exceeding those foreseen in the HNB. Source spectroscopy will use a reduced number of lines of sight (LOSs). The beam optics will be investigated between BLCs with beam emission spectroscopy and tomography, through narrow

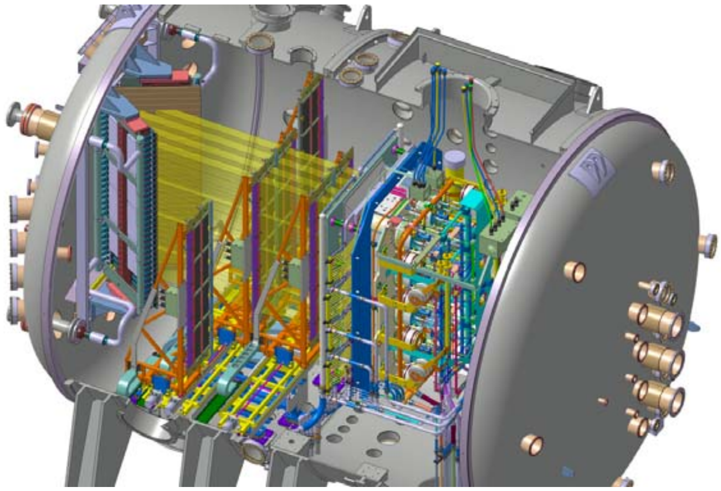


Fig.3.2.19: CAD model of SPIDER, with cut through view of the internal components. The beam is intercepted either by the calorimeter or by STRIKE,

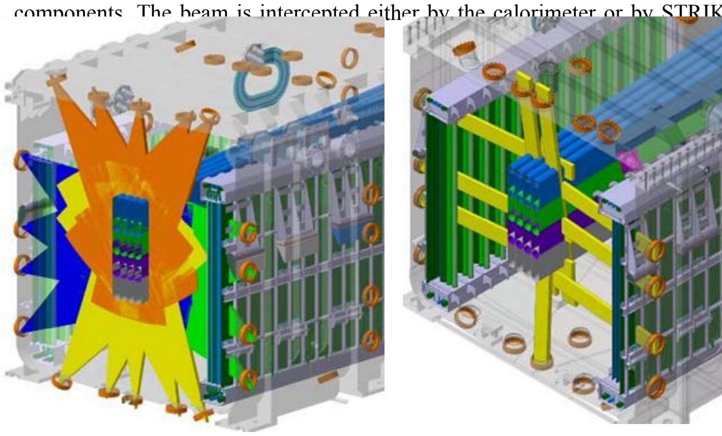


Fig.3.2.20: Vertical section perpendicular to the beam of MITICA between BLCs, with representation of tomography (left) and BES (right) lines of sight.

apertures on the cryopump backplane (Fig.3.2.20), and by neutron imaging installed on the calorimeter. Electrostatic probes will monitor the plasma inside RID and neutralizer.

The impact on installed instrumentation of neutron and gamma radiation has been evaluated for MITICA, when it is operated in deuterium [Bagatin11a, Bagatin11b].

Particular effort has been dedicated this year to some specific diagnostics: development of the inversion algorithm for visible tomography on MITICA; simulation of neutron detector performance on MITICA, both required for final acceptance of these diagnostics by ITER Organization; procurement and test of sample tiles for STRIKE, using a high power laser instead of a particle beam and an IR camera specifically purchased, to start qualifying possible tile manufacturers and validate the layout of the system; in house manufacturing and test in the local magnetron of prototype electrostatic probes for the SPIDER source. For several other diagnostics the design has been completed or optimized and final functional specifications delivered to F4E.

3.3 NBI accompanying activities

3.3.1 High Voltage studies

Fig. 3.3.1: 300 kV tank and AlO_2 feedthrough and the internal electrodes

In 2011 the experimental campaign with voltage up to 300 kV has been completed in July at the High Voltage Padova Test Facility - located at the Department of Electrical Engineering of the Padova University. The campaign was mainly aimed at validating the Voltage Breakdown Predictive Model VBPM developed by Consorzio RFX [Pilan11]. The tests have been carried out on four kinds of SS electrodes (three parallel plane and one

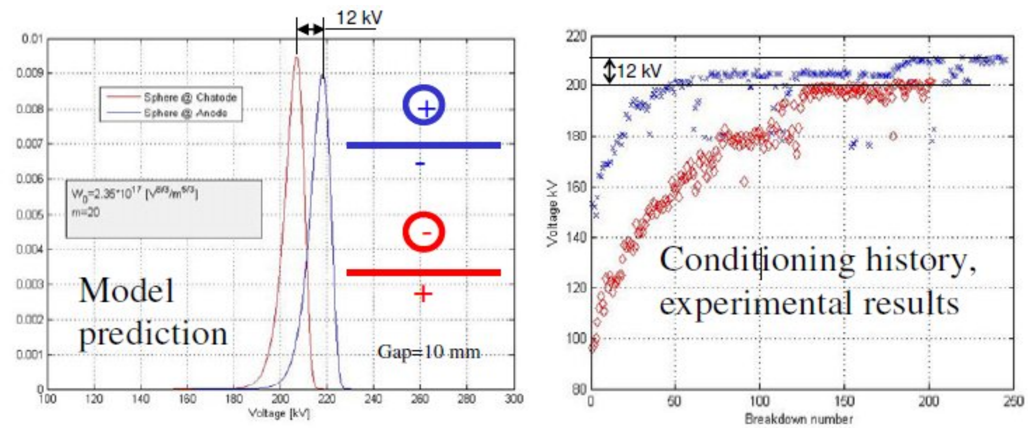


Fig. 3.3.2: Effect of polarity reversal in Sphere-plane geometry

sphere-plane electrode geometries), using the 300 kV setup shown in Fig. 3.3.1. In Fig. 3.3.2 is reported the comparison between the experimental results relevant to the polarity reversal in the sphere-plane geometry and the VBPM prediction; the model parameters have been derived experimentally from the campaign performed on the parallel plane geometries.

Due to contractual aspects of the F4E Grants supporting this R&D, the campaign has been stopped in order to step up the Facility to the 800 kV voltage level. Figure 3.3.3 shows the vacuum tank and one of the 400 kV Power Supplies forming the 800 kV setup, as indicated in the sketched layout. The two feedthroughs are made also in this case in Alumina. The commissioning completion is scheduled by the end of the current year.

The experimental program is accompanied by a theoretical investigation on the mechanisms (clumps theory and electron photo-emission) underlying the breakdown initiation. This activity, performed under

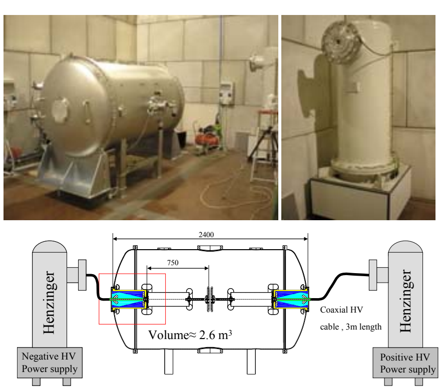


Fig. 3.3.3: 800 kV tank, one of the two 400 kV-1mA power supply and the relevant layout.

the EFDA task WP11-DAS-HCD-NBI (Assessment of NBI for DEMO) has started mid 2011 and the preliminary results show that for both mechanisms the driver of the breakdown is the quantity:

$W = E_K \cdot E_A^{\alpha} \cdot U$, which is at the basis of the VBPM formulation.

3.3.2 R&D on radiofrequency

In 2011 the collaboration with IPP continued. In January and February, IPP and RFX staff performed a joint campaign of electrical measurements on the RADI test bed in Garching. The results enlarged the existing experimental database for the estimate of the equivalent electrical parameters of the RF circuit under different operational conditions.

In the RFX RF laboratory, a matching circuit was developed for igniting an RF plasma at 1MHz on the Magnetron facility. This was achieved reliably and up to the rated power of the available RF amplifier, allowing testing in a truly RF plasma of prototype Langmuir probes for the SPIDER experiment. As an improvement to RF operation on the Magnetron and as a test of concepts to be tried later on SPIDER, an automatic system for load matching based on frequency variation was implemented and operated with good results. Moreover, a new and significant activity was launched within the RFX RF laboratory, consisting in the development of a test stand for RF insulation in vacuum. A suitable resonant circuit and associated components were identified and procurement initiated.

The experimental activities were consistently supported by models and simulations. In particular, a circuit model for power and frequency regulation of the tetrode oscillator was set up. The next step will be represented by the definition of a suitable verification of the model on the Himmelwerk generators in Garching.

3.3.3 Construction of an ion source with extraction system (NIO1)

During 2011 the procurement of the NIO test facility has proceeded. Specifically an order was issued for the procurement of the high current power supplies, including the plasma grid bias with respect to the source walls and power supply for the current flowing in the plasma grid.

A call for tender was launched for the procurement of the beam source, comprising the ion source and the accelerator, and the corresponding offers have been received. When the new rules came into force concerning the purchase of material, some time was dedicated to the definition of the proper procedure to be followed for the NIO experiment. Moreover, several issues were discussed with the companies in order to reduce the overall cost. This led to some delay in the order, which will be issued at the end of 2011. Regarding the mechanical parts, the supporting structure has remained outside the order in 2011. As for the site adaptation, the features of the proposed area for NIO positioning are under revision, particularly concerning the X-ray screening requirements. The capacity of the floor is suitable for the expected loads.

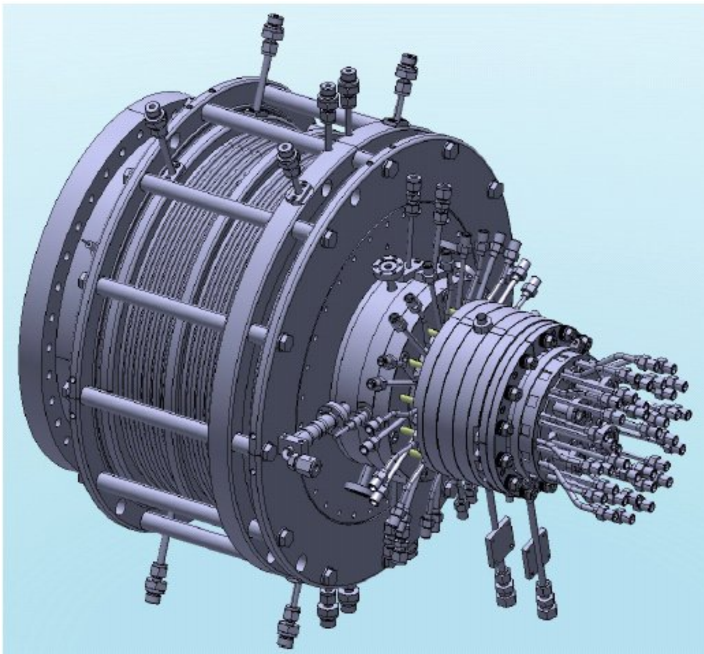


Fig.3.3.4: The beam source of the NIO experiment.

3.3.4 Modeling and numerical simulations of the negative ion beam

The comprehensive set of numerical codes (STRIP, SLACCAD, OPERA, EAMCC, ALIGN and ANSYS) presently available for the electrostatic, magnetic and particle tracking simulations has been applied to the thorough investigation of several proposed designs of the MITICA accelerator under normal conditions.

Starting from the previous work on this subject and following discussions with external experts from ITER IO, CEA, JAEA and IPP, improved solutions have been developed. Different options have been conceived and compared, aiming at a better operating behavior in terms of beam optics, suppression of co-extracted and stripped electrons inside the accelerator, reduction of secondary electrons inside the accelerator, thermo-structural behavior, voltage holding, compatibility with a Radio Frequency ion source, compatibility with long pulse operations, compatibility with possible variations of the operating scenario.

In particular, the following objectives have been considered with high priority:

- Reducing the heat loads due to co-extracted and stripped electrons on the grids to an acceptable level;

- Minimizing the power associated with the residual electrons at the accelerator exit, which is then deposited on the beam line components;
- Optimizing the ion beam optics and uniforming beam divergence for all beamlets under a wider range of operating conditions.

The resulting optimized configuration is characterized by equal acceleration gaps for best voltage holding and by diagonal magnetic field, which guarantees both a good beam optics (beamlet divergence, beam aiming) and a sufficient capability to dump the co-extracted electrons and the electrons generated by stripping.

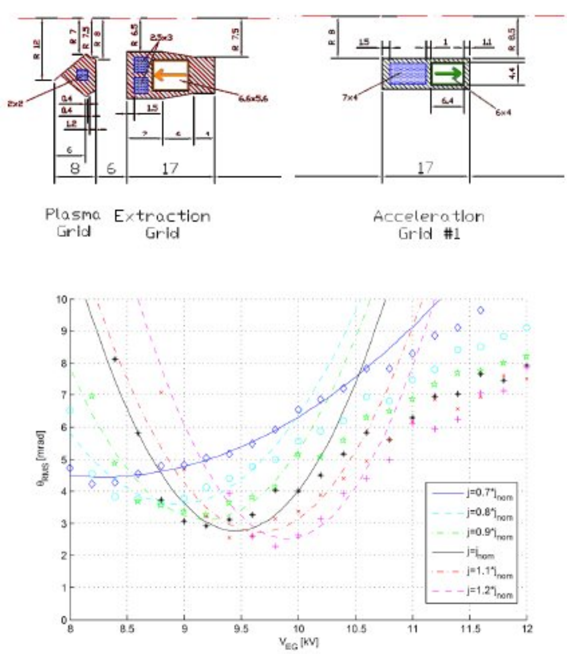


Fig.3.3.5: MITICA accelerator structure and divergence in different operating condition..

The thermo-mechanical behavior of the grids (stress, strain, deformation, fatigue life) and of all the components located downstream of the beam source (neutralizer, ion dump, cryopumps, vessel) has been verified.

This design configuration has been studied in detail also considering the effect of beam halo and possible variations of the operating scenario. The alignment among the grids and their thermo-mechanical behaviour have been investigated in detail with dedicated analytical and numerical models.

The simulation of negative ion generation has continued, extending to the treatment of the electrostatic sheath determining the extraction of negative ions.

The investigation of space charge compensation by a PIC-Monte Carlo code has been extended to the determination of radial and axial confinement of secondary particles.

The input files to the CRONOS code have been assessed for the simulation of the effect of NBI on the ITER plasma.

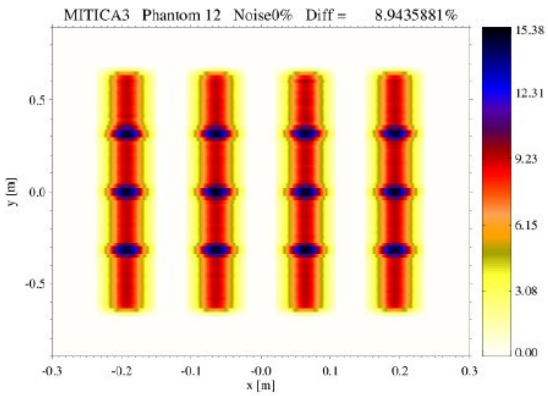


Fig.3.3.6: Tomographic inversion of the MITICA beam.

The tomographic system for MITICA has been developed, along the following steps: the beam has been simulated and the algorithm for computing synthetic line integral ("experimental") signals has been developed. Some difficulties have been found, as the beam is physically intercepted by some surfaces of the beam line components (Neutralizer and the RID). A computer program has been realized in order to evaluate the experimental data. The tomographic inversion scheme based on the pixel method has been designed and realized, by dividing the beam into Gaussian-shaped pixels, with unknown amplitudes. In order to obtain the amplitude of each pixel from the integrated signals previously calculated, the linear system of the emissivity has to be inverted: an algorithm has been developed to this purpose and it has been applied to the synthetic data.

3.3.5 Participation to operation of Ion sources and Neutral beam injectors at other facilities

Some people from Consorzio RFX have visited IPP, Garching (Germany). The activity has regarded analyses and optimisations for the grids of the NBI accelerator ELISE, under construction at IPP, definition of mechanical procedures for the realization of source components and preparation for joint experiments for 2012, including the tests of RFX diagnostics.

Concerning LHD at NIFS (Japan), the activity for the next year has been agreed upon and planned; it will include joint experiments in the LHD NBI test facilities, measurements by diagnostics and tests on the magnetic configuration of the accelerators.

3.4 Diagnostics

3.4.1 ITER Magnetic Diagnostics

During 2011 the activities related to the design of electro-magnetic sensors for ITER progressed with a contribution from Consorzio RFX articulated in a wide framework of collaborations, supported by Fusion for Energy through three Grants.

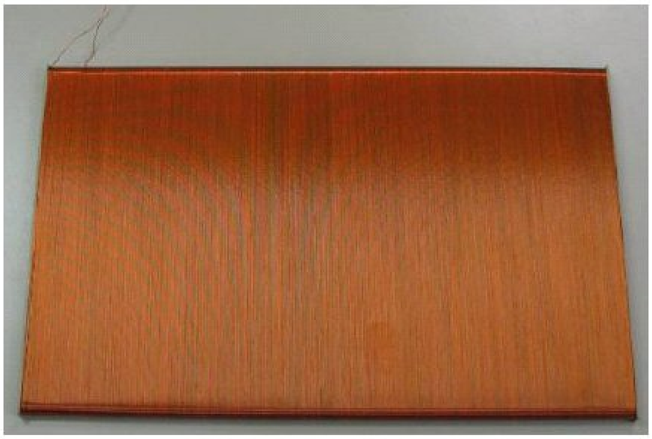


Fig.3.4.1: Prototypes of tangential coils manufactured in the framework of F4E-GRT-012 (overall dimension: 200x159x9 mm; nominal effective area :2 m^2)

The first Grant (F4E-2008-GRT-012), established in 2010 in the framework of the "ITERMAG Consortium" (in collaboration with CEA and CRPP), was aimed at the definition of a calibration and test strategy for the whole ITER magnetic diagnostic and at the manufacture and test of a first set of prototypes for ex-vessel sensors (Mirnov Coils and Rogowski Coils). The scientific/technical activities of the Grant were completed in the first half of 2011, with the closure of all the 3 Actions foreseen in the Grant Agreement.

The requirements for calibrating and qualifying all ITER magnetics diagnostics were developed and reviewed among the three teams involved in the Grant and a survey was made of industrial sites capable of meeting the calibration requirements for all ITER magnetics diagnostics, with two European sites identified and reported to F4E [Lister11a].

The design and procurement of 4 prototypes of Continuous External Rogowski coils and 2 prototypes of ex-vessel tangential coils was driven by CEA with CRPP and RFX in a reviewing role (Fig. 3.4.1) [Moreau11].

CEA and CRPP shared the technical testing and evaluation of the prototype sensors, with RFX in a reviewing role. The successful results of the tests indicated that the proposed Rogowski cables and the ex-vessel sensors are essentially appropriate for use on ITER, with an encouragingly small number of R&D issues identified, that should be carried out in the early next future to finalize the detailed design of the sensors [Lister11a].

The second Grant (F4E-2009-GRT-047), which started in 2010 in collaboration with CREATE, ENEA (UTFUS) and CCFE, is aimed at the optimization of the ITER magnetic diagnostic system through the development and exploitation of numerical tools for performance evaluation of the magnetic diagnostics in achieving the target technical requirements. During 2011 the activities have been focused on two main tasks.

An integrated procedure for the assessment of the performance of the halo current diagnostic system for ITER has been developed. The procedure is based on two simulation codes and a reconstruction code has been tested with simple test cases (Fig.3.4.2). The preliminary results indicate that an alternative distribution of the present layout of halo current sensors could improve the reconstruction capability of this diagnostic system. Further developments are in progress to widen the set of the simulated test cases and to refine the model of the ITER structure [Peruzzo11].

