High current regimes in RFX-mod.

M Valisa, T Bolzonella, P Buratti[1], L Carraro, R Cavazzana, S Dal Bello, P Martin, R Pasqualotto, J S Sarff[2], M Spolaore, P Zanca, L Zanotto, M Agostini, A Alfier, V Antoni, L Apolloni, F Auriemma, O Barana, M Baruzzo, P Bettini, D Bonfiglio, F Bonomo, M Brombin, A Buffa, A Canton, S Cappello, M Cavinato, G Chitarin, A De Lorenzi, G De Masi, D F Escande, A Fassina, P Franz, E Gaio, E Gazza, L Giudicotti, F Gnesotto, M Gobbin, L Grando, L Guazzotto, S C Guo, V Igochine[3], P Innocente, R Lorenzini, A Luchetta, G Manduchi, G Marchiori, D Marcuzzi, L Marrelli, S Martini, E Martines, K McCollam[2], F Milani, M Moresco, L Novello, S Ortolani, R Paccagnella, S Peruzzo, R Piovan, L Piron, A Pizzimenti, P Piovesan, N Pomaro, I Predebon, M E Puiatti, G Rostagni, F Sattin, P Scarin, G Serianni, P Sonato, E Spada, A Soppelsa, S Spagnolo, G Spizzo, C Taliercio, D Terranova, V Toigo, N Vianello, D Yadikin[3], P Zaccaria, B Zaniol, E Zilli and M Zuin

Consorzio RFX, Associazione EURATOM-ENEA sulla Fusione, Corso Stati Uniti, 4, 35127-Padova, Italy
[1] *Associazione Euratom-ENEA sulla Fusione, C.R. Frascati, CP 65, I-00040, Frascati, Roma, Italy*
[2]*Department of Physics, University of Wisconsin–Madison, Madison, Wisconsin 53706, USA*
[3]*MPI für Plasmaphysik, Euratom-Association, D-85748 Garching, Germany*

Abstract.
Optimization of machine operation, including plasma position control, density control, and especially feedback control on multiple magnetohydrodynamic modes has led RFX-mod to reliably operate at 1.5 MA, the highest current ever achieved on a Reversed Field Pinch (RFP). At high current and low density the magnetic topology spontaneously self-organizes in an Ohmical helical symmetry, with the new magnetic axis helically twisting around the geometrical axis of the torus. The separatrix of the island disappears leaving a wide and symmetric thermal structure with large gradients in the electron temperature profile. The new topology still displays an intermittent nature but its overall presence has reached 85 % of the current flat top period. The large gradients in the electron temperature profile appear to be marginal for the destabilization of Ion Temperature Gradient modes on the assumption that ions and electrons have the same gradients. There are indications that higher currents could provide the conditions where to prove the existence of a true helical equilibrium as the standard RFP configuration

1. Introduction

Research on Reversed Field Pinch (RFP) configurations has experienced in the recent years substantial progress [Marrelli 2007, Wyman 2008, Brunsell 2006, Hirano 2006], with significant advances both in terms of plasma performance and control, and of understanding of relevant physics. The aim of this paper is to add to the line of such progress new interesting physics results, which are emerging from the reliable operation of RFX-mod in the regime with plasma current above 1 MA.

RFX-mod is an RFP device equipped with a state-of-the art system for active control of MHD stability, designed for operation at plasma current up to 2 MA. Optimization of the many aspects of the machine operation and accurate control of main plasma parameters and of plasma stability has allowed reaching reliably I_p=1.5 MA of plasma current, the highest ever obtained on a RFP. Such high current experiments have disclosed a new interesting physics regime, where the RFP spontaneously evolves towards an Ohmic helical symmetry, theoretically predicted. This new magnetic configuration is accompanied by well preserved helical magnetic surfaces in the plasma core, and is characterized by a principal helical magnetic axis. This leads to decrease of transport and to the formation of steep core electron temperature profiles.

This is an important result since it represents a further step in a known path towards the theoretically predicted laminar and chaos-free RFP, not any longer conceived as an interesting physics experiment inevitably associated to a sea of turbulence, stochastic fields, high transport and therefore marginal to the fusion world. Moreover, recent results and the commonalities between the RFP and the tokamak on issues like non-linear MHD dynamics and stability control, fast ion confinement, density limits - to mention only some - make the RFP of increasing interest for the wider fusion community.

The paper is organized as follows: Section 2 and 3 provide the background, by briefly recalling some important background theory (Section 2), and providing a description of the RFX-mod device and in particular of the MHD stability control system (Section 3). Section 4 is dedicated to the main experimental results and to their discussion, while conclusions and future perspectives are described in Section 5.

