CONSORZIO RFX
Ricerca Formazione Innovazione

2010 Activity Report

SUMMARY

1. INTRODUCTION AND SUMMARY OF KEY RESULTS

A substantial advancement in the main research topics of the Consorzio RFX has been achieved during the year, in line with the objectives pointed out in the 2010 Activity Programme.

In fact, despite the persistent difficulties in the budget which resulted in delay of some investments foreseen in 2010, most activities foreseen in the year have been carried out with several significant results broadly recognized and appreciated by the international community, as proved by the scientific production, by the number of the contributions to international conferences and by the invited talks at major fusion conferences.

RFX-mod has operated according to the schedule and, after the long shut-down at the end of the year, restoration of the full toroidal field capability has been achieved. During the year, also the possibility of operating the device at its maximum design current value of 2 MA in a safe and reproducible way has been demonstrated.

Experiments in RFX-mod have allowed for the first time in an RFP to explore the properties of energy and particle confinement at currents above 1.5 MA, where SHAx states were frequently observed. A reliable and accurate control of toroidal field reversal and of the flat-top plasma current has been achieved with benefits in terms of pulse reproducibility and global efficiency in operation. The key open issue on density control has been tackled in 2010 with different approaches which involved recycling process control and plasma-wall interaction mitigation by accurate wall conditioning procedures, by optimization of the magnetic boundary and by lithisation with pellet injection and with insertion of the Liquid Lithium Limiter. First experimental results on the effectiveness of these different techniques have been obtained, which have oriented the next year program on this topic.

The implementation of the Test Facility for the development of Neutral Beam Injectors for ITER has substantially stepped forward thanks to the start of the first F4E procurement of components for the Padua facility, the start of the tender for buildings construction and the signature of the the Procurement Arrangement between ITER IO and F4E for all the equipment foreseen in the European contribution.

The NBI development activities have progressed under the F4E Grant GRT-032 stipulated two years ago and foreseen to close in March 2011. During this year the design of most of the SPIDER mechanical components has been completed; after the completion of the F4E tender for the procurement of the Source Power Supplies and the start of the work, RFX is involved in the follow-up of this contract. The MITICA design activity was continued in order to lay the bases for the completion of the tender specification in the next future. An other significant result of 2010 is the call for tender by F4E for the procurement of the PRIMA cooling system on the basis of the documents and specification developed by RFX. The building design has been completed and the call for tender for the Test Facility buildings is in progress. The negotiation for the definition of the roles and responsibilities among the main stakeholders of the NBI Test Facility is still ongoing, even if a common convergence for a quick conclusion of a framework agreement is handy. This document will be the basis for the implementation of a number of formal agreements and contracts between IO and F4E and between F4E and Consorzio RFX.

An other main line of the program, the Broader Approach contribution to the satellite tokamak JT60SA, which implies the "in kind" procurement of two power supply systems, has substantially stepped forward in 2010, since the tender was completed for the procurement of the most relevant package – the protection system of the superconducting magnets of the machine – and on 21st December the kick-off meeting with the supplier was held.

The collaboration with tokamaks and stellarators has been reinforced on key areas as MHD control, transport studies, first wall conditioning and impurity behaviour. The activity on MHD control has confirmed RFX as an important experiment with unique features to test control tools useful for ITER and the whole fusion community. Further collaboration with tokamak and stellarator took place in the field of beam-plasma interaction. The support to the FAST Project and the interaction with other international laboratories have been continued.

Progresses have been achieved also in the other research areas of Consorzio:

- In the ITER LIDAR Consortium, RFX has defined the available competencies and the share of responsibilities, in order to be prepared for the F4E calls;
- The ITER Integrated Tokamak Modelling activities were continued along the four identified research lines;
- The theory and modelling program has successfully tackled crucial issues in several areas and in particular: a) a better MHD simulation of RFP plasmas has been achieved with an extensive benchmark of advanced non-linear MHD codes, b) the assessment of the role of the q profile in SHAx states and c) the investigation of the role of the microturbolence in the ITB formation.

Diagnostic development was the program most severely affected by budget limitations, with the consequence of several projects stopped or postponed. Nevertheless significant achievements have been reached anyway, e.g. with improvements in the pellet system and the microwave reflectometer.

In the educational training activities, it is worthwhile to mention the start of the Goal Oriented Training program and the continuation of the other doctorates in which RFX is involved.

RFX has continued the progressive implementation of the Quality Management system, with a more precise identification of the relevant processes and of the operating procedures, in preparation to the ISO 9001 certification.

2. RFX-MOD AND RFP PHYSICS

2.1 Background: achievements and perspectives

As in the previous years, the 2010 experimental program has been built on the basis of a public call for experimental proposals, open to researchers both from Consorzio RFX and from external laboratories. About 100 proposals have been collected, processed and elaborated by four Task Forces. The resulting experimental program headlines have been discussed during the RFX-mod programme workshop (10-12 February 2010) before the beginning of the 2010 campaigns.

The experiments were distributed in 28 operation weeks. Maintenance and verification of the toroidal coil contacts, necessary after the failure in 2009, have been executed in 24 weeks of shut-down.

About 1200 plasma discharges have been executed in 2010, 450 of them with a plasma current exceeding 1.5 MA.

The main challenges envisaged for the 2010 scientific programme were:

a) exploring and optimizing RFP confinement in the high current helical regime, starting to develop a viable scenario for next generation of devices;
b) keeping the leadership in active MHD stability control, with further apertures and collaboration with the tokamak community, and
c) providing contributions on key fusion science and technology issues, in particular accessing parameter regions otherwise inaccessible to other magnetic configurations.

As to the first point, the operation at Ip >1.5 MA has been optimized and consolidated, confirming the positive temperature and confinement scaling laws with plasma current (electron temperatures up to 1.5 keV have been observed). The current level of 2MA (target value for RFX-mod) has been reached, though in still unoptimized conditions.

The reliable operation at high current was allowed by an improved control of recycling and plasma-wall interaction, achieved on the one hand by careful wall conditioning procedures (GDC sessions and wall boronisation), and on the other hand by the optimization of the magnetic boundary (point b). A significant part of the experimental campaign has been dedicated to test the effectiveness of lithization as a wall conditioning technique: this has been mainly accomplished by solid non-cryogenic Li pellet injection. Only a small amount of Li (< 1g totally) has been deposited onto the wall, but some positive effect on edge profiles has been already observed. First technical tests with a Liquid Lithium Limiter (LLL) have also been performed, in view of future campaigns with a larger amount of Li deposited on the wall.

The operation at Ip> 1.5MA allowed a significant extension of the database of electron Internal Transport Barriers; also at the highest current, a stiff electron temperature profile is not yet observed. Under some conditions dge electron transport barriers also develop, representing a promising regime in terms of confinement improvements: studies about their positioning and duration are part of the 2011 RFX programme.

As to point b), RFX confirmed its international leading role in physics and technology of feedback control of MHD stability. Further improvements in the resistive wall modes and tearing modes control have been obtained in RFP operation, together with a more precise error field control. The characterization of the influence of magnetic boundary (e.g. axisymmetric vs. helical, radial field at the wall) has been a significant part of the optimization effort, as well as a further optimization of the feedback control system necessary at the highest currents.

Fruitful collaborations with Tokamaks and Stellarators, continued and reinforced during 2010 (point c), allowed to share with these communities a number of tools useful for magnetic equilibrium reconstruction, neoclassical transport and stability calculations. Such effort allowed the benchmark of codes originally developed for different plasmas in a parameter space inaccessible for other configurations.

Finally, results on the physics of chaotic magnetic fields, turbulence, particle transport and density limit, provided significant contributions to the advancement of fusion science.

The results obtained in 2010 were awarded invited lectures in all major plasma physics conferences, and were reported in a number of seminars in various laboratories.

They open a large number of interesting perspectives for the next activities on RFX-mod: first of all the optimization of the 2MA RFP discharge with advanced wall conditioning techniques to control recycling. Thanks to the flexibility of the power supply and of the MHD control system, RFX-mod can be operated as a low current Tokamak, aiming at the active stabilization of the (m=2, n=1) mode: such operation is of great interest for the Tokamak community. At the same time, the synergetic collaboration with the stellarator world will be reinforced, extending the sharing of 3d numerical models and offering the possibility of extended code benchmarking.

2.2 Boundary conditions and operation

The main operation program schedule for the 2010 experimental campaigns of RFX-mod is shown in Fig. 2.2.1 and has been laid out to fit at best the following major technical and scientific requirements:

- The completion of the refurbishment for the toroidal field coil contacts on the low field side of the torus, which required a 3 month shutdown period.
- The power supply re-organization and commissioning to achieve the goal of routine operation of RFX-mod close to its maximum current capability.
- The extensive operation at Ip > 1.5 MA to further explore the RFP physics in the high plasma current regime
- The application of new wall treatment techniques, mainly using Lithium, in order to achieve better density control and plasma performance.

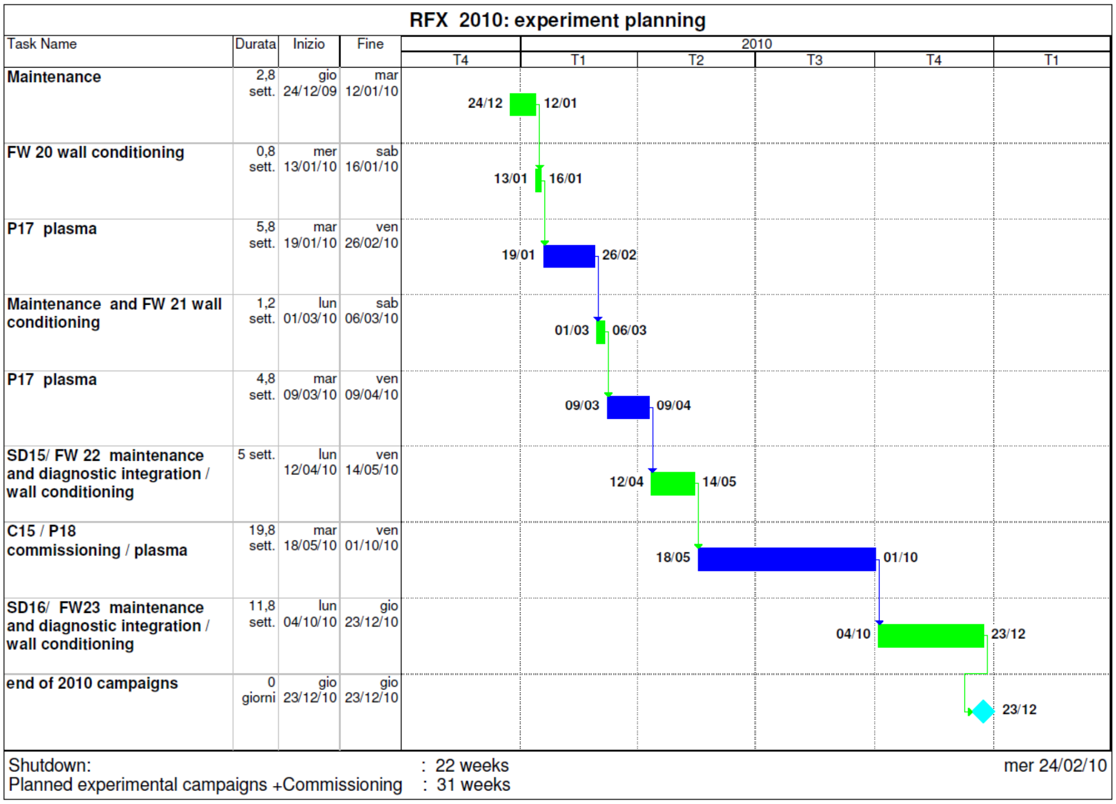

Fig.2.2.1: RFX-mod program schedule for 2010.

The scientific programme definition based on the scheme of open experimental proposals has been pursued, by participation through four thematic Task Forces:

- *MHD stability active control*
- *Density control and plasma-wall interaction*
- *Physics integration for high performance RFP*
- *Scenario optimization and development for present and future RFX operation*

At the annual programme workshop, 98 experimental proposals have been presented, involving, besides internal people, scientists from KTH Stockholm, MST-Madison, Kyoto Institute of Technology, IPP Garching, ENEA Frascati, IFP/CNR Milano, JT60SA, TJII-Madrid. It is worth to mention that even in the framework of the two main highly focused themes, more than half of the submitted proposals have received experimental time, in highly integrated environment.

On the operational side, the cooling system of the magnetizing winding has been improved, allowing continuous operation at high current, with more than 15 shots per day using the full available magnetizing current. Due to the heating of the magnetizing coils, the number of pulses was previously limited to four-six shots per day; in addition, the complete passive cooling required more than one day.

During the short shutdown in April and the following commissioning a strong effort has been devoted to the power supply reorganization and qualification for optimal operation of RFX-mod close to its maximum plasma current. The 12 modular AC/DC converters that feed the toroidal and poloidal field circuits have been reconfigured to make more energy available for the magnetizing windings driving the loop voltage. This modification allowed the extension of the initial current ramp-up and the achievement of 2 MA plasma current.

The work of power supply reconfiguration has been accompanied by the implementation and commissioning of new axial-symmetric real time feedback control algorithms for plasma current and F parameter (see sec. 2.4). During 2010 the 1.8 MA range database has been largely extended. About 30 plasma pulses reaching the RFX target value of 2 MA of plasma current have been performed, and Oscillating Field Current Drive (OFCD) experiments at current up to 1.7 MA as well.

The main focus of density control on the operational side has been on testing Lithium related techniques and on increasing the duration of boronisation sessions in order to deposit a larger and more uniform B layer on the plasma wall. At the same time, first experiments of plasma wall lithization by means of Li non cryogenic pellet injection and the installation and test of a Liquid Lithium Limiter (Li^3) on loan from ENEA/Frascati have been performed (see sec. 2.7).

2.3 High current operation

RFX-mod is in a unique position to test scaling of plasma performance with current and to explore RFP physics in the MA range. Actually, plasma current is a major control parameter for performance. Past experience indicated significant changes in RFX-mod plasma performance as plasma current was raised. The extension of the current operational range in 2010 showed that the central electron temperature increases with Ip up to values ≥1.5 keV (see Fig. 2.3.1) when the plasma current exceeds ≈1.7 MA. Increased electron heating translates in increased magnetic Lundquist number S, and the decrease of the amplitude of internally resonant tearing modes with increasing S has been confirmed in a broader S range.

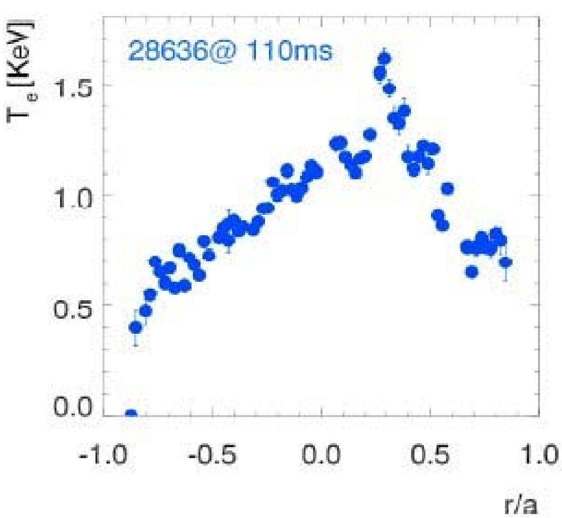

Fig.2.3.1:electron temperature profile at Ip=1.7MA

About six experimental weeks have been dedicated to high current operation, aimed at exploring the plasma currents toward the maximum RFX-mod design value of 2 MA.

A number of technical improvements allowed performing well controlled plasma discharges at plasma current Ip ≈ 1.8 MA and preliminary experiments at 2 MA. The latter, though far from being optimized, show no technical limit for operation at 2 MA and confirm the robustness of the device.

Previous high current experiments highlighted that the level of current required to the coils for active mode control was increasing with the plasma current, often reaching the saturation level of 300A. Consequently, the maximum available current of the active coils has been increased from 300 to 380A. The effect of such upgrade on MHD control has been checked by the RFXlocking code.

In RFX-mod, during the current ramp-up phase, the vertical magnetic field penetrates faster through the two poloidal gaps in the shell and reproducible field errors of few mT are observed, toroidally localized at the gap positions. Reference signals recorded in dry runs have been used for active correction in feed-forward mode. Such reference signals are computed with a dynamic decoupler which uses the frequency dependence of the coupling between actuators and sensors.

Adding to the pre-programmed error control the feedback for the main modes contributing to the error field (i.e. m=1, n=±2, n=±4, n=±6) a good and robust correction is achieved.

During this experimental campaign more than 100 good discharges at current ≥1.8 MA have been collected. An example of a current waveform is given in Fig. 2.3.2.

This campaign confirmed that the most critical issue for high current operation is presently the density control.

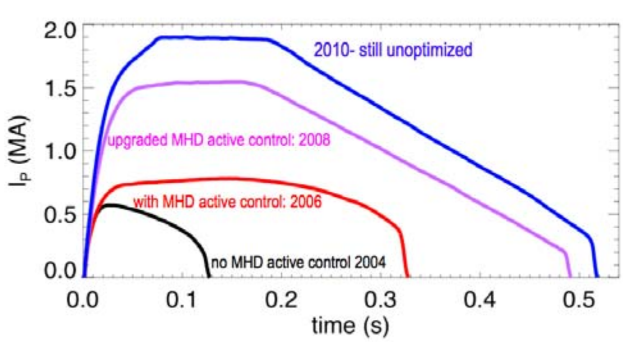

Fig.2.3.2: Plasma current waveforms obtained in RFX-mod after its restart.

During the high current experimental campaigns two wall treatments by boronization have been performed in order to lower wall recycling and to increase the number of shots performed between two successive glow discharge cleaning (GDC) sessions. In both cases a better density control has been obtained two weeks after the boronization. This fact has been interpreted as a marker of non-homogeneity of the deposited boron layer, which becomes more homogeneous due to the redeposition induced by the plasma itself (see section 2.7).

The analyses confirmed the increase of the plasma temperature with current as shown in Fig 2.3.3. The central temperature achieves values ≥ 1.5 keV at current above 1.7 MA.

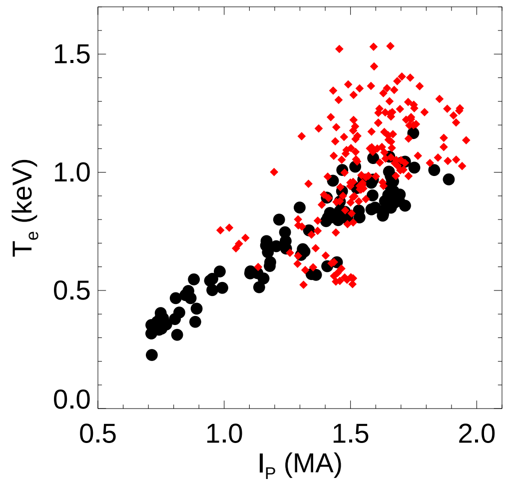

Fig.2.3.3: Electron temperature vs plasma current for two different ranges of n/ngw: [0.05,0.13] red diamonds,[0.14,021] black circles. Each point is the average during the flat top.

The temperature profiles measured by the Thomson Scattering diagnostic show the presence of Internal Transport Barriers associated to the Single Helical Axis States. Their observation is made more frequent thanks to a real-time trigger for TS implemented to fire the TS laser during the helical phase thus increasing the diagnostic capability of SHAx states.

In some discharges, very strong electron temperature gradients at the plasma edge (r/a≈0.8) have also been observed, identifying external transport barriers with a pedestal of up to 1 keV developing in few cm (sec.2.5.2)

2.4 Feedback control optimization

Reversal Parameter control

The best performance of RFX-mod is most likely to occur at shallow F (-0.05≤F<0). The main drawback is that whenever F gets positive the configuration becomes a paramagnetic pinch with very poor confinement. Thus only very small deviations of Bt(a) can be tolerated and a very precise and fast control system is mandatory.

To this end, a closed-loop control system of the F parameter has been implemented in RFX-mod on the basis of a model of the toroidal field system including the toroidal power supply circuit, with a description of the coupling with the plasma current and the local control of the power section [Barp10]. An example of the model accuracy is given in Fig.2.4.1, where the simulated F parameter is compared to the experimental curve in a case of open loop F control. The evolution is well reproduced apart from the fast oscillations due to the plasma reconnection events which are not included in the model. The applied reference is also plotted in the figure. In the closed loop control system the $F_r(t)$ parameter reference is transformed into an edge toroidal field reference $r(t)$ using the measured average toroidal field:

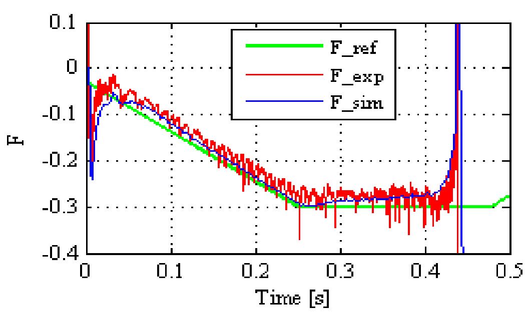

Fig.2.4.1: Comparison of simulated and experimental evolution of the F parameter in pulse 27747.

$$r(t) = F_r(t) < B_t > (t)$$

The toroidal winding current reference sent to the inverter local control system is obtained by summing a feedforward and a feedback component. The former is an evaluation of the toroidal winding current necessary to create the desired field after subtracting the estimated contribution of the vessel poloidal current, the latter is computed by a PID regulator which processes the edge toroidal field error signal, again estimated in real time by including the contribution of the vessel poloidal current. The closed loop system proved to be very effective in order to allow the shallow F operation of RFX-mod: discharges maintaining F=-0.02 have been reliably performed. In Fig. 2.4.2 a discharge driven by the new F controller (28515) is shown.

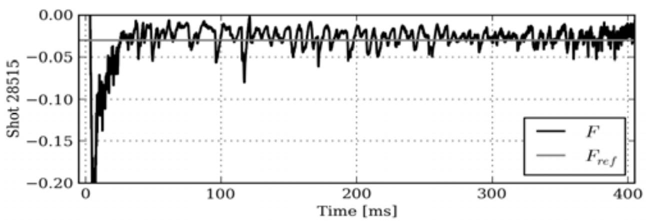

Fig.2.4.2: Example of closed loop control of the reversal parameter F.

Adaptive plasma current control

In addition to the revised version of the toroidal field control, the successful experience of many years with a full real time digital control system of the magnetic configuration and a much better knowledge of the plasma response suggested to resume the idea of the plasma current feedback control [Fiorentin1996] in order to improve pulse reproducibility and disturbance rejection. The flexibility of a digital control system has been fully exploited defining different control actions according to the discharge phase and the actual values of the plasma parameters.

The good tracking performances presently achievable can be appreciated in Fig. 2.4.3. The small oscillations before 200 ms are due to the control system reaction to a plasma resistance increase caused by electron density variation. The control system responds varying the applied voltage and the plasma current is recovered, showing the satisfactory capability to cope with parameter variations.

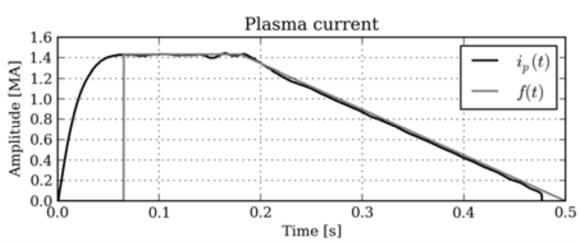

Fig.2.4.3: Plasma current controlled discharge (#28526). Start time is about 65 ms.

RWM studies: modeling and experimental results

Following the encouraging results obtained in 2009 when a full electromagnetic model of the RWM active control system was successfully validated in the case of a purely proportional regulator [Baruzzo09], further tests to assess its predictive capability were carried out implementing a PI controller.

The possibility of performing extensive, independent scans in only two parameters (Kp and Ki) seemed particularly suitable to start the study of a dynamic controller effect on the closed loop response along with a straightforward experimental benchmark.

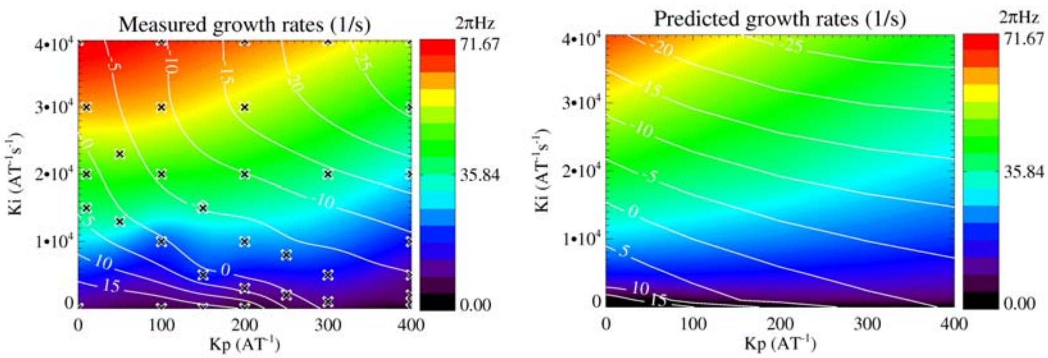

Fig.2.4.4: Measured and predicted growth rates and oscillation angular frequencies in the presence of PI regulator of m=1, n=-6 harmonic component.

The analyses were focused on the most important RWM in RFX-mod, which is related to the m=1, n=-6 harmonic component. The results are summarized in Fig. 2.4.4, where growth rates are represented by contour lines and oscillation angular frequencies are represented by colour shading. A fairly good agreement is observed for Kp>50 and Ki<30000, while further investigations are on going for larger Ki and lower Kp. In particular, the stability boundary, dividing the stable and unstable experiments, is correctly predicted by the model in the above mentioned range of parameters.

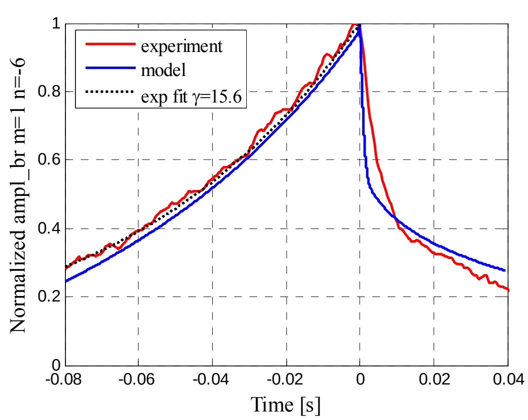

Fig.2.4.5: Kp=100 (subcritical gain) for t<0 s; Kp=800 for t>0 s.

First time domain simulations were also performed and the numerical results compared with the experimental ones after normalization with respect to the respective maximum values. In Fig. 2.4.5 the experimental evolution is correctly reproduced by the model in a shot where two proportional gains were used. RWM studies were also carried out on by potential energy analysis in a MHD cylindrical model, with the aim of understanding the role of F, Θ, β_p parameters on RWM instability. The effects of the controller proportional gain on the radial field profile have been investigated by introducing the feedback system in the boundary condition [Wang10].

Active MHD control under different coil configuration and mode rigidity studies

In any real device active coils are finite in dimension and number and often cover only partially the outer surface of the plasma, unavoidably producing unwanted magnetic field components which can be amplified by the plasma itself and seriously compromise the stabilization effect of the active system. Due to the obvious limitations on changing active coil hardware on the same machine, most of existing studies can only compare the effect of different coil configurations on different machines. On the contrary, the 192 active coil system of RFX-mod can be easily downgraded by its control software in number or space resolution. In this way it is possible for the first time to easily compare the action of many different coil configurations on the same machine and on the same plasma [Bolzonella10]. The real time control can act only on a subset of selected modes with the reduced set of coils, while all the remaining field errors and MHD instabilities are controlled with full system capabilities. Thus the problem of discharge optimization is decoupled from the study of a specific mode active control. In order to achieve this result, the modal current references of the harmonics that undergo "standard" control are separated from the ones that will be controlled by a "reconfigured" system. When the latter set is reconverted into 192 real space current references, it is then simple to mimic a control system with a smaller number of actuators by zeroing the corresponding references. The "standard" and "reconfigured" references are then summed and sent to each power supply. The first set of experiments was carried out in vacuum to compare the harmonic content of different coil configurations trying to follow the same control request. An example of the Fourier spectrum deterioration is presented in Fig. 2.4.6 where the requested waveform was a single, constant (1,-6) harmonic and the measured field was produced by a 8(φ)x1(ϑ) configuration. To test the effects on plasma under reproducible conditions, it was decided to apply the reconfiguration algorithm to the control of one or more unstable Resistive Wall Modes (RWMs). First results clearly indicate that unwanted sidebands can be very deleterious for MHD control. In Fig.2.4.7 an example is shown for the 12x1 configuration where, due to the specific mode periodicities, evenly spaced coils were not able to stabilize the mode: in fact

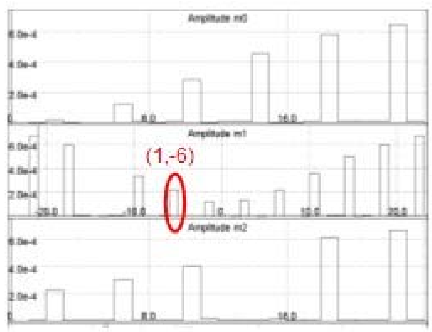

Fig.2.4.6: measured Br harmonics produced for a pure (1,-6) harmonic request in 8x1 configuration.

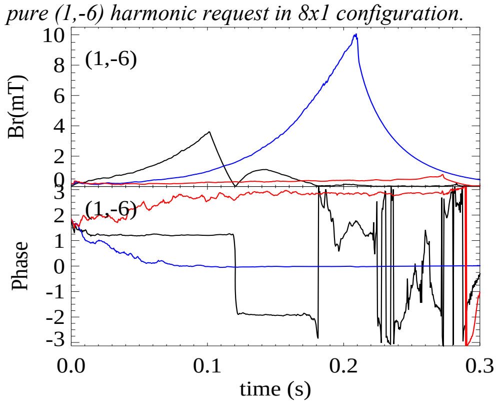

Fig. 2.4.7: control experiments with full system (black, control on from 0.1s) and downgraded 12 x 1 (blue for evenly spaced coils and red for unevenly spaced ones)

during the control the mode changed its phase in order to place amplitude nodes over the active control position (blue lines). Full control in this case was recovered without increasing the number of active coils, but simply by using an uneven coil distribution (red lines).

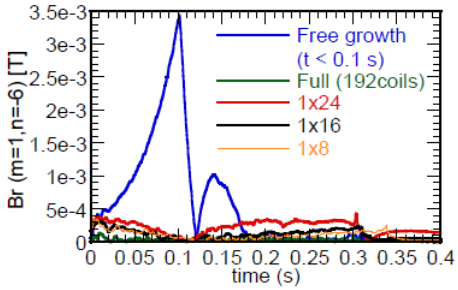

Fig.2.4.8: Time evolution of m=1,n=-6 RWM amplitude. RWMs are stabilized with only 8 coils.

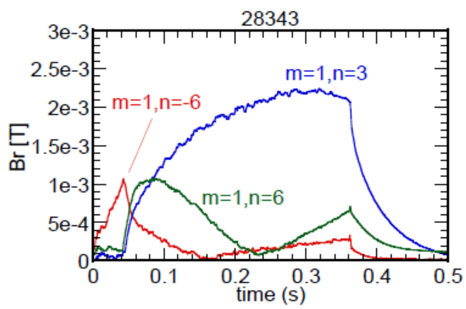

Fig.2.4.9: Time evolution of stabilized m=1,n=-6 RWM and m=1,n=3-6 sideband amplitude without stabilization of sideband modes.

Plasma experiments were performed in collaboration with JAEA with the explicit intention of supporting the design of the RWM control system for the JT-60SA new device, which aims at producing and sustaining high β_N AT plasmas [Takechi10]. The problem of mode-rigidity is very important for JT-60SA, because the coverage of plasma surface by coils is very small (6.8%). In Fig. 2.4.8 the temporal evolution of m=1,n=-6 RWM amplitude is shown for coil number decreasing from 192 to 8, which corresponds to a coil coverage from 100% to 4.2%. RWMs are stabilized with only eight coils without stabilization of some sideband modes. The harmful effect of sidebands modes appeared when the control was activated later in the discharge and the modes got too large. The destabilization of sideband mode, marginally stable without mode control was also observed. In Figure 2.4.9 stabilized m=1,n=-6 RWM and m=1,n=3, 6 sideband amplitudes are presented. The mode was stabilized with four coils in the poloidal direction and three coils in the toroidal direction. Usually, sideband mode amplitude decreases together with the stabilized mode because the active coil current decreases. However in this experimental campaign the m=1,n=3 mode was marginally stable and actually increased during the discharge, its growth being a clear exemplification of the so-called resonant field amplification (RFA), due in this case to a sideband generated field.