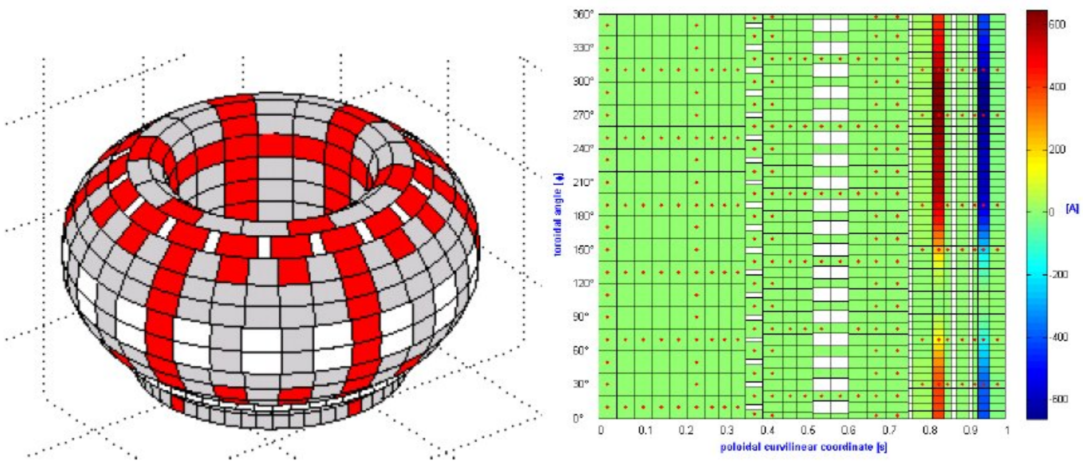


Fig.3.4.2: Left hand side: 3D plot of the First Wall geometry adopted for halo current reconstruction based on present sensor layout (red tiles). Right hand side: Reconstruction of halo current pattern on a 2D projection of the First Wall surface for an asymmetric VDE in the divertor region.

The evaluation of expected range of measurement errors for all the sub-systems of the ITER magnetic diagnostic was carried out on the base of existing literature and experience from present devices [Brombin11]. This study will be used to assess the capability of numerical tools for plasma reconstruction analysis in presence of measurement errors.

The third Grant (F4E-2010-GRT-155), launched in the second half of 2011, is aimed at the achievement of the detailed design of the ITER in-vessel magnetic sensors for plasma control and equilibrium reconstruction. The activities in the early phase of the contract were mainly dedicated to the review of sensor requirements and assessment of the existing design and a contribution from RFX Team was provided to the Conceptual Design Review held by ITER-O. The project is presently progressing with the specification of a complete R&D programme for the qualification of sensors up to the design of the final hardware to be installed on ITER experiment.

3.4.2 ITER core LIDAR Thomson Scattering (TSCL)

RFX continued participating in the activities of the “ITER core LIDAR Consortium”, to optimize the overall diagnostic design, in preparation of a future contract from F4E to design and procure this ITER diagnostic. Such a contract is now foreseen in mid 2012. Meanwhile, a small contract (F4E-OPE-264) has been granted to CCFE, the leading Association in the Consortium, with participation of RFX, together with other Associations, as subcontractors, to revise the risk evaluation and cost assessment of the entire diagnostic. RFX contributed with the section on detectors, of particular relevance, because availability of suitable detectors strongly impact on the laser choice. The proposed design, which has resulted the best performing and most economical one also from this new assessment, is based on detector technologies that still require R&D. RFX has contacted the potential manufacturers, updating the cost evaluation and negotiating their proposed R&D programmes. In particular, more extensive contacts with one of these companies have resulted in higher availability and interest in this development. In parallel, the test on the detectors on loan from JET have been completed, with useful indications of their suitability for ITER LIDAR system [Giudicotti11].

3.5 ITER Plasma Modelling

3.5.1 ITM

The Integrated Tokamak Modelling (ITM) taskforce EFDA initiative aimed at creating a simulation platform to facilitate the use, the benchmark and the validation of several codes developed to simulate various physical aspects of magnetic confined plasmas has continued in 2011.

The ITM related activity of Consorzio RFX has been mainly focused in 2011 along three activities which have received priority support (PS) plus one other activity under baseline support (BS).

The activities under PS have been:

- the coordination of the Infrastructure and Software Integration Project (ISIP) group (G. Manduchi): ISIP , the project group responsible for the architecture and the software developments of the ITM initiative, has continued its activity in 2011 mainly on data structure (the UAL: universal access layer), on the remote data access (through the MDSplus protocol) and on user oriented software tools developments. New and improved versions of the UAL have been released in 2011.
- the coordination of the IMP12 taskforce : the ITM IMP12 project has several important tasks on software integration in the field of linear and nonlinear MHD under development, including free-boundary equilibrium modules, ideal and resistive instabilities codes and 3D nonlinear codes. Progresses have been done during 2011 in the completion of different tasks including: free-boundary equilibrium models, integration of equilibrium and transport codes and a complete equilibrium stability chain suitable for parametric studies and running under Kepler (Kepler being the orchestrator of ITM simulations).
- a specific activity (as a continuation of a 2010 and 2009 task) on control coordination (T. Bolzonella, task under the Experimentalists and Diagnosticians Resource Group (EDRG), with the final aim to build an integrated suite of modeling tools targeting the simulation of a magnetically confined plasma discharge, in realistic free boundary equilibrium experimental conditions.

Progresses have been done also in completing the CHEASE (equilibrium) and MARS-F stability chain which can be used for feedback stabilization studies.

Under BS a specific project aimed at the integration of the CarMa (Resistive wall modes) code under ITM in collaboration with CREATE, Chalmers and CCFE, was also pursued in 2011, as a continuation of a multi year effort.

3.5.2 Disruption modeling

The disruption modeling activity for ITER using the M3D code in collaboration with PPPL (S. Jardin, J. Breslau) and HR-fusion (H. Strauss) has continued.

Progresses in the force and halo current characterization have been done.

Consorzio RFX has signed in 2011 an F4E grant (GRT-334) of 1 My titled:

" Model validation of M3D MHD code and construction of ITER model for simulation of asymmetric VDEs and associated electro-magnetic load ". This grant will be carried out in strict collaboration with the US group.

3.5.3 ITER Beam-plasma modeling

The CRONOS suite of codes has been used to develop self-consistent simulations of the effect of NBI on the ITER plasma. Different phenomena, such as beam power deposition, fast particle slowing down, ion and electron heating, beam shine through occurring as the beam traverses the ITER plasma were preliminarily studied.

The effects of NBI details on the plasma scenario have been initially simulated using offline NEMO+SPOT on target density and temperature profiles coming from a CRONOS simulation of ITER Scenario 2 equilibrium with a total plasma current of 15MA, 10MW of ECRH on the q=2 surface, 7MW ICRH and 33MW NBI carried by 1Mev deuterium atoms. The NBI parameters that have been varied are the injection energy, the injection angle (on-axis/off-axis), and the beam divergence.

The original CRONOS self-consistent scenario evolution with the standard on-axis beams has been repeated, and a new version with Off-axis NBI has been carried out.

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4. TOKAMAK PHYSICS AND TECHNOLOGY

4.1 Background

Awareness of the relevant themes and issues emerging in fusion research is also the result of a strict and active collaboration with the main fusion experiments. Such an exercise is fundamental for a thorough integration of the RFP line in the mainstream of the fusion research, now strongly converging towards the practical realization of a fusion reactor while a number of physics and technology questions are still pending.

In the past years various Tokamak and Stellarator aspects have been matter for a thoughtful redirection of the RFX programme. For instance, emphasis has been put on topics where the RFP may give a significant contribution to the wider fusion community, such as the density limit, the physics and technology of MHD control, 3D physics in both RFP and Tokamak configuration and the role of turbulence in determining the edge profiles. Vice versa RFX has drawn ideas from Tokamaks to deal with an exceeding hydrogen recycling or from stellarators, with codes to describe the 3D equilibrium.

In 2011, collaboration with Tokamaks has concentrated mainly on edge turbulence (Cmod, TJII, Compass, AUG), impurity transport (JET) and MHD control (DIIID, JT60SA). A novelty is represented by the collaboration with TCV on the physics of L to H mode transition, which follows the interest arisen at RFX about enhanced confinement modes after that large temperature gradients have occasionally been observed at the edge [Puiatti2011]. The increased interest for the L to H mode transition, which adds to the already established collaboration with C-mod and ASDEX on edge turbulence, regards in particular the possibility to reach an ohmic H-mode in RFX in the tokamak configuration, which would open interesting possibilities to further exploit the powerful feedback system of modes, for instance to control Edge Localized Modes.

4.2 ASDEX Upgrade

4.2.1 Edge Physics

The already established collaboration between RFX and Euratom-IPP Garching for the studies of edge electromagnetic turbulence in ASDEX-Upgrade has continued also during 2011. It is worth remembering that RFX-mod, in collaboration with Euratom-ÖAW and Euratom-Risø association, has installed a probe, which combines electrostatic and magnetic measurements, which has already given significant contribution in the studies of ELM filaments [Vianello11]. In 2011 a new experimental campaign has been performed to which a researcher from RFX-mod has actively participated. Two main topics have been addressed: a detailed study of electromagnetic turbulence features in L-mode plasmas, with emphasis on the spatial region of shear layer and the electromagnetic turbulence observed in H-mode and H-L transition. Concerning the first point the shear layer location has been detected considering the cross-

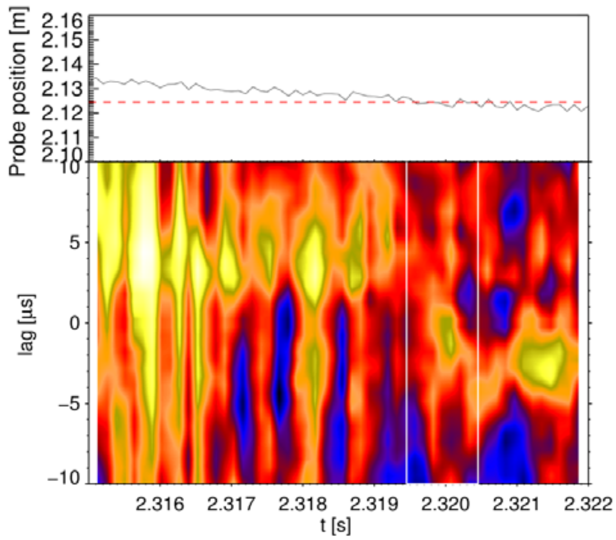

Fig.4.2.1: Top panel: radial position of the probe head. Bottom panel, cross-correlation between two poloidally separated ion saturation current tips. The change of sign reveals the location of the shear layer

correlation between two poloidally separated ion saturation current measurements, and searching for a jump in the sign of the maximum of the cross-correlation.

Examples of the analysis can be observed in figure 4.2.1. The probe has been used parasitically also in experiment devoted to the studies of Edge-Snakes [Sommer11], which are MHD instabilities observed in type-I Elmy H-mode plasmas characterized by strongly localized current-wire where temperature and density profiles flatten. Analysis is in progress to provide further insight on this instabilities and its relation with type-I ELMs filamentary structure.

4.3 JT60-SA

In 2011 EFDA started the organization of activities in the area of JT-60SA Physics with the aim of preparing the scientific exploitation of the future device as joint effort between Japanese and European scientific communities. Consorzio RFX contributed to these initial activities providing the European contact person in charge of organizing the JT-60SA Research Plan review in the field of MHD stability and control, and collaborating on JT-60SA diagnostic review and on scenario modeling efforts. This contribution consisted in organizing several meetings with European experts provided by many associations, coordinating all the European proposals for JT-60SA Research Plan modifications and direct interactions with Japanese colleagues. Direct contributions in the field of RWM physics and control research activities to be performed in the new device were also given.

RFX-mod contributed to the JT-60SA Research Plan also in the fields of diagnostics (more specifically on Thomson scattering diagnostics) and NBI modeling (starting the work of benchmarking beam-plasma interaction models, in collaboration with CEA association).

At the same time one researcher from JAEA visited RFX-mod to collaborate on the specific issue of RWM control with reduced number of active coils in RFX-mod tokamak plasmas. This experiment was realized in summer 2011 in the framework of the scientific activities described in section 2.3.2.

4.4 PPPL / ORNL

As explained in Section 2.2.3 (*Physics understanding: data analysis and modeling*) of the chapter on RFX-mod program, the interpretation of the 3D ambipolar electric field in the edge of SHAx states, and the development of the a 2D model of an ambipolar edge potential in high-density MH discharges, have taken advantage of the collaboration with Dr.Roscoe White at PPPL, for the use and development of the Hamiltonian guiding centre code ORBIT [White84]. In particular, during year 2011 the development of an energy-exchanging collision operator has been undertaken, on the basis of experimental results [Vianello11] showing a dependence of the potential phase on collision frequency. The development of this energy-dependent collision operator is the natural extension of the trapping mechanism in a potential well, in the same way a pitch-angle scattering operator acts on particle trapping in a magnetic mirror. The development of this operator requires the use of the energy-dependent part of the Boozer-Kuo theory on pitch angle scattering [Boozer81]. The electron version of this operator is missing in ORBIT, and it will be added, together with a realistic profile of impurities (C and O).

The presence of this energy dependence will require also to integrate the operator with a code giving a realistic treatment of the wall, in particular with the calculation of the ion reflection from the graphite wall, as a function of the energy of the incident ion, as already done in RFX-mod by the code NENÈ [Lorenzini06].

4.5 FAST

The project of a new European Tokamak device with a vocation for worldwide collaboration that may accompany ITER and tackle DEMO issues has been strongly supported by Consorzio RFX by taking the initiative of a thorough review of the original FAST design to be carried out within the Italian association and to be then promoted in Europe. This on the grounds of two fundamental convictions: firstly that the path towards a sustainable thermonuclear fusion production in Europe and the success of ITER itself requires a modern, reliable and flexible experiment to explore solutions to technological and advanced scientific issues and, second, that the Italian association deserves a new experiment to preserve and improve the technological and scientific knowledge developed over more than five decades of research within the Euratom collaboration. The first consequence of this action will lead to a national workshop on the Italian fusion perspectives to be held in Frascati in January 2012.

The actual FAST design appears as a good compromise between the ambition to explore truly reactor relevant scientific and technology issues and the needs of a severe containment of the financial efforts. A thorough discussion at international level is now needed to optimize such a compromise, share a careful evaluation of all the technical risks and yield the best possible project that constitutes a modern European satellite to ITER.

4.6 LHD

The collaboration with LHD was considered particularly attractive in many respects, with regard in particular to 3D physics aspects, the physics of internal transport barriers, and the presence of regimes with outward convection of impurities. However a number of circumstances have made it impossible to allocate resources on such projects in 2011

4.7 DIII-D

In the framework of the collaboration between the DIII-D and RFX-mod, Dr. M. Okabayashi and Dr. Yin visited RFX-mod in order to perform common experiments on active control of MHD instabilities and error fields in tokamak discharges. In particular, the experimental proposals were the following:

#105: Identification of RWM at ultra-low edge safety factor with error field correction

#106: MHD spectroscopy on stable and feedback stabilized RWMs in tokamak

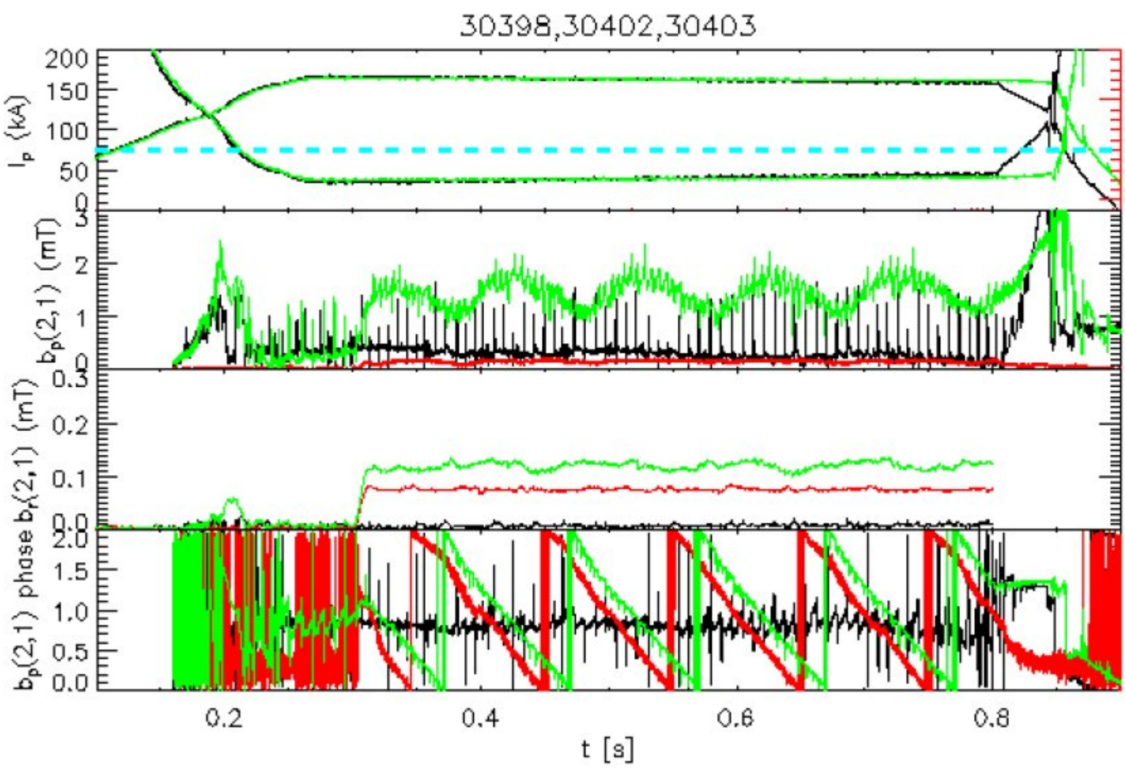

Fig.4.7.1:Comparison of a feedback stabilized (black), helical boundary (green) and vacuum shot (red). a) Plasma current and $q_{cyl}(a)$; b) poloidal (2,1) harmonic amplitude; c) clean (2,1) radial field harmonic; d) phase of the poloidal (2,1) harmonics. The maximum of the green trace in panel b) correspond to times where the phase (green trace) crosses the phaseof the residual mode amplitude in stabilized conditions (black).

The first proposal aimed at replicating the iterative Dynamic Error Field Correction technique, routinely used on DIII-D, in order to reduce the intrinsic error field and avoid mode locking. A preliminary test was performed but more experiments are required. A second set of experiments aimed at feedback controlling the boundary conditions by setting a rotating non zero reference value on the (2,1) clean radial harmonic (see par 2.3.2 for a description of feedback controlled tokamak discharges with q(a)<2). As a result, it was observed that the amplitude of the mode, as estimated from the (2,1) harmonic of the poloidal field, oscillates and reaches its maximum value when the phase corresponds the "natural" phase during feedback controlled discharges (see Fig. 4.7.1). Further analysis, experiments and visits are foreseen to investigate on the issue of error fields in ohmic discharges.

4.8 TCV

A systematic investigation of the influence of the divertor-leg-length on the L-H transition at TCV tokamak has started. This activity is justified by the widely observed, but not well documented, L-H power threshold dependence on the spatial position of the X-point. Examples of this dependence have been highlighted in different machine: in JET an increase of the power threshold P_{LH} with X-point height has been seen [Andrew2004], on the contrary a decrease of P_{LH} with X-point height has been reported in C-Mod [Meyer2011]. The extremely flexible shaping capability of TCV allows to plan a systematic investigation of this influence foreseeing to move the X-point both vertically and radially.

