Single-Helical-Axis States in Reversed-Field-Pinch Plasmas

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The transition to a new magnetic topology, characterized by a quasi-single-helicity state with a single helical magnetic axis has been experimentally observed for the first time in a reversed-field-pinch plasma. The occurrence of the new state, which has been dubbed a single-helical-axis state, was found to provide magnetic chaos healing and enhanced thermal content of the plasma. The helical structure extends on both sides of the vessel geometric axis, and is related to exceeding a threshold in the ratio between the amplitude of the dominant MHD mode and the amplitude of the secondary ones.

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The reversed field pinch (RFP) is a toroidal configuration for the magnetic confinement of fusion-relevant plasmas [1,2]. Its main difference from the tokamak is the much larger toroidal current for a given toroidal magnetic field. This brings some very attractive features. One of them is that it may be possible to achieve reactor-relevant conditions using Ohmic heating only, without the need of large, expensive and relatively inefficient additional heating systems. Another one is that a large fraction of the toroidal magnetic field is produced by currents flowing in the plasma itself, and not in the external coils; thus, a major technological limit of the tokamak does not apply to the RFP. On the other hand, since it produces much of its magnetic field by internal currents, the RFP is by a large extent a self-organizing system. In particular, the poloidal current giving rise to the toroidal field is not driven by an external electric field, which is not present in stationary conditions. Rather, it is generated by the plasma through a nonlinear MHD mechanism dubbed dynamo [3,4].

In conventional RFP plasmas, many kink-tearing MHD modes with poloidal periodicity $m = 1$ and toroidal periodicity $n \gtrsim 2R/a$ (R and a are the major and minor radii of the torus) are simultaneously present and nonlinearly interacting. Their magnetic field and velocity patterns give rise to an effective electric field in the Ohm's law, which is responsible for the dynamo effect. This phenomenon may happen intermittently, in so-called relaxation events, or in a more steady fashion, with the modes having a more or less constant saturated amplitude. This situation is called multiple helicity (MH) state [3]. MH states are plagued by a high level of magnetic chaos in the plasma core, since the magnetic islands generated by the different modes superpose, destroying well conserved magnetic surfaces over a large part of plasma domain. Thus, the energy confinement properties of RFP plasmas in MH states are relatively poor, with only the outer plasma layer being able to sustain temperature gradients. This is the reason why, at the moment, the RFP is not regarded as a real alternative to the tokamak for building a fusion reactor, despite the attractive features outlined above. However, MH states are not the only condition in which a RFP plasma can exist. A great deal of theoretical work has been devoted in recent years to investigate the possibility of achieving a single helicity (SH) RFP state, i.e., one where only one helical MHD mode is present and drives the dynamo. Such a state would not show any magnetic field stochasticity, and its confinement properties are therefore expected to be greatly improved with respect to MH states, up to levels similar to those of tokamak plasmas.

An important result which has been achieved is that SH RFP plasmas are found to indeed occur in 3D MHD simulations [5]. For appropriate plasma conditions, the simulations display a spontaneous transition from MH to SH state, which then lasts indefinitely.

Depending on the amplitude of the dominant mode two different types of SH states exist: for amplitudes below a certain threshold [6], the resonant magnetic surface of the mode is torn into a magnetic island centered around a secondary magnetic axis (O point), while the main magnetic axis is still present and eventually shifted by a certain amount. Poloidally symmetric to the island O point is an X point, which is related to the island separatrix. Beyond the threshold [6], on the other hand, a different magnetic topology appears: the main magnetic axis, the island X point and the related separatrix disappear, and a single, helically distorted, magnetic axis (the former O point of the island) remains.

One can describe this as the transition from an axisymmetric equilibrium with an added perturbation to a new single-helical-axis (SHAx) state. This transition occurs when the O point collides with the X point and an inverse saddle-node bifurcation suppresses the separatrix related to the magnetic island. Crucially, it has been shown that, in case the secondary modes retain a nonvanishing amplitude, the SHAx state is much more resilient to the chaos that they induce than the state where the separatrix is still present [6]. This result, which has been illustrated for the magnetic chaos in QSH states of the RFP, is of general interest in Hamiltonian dynamics.

