Emergence of the helical ohmic state in the reversed field pinch

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1. *Introduction*

As exemplified by the story of the ZETA machine, which revealed the existence of the RFP state after being shut down, the story of the RFP is a series of strokes of fate and of strokes of luck. The emergence of the helical ohmic state is typical of this story. Indeed, during three decades, the attractive features of the ohmic RFP as a fusion reactor were handicapped by terrible confinement properties: weak confinement resulted from chaotic magnetic field lines and from strong plasma-wall interaction due to a slinky, a toroidally localized large helical deformation of the plasma. This was meant to be intrinsic to the ohmic configuration. The emergence of the *helical ohmic state* broke through this stereotype, but it was initially unnoticed.

Since 1990, MHD numerical simulations had revealed a bifurcation from a toroidally localized to a toroidally uniform helical deformation of the plasma coming with magnetic order. However, this bifurcation was overlooked, even though since 1993, all RFP's had progressively revealed the existence of transient states with an almost regular helical deformation of the plasma, later called *quasi single helicity* (QSH) states. Revisiting the 1990 simulations and extending them with a different perspective was an incentive to scrutinize the RFX data base in 1999. Surprisingly, many shots with long lasting QSH states were found to have been present for quite a time in the data base, but the emergence of these helical ohmic states had been overlooked, because it was out of the traditional paradigm of the configuration.

The RFX data base revealed that increasing the current led to better QSH states, but strong plasma-wall interaction prevented from operating the machine above 1 MA. In December 1999, a stroke of fate, the toroidal power supplies of RFX were destroyed by a fire and the machine had to be shut down for five years. This eventually turned out to be a stroke of luck, since it was the occasion to upgrade RFX into RFX-mod, which provided a good control of the edge radial magnetic field. This control enabled overcoming the previous 1 MA operational bound, and eventually reaching the 2 MA nominal current of the machine. A new stroke of luck, at about 1.5 MA, a topological bifurcation to a *single helical magnetic axis* was found to occur, coming with a broad hot helical central domain bounded by an electron internal transport barrier (eITB). This was a change of paradigm for the ohmic RFP, as was symbolically exhibited by the cover story of the August 2009 issue of Nature Physics: ``Reversed-field pinch gets self-organized" (Lorenzini *et al* 2009b). The possibility of this helical state and of a corresponding improvement in confinement had been already theoretically predicted in 2000. After the discovery of a positive isotopic effect, there is now the emergence of driven helical ohmic states with a hot helical domain covering most of the non reversed region.

The emergence of the helical ohmic states occurred in three stages: a first one where it was almost unnoticed (section 2), a theoretical reinterpretation (section 3), and an experimental stage (section 4). Section 5 is devoted to the corresponding vision of the dynamo, and section 6 to the single helical axis version of these states. Section 7 describes such states when driven, section 8 the confinement properties of the helical ohmic states, section 9 provides further theoretical results, and section 10 concludes.

2. *First stage*

Because of the limited power of computers, the initial MHD numerical simulations of the RFP might have been the occasion to trigger an interest in the helical ohmic states of the RFP. Indeed, some indication of its existence was already present in the first numerical simulation of the RFP (Sykes, A. and Wesson, J. 1977). Furthermore, since 1983, in order to save computer power and memory, numerical simulations had $\beta = 0$, and worked with a forced single helicity (SH): only one ratio m/n for the Fourier harmonics was retained beyond (0,0) (Caramana *et al* 1983) (Aydemir and Barnes 1984) (Holmes *et al* 1985) (Schnack *et al* 1985) (Kusano and Sato 1986). These simulations used an elementary visco-resistive compressible nonlinear MHD model in the constant-pressure, constant-density approximation, whose equations are

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) - \nabla \times (\eta \mathbf{J}), \qquad (1)$$

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} = \mathbf{J} \times \mathbf{B} + \nabla^2 (\nu \mathbf{v}), \qquad (2)$$

where η and ν are the radial distributions of respectively the resistivity and of the kinematic viscosity, and $\mathbf{J} = \nabla \times \mathbf{B}$ and $\nabla \cdot \mathbf{B} = 0$. Here $\mathbf{B}$ is normalized to the value B_0 of the axial magnetic field on axis, time and velocity are normalized to the Alfvén time τ_A and velocity v_A respectively computed with B_0, and the position to the plasma radius a. In these units η is the inverse Lundquist number, $\eta = \tau_A / \tau_R \equiv S^{-1}$, and $\nu = \tau_A / \tau_V \equiv M^{-1}$. The RFP is simulated as a straight periodic cylinder with axial periodicity $2\pi R$. The plasma current and the axial magnetic flux are taken as constant, which implies the constancy of the pinch parameter $\Theta \equiv B_\theta(a) / \langle B_z \rangle$ where the averages are done over the toroidal and poloidal angles. This type of model has been widely used for other RFP simulations (see (Ortolani and Schnack 1993) (Cappello 2004) and references therein). Usually, numerical simulations start from a paramagnetic pinch state with a slightly positive $B_z(a)$. For Θ ‰1.55 the system which is (resistive) kink unstable, relaxes toward a RFP state where the reversal parameter $F \equiv B_z(a) / \langle B_z \rangle$ is in the range $0 > F > -0.5$. From 2008 on, the simulations with the SpeCyl and PIXIE3D codes were performed with a constant loop voltage instead of a constant Θ.

However, the initial numerical 2D SH states were deemed too far from the multiple helicity (MH) experimental ones, and computational physicists took advantage of the increase of the power of computers to deal with the full 3D problem. The parameters of initial numerical simulations led them into the MH state, an unfortunate convergence with the then dominant state of ohmic plasmas. Furthermore, Taylor relaxation was meant as the explanation of the RFP state, and this further prevented RFP physicists from focussing on SH physics. In 1990, 3D numerical simulations revealed a *bifurcation of the magnetic configuration from the MH state to the SH state* when viscosity is increased (Cappello, S. and Paccagnella, R. 1990) (Cappello and Paccagnella 1992) (Finn *et al* 1992) (Cappello and Biskamp 1996).