2. The RFP: a paradigm for self-organized plasma

Two are the main aspects that since the beginning have made the RFP an appealing configuration and, in principle, an interesting solution as an alternative reactor line: the robustness and the elegance of a self-organized system and the inherent simplicity of the toroidal coil system, which has to sustain relatively low toroidal fields. In the real experiment, self-organization means that upon application of a toroidal loop voltage, the RFP plasma spontaneously self-organizes by converting a fraction of the toroidally driven electrical current into a poloidal one, the so called RFP dynamo mechanism. The safety factor $q(r) = r/a\ B_T/B_p$ is much less than 1 everywhere and becomes negative at the edge. With such a q

profile the average poloidal and toroidal fields are of the same magnitude and the core toroidal flux is generated by currents flowing in the plasma itself, with relief of the external toroidal coils. Visco-resistive MHD simulations [Cappello 1992, Cappello 2004 and references therein] have predicted that the dynamo mechanism required to sustain the equilibrium fields can be provided by a kink-like deformation of the plasma that attributes to the configuration a global chaos free helical symmetry: the single helicity (SH). SH is an Ohmic helical state that retains all the good features of the RFP without the problems connected with the high level of magnetic turbulence typical of the Multiple Helicity scenario, where instead many modes of comparable amplitude are simultaneously present. Abundant experimental evidence [Martin 2003, Piovesan 2004] shows that similar SH are indeed approached in modern devices, accompanied by significant degree of order in the magnetic topology and, correspondingly, by clear helical thermal structures in the plasma core. Such regimes in which one mode, a saturated resistive kink instability, intermittently grows much higher than the others, or secondary modes, has been named Quasi Single Helicity. The full experimental realization of SH spectra would require that the amplitude of "secondary" modes becomes negligible. In [Marrelli 2007] it was shown that the probability to develop QSH increases with current and that above 1 MA QSH occupies a significant fraction of the current flat top. One important and recent experimental result obtained in a transient way by oscillating the toroidal flux [Terranova 2007] is that the helical structure associated with the dominant m=1 mode grows up to the point where a Single Helical Axis (SHAx) becomes the main magnetic axis, and the original symmetric magnetic axis ceases to exist [Lorenzini 2008]. A broad volume of conserved helical flux surfaces is present. Current interpretation is that the disappearance of the magnetic separatrix, following the high amplitude dominant mode saturation, is what makes the remaining topology more resilient to chaotic perturbations [Escande 2000] despite the presence of residual small modes in the spectrum. The relevance of this experimental finding is that it represents an important step towards the theoretically predicted Single Helicity (SH) In the following we will see that at high plasma current regimes the new interesting topology that may be artificially excited with oscillating poloidal currents develops spontaneously.

It may be interesting to note that the described helical magnetic symmetry is to some extent similar to the Stellarator case, where, however, the field configuration is imposed by external coils and not reached by an ohmically driven self-organization mechanism.

3. RFX-mod: a device with feedback controlled magnetic boundary

RFX-mod is the largest RFP, with minor radius a=0.46 m and major radius R= 2 m. Its main missions are to explore high current RFP plasmas, up to 2 MA [Sonato 2003, Ortolani 2006, Marrelli 2007, Martin 2007], and to contribute to the community effort on MHD stability active control.

The first wall is made of a full coverage of graphite tiles, positioned and shaped in such a way as to minimize the probability of local hot spots. The presence of a large graphite surface makes density control not an easy task. Optimization of the current start up with careful control of the plasma position and minimization of fuelling rates have significantly improved the reproducibility of high current discharges at low (n/ n_G = 0.1) and intermediate density (n/ n_G = 0.4 where $n_G= Ip/\pi a^2$ is Greenwald density, with *Ip* the plasma current and *a* the minor radius) [Canton 2008].

Important progress has been made also on the feedback control system [Marrelli 2008]. This has been one of the key elements that has allowed reaching reliable operation of RFX-mod at high current. The active magnetic boundary is based on 192 saddle coils independently powered and positioned outside a thin copper shell with a penetration time constant of 100 ms. The cycle frequency of the feedback action has been increased from 1.7 kHz to 2.5 kHz. Also the power supplies feeding the saddle coils have been optimized and their dynamic response ameliorated. Fine optimization has been finally applied to the gains of the amplifiers to maximize phase and wall unlocking of the tearing modes [Marrelli 2008]. By inducing the rotation of the tearing modes with different phases the maximum radial displacement of the plasma can be kept close or below 1 cm and, in addition, the position where the modes interfere positively changes continuously in time. This double effect reduces the plasma wall interaction to bearable levels, avoiding tiles overheating and uncontrolled recycling. Fig. 1 shows an example of the result of the feedback control on the radial displacement of the last closed surface in a 1.5 MA discharge: the maximum radial excursion of the plasma column changes in space (top figure) and oscillates around 12 mm. Current efforts [Marrelli 2008] are addressing the way to optimize the capability of the feedback system to control the amplitude of the tearing modes and more specifically of the innermost one in order to reduce the intermittency of the QSH.