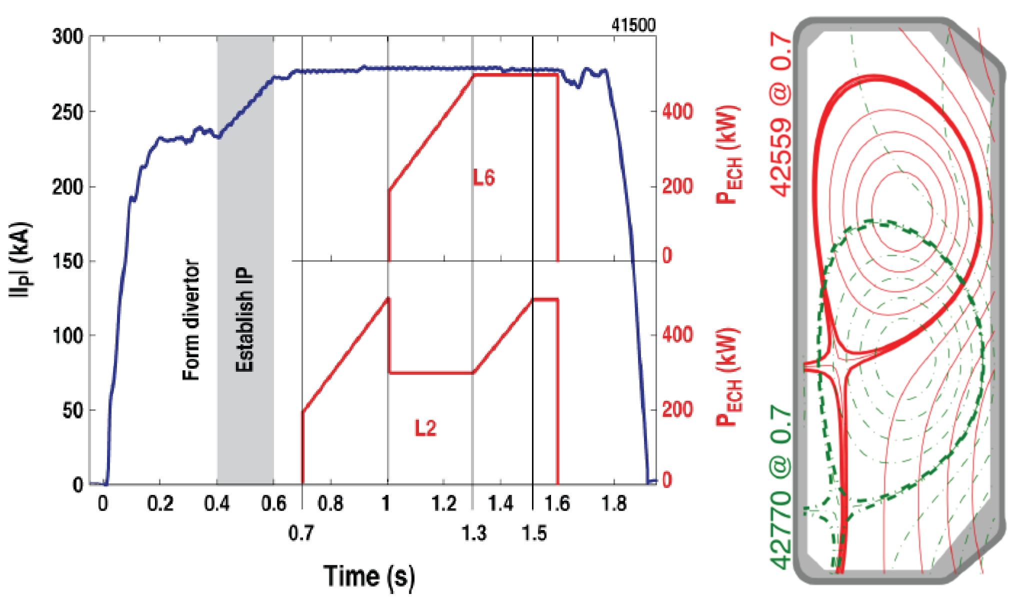

Fig. 4.8.1: (LEFT) Example of a discharge: plasma current time evolution and X2 power input from L2 and L6 ECRH launchers. (RIGHT) Example of two discharges with two Lower Single-Null configurations at two different heights. The two configuration have the same plasma shape, surface and volume, similar main plasma parameter, so they differ from each other only for the length of the outer divertor leg.

The experimental procedure foresees to perform different discharges in Lower Single-Null (LSN) configuration at different vertical positions, keeping main plasma parameters and shape as constant as possible. In each discharge the ECRH power was increased and measured in order to precisely track the power at which the L-H transition occurs, see Fig 4.8.1. A further density and current scan for each position have given the possibility to track the X-point height influence on the international multi-machine P_{LH} scaling [Martin2008].

First results seems to confirm the JET observation: reducing the X-point height the P_{LH} decreases. Further investigation is needed to complete the systematic investigation and to reveal what physical parameter is hidden behind the X-point height variation.

4.9 JET

4.9.1 Impurity transport

The effects of the application of central Ion Cyclotron Radiofrequency Injection in JET on Ni and Mo transport of have been published [Valisa 2011], showing a strong as well as clear correlation between injected ICRH power and metal impurities outward convection. Interesting effects of ICRH power on both rotation and ion temperature gradients have also been shown. Which parameter is mainly responsible for the observed outward pinch of Ni and Mo remains an open question that has been turned into proposals of new experiments for the oncoming campaigns. The foreseen 2011 experiments on W accumulation and control have migrated to 2012 following several schedule rearrangements of the JET experimental plan. In 2011 we have participated to the discussions on the JET programme through meetings and posts in the related web forum. In addition, tools for the analysis of W transport have been tested and made ready for use as soon as data are provided.

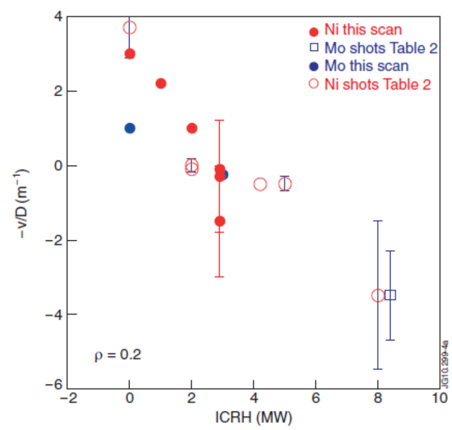

Fig.4.9.1.: Experimental relationship between Ni convection and applied ICRH power in JET . Positive convection means inward transport and conditions for impurity accumulation

4.9.2 Edge recycling

Among the actions aiming at improving our knowledge of the plasma wall interactions we have started a collaboration with JET on the analysis of the Residual Gas Analizer (RGA) data. The just started work has regarded the processing of raw RGA data to help improving its measurements, to correlate the measured pressures of extracted gases to JET discharges phases and operating conditions, and the processing of the out-of-pulse measurement to associate them to the pulse sequence.

The new Hiden Residual Gas Analyser diagnostic (KT5P) is able to measure masses from 1 to 200 with a time resolution of about 1-2 sec. Native software provides standalone measurement visualization of selected masses versus time and data storage on coma-separated values (CSV) files. To ease the visualization and the analysis of partial pressure of various masses during and after shots, CVS files have been re-processed to re-order measured pressures for each mass versus the discharges time and stored in the JET PPF database. A preliminary work in this sense has shown many problems related to the Hiden firmware and measurement setup; actions to solve them are in progress.

Analysis of fuel retention requires residual gas measurements on a time scale longer than that usually stored in JET pulses. This problem can be solved adding to the PPF pulses the signals stored during the out-of-pulse time sequence. The required software has been developed and installed.

4.9.3 Density profiles

Different methods have been applied to analyze the multi-channel reflectometer data to describe the pedestal region during ELM instabilities and the results have been compared with those of the High Resolution Thomson Scattering (HRTS) system, providing edge density and temperature profiles. Whilst the agreement between reflectometer and HTRS appears quite good, the presence of fast dynamics, such as during an ELM, requires an accurate data filtering of the I/Q reflectometric signal and this observation highlighted the importance of the heterodyne detection with respect to the homodyne one.

4.10 TJ-II, COMPASS AND TORPEX

The study of turbulent features characterizing plasmas in the edge of magnetic confined devices is a hot topic, due to the role played by coherent structures in contributing to the transport of particles and energy.

Recently an increasing interest was devoted to the study of such plasma structures not only in the cross field plane but also on their whole 3D filament features and including both their electrostatic and electromagnetic properties. On this respect a strong effort on the experimental side is in progress in order to provide accurate information on structure features in order to gain insight on their driving mechanisms. The combination of electrostatic and magnetic fluctuation measurements can provide useful elements for understanding physics underlying turbulent structures.

In RFX-mod coherent pressure structures are detected within the turbulence background and exhibit both electrostatic patterns, with vortex features and magnetic patterns, characterized as localized current density filaments essentially aligned with the edge magnetic field and travelling according to the E×B flow [Spolaore09]. Such structures exhibit features analogous to phenomena detected in astrophysical plasmas and have been identified as Drift Kinetic Alfvén vortices [Martines09, Vianello10].

Comparison between different magnetic devices in order to gain insight on general features and role of such phenomena is advisable. Following results obtained in the edge region of RFX-mod, different collaborations are in progress and coordinated by the RFX-mod personnel on the topic of investigation of filamented current density turbulent structures [Spolaore2011].

4.10.1 TJ-II stellarator:

Fig.4.10.1: Picture of the probe head installed and commissioned in the TJ-II experiment

A joint collaboration has been established in order to perform in the TJ-II stellarator experiment simultaneous measurements of pressure perturbation, vorticity and parallel current density within the turbulence background.

On this purpose a newly developed diagnostics was designed last year, following the "U-probe concept" conceived and used in the edge region of RFX-mod. During 2011 the probe design was finalized and the probe head was realized, assembled and installed on TJ-II experiment. The picture of the probe head is shown in fig. 4.10.1, where the boron nitride case is visible as well as the electrostatic pins for local vorticity measurements. Three 3-axial magnetic coils are embedded into the boron nitride case.

The commissioning was successful and the first measurements have been performed in TJ-II, inserting the probe progressively deeper in the edge region. Different plasma regimes are achievable: exploiting the NBI and ECH a beta scan can be performed and different equilibria have been explored. One example of the probe signals measured during a shot is shown in fig. 4.10.2 [Carralero2011], where it is worth noting the simultaneous measurements of local parallel vorticity, $\omega_{||}$, and current density $J_{||}$. The first analysis evidenced the presence of filamentary current structures also in the edge region of TJ-II.

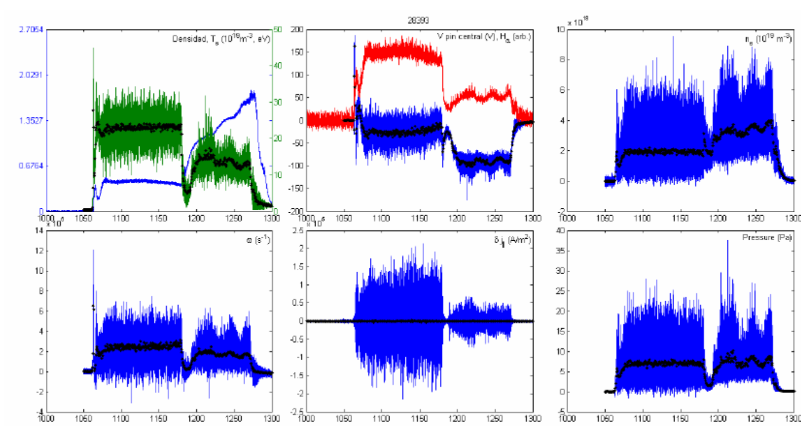

Fig.4.10.2: Time evolution of the main quantities measured during a shot of the experimental campaign devoted to the first test of the probe head.

4.10.2 COMPASS tokamak.

An analogous joint collaboration is in progress with the IPP Prague association in order to perform measurement in the COMPASS tokamak. In this case a probe head similar to the U-probe used in RFX-mod [Spolaore10] is planned to be mounted on the diagnostic port at the LFS above mid-plane. The probe head design is in progress in collaboration with the

COMPASS team and the key information on the installation of magnetic sensors has been defined.

4.10.3 TORPEX experiment

A detailed investigation of the electromagnetic features of filamentary structures emerging from turbulent background was performed in the TORPEX experiment.

The TORPEX device is a simple magnetized torus (R=1 m, a=0.2 m), characterized by open nearly toroidal magnetic field lines, where plasma is produced by EC waves. Field-aligned blobs originate from ideal interchange waves and propagate radially outward due to ∇ B and curvature induced drifts. The features of the plasma obtained in the TORPEX device allow a great versatility and a direct investigation through the whole poloidal section is possible. In figure 4.10.3 the experimental setup scheme adopted for the study on filaments is shown [Furno2011a], in particular the two insertable probe heads used for the measurements of the current density associated to blob structures are highlighted: a directional Langmuir probe and a specially designed magnetic probe, dubbed “current probe”,

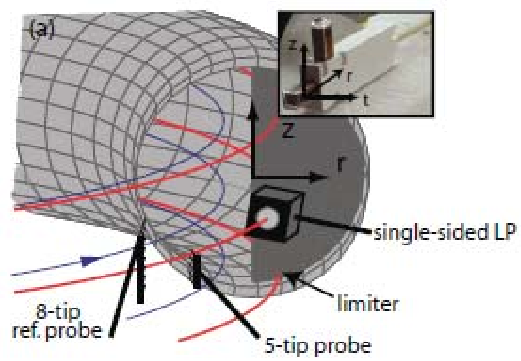

Fig.4.103: Schematic of experimental setup for filaments study on TORPEX device

based on three 3-axial magnetic coils arranged in order to obtain a direct estimate of $J_{||}=\nabla\times B/\mu_0$. The experimental setup is

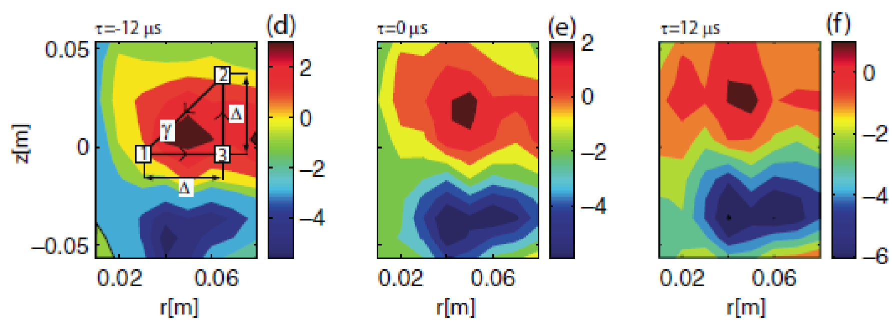

Fig.4.10.4: 2D map of J|| obtained with the current probe, the 3-axial coil positions are highlighted by the small squares in the left frame. The three frames represent the time evolution of the dipolar current density filaments, as result of the conditional average technique.

completed by electrostatic probe arrays used for identification of blobs and for conditional averaging technique. Measurements have been performed in the proximity of the stainless steel limiter covering half of the poloidal section on the low field side (see fig. 4.10.3). For the first time a direct measurements of a 2D map of the field aligned current density associated to a blob structure has been carried out [Furno2011a, Furno 2011b]. An example of results is shown in figure 4.10.4, where the time evolution of a radially propagating current density structure associated to a density blob is shown. The structure of $J_{||}$ results clearly dipolar and asymmetric, this behavior being ascribed to the non-linear dependence of $J_{||}$ at the sheath edge upon the floating potential.

4.11 Alcator C-Mod

The collaboration with the Alcator C-Mod experiment in the study of the edge plasma and turbulence, started in 2008, is going on, and in 2011 it has been focused in the characterization of the edge plasma during the L-H transition. The edge plasma is studied with the GPI diagnostic installed in the outer midplane, which measures the D_α light fluctuations (proportional to the local electron density) across the separatrix.

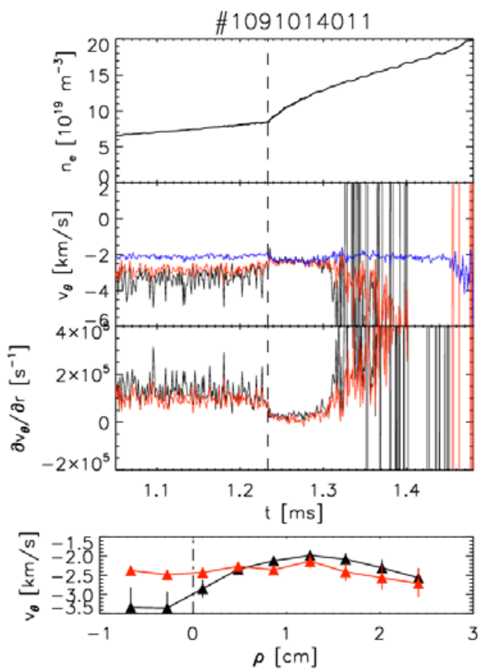

Fig.4.11.1: Time evolution of the electron density, poloidal edge velocity (red and black at the separatrix, blue outside the separatrix), and radial shear. The vertical line indicates the L-H transition.. In the last panel radial profile of the poloidal velocity during L- (black) and H-mode (red) plasma.

During the L-mode phase of the discharge the fluctuations have a broad frequency spectrum, extending from 1 to 500 kHz; when the plasma reaches the H-mod, near the separatrix (but outside) the highest frequency fluctuations (about 150-200 kHz) disappear, and the low frequency ones increase.

A strong difference between the two regimes has been found also in the edge poloidal velocity and in its radial profile, as highlighted in Figure 4.11.1. After the L-H transition, the velocity estimated near the separatrix (red and black lines) diminishes its absolute value, going from about -3 km/s up to -2 km/s (in the ion diamagnetic drift direction). Instead outside the separatrix the velocity seems not to change (blue line in the figure). It is also important to notice that during H-mode the fluctuations in the poloidal velocity are suppressed. Then, when the Quasi Coherent Mode [Terry11] develops (t >1.3 s in this example), it is no more possible to estimate a poloidal velocity near the separatrix. Since the velocity calculated in the different radial positions decreases almost to the same value, the profile of v_θ in the H-mod is flat (last panel of the figure), and consequently its radial shear goes to 0.

A great effort has been dedicated also in the search and characterization of zonal flows [Zweben11_1, Zweben11_2] in the C-Mod edge. They have been found only in few discharges, and so a dedicated experimental campaign is expected at the end of 2011.

Collaboration with Cagliari University on disruption prediction

4.12.1 Visualization and exploration of high dimensional tokamak operational space in ASDEX Upgrade and JET

Unsupervised techniques, such as Self Organizing Maps (SOMs) demonstrated to be suitable to identify regions in the ASDEX Upgrade operational space with high risk of disruption, based on the idea that revisiting the plasma states of different campaigns may highlight data grouping or clustering structures. The high-dimensional operational space of ASDEX Upgrade has been mapped into a low-dimensional space, while retaining most of the underlying structure in the data [Camplani 2011] [Aledda 2012]. The produced mapping can be used both "off-line" as a highly visual data to display the operational states of the plasma or "on-line" to visualize the plasma state and its time history a trajectory on the map. In Fig. 1.1.1, the SOM map of the 7-D AUG operational space is shown. The clusters in the green region are associated to a low disruption risk, whereas red clusters are associated to high disruption risk. The grey region is a transition region, which is between the former two regions, and white clusters are empty. The temporal sequence of the samples of a discharge forms a trajectory on the map depicting the movement of the operating point. The majority of disruptive discharges starts in the safe green region and ends in the red cluster (Figure 1.1.1, black bold trajectory). Conversely, the great majority of safe discharges evolves within the safe region (Figure 1.1.1 blue trajectory).

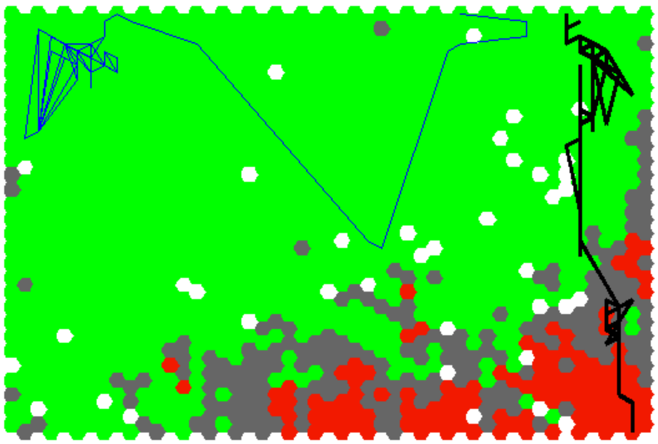

Fig.1.1.1: Trajectory of the discharge n° 21011 on the SOM map of the 7-D AUG operational space. Green: low disruption risk region; red: high disruption risk region; grey: transition region, white: empty clusters..

Visualization of the high-dimensional operational space of JET for disruption prediction has been performed also at JET, including algorithms to pre-process the diagnostic signals and obtain a data set of real–time reliable observations , as well as a statistical analysis to recognize the presence of outliers. A 2D map of the JET parameters space has been built to improve understanding and predictive capability of disruptions.

4.12.2 Data Analysis Techniques for knowledge extraction from experimental signals at JET

Several measurements in tokamak plasma show that certain instabilities present a behaviour with aspects, such as intermittency, unpredictability, etc., which could indicate the presence of chaotic dynamics. After developing and testing a de-noising algorithm based on the wavelet transform and cross correlation between residuals and signals, a database of Dα signals has been built in order to investigate the dynamics of ELMs. In the following step the probability distribution of inter-ELM times and the correlation between ELM energy and inter-ELM times will be investigated.

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5. THEORY AND MODELLING

5.1 Background

In 2011 this program focused on the following crucial issues: (i) a better MHD simulation of RFP plasmas; (ii) the assessment of the q profile in SHAx states; (iii) the kinetic stabilization of resistive wall modes in the RFP. Several important results were obtained, and some thereof are outlined here. First MHD simulations of the RFP in toroidal geometry were carried out with the PIXIE3D code. The QSH state was found not to be stationary like in the cylindrical case, and to be interrupted by crashes similar to the experimental ones. Linear analysis and gyrokinetic simulations showed that, due to their strongly hollow profiles, RFX-mod impurities can drive ITG mode destabilization, and, in the case of peaked enough electron density profile, impurity mode destabilization. Several new results were obtained on the kinetic stabilization of resistive wall modes in the RFP. In particular this stabilization was shown to be quite efficient, since it enables the suppression of these modes for acoustic rotation speeds, and not for Alfvenic ones like in the fluid case. A new technique was derived for the calculation of transport profiles for modulation experiments, which sheds light on the accuracy of transport codes. The accuracy of reconstructions provided by the VMEC code was checked for given current profiles by benchmarking VMEC with a code developed in the past in the laboratory. The q profile reconstruction from experimental measurements was improved by adding SXR emissivity and T_e measurement from Thomson scattering to the V3FIT code coupled to the VMEC code. The study aiming at the calculation of the ambipolar electric field led to the derivation of a reduced fluid model where only perpendicular dynamics is involved including drifts and collisional diffusion.