On the experimental side, since 1993, plasmas with transient QSH states were detected in all large RFP's (Brunsell *et al* 1993) (Nordlund and Mazur 1994) (Hirano *et al* 1997) (Sarff *et al* 1997) (Martini *et al* 1999) (Martin 1999), and found to last for several energy confinement times. However, neither these results, nor the 90-92 simulations triggered more interest in SH.

3. *Theoretical reinterpretation*

The helical ohmic states fully emerged by revisiting the 90-92 simulations. An appropriate rescaling of time and velocity in equations (1-2) shows that, for given radial distributions of η and ν, the dynamics is ruled by the magnetic Prandtl number $P = \nu(0)/\eta(0)$ and by $d = \eta(0)\nu(0)$ the dissipation of the system, also quantified by the Hartmann number $H = d^{-1/2}$, a classical dimensionless number in conductive fluid MHD; however, *dissipation is the dominant parameter* when the inertia term becomes negligible, which happens for a large range of simulation parameters (Cappello and Escande 2000) (Cappello 2004). These simulations reveal that d (or H) is the right control parameter independently of P and Θ .

Therefore, the previous ``high viscosity" simulations turned out to be in reality ``high dissipation" or “small H ” simulations. As usual in nonlinear dynamics, an increase of dissipation (decrease of H) is favourable to a laminar behaviour of the system. Depending on the initial conditions, two nearby different helicities were found to be selected by the plasma when relaxing to SH (Cappello and Escande 2000) (Cappello 2004).

When d decreases, the pure helix develops a toroidally (axially) localized bulging, and longer and longer intermittent slinky phases interrupt this bulged helix, up to the point where it bulges enough to be called a slinky. Concomitantly, secondary modes with other helicities show up in the Fourier spectrum. The bulged helix corresponds to a QSH state where secondary modes are smaller than the original one, and the slinky corresponds to a MH state where at least two modes have similar amplitudes. When d decreases, the duration of the QSH phases decreases, as well as the percentage of time where QSH dominates, and after a transition region corresponding to 10^3 ˆ H ˆ 10^4, the system reaches a non-stationary MH regime (Cappello and Escande 2000). This is shown in figure 1 where the energy of the $m = 0, n \neq 0$ modes is used as an order parameter for the SH-MH transition; indeed these modes vanish in the SH state, since they result from the beating of at least two different helicities. Furthermore, *magnetic chaos sets in progressively during the transition.*

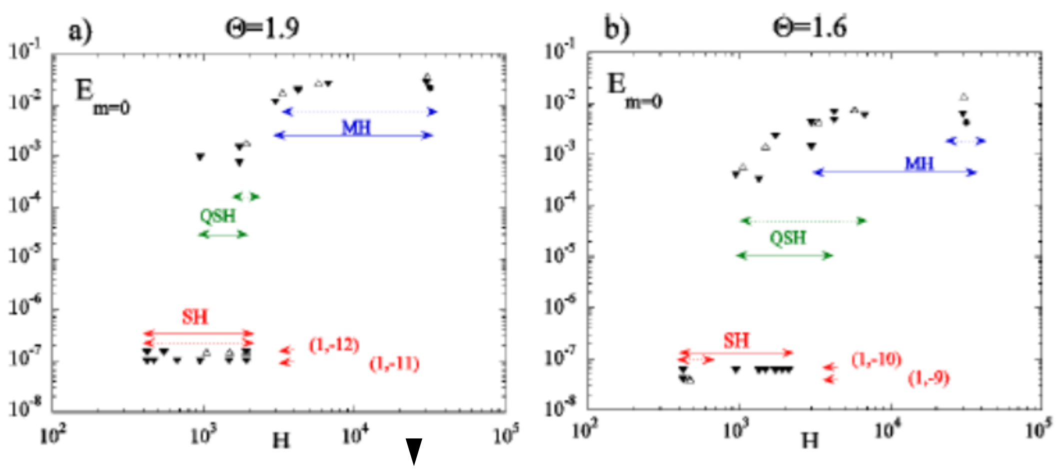

FIG. 1: Transition diagrams at two values of the pinch parameter: a) Θ = 1:9, b) Θ = 1:6. $E_{m=0}$ is the time averaged magnetic energy of the *m* = 0 modes and H is the Hartmann number. The symbol ∆ corresponds to S = 3:3 10^3 with P = [0:012; 50],   to S = 3:0 10^4 with P = [1; 5000], and • to S = 10^5 with P = 10. The vanishing SH *m* = 0 modes energy is represented as a finite conventional value with different offsets associated to the different preferred helicities (reproduced by permission from (Cappello 2004) doi:10.1088/0741-3335/46/12B/027).

4. *Emergence in experiments*

As told in the introduction, the numerical scenario of the transition from MH to SH led to the discovery that shots with long lasting QSH states had been present for quite a time in the RFX data base, and were lasting over the whole flat top at about 1 MA (Escande *et al* 2000b). The dominant magnetic mode had an amplitude 1 to few percents of the central magnetic field, and several times that of the other modes (Martin *et al* 2000) (Escande *et al* 2000b) (Piovesan *et al* 2004) (Martin *et al* 2002). On top of the one found in the reversal region, a strong temperature gradient was found at the edges of a magnetic island with the dominant helicity: an *electron internal transport barrier* (eITB) was found to exist (Alfier *et al* 2008) (Puiatti *et al* 2011); with a *``bean"-like hot structure* corresponding to the magnetic island (Martin *et al* 2000) (Escande *et al* 2000b) (Piovesan *et al* 2004) (Martin *et al* 2003) (Marrelli *et al* 2002) (Franz *et al* 2006). For such states, termed *Double Axis (DAx) states*, the magnetic field displays two magnetic axes: the unperturbed axis-symmetric one and the one related to the island O-point.

