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Abstract
Optimization of machine operation, including plasma position control, density control and especially feedback control on multiple magnetohydrodynamic modes, has led RFX-mod to operate reliably 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 under which

to prove the existence of a true helical equilibrium as the standard RFP configuration.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Research on reversed field pinch (RFP) configurations has experienced substantial progress in recent years (Brunsell *et al* 2006, Hirano *et al* 2006, Marrelli *et al* 2007, Wyman *et al* 2008), 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 the main plasma parameters and of plasma stability has allowed reaching reliably $I_{\mathrm{p}} = 1.5$ MA of plasma current, the highest ever obtained on an 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 a decrease in 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 with 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: sections 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

The two main aspects that since the beginning have made the RFP an appealing configuration and, in principle, an interesting solution as an alternative reactor line are 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 $q(r) = r/aB_{\mathrm{T}}/B_{\mathrm{p}}$ 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 and Paccagnella (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 is attributable 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 (Marrelli *et al* 2002, Martin *et al* 2003, Piovesan *et al* 2004) shows that similar SHs are indeed approached in modern devices, accompanied by a 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-SH. The full experimental realization of SH spectra would require that the amplitude of 'secondary' modes becomes negligible. In (Marrelli *et al* 2007) it was shown that the probability of developing 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 *et al* 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. The 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 *et al* 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 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 *et al* 2003, Ortolani and the RFX Team 2006, Marrelli *et al* 2007, Martin *et al* 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 fueling 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 $n_G = I_p/\pi a^2$ is Greenwald density, with I_p the plasma current and a the minor radius) (Canton *et al* 2008).

Important progress has also been made on the feedback control system (Marrelli *et al* 2008). This is 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 to 2.5 kHz. Also

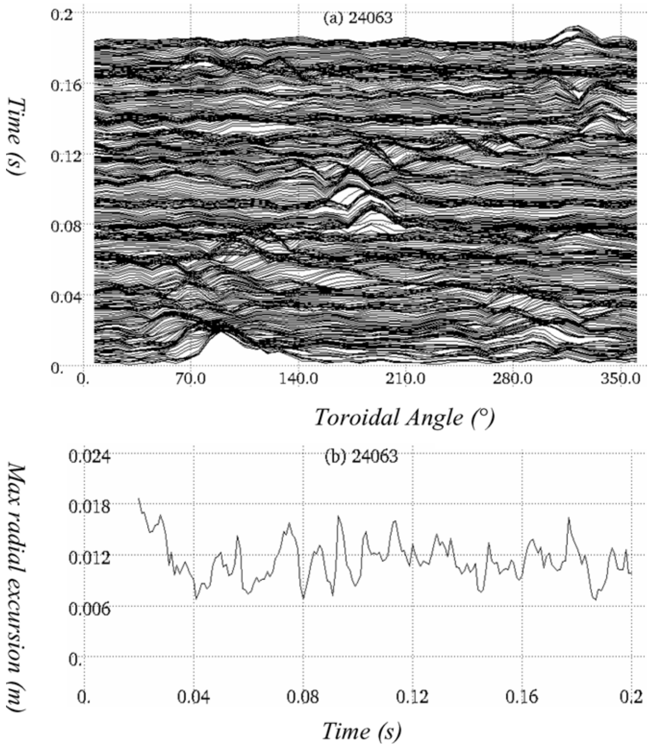

Figure 1. Radial displacement (a.u.) of the last closed magnetic surface due to $m = 1$ modes in shot 24063 as a function of the toroidal angle and of time (vertical direction). (*b*) Absolute maximum radial displacement (m) of the plasma as a function of time.

