CONSORZIO RFX
Ricerca Formazione Innovazione

2009 Activity Report

SUMMARY

1. INTRODUCTION AND SUMMARY OF MAIN RESULTS

The research activities foreseen in the 2009 Workprogramme have been mostly completed according to the plan: in particular, the NBI Test Facility has been included into the ITER baseline, so that the construction of the buildings can start and RFX-mod, despite a longer shut-down following the failure of a coil contact in the toroidal field winding, has successfully operated completing most of its scientific programme. A brief overview of the objectives achieved is provided by this introduction to the main results, which are presented in deeper detail in the following chapters.

During 2009 RFX has operated for a total of 32 operation weeks (including commissioning and plasma pulses) with about 900 plasma discharges, more than 400 of which with plasma current exceeding 1 MA. Operation up to 1.8MA has been performed, achieving record temperature and confinement values in Single Helical Axis States (SHAx). The results, along with the first observation of transport barriers, have led to a publication in Nature Physics and to several invited lectures at international conferences.

The 1.5 MA scenario, developed in 2008, has been further studied and optimized. The diagnostic capability has improved: new systems such as the edge Thomson scattering, the Laser Blow Off system and the FIR polarimeter contributed to a better understanding of the single helicity states. The feedback control system has been further optimized on the basis of a model, allowing operation at plasma current values exceeding 1.5 MA (maximum reached value 1.8 MA), with peak electron temperatures of ~1.5 keV and a significant decrease of the error field amplitude in the ramp-up phase of the plasma current.

A better Tearing Mode (TM) control has been obtained by optimization of the gains to be applied in the Clean Mode Control of the RFX-mod boundary. This improvement has been made possible by the development of a RFX locking model which considers the non-linear dynamics of interacting Tearing Modes (TM) balancing the viscous and electromagnetic torques and including their feedback control.

The electron internal transport barriers developing in the SHAx regimes have been characterized and compared with the electron transport barriers observed in Tokamaks and Stellarators. A null q shear point has been found, well correlated with the barrier foot. The results on the helical state in RFX-mod have been consolidated, with a deeper understanding of the underlying physical mechanisms. The helical flux surfaces in SHAx states have been reconstructed and dedicated experiments related to transport studies have allowed the strong electron barriers associated to the occurrence of SHAx to be better characterised. It has been found that barriers correspond to a regime of reduced energy and particle transport ($\chi \sim 10$ m^2/s, $D \sim 4$ m^2/s).

Density limit and density control studies have been developed to improve RFX-mod performance. Experiments with plasmas approaching the Greenwald density limit have been performed and the role of both magnetic field ripple and edge turbulence in the formation of the radiating belts associated to high density plasmas has been studied. In particular experiments at high density with Neon injection have been done to better characterize the radiative regimes studying the role of both MHD modes and edge electric field in the formation of the radiating belt.

The revision of the pellet injector has allowed experiments of hydrogen pellet injection in order to optimize the fuelling of the core helical structure (referred as 'short term step' in the 2009 activity program). The capability of penetrating the helical hot structure with H pellets has been proved, resulting in peaked density profiles and improved particle transport in particular when the pellets are injected in the formation phase of the helical structure.

Impurity behaviour has been studied by Laser Blow Off injection, showing that impurities do not accumulate inside the helical structure.

A reconstruction of the helical equilibrium in SHAx states has been obtained by the superposition of the axisymmetric equilibrium and the dominant mode eigenfunction resulting from the solution of Newcomb's equation in toroidal geometry. This equilibrium has been demonstrated to be representative of the actual helical flux surfaces present in the plasma through a detailed comparison with spatially resolved electron temperature, plasma density and soft X-ray emission measurements.

The edge plasma profiles and turbulence have been better characterized, by means of new diagnostic systems (edge Thomson scattering and Thermal Helium Beam) and dedicated experimental campaigns with the insertion of edge probes. These new systems allowed measuring edge pressure profiles at high current. The experimental study of the nature of turbulent structures and filaments at the edge has been pursued, and related to the measured edge pressure profiles. The results obtained on RFX-mod have been compared to those obtained in other fusion devices thus contributing to the general understanding of the properties of the edge plasmas.

Finally, Current Drive experiments with the OFCD technique have been successfully done at high current with low oscillation frequency.

On 18 November 2009 the ITER Council has approved the ADI (Additional Direct Investment) and the sharing among ITER parties for the establishment of the Neutral Beam Test Facility in Padova.

With this decision, it has been established that all experimental apparatus installed in Padova in the PRIMA buildings are part of the ITER system procured with the contribution of all ITER parties. The agreed direct sharing of the components to be installed in the facility foresees:

- realization of the following components for MITICA by the Japan Domestic Agency: the 1 MV power supply, the 1 MV transmission line and the High Voltage Deck 2, the bushing on the top of the beam source vessel to feed all the active components of the beam source up to 1 MV;
- realization of the following components for SPIDER by the India Domestic Agency: the 100 kV accelerator power supply and the Beam dump operating at full energy.

A number of intermediate approval steps have been taken during 2009 before the decision of the IC, which required strong support by the RFX team: among them it is worth mentioning:

- a Project Change Request (PCR-170) to include the NBI test facility into the ITER Baseline by IO-Domestic Agencies representatives positively closed on 31 July;
- the approvals by two internal ITER committees CCB1&2 (Configuration Control Board), by the ITER Scientific and Technological Advisory Committee (STAC) and by the ITER Managerial Advisory Committee (MAC) for the related Additional Direct Investment;
- two independent EU review panels, aimed to assess the Heating system mix in ITER and the NBI system, have both confirmed the need for ITER of the NBI system with the present parameters and recommended to start the construction of the related Test Facility as soon as possible;
- the EU-Procurement Arrangement for the NBI Power Supply signed between IO and F4E on 10 July and the Call for Tender for procurement of the Ion Source Power Supply launched on 15 September.

During 2009 the NBI development activities at Consorzio RFX continued under F4E Grant Agreements and in particular:

The F4E Grant Agreement 2008 for the design of the main components and systems of SPIDER, MITICA and PRIMA has been successfully closed on 15 February. After a revision process by the client, the 97.5% of the contractual activities have been recognised as completed.

From 15 March 2009 the new Grant Agreement with F4E is retroactively in force, after a long and complex administrative approval procedure. The call for Proposal has been issued on 8 June 2009, the Grant Agreement has been signed at the end of November 2009. It covers all the design activities and the follow up of the components and plants procurement up to 14 March 2011. They are performed by RFX, with the contribution of CCFE (former UKAEA) for the design of some beam line components of MITICA, of KIT (former FZK) for the design of the MITICA cryogenic pumps, of IPP for the support in the design of the plasma source and of some diagnostics and of CNRS (Délégation Ile-de-France Sud) for the development of a numerical code for the simulation of the MITICA neutraliser.

During 2009 RFX has supported both F4E and the IO to complete the process of approval of the Neutral Beam Test Facility. In particular RFX in spring 2009 has produced for the IO all the documents for the 23 Procurement Packages that are essential to the preparation of the Procurement Arrangement between IO and Domestic Agencies for the in kind contributions to ITER.

Moreover RFX has supported IO for the preparation of the SRD (System Requirement Document) describing the Neutral Beam Test Facility and the two experimental devices SPIDER and MITICA, that has been required by the IO decision bodies.

For the PRIMA buildings the design and the licensing procedure have been completed. Preliminary activities to the start of construction have been initiated.

A particular effort has been dedicated by the project team to the integration of all the experimental components and plants. Irradiation modeling and safety activities have been progressed to verify the building design, to support the design of the components inside the biological shields and to prepare the documentation to obtain the license for operation of the facility.

The PRIMA cooling system design and the Call for Tender documentation, as required by F4E, have been completed and delivered. For this system, the Requirements issued by the IO have been changed during the year and this implied a complete revision of the overall design up to the end of the year.

For SPIDER the design at the level of Call for Tender required by F4E has been completed for all the power supplies required to feed the active components of the beam source (ISEPS). For this system the Call for Tender has been launched on 15 September 2009 and the offers evaluation is presently under progress with the official support of RFX. Moreover, the design at the same level has been completed for the 100 kV insulated transmission line and High voltage deck, the beam source and the vacuum vessel.

Whereas for the other systems and components the design has progressed and completion is foreseen in 2010: vacuum and gas injection system; diagnostic calorimeter; caesium ovens; diagnostics; control and data acquisition system; protection system; auxiliary installation tools.

The design of MITICA components and plants has progressed in many relevant and critical areas:

- accelerator grounded potential power supply that is under the European in kind contribution to ITER and therefore also to the facility;
- cryogenic pumps (KIT) and definition of the requirement for the cryogenic plant;
- calorimeter (CCFE);
- beam accelerator, in parallel with the activity performed in Japan;
- vacuum and gas injection system;

High voltage deck 1 and bushing for the connection to the SF_6 insulated transmission line;

Moreover, RFX provided support to the design activities of the components and systems that are under responsibility of the Japan Domestic Agency and support to IO for the integration of the HNB system in ITER.

Finally, negotiations with the main EU Associations involved in the development of the ITER NBI have been initiated to establish a consortium to jointly carry out the development, the realization and operation of the NBI at the Test Facility.

The activity aimed to prepare the RFX team of Physicists and Engineers for the operation at the Test Facility has been carried out achieving all the objectives related to the numerical simulation tools and only partially those related to the construction of the ion source NIO1 and the High Voltage tests, due to financial constraints and to the delay on the recruitment of the personnel under the Goal Oriented Training programme.

Several numerical codes have been acquired and applied to simulate the beam optics and performance of the ion sources SPIDER and NIO1; in particular, the code BYPO has been upgraded to 3D geometry and some atomic processes have been added.

The design of the ion source (NIO1) has been completed and the procurement of some components has been initiated.

The procurement of the components for the High Voltage Test Facility has been completed and the collaboration with JAERI (Naka) on HV studies has been successfully continued. Training of RFX personnel has been carried out by direct participation to the operation of the NBI at LHD, which at present is the only NBI based on negative ions in operation, and of the RF ion sources at IPP.

RFX has continued the activities oriented to ITER diagnostics. For this purpose in 2009 RFX joined two European consortiums:

a) The “ITERMAG Consortium”, with CEA, CIEMAT and CRPP which has been established to jointly respond to F4E calls for grants on the design and procurement of the whole ITER magnetic diagnostic system.

b) The “LIDAR Consortium” which has been established among EU Associations (under the leadership of CCFE) for the development of the ITER core LIDAR Thomson scattering.

RFX has completed the pending EFDA Tasks on design development and prototype testing of ITER magnetic sensors. Furthermore, two specific contracts with IO have been carried out: the first for manufacture and test of “in-vessel low temperature co-fired ceramic (LTCC) magnetic coil prototypes” , the second, not foreseen in the Activity program 2009, for the secondment of a Senior Engineer for 3 months to work within the ITER Diagnostic Division on “Development of integration of ITER In-Vessel magnetic diagnostics”.

Concerning the core LIDAR Thomson scattering for ITER, RFX has expressed its interest to cover the test of high-speed high-efficiency detectors in the near-IR and the calibration schemes and to contribute to the overall design and to the specific and overall project planning and cost estimates.

Activities on ITER modelling have been carried out, though with limited resources, in several areas as fast access to memory mapped data, equilibrium and stability studies by the FLOW code, Nonlinear MHD studies by the code CarMa and Disruption modelling.

During 2009, collaborative activities with the Tokamak community have been further developed. In particular RFX has:

provided support to FAST by participating to the project coordination board with responsibility for the activities on the Neutral Beam Injector;

supported JET by leading the Task Force on Diagnostics, by providing test and commissioning of EP2 Enhanced Radial Field Amplifier, by continuing the work on the beta value limiting

MHD modes, on impurity transport analysis and on prediction of disruptions, in collaboration with the University of Cagliari;

continued the collaboration with IPP-Garching, EURATOM- ÖAW and EURATOM-RISØ for electromagnetic turbulence studies on Asdex Upgrade on ELM and associated current filaments in the Scrape Off Layer, on physics of momentum transport and burst-like behavior during ELM phases and on turbulence and turbulent particle flow in between ELMs, focusing on convective structures radially propagating in the Scrape Off Layer;

participated to tests on DIII D of the dynamic decoupling (actuators and sensors), technique developed at RFX-mod;

participated to turbulence characterization studies in the edge plasma of C-mod.

Theory and modelling activities have been successfully carried out during 2009 contributing to better clarify the RFP physics. Among the areas with significant achievements are the magnetohydrodynamics by more detailed benchmark of different codes and successful interpretation of experimental results, the turbulence and related transport by benchmarking and applying codes developed for other configurations, the Resistive Wall Mode behaviour by developing a model taking into account plasma pressure and other effects (compressibility, plasma inertia, longitudinal rotation and parallel viscosity) and feedback effects.

The 2009 work plan entailed not only continuing the development of existing diagnostic systems, but also the realization of new ones, necessary to improve the fundamental diagnostic data set, to enhance the analysis capability at high current, or to provide important information to supplement the operation of the new neutral beam injector on loan from TPE-RX. Among the main objectives achieved in this area during 2009 are:

the upgrade of the FIR polarimeter by a reduction of the measurement error mainly by lower FIR attenuation in the beam path and better beam alignment: this upgrade has allowed polarimetric measurements to be performed at the highest plasma current with a low relative error;

successful commissioning of the first band of the Microwave reflectometer;

installation of a new horizontal SXR camera and a new SXR multifilter;

upgrade of the thermal helium beam diagnostic to increase its time resolution;

installation of an impurity pellet injector also suitable for Lithium wall conditioning;

installation of an Ion temperature measurement system with a NPA diagnostic, in collaboration with IPP Greifswald.

In the framework of the Broader Approach activities, the on-going studies aimed at the design the Quench Protection Circuits (QPC) and the Power Supply (PS) system for the RWM control for the Satellite Tokamak JT-60SA to be procured by CNR, acting through Consorzio RFX, have proceeded during 2009 according to plans. On 3 December, an important agreement has been signed among CNR, F4E and Japan Domestic Agency which assigns to RFX the realization of these power supplies.

During 2009, though with limited resources, activities have been performed in the area of Energy Strategies mainly by developing a model of a pulsed Fusion Reactors to estimate construction, operation and maintenance costs and cost of electricity, in the area of plasma propulsion by participating to the preliminary design of a new Magneto-plasma-dynamic thruster carried out by Alta s.p.a., and in the area of Biomedical applications.

Following the ISO 9001 guidelines, all the main and support processes for the quality management system have been identified, together with their owners, interactions and customers. A draft version of the quality manual has been prepared so that the procedure for the ISO 9001 certification can start in 2010.

Finally the programme concerning education has been carried out and in particular a new Advanced Course on Engineering has been organized by Consorzio RFX for the Joint Research Doctorate in Fusion Science and Engineering.

2. RFX-MOD AND RFP PHYSICS

Following the positive experience of the year 2008, the 2009 experimental program has been built on the basis of a public call for proposals, open to researchers both from Consorzio RFX and from external laboratories. More than 140 proposals have been collected, some of them (about 12) coming from external laboratories. Such proposals have been processed and elaborated by four Task Forces, and the resulting experimental program headlines have been discussed during the RFX-mod program workshop (20-22 January 2009) before the beginning of the 2009 campaigns.

A serious failure involving the removable contact between two half-turns of the toroidal field (TF) winding in July has determined a 2 month delay in the 2009 scientific programme; therefore some of the program items have not been fully accomplished and postponed to year 2010. In particular RWM control experiments in collaboration with researchers from the DIII-D and JT60-SA teams, some of which required the RFX-mod operation in Tokamak configuration, have been only partially performed; nevertheless, the first preliminary results are extremely encouraging.

Apart from the three month shut-down following the coil contact failure, the operation of the machine was reliable and efficient, so that, in spite of the program delay, about 900 plasma discharges have been executed in 2009, and more than 400 of them with a plasma current exceeding 1 MA. This allowed the substantial accomplishment of the year 2009 RFP program:

- the feedback control system has been further optimized on the basis of a model, allowing operation at plasma current values exceeding 1.5 MA (maximum reached value 1.8 MA), with peak electron temperature of ~1.5 keV.
- the results on the helical state in RFX-mod have been consolidated, with a deeper understanding of the underlying physical mechanism. The helical flux surfaces in Single Helical Axis (SHAx) states have been reconstructed; moreover, collaborations with external laboratories have started to adapt both helical equilibrium and transport codes (originally developed for stellarators) to the RFP topology, in order to reconstruct the RFX-mod experimental results.
- Dedicated experiments related to transport studies allowed characterizing the strong electron barriers associated to the occurrence of SHAx: such barriers correspond to a regime of reduced energy and particle transport ($\chi \sim 10$ m^2/s, D ~ 4 m^2/s), and, as in Tokamaks, to a null shear point of the q profile.
- The possibility of penetrating the helical hot structure with H pellets has been proved. However, the density control has been identified as a main issue to improve the RFX-mod performance; this will be a main objective of the 2010 experimental campaigns.
- Experiments with plasmas approaching the Greenwald density limit have been performed, and the role of both magnetic field ripple and edge turbulence in the formation of the radiating belts associated to high density plasmas has been studied.

- The edge plasma profiles and turbulence have been characterized, by means of new diagnostic systems (edge Thomson scattering and Thermal Helium Beam) and dedicated experimental campaigns with the insertion of edge probes.

2.1 High current operation: optimization towards 2 MA

In the first half of the year an experimental campaign has been devoted to the optimization of the 1.5 MA discharge. The optimization process had as final target the improvement of the experiment performance in terms of particle and energy confinement and of machine operation efficiency.

As an optimization strategy three main aspects have been identified:

- Error Field (EF) correction
- Tearing Modes (TM) control
- Start-up optimization

The EFs have a detrimental effect on plasma performance since they interact with the deformation of the Last Closed Flux Surface (LCFS) produced by the locking in phase of tearing modes. In presence of strong EFs the deformation locks at the wall and enhances plasma-wall interaction.

In RFX-mod the EFs are important mainly during the ramp-up phase of the plasma current. In this phase, lasting tens of milliseconds, the vertical magnetic field necessary to maintain the plasma in the correct position penetrates faster through the two poloidal gaps. As a consequence, an EF of few mT is observed, toroidally localized at the position of gaps as shown in Fig. 2.1.1.

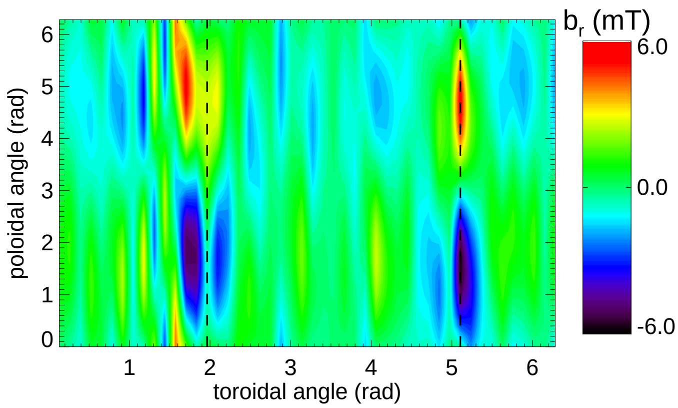

Fig.2.1.1: Contour plot of error fields for the discharge 26135 at t=10ms.

The two-fold approach adopted to control EFs, described with more detail in sec. 2.3, allowed a significant decrease of the EF amplitude in the ramp-up phase of the plasma current.

The TM control scheme presently used in RFX-mod is the so-called Clean Mode Control (CMC) [Zanca07]. Such control scheme allowed the improvement of the RFX-mod performance and the achievement of plasma currents up to 1.8 MA for the first time in a reversed field pinch.

A model (RFXlocking) of the non-linear dynamics of interacting TMs has been developed in [Zanca07], describing the TM dynamics as a function of different control parameters and the predicted trends are confirmed by the experimental data. The RFXlocking code has been used to optimize the mode controller in RFX-mod, using a procedure described in sec. 2.3. The optimization campaign resulted in the selection of a new set of gains, different from that used

in 2008 experimental campaign, which systematically gives a reduction of 20% of the edge radial field, though paying the price of increasing the current flowing in the active coils by 20%.
The RFP configuration is obtained by increasing the plasma current in a bias toroidal field, starting with a tokamak-like configuration, through a succession of low-q states inside a conductive shell, until the toroidal field at the edge reverses its direction. During the 2009 campaign different start-up styles have been compared in order to identify the most convenient for the high current operation. The difference among them relies mainly on the bias toroidal field.
The ‘ramped’ start-up [Sprott88] is characterized by a weak bias toroidal field with early field reversal, peaked current density profiles and self generation of the toroidal magnetic flux.
In a ‘matched’ start-up the plasma current grows in a stronger bias toroidal field, corresponding to the toroidal flux expected in the final state. In principle, the self-generation of flux should be avoided, with a flatter toroidal current density profile and consequently a lower inductance, ending up with a higher plasma current value for the same expense of poloidal flux.
Finally, the ‘aided’ start-up is obtained at an even higher bias toroidal field. However, in the ‘matched’ and ‘aided’ cases, the low-q states, characterized by strong ideal MHD unstable modes are slowly passed through, giving the mode time to grow. The net effect is a dramatic increase of effective start-up resistivity that, during this phase causes the loss of most of the toroidal flux. The case for RFX-mod is reported in Fig.2.1.2.

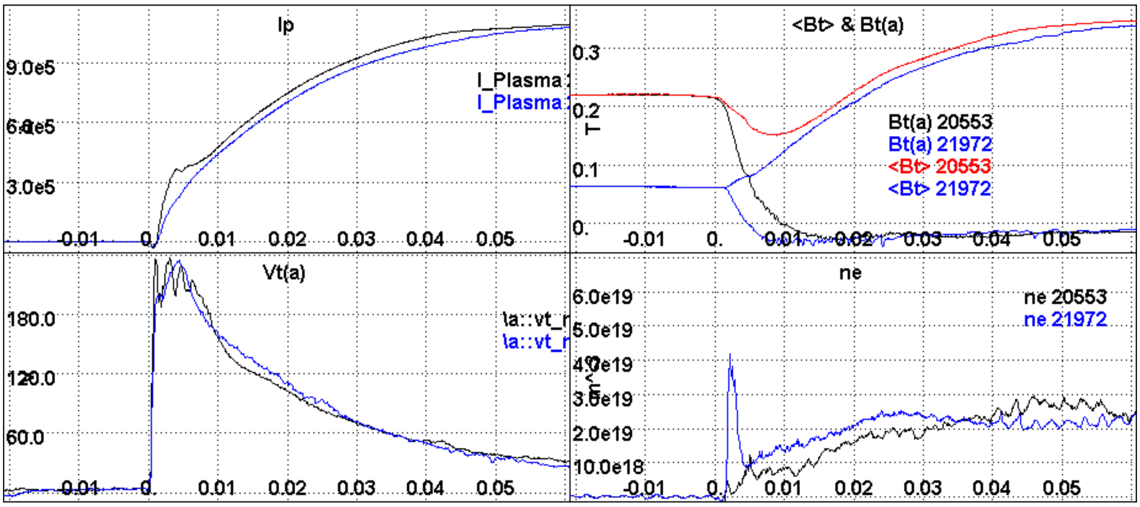

Fig.2.1.2: Start-ups with different initial toroidal bias field (lower for shot 21972, blue lines). Despite the large difference in the bias field values, the final currents are comparable.

The final current is increased only slightly with respect to the ‘ramped’ start-up. In addition, the unstable phase exhibits an extremely poor particle confinement, which requires an increased initial filling or robust gas puffing. This in turn increases the Hydrogen trapped shot by shot on the graphite first wall, requiring time consuming glow-discharge wall treatments during experimental sessions to recover the density control. In RFX-mod high current operation, the above results led to choose a ‘ramped’ start-up with a bias toroidal field as low as possible, between 30 and 50 mT; lower values are critical in the breakdown and early plasma formation.

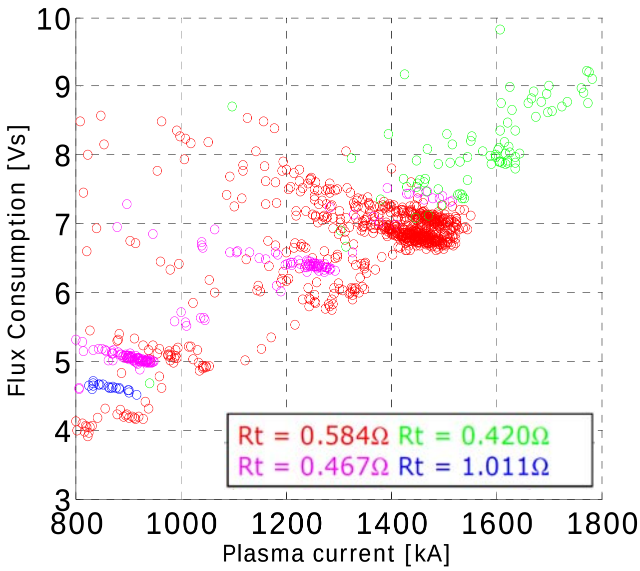

Fig.2.1.3: Flux consumption at different transfer resistances.

Once the start-up is defined, the plasma current value is basically determined by the amount of magnetic flux stored in the magnetizing winding. The flux is transferred to the plasma by diverting the freewheeling current circulating in the magnetizing winding into the energy transfer resistors. The applied loop voltage and thus the plasma current rise time can be modulated by changing the resistor values. The choice is basically a trade-off between two conflicting requirements: while a higher resistance maximizes the energy transferred to the plasma, on the other hand it makes available more free energy for instabilities, whose control is much more difficult, leading to a worse plasma wall-interaction. Since the optimal value was not known, for the sake of safety the initial exploration of RFP at plasma currents higher than 1.5MA was carried out using a rather low transfer resistance (0.420 Ω), which guaranteed a slow ramp-up of the plasma current. Other values of resistance have been tested at 1.5MA to quantify their effect on the efficiency. Fig. 2.1.3 shows the flux consumption as a function of the flat-top plasma current for different values of transfer resistor.

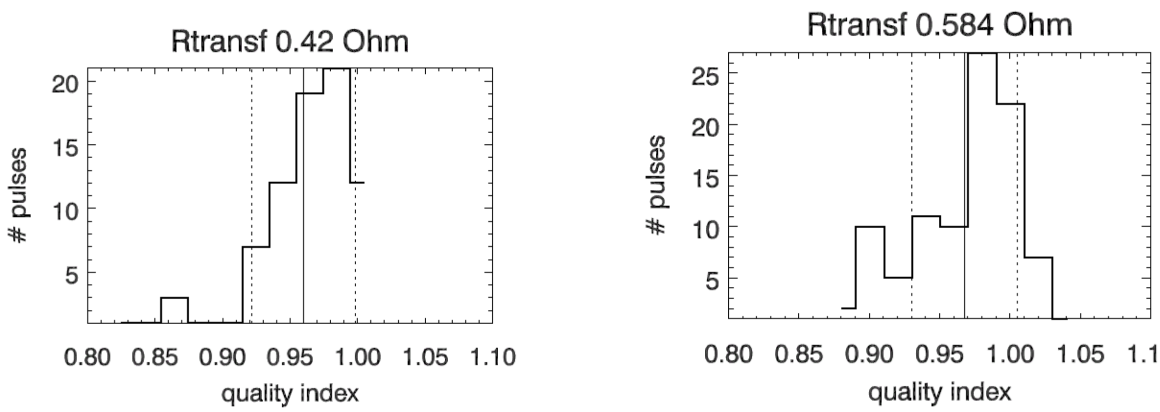

Fig.2.1.4: Quality Factor associated with flat-top current for two transfer resistances.

As expected, the higher is the transfer resistance, the higher is the efficiency of the energy transfer. However, in order to verify whether the slow ramp-up is actually beneficial to limit the plasma-wall interaction (PWI), the effect of the different transfer resistance has been discriminated by using a simplified electrical model of the power supply circuit coupled with the plasma, which gives the typical maximum plasma current expected for different magnetizing currents and transfer resistances. A quality index has been defined by normalizing the experimental plasma current with the model output value and with the magnetizing current. The results are reported in Fig. 2.1.4 for different transfer resistances.

It comes out that there is a slight increase in effective performance with a higher transfer resistance. This effect can be mainly ascribed to the fact that the strong PWI, associated with the MHD modes during the ramp-up phase, persists for a shorter time, being the mode control system only marginally effective in controlling MHD modes during current ramping.

The described optimization campaigns allowed performing the first RFX-mod discharges beyond 1.5MA. Fig. 2.1.5 shows a plasma shot at 1.8MA.

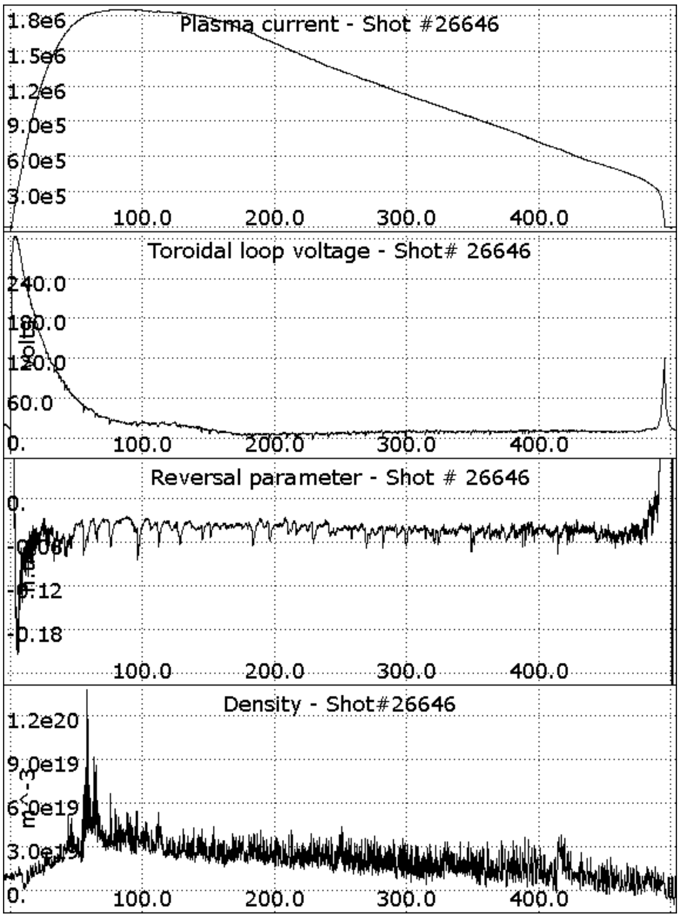

Fig.2.1.5: Example of plasma shot at 1.8MA.