After the fire and the upgrade of RFX into RFX-mod, QSH states were rapidly recovered (Paccagnella *et al* 2006). At currents of 0.6 MA or above, and at shallow reversal, QSH states with m=1, n=7 dominate: a QSH persistency up to 85% of the discharge flat top is obtained (Piovesan, P. and al 2008), and the duration and amplitude of the dominant helical mode grows with the plasma current (Marrelli *et al* 2007) (Piovesan *et al* 2009); the ratio of this amplitude to the central magnetic field tends to become a constant (Piovesan, P. and al 2008) (Valisa *et al* 2008) (Piovesan *et al* 2009). The probability of obtaining long-lasting QSH spectra is enhanced when forcing a sudden decrease of the edge toroidal magnetic field (Cravotta *et al* 2003) (Puiatti *et al* 2003).

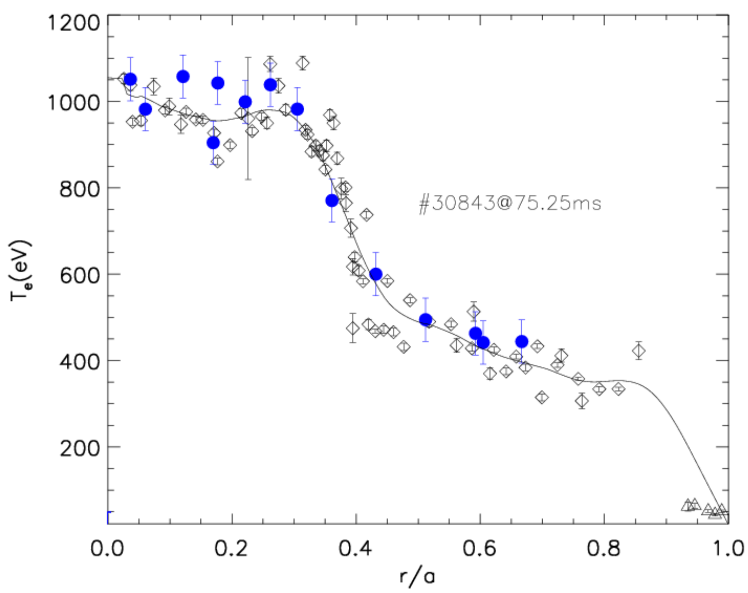

FIG. 2: Temperature distribution in a SHAx state; data from Thomson scattering (diamonds), double filter (blue circles) and thermal helium beam (triangles) diagnostics (Gobbin *et al* 2013)

The RFX results were an incentive to investigate the data bases of other RFP's. The same phenomenology was found to exist in MST (Marrelli *et al* 2002), in TPE-RX (Piovesan *et al* 2004), in EXTRAP T2R (Frassinetti *et al* 2007), and in RELAX (Ikezoe *et al* 2012). In TPE-RX, long-lasting highly reproducible QSH states were obtained by applying a delayed reversal of the toroidal field at the edge (Hirano *et al* 2005), and were systematically triggered by applying a small positive pulse in the initially weakly reversed edge magnetic field (Hirano *et al* 2006). The end of the QSH phase came with a distortion of the m = 0 magnetic island chain, and the occurrence of a chaotic region, expelling energy at the location of the slinky (Frassinetti *et al* 2006). QSH could also be found at low current and deep reversal, but it was more intermittent than in the high current and shallow reversal case (Piovesan *et al* 2004). In RELAX, QSH states lasting above 30 % of the flat-top can be obtained (Oki *et al* 2012). The good features of QSH in RELAX suggest an advantage of a low aspect ratio configuration to reach QSH, as expected from the scarcer density of the central $m = 1$ tearing modes in this case (Oki *et al* 2012) (Oki *et al* 2013).

The results obtained in the various RFPs have common features: QSH is favoured by shallow reversal and the dominant mode resonates near the magnetic axis (Hirano *et al* 2006) (Oki *et al* 2012) (Oki *et al* 2013) (Sarff *et al* 2015). The latter point is in contrast with the outcome of numerical simulations with a vanishing edge radial magnetic field (Cappello and Escande 2000). There is a higher probability to obtain QSH spectra with higher plasma current (Marrelli *et al* 2002) (Bolzonella and Terranova 2002) (Martin *et al* 2003). Therefore, the current plays the role of a bifurcation parameter analogous to dissipation in MHD simulations. Numerical simulations with an edge magnetic perturbation show the scaling with S at fixed P is closer to the experimental trend, which indicates a hidden viscosity effect in the experimental dependence of secondary modes on S (Bonfiglio *et al* 2013).

5. *Ohmic dynamo*

Theoretically, the RFP dynamo is a mere consequence of ohmic magnetic relaxation, and is analogous to the one occurring in the saturated tearing mode: the helical displacement of magnetic surfaces causes a modulation of the parallel current density along each flux tube, which requires the build-up of a helical electrostatic potential producing the dynamo flow as an *electrostatic drift* (Bonfiglio *et al* 2005) (Cappello *et al* 2006) (Cappello *et al* 2011). In the plasma core, the contribution from the loop voltage is larger than that from the mean parallel current density, but it is smaller in the edge. The difference is balanced by the electrostatic term, which provides an anti-dynamo contribution in the core and a genuine dynamo contribution in the edge (see figure 5 of (Cappello *et al* 2006)). It is worth noticing that a recent theory explains the hybrid mode of operation of the tokamak by invoking a dynamo explicitly stated to be analogous to the RFP one (Jardin *et al* 2015). This type of dynamo is also present in a flux rope configuration susceptible to the kink instability (Lapenta and Skender 2017).

As told above, the MH slinky is the result of a continuous deformation of the SH uniform helical shape. This continuity bears on the dynamo as well. Indeed, though a fluctuating inductive electric field be present in the MH state, the velocity field is still dominated by the electrostatic contribution; the velocity field in the SH state is topologically equivalent to the radial pinch velocity field of an axis-symmetric paramagnetic pinch (Bonfiglio *et al* 2005) (Bonfiglio *et al* 2006) (Cappello *et al* 2006). The pinch velocity leads to a build-up of the plasma density on the helical axis in MHD simulations where density is free to evolve (Onofri *et al* 2008). This does not occur in a genuine plasma where the central density profile is flat, which proves the existence of an outward transport mechanism. This build-up was avoided in (Delzanno *et al* 2008) by adding a diffusive term in the continuity equation for the density. The pinch flow present in this case and in the case with constant density can generate an electrostatic instability related to angular momentum conservation for some boundary conditions at the wall; this instability can be stabilized by using homogeneous Dirichlet no-slip boundary conditions (Delzanno *et al* 2008).

