Quasi-Single-Helicity Reversed-Field-Pinch Plasmas

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The reversed field pinch (RFP) is a configuration for plasma magnetic confinement. It has been traditionally viewed as dominated by a bath of MHD instabilities producing magnetic chaos and high energy transport. We report experimental results which go beyond this view. They show a decrease of magnetic chaos and the formation of a coherent helical structure in the plasma, whose imaging and temperature profile are provided for the first time. These quasi-single-helicity states are observed both transiently and in stationary conditions. The last case is consistent with a theoretically predicted bifurcation. Our results set a new frame for improving confinement in high current nonchaotic RFP's.

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The magnetic confinement of toroidal plasmas for thermonuclear fusion is presently sought in several types of devices. Among these the largest are the stellarator, the tokamak, and the reversed-field pinch (RFP). This order corresponds to systems with increasing self-organization. While in the stellarator the highly nonaxisymmetric configuration can be entirely produced by external windings, in both the tokamak and the RFP the poloidal magnetic field is due to a toroidal current. However, in contrast to the tokamak where the toroidal field is essentially produced by external coils, in the RFP this component is also mainly self-generated by the plasma and has an amplitude similar to the poloidal one [1]. This feature makes the plasma ring prone to magnetohydrodynamic (MHD) instabilities which break the toroidal symmetry of the magnetic field. These instabilities, which can be characterized by poloidal and toroidal mode numbers m and n, are the drive, through a solenoidal effect, of the reversed toroidal field regeneration mechanism. The ratio m/n gives the pitch or helicity of a corresponding perturbation. Until now most of the experimentally studied RFP configurations showed the presence of an MHD turbulence: there is a wide time-fluctuating spectrum of $m = 0$ and $m = 1$ modes in nonlinear interaction. Such a spectrum also induces chaos in magnetic field lines, hereafter referred to as magnetic chaos. This weakens energy confinement and also produces, through mode phase locking [2], a localized bulging of the plasma with strong plasma-wall interactions. This plasma state is dubbed the multiple helicity (MH) state. On the basis of a wide experimental database, this magnetic topology was considered to be intrinsic to the configuration, although some edge magnetic measurements of temporary transitions to a narrow $m = 1$ spectrum have been reported in several RFPs [3–7]. However, from a theoretical point of view [8–11] a single $m = 1$ helicity can be sufficient to drive the poloidal current necessary for the plasma to generate its toroidal magnetic field, and there is a bifurcation to a single pitch state, which provides good magnetic surfaces and a less localized plasma-wall interaction.

In this Letter we report the first experimental results which, by means of a direct tomographic imaging of the plasma and of highly spatially resolved temperature measurements, show the existence of quasi-single-helicity (QSH) states, where a single ($m = 1, n = n_0$) mode is dominating the n spectrum. We show that in these states a coherent helical structure appears in the plasma core. With direct temperature measurements we observe that this helical structure is hotter than the plasma nearby. It acts as an insulating barrier and it has better confinement properties. Finally we report the first experimental results where the QSH state is consistent with a bifurcation: it exists during the whole duration of the plasma. The results presented in this Letter open a path beyond the standard paradigm that a bath of magnetic turbulence is intrinsic to the RFP configuration.

The experiments have been performed in RFX [12], an RFP with minor and major radii, respectively, equal to $a = 0.46$ m and $R = 2$ m. QSH states are obtained either in transient or in stationary conditions. In the first case they last for a few ms, whereas in the second case they last for the entire pulse length. A key measurement is the tomographic imaging of the plasma soft x-ray (SXR) radiation, which was first used for an RFP in the ZT-40M device [13]. SXR isoemissive surfaces can, in fact, be considered representative of magnetic surfaces in the magnetohydrodynamic framework. Figure 1 shows the n spectrum of the $m = 1$ magnetic modes, measured with pickup coils located at the plasma edge, taken in a MH [Fig. 1(a)] and in a QSH [Fig. 1(c)] plasma with similar global parameters and the corresponding images of the SXR emissivity. The emissivity is poloidally symmetric in the MH state [Fig. 1(b)], where it has been shown that

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transport is consistent with a strong magnetic chaos [14]. In contrast, a hotter $m = 1$ island is evident in the QSH case [Fig. 1(d)]: helically symmetric closed magnetic surfaces are generated, which shows that magnetic chaos is lower in this part of the plasma. The location of the island agrees well (within $\approx 20°$) with the poloidal phase angle, reconstructed from magnetic measurements [15], of the dominant $m = 1$ mode (resonant inside the toroidal field reversal surface) at the tomography toroidal location. In the case shown in Fig. 1 the island corresponds to $n = 8$. The presence of the island and the accurate correspondence with a magnetic mode is a clear experimental signature of the QSH. We note that this is not Taylor's helical state [16], which has $ka = 1.25$ and pitch direction corresponding to a mode resonating outside the reversal surface (this corresponds for RFX to $n = -5$, i.e., opposite to that of our measurements).