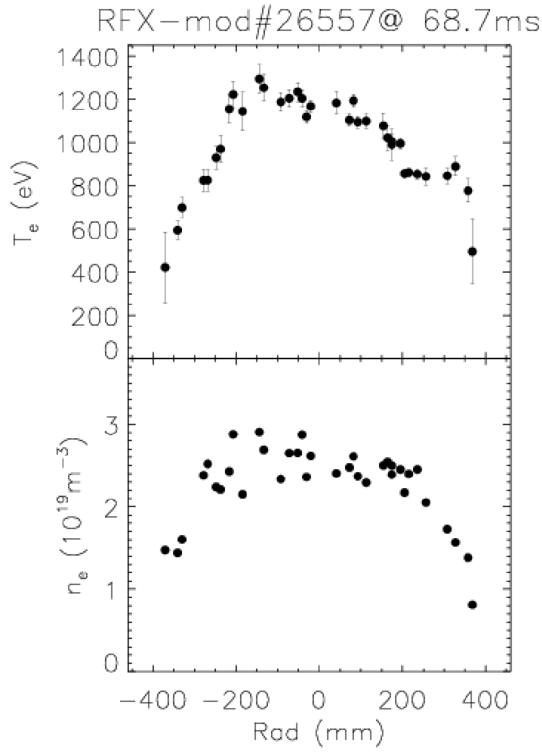

Fig.2.1.6: Temperature and density profiles for shot #26557, at t=68.7ms.

The total number of shots per day above 1.5MA has been strongly limited by the maximum allowed temperature of the magnetizing winding. Despite of that good performance has been obtained on some shots, where electron temperature profiles showed steep gradients corresponding to a well identified transport barrier. An example is shown in Fig. 2.1.6. Temperatures as high as 1.4keV have been measured.

Starting from the achieved scenario, further optimizations are possible along the path of the full machine capability. In particular, the optimization process carried out so far gave the clear indication that wall conditioning is a the key ingredient to improve efficiency and performance. The other key element is a better control of the MHD activity during the start-up since it can potentially further reduce the plasma-wall interaction with consequent increase in the machine efficiency.

2.2 Density control

The experiments aimed at optimizing the fuelling of the core helical structure (the 'short term step' in the 2009 activity program) led to promising results: pellets have been injected inside the helical structure either during its formation phase (see Fig. 2.2.1) and its sustained phase, without compromising the transport barrier. Peaked density profiles, associated to improved particle transport in the neoclassical range has been achieved. This result is of particular importance since it suggests that the RFP in QSH/SHAx state can sustain higher density, whereas the actual density limit appears to be related, with increased radiation, to the bulging of the electron density profile close to the edge (see §2.4.3).

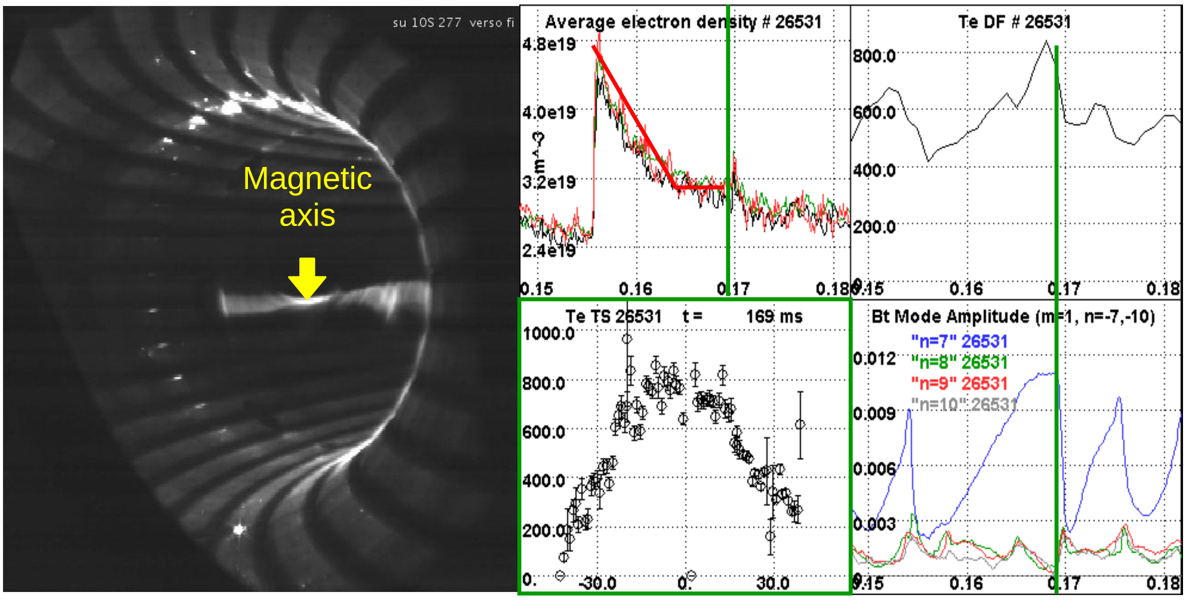

Fig.2.2.1: Image and graph of density and temperature during pellet injection inside the m=1,n=-7 island during its formation. The plasma current was 1.2 MA

On the other hand the ability of controlling the average density from first wall recycling has been confirmed to become more and more challenging as the plasma current is increased (§2.1). Thus a better control of the wall recycling remains a primary requirement. In 2009 new wall lithization experiments on the TJII [Tabarés08] and NSTX [Maingi09] devices, adding to other already using lithization as a wall conditioning technique (for example FTU and T-11), have given excellent results; besides the reduction of recycling, the most promising results for RFX-mod are the dramatic reduction of the electron density and the increase of temperature in the edge region. The first part of the Lithization Project on RFX-mod (indicated as a 'medium term step' in the 2009 activity program) using the solid pellet injector, originally planned in July, has been shifted to November and December because of the shutdown following the toroidal coil contact failure. Lithium pellets on Hydrogen discharges at 1 MA have been completely ablated, showing the expected increase in electron density and the foreseen spectroscopic emission (see Fig. 2.2.2).

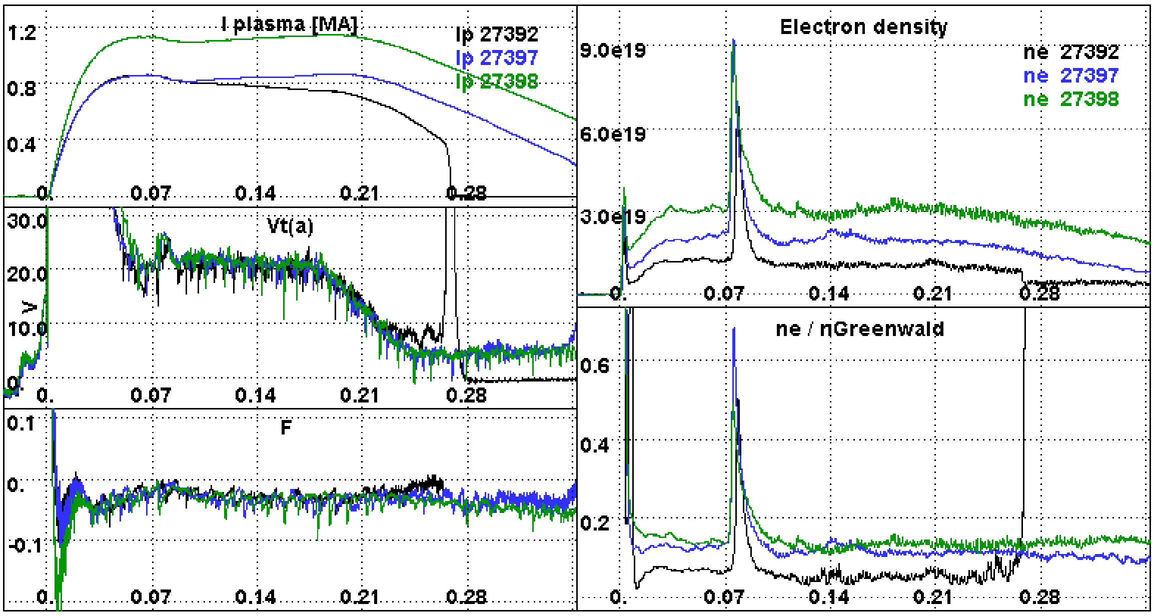

Fig.2.2.2: Viewgraphs of discharges with Lithium Injection .

One of the primary issues of these first experiments was the observation of the decaying of the Lithium presence and care has been taken to maintain very limited quantity of Lithium (in the order of some tens of mg). This has confirmed the subsequent shots can reduce the Lithium content (Fig 2.2.3).

The limited amount of Lithium used during this first phase is aimed at preventing the formation of Lithium Carbonate (Li_2CO_3), which is formed when Lithium is exposed to air. In order to be able to efficiently remove the deposited Li before each machine opening, a new Argon venting system is being installed.

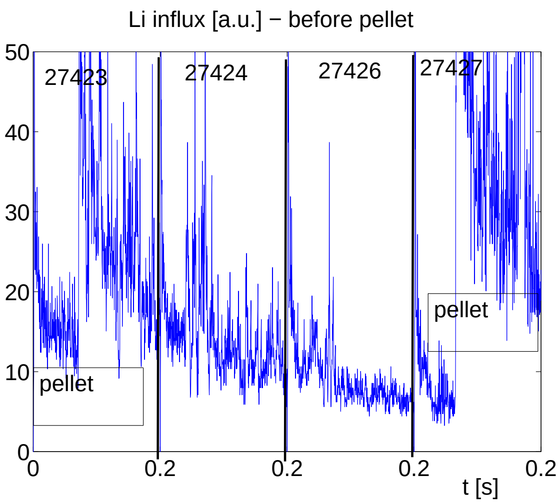

Fig.2.2.3: Decay of the intensity of Lithium emission on consecutive discharges after pellet injection. Li pellets were only injected in discharges 27423 and 2742.

Although Ar Glow Discharges are able to completely remove the Lithium and its compounds from carbon machine (NSTX, T10), their use for this purpose must be well established before increasing Lithium concentration, also considering the possible darkening of the diagnostic windows on RFX-mod caused by prolonged treatments.

During 2009 a dedicated handling system for the Liquid Lithium Limiter (LLL) has been designed, and is now being assembled. It is planned to be installed in the first quarter of 2010. A reorganization of this project has been decided at the beginning of the year, when it was verified that the handling system of FTU [Apicella07] is not compatible with the installation on RFX-mod, as was originally planned. Along with the LLL, two ancillary handling systems have been designed and are being installed for the exposure of a quartz microbalance and graphite samples to the plasma, providing two basic diagnostic tools needed for monitoring the condition of the first wall.

2.3 Real-time control of MHD stability

2.3.1 Tearing modes

The optimization of the gains to apply in the Clean Mode Control of RFX-mod boundary has been addressed by means of the RFXlocking model [Zanca07]. This model considers the non-linear dynamics of interacting Tearing Modes (TM), including their feedback control, balancing the viscous and electromagnetic torques.

As the system allows the definition of the PID gains for each mode, the model was used to simulate the dynamics of each TM independently by changing the proportional (Kp) and derivative (Kd) gains aiming at a configuration with the minimum value of the radial field. This was done considering also two more elements as representative of an improvement in control effectiveness: the rotation of the modes (or at least of the locking structure) and the reduction of the required current in the coils. Both aspects are required in order to assess the problem of the control in high plasma current regimes.

Since the number of variables involved in the optimization is high: 10 modes with m=1, n=(-7,-16), the 2D scan has been applied on each single mode at a time, neglecting the non linear interaction in the electromagnetic torque.

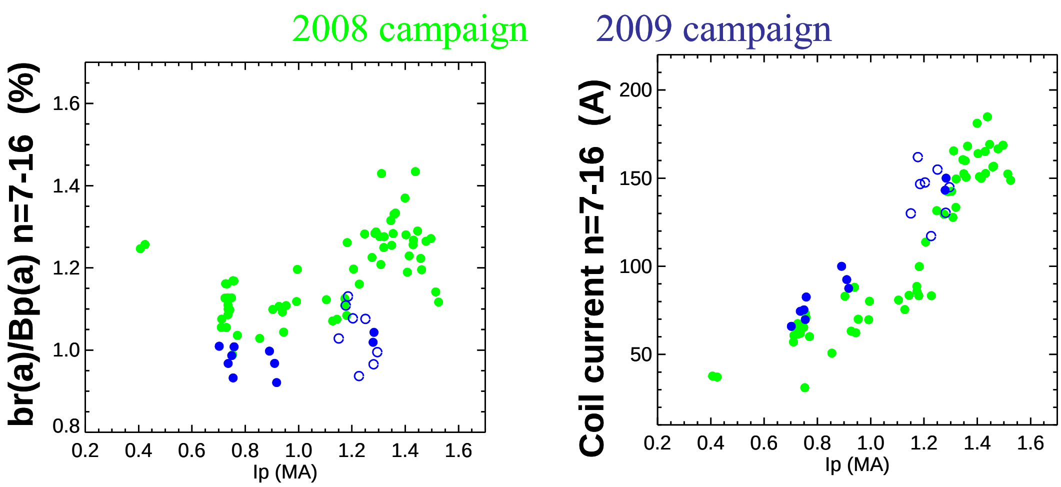

Fig.2.3.1: Normalized amplitude of the radial magnetic field fluctuation at the edge (left) and currents required from the active control system (right).

The gains determined with the model have been tested in an experimental campaign of reproducible discharges [Piron09] in the range of plasma current I_p = (0.8, 1.1) MA with magnetic equilibrium fixed through the parameter $F=B_t(a)/<B_t(a)>$ = (-0.05,-0.02). An experimental gain scan has been performed by multiplying all proportional gains and all derivative gains by some factors, varied independently. Such a scan confirmed that the minimum of radial field is obtained for the proportional gain predicted by the model, while a slightly lower derivative gain is required. In figure 2.3.1 some results of the 2009 optimization campaign are shown as compared to 2008 results: a reduction of the radial field at the edge was obtained (left panel) though with an increase in the coil current request (right panel). The experimentally tuned gains have been used in the 2009 campaign systematically giving lower values of the edge radial field compared to similar discharges of the 2008 campaign.

The effect of an external perturbation on resonant modes has also been tested in preliminary experiments based on the work presented in [Boozer09]: an external perturbation with a well defined helicity should be able to sustain a helical state. The paper, based on the VMEC equilibrium solver (still in the stellarator version), suggests that an external perturbation with a helicity opposite to the dominant mode of the SHAx spectrum should be able (if large enough) to prevent its interruption. First experiments were done with both helicities but no clear indication has been obtained yet on the effectiveness of the technique. Data analysis is still ongoing and should provide indication on a possible improvement of the experimental arrangement.

Real time control is also the means by which the magnetic boundary is made as uniform as possible. Indeed the normal operation of every fusion research device is characterized by the presence of undesired magnetic field components (error fields), which perturb the equilibrium magnetic field configuration. They can be both fields directly due to the features of the machine windings, for instance the ripple of the toroidal field due to coil discreteness or the spurious fields produced by currents in the bus-bars, and fields due to the interaction between the varying winding fields and the passive structures. In RFX-mod the active coil system for the control of MHD modes, appeared the most suitable tool to also tackle the task of compensating for these error fields. For a chosen operational scenario, the error fields and their time evolution are fairly reproducible so that characterization measurements could be acquired in dedicated dry-shots. As in the startup phase the configuration evolves on time scales faster than what the feed-back system can cope with, the goal was to add a feed-forward scheme for error correction based on this reproducibility. The magnetic field measurements provided by the saddle sensors underlying the active coils are routinely used to derive the feedback signals for the active coil control system. They were analyzed in the dedicated shots for an off-line evaluation of the additional current references to be used in the shots with plasma. The magnetic field measured by each sensor is the result of the contribution of many coils and this must be taken into account to optimize the system dynamic response. In the past years a dynamic decoupler of the active coil system was designed. It was based on the estimated transfer function matrix between the active coils and the sensors. By feeding the dynamic decoupler with the opposite of the magnetic field waveforms measured by the sensors, the optimal set of current reference waveforms could be evaluated off-line. They are then applied during the pulse as feed-forward reference signals to the coil current controllers and summed to the current references produced by the MHD mode feedback control system.

Experimentally two approaches were adopted [Piovesan09] and applied to the start-up phase of a reference discharge of RFX-mod: a direct feed-forward scheme for local error field correction and a mode-control scheme that requires to infer the best gains for the main modes contributing to error fields (i.e. m=1, n=±2, ±4, ±6). Both approaches were determined with the above described off-line procedure. In figure Fig.2.3.2 we show the results of these control schemes: the time evolution of the radial magnetic field at the edge with no correction is compared to just gain optimization scheme, just feed-forward scheme and the combination of both. As it is clearly visible, the latter scheme provides best results.

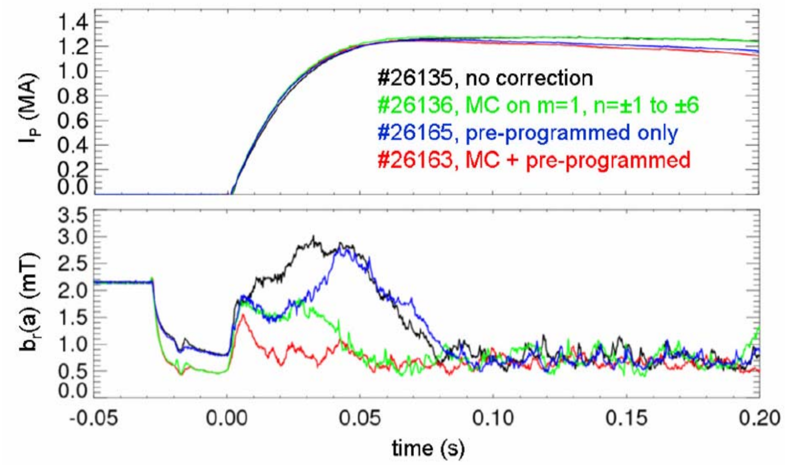

Fig.2.3.2: Time evolution of the total radial magnetic field fluctuation at the edge for m=1, n=±2, ±4, ±6 with different control schemes acting both in feed-forward and with optimized gains.

As it was not possible during this year to allocate experimental time to the experiments on neoclassical toroidal viscosity and non resonant magnetic braking, these aspects will be addressed in future campaigns taking advantage of the optimization level reached both in terms of mode control and error field correction.

2.3.2 Resistive Wall Mode physics and control

In 2009 studies on RWM physics and control focused on specific subjects such as the role of pressure profiles in affecting the RWM stability properties (in support to a new stability code developed in Padova [Guo09]), see more in Sect. 5), the experimental poloidal and toroidal harmonic composition of a single unstable RWM, the mode behavior under subcritical control conditions (in support to a new simulation tool of the whole control loop), and the control of RWM instabilities with a set of active coils reduced by software. In general, the 2009 experimental RWM studies evolved improving and extending their coordination with related theory and technology activities already present in Consorzio RFX. Last but not least, the results obtained confirmed the maturity of RWM studies on RFX-mod and the high level of integration within the international scientific program, as proved by the visits of colleagues from CREATE (Italy), DIII-D (USA), Kurchatov Institute (Russian Federation), and Naka (Japan). Unfortunately new RWM experiments were greatly affected by the toroidal coil system failure in July. In fact 3 full weeks of RWM studies, including experiments in collaboration with external labs (DIII-D and JAEA) had to be cancelled. In the following the main new results obtained in 2009 will be summarized.

A model-based full simulator for RWM control in RFX-mod was developed in collaboration with Create and CCFE (Culham, UK, former UKAEA) since it is considered an important step to achieve further progress of the system performance, as well as a key demonstration of ITER-relevant controller design techniques. This new tool can be imagined as a full “flight simulator” for RWM control in RFX-mod, where realistic PID gains can be given as inputs and closed-loop growth rates of multi-mode RWM spectrum result as outputs. To accomplish that task, two fundamental advances were necessary: the first was the adaptation of the CarMa code to RFX-mod in order to get a model coupling between the relevant MHD physics and a three-dimensional description of passive and active boundary, and the second was the development of dynamic models of the control system cast in the state variable representation. As first, non-trivial application of the new integrated tool, closed-loop RWM stability analyses have been benchmarked against experimental data provided ad hoc [Baruzzo09]. In this way it was possible to experimentally prove that the control simulator correctly reproduces closed-loop RWM growth rates under subcritical control conditions, i.e. when a proportional gain lower than the critical one is applied to the control loop (see Fig. 2.3.3).

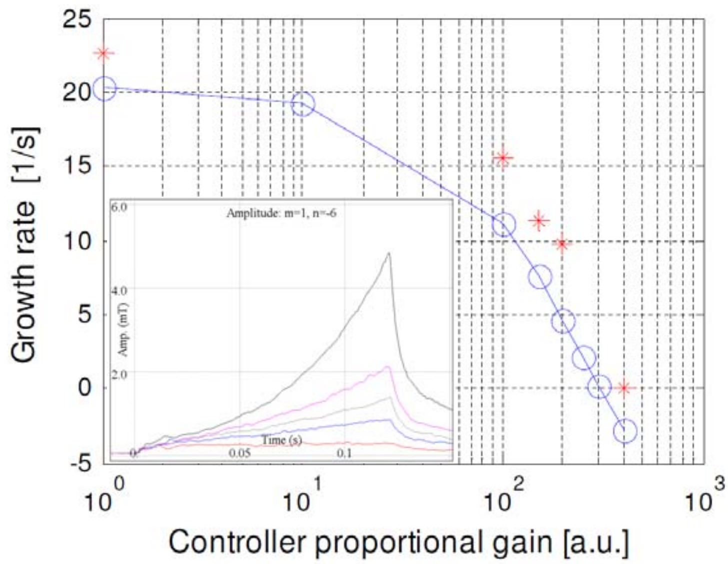

Fig.2.3.3: Results of the RWM control experiments benchmarked against the model. The model correctly reproduces RWM growth rates under subcritical control conditions, i.e. when a proportional gain lower than the critical one is applied to the control loop. In the figure experimental data (red asterisks, see inlet for the full time behavior) and simulations (in blue) are compared.

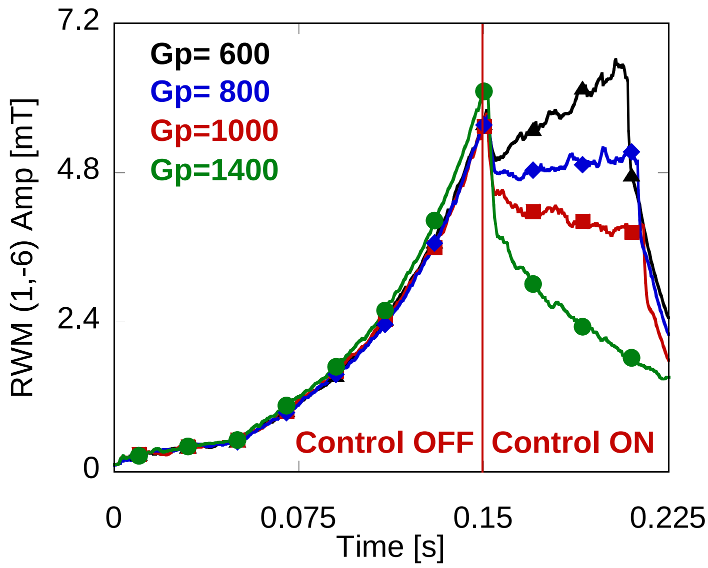

Fig.2.3.4: Proportional scan on the (1,-6) unstable RWM with only 25% of active coils coverage (inner toroidal array only).The mode is stabilized for Gp>800 (critical gain with full coverage is 400).

Preliminary experiments on mode control system reconfiguration were executed in 2009 in collaboration with JAEA colleagues. Final aims of these experiments are to study the mode rigidity issue and to explore the optimum requirements of a RWM control system in terms of coil number, position and shape. To reach these targets, an improved control software was developed, able to reconfigure the actuator system only on selected harmonics (RWMs in our case), leaving a full control on the remaining of the plasma in order to work on an optimized background plasma. As a test configuration we show in Fig. 2.3.4 a proportional gain scan on the (1,-6) unstable RWM when only 25% of the active coils are used. An important result of these tests is that the most unstable RWM can still be controlled with a reduced set of coils and that the critical proportional gain can be experimentally evaluated, leading to an easy comparison with numerical models. New experiments will be needed in 2010 to complete these studies and to support the project of the RWM active coil system in JT-60SA, as part of the Consorzio RFX involvement in the Broader Approach activities (see Sect. 7).

Finally, the analysis of the RWM experimental database allowed investigating the harmonic composition of unstable RWMs. Both toroidal and poloidal components were characterized; it results that, in the RFP configuration, interaction between different toroidal harmonics is negligible, while more than one poloidal harmonics contribute to the correct mode description ([Bolzonella09]). It is interesting to note that the ratio between the different poloidal harmonics considered can not be fully resolved by simple geometrical considerations (toroidal coupling). Our interpretation is that this discrepancy can be explained by the coupling between the main unstable RWM and the passive boundary (mainly the toroidal gaps), as already suggested by 3D computations [Villone08].

2.4 Transport studies

2.4.1 Energy and particle transport in the core

Much effort has been devoted in understanding energy and particle transport in the core of RFX, in particular after the discovery of the helical SHAx state [Lorenzini09a]. The helically nested flux surfaces, which change the topology around a new helical (m=1,n=-7) axis, deeply affect particle trajectories, their transport, and heat fluxes. Experiments and related research have been performed along three mainstreams: trying to explain the Thomson Scattering electron temperature profiles in terms of a steady-state (power balance) approach; estimating the particle diffusivity through perturbative (pellet and laser blow-off) experiments; understanding the electron transport barrier of the SHAx in terms of equilibrium change which affects the helical q profile, by exploiting the similarity to internal electron transport barriers in Tokamaks and Stellarators. Generally speaking, the steep temperature gradients which develop in the helical SHAx are consistent with neoclassical values of diffusivity, being at the same time suitable to be treated with the standard tools of neoclassical transport developed within the Stellarator community (see Section 5.2).

To take into account the effect of the helical geometry in the transport analysis of SHAx states, the Automatic System for TRansport Analysis ASTRA [Pereversev2002] code has been adapted to the RFP topology.

ASTRA is a transport code that combines a 3D description of the equilibrium with a 1D description of transport (the so-called 1.5-D codes). The transport equations of particle, electron and ion energy are solved according to the formulation derived in [Hinton1976]. The 1D transport equations are written by averaging out all quantities on the flux surfaces defined by the magnetic equilibrium.

ASTRA needs, as initial conditions, experimental temperature and density profiles as well as the source term profiles, all averaged on the flux surfaces. Further input to the code is the radial profile of the specific volume V' and of the first element of the metric tensor G11 as a description of the magnetic equilibrium.

For SHAx states the latter quantities have been calculated using the description of the equilibrium based on the calculation of tearing mode eigenfunction in toroidal geometry for a RFP plasma [Zanca04]. The helical equilibrium is expanded in a perturbative approach as a dominant, saturated tearing mode summed with an axisymmetric equilibrium. In this description the effective radial coordinate is the square root of the helical flux ρ, which is a flux function.

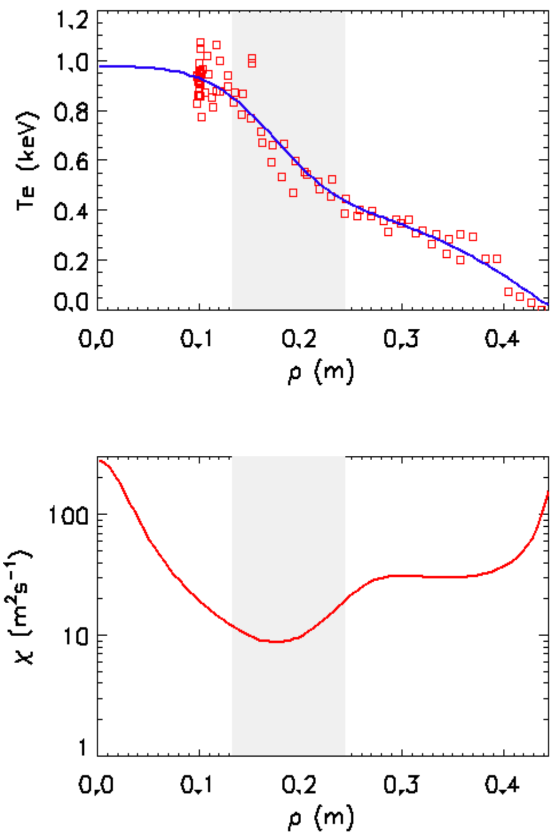

Fig.2.4.1: (top) Electron temperature profile as measured by the Thomson Scattering (squares), and splined profile (solid, blue). The splined profile is used as input to ASTRA; (bottom) profile of electron thermal conductivity (solid,red). The dashed, gray region corresponds to the temperature maximum gradient, and minimum χ.

Figure 2.4.1 shows the thermal conductivity profile χ calculated by ASTRA for the shot #24598 at t=173 ms, when the Thomson Scattering diagnostic is measuring a SHAx profile: the grey area highlights the region where the transport barrier is located. In this region the thermal conductivity reaches the minimum value of 10 m^2s^{-1}.

A simpler approach has also been used, mapping the terms appearing in the flux-averaged power balance equation, namely temperature, density and ohmic input power, onto a two-dimensional Cartesian grid, where flux surface contours are also defined.

Temperature and density profiles are measured by the Thomson Scattering diagnostic (the latter after cross calibration with the interferometer), while the current pattern required to define the heat source term is reconstructed via a cylindrical, force-free equilibrium (the so-called μ&p model), being direct measurements yet unavailable.

The surfaces used in computing the heat flux are chosen as helical flux levels (actually levels of the normalized square root of the helical flux, ρ) and the diffusivity is calculated via the following formula:

$$\chi_e(x,y) = \frac{1}{n_{\rho_0}\nabla_r T_{\rho_0} S_{\rho_0}} \int_{\rho<\rho_0} \eta\,(j_\phi^2 + j_\theta^2)\,dxdy$$

where the ohmic input integral runs over ρ levels and the result is corrected accounting for the helical deformation of the surfaces [Fassina2009]. This formula gives a local value which is mainly influenced by the module of the temperature gradient. Finally, the diffusivity value, which in principle is obtained on the Cartesian grid, is averaged on flux contours to express it as a function of $\tilde{\rho}$ in order to compare it to the values given by ASTRA.