The feedback system is very flexible, and several feedback schemes have been applied [Paccagnella 2006 and 2007, Zanca 2007, Bolzonella 2006] The most efficient control scheme is the so called 'Clean Mode Control' and consists in the direct and simultaneous control of a subset of the identified Fourier modes, with the advantage that the actuators gains can be tailored on each mode in amplitude and modality [Marrelli 2007]. The treatment of the sidebands generated by the coils, for their being finite in number, and producing an aliasing in the spectrum measured by the sensors [Paccagnella 2002, Zanca 2007] has been fundamental for an efficient operation. It has also been important to model the entire system, including feedback system, vacuum liner, thin shell and the mechanical structure that holds the saddle coils, to understand the role of each component, simulate various gains options and feedback laws and restrict the parameter space to explore experimentally [Zanca 2007].

The flexibility of the feedback control system includes the possibility to treat the modes in a selective way, allowing for instance one or more modes to grow. This has been very useful to study the properties (growth rates) of tearing and resistive wall modes [Bolzonella 2007, Igochine 2008] and to study their non linear interaction. Availability of such data has been useful to benchmark ITER relevant codes such as CARMA [Villone 2008]. The system allows also adjusting the phase of the specific mode to be studied in order to allow a proper investigation at the various diagnostic sections, whereby a non symmetric phenomenon such as the QHS could be completely missed by the many diagnostics that do not cover the whole poloidal section [Bonomo 2008].

4. High current RFX-mod plasmas: the natural environment for Single Helicity

Thanks to the feedback control of MHD instabilities, reliable operation at 1.5 MA is routinely and reliably carried out in RFX-mod. Plasma discharges as long as approximately 0.5 s (i.e. 10 times the resistive wall constant) are produced, thus demonstrating that the RFP does not need for its operation a thick conductive shell. A typical 1.5 MA plasma current discharge in RFX-mod is illustrated in Fig. 2, which displays some relevant time traces (see caption). The plasma current is sustained by static units till *t*=150 ms. During the long decay phase only the vertical field and the edge magnetic field required to maintain a prescribed edge safety factor q(a) are actively controlled. One may notice how the average toroidal field waveform is in practice a replica of the plasma current. This is because the toroidal field is generated by internal currents by draining power, in a self-organized way, from the only (Ohmic) driver.

After the reversal of the toroidal magnetic field and when the plasma current has reached almost 1.4 MA, the innermost resonant (*m*=1, *n*=-7) mode develops higher than all of the other modes, which instead decrease. This gives to the magnetic topology a strong and tidy helical character. This QSH state has an intermittent nature with occasional crashes of the dominant mode to lower values, still higher than the amplitude of the remaining “secondary” modes. These events are accompanied by small dynamic of *q* and small variations of the toroidal flux, hardly visible in the figure, associated to the activity of the residual modes. The frequency of the oscillations varies in the shot of Fig.2 from 30 to 200 Hz approximately and the amplitude of the dominant mode saturates practically at a given level at all frequencies. As shown in the figure, there are phases where the amplitude of the dominant mode persists high for tens of ms (up to 50 ms), that is several times the energy confinement time. During the decay phase of the current the amplitude of the QSH signal (amplitude of mode m=1, n=-7) reduces but remains proportional to the current itself. Interestingly, during the decay phase the QSH persists well below the current level required for its existence during the discharge setting up, in a sort of hysteresis process. The main difference between the two situations is the dynamo requirement, which at the beginning is strong in order to raise the toroidal flux, while it is smaller during the decay phase.

Despite the intermittent behavior, long lasting QSH periods are more probable as plasma current increases. This is shown in Fig. 3, where the QSH persistency is reported as a function of the plasma current for a large number of discharges. The evidence that by increasing the current the plasma more frequently spontaneously accesses QSH states is one of the most important results of the high current regime exploration in RFX-mod.

The helical states spontaneously accessed at high current are of two types: (1) the first type is that where a helical structure is present, but the plasma maintains its axisymmetric magnetic axis. In this case the helical structure is bounded by a magnetic separatrix. (2) The second type are closer to a helical equilibrium, since the dominant *m*=1 mode grows up to the point where its helical axis becomes the main magnetic axis, and the original symmetric magnetic axis ceases to exist. These type 2 helical states are of the same kind of SHAx transiently found during Oscillating Poloidal Current Drive plasmas [Lorenzini 2008], but the important difference is that they appear as a natural outcome of the high current operation, with positive perspectives for the confinement, as discussed later.

As a result of the mode dynamics underlying the two kinds of QSH states, the electron temperature profiles in plasmas with a helical structure display different shapes, which reflect the magnetic topology. In the first type of QSH plasmas there are profiles where a small island located at the mode resonant surface produces a strong temperature peak, which extends throughout the island width (corresponding to approximately 10 – 20 % of the plasma major diameter). To the second category belong more symmetric profiles, where a strong internal electron transport barrier appears. As previously discussed, these profiles correspond to situations where the expulsion of the separatrix by the dominant island leaves a relatively well ordered structure of nested magnetic surfaces, resilient to the influence of surviving secondary modes. In the latter case a more symmetric and wider Te profile appears.