Transient QSH states are obtained in RFX either spontaneously [7] or as a result of pulsed poloidal current drive (PPCD) experiments [5,17]. A PPCD case is shown in Fig. 2. In both cases a significant plasma heating and improvement of confinement are measured, but the largest increase is observed in the latter case, where the overall level of magnetic fluctuations is reduced. When a magnetic island is present, a state close to pure SH is reached (Fig. 2). The highest of the energy confinement times τ_E of RFX are obtained in this case. An $n = 7$ island is shown in [Fig. 2(a)]: in this case the island grows in amplitude until it becomes the main magnetic and thermal core of the plasma, whose central topology is now helical. Measurements of the electron temperature profile [Fig. 2(b)] with Thomson scattering diagnostic [18] confirm that the island is heated during the QSH phase. The temperature profile is, in fact, asymmetric, with the hotter core region corresponding to the island. It is worth noting that the poloidal locations of the hot island core detected by the SXR tomography and the Thomson diagnostics, which measure at two different toroidal angles, do indeed correspond to the same helical magnetic axis. The difference in the electron temperature gradient between the inner and outer sides of the island [Fig. 2(b)] is consistent with the usual effect of the magnetic field line curvature, since the steeper $T_e(r)$ gradient is present in the good curvature region. All of the above experimental information suggests the schematic reconstruction of the helical structure for a $n = 7$ case shown in Fig. 3. Figure 2(c) shows a growth in the time evolution of the core electron temperature $T_e(0)$ for the same discharge where the profiles of Figs. 2(a) and 2(b) are measured. $T_e(0)$ is obtained from SXR double filter measurements. This indicates that a better thermal insulation has been built up in the plasma core due to the presence of ordered flux surfaces separating the helically symmetric region from the surrounding plasma. A magnetic island hotter than the external plasma can be expected for several reasons: First, there is a stronger heat deposition close to the helical magnetic axis of the island because here the electrical circuit is the shortest. Second, when the island becomes hotter, its resistivity decreases, and it looks like a short circuit in the discharge where dissipation is higher. Third, the magnetic island itself may

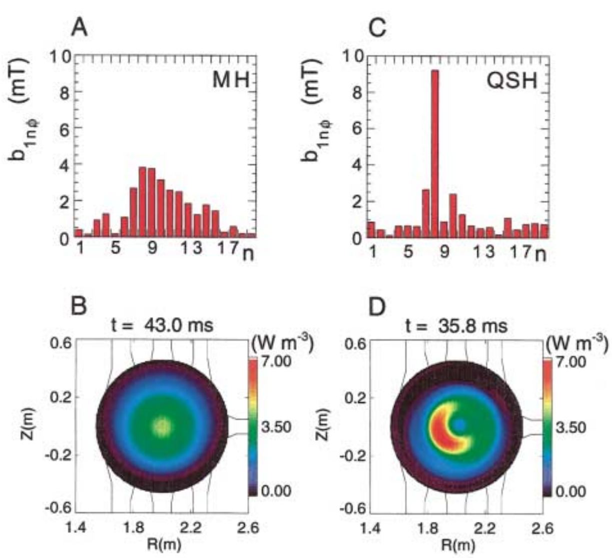

FIG. 1 (color). Comparison between MH and QSH states. (a) n spectrum for $m = 1$ modes and (b) corresponding tomographic SXR images during a MH state (RFX pulse No. 8818, $t = 43$ ms). R is the radial coordinate measured from the torus major axis. (c), (d) The same quantities during a spontaneous QSH state (No. 11407, $t = 35.8$ ms) with dominant mode $n = 8$.