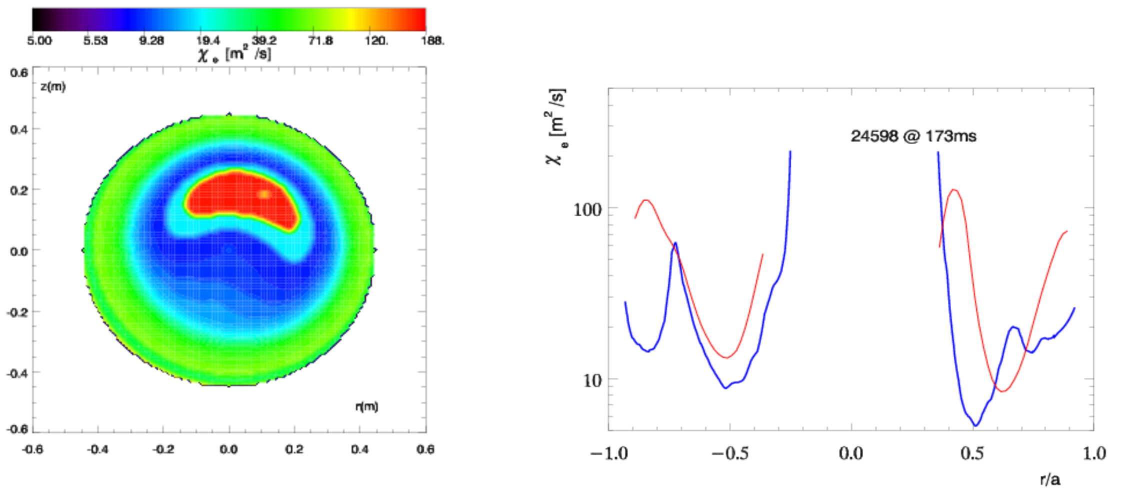

Fig.2.4.2: 2D electron diffusivity map and, on the right, comparison between the 1D model (blue) and related 2D model slice (red): the values given by the2D model tend to be higher at the edge, mainly because the temperature gradients are smoothed once the temperature itself is averaged on ρ surfaces. The data refer to a SHAx plasma.

This calculation can attain a better precision in the evaluation of diffusivity in the vicinity of the SHAx state, while it is in good agreement with a 1D, cylindrical estimate as one moves towards the edge (see Fig.2.4.2), consistent with the physical fact that the edge plasma is still axisymmetric. The 2D χ_e profile is usually smoother, being all the data averaged on ρ before being processed; this can lead to underestimating temperature gradients (and thus to higher values of heat diffusivity) near the plasma boundary. Actually this is the main limit of this 2D approach and should be taken into account when only focusing only at the edge behavior. The minimum value of χ is in agreement with the value given by ASTRA, being in the range of 10 m^2s^{-1}.

The evaluation of *particle transport* in SHAx states is more difficult to attain, since density profiles are usually flat inside the helical flux surfaces, as a consequence of the absence of a particle source inside the structure. To this purpose, perturbative transport studies on the main gas (with pellets) and on impurities (laser blow-off) have been performed during 2009.

Pellet injection campaigns extended the results of year 2008. A good database of discharges allowed for the study of the correlation between density asymmetries and the SHAx state, showing that during the ablation phase (lasting for about 1 ms) the deposited particles are constrained to follow the helical structure [Terranova09a]. In order to correctly interpret the measurements provided by the interferometer, a new, flux-coordinate inversion algorithm has been adopted. This allowed for the determination of a density profile and also the estimate of the particle confinement time.

In figure 2.4.3 we show three examples of density profiles for discharges with different pellet penetrations as shown by the position of the maximum density. Taking into account the H influxes the global particle confinement time has also been estimated. For the three cases presented, we obtained a value of 8 ms for the pellet with shallow penetration (blue dotted-dashed line), 12 ms for a better penetration (red dashed line) and 8 ms for the core pellet (black continuous line) that actually deposited within the helical core structure. These values are to be compared to a typical particle confinement time of about 4 ms in a standard MH state. The corresponding value of diffusivity *D*, calculated in a cylindrical geometry with the 1D code TED, is in the range 4—6 m^2s^{-1} [Puiatti09a] as shown in Fig. 2.4.4. This value is consistent with (though slightly larger than) the values obtained in helical geometry [Gobbin09a] via the test-particle code ORBIT [White1984].

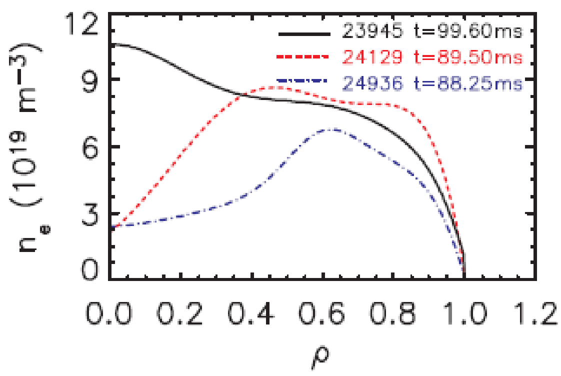

Fig.2.4.3: Density profiles in SHAx states with different pellet penetration depth.

These results indicate that helical states are characterized by an overall reduction of chaotic transport.

Regarding impurity transport, a series of experiments were carried out by injecting Nickel into the high current (Ip>1.MA) plasma via the laser blow-off (LBO) technique. Neon transport in SHAx has also been studied in Neon puffing experiments.

The impurity diffusion coefficient *D* and "pinch" velocity *V* are estimated by simulating the experimental radiation

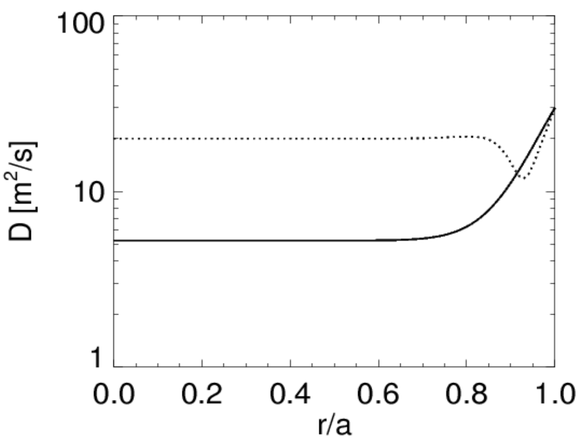

Fig.2.4.4: Particle diffusion coefficient radial profile in MH case (dashed line) and in SHAx state (continuous line) computed by the TED code, according to the experimental density and particle source profiles.

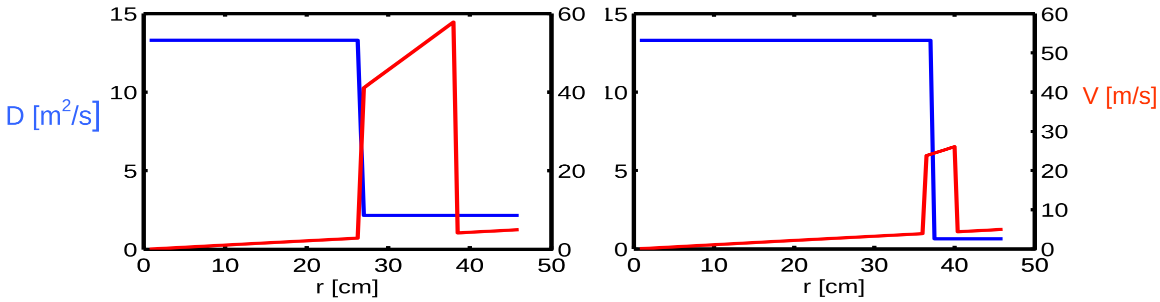

Fig. 2.4.5: Nickel diffusion coefficient (solid, blue) and pinch velocity profiles (solid, red) in high current SHAx (left, RFX discharge #26607) and MH (right, #26613).

pattern following the Ni injection with a 1-dimensional collisional-radiative model [Mattioli2002]. Within the limits of a cylindrical approach, the results, shown in Fig.2.4.5, indicate a strong outward pinch velocity at the plasma edge opposing the impurity penetration both in SHAx and MH regimes [Menmuir2009]. The position of the velocity barrier is more internal in SHAx, consistent with the extension of temperature gradients towards the plasma core (see Fig.2.4.6).

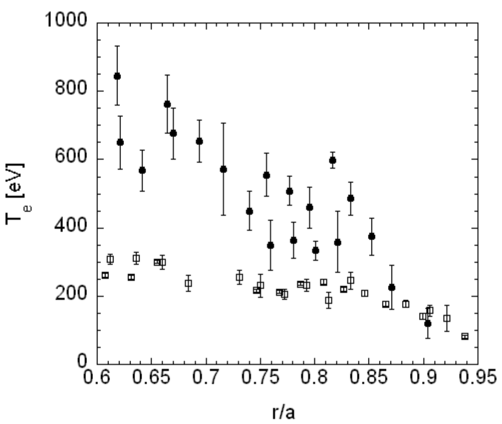

Fig. 2.4.6: Electron temperature profiles at the edge in SHAx (#26607, full circles) and MH (#26613, empty squares).

The Ni diffusion coefficient is found to be about the same in the MH and SHAx regimes (D=10 m^{2}s^{-1}), confirming the trend found in ORBIT simulations, namely that the collisional regime of Nickel in RFX is such that random-walk diffusion processes due to classical collisions are dominant and Ni ion transport is little influenced by the magnetic field topology. As a consequence, Ni transport should be in the Pfirsch-Schlüter regime, even if the large pinch velocity V, and the mismatch of almost one order of magnitude between experimental and ORBIT evaluations cannot exclude some turbulent contribution (and likely to be not driven by magnetic turbulence) [Carraro2009].

The outward pinch found for Ni in QSH is also suitable to describe Neon transport and carbon (intrinsic impurity) as well. A summary of the findings regarding transport in SHAx vs MH are reported in Table 2.4.1

Codes/calculation:	*ASTRA*	*χ 2D*	*ORBIT*	*TED (pellet)*	*1D LBO*
χ SHAx	10	10	-	-	-
χ MH	-	50—100	-	-	-
D H+ SHAx	-	-	1—4	4—6	-
D H+ MH	-	-	20	20	-
D Ni SHAx	-	-	1	-	10
D Ni MH	-	-	1	-	10

Table 2.4.1: Summary of the results obtained for heat and particle diffusivity [m2/s] in SHAx and MH with the different approaches used in RFX-mod during year 2009.

Understanding the nature and origin of the electron temperature barrier associated to SHAx is a much more difficult subject, and large efforts have been devoted to this topic. The radial position of the temperature gradient, shown in Fig. 2.4.1, has been linked to the shape of the safety factor profile *q*. In particular, the *q* profile of these states has been numerically reconstructed by the ORBIT code [Martin2009], the results being confirmed by an analytical calculation based on the Hamiltonian treatment of the magnetic field line in toroidal geometry [Escande2009]. For each helical surface the *q* value is calculated as the inverse of the average poloidal angle crossed by the field line after a toroidal transit around the helical axis [D'Haeseleer1991]. It has been observed that, in the region occupied by the helical structure, the q profile is slightly reversed with a maximum value lower than 1/7. Otherwise, in the outer region till the edge, the *q* profile in a SHAx state does not differ significantly from the one computed in an axisymmetric plasma. The evaluation of *q* in a similar way can be performed even in Double Axis (DAx) cases, characterized by the presence of a separatrix and generally corresponding to magnetic islands of smaller width. In the region inside the island of DAx states, the *q* is lower than 1/7 and has still a maximum at about the separatrix position.

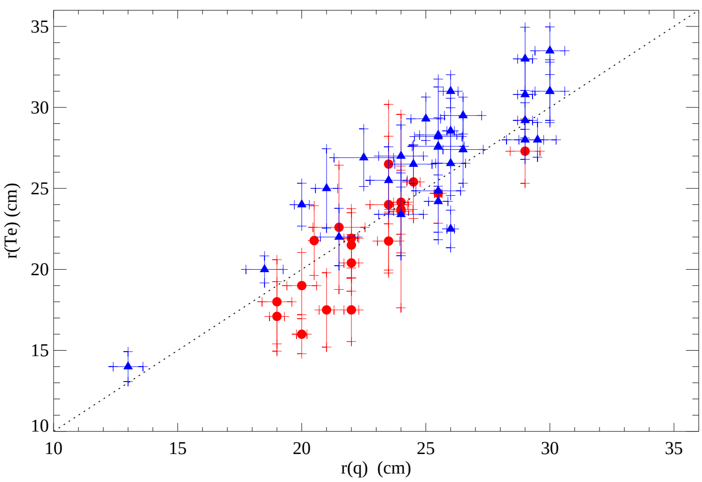

Fig. 2.4.7: Correlation between the maximum q position r(q) and the temperature gradient position r(Te). Blue-triangles are relative to SHAx states while the red dots to DAx.

By analysing Thomson Scattering data, a correlation between the maximum of *q* and the region where the electron temperature gradient starts increasing has been found. This study has been performed on a database of 55 Thomson profiles corresponding to high current plasmas both in SHAx and DAx regimes. Results are reported in Fig.2.4.7 with the position of the temperature gradient location, $r(T_e)$ versus the position of the *q* maximum, $r(q)$.

Measurements are in centimeters and are the absolute values of the distances $r(q,\mathrm{Te})$ from the camera geometric center (i.e. R_0=200cm). Dot symbols correspond to DAx cases while the triangles to the SHAx ones.

The correlation between r(q) and r(Te) suggest that the electron temperature barrier is associated to the shearing of the magnetic field lines, with an interesting similarity with ITB in Tokamaks, where the shear acts as a stabilization mechanism for drift-wave turbulence.

2.4.2 Turbulence studies

Flow measurements in the edge region.

A detailed analysis of the edge flow properties has been performed on the outer region of RFX-mod, involving both a complete reconstruction of the radial profiles of the averaged flow components and a study of the flow transients during induced changes in the reversal parameter F (F-steps).

Plasma flow components parallel and perpendicular to the edge magnetic field (mainly poloidal), have been measured by an insertable system, the so called Gundestrup probe [MacLatchy92]. Radial profiles have been obtained on a shot to shot basis by inserting the probe up to about 10% of the minor radius of RFX-mod in several low current (< 400 kA) discharges with a shallow F equilibrium (F > -0.07).

The two flow components have been evaluated by means of a new method based on the floating potential measurements deduced and validated through different cross checks including various models based on the ion saturation current measurements and also previous results from another insertable system [DeMasi09].

It can be observed that the parallel flow radial profile, M_{par}(r) (fig. 2.4.8) remains quite small in absolute value near the first wall (r = 459 mm) and at the maximum insertion explored, while it exhibits the highest shear around 1-2 cm far from the wall. This behavior can be directly linked with the radial position of the m = 0 islands chain for the shallow *F* equilibrium. To support this thesis, in the F-step experiments the Gundestrup probe has been located at the radial position corresponding to the maximum parallel shear in the average radial profile (r = 439 mm). Fig. 2.4.8 shows that the measurement point, during the transition from a shallow *F* equilibrium toward a deep *F* equilibrium, collides with a m = 0 island, showing a peak in the $M_{par}(t)$ (fig. 2.4.8) corresponding roughly to the centre of the island. Hence, the time behaviour can be considered as an indication of the M_{par} radial profile within the magnetic island, suggesting that the magnetic island m=0 is characterized by a sheared parallel flow.

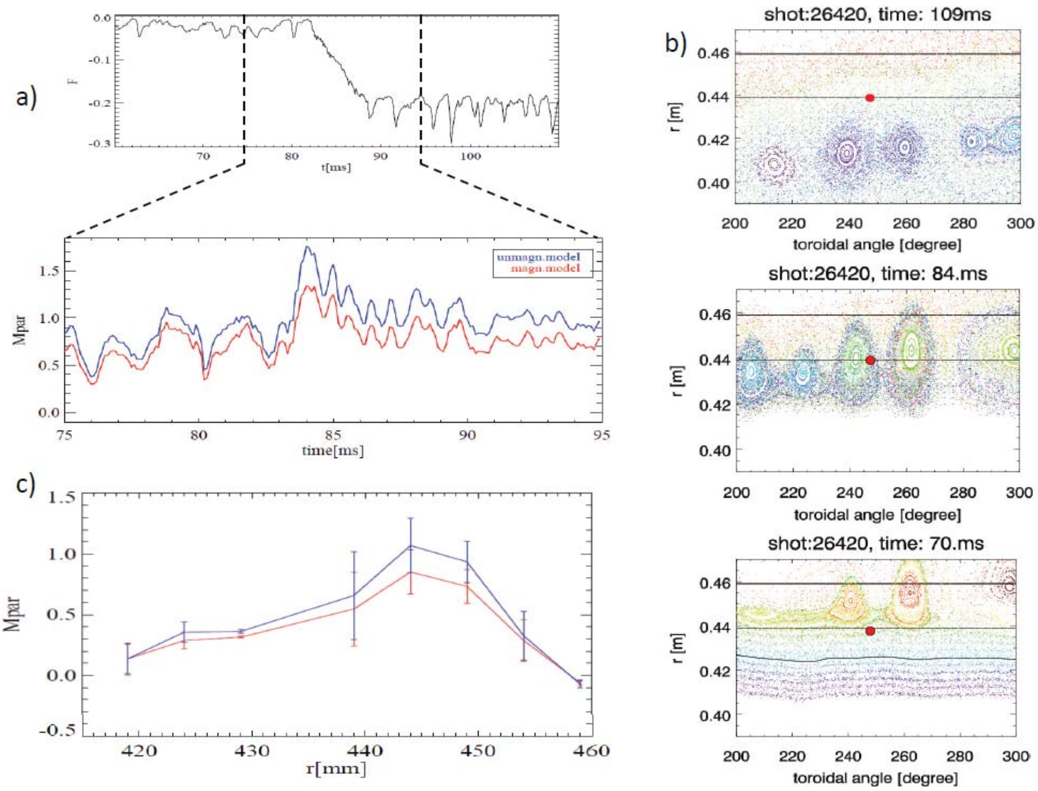

Fig.2.4.8: a) [#26420] Time evolution of M_{par} at r=439mm, during a transient of the F parameter; b) [#26420] Plots on the (r,φ) plane of local magnetic topology at three different time instants: before, during and after the F-step. The red dot indicates the probe measurement point; c) Average radial profiles of M_{par} as measured by the Gundestrup probe for a set of discharges with shallow reversal. The blue and red curves indicate the flow reconstruction through a magnetized and unmagnetized model.

The perpendicular flow radial profile seems to show a slightly different behavior; anyway it is in good agreement with the same quantity measured by the U-probe, with the presence of a radial sheared electric field affecting the edge perpendicular flow.

Current filamentary structures in the edge region.

An extensive study on the turbulence structures in the periphery of RFX-mod has been done using an insertable probe, dubbed "U-Probe" designed to study electromagnetic turbulence at the edge. It is well known that the edge region of RFX-mod, as well as the edge region of all magnetically confined plasmas, is populated by *blobs* or structures, which appear as pressure perturbations in the perpendicular plane with an associated velocity pattern and are elongated along the guiding magnetic field as filaments. Present theories of blobs formation and dynamics suggest different originating mechanisms as interchange turbulence with effects induced by sheath boundary condition or mechanism deriving from the coupling between drift and kinetic Alfvén waves (KAW). During 2009 RFX-mod has performed the first direct measurement of the current density associated to these filaments [Spolaore09] and has established the Drift-Alfvén origin of these structures at shallow reversal equilibrium allowing identifying them as Drift-Kinetic Alfvén vortices (DKA). These results have been obtained using the aforementioned probe which allows the simultaneous measurements of plasma density, electron temperature, electron pressure, plasma potential and their radial profiles at the same toroidal location as well as the radial and toroidal components of the electric drift velocity and of the local fluctuation of the vorticity $\omega=\nabla\times$ v where v is the electric drift velocity, from floating potential ones V_f as $\omega_{||} = \nabla_\perp^2 V_f/B$. Moreover at the same nominal position the probe allows evaluating the parallel current density, directly calculated from Ampere's law (fig. 2.4.9).

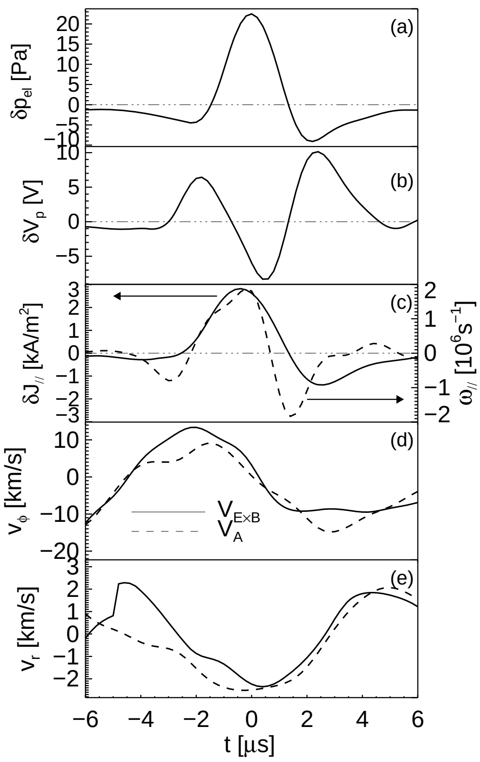

Fig.2.4.9: Average coherent structure detected at τ = 4μs using electron pressure as reference signal. (a) Electron pressure (b) plasma potential (c) parallel current density and parallel vorticity (d) (d) E × B toroidal velocity and alfvén velocity (solid and dashed lines respectively), (e) E × B radial velocity and alfvén velocity (solid and dashed lines respectively)

The figure shows the results of a conditional average applied to the relevant plasma parameters performed using as a triggering event the presence of an intermittent structure on electron pressure at typical scales of $\tau = 4$ μs (panel (a)). The pressure perturbation is found to be essentially due to the density. Panel (b) shows the electrostatic potential perturbation which displays a minimum slightly out of phase with respect to the pressure one, underlying the drift origin of the coherent structure. The electrostatic potential gives rise to an electric field in the perpendicular plane responsible for the vortex-like fluid motion. Panel (c) shows both the parallel current density and the parallel vorticity: a clear parallel current perturbation is observed in phase with the pressure peak and the measured vorticity proving the proportionality existing between scalar and vector potential. The two last frames display the two components of the perpendicular **E**×**B** velocities compared to the corresponding Alfvén velocity perturbation: this comparison is equivalent to the observation that $E\perp/B\perp = V_A$ with V_A Alfvén velocity calculated from equilibrium magnetic field, thus confirming the alfvenic character of the fluctuating velocities. The dimension in the radial direction can be estimated using spatially resolved measurements of electron pressure shown in panel (a) of figure 2.410.

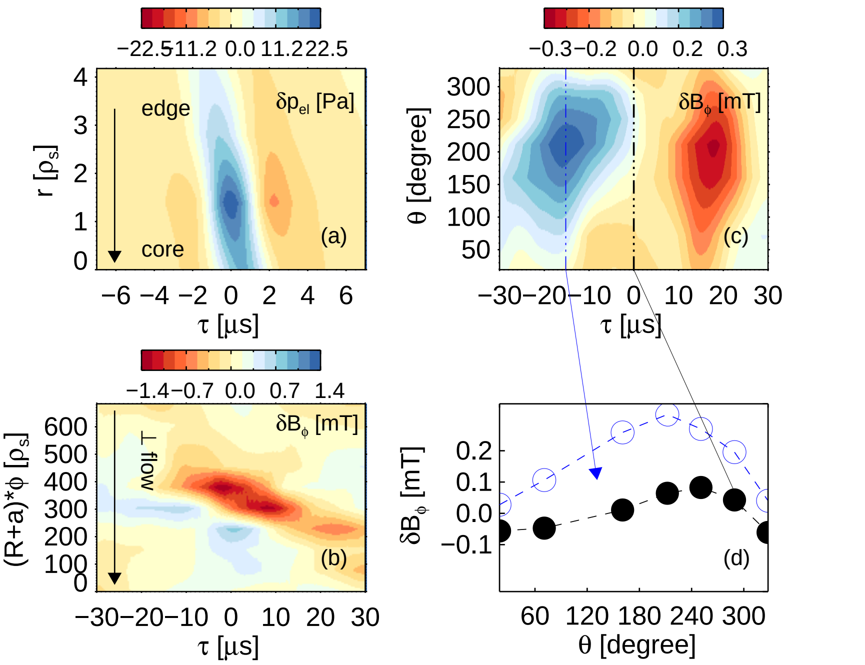

Fig.2.4.10: (a) electron pressure as a function of time and radial position normalized to ion sound gyroradius ρs. (b) toroidal magnetic field as a function of time and toroidal coordinate normalized to ρs. (c) toroidal magnetic field as a function of time and poloidal angle (d) poloidal distribution of the toroidal magnetic field perturbation in the two time instants marked on panel (c)

In the plot the radial dimension has been normalized to the local ion sound gyroradius ρ_s in order to show that the radial extent is of the order of 2-3 ρ_s as theoretically expected for the DKA vortices. Panel (b) of the same figure 2.4.10 shows that the structure propagates toroidally in the electron diamagnetic direction (measurements from the toroidal distributed array of pick-up coils pertaining to the ISIS system), thus supporting the drift origin of the observed structure. The parallel wave vector has been estimated using a poloidal distributed array of pick-up coils. The result is shown in panel (c) as obtained from a conditional average procedure where still the presence of a peak on the electron pressure measured by the U-probe is used as a trigger. Clearly the magnetic perturbation is poloidally localized; its poloidal extension is shown for two different times in panel (d). The structure extends up to 300 degrees corresponding to a $k_{//} = 2.6\ \mathrm{m}^{-1}$: the finiteness of the parallel wave vector definitely proves the drift-origin of this type of structure and this information combined with the alfvenic character of the fluctuation identifies them as Drift-Kinetic Alfvén vortices.

Edge temperature and density profile.

The Thermal Helium Beam (THB) is an active spectroscopic diagnostics based on the measurement of the intensity ratios of spectral He lines emitted by a beam injected at the plasma edge. Such ratios depend on electron temperature and density and allow the experimental determination of the radial profiles of the electron density, temperature and pressure in the plasma edge (0.94<r/a<1), also at high plasma current. Data from THB have been used to study the relationship between the electron profiles, the magnetic topology in the plasma edge and the turbulence.

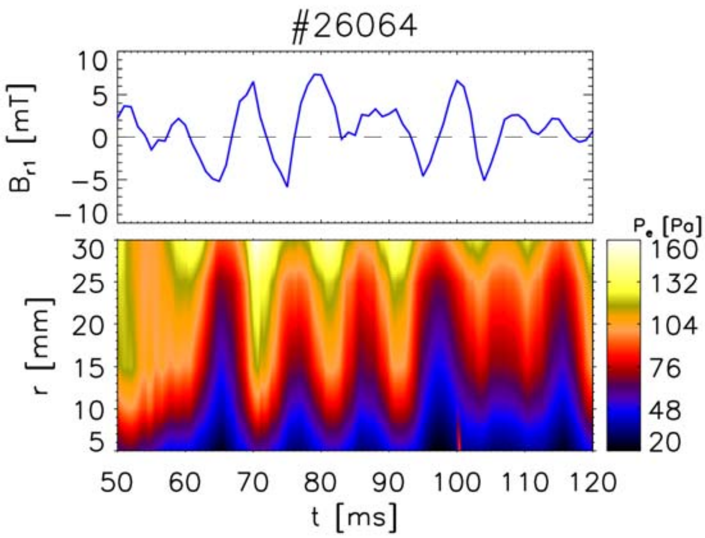

Fig 2.4.11: Time evolution of the radial component of m=1 modes (top) and of the electron pressure profile (bottom) in the far edge (r=0 is the first wall).

An evidence of the relationship between the magnetic topology and the edge profiles is shown in Fig 2.4.11. The cyclical oscillations in $P_e(r)$ are in phase with the fluctuations of the radial component of the *m=1* magnetic modes (B_{r1}): when B_{r1} assumes positive values (outward), plasma pressure increases and the gradient becomes steeper. Also the connection lengths in the two magnetic configurations are different: when the pressure gradient is inward shifted the THB is measuring in a region connected to the wall with short connection lengths while, when the gradient is shifted outwards, the THB is measuring in a region which is connected to the wall with long connection lengths. This picture is in agreement with the idea that longer flux tubes receive higher amounts of particles and energy by diffusion through their sides; according to this vision the plasma-wall interaction in different regions can be quantified, as a first approximation, by looking at the connection lengths [Lorenzini09b].

Beyond these relationships between the magnetic field and the low-frequency fluctuations of the edge parameters, it has been shown that (B_{r1}) can modify also the high frequency fluctuations, related with the turbulence. When the amplitude of the secondary modes decreases, also the radial characteristic pressure length L_p decreases, i.e. with an improved magnetic boundary, the edge pressure profile becomes steeper. At the same time also the toroidal width of the edge blobs decreases. These results indicate a significant interplay between the magnetic topology, the electron profiles and the edge turbulence.

The THB diagnostic, coupled with the Gas Puff Imaging [Scarin09], can also identify and measure the density and temperature of the edge coherent structures (blobs), up to a time scale of $3\mu s$. It has been shown that the edge blobs are peaks in density and pressure, while they exhibit a double structure in temperature, with a minimum corresponding to the n_e maximum [Agostini09_2]. For high plasma current discharges, these structures have a radial extension of about 10-15 ρ_s (ion sound radius).

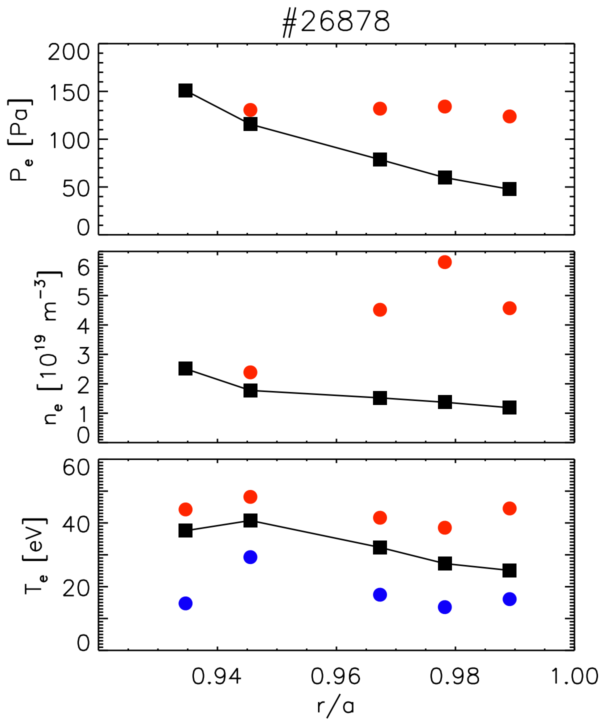

Fig 2.4.12: Average profiles (black squares) and peaks of edge fluctuations (circles).

In Fig.2.4.12 the radial profiles (black squares), the peak value of the edge structures (red circles) and of the minimum value of the temperature structure (blue circles) are shown. For the outermost radial points, the edge blobs show a density and pressure drastically exceeding the average ones; instead for $r/a \simeq 0.94$, n_e and P_e are similar to the average values [Agostini09]. This behaviour could suggest that the edge blobs are born near $r/a=0.4$ with the background density and pressure, and then evolve outwards, increasing themselves. Figure 2.4.12 also shows that the edge fluctuations of n_e and P_e are larger than the T_e ones, as already observed for low plasma current discharges with the electrostatic probes.