Two sample profiles from the two categories are shown in Fig. 4, which offers also, below each profile, the reconstruction of the corresponding magnetic surfaces in the Poincaré plots resulting from the field line tracing code ORBIT. In panel *d* of the figure, one can notice in green the toroidal magnetic axis that is instead absent in the other case, where the new axis coincides with the O point of the original island [Bonomo 2008].

The discharges, which spontaneously develop helical equilibrium, are those in which the ratio of the dominant to the secondary mode is large enough [Bonomo 2008]. These conditions are favored by high currents, low densities and high electron temperatures, or in other words by high Lundquist number $S = 30 I_\phi Te(0)^{3/2} \big/ z_{eff} \lg\Lambda \sqrt{m_i n_e}$, that is the ratio of resistive to Alfven times. Indeed the normalized amplitude of the dominant mode increases with S and tends to asymptotically saturate, while the amplitude of the secondary or residual modes keeps decreasing as $S^{-0.3}$ [Piovesan 2008]. Interestingly the decay rate of the secondary modes is approximately the same found on several experiments and obtained essentially in regimes dominated by turbulent, i.e. multimode, dynamo [Intravaia 1999, Stoneking 1997, Terranova 2000]. The highest currents regimes, with high S are a favorable environment for the island of the dominant modes to spontaneously expel the separatrix and develop SHAx. This regime is the closest ever achieved to the predicted Single Helicity regime. This finding suggests that at even higher currents, should the secondary modes keep decreasing, this regime should naturally become the standard RFP scenario.The reason why S is a good reference parameter to describe the behavior of the modes and therefore of SH remains to be clarified.

4.1 Confinement and transport at high current

Exploratory high current plasmas at relatively high density (n/n_G = 0.5) display a lower Lundquist number and consistently a lower dominant to residual modes ratio and a lower amplitude of the QSH. When a transition to a multiple mode dynamo occurs confinement degrades by approximately a factor two. This is one of the reasons why RFX-mod high current discharges have been run mainly at low densities, with electron densities normalized to the Greenwald density n/n_G typically below n/n_G= 0.3 A second reason Is rather operational: at high current the input power increases and therefore the requirements for a low recycling wall become more stringent. Finding suitable conditions for high current high density discharges will be matter of future investigations.

In the range of density in which the QSH persists, confinement increases linearly with density for any given current. In order to access high density regimes while maintaining good confinement it is planned to rely mainly on hydrogen pellets, to be injected into high current low density target plasmas, corresponding to a low wall recycling situation, with the specific aim of refueling the core of the QSH and build a peaked density profile. Exercises in that direction have been only preliminary attempted (see below).

Record electron energy confinement times are around 2.5 ms obtained at $n/n_{G=}$ 0.25 in a 1.5 MA discharge with pellet injection. Such result is encouraging as it has been obtained at relatively low density. Ion temperature could not be estimated so that a total energy confinement time is not available.

The electron temperature is seen to increase with current, with no signs of saturation. This is seen in Fig. 5 where Thomson scattering [Alfier 2008] values are plotted as a function of current. At the highest currents, where strong QSH occurs, several Te values come close to 1.2 keV and seem to be slightly higher than the general trend. For those shots n/n_G is comprised between 0.1 and 0.25.

Besides the indubitable interest for the improved transport the question arises whether the volume affected by the ameliorated condition represented by QSH is large enough to have an impact on global confinement. SHAx, in virtue of their broader temperature profiles have confinement times that can be a factor 2 higher than that of a QSH that has developed an island [Piovesan 2008].

4.2 Particle confinement

The effect of QSH on electron density profiles is less evident in absence of a substantial source inside the transport barrier. Experiments with hydrogen pellets and Ni Laser Blow Off have been devised to probe the capability of the ordered magnetic structures to better contain particles. Injecting pellets into the islands turned out to be not a simple task since the ablation is largely enhanced in the region of the temperature gradient, significantly reducing the number of particles that can proceed across the barrier. However preliminary evidences exist of stickiness in the region around the island - with poloidal asymmetries that can be tracked at different toroidal positions with the expected phase change - and also that radial density gradients can hold, at least for a short time, during pellet injection [Carraro 2008]. Ni particle behavior is particularly difficult to deconvolve because Ni confinement time into the discharge is typically longer (40-50 ms) than the average lifetime of a QSH.

Ionization states (Ni XVIII) expected at the temperatures of 0.8-1 KeV that exist inside the island have been observed indicating that Ni has indeed reached the plasma core.