2.5 Transport and turbulence studies

2.5.1 Internal transport barriers

Internal Transport barrier (ITB) studies are crucial to understand the mechanisms behind the improved confinement regimes of a magnetically confined plasma. Internal transport barriers have been observed in all the magnetic configurations, Tokamaks, Stellarators and RFP, and their effect is a significant reduction of thermal and/or particle diffusivity.

In RFX-mod electron internal transport barriers are evident at high current, when the plasma accesses the helical equilibrium. In such regime, as shown in Fig.2.5.1a, the equilibrium is governed by the geometry of one single saturated tearing mode (the dominant mode), which grows while the secondary modes maintain a very low amplitude. In correspondence of the ITB, electron temperatures as high as 1.5 keV in the plasma core, with very strong gradients have been measured, featuring a minimum of the thermal conductivity (an example is given in Fig 2.5.1b).[Cappello00, Valisa08, Lorenzini09, Puiatti09, Martin09].

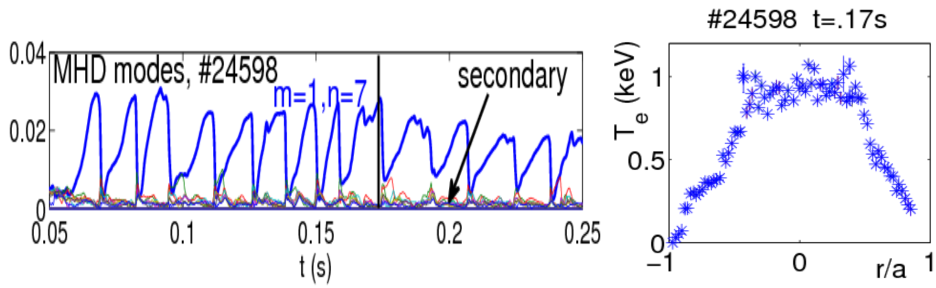

Fig. 2.5.1: (a) time evolution of m=1 MHD mode amplitude. (b) Electron temperature profile from Thomson scattering at the time marked by a vertical black line in (a)

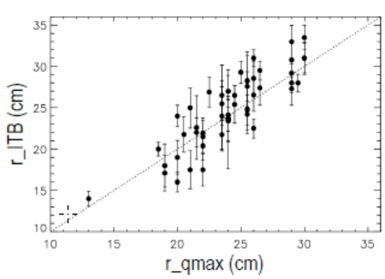

Fig. 2.5.2 Radial location of the ITB foot vs. the q shear null point.

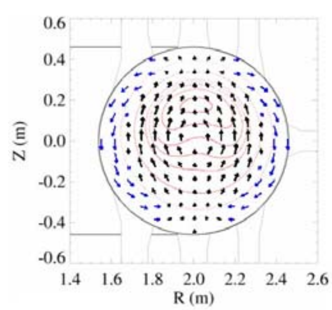

Fig. 2.5.3 Reconstruction of the poloidal flow pattern from passive spectroscopy

ITBs are always associated to a point of null shear in the q profile [Gobbin10b], well correlated with the barrier foot (fig. 2.5.2), which in the case of the RFP is a maximum of q. Simulations by the 3-D MHD code Specyl show that such point of null q shear is intrinsically associated to the helical topology of the new equilibrium and, in addition, the generation of the dynamo field necessary to sustain the configuration is accompanied by a flow field characterized by a strong shear in the poloidal component. The poloidal flow pattern has been experimentally reconstructed by means of passive spectroscopic flow measurements coupled to an impurity transport code estimating the ion impurity localization (Fig. 2.5.3). The flow reconstruction in Fig. 2.5.3 does indeed show an inversion of the flow internal to the field reversal surface though the space resolution of such measurements is not sufficient to precisely localize the region with the strongest gradient with respect to the position of the q shear null.

The heat diffusivity χ, evaluated by a power balance equation with the helical 3D magnetic equilibrium as an input decreases to values in the range 5-10 m^2/s in the barrier region. An example is given in fig. 2.5.4. In fig. 2.5.5 the minimum χ value is plotted as a function of the secondary mode amplitude for a number of discharges: the lowest χ_{min} are obtained for the lowest mode amplitude. The lowest values of χ_{min} are still higher than the thermal diffusivities observed in Tokamaks and stellarators in the presence of an ITB. Residual magnetic chaos is believed to contribute to such diffusivity.

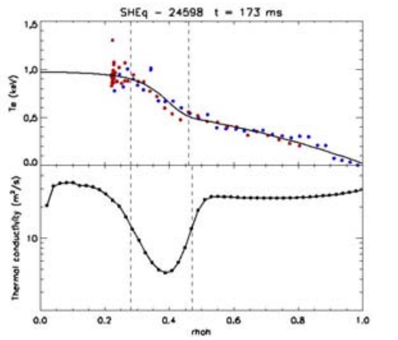

Fig. 2.5.4 Example of electron temperature profile (top) and corresponding thermal diffusivity from power balance (bottom). The radial coordinate is the helical flux

In addition, gyrokinetic calculations show that a candidate process that might limit the temperature gradient is the micro-tearing instabilities that appear as the dominant micro-turbulence mechanism acting on the ion Larmor radius scale. In the T_e gradient region micro-tearing modes are unstable and the quasi-linear estimate of the electron thermal conductivity related to such modes, $\chi \approx 5 \div 20$ m^2/s, is in the range of the experimental values [Predebon10].

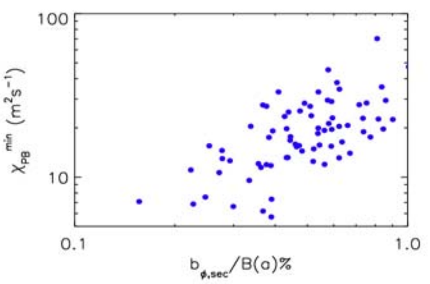

Fig. 2.5.5 Minimum χ at the barrier vs secondary mode amplitude

Inside the barrier the particle confinement is increased: the hydrogen diffusivity, experimentally evaluated by reproducing the density profile evolution, decreases to values of ≈ 5 m^2/s. As to impurities, laser blow-off injection experiments have shown that, due to a strong outward convection around the ITB location, they do not penetrate the hot structure [Menmuir10]. The favorable situation therefore is reached in which, besides the presence of a thermal barrier, the electron density in the core may be refurbished via pellet injection while impurities remain confined in the external region.

2.5.2 Edge transport barriers

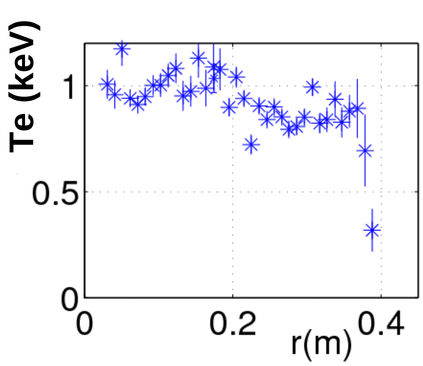

Fig.2.5.6: Example of external electron transport barrier

A barrier for the electron heat flux has been observed to develop more externally with respect to the eITB, around r/a=0.8, inside the field reversal radius, and not necessarily contextual with the ITB. An example is given in Fig. 2.5.6. Such external barriers (ETBs) are characterized by very strong T_e gradients that may reach values of 80-100 keV/m. They correspond also to a pressure barrier, where however the dominant contribution derives from the temperature gradient. While the internal barrier is clearly associated to the onset of a Single Helicity equilibrium, the external barriers do not appear to depend on a bifurcation step of the MHD dynamics. The ETB's develop in regimes where the secondary modes are relatively low, at low collisionality and are favoured by regimes of shallow reversal. Fig 2.5.7 (left) shows the relationship between edge ∇T_e and the density normalized to the Greenwald density. The strongest barriers with $\nabla T_e > 50$ keV/m and $L_{Te} < 2$cm appear below n/n_G=0.15.

This range is presently more limited than that for the development of internal transport

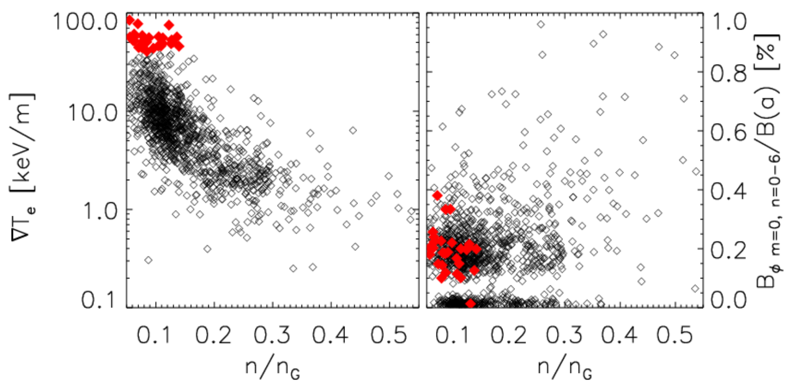

Fig.2.5.7:. Te gradient (left) and secondary m=0 mode amplitude versus the Greenwald fraction. Red diamonds correspond to ETBs.

barriers at high current, which are observed up to $n/n_G \approx 0.3$, and is not related to a dependence on density of the secondary mode amplitude (fig. 2.5.7, right). Fig. 2.5.8 shows that the strong edge gradients develop for a large interval of the central electron temperature and are therefore uncorrelated with the processes occurring in the center.

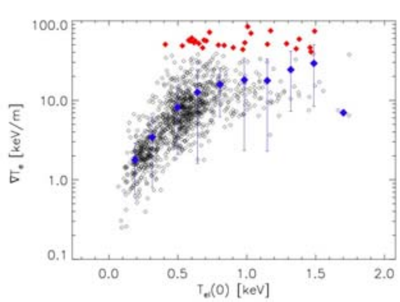

Fig.2.5.8: Edge Te gradient versus the central electron temperature; red points correspond to ETBs

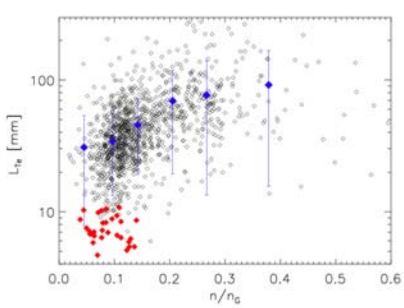

Fig.2.5.9: Edge Te characteristic length as a function of the Greenwald fraction

The pattern of the MHD perturbations has been reconstructed by means of the FLiT field line tracing code [Innocente07], showing that, in the presence of a strong barrier, the volume of the plasma characterized by short magnetic connection lengths is smaller. The barrier develops around r=38 cm, where, according to the FLiT reconstruction, ordered magnetic surfaces start to show up out of the chaotic region at inner radii. Likely, the strength of the barrier reflects the local reduction of magnetic chaos. The onset of the ETB typically increases confinement by about 20% with respect to standard plasmas with similar density, and the electron heat diffusivity in the barrier region decreases to values as low as 6 – 10 m^2s^{-1}, of the same order as in the ITB cases.

The edge T_e characteristic length, L_{Te}, associated to the ETBs appears to hit a lower limit; Fig. 2.5.9 shows L_{Te} as a function of the Greenwald fraction.

This fact is a matter of current investigation. The fact that ETBs are also pressure barriers does not justify any premature attempt to compare them with the H-mode of Tokamaks or Stellarators. Even if the role of the X-point physics in the Tokamak H mode and of the analogous island divertor in the Stellarator could be somehow played by the X-points of the m=0 island chain at the edge of RFX-mod [Martines10], there remain a variety of complex dependences of the L-H transition on power input, density, magnetic field as well as scrape off and target electron temperatures where analogies and differences should be investigated in detail. Certainly the existence of a significant transport barrier at the edge of RFX is an important finding that expands the possibilities of operating improved confinement regimes in the RFPs.

2.5.3 Turbulence and edge momentum transport studies

The analysis of the external region of RFX-mod has been intensively carried out in 2010, focusing on its characterization in high-current helical regimes. Indeed equilibrium reconstruction during helically-shaped high-performance discharges has revealed that a quasi symmetric boundary surrounds the helical core exhibiting a small residual ripple which nevertheless influences much of the properties of the external region.

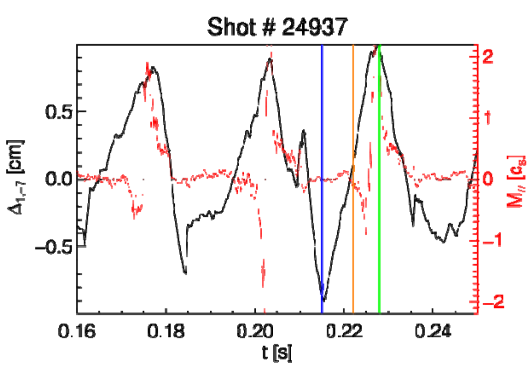

Fig.2.5.10: Time evolution of parallel mach number (red line) at the edge compared with the local shift of the dominant mode. Vertical lines indicates the time istant of maximum (blue), intermediate(yellow) and minimum(green) distance of island O-point.

The first experimental observation of the influence of helical core at the edge has been obtained by monitoring parallel and perpendicular flow at the boundary, as measured by the Gundestrup probe [DeMasi10] at fixed radial position r/a=1 (Fig 2.5.10). In this plot the time evolution of the parallel Mach number (obtained with a constant value of edge electron temperature) is compared with the local radial shift induced by the dominant mode $\Delta_{1,-7}$. The helical structures rotate toroidally, and this causes periodic oscillations of Δ. These oscillations can be interpreted as different poloidal position of the helical island with respect to the measurement point, with positive value of the shift meaning that the magnetic perturbation radially approaches the probe. Around the maximum value of the shift an abrupt change of the parallel flow sign is observed. This observation is consistent with the presence of a sheared poloidal velocity surrounding the helical core [Spolaore10]. Different methods have been adopted to infer the behavior of the toroidal flow at the edge. In particular the use of the toroidal distributed array of floating potential measurements belonging to the ISIS system, and the use of the Wavelet Time Delay technique has allowed the evaluation of the toroidal path of the toroidal velocity oscillations.

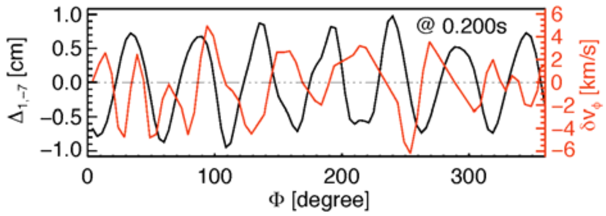

Fig 2.5.11: Fluctuation of toroidal velocity as measured by ISIS system, compared with local estimate of horizontal shift induced by the dominant mode

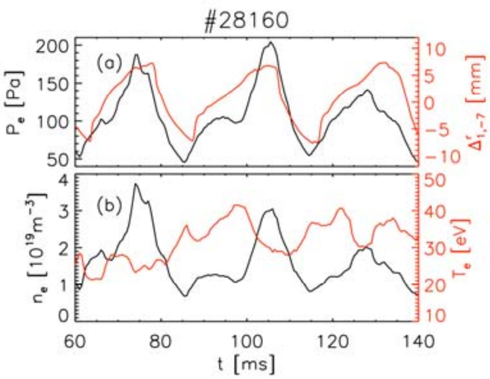

Fig 2.5.12(a) Electron pressure as a function of time compared with local horizontal shift (b) Electron density and temperature compared with local horizontal shift.

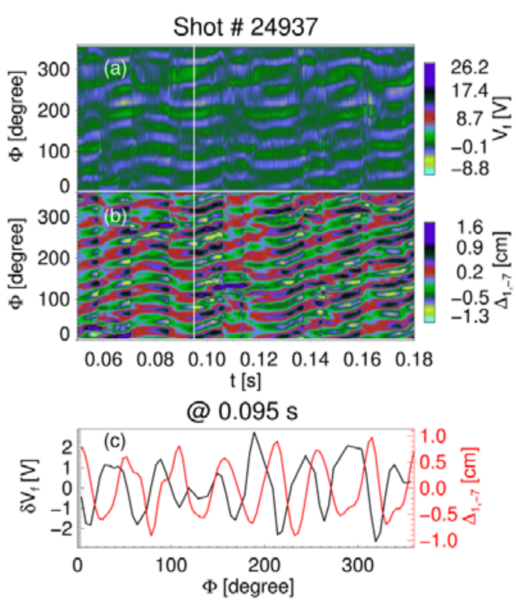

Fig.2.5.13(a) Floating potential as a function of time and toroidal angle. (b) Horizontal shift induced by the dominant mode as a function of time and toroidal angle. (c) Comparison between floating potential and horizontal shift as a function of toroidal angle

These fluctuations are shown in figure 2.5.11 as a function of the toroidal angle at a fixed time for the same shot of Fig. 2.5.10 together with the values of $\Delta_{1,-7}$ displacement: a good correlation exists, with the minimum of the velocity corresponding to the maximum extrusion induced by the dominant mode. These oscillations have been confirmed also by local observations coming from the GPI system and the Gundestrup probe, and all this information, combined with the aforementioned oscillation of the parallel component, suggests the existence of a helical flow associated to the dominant mode at the edge.

The helical ripple induced by the dominant mode is found to modulate all the plasma behavior at the edge. This can be observed for example by considering the time oscillation of the electron pressure as measured by the Thermal Helium Beam diagnostic (Fig 2.5.12), which is correlated with the local measurement of the horizontal shift $\Delta_{1,-7}$. Furthermore, the oscillation is mainly induced by electron density, whereas a slight decrease of electron temperature is observed in correspondence to the maximum of the shift. The same modulation is observed on the floating potential V_f (Fig. 2.5.13) as measured by ISIS. The time evolution of the toroidal pattern of V_f is shown in panel (a) of fig 2.5.13 together with the pattern of $\Delta_{1,-7}$ exhibiting a strong correlation between the two components. In panel (c) of the same figure the two quantities are compared as a function of the toroidal angle for a fixed time, showing how the strongest negative values of V_f correspond to the maximum horizontal shift.

This can be explained as an enhancement of electron diffusion corresponding to positive value of $\Delta_{1,-7}$, consistent with the observed reduction of electron characteristic length $L_{||}$ [Spizzo10]. Concerning blobs and turbulent structures, the upgrade of the Thermal Helium Beam (THB) diagnostic allows a detailed characterization of the plasma edge blobs and their role on the particle transport. It has been shown that the blobs are positive structures of density and pressure, with a radial extension, for discharges with plasma current larger than 1.5 MA, of about 10 ρ_s, where ρ_s, is the ion sound radius; moreover, they are associated to a valley in the electron temperature [Agostini10]. By measuring the electron density fluctuations associated with the blobs, it is possible to estimate the particle flux toward the wall due to these edge structures. In figure 2.5.14 the particle out-flux due to the blobs for standard discharges (black) and for lithizated wall (red) is shown, with both positive (dotted line) and negative (continuous line) plasma local displacement Δ, as a function of the blobs amplitude [Scarin10]. This is the first estimate of particle flux due to the edge turbulence made for high plasma discharges (Ip>1.5MA). From the graph, it is clear that the lithization of the first wall results in a reduction of the particle transport due to edge structures; moreover the blob outflux is almost insensitive to the local magnetic topology (positive or negative magnetic shift Δ).

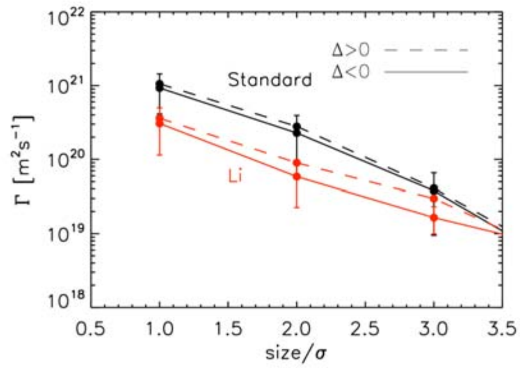

Fig 2.5.14: Particle outflux due to edge blobs as a function of blob amplitude. Continuous line: negative plasma displacement. Dotted line: positive plasma displacement. Red point are referred to lithizited discharges

2.5.4 High density limit

New detailed analyses have significantly improved the understanding of the processes that develop at the boundary of the RFX-mod plasma and of the way they affect the overall confinement when increasing density [Scarin10, Spizzo10]. An upper critical density threshold $n_C \approx 0.4n_G$ (n_G Greenwald density) is seen to limit the operational space for the onset of the improved Quasi Single Helical (QSH) regime: magnetic topology reconstructions and diagnostic observations point at explaining this limit as due to helical plasma wall interaction (PWI) in combination with toroidally localized edge density accumulation and cooling. At densities close to the Greenwald density, $n \approx n_G$, poloidally symmetric and toroidally and radially localized density accumulation and radiation condensation are observed, together with a fast resistive decay of the plasma current, which becomes the real operative limit of the device [Spizzo10]. Advanced wall-conditioning and plasma-fuelling techniques (such as wall lithization and pellet injection) are expected to provide effective means for overcoming these limits.

The experimental evidence is provided by a detailed reconstruction of the magnetic topology, the space and time resolved pattern of the floating potential measured at the wall by a toroidally distributed array of electrostatic probes, the plasma shift induced by the dominant (m=1,n=-7) toroidal MHD mode, the electron pressure profiles measured by a Thermal Helium Beam (THB) diagnostic and the toroidal plasma flow obtained by a Gas Puffing Imaging (GPI) system [Agostini09]. The latter provides also a time resolved imaging of the turbulence, while the former yields, on the same region (the outermost 35mm of the plasma) the radial profiles of electron density and temperature and therefore the pressure profiles.

In this analysis a central role is assumed by the edge radial electric field $E_r \approx v_\phi \bullet B_\theta$, which is experimentally evaluated from the measurements of the toroidal flow $v\phi$. Numerical estimate of E_r is provided by the Hamiltonian guiding centre code ORBIT [White84]. The code follows both the electron and ion dynamics in a layer close to the wall and evaluates the radial ambipolar electric field from the balance of the two fluxes, the latter being influenced by wall recycling (particle source). The structure of the radial electric field depends on the way the electron diffusivity is modulated by the magnetic pattern, which is made of a chain of m=0,n=7 islands (QSH case), or m=0,n=1 (density limit discharges) [Spizzo06]. The electron diffusion in fact is lower in the X-points than in the O-points of such islands, while ions have comparatively larger drifts (due to their larger mass) and their radial motion is more uniform along the toroidal angle. The X-points are therefore regions where localized particle accumulation likely develops and they form a divertor–like configuration [Martines10]. The phenomenon of density accumulation in the X-points sets an important analogy with the Tokamak density limit, where the critical density for the onset of the Multifaceted asymmetric radiation from the edge (MARFE) depends on the parallel connection length $L_{||}$ as $n_{cr} = \sqrt{\kappa_{\parallel} / 20 D_{\perp} L_{\parallel} \sigma_{at}}$ (larger connection length, smaller critical density [Tokar99]). The formula for the critical density envisages also a way to dodge the density limit, namely increasing the input power, a way which has been demonstrated e.g. in TEXTOR [DeVries98].

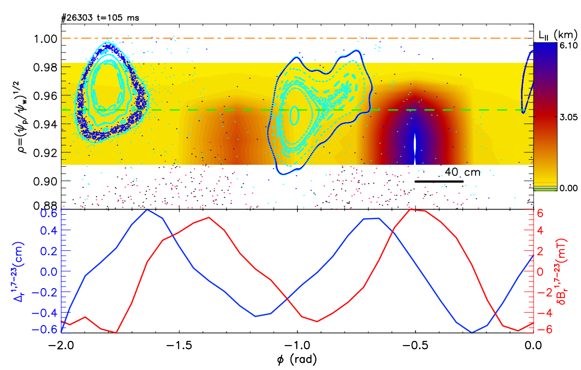

Fig.2.5.15: (top) Edge Poincarè plot (at θ=0°) of the (0,7) island chain and parallel electron connection length $L_{||}$ (contour plot); (bottom) toroidal behavior of the shift of dominant mode (blue) and of corresponding radial magnetic field (red)

Fig.2.5.15 (top panel) shows a toroidal Poincaré plot of the magnetic structure with the (m=0, n=7) islands together with the contour map of the electron parallel connection length $L_{||}$ (r,ϕ). The latter represents the length of the electron path to the wall from their initial position. In the bottom panel of Fig.2.5.15 the shift of the dominant (m=1, n=-7) mode and the corresponding radial magnetic field are also shown as a function of the toroidal angle ϕ. The maximum of the radial shift falls between the O- and X-points of the islands, whereas the maximum radial magnetic field corresponds to the X-points, due to the phase relation between the m=1, n=-7 mode and its m=0 counterpart. The time modulation of the local shift and of the corresponding local electron pressure is in phase (Fig.2.5.16), indicating a toroidally modulated electron pressure: the maximum pressure values correspond to the outwards magnetic shift. The ratio between the maximum and minimum values of the local edge electron pressure as well as the ratio of the corresponding particle out-fluxes estimated from turbulence measurements (local formation rate, density and width of the blobs) increase with plasma current. It has also been pointed out that the edge m=0 islands influence parallel and perpendicular flow [Spolaore09] enhancing the parallel component in the centre of the islands and the shear of the perpendicular one at their boundary. In QSH regimes the toroidal modulation of electron pressure, floating potential and plasma shift of dominant mode are mainly determined by a helical PWI, with a source term localized where the radial shift of dominant mode is outwards and a (possible) stagnation point at the m=0 island X-points exists. Moreover, the helical interaction in QSH increases with plasma current. The mechanism of source and stagnation points is the key mechanism of the density limit at $n \approx n_G$, and an analog driven by the (0,7) islands could govern the back-transition from QSH to the multi-helical (MH) state at $n_C \approx 0.4 n_G$.

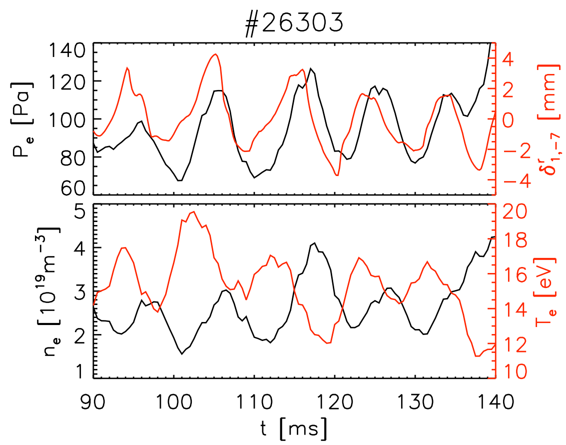

Fig.2.5.16: (top) Local time behavior of electron pressure (black) at r/a=0.97, compared with the local plasma shift due to the dominant mode (red); (bottom) time behavior of electron density (black) and temperature (red).

The possibility to increase n_C with proper wall conditioning (e.g. lithization) is an open issue, and it would be likely to decouple the magnetic pattern from the in-fluxes from the wall. In fact, in the present RFX-mod wall condition, neutrals are released more or less in the same toroidal and/or poloidal location where the ions are preferably lost from the plasma, in such a way that the recycling pattern reproduces the magnetic pattern of O- and X-points. It is worth mentioning that in TEXTOR the MARFE disappeared by applying a 1 kHz ac magnetic perturbation with the DED, while it appeared again in the case of fixed X-points (dc operation): this fact was explained in terms of rotation frequency of the DED X-points, which in the ac case was larger than the neutral desorption rate from the wall, allowing for smoothing the recycling pattern at the wall [Liang05].

2.6 3D physics

Equilibrium reconstruction and match to experimental data

The equilibrium of helical states for RFX-mod is generally described with the SHEq code [Momo10] that is based and linked to experimental measurements through the NCT code [Zanca04]. This approach is based on a perturbative analysis with some assumptions and limitations both on the background unperturbed equilibrium and the matching to experimental data. An alternative and complementary approach was considered by porting the stellarator code VMEC [Hirshman83] to the RFP configuration. This is a non-linear spectral code that is widely used in the stellarator community and has been extensively used also for RFX-mod during this year in strict collaboration with colleagues from ORNL and PPPL.

Besides the different approach in solving the force balance equation and different input assumptions (parallel current density (σ) profile for SHEq and safety factor (q) profile for VMEC), the two codes can take into account different physics aspects as, for example, the role of pressure that is neglected in SHEq and can be considered in VMEC, and the matching to experimental data. The latter aspect is embedded (though with some approximations) in SHEq as the equilibrium solver code NCT was specifically developed for the RFP configuration (with some assumptions on σ parametrization) and the RFX-mod magnetic diagnostics layout. In the case of VMEC, on the other hand, the free-boundary approach would be the best option. However, as this is not yet a viable solution for the case of the RFP, a different approach was considered based on the fixed-boundary solution by trying to determine suitable boundary conditions (LCFS shape) and q profile (presently obtained from SHEq through the algorithm described in section 5.3) in order to match experimental data.

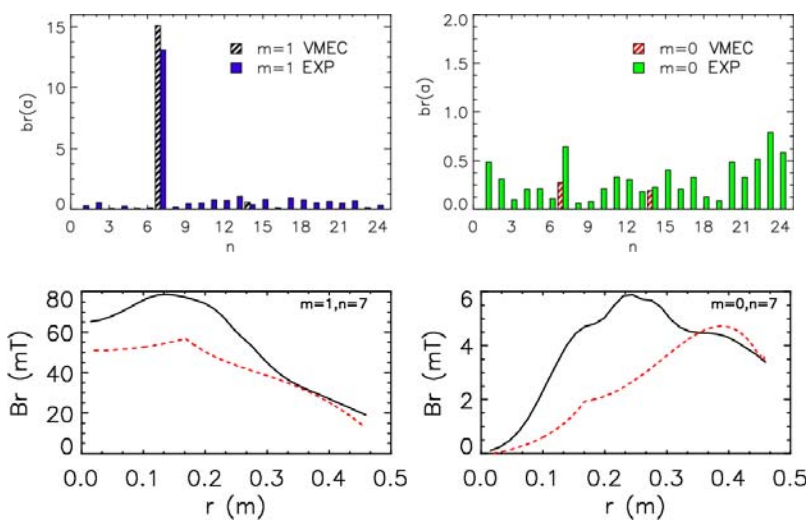

Fig.2.6.1: Top: comparison between magnetic fluctuations spectra from experimental data and from VMEC. Bottom: radial profile of the radial component of the magnetic field used in SHEq (red-dashed) and from VMEC (black-continuous).

In figure 2.6.1 we show a comparison between experimental data and the corresponding quantities as reconstructed from VMEC (by means of the Extender code) [Terranova10]:

magnetic spectra for the radial component show a good correspondence both for m=1 and m=0 modes (top panels). Also the eigenfunctions profiles (bottom panels) - that are the basic ingredient for the SHEq code - compare well considering that the two codes have different approaches in solving the force-balance equation. The perturbative approach assumes a thin current density layer concentrated around the resonance of the mode in the axisymmetric background field, so that a cusp appears in the profile. This is not the case for VMEC where only a diffuse current density can be modeled and the profile is therefore smooth. VMEC results can possibly be improved by removing the requirement of determining the q profile by SHEq, so that a self-consistent solution is obtained. To this end a minimization algorithm is being developed based on the comparison between experimental data and the corresponding VMEC-calculated quantities (e.g. magnetic fluctuations measurements, flux loop measurements, etc.) considering a general parametrization of the safety factor profile [Marrelli10].

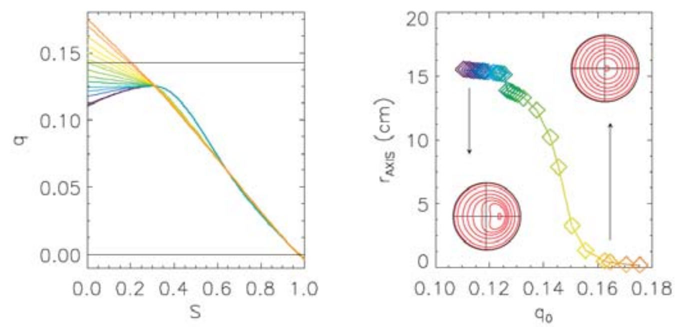

Fig.2.6.2: Scan of the q profile changing the value on axis q_0 (left) and corresponding position of the helical axis as function of q_0 (right).

This parametrization allowed us to start addressing the issue of the sensitivity of helical equilibria to the q profile. An example is shown in figure 2.6.2, where by changing the value of q on axis (q_0, left panel) one can move from a configuration with monotonic q to one with reversed shear corresponding respectively to a transition from an axi-symmetric configuration to a helical one (right panel).