Density limit in RFX-mod.

In all major confinement devices (tokamaks, stellarators, spheromaks and reversed-field pinches), a density limit has been found (the so-called Greenwald and Sudo limits). Results summarized in [Puiatti09b] and [Puiatti09c] show that in the RFX-mod high density does not cause a disruption, but a sequence of phenomena leading to the disappearance of quasi-single helicity (QSH)/Single Helical Axis (SHAx) [Puiatti09a], density increase, radiation condensation and fast resistive decay of the plasma current. During 2009 significant advances in the understanding of the density limit have been achieved: on the one hand, the role of the coherence of the magnetic ripple, and its effect on particle motion, on the other hand, the impact of edge turbulent transport through "blobs". The competition between collisional and turbulent transport and the back-transition from SHAx to the chaotic MH are envisaged to rule the observed density limit.

In Fig.2.4.13 temperature and density profiles, measured by the main and edge Thomson Scattering (TS) diagnostics, are plotted as a function of the normalized poloidal flux coordinate $\rho = (\psi_p/\psi_{p,w})^{1/2}$ in four different discharges with increasing density, normalized to the Greenwald density, $n_G=I_p/\pi a^2$. Edge TS density profiles are absolutely calibrated, while those of the main TS are calibrated against the corresponding inverted interferometer profiles. There is an edge density increase, which is poloidally symmetric ($m = 0$, see the good matching between inner and outer main TS profiles) and toroidally localized at $\phi - \phi_{lock} \sim 100°$, being ϕ_{lock} the toroidal position of the maximum coherent superposition of m = 1 MHD modes (often called "slinky" or "locked mode").

By increasing n/n_G the "ring" expands towards the plasma core. As it is evident in Fig.2.4.13, the density increase is correlated with the widening of the radial region at low temperature (< 50 eV) where low ionization stages of impurities mainly emit. As explained in detail in [Puiatti09b,c], all these observations are likely explained by a classical, radiative instability [Wesson1989] which increases resistivity and finally chokes the current. In this respect, by

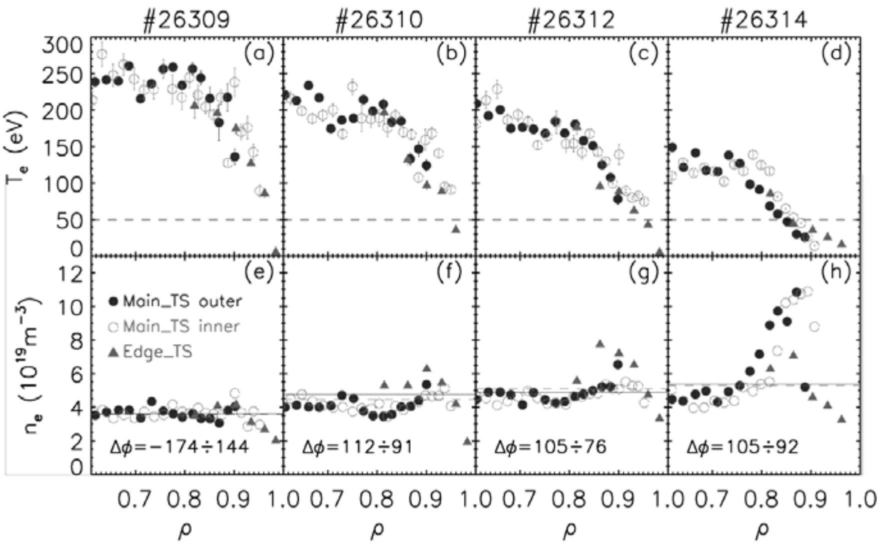

Fig.2.4.13: TS profiles of temperature (a)–(d) and density (e)–(h) for a series of discharges with increasing n/n_G (left to right, n/n_G = 0.28, 0.35, 0.44 and 0.6). Dashed line in (a)–(d) marks Te = 50 eV.

exchanging poloidal and toroidal directions, the phenomenon of radiative instability in RFX-mod resembles the MARFE in tokamaks [Lipschultz1987]. It is worth noting that the coherence of the m = 0 ripple increases as a function of n/n_G, as shown in Fig.2.4.14 for the m=0 phase

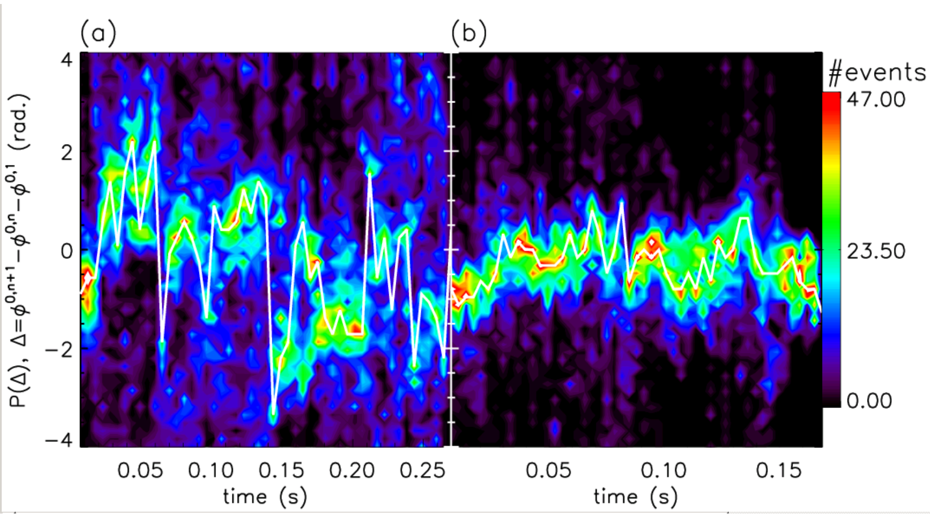

Fig.2.4.14: Distribution of the m=0 phase dispersion Δ^n, n = 1−9, as a function of time for two different discharges with (a) n/nG = 0.17 and (b) 0.52. A constant, Δ=0 means that the maximum coherence is maintained throughout the discharge.

dispersion parameter $\Delta^n = \varphi^{0,n+1} - \varphi^{0,n} - \varphi^{0,1}$ [Zanca01] (note that Δ=0 means maximum coherence). This confirms that the coherence of MHD modes is a fundamental ingredient in determining the toroidally asymmetric density accumulation

In addition to this, we observe a sharp increase of $m = 0$ amplitude in a rather narrow density range ($n/n_G \approx 0.4\div0.5$) [Puiatti09a], similar to the phase transition between multiple and single-helicity (MH-QSH/SHAx) states seen in MHD simulations [Cappello2000]. Since the level of coherence depends on the amplitude of the m=0 modes, the back-transition from QSH/SHAx to MH is likely to explain both the high coherence of m=0 modes and the radiative instability phenomenon, which is intrinsically due to the m=0 edge islands, shown in the following.

In fact, the radiative instability is only the final outcome of a dynamical accumulation of density, toroidally localized and poloidally symmetric. Gas-puff imaging (GPI) [Agostini2006] and internal system of sensors (ISIS) [Serianni2003] blob toroidal velocity measurements v_ϕ show the presence of two null points: a source at $\phi = \phi_{lock}$ and a sink (stagnation point) at $\phi - \phi_{lock} \sim 100°$ [the radial electric field averaged in the last 2-3 cm next to the wall, $\langle E_r(r,\phi)\rangle_r = v_\phi \cdot B_\theta$, corresponds to the GPI flow v_ϕ and is plotted as a solid line in Fig.2.4.15(e)]. The flow of blobs is (within a good approximation) the plasma flow itself [Scarin09]. We observe that the reversal of v_ϕ along the toroidal direction $\hat{\phi}$ conveys the edge robust toroidal flux ($\approx 10^{23}$ m^{-2} s^{-1}, much larger than the radial diffusive flux), to the stagnation point, where density accumulates, temperature decreases, resistivity increases and plasma emits radiation: this accumulation is therefore convective in the toroidal angle, and *not driven by any density gradient*.

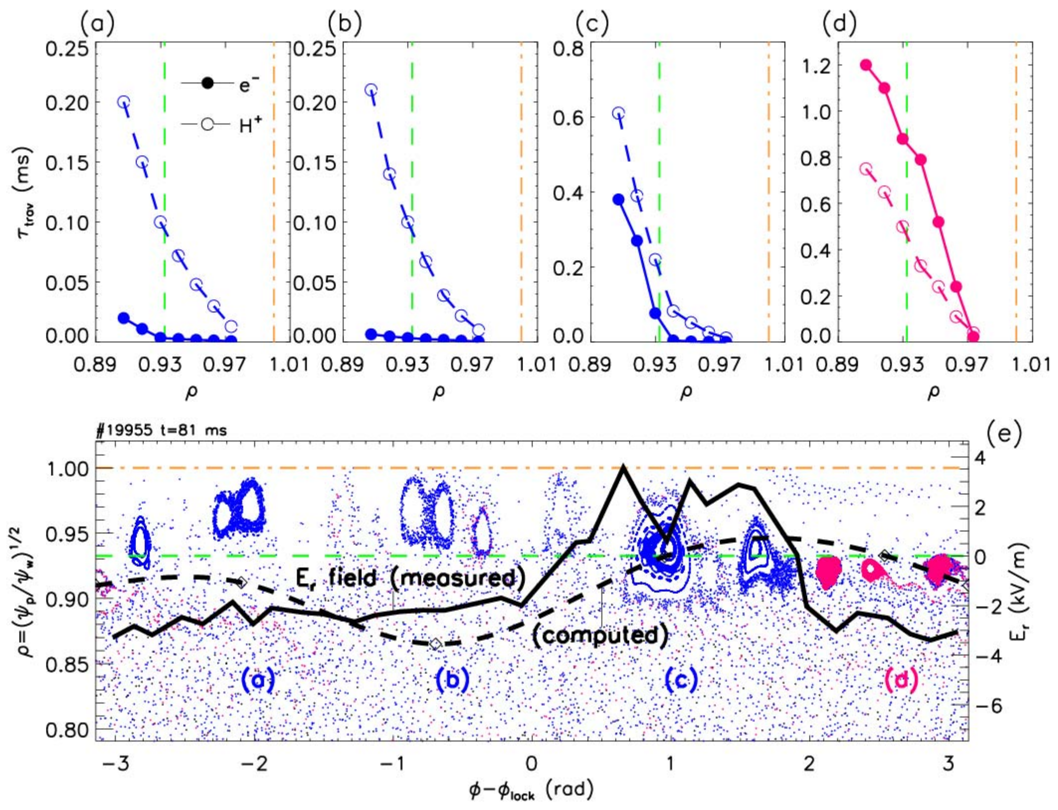

Fig.2.4.15: (a)–(d): Travel times as a function of ρ for particles deposited at ρ = 0.98 and at toroidal angles corresponding to the labels (a)–(d) in frame (e); (e) Toroidal Poincaré plot with measured (solid) and computed (dashed) electric field.

To study the modulation of E_r along ϕ, $\langle E_r(\phi)\rangle$, the Hamiltonian guiding centre code ORBIT [White1984] has been applied, using as input the eigenfunctions calculated from the Newcomb's equations in toroidal geometry [Gobbin09b]. It is worth noting that during 2009 the ORBIT code has been upgraded in order to take into account a recycling wall (in its standard configuration ORBIT has a perfectly absorbing wall). Fig.2.4.15 shows the Poincaré plot for a discharge with n/n_G = 0.8, at the time of the density peak. A chain of m = 0 islands is evident, with their O-points aligned in the vicinity of the unperturbed reversal (horizontal, dashed green line), and shifted outwards or inwards according to the toroidal modulation of ψ_p. At $\phi < \phi_{lock}$ the islands are pushed towards the wall (orange, dash-dot line in all frames), while at $\phi > \phi_{lock}$ they are shifted towards the axis.

In the toroidal region marked by the letter (c) in Fig.2.4.15 the plasma flow (electric field) reverts its direction and, as a consequence, density peaks in region (d). It is therefore natural to study the radial motion of electrons and ions deposited near the wall and in the vicinity of the m=0 islands marked by the letters (a)–(d) in the Poincaré plot.

Electron radial losses are found much larger than ions in (a) and (b), since the "blue" islands [see Poincaré plot in Fig.2.4.15] act as a short-circuit for their trajectories; ions are comparatively less mobile and reflect less the magnetic topology due to their larger drifts. As a consequence, a cloud of positive charges forms next to the wall and, as a result the ambipolar field would be directed inwards, which is the usual condition on the RFP [Puiatti09b]. This picture is changed only in the vicinity of the "red" islands in (d), where the magnetic topology is different: m = 0 islands are smaller, more conserved, topologically detached from the wall, and they comparatively reduce the electron mobility. In this region ion losses are larger than electrons. Estimating the radial electric field required to balance the fluxes we obtain the dashed curve in Fig.2.4.15: this radial electric field is negative almost everywhere, except for a region at $\phi > \phi_{lock}$, and approaches the measured E_r.

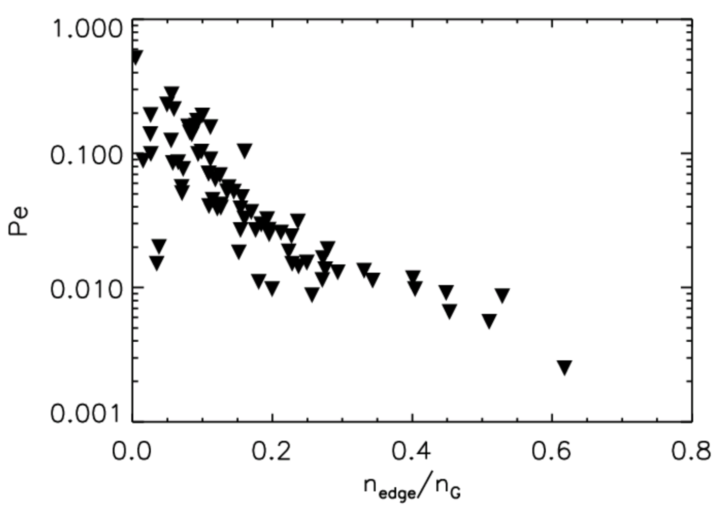

Fig.2.4.16: Parameter Pe = $\tau_{e,i}/\tau_{tr}$ as a function of density normalized to Greenwald..

The role of electrostatic turbulence in the density limit mechanism is still an open issue: whether it is a by-product of the back-transition between SHAx and MH, and in this case the density limit would be a phenomenon thoroughly described in a MHD context, or if there is some active co-operation between turbulence and MHD.

During 2009 analyses on the GPI data have shown that the trapping process by blobs weakens as a function of collisionality. We define as an indicator the ratio Pe = $\tau_{e,i}/\tau_{tr}$ [Vlad2000] between electron-ion collision time and transit time of blobs $\tau_{tr} = L_\phi / V$, being L_ϕ the toroidal dimension of blobs and V the r.m.s. of v_ϕ, both measured by the GPI [Scarin09]. In Fig.2.4.16 we show Pe as a function of n_{edge}/n_G: the parameter Pe falls off from 0.5 to 0.01 when n/n_G > 0.35, corresponding to a change from 2 to 100 electron-ion encounters per blob transit. This shows that at high density, collision scattering particle trajectories are dominant in comparison to particle trapping within blobs, changing transport towards a Bohm-like scaling.

2.5 Equilibrium and stability

A simple, yet effective method for computing helical equilibria in RFP SHAx states has been developed. The method starts from the symplectic representation of the magnetic field, B = $\nabla F\times\nabla\theta - \nabla\Psi\times\nabla\phi$, where (r,θ,ϕ) is a generic system of curvilinear coordinates used to describe the toroidal system and in general $\Psi(r,\theta,\phi)$ and $F(r,\theta,\phi)$ are not constant over flux surfaces (flux surface existence is not even guaranteed in the general 3D case). If one assumes a helical symmetry, so that Ψ and F depend only on r and on $u=m\theta-n\phi$, then it is straightforward to show that the helical flux $\chi(r,u) = m\Psi-nF$ is a flux function, that is $B\cdot\nabla\chi = 0$. Thus, the knowledge of $\chi(r,u)$ enables to display the shape of the SHAx magnetic surfaces.

The $\Psi(r,u)$ and $F(r,u)$ functions have been computed as the superposition of an axisymmetric zeroth-order equilibrium and of a first-order single-helicity perturbation, which is calculated using an existing code which solves the force-free Newcomb's equation [Zanca04]. An example of the resulting flux surfaces is displayed in fig. 2.5.1. This equilibrium reconstruction was the basis for the paper published in the August 2009 issue of Nature Physics [Lorenzini09a].

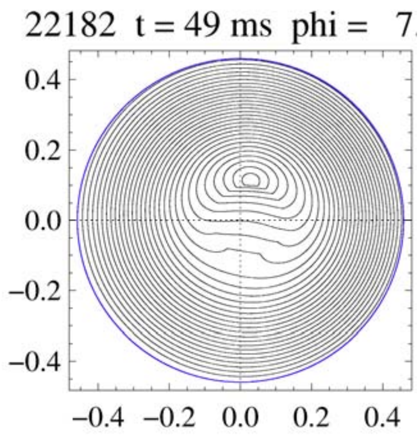

Fig.2.5.1: Flux surfaces for a 1.5 MA SHAx state, as given by the equilibrium reconstruction method based on Newcomb's equation

An algorithm for computing flux surface averages on the equilibria derived from Newcomb's equation has been developed. This involves defining a new coordinate system, with a poloidal angle which revolves around the helical magnetic axis. The metric coefficients of these new coordinates have been computed, and in particular the specific volume V' and the g_{11} component of the metric tensor, which enter the flux surface average formula, have been obtained.

The metric coefficients and flux-surface averaged quantities computed in this way will be used within the ASTRA code to perform more sophisticated transport calculations in helical geometry, as discussed in sec. 2.4.

Helical equilibria have been also reconstructed by means of the 3D code VMEC [Hirshman83], a spectral code solving the force balance equation also including the effect of pressure. As

VMEC was developed for stellarator equilibria, it had to be adapted in order to be able to run for the RFP configuration: to this end the poloidal flux instead of the toroidal flux (a non-monotonic function in the RFP) was considered as independent variable.

VMEC axisymmetric equilibria have been benchmarked against the force-free toroidal reconstruction [Zanca04] used in RFX-mod providing a very good match between the two solutions in the β=0 configuration.

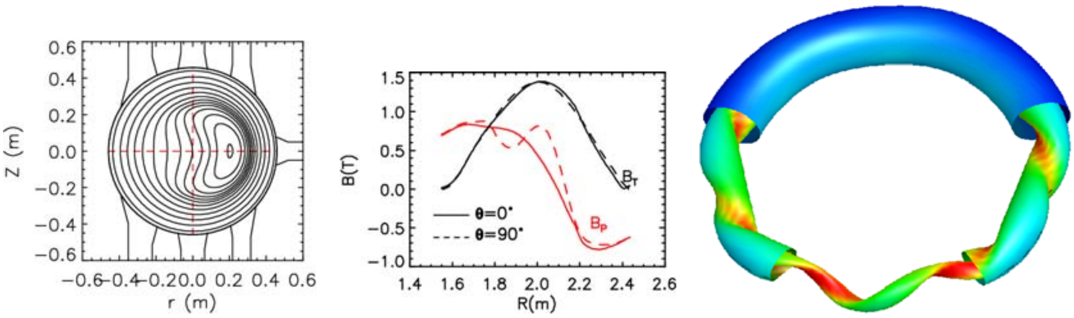

Fig.2.5.2: VMEC reconstruction: flux surfaces in a helical state (left), magnetic field profiles along two directions (centre) and 3D reconstruction of the global equilibrium showing 3 flux surfaces

Given these good results, also helical states have been reconstructed by means of VMEC providing as input parameters the total toroidal flux, plasma current, LCFS shape, helical axis and radial q profile [Terranova09b, Gobbin09b]. In particular the latter is the main element to make VMEC converge to a helical equilibrium and was calculated by means of the ORBIT code or the semi-analitical approach above described: the reversed/almost null shear in the plasma core is the key element characterizing SHAx states.

In figure 2.5.2 we show the results of a typical VMEC run: in a configuration with helical flux surfaces (left) the magnetic field profiles do show asymmetries with respect to the axisymmetric case. In the central panel we also show asymmetries of the profiles taken along different directions on the same poloidal cross section putting into evidence the helical structure.

As it is customary in stellarators, in the right panel we show a 3D image of magnetic surfaces in a SHAx state as reconstructed from VMEC equilibrium. The figure clearly shows the fact that SHAx states are characterized by a helical core that changes towards an axisymmetric shape towards the edge of the plasma.

2.6 Current drive

In 2009 the experimental range of Oscillating Field Current Drive (OFCD) operations has been successfully extended towards high current plasmas and low oscillation frequencies. Experiments were done in collaboration with the MST group (Madison).

Experiments proved the full compatibility of the OFCD technique with high current operations. Particular care was taken to keep plasma macroscopic parameters as constant as possible in order to allow a clear comparison of the results. An example is shown in Fig 2.6.1. where a reference discharge is compared to two OFCD ones (20 Hz is the oscillation frequency): thanks to the long period, the main plasma parameters are not affected while the plasma current in one of the two OFCD cases seems to show an increase after 3 full OFCD cycles. Though a more extended statistics would be needed to conclude that we are in the presence of a net current drive effect, certainly the comparison shown in the figure suggests that, by changing the phase difference of the two oscillating fields, “good” (cyan) and “bad” (blue) cases can be found as suggested by theory and recently confirmed experimentally by MST results. It is important to

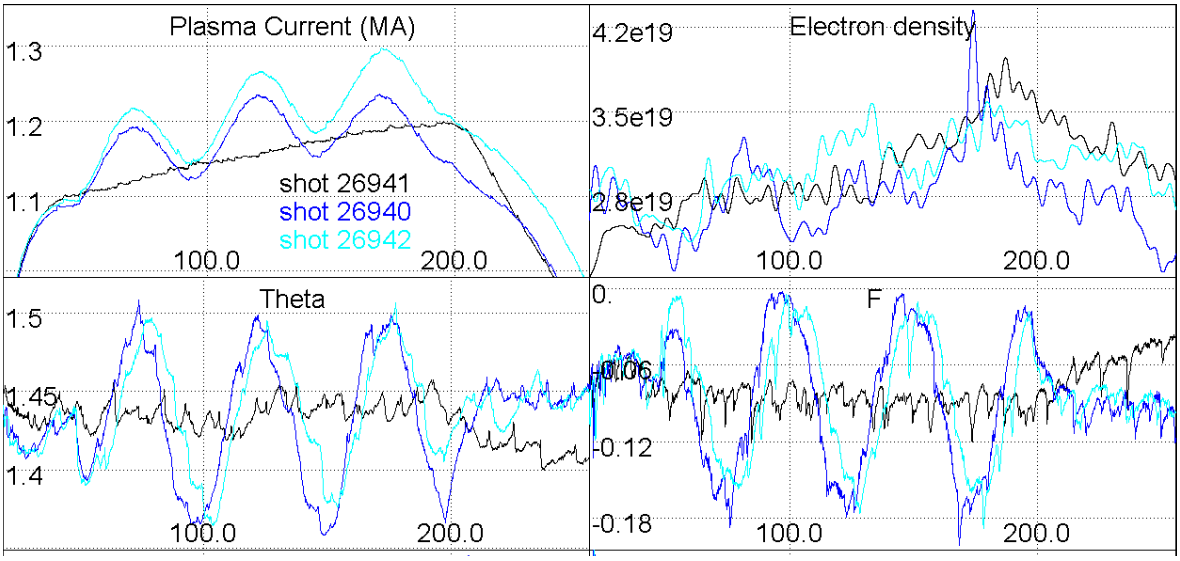

Fig.2.6.1: A reference discharge (black lines) is compared with 2 OFCD experiments at 20 Hz oscillation frequency with the same macroscopic plasma parameters.

note that the helicity injection rate should scale favorably with both the Lundquist number S and the oscillation period, pointing towards new experiments at higher plasma currents and hopefully even lower oscillation frequencies.

2.7 Preparation for the power beam injector installation

The installation of the 1.5 MW beam on loan from AIST Tsukuba required a significant amount of bureaucratic work together with the legal offices in Brussels to find an agreement on the intellectual property sharing that suited to both EU and Japan policies. The collaboration agreement was signed in March 2009 and the specific Free Leasing Contract in October 2009. The beam itself has been packed and delivered in November 2009. Regarding the installation of the beam on RFX, a list of specific issues has been drafted in order to find the human resources and start advancing towards suitable provisions. An AIST_BEAM group has been formed within RFX to cover the various aspects related to the beam installation: that is the mechanical interface, the Residual Ion Dump, the beam trajectory simulation, vacuum,

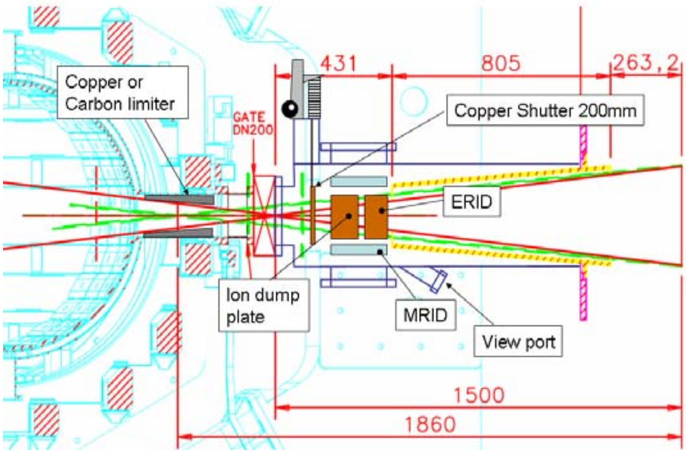

Fig.2.7.1: poloidal cross section of RFX and, schematically, a preliminary solution for the mechanical interface of the power beam.

ancillary equipments, power supplies, controls and safety. Regular remote meetings with AIST started on April 2009. A general layout for the beam on RFX has been decided whereby the power supply is positioned in the main power supply hall of RFX in order to easy fulfill the fire prevention requirements. This decision implied the procurement of a special stand for both acceleration and arc power supply. A design for the stand has already been completed by an external company. Preliminary computation of a magnetic shield to protect the beam and the neutralizer from the strong magnetic stray fields of RFX has been completed. The insertion of a Residual Ion Dump (RID) to deflect the ions that survive the neutralizer stage has been verified by Montecarlo simulations to be necessary for all the plasma currents above 300 kA. Two types of RID have been studied: an electrostatic one which would require a voltage across the plates around 10 to 20 kV and a magnetic one with in-vacuum Helmholtz coils. Preliminary considerations on the mechanical interface have provided ideas for viable solutions to the difficult task of accommodating vacuum pumps, residual ion dump, insertable beam interception plate, duct protection tiles, ports for diagnostics in an overall narrow space. Figure 2.7.1 shows the poloidal cross section of RFX and a preliminary solution for the mechanical interface and radial position of the beam. A full beam simulation is being developed to ascertain that re-ionization in the beam duct will not stop the beam. In the same time a vacuum model is being studied to correctly specify the vacuum pumps needed to keep the neutral pressure in the duct below 10^{-4} mbar.

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3. ITER

In spite of many uncertainties and delays in decisions by the ITER Organization and F4E, that did not allow reaching the key milestones set in the 2009 workprogramme and specification preparation. In particular, for the Neutral Beam Injector system, the design activities have been regularly carried out under two F4E grants, while for the Neutral Bean Test Facility key decisions have taken at the end of the year, so that it is now possible to plan, with good confidence, the start of construction by the middle of 2010.
In the following, the main 2009 achievements in the areas of NBI, diagnostics and modeling are presented.

3.1 NBI development

During 2009 the development activity has been continued under a F4E grant along the three main lines: Ion Source development, full Neutral Beam Injector (NBI) development and Test Facility construction. A description of the main achievements is reported for PRIMA (Padova Research on Injectors Megavolt Accelerated), MITICA (Megavolt ITER Injector & Concept Advancement) for the 1 MV injector Test facility and SPIDER (Source for the Production of Ions of Deuterium Extracted from RF plasma).
On February 15th 2009 the 2008 Grant Agreement with F4E (GRANT-F4E-2008-GRT-011-01) has been completed and after a revision process by the client the 97.5% of the contractual activities have been recognized as completed in time. More than 3000 pages of documents and 800 drawings have been delivered to F4E.
From March 15th 2009 the new Grant Agreement with F4E (GRANT-F4E-2009-GRT-032-PMS) is retroactively in force. The administrative procedure to sign the contract has been rather long and complicated. The call for Proposal has been issued on June 8th 2009, the F4E Executive Committee has approved the Grant Agreement on July 30th 2009, the Grant Agreement has been signed on November 27th 2009.
The new Grant Agreement will cover all the design activities and the follow up of the components and plants procurement activities up to March 14th 2011.
The Grant Agreement includes the contribution of third parties (similarly to the previous one), in particular the design of the beam line components of MITICA is being developed with the contribution of CCFE (former UKAEA), the design of the MITICA cryogenic pumps with the contribution of KIT (former FZK), the support in the design of the plasma source, for the design of some diagnostic and for some experimental and R&D activities with the contribution of IPP and the development of a numerical code for the simulation of the MITICA neutralizers with the contribution of CNRS (Délégation Ile-de-France Sud).
Some activities under the responsibility of RFX will be performed with the contribution of Italian research institutions: CNR-IFP (Milano) and University of Milano Bicocca for the

design of the Neutron and X-ray diagnostic for SPIDER, CNR-IMIP (Bari) and University of Bari for the simulation of the caesium distribution and surface negative ion production.

For this new Grant Agreement on December 23rd 2009 a first set of new design documents has been delivered, corresponding to the first intermediate hold point foreseen at the signature of the contract.

During 2009 RFX has supported both F4E and ITER Organization (IO) to complete the process of approval of the Neutral Beam Test Facility. In particular RFX in spring 2009 has produced for IO all documents for the 23 Procurement Packages, needed for the preparation of the Procurement Arrangement between IO and Domestic Agencies for the in kind contribution to ITER.

Moreover RFX has supported IO for the preparation of the SRD (System Requirement Document) required by the IO decision bodies, that describes the Neutral Beam Test Facility and the two experimental devices SPIDER and MITICA.