5.2 Extended magnetohydrodynamics modeling

5.2.1 Study of toroidal effects for the RFP

First MHD simulations of the RFP in toroidal geometry were carried out with the PIXIE3D code. Because of the limited capabilities of the local computing system, such a study is considered as a preliminary one. Nevertheless interesting features are observed, which deserve further development in the next year, 2012. The full nonlinear mode dynamics showed that a QSH state is found for the same dissipation parameters which provide a QSH regime in the cylindrical runs. The dominant mode (preferred helicity) is also the same. However, the QSH state is not stationary like in the cylindrical case. Instead, it is interrupted by crashes which may be reminiscent of the experimental phenomenology [Cappello11]. Since full nonlinear runs with a long target time proved to be rather demanding for the local computing system, in anticipation of porting the code into the HPC-FF facility in Juelich we focused on the study of the properties of helical states in toroidal geometry obtained after the perturbation of a single m=1 unstable mode. Due to the toroidal coupling, a full set of poloidal and toroidal harmonics

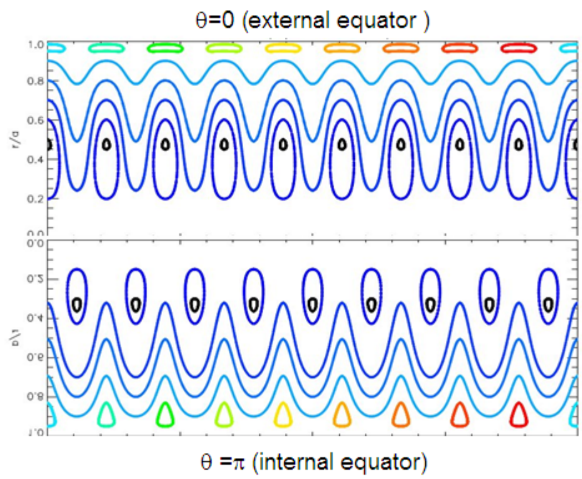

Fig.5.2.1: Poincare plot (NEMATO code) on a toroidal section, obtained from an RFP dynamical simulation in toroidal geometry (PIXIE3D code). The m=0 mode with the same toroidal periodicity of the main helical equilibrium component appears (m=1, n=9), which causes the presence of m=0 island chain around the reversal surface of the toroidal field.

of the unstable mode were found in toroidal geometry. In particular, the m=0 mode with the same toroidal periodicity as the m=1 appears, which causes the presence of m=0 island chain around the reversal surface of the toroidal field (see Fig.5.2.1). Despite the helical symmetry of the cylindrical SH state is lost when going to the toroidal geometry, magnetic chaos was invisible in these toroidal helical states, at least for the chosen aspect ratio R/a=4.

5.2.2 Study of the chaos healing properties of quasi helical RFP states

The continuation of this study, which started in 2009, led to the observation of a strong resilience to chaos in quasi helical RFP states characterized by a non-resonant dominant mode. Indeed, the study of the magnetic topology of such states (provided by the nonlinear MHD code SpeCyl) by means of the field line tracing code NEMATO showed conserved magnetic surfaces in the whole plasma volume, despite the growth of secondary modes up to a magnitude of the same order as the dominant helical component [Cappello11]. In addition, reduced amplitude of the shear flow associated with the macroscopic helical equilibrium was observed, thus potentially suggesting significant changes in transport properties if reproduced experimentally. The NEMATO field line tracing code was also the subject of a benchmark with the guiding center code ORBIT, which may also be used to compute the field line trajectories. First results showed a good agreement between the two codes, at least in the case of symmetric magnetic configurations [Ciaccio11].

5.2.3 Closer comparison of the nonlinear MHD dynamics in RFP and tokamak experiments

We made many efforts to draw a closer comparison between nonlinear MHD simulations and experiments. The similarities and differences between the numerical and experimentally estimated helical plasma flows associated with helical RFP states were discussed [Bonomo11]. The above mentioned observation of a better resilience to chaos for non-resonant modes inspired an experimental activity on RFX-mod consisting in stimulating a QSH with non-resonant (i.e., n=-6) dominant mode. This was obtained by applying a finite edge Br perturbation of the relevant periodicity with the MHD feedback system.

First numerical tests based on visco-resistive MHD simulations with SpeCyl supported the observed capability of a finite Br perturbation to stimulate a dominant mode different from the spontaneous one.

Concerning Tokamak-like simulations, a study of the nonlinear effect of MHD modes on the sawtooth dynamics was also performed with SpeCyl, which showed some similarities with the tokamak experiments made on RFX-mod [Bonfiglio11, Piovesan11]. In particular we found a decrease of the sawtoothing when allowing for a finite helical magnetic perturbation (Fig. 5.2.2), a fact also predicted theoretically.

Finally, in order to back up our theoretical studies, some effort has been devoted to the important aim of checking the universality of RFP helical self-organization (sec. 5.7 of Activity Report 2010, Franz P. PP9.00049 Bull. 52nd APS Chicago,USA(2010) http://plasma.physics.wisc.edu/uploadedfiles/talk/apsdpp10Franz722.pdf). New data collected at MST during 2011 are being analyzed.

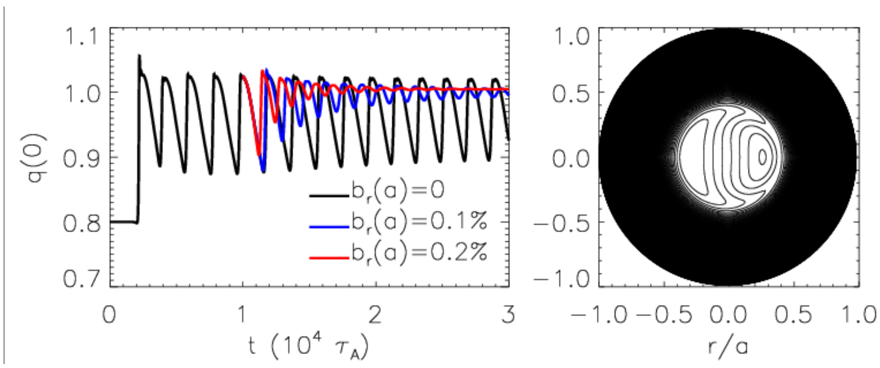

Fig.5.2.2: 3D nonlinear viscoresistive MHD simulation (SpeCyl code) of circular ohmic Tokamak configuration. Time evolution of on axis safety factor q(0) for different values of the imposed boundary condition (edge value) for the radial magnetic component of resistive kink mode (m=1, n=1). Sawtoothing is strongly reduced when allowing for finite edge amplitude. On the right: Helical flux surfaces of the resulting equilibrium with largest edge amplitude, featuring a helical core resembling snake phenomenology.

5.3 Transport and microturbulence

ITG modes have been already found to be marginally unstable in RFX-mod only in correspondence to the transport barriers occurring during SH states. This topic has been revisited considering realistic multi–species plasmas, to understand the possible excitation of ITG and/or impurity–drift instabilities. Due to their strongly hollow profiles, RFX-mod impurities can drive ITG mode destabilization, and, in the case of peaked enough electron density profile, impurity mode destabilization (Fig.5.3.1). This effect has been analyzed by using the eigenvalue solver HD7 [Liu11] and the gyrokinetic code GS2 [Predebon11], the results being in good agreement. The back–reaction of ITG turbulence on impurity transport has been studied with GS2. Quasi-linear studies of trace impurity transport have shown that ITG dominated plasmas provide impurity accumulation in the core. This result – consistent with tokamaks – is not consistent with the experimental data of RFX-mod, where a strong outward impurity convection is found.

Nonlinear 3-species ITG turbulence simulations have confirmed the quasi-linear findings. The ion conductivity, which in the absence of impurities satisfies a gyro–Bohm scaling (for ion temperature gradients well above the threshold), is enhanced when impurity profiles are hollow, while the impurity convection remains inward. Concerning 2-species ITG turbulence, a good agreement is found between GS2 and TRB (gyrofluid full radius) simulations [Cappello11]. Electromagnetic calculations of microtearing modes have been preliminarily checked against experimental data of high mode number magnetic fluctuations in the edge. Microtearing instabilities have been also investigated in low–collisionality regimes, to understand their consistency with the analytic estimates obtained in the 1970s for a slab plasma [Drake77].

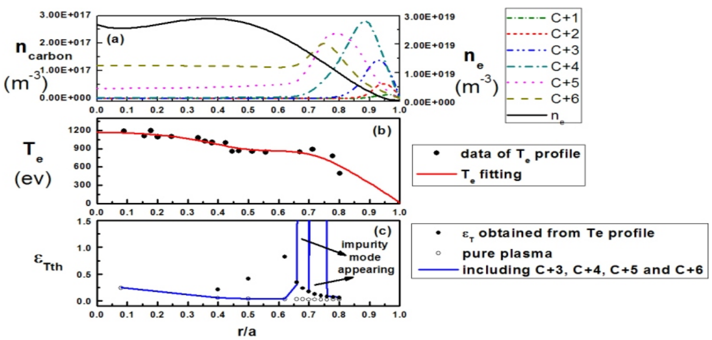

Fig.5.3.1: Experimental electron and carbon density profiles for shot 26557, with the stability threshold obtained in a pure hydrogen and in a partially carbon-contaminated plasma. From [Liu11].

The collaboration with IPP Greifswald has started to interface the 3D RFP-VMEC equilibria with the gyrokinetic code GENE, already benchmarked with GS2 in tokamak and stellarator geometry.

5.4 Resistive Wall Modes (RWMs) studies

MARS-K hybrid toroidal stability code has been adopted in the study on kinetic stabilization of RWMs. The work is in collaboration with Dr. Y.Q.Liu in Euratom/CCFE. We have modified the code in several aspects: The kinetic part has been parallelized, which leads to a significant improvement in performance; the new module for computing the various potential energy components has been developed and integrated into MARS-K ; some new functions have also been created. These modifications allow us to do extensive analysis and to obtain in-depth physical understanding.

5.4.1 Kinetic dissipation on RWMs in RFP plasmas

The numerical result is plotted in Fig.5.4.1, which shows the critical plasma rotation frequency for stabilizing the mode as a function of the wall position and the value of plasma β_p. The typical RWMs in RFX-mod with the toroidal mode numbers n=6, 5, 3 are presented. The physical analysis on the kinetic effects indicates that the transit resonance of the passing ions can provide ion acoustic Landau damping, which can stabilize the mode for high β_p plasmas. The required plasma rotation frequency for the most unstable mode (n=6, in RFX-mod) is in the region of the acoustic speed, which is much slower than what predicted previously by the fluid theory (in Alfvén region). This is due to the fact that the fluid theory cannot provide the

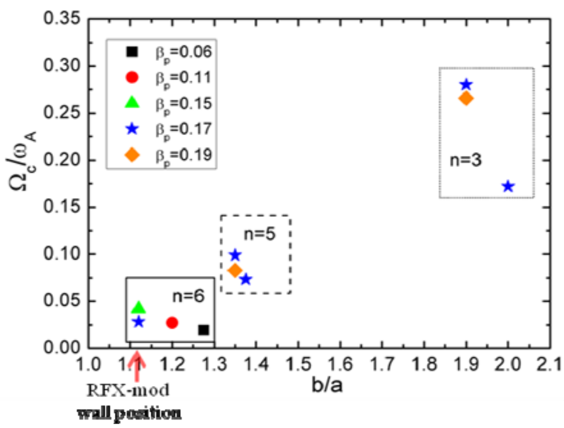

Fig.5.4.1 The critical velocity for stabilizing n=6 (solid), n=5 (dashed), and n=3(dotted) modes versus wall position for various β_p values. The full kinetic effect is considered. The RFX-mod system parameters are used, and F ≈ -0.062, q_0≈0.144. q_a≈-0.01.

complete description of the acoustic resonance due to the lack of the physics of the wave-particle resonance.

In addition, neither the precession nor the bounce motions of the trapped particles can stabilize the mode. We also found that when the resistive wall is close to the plasma, the stabilization by kinetic transit resonance can only occur for the mode with the rational surface closest to the plasma edge (closest to the magnetic axis, for the internally non-resonant modes (INRM)); for the RFX-mod parameters, this is the n=6 INRM, which can be stabilized for b/a=1.12 and $\Omega_c \sim 0.028\omega_A$ with β_p=0.17; or $\Omega_c \sim 0.041\omega_A$ with β_p=0.15. The other modes with smaller toroidal wave number n are hardly stabilized for this wall position. However, moving the resistive wall farther from the plasma edge until being close to the critical wall position (corresponds to $\delta W_b \approx 0$) will cause the kinetic effect to be much more important in the RWM stabilization. In fact, we found that the stabilizations of the n=5 and n=3 modes appear in the farther wall position b/a=1.35 and b/a=1.9 respectively. Furthermore, a careful analysis has been carried out to provide the physical understanding on the behaviors of the RWM stabilization described above [Wang11].

5.4.2 Comparison of RWM physics between RFP and Tokamak configurations

Although RWMs share certain similar behaviour in both tokamaks and RFPs, there are a few dissimilarities resulting from the differences between the two configurations, which lead to different conditions for the mode stabilization. A comprehensive comparison has been made on the characteristics of the RWM stability between RFP and circular cross-section tokamak. Apart from the comparison of the mode driving mechanism, mode spectrum, mode coupling and mode ballooning structures in the fluid theory, the comparison of the kinetic effects is emphasized. We also found that the kinetic effects work differently on the RWM instability in the two configurations. In tokamaks, for the pressure driven modes (this is the general case in the advanced tokamaks), the kinetic stabilization is provided by the mode resonance with the precession motion of the trapped particles; the required plasma rotation frequency for the stabilization is very low, even a vanishing frequency can stabilize the mode. The current driven RWMs in tokamak cannot be stabilized by the precession resonance. In contrast with tokamaks, the RWMs in RFPs are only current driven modes. These modes can be stabilized only by the transit resonance of the passing ions for high β_p plasmas. The required flow velocity is in the range of the ion acoustic speed, which is much higher than that in tokamak. The physical reasons causing the different kinetic stabilization in two configurations are provided by the detailed numerical analysis. The common features for the passive stabilization of RWM in two devices have also been discussed [Guo11].

5.5 Transport

The problem of the time evolution of the rotational transform profile has been attacked, in collaboration with scientists from Ciemat in Madrid, taking as a starting point the approach developed by Strand and Houlberg [Strand01] for a generic coordinate system. They derived an evolution equation for the rotational transform profile in a 3D toroidal plasma with conserved flux surfaces, which results from Faraday's law and Ampère's law. This equation was modified in order to use the poloidal flux instead of the toroidal one as "radial" coordinate. Furthermore, the equation has been rewritten so as to give the evolution of the safety factor, in order to avoid numerical problems with the divergence of the rotational transform on the reversal surface of RFP plasmas.

The susceptance matrix is a 2x2 matrix which relates toroidal and poloidal (in a general sense) fluxes to the corresponding currents for a 3D toroidal plasma with conserved flux surfaces. The relationship between the two quantities is derived from Ampère's law. The susceptance matrix, which is required in order to evolve the rotational transform, is computed from equilibria obtained with the VMEC code (computation using SHEq equilibria are in progress). The time evolution is then computed using the ASTRA transport code as a solver of the equation. From time to time a new equilibrium is computed, according to the evolved safety factor profile, and a new susceptance matrix is evaluated, in an iterative way. This scheme, used also to simulate experiments performed on the TJ-II stellarator where some plasma current can be driven, has been successfully implemented. Some optimization is still required, due to the occurrence of numerical errors, possibly through a rewriting of the evolution equation in a more suitable form. This will be the object of next year's work.

A one-dimensional transport model for Lithium has been implemented, including the possibility of a lithium source within the plasma, so as to reproduce experiments with Li pellet injection. The code calculates the time evolution of the lithium ions profile within the plasma. The diffusion coefficient and the pinch velocity are varied so as to reproduce the experimental emission pattern and the electron density profiles. First tests of the code applied to RFX-mod discharges with Li pellet injection are ongoing.

The Field Line Tracing code (FLiT) has been modified to take advantage of the new RFX-mod multi-CPU computer infrastructure. To avoid expenses associated to the previous use of a commercial library for the numerical integration of field line differential equations and to gain in control of integration process a free ordinary differential equation package has been selected and implemented. The new package proved to be able to outperform previous commercial routines in terms of accuracy and speed. The configuration will allow an easy implementation in the FLiT code of collision and its parallelization to take full advantage of the multi-CPUs RFX cluster.

The calculation of transport profiles from experimental measurements belongs in the category of inverse problems which are known to come with issues of ill-conditioning or singularity. A reformulation of the calculation, the matricial approach, was derived for modulation experiments and the standard advection-diffusion model where these issues are related to the vanishing of one of the eigenvalues of a 2x2 matrix to be inverted. This sheds light on the accuracy of calculations with transport codes, and provides a path for a more precise assessment of the profiles and of the related uncertainty.

5.6 Equilibrium reconstruction

As described in section 2.4.1 equilibrium reconstruction is a delicate procedure that requires a good knowledge of the diagnostics set-up as well as of the load assembly. An important step in the verification of an equilibrium code is the benchmarking with other codes. In the past a comparison between SpeCyl and VMEC was done showing that the two codes provide the same result starting from the same input data. A similar analysis was now considered comparing the NCT code [Zanca04] and the VMEC code [Hirshman83] on actual experimental cases. The V3FIT code was used to provide modelled data to compare with experimental data. The analysis was done following the forward problem (as described in section 2.4.1).

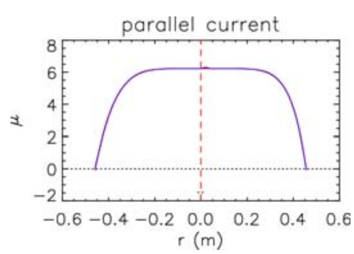

Fig.5.6.1: Comparison of the parallel current profile from NCT (blue) and VMEC (red), axi-symmetric case.

As NCT is a peculiar code that in some way adopts an approach that is in between a free and a fixed boundary mode, the additional reference global quantities that were considered as markers of a good match (apart from the profiles) between the two codes, but also with respect to experimental data, are the redefined F and Θ parameters:

$$F^* = \frac{\frac{1}{\mu_0}\oint_{\Gamma_{tor}} B_t}{\Psi_t} \qquad \Theta^* = \frac{\frac{1}{\mu_0}\oint_{\Gamma_{pol}} B_p}{\Psi_t}.$$

These quantities were adopted as they are the starting point with which the NCT code is interfaced to the experimental data to obtain an axi-symmetric equilibrium. Note that they are similar but not quite the same as the usual reversal and pinch parameters, but their use is more straightforward as far as we are concerned.

As we are considering a forward problem, the NCT output was used to provide the input for VMEC. For an axi-symmetric case in figure 5.6.1 we show the resulting comparison for the parallel current density profile. Both of these profiles as well as the flux surfaces (and corresponding differential shift) agree very well. Also, the two parameter F* and Θ* differ by less that 0.9%, so that we have a good correspondence between the two codes. Also by using the V3FIT [Hanson09] code we were able to compare the resulting equilibrium with experimental data obtaining again a good match.

On the side of the inverse problem, in order to improve the diagnostics information, in the V3FIT code both the SXR emissivity and the T_e measurement from the Thomson scattering diagnostic were added by James Hanson (Auburn University). The implementation at the moment is simply based on the assumption of both SXR and T_e being flux surface functions as it is true for the RFX-mod experiment (see the paper [Lorenzini09]). Different profile parameterizations are available but no modelling is presently available to back-link them to the pressure profile that is part of the force balance equation.