The determination of suitable helical equilibria allowed us a correct interpretation of experimental temperature and density profiles by a correct mapping of the quantities on magnetic flux surfaces. This means that suitable flux coordinates are determined and their link to geometrical coordinates is required so that a corresponding metric tensor can be calculated. These quantities are necessary to address stability and transport at different approximation levels (fully 3D or reducing the analysis by flux-surface averaging) but still retaining the important information on the 3D nature of the configuration. Such information is already provided by VMEC and used in both stability and transport codes that are linked to it. On the other hand, suitable flux coordinates had to be determined in the case of SHEq and an extensive work was dedicated to this issue. The possibility to compute flux surface averages allowed to interface both SHEq and VMEC to the ASTRA code.

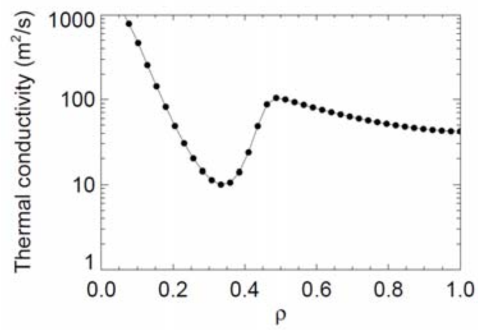

Fig.2.6.3: Thermal conductivity profile computed from the surface-averaged power balance (#22182 at 49 ms).

A similar procedure allowed the evaluation of the average ohmic power, $<\eta J^2>$, and thermal conductivity $<\chi>$ with the assumption of stationary conditions, the Spitzer-Härm resistivity formula (with the experimental T_e profile), a uniform effective charge profile (determined comparing the dissipated power to the actual input power). In figure 2.6.3 we show an example obtained by SHEq. It can be seen that the thermal conductivity displays a minimum, at a value around 10 m²/s, corresponding to the strong gradient in the temperature profile (see sec. 2.5.1). This is an order of magnitude lower than values obtained in Multiple Helicity conditions, when the core transport is dominated by magnetic chaos.

In the RFP the helical state is reached by a self-organization process where plasma current plays a significant role and in particular is the only heating source, so that the natural question arises whether the resulting equilibrium is consistent with Ohm's law that in a simplified version, considering flux surface averages can be written as $\frac{1}{2\pi}V_t\left\langle B^{\phi}\right\rangle = \eta\left\langle J \cdot B\right\rangle$.

This relation has been calculated for both SHEq and VMEC equilibria and in both cases the resulting equilibrium does not comply with Ohm's law: the two terms do not match and though in the core this could be in some way corrected, this is particularly true at the edge where only the left-hand-side reverses sign.

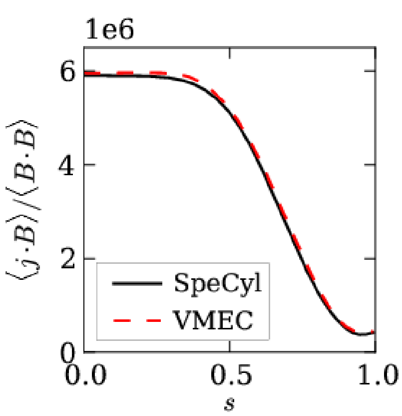

Fig.2.6.4: SpeCyl and VMEC parallel current density profiles for an ohmic helical equilibrium.

In the case of SHEq one is led to the conclusion that possibly the modelization of σ (the basic input profile for the determination of the equilibrium) is probably not appropriate requiring either to assume a profile of σ changing sign at the edge, or a residual dynamo contribution of the secondary modes that cannot be modeled with the approach of the NCT code. These considerations point to the need of performing equilibrium calculations which take into account the Ohmic constraint. The same result is true for VMEC. It is expected that the agreement can improve once a self-consistent treatment of the q profile is fully addressed.

In order to verify whether the discrepancy could be solved with different input constraints, VMEC was run providing as input the q profile from an ohmic-helical equilibrium determined with the cylindrical MHD visco-resistive SpeCyl code. As can be seen in figure 2.6.4 running

VMEC on a SpeCyl force-free equilibrium (with a uniform resistivity profile) the agreement is very good [Terranova10]: the parallel current density profile calculated by VMEC (using SpeCyl q profile) and that of SpeCyl are basically the same. This result proves that the issue of a helical ohmic equilibrium for both VMEC and SHEq is essentially linked to an adequate determination of the input data and constraints.

Stability

Helical states observed in RFX-mod last for several energy confinement times, but temporary back transitions through reconnection events are experimentally observed and lead to a more chaotic, lower confinement state [Lorenzini09]. This at the moment prevents the helical equilibrium from being fully stationary and a first stability analysis has been implemented to address the issue. As a full 3D analysis (already in cylindrical geometry) would be highly demanding (from the numerical point of view) we started from an ideal linear stability calculation by means of the Terpsichore code [Cooper06], looking for periodicity breaking modes, i.e. modes that have a helicity close to the one corresponding to the dominant mode. Considering kink instabilities driven by parallel current, it has been found that the helical states with monotonic q profile are significantly more unstable than the case with reversed shear. The periodicity breaking modes found are mainly the m=1,n=8 coupled with the m=2,n=15 components. As a direct extension of these results, a parametric study is foreseen to assess the role of the reversed shear region and of the resonances (also double resonances in the case of reversed magnetic shear) associated to the instability of periodicity breaking modes. At the same time this result shows the criticality of the q profile and the need of the optimization procedure described above, that will allow a more comprehensive determination of the experimental helical equilibrium.

Neoclassical effects on transport

3D fields significantly affect magnetic topology, but also play an important role in determining transport. Low confinement, globally axi-symmetric states, characterized by the simultaneous presence of many resonant modes are in fact dominated by chaotic transport, but not far above the stochastic threshold. The resulting transport in the helical region is subdiffusive and cannot be described by Rechester-Rosenbluth diffusion: trapped particles (which plague un-optimized Stellarators at low collisionality) can be present and neoclassical effect should be taken into account. At a basic level particle trapping was investigated by looking at the magnetic field ripple [Mynick06]. In figure 2.6.5 we show the ripple along a magnetic field line over a surface in the core (blue) and at the edge (red) as obtained from a VMEC helical equilibrium.

The oscillations observed correspond to both the toroidal ripple (ε_t) - present in the core and the edge - and helical ripple (ε_h) – present only in the helical core. The trapped particle fraction due to ε_t in the helical state increases by about 10% compared to a standard axi-symmetric RFP but still with a negligible value of the bootstrap current [Gobbin09]. At the same time, detailed studies of collisionless orbits of H ions performed with Orbit show that neoclassical effects, such as the 1/ν ("superbanana") regime arising at low collisions in stellarators, are not an issue for the RFP, since the helically trapped population appears to be a negligible fraction of particle orbits [Gobbin10a]. Furthermore as the configuration becomes essentially axi-symmetric at the edge, any trapped particle drifting out of the helical core becomes passing reducing any contribution to transport from this mechanism.

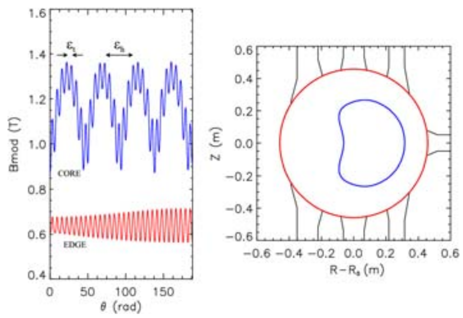

Fig.2.6.5: Left: magnetic field ripple along a field line at the edge (red) and in the core (blue) showing possible particle trapping in the helical state. Right: flux surfaces corresponding to the lines on the left.

In the region of the electron internal transport barrier (eITB) we may expect to be approaching the neoclassical transport so that the codes DKES/PENTA have been applied to study this mechanism at the eITB. Input to the code DKES is the output from VMEC. The local mono-energetic coefficients for neoclassical radial transport (D_{11}) at a given magnetic surface are computed by solving a drift kinetic equation. The calculation of the coefficients D_{11} is made at several values of collisionalities normalized to velocity (ν/v) and radial electric field E_r. An example is shown in Fig.2.6.6 (a) for a magnetic surface around the ITB. The black thick line corresponds to the case with $E_r = 0$: in the region of experimental RFX-mod collisionality $D_{11} \approx 0.5-1 m^2/s$ a value close to the one found in ORBIT simulations. In fig.2.6.6 (b) the radial dependence of D_{11} on collisionality is shown at four values of E_r. D_{11} decreases rapidly away from the helical core, following the q profile and the low helical ripple as in that region neoclassical effects are negligible.

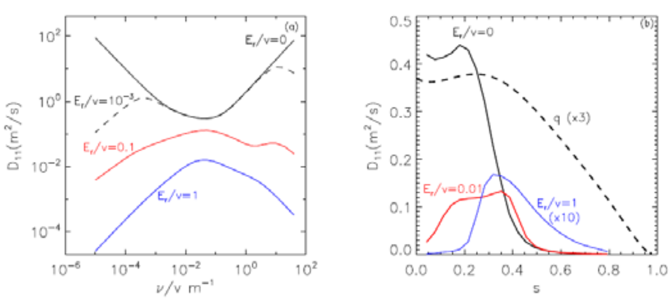

Fig.2.6.6: (a) Mono-energetic coefficients D11 as function of collisionality at several values of the radial electric field; (b) Radial profile of D11 at different Er and compared with the q profile decreasing.

The database of the coefficients D_{11} obtained by DKES is passed, along with the VMEC equilibrium, the experimental profiles of temperature and density, to the code PENTA to obtain a neoclassical estimate (satisfying the ambipolar constraint) of the electron thermal diffusivity χ_e. The radial electric field expected at the ambipolarity constraint for T_i=0.7 T_e is

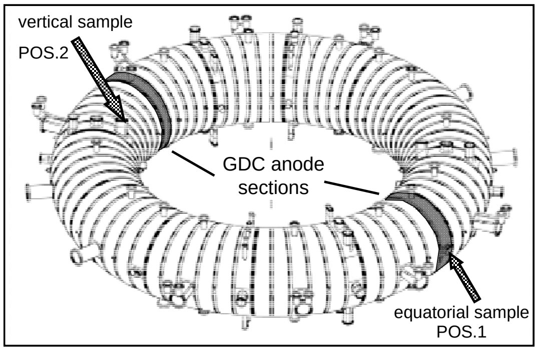

Fig.2.7.1: Picture of RFX-mod vessel with the GDC's anode sections and sample insertion ports highlighted.

negative and of about $E_{amb} \approx -1.7$ kV/m. As the T_i gradient is lowered, E_r increases and becomes slightly positive (0.2 kV/m) for a completely T_i = 300 eV flat profile. The PENTA estimates for electron thermal diffusivities are in the range 1.5-3 m^2/s that are about a factor 2 to 10 smaller than those obtained from a power balance analysis. This means that even at the barrier the effect of residual chaos or other kind of instabilities, such as microtearing modes, is still relevant (see sec. 2.5.1).

2.7 Plasma-wall interaction, wall conditioning and fuelling studies

In RFX-mod the graphite first wall prevents an easy operation at a given desired density, due to the high recycling of the wall coupled to a strong plasma-wall interaction. The extension of the RFX-mod operation towards high plasma current (I_p>1.5 MA) has made more critical this issue. Indeed at high plasma current the large wall hydrogen influx prevents density profile control by external core refuelling; in this condition high density is associated to hollow density profiles with a dense and cold plasma edge that can strongly affect the global performance.

To improve density control in 2010 the following actions have been taken:

- Characterization of first wall status by measuring stored and desorbed hydrogen and by measuring the effectiveness of first wall treatments using insertable samples;
- Wall conditioning by boronization extensively applied to perform plasma discharges at the highest current (up to 2 MA);
- Application, for the first time on a RFP device, of lithization by pellet injection as a means to control hydrogen and impurity influx from the wall.
- Preliminary test with a Liquid Lithium Limiter on loan from ENEA Frascati.

As for the characterization of the first wall, since January 2010 two manipulators, in two toroidal positions, have been available. One position (Pos. 1) is in correspondence of one of the two anodes for the Glow Discharge Cleaning (GDC), and samples are inserted from a port on the equatorial plane. The other position (Pos. 2) is vertical and 30 toroidal degrees far from the other anode (Figure 2.7.1). At this last position four samples are exposed at the same time, and can be replaced independently. To gain information on the wall status, graphite samples have been exposed both to wall conditioning treatments and to plasma discharges. Extracted samples have been analyzed by Secondary Ions Mass Spectrometry (SIMS) to measure the depth profiles of the present species. SIMS analysis pointed out the presence of a large toroidal asymmetry on boron deposition following boronizations (Figure 2.7.2) [Barison10]. The asymmetry is related to the distance from the GDC anodes (used for boronization too). Since plasma discharges take a while to toroidally uniform boron coating by local removal and redeposition, the measured initial asymmetry can partially explain why in RFX-mod the first (≈100) shots after boronization do not perform as well as the following ones. Ion density measurement performed during He GDCs confirmed the toroidal asymmetry of glow discharge as related to anodes position. Following these results, a new GDC setting up is being developed to improve the efficiency of extracting the hydrogen from the graphite tiles by He-GDC and boronization wall conditioning.

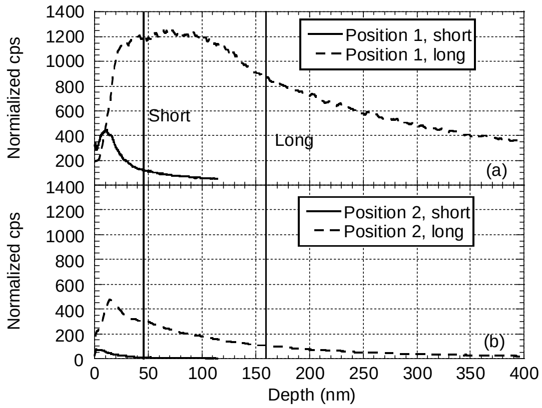

Fig.2.7.2: Boron profiles of samples exposed at Pos. 1 (a) and Pos. 2 (b) to two different boronizations. Vertical lines correspond to nominal thicknesses of the Boron layers for the two treatments.

However, boronization has been extensively applied to control hydrogen influx from the wall, allowing a partial control of operational density by gas-puffing. After boronization, differently than in clean graphite case, low or medium density discharges have been obtained switching gas-puffing on/off (Figure 2.7.3).

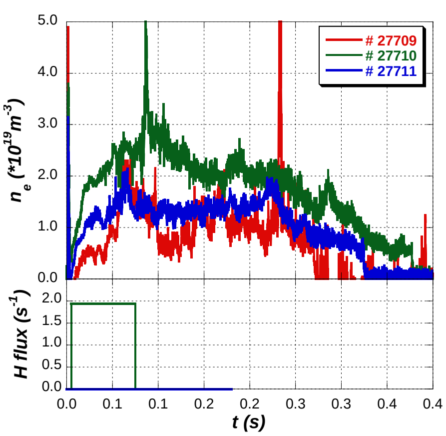

Fig.2.7.3: Line average density in a sequence of discharges with (#27710) and without (#27709, #27711) gas-puffing.

To study the influence of boron coating thickness, boronizations with a theoretical thickness of 45, 160 and 320 nm have been tested. No clear difference has been found between the three cases, neither in terms of plasma behaviour nor of duration of the boronization effect (about 200-300 shots). This suggests that only a small fraction of the boron layer is affected by the plasma wall interaction, and that the duration of boron beneficial effect is not limited by boron removal but by carbon redeposition from toroidal locations far from GDC anodes. An improvement in this direction is expected after improving the toroidal uniformity of boron coating.

Aiming at reproducing the good results obtained in several tokamak and stellarator experiments with a lithium wall coating, lithization by pellet injection has been performed at

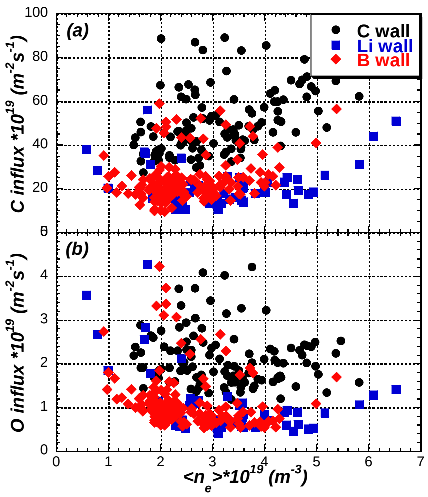

Fig.2.7.4: Variation of influx (a) C and (b) O with ne for 3 sets of discharges.

the beginning of 2010, while first test of a Liquid Lithium Limiter device have been executed in the second half of the year.

Initially lithium pellet experiments have been devoted to optimize the technique. To such purpose lithium pellets have been injected on medium current (≈1 MA) hydrogen and helium discharges. The best results in terms of lithium influx were obtained with short helium discharges. In this way, lithium coatings with a nominal thickness ranging from 5 to 14 nm have been deposited over clean and boronized graphite. After lithization, high plasma current experiments have been performed to evaluate the effect.

Lithium coating proved to be very effective in controlling hydrogen and impurity influxes, Lithization is equivalent to boronization in Oxygen reduction while it slightly outperforms boronization in Carbon reduction (but this last effect could be due to the initial non-toroidal uniformity of boron coating). Lithization is more effective than boronization also in terms of particle confinement time: while boronization does not improve particle confinement over the clean graphite case, lithization provides on average a particle confinement time higher than clean graphite. This result can be related to a different particle transport at plasma edge induced by the lithium coating. Thermal Helium Beam measurements show that after lithization edge temperature increases and electron density decreases; the resulting edge pressure is higher when compared to discharges performed with clean graphite (figure 2.7.5). Edge profiles variations are due to a modification of the edge transport as confirmed by density fluctuation measurements by the Gas Puff Imaging diagnostic, which shows a reduction of edge particle flux due to density blobs [DalBello10].

The main drawback of lithization is the time duration of its effectiveness: after a few high

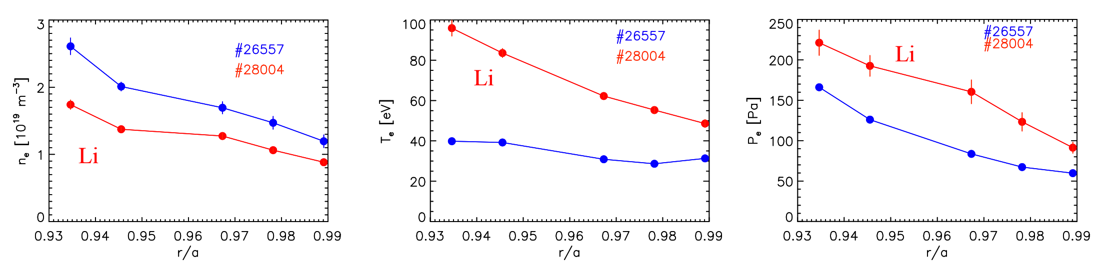

Fig.2.7.5: Edge density, temperature and pressure measured by Thermal Helium Beam diagnostic on similar discharges before #26557 and after lithization #28004.

current shots (≈10÷20) lithium coating looses its ability in controlling hydrogen influx. This effect is probably related to the small lithium coating thickness. Attempts have been made to inject Li pellets at the end of hydrogen discharges to replace lost lithium with fresh one. However, the rate of lithium loss was higher than that of replacement.

To obtain a thicker lithium coating in the second part of 2010 a Liquid Lithium limiter (LLL), with a capillary porous system (CPS) configuration (see fig.2.7.6), has been tested in RFX-mod [Alfier10]. This was the first time a CPS head was exposed to RFP plasmas and the absence of previous experience required a gradual approach. Initial experiments have been mainly devoted to study the interaction of the LLL with the RFP plasma. The techniques have been tested for wall conditioning, setting the LLL at 3 mm inside the internal convolution of the full cover graphite wall on RFPs plasma at low current (0.5 MA with He discharges). Interaction with few target hydrogen RFP plasma of 1.2MA has been also studied. The LLL has been used both as limiter than as evaporator. The use as evaporator has been followed by He low current plasma discharges to spread Lithim. Till now the evaporator only has provided an evidence of the wall conditioning on plasma discharges: after conditioning by evaporation Hydrogen discharges showed a remarkably high adsorption capacity of the first wall. As a preliminary result, though on a single shot, a sensible reduction of the resistive loop voltage at $n/n_G > 0.15$ was observed. In addition, a Quasi Single Helical State associated to the formation of an Internal Transport Barrier appeared at 1.2 MA, whereas both usually develop at higher plasma current and lower density. First experiments have shown the difficulty in controlling LLL interaction with RFP plasmas. In particular, the LLL has been damaged when the MHD modes locked just at the position where it was located.

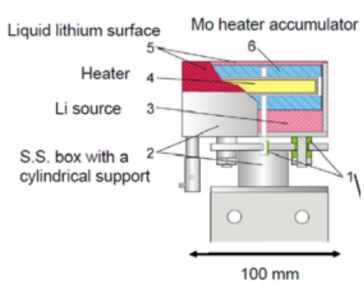

Fig.2.7.6: LLL schematic section.

2.8 Power neutral beam injector

In view of the installation of the 1MW beam on loan from AIST Tsukuba and, more specifically, in support of the design of the beam front end, progress has been made on the simulation of the beam behavior along its path from the source grids to the plasma.

The 3D Monte Carlo simulation code EAMBC has been developed for the purpose [Pilan 2010]. The code simulates the trajectories of both charged and neutral particle including the interaction between the accelerated particles and the magnetic fields produced by RFX and the Residual Ion Dump respectively and the interactions between the accelerated

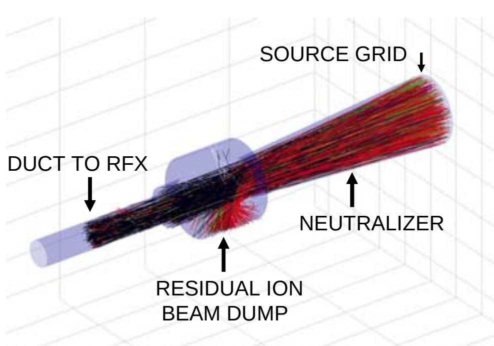

Fig.2.8.1: Simulation of the effect of a residual ion dump (in the centre) on the particle trajectories.. In black the trajectories of neutrals. In colour the trajectories of charged particles of full, half and one third energy. Note how some reionization occurs after the neutralizer and the residual ion dump. (from [Pilan2010])

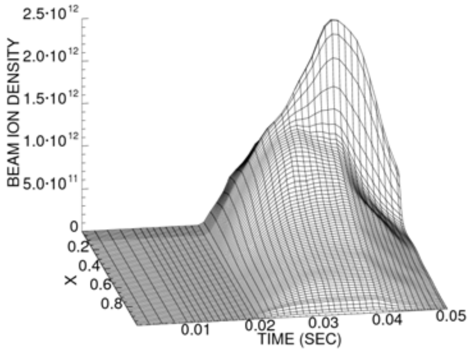

Fig2.8.3. TRANSP Simulation of the fast ion density population following the injection of the 25 keV, 1 MW beam.

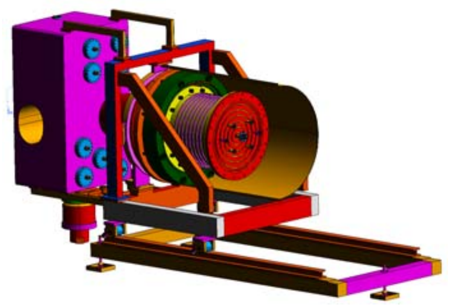

Fig.2.8.2: Sketch of the developed mechanical interface. In purple the expansion volume and in blue the NEG pumps.

beam and the background gas. The efficiency and the main specifications of neutralizer and Residual Ion Dump (RID) have been assessed together with the necessary degree of magnetic screening of the entire system.

The mechanical interface designed to couple the beam to RFX, fulfilling the specifications emerged by the simulation analysis, maximizes the volume admissible by the geometrical constraints and the pumping speed required to avoid re-ionization and the consequent beam stopping. At the moment the required pumping is provided by a number of Non Evaporated Getter (NEG) pumps, though other solutions are being considered. Finally a simulation analysis of the beam-plasma interaction has started in collaboration with the University of Wisconsin, Madison. TRANSP runs (D Liu and J Anderson) have shown that if the nominal beam is successfully injected into RFX a significant population of fast ions should build up in the plasma, with minor effects on electron density and temperature.

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3. CONTRIBUTIONS TO ITER

3.1 The role of Consorzio RFX

In the framework of the activities devoted to the ITER project, Consorzio RFX has continued its activity on the development of the NBI system, on the realization of the Magnetic sensors and of the LIDAR systems and on the modeling. These activities have been carried out keeping the same level of resources as in the previous year. The activities have been carried out in close collaboration with other European associations and the results are reported in the following

3.2 NBI development

3.2.1 Status of the project

Several important events took place in 2010. The Procurement Arrangement between EU-DA (F4E) and IO for the in kind contribution of the components and plants for PRIMA, MITICA SPIDER has been signed on 25 October 2010, so that the Call for Tender activities for all the subsystem are ready to start. The call for tender of the Test facility buildings started in July 2010 and the selection of the companies is now under completion. The procurement of the power supply for SPIDER (ISEPS) started in June 2010 with a company that is called to manufacture the Power Supplies for the sources of SPIDER, MITICA and then for the 2 ITER Heating Neutral Beams (HNBs). The SPIDER High Voltage Deck and the Transmission line call for tender has been launched. The SPIDER Beam Source, Vacuum Vessel and Assembly Tools design has been finalized so that the call for tender for these components can be launched. The SPIDER Control and Data Acquisition System is ready for the preparation of the Call for Tender. The design for all the SPIDER subsystems and components is almost completed and ready for the manufacture phase in agreement with the procurement plan of F4E. At present negotiations are in progress to define the role and relationships among the main stakeholders of the Test Facility namely ITER, F4E and Consorzio RFX. In particular a framework agreement and a back-to-back agreement are under definition between F4E and Consorzio RFX.

3.2.2 PRIMA: buildings

An important effort was devoted by RFX in order to support the final stage of PRIMA Buildings executive design, performed by external resources (architectural, structural and plant design companies). In July 2010 the final version of PRIMA design was approved by RFX after a long work of revision of previous versions (delivered to RFX in January 2010). More than 1300 comments were made; all the aspects of the design were carefully and deeply checked and commented (architectural, structural, Heating Ventilation and Air Conditioning plants, electrical plants, lighting, fire protection, safety, lightning and acoustics). Particulare attention has been paid in order to comply with general budget limitations without impacting on experimental and safety requirements.

Another activity was the complete definition of layout for the High Voltage Transmission Line to meet the requirements of the JADA (in charge of the supply of the SF6 insulated transmission line @ -1000 kV for MITICA experiment).

Finally, the complete design meets the Test Facility requirements and also other important aspects like maintenance, operability, flexibility; as an example, Building n° 2 (auxiliary system) was modified to fit a suspended floor covered by modular and movable concrete slabs (the underground space is necessary to install all the piping system of the Cooling Plant, without interference with other equipment installed at ground floor).

Main result of this activity was the launch of the Call for Tender for the PRIMA buildings (August 2010) after the approval by the RFX management. Seventeen companies answered to the Call for Tender; the on-going activity is the verification of presented documents and the selection of a restricted list of ten companies. Figure 3.2.1 shows an overview of PRIMA buildings area with the two experiment bunkers.

A critical issue for the installation of the HV Transmission Line is represented by the maximum displacements of the buildings and support structures in case of an earthquake. In fact, the external structure of the line characterized by a cross section of 1.5 ÷ 2.5 m and consisting of a metallic sheet of about 2.5 cm thickness to sustain the internal gas pressure of 0.6 MPa, makes the structure rigid and not able to withstand significant shifts.

In MITICA, part of the TL will be sustained by the biologic shield of the injector. It consists in a

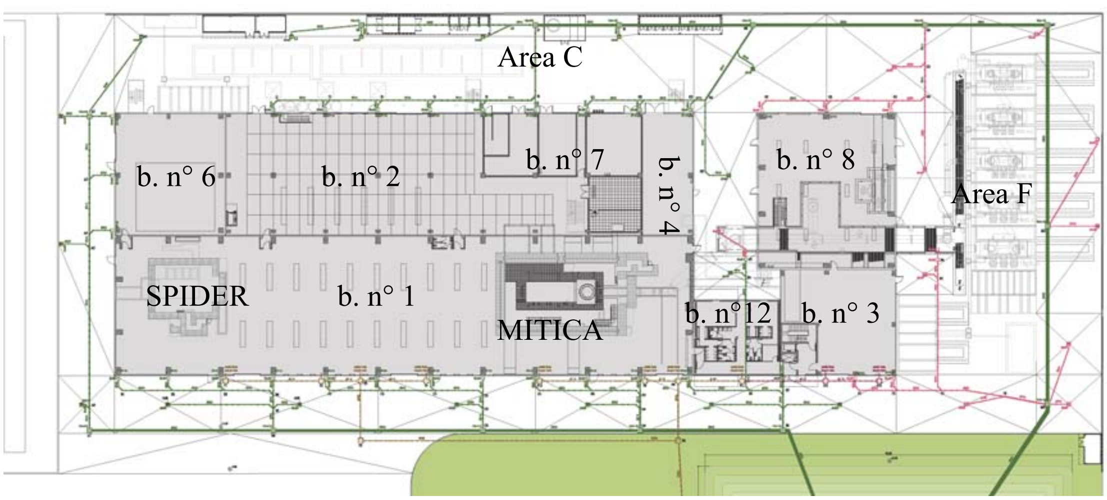


Fig.3.2.1: Overview of PRIMA buildings area with the two experiment bunkers (Building n°1, bottom left) and the Building n° 2 (auxiliary plants) with the tiles of movable concrete slabs. On the right, the Buildings n°12 (central Control Rooms), the MITICA Power Supplies Buildings n° 3 and 8, the area F for step-up transformers and (area C) for gas storage.

very heavy structure formed by concrete blocks 1.8 m thick placed one on top of the other to completely cover the injector. During 2010, in collaboration with experts of the Padua University, a dynamic 3D model of the MITICA biologic shield has been developed (see Figure 3.2.2) and seismic analyses were performed. The results gave a maximum displacement smaller than 10 mm also in case of a SLV seismic event, as defined by the Italian rules and to be considered for the design of the PRIMA buildings. This maximum displacement has been considered acceptable by JAEA colleagues responsible for the TL design.

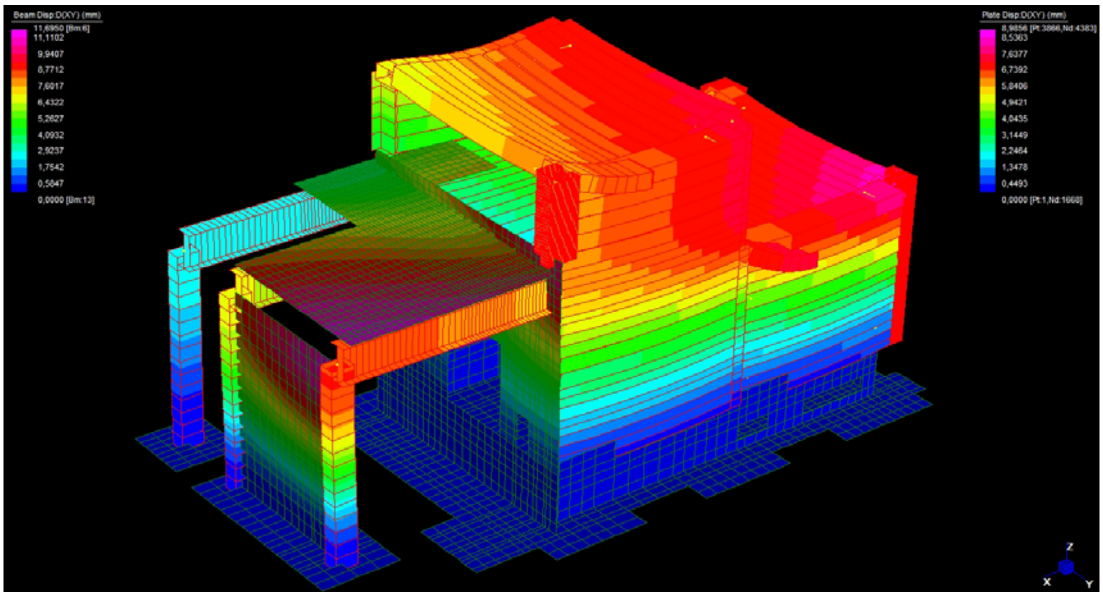


Fig.3.2.2: 3D model of the MITICA Biological shield showing the horizontal displacement in case of a SLV seismic stress

3.2.3 PRIMA: auxiliary plants

The main auxiliary plants for the two facilities SPIDER and MITICA are the Cooling Plant (see Fig. 3.2.3), the Vacuum and Gas Distribution and Injection System and (for MITICA only) the

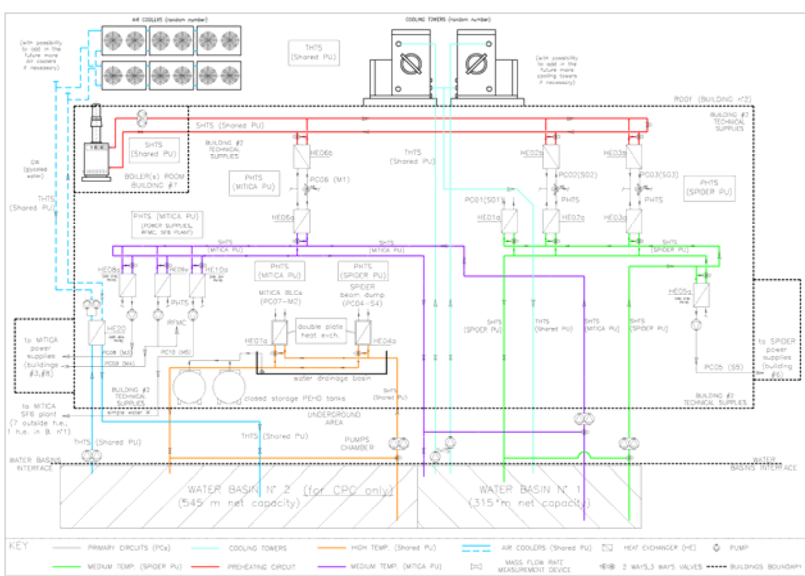


Fig.3.2.3: Final Conceptual Design of Cooling Plant (up to 70 MW of rejected power to environment)

Cryogenic Plant.