A number of intermediate approval steps have been required during 2009 before the decision of the IC: for all these steps the support of the RFX NBI project team has been guaranteed. Among them, it is worth mentioning:

a) A Project Change Request (PCR-170) to include the NBI test facility into the ITER Baseline by IO Domestic Agencies representatives, positively closed on July 31st 2009.

b) The approvals by two internal ITER committees CCB1&2 (Configuration Control Board), by the ITER Scientific and Technological Advisory Committee (STAC) and by the ITER Managerial Advisory Committee (MAC) for the related Additional Direct Investment.

c) The support provided by two independent EU review panels aimed to assess the heating system mix in ITER and the NBI system, both of them confirming the need for ITER of the NBI system with the present parameters and recommending to start construction of the related Test Facility as soon as possible.

d) The EU-Procurement Arrangement for the NBI Power Supply signed between IO and F4E on July 10th and the Call for Tender for procurement of Ion Source Power Supply launched on September 15th and closed on December 10th 2009.

On November 18th 2009 the ITER Council has approved the ADI (Additional Direct Investment) and the sharing among ITER parties for the establishment of the Neutral Beam Test Facility in Padova.

Therefore, with the recent decision taken by the ITER Council it has been established that all the experimental apparatus installed in Padova inside the PRIMA buildings are part of the ITER system procured with the contribution of all ITER parties. The agreed direct sharing of the components to be installed at the facility foresees:

- The realization of the following components for MITICA by the Japan Domestic Agency:
    - the 1 MV power supply;
    - The 1 MV transmission line and the High Voltage Deck 2;
    - The bushing on the top of the beam source vessel to feed all the active components of the beam source up to 1 MV;
- The realization of the following components for SPIDER by the India Domestic Agency:
    - the 100 kV accelerator power supply;
    - the beam dump operating at full power.

All the activities have been performed by the RFX NBI project team under the Quality Management Specification required by F4E; the activities are planned and controlled with the help of a project management tool (PRIMAVERA) following the requirements issued by IO and F4E and customized for the internal use at RFX.

3.1.1 PRIMA

The design and licensing procedure for the buildings have been completed. Some works preliminary to the construction have been initiated.

A particular effort has been dedicated by the project team to the integration of all the experimental components and plants.

The PRIMA cooling system design and the Call for Tender documentation, as required by F4E, has been completed and delivered. For this system the Requirements issued by IO have been changed during the year and this has required a complete revision of the overall design up to the end of the year.

Irradiation modelling and safety activities have progressed to verify the building design (see Fig.3.1.1 and Fig.3.1.2 for a couple of views of the buildings) to support the design of the components inside the biological shields and to prepare the documentation to obtain the license to operate the facility.

Fig.3.1.1: PRIMA building, architectural view

In Fig.3.1.3 the PRIMA building ground floor is shown, while some building parameters are listed below:

Total involved area	17.500 m2
Covered surface	7.050 m2
Trampling surface	9.170 m2
Max building height	26.40 m

Fig.3.1.2: PRIMA building, entrance view

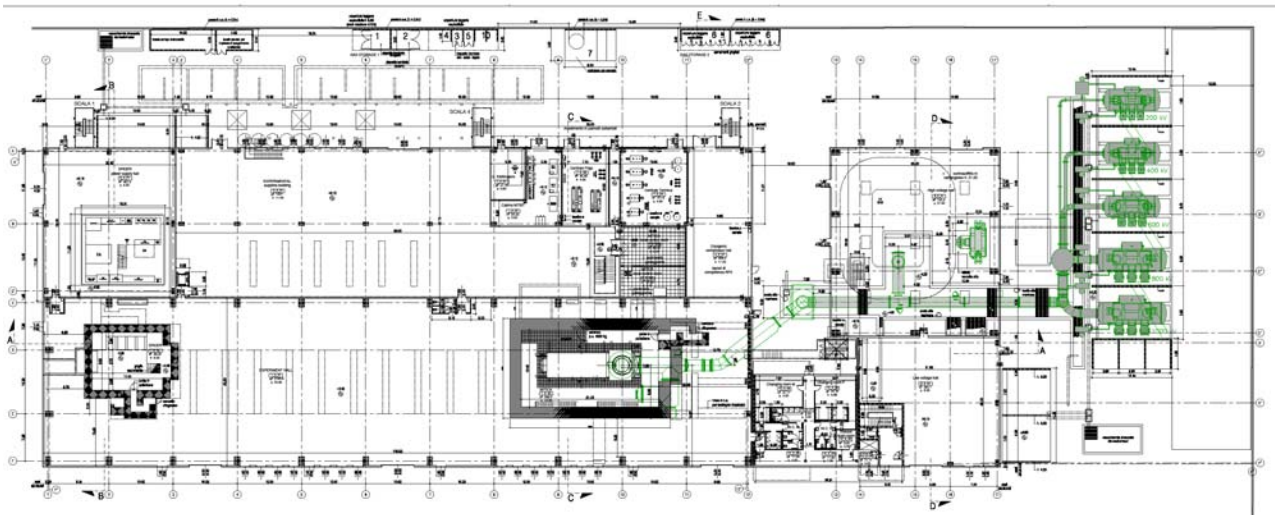

Fig.3.1.3: PRIMA building ground floor

3.1.2 SPIDER

The design at the level of Call for Tender required by F4E has been completed for the following components and systems:

- the power supplies required to feed the active components of the beam source (ISEPS). For this system the Call for Tender has been launched on September 15th 2009 and the evaluation of offers is presently under progress with the official support of RFX;
- the 100 kV insulated transmission line and High Voltage deck;
- the beam source;
- the vacuum vessel.

The design of all the other components and systems of SPIDER is in progress and the completion is foreseen in 2010:

- the vacuum and gas injection system;
- the diagnostic calorimeter;
- the caesium ovens;
- the diagnostics;
- the control and data acquisition system;
- the protection system;
- the auxiliary installation tools.

Support and interface activities are in place for the in kind contribution of the components and systems from the India Domestic Agency.

In Tab 3.1.1 some parameters of SPIDER are reported.

Fig. 3.1.4 shows an overall picture of the SPIDER vacuum vessel with its support structure, diagnostic access, power, vacuum and gas feed troughs.

Fig. 3.1.5 shows a 3D CAD schematics of the beam source.

	Unit	H	D
Beam energy	keV	100	100
Maximum Beam Source pressure	Pa	<0.3	<0.3
Uniformity	%	±10	±10
Extracted current density	A/m2	>355	>285
Beam on time	s	3600	3600
Co-extracted electron fraction (e-/H- or e-/D-)		<0.5	<1

Tab.3.1.1: SPIDER parameters

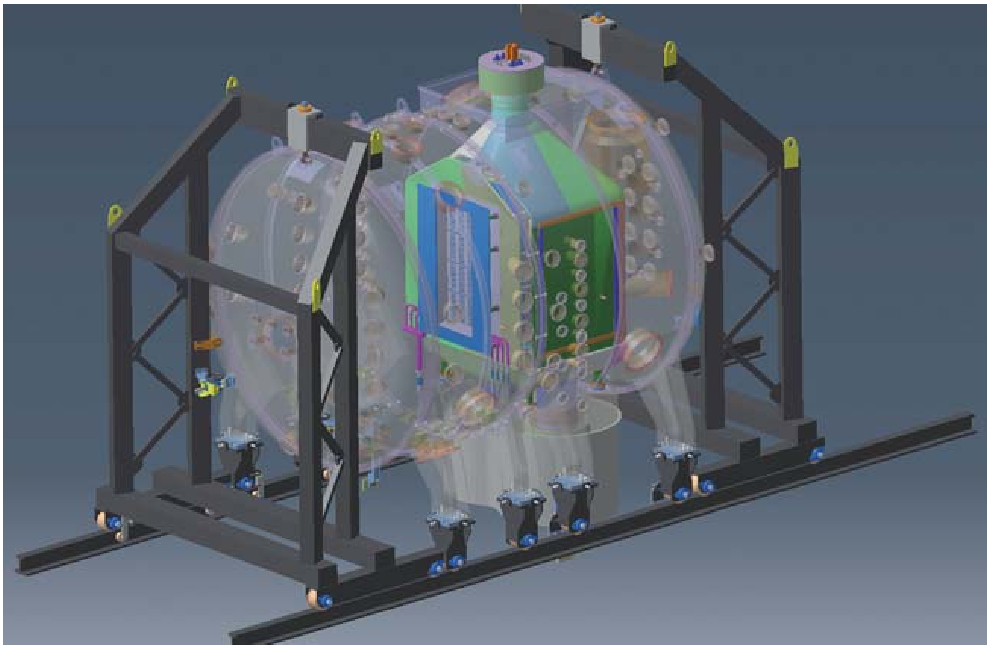

Fig.3.1.4: SPIDER overall view

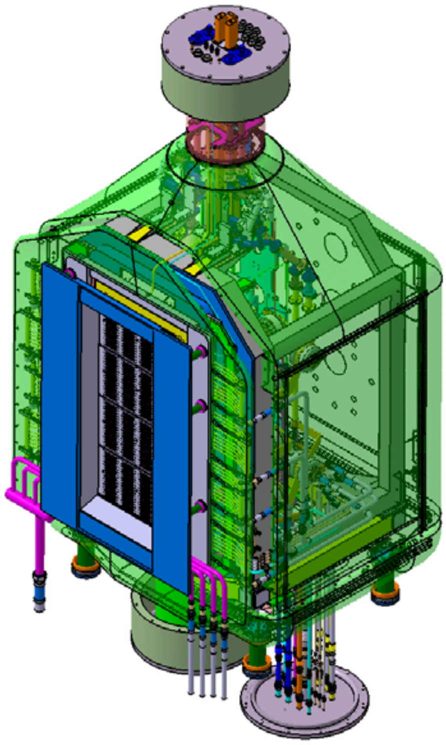

Fig.3.1.5: The beam source

3.1.3 MITICA

In 2009 the design activities have been continued in collaboration with UKAEA and FZK and the interfaces with IO (ITER Organization) and JA-DA (Japan Domestic Agency) have been defined.

The design has progressed in many critical areas:

- the accelerator power supply referred to ground potential, that shall be procured under the european in kind contribution to ITER and therefore also to the facility;
- the design activities of the components and systems that are under responsibility of the Japan Domestic Agency;
- the cryogenic pumps (KIT) and the definition of requirements for the cryogenic plant;
- the full power calorimeter (CCFE);
- the beam accelerator in strict connection with the activity performed in Japan;
- the vacuum and gas injection systems;
- the High Voltage deck 1 and the bushing for the connection to the SF6 insulated transmission line;
- support to IO for the integration of the heating neutral beam system in ITER.

3.2 NBI accompanying activities

The activity aimed to prepare the team of Physicists and Engineers for the operation at the Test Facility has been initiated and is in progress. The activities related to the construction of the ion source and the High Voltage tests have been delayed due to financial constraints and to the delay on the start of the Goal Oriented Training programme and the consequent delay on the recruitment of the personnel. The present status of the programme for the four areas is described in the following.

3.2.1 Modelling and numerical simulations of the negative ion beam

Several numerical codes have been acquired and applied to simulate beam optics and performance of the ion sources SPIDER and NIO1. The set of programmes includes the Poisson solver SLACCAD developed by CEA and aimed to determine the electric field in the accelerator, the commercial code OPERA aimed to study the beamlet-beamlet interaction, and the Montecarlo code EAMCC developed by CEA and aimed to study the trajectories of the single particles including secondaries and collisions with the background gas. In particular:

a) the development of the numerical code BYPO, aimed to compute in a self-consistent way the particle trajectories in electric and magnetic fields, has been continued in collaboration with INFN Legnaro, upgrading the code to 3D geometry and adding some atomic processes; the inclusion of secondary particles has been started and is in progress;
b) the database of atomic processes for Hydrogen has been updated, now including more than a thousand cross-sections;
c) the programme OPERA has been acquired and applied to study the beamlet-beamlet interaction, to devise ways to compensate for it and to compute the self-consistent electric field in the extraction region, including the effect of the magnetic field;
d) 3D version of the Montecarlo code EAMCC has been acquired and its application is starting. Its benchmark against the BYPO code and with the experimental results is still to be performed. The 2D version of the EAMCC code has been applied to the study of the trajectories of electrons downstream of the grounded grid, in order to investigate various possibilities to dump the power load associated to electrons. The present design involves the use of three arrays of actively cooled tubes which accept most (more than 95%) of the power carried by electrons;

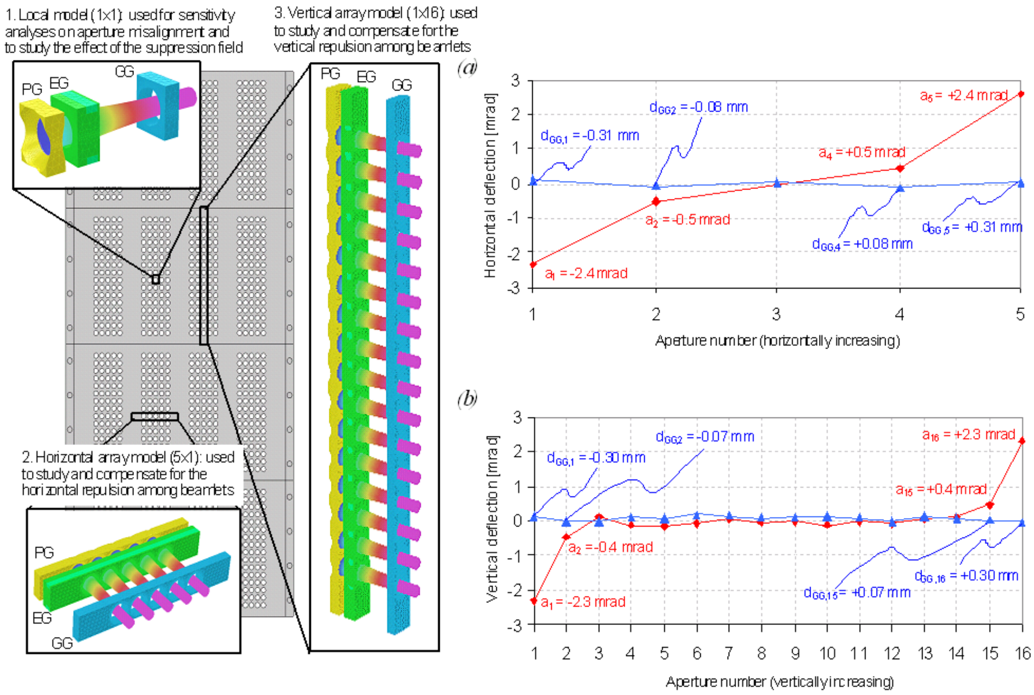

Fig. 3.2.1: Beamlet repulsion compensation: left: schematic of the overall geometry; right: (a) effect of horizontal deflection; (b) effect of vertical deflection. The red dots represent the beamlet deflections due to the interaction between beamlets; deflections angles for each beamlet are reported in red. The blue dots represent the beamlet deflections after introducing proper offsets to the GG apertures that compensate for the repulsion between beamlets; the optimised values of the aperture offsets are reported in blue.

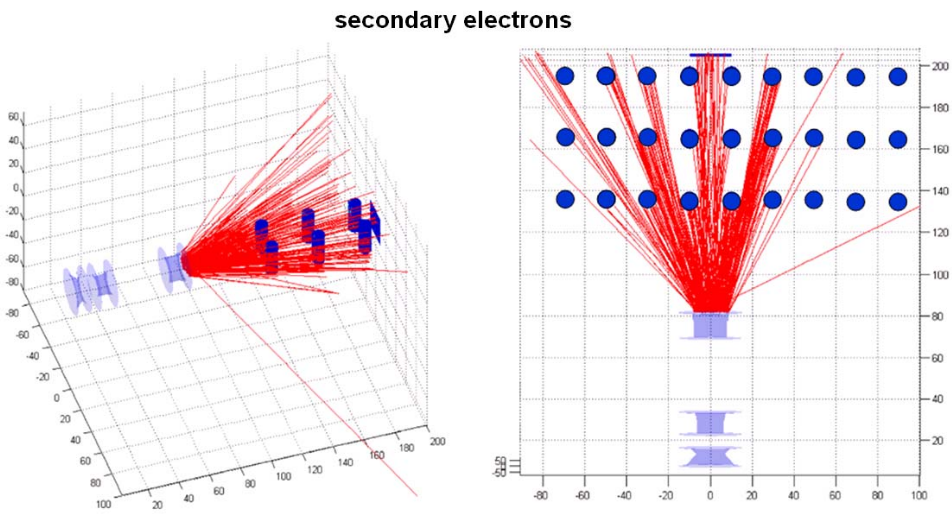

Fig. 3.2.2: schematic of the electron dump for SPIDER and view of the electron trajectories.

e) the whole suite of codes has been applied to the optimization of the accelerator for SPIDER, including a ferromagnetic layer on the downstream side of the grounded grid (to reduce the magnetic field outside of the accelerator region) and permanent magnets in the grounded grid (to compensate for the beamlet deflection due to the electron suppression field); these improvements have been applied to the source magnetic configuration resulting from the work carried out in 2008, which foresaw only electrical currents for the filter field;

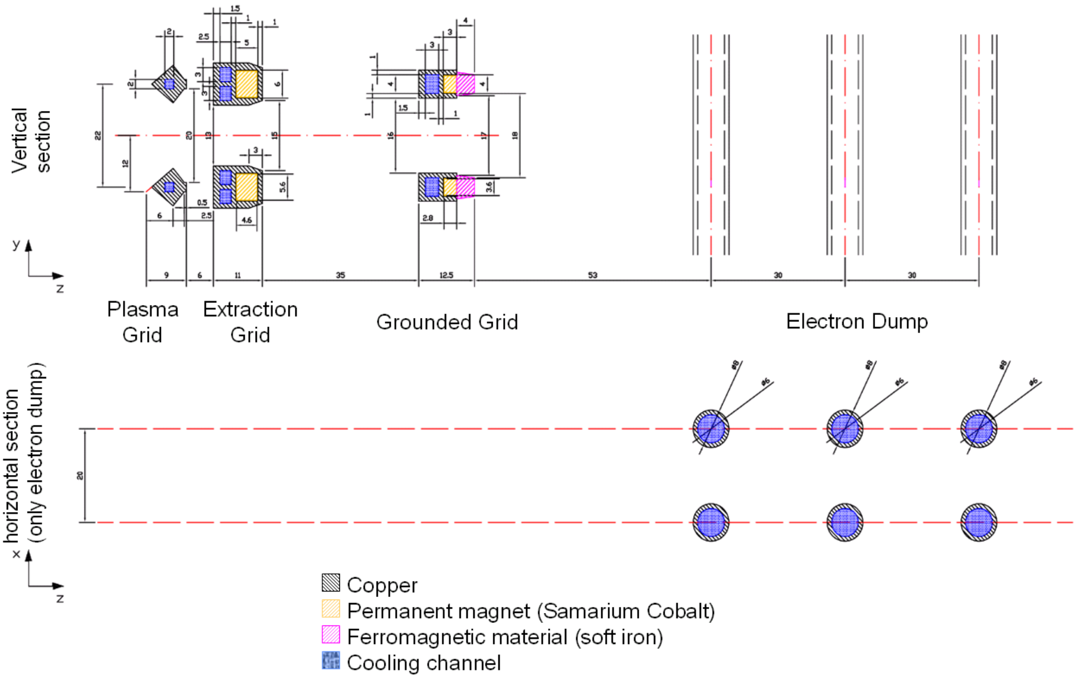

Fig. 3.2.3: Conceptual design of the SPIDER grid system: present status

f) The codes have been extensively applied to the design of SPIDER and the benchmark with experimental results of NBI at LHD (NIFS, Japan) has been initiated;

d) Modeling of beam emissivity for spectroscopic diagnostics in SPIDER and MITICA is in progress.

The feasibility studies of a tomographic system prototype for the NBI systems in Naka have been cancelled.

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

The design of the ion source (NIO1) has been completed and the procurement of some components has been initiated. The preparation of the built-to-print design is in progress, while the procurement of the remaining components has been delayed to 2010. The assessment of the site for the NIO1 experiment is in progress, while the adaptation has been delayed to 2010.

3.2.3 High Voltage tests

All the components of the High Voltage Padova Test Facility –HVPTF [De Lorenzi09] have been now procured and installed to carry out the 300 kV campaign; the system commissioning has started.

After the explicit requirement from the ITER Organization through F4E, provisions to upgrade as soon as possible the HVPTF to 800 kV operations are scheduled for mid 2010, in order to start with 800 kV experiments by the end of 2010.

The 300 kV campaign will be mainly devoted to the validation of a new model for breakdown prediction for multi electrode-multi-potential electrode configurations. This model, fully developed by RFX [Pilan09], is based on a combination of the statistical property of voltage breakdown and the clump-based theory of breakdown initiation, known as Cranberg-Slivkov theory. Nowadays, a consolidated and commonly recognized criterion for the electrode design is not available.

Basically, the voltage breakdown probability is associated to the number N of clumps per unit surface laying on the emitting electrode (the cathode):

$$P_{BD} = 1 - \int_A N dA$$

where A is the whole clump emitting area of the multi-electrode, multi-potential system. N is assumed to be an increasing function of the variable W, derived from the Cranberg-Slivkov theory, which has the following expression

$$W = U_{C-A} \cdot E_C \cdot \left(E_A\right)^{\frac{2}{3}}$$

where E_C is the electric field at the cathode (sending electrode), E_A is the electric field at the clump clash point on the anode (receiving electrode) and U_{C-A} is the potential difference between the two.

We assume that N follows the three parameters Weibull distribution

$$N(W) = \left(\frac{W - W_s}{W_0}\right)^m .$$

The calculation of W requires clump trajectory calculation to identify the receiving electrode for the determination of U_{C-A} and E_A. The method has been applied to the SinGap and MaMuG geometries tested at the Megavolt Test Facility -MTF- in Naka (JP), and the predicted voltage breakdown has been found to be in good agreement with the measurement result.

Fig. 3.2.4 shows the two configurations, both consisting of a multi-electrode, multi-potential electrostatic configuration with 2D geometry.

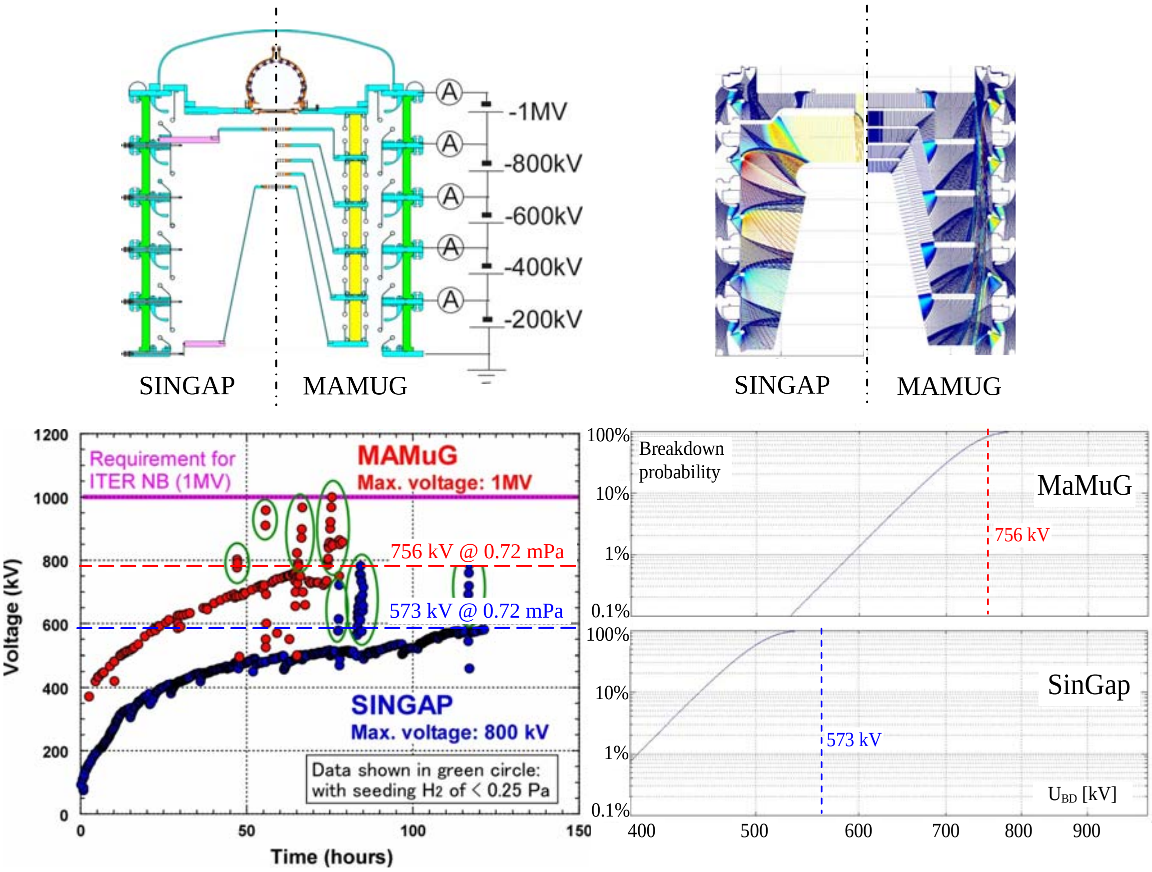

Fig.3.2.4: Comparison between SinGap vs MaMuG configurations in the MTF at Naka

In the top-right panel the trajectories are drawn, coloured in a non linear scale where the colder the colour the lower W. In the bottom-right panel the breakdown probability for the two configurations is reported as a function of the applied voltage, compared to the measured highest breakdown voltage (corresponding to the 100% breakdown probability), reported in the bottom-left panel, which shows the voltage conditioning time curves of the MTF for the two electrostatic configurations.

A dedicated test campaign has been then planned to attain a more solid model validation, especially as far as the Weibull parameters determination is concerned.

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

The first European Meeting on NBI Simulation took place in Padova on 23-25 March 2009 and in that occasion the need was recognized of further benchmarks between numerical codes applied to the design of the ITER NBI and experimental results. This need was recognized by EFDA during the CCNB Meeting in Madrid (3-5 June 2009). According to that, the programme at RFX has been re-oriented to the only NBI based on negative ions in operation, i.e. the system in operation at LHD. A collaboration on this area has been initiated and is in progress.

Preliminary results show a good agreement between the experimental pattern of the beam and the numerical simulations (Fig.3.2.5).

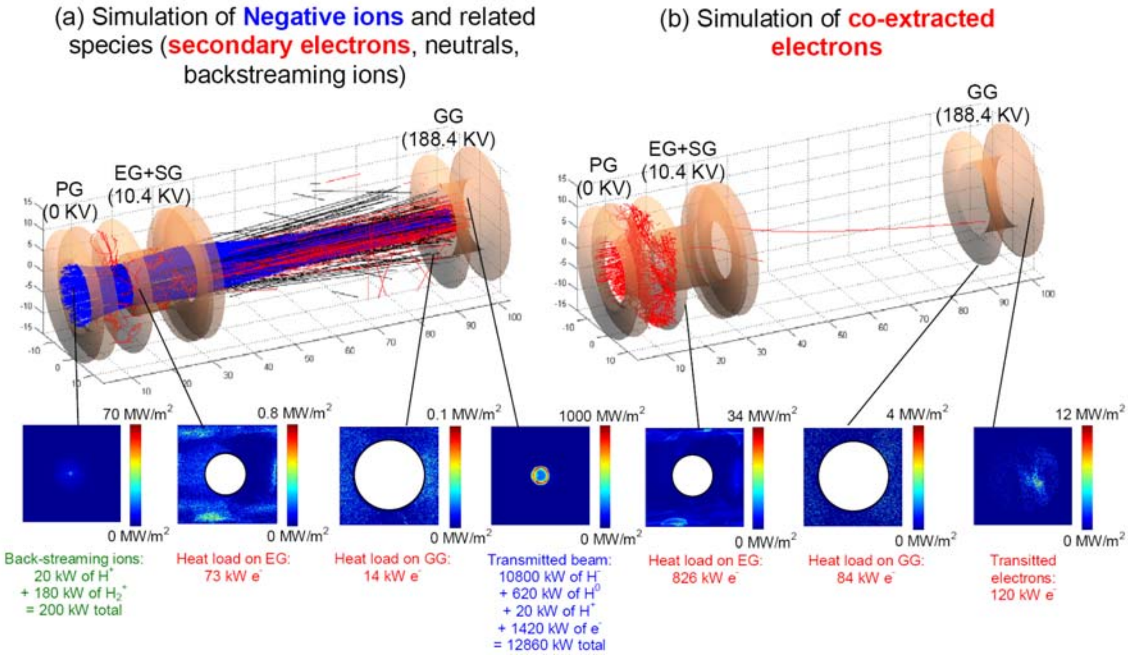

Fig. 3.2.5: Simulation of negative ions and co-extracted electrons through the grid system of LHD injector BL2.

Participation to operations of RF sources at IPP has been only partially performed, concerning the spectroscopic diagnostic and their interpretation, and is foreseen to continue next year. Participation to operation at JAEA at the HV test facility is in progress.

Participation to operation at UKAEA has been cancelled due to the delay on the GOT programme.

3.3 ITER Diagnostics

3.3.1 Magnetic sensors

Consorzio RFX has been involved in design studies for ITER magnetic diagnostic since 2003 in the framework of several EFDA Tasks. The activities carried out during 2009 were mainly dedicated to four topics, described here below.

A considerable effort was devoted to the completion of the EFDA Tasks on design development and prototype testing of ITER magnetic sensors (Contract EFDA 06-1442 and Contract EFDA 07-1702/1562). The activity required a review of the design activities carried out in the previous year (manufacture and test of pick-up coil prototypes made of fibreglass braided cables or Low Temperature Co-fired Ceramic; development of a numerical tool for halo current modelling and reconstruction; design of a connection system for ITER in-vessel magnetic sensors) and in particular the development of a Project Plan for the procurement of the whole ITER magnetic diagnostic, carried out in

close collaboration with the other institutions involved in the same EFDA Contract (CEA, CIEMAT, CRPP) [Chitarin09a], [Chitarin09b], [Peruzzo09a], [Peruzzo09b].
A specific contract with ITER Organization (ITER/CT/08/529) has been carried out for the manufacture and test of "in-vessel LTCC magnetic coil prototypes". A set of prototypes was produced by an external Supplier and a variety of tests was carried out mainly within Consorzio RFX for the characterization of the technology which seems to be the most suitable to comply with the ITER measurement requirements and operating conditions (Fig.3.3.1).