From the modelling point of view, as a general remark, the full diagnostics layout has been implemented in V3FIT, but as there is a periodicity constraint on the helical states, this set is actually redundant. A first analysis was started to address the best way to reduce the number of diagnostics to a reasonable level and in particular to consider the option of synthetic diagnostics, i.e. numerical diagnostics not really present on the machine, but that can be easily implemented in the model and that carry the full information required (e.g. the equilibrium has a periodicity 7 so there is no need to provide a full coverage of the machine as the numerical solution will comply with this periodicity). This option might also allow for an easier way to model and solve the issue of shell penetration and passive structures effect.

5.7 Independent feedback on the radial and toroidal edge magnetic fields

In the present Clean-Mode-Control scheme the feedback variable b_f is the combination of radial b_r and toroidal b_ϕ measured harmonics which, according to the vacuum cylindrical formulas, gives the radial field $b_r(r)$ at any radius between the sensors r=b, and plasma edge r=a (neglecting the vacuum vessel contribution). A more general scheme based on an independent feedback of these two field components has been recently speculated improving the control on tearing modes, possibly stabilizing them [Richardson10]. The analysis has been performed with a linear model, missing some important issues such as the electromagnetic torque due to the conductive structures and the feedback as well the viscous torque related to the plasma flow. Therefore, before commissioning this new scheme, we felt

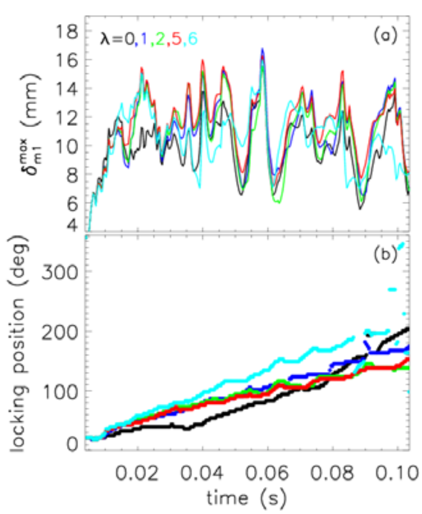

Fig.5.7.1: Time evolution of (a) the maximum m=1 displacement and (b) the locking position for different λ values.

necessary to check it into the RFXlocking code [Piron10], to verify if any improvement of the edge boundary conditions for the dynamo tearing modes is seen both in terms of amplitudes and frequencies. Figure 5.7.1 shows the simulations varying the parameter λ, which modulates the relative weight of radial and toroidal field measured harmonics in b_f. As special cases, $\lambda=0$ means $b_f=b_r(b)$, whereas $\lambda=1$ means $b_f=b_r(a)$, which is the present standard choice in RFX-mod. Upon gains optimization, which makes the currents request in the coils comparable in the different cases, the edge radial field control turns out to be almost independent on λ. This result, from the one hand does not encourage the implementation of the general scheme, and from the other hand suggests reconsidering the case $b_f=b_r(b)$ in the experiment. In fact there is the possibility that this option could be not-optimized, since it has been tried only at the beginning of the Clean-Mode-Control operations.

5.8 Ambipolar electric field

The non axi-symmetry of RFP plasmas implies the existence of an ambipolar electric field like in stellarators. This field, the associated electric drift field and its shear, are expected to play a major role both in microturbulence and MHD studies, in connection with such issues as transport barriers, dynamo fields… It is therefore important to assess it in a precise way in RFX-mod, especially in the core. Addressing the full self-consistent problem is a demanding task, since this involves solving the coupled dynamics of particles and fields. Unavoidably, some sort of approximations must be introduced, that in their turn make questionable the accuracy of any result eventually obtained. From this point of view, using multiple approaches with different kinds of approximations involved could, if possible, represent a check of mutual correctness. Local neoclassical estimates are presently being done with the DKES code. On the other hand in 2011 we considered the development of a PIC (Particle-in-Cell) code inspired from that developed by K.H. Spatschek in Düsseldorf for the TEXTOR dynamic ergodic divertor. It would involve the development of a Poisson solver and of a particle pusher. First tests carried out in simplified but fully 3-dimensional geometries highlighted the insurgence of a problem common among PIC codes, namely the statistical noise consequence of too small a ratio between the number of tracer particles and that of computational cells, which makes unreliable the step of solving the Poisson equation. Since the option of increasing the number of test particles must be ruled out due to the unacceptable amount of CPU time required, we are considering the alternative of reducing to 2-dimensional geometries. This path is acceptable as long as one accepts to study the core of SHAx discharges. However it has the drawback of preventing the matching of core and of edge physics.

In the course of these studies we started a new alternative approach, presently still under investigation: exploiting the fact that—in the presence of good magnetic surfaces—the parallel dynamics plays a trivial role, one could think of a reduced model where only perpendicular dynamics is involved: drifts and possibly collisional diffusion. Each of these terms is known in advance from the magnetic geometry and can be used to provide a fluid expression for the particle fluxes—needed to estimate the particle density and then ultimately the electric field via Poisson equation—thereby removing the complications related to the particle approach.

5.9 Classical and neoclassical domains of RFP plasmas

The existence of internal transport barriers in RFX-mod was an incentive to consider the magnetic self-organization of domains where transport is classical or neoclassical. As a first step we considered paramagnetic pinches with fully classical transport.

This kind of system is driven mostly by self-consistent dynamics, depending upon few external knobs; the main plasma parameters (plasma temperature and density, current or magnetic field) turn out to be coupled self-consistently via few equations of state that have been studied either analytically or by means of simple numerical techniques. It is straightforwardly recovered that a self-consistent Ohmic equilibrium implies a virtuous relationship between the applied voltage, the plasma current and temperature, namely higher currents produce higher temperature requiring lower voltages. Realizing experimentally such radially global scenarios has been impossible till now. Our study exhibits in particular then issue of the coupling of the core with the edge region. However still some signatures could show up in real plasmas, if conditions are not too far from ideal ones. This led to propose experiments with feedback control of loop voltage have been proposed during the 2011 experimental campaign: the goal was to monitor a self-consistent (I,V) characteristic, and assess how close to the neoclassical predictions it was. The same investigation, in parallel, might be carried out by inspecting the existing discharge databases and looking for ohmic fingerprints in the (I,V) characteristic.

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6. DIAGNOSTICS

6.1 Background

The realization of the 2011 diagnostic development program was significantly hindered due to the budget limitation. In particular some projects were delayed for the second consecutive year, namely the Fast Reciprocating Manipulator, the new sources for the microwave reflectometer, the power supply for ion saturation current measurements and the Lithium neutral beam diagnostic. These projects are of interest in particular to improve the diagnostic capability devoted to study of the edge confinement barriers at high current and have been transferred to the next year program.

The insufficient funding also affected the maintenance/upgrade of some well-established diagnostic such as the CO_2 interferometer and the probe insertion systems, as it will be mentioned in the following.

Nevertheless some important progress in the diagnostic capability was achieved in 2011, in particular in the area of time and space resolved electron and ion temperature measurements: the new laser for the main Thomson scattering was fully commissioned and significantly improved both the repetition rate (100Hz) and the number of available measurements per plasma pulse, the new horizontal SXR camera started producing accurate time resolved T_e profiles, the improved vacuum level obtained in the DNBI duct allowed to achieve CXRS measurements both in tokamaks and medium current RFP pulses. Among the activities which were completed as scheduled is the new Z_{eff} diagnostic with toroidal LOS that was fully commissioned and routinely operated.

Also to be mentioned is the start of an important collaboration with PPPL to realize a multi solid pellet injector to be used mainly for wall lithization.

6.2 FIR polarimeter

Year 2011 has been devoted to consolidate previous improvements on polarimeter measurement mainly by further reducing detectors noise, which is presently the only remaining significant measurement error source, and increasing Faraday rotation amplitude by using a longer laser wavelength.

Following the 2011 activity plan, the following actions have been taken:

- A new faster pyroelectric detector has been tested: the detector allowed extending the polarimeter bandwidth, but no noise reduction was achieved.
- Because of this, further investigations on the source of the noise have been undertaken. New tests have given indication that, after the 2010 installation of the improved detector pre-amplifier, the residual noise is probably due to acoustic and/or mechanical vibration acting on detectors. This because the pyroelectric detectors used in the polarimeter are sensitive to acoustic/vibration noise. To solve the problem then acoustic

shields have been installed around the detectors. Preliminary results with these shields are expected by the end of 2012.

- Following the good results obtained in 2010 operating at the longer wavelength (185 μm) with non-optimized half-wave plates, a supplier for half-wave plates optimized for such wavelength has been selected, but due to budget constrains the purchase has been delayed;
- The design of a new detection section able to accommodate also the sixth started, but it was interrupted to wait for results of the acoustic shielding.

6.3 Main Thomson Scattering

The new laser system bought from the Russian company L.o.S. has been tested and installed in the room during the first part of the year. This laser has replaced the old YLF laser, and is capable of a higher repetition rate (100Hz) and a higher number of available pulses. The installation itself required just a few weeks, but the laser showed since the beginning some stability problems. There has been an extensive work to solve these issues, with a few parts replaced and two visits by technicians of the L.o.S. In particular, the master oscillator in the laser head was replaced and the timing was corrected, together with improvements of the total energy of the pulses. The new laser is now fully operative, with up to 45 T_e profiles available in a single (high current) plasma discharge. Fig.6.3.1 shows a T_e profile during a SHAx state, with a robust barrier between r=-20 and r=20 cm; the error bars are particularly small (20 eV or less in the best case), but a few points show that residual stray light might be present in some signals. Due to the higher number of pulses, the beam dump installed in the RFX vessel has been reconditioned already two times. A more robust dump is under study.

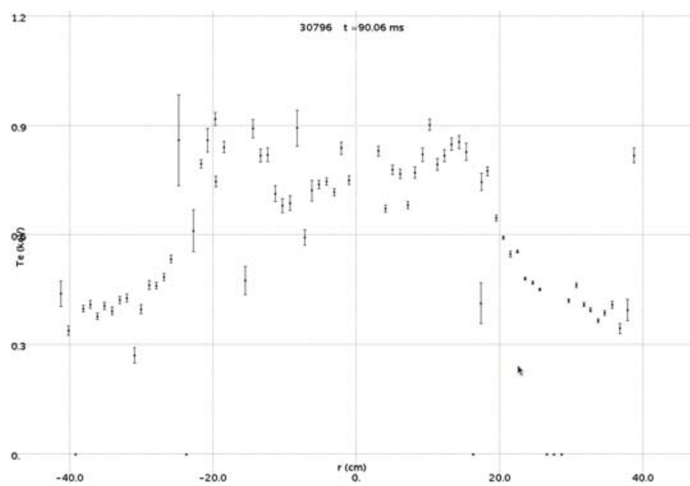

Fig.6.3.1: Electron temperature profile (keV) during SHAx, shot #30796, t=90 ms.

The whole analysis software has been completely rewritten in IDL, implementing a new technique in order to take into account the laser pulse shape in the calculations. Stray light subtraction was also added.

During the installation, and also when disconnecting the diagnostic from RFX-Mod for maintenance, a beam profiler system composed by a fast camera was installed near the laser entrance window in order to facilitate the operations of alignment and control of the laser beam. This new system allows us to perform a very quick alignment of the laser (in one day). The camera and the control PC can be placed close to the diagnostic very easily, but it is foreseen to have them in place all the time in order to check the alignment also during plasma operations.

Optical components for improving the old YLF laser have been purchased, but this work only started at the end of the year. This laser will be then installed on the Edge Thomson (see paragraph 6.9). A modification of the mechanical structure of the diagnostic (to make all the operations of mounting and installation of the collecting optics easier) is ongoing, but will be completed in the beginning of next year.

6.4 Soft X-Ray (SXR) diagnostics

6.4.1 Horizontal SXR camera

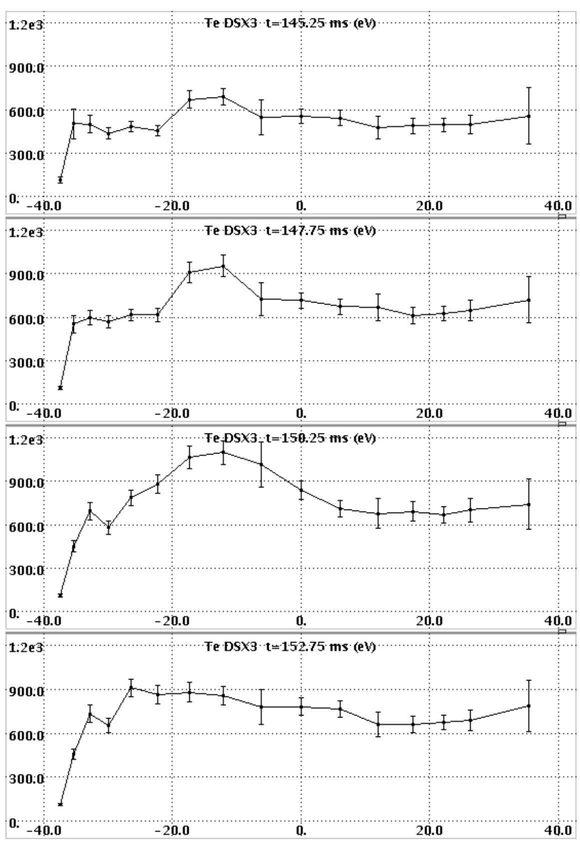

Fig.6.4.1: time evolution of the HOR T_e profile (eV) in a QSH; x-axis is radius (cm). Shot #30839, from 145 to 153 ms.

Throughout this year the SXR tomography and in particular the new horizontal camera (HOR) have been run and SXR reconstructions and T_e profiles have been calculated and saved in the pulse file. Initial comparison with Thomson Scattering shows good agreement, both in profile shape and T_e values. Fig. 6.4.1 shows examples of T_e profiles from the HOR camera during a QSH: now the time evolution of the profile can be followed [Ruzzon11a, Ruzzon11b]; the default time resolution in the calculations is 0.5 ms but can be lowered down to 0.1 ms when large SXR signals and low amplifier gains are both present.

In order to reduce the noise in the signals (switching noise due to the toroidal system and MHD control) different electronic layouts have been tested (shorter cables, different location of the amplifiers, screens) but with no major improvements. At present the only modification that could reduce the noise entails changing the present amplifiers with differential ones, either commercial ones or designed and built at our local electronic shop. This will be discussed soon: a prototype from MST is going to be tested at the beginning of 2012.

6.4.2 SXR Multifilter

A prototype logarithmic amplifiers should have been used, instead of the present linear ones, in order to increase the operational range of the diagnostic, but during the tests the amplifier stopped working, and there has been no time to repair it (due to high priority works on SXR tomography and main Thomson Scattering). A new prototype will be assembled and tested next year. The aim is to have a couple of signals to measure the on axis T_e for almost all operational regimes of RFX-mod, and to follow in detail the initial and ending phase of a discharge when the signals are very low (and thus high gains are required).

6.5 Neutral Particle Analyzer

The 11-channel Neutral Particle Analyzer on loan from IPP-Greifswald has been fully operational during 2011. Data about the fluxes and energies of neutral H^0 particle produced by charge exchange (CX) processes and leaving the plasma have been collected in a wide range of experimental conditions, yielding information on T_i and suprathermal ion tails.

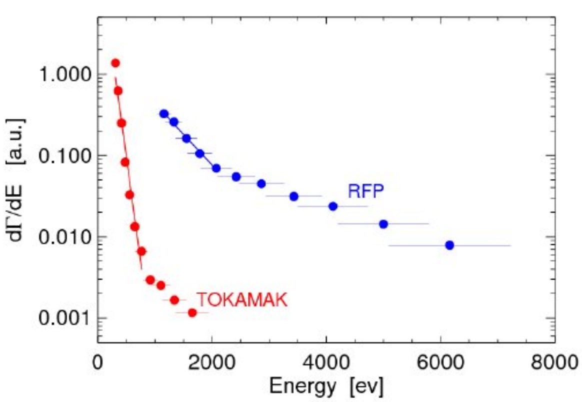

Fig.6.5.1: Typical CX spectra measured in RFP (blue) and tokamak (red) plasmas.

Two examples of the measured CX spectra collected in RFP and tokamak configurations are shown in Fig. 6.5.1.

Some optimization of the system has been performed in terms of an improved shielding to reduce the electrostatic noise, while those related to the shielding of the external magnetic field and to the control of the applied voltages by means of SIGMA are still in the design phase.

During 2011 the dependence of the collected fluxes on the pressure of the stripping Nitrogen chamber has been investigated, along with that on the applied magnetic field for particles deflection and energy discrimination. Particular attention has been devoted to the impulsive ion heating occurring during the spontaneous magnetic reconnection events characterizing RFP plasmas and to the effect of the sawtoothing activity in tokamak ones.

The activity aimed at the interpretation of the spectra using Nené, a Monte Carlo code, for the reconstruction of the ion temperature profiles has been started.

6.6 Fast Reciprocating Manipulator (FaRM)

A fast reciprocating manipulator is foreseen to be built and installed on RFX-mod.

The system will allow studying the average edge plasma parameters and their fluctuations at plasma currents higher then those which can be safely explored with the manipulators presently available, which can be moved only on a shot-to-shot basis.

The mechanical design of the manipulator has been checked and revised by the RFX project team working in tight collaboration with the external company in charge for the manipulator design [Agostinetti09, Agostinetti10a, Agostinetti10b]. The design has then been officially finalized, delivered to RFX and finally registered by the RFX Drawing Office.

The activity now is devoted to the study of the suitable solution for the interface between the assigned port in the RFX-mod device and the manipulator itself. Both the possibilities of supporting the manipulator with a frame anchored to the floor or with a system attached to the supporting structure of RFX-mod are presently under evaluation [Agostinetti11]. The figure 6.6.1 shows the complete 3D view of the Fast Reciprocating Manipulator, the pre-vacuum chamber and one of the solution for the interface with RFX-mod are visible.

A collaboration with the EPFL, Lausanne, has been agreed in order to build a similar fast reciprocating manipulator for analogous plasma edge investigations, to be performed in the TCV tokamak experiment.

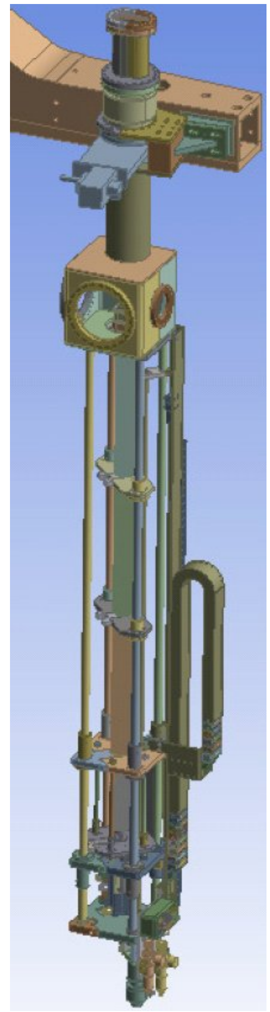

Fig.6.6.1 3D view of the Fast Reciprocating Manipulator (FaRM) completed with the pre-vacuum chamber and the interface structure.

6.7 Arcless power supply for ion saturation current measurements

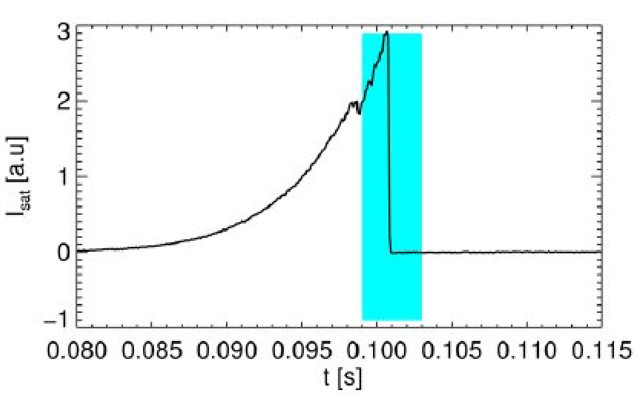

Fig.6.7.1: Time evolution of the ion saturation current where the action of the arcless power supply has been highlighted.