In this Letter we describe the first experimental observation of the transition towards a SHAx state in a RFP plasma. Up to now, only states with a dominant mode and a

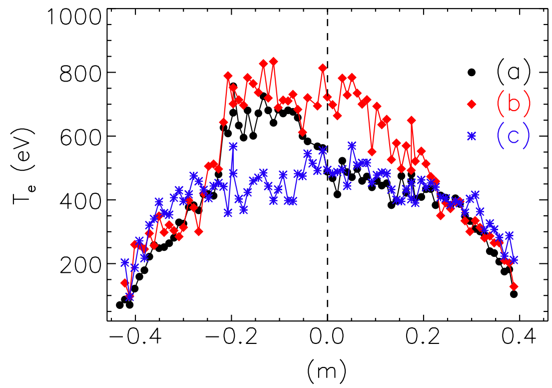

FIG. 1 (color online). Electron temperature profiles for a QSH_i state (a), for the new class of temperature profiles (b) and for a MH state (c), all obtained during OPCD operation.

non-negligible amplitude of the secondary modes have been observed experimentally [7]. Such conditions have been generally dubbed as quasisingle helicity (QSH), to distinguish them from true SH states, since they may be characterized by a still high level of magnetic chaos [8]. In the RFX-mod [9] reversed-field-pinch device ($R = 2$ m, $a = 0.459$ m), QSH states lasting tens of milliseconds have been frequently observed in standard discharges with $I_p \sim 1$ MA [10]. Furthermore, QSH states are routinely induced by the application of the oscillating poloidal current drive (OPCD) [11]. The OPCD technique [12] relies on modulating the toroidal flux, as a periodic application of the pulsed poloidal current drive (PPCD) [13].

The occurrence of a magnetic island in QSH states gives rise to a thermal structure coincident with it, which has been thoroughly characterized in the past [10]. An example of Thomson scattering data [14] from a QSH state with island (hereafter referred as QSH_i state) obtained during a OPCD campaign at a plasma current of 1 MA is shown in Fig. 1. It can be seen that the island appears as a thermal structure in the nearly flat temperature level of the stochastic plasma core which characterizes MH states; an example of MH profile measured during OPCD operation is also shown in Fig. 1. The width of the thermal structure, defined as the width of the flat high temperature region, reaches at most 30% of the radius and is always located off axis.

A new class of temperature profiles has been recently observed in RFX-mod [15]. These profiles, an example of which is shown in Fig. 1, were obtained in 1 MA discharges with OPCD. The new profiles are characterized by a temperature structure, superposed to the MH background, which is much larger than the usual islands (more than 50% of the minor radius), and extends to both sides of the geometric axis. In the transition to the new class of profiles the plasma density does not change appreciably, so that the thermal structure enlargement corresponds to an increase in the thermal energy content of the plasma.

In order to interpret the new condition in terms of magnetic topology, the field-line tracing code FLIT [16] has been used. The peculiarity of this code is that it uses mode eigenfunctions computed, in toroidal geometry, according to Newcomb equation supplemented with boundary conditions derived from Mirnov coil measurements [17]. This representation of nonaxysimmetric magnetic field perturbations has been proved to be very reliable by means of the comparison between the reconstruction of the last closed flux surface and the experimental data [18,19].

Figures 2(a) and 2(b) display Poincaré plots in the same poloidal plane where the temperature profiles reported in Fig. 1 have been measured. The plots have been made using eigenfunctions computed from the boundary conditions measured at the same time when the Thomson scattering system was measuring; the line of sight of the Thomson scattering coincides with the horizontal diameter. In these plots only the $m = 1$, $n = -7$ mode has been added to the axisymmetric fields. This mode, which is the innermost resonant one, becomes the dominant one in the QSH states. The comparison between the two Poincaré plots shows that the development of the wide temperature structure is related to the transition to a SHAx state, where a single helical magnetic axis is present. In fact it can be clearly seen that in Fig. 2(a) the $m = 1/n = -7$ island displaces the main magnetic axis, which, however, retains its identity together with the separatrix (the thick line in red), while in Fig. 2(b) a single helical magnetic axis is present.

The relationship between the occurrence of a large thermal structure and the observation of SHAx states on the Poincaré plot including only the dominant mode is

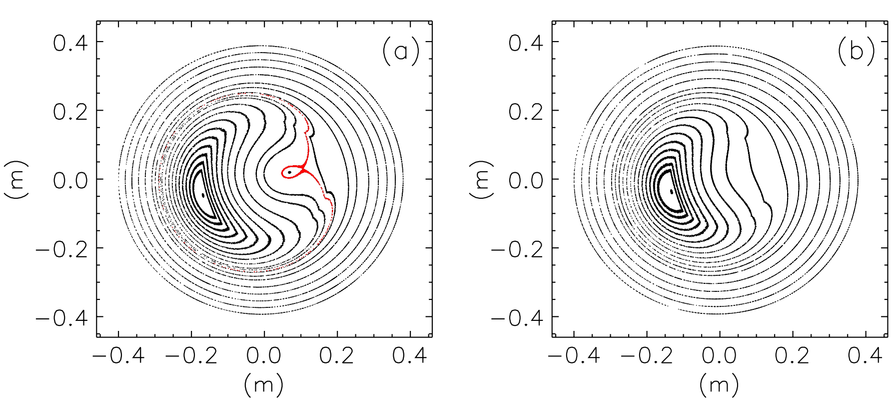

FIG. 2 (color online). Poloidal section of the magnetic surfaces calculated adding to the axysimmetric field the contribution of the $m = 1$, $n = -7$ mode, for the QSH_i temperature profile (a) and for the new profile (b) shown in Fig. 1.