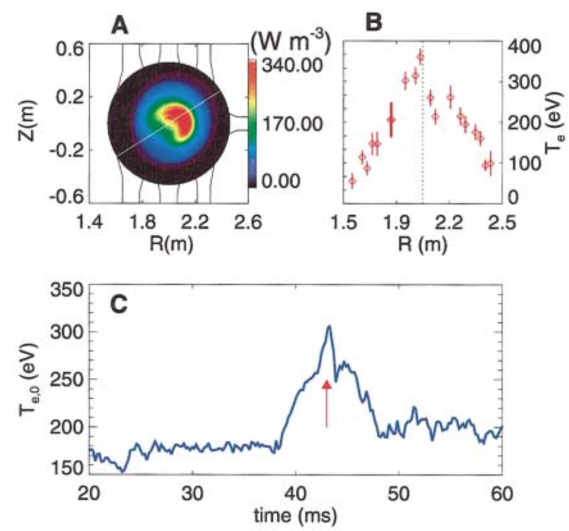

FIG. 2 (color). (a) SXR emissivity profile during a transient QSH state induced by PPCD (No. 11191). The white line indicates the poloidal diameter along which the Thomson scattering (located in a different toroidal position) measures the temperature. (b) $T_e(r)$ profile at the same time. The dotted line indicates the torus minor axis. (c) Time evolution of the core electron temperature $T_e(0)$. The PPCD is active between 0.038 and 0.044 s. Profile measurements [frames (a) and (b)] are taken at $t = 0.043$ s.

FIG. 3 (color). Schematic view of a $n = 7$ helical structure inside the RFX vessel.

be a magnetic well [19], which is a zone of good confinement as it exists in many stellarator configurations. Fourth, an explanation of the observed local confinement improvement in the helical structure could be given in terms of the resilience to chaotic perturbations of a one parameter 1 degree of freedom Hamiltonian dynamics, which is shown to increase when its corresponding separatrix vanishes due to a saddle-node bifurcation. The chaos healing by separatrix disappearance, which is observed in numerical simulations and hinted by SXR tomography measurements, strongly decreases magnetic chaos next to the helical axis [11]. In this case the island helical axis becomes the main magnetic axis of ordered helical flux surfaces. On the contrary, for the MH case the usual small amplitude island width overlapping criterion may be applied [20], corresponding to magnetic chaos.

The n number of the dominant mode in the QSH state can be experimentally controlled by the reversal parameter F, defined as $F = B_\phi(a)/\langle B_\phi \rangle$, where $B_\phi(a)$ is the toroidal field at the wall and $\langle B_\phi \rangle$ is the cross-section averaged toroidal field. This is shown in Fig. 4(a). Moreover, an n dependence is found also for the core temperature T_{e0}: the cases where the $n = 7$ mode becomes dominant show a stronger improvement in temperature when compared to the cases where $n = 8$ is dominant. The core electron temperature vs n is shown in Fig. 4(b).

A further important step in the search for laminar RFP states is the observation of stationary QSH states, which have been obtained in a wide range of plasma current, from $\approx$0.6 MA to $\approx$1 MA. This corresponds to the present operational range of RFX. As shown in Fig. 5, in these conditions one mode is permanently dominant in the $m = 1$ n spectrum. A core helical plasma is obtained, as displayed by the two instantaneous emissivity patterns in Fig. 5. The observation of stationary QSH is important since it goes in the direction of the theoretically expected bifurcation [8–10]. Indeed, this bifurcation means that stationary QSH are possible.

Finally, Fig. 6 shows the effect on the magnetic equilibrium of a broad and of a narrow n spectrum. Figures 6(a) and 6(b) report the vertical displacement of the plasma column, Δ_v, for a MH and a QSH plasma, respectively. In the MH case, because of the mode phase locking [2], Δ_v is toroidally localized and it reaches a peak-to-peak amplitude $\approx$10% of the minor radius a. In the QSH state Δ_v is $\approx$4% of a and close to be periodic with a $2\pi/8$ period ($n = 8$ is the dominant $m = 1$ mode in this case), which gives a less localized plasma-wall interaction.

The necessary conditions for the *ab initio* onset of QSH states are not yet well established. However, a combination of plasma parameters, such as low impurity level, relatively low initial density, and low magnetic error field seems to be important in this respect. Furthermore, as shown in Fig. 4(a), a shallow toroidal field reversal (low pinch parameter) favors the onset of lower n higher amplitude helical modes resonant in the central plasma region.