During 2010 a large effort was dedicated to finalize the conceptual design and to write the Technical Specifications (Annex B), needed for the launch of F4E Call for Tenders.

The work on Cooling Plant [Fellin10] has been finished this year with the last document update (October) and the consequent F4E launch of Call for Tender (published on 14 November 2010). Several interactions between F4E and RFX took place till July in order to get a positive and constructive assessment of some parts, like diagnostics, Local Control System, Electrical Plant, spares, tests and so on. The proposed design for the Cooling Plant has been modified in order to meet the requirements for the MITICA facility, in particular regarding the interfaces between Cooling Plant, MITICA Source Vessel and High Voltage Transmission Line plus High Voltage Deck 2 (supplied by JADA). Other modifications were necessary in order to meet the cooling requirements for the Residual Field Magnetic Coils and specific safety requirements to handle with activated corrosion products inside the water cooling MITICA Beam Line Components and SPIDER Beam Dump.

For the Vacuum and Gas Distribution and Injection System, after two revision stages, the Annex B was finally delivered to F4E and published on F4E IDM (November 2010, [Dal Bello10)].

For the Cryogenic Plant, foreseen for MITICA only, the original conceptual design has been deeply modified in order to reduce capital and operational costs and to meet MITICA cryopump requirements (still under final definition by F4E and IO during 2010). The Cryogenic Plant conceptual design is strictly related to Cryopump requirements, which were modified during this year in order to allow the line of sight for MITICA diagnostics through the cryopump backplate. Another important input regards the cryopump expected heat loads, in particular with reference to electron contribution on cryopanels (the presence of an electron dump has still to be taken into account). A dedicated RFX-team has also attended a training programme on Cryogenics, in order to get know-how and information. A new collaboration with Karlsruhe Institute of Technology (KIT) was set-up to complete the experts team. The first release of updated MITICA Cryogenic Plant Technical Specifications is planned to be delivered to F4E in December 2010.

On the basis of the international agreement for the realization of the NBTF in Padua, the Italian Government, in addition to financing the building construction will also provide the medium voltage grid to supply both SPIDER and MITICA experiments.

During 2010, the conceptual design of the Medium Voltage grid has been finalized, taking into account the following boundary conditions:

- high level of operational flexibility;
- constraints due to the PRIMA building layout;
- cheapest solution, in particular optimizing the power cables paths and the installation techniques.

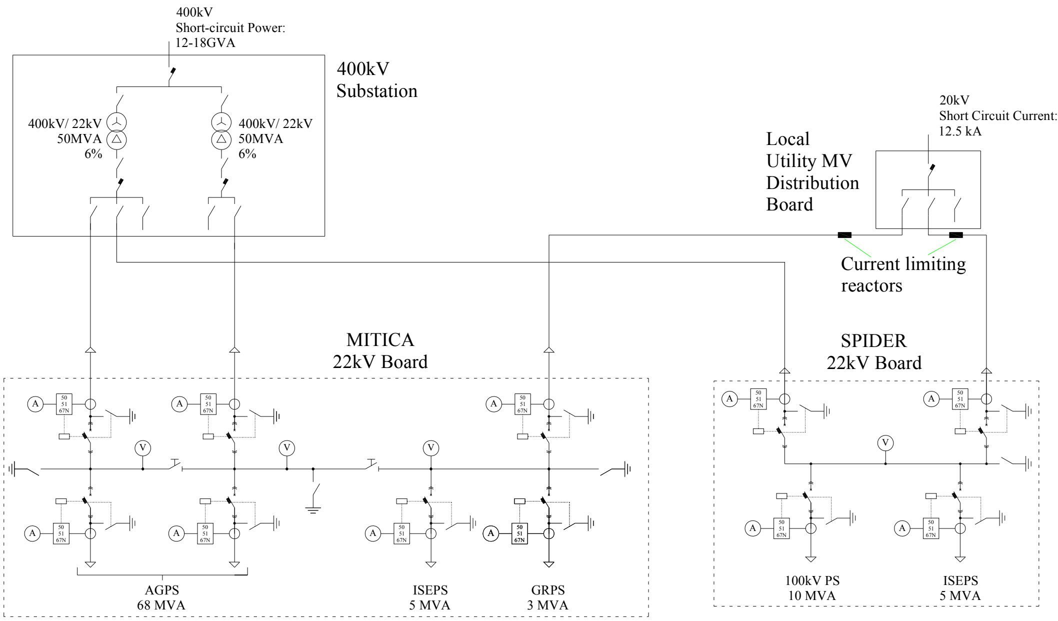


Fig.3.2.4: Simplified scheme of the PRIMA 22 kV power distribution system

Figure 3.2.4 shows a simplified scheme of the PRIMA 22 kV power distribution system. The adoption of a Medium Voltage loop can be appreciated, including also the 20kV Local Utility Distribution Board normally used to feed the auxiliary systems, to satisfy the high level of operational flexibility requirement.

3.2.4 SPIDER: injector

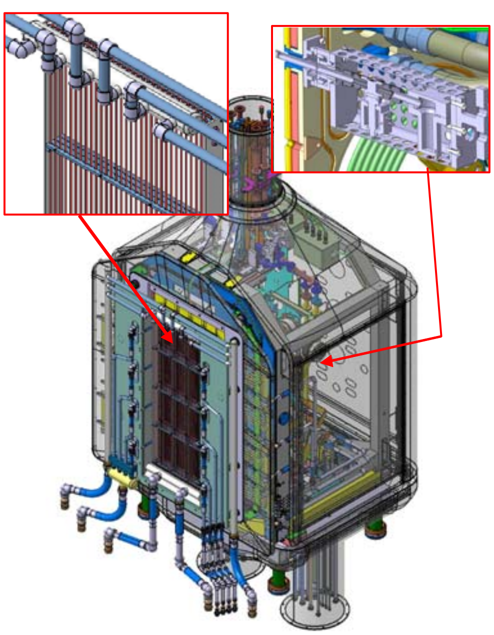


Fig.3.2.5: The Beam Source for the SPIDER experiment, with details on electron dump and Cs oven.

During 2010, the decision of most of SPIDER mechanical components has been completed.

The beam source [Marcuzzi10], where the H_2/D_2 negative ions are generated and 100 kV accelerated, was developed to a build-to-print level, as shown in fig.3.2.5.

The electron dump was integrated in the beam source [Agostinetti10], immediately downstream of the grounded grid: three arrays of 34 vertical actively cooled pipes shall remove the power deposited by the electrons leaking through the accelerator, as shown in fig.3.2.5.

Extensive calculations were carried out in order to assess the distribution of electron trajectories, to maximize the percentage of dumped electrons and to optimize the thermo-mechanical behavior of the whole component.

The electron dump supporting structure and cooling loops were linked to the grounded grid frame, in order to minimize possible misalignments between accelerator apertures and dump pipes.

The Cs oven is an essential component of the ion source, as caesium is needed on the plasma grid surface to enhance negative ion production. The design was completely revised with respect to ITER previous version, succeeding in the simplification of the design, as shown in fig.3.2.5, and in the optimization of the integration of three ovens on the rear side of the RF plasma source, in order to facilitate a uniform distribution of caesium across the source.

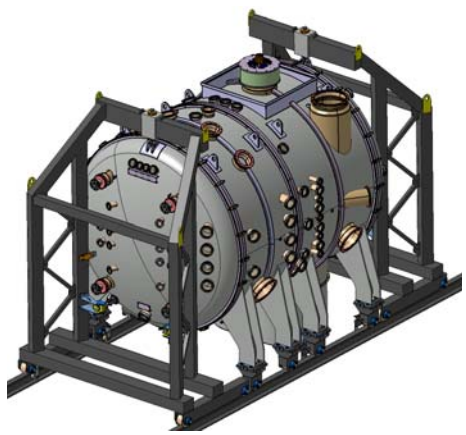


Fig.3.2.6: The Vacuum Vessel for the SPIDER experiment.

The technical specifications for procurement were completed with all requirements regarding materials, prototypes, specific manufacturing steps, assembly procedures, tests at the factory and on site.

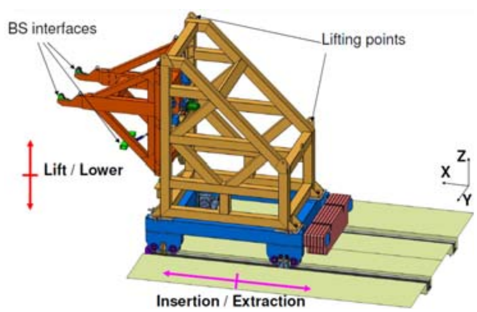


Fig.3.2.7: The Beam Source Handling Tool

The design of the vacuum vessel was finalized [Rigato10], as shown in Fig.3.2.6. The mechanical behavior was fully verified with respect to all relevant load cases. All interfaces with internal and external components were integrated. The technical specifications for procurement were completed. A handling tool was designed (Fig. 3.2.7) in order to manage the assembly of the beam source inside the vacuum vessel with the necessary precision, in order not to damage any of the involved components. The technical specification for procurement was completed accordingly. A formal design review held by ITER Organization was carried out simultaneously on the three cited components, which led to the formal approval of the design and of the technical specifications, and should result in the launch of the unified call for tender before the end of 2010.

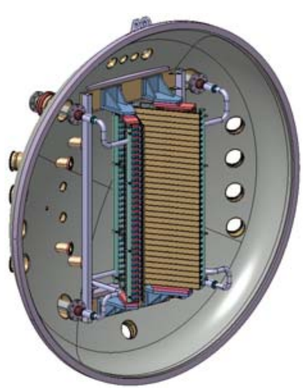


Fig.3.2.8: The Beam Dump for the SPIDER experiment.

The Beam Dump is the component that intercepts the full beam of H_2 or D_2 negative ions exiting from the SPIDER beam source. The design and the procurement are responsibility of IN

DA. The RFX contribution consisted in the definition of the requirements for the design, the definition of all interfaces with the vacuum vessel and the integration of the designed component, as shown in fig.3.2.8.

3.2.5 SPIDER: power supplies

The ISEPS (Ion Source and Extraction Power Supply) [Bigi10a] Call for Tender has been the first one to be launched, on September 15th 2009. During the first months of 2010, the evaluation of the offers received by F4E was performed with the support of RFX. In particular the Tender Evaluation Group included as external expert an RFX member.

The ISEPS procurement contract was signed in June. Two RFX researchers will manage all the technical aspects of the contract as liaison and deputy-liaison persons. In the second part of 2010 work has continued with the follow-up of the detailed design phase of the ISEPS set for installation on SPIDER, including the definition of the layout (see Figure 3.2.9) and the revision of the First Design Report.

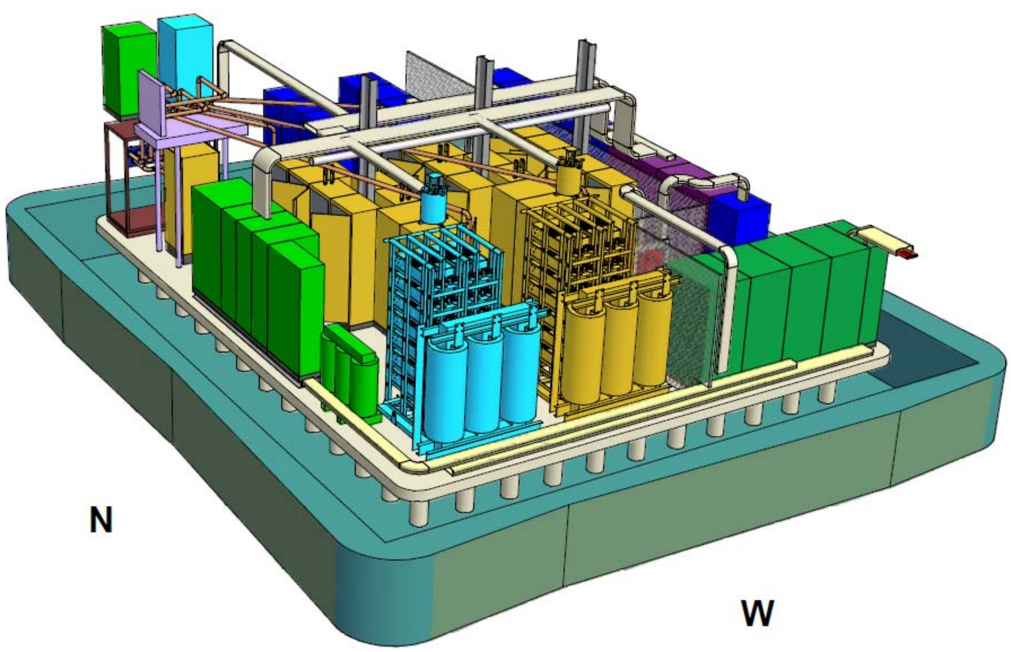


Fig.3.2.9:ISEPS Layout for SPIDER experiment

The SPIDER High Voltage Deck and Transmission Line technical specification [Boldrin10a] and the relevant documents for Call for Tender were completed in spring 2010. During the following months, further updating of the technical specification documents were made on the basis of the ISEPS detailed design that will be hosted inside the HVD. The Call for Tender procedure has been lunched on 16th November and will be closed in January 2011. All these activities have been performed with the support of RFX.

During the first part of 2010, the procurement sharing of some components has been defined between F4E and INDA. In particular, the Acceleration Grid Power Supply (also known as -100kV PS), initially foreseen under the F4E scope of procurement, was passed to INDA. As a consequence, the RFX specific activities on this item have been rearranged in agreement with F4E, resulting in RFX supporting IO and INDA in the finalization of the Annex B document (Technical specification) of the relevant Procurement Arrangement. This activity was concluded in September and now, after the signature of PA foreseen at the end of year, a new contribution is expected by RFX on the definition of the technical specification for the industrial procurement, mainly in the areas of interfaces, site conditions, passive protections and circuit analyses at system level.
The FMEA analysis of SPIDER system has been completed in spring 2010. Then, on the basis of this analysis, a conceptual design of the SPIDER interlock system has been developed and presented to IO and F4E.

3.2.6 MITICA: Injector

A substantial progress on MITICA Injector design has been achieved during 2010, mainly regarding the Beam Source, the Vessel, the Neutralizer and the Residual Magnetic Field Coils, all in charge of RFX according to F4E Grant032 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 Grant032 for CCFE (design development of Electrostatic Residual Ion Dump and Calorimeter) and for KIT (design of ITER HNB and MITICA Cryopumps).

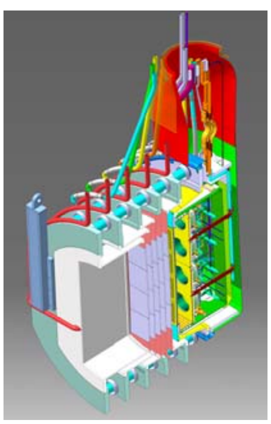


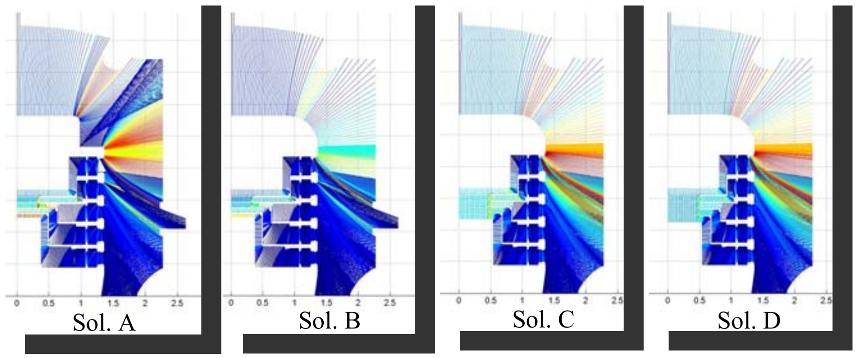
Fig. 3.2.10: Isometric section view of MITICA 1MV Beam Source.

Beam Source: requirements and interfaces have been preliminarily identified and formalized after several discussions and meetings among the different parts involved in the design (IO, F4E, RFX and JADA). Design activities started in September 2010 and are planned to continue all over 2011. Some important requirements coming from beam optics optimization analyses, identified by JADA and RFX, have been preliminarily assessed from the point of view of feasibility and reliability, with an iterative development process requiring repeated engineering and physics analyses. The process is still going on and will continue during next year. The overall view of the MITICA Beam Source now under development is shown in Figure 3.2.10.

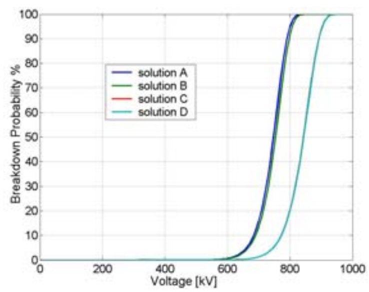
The main activities carried out in 2010 regarded:

- the update and integration of MITICA ion source according to the final design adopted for SPIDER ion source;

- the review and final assessment of the interfaces with the HV Bushing (interactions with JADA in charge for HV Bushing design);



(a)

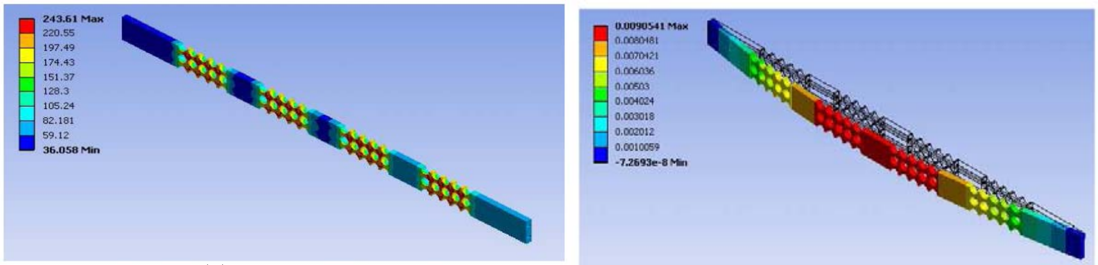


(b)

Fig. 3.2.11: Electrostatic analyses and design optimisation for MITICA Beam Source: contour plots of probabilistic discharge analyses (a) and breakdown probability vs applied voltage for different design options (b).

- electrostatic analyses for design optimization, also using a specific code developed at RFX for the estimate of breakdown discharges by a probabilistic approach [Pilan-2010]; some results of these analyses are shown in Figure 3.2.11;
- preliminary thermo-mechanical and thermo-hydraulic analyses to identify guidelines and requirements for engineering design of acceleration grids and support frames; some of the results are shown in Figure 3.2.12;
- a general assessment of the complete hydraulic circuits for cooling of Beam Source components taking into account the integration with JADA design of HV Bushing and Transmission Line.

Design optimization and relevant engineering analyses shall also continue during 2011, in parallel with new beam optics analyses at JADA and RFX.



(a) (b)

Fig. 3.2.12: Contour results of thermo-mechanical analyses for sensitivity analyses of acceleration grids under maximum heat load (2.6 MW): temperature contour [°C] (a) and out of plane deformation [m] (b)

Vacuum Vessel (figure 3.2.13): most of the activities in 2010 have been dedicated to identify requirements and interfaces, in strong collaboration with design teams from different parties involved in the design (IO, F4E, RFX and CCFE (in charge for ITER HNB Vessels)). Most of requirements are still under development at IO and several interfaces suffer from lack of definition and on going reviews by different design teams within IO organization and other involved Associations (CCFE and KIT). Many design revisions of interfaces were required due to newly identified remote handling requirements from IO and the progressive review of several diagnostic accesses to be agreed with IO and F4E. A significant effort has been dedicated to prepare a skeleton interface model in CATIA (see Fig. 3.2.14) that resulted to be a powerful tool to effectively manage the changing requirements and interfaces, guaranteeing a well controlled configuration management and fast exchange of updated information among all the involved design teams. Preliminary structural analyses have been completed to compare different design solutions, aiming to fulfill all the coming up new IO requirements and to assess the progressive definition of interfaces with in-vessel components, external service lines (cooling, gas, electrical power, actuators) and HV Bushing (in charge of JADA). In December 2010 most of the Vessel requirements and interfaces shall be agreed with IO, F4E and CCFE, allowing RFX to proceed with the design development and Technical Specification preparation foreseen during 2011.

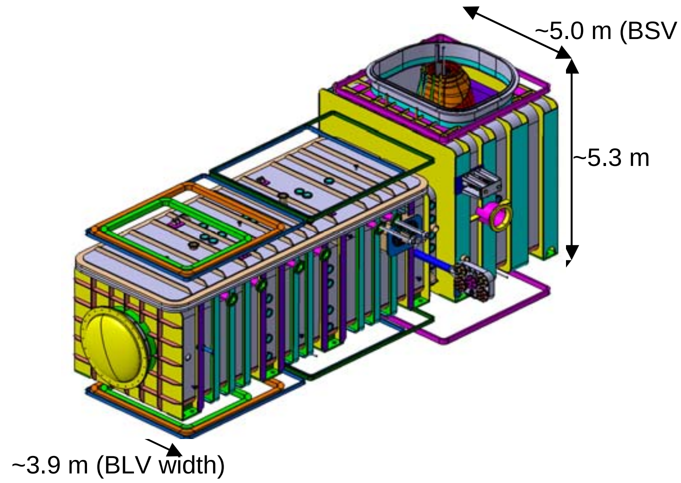


Fig. 3.2.13: Isometric view of the MITICA Vessel

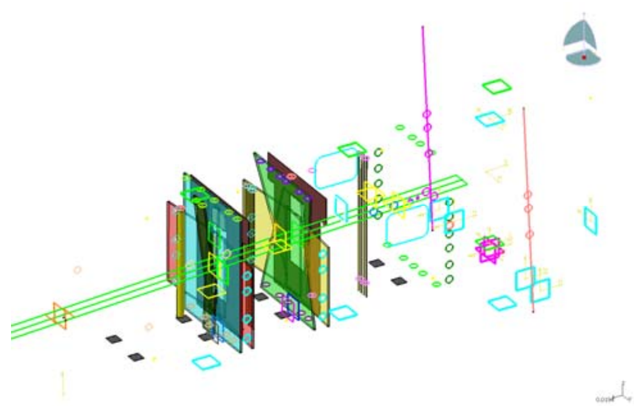


Fig. 3.2.14: Isometric view of interfaces skeleton in CATIA for MITICA Vessel

Neutralizer and Electron Dump: revision of Neutralizer design according to updated requirements started in July 2010.

The main aspects for design revision have been:

- interfaces review according to RH requirements;
- changes of gas injection configuration;
- design improvements to simplify manufacturing and reduce production costs;
- implementation of embedded beam diagnostics;
- preliminary conceptual design of an additional gas baffle, as requested by IO.

Preliminary requirements and interface documents have been prepared by RFX, but these can be object of further changes following discussions and agreements with IO and F4E. In support to the design, new analyses have been carried out to calculate power loads and power densities applied to the Neutralizer panels under different beam scenarios (see Figure 3.2.15).

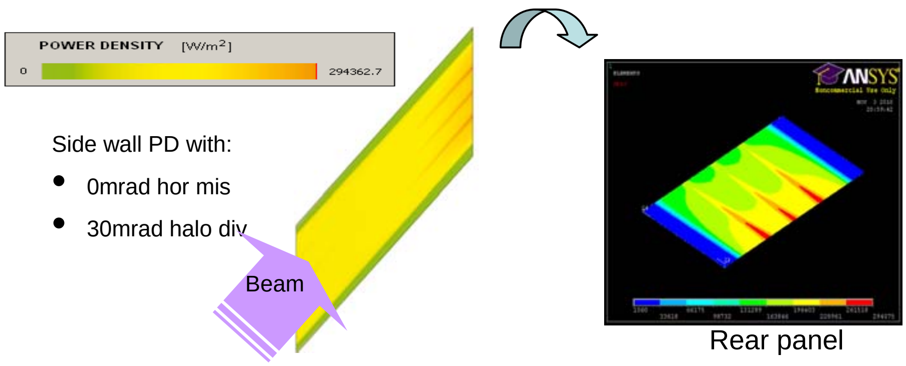


Fig. 3.2.15 Power density contour on the most heated Neutralizer panel

Thermo-mechanical analyses of the panels have been also carried out to verify temperatures, stresses and deformations considering different cooling conditions and beam scenarios (see Figure 3.2.16 for temperature contours). Final assessment of hydraulic circuits and cooling parameters is foreseen by the end of 2010.

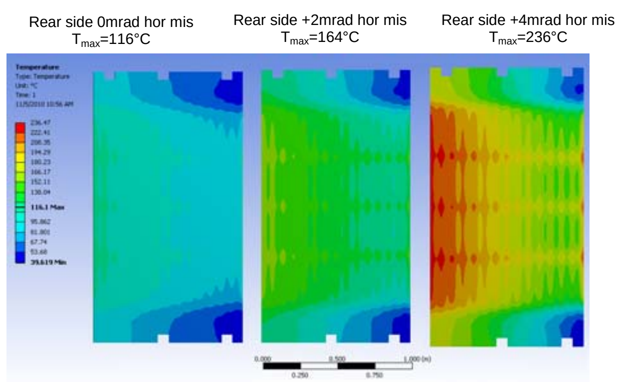


Fig. 3.2.16 Temperature contours on the most heated Neutralizer panels

The Electron Dump design is going to be conceptually developed referring to first estimates of electrons escaping from the MAMuG accelerator, with different proposed configurations. All these design activities and engineering analyses will go on during 2011.

Residual Magnetic Field Coils: design revision started during the last months of 2010, with collection of requirements and identification of interfaces. The RMFCs as presently designed for the updated MITICA Injector are shown in Figure 3.2.17. Electro-magnetic analyses are foreseen to assess the actual magnetic field distribution inside the injector volume. FEM models have been prepared and first benchmarking has been completed comparing the results with previous similar calculations carried out by CIEMAT, as shown in Figure 3.2.18. Final verification of actual requirements for RMFCs in MITICA will be completed within the end of 2010 and further design optimizations are foreseen in 2011.

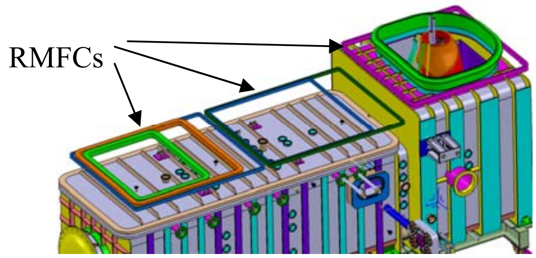


Fig. 3.2.17 Residual Magnetic Field Coils present design.

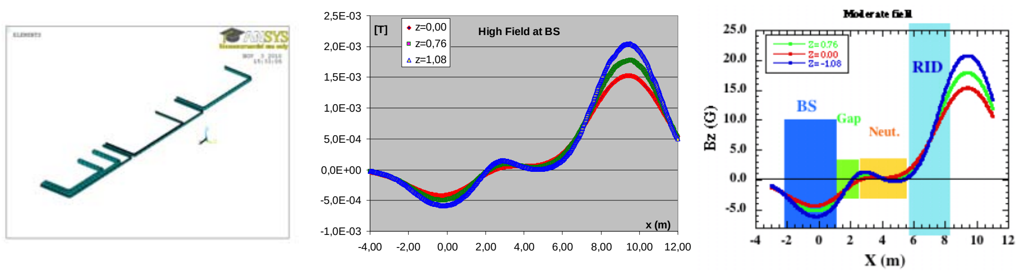


Fig. 3.2.18 FEM model of RMFCs and generated magnetic field profile for benchmark

3.2.7 MITICA: power supplies

During 2010, many efforts have been dedicated to complete the conceptual design of the Acceleration Grid Power Supply conversion system (AGPS-CS) and the Grounded Related Power Supply (GRPS) and to draw up a first version of the associated technical specifications.

The AGPS-CS is part of the AGPS system which includes, in addition to the AGPS-CS, HV components procured by JADA and named Direct Current Generator (AGPS-DCG). From a technical point of view, the tests and the commissioning of the AGPS-CS should be performed together with the HV components procured by JAEA; but this will not be possible both for reasons of responsibility and different time schedule. As a consequence, specific analyses in support to the technical specification preparation were necessary; in particular:

- to study the set of tests to be performed on AGPS-CS to simulate the grid breakdown;
- to study specific dummy loads for AGPS-CS testing and commissioning;
- to analyze and propose a set of tests for the AGPS voltage control loop without the JAEA HV components.

Further analyses are in progress to evaluate the impact of the AGPS load on the 400kV Italian grid. These analyses started at the end of 2010 and will be finalized before the end of F4E's Grant 032.

The most critical component of the NBI PS to be procured by F4E is the HV Bushing connecting HVD1 to the HV Transmission Line. A specific procedure for the procurement of this component has been adopted by F4E, named “Competitive Dialogue”. In a first phase, RFX supported F4E in the preparation of the technical documents necessary to launch the call for expression of interest and then, since the selection of competitors, RFX has made all the technical activities necessary for the definition of the technical specifications, including the participation to the technical meeting with industry. This activity will be concluded in spring 2011 and will be followed by the preparation of the technical specifications.

Another important activity has been managing all the interface activities with the IO and JADA to keep the overall design of MITICA aligned with the progress of the design of the AGPS-DCG in charge to JADA, AGPS-CS in charge to F4E and of the PRIMA buildings in charge to Consorzio RFX. Periodic meetings among the IO, JADA, F4E and RFX were made to progress this matter.

A particular issue, closed during 2010, consisted in the clarification of the Italian rules to be applied to the design of the HV transmission line and all other HV components insulated by pressurized SF6 gas. RFX, with the support of an external consultant, prepared a document describing the procedure that must be followed by JADA in order to obtain the homologation of these specific components by the Italian body in charge of this certification (ISPESL).

3.2.8 NBI Control and Data Acquisition Systems

The priority during 2010 has been the definition of the requirements for the Control and Data Acquisition Systems (CODAS) of the SPIDER and MITICA test-beds, and of the information technology infrastructure common to both, referred to as PRIMA CODAS. Particular care has been used to define data acquisition, as it poses the most challenging requirements, due to the fast dynamics of some signals and the long-pulse operation required [Taliercio10]. Parameters for SPIDER CODAS are now consolidated, whereas those for MITICA are still in evolution.

Taking into account the system requirements and the interfaces and specifications for plant system Instrumentation and Control coming from ITER, a conceptual design has been established for SPIDER CODAS [Luchetta10a]. SPIDER will not be part of ITER and, thus, the ITER prescriptions are not mandatory for SPIDER CODAS but, as the final outcome of the test facility will be the procurement of the ITER Heating Neutral Beam Injectors, we decided to adopt in SPIDER CODAS some ITER approaches, such as: segregation among conventional control, investment protection and safety; two- level system architecture split into Central and Plan System levels; adoption of the EPICS control framework as standard software interface between Central and Plant System levels and to implement slow and fast control; selection of Siemens PLCs as plant system slow controllers. To complement the EPICS framework, that is control-oriented, we agreed with ITER to use MDSplus for data handling.