Simulation of particle transport has been carried out by means of the field line tracing code ORBIT [Gobbin 2008] that replicates the magnetic topology of the experiment by superimposing the experimental modes spectrum to the global equilibrium. One interesting finding is that at the low collisionality, typical of the regimes where SH develop, particle transport is not diffusive in the sense that it is different for passing and trapped particles. In particular trapped ions and to a less extent trapped electrons are easily lost from the island. Passing particles instead display a very low diffusivity, which is determined basically by secondary modes. Conversely, particles in the plasma periphery have little probability to cross the transport barrier. This fact highlights the problem of fuelling the QSH region. Globally, SHAx states appear to confine ions better than QSH in which the island retains the separatrix. The estimated diffusivity results to be of the order of 1-3 m/s^2 for the SHAx case against 20 m/s^2 of the latter case. Particle diffusivity results also to be a clear decreasing function of the ratio between dominant and secondary modes, which again suggests that at even higher currents, where this ratio is expected to further increase, and correspondingly flux surfaces should be less perturbed, we should meet conditions of higher particle confinement in the plasma core.

4.3 Transport Barriers and electrostatic instabilities

The study of QSH regimes with large gradients in the electron temperature is now exploring the possibility that in that region the magnetic turbulence is becoming so small that drift modes, of electrostatic nature, may become important. Indeed, normalized gradients R/L_{Te} of the order of 20 to 40, where L_{Te} is the inverse logarithmic gradient of Te, have been found in several cases of QSH. Both gyrokinetic and fluid approaches have been adopted to the study of Ion Temperature Gradient (ITG) modes in RFP plasmas. The result is that these instabilities are in general more stable in a RFP than in a Tokamak, due to the shorter connection length in RFP, but could be excited in the RFX-mod regions where experimentally very high Te gradients are found, namely at the edge of the islands associated to a SH and at the edge of the plasma [Guo 2008]. The results hold on the assumption that ion and electron temperatures have the same normalized gradient $\nabla T/T$. Ion temperature measurements will therefore clarify if the scenario of a RFP region dominated by electrostatic instability is plausible. This would be a change of perspective of the RFP physics, where urgency on healing magnetic turbulence is gradually substituted by the emerging of the electrostatic turbulence, entering a field well known to the Tokamak community. In this sense it is worth mentioning that other tools developed to study drift turbulence in Tokamaks such as TRB [Garbet 2001] and GS2 [Kotschenreuther 1995] are also being adapted to investigate RFP plasmas.

5. **Conclusions**

The panorama of the remarkable progress achieved in RFP research in the recent past is enriched by the experience at high current, up to 1.5 MA, that has been reliably achieved on RFX-mod with the overall optimization of the machine operation, including continuous progress in the active feedback system for the MHD modes control. High current and in particular plasmas featuring high Lundquist number, appear to be the natural condition where an RFP with ohmical helical symmetry (SHAx) can spontaneously develop. In these regimes the temperature assumes wide and relatively symmetric profiles with very steep gradients, reaching values up to 1.2 keV. This is an important step towards the Single Helicity predicted by MHD simulations in which the configuration is sustained in a stationary way by a global and chaos free helical deformation of the plasma. Extensions to include transport modeling are planned; the PIXIE3D code has been implemented to include this physics. In order to improve the current approximation of the SH regime, secondary modes should further decrease. Indeed, we have seen that while the normalized amplitude of the dominant mode shows a tendency to saturate with the Lundquist number S, and therefore with increasing current, the secondary modes keep decreasing. Higher currents should therefore provide the condition where to seek the improvement. This direction would in particular help understanding whether QSH regimes can provide a stationary dynamo as predicted, or will conserve an intermittent nature. In the experiment, in fact, surviving secondary modes give to long lasting periods of QSH a dynamical character and cause quasi periodical crashes of the helical symmetry through non linear interactions. There are also reasons to believe that improvements can be expected from further optimization of the active mode control, where it has been seen that fine tuning of the gains on the dominant mode control have an impact on the QSH persistency [Piovesan 2008].

A new open issue is presently faced concerning the ability to increase the density inside the SHAx region. Particle transport simulations show that it is very unlike that particles from the plasma periphery can reach the region enclosed by the large temperature gradients. Increasing the density by gas puffing or through an enhanced wall recycling is deleterious for the QSH because the secondary modes are more easily excited, most probably due to the increased resistivity in the outer region of the plasma. Future experiments will therefore address the issue of refueling directly the plasma core, in the attempt to reach a situation of relatively peaked density profiles, in particular with low densities at the edge, together with relatively peaked temperature ones, towards a QSH regime as close as possible to the SH equilibrium predicted by the theory.