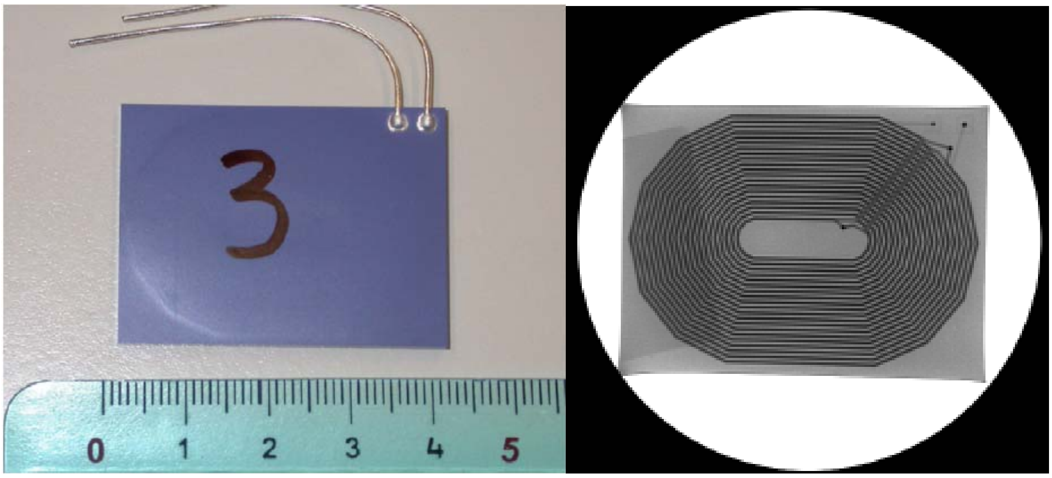

Fig.3.3.1: Prototype of LTCC magnetic sensor (left). X-ray image showing the actual layout of conductor (right)

A further contract with ITER Organization (ITER/CT/09/4100000486), not foreseen in the Activity program 2009, has been carried out, which implied the secondment of a Senior Engineer for a period of three months to work within the ITER Diagnostics Division on "Development of integration of ITER In-Vessel magnetic diagnostics". The contribution of Consorzio RFX was dedicated mainly to the update and reorganization of the reference numbering and positioning of the in-Vessel magnetic sensors in ITER CATIA models and ENOVIA database, to the design and integration of conduits and cable looms to serve in-vessel diagnostics, and to the study of the integration of the in-vessel magnetic diagnostics in the Alternative Vacuum Vessel and Self Supporting Blanket (VV & SSB). In particular, for this last topic, proper thermal and electromagnetic f.e.m. analyses were performed for the design of the sensor pedestals, necessary for the relocation of the in-vessel magnetic coils with the new SSB concept (Fig.3.3.2). This activity contributed to the final assessment of the impact of the Alternative VV & SSB on the diagnostic system from the measurement and integration point of view, presented by the ITER Diagnostics Division at the final Design Review meeting [Vayakis09a] and fully described in the final report [Vayakis09b].

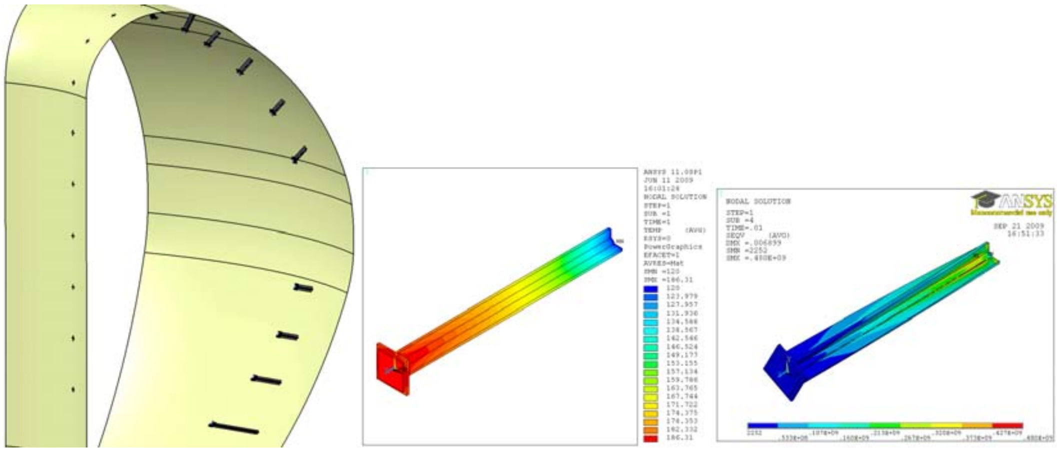

Fig.3.3.2: Thermal and electromechanical analyses on pedestal for in-vessel magnetic sensors, proposed for the alternative design of ITER Vacuum Vessel and Blanket

A significant commitment was finally dedicated to the setting up of the "ITERMAG Consortium", agreed together with CEA, CIEMAT and CRPP to respond jointly to F4E calls for grants on the design and procurement of the whole ITER magnetic diagnostic system. The collaborative structure was exploited for the preparation of an offer to the call for proposal for a Grant (F4E-2009-GRT-047) issued by Fusion for Energy and dedicated to the "System-level optimisation of the ITER magnetics diagnostic and R&D/Design of magnetics sensors assemblies". The tasks of the grant cover both technological aspects, for the manufacture of the sensors and their integration in the ITER machine, and developments of codes for the usage of the diagnostic. The proposal is presently in the evaluation phase by F4E.

3.3.2 Core LIDAR Thomson Scattering

RFX participates to the development of the core LIDAR Thomson scattering for ITER, which in previous years was done under EFDA by a cluster of EU Associations, led by UKAEA. In 2009 a Collaboration Agreement has been signed by the same EU Associations, by which they have set a strategic and organizational cooperation to determine the rules they agree to apply in order to make proposals to implement contracts they may conclude with F4E or with other legal entities, to develop, produce, qualify, install and operate the core ITER LIDAR diagnostic. The purpose of this Agreement is to set forth the principles according to which the parties agree to cooperate on an exclusive basis to jointly run the cooperation, by forming a consortium. The contribution from RFX has not been formally defined yet, but it should cover the following topics, to which RFX has already contributed so far:

a) contributing to the specification, simulation, procurement and test of high-speed high-efficiency detectors in the near-IR, such as detectors based on the transferred-electron (TE) III-V InGaAs/InP photocathode;

b) finalising calibration schemes for both the in-vessel and ex-vessel parts, further developing the methods investigated and proposed in the past EFDA contract;

c) contributing to the overall design of the diagnostic, with particular attention to those components that have an interface with the detectors or with the calibration methods;

d) contributing to the specific and overall project planning and cost estimates.

On these topics some voluntary work has been done this year. In particular under topic a), the investigation of NIR detectors has been consolidated [Giudicotti09] and an R&D program to develop prototypes suitable to the ITER core LIDAR has been drafted and inserted in the overall diagnostic project plan, while under topic b), the study of possible calibration schemes continued with an optical ray tracing model of the back-illumination method and analysis of different laser combinations for the dual-wavelength method [Pasqualotto09].

3.4 ITER Tokamak Modeling

In 2009 RFX has given a significant contribution to the EFDA Integrated Tokamak Modeling (ITM) Task Force. The main results on the tasks in which RFX is involved are summarized in the following.

3.4.1 ISIP (Infrastructure Support Project)

In 2009, the activity has been mainly devoted to the development and optimization of the Universal Access Layer (UAL) .This software layer represents the unique interface to data in the ITM simulations and has been currently ported to the following language platforms: Fortran90, C++, Java, Matlab and Python.

Besides the development of the language-specific libraries, work in 2009 has been devoted to:

1) The development of a set of routines for interfacing the UAL with the Simulation Database, used by KEPLER to organize shot and run number as well as to manage external references for Consistent Physical Objects (CPOs).

2) The development of an optimized remote data access protocol in order to improve performance remote data access in configurations where the KEPLER engine activates the execution of simulation code in remote components which nevertheless need to read and write pulse files stored in the Gateway.

3.4.2 IMP#1 (equilibrium and stability)

The code FLOW, which solves the MHD equilibrium in the presence of flow has been integrated on the ITM platform, accessible through the Gateway server. The code can be compiled and run on this server. Still some open problems remain on its full integration under the Kepler environment that we hope to solve as soon as possible.

3.4.3 IMP#2 (Nonlinear MHD and RWM)

The integration of the MARS-F and Cariddi codes (named CarMa) which solve the MHD stability problem in presence of 3D passive structures for the RWMs has begun in 2009 under the ITM framework on the Gateway.

The structure/organisation of the data for running CarMa within the ITM has been decided and the necessary software integration activities have been initiated. A full development of the project is expected in early 2010.

3.4.4 IMP#3 (Impurity Transport)

During 2009 the implementation and benchmarking of the 'superstages' description of heavy impurities in the integrated transport codes at JET has been successfully and intensively used.

Tests have been carried out (in collaboration with IST Lisbon and FZJ Juelich) for Neon in bundled and unbundled partitions with EDGE2D. The simulations seem pretty much 'partition -independent'. After this, we now can reasonably assume that partitioning impurities into super-states still captures the physics of impurities and we feel confident in using this description for heavy impurities, such as Tungsten.

The bundled description for W has been used for simulations of JET and ITER scenarios (ISM Task Force). EDGE2D simulations with heavy impurities are now in progress in collaboration with PPPL for the JET EP-2 Tungsten wall which will be installed during the 2009-2010 shut-down.

On the other side, work for the Task agreement 2009 is nearly completed: it will now be possible to simulate the impurities using the same radial coordinate as in Jetto code: this will allow running long simulations, when plasma equilibrium is updated during the run. The implementation to run the impurities imposing the boundary conditions on the densities (instead than the flux) is nearly completed too. This will give more flexibility to the impurity transport code.

3.4.5 EDRG (Experimentalist and Diagnosticians Resources Group)

Consorzio RFX obtained in 2009 the coordination of the ITM activities in the field of Control, with a new task which started in 2009. The group began its activity with a meeting in Cadarache held last June and with a fully dedicated session at the ITM general meeting held in September in Juelich.

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4. TOKAMAK PHYSICS AND TECHNOLOGY

Collaboration activity with Tokamak experiments has been particularly profitable in 2009, well in line with the general strategy outlined in the past two years, which seeks for RFX a closer integration with the wider fusion community. The integration is pursued by addressing collaborations on themes that are of common interest and in the same time of absolute relevance in the fusion framework.

Collaborations have concentrated on issues regarding MHD, with mode recognition and control studies (JET, AUG and D-IIID); edge physics, whereby important commonalities have been demonstrated between RFP and Tokamak turbulent phenomena (AUG, C-Mod); impurity transport (JET) and disruption studies (AUG, JET). The presence at RFX of international teams (JT-60 SA and DIIID) to perform Tokamak relevant experiments on RFX testifies that RFX has gained visibility in the international horizon. Of particular importance is the fact that in 2009 RFX has started direct collaboration with Stellarator groups in Europe ad overseas as a natural consequence of the evolution towards the study of 3D effects.

Finally, collaboration with Tokamaks includes the work in support of FAST, the Italian proposal for a European satellite to ITER.

The results of the technological activities on JT-60 SA are reported in Sect. 7

4.1 FAST

As the discussions towards the definition of the specifications of a European ITER Satellite develop, the proposal of a new device sponsored by the Italian Association has formed in 2010 a preliminary project management structure, in which RFX leads the task on Neutral Beam Injection and participates to the physics and diagnostics groups. In FAST, the beam should provide around 10 MW of heating power, induce momentum and in particular populate the phase space with super-Alfvenic particles, whose study is one of the main scientific targets of the device. As a consequence the energy of the beam should be between above 0.7 keV.

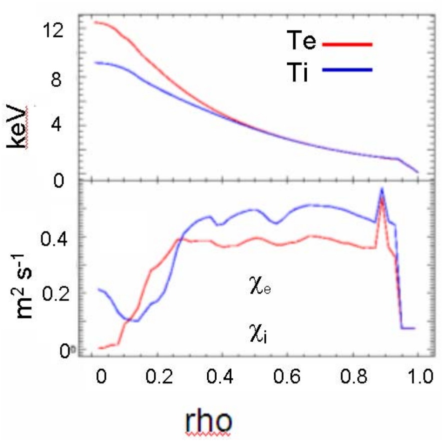

Fig 4.1.1 Ti and Te (top) and heat diffusion profiles (bottom) in FAST simulated with 15MW of ECRH, 15 MW of ICRH and ne= 4.5E20m-3.

Simulations of the main FAST scenarios have started by means of the code JETTO in which the equilibrium of FAST has been implemented. Heating mix has so far been limited to ICRH, ECRH and LH, with plans to include NBI heating through the code ASCOT. ECRH deposition profiles have been calculated by CNR Milan, the ICRH ones by ENEA Frascati and both have been introduced as input to the code. Among the main results, though of very preliminary nature, we mention the fact that the scheme with a mix of 15 MW of ECRH and 15 MW of ICRH appears to be a good alternative to the original conceived one with 30 MW of ICRH only, that might instead be associated to high impurity influx generation. Figure4.1.1 shows as a sample result Te (red) and Ti (blue) and heat diffusivity profiles in a reference H-mode with a density of $4.5x10^{20}$ m^{-3}. Despite heating is mainly on electrons, Te is only slightly higher than the ion temperature due to the large density. Work has started also on the code CRONOS (CEA), in collaboration with CEA CADARACHE and ENEA Frascati, specifically to study the fast particle distribution generated by the NBI and to provide suitable specifications for the beam injector. A further interest in this exercise is that similar studies will be applied to ITER so that the RFX team who is designing the beam injector for ITER may gain direct experience of the relationship between variations of the beam injector performance in terms power, energy and divergence and the related effects on the plasma.

4.2 DIII-D

The collaboration with GA on DIII-D, started in 2008, was broadened in 2009 with an exchange of visits by staff of both laboratories. RFX scientists participated to experiments aimed at characterizing the performance of fast feedback (i.e. with control loop cycle time shorter than the typical current driven Resistive Wall Mode growth rate). This kind of RWM is rather reproducible as it occurs during tokamak discharges with ramping plasma current when the edge value of the safety factor q_{95} reaches rational values. Discussions on experimental results continued during remote meetings held almost regularly on a weekly basis. The results have been presented at the 32nd EPS meeting in Sofia [Okabayashi09] and at the 14th workshop on MHD control, held in Princeton Nov 9 – Nov11, 2009.

Thanks to this collaboration, DIII-D scientists suggested a series of experiments on the RFX-mod machine, both in the RFP and in the tokamak configuration. In particular a preliminary series of tokamak experiments aimed at stabilizing the (2,1) mode when q(a) is below 2 was performed on RFX-mod, giving encouraging results. Unfortunately, the toroidal field contact failure did not allow performing new experiments.

Regardless the differences between both control systems and feedback laws in RFX and DIII D, the investigations on the coupling between active coils and pick-up probes was found to be an issue of common interest that could be experimented with common tools. Potentially, the thorough characterization of these couplings can be used to improve the performances of both feedback systems. A careful analysis of DIII-D couplings between sensor coils and both axi-symmetric and non axi-symmetric coils has been performed by RFX, in close collaboration with the GA staff, in order to assess whether a modification of the DIII-D real time feedback law was necessary: analyses are on-going.

4.3 JT60-SA

The collaboration on RWM physics and control continued in 2009 and details on experiments carried out in RFX-mod with the collaboration of JAEA colleagues are given in the RFX-mod chapter. Modeling studies on RWM stability and control in JT60-SA plasmas continued as well as a common effort. This collaboration is well integrated in the larger Broader Approach framework, which also includes common activities on technological issues and the participation of an RFX scientist to the newly constituted JT60-SA Physics Integration Unit.

4.4 JET

4.4.1 Enhanced Radial Field Amplifier for JET

During 2009 Consorzio RFX continued contributing to the ERFA project with a senior engineer with the role of consultancy and a junior engineer on secondment at JET working full time on the project till end July.

Work was mainly devoted to follow the commissioning of the systems till ERFA amplifier has been put in service, guaranteeing the correct development of operations on the plant and also evaluating modifications and improvements made by the manufacturer such that the performance of the amplifier fully meet the contract specifications. This contribution can be considered successfully concluded.

4.4.2 MHD studies

As an evolution of the work carried out in 2008, which mainly consisted in implementing and developing a reconstruction code for the radial localization of Neoclassical Tearing Modes, the 2009 MHD activity consisted in the benchmark of the code and in its application in several physics studies.

The code is based on the calculation of coherence between fast magnetic coils and the Electron Cyclotron Emission radiometer signals (ECE), exploiting the fact that a magnetic island is intrinsically associated with a NTM, and this makes possible to obtain important information about the position of the mode resonant surface, and then on plasma's q profile.

The results given by the code have been benchmarked againts respect to another MHD mode localization code, which assigns to the island the radius where its rotation frequency matches the ion diamagnetic frequency profile in the frame with zero radial electric field.

The result of the benchmark has shown a systematic discrepancy in the localization of NTMs using the two independent techniques. A clear source of this discrepancy is the error in evaluating JET total magnetic field, which can shift all ECE channels radii in a systematic way. A statistical ensemble of hybrid scenario discharges has been considered for the benchmark, with the result of an average shift of 9 cm between the two localization methods, which is compatible with an error of 3% in JET total magnetic field [Buratti09].

The code has also been used for the characterization of the mode impact on the discharge confinement and performance. In particular, the drop in confinement due to the mode onset has been studied as a function of mode's position, with a clear trend of a higher drop in H98 for a larger mode radius, giving an important contribution to a JET oral presentation at the last

EPS conference [Challis09]. This is in good agreement with the simple argumentation that the mode affects just the volume that is contained inside its resonant surface.

The results given by the code have also given new insights on NTMs radial and poloidal mode structure, thanks to the measurements of a double phase inversion structure in the low field side, associated to a single toroidal mode number (n) NTM. This structure has proven to be well explained by a poloidal mode number (m) spectrum made by two different components, one with a tearing nature and the other with a kink nature. The effects of the multiple m mode structure on the plasma have been studied, with a particular care for plasma rotation profile as explained in detail in ref [Baruzzo09].

4.4.3 Impurity transport

Analysis of metal impurity transport in JET H-mode discharges has continued. It has been shown that the addition of ICRF in the center of the plasma causes a reversal of the radial flow of metal impurities such as Ni and Mo when the power exceeds about 2-3 MW. More precisely the outward flow decreases more or less linearly with the applied power and such decay is also well correlated with the increase of the inverse logarithmic gradient of the electron temperature as shown in Fig.4.4.1 [Valisa09]. Additional analysis has addressed the spread of the impurities flow velocity for a given radiofrequency power, showing in particular that such variations may be attributed to differences of the density profile. The experimentally found behavior remains unexplained. The gyrokinetic code GS2 that has been acquired and can now be run at RFX, in fact, does not predict any flow inversion in the experimental conditions obtained in the analyzed discharges.

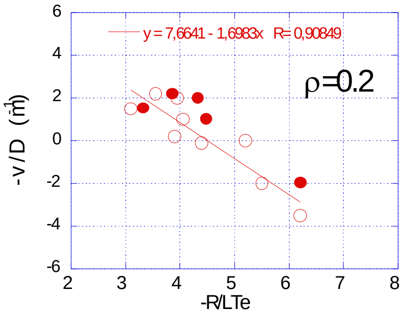

Fig. 4.4.1: Dependence of the convection to diffusion ratio on the inverse logarithmic temperature gradient.

4.5 ASDEX-Upgrade

During 2009 the collaboration with IPP-Garching, EURATOM- ÖAW and EURATOM-RISØ for electromagnetic turbulence studies on Asdex Upgrade has continued. The activity has been focused on the electromagnetic signals collected during type I ELMy discharges using a specially designed probe that combines electrostatic and magnetic pins. The probe head contains 6 electrostatic pins arranged in order to simultaneously measure radial and poloidal electric field components plus one pin measuring the ion saturation current in order to infer local density fluctuations. Inside the case, 20 mm behind the front side a magnetic sensor measuring the time derivative of all the three components of the magnetic field is mounted. During the analysis the ion saturation current signals have been used to infer the passage of ELM structure in front of the probe [Vianello09]. In analyzing the magnetic data, the idea has been applied that the magnetic signals during ELMs event can be separated into different frequency domains: the high frequency part (a few hundred kHz) expected to be generated mostly by high frequency turbulence and the lower frequency domain assumed to be mainly generated by moving currents convected with the filaments. This hypothesis can be checked through the so called Degree of Polarization (DOP) analysis technique [Samson1980]. This technique may be interpreted as a test for plane wave ansatz and it is based on the evaluation of the spectral matrix S = ⟨B_iB_j⟩ calculated in the Fourier space. A high value of DOP implies that the fluctuations are correlated over several wavelengths and thus can be approximated by a plane wave.

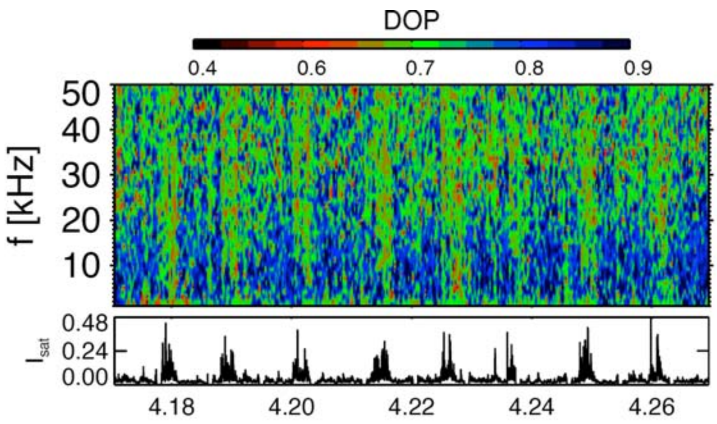

Fig.4.5.1: Top:Degree of Polarization analysis as a function of time and frequency. Bottom: Ion saturation current

The results of this analysis are shown in figure 4.5.1 where a strong reduction of the DOP is observed in correspondence with the sharp increase of the ion saturation current signals confirming that during ELMs magnetic fluctuations are better represented as coherent structures rather than a plane wave. A closer look on one of the events previously shown is given in figure 4.5.2.

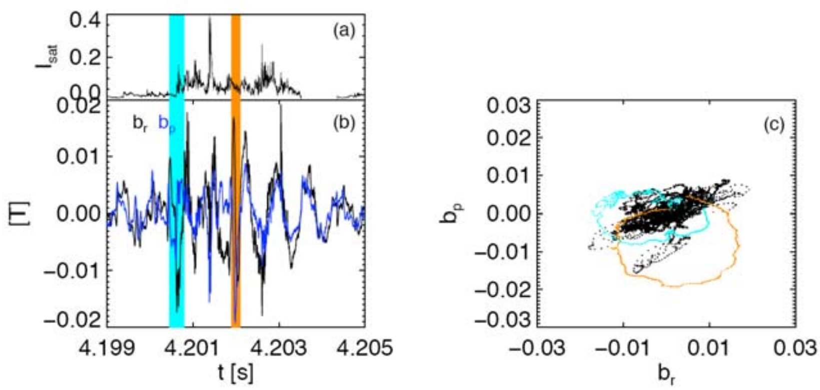

Fig.4.5.2: (a) Ion saturation current measured in a zoomed window (b) Radial and poloidal components of the magnetic field (c) hodogram of the perpendicular magnetic field. The two highlighted closed loops correspond to the highlighted time windows in panels (a) and (b)

In panel (b) the radial and poloidal components of the magnetic field are shown. These two components are perpendicular to the background magnetic field. It can be clearly observed that during ELMs, the magnetic activity increases and the radial and poloidal components change their phase relationship, moving from approximately in phase to approximately in quadrature as highlighted in the color shaded regions. This can be more clearly seen by looking at the hodogram of the two components, shown in panel (c) i.e. by considering the magnetic field perturbation trajectory in the b_r-b_p plane. Indeed the shaded region corresponds to close loops whereas outside of the ELM the magnetic field exhibits an almost linear polarization. Using all the three components it is possible to reconstruct the 3D hodogram shown in figure 4.5.3.

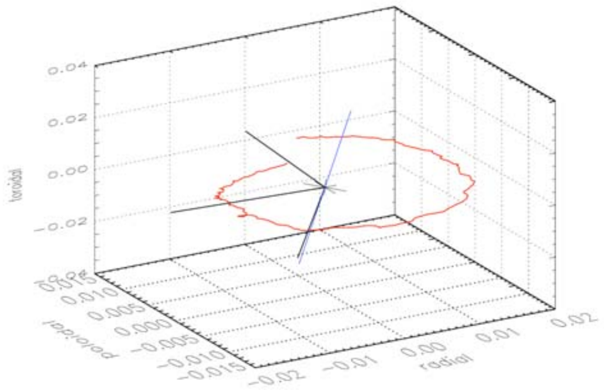

Fig.4.5.3: 3D hodogram of the magnetic perturbation associated to an ELM filament in all the three components. The direction normal to the plane where the ellipse lies is shown together with the direction of the equilibrium magnetic field in a blue line

The magnetic field trajectory spans an ellipse lying on a plane slightly tilted with respect to the nominal toroidal direction. The direction perpendicular to the plane where the ellipse lies is found parallel to the direction of the equilibrium magnetic field (blue and black line in Fig. 4.5.3). Such hodogram is consistent with a monopolar current distribution: under the assumption of constant radial velocity propagation of the order of 1 km/s an estimate of the current associated to ELM filaments has been done obtaining values up to 6 MA/m^2 [Vianello09a].

4.6 Alcator C-mod

During 2009, the collaboration with the Alcator C-mod group at MIT for the analysis of the edge plasma continued [Sattin09]. In C-mod a Gas Puff Imaging diagnostic measures the fluctuations of the edge plasma in the outboard midplane, and the main goal of the collaboration is studying the relation between the edge turbulence and main plasma parameters such as collisionality and pressure profile, similarly to what is being done on RFX-mod [Scarin09]. At the same time, also the universal statistical properties of the edge turbulence are characterized, comparing the data of C-mod and RFX-mod.

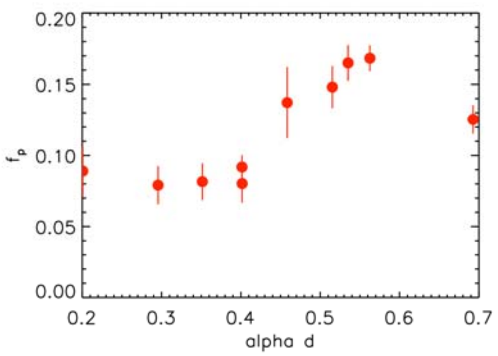

Fig.4.6.1: Packing fraction of the edge turbulence as a function of the inverse of the collisionality (α_d)

Preliminary analyses have shown that there is a link between the packing fraction of the edge turbulence f_p (i.e. the percentage of edge plasma occupied by coherent structures) and α_d, a parameter proportional to the inverse of the collisionality (see Fig. 4.6.1).

Decreasing the collisionality, f_p increases from 8% to 15%, reflecting also a change in the edge pressure profiles. For α_d<0.4, when f_p assumes a constant value of about 8%, it is possible to decrease L_p (making the edge pressure profile steeper); then, for α_d >0.4, when the turbulent activity increases, it is not possible to further reduce L_p [LaBombard05]. This behavior suggests a link between edge turbulence and edge profiles, similarly to what has been observed for RFX-mod

4.7 Contribution to the Asdex Upgrade enhancement

Consorzio RFX, being one of the four Associations involved in the ASDEX Upgrade (AUG) Priority Support Action, consisting of a system of active in-vessel coils and conducting wall for MHD stabilization, has continued the work with the agreed contribution during 2009.

The enhancement is organized in five Stages: in Stage 1 and 2 the coils are provided, the upper and lower ones (the B-coils) first and the central one (the A-coils) in stage 2. In Stage 3, twelve fast ac power supplies will be added, in Stages 4 and 5, the conducting shell and the remaining 12 power supplies will be procured respectively.

Stage 1 activities proceeded during 2009, the B-coils prototype was completed in autumn; the installation of the first 8 coils is foreseen next year, while the remaining coils will be installed in 2011. The Stage 2 proposal is delayed due to some pending issues concerning the design and the installation of the A-coils; in late 2009 IPP proposed to present Stage2 & Stage3 proposals together; the presentation is presently foreseen not before Spring 2010.

In parallel to these activities, RFX has continued working at the development of the conceptual design of the power supply system and the assessment of the main specification data in close collaboration with IPP colleagues. Various topologies were studied by RFX and the performance evaluated by means of numerical simulations to verify that the requirements can be satisfied with semiconductors available on the market and to compare the advantages and limits of different design solutions.

A scheme was identified as the best compromise in terms of satisfaction of contrasting requirements and on this scheme more in-depth analyses are in progress to study other specific issues, like common mode disturbances, delay time, reactive power exchanged with the grid [Suttro09a, Suttrop09b].

During 2009, IPP performed some tests on the feed-through of the B-coil prototype: isolation tests and tests with AC currents with magnetic field (PF and TF) were foreseen. To perform the ac tests, one of the RFX inverters was lent to IPP in spring; RFX studied and performed the firmware adaptation of the inverter to allow stand-alone operation in this new dedicated configuration, and assisted IPP in setting-up the test arrangement and starting the experiments. A joint (IPP-RFX) work was then performed in December to execute dedicated test at IPP aimed at measuring the noise produced by the switching converter on the diagnostic equipment, to evaluate the effectiveness of different filters, to customize the RFX simulation code of the inverter to the circuit under test in IPP and validate it via the comparison with the experimental results.

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5. THEORY AND MODELLING

This section is a natural complement to the experimental RFP physics reported in section 2. Extended magnetohydrodynamics modeling was used to better understand RFP self-organization: weak sensitivity to dissipation of the saturation amplitude of the dominant mode in single helicity, shear flow concomitant with a transport barrier, existence of a flow inversion near the reversal of the toroidal field. An extensive benchmark of the advanced MHD code PIXIE3D with the SpeCyl code was performed. Simulations on disruption and Vertical Displacement Events in full 3D toroidal geometry confirmed that for ITER the toroidal peaking factor and halo are within the limits of the design specifications.

The role of microturbulence as a source of transport for both impurities and main gas was addressed concurrently by using the codes TRB (gyrofluid, full radius) and GS2 (gyrokinetic, flux tube), as well as the solver of a linear gyrokinetic integral. They confirmed the result of a previous semi-analytical work that the RFP plasmas are much more stable to ITG instabilities than Tokamak ones. In order to take into account the effect of the helical geometry in the transport analysis of single helical axis (SHAx) states, the ASTRA code was adapted to the RFP topology.

A study of RWM instabilities in a cylindrical RFP taking into account plasma pressure and other effects like compressibility was performed and applied successfully to RFX-mod experiments. In the framework of the innovative feedback schemes for the control of the m=0,1 dynamo tearing modes, a configuration with the active coils placed between the first wall and the vacuum vessel was investigated and was proved to provide in principle an almost vanishing radial magnetic field at the plasma edge.