The *QSH dynamo* was first *measured* in MST, and showed: (i) the magnetic and velocity fluctuation spectrum to have the same dominant wave number; (ii) the corresponding component of the velocity to extend throughout the plasma volume and to couple with magnetic fluctuations, which produces a significant MHD dynamo electric field; (iii) the radial profile of this component to be consistent with the one obtained in QSH runs of the SpeCyl MHD code (Piovesan *et al* 2004). A similar study was performed in RFX-mod (Bonomo *et al* 2011): a helical plasma flow was observed to form a $m = 1$ convective cell creating a localized sheared flow outside the eITB; however, the experimental pattern revealed the maximum flow shear to be external to the null of the magnetic shear, in contrast with the predictions of 3D MHD simulations; this might be due to an ambipolar component of the helical electric field on top of the MHD one. Even weak external 3D fields can modify significantly the flow profile and in particular its shear (Piovesan *et al* 2011). In RFX-mod, the edge flow displays a QSH modulation (Scarin *et al* 2011). Probes may be used in low current discharges (up to 0.45 MA) of RFX-mod; this enabled to exhibit in forced QSH states a modulation of the perpendicular components of the flow (Vianello *et al* 2015) concomitant with the density modulation along the toroidal angle, first found in (Puiatti *et al* 2013).

The von Karman Sodium experiment exhibited a dynamo in the flow generated inside a cylinder filled with liquid sodium by the rotation of coaxial impellers, when at least one is made of a ferromagnetic material (Monchaux *et al* 2009). It is worth noting that he magnetic field averaged over a long enough time corresponds to a SH RFP magnetic state with a large dominant $m = 0$ mode (see Fig. 7 of (Monchaux *et al* 2009)). The location of reversal is controlled by a copper wall surrounding the turbulent fluid. The reversed field is maximum on this wall, because the azimuthal component of the electric field must vanish there.

6. *Single helical axis states*

On top of the MHD bifurcation leading from MH to SH, there is another one suppressing the magnetic island and making the *magnetic topology kink-like*. Indeed, when the amplitude of the SH mode increases, the island X-point collides with the unperturbed axis of the configuration, which leads to a topology with a single helical axis (SHAx) corresponding to the former island O-point (Escande *et al* 2000c). This occurs because the inner loop of the separatrix becomes tighter and tighter about the former axisymmetric O-point and vanishes when its inner area vanishes. As a consequence of the separatrix disappearance, the helical safety factor profile goes through a maximum located in the vicinity of the former separatrix (Gobbin *et al* 2011a) (Gobbin *et al* 2011b). This maximum corresponds to a minimum of the rotation frequency of the pendulum-like Hamiltonian describing the SH dynamics; when the amplitude of the SH mode increases further after the separatrix disappearance, a stronger and stronger amplitude of secondary modes is required to produce chaos about the maximum of the helical safety factor: there is magnetic chaos healing (Escande *et al* 2000c). As a result, SHAx states are typically more resilient to chaos than DAx ones (Escande *et al* 2000c) (Bonfiglio *et al* 2010) (Cappello *et al* 2011) (Veranda *et al* 2013).

This theoretical scenario turned out to occur in RFX-mod. SHAx states were first triggered by forcing an oscillation of the edge toroidal magnetic field (Lorenzini *et al* 2008): an initial small localized hot island is replaced by a large plateau which is then warmed up (Lorenzini *et al* 2009b) (Bonomo *et al* 2009) (see figure 2). At currents of the order of 1.4 MA or higher, SHAx states occur spontaneously (Lorenzini *et al* 2009a). The thermal content of the plasma increases and magnetic reconstructions display magnetic chaos healing (Lorenzini *et al* 2008) (Lorenzini *et al* 2009a). The helical q profile has a maximum (Terranova *et al* 2010) (Gobbin *et al* 2011a) (Gobbin *et al* 2011b). An eITB occurs in the vicinity of this extremum (Puiatti *et al* 2009) (Gobbin *et al* 2011a) (Gobbin *et al* 2011b), in analogy with tokamak eITB's. The region inside the eITB has a flat temperature profile, and spans a significantly bigger volume than in DAx states (Valisa *et al* 2008) (see figure 3). Plasma properties such as electron temperature, SXR emissivity and electron density are constant on helical magnetic surfaces (Lorenzini *et al* 2009b) reconstructed with independent measurements (see figure 4), indicating that SHAx states have almost invariant magnetic surfaces, in contrast with the low current MH states. As plasma current increases, long-lasting QSH states occur more frequently and their total persistency increases; at currents above 1.5 MA the latter exceeds 90% of the plasma current flat-top (Carraro *et al* 2013). The amplitude of the dominant mode and that of the secondary modes scale in opposite ways with the current; when the dominant mode amplitude, normalized to the edge magnetic field, is larger than about 3-4 %, all QSH states become SHAx states (Lorenzini, R. *et al* 2016). In agreement with the theoretical description (Escande *et al* 2000c), the transition from narrow to wide eITBs occurs above the DAx/SHAx threshold (Lorenzini, R. *et al* 2016).