References

Alfier A, Pasqualotto R 2008 Rev Sci Instrum **78** 013505
Bolzonella T et al *2006 33rd EPS Conf. on Plasma Physics 2006 (Rome) (ECA)* **30I** P-5.087
Bolzonella T et al 2007 *Fusion Engineering and Design* **82** 1064
Bonomo F et al. 2008 *35th EPS Conf. on Plasma Physics, Herssonissos, Crete* P2.054
Brunsell PR, Kuldkepp M, Menmuir S, Cecconello M, Hedqvist A, Yadikin D, Drake J R and Rachlew E, 2006 *Nucl. Fusion* **46** 904
Canton A et al. 2008, *35th EPS Conf. on Plasma Physics*, *Herssonissos, Crete* D1.002
Cappello S, Paccagnella R 1992 *Phys. of Fluids* **B4** 611
Cappello S 2004 *Plasma Phys. Control. Fusion* **46** B313
Carraro L et al. 2008 *35th EPS Conf. on Plasma Physics*, *Herssonissos Crete* p4.019
Escande D, Paccagnella R, Cappello S, Marchetto C, D'Angelo F 2000 *Phys. Rev. Lett.* **85**1662
Garbet X, Bourdelle C, Hoang G T, Maget P, Benkadda S, Beyer P, Figarella C, Voitsekovitch I, Agullo O, Bian N 2001 *Phys. Plasmas* **8** 2793
Gobbin M. et al. 2008 *35th EPS Conf. on Plasma Physics Herssonissos, Crete* P5.035
Guo S.C. 2008 *Phys. Rev. Lett*. Submitted.
Intravaia A et al. 1999 *Phys. Rev. Lett*. **83** 5499
Kotschenreuther M, Rewoldt G, Tang W M 1995 *Comput. Phys. Commun*. **88** 128
Hirano Y, Koguchi H, Yambe K, Sakakita H, and Kiyama S 2006 *Phys of Plasmas* **13** 122511
Igochine V et al *35th EPS Conf., Herssonissos,Crete* paper P2.066
Lorenzini R, Terranova D, Alfier A, Innocente P, Martines E, Pasqualotto R, and Zanca P, *2008 Phys Rev Lett* **101** 025005
Marrelli L, Martin P, Spizzo G, Franz P, Chapman B E, Craig D, Sarff J S, Biewer T M, S C Prager, Reardon J C2002 *Phys.of Plasmas* **9** 2868
Marrelli A et al. 2007 *Plasma Phys. Control. Fusion* **49** B359
Marrelli L et al. 2008 *35th EPS Conf., Herssonissos,Crete* P5.065
Martin P et al 2003 *Nucl Fusion* **43** 1855
Martin P et al. 2007 *Plasma Phys. Control. Fusion* **49** A177
Ortolani S and the RFX Team 2006 *Plasma Phys. Control. Fusion* **48** B371
Paccagnella R, Gregoratto D, Bondeson A 2002 *Nucl. Fusion* **42** 1102
Paccagnella R et al 2006 *Phys. Rev. Lett.* **97** 075001
Paccagnella R,Terranova D, Zanca P 2007 *Nucl. Fus.* **47** 990
Piovesan P et al. 2004 *Phys. Rev. Lett*. **93**, 235001
Piovesan P et al. 2008 *35th EPS Conf. on Plasma Physics, Herssonissos, Crete* O4.029
Sonato P et al. 2003 *et al. Fusion Eng. Des*. **66** 161
Stoneking M.R. et al. 1997 *Phys. Plasmas* **4** 1632
Terranova D ,Bolzonella T,Cappello S,Innocente P ,Marrelli L, Pasqualotto R 2000 *Plasma Phys. Control. Fusion* 843-854
Terranova D, Alfier A, Bonomo F, Franz P, Innocente P, Pasqualotto R 2007 *Phys. Rev. Lett*. **99** 095001
Terranova D et al 2008 *35th EPS Conf. on Plasma Physics Herssonissos, Crete* P4.019
Villone F, Liu Y Q, Paccagnella R, Bolzonella T,Rubinacci G2008 *Phys. Rev. Lett*. **100,** 255005
Wyman M D et al. 2008 *Phys. Plasmas* **15** 010701
Zanca P, Marrelli L, Manduchi G, Marchiori G 2007 *Nucl. Fusion* **47** 1425