The prototype of the new power supply system for edge probes, incorporating the arc-detecting circuit has been successfully tested on the U-probe system during a low current experimental campaign. The system has been found to work properly, according to the specification, as shown in figure 6.7.1. A final engineering effort is foreseen during 2012, and, if funds will be available, the production will start once the factory will be selected. It is worth noting that the same system could be used with the poloidal/toroidal array of ISIS system giving toroidally and poloidally resolved measurements of electron density and temperature.

6.8 Revamping of the shot-to-shot probe insertion systems

RFX-mod is equipped with two insertions systems, which allow the insertion of probes in the edge plasma on a shot-to-shot basis. These systems are ageing and suffered failures, which could not be repaired. A project for substituting the present manipulator system with a simplified and more robust one was finalized during this year. The orders for all the equipment have been prepared, and the suppliers have been identified. Due to the economic limitation these orders have not been placed yet. If no action will be taken in a near future operations of these systems cannot be guaranteed.

6.9 Edge Thomson Scattering

During 2011 we have completed the mechanical and optical upgrades to the diagnostic in order to make it completely independent from to the Main Thomson Scattering. The optical shutter on the collection pipe has been built, installed and commissioned, a new set of optical wedges designed to reduce stray light has been designed and manufactured (though not yet commissioned). The acquisition system for the diagnostic has been installed and tested: it is now ready and it proved to work correctly during RFX-mod shot sequence.

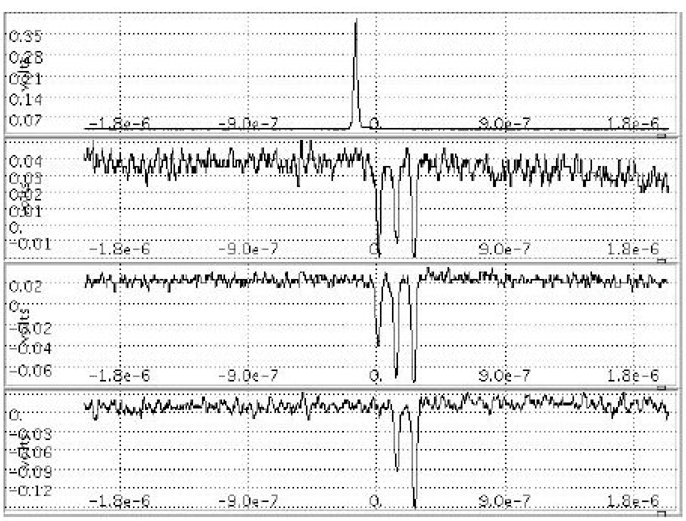

Fig.6.9.1: Signals acquired by the edge TS during RFX-mod 30831: from above, laser pulse (2.5 J, about 75 % of maximum available energy) and diffused radiation from 3 scattering volumes, 3 spectral channels.

We have good levels of signals, which means that the substitution of the collection optics operated in 2010 was successful: the present dataset (about ten shots obtained at the end of October) does not allow a direct comparison with the previous setup – mainly because we did not have a reliable, independent measure of plasma density. At the moment we are confident to get a complete T_e profile within the next experimental campaign.

On the laser side, we started an optical modification of the Nd-YLF laser (installation of a cylindrical telescope and of spatial filters), in order to use it on the Edge TS and get 10 profiles per discharge. The ruby laser in use at the moment cannot fire more than 2-3 times, and only within a lamp discharge time (800 μs); we verified the possibility to increase the fire rate by changing the power supply, but it is possible to add only another pulse at about 10 ms delay from the first one.

This laser underwent a general maintenance in the summer 2011. We still had some problems of electronic stability, which are now solved, but this suggests the need to change the laser system in the future.

6.10 Upgrade of the Diagnostic Neutral Beam Injector

The diagnostic neutral beam injector performance benefited from the installation of two cryopumps on the beam duct, in the proximity of RFX. This operation had been indicated as necessary by tests carried out in 2010, when the beam was injected into RFX filled with gas and a scan of the magnetic field intensity showed that the beam emission was strongly decaying with the field strength, whereas, instead, the source was not affected. The two 2000 l/s pumps have been recovered from the old lot of RFX pumps and adapted to our needs only with the installation of a charcoal to optimize the pumping of hydrogen and helium. Vacuum level in the duct has thus been improved by a factor 4 to 5. With this setup, beam emission spectroscopy has been detected systematically both in Tokamak discharges and in low density medium current (800kA) RFP shots.

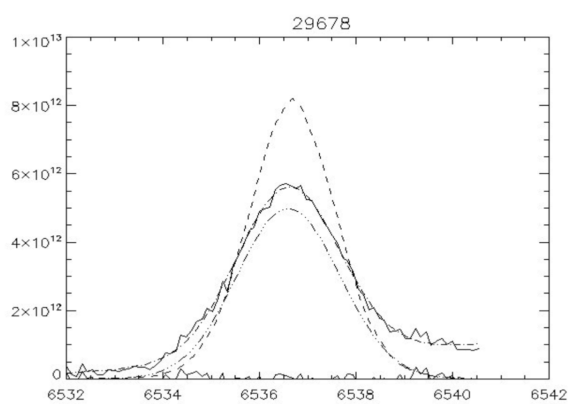

Figure 6.10.1: Simulated (continuous) and experimental (dashed) Doppler shifted H alpha spectrum emitted by the beam at mid radius in Ph/m^2/s .

In the past only seldom such a measurement had been successful and only in discharges below 400 kA. In those cases, the beam power inside the plasma was estimated to be ten times less than expected.

Fig. 6.10.1 shows the case of a full energy Hα line emitted by the beam at mid radius (continuous curve) in a Tokamak discharge. The dotted line shows for comparison the expected line simulated by means of the Von Hellermann code and assuming that the neutralisation efficiency in the source is 50%. The ratio between the expected and experimental integrals of the lines is 0.7. Considering other examples at higher densities it can be said that the extra pumping has allowed an improvement by a factor 5, approximately proportional to the improvement of the vacuum level. Such result indicates that we could try

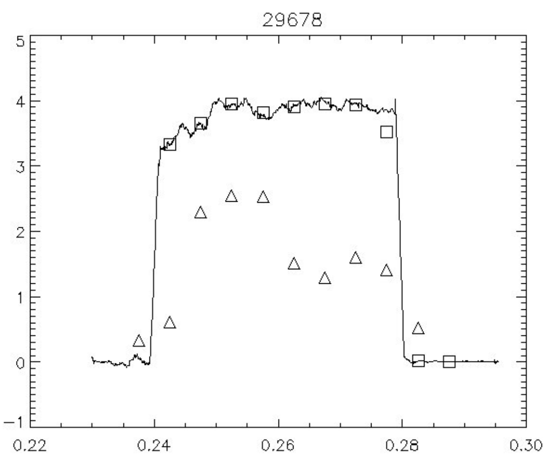

Figure 6.10.2: Ion beam current (in A) and normalized beam emission intensity (triangles) vs time (sec).

now to exploit the beam emission for motional Stark measurements, at least in the limited range of discharges where the signal has proven sufficient. In parallel, work is in progress to improve the vacuum in the volume between pumps and RFX. The RFX plasma, in fact, with its high recycling due to the carbon wall, represents the main source of gas that, in conjunction with the strong stray magnetic fields, stops the beam. Such extra pumping is necessary not only to extend the range of plasma parameters with measurable signals, but also to prevent what appears to be a loss of beam during the pulse itself, as indicated by Fig. 6.10.2, where the overlapping of ion beam current at the source (continuous line) and the normalized mean beam emission (triangles) inside the plasma shows that, after the first three or four 5 ms frames, the beam emission decreases sharply, while the beam current stays constant, with no signs of loss of beam divergence.

6.11 Microwave Reflectometer

During 2011 the prototype Ka band has been in operation, providing significant data. An assessment of the measurements carried out by a comparison with the edge Thomson scattering data confirmed the correct reconstruction of the density cut-off position (Fig. 6.11.1) [DeMasi11]. In the meanwhile the final version of the new driver system for controlling the existing microwave IMPATT sources has been designed and built using the technical facilities at Consorzio-RFX [Cavazzana11]. These drivers have been then integrated into the four existing cabinet maintaining dimensional compatibility (Fig. 6.11.2).

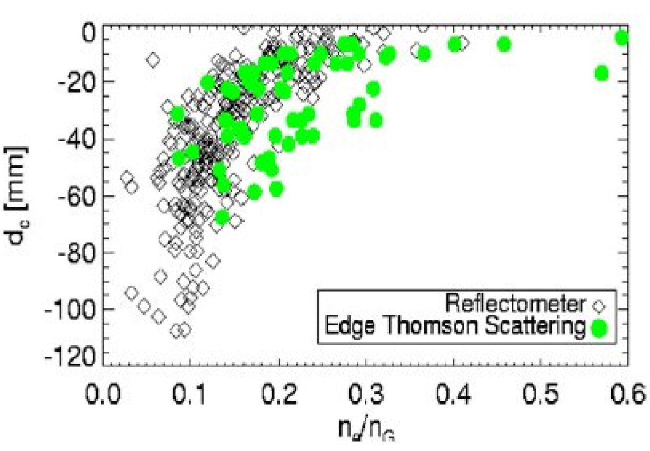

Fig.6.11.1: Comparison between the cut-off position of $ne=1.4 \cdot 10^{19}\ m^{-3}$ as measured from the reflectometer and obtained from TS data, as function of the Greenwald density fraction.

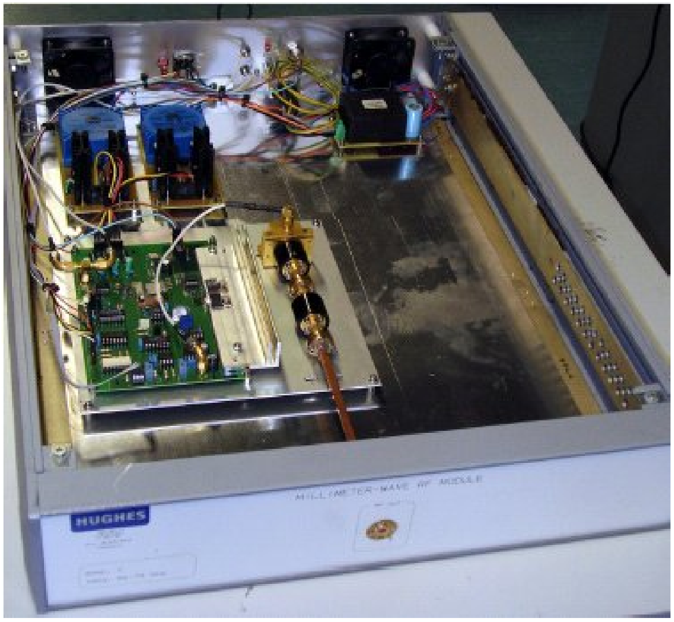

Fig.6.11.2: A complete microwave source unit (V band) using the new IMPATT driver.

The new units are to be installed after a frequency bench calibration. These four units are designed to take the measurements simultaneously in the density range $1.5 – 7 \cdot 10^{19}\,m^{-3}$, which, coupled to the ultrafast modulation capability (4 GHz sweep in 250 ns) of the new driver, will allow edge density profile reconstruction and turbulence characterization at the same time.

6.12 CO2 multi-chord interferometer

Due to budget constrain only minor improvements have been possible: a moving retroreflector for calibration purpose on one of the interferometric modules and a system for remote measurement of lasers power emission and control of laser cooling temperature were installed. On the contrary, the purchase of a new CO_2 laser, which is expected to improve measurements reliability, has been delayed at the end of 2011 and the new laser will be installed at the beginning of 2012.

6.13 Pellet injectors (cryogenic, solid, multi-solid)

No major modifications have been performed on the existing cryogenic and room temperature pellet injectors. Both injectors have extensively been used in 2011: the cryogenic one worked well in injecting hydrogen pellets for density control; the room temperature one has been used to inject graphite pellets for carbon transport studies. In the latter case some problems were encountered when injecting small pellets (diameter of the order of 1 mm). A preliminary work to understand and solve these problems has been started at the end of 2011.

A new collaboration with the Princeton Plasma Physics Laboratory (PPPL) for the realization and installation on RFX-mod of a multi-pellet injector has been started in the second half of 2011. The new room temperature multi-pellet injector will be able to inject spherical pellet of 0.5-1.0 mm diameter with a maximum speed of about 100 m/s and an injecting rate from few hertz up to the kilohertz range. The new multi-pellet injector will be mainly used for lithium wall conditioning: it will allow injecting in a single discharge the same amount of lithium that presently requires a full experimental day using the single shot room temperature injector.

The new PPPL multi-pellet injector is a two-stage system: in the first stage a modified dropper is used to supply in a controllable way the pellet to the second stage (the impeller). In the second stage the impeller quickly accelerate pellets by hitting them with a fast rotating wheel. PPPL developed this scheme for ELM triggering by lithium pellet injection to the separatrix surface [Mansfield11]. Previous droppers have been successfully used for lithium wall conditioning both on NSTX and EAST tokamaks by supplying low speed (≈5 m/s) lithium sub-millimetre size pellets to the scrape-off layer of plasma. This scheme is not suitable for RFX-mod since, because of the different magnetic field configuration in RFPs, core pellet ablation is necessary to achieve an uniform toroidal lithium deposition. To achieve core pellet ablation on medium plasma current discharge on RFX, millimetre size pellet injected with a speed of about 100 m/s are required. Fortunately these specifications are similar to those required for ELM triggering in tokamaks. In the framework of the collaboration with Consorzio RFX, the PPPL agreed to provide most of the necessary components. In particular they will deliver to RFX the dropper and the fast rotating components of the impeller. RFX will provide the entire electronic, the vacuum interface to RFX-mod, the impeller vacuum enclosure and the lithium for wall conditioning. The mechanical structure and vacuum interface has been designed. In figure Fig.6.13.1 a 3D drawing shows the multi-pellet injector installed on an equatorial port of RFX-mod. All the necessary components will be purchased at the beginning of 2012 and installation is scheduled for spring of 2012.

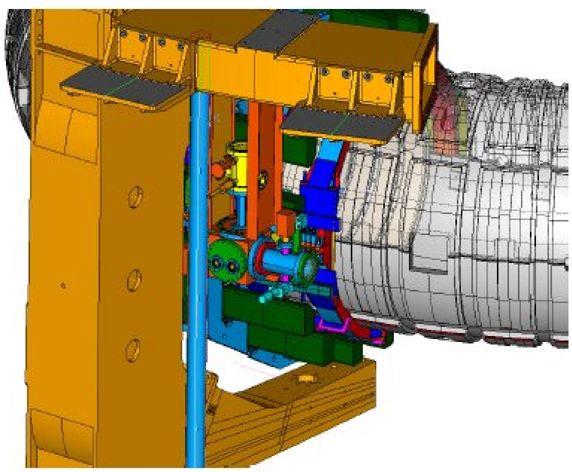

Fig.6.13.1: Drawing of the multi-pellet injector installed on RFX-mod

6.14 Continuum Bremsstrahlung absolute measurements in the visible range: Zeff diagnostics

Previous measurements of Continuum Bremsstrahlung performed on a vertical diameter of RFX-mod, evidenced contamination by edge radiation (molecular pseudo-continuum), resulting in a not realistic effective charge Z_{eff} estimation. To overcome the problem, a toroidal line of sight (LOS) measurement of Continuum Bremsstrahlung has been implemented, to minimize the effect of the edge radiation with respect to the plasma continuum emission. A mirror is used to have a central toroidal LOS, oriented in counter current direction, to avoid reflectivity reduction due to strong C,B deposit; another insertable mirror and a calibrated source allow us to measure the reflectivity variation (day by day monitor).

The diagnostic is operative since February 2011, providing the toroidally averaged Z_{eff} time evolution on a shot by shot basis, provided that the electron density profile is available (inversions of CO_2 interferometer data, see an example in Fig 6.14.1). For a given PWI

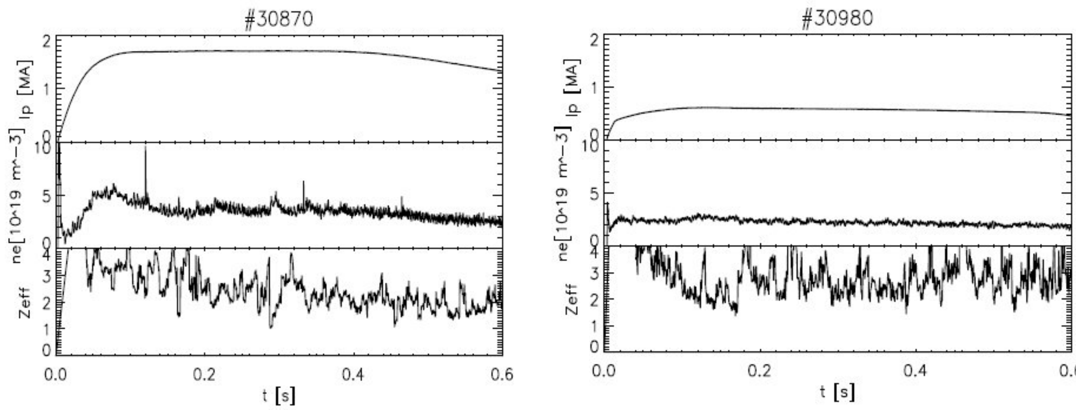

Fig.6.14.1: Time evolution of: plasma current, electron density and Zeff for a high current (left) and medium current (right) discharge.

scenario, the residual contamination of the continuum spectrum strongly affects the Bremmstrahlung diagnostic at the lower densities (i.e. $n_e<2 \cdot 10^{19}$ m^{-3} for the old RFX [Carraro L. et al EPS Conference Berchtesgaden (P1)0329 (1997)]). Systematic statistical analysis is necessary to identify the density 'threshold' for the different plasma current and wall conditioning scenarios.

6.15 Lithium neutral beam diagnostic

No work was performed on this task on 2011 because no money was allocated for it on the 2011 budget.

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7. BROADER APPROACH

7.1 Background

Consorzio RFX researchers have continued working both on the design of the systems to be procured by CNR, acting through Consorzio RFX, and participating in the general activities in the framework of the JT-60SA International Project Team, regulated by the EU-JA Common Quality Management system.

They participated in Technical Coordination Meetings (three in 2011), which are mainly devoted to discuss the development of the overall JT-60SA design and the interface issues in particular [Barabaschi11]. In addition several Design Review Meetings were held in the Power Supply topic to discuss the system design development.

Analyses were made on specific topics in collaboration with EU and JA colleagues like the conceptual design for the error field correction coil power supply [Matsukawa11] and the models of the poloidal field coils to reproduce the transient voltage in the JT-60SA PF Coil Circuits [Yamauchi11].

7.2 Quench protection circuits

At the beginning of the 2011, additional experimental tests have been performed on the 10 kA prototype of hybrid Circuit Breaker (CB) developed by Consorzio RFX to further study the current commutation between the mechanical ByPassSwitch (BPS) and the static CB and to confirm the feasibility and reliability of this design solution to be adopted for the Quench Protection Circuits (QPC) of the JT-60SA Satellite Tokamak. Dedicated tests were also made to verify the performance of some current transducers in order to judge their suitability for the implementation in the QPC units [Novello11].

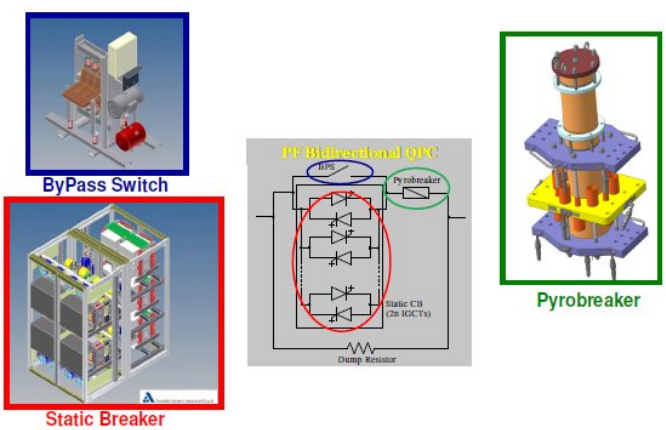

Fig.7.2.1: Drawings of main components of the Quench Protection Circuit.