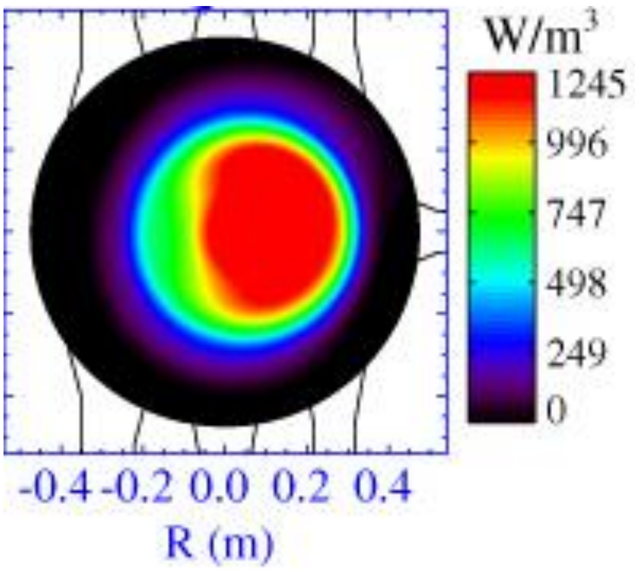

FIG. 3: 2D soft X-ray emissivity map in a SHAx state with a wide hot domain in RFX-mod, shot #23977, t=168ms (Bonomo *et al* 2009)

The best plasma performances at high current in QSH regimes have been reached with shallow reversal ($-0.01 < q_a < 0$, where q_a is the edge safety factor), when the amplitudes of secondary modes is minimum (Carraro et al 2013). As yet, spontaneous SHAx states are observed at plasma densities $n / n_{\mathrm{G}} \leq 0.35$ (with $n_{\mathrm{G}}[10^{20} / \mathrm{m}^3] = I_{\mathrm{p}}\,[\mathrm{MA}]/ \pi a^2$ Greenwald density) (Puiatti et al 2015).

QSH periods end by crashes where the amplitude of secondary modes increases, inducing magnetic reconnection with the formation of poloidal current sheets (Zuin et al 2009). These crashes are spiky: an abrupt increase of the amplitude of secondary modes is immediately followed by an abrupt return to QSH. The strongest crashes lead to MH (Lorenzini et al 2015).

There is a positive isotopic effect on the magnetics of SHAx states: in deuterium, only 55 % of the crashes lead to MH while this fraction is 75% in hydrogen (Lorenzini et al 2015), QSH periods last longer, the secondary mode amplitude is lower by about 20 % with respect to hydrogen (Gobbin et al 2015).

SHAx states were also found in MST, at lower density and higher temperature, and thus similar Lundquist number S despite lower plasma current (about 0.5 MA) than in RFX-mod, but also with shallow toroidal field reversal (Auriemma et al 2011). The dominant n = 5 helical mode grows as large as 8 % of the axisymmetric field; when S increases, the secondary m = 1 modes decrease, which implies reduced magnetic chaos (Sarff et al 2013). A direct measurement of the internal magnetic field structure associated with SHAx states was obtained by using the Faraday Effect (Bergerson et al 2011). The steeper electron temperature gradient, which appears during the QSH state in RELAX suggests the existence of an eITB in this machine too (Sanpei *et al* 2017).

7. Driven helical states

The SH ohmic state can be described analytically as a small helical perturbation of an axis-symmetric ohmic pinch with small edge axial magnetic field and conductivity. This description uses the *pinch-stellarator equation*, which shows how the axial field of a cylindrical SH RFP evolves radially because of the pinch effect and of a stellarator contribution due to the helical deformation of the plasma (Pustovitov, V.D. 1982b) (Pustovitov, V.D. 1982a) (Finn *et al* 1992) (Bonfiglio *et al* 2011). Reversal is due to the edge stellarator contribution, which is more efficient when the edge pinch contribution is weak. The latter condition corresponds to a resistive edge plasma, which contradicts the idea suggested by Taylor theory that edge resistivity prevents reversal. Furthermore, simulations performed with a flat resistivity profile display a reduction of the dynamo action, which brings to marginally-reversed or even non-reversed equilibrium solutions (Bonfiglio, D. *et al* 2006) (Onofri *et al* 2008) (Onofri *et al* 2009) (Onofri *et al* 2010b). This occurs for the following reason: with a larger resistivity at the edge, the electrostatic field is larger too, in order to balance parallel Ohm's law ; then the electrostatic drift due to this larger electrostatic field provides an enhanced dynamo action, which is sufficient to sustain the reversed configuration (Bonfiglio *et al* 2006).

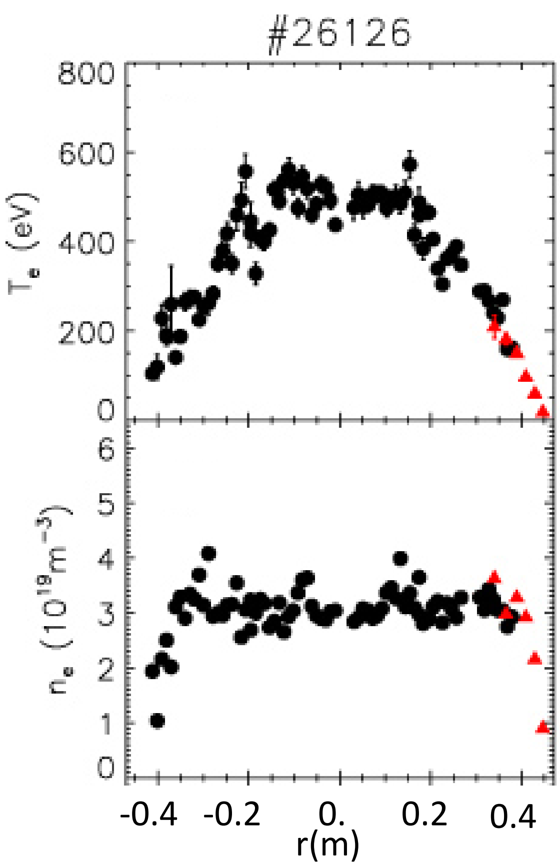

FIG. 4: Temperature and density profiles as a function of the helical flux. Black points: central Thomson scattering, red points: edge Thomson scattering (Alfier *et al* 2010)

The edge resistivity of real RFPs is high enough for the reversed axis-symmetric part of the toroidal field to be rather constant in the reversal domain after a steady decrease in the non reversed one (see Fig. 2 of

(Bodin, H.A.B. 1984)). The pinch-stellarator equation enables the derivation of a necessary criterion for the reversal of the edge axial field (Bonfiglio *et al* 2011). This criterion and MHD simulations show that a finite edge radial magnetic field is favourable for field reversal. The criterion is found to be satisfied in RFX-mod with forced QSH states, but only marginally in spontaneous ones (Bonfiglio *et al* 2011). In RFX-mod, the control of the radial edge magnetic field is unable to force it to vanish (Zanca 2010). The criterion shows this undesired feature to be useful, one more instance where an apparently negative fact turns into a positive one!