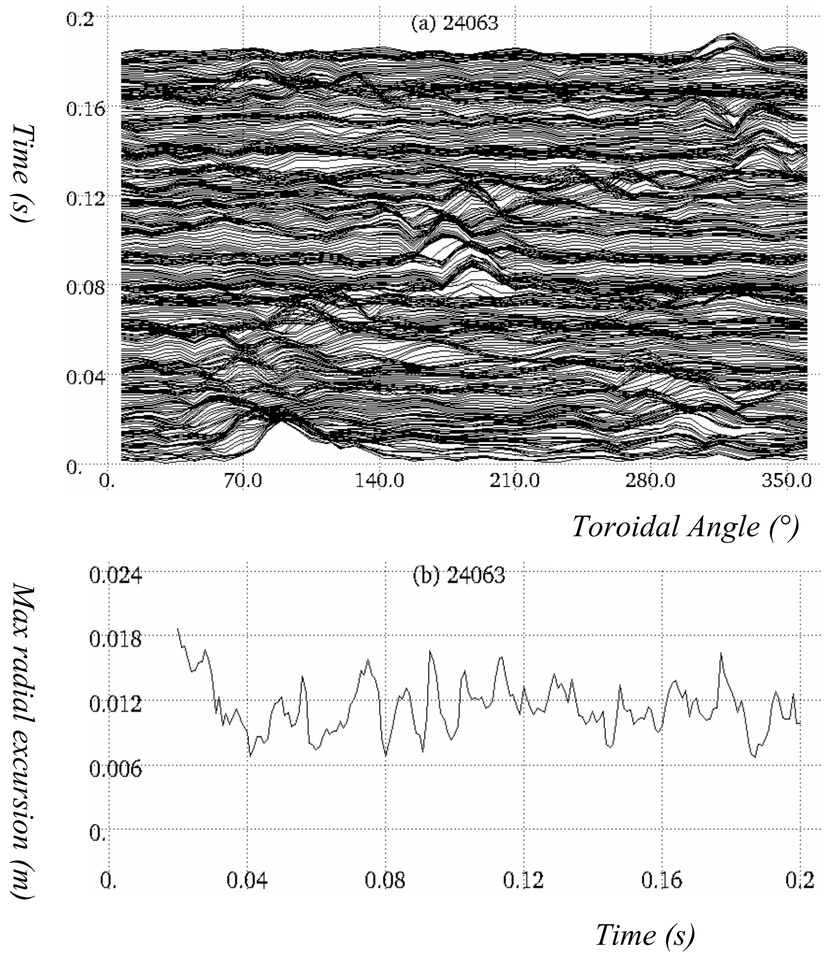

Fig 1.Radial displacement (a.u.) of the last closed magnetic surface due to m=1 modes in shot 24063 as a function of the toroidal angle and of time (vertical direction).

b) Absolute maximum radial displacement (m) of the plasma as a function of time.

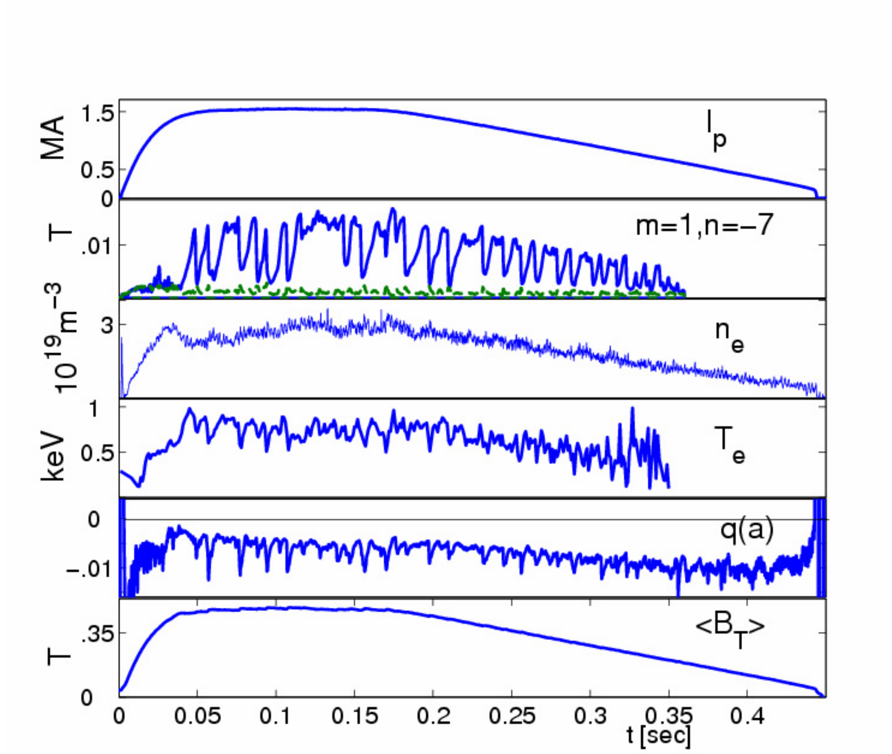

Fig. 2. High current RFX-mod discharge #24063. From top: Plasma current; Amplitude of m=1 n= -7and (dashed line) average amplitude of "secondary" modes m=1 n=- 8/-14; ne (m^{-3}); Te from Double SXR filter; q(a) and finally average toroidal flux.