5.1 Extended magnetohydrodynamics modeling

A detailed benchmark in 2D case of the PIXIE3D nonlinear code (by L. Chacon) with the SpeCyl code has been completed with excellent agreement. The delay in the adjustment of the pre-conditioner tool, expected to speed up the 3D calculations, still slows down the completion -with full satisfaction- of the 3D benchmark, despite first results confirm a good qualitative agreement of results from the two codes [Bonfiglio 2009a]. A post-processor module (NEMATO code) of PIXIE3D, enabling magnetic field line tracing (using a volume preserving algorithm to guarantee accuracy), has been implemented as a stand-alone tool and is available now for post processing also of the SpeCyl code. A verification study has been started and successfully checked for the case of m=1 perturbations. In particular, it was possible to highlight once again [Bonfiglio 2009b], but more in detail and following the real self-consistent dynamical evolution of QSH formation (SpeCyl code), the process of magnetic chaos healing by separatrix expulsion (SHAx regime), Figure 5.1.1, as anticipated by previous studies [Escande 2000].

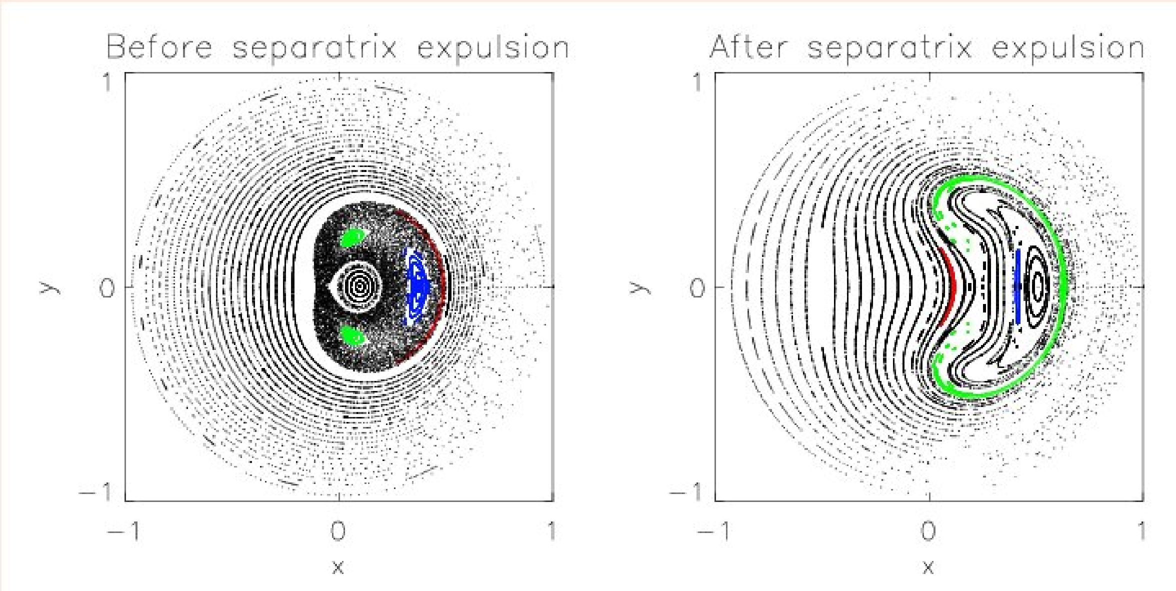

Fig.5.1.1: Two frames with Poincare' surface of section obtained along the spontaneous formation of QSH in a 3D nonlinear dynamic simulation (SpeCyl code). Note the intermediate stage of remnant chaos inside the helical core, before dominant mode saturation, and complete chaos healing after dominant mode saturation

The SpeCyl code was used to perform scaling studies for interpreting experimental data: the saturation amplitude of the helical equilibrium is independent of both resistivity and viscosity (while the growth rates are dependent) Figure 5.1.2a. This would lead us to expect a similar saturation (constant normalized amplitude of helical modulation) when entering a fully developed self-organization regime, indication which may be partially recognized in RFX-mod data at currents above 1.5 MA [Piovesan 2009].

In Figure 5.1.2b the result of a preliminary analysis is shown, aiming at clarifying the possible synergy between the presence of q-profile extrema and of shear flow, in order to explain the strong transport barriers in the electron temperature of RFX-mod in QSH. Finally, the SpeCyl code was modified to check the effect of a helical boundary condition on SH equilibria [Escande 2009].

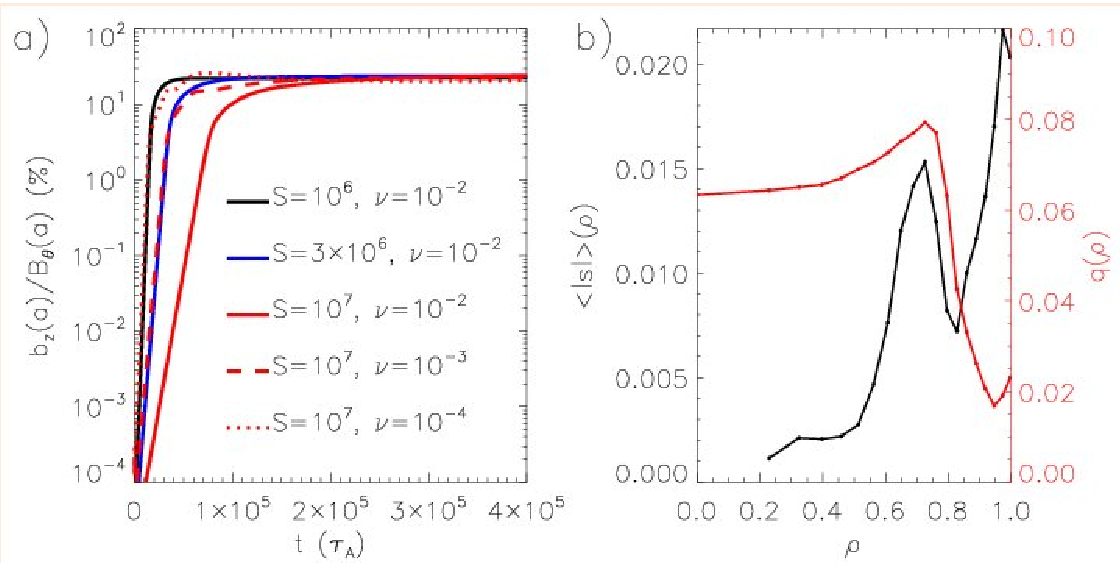

Fig.5.1.2: a) Temporal evolution of resistive-kink/ tearing modes amplitude for different values of resistivity and viscosity. b) Shear flow and q profile for a helical equilibrium: a maximum occurs at the same radial position as the strongest shear flow

Simulation work on disruptions and VDEs (Vertical Disruption Events) in full 3D toroidal geometry using the nonlinear visco-resistive MHD code M3D has been performed [Paccagnella 09]. For relatively slow growing modes, i.e. Resistive Wall Modes whose growth rate is linked to the wall penetration time, the simulations confirmed that the toroidal peaking factor (TPF) and halo fraction (hcf) (i.e. the ratio of the normal current going to the wall to the total toroidal plasma current) are within the limits of the ITER design specifications: TPF*hcf < 0.75.
A work about the effects of mean flow for Tokamaks, Spherical Tokamaks and also Reverse Field Pinches equilibria has been completed [Guazzotto09]. An interesting observation for RFP plasmas is that a flow inversion is detected near the reversal of the toroidal field, in some agreement with previous experimental edge measurements.

5.2 Turbulence and transport

The Single Helical Axis (SHAx) states exhibit strong temperature gradients proving that magnetic chaos is no longer ruling the transport. This confirms the need for understanding the role of microturbulence as a source of transport for both impurities and main gas.
This issue has been addressed concurrently by using the codes TRB (gyrofluid, full radius) and GS2 (gyrokinetic, flux tube), as well as the solver of a linear gyrokinetic integral equation (in collaboration with Nankai University of China). All codes were appropriately modified to include the reversed field pinch geometry and have been run independently. Their results in the linear stage confirm the conclusion obtained by a semi-analytical work in 2008 [Guo 2008] showing that the RFP plasmas are much more stable to ITG instabilities than Tokamak ones. Some benchmarks have been performed and will be completed in the next year: in Fig. 5.2.1 and Fig. 5.2.2 the first results are shown concerning the comparisons between TRB and both the calculations by GS2 and S. Guo respectively [Sattin09d]. We have assessed the stability (although in some cases close to marginal stability) of ion-temperature-gradient (ITG) modes in present-day RFX-mod discharges. It is envisaged that, should the current trend towards formation of steep temperature gradients be confirmed (or even reinforced) also in the ion temperature profile, ITG modes could become a concern in the near future.
GS2 has been recently run to investigate the occurrence of other kinds of instabilities. Preliminary linear runs have shown some evidence for the instability of microtearing modes.

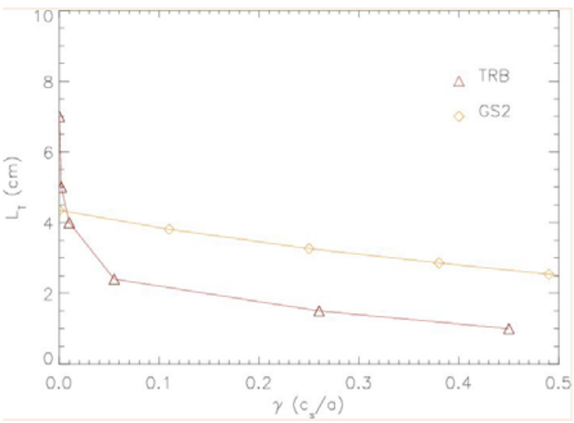

Fig.5.2.1: Temperature length scale versus growth rate. The critical length scale is L_T at zero growth rates.

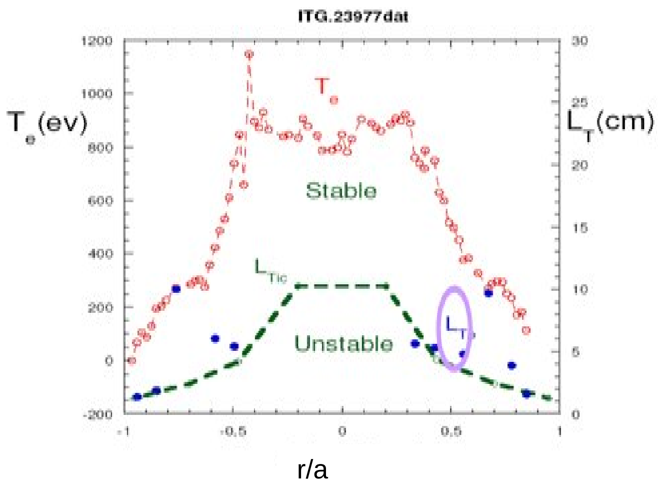

Fig.5.2.2: Red dots, experimental temperature profile; blue dots, local LT, green dashed curve, critical LT from analytical code; pink circle, the same quantity from TRB: the scatter depends on different choices of plasma conditions.

As far edge transport is concerned, the current trend, alongside with theoretical study by means of first-principle equations, is to interpret its features by means of phenomenological models. Continuing earlier investigations from 2008, we made some critical assessments concerning this line of study. The convenience/need of basing upon a pattern of measurements as large as possible was highlighted, rather than relying upon just selected features of the signals (power spectra, PDFs, ...) — although the second approach allows for a larger freedom in building models that may be compared with experiment [Sattin09a, Sattin09b, Sattin09c].

Continuing earlier analysis since 2008, we investigated the usefulness of the diffusive-advective (or Fokker-Planck) formalism in the modelling of large-scale heat and matter transport processes. Explicit comparisons with tokamak's data were successfully performed.

The one-dimensional transport code RIPORT (MHD, main gas and impurity transport) has been used to simulate plasma discharges close to the high density limit, in multiple helicity conditions [Predebon 2009]. Some preliminary tests to characterize the temperature and density profiles, both for main gas and impurities, have been carried out in SH states, in a simple cylindrical approximation. This activity is going to be continued during the next year.

To take into account the effect of the helical geometry in the transport analysis of SHAx states, the Automatic System for TRansport Analysis ASTRA [Pereversev02] has been adapted to the RFP topology. ASTRA is a 1.5-D transport code that allows combining a 3-D description of the equilibrium with a 1-D description of transport. The code is able to solve transport equations of particle, electron and ion energy according to the formulation derived in [Hinton76]. The 1-D transport equations are written in terms of amounts averaged on the flux surfaces of the magnetic equilibrium. To solve the equations ASTRA needs as initial condition experimental temperature and density profiles as well as the source term profiles, all averaged on the flux surfaces. Furthermore ASTRA needs the radial profile of the specific volume V' and of the first element of the metric tensor G11.

For SHAx states these quantities have been calculated using the description of the equilibrium based on the calculation of tearing mode eigenfunction in toroidal geometry for a RFP plasma and the results are reported in Section 2.4.

The simulations of transport in the presence of impurity atoms have been completed in 2009, with the description of the RIPORT code [Predebon09]. Good agreement has been found between simulations and experimental observations in high density RFX-mod discharges.

5.3 Resistive Wall Mode (RWM) studies

A study of RWM instabilities in a cylindrical RFP taking into account plasma pressure and other effects (compressibility, plasma inertia, longitudinal rotation and dissipations) was performed and applied to the RFX-mod experiments [Guo09]. The specific features of RWM instability in RFP plasmas (both aspects: similar to and different from Tokamaks) have been investigated and a better physical understanding has been obtained. Differently from tokamaks, in RFP configuration the poloidal magnetic field B_θ is of the same order as the toroidal field B_T, the poloidal asymmetry in the equilibrium magnetic field is much weaker than in a tokamak, which leads to weaker effects of the toroidal coupling.

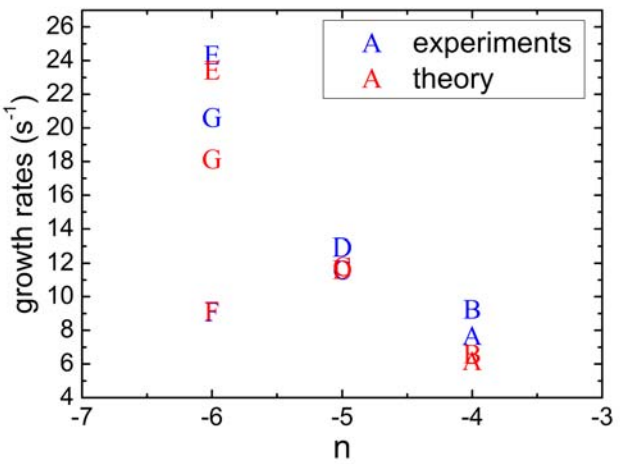

Fig.5.3.1: Comparison of the RWM growth rates between theory and experiments. Seven shots (letters A-G) for mode numbers of m=1, n=-6,-5, -4 are shown in the figure. The red letters give the theoretical results while the black ones are experimental measurements.

Furthermore, due to the fact that in the RFP the magnetic curvature is dominated by B_θ, the bad curvature is everywhere along the poloidal angle, which leads to a weak ballooning for many instabilities. In particular, for current driven RWMs (in tokamak it is a pressure driven mode), there are almost no ballooning structures. For these reasons the cylindrical model is actually very good for the RFP configuration. Careful comparison with experimental observations has been made for mode spectrum and growth rates and showed good agreement. An excellent example is shown in Fig. 5.3.1, which plots the comparison between the theoretical computation and experimental measurements of the RWM growth rates in seven shots of RFX-mod. The theoretical equilibrium (μ&p model) is carefully matched to the experimental estimates of the parameters F, Θ, and β_p, for each shot. The sensitivity of the mode growth rate to those parameters is also studied. Feedback effects were added in the model, and first results show better agreement with experimental observations.

5.4 Control optimization

In the framework of the innovative feedback schemes for the control of the m=0,1 dynamo tearing modes (TMs), a configuration with the active coils placed between the first wall and the vacuum vessel has been investigated. The first wall is non-conducting (as the graphite tiles of

RFX-mod), and the vacuum vessel is modelled as a resistive shell. A previous study with the active coils placed outside the vacuum vessel and the radial field sensors located inside the vacuum vessel has shown that for any TM the ratio $b^{\wedge}_{f}$ between the radial field at the sensors radius and at the resonant surface cannot be made smaller than the ideal-shell limit. Instead, the in-vessel feedback coils are able to reduce the ratios close to zero (figure 5.4.1 left), keeping the TMs rotation frequencies nearby their unperturbed values ω_o (figure 5.4.1 right). A feasibility study considering the electrical and measuring issues has been started.

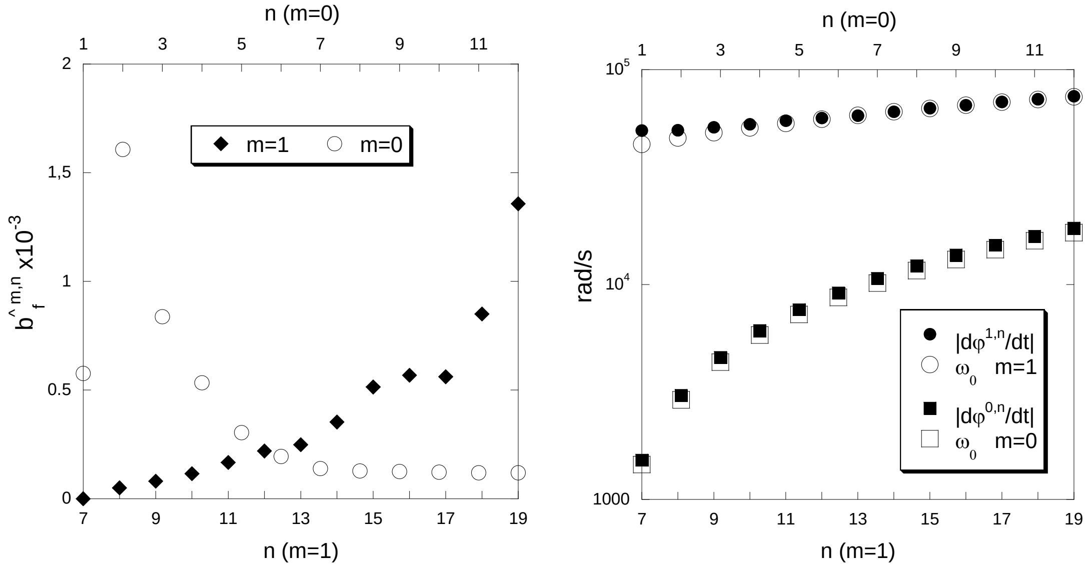

Fig.5.4.1: In-vessel feedback coils: $b^{\wedge}_{f}$ ratio (left) and TMs rotation frequencies (right) for m=0,1 poloidal harmonics in function of n toroidal harmonics.

Model Based Design of Tearing Modes control

A model of the non-linear dynamics of interacting Tearing Modes (TM), including their feedback control, was developed [Zanca07], using a balance equation between the viscous torque due to the fluid motion and the electromagnetic torque developed by the image currents induced onto the shell, by the feedback currents, and by the non-linear interaction between different TMs modes. This model has been used to optimize the mode controller in RFX-mod, looking for a set of gains on each TM, which reduces the edge radial field to the lowest possible value. The experimental results obtained are summarized in Section 2.3.

5.5 *Electron Cyclotron Waves heating and current drive*

In collaboration with IPP Garching, IFP-CNR Milano, University of Wisconsin, Madison and University of Stuttgart a preliminary study of electron cyclotron (ECH) direct heating in RFX has been initiated. As a result of this assessment it has been established that this scheme is feasible for currents above 1 MA and I/N values above 5 10^{-14} [A m] using the X-mode at the second electron cyclotron harmonic. This corresponds to wave frequencies of the order of 60-70 GHz. Besides this work, the assessment of a possible Electron Bernstein Wave (EBW) current drive scheme has also been completed [Bilato09].

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6. DIAGNOSTICS

In agreement with the approved workprogramme, the 2009 diagnostics work plan entailed the continuation of the development of existing systems, but also acquiring new diagnostics necessary to improve the fundamental diagnostic data set and/or to enhance the analysis capability at high current. Despite some delay in the assignment and the reduction of the 2009 financial budget, substantial work on the new systems has been done, as well as successful completion of activities already undertaken in previous years.

Among the most significant advancements it is worth mentioning the successful commissioning of the fast scanning reflectometer (although only for one band and with only one IMPATT source), which could become a standard and powerful tool in the future, the installation of the new SXR multifilter, which now provides precise measurements of the plasma core electron temperature Te(0) on 8 channels, the upgrade of the detection section of the THB diagnostic, which now routinely provides time resolved measurements (in the kHz range) of the edge temperature and density gradients, and the first experiments with the room temperature impurity pellet injector, which allowed starting the lithization studies that are deemed to be very important in order to achieve a good density control on RFX-mod.

Other two new systems, namely the fast insertable pneumatic system for edge probes and the NPA, made important progress, but will be completed next year. As for the Diagnostic Neutral Beam, the identification of the strong attenuation of the beam in the duct could really represent the key to the solution of the problems encountered in the previous years for this important diagnostic.

In the following a summary of all the activities is given according to the scheme adopted for the 2009 programme.

6.1 FIR Polarimeter

Following the successful commissioning of the polarimeter in 2008, most of 2009 was devoted to the improvement of the S/N ratio. This has been done by performing several different actions:

- Installing the whole laser on a dry air box to reduce FIR attenuation in the beam path;
- Beam alignment has been improved by replacing the wire grid beam splitter with a thin slab beam-splitter: this will allow to align the FIR beam by a visible laser up to the detector section, while previously it was up to the splitting section;
- Beam alignment has been also improved by a better superimposition to the visible laser increasing the path length used for FIR-Visible superimposition;
- A better centring of the FIR beam with the port is also underway by installing an iris on the ports, this will allow to reduce polarization noise due to the interaction of the beam with the ports pipes.

The design of a new detection section has been undertaken, with the aim of deploying the sixth chord and reducing the magnetic noise on the detectors. Preliminary studies of a different technique to improve the time resolution have also been started.

Polarimetric measurements have been performed at the highest plasma current with a low relative error; a preliminary analysis of the inferred internal magnetic field in terms of the μ&p model has been presented at the APS conference. The polarimetric measurements used together with the μ&p model allowed to improve the internal magnetic field reconstruction compared to that obtained using external magnetic field measurements only. An example of the results is given in Fig. 6.1.1, where the poloidal field, toroidal field and safety factor computed with and without the polarimetric measurements are compared. The small differences between the two evaluations prove on the one hand the substantial correctness of the model used up to now, but on the other hand the improvement achieved by using the polarimetric measurement.

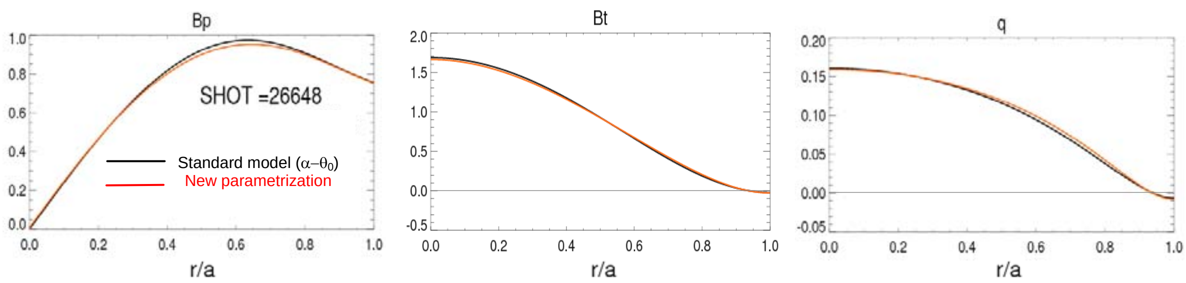

Fig.6.1.1: Poloidal field, toroidal field and safety factory computed by the μ&p model fitting only the measured external magnetic fields (black lines) and fitting also the polarimetric measurements (red lines).

6.2 Microwave reflectometer

The first sub-band of the reflectometer has been successfully installed on RFX-mod. The unit has been calibrated by repeated reflectometric measurements on a metallic mirror placed at known positions.

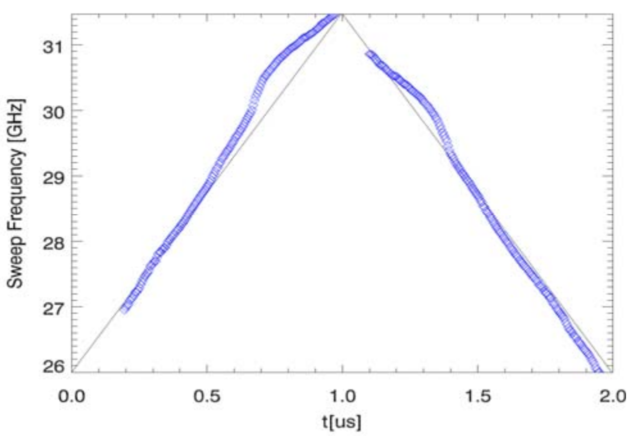

Fig.6.2.1: Frequency vs. time calibration curve of an IMPATT source. The equivalent time resolution for this measurement is 10 ns.

From such measurements it is possible to recover the time-frequency sweep law for the source (see Fig 6.2.1). Such calibration technique, needed to obtain correct plasma measurements, has been developed since instruments with such high time resolution capability are extremely expensive.

The system with one IMPATT source has been routinely operating on RFX-mod since last summer. The actually measured quantity is the group delay for the frequency range 27÷31 GHz, corresponding to a critical density in the interval

0.9÷1.2·10^{19} m^{-3}. Given the fact that the edge density gradient on RFX-mod is approximately linear, this can be directly translated into an estimate of the position of the cut-off layer. The data gathered to date confirmed the capability to obtain reliable reflectometric measurement even in the presence of strong electron density fluctuations [DeMasi09]. An example of a measurement obtained during a pulse is reported in Fig 6.2.2

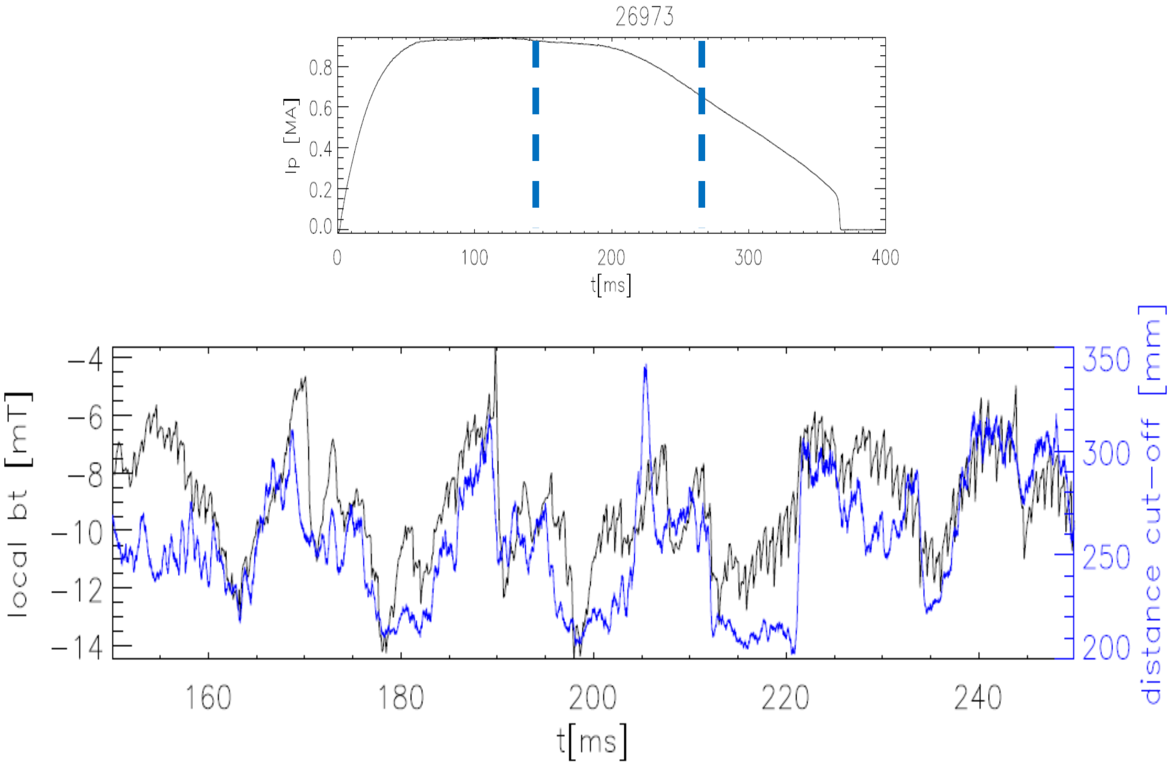

Fig.6.2.2: An example of the cut-off layer position estimate for n_e=1.x 10^{19} m^{-3}, compared with local magnetic toroidal field, showing the strong correlation between the local field and the density.

Unfortunately, during the calibration, one of the IMPATT diode source suffered a severe damage. It was not possible to find a replacement part, nor having it repaired, since these components are no longer used and are out of production. Possible equivalent or better devices, based on a transistor oscillator coupled with an active frequency multiplier and microwave amplifiers are being considered.

6.3 Soft X-Ray (SXR) diagnostics

6.3.1 New horizontal SXR camera

The diagnostic has been assembled and installed on RFX-mod. Due to various delays, including the coil contact failure, the electronics has been installed, but not yet in its final configuration. Additional tests are planned and will be completed by the end of the year.

6.3.2 SXR Multifilter

The new multifilter has been designed and entirely built at the RFX mechanical workshop. 8 channels are now available for precise measurements of the plasma core electron temperature Te(0). Different Be foils have been installed, hence several (up to 6) independent measurements of Te(0) are available, with a temporal resolution of up to 5 kHz. The Be foils have been chosen so that the temperature calculations will be possible even at low plasma current or in Laser Blow Off or Neon injection experiments. The diagnostic has been installed on RFX-mod during the (long) summer-fall shutdown and the first results have been obtained in November (see an example in Figs.6.3.1 and 6.3.2). A modification of the power supplies of the amplifiers is probably required, in particular for the high current operation of RFX-mod.

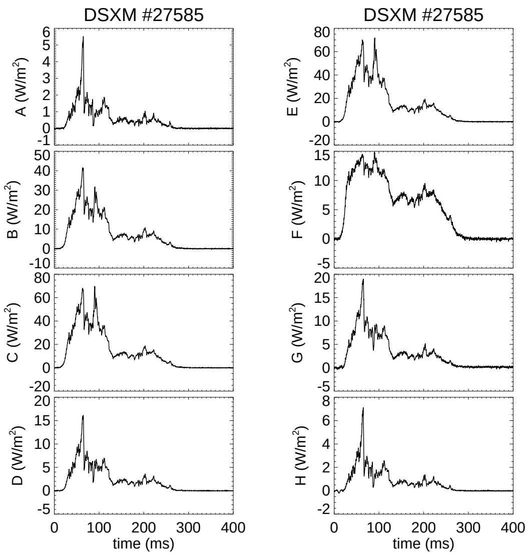

Fig.6.3.2.1: Time evolution of the 8 channels of the multifilter system for a 1 MA plasma shot with pellet injection (at about 105 ms).