Until recently, QSH states obtained in SpeCyl calculations had a temporal behaviour which was very far from the experimental one. However, the former had a vanishing radial magnetic field at the edge, while the latter correspond to a finite one, as just recalled. A temporal behaviour close to that of experimental QSH states was found in numerical simulations performed with a small m = 1, n = 7 resonant magnetic perturbation (RMP) with an amplitude similar to the experimental one (about 1.5 % of the central magnetic field) and with $S = 10^7$ (Bonfiglio *et al* 2013). A more recent work shows that the similarity with experiments bears on several features (Bonfiglio *et al* 2015): (i) the dependence of the temporal behaviour of QSH states on the RMP amplitude, (ii) the dependence of the amplitude of the dominant mode on the same parameter, (iii) and that of the position of shear reversal and maximum q, (iv) the amplitude of the dominant mode is independent of dissipation, whereas the amplitude of secondary modes decreases with increasing resistive and viscous Lundquist numbers. Numerically, a stationary state is reached for a RMP of 10%.

In agreement with numerical simulations, imposing a $m = 1$, $n = 7$ RMP to RFX-mod with shallow reversal, strongly increases the persistence of the helical equilibrium (Piovesan *et al* 2011). However, in hydrogen plasmas the resulting average eITB duration decreases from 2 ms to 1.5 ms, while in deuterium almost stationary eITBs are observed with record values of duration up to 18 ms (Gobbin *et al* 2015). Furthermore, QSH states can be obtained at higher densities ($n / n_{\mathrm{G}} \approx 0.5$) than in the spontaneous case (Piovesan *et al* 2013). An increase of the QSH probability up to 10 % and a larger magnetic island occurred in EXTRAP T2R by applying a resonant magnetic perturbation (RMP) with the corresponding helicity (Frassinetti *et al* 2009b).

As predicted by numerical simulations (Veranda *et al* 2013, 2017), by providing a corresponding helical boundary condition in RFX-mod, it is possible to excite non resonant QSH n = 6 states in RFX-mod (Cappello, S. *et al* 2012), whose best ones have a hot region covering most of the non reversed domain.

8. Confinement properties in the helical ohmic state

In RFX, *DAx states* displayed a magnetic island with high temperature and soft X-ray emissivity (Escande *et al* 2000b). In RFX-mod, at high current (above 1.1 MA), this island comes with steep core gradients, peak electron temperatures exceeding 1 keV, and heat diffusivity inside the island between 6 and 35 m^2/s falling in the tokamak range; the corresponding electron confinement time is higher than in MH states, with a best electron energy confinement time of about 1.3 ms (Alfier *et al* 2008). Simulations of test ion and electron transport show the average diffusion coefficients inside the helical core to be about one order of magnitude lower than those found in MH plasmas (Gobbin *et al* 2007). In TPE-RX, the transition from MH to QSH came with an enhancement of particle confinement of about 30 %, together with strong indications of a higher energy confinement (Frassinetti *et al* 2006). In EXTRAP T2R, the heat diffusivity inside the DAx island is one to two orders of magnitude lower than the diffusivity in the surrounding plasma; this diffusivity is divided by about 3 and the temperature increment inside the island is multiplied by about 4, when the current is doubled (Frassinetti *et al* 2009a).

When DAx states are stimulated by a helical edge toroidal magnetic field, there is a decrease of magnetic chaos involving also the plasma outside the island, and allowing for a global enhanced confinement with an improvement up to 50 % (Terranova *et al* 2007). A similar improvement is found in self-similar current decay experiments, where an initial fast decrease in the mode amplitudes (about 40 % of the initial value) is observed (Zanca 2007).

The remaining of this section deals with the *SHAx state*. In MST, it comes with an improvement of the global energy confinement by about 50 %; a three-fold improvement in confinement is obtained by forcing a slow decay of the plasma current (Sarff *et al* 2013).

We now summarize the *SHAx results in RFX-mod. eITBs* with high electron temperature gradients comparable to those achieved in tokamaks are characterized by an electronic thermal diffusivity lower than $20\mathrm{m}^2/\mathrm{s}$ with values approaching $2\ \mathrm{m}^2/\mathrm{s}$, still higher than neoclassical predictions (under $1\mathrm{m}^2/\mathrm{s}$), but much lower than outside the barrier or in MH states (about $100\mathrm{m}^2/\mathrm{s}$) (Gobbin *et al* 2013). Both the diffusivity and the electron temperature gradient length scale with the total amplitude of the secondary $m = 1$ modes (Puiatti *et al* 2011) (Lorenzini *et al* 2012). So does the inverse of the maximum electron temperature gradient (Carraro *et al* 2013) (Lorenzini *et al* 2012). These scalings indicate a strong link between the level of magnetic chaos and the strength of the barrier. However, this is not the whole story, since the electron temperature gradients are the highest (above keV/m) in the rising phase of the QSH state, and display oscillations during the flat top (Carraro *et al* 2013) (Franz *et al* 2013). The minimum electron diffusivity is the same in DAx and SHAx states (Fassina *et al* 2013).

The *electron energy confinement time* τ_{Ee} increases on average by a factor about 2 in DAx states with respect to MH states. In SHAx states an additional factor about 2 is gained, which leads to an overall gain by a factor about 4 with respect to standard RFP plasmas (Piovesan *et al* 2009) (Martin *et al* 2009) (Puiatti *et al* 2015). Under stationary conditions at $n/n_{\mathrm{G}} < 0.3$, the largest τ_{Ee}'s are around 2 ms (Martin *et al* 2009). If one assumes equal ionic and electronic temperatures, then the global energy confinement time is twice. A three-parameter fit with plasma current, average density and b_{r}, the amplitude of the radial magnetic field of secondary modes measured at the plasma edge, yields a τ_{Ee} scaling like $b_{\mathrm{r}}^{-0.88\pm0.03}$ (Innocente *et al* 2009). This result is an incentive to decrease the amplitude of b_{r} by moving the thin shell closer to the plasma edge, as in the presently proposed modification of the front-end for RFX-mod.