In parallel, prototyping activity has been carried out to measure the performance of candidate technologies for the implementation of CODAS, including testing on the Time Generation and Distribution System; the management of signal analogue to digital conversion; the usability and performance of CODAC System v.1, the suite of EPICS tool selected by ITER; the data throughput performance achievable by MDSplus; and the MDSplus streaming capability [Manduchi10a].
Using the information on both requirements and candidate technologies performance, two documents have been prepared reporting the functional technical specifications of SPIDER and PRIMA CODAS, respectively [Luchetta10b, Luchetta10c].
To integrate in a single, effective system both EPICS and MDSplus, software interfaces have been design and implemented to permit transparent data exchange between the two frameworks. A new implementation of the EPICS Channel Archiver has been developed, so as to base data archiving in the MDSplus pulse file, granting EPICS access via Channel Access, its communication protocol. The new implementation shows much faster data access than the original one [Manduchi10b]. Four new EPICS records have been developed: the *mdsput record* to let EPICS write directly into the MDSplus pulse file without affecting Channel Access; the *mdsaction record* to let MDSplus execute actions dispatched by EPICS; the *mdsexpression record* to have MDSplus expression evaluation under EPICS; and the *mdsevent record* to handle in EPICS MDSplus asynchronous events [Luchetta10d].
The activity carried out in 2010 will permit to pass in the near future from the current design phase of SPIDER and PRIMA CODAS to the actual implementation phase.

3.2.9 Diagnostics

The design of SPIDER diagnostics has progressed and that for MITICA has started, according to the plan of F4E Grant 32. The global objective has been to present to ITER IO a proposal for a suite of diagnostics for both SPIDER and MITICA that were clearly supporting the mission of the NB test facility, i.e. suitable to verify that the two experiments will fulfill the requested specifications, are feasible and within the budget allocated for diagnostics. This work has been structured both as a central coordination of the proposed diagnostics techniques, their scientific motivations and interfaces with other systems of the facility, and also as the specific development of each diagnostic. The latter was carried out for each diagnostic by a dedicated team and resulted in technical reports to F4E and published papers describing requirements, systems design and specifications, modeling of the measurements, market survey of available instrumentation and in some cases also R&D to validate the proposed techniques and instrumentation [Pasqualotto10a, Pasqualotto10b, Spolaore10, DallaPalma2010b]. The suite of diagnostics comprises systems dedicated to the operation of specific plants, i.e. electric, cesium oven and vacuum measurements and cooling plant calorimetry and systems to characterize the plasma and the beam, i.e. thermocouples on the source and beam components, source and beam emission spectroscopy, absorption spectroscopy, electrostatic probes, beam tomography, beam imaging and inspection monitors, neutron imaging and, only for SPIDER, a short pulse calorimeter instrumented with infrared cameras, thermocouples and electric measurements. The design of SPIDER diagnostics is now nearly finalized, at the level of functional specifications, with build to print drawings for the instrumented calorimeter, and all important interfaces are defined. For MITICA diagnostics, the conceptual design has started and constraints and interfaces are identified; the viewports on the vacuum vessel are designed and requirements for beam line components identified. In November the full set of diagnostics to be installed in SPIDER and MITICA, proposed by RFX, has been agreed with F4E and IO, opening the way to a contract from F4E to RFX for their final specifications and procurement.

3.3 NBI accompanying activities

3.3.1 Introduction

The acquisition and test phase of the numerical codes identified as essential to carry out the source and beam simulation has been concluded. At present, several codes are available or under development at Consorzio RFX. With the codes acquired so far, the modeling activity has been carried out focusing on the optimization of the Ion Source design for the two sources to be realized at Consorzio RFX, namely SPIDER , the full size ITER source at 100kV, and NIO1 the test source at 60kV, 300mA. The development of the code BYPO has been carried out adding the effect of atomic processes and secondary particle production. The benchmark activity has been carried out by comparing the results of the codes (OMNITRACK, OPERA, BYPO, SLACCAD, EAMCC) with the experimental results available from the negative ion NBI in operation at NIFS. In close collaboration with the Tokamak program and coordinated with the Theory program, some activities on simulation of plasma - beam interaction by the numerical transport code CRONOS have been carried out to define the main parameters of a neutral beam based on negative ions for the FAST project.

3.3.2 Modeling and numerical simulations of the negative ion beam

Concerning the numerical codes identified as essential to carry out the source and beam simulation, the codes BTR and PDP, realized by the Russian Federation have been acquired and the following codes have been developed at Consorzio RFX:

- EDAC (Electron Dump Accountancy Code), 3D code, to estimate the heat load on the electron dump
- BACKSCAT, 2D code, to estimate transmitted and dumped particle fluxes on the electron dump, taking into account also electron backscattering over material surfaces.

The development of the code BYPO has been continued, by improving the details of the treatment of atomic processes and by addressing the two-dimensional investigation of the space charge compensation downstream with respect to the grounded grid.

The modeling activity in 2010 has been focused on the optimisation of the Ion Source design for the sources of SPIDER [Agostinetti 2010a, Veltri 2010] and MITICA [Agostinetti 2010b].

The SPIDER electron dump has been optimised and characterised. Off-normal conditions for the SPIDER accelerator have been investigated and the device resulted stable: beam optics reasonably retains its quality for small deviations of the tested parameters (voltage and magnetic field ripple and field uniformity; deviations of operational parameters from the reference values; manufacturing tolerances or thermal expansion or vibrations); cooling systems seem to be able to handle the increased thermal loads in case of some failure in magnetic fields or increased production of secondary particles. When the load appeared too high some modifications to the cooling systems were implemented, as it was the case of the overheating of the ferromagnetic material covering the rear part of the GG.

In parallel, a 3D numerical model has been developed for the magnetic design of the SPIDER facility, aiming at investigating the local lack of uniformity of the magnetic field configuration.

Concerning the MITICA accelerator, the assessment of different possible geometries has begun, using a comprehensive set of codes (STRIP, SLACCAD, OPERA, EAMCC and ANSYS). The starting configurations are the accelerator geometry of the ITER document DDD 5.3, including the adaptation of the extractor for the Radio Frequency source and the analyses carried out by JAEA and CEA; also the electrostatic and magnetic configuration adopted for SPIDER has been considered. Improved solutions are being developed, aiming at a better operating behaviour in terms of: voltage holding compatibility with an RF ion source, long pulse operation, beamlet divergence and deflection, suppression of co-extracted and stripped electrons inside the accelerator, reduction of secondary electrons inside the accelerator, and better thermo-structural behaviour.

The whole set of codes has been applied to the LHD NBIs in a joint activity between Consorzio RFX and NIFS, Japan, with the goal of comparing and benchmarking the codes to experimental data, to support the soundness of the design for SPIDER and MITICA. Concerning optics, heat loads and currents on the accelerator grids and exiting the accelerator have been computed, and they generally show good agreement with experimental data [Agostinetti 2010c]. Regarding magnetic simulations, a comprehensive 3D magnetic field model of the LHD BL2 device has been developed based on the same assumptions as for SPIDER and a detailed experimental magnetic map of the BL2 device has been obtained using a suitably designed 3D structure for fine positioning of the magnetic sensors. Comparison between calculated values and experimental data confirms the quality of the numerical model and even provides information on the non-uniformities due to edge effects, to the tolerances on magnetic characteristics, and to the maximum error due to probe tilting and offset [Chitarin 2010a].

Simulation activities have been devoted to the simulation of the data expected from some diagnostic systems. Concerning beam spectroscopy, the broadening effects playing a role in spectrally resolved measurement have been analysed in relativistic conditions; a consistent

study of error propagation has assessed the accuracy in the beam angular divergence measurement and gave prescriptions for the design. As for the instrumented calorimeter for SPIDER (STRIKE), the influence of thermal characteristics of the tile material, exposure angle, and features of some dedicated diagnostics as well as the resulting diagnostic capabilities (determination of uniformity, divergence and stripping) of the system have been assessed [Dalla Palma 2010a]. The tomographic diagnostic for SPIDER has been studied in terms of the geometry of the lines of sight and the inversion algorithm; the reconstructions obtained for different beam configurations have been investigated; it is found that the disuniformity of the beam is correctly reconstructed also with noisy data and that the system is not too sensitive to misalignments, due for example to vibration of the vacuum vessel.
The planned activity on the simulation of beam-plasma interaction has been deferred to the beginning of 2011 due to lack of manpower.

3.3.3 High Voltage studies

During 2010 the High Voltage Test Facility has been commissioned and entered into operation with one of the two experimental set-ups aimed to tests up 300 kV. The second experimental set-up, aimed to tests up to 800kV, is in the process of completion so that commissioning is expected at the beginning of the next year. The 300 kV campaign has been mainly devoted to the experimental validation of a probabilistic model for voltage breakdown prediction which has been developed at RFX. The tests have been carried out on a set of electrodes with different areas and with different gap lengths.

3.3.4 R&D on mechanical topics

During 2010, several R&D activities were carried out in support of the design of mechanical components, relevant for SPIDER and MITICA test beds.
Electro-deposition of copper is an essential manufacturing procedure for components having tight geometrical constraints that need maximized capabilities of removing high and concentrated heat fluxes, like accelerator grids and source walls. Prototypes were procured and tested, in order to assess material properties, to verify the proposed design of corresponding components and to operate a market survey in search of alternative suppliers.
Other issues were tackled as well with said prototypes, like the joint between the copper plate and the stainless steel cooling manifold: friction welding was considered and a dedicated campaign allowed to identify a possible supplier and to assess the manufacturing procedure.
Most of the samples have been manufactured and partially tested with positive results during 2010. Production of further samples and full qualification tests are also foreseen during 2011.
In order to optimize the magnetic field distribution inside the beam source, an electric current is needed along the plasma grid, therefore the four segments are to be put in series. Customized electrical contacts have been designed and procured, optimized in order to carry

the required current and to keep the thickness within the grid segment dimension. A dedicated testing campaign was carried out for the identification of the reference configuration and the thorough assessment of electrical and mechanical behavior. All the foreseen work has been completed during 2010.

Within the beam source accelerator, several re-combination reactions occur: positive ions are accelerated back toward the ion source impinging on vertical rear plates of the source case and the Faraday shields. In order not to have sputtering of copper, that would pollute the plasma and reduce source performance, a thin coating of molybdenum is commonly deposited on source inner surfaces. Long pulses and higher particle energy will require thicker layers; hence different techniques and suppliers have been investigated in order to deposit layers of molybdenum up to 1 mm thick, such as explosion bonding and vacuum plasma spray. R&D activities on Mo coating are foreseen to be carried out during the first half of 2011.

A new test facility named ICE (Insulation and Cooling Experiment) was designed, built and assembled at RFX, and is currently in commissioning phase. Its aim is to test some critical issues related to actively cooled components.

3.4 ITER Diagnostics

3.4.1 Magnetic sensors

Consorzio RFX has been involved in design studies for ITER magnetic diagnostic since 2003 in the framework of a variety of international collaborations. The development of the activities during 2010 has significantly changed with respect to what was foreseen in the 2010 Activity Program, due to changes in the Fusion for Energy grant assignment strategies. This event led to a rearrangement of the activities and of the commitment of Consorzio RFX for setting up different frameworks of collaborations supported by ITER Organization or Fusion for Energy, as indicated here below.

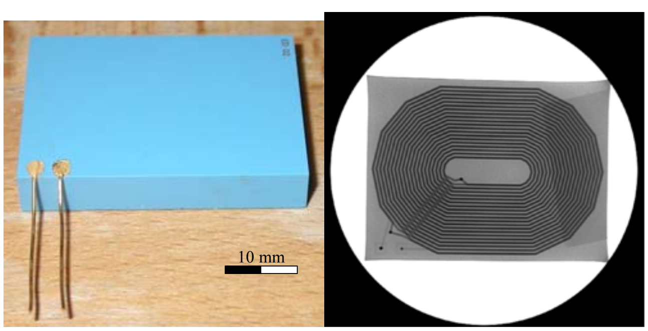


Fig.3.4.1: LTCC magnetic sensor overall view and X-ray image

During the first Quarter of 2010 a significant effort was devoted to the completion of a Service Contract with ITER Organization (ITER/CT/08/529) for the manufacture and test of "in-vessel LTCC (Low Temperature Cofired Ceramic) magnetic coil prototypes".

After the good results obtained in the past with a first set of pick-up coil sensors made with the same technology, new prototypes (Fig. 3.4.1) have been developed and built using different materials in order to improve the reliability in the expected operating conditions in ITER.

In this second set of sensors, gold (Au) has been used for the conductors instead of silver (Ag), and Alumina containing smaller percentages of other materials has been used for the insulation, aiming at complying with ITER requirements in terms of improved radiation hardness and reduced spurious voltage due to RIEMF and TIEMF effects (Radiation- and Thermal- Induced Electro Motive Force) in comparison with sensors made of Mineral Insulated Cables, already used in other fusion devices such as JET. The tests confirmed the general reliability of the manufacturing process, but evidenced also a significant Temperature Induced ElectroMotive Force (TIEMF) which could affect the measurements of the magnetic fields inside the ITER vacuum vessel because of the drift produced during long integration times (Fig. 3.4.2).

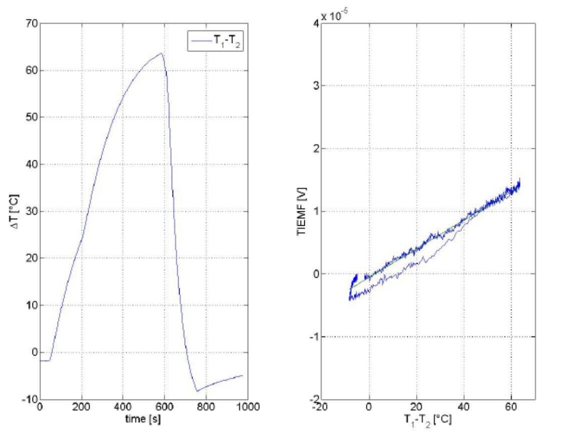


Fig.3.4.2: TIEMF effect measured on a prototype as a function of temperature gradient across the sensor

Further R&D is therefore necessary to minimize this effect for the detailed design of the sensors [Chitarin10b, Gallo10].

A further contract with ITER Organization (ITER/CT/4300000204), not foreseen in the Activity program 2010, was carried out during the second half of 2010 to provide a "Technical Officer on the ITER Diagnostics for the Outer vessel discrete inductive sensor". The contribution of Consorzio RFX was dedicated to the preparation of the supporting documents towards the Conceptual Design Review (CDR) of the Outer Vessel Discrete Inductive Sensors. During the contract a number of documents were generated to meet the requirements of the ITER Design Review Procedure, in particular a new Design Description Document of the specific diagnostic sub-system with relative engineering specification and risk assessment [Peruzzo10] and several presentations for the CDR which was finally held at ITER on 29 November – 2 December 2010.

During 2010 Fusion for Energy launched two Grants related to the design of magnetic sensors for ITER, in which Consorzio RFX has been contributing.

The first Grant (F4E-2008-GRT-012), in the framework of the "ITERMAG Consortium" (in collaboration with CEA and CRPP), is 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 activity is still in progress and is expected to be completed by the first half of 2011.

The second Grant (F4E-2009-GRT-047 / Tasks 1-3), in collaboration with CREATE, ENEA (UTFUS) and CCFE, is aimed at optimizing 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. The contribution of Consorzio RFX has been mainly dedicated to the development of two numerical codes: the first for evaluating the effects on individual magnetic measurements of ferromagnetic inserts, in-vessel coils and eddy currents in the First Wall and Vacuum Vessel structures; the second for the reconstruction of halo currents measured on the First Wall components. Also this Grant is still in progress but with a longer time schedule, the completion being expected by 2012.

Finally a significant effort was dedicated to the issue of a proposal for a third Grant F4E-2010-GRT-155, submitted by Consorzio RFX as a single beneficiary, focussed on R&D and detailed design of the ITER in-vessel magnetic sensors for plasma control and equilibrium reconstruction. The proposal of this Grant, which has an overall planned duration of 43 months, is presently under evaluation by F4E.

3.4.2 ITER core LIDAR Thomson Scattering (TSCL)

After the “ITER core LIDAR Consortium” was set up in September 2009, during 2010 the activities of Consorzio RFX and other European partners have focused on defining the available competencies and the share of responsibilities and on preparing for the first F4E call for a Grant agreement. RFX has been assigned specific responsibility for NIR detectors and calibration methods and broad participation to laser and overall design development. However the issue of the first Grant by F4E has been delayed to 2011, after TSCL will undergo a Conceptual Design Review by ITER Organization. Based on the new ITER plan, which foresees a late installation of the TSCL diagnostic, and on the budget constraint, the Consortium has developed a two phases approach: a) development of a basic performance JET-like system for early operations; b) full performance system after R&D on critical technologies. The RFX team (L.Giudicotti, R.Pasqualotto and A.Alfier) has contributed to the definition of the new proposal and has continued its specific work on detectors and on window cleaning by laser blow off. Specifically on detectors, RFX has started testing some detectors currently in use on the JET LIDARs, to investigate their suitability to the ITER TSCL.

3.5 ITER Modelling

3.5.1 Integrated Tokamak Modelling Activity

The Integrated Tokamak Modelling (ITM) taskforce is an EFDA initiative aimed at creating a simulation platform to facilitate the use, the benchmark and the validation of several codes developed (in the course of the years in Europe) to simulate magnetic confined plasmas and in particular tokamaks. Within ITM the activity of Consorzio RFX has been mainly focused in 2010 along four activities which have received priority support (PS) plus other three activities under baseline support (BS).

The activities under PS are summarized below.

a) The coordination of the Infrastructure and Software Integration Project (ISIP) group:

ISIP is the group responsible for the architecture and the software developments and it is the core of the ITM initiative. In 2010 activities on data structure (the UAL: universal access layer), remote data access (through the MDSplus protocol) and various software developments have been carried out.

b) The coordination of the IMP12 project:

IMP12 has several important initiatives underway on software integration in the field of linear and nonlinear MHD, including free-boundary equilibrium modules, ideal and resistive instabilities codes and 3D nonlinear codes. Several actions have been taken within IMP12 during 2010 to help the completion of different tasks including: free-boundary equilibrium models, disruption modelling, integration of equilibrium and transport codes etc.

c) An activity on control coordination (task under the Experimentalists and Diagnosticians Resource Group, EDRG): to coordinate a collaborative effort within all the control related ITM activities and to provide an external connection to other similar EFDA activities. The final aim is to build an integrated suite of modeling tools targeting the simulation of a magnetically confined plasma discharge, in realistic free boundary equilibrium experimental conditions. This activity has started in 2009 and will very likely continue through 2011.

d) An activity devoted to the development of a software layer which allows the integration of control modules written in Simulink into the Kepler framework.

A proof of principle test case was successfully completed in 2010.

The BS activities have been oriented to three specific projects:

- integration of the CarMa (Resistive wall modes) code under ITM in collaboration with CREATE, Chalmers and CCFE;
- the integration of the FLOW code under ITM in collaboration with Rochester University;
- the development of a transport code for impurities and its benchmark with JET data.

All these activities are still under way.

3.5.2 Disruption modeling

The disruption modeling activity for ITER (under EFDA support) using the M3D code in collaboration with PPPL and NYU (Courant Institute) have been pursued in 2010 and new results have been published [Strauss10].

The main finding is that the intensity of the horizontal force acting on the ITER wall is in the range of 60-70 MN, a value which is slightly above the chosen ITER project figure of merit.

The value of these forces however seems also to critically depend on the degree of instability of the plasma determined by the safety factor profile during the disruption. For the moment the simulations are not completely self-consistent since the initial current profile is artificially rescaled in order to amplify the kink instability.

In 2010 Consorzio RFX has participated also to an ITER call for further activities in this area (for the next three years). This proposal is actually under F4E scrutiny.

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4. TOKAMAK PHYSICS AND TECHNOLOGY

4.1 Background and strategy

In this chapter the work done in collaboration with Tokamak and Stellarator experiments is summarized. This collaboration is an outcome of the strong link between the work carried out at RFX and the mainstream activities in fusion research and of the fact that in certain areas RFX can provide an important contribution to the progress of the magnetically confined fusion concept. MHD control and edge physics certainly represent topics where RFX shares an absolute interest with the rest of the fusion community. An area of additional interest is also represented by the beam–plasma interaction, since RFX plans to install a power beam and especially after the relevant agreements for the construction of the Test Facility at Padova for the procurement of the ITER beam have been signed. The collaboration activity described in more details in the following chapters mostly falls in one of those three topics.

The improvement obtainable by AC compensation in MHD feedback control has been studied on DIII-D while mode rigidity issues and effects on control of a downgraded mesh of coils have been investigated in collaboration with JT60 SA on RFX itself . At AUG the characteristics of the current filamentation in presence of ELM's have been measured showing the monopolar nature of those currents, while on C-mod the behavior of turbulence outside the separatrix at the L-H transition phase has been analyzed, revealing also interesting analogies of the blobs behavior with RFX. Collaborations started this year will extend the characterization of the filamentary structures observed in RFX and AUG to the tokamak COMPASS and to the Stellarator TJ II to explore the universality of those processes.

The activity on beam–plasma interaction has been concentrated in the collaboration with ENEA Frascati in support of the FAST Project, in which RFX is in charge of the project of a 1MeV beam. Analysis tools have been set up for the purpose in collaboration with CEA Cadarache, CCFE Culham and IFP Milan. The expertise that is being developed is intended also for investigating similar problems on ITER in support of the Test Facility activities.

Activity on JET has mainly concentrated on residual data analysis and on studying proposals for the 2011/2012 campaigns based on exploitation of the ITER–like–wall. It is also worth reminfing that a RFX physicist is still in charge of JET diagnostics within CSU Culham.

On the technology front, besides the activity on JT60 SA reported in Section 7, RFX has continued its collaboration with AUG in the context of the procurement of the power supplies for the in-vessel coils.

4.2 TJ-II , COMPASS and TORPEX

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. It is worth noting that simultaneous measurements of magnetic and electrostatic fluctuations allow obtaining useful information also on electromagnetic features characterizing ELMs can also be obtained, see par. 4.7.1.

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 such kind of structures.

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 specific probe design is in progress including both electrostatic and 2D magnetic sensors arrays. Work is in progress for the final assessment of the probe head design. A 2D view of the current status of the design is shown in Fig. 4.2.1

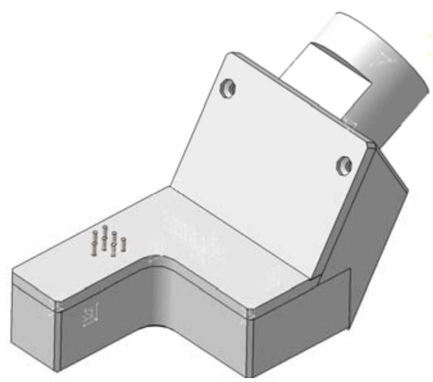

Fig.4.2.1: 2D view of the current status of the design for the probe head to be used in the TJ-II experiment

The experiments in TJ-II will allow to explore also in the stellarator configuration the topic of current density filament structures and to exploit the chance of investigating their presence as a function of beta.

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 is planned to be mounted on the diagnostic port at the LFS above mid-plane. At present the probe head design is in progress in collaboration with the COMPASS team [Spolaore10].

In the TORPEX experiment a detailed investigation of the electromagnetic feature of the blobs emerging from turbulence background has been performed. TORPEX is a toroidal plasma device (R=1 m, a=0.2 m), characterized by open nearly toroidal magnetic field lines, where plasma is produced by EC waves. The drive mechanism for turbulent structures in this case is identified to be ideal interchange. A Stainless steel limiter covers half of the poloidal section on the low field side (see Fig. 4.2.3a). Current density measurements have been performed comparing two independent methods [Furno10]: a directional Langmuir probe and a specially designed magnetic probe, based on three 3-axial magnetic coils arranged so that a direct estimate of $J_{//}=\nabla\times B/\mu_0$ is obtained, a good agreement is found with the two methods. A picture of the current probe and a schematic of probe positioning is shown in Fig. 4.2.3a. A conditional average technique is applied, using as a trigger for blob identification a vertical array of ion saturation current measurements. As an example of the results, a 2D map of the parallel current density corresponding to the field aligned blobs, as measured with the magnetic probe [Vianello10b], is shown in Fig. 4.2.3b.

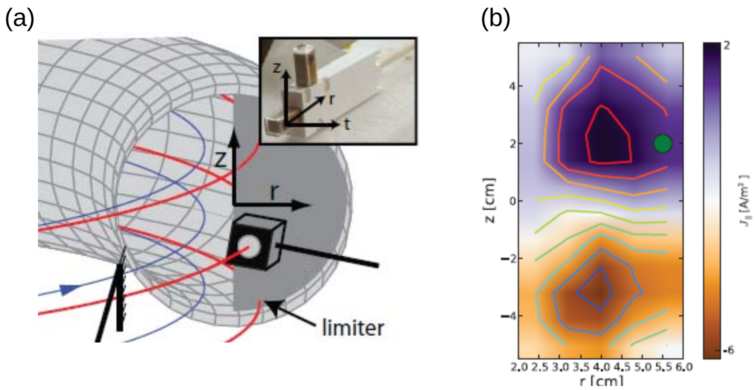

Fig.4.2.3: (a) Picture of the current density probe used in the TORPEX experiment and schematic of its positioning into the vacuum chamber. (b) 2D reconstruction of the current density filaments corresponding to a density blob, obtained on the cross-field plane (r, z)

4.3 FAST

As the discussions towards the definition of the specifications of a European ITER Satellite continue, the FAST project sponsored by the Italian Association has formed in 2010 a preliminary management structure, in which RFX leads the task of the project of a Neutral Beam Injector and participates to the physics and diagnostics groups. In this framework the activity consisted in the development of a preliminary 3D configuration for a NBI in FAST, and in the test of this configuration using NEMO code. Besides contributing to the heating mix, an important scope of an NBI in FAST is the production of a super-alfvénic fast ions population, to excite alfvénic instabilities and study the enhanced fast ions transport these modes produce. The NBI configuration used is similar to the ITER one, with a total injected power of 10MW, 1MeV deuterium ions, a source-plasma distance of about 24 m, a beam tangency radius of 1.285m, and a beam divergence of 0.087*e-3 rad. A scan within a several parameters space was performed using NEMO; the explored quantities were the injection power, species (H and D) , injection angle (on-axis, off-axis) and beam divergence. Among these the most important for FAST conceptual studies are the generated ion density profile as a function of plasma radius and ion velocity, the beam driven current profiles and the beam driven torque profile. Other interesting quantities were calculated as well, such as the lost ion fraction and the beam shine-through. Also full CRONOS simulations were launched: the most relevant study was performed on a target with Ip=7MA, ne0=2.50e20 Te0=15.27e3eV, Ti0=11.48e3eV, which was obtained with 30 MW of injected ICRH power, both in on axis and off axis injection configuration (Fig.4.3.1) [Baruzzo10]. The technical requirements for FAST NBI have been studied as well, the most stringent one being the respect of the space and the distances inside the equatorial port assigned to the NBI. The requirements and the conceptual design of a dedicated system composed by a Beam Source (BS) complete with 1MV extraction and acceleration grids, a Neutralizer, a RID, a Calorimeter, a Vacuum vessel, a vacuum pumping system and a High Voltage Bushing and Transmission Line have been drafted, allowing an estimation of components dimension and features (Fig.4.3.2).

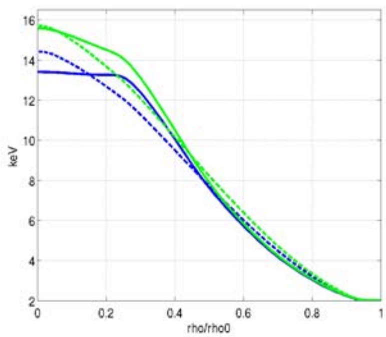

Fig.4.3.1: Electron (dash) and ion temperature (fill) as a function of normalized radius without (blue) and with NBI (green).

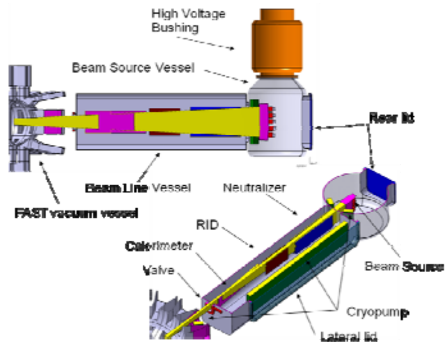

Fig.4.3.2: Beam Source, Beam Line Components and Cryopumps.

4.4 DIII-D

Improved dynamic response of magnetic feedback in DIII-D through AC compensation

The collaboration with the DIII-D team on the magnetic feedback control of MHD instabilities has continued during the last year, with the participation of RFX-mod scientists to the DIII-D experimental campaign. An improvement of the magnetic feedback scheme routinely used in DIII-D has been proposed and developed in collaboration with DIII-D scientists and tested in the machine [Piron2010]. The feedback variable normally used in DIII-D is the so-called "plasma response", i.e. the perturbed n=1 magnetic field at the sensors only due to the plasma. This is calculated in real-time by subtracting from the total sensor signal all the contributions not related with the plasma, e.g. the fields produced by the feedback coils themselves or error fields associated with slightly non-planar equilibrium coils. All these contributions are estimated from vacuum measurements and then used in real-time. Only the DC coupling between the various magnetic field sources and the sensors are normally included in this analysis. In the present work, these couplings have been characterized in a more complete way by measuring the transfer functions between the coils and the sensors as a function of frequency. Any time-varying magnetic field induces eddy currents in the wall, which significantly modify the above mentioned couplings with respect to the DC behavior. A frequency-dependent (AC) compensation scheme has been thus developed and a discrete-time version of it implemented in real-time. Such AC effects are important both for slow dynamic error field correction and for fast direct feedback on plasma instabilities. It has been shown that neglecting the dynamic response of the wall may introduce unwanted error fields in the feedback loop, which eventually play a destabilizing role. This may be particularly relevant in high-β plasmas, where even small error fields are amplified by the strong plasma response. The new AC compensation algorithm has been successfully tested in vacuum and Ohmic discharges. Some preliminary tests at high-β have been also done, but a more detailed assessment of its relevance in these conditions will be the focus of the next 2011 DIII-D campaign.

4.5 JET

Impurity studies

The scan of Ion Cyclotron Resonant Heating power carried out to study the pump out effect of central electron heating on impurities such as Ni and Mo in H mode low collisionality discharges in JET [Valisa 2010] has been studied and documented. The analysis of the transport properties of Ni and Mo injected via the Laser Blow Off has shown that in the plasma centre (at normalized poloidal flux ρ=0.2) the application of ICRH, induces on Ni and Mo an outward drift approximately proportional to the amount of injected power, which above about 3 MW changes the radial flow of Ni and Mo from inward to outward. As a consequence the impurity profiles, extrapolated to stationary conditions, become hollow. The pinch parameter v/D of Ni is particularly well correlated with the change of the ion temperature gradient (see Fig.4.5.1), in qualitative agreement with the neoclassical theory. However, the experimental radial velocity is larger than the neoclassical one by up to one order of magnitude. Gyrokinetic simulations of the radial impurity fluxes induced by electrostatic turbulence do not foresee a flow reversal in the analyzed discharges.

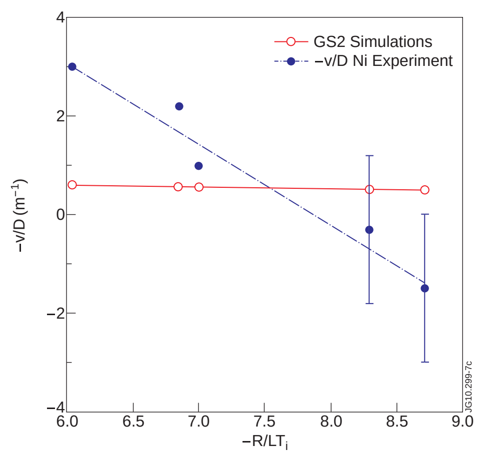

Fig.4.5.1 Relationship between the pinch parameter –v/D of Ni and the logarithmic electron temperature gradient for the shots of a ICRH power scan . The experimental results (full symbols) are compared with the quasi linear simulations (open circles). A linear fit to the data is also drawn.

High Resolution Thomson Scattering

Some work and a visit to JET have been spent to contribute optimising the performance of the HRTS diagnostic, developed by RFX and delivered in February 2009. The work focused on recently discovered problems due to mispositioning of the detectors in the polychromators, on loan from General Atomics and resulted in defining modifications to the polychromators layout, feasible during the 2010 JET shutdown. Collaboration on HRTS data analysis continued and resulted in a publication [Giovannozzi2010].

Preparation of 2011-2012 campaigns

There has been partecipation to the discussion within the working groups set up to prepare the programme of the next campaigns especially in the field of Transport (WG14), Impurity Control (WG5) , Scenario Integration (WG4) and Disruption and Mitigation (WG8).

4.6 JT60-SA

The collaboration with JAEA on the field of active control of RWMs continued in 2010 with the specific subject of studying the effect on the plasma of localized external radial fields. This was done with the help of a set of joint experiments performed on RFX-mod that used a software downgrade of the RFX-mod system of active coils. In this way the negative impact of induced sidebands was highlighted as thoroughly discussed in section 2.4. This collaboration was also coordinated with the Broader Approach activities presented in chapter 7, with the specific aim of giving information useful to the definition of the active RWM control system under design for the new JT-60SA device.