After the start of the contract activities for the Quench Protection Circuits procurement (entrusted to the company Ansaldo Sistemi Industriali (ASI) on December 20th 2010), the detailed design phase was developed in the first semester 2011; the First Design Report (FDR) was delivered at the beginning of July, in time for the approval, scheduled on 15th July 2011 [Gaio11]. The conceptual design proposed was confirmed (Fig. 7.2.1); the QPC is based of an

Hybrid CB composed of two branches in parallel, a mechanical switch (BPS) and a static one, made of Integrated Gate Commutated Thyristors. An explosively actuated breaker (pyrobreaker) is provided in series and acts like backup protection; the dump resistor in parallel completes the protection unit.

Special studies were made during the design to investigate the possibility to reduce the TF QPC dump resistance value up to 0.075 Ω, till assuring that the maximum I^2t in the coils after quench remains well within the maximum threshold of 4.6 GA^2s; this target was reached thanks to the reduction of the QPC intervention time with respect to the specification, to the assumption of an higher TF resistor maximum temperature and the exploitation of the resistance variation with the temperature. These provisions, together with the minimization of the stray inductances and the design of suitable clamp circuits allow maintaining the voltage across the TF magnets lower than the maximum value of 2.8 kV, even in transient conditions, as shown in Fig. 7.2.2.

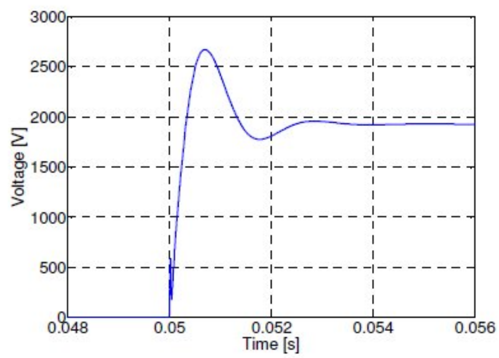

Fig.7.2.2: TF QPC resistor voltage at the commutation

The contract follow-up activities proceeded in parallel to the company detailed design development. Specific analyses have been made:

- to study in detail the topology of the static circuit breaker proposed by the company
- to verify the thermal analyses for the identification of the maximum semiconductor junction temperature in the different operating conditions
- to study suitable provisions to limit the maximum voltage across the magnets

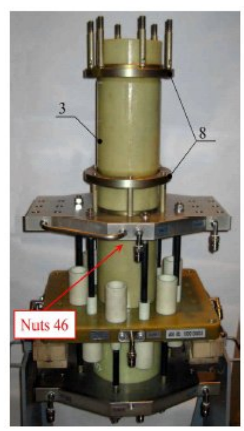

Fig.7.2.3: Prototype of pyrobreaker

The level of innovation of this design required the development of a full scale prototype, which started after the conclusion of the design phase and which manufacturing is planned to be completed at the beginning of 2012; the type tests will be expected to be completed end September 2012.

In the second semester 2011, the type tests were performed on the first components as soon as they were ready

The official witnessed tests of the first prototype of the pyrobreaker (Fig. 7.2.3) were performed in June; four interruption tests up to 40 kA, insulation tests (28 kV), temperature rise test (two hours conduction time at 30 kA); the temperatures measured with thermocouples in several points were all below 70 degrees. The tests were performed at current and voltage levels quite higher than those specified; the results were very successful.

As for the Bypass Switch prototype (Fig. 7.2.4), which was ready in late May 2011, it was agreed to perform part of the type tests at the Consorzio RFX facility during the RFX-mod shutdown, from July 25th to August 12th.

Fig.7.2.4: BPS prototype

The tests performed were addressed to verify the electro-dynamic robustness of the BPS (6 pulses with a dc current of 51.4kA applied for 100ms) and to verify the electric wear of the sacrificial contacts (200 pulses commutations of a dc current of 26kA).

In spring 2011, the analyses necessary for the design and set up of the test facility were performed by Consorzio RFX team. Then, the works was devoted to the execution of the tests and the elaboration of the measures; post processing analysis has been performed in order to verify the accuracy of the measures and a critical evaluation of the results was made to check the fulfilment of the technical specification requirements.

The results confirmed the expectations; Fig. 7.2.5 shows the status of the BPS sacrificial contacts after 200 operation without maintenance, which are still not so damaged.

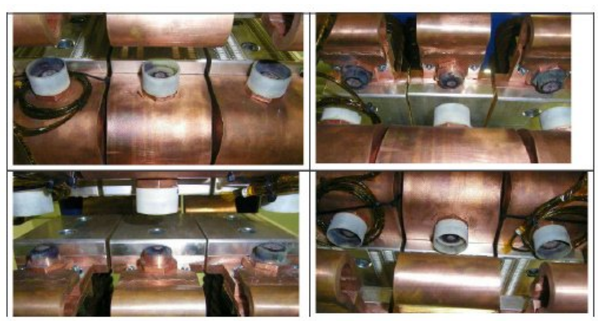

Fig.7.2.5: Contact picture after 200 commutation at nominal current without maintenance

The set of required type tests were completed at the manufacturer premises in November; withstand voltage capability, mechanical robustness, resistance measure at closed contacts and temperature rise tests were the most significant. The analyses of the results collected so far demonstrates that both the BPS and the pyrobreaker performance are in line with expectations.

7.3 Power supplies of the in-vessel sector coils for RWM control

The CDR design of the RWM control system of JT-60SA is based on 18 sector coils (SC), six located in toroidal direction and three in the poloidal one, to be installed on the outer side of the stabilizing plate (SP). However, since 2009 JAEA is studying also the opportunity to install internal sector coils, located between SP and first wall (Fig.7.3.1). This solution has a set of advantages, as for example easier maintenance and higher efficiency of the SC in producing the magnetic field, due to the lower shielding effect of the SP and the proximity to the plasma. On the other hand, the smaller space available for the coils constrains to reduce the number of turns from 8 to 2. Nevertheless, if relatively low time delays between field measurements and PS output current (latency of the control loop) can be achieved, the magnetic field necessary to control the RWM can be reduced, because of the exponential growing of the modes.

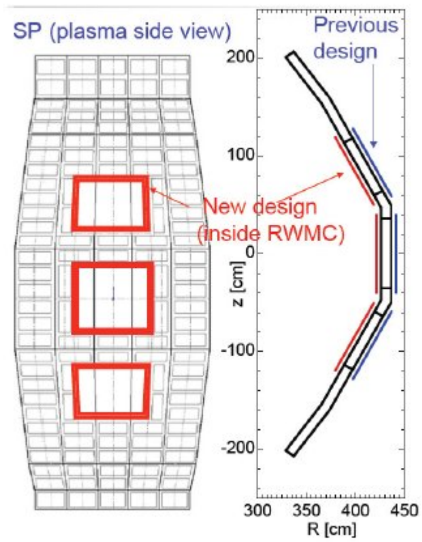

Fig.7.3.1: New solution with RWM sector coils installed on the plasma side of the SP.

In 2011, JAEA made further progresses in these studies, considering 2-turns internal SC, having the same dimensions as in the CDR design (0.8×0.8m) and based on Mineral Insulated Cable (MIC) with sheath made of SS316 (Fig.7.3.2). New Valen-code simulations have been performed by JAEA, taking into account several non-idealities. It has been found, for example, that the RWM can be controlled up to $\beta_N = 4.1$ if the overall latency of the control system (including PS) is less than 150 μs. This stringent requirement implies a set of technological issues for the RWM control system, as for example on the switching frequency of the PS.

Proceeding with the activities carried out since 2008, RFX supported these studies with a critical evaluation of the results and their implication on the PS design. In particular, periodical progress meetings have been arranged, to allow a continuous update and exchange of information and opinions. Experimental time on RFX-mod has been devoted in July 2011 to study the RWM control in tokamak configuration, in collaboration with one JAEA colleague who participates to the experimental sessions (see also par. 4.3). Moreover a dedicated RFX-JAEA Joint-Work has been arranged in September 2011 to discuss several technical aspects. The encouraging outcomes produced the setting up of the internal SC solution as the official reference design.

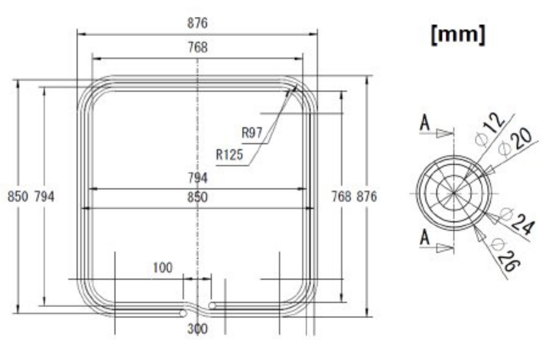

Fig.7.3.2: Present reference design of RWM sector coils. On the left: coil geometry. On the right: MIC section.

In the Joint-Work of September, several issues have been discussed; in particular, the updated requirements for the RWM PS, the layout of the installation, the outline of the RWM control system and the connections between PS and SC. About the last point, the use of coaxial cables is presently foreseen. The impedance of the cables as a function of frequency has been quantified from data-sheets and verified with 2D FEM analyses. The electrical characterization of the MIC feeders under vacuum is still in progress. Starting from the detailed 2D FEM analyses on internal SC performed in 2010 and the requirements obtained by JAEA with the latest Valen-code simulations, the necessary voltage and power at the PS outputs have been quantified, considering also the voltage drop in the cable feeders (Fig.7.3.3).

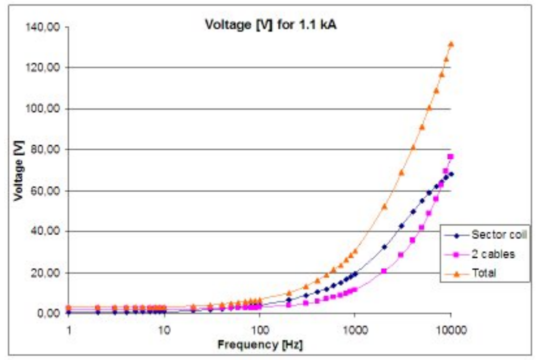

Fig.7.3.3: Voltage at the PS outputs at 1.1 kA

Basing on these results and the dynamics required, some first considerations about PS topology and possible suitable technologies for the power switches have been performed. Due to the very low latency required, the use of MOSFETs is under consideration. In addition, being the maximum acceptable output current ripple not specified, some studies have been carried out to quantify the attenuation of the passive structures at the frequency of the ripple.

Further studies are still in progress in order to identify the minimum requirements of the RWM PS for the Initial Research Phase of JT-60SA. The opportunity to connect the SC in series or in parallel and to use a subset of PS is under consideration. Studies are in progress to verify both the impact on the PS system and the controllability of the RWM.

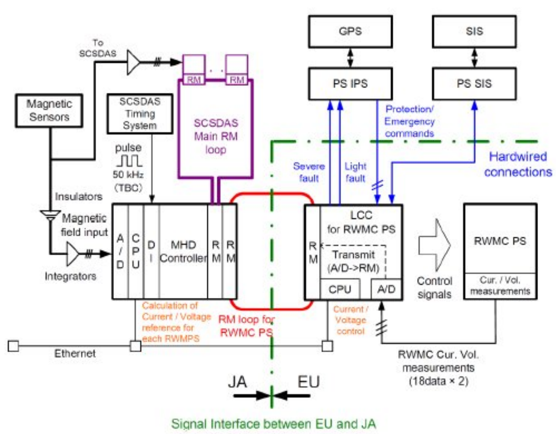

Fig.7.3.4: Tentative scheme of the RWM control system

During the Joint-Work, a tentative scheme for the RWM control system has been identified and agreed between RFX and JAEA, as represented in Fig.7.3.4. Starting from this scheme, analyses on possible hardware architectures for the RWM PS local control system (EU side) have been carried out. Pros and cons of different options have been evaluated and the overall delay due to the hardware implementation of the signal transmission has been roughly estimated, considering the present technology. These studies, in addition to the analyses still in progress for the power section, will permit to assess if the required latency is achievable at reasonable cost. In parallel, JAEA is designing the MHD control system, also with the aim to verify the feasibility of the overall latency requirement.

References

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[Gaio11] E. Gaio, A. Maistrello, A. Coffetti, T.Gargano, M. Perna, L. Novello, A. Coletti, M. Matsukawa, and K. Yamauchi, “Final Design of the Quench Protection Circuits for the JT-60SA Superconducting Magnets”, accepted for publication in Transaction on Plasma Science

8. OTHER ACTIVITIES

8.1 Energy strategies

1. Fusion Energy as base-load electricity source.

   The simplified model of a Fusion Reactor for the cost analysis in different working condition (FRESCO code) has been adjusted in several parts, in order to get a better tuning with other similar code (e.g. PROCESS). Moreover the effect of inductive operation on some mechanical structures (such as the central solenoid and toroidal field coils) has been simulated more accurately.

   A contribution has been provided to EFDA task WP11-SYS on the system codes and to EFDA task WP11-DAS-PLS on the preliminary analysis of an inductive Demo.

2. Keep-in-touch activity regarding other future technologies for base-load electricity generation, and the role of Fusion.

   The parameters for the simulation of a MARKAL-TIMES energy scenario from 2050 onwards have been further improved, also through the collaboration established with the Max Planck Institut fur Plasmaphysik, and a solid contribution has been provide to the EFDA task WP11-SER-ETM

   In this context, the fuel cycles of thermal and fast fission reactors have been better simulated and their cost parameters updated.

   Moreover a code for the evaluation of the average cost of electricity in different scenarios from 2050 on has been initiated; this will allow to asses the role of a CO2-free base-load technology (either fission of fusion), in the long run, in terms of mitigation of the cost of electricity, when very tight constrains on CO2 emissions are set. The code will allow to consider the main technologies for power generation, transport and distribution and energy storage.

8.2 Non-fusion plasma applications

8.2.1 Magneto-plasma-dynamic thrusters

During 2011 experimental activities have been performed by Consorzio RFX in collaboration with Alta S.p.A., in the laboratories located in Pisa, aimed at testing the effectiveness of a new passive stabilizing method for the control of MHD kink instability in magneto-plasma-dynamic thrusters for space propulsion.

The method is based on the use of resistive metallic shells surrounding the plasma, as was proposed by the researchers of Consorzio RFX on the basis of the similarities recently highlighted between MPD plasmas and those produced in toroidal devices of fusion interest [Zuin04]. The experimental activity was performed on a new thruster, designed and built by Alta S.p.A., which is able to accommodate conductive shells of different materials and having different thicknesses, in order to test the effect of different penetration times of the magnetic field on the plasma performance. Tests have been made into a new, extremely large vacuum chamber, thus allowing a longer pulse duration better mimicking a real operative space mission, in a wide variety of experimental conditions in terms of plasma current, applied magnetic field and mass flow rate.

The effect of the different shells on plasma stability are investigated by means of special magnetic probes, designed and realized to investigate in good detail the growth rate of MHD modes and to monitor their saturation level. Data analysis is still in progress, but first results seem to indicate that shell proximity was probably not enough to ensure a strong stabilizing effect on the high frequency, large scale, kink modes in this kind of thrusters.

8.2.2 Biomedical applications

In the course of 2011 an extensive set of in-vitro tests of the effect of the plasma source for biomedical applications developed at Consorzio RFX [Martines09] was carried out, in collaboration with Department of Histology, Microbiology and Biomedical Applications of the University of Padova. Most of the tests regarded the effect of the plasma on human cells, with particular attention to possible DNA alterations. The aim was on the one hand to try to elucidate the mechanism by which the plasma affects human cells (conjunctival fibroblasts and keratocytes), and on the other hand to assess the safety of plasma-based treatments, considering also genetic damage which could manifest itself in the long run. The main outcome is represented by the observation that the plasma treatment induces the formation of Reactive Oxygen Species (ROS) within the cells, as detected using 2',7'-dichlorodihydrofluorescein diacetate, a non-fluorescent probe that is rapidly oxidized to the fluorescent 2',7'-dichlorofluorescein in the presence of intracellular ROS. A vast literature shows that ROS, which are constantly produced and destroyed inside the cells, play a very important role in the cell metabolism. This result elucidates a possible mechanism through which plasma exposure can be used to manipulate the cell inner mechanisms, with the potential of inducing therapeutic effects. It is worth noting that ROS levels returned to control values within 12-24 hours from the treatment. Of note, the burst of intracellular ROS driven by the plasma treatment was dampened by cell pretreatment with 5 mM *N*-acetylcystein (NAC), a ROS scavenger currently used in ophthalmological surgery.

The safety of the plasma treatment with respect to possible UV irradiation was evaluated checking the formation of thymine dimers (TD). The formation of pyrimidine dimers (thymine or cytosine dimers or thymine-cytosine heterodimers) indicates impairment of DNA replication and transcription due to lesions. The nuclei exposed to plasma treatments up to 5 minutes in duration did not show TD signals, demonstrating that the level of UV irradiation is too low to induce DNA damage.

Other findings regard the detachment and migration of living cells, namely conjunctival fibroblasts. It is found that the plasma treatment enhances the ability of the cells to migrate. This effect could be involved in the wound healing capability displayed by some kinds of plasma treatment. Furthermore, it has been found that the plasma has the effect of increasing the cellular strength of adhesion to the substrate.

To validate the potential use of the plasma source as an antiseptic agent, the study was expanded to *ex vivo* human corneas infected with *E. coli*, *S. aureus* or *P. aeruginosa*. A 2 min. treatment significantly decreased the surviving microorganisms recovered from infected tissues, thus confirming at the tissue level the disinfectant APCP effects obtained *in vitro*.

8.3 QUALITY MANAGEMENT

8.3.1 ISO 9001 Certification

During 2011 Consorzio RFX conformed its quality management system to the requirements of ISO 9001 and obtained the ISO 9001 certification for the following products and services:

1) Design and development of new technologies in the field of controlled nuclear fusion; construction and deployment of relevant equipment, diagnostics and systems devoted to research activities and industrial evolution;

2) Education and training in fusion science and engineering at the post-graduate - doctoral level.

The certification for "Scientific and technological research and new knowledge in the field of controlled thermonuclear fusion as a possible energy source" remains a goal for the following years.

The ISO 9001 certification involved both the main processes (the projects and the education process) and all the support processes (resource management, competence management, management of information and data, improvement processes, …).

The required documentation (quality manual, quality plans, procedures, work instructions, forms, templates) have been prepared and used to train the personnel.

In some areas the new procedures are still (at the end of 2011) in the implementation stage, i.e. some procedures just started to be used (e.g. competence management, purchasing) and people need to practice with them.

8.3.2 Management

Objectives have been defined for the main processes, excluding the support processes, and the first performance measurements start to be available and to be used by the management to identify problems or recognize good performances.

Risk management has been implemented in the main processes (projects and education) as a useful tool to manage the preventive actions required by ISO 9001. Its positive effects include more awareness on potential problems, a reduction of possible failures and losses and an increase in the probability of success.

8.3.3 Planning

The planning of the activities, as a means to define the way to achieve the objectives and to share a vision of the things to be done, is partially used at different levels and results are generally good, so the planning itself can be considered effective; the standardization of the planning tools and methods for all the projects is underway, since at the moment different tools and methods are used in different projects.

8.3.4 Quality Policy

The quality policy, as a document, is now annexed to the quality manual.
The management of the requirements is done with simple office tools (text documents); the idea to use a more sophisticated database for requirements management has been explored but at the moment it is not considered beneficial.
The use of the failure mode and effects analysis (FMEA) which reduces project risks, improves quality and helps in the definition of the verifications; has been introduced even if it is not systematically used.

8.3.5 Monitoring

Internal audits have been planned and performed according to ISO 9001 requirements from which indication was provided about customer satisfaction, even if the measurement still requires improvement.