rather robust. In fact, the analysis of a set of 7 discharges comprising 10 time instants at which the Thomson scattering was measuring a temperature profile of the type shown in Fig. 1(b) has shown that in all the cases this corresponds to a SHAx state. On the other hand, whenever an island is observed in the temperature profile this corresponds to a state with two magnetic axes and a separatrix (about 20 cases in this study). It is worth to remark that the uncertainty in the classification of SHAx states based on the Poincaré plots is rather small, since it is determined by the uncertainty on the dominant mode eigenfunction measured at the plasma boundary. This is estimated to be around 1%. As the transition from QSH_i to SHAx takes place at a well defined value of the dominant mode, uncertainty in the classification occurs only within 1% from this threshold. Therefore, the classification of the discharges under study is unaffected by this uncertainty, as can be clearly seen from the amplitudes which will be displayed in Fig. 3.

Having established a strong correlation between the occurrence of SHAx states and the measurement of a large thermal structure in the plasma, the relationship between the states and the mode amplitudes has been investigated. Figures 3(a)–3(c) show the amplitude of the dominant mode, the square root of the sum of the squared amplitudes of the secondary modes, and the ratio of the two, all normalized to the edge mean poloidal field, for the MH, QSH_i and SHAx states of the OPCD campaign. The amplitude of each mode pertains to the radial field component and is computed at its resonant surface, using the reconstruction based on Newcomb's equation. It can be observed that moving from MH to QSH_i to SHAx the amplitude of the dominant mode increases and the total amplitude of the secondary ones is reduced. It is worth mentioning that some indication of the occurrence of states with a single helical axis had been deduced in RFX from soft x-ray tomographic reconstructions during PPCD operation [20] although no correlation with an increase in the dominant mode amplitude could be established. A closer inspection of Fig. 3(b) reveals that the sets of the secondary mode amplitude in QSH_i and in SHAx states are partially overlapping. This shows that it is actually the amplitude of the dominant mode which plays the major role in the transition from one type of state to the other, as expected since the island amplitude and the separatrix expulsion are ruled by the dominant mode amplitude. Indeed, a good indicator seems to be the ratio of the two amplitudes, shown in Fig. 3(c), since the two sets appear to be fully disjoint in this case. Similar conclusions can be drawn also by looking at the mode amplitudes measured at the edge on the toroidal field component, shown in Figs. 3(d)–3(f), that is on the raw data which constitute the boundary condition for the Newcomb's equation solver. This rules out the possibility of artifacts introduced by the solver.

The transition to SHAx states is actually found to mark a discontinuity in the extension of the thermal structure. This is clearly shown in Fig. 4, where the width of the structure is plotted as a function of the dominant mode toroidal field

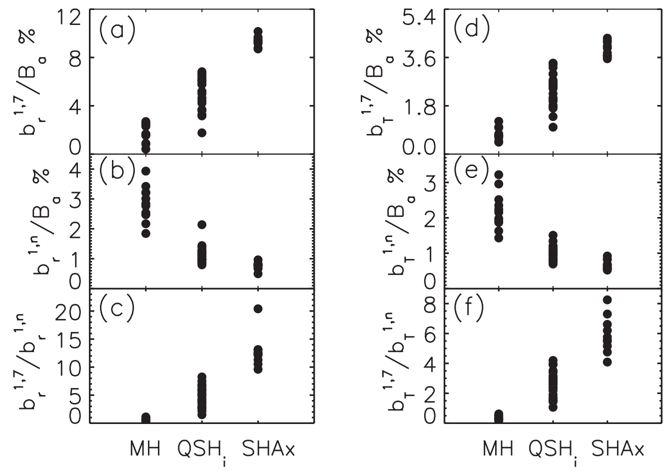

FIG. 3. Normalized radial field amplitude of the dominant mode (a) and of the secondary ones (b) at the resonances, and ratio between the two (c), in the MH, QSH_i, and SHAx states. Normalized toroidal field amplitude of the dominant mode (e) and of the secondary ones measured at the edge (f), and the ratio between the two (g) at the same times than graphs (a),(b), and (c).

normalized amplitude at the plasma boundary, with open symbols representing QSH_i states and dark symbols representing SHAx states. It is seen that at the transition from one state to the other, which takes place for $b_r^{1,7}/B(a) =$ 3.5%, the width of the thermal structure is increased by more than 10 cm. This corresponds to the fact that the disappearance of the X point allows the extension of the structure beyond the geometrical axis of the vacuum chamber.