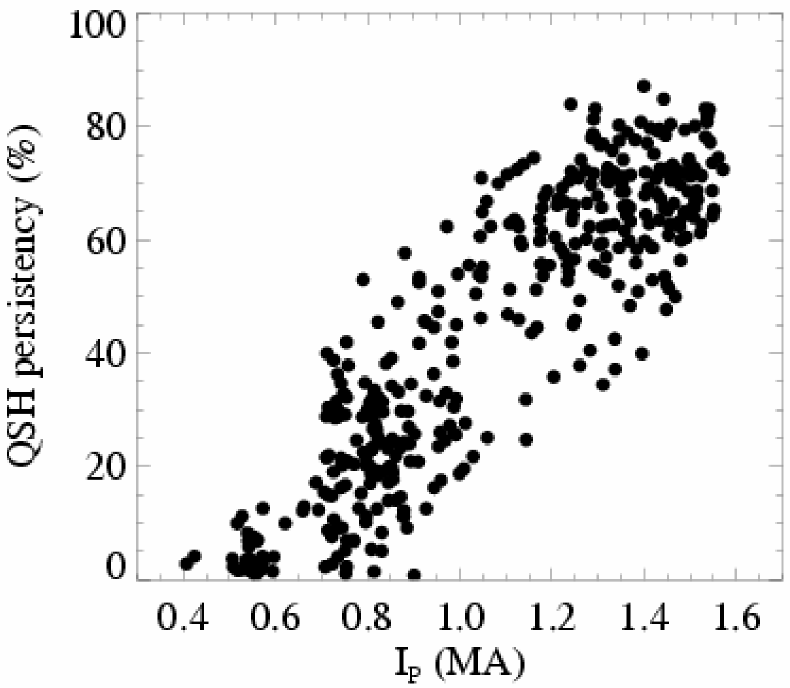

Fig.3. Persistency of the QSH phase as a function of plasma current Percistency is defined as the fraction of the plasma current flat-top featuring a QSH phase. The highest current persistency exceeds 80 %.

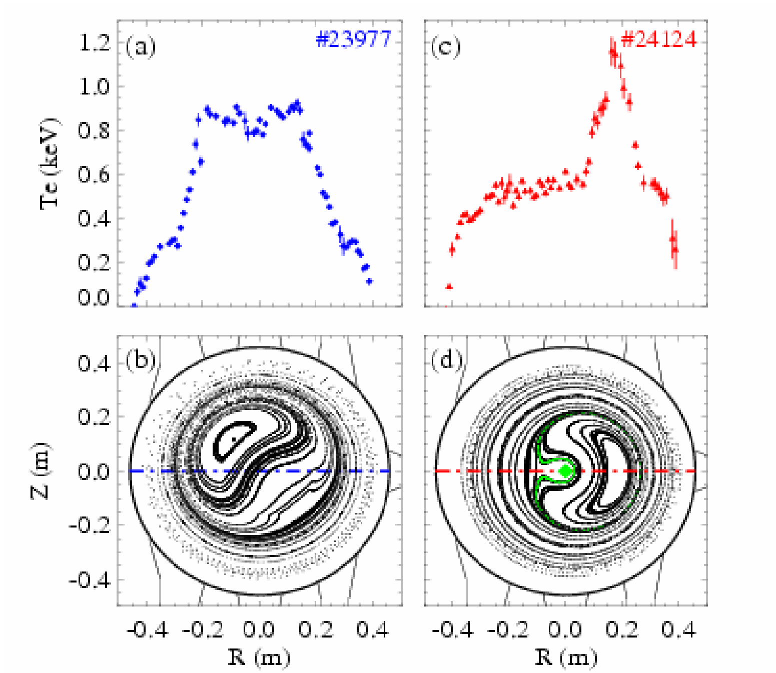

Fig. 4 Electron Temperature profiles from Thomson Scattering diagnostic for (a) a high Te plateau case and (c) a localized Te structure, together with the corresponding Poincaré plots (b) for a SHAx case and (d) for the dominant m=1,n=-7 magnetic mode preserving the island separatrix.

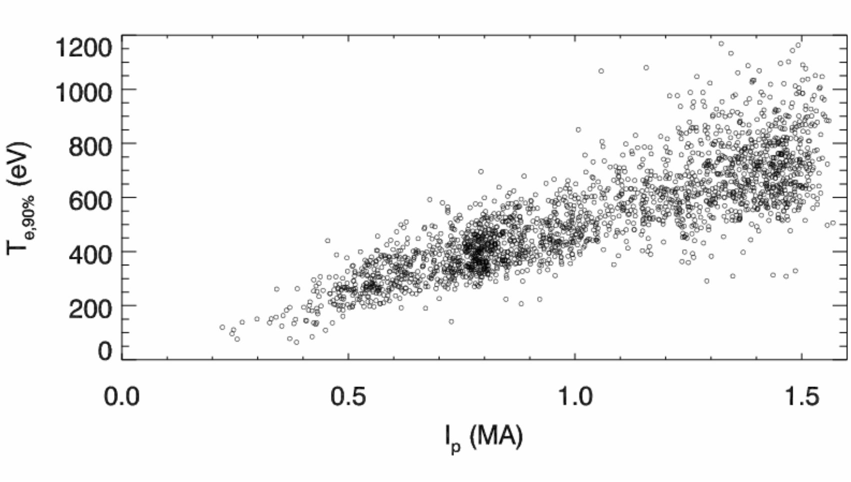

Fig. 5 Electron temperature vs plasma current.