References

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[Zuin04] M. Zuin, R. Cavazzana, E. Martines, et al., Phys. Rev. Lett. **92**, 225003 (2004).

9. EDUCATION TRAINING AND INFORMATION TO THE PUBLIC

International Doctorate in Fusion Science and Engineering

In 2011, both the "Joint Research Doctorate in Fusion Science and Engineering" (by Padua and Lisbon universities), and the "European Interuniversity Doctoral Network in Fusion Science and Engineering", among the same two universities and the Ludwig Maximilian University of Munich (Garching), continued under the responsibility of Padova University and of Consorzio RFX.

The total number of students participating to the doctorate was 34 (3 cycles, starting in 2009, 2010 and 2011), of which 15 in Padua.

For the Doctorate, during 2011, were organized 4 courses, of which 2 in Padua, 1 in Lisbon and 1 in Munich.

The 2 courses organized in Padua were: a Basic Course on Engineering (9-13 May), of 34 hrs of frontal teaching plus 6 hrs of laboratory and RFX visit, and an Advanced Course in Engineering (10-21 October), of 48 hrs of frontal teaching plus 12 hrs of student's seminars.

The topics and the teachers of the two courses were:

1. Basic Course on Engineering

- Fusion power plants (G. Casini, EURATOM/ RFX Padova);
- First wall/Divertor/Vacuum vessel (P.L. Zaccaria, RFX Padova);
- Axisymmetric equilibrium and stability of toroidal plasmas (F.Gnesotto, UNIPD/RFX Padova) ;
- Magnets (G. Chitarin, UNIPD/ RFX Padova) ;
- Feedback control theory with application to tokamak control (A.Cenedese, UNIPD Padova).

2. Advanced course on Engineering

- Materials for fusion reactors: Structural materials (S. Dudarev, CCFE Culham), Superconducting magnets (P.L. Bruzzone, CRPP Lausanne), IFMIF facility for testing of materials (A. Pisent, INFN Legnaro);
- Power reactor issues: Internal components (M. Merola, ITER Cadarache), Power plant Studies (D. Maisonnier, EU Commission Bruxelles), DEMO (D. Maisonnier, EU Commission Bruxelles).
- NBI heating and current drive: Introduction and basic physics (V. Antoni, RFX Padova), Injector components and service plants (P.L. Zaccaria RFX Padova), Power supplies (V.Toigo, RFX Padova), HV Insulation in vacuum and HV laboratory (A. De Lorenzi, RFX Padova), Beam-plasma interaction and current drive (C. Hopf, IPP Garching);
- RF heating and current drive: Introduction (A. Cardinali, ENEA Frascati), ECRH (G. Granucci, CNR Milano), LH/ICRH (F. Mirizzi, ENEA Frascati), Antennas for LH and IC plasma heating (D. Milanesio, Politecnico Torino).

Teachers from RFX contributed also to the courses held in Lisbon and in Munich.

Other university activities

The other educational activities of Consorzio RFX on fusion related disciplines continued with a significant effort also in 2011.

In particular, RFX professionals were in charge of 20 postgraduate students, preparing their PhD thesis in the doctorate of Fusion Science and Engineering, or of Physics, or of Energy Research, or of Electrical Engineering, and of 15 students preparing their graduation thesis on fusion related subjects.

Seven regular courses, on fusion related disciplines, of the Padova University were given by teachers from Consorzio RFX:

- 4 for engineering students: "Fission and Fusion Nuclear Plants", "Thermonuclear Fusion", "Industrial Applications of Plasmas" and "Energy Technology and Economics";
- 3 for physics students: "Introduction to Plasma Physics", "Fluid and Plasmas Physics" and "Physics of Nuclear Fusion and Applications of Plasmas".

Goal oriented training

In the frame of the EU actions to train young engineers in Fusion research, Consorzio RFX is involved in the EFDA "Goal-oriented training" programmes.

During 2011 six trainees have been trained at RFX, 2 on power supply technology and 4 on neutral beam injection physics and technology.

1.GOT on Power Supply Engineering

It is recalled that this training program is divided in two main areas:

- General engineering training and experience to provide an overall view of the features and issues concerning fusion power systems
- Specific training and experience in the selected technical areas

The General Training is mainly performed via integrated courses and shadowing activities jointly organized among the Partners (CCFE, CEA, ENEA, KIT and Consorzio RFX, who is the program coordinator); the Specific Training via the involvement of the Trainees in specific projects mainly at their own Institutions.

The details of the integrated courses performed during the second year (2011) can be found in the GOT-PSE website (https://www.igi.cnr.it/gotpse/), which has been developed by Consorzio RFX for the sharing of the GOT-PSE documentation and really proved to be very useful.

The specific training of the two Consorzio RFX Trainees is very well progressing; their involvement in the activities of the RFX, NBI and BA programs has further increased in the second year, with effective contributions.

2. GOT on Neutral Beam Engineering

The Goal Oriented Training program in Neutral Beam Engineering (GOT- NIPEE) is a collaborative program among the following three participant Associations: KIT, IPP and Consorzio RFX, who is the Program Coordinator.

In 2011 the specific training of the 4 Consorzio RFX Trainees has been regularly carried out by their participation to the RFX experiment activities and NBI design and by their participation to specific courses and visits to other laboratories and facilities.

Information to the public

In 2011, the activity of public information developed both in the field of fusion research and energy related matters, upon reaffirmation of the importance of a complete and timely information to get the responsible support from the public to the objectives and choices of research.

At this aim, an effective dissemination of information materials was carried out; speeches and participations to meetings or television programs were given whenever requested and interviews or insight articles were published on newspapers.

The activity was particularly frenetic in the weeks that followed the Fukushima nuclear accident in March, both at a local and a national level. We recorded a strong public concern about the risk of nuclear activity in requests for technical explanations. To each, we tried to give a response. The experience proved that while facing a crisis communication, as it was the communication after Fukushima, it is essential to meet the legitimate need from the public for information and reassurance.

Consorzio RFX participated in the organization of "Sperimentando", a large interactive exhibition on science phenomena and principles, annually organized in Padova and finalized to young students experimenting small devices and exhibits to explain a specific science topic chosen year by year. In 2011 the exhibition focused on "vision and illusion"; it was visited by almost 10,000 persons.

Furthermore, lectures were given, as in the past, on the occasion of visits of secondary school students to the plant.

PUBLICATIONS AND REPORTS

2011

INTERNATIONAL AND NATIONAL JOURNALS

R.1 Metal impurity transport control in JET H-mode plasmas with central ion cyclotron radiofrequency power injection
M. Valisa, L. Carraro, I. Predebon, M.E. Puiatti, C. Angioni, I. Coffey, C. Giroud, L. Lauro Taroni, B. Alper, M. Baruzzo, P. Belo daSilva, P. Buratti, L. Garzotti, D. Van Eester, E. Lerche, P. Mantica, V. Naulin, T. Tala, M. Tsalas and JET-EFDA contributors
Nucl. Fusion 51 (2011) 033002 (11pp) febbraio

R.2 Physics and engineering design of the accelerator and electron dump for SPIDER
P. Agostinetti, V. Antoni, M. Cavenago, G. Chitarin, N. Marconato, D. Marcuzzi, N. Pilan, G. Serianni, P. Sonato, P. Veltri and P. Zaccaria
Nucl. Fusion 51 (2011) 063004 (16pp) aprile

R.3 Edge turbulence in different density regimes in Alcator C-Mod experiment
M. Agostini, J.L. Terry, P. Scarin1and S.J. Zweben
Nucl. Fusion 51 (2011) 053020 (9pp) aprile

R.4 Physical understanding of the instability spectrum and the feedback control of resistive wall modes in reversed field pinch
Z.R. Wang and S.C. Guo
Nucl. Fusion 51 (2011) 053004 aprile

R.5 Dynamic decoupling and multi-mode magnetic feedback for error field correction in RFX-mod
L. Piron, L. Grando, G. Marchiori, L. Marrelli, P. Piovesan, A. Soppelsa and D. Terranova
Nucl. Fusion 51 (2011) 063012 maggio

R.6 Topology and transport in the edge region of RFX-mod helical regimes
P. Scarin, N. Vianello, M. Agostini, G. Spizzo, M. Spolaore, M. Zuin, S. Cappello, L. Carraro, R. Cavazzana, G. De Masi, E. Martines, M. Moresco, S. Munaretto, M. E. Puiatti, M. Valisa and the RFX-mod Team
Nucl. Fusion 51 (2011) 073002 (11pp) maggio

R.7 Necessary criterion for magnetic field reversal in the reversed-field pinch
D. Bonfiglio, D.F. Escande, P. Zanca and S. Cappello
Nucl. Fusion 51 (2011) 063016 (10pp) maggio

R.8 Edge density characterization in the RFX-mod experiment using the ultrafast reflectometry technique
G. De Masi, R. Cavazzana, A. Fassina, E. Martines, B. Momo and M. Moresco
Nucl. Fusion 51 (2011) 053016 (7pp) maggio

R.9 Internal and external electron transport barriers in the RFX-mod reversed field pinch
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R.11 Alfvén eigenmodes in the RFX-mod reversed-field pinch plasma
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F. Bonomo, D. Bonfiglio, P. Piovesan, L. Piron, B. Zaniol, S. Cappello, L. Carraro, R. Cavazzana, M. Gobbin, L. Marrelli, E. Martines, B. Momo, M.E. Puiatti and M. Valisa
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B. Zaniol
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P Piovesan, D Bonfiglio, F Bonomo, S Cappello, L Carraro, R Cavazzana, M Gobbin, L Marrelli, P Martin, E Martines, B Momo, L Piron, M E Puiatti, A Soppelsa, M Valisa, P Zanca, B Zaniol and the RFX-mod team
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R.21 Analytical and numerical solutions of force-free equilibria with flow
R Paccagnella and L Guazzotto
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R.22 Magnetic reconstruction of nonaxisymmetric quasi-single-helicity configurations in the Madison Symmetric Torus
F Auriemma, P Zanca, W F Bergerson1, B E Chapman2, W X Ding1, D L Brower1, P Franz, P Innocente, R Lorenzini, B Momo and D Terranova
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B Momo, E Martines, D F Escande, M Gobbin
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R.24 Ion heat transport studies in JET
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R.25 On the mutual effect of ion temperature gradient instabilities and impurity peaking in the reversed field pinch
I Predebon, L. Carraro, Angioni
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V. Naulin, N. Vianello, R. Schrittwieser, H.W. Müller, P. Migliucci, M. Zuin, C. Ionita, C. Maszl, F. Mehlmann, J.J. Rasmussen, V. Rohde, R. Cavazzana, M. Maraschek, the ASDEX Upgrade team, JET EFDA contributors
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E. Nardon, P. Cahyna, S. Devaux, A. Kirk, A. Alfier, E. De La Luna, G. De Temmerman, P. Denner, T. Eich, T. Gerbaud, D. Harting, S. Jachmich, H.R. Koslowski, Y. Liang, Y. Sun, The MAST team and JET-EFDA contributors
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S.J. Zweben, J.L. Terry, B. LaBombard, M. Agostini, M. Greenwald, O. Grulke, J.W. Hughes, D.A. D'Ippolito, S.I. Krasheninnikov, J.R. Myra, D.A. Russell, D.P. Stotler, M. Umansky
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E.M. Hollmann, G. Arnoux, N. Commaux, N.W. Eidietis, T.E. Evans, R.S. Granetz, A. Huber, D.A. Humphreys, V.A. Izzo, A.N. James, T.C. Jernigan, M. Lehnen, G. Maddaluno, R. Paccagnella, P.B. Parks, V. Philipps, M.L. Reinke, D.L. Rudakov, F. Saint-Laurent, V. Sizyuk, et al.
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Marco Boldrin, Antonio De Lorenzi, Mauro Recchia, Vanni Toigo, Tullio Bonicelli , Muriel Simon
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R.36 Near-infrared detectors for ITER LIDAR Thomson scattering
L. Giudicotti,, R. Pasqualotto, A. Alfier, M.N.A. Beurskens, M. Kempenaars, J.C. Flanagan, M.J. Walsh, I. Balbo
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Marco Barp, Roberto Cavazzana, Giuseppe Marchiori, Anton Soppelsa, Loris Zanotto
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R.41 A comparison between a steady state and a pulsed fusion power plant
G. Zollino, G. Casini, D. Pierobon, V. Antoni, T. Bolzonella, R. Piovan
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R.42 Integration design of TPE-RX Neutral Beam Injector on RFX-mod
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R.43 EM signal integrity via neural network analysis for the RFX-mod experiment
Rita S. Delogu, David Terranova
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F. Villecroze, L. Christin, H.P.L. de Esch, A. Simonin, A. Pesce, A. De Lorenzi
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M. Recchia, M. Bigi, M. Cavenago
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E. Gaio, A. Zamengo, V. Toigo, L. Zanotto, M. Rott, W. Suttrop, the ASDEX Upgrade Team
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Alberto Pesce, Antonio De Lorenzi, Marco Boldrin
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F. Crisanti, A. Cucchiaro, R. Albanese, G. Artaserse, M. Baruzzo, T. Bolzonella, G. Brolatti, G. Calabrò, F. Crescenzi, R. Coletti, P. Costa, A. della Corte, A. Di Zenobio, P. Frosi, D. Harting, L. Lauro Taroni, G. Maddaluno, D. Marcuzzi, F. Maviglia, L. Muzzi, et al.
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R.65 Computationally efficient SVM multi-class image recognition with confidence measures
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R.66 The thermal measurement system for the SPIDER beam source
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R.67 Determination of the pellet parameters by image processing methods
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R.69 The European contribution to the development of the ITER NB injector
Masiello A., G. Agarici, T. Bonicelli, M. Simon, J. Alonso, M. Bigi, D. Boilson, G. Chitarin, C. Day, P. Franzen, S. Hanke, B. Heinemann, R. Hemsworth, A. Luchetta, D. Marcuzzi, J. Milnes, T. Minea, R. Pasqualotto, N. Pomaro, G. Serianni, et al.
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Adriano Luchetta, Gabriele Manduchi, Antonio Barbalace, Anton Soppelsa, Cesare Taliercio
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R. Prokopowicz, B. Bienkowska, K. Drozdowicz, S. Jednorog, E. Kowalska-Strzeciwilk, A. Murari, S. Popovichev, K. Pytel, M. Scholz, A. Szydlowski, B. Syme, G. Tracz, JET-EFDA Contributors
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R.83 Monitoring the leakage of 3.0 and 14.7 MeV protons from a fusion plasma
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CONFERENCE PROCEEDINGS

2nd International Symposium on Lithium Applications for Fusion Devices, PPPL, Princeton, NJ, USA, 27-29 aprile 2011

P.1 P. Innocente: “Lithization on RFX-mod reversed field pinch experiment”, 2nd International Symposium on Lithium Applications for Fusion Devices, PPPL, Princeton, NJ, USA, 27-29 April 2011, proc. to be published in a special issue of a widely-circulated journal

Technical Meeting on Control, Data Acquisition and Remote Participation for Fusion Research, San Francisco CA. 20-24 June 2011, to be published in a special issue of “Fusion Engineering and Design” (FED)

P.2 Luchetta Adriano, G. Manduchi, C. Taliercio, A. Soppelsa, A. Barbalace, et al.: “Architecture of SPIDER control and data acquisition system” (oral), Technical Meeting on Control, Data Acquisition and Remote Participation for Fusion Research, San Francisco CA. 20-24 June 2011, to be published in a special issue of “Fusion Engineering and Design” (FED)

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P.5 Murari Andrea Latest Developments in Image Processing for the next Generation of Devices with a view on DEMO (oral), Technical Meeting on Control, Data Acquisition and Remote Participation for Fusion Research, San Francisco CA. 20-24 June 2011, to be published in a special issue of “Fusion Engineering and Design” (FED)

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P.9 Soppelsa Anton, G. Marchori, N. Marconato, P. Piovesan, F. Villione: “Modeling of spatial harmonic transfer functions and its application to the decoupling of the RFX-mod”, 38th EPS Conference on Plasma Physics, Strasbourg, 27/6-1/7-2011, ECA vol.35G P5.106

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P.29 Demuri Michela, M. Dalla Palma, D. Fasolo, R. Pasqualotto, N. Pomaro, A. Rizzolo, G. Serianni, M. Tollin: "Design and specifications of the diagnostics for the instrumented calorimeter of SPIDER", ICIS11 - 14th International Conference on Ion Sources, Giardini Naxos, Italy, 12-16 settembre 2011, proc. to be published in Review of Scientific Instrum.

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P.31 Chitarin Giuseppe, P. Agostinetti, N. Marconato, D. Marcuzzi, E. Sartori, G. Serianni, P. Sonato: "Concepts for the Magnetic Design of the MITICA Neutral Beam Test Facility Ion Accelerator"

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P.33 Zaccaria Pierluigi, P. Agostinetti, D. Marcuzzi, M. Pavei, N. Pilan, F. Spada, L. Trevisan: "Progress in the MITICA beam source design", ICIS11 - 14th International Conference on Ion Sources, Giardini Naxos, Italy, 12-16 settembre 2011, proc. to be published in Review of Scientific Instrum.

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P.39 Giudicotti Leonardo, Pasqualotto Roberto: "Characterization of fast microchannel plate photomultipliers for the ITER core LIDAR Thomson scattering", 15th International Symposium on Laser-Aided Plasma Diagnostics (LAPD-15), Jeju, Korea, 9-13 ottobre 2011, to be published on The Journal of instrumentation (JINST)

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COMMUNICATIONS AND PARTICIPATIONS TO CONFERENCES AND WORKSHOP

C.1 M. Agostini, A. Scaggion, P. Scarin, N. Vianello: "Role of the pressure gradient in the generation and evolution of the plasma edge turbulence in RFX-mod", TTF 2011: US Transport Task Force Workshop, San Diego, CA, 6-9 aprile 2011

C.2 M. Agostini, J.Terry, P. Scarin, S.Zweben: “Edge turbulence in different density regimes in Alcator C-mod” (oral), TTF 2011: US Transport Task Force Workshop, San Diego, CA, 6-9 aprile 2011

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C.7 Canton A., S. Dal Bello, P. Innocente: “Hydrogen Retention and Release in the RFX-mod Graphite First Wall”, abstract online, 13th PFMC Workshop / 1st FEMaS Conference, Rosenheim – Germany, 9-13 maggio 2011, to be published in Physica Scripta

C.8 M. Pavei, S. Dal Bello, H. Groenveld, D. Marcuzzi, P. Sonato, P. Zaccaria: “R&D activities for the production of 1,0 mm thick molybdenum armour layer on copper substrates”, abstract online, 13th PFMC Workshop / 1st FEMaS Conference, Rosenheim – Germany, 9-13 maggio 2011, to be published in Physica Scripta

C.9 P. Sonato: “La Neutral Beam Facility per ITER”, oral, XX Congresso Nazionale A.I.V. "Energia e materiali: Tecnologie a confronto e prospettive", Padova, Italy, 17-19 maggio 2011

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C.13 V. Cervaro, S. Dal Bello, M. Dalla Palma, M. De Muri, D.Fasolo, L. Franchin R. Pasqualotto, N. Pomaro, D. Ravarotto, A. Rizzolo, G. Serianni, M. Tollin: “STRIKE, the diagnostic calorimeter for SPIDER: design and dedicated diagnostics”, XX Congresso Nazionale A.I.V. "Energia e materiali: Tecnologie a confronto e prospettive", Padova, Italy, 17-19 maggio 2011

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4) P. Zanca, D. Terranova "Descrizione degli output delle routine di analisi toroidale", FC-NT-81, 18/08/2011;

5) P. Zanca "Effetto della costante di tempo della shell sul CMC del modo m=2 n=1", FC-NT-82, 08/09/2011;

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8) P. Franz "The horizontal manipulator dsx3 of the sxr tomography", FD-NT-79, 01/09/2011;

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28) Barbato P., Migliorato L. “Autenticazione forte basata su RSA SECURID”, SC-NT-105, 14/11/2011;

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