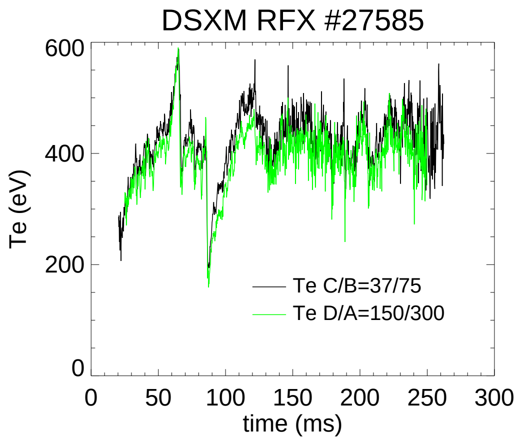

Fig.6.3.2.2: Time evolution of two core electron temperatures calculated from the multifilter system. The black line refers to the Te(0) calculated from the ratio of the signals C and B, while the green Te is obtained from the ratio D/A. The thicknesses of the installed Be foils are also shown. The two Te are basically the same, showing the cooling of the plasma when the pellet is ablated. The time resolution is 5 kHz.

6.3.3 Tomography vacuum and control system

The auxiliary vacuum and control system of the tomography has been installed and put into operation at the beginning of 2009. The new system worked perfectly since its installation and has been used throughout the entire year.

6.4 Edge measurements

Temperature and density profile from thermal He beam

During 2009, the Thermal Helium Beam (THB) diagnostic [Agostini09] has been upgraded, installing multianode photomultipliers instead of the CCD camera as detectors. In this way we have increased the time resolution, and it is now possible to measure the edge (0.94<r/a<1) profiles of the electron temperature T_e, density n_e and pressure P_e (and their time-evolution) with a resolution up to 0.5 ms. Moreover, using the conditional average technique, it is possible to study in a statistical way the high frequency fluctuations, and characterise the edge structures (“blobs”).

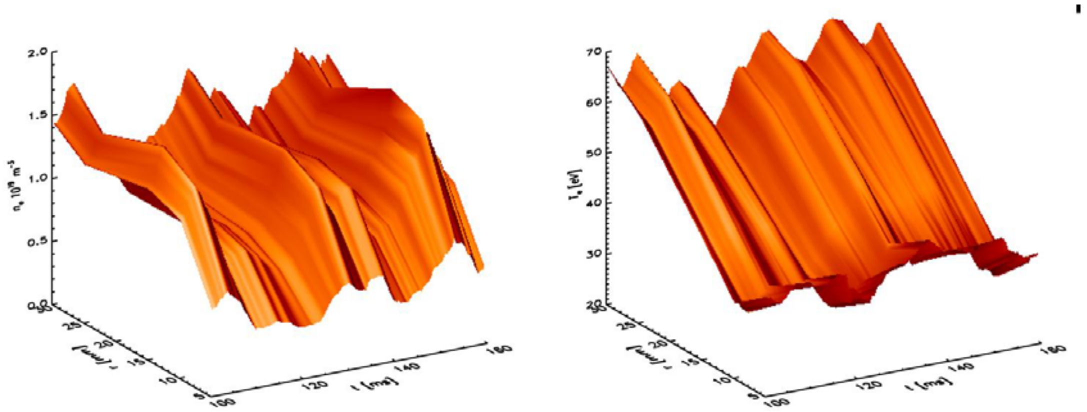

Fig.6.4.1: Time evolution of the edge electron density (left) and temperature (right) profiles

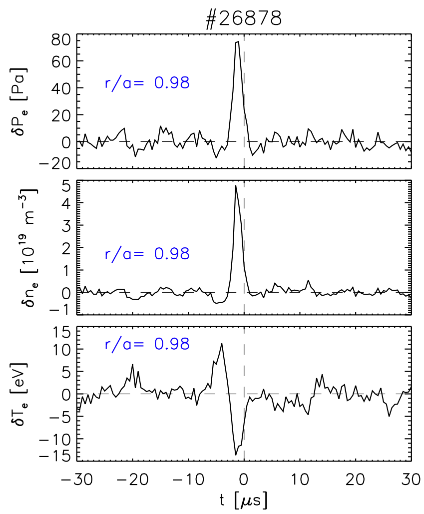

Fig.6.4.2: Edge coherent structures measured by the THB diagnostic

In Fig.6.4.1 an example of the time evolution of $n_e(r)$ and $T_e(r)$ measured with the THB is shown. It can be seen that the development and the time evolution during the discharge of both density and temperature gradients at the plasma edge is very well diagnosed.

As mentioned above, with the conditional average technique the edge blobs are detected and characterised, and an example is shown in Fig.6.4.2. The coherent structures are seen as peaks in density and pressure, with a more complicated pattern of temperature. All these measurements are routinely available for all RFX-mod discharges, both at low and high current, since the diagnostic is not in contact with the plasma.

Fast insertable pneumatic system for edge probes

According to the plans, the project for the fast reciprocating manipulator for RFX-mod has been started. 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.

During the year a working team has been set-up, involving all the expertise within RFX resources concerning different aspects of the project to be accounted for (mechanical, diagnostics, controls, etc.). A visit to the ASDEX –Upgrade experiment has been performed in order to get experience on a similar working system. The mechanical technical specifications have been defined [Agostinetti09]. Then some delay occurred for the placement of the order for the design of the system, due to the lack of an approved financial budget before summer.

In Fall finally the problem was overcome and an external company is now in charge of the system design and design progress is periodically checked with the contribution of the RFX working team as specified in the contract.

Arcless power supply for ion saturation measurement

The design of the power supply and arc-limiting circuit has been refined according to the scheme shown in figure 6.4.3

A prototype of the circuit board for current limitation has been realized in the RFX electronic workshop. The prototype has been tested, using the present power supply based on capacitors, and it has been found to properly work and to satisfy the requirements in terms of time response. A test on the fixed triple probe diagnostic is foreseen for the end of 2009. The complete system including power supply is expected to be finished and operating by June 2010.

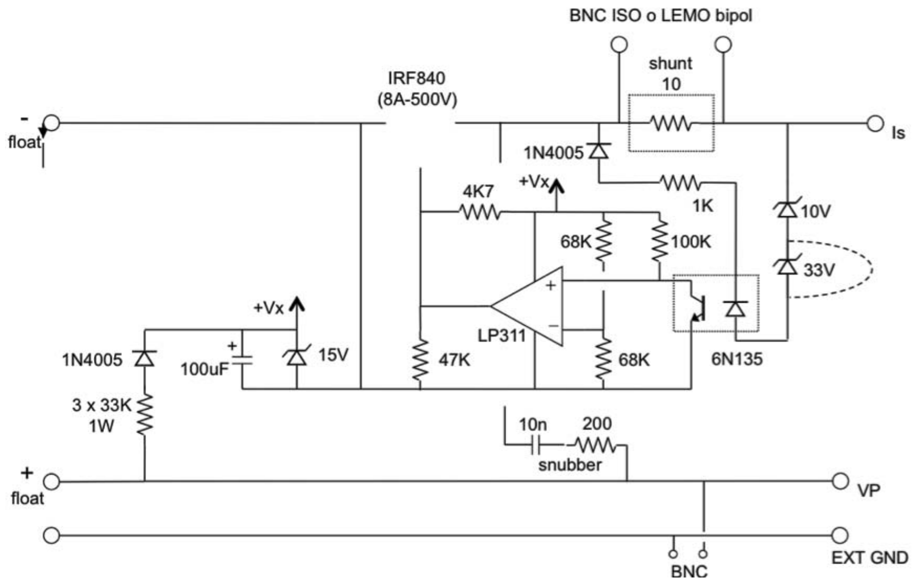

Fig.6.4.3: Power supply and arc-limiting circuit scheme.

6.5 Upgrade of the Diagnostic Neutral Beam Injector

In order to exactly identify which parameters of the diagnostic neutral beam injector should be improved to raise the signal-to-noise-ratio of Charge Exchange Recombination Spectroscopy up to a useful level, a series of specific tests have been carried out. These tests have confirmed that the beam is stopped in the duct connecting the injector to RFX. An absolute pressure gauge has been connected to the duct and a metal mirror has been positioned to allow a view along the beam itself in order to directly see the process of beam deflection in the duct. Neutral beam loss occurs as an effect of the re-ionization caused by the relatively high neutral pressure in the region, produced by the RFX-mod plasma, and by the simultaneous presence of a relatively large perpendicular field, mostly produced by the field shaping coils. Tests with beam fired into the RFX-mod vacuum chamber filled with a little amount of gas have shown that the fraction of the beam reaching RFX-mod decreases almost linearly with the strength of the transverse magnetic field. Montecarlo simulations of the 50 keV ion trajectories have confirmed that re-ionized ions are indeed lost whenever the plasma current is higher than 300 kA. More tests are ongoing to quantify the process, while solutions to keep the neutral pressure in the duct region below 1×10^{-4} are being devised. In this respect two solutions can be adopted, perhaps simultaneously, in the direction of increasing the duct volume and the pumping speed respectively. Additional tests on the neutralization degree of the ion beam extracted from the source have also been carried out. It appears that the original ion beam is not completely neutralized and therefore an extra gas valve has been added to directly feed the neutralizer. The effect of this modification has not yet been verified. It is expected that at a certain point the extra gas from the neutralizer will induce over pressure in the duct. Therefore, optimization of neutralization and beam transmission have to be studied together.

6.6 Room Temperature pellet injector

The impurity pellet injector has been installed in summer and has been used to perform the first tests of lithization in the second half of the year. To such purpose lithium pellets with a diameter of 1.5 mm and a length of 5 mm have been injected at a speed of about 100 m/s on 1.2 MA current RFP plasmas. In figure 6.6.1 is shown edge and core density traces of a Lithium pellet entering a 1.2 MA pulse at 80 ms.

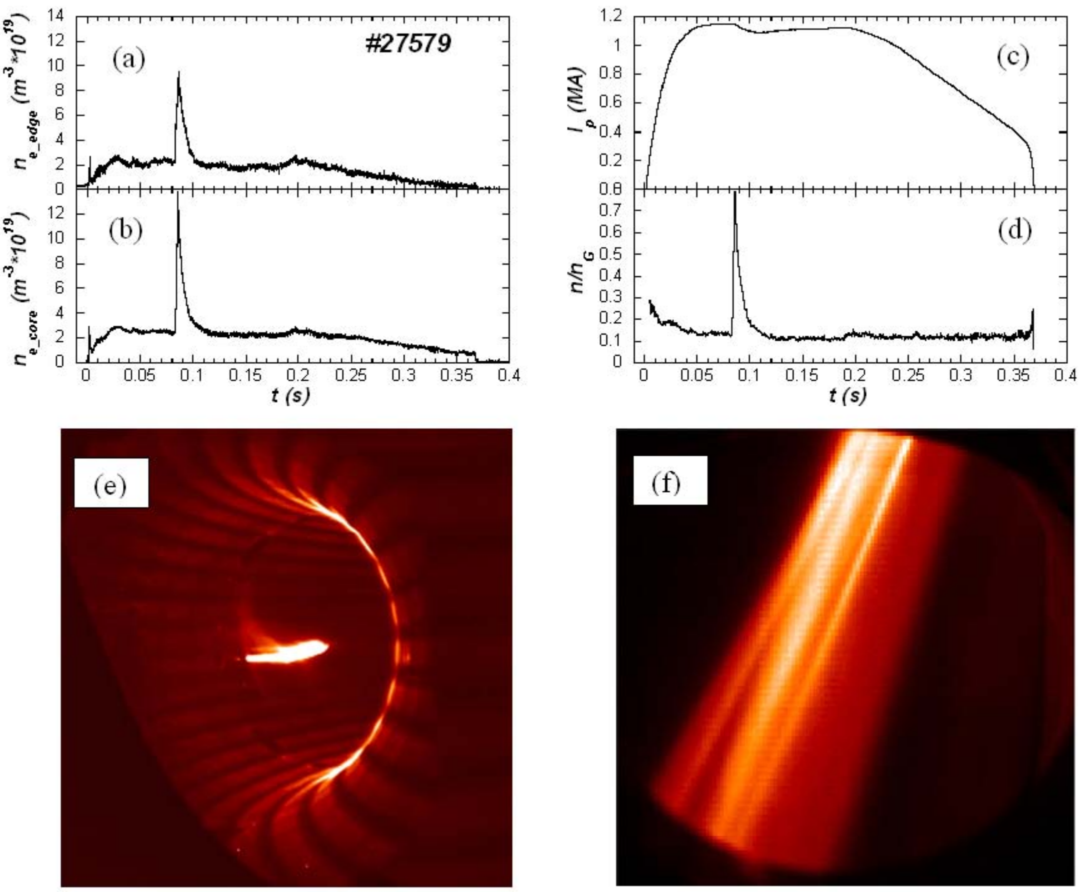

Fig.6.6.1: Lithium pellet entering on a 1.2 MA discharge at 80 ms. a) edge line average line density; b) core average density; c) plasma current; d) Greenwald normalized density n/n_G; e) CDD toroidal view image of the ablating pellet; f) Fast CMOS back side image of the ablating cloud aligned with the local magnetic field direction.

Each pellet can provide on average a first wall coating of the first wall with a thickness of about 0.25 nm thick. Up to now only small variations on plasma and wall behaviour have been observed, probably due to the limited number of pellets injected (about 10 pellets).

6.7 Ion temperature measurement from NPA diagnostic

During 2009, a diagnostics for ion temperature measurements based on magnetic deflection was borrowed from IPP Greifswald. The mechanical structure required for the alignment of the system on a plasma line of sight and the vacuum equipment have been prepared, along with the high frequency acquisition system for the 22 channels. The high frequency requirements for the signals coming from the NPA diagnostics are essential in order to reconstruct, along with the average T_i value, the generation of fast ion tails during spontaneous magnetic reconnection events in RFP plasmas. The first tests and the calibration procedure by means of a source of ions at a given energy were established. The work to adapt the Nenè code, originally developed for the reconstruction of the particle source term in transport simulations, for the simulation of the neutral production processes inside the plasma also started.

6.8 Fast Ion Losses Diagnostic

The existing fast ion losses diagnostics installed in various laboratories (for example at JET) have been analyzed and a feasibility study has been prepared for RFX-mod. A Faraday cup collector type is considered as a possible solution, mainly because of its simplicity.

6.9 Lithium neutral beam diagnostic

No work was performed on this task in the first half of 2009 because no money was allocated for it on the 2009 budget. During the second half of the year will be performed the feasibility study of the diagnostic installation on RFX-mod.

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7. BROADER APPROACH

The contributions to the overall design of the Satellite Tokamak JT-60SA Power Supplies, in the framework of the Broader Approach activities, regularly proceeded during 2009 [Matsukawa09], [Yamauchi09], [Shimada09]. In particular, the RFX specific on-going studies on the Quench Protection Circuits (QPC) and the Power Supply (PS) system for RWM control to be procured by CNR, acting through Consorzio RFX, proceeded as described below.

7.1 Quench Protection Circuits

The analyses of the poloidal circuit operation in case of plasma disruption and fault conditions, aimed at identifying the maximum overcurrents to be sustained by the circuit components and QPC in particular, were completed in collaboration with JA colleagues [Novello09a]. Studies went in deeper detail of plasma disruption effects on the amplitude of the overcurrents in the coils; the impact of the shape, position, and distribution of the plasma current were evaluated. Vertical Displacement Events were considered in particular.

The conceptual design of the QPCs, based on an advanced Hybrid Circuit Breaker, composed of a mechanical bypass switch and a static interrupter was completed [Gaio09]. Studies were made on the dump resistor design and on the provisions to dissipate the large amount of energy stored in the magnets avoiding exceeding the maximum admissible room temperature and succeeding in cooling down the resistor within the nominal JT-60SA pulse duty cycle. Again on the conceptual design assessment, analyses were also devoted to improve the reliability of the QPCs with a suitable selection of the dump resistance value such to achieve the best compromise in terms of reduction of both the voltage applied to the coils and the I^2t value during the discharge. The calculations made at this purpose were based on the complete model of the poloidal circuits developed for the fault analyses.

In the second semester the Technical Specifications were prepared and the subsequent revision process made by the EU and JA Home Teams, was completed successfully in November 09. The Procurement Arrangement documents between F4E and JAEA and the Agreement of Collaboration between F4E and CNR were also assessed and finally signed on 3 December 2009.

The design solution proposed for QPCs is quite innovative; there is no experience of similar solutions at this power level either in industrial or scientific field. This suggested performing preliminary tests, made late 2007/beginning 2008 to study the turn-on of the static devices with low voltage applied between anode and cathode [Novello09b]. Then a hybrid circuit breaker prototype of sufficient power level was realized to verify in detail the issues related to the transfer of current between the bypass switch and the static interrupters in parallel. The studies to develop the prototype were made in the first semester 2009 and in the second the control system was designed and set up in parallel to the arrangement of the test bed shown in

Fig. 7.1.1. The first results are very encouraging; the experimental campaign will proceed during 2010.

Fig.7.1.1: Development of a hybrid dc circuit breaker (10kA, 1kV) – test arrangement

7.2 Power supplies for in-vessel sector coils for RWM control

A revision of the present design of the sector coils for the stabilization of the RWMs, based on 18 coils, six along the toroidal direction and three in the poloidal one, to be installed behind a stabilizing plate (SP), has been continued in collaboration with JAEA colleagues. Considering the results of the FEM analyses made by RFX in 2008, which showed an excessive shielding effect of the copper shield of the conductors, JAEA changed the reference design of the coil conductor. Presently, it is based on Mineral Insulated Cable (MIC), with sheath made of high resistivity stainless steel to reduce its shielding effect (Fig. 7.2.1).

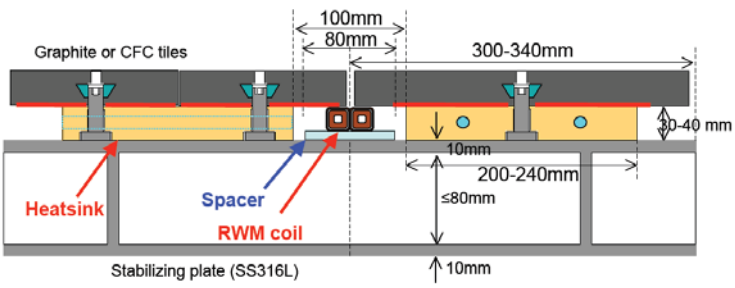

Fig.7.2.1: Conceptual desing of internal sector coils

During 2009, additional FEM analyses on sector coils have been carried out, aiming to estimate the load parameters (coil resistance and inductance as a function of frequency) and coil efficiency in producing the magnetic field. The external sector coils have been studied in deeper detail, in the optimistic assumption of a stabilizing plate (SP) made of a single layer of SS316L, having a thickness of 2 cm. At the moment, the details of the internal structure of the SP are still unfixed, but it shall probably be made of two plates, each 1 cm thick, connected together by ribs. As in 2008, the model is axisymmetric with respect to the centre of the coil; as a consequence, the coil is approximated as having circular shape.

An alternative design solution, with internal sector coils, located between the SP and the first wall, as sketched in Figure 7.2.2, was proposed by JA.

Fig.7.2.2: Picture of MIC with sheath made of SS316L

This solution presents advantages and drawbacks, part of which were studied this year; additional input data, from freezing the stabilizing plate geometry (expected for next spring 2010) are necessary to complete the work.

The internal coils are elongated in the toroidal direction, therefore a new 2D axisymmetric model has been developed, where the axis is the same of the torus. The model also includes the heat-sink for the first wall, made of copper blocks (see Figure 7.2.1). Being a 2D model, the copper is represented as toroidally continuous, therefore showing a strong shielding effect. Also the effect of the port holes in the SP has been analyzed, within the limits of the 2D model. An example of the preliminary results is reported in Figure 7.2.3; comparing the magnetic field produced, the figure shows that, for the same coil current (2.5 kA in the assumption of the analyses), the magnetic field produced by the internal sector coils (at the coil centre, 14 cm from SP) is lower than for the external sector coils. This is due to the lower turn number and the larger area of the coils.

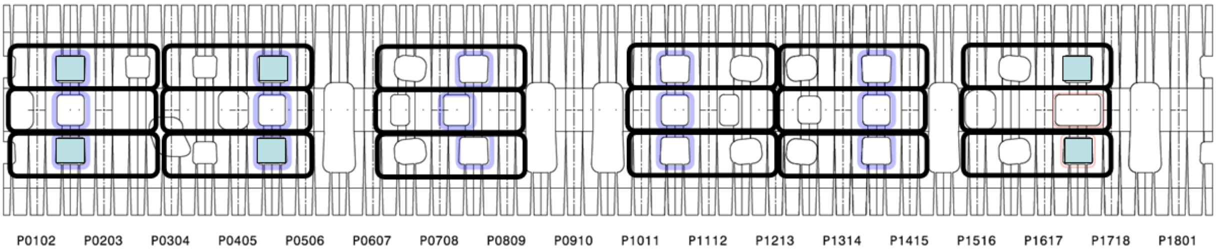

Figure 7.2.3: Internal sector coils (in black) on the stabilizing plate.

The analyses foreseen for 2009 on different technical solutions and conceptual studies of the Power Supply system have been postponed to 2010 when the specification of the system will be more deeply assessed by JAEA.

7.3 Physics studies

Physics studies in support to the JT-60SA project development started in 2009 including both collaborative experiments on RFX-mod (in particular on RWM physics and control, see Chapter 2) and RFX-mod participation to the European contribution to the Physics Integration Unit.

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8. OTHER ACTIVITIES

8.1 Energy strategies

8.1.1 Fusion Energy as base-load electricity source

Modeling of a pulsed Fusion Reactor to estimate construction, operation and maintenance costs and cost of electricity has gone ahead during 2009: the reactor block diagram has been fully revised to make pulsed operation simulation feasible and to include internal energy storage.

A more accurate simulation of power supply and magnets during start-up as well as of heat exchange regime in the blanket have been implemented.

Cost estimates have been obtained for several machine parameters and operating conditions; first results show that costs of a pulsed reactor are very close and in some cases lower than a steady state one, while the requested operating conditions are less challenging.

8.1.2 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 gained during 2009 and all the routines have been installed and tested at RFX.

Contacts have been established with ERSE (former CESI Ricerca) to learn how to use models already set up for outlooks to 2030 and beyond to understand which parts of those models can be adapted to a longer time horizon, and thus to make those parts suitable for a "Fusion model".

Such activity has been carried out as part of the research programme of one doctoral student in Energetics in the University of Padova. On the other hand, the level of knowledge and competence achieved so far is not yet enough to significantly contribute to the development of the EFDA-TIMES model.

8.2 Non Fusion applications

8.2.1 Magneto-plasma-dynamic thrusters

In 2009 the activity on the study of Magneto-plasma-dynamic thrusters has been mainly focused on planning and design of new strategies for the control of the large scale magnetohydrodynamic plasma instabilities (kink modes), which have been demonstrated to be responsible for the loss of efficiency of this kind of devices when brought to operate at high plasma current levels [Zuin2004]. The activity is mainly performed within the Seventh Framework Programme for space exploration of the European Union, being Consorzio RFX a member of the HIPER (High Power Electric Propulsion, a Roadmap for the future) Consortium.

In the last years, a successful control method for plasma instabilities was proposed, based on the insertion in the discharge chamber of the thruster of an insulating plate, with the aim of intercepting the undesired helical current components induced by the kink modes. In future experiments new, less intrusive, alternative methods to suppress plasma instabilities will be tested. These new methods, which involve the use of a nearby conducting shell, also referred to as a wall, surrounding the plasma, have been planned and designed during 2009. In particular, the idea proposed is to attempt to convert the growing ideal kink modes into a RWM mode branch exhibiting a sufficiently slow growth rate, so that various additional active approaches could be proposed in the future to totally suppress or control mode amplitude. Different geometries, shapes and thickness of the shell have been developed, along with different shell materials (Aluminum, Copper, Stainless Steel), in order to obtain different characteristic penetration times for the magnetic field. The aim is to obtain a variation of growth rate of the modes, spanning from times shorter to much larger than the discharge duration.

8.2.2 Biomedical applications

In 2009 several tests have been performed concerning the effect of the plasma source for medical applications built and patented at Consorzio RFX on bacteria and cell cultures. The sterilizing effect of the plasma has been tested by treating different types of bacteria cultures, namely, in order of resistance, Escherichia Coli, Staphylococcus Aureus and Pseudomonas Aeuroginosa. The tests have demonstrated the capability of the source to kill the bacteria with decimal reduction times of 1-2 min. The germicidal effect was attributed, at least partially, to the presence of OH radicals in the gas flow, as confirmed by spectroscopic measurements. The consequences of the plasma interaction with tissue cells were studied using conjunctival fibroblasts. To estimate intracellular oxidative level due to reactive oxygen species (ROS) after plasma treatment, a fluorigenic probe, the 2',7'-dichlorodihydrofluorescein (H2DCFDA), was used. The maximum emission detection was relieved 30 seconds after treatment; subsequently the emission was reduced to zero in 30 minutes. This means that fibroblasts react well against ROS attack and they can shortly activate anti-oxidative systems. Among specific UV effects on cells there is the formation of thymine dimers (TD) in DNA strands that inhibits the ability of cells to replicate properly. For this reason, the presence of TD in DNA of cells after a 2 min plasma treatment was investigated by immunofluorescence microscopy using a monoclonal antibody raised against thymine dimers. No TD detection was obtained. The global effect of the source on living fibroblast cells has also been tested by the MTT test. This test is based on the fact that only the viable cells, i.e., those containing functioning mithocondria, are able to oxidise MTT, giving a violet-red coloured reaction product. For the tested time intervals cell cultures were found to maintain a viability comparable to that of untreated cells (control cultures). Finally the effects of ex-vivo plasma treatment on human cornea were histologically evaluated. For this purpose, after 5 minutes of treatment, corneas were fixed in formalin, paraffin-embedded, and stained with ematoxylin and eosin. No significant morphological changes were observed when compared to untreated control samples. The results are described in a paper which has been accepted for publication on the New Journal of Physics [Martines09].

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9. QUALITY MANAGEMENT

Following the ISO 9001 guidelines, during 2009 all the main and support processes have been identified, together with their owners, interactions and customers.

A draft version of the quality manual is now available and its review process is ongoing.

The design of the quality management system is practically completed; only few procedures (already prepared) still need to be reviewed and approved.

In the development and implementation of the quality management system a first effort has been done in identifying practices, procedures and tools needed to manage quality in a project environment, within the environment of the NBI Project, the Diagnostics Programme and the Broader Approach Programme.

A second effort has been done and is still ongoing in the extension of the above mentioned practices, procedures and tools to the different programmes and support processes.

At the moment the quality management system has been extended to the Neutral Beam Project and related Scientific Support Programme, and to the Diagnostics Programme; however also these processes still need quality advice and support.

The extension of the quality management system to the following main and support processes started in the second half of 2009 and at the end of this year is still not completed:

- RFX Operation and Maintenance Process,
- Education Process,
- RFX Programme,
- Broader Approach Programme,
- Technical (mainly drawing office) Support Process,
- Competence Management (support) Process (as an important part of human resources management),
- Measuring Equipment Management.

A survey by students, about the quality of the Education Process, has been launched.

The Top Management decided that the implementation of the Competence Management Process needed special attention and put the proposed (designed) process under review to ensure its usefulness and full comprehension by the group heads.

The extension of the quality management system to the maintenance process and to the information and data management process did not started and is planned to start in 2010.

In the processes where the quality management system was implemented, the process owners and the involved personnel experimented the following benefits:

- clearer and measured objectives in terms of quality, time and cost,
- documented action plans for each objective, with clear responsibility allocation and resource estimation,
- support of top management, improved top-down and bottom-up communication,
- identification of risks, focus on risk reduction and loss prevention,

- identification of problems, focus on problem solving and continuous improvement.

The “process review” has been used until now only in the presence of an external stimulus from the customer (F4E in the case of the NBI project review); more broadly, the initiative of regularly reviewing processes and projects for improvement should be taken.

No “management reviews” (prescribed by ISO 9001) have been done yet.

A certain resistance to change is perceived at all organization levels ; from this point of view this research environment is not an exception; this widespread resistance or simply a lack of due priority is the cause of delays which shifted the certification audit from the end of 2009 to the first half of 2010.

10. EDUCATION TRAINING AND INFORMATION TO THE PUBLIC

In 2009 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 as a consequence of the start of the second cycle (2009-2011) of the Doctorate.

The total number of students grew from 13 to 27 (from 5 to 11 in Padua) and the number of dedicated courses grew from 2 to 4, of which 2 organized in Padua, 1 in Lisbon and 1 in Munich.

The 2 courses organized in Padua were: a Basic Course (4-15 May) of 47 hrs, similar to that given in May 2008, and a new Advanced Course in Engineering (9-20 November) of 58 hrs.

The new Advanced Course in Engineering dealt with the following topics and had the following teachers:

1. **Materials for fusion reactors**: Structural materials (J.L. Boutard, EFDA), Superconducting magnets (P.L. Bruzzone, CRPP), IFMIF (A. Pisent, INFN);
2. **Power reactor issues**: Breeding blanket (G. Casini, RFX), Shielding blanket and Divertor (M. Merola, ITER), Remote maintenance, power plant issues and DEMO (D. Maisonnier, EU Commission);
3. **NBI heating and current drive**: Introduction (V. Antoni, RFX), Ion sources and electrostatic acceleration physics (M. Cavenago, INFN), Ion sources, bean-line components and electrostatic accelerators technology (P.L. Zaccaria/D. Marcuzzi, RFX), High voltage components (A. De Lorenzi, RFX), Vessel and vacuum (P. Sonato, RFX), Power supplies and control systems (V. Toigo/A. Luchetta, RFX), Beam-plasma interaction and current drive (A. Staebler, IPP);
4. **RF heating and current drive**: Introduction (A. Tuccillo, ENEA), ECRH (G. Granucci, CNR) LH/ICRH (F. Mirizzi, ENEA), ICRH (M.Maggiora,PoliTo).

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

The other educational activity of Consorzio RFX on fusion related disciplines continued with a significant effort also in 2009.

In particular, RFX scientists were in charge of 19 postgraduate students preparing their thesis of PhD in Fusion Science and Engineering, Physics, Energy Research and Electrical Engineering and of 13 students preparing their graduation thesis on fusion related subjects.

Eight regular courses 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 Plasma Physics” and “Electrodynamics”.

As far as public information is concerned, the permanent organization of visits to the RFX site continued with growing success.

CONSORZIO RFX

PUBLICATIONS AND REPORTS

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