4.7 ASDEX UPGRADE

Edge turbulence

Data analysis on the data collected during 2008 and 2009 campaigns has continued. Strong emphasis has been devoted in the determination of current associated to type I ELMs filaments. It has been previously reported that during ELM crashes, magnetic perturbation as recorded by miniaturized 3-axial pick-up coils lodged on the mid-plane manipulator are essentially due to current filaments passed in front of the measurement points, as the spectral properties revealed by the Degree of Polarization method are inconsistent with propagating MHD waves. Current associated to the ELM filaments may be experimentally observed on magnetic signals looking at the hodogram, i.e. considering the magnetic field trajectory on the plane perpendicular to the direction of the current, shown as an example in figure 4.7.1. In the same figure (panel (b)) simulated hodograms for a monopolar (red) or bipolar (blue) current distribution are shown. The shape of the hodogram in the case of a bipolar current reveals the presence of a cusp at the origin, and the fields fluctuations occupy at least 3 of the quadrants in the perpendicular plane: all these characteristics can't be recognized in the experimental data, so that we can state that monopolar currents are associated to ELM filaments.

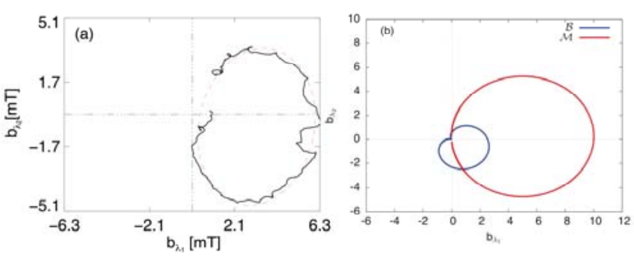

Fig.4.7.1: (a) Hodogram of the magnetic field associated to an ELM filaments (b) Simulation of the expected hodogram associated to a monopolar (red) and bipolar (blue) current

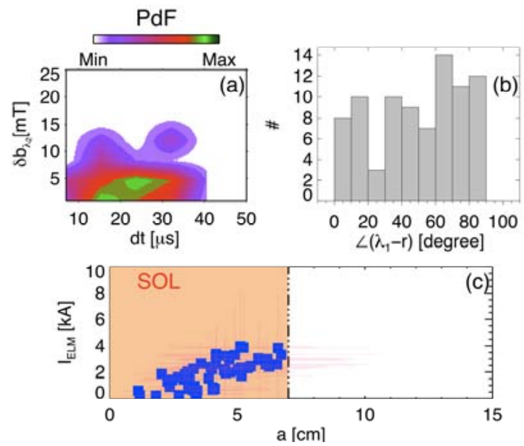

Fig.4.7.2: (a) 2D PdF of Δt and b fluctuations used for the estimate of the current (b) angle between filament propagation and radial direction c) current associated to single filaments plotted vs the distance of closest approach

Within this assumption an estimate of the current associated to single filaments may be done: assuming that a filaments with velocity *v* is propagating in the λ_1 direction perpendicular to λ_2 and naming *a* the distance of closest approach the current may be estimated as $|b_{\lambda_2}(\lambda_1 = a)| = \frac{\mu_0 I}{4\pi\Delta t v}$ being Δt the time delay between the maxima of the magnetic field perturbation of the two components. The statistics on a set of filaments obtained in 4 similar discharges is shown in figure 4.7.2. Current up to few kA are observed and within the assumption of the method, all the filaments are observed within the Scrape Off Layer [Vianello09].

Power supply system for AUG in-vessel coils

In 2007 IPP and other European laboratories (FZJ, KTH, and Consorzio RFX) proposed a 5 stage project to install in-vessel coils (of two types, dubbed "A" and "B") and a partial Conducting Wall (CW) inside ASDEX-Upgrade together with the coil Power Supplies (PS). In stage 1, 2 the B and A coils are provided; in Stage 3, 4 and 5, twelve fast ac PS, the CW and the remaining 12 PS will be procured respectively. The physical objectives of the new system is to study the ELM suppression/mitigation, contributions to NTM control and studies of Resistive Wall Modes including Resonant Field Amplification for stability testing.

Stage 1 should be concluded in 2011 with the installation of the last B coils, Stage2 & Stage3 proposals have been presented together at the Ad-hoc Group (AHG) meeting on 10-11th November; AHG expressed positive judgment and recommendation that Stage 2 & 3 proceed.

The Consorzio RFX contribution during 2010 has mainly consisted in the development of the Conceptual Design of the Power Supply System. The initial phase was devoted to the definition of the electrical requirements needed to assure the system performance; this activity has been performed in strong collaboration with IPP colleagues to assure a deep reciprocal understanding of the physical and technological aspect of the project. In parallel the conceptual scheme has been worked out: the selection of the topology, the semiconductor rating and switches modulation law has been derived from an iterative process aimed at reaching a satisfactory compromise among performance, availability, cost and size.

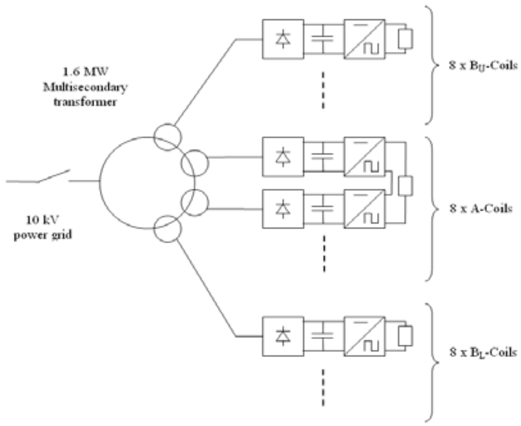

Fig.4.7.3: Overall scheme of A and B coils Power Supply. The input section is composed of a Multisecondary Resin Transformer, the input sections of each power module are composed of a precharge circuit, a diode bridge rectifier and a dc-link capacitor. The dc-ac converters are based on IGBTs H-bridges.

The solution adopted for the A-Coils Power Supply, which requires 1 kV output voltage, 1kA output current with 3 kHz bandwidth, is based on a multilevel inverter in Cascade topology, while the B coils requirements can be fulfilled by a single PS module.

The overall power supply system is depicted in Figure 4.7.3; it is customized for the different demands relevant to the specified controls for A and B coils but, at the same time, it has a sufficient modularity degree.

Further design work is still in progress to analyse the effect of different location of the grounding connections and schemes for EMI filters to mitigate the common mode stray currents.

4.8 ALCATOR C-MOD

The behavior of turbulence (measured with the GPI in the outer midplane) of Alcator C-mod tokamak for different normalized density have been characterized, in order to study the role of the plasma edge and SOL as a function of plasma density, with an eye toward the role that the turbulence may play in the physics of the empirical density limit [Greenwald02]. The properties of the edge change with increasing the plasma density.

The poloidal velocity v_θ measured outside the separatrix, for $n/n_G > 0.3$ can reverse its "standard" direction. For low density the poloidal phase velocity is in the ion-diamagnetic drift direction. At higher densities ($n/n_G > 0.3 \div 0.4$) the fluctuation phase velocities in the most external region are observed to propagate in both the ion and electron diamagnetic drift directions. If the velocity of the edge fluctuations is mainly the **E**×**B** one, this should mean a change in the sign of the radial electric field that occurs at higher density in the far SOL. This behavior reminds a similar phenomenology observed also in RFX-mod at high n/n_G [Spizzo10].

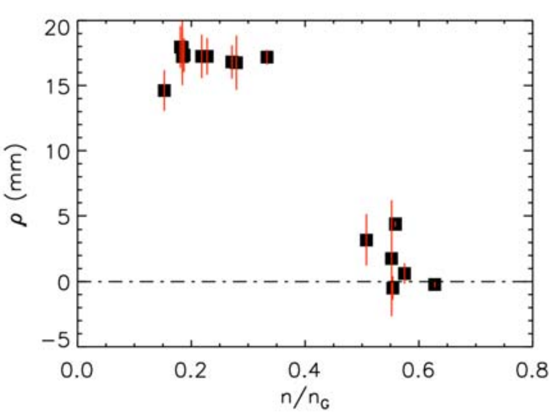

Fig.4.9.1: Radial position (respect to the separatrix) where the blobs are "born" as a function of the density normalized to the Greenwald one.

Looking at the radial velocity of the SOL fluctuations using the cross-correlation technique, it shows a strong scaling with n/n_G: v_r increases with the normalized density, from about 0.5 km/s at $n/n_G \sim 0.2$ to 1.5 km/s for $n/n_G \sim 0.8$.

Increasing the normalized density, together with the increase of the outward radial velocity, the edge region dominated by the turbulence extends more inside, toward the separatrix; at low density, most of the fluctuations are in the far SOL. Moreover, with the conditional average technique, it is possible to measure the radial position respect to the separatrix, where the blobs are born, on different discharges characterized by different densities. For $n/n_G < 0.3$ the blobs are born about ρ = 20mm outside the separatrix, and both the spatial and temporal correlation is high only for $\rho > 0$; for $n/n_G > 0.3 - 0.4$ the blobs are born near or inside the separatrix as shown in figure 4.9.1, and so the radial region dominated by structures and strong correlated fluctuations moves also at $\rho < 0$ [Agostini10].

All these observations suggest that the edge plasma and the perpendicular transport due to edge and SOL turbulence is clearly involved with the empirical density limit, though the casual relationships are still unclear.

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5. THEORY AND MODELLING

5.1 Background: achievements and perspectives

In 2010 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) uncovering the relevant micoturbulence ruling transport at internal transport barriers.

The extensive benchmark of the advanced MHD code PIXIE3D with the SpeCyl code, initiated in 2009, was extended to the 3D case for both tokamak and RFP cases, and a paper was published. This is the first successful nonlinear 3D verification benchmark of MHD codes in the fusion community. Numerical studies of finite beta and toroidal geometry effects in the RFP with PIXIE3D are now ongoing. The benchmark of the volume preserving field line tracing code NEMATO coming with PIXIE3D was completed. A paper with both this benchmark and a study of chaos healing in the quasi-helical RFP was submitted for publication.

The study of the effect of rotation and dissipation on resistive wall modes (RWM) in RFP's was completed by a numerical approach. This clarified the difference between internal and external RWMs. The response of the plasma to feedback control was completed and a paper was submitted for publication.

The q profile computed with respect to the helical axis was found to have a maximum both in DAx and SHAx states for experiments and numerical simulations performed with the visco-resistive MHD code SpeCyl. A simple code to compute cylindrical ohmic RFP equilibria, was developed; it questions the validity of discarding the velocity field in such calculations.

The nonlinear fluid code TRB and the GS2 gyrokinetic code were used to simulate ion temperature (ITG) gradient dynamics in RFPs. It was shown that, whenever impurity effects are neglected, ITG modes can hardly become unstable in present experimental conditions because of a stronger Landau damping than in the tokamak. Analytical calculations showed impurities may destabilize ITG modes. GS2 linear simulations revealed that microtearing modes may be unstable at the electron temperature barriers of RFX-mod, and may provide a contribution to the thermal diffusivity compatible with experimental power-balance estimates.

Transport modeling was performed with the ASTRA code. The conductivity profiles exhibit a minimum at the middle of the SHAx transport barriers, with values as low as 5 m^2s^{-1}. The thermal conductivity in the barrier decreases with the amplitude of secondary modes, confirming that magnetic chaos created by the secondary modes still plays a role in the energy transport through the barrier.

In order to understand the link found experimentally between the edge turbulence level and the ratio of the edge density to the Greenwald limit, the study using the ORBIT code to compute the edge electric field was continued with the inclusion of a recycling at the wall. A good agreement with the experimental profiles of the edge electric field was found and a paper was published.

5.2 Extended magnetohydrodynamics modeling

PIXIE3D - SpeCyl and NEMATO numerical codes: verification studies

The nonlinear 3D MHD codes SpeCyl and PIXIE3D have been carefully benchmarked in their common limit of application (visco-resistive MHD in a cylinder) [Bonfiglio10a, Bonfiglio10b]. The two codes agree in their description of the nonlinear dynamics for (2D) Tokamak-like and (both 2D and 3D) RFP configurations, providing for the first time a successful nonlinear 3D verification benchmark of MHD codes in the fusion community. To show the excellent

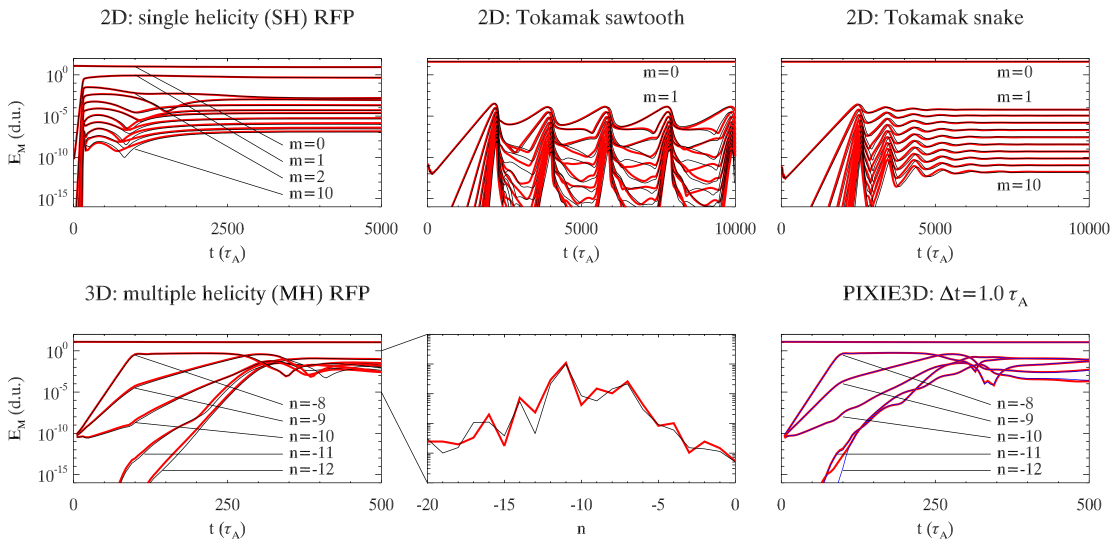

FIG. 5.2.1: Nonlinear verification benchmark: Magnetic energy evolution from SpeCyl and PIXIE3D (black and red curves respectively). Top panels) RFP and Tokamak 2D dynamics. Bottom left) 3D RFP case. Bottom right) PIXIE3D with different time steps (red Δt=5x10-3 τ_A and blue Δt=1 τ_A)

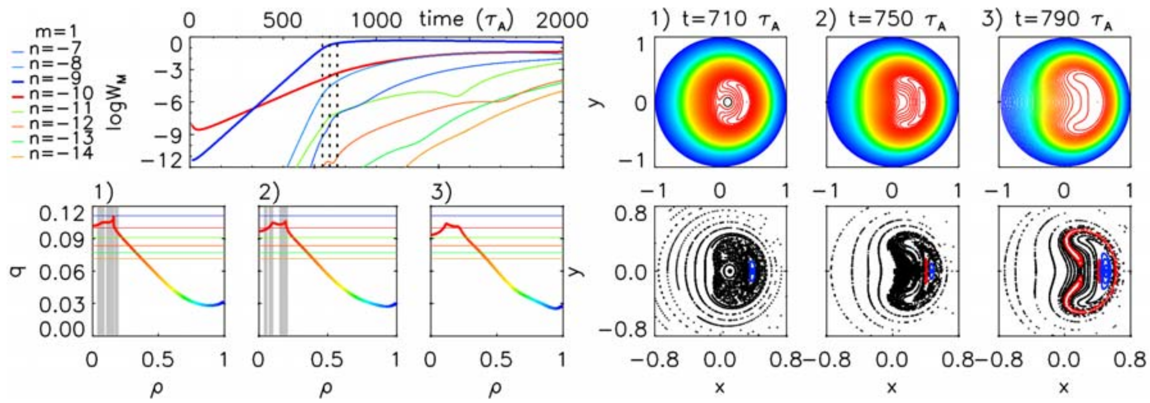

FIG. 5.2.2: Chaos healing effect at a transition to quasi-helical SHAx state along a SpeCyl simulation. . Temporal evolution of the magnetic energy of m=1 modes (top left panel). For three chosen times are shown: helical flux surfaces (top right) and helical q-profile (bottom left) given by the dominant n=-9 mode (being ρ the flux function label), Poincaré plots (bottom right) by the code NEMATO

agreement between the two codes in both linear and nonlinear phases, the temporal evolution of magnetic energy for MHD modes is plotted in Fig.5.2.1 for different 2D and 3D simulation cases. The capability of the fully implicit PIXIE3D code to work with time steps comparable with the Alfvén time without loss of accuracy is also shown. Numerical studies of finite beta and toroidal geometry effects in the RFP with PIXIE3D are now ongoing. Together with this MHD tool, the field line tracing code NEMATO [Finn05] for magnetic topology studies has also been benchmarked against the magnetic flux surfaces computed from a 2D magnetic field (with either helical or poloidal symmetry) provided by MHD simulations.

This volume preserving tool is suitable to deal with 3D cases characterized by weak chaos, like in the RFP. In Fig.5.2.2. we show a first application on a SpeCyl simulation case featuring a transition to a SHAx regime: the chaos healing effect after the expulsion of the magnetic separatrix of the dominant mode's island, highlighted in previous works [Escande00], has been clearly confirmed. In DAx stage a maximum in the helical q profile indicates the position of the dominant mode island separatrix. While mode amplitudes increase the magnetic chaos by secondary modes spreads inside the dominant island. A secondary reversal of the magnetic shear occurs rather soon in DAx stage. Minor conserved structures start to appear at the location of such secondary q-maxima (local healing of the chaos previously generated). Finally, after expulsion of the dominant mode separatrix -SHAx stage- chaos is definitely removed, despite further growth of secondary modes [Bonfiglio10c, Cappello10].

Resistive Wall Modes (RWM) and its feedback in RFPs : Physical understanding and kinetic effects

A cylindrical MHD model integrating feedback was applied to the study of RWM in Reversed Field Pinch plasmas. The model takes into account the compressibility, longitudinal flow, viscosity, and resistive wall with finite thickness [Guo99, Wang10a]. The study, via both analytical and numerical (CMR-F code) analysis, clarifies several issues [Wang10b]:

(1) The nature of the instability spectrum of the RWM observed in RFP plasmas. Specifically, the growth rates of the two groups of RWMs, internally non-resonant modes (INRM) and externally non-resonant modes (ENRM), have opposite dependence on the variation of the field reversal parameter F. The study follows the variation of F-Θ curve provided by experiments. It is found that for each RWM (m=1,n) perturbation, along the F-Θ curve the plasma potential energy δW_p remains almost a constant value. It seems for whatever reversal (F) of the discharge, RFP plasmas automatically adjusts its current profiles and the Θ value, in order to keep constant and small its potential energy. Therefore, the dependence of the growth rates of the RWM instability on the parameter F or Θ is due to the variation of the vacuum potential energy component δW_{vb}. Since the q values of INRM and ENRM are opposite in RFPs, they bend in opposite ways the magnetic field lines in the vacuum region. As a result their vacuum potential energy δW_{vb} varies in opposite directions with F, and leads to opposite shifts of the mode growth rates. Fig. 5.2.3 shows the potential energies δW_p, δW_{vb} and $\delta W_{v\infty}$ as functions of F and the associated growth rates for (1,-6) and (1,3) modes.

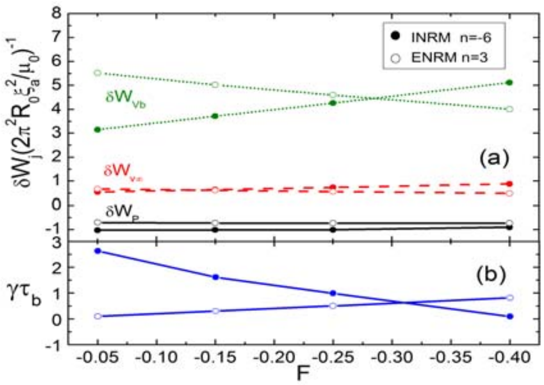

Fig.5.2.3: (a) plots the potential energy components of INRM m=1, n=-6 (solid circle) and ENRM m=1, n=3(hollow circle) as the function of reversal parameter F along experimental F-Θ curve, where δW_p,$\delta W_{V\infty}$,δW_{Vb} are presented by solid line, dash line and dot line respectively. (b) The growth rate of two modes is plotted as the function of F.

(2) The study also clarifies how the plasma responds to the feedback control action. The investigation considers two cases, without and with plasma rotation. It is found that actually the eigenfunction inside the plasma is uniquely determined by the plasma equilibrium (except for a normalization factor) and is independent of the feedback actions. The plasma is found to be potentially unstable to the external kink (δWp<0) even when the feedback stabilization of RWMs exists. The role of the feedback control is to contribute a new eddy current to modify the one induced by RWMs in the wall. Therefore the investigation of the feedback control can be limited to the vacuum region if the RWM growth rate without feedback is known, and if the change of the plasma equilibrium during the feedback can be ignored.

(3) The linear solutions of time evolution of the RWM instability under various feedback scenarios were given. The effects of the wall proximity, the sensor location and the system response time were analyzed. Fig.5.2.4 is an example of the time variation of the radial magnetic perturbation under the feedback control both inside and outside the plasma.

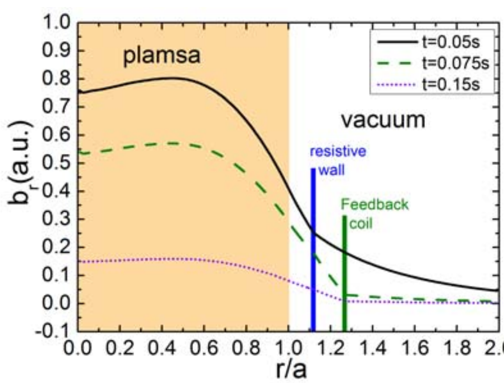

Fig.5.2.4: Evolution of the magnetic perturbation br(r,t) of m=1 n=-6 mode versus radial position r in both plasma and vacuum regions, when the mode is damped by the feedback system (the feedback control is applied at t=0.05s), where F=-0.05, Θ=1.417 and βp=0.02, and RFX-mod parameters are adopted.

The RWM study in toroidal (2D) started by using the Mars-k code, which is taking into account kinetic resonance effects. This code was transferred to the RFX server, and several improvements have been made: the parallelization for improving the efficiency, and the implementation of new functions for calculating and plotting the trapped/passing particle fractions and their corresponding frequencies. The preliminary study shows kinetic effects do not influence RWMs significantly in RFP. Several parameters (e.g. equilibrium parameters and plasma rotation) must be scanned to check this result.

5.3 Reconstruction of helical equilibria

Since the non-axisymmetric magnetic field amounts only to a few percents of the axisymmetric one, a first description of SHAx states was obtained by computing the perturbative solutions of the force balance equation in toroidal geometry with no pressure, performed by means of the NewCombToroidal code (NCT) [Zanca04]. The SHAx equilibria can be modeled as pure Single Helicity states, composed by the superposition of the zero-th order axisymmetric equilibrium and of the $m=1,n=-7$ eigenfunction. As had been done previously in numerical simulations, the shape of helical flux surfaces was computed through the helical flux. This enabled re-mapping the profiles for diagnostics giving multi-point or multi-chord measurements, such as electron temperature by the TS diagnostics, electron density and SXR brightnesses.

The safety factor q of the helical equilibria differs from the q profile of the axi-simmetric equilibrium (q_{axi}). The q value is computed using the helical flux function χ which turns out to be the Hamiltonian of magnetic field lines. Action-angle coordinates enables to compute the pitch ι_h of magnetic field lines in a frame where the contour of magnetic surfaces is stationary. Taking into account the 7-fold twist of the magnetic axis, one finally finds that $q=1/(\iota_h + 7)$.

The q profile in SHAx states exhibits a maximum and its slope changes sign, implying the presence of a significant magnetic shear. The location of the change of q maximum is well correlated with the location of the ITBs, as measured by the TS diagnostic [Gobbin10].

The presence of a maximum in the q profile is also found in 3D MHD simulations performed in cylindrical geometry with the SpeCyl code [Cappello2004], when the final SHAx state is the result of a transition from a DAx state. Helical equilibria are obtained in the code through the non linear saturation of a single perturbed m =1,n mode. The geometry of the SpeCyl simulations and their initial conditions are such that the innermost resonant mode is the n = −10 one. The q profile of the nonlinearly saturated helical state is obtained by applying the standard definition $d\psi_{tor}(\rho)/d\psi_{pol}(\rho)$. The shape of the q profile depends on the n number of the mode, as can be seen in Fig. 5.3.1. In particular the n = −8 and n = −9 SHAx equilibria, which are obtained after the saturation of a non-resonant kink mode (without going through a DAx state), are characterized by a monotonic q profile. On the other hand, when the SHAx equilibrium is reached as a saturation of a resonant resistive kink-tearing mode (as for −10 and for −11 helicities) i.e. after a transition from a DAx to a SHAx topology, the corresponding q profile takes a peaked shape.

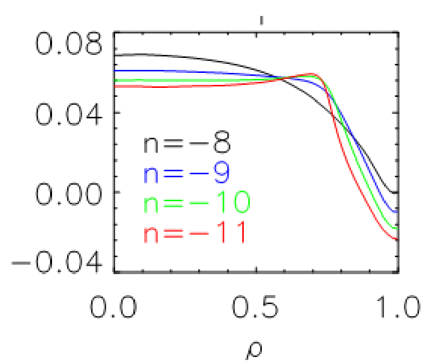

Fig. 5.3.1 q profiles corresponding to different helical equilibria provided by visco-resistive MHD simulations (SpeCyl code) for m = 1 modes with n varying from n = −11 to n = −8.

The helical states have also been described by the VMEC code (see section 2.6), which was modified because, differently from tokamaks and stellarators, the RFP requires the poloidal flux as a surface label, due to the reversal of the edge toroidal field.

Helical Grad-Shafranov equation and ohmic constraint

Numerical methods for the reconstruction of the single helicity ohmic equilibria are being developed in cylindrical geometry. The simplest approach appears to be the iterative solution of the helical Grad-Shafranov equation coupled with the ohmic constraint. In fact, this model consists in solving equilibrium equations, which involve the magnetic field only. The velocity related terms are discarded in the Grad-Shafranov reduction of the motion equation, while the $\mathbf{V}\times\mathbf{B}$ product of the Ohm's law is eliminated in the ohmic constraint by the scalar product with $\mathbf{B}$. The method iterates two steps. In the first step the parallel current profile λ is defined as a function of the helical flux χ by the ohmic constraint. The second step transforms λ into a function of the geometrical co-ordinates, and uses it as input for the Grad-Shafranov equation. This equation is in fact solved as a system of independent ordinary non-homogeneous differential equations for the harmonics of the new χ. A fixed pressure profile $p(\chi)$ can be included in the computation. The initial equilibrium is assumed to be a zero-pressure paramagnetic pinch with a small helical perturbation whose radial profile satisfies the Newcomb's equation. The iteration converges to a solution for the m=2, n=1 helicity of a tokamak. On the contrary, the method fails for the m=1 helicities of RFP configurations computed with the visco-resistive MHD code SpeCyl. This suggests that the velocity terms, viscosity in particular, discarded by the Grad-Shafranov equation are crucial for the RFP helical ohmic equilibria. The study of an equilibrium computation which includes these effects is under consideration.

Necessary criterion for the reversal of magnetic field in RFP's

A necessary criterion for the reversal of the axial magnetic field of ohmic single helicity states of the RFP was derived analytically. This was done in the frame of resistive magnetohydrodynamics in cylindrical geometry by using perturbation theory for a paramagnetic pinch with low edge conductivity and axial magnetic field. The criterion involves the radial profile of the logarithmic derivative of the Newcomb eigenfunction of the pinch. It is suggestive that a finite edge radial magnetic field might be favourable for field reversal. In accordance with this, visco-resistive MHD simulations showed that helical equilibria with smaller maximum radial magnetic fields achieve reversal when a finite edge radial magnetic field is applied. Numerical simulations also show that the criterion works for large perturbations of the pinch too, in particular those leading to states with a single helical axis. The necessary criterion was found to be satisfied for reversed states where a finite edge radial magnetic field is driven in the RFX-mod machine [Bonfiglio10d].

5.4 Electrostatic and electromagnetic microinstabilities

In the helical RFP transport appears to be no longer dominated by magnetic chaos. This raises the question whether small-scale transport mechanisms, until now overshadowed by the large scale MHD turbulence, may rule the fundamental properties of the RFP plasma. To this purpose, Ion Temperature Gradient (ITG) turbulence has been considered first. In 2008 Guo showed analytically that ITG modes are more stable in the RFP than in the Tokamak because of a stronger Landau damping due to the shorter field connection length [Guo08]. In the last two years different numerical tools, originally developed for tokamak turbulence studies, have been adapted to the RFP: the nonlinear electromagnetic flux-tube gyrokinetic code GS2 and the full-radius fluid electrostatic code TRB. In addition, an integral eigenvalue approach, retaining full Finite-Larmor-Radius effects has also been used. The main modifications needed to deal with the RFP geometry are related to the large poloidal component of the magnetic field: hence curvature and grad B drifts enter the equations within a different ordering than in a tokamak.

All approaches agree that, neglecting impurity effects, ITG modes can hardly become unstable in present experimental conditions. Due to a lack of direct measurement of ion temperature gradients, such studies have been carried out considering them in the range of 0.5÷1.0 times the electron ones. Marginal stability conditions are reached locally in QSH states with the steepest temperature gradients, or in the plasma edge. Landau damping is confirmed to be the most important vehicle to damp ITG turbulence. At mid-radius the normalized logarithmic temperature gradient R/L_{Ti} has typically to exceed a threshold more than a factor R/a larger than in a tokamak to trigger this instability (Fig.5.4.1), see Refs. [Predebon10, Sattin10, Liu10]. Other analyses carried out in this field include: i) studies on the effect of impurities and non-adiabatic electrons on ITG instabilities; ii) occurrence of Trapped Electron Modes (TEM); iii) first nonlinear (fluid) simulations of ITG turbulence; iv) extension to linear investigations on electromagnetic instabilities; non-linear electrostatic drift wave simulations of the electron temperature flattening in the core.

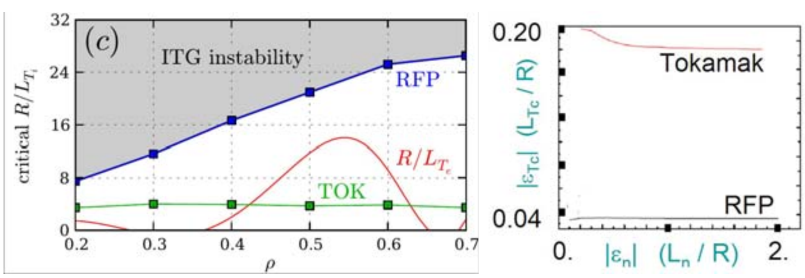

Fig.5.4.1: Comparison of ITG threshold values between RFP and tokamak. a) GS2 results: threshold (critical R/L_{Ti}) as a function of the normalized plasma radius for a typical RFP (blue line) and tokamak (TOK green line) case, with the experimental estimate of R/L_{Te} (red curve). b) Integral eigenvalue approach results: the ITG stability threshold is shown as a function of the density gradient (ε_n=L_n/R) for both RFP and tokamak.

RFX-mod plasmas are ordinarily polluted by carbon and oxygen impurities, yielding Zeff ≥ 2 throughout most of the radius, which could modify the ITG stability threshold. Analytical calculations showed impurities can destabilize ITG modes when $L_{eZ} = L_n/L_Z < 0$ (L_n and L_z are the density gradient scale length of the hydrogen and of the impurity respectively). In RFX-mod the impurities tend to remain concentrated nearby the plasma edge, around the region of r > 0.6a, where the condition $L_{eZ} < 0$ is easily verified. In fact, an integral eigenmode equation shows that in the r>0.6a region ITG modes can be unstable. The Impurity Driven Mode [Dong95] may also become unstable in the experimental conditions.

In the ITG mode study, the trapped-electron effect has not significant influence on the mode behavior. This is expected since the mode propagates in the ion diamagnetic drift direction and no resonance is found in the trapped-electron response. Only a slightly destabilizing effect is found, but the critical temperature gradients are essentially unaltered.

There are preliminary indications that Trapped Electron Modes (TEM) instabilities can arise in the presence of strong enough density gradients. In the limit R/L_n » 1, GS2 simulations show that TEMs are the dominant electrostatic instability at work at the ion Larmor radius scale. This result is also confirmed analytically, by solving the differential eigenmode equation. However, RFX-mod plasmas are usually characterized by flat core density profiles. TEM turbulence is therefore expected to potentially play a role in the edge of the RFP plasma only.