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 *et al* 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. Figure 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 *et al* 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 (Bolzonella *et al* 2006, Paccagnella *et al* 2006, 2007, Zanca *et al* 2007). The most efficient control scheme is the so-called 'clean mode control' and consists of 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 *et al* 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 *et al* 2002, Zanca *et al* 2007) has been fundamental for an efficient operation. It has also been important to model the entire system,

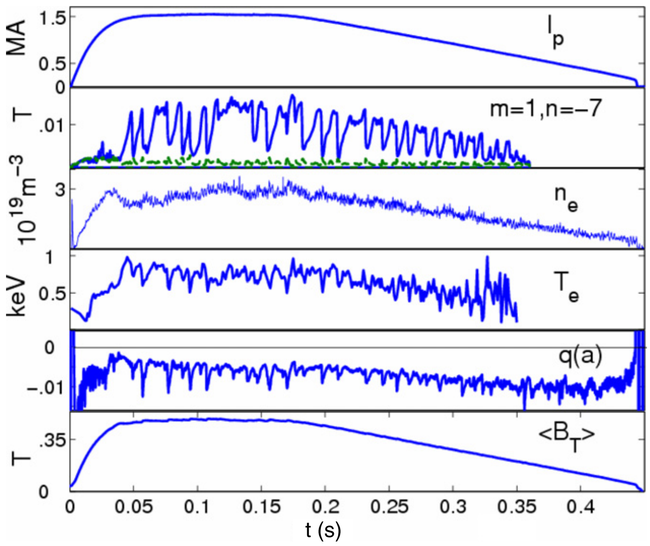

Figure 2. High current RFX-mod discharge #24063. From top: plasma current; amplitude of $m = 1, n = -7$ and (dashed line) average amplitude of 'secondary' modes $m = 1$ $n = -8/-14$; n_e (m^{-3}); T_e from double SXR filter; $q(a)$ and finally average toroidal flux.

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 *et al* 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 in studying the properties (growth rates) of tearing and resistive wall modes (Bolzonella *et al* 2007, Igochine *et al* 2008) and to study their non-linear interaction. Availability of such data has been useful to benchmark ITER relevant codes such as CARMA (Villone *et al* 2008). The system also allows 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 *et al* 2008).

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

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 figure 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

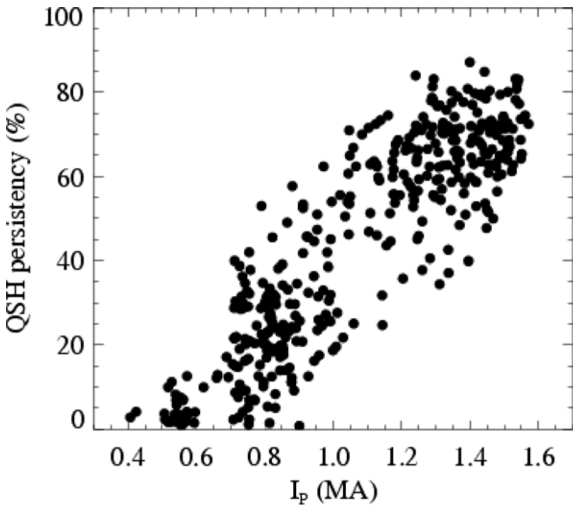

Figure 3. Persistency of the QSH phase as a function of plasma current. Persistency is defined as the fraction of the plasma current flat-top featuring a QSH phase. The highest current persistency exceeds 80%.

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 with the activity of the residual modes. The frequency of the oscillations varies in the shot of figure 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 remains high for tens of milliseconds (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 remains 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 figure 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 is 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 *et al* 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.