The confinement parameters of these stationary QSH states are usually in the high range of those so far obtained in standard MH stationary conditions in RFX, although the maximum values found in transient QSH conditions have not yet been reached. Indeed, magnetic chaos is probably not reduced outside the hot helical domain, since the nondominant modes are not strongly decreased as in the best PPCD shots. The origin of this and its possible cure are presently sought in two directions: (i) the shell in RFX has gaps which prevent the flow of the helical boundary

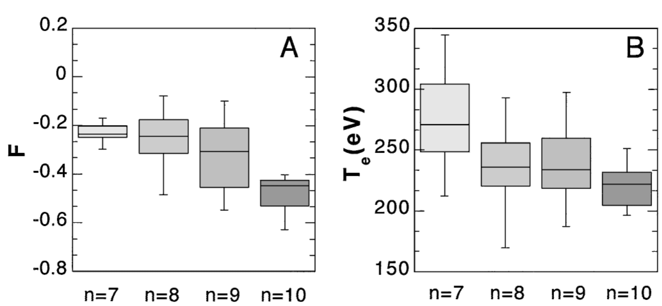

FIG. 4. Distributions of the values of (a) reversal parameter F and (b) of the core electron temperature $T_e(0)$ for four categories of QSH plasmas, with dominant mode ranging from 7 to 10. In both figures each box encloses 50% of the data of one category with the median value displayed with a line. The lines outside the boxes indicate the maximum and minimum value for each category.

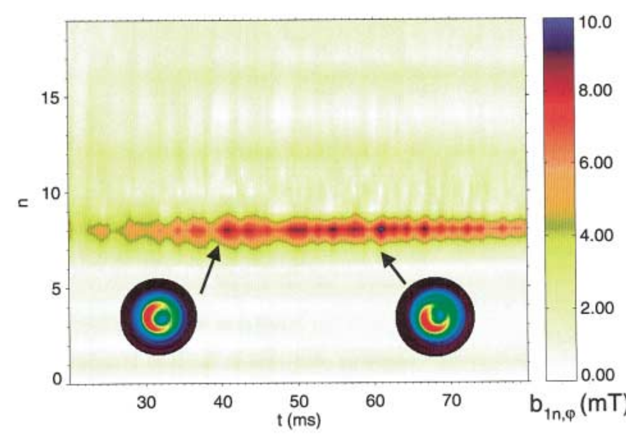

FIG. 5 (color). $m = 1$ modes n-spectrum vs time and SXR emissivity patterns at selected times ($t = 40$ ms and $t = 60$ ms) in a plasma (No. 11336) where the QSH state is permanent. The dominant mode in this case is $n = 8$.

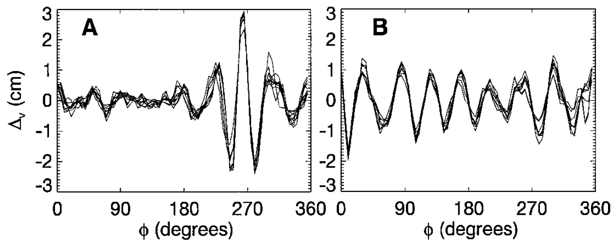

FIG. 6. Vertical displacement Δ_ν of the plasma column as a function of the toroidal angle ϕ (a) for a MH plasma (shot 9442) and (b) for a QSH plasma (shot 11336). Various curves taken at equally spaced times in the time lags [0.05–0.09] s for frame (a) and (0.05–0.08) s for frame (b) are shown.

currents present in theoretical models; these gaps act like an ergodic divertor exciting internal resonant modes. Accurate field error correction is therefore important, and/or helical windings could be desirable. (ii) Numerical simulations [11,21] show that the bifurcation process is ruled by a unique parameter, i.e., the ratio P/S^2 between the Prandtl number P and the Lundquist number S. P is defined as $P = \tau_R/\tau_\nu$, where $\tau_R = \mu_0\lambda_R^2/\eta_R$ and $\tau_\nu = \lambda_\nu^2/\nu$ are the resistive and viscous diffusion times, respectively. S is defined as $S = \tau_R/\tau_A$, where τ_A is the Alfvén transit time. The kinematic viscosity ν is equal to the plasma viscosity η divided by the mass density, η_R is the electrical resistivity, λ_R and λ_ν the scale lengths for resistive and viscous dissipation, respectively. P/S^2 has been chosen in agreement with viscoresistive MHD calculations and theories [22–24] and is proportional to the product of viscosity by resistivity. Numerical SH states are obtained when P/S^2 exceeds a threshold value, which indicates that a higher dissipation acts in the RFP, as in other dynamical systems, so as to decrease the number of degrees of freedom in the plasma dynamics [25]. Increasing this parameter should be looked for, but to do this in a controlled way the difficult problem of the definition and of the measurement of viscosity in fusion plasmas has to be overcome. The experimental demonstration of *ab initio* permanent QSH states in RFX suggests that a wide spectrum of magnetic MHD modes is not necessary to sustain the RFP profile, and it makes more likely the existence of the theoretically predicted pure single helicity states with good helical flux surfaces [9,11].

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