A strong improvement of *particle confinement* in QSH states was predicted by a numerical study of particle transport (Predebon *et al* 2004). This improvement was progressively confirmed, in particular by using pellet injection (Terranova *et al* 2010). Inside the eITB, the particle diffusion coefficient is smaller by a factor of about 2 to 5 with respect to the MH regime, the pinch velocity is outwards, independent of the temperature gradient length, of the order of 10 m/s, and lower than the estimate based upon transport in a chaotic magnetic field; this rules out a dominant chaotic transport inside the eITB (Auriemma, F. *et al* 2012) (Carraro *et al* 2013). The eITB prevents penetration from outside too (Puiatti *et al* 2011). When passing from MH to SHAx, a pellet entering the central hot region triggers an enhancement of τ_{Ee} by a factor 2 to 3, and a higher density with a possibly peaked profile; a record particle confinement time of 12 ms was obtained at 1.5 MA (Terranova *et al* 2010). Particle confinement may be also estimated by an effective diffusivity with a vanishing pinch velocity (Auriemma *et al* 2015): (i) in the core region of the SHAx state, this diffusivity is about $1\ \mathrm{m}^2/\mathrm{s}$ along the central 90 % of the radius, while it is about $50\ \mathrm{m}^2/$

s in MH, (ii) however, transport is still anomalous, since neoclassical diffusivity is about 0.01 to 0.4 m^2/ s, (iii) in the external 10 % of the radius, the edge diffusivity is linked with the presence of pressure coherent structures. The edge temperature gradient scales almost linearly with plasma current, and increases when the secondary modes decrease (Vianello *et al* 2009).

Inside the core region of SHAx states, the *confinement of Ne and Ni impurities* does not increase, which makes unlikely their central accumulation (Carraro *et al* 2009). This was further confirmed in (Menmuir *et al* 2010), which estimated a core diffusivity one order of magnitude higher than at the edge, and an outwardly directed pinch velocity over the whole plasma with a strong maximum around the core/edge transition point of the diffusivity. An external velocity barrier was found to exist also for light impurities (Barbui *et al* 2015).The computation of single particle trajectories exhibits a *different influence of helical states on main gas and impurity transport* (Gobbin *et al* 2007). It also shows that, while passing particles are confined for a very long time, particle trapping dominates transport across the helical structure at the rather low collisionality achieved in QSH regimes of RFX-mod: the neoclassical diffusion coefficient is one order of magnitude larger than the classical one (Gobbin, M. *et al* 2009). When trapped particles drift out of the helical core, at *r/a* about 0.6 they become almost passing without being lost, because the helical distortion decreases when going outwards; this results in an almost total *absence of superbanana particles* at the experimental levels of helical magnetic fields (about 10 % of the total) (Gobbin *et al* 2010). Therefore, transport is proportional to the collision frequency, in contrast with unoptimized stellarators where the lower bound of transport scales inversely with this frequency (Gobbin *et al* 2010). The diffusion coefficients computed by this approach were confirmed by local neoclassical transport computations including the radial electric field; a comparison with power balance estimates shows that residual chaos due to secondary tearing modes and small-scale turbulence still drives anomalous transport in the barrier region. For an ion temperature of 0.7 keV, in the absence of chaos and of impurities, the radial electric ambipolar field near the eITB is about -2kV/m. The toroidal and poloidal flows have a magnitude of about 10-20 km/s and 2-8 km/s respectively, decreasing with lower ion temperature gradients (Gobbin *et al* 2011a).

There is a *positive isotopic effect* on the confinement of SHAx states similar to the one in tokamaks. For plasma currents about 1.5 MA, the energy confinement time scales like $M_i^{0.3}$, where M_i is the ion mass; the particle influx is significantly reduced and the particle confinement time scales like $M_i^{0.45}$; the effect on confinement is mainly due to the mitigation of transport at the edge (Lorenzini *et al* 2015). In deuterium plasmas, the electron temperatures are higher by about 0.2 keV over most of the plasma volume ($r/a < 0.8$); the numerical calculation of particle orbits shows that the loss time in QSH regimes is about 1.3 times higher in deuterium than in hydrogen for both spontaneous and induced helical states (Gobbin *et al* 2015).

Linear gyrokinetic calculations show that *microtearing* (MT) modes are unstable at the eITB; for the strongest eITB's, quasi-linear estimates of the associated transport show MT-driven thermal transport to be comparable to the experimental one (Predebon *et al* 2010b). MT modes were observed in RFX-mod (Zuin *et al* 2013).

The stability of *ion temperature gradient* (ITG) modes was investigated by gyrokinetic calculations. In axisymmetric RFP plasma states, such instabilities are strongly stabilized compared with tokamak plasmas, due to the stronger Landau damping acting in low-q configurations such as the RFP (Predebon *et al* 2010a). However, their stability decreases in SHAx states, because of the enhancement of temperature gradients in the outer part of the helical deformation where magnetic surfaces are close-packed; therefore, ITG turbulence might be an important contributor to the total heat transport (Predebon and Xanthopoulos

2015). The stability of ITG modes might be further decreased in the presence of strongly outwardly peaked impurity profiles (Liu *et al* 2011). However, quasilinear and nonlinear three-species simulations of ITG turbulence prove that the inward impurity flux corresponding to a strong ITG would not be compatible with the measured outward flux (Predebon *et al* 2011).

Gyrokinetic simulations show that at a β of 4.5%, a transition between an ITG and a MT mode is observed through coupling to shear Alfvén waves, and that there is evidence for a collisionless MT mode (Carmody *et al* 2013).