Being a global code, TRB allows for studying possible synergies between different turbulence drives, spatially extended and not necessarily localized at the same position. As a first case test we started studying the relaxation of an initial linearly-ITG-unstable temperature profile under the action of the self-consistent ITG-driven conductivity with a given fixed heat source across the plasma radius. Initially ITG-unstable ion temperature profiles evolve consistently under self-generated turbulent transport towards marginal conditions for ITG turbulence.

GS2 linear simulations have been performed including fluctuations in the magnetic vector potential. The occurrence of microtearing (MT) instability has been revealed at the electron temperature barriers of RFX-mod [Predebon10b]. The growth of MTs may lead to chains of overlapping magnetic islands and subsequent local stochastization of magnetic field lines. Hence MTs may provide an effective contribution to the thermal diffusivity through electron parallel motion along the wandering field lines. An estimate of the related heat conductivity via the usual Rechester–Rosenbluth quasi-linear expression yields the value ≈ 5÷20 m^2/s, compatible with experimental power-balance estimates at the ITB. Concerning the central flattening of the temperature in SHAX states, a model has been developed to describe radial heat transport as a result of electrostatic drifts, originating from magnetic field curvature [Sattin11]. The resulting profiles fairly agree with the experimental ones.

5.5 Experimental transport simulations

The ASTRA code (Automated System for Transport Analysis) is used for transport simulations of tokamak and stellarator plasmas. In collaboration with IPP-Garching and CIEMAT-Madrid its implementation started at RFX in 2009, with the view that the SHAx states require transport modeling suited for helical symmetry.

ASTRA is a 1.5-D transport code which solves transport equations of quantities (particle, electron and ion energy) averaged on the flux surfaces. The equilibrium given as an input to the code was calculated as the composition of the axisymmetric equilibrium plus the dominant mode eigenfunction. The thermal conductivity, estimated on the basis of a power balance analysis, has been calculated for more that 100 SHAx states. The corresponding profiles exhibit a minimum at the middle of the barrier, with values as low as 5 m^2s^{-1}. The thermal conductivity in the barrier decreases with the amplitude of secondary modes, as shown in Fig. 5.5.1. This is valid both for the minimum value and for its average value. This fact confirms that the magnetic chaos created by the secondary modes still plays a role in the energy transport through the barrier.

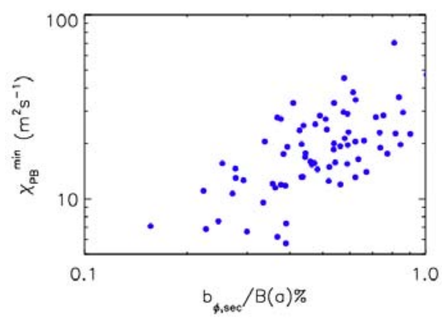

Fig.5.5.1 Minimum of the thermal conductivity at the barrier vs secondary mode amplitude

5.6 Greenwald density limit

As explained in Section 2.5.4 (*High density limit*) of the chapter on RFX-mod program, the Greenwald density limit in RFX-mod is likely to be explained by the presence of two null points of the edge radial electric field $E_r \approx v_\phi x B_\theta$ along the toroidal angle. ϕ. A numerical estimate of E_r is provided by the Hamiltonian guiding centre code ORBIT [White84]. The code follows both the electron and ion dynamics in a layer next to the wall and evaluates the radial ambipolar electric field from the balance of the two fluxes, the latter being influenced by wall recycling (particle source). The structure of the radial electric field depends on the way the electron diffusivity is modulated by the magnetic pattern, namely by the (m=0,n=1) island. The electron diffusion in fact is lower in the X-points than in the O-points of such islands, while ions have comparatively larger drifts (due to their larger mass) and their radial motion is more uniform along the toroidal angle. The X-points are therefore regions where localized particle accumulation likely develops, bringing about a modulation of E_r of the same geometry as the parent magnetic island [Spizzo10].

5.7 Check of the universality of the RFP helical self-organization process

A comparison between QSH regimes obtained in MST & RFX-mod experiments has been undertaken. First analyses have been presented at the American Physical Society conference Division Plasma Physics [Franz10]. Helical magnetic self-organization is observed on a clear statistical basis in both MST and RFX, with similar qualitative trend. Magnetic bifurcation and thermal properties (i.e. presence of transport barriers, density control & refueling…) still need a detailed diagnosis, in particular concerning the temporal behavior/dynamics within QSH stages in both machines. The comparison will contribute to clarify the issue of the relevant dimensionless parameters ruling the experimental bifurcation to SHAx.

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6. RFX-mod DIAGNOSTICS

6.1 Background: achievements and perspectives

Significant progress in the diagnostic capability was achieved in 2010 as most of the planned activities were successfully completed. Among the most significant achievements it is worth mentioning:

- The commissioning of the room temperature solid pellet injector which has been extensively used for wall conditioning
- The routine operation of the Ka band of the microwave reflectometer, which now complements the measurements of the Thermal He beam diagnostic and of the edge Thomson scattering to investigate the edge confinement barrier
- The first ion temperature data coming from the new NPA diagnostic on loan from IPP Greifswald
- The commissioning of the new horizontal SXR tomography camera
- The repair of the FIR polarimeter, which now has improved resolution thanks to the modification to operate at longer wavelength
- The significant progress in the understanding and solution of the measuring problems of the CXRS/DNBI, which started producing some preliminary data.

On the other hand, the realization of the 2010 diagnostic development program was severely affected by budget limitations. In particular some projects were stopped or postponed, such as the Fast Reciprocating Manipulator, the new sources for the microwave reflectometer, the power supply for ion saturation current measurements and then Lithium neutral beam diagnostic. These projects have been transferred to the 2011 program.

6.2 FIR Polarimeter

At the end of 2009 the 150W CO_2 laser that optically pumps the FIR cavity of the polarimeter caught fire, likely because of an electrical discharge inside the case of the laser. Not only had the fire destroyed cables and cooling pipings and damaged the discharge tube and the cavity optics of the CO_2 laser, but also the acid smoke generated by the combustion of PVC components caused a chemical corrosion process of all the metal parts of the components installed in the FIR room, including mountings of the optics, wheel of the chopper, some parts of the mechanical structure of the dry air box that contains lasers and beams and some parts of the air dryer machine.

The first six months of 2010 were devoted to restore the damaged parts. The CO_2 laser was sent to the manufacturer (Edinburgh Instruments) for repair, whereas professional treatment or replacement of rusted parts was performed. In the meantime, two important actions to further improve the performance of the diagnostic have been done:

- the design and realization of new pre-amplification boards for the detectors, with miniaturized components and shorter PCB tracks, in order to reduce their sensibility to stray magnetic field and to better the S/N ratio,
- the modification of the diagnostic to allow operation at the longer 184 μm FIR wavelength (as an alternative to the design one at 119 μm), which gives an improved measuring resolution since the Faraday rotation of the polarization angle depends on the square of the wavelength.

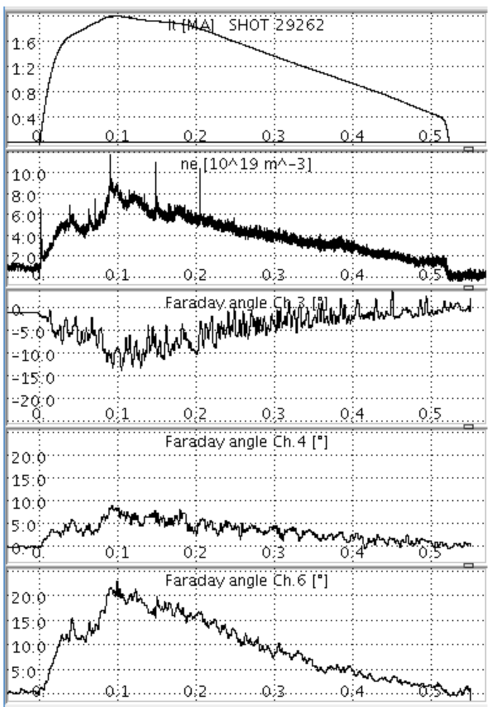

Fig.6.2.1: Time evolution of the Faraday angles measured after the upgrade to λ=184 μm

We studied the possible critical aspects of the operation at the longer λ. We found that an adequate focusing and beam diameter along the whole beam path is possible simply with a proper tuning of the telescope, that transmission/reflection coefficients of beam splitters and windows are acceptable also at the new λ, and that the only components that need to be changed are the half wave plates. When, in June 2010, the repaired CO_2 laser was set in place, we decided to switch to the 184 μm operation, even if we had the half wave plates for three chords only (they were installed on chords #3, 4, 6 with impact parameters respectively -0.06, +0.06, +0.31 cm), in order to test the advantages of the new configuration. The beam diameters across the windows, the most critical point along the path as regards the optic/beam diameters ratio, were tested by irises mounted on the ports, that also allowed a very good centering of the beams through the pipes. After alignment of the whole line, the polarimeter has been running during the summer experimental campaigns at high current, up to the shutdown. Fig.6.2.1 shows the Faraday rotation signals measured by the chords in a discharge at 2 MA of plasma current. The advantage of higher sensitivity is particularly evident for the central chords (#3 and 4) for which the angle to be measured is small: at 119 μm the angles are 2.4 times smaller, and the relative error would have been >100% for a large part of the discharge. The absolute error on the measure (as deduced by the zero-line before and after the pulse) is estimated to be 1-2°, the same as the best results obtained in 2009 in discharges at lower plasma current, proving that the new electronics allows good measurements also in the worst environmental conditions (i.e. Ip 2MA).

6.3 Thomson Scattering

As far as the Main Thomson Scattering is concerned, in 2010 a new laser was ordered to replace the present one. This latter was produced and installed at the beginning of 90s, and it suffers now from lack of reliability.

The new laser was bought from the Russian company L.o.S.; it will have the same beam characteristics as the present one (e.g., laser energy, beam diameter, beam divergence), with a higher repetition rate and a higher number of available pulses: instead of 10 pulses at 40, the new diagnostic will produce 100 pulses at 100Hz. The new laser is scheduled to be delivered by January 2011. The Laser room has been remodeled (new walls, moved electronic cubicles, new cabling) in order to accommodate the new laser. An automatic windows cleaning system (not requiring a vacuum break) was further developed and used for TS main windows, which typically loose their transparency during RFX-mod operation (due to frequent GDCs, boronization and more severe impurity deposit due to stronger plasma-wall interaction at high plasma current). The system was also tested on the internal mirrors of the Zeff diagnostic.

Regarding the Edge Thomson Scattering, a new acquisition system has been tested during the year. A modification of the shutter in the entrance window has been also designed and built in order to reduce the contribution of stray light (which was the measurement main problem).

6.4 New horizontal SXR camera

The soft x-ray (SXR) tomography has been upgraded with the installation of a modified version of the horizontal manipulator. The new movable camera is equipped with a total of 65 photodiodes (instead of the 21 of the previous camera) grouped in three arrays of 19, 27 and 19 diodes respectively. Each array has its own Be foil, allowing the measurement of the SXR emissivity in different energy ranges. In this way, the SXR tomography can be extensively used either to reconstruct the SXR emissivity (through the measurements of all the arrays with the same Be foil) or the plasma electron temperature, T_e, along the entire plasma radius (through the two-foil technique, by using the measurements from the diodes with different Be filters). The spatial resolution is about 2 cm and time resolution is 10kHz or better (up to 50kHz) if the plasma is hot enough. A significant effort has been devoted to reducing electrical noise due to currents flowing in the toroidal windings: a suitable combination of screening and reduced signal cable length was finally found in June, allowing to place the order for the cables. Final

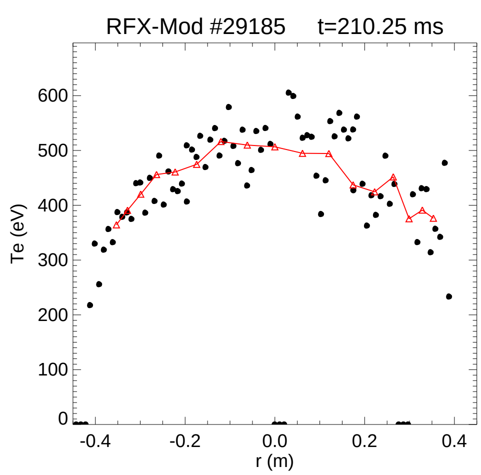

Fig.6.4.1: Electron temperature radial profiles from Thomson Scattering (black points ●) and SXR tomography (red triangles Δ).

cabling was performed in June and July and the final setup was available, together with the first measurements, by the end of July. The new system was put in operation just before the RFX-Mod high current campaign. An example of the capabilities of the upgraded tomography is illustrated in Fig.6.4.1. The radial profiles of T_e measured from Thomson Scattering (black points) and calculated from the SXR data (red triangles) at the same time in a Multiple Helicity RFP plasma as are compared, showing good agreement between the two data sets.

6.5 SXR Multifilter

An improvement of the measuring dynamic range of the SXR Multifilter diagnostic for the measurement of the on axis T_e is being seeked by using logarithmic amplifiers instead of the present linear ones. This will allow for having a pair of signals to measure T_e for almost all operational regimes of RFX-Mod.

A prototype has been prepared during 2010 but actual tests on the diagnostic have not be performed as the noise reduction work on the new horizontal camera (see paragraph 6.4) took longer than expected.

6.6 Fast insertable pneumatic system for edge probes

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

Fig.6.6.1 3D view of the Fast Reciprocating Manipulator (FaRM).

The system will allow studying the average edge plasma parameters and their fluctuations at plasma currents higher than those which can be safely explored with the manipulators presently available, which can be moved only on a shot-to-shot basis and keep the probes exposed to high power fluxes through the plasma discharge.

During the year 2010 the project team constituted by RFX personnel worked in tight collaboration with the external company in charge for the manipulator design. The mechanical design of the manipulator has been completed according to the technical specifications as defined in [Agostinetti09]. Fig. 6.6.1 shows a 3D view of the Fast Reciprocating Manipulator (FaRM). The design activity was accompanied and verified by a series of mechanical simulations, performed in order to verify the mechanical stress of different part of the manipulator, including the manipulator shaft and the probe head support, during the foreseen fast movement. Results of mechanical analysis are reported in [Agostinetti10a]. A dedicated benchmark was set up in order to better define the suitable components to be used in the pneumatic circuit, the core of the system, responsible for the fast movement of the manipulator. The pneumatic circuit was tested simulating a range of experimental operations of the manipulator, accounting for the real weight of the moving part and the installation position as well on the RFX-mod device. The results are described in detail in [Agostinetti10b]. The actual order and commissioning of the diagnostic was postponed due to lack of budget.

6.7 Arcless power supply for ion saturation measurement

The design of the power supply and arc-limiting circuit has been postponed during 2010 and restarted only in November. Presently the arcless circuit design has been completed, and it has been found to work properly and with the correct time response for the insertion. A complete design and project of the power supply unit, including remote control of voltage applied, and with the inclusion of arcless circuit is under development with the joint work of SXD-Diagnostic and Electronic workshop.

6.8 Upgrade of the Diagnostic Neutral Beam Injector

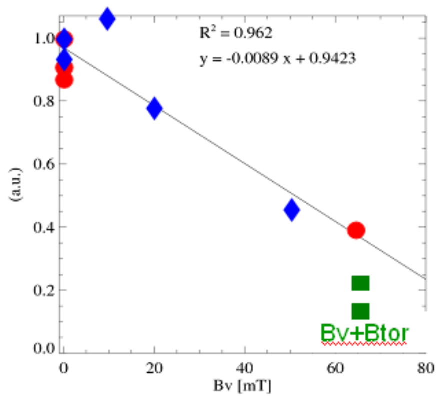

Fig.6.8.1: Summary of the tests performed injecting the beam into RFX filled with H; beam signal inside theRFX chamber as a function of the field generated by the F coils.

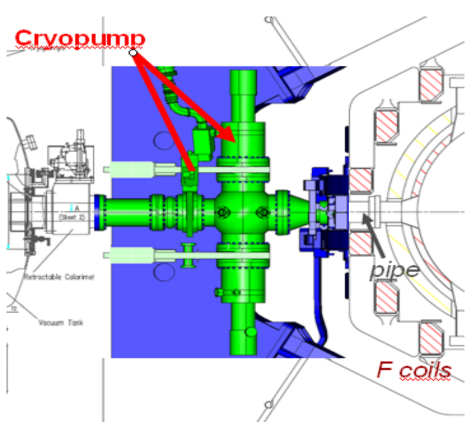

Fig.6.8.2: The new duct with two 2000 l/s criopumps

Early in 2010, tests on the impact of various factors on the beam performance showed that the amount of neutral beam particles reaching the RFX plasma was highly sensitive to the amplitude of the stray field generated outside the machine by the F filed shaping coils (F coils). Also the Toroidal field had an impact, suggesting that reionization in the duct, particularly in the region close to the plasma, was most probably the mechanism that stopped the beam, preventing it from reaching the plasma. If was then conjectured that reducing the gas in the duct should have improved the beam performance. The beam duct has been therefore modified introducing two cryopumps (belonging to the RFX park of unused pumps) as close as possible to RFX and the duct cross section has been slightly increased, form 10 to 15 - 20 cm (see Fig 6.8.2). In the one day of operation before the shutdown we could see that hints of charge exchange signal showed up in the spectrum when comparing chords

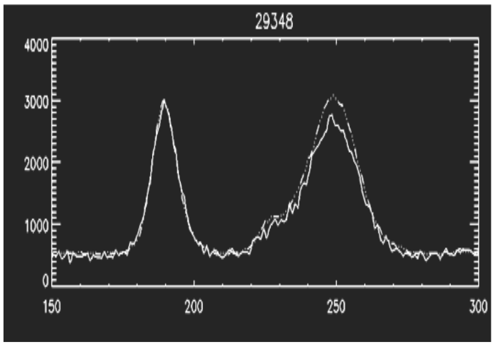

Fig. 6.8.3 Comparison of two spectra with and without beam. The difference corresponds to the active signal.

intersecting the beam with chords with line-of-sight off the beam. An example is shown in fig 6.8.3. Further improvement of the active signal is now expected from an increased pumping speed in the region, by further otpimisation of the beam current density itself, and from accessing specific plasma scenario that minimize the flow of neutrals from RFX into the beam duct (such as inward shifted discharges and/or low recycling wall).

6.9 Ion temperature measurement from NPA diagnostic

During 2010, in collaboration with Greifswald IPP laboratory, a diagnostics for ion temperature measurements based on magnetic deflection was installed on RFX-mod. The first experimental phase was dedicated to the verification of the effect of the stray magnetic field produced during RFP plasma operation. This was done by analysing the collected fluxes of the ions produced by a source internal to the NPA diagnostic system. The second phase was then dedicated to the analysis of the neutral H ions fluxes coming form the plasma and entering the diagnostics, by which the estimation of the ion temperature is obtained.

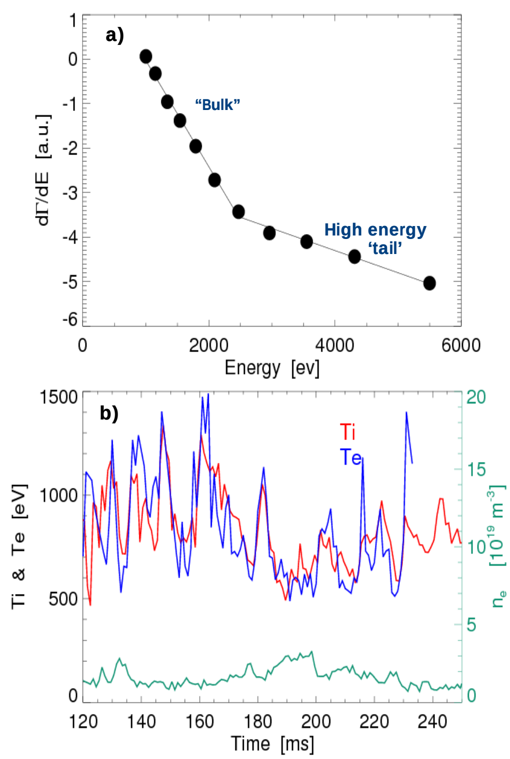

Fig.6.9.1: a) Atomic Hydrogen fluxes collected by the NPA diagnostic as a function of the energy; b) Ti (red) and Te (blue) time evolution during a low density (green) plasma discharge.

A reconstruction of the distribution function of the energy of the neutral particle fluxes, by means of the 11 energy channels dedicated to the Hydrogen atoms (the remaining 11 out of the total 22 are designed for Deuterium plasmas), revealed the existence in the RFX-mod plasma of at least two populations with different energies. The first population is likely to be associated to the bulk Maxwellian distribution as an exponential dependence on the energy is recognized for the fluxes relative to the low energy channels (E<2.5 keV). A high energy non-Maxwellian tail is also observed for larger energy channels (E>2.5 keV), as shown in Fig. 6.9.1a. A preliminary analysis of the ion temperature T_i, deduced by the exponential interpolation of the low energy component of the Hydrogen atomic fluxes, exhibits a correlation with the electron temperature T_e (measured by SXR multifilter diagnostic) which depends on the plasma condition, and in particular on the electron density. An example of good correlation between the T_i and T_e measurements, resolved in time, is shown for high density plasma in Fig. 6.9.1b. Despite the limited statistics and the necessity of further data validation, the T_i/T_e ratio is observed to strongly depend on the electron density and to be not less than 0.5. During the cyclic magnetic reconnection events, which characterize RFP operations, the generation of fast ions (E>5 kEV) has also been observed. The analysis and the interpretation of the Hydrogen fluxes collected with the NPA system is in progress by means of the Nenè code, originally developed for the reconstruction of the particle source term in transport simulations,.

6.10 Microwave reflectometer

The first Ka band of the whole RFX-mod microwave reflectometer system, after a preliminary source calibration tests, has been successfully operational since the second part of 2009. The actual configuration of the system allowed to evaluate the distance d_c of the so called cut-off density layer (n_e in the range $1\div1.2\cdot10^{19}$ m^{-3}) from the first wall, with a high time resolution ($\Delta t = 2\mu s$). From the very beginning the data gathered showed a peculiar correlation of the time evolution of d_c with the edge components of the magnetic field (the toroidal and radial components, see Fig 6.10.1). This suggested a relation between edge density and the local magnetic topology. More accurate studies highlighted the different roles played by the m=0 MHD modes and the (m=1, n=7) tearing mode (leading to the main helical plasma deformation). From the edge density point of view, the time evolution of d_c has been found to be related with the local shift induced at the edge during the QSH states [Scarin10], outlining the local interplay between the m=0 and m=1 perturbations on the edge plasma wall interaction. An extensive analysis over a large discharge database shed light on the average behaviour of d_c during the QSH states and on the role of global parameters affecting the edge density, such as the plasma current and the different magnetic equilibrium. An interesting scaling of d_c has been found with respect to the parameter n_e/n_G (n_G being the Greenwald density), showing (in the wake of other previous diagnostic results) a higher local plasma-wall interaction associated to higher n_e/n_G values and

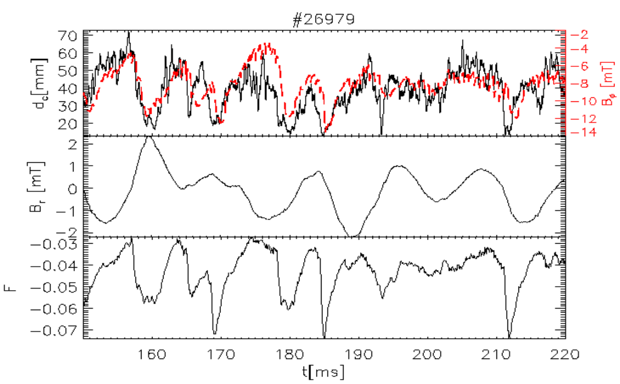

Fig.6.10.1: [top] Time evolution of d_c (black) and of the local toroidal magnetic field (red); [middle] time evolution of the local radial magnetic field; [bottom] time evolution of the reversal parameter F.

usually leading to low plasma performance [DeMasi10]. Finally, the beneficial effect of the first wall conditioning with Lithium has been investigated [DalBello10].

6.11 Room temperature solid pellet injector

Room temperature pellet injector (RTPI) launches solid pellets using sabots that are accelerated by a driver gas till they hit a bumper with a central hole. Through the bumper hole the pellets fly to plasma. This set-up allows the RTPI to inject pellets of different sizes and made of any kind of solid material at room temperature. A sabot loader provides a reserve of about 25 pellets allowing a full day operation. In the first part of 2010 RTPI has been extensively used to inject lithium pellet for wall conditioning purpose. Wall lithization has been performed by injecting the largest pellets allowed by the RTPI (Ø1.8x5 mm). To get a complete pellet ablation we injected them at a speed of about 100 m/s into He discharges with a plasma current over 1 MA. Lithium injection has been performed also on standard H discharges with plasma current over 1.5 MA to provide fresh lithium to the wall. At plasma current lower than 1.2 MA, pellets are ablated in about 5 ms (figure 6.11.1) and arrive close to the plasma centre (figure 6.11.2). The deep pellets penetration provides a uniform toroidal and poloidal lithium deposition over the wall. A total number of about 150 pellets have been injected in the various lithization campaigns. Lithization effects on plasma performance have been described in section 2.7.

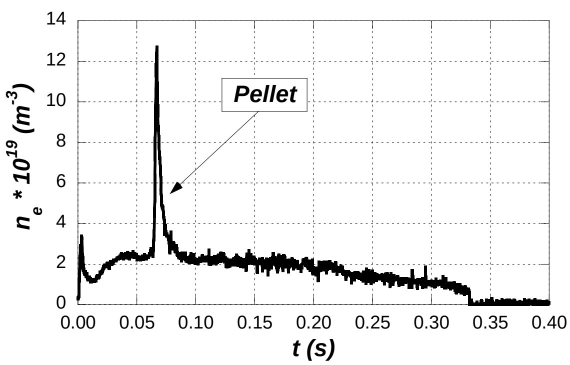

Fig.6.11.1: Line average electron density.

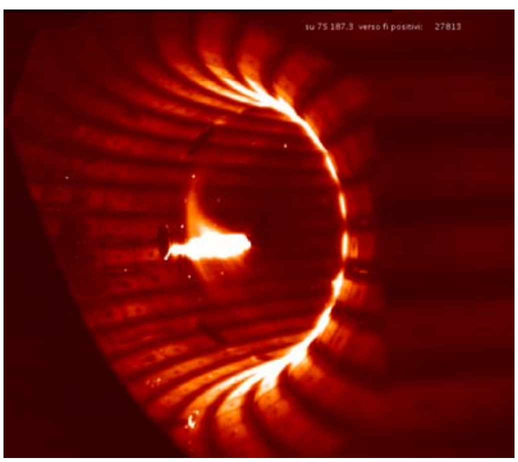

Fig.6.11.2: Image of an injected lithium pellet.

The large number of injected pellets needed for lithization has required a reliable RTPI operation, to such purpose RTPI has been improved in following components:

- The fast driver gas valve has been magnetically shielded to avoid spurious valve opening when operating at the highest plasma current with a magnetizing current over 40 kA;
- The sabot used to launch the pellet has been optimized both in terms of shape and of material to avoid breaking or sticking to the bumper;

- The optical diagnostic system used to measure the pellet speed has been improved to avoid EMI noise;
- The pneumatic movements necessary for sabot loading/disposal have been optimized to provide smoother and more reliable action.
- Microcontroller software has been improved to allow a better remote control of the injector operation.

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7. BROADER APPROACH

7.1 Background

During 2010, the researchers involved in the Broader Approach (BA) activities, have continued working both on the design of the systems to be procured by CNR, acting through Consorzio RFX, and participating to the general work in the framework of the JT-60SA International Project Team.

The first set of activities was mainly related to the procurement of the Quench Protection Circuits (QPC) and of the Power Supply (PS) system for RWM control and included engineering analyses, development work and experimental tests to assess the conceptual design of the systems, as described in sections 7.2 and 7.3.

The second set consisted in the participation in the project management and technical integration, with particular regard to the systems to be procured; this implied in particular the participation to three Technical Coordination Meetings and two Design Review Meetings with the preparation of the necessary inputs, revisions of the outputs and performance of the specific actions.

The activities of the Physics Integration Unit, which is part of the JT-60SA International Project Team, definitively started this year; the specific involvement of Consorzio RFX and the work made is described in section 7.4.

7.2 Quench Protection Units

The analyses of the JT-60SA poloidal circuit operation in case of plasma disruption and fault conditions, performed in the last years by means of a complete model of the poloidal circuits including all passive and active conductors, have been reviewed and finalized in the first months of 2010 [Novello10], allowing identifying the maximum over-currents to be sustained by the circuit components and Quench Protection Circuits (QPC) in particular.

The main function of the Quench Protection Circuits (QPC) is the protection of the superconducting magnets in case of quench, based on a fast removal of the magnet stored energy. These protection units must sustain steady state currents up to 25.7 kA and, when activated, they have to interrupt the current diverting it into discharge resistors, with a reapplied voltage of the order of 5 kV. The QPC will be activated also in case of power converter fault, so as to decrease the magnet current.

An advanced conceptual design was proposed by RFX and approved by JAEA and F4E at the end of 2009, based on a Hybrid Circuit breaker composed of a mechanical By-Pass Switch (BPS) to handle the current in steady state operation, connected in parallel to a Static Circuit Breaker (SCB) for current interruption (see figure Fig.7.2.1). This design solution is quite innovative: there is no experience of similar solutions at this power level either in industrial or scientific field. This situation suggested the realization of a hybrid circuit breaker prototype of sufficient power level to verify in detail the problems related to the current commutation from the BPS to the SCB.

The realization of a 10 kA prototype has been worked out during 2009 and it has been extensively tested during 2010 up to the maximum interruptible current.

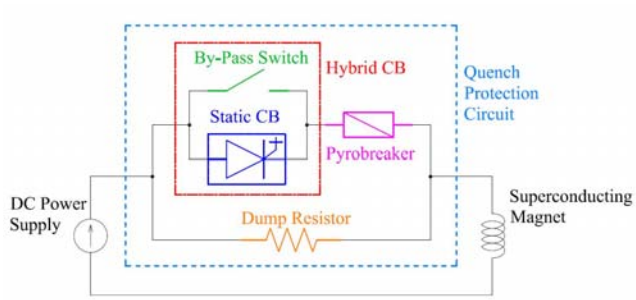

Fig.7.2.1: Scheme of the QPC conceptual design.

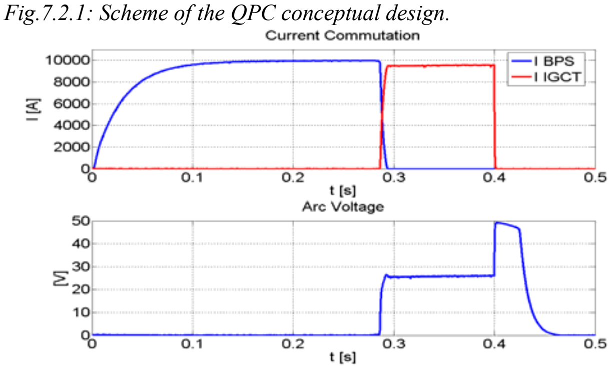

Fig.7.2.2: Results of 10 kA current commutation test

The obtained results are very satisfactory, as shown in figure Fig.7.2.2: at the time of BPS opening an arc voltage is formed which leads the current commutation from the BPS to the SCB. The arc voltage presents a regular and increasing trend; as a consequence the 10 kA current commutation is rapidly completed in about 8 ms without any current re-strike. The paralleled IGCTs turn-on without any problem, showing a good current sharing. When the BPS is completely open the IGCTs are turned-off and the current is rapidly transferred to the discharge resistor, without any current re-strike. With the hybrid circuit breaker prototype more than 100 commutation and interruption tests have been performed. In every performed test a good IGCT turn-on has been observed, the current commutation has always been rapid and complete driven by an increasing arc voltage, assuring the reliability of the proposed design.

During 2010, detailed studies have been performed in collaboration with F4E and JAEA to better define the interface requirements with the other Power Supply systems of JT-60SA both for the control and for the auxiliaries (auxiliary power supply, cooling water, compressed air, …) of the QPC system.

After the signature, in December 2009, of the Procurement Arrangement between F4E and JAEA and of the Agreement of Collaboration (AoC) between F4E and CNR, the detailed Technical Specifications for the Supplier were assessed and completed with the Supplier Quality Requirements during the first semester 2010.

In parallel, the establishment of the AoC Implementation Plan was done and the documents prepared including the Consorzio RFX Quality Plan for this procurement.

In the second semester 2010, the tendering procedure was completed with the contract award and the establishment of the contract is expected within December 2010.