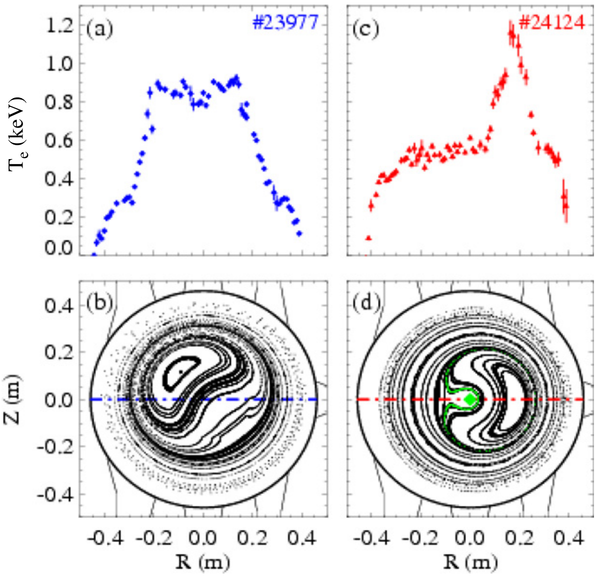

Figure 4. Electron temperature profiles from Thomson scattering diagnostic for (*a*) a high T_e plateau case and (*c*) a localized T_e structure, together with the corresponding Poincaré plots (*b*) for a SHAx case and (*d*) for the dominant $m = 1$, $n = -7$ magnetic mode preserving the island separatrix.

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 T_e profile appears.

Two sample profiles from the two categories are shown in figure 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. One can notice how in panel (*b*) the toroidal magnetic axis clearly visible in panel (*d*) has disappeared: the new helical axis coincides with the O point of the original island (Bonomo *et al* 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 *et al* 2008). These conditions are favoured by high currents, low densities and high electron temperatures, or in other words by high Lundquist number $S = 30 I_\phi T_e(0)^{3/2}/z_{\text{eff}} \lg \Lambda \sqrt{m_i n_e}$, 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 *et al* 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 (Stoneking *et al* 1997, Intravaia *et al* 1999, Terranova *et al* 2000). The highest currents regimes, with high S, are a favourable environment for the island of the dominant modes to spontaneously expel the separatrix and

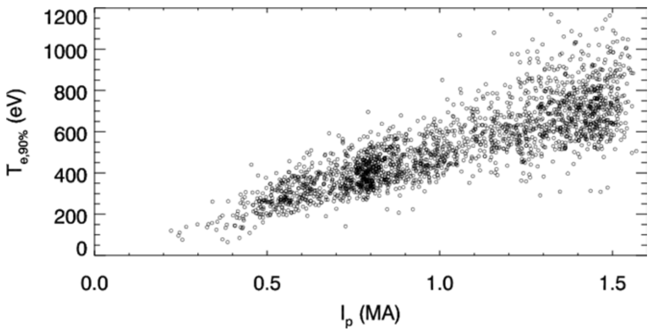

Figure 5. Electron temperature versus plasma current.

develop SHAx. This regime is the closest ever achieved to the predicted SH 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 of 2. 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 a 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 building a peaked density profile. Exercises in that direction have been only preliminarily 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 a 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 figure 5 where Thomson scattering (Alfier and Pasqualotto 2008) values are plotted as a function of current. At the highest currents, where strong QSH occurs, several T_e values come close to 1.2 keV and seem to be slightly higher than the general trend. For those shots n/n_G lies 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 *et al* 2008).

4.2. Particle confinement

The effect of QSH on electron density profiles is less evident in the 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 evidence exists 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 *et al* 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 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 *et al* 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 of crossing the transport barrier. This fact highlights the problem of fueling the QSH region. Globally, SHAx states appear to confine ions better than QSH in which the island retains the separatrix. The estimated diffusivity turns out 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 also turns out 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 electron temperature is now investigating whether in that region the magnetic turbulence is becoming so small that drift modes, of electrostatic nature, may become important. Indeed, normalized gradients R/L_{T_e} of the order of 20 to 40, where L_{T_e} is the inverse logarithmic gradient of T_e, 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 T_e gradients are found, namely, at the edge of the islands associated with a SH and at the edge of the plasma (Guo 2007). 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 an 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 *et al* 2001) and GS2 (Kotschenreuther *et al* 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 SH 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 at which to seek the improvement. This direction would in particular help in 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 has an impact on the QSH persistency (Piovesan *et al* 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 unlikely 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 directly refueling 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.

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