Transport related to self-consistently generated vortical drift motions due to electrostatic turbulence was proposed to interpret the flat temperature profile of the hot region of SHAx states (Sattin *et al* 2011).

When *3D non-axisymmetric magnetic fields* are applied in RFX-mod, at the edge the electrostatic turbulence induced flux is modulated by an induced *m* = 0 magnetic island, with an enhancement close to the O-point and a reduction at the X-point; there transport is due to fluctuations propagating in the electron diamagnetic drift direction, with a spectrum peaked at $k_{\mathrm{perp}}\rho_i \approx 0.1$ (Rea *et al* 2015).

9. *Further theoretical results*

A simple *toy model* makes magnetic field reversal intuitive: it consists in a current-carrying resistive wire initially placed on the axis of a cylindrical flux conserver, whose spontaneous kink leads to the reversal of the edge axial magnetic field, and not to a "disruption" (Escande, D. F. and Bénisti, D. 1997) (Escande *et al* 2000a). This effect is present in a genuine RFP, but most of the current corresponds to the paramagnetic pinch component of the configuration, as discussed in section 7.

When performed in toroidal geometry, 3D nonlinear visco-resistive MHD simulations show that toroidal coupling prevents the system from reaching a pure SH state when dissipation increases, but that magnetic chaos due to toroidal coupling stays limited in the close to SH states for the aspect ratios of the largest present RFP's (Sovinec *et al* 2003). This is confirmed by toroidal simulations with the PIXIE3D code, also showing an m=0 islands chain induced by the toroidal coupling at the q=0 reversal surface (Cappello, S. *et al* 2012). Incompressible 3D nonlinear visco-resistive MHD simulations show that, in contrast with the cylindrical case, the toroidal one presents a double poloidal recirculation cell with a shear localized at the plasma edge (Morales *et al* 2014).

Analytical calculations in (Cappello *et al* 2011) show that (i) the SH state is the same on using single or two-fluid Ohm's law, which backs up a numerical result (section VA of (King *et al* 2011)); (ii) the SH mode amplitude is insensitive to *S*, which backs up experimental (Piovesan *et al* 2009) and numerical results in a two-fluid context (King *et al* 2011). Adding gyroviscosity in the force balance equation enables to get the experimental ratio of secondary to primary modes, while it is twice too large otherwise (King *et al* 2011). More analytical results can be found in the course (Escande, D. F. 2015).

QSH states were obtained in simulations performed with an anisotropic thermal conductivity, and using a multiple-time-scale analysis to this end; the temperature distribution indicates the existence of closed magnetic surfaces, and there is a hot confined region (Onofri *et al* 2010a). When resistivity increases steeply at the edge, SH states are obtained for parameters similar to the case without thermal transport (Onofri 2011) (Onofri and Malara 2013).

The magnetic topology of both SHAx and DAx states of RFX-mod can be reproduced by a one parameter fit of a minimally constrained equilibrium model using only five parameters, and resulting from a two-domain generalization of Taylor's theory. Both states appear as a consequence of the formation of a transport barrier in the plasma core, in agreement with experimental results (Dennis *et al* 2013).

Recently, a new MHD approach was proposed to explain why high current is favourable to SHAx states, why the innermost resonant m = 1 mode is the spontaneous dominant mode, and why there are crashes of this mode. It invokes the shear stabilization associated with the 3D structure of the dominant mode to interrupt the nonlinear mode–mode coupling occurring in the MH regime (Terry and Whelan 2014), and to also suppress magnetic-fluctuation-induced thermal transport, producing temperature-gradient steepening in the strong shear region (McKinney and Terry 2017). This kind of ideas had been first introduced in (Kim and Terry 2012). The crashes can also be interpreted as the consequence of pressure-driven resistive modes, which introduce a feedback between transport and the MHD stability of the system (Paccagnella 2014).

The aspect ratio scaling law for the toroidal mode number of experimental QSH states was shown to be close to the one corresponding to the optimal electromagnetic response of the toroidal shell surrounding the plasma (Paccagnella 2016a). The observed scaling with the aspect ratio and reversal parameter for the dominant mode in the Single Helical states can be obtained (Paccagnella 2016b) by minimizing the distance of the relaxed state described in (Bhattacharjee *et al* 1980) from a state which is constructed as a two region generalization of the Taylor's relaxation model (Tassi *et al* 2008).

MHD simulations show increased magnetic order and reduced transport of magnetic field lines in regimes with the twist of a non-resonant mode, and reveal the existence of Cantori encompassing the region characterized by conserved magnetic surfaces, which act as barriers to transport of magnetic field lines (Veranda *et al* 2017).

10. Conclusion

The above results show that RFP physics moved away from the Taylor-chaotic RFP paradigm (see section 7 of (Cappello *et al* 2008) for more information about this issue). The new paradigm stems from the existence of two bifurcations: that from multiple to (quasi) single helicity, and that from a double to a single helical axis. This new paradigm comes with other good news. First, no poloidal currents need to be driven in the resistive edge of the plasma. Second, the dynamo mechanism is no longer mysterious: it is a mere electrostatic drift due to the helical deformation of the current lines, as occurs for the nonlinear tearing mode.

However several mysteries are still present on top of those listed in the last paragraph of the previous subsection: How far can magnetic chaos recede when increasing the current and when improving magnetic boundary, particle fuelling, and plasma-wall interaction? What are the mechanisms limiting confinement in the eITBs?

MHD numerical simulations have played an important role to introduce relevant concepts, and to suggest experimental investigations. Until now, these simulations have been done with fixed resistivity profiles. However, there is an actual interplay between transport and resistivity through the temperature profile, which should be investigated numerically.

It is worth noting that the above results were obtained by a small community with a budget more than two orders of magnitude smaller than the tokamak one. Since December 2015 is operated the KTX RFP in

Hefei whose size is similar to RFX-mod. This opens the prospect of further studies on the helical ohmic state. So would do the realization of the proposed upgrades of RFX-mod: optimized 2 MA discharges in deuterium and with a forced $n = 6$ dominant mode are an exciting prospect.

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