2.3 Power supply system for 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), as in Fig.2.3.1. Since 2009, JAEA has been studying also an alternative solution with internal sector coils, located between SP and first wall. This solution would have a series of advantages, as for example higher efficiency of the SC in producing the magnetic field, due to the lower shielding effect of the SP. On the other hand, the smaller space available for the coils constrains to reduce the number of turns from 8 to 2 and the mechanical and electrical stresses in case of fast plasma transients could be higher, therefore deep studies are necessary to check the feasibility.

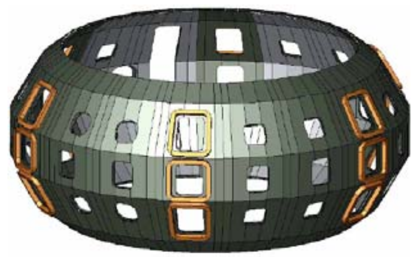

Fig.2.3.1: Reference design of RWM sector coils, to be installed on the outer side of the stabilizing plate.

In 2010, JAEA made further progresses in these studies, considering both external and 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.

Proceeding with the activities carried out in 2008 and 2009, RFX supported these studies with more detailed 2D FEM analyses on SC [Ferro10], aiming at estimating the load parameters (coil resistance and inductance as a function of frequency, Fig.2.3.2) and coil efficiency in producing the magnetic field (Fig.2.3.3). These analyses are based on axisymmetric models of the SC, including the MIC sheath and the SP. In addition, an axisymmetric 2D FEM model of the JT-60SA tokamak has been implemented (Fig.2.3.4), in order to quantify the magnetic flux time derivatives on the SC during fast plasma transients. In particular, a 10 ms linear plasma disruption and a downward VDE have been simulated, the first using a simple 6 filaments plasma model, the latter by imposing a time varying current density distribution inside the vacuum vessel, obtained from the results of the JAEA analyses carried out with DINA code. The induced

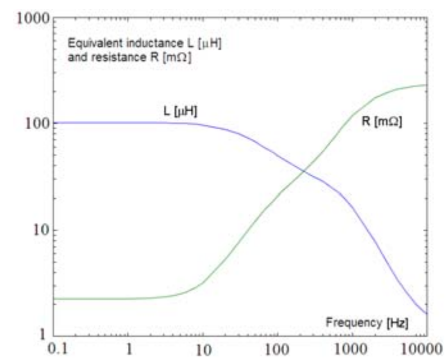

Fig.2.3.2: Equivalent inductance (L) and resistance (R) of the external sector coil (8 turns) versus the frequency of the current.

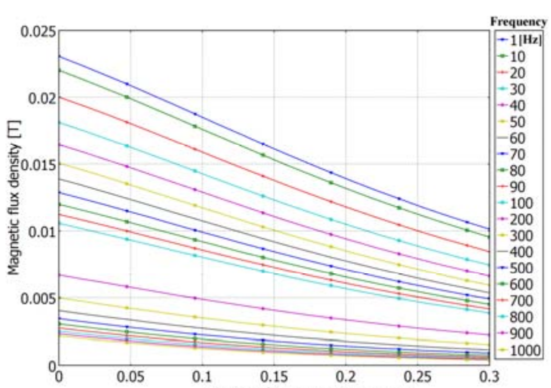

Fig.2.3.3: Magnetic flux density, measured on the SC axis, versus the distance from the SP and the frequency for a 2.5 kA coil current.

voltages derived from the magnetic flux variations have been applied to the 2D FEM model of the SC, to obtain the over-currents induced in the SC.

In October 2010, a dedicated RFX-JAEA Joint-Work has been set up on this topic. For 2 weeks, a RFX researcher stayed in Naka to exchange information and to perform joint studies, with the aim to proceed further in the RWM control system design. In this occasion, the 2D FEM models of the SC have been updated (Fig.2.3.5) and the performances of external and internal SC have been compared, obtaining interesting results. It has been found, for example, that, for the same current (2.5 kA) the internal SC, despite the lower number of turns (1 or 2 instead of 8) produce higher magnetic fields at the SC axis for frequencies higher than 200÷400 Hz (Fig.2.3.6), and the magnetic field is also more constant changing the distance from the SP. In addition, at these frequencies, the internal SC requires much less voltage (and power) to produce the same magnetic field. However, the higher is the frequency, the lower is the produced magnetic field, because of the shielding effect of the passive structures. Nevertheless, if relatively low time delays between field measurements and PS output current (cycle time 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. Therefore, the internal SC could be an attractive solution if the coils are operated at high frequencies (> 1 kHz) and if they are associated with a fast control and power supply system, based for example on audio amplifier (as in DIII-D experiment). Basing on the over-currents calculated with the procedure described above, preliminary results about the forces acting on the internal SC during plasma disruption and VDE have been achieved and will be jointly evaluated in the near future.

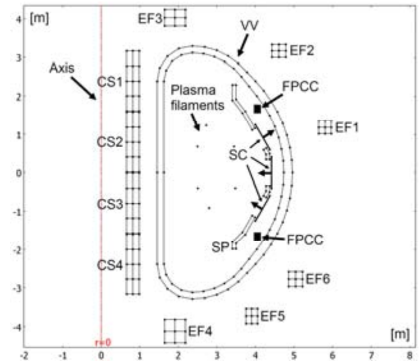

Fig.2.3.4: 2D axisymmetric FEM model used to quantify the electrical stresses in the sector coils during fast plasma transients.

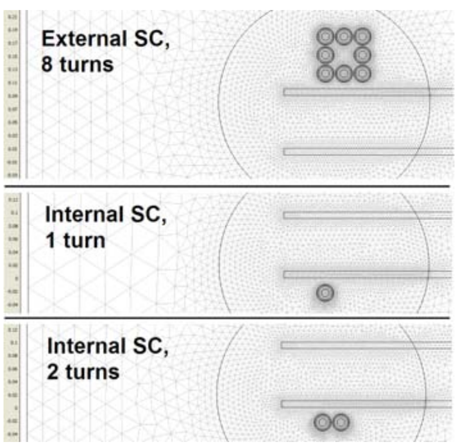

Fig.2.3.5: Axisymmetric 2D FEM models of the sector coils.

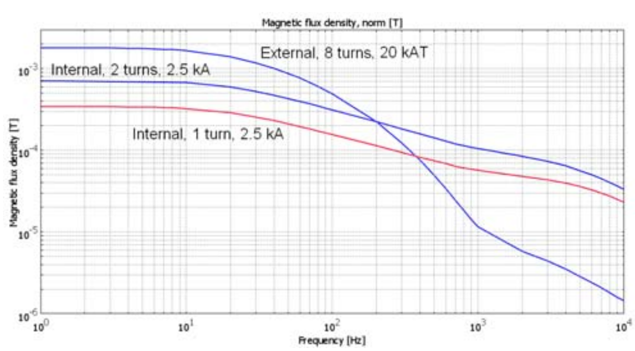

Fig.2.3.6: B field produced by the external and internal SC at 0.849 m from the SP (which corresponds about to the q=3 plasma surface).

Further studies, both in support of the feasibility assessment of the internal SC solution and to work out the most suitable PS topology, will proceed next year.

7.4 Participation in the Physics Integration Unit

In 2010 the European Physics Integration Unit (PIU) started its activities and one researcher of Consorzio RFX officially participated to them. This lead to an intense discussion with JAEA colleagues on the present version of the JT-60SA Research Plan and on how it can be best integrated in the European future plans [Kamada10]. At the same time PIU activities in 2010 aimed at spreading in EU the knowledge of machine capabilities and mission, in particular by promoting and organizing seminars in all the main European laboratories and stimulating at different levels discussions on possible cooperation areas.

Specific areas of possible collaboration for Consorzio RFX were identified in the fields of active MHD control and scenario integration.

Discussions on RWM active control schemes were tightly linked to an experimental campaign on the same subject, performed in collaboration between Consorzio RFX and JAEA, as reported in section 2.4.

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8. OTHER ACTIVITIES

8.1 Energy strategies

Fusion Energy as base-load electricity source.

Modelling of Fusion Reactors in order to estimate construction and O&M costs and cost of electricity has gone ahead during 2010. An external thermal energy storage system has been included and most of the blocks simulating different reactor components have been improved.

Cost estimates have been carried out for a pulsed reactor, in many operating conditions, in a wide range of burn-up time. Results of the simulations have been tested against the outcome of the two Plant Models B and AB of the European PPCS study.

One paper on the subject has been accepted for publication in the SOFT2010 special issue of Fusion Engineering and Design.

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

Confidence with the MARKAL-TIMES simulation code has been improved during 2010, through a collaboration established with the Max Planck Institut fur Plasmaphysik, in view of delivering a contribution to the development of the EFDA-TIMES model. In this context, the costs of the nuclear fission fuel cycle were fully revised.

In addition, the cooperation with ERSE (former CESI-Ricerca) has been continued on a MARKAL-TIMES regional model, able to provide outlooks to 2030, where the nuclear technology is included.

Such activity has been carried out as part of the research programme of one doctoral student in Energetics. The level of knowledge and competence achieved so far is sufficient to contribute to the development of the EFDA-TIMES model.

8.2 Non-fusion plasma applications

8.2.1 Magneto-plasma-dynamic thrusters

During 2010 an experimental activity was planned to test the effectiveness of a passive control method for MHD instabilities in MPD thrusters based on the use of resistive shells surrounding the plasma. With this aim, a preliminary design of a new thruster was carried out by the Alta s.p.a. team, with collaboration of the RFX group. This thruster is intended to achieve a better efficiency than the previous ones, and to be mounted also in larger vacuum chambers available on the Alta s.p.a. premises, with the aim of better simulate real space conditions. A set of conductive shells with different time penetration constants will be tested. Special magnetic probes were designed and realized to investigate the growth rate of MHD instabilities and to monitor their saturation level. The first experimental activity will be performed before the end of 2010, and will then continue in 2011.

8.2.2 Biomedical applications

During 2010 several tests of the effect of the plasma source for biomedical applications developed at Consorzio RFX have been performed, mainly on cell samples extracted from different tissues (cornea and epithelium) constituting the human eye and on ex-vivo corneal surfaces. The tests have been conducted at the Department of Histology, Microbiology and Medical Biotechnology of the University of Padova, by a research team including ophthalmologists, histologists and biologists, having in mind the possible application of the plasma source as a cure for corneal infections, which are difficult to treat by traditional techniques and can lead, in the worst cases, to blindness. The aim of the tests was mainly to investigate the existence of possible genetic modifications induced by the plasma treatment and to determine the processes occurring in the eye cells, in order to understand their observed capability of self-repairing against the action of free radicals produced by the plasma. Cell vitality has been estimated for different treatment times and at different time distances from the treatment, showing that after 24 hours the vitality comes back to almost 100%. The time dependence of the production of reactive oxygen species by the cells, induced by the oxidative stress due to the plasma application, has been used as an indication of the effectiveness of the cell self-reparation mechanisms. No significant genetic damage has been observed.

9. QUALITY MANAGEMENT

Quality Assurance (a branch of Quality Management) has been implemented, and is currently ongoing, in the following projects:

F4E grant 032 (2 years contract related to PRIMA, MITICA and SPIDER, i.e. the Neutral Beam Test Facility project)

F4E grant 155 (ITER magnetic sensors, the grant is now at a proposal stage)

F4E grant 051 (Neutral Beam Injector Remote Handling) which started in October 2010

Broader Approach (CNR supplies to JT-60SA)

The implementation of Quality Assurance in these projects has been required by the customer (F4E, ITER Organization).

Quality Assurance has been implemented also in the subcontracted activities involving Consorzio RFX suppliers (like industries) and partners (like CCFE and KIT) related to the above mentioned projects.

The grant 032 (PRIMA, MITICA, SPIDER) has been quality-audited during 2010 by internal auditors and then by external (F4E) auditors. Corrective action plans are currently ongoing to solve the nonconformities identified during the audits.

Some design reviews of PRIMA, MITICA and SPIDER (grant 032) components or systems have been done; both F4E and ITER Organization participated in these design reviews; problems identified during the design reviews have been documented (by the customer) and are going to be solved (by the project organization).

The PRIMA design review collected many hundreds of problems that have been transmitted to the company responsible for the design of the architecture, building structures and facility equipment. A big effort has been done and is still in progress to assure that buildings and related equipment are designed according to the experimental requirements.

The process for the ISO 9001 certification was finalized in 2010 indentifying the Consorzio activities which have to be included in it. Two products are identified:

- design, development, realization and deployment of technologies, equipment, diagnostics and systems devoted to research activities and industrial evolution;
- education and training in fusion science and engineering at the post-graduate, doctoral and post-doctoral levels.

10. EDUCATION TRAINING AND INFORMATION TO THE PUBLIC

International Doctorate in Fusion Science and Engineering

In 2010 the activity on the International Doctorate in Fusion Science and Engineering, set up in 2008, on the initiative of Consorzio RFX, among the universities of Padua, Lisbon and Munich, increased again, as a consequence of the start of the third cycle (2010-2012), and reached its regime, corresponding to the contemporary presence of students of all the three years of doctorate.

The total number of students grew from 27 to 38 (14 in Padua).

For the Doctorate, during 2010, were organized a total of four dedicated 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 (3-7 May), of 34 hrs of frontal teaching plus 9 hrs of laboratory/experiment visit, and an Advanced Course in Engineering (18-29 October), of 46 hrs plus 15 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. Beghi, 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 and high voltage components (V.Toigo, RFX Padova), Beam-plasma interaction and current drive (A. Staebler, IPP Garching);
- *RF heating and current drive*: Introduction (A. Tuccillo, ENEA Frascati), ECRH (G. Granucci, CNR Milano), LH/ICRH (F. Mirizzi, ENEA Frascati), ICRH (M.Maggiora, Politecnico Torino).

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

Other educational activities

The other educational activities of Consorzio RFX on fusion related disciplines continued with a significant effort in 2010.

In particular, RFX professionals were in charge of 21 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 8 students preparing their graduation thesis on fusion related subjects.

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

- 4 for engineering students: "Plasma Physics", "Plasma and Controlled Thermonuclear Fusion", "Industrial Applications of Plasmas" and "Energy Technology and Economics";
- 4 for physics students: "Introduction to Plasma Physics", "Experimental and Numerical Methods for Fluid Dynamics and Plasma Physics", "Fluid and Plasmas Physics" and "Electrodynamics".

Goal oriented training in Power Supply Engineering

The Goal Oriented Training program in Power Supply Engineering (GOT-PSE) is a collaborative program among the following five participant Associations: Culham Centre for Fusion Energy (CCFE), Commissariat à l'Énergie Atomique (CEA), Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile (ENEA), Karlsruhe Insitute of Technology (KIT) and Consorzio RFX, who is the Program Coordinator.

The training is based on a specific research program for each Trainee and a general program achieved by means of a comprehensive set of courses and shadowing activities on the operation of the facilities present in the participating laboratories.

The kick-off meeting was held in January 2010, but the Trainees recruitment was completed by the end of May. Nevertheless the 2010 integrated course program was performed as scheduled:

ENEA – Frascati ---- July 5th to 16th

Basic concepts and peculiar features of the Power Supplies (PS) of RF gyrotrons. FTU PS for the RF LH and ECRH systems. Orcad-PSpice, with applications in the gyratron PS field.

KIT ---- September 6th to 17th – 2 weeks course

Summer school on Fusion Technology and visits to the test facilities: Helium Loop Karlsruhe (HELOKA), Superconducting Coil Test Facility TOSKA, Tritium Laboratory Karlsruhe (TLK)

Consorzio RFX---- October 11th to 22th – 2 weeks course

Matlab/Simulink and PSIM use in electric/electronic system simulation. RFP machines and relevant Power Supply systems. Quench Protection Circuits for superconducting magnets.

CEA ---- Nov. 15th to 24th – 2 weeks course

Tokamak and Tore Supra Power Supplies. Shadowing on Tore Supra Operation. ITER site visit

The specific training of the two Consorzio RFX Trainees is well progressing with an increasing involvement in the activities of the RFX, NBI and BA programs.

A website (https://www.igi.cnr.it/gotpse/) has been also developed by Consorzio RFX for the sharing of the GOT-PSE documentation.

Goal oriented training in 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.

Four Trainees have been recruited by RFX by the beginning of June.

The specific training of the 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.

CONSORZIO RFX

PUBLICATIONS AND REPORTS

2010

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C.10 P. Martin: “The RFP IEA implementing agreement and its perspectives”, 14th Workshop of the IEA Implementing Agreement on RFP Research, Consorzio RFX, Padova, 26-28 April, 2010

C.11 L. Piron: “Control of tearing modes and error fields in RFX-mod”, 14th Workshop of the IEA Implementing Agreement on RFP Research, Consorzio RFX, Padova, 26-28 April, 2010

C.12 Z. Wang: “Physics studies on RWM and feedback control in RFPs”, 14th Workshop of the IEA Implementing Agreement on RFP Research, Consorzio RFX, Padova, 26-28 April, 2010

C.13 G. Marchiori: “Advances in active control engineering”, 14th Workshop of the IEA Implementing Agreement on RFP Research, Consorzio RFX, Padova, 26-28 April, 2010

C.14 P. Zanca: “Perspectives of tearing mode control in RFX-mod”, 14th Workshop of the IEA Implementing Agreement on RFP Research, Consorzio RFX, Padova, 26-28 April, 2010

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C.17 S. Munaretto: “Wall-conditioning techniques in RFX-mod: status and perspectives”, 14th Workshop of the IEA Implementing Agreement on RFP Research, Consorzio RFX, Padova, 26-28 April, 2010

C.18 L. Zanotto: “RFX-mod: machine status and perspectives”, 14th Workshop of the IEA Implementing Agreement on RFP Research, Consorzio RFX, Padova, 26-28 April, 2010

C.19 M. Baruzzo: “RWM control under different coil configuration and implications for JT60-SA”, 14th Workshop of the IEA Implementing Agreement on RFP Research, Consorzio RFX, Padova, 26-28 April, 2010

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C.21 D. Escande: “Single Helicity ohmic states: calculation and measurements”, 14th Workshop of the IEA Implementing Agreement on RFP Research, Consorzio RFX, Padova, 26-28 April, 2010

C.22 L. Marrelli: “Neoclassical transport in helical RFX-mod plasmas”, 14th Workshop of the IEA Implementing Agreement on RFP Research, Consorzio RFX, Padova, 26-28 April, 2010

C.23 E. Martines: “The SHeq code: an equilibrium calculation tool for SHAx states”, 14th Workshop of the IEA Implementing Agreement on RFP Research, Consorzio RFX, Padova, 26-28 April, 2010

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C.25 M. Zuin: “Alfvénic modes in RFX-mod”, 14th Workshop of the IEA Implementing Agreement on RFP Research, Consorzio RFX, Padova, 26-28 April, 2010

C.26 Soppelsa: “Modal decoupling in RFX-mod”, 14th Workshop of the IEA Implementing Agreement on RFP Research, Consorzio RFX, Padova, 26-28 April, 2010

C.27 S.C. Guo: “Microturbulence in RFX-mod”, 14th Workshop of the IEA Implementing Agreement on RFP Research, Consorzio RFX, Padova, 26-28 April, 2010

C.28 S.Menmuir: “Impurity transport studies in RFX-mod”, 14th Workshop of the IEA Implementing Agreement on RFP Research, Consorzio RFX, Padova, 26-28 April, 2010

C.29 P. Scarin: “Plasma pressure gradients in the boundary of RFX-mod helical regimes”, 14th Workshop of the IEA Implementing Agreement on RFP Research, Consorzio RFX, Padova, 26-28 April, 2010

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C.33 P.Scarin,M.Agostini,L.Carraro,R.Cavazzana,F.Sattin,G.Serianni,M.Spolaore,N.Vianello : “Plasma Pressure Gradient in the Edge of RFX-mode Helical Regimes”, 19th International Conf. on Plasma Surface Interactions PSI, May 24-28, San Diego CA USA

C.34 M. Spolaore, G. De Masi, N. Vianello, M. Agostini, R. Cavazzana, R. Lorenzini, E. Martines, B. Momo, P. Scarin, G. Serianni, S. Spagnolo, M. Zuin: “Parallel and perpendicular flows in the RFX-mod edge region”, 19th International Conf. on Plasma Surface Interactions PSI, May 24-28, San Diego CA USA

C.35 P. Innocente, A. Canton, S. Dal Bello, S. Munaretto, D. Terranova, F. Rossetto: “Graphite first wall conditioning by Lithium pellet injection in the RFX-mod experiment”, 19th International Conf. on Plasma Surface Interactions PSI, May 24-28, San Diego CA USA

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C.40 D. Bonfiglio, S. Cappello, L. Chacon, G. Spizzo, M. Veranda: “Magnetic chaos healing in the helical reversed-field pinch: indications from the volume preserving field line tracing code NEMATO”, Theory Of Fusion Plasmas, Joint Varenna - Lausanne International

C.41 M.E. Puiatti, M. Valisa and the RFX-mod team: “Electron transport barriers in the RFX-mod Reversed Field Pinch with helical equilibrium”, oral presentation 3rd EFDA Transport Topical Group Meeting, combined with the 15th EU-US Transport Task Force Meeting, Córdoba, Spain, September 7 - 10, 2010

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C.43 R. Schrittwieser1, F. Mehlmann1, C. Ionita1, V. Naulin2, J.J. Rasmussen2, H.W. Müller3, N. Vianello4, Ch. Maszl1, V. Rohde3, M. Zuin4, R. Cavazzana4, M. Maraschek3, ASDEX Upgrade Team3: “Transport phenomena in the SOL of ASDEX Upgrade”, poster 3rd EFDA Transport Topical Group Meeting, combined with the 15th EU-US Transport Task Force Meeting, Córdoba, Spain, September 7 - 10, 2010

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C.53 Marco Gobbin: "Three-dimensional equilibria and transport in RFX-mod: a description using stellarator tools", invited presentation, 52nd Annual Meeting of the APS Division of Plasma Physics, November 8–12, 2010; Chicago, Illinois, Bulletin of the American Physical Society, Volume 55, Number 15, BI3.00003

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C.62 R. Cavazzana, G. Marchiori, L. Novello, P. Piovesan, L. Piron, A. Soppelsa, A. Zamengo, L. Zanotto and the RFX-mod Team: "Development of a Reliable Operational Scenario for High Current Operation in RFX-mod", 52nd Annual Meeting of the APS Division of Plasma Physics, November 8–12, 2010; Chicago, Illinois, Bulletin of the American Physical Society, Volume 55, Number 15,, GO4.00001

C.63 "Optimization for low-aspect-ratio RFP con¯guration in Relax" S. Masamune, A. Sanpei, K. Oki, M. Nakamura, A. Higashi, H. Motoi, D. Fukabori, H. Himura, R. Ikezoe, U. T. Onchi, U. Saskatchewan, D. Den Hartog, R. Paccagnella, 52nd Annual Meeting of the APS Division of Plasma Physics, November 8–12, 2010; Chicago, Illinois, Bulletin of the American Physical Society, Volume 55, Number 15, Go4.00005

C.64 K.J. Caspary, B.E. Chapman, A.F. Almagri, J.K. Anderson, D.J. Den Hartog, F. Ebrahimi, G. Fiksel1, J.A. Goetz, J. Ko, S. Kumar, S.T. Limbach, D. Liu, R.M. Magee, M. Nornberg, S.P. Oliva, E. Parke, J.A. Reusch, J.S. Sarff, J. Waksman, Y.M. Yang, P. Franz, D.L. Brower, W.X. Ding, L. Lin, S.K. Combs, C.R. Foust:

"Investigating the limit on MST with pellet injection and NBI", 52nd Annual Meeting of the APS Division of Plasma Physics, November 8–12, 2010; Chicago, Illinois, Bulletin of the American Physical Society, Volume 55, Number 15, PP9.00044

C.65 Meghan Mcgarry, Paolo Franz, John Goetz, Daniel Den Hartog: "An Upgraded Soft X-Ray Tomography Diagnostic to Measure Electron Temperature on MST ",52nd Annual Meeting of the APS Division of Plasma Physics, November 8–12, 2010; Chicago, Illinois, Bulletin of the American Physical Society, Volume 55, Number 15, PP9.00061

C.66 H.R. Strauss, R. Paccagnella, J. Breslau: "Wall forces produced during ITER disruptions", 52nd Annual Meeting of the APS Division of Plasma Physics, November 8–12, 2010; Chicago, Illinois, Bulletin of the American Physical Society, Volume 55, Number 15, UO4.00003

INTERNAL TECHNICAL NOTES

1) "On the relation between modes and output patterns of multipleinput multiple-output linear time invariant systems" G. Marchiori, A. Soppelsa, gruppo AI – NT 24, 2010;
2) "Proposal for update of RFX feedback control" A. Barbalace, G. Manduchi, gruppo AI – NT 25, 2010;
3) "Coefficienti metrici delle coordinate utilizzate per il calcolo delle medie sulle superfici di flusso elicoidali" B. Momo, E. Martines, gruppo FB – NT 107, 2010;
4) "Parallel and perpendicular edge flow: Interpretation models for electrostatic probes" G. De Masi, M. Spolaore, E. Martines, gruppo FB – NT 108, 2010;
5) "Misura della distribuzione toroidale della densità di plasma durante Glow Discharge Cleaning con ISIS" R. Cavazzana, L. Grando, L. Marrelli, M. Zuin, gruppo FB – NT 109rev1, 2010;
6) "New set-up for outgassing rate evaluation for pick-up coils for ITER" A. Gallo, gruppo IE – NT 13rev1, 2010
7) "Final Report on ITER Contract ITER/CT/08/529: LTCC sensors prototypes and tests" G.Chitarin, R.Delogu, A.Gallo, S.Peruzzo, gruppo IE – NT 15, 2010;
8) "Design of a structure with 3 linear degrees of freedom for magnetic field measurements" G. Chitarin, A. Gallo, gruppo IE – NT 16, 2010;
9) "Determinazione del coefficiente elastico dei collegamenti flessibili delle bobine di campo toroidale" S. Peruzzo, gruppo IE – NT 17, 2010;
10) "Review of the preliminary list of ITER magnetic sensors and their positions" S. Peruzzo, gruppo IE, NT 18, 2010;
11) "Comments to the comparison of results on the CEA MV testbed and simulations on the model" A. Pesce, gruppo IE – NT19, 2010;
12) "Measurement of spurious voltages due to TIEMF effect inside LTCC sensors" A. Gallo, G. Chitarin, gruppo IE – NT 20, 2010;
13) "Ionizing Radiation Compatibility - Issues in the MITICA Experiment" M. Bagatin, R. Pasqualotto, M. Darienzo, gruppo IE – NT21, 2010;

14) "Intermediate report" V. Cervaro, A. De Lorenzi, L. Lotto, M. Fincato, L. Franchin, N. Pilan, gruppo IE – NT 22, 2010;
15) "Verifica mecanica del supporto del manipolatore per la movimentazione del limiter di litio di RFX" M. Pavei, gruppo IP – NT 165, 2010;
16) "Analisi meccaniche sul Manipolatore Veloce per RFX (progetto FaRM)" P. Agostinetti, S. Dal Bello, gruppo IP – NT166, 2010;
17) "Prove di laboratorio sul Manipolatore Veloce per RFX (progetto FaRM)" P. Agostinetti, A. Barzon, V. Cervaro, S. Dal Bello, L. Lotto, M. Spolaore, gruppo IP – NT167rev2, 2010;
18) "Prima I&C Network Topology and Cabling Specifications" P. Barbato, gruppo SC – NT 89, 2010;
19) **"**Analisi delle soluzioni per lo sviluppo del sistema di accesso al database BBS" M. Carraro, E. Scekosman, P. Barbato, gruppo SC – NT90, 2010;
20) "Criticità del sistema di controllo ed acquisizione dati dell'esperimento RFX. Analisi **e** proposta di soluzione con una architettura di virtualizzazione" S. Polato, gruppo SC – NT 91, 2010;
21) "Risultati della virtualizzazione del sistema di controllo ed acquisizione dati dell'esperimento RFX Parte I: La virtualizzazione del server ROSERVER" S. Polato, gruppo SC – NT 92, 2010;
22) "Dimensionamento e operazione del banco di prova per la caratterizzazione degli inverter dell'impianto PR" A. Ferro, F. Baldo, gruppo SE – NT134, 2010;
23) "Prevenzione incendi del Consorzio RFX. Descrizione dei nuovi criteri adottati per estintori e vie di esolo" M. Battistella, A. De Biagi, gruppo UM – NT 136, 2010;
24) "Definizione colorazione standard per porte antincendio ed altri elementi del Consorzio RFX" M. Battistella, A. De Biagi, G. Lazzaro, gruppo UM – NT 137, 2010;
25) "Nota descrittiva impianti spegnimento aerosol" M. Battistella, A. De Biagi, gruppo UM – NT 138, 2010;
26) "Verifica annuale del piano di emergenza del Consorzio RFX del 15 ottobre 2009" A. De Biagi, M. Battistella, gruppo UM – NT 167, 2010;
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28) "Sonda tripla di langui: upgrade costruttivo" R. Rizzieri, gruppo SXD – NT 83, 2010;
29) "L.B.O. – Laser Blow Off: progressus et principia" R.Rizzieri, A.Fassina, A.Tiso, gruppo SXD – NT 84, 2010;
30) Upgrade del Sistema di Controllo per un gruppo da vuoto realizzato con μPLC SIEMENS LOGO! 12/24RC" (SXD-NT-78) per campagne sperimentali ad elevate correnti" F. Molon, R. Rizzieri, gruppo SXC – NT 30, 2010;
31) "Modifica al rack trasmettitore del sistama di controllo remoto degli amplificatori Femto (OEN-NT-15) per l'utilizzo tramite interfaccia seriale RS232" F. Molon, gruppo SXC – NT 31, 2010;
32) "Progettazione e realizzazione del device FEMTO in MDSPlus con riferimenti all'installazione e utilizzo di Python in ambiente Windows" F. Molon, gruppo SXC – NT 32, 2010;
33) "Studies on AGPS dummy loads" A. Ferro, C. Finotti, gruppo NBTF – NT 98, 2010;
34) "Measurements available at QPC local control cubicles (Answer to action lost PS 56)" L. Novello, gruppo BA – NT 19, 2010;

35) "Draft ITER Procurement Package Document for PRIMA Control, Interlock and Safety Systems" A. Luchetta, gruppo PRIMA – NT 5rev2, 2010;
36) "Draft of ITER Procurement Package document for MITICA SF6 Gas Handling and Storage Plant" M. Boldrin, gruppo PRIMA – NT7rev2, 2010**;**
37) "Basic Terminology for Control and Data Acquisition in the ITER Neutral Beam Test Facility" A. Luchetta, gruppo PRIMA – NT 15rev1, 2010;
38) "15/01/10 Resources planning update" A. Sottocornola, gruppo PRIMA – NT 21, 2010;
39) "Plant Breakdown Structure for the ITER Neutral Beam Test Facility" A. Luchetta, gruppo PRIMA – NT 22, 2010;
40) "PRIMA I&C Network topology and cabling specifications" P. Barbato, gruppo PRIMA – NT 24, 2010;
41) "Grounding System and Electrical Screening NBTF Grounding System Analyses" N. Pomaro, L. Grando, gruppo PRIMA – NT 25, 2010;
42) "Osservazioni sul quadro di media tensione Prisma" L. Novello, G. Lazzaro, gruppo PRIMA – NT 26, 2010;
43) "Revisione del progetto esecutivo degli edifici del complesso denominato PRIMA. Osservazioni sui quadri elettrici di bassa tensione" G. Lazzaro, gruppo PRIMA – NT 27, 2010;
44) "PRIMA CODAS Technical Specification Document" A. Luchetta, gruppo PRIMA – NT 28rev1, 2010;
45) "Design of the PRIMA general information technology infrastructure" P. Barbato, gruppo PRIMA – NT 30, 2010;
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50) "Requirements for MITICA control and data acquisition system" A. Luchetta, gruppo MITICA – NT 10, 2010;
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53) "Interfaces Control Document (ICD) Neutralizer and Electron Dump (PBS 53-MI-N1 and 53-MI-ED)–Neutral Beam (PBS 53)" M. Dalla Palma, gruppo MITICA – NT 13rev1, 2010;
54) "Requirements and interfaces for the MITICA Beam Source" D. Marcuzzi, gruppo MITICA – NT 14rev1, 2010;
55) "Request of clarification to F4E/IO on the ratings of the Residual Ion Dump power supply" M. Bigi, gruppo MITICA – NT 15, 2010;
56) "Studies on dummy loads for AGPS conversion system" A. Ferro, C. Finotti, gruppo MITICA – NT 16, 2010;
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59) “Technical specification for the research and development activities on thick molybdenum coating” M. Pavei, F. Degli Agostini, D. Marcuzzi, gruppo MITICA – NT 19, 2010;
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