Up to this point, the occurrence of SHAx states and its correlation with enhanced temperature profiles has been studied using Poincaré plots including the dominant mode only. However, secondary modes still have a non-negligible amplitude also in SHAx states (so that it is not yet possible to speak about a real SH). Although the SHAx state is more resilient to chaos [6], nevertheless some

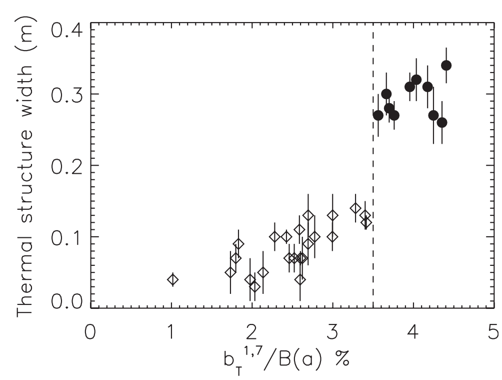

FIG. 4. Width of the thermal structure plotted as a function of the dominant mode amplitude at the plasma boundary, normalized to the average poloidal field. The open symbols correspond to QSH_i states and the dark ones correspond to SHAx states, as identified from Poincaré plots

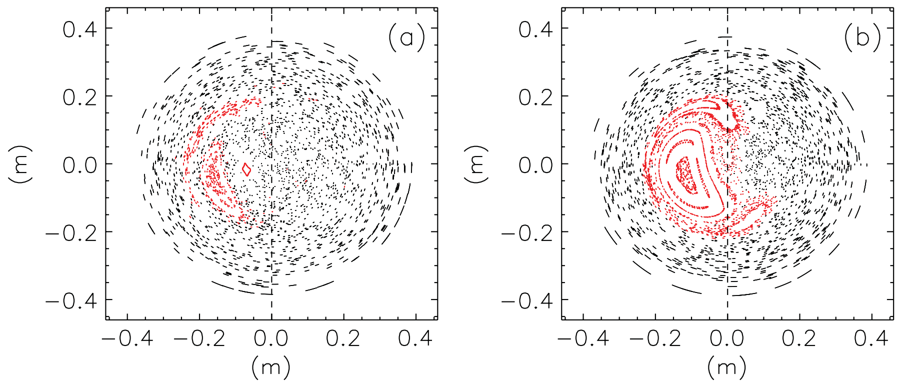

FIG. 5 (color). Poloidal section of the magnetic surfaces calculated adding to the axisymmetric field the contribution of the $m = 1$ secondary modes and of $m = 0$ modes for the QSH$_i$ state shown in Fig. 2(a) (a) and for the SHAx state shown in Fig. 2(b) (b)

stochastization of magnetic surfaces is to be expected. This has been investigated with the FLIT code, performing a field-line tracing including the effect of modes with $m = 0$, 1 and $n = 0$, [23], that is all the modes which are fully measured at the edge by the set of 48×4 pick-up coils and which can therefore be reconstructed into the plasma using Newcomb's equation.

Figures 5(a) and 5(b) display the Poincaré plots on the poloidal plane where the Thomson scattering is measuring, for the QSH$_i$ and SHAx states whose temperature profiles are shown in Fig. 1. These two states have similar values of the secondary mode amplitudes. In order to better understand the confining role of the islandlike structures, field lines starting in them are plotted in red, while the others are plotted in black. The pictures clearly show that the transition from QSH$_i$ to SHAx corresponds to a strong widening of the islandlike structure where nearly conserved magnetic surfaces exist. Moreover, in the SHAx case the structure crosses the vertical dashed line which marks the position of the vessel geometric axis, and expands to the other side. This is in agreement with the observation that in the SHAx state the thermal structure extends beyond the geometric axis position. The fact that the red points remain within the structure or in its vicinity suggests that magnetic field stochasticity does not significantly contribute to transport of energy from inside the structure to outside. Overall, this shows that the transition to the SHAx state brings the formation of a region with good thermal insulation from the stochastic background in a larger fraction of the plasma volume.

In conclusion, we have shown that an increase in the plasma thermal content observed in the RFX-mod experiment is clearly associated to a transition concerning the magnetic topology, from a QSH state with a magnetic island and a secondary magnetic axis divided by a separatrix from the main magnetic axis to a SHAx state, characterized by a single helical magnetic axis. Thanks to the increased resilience to chaos of the SHAx state, a hotter core region occupying a good fraction of the total plasma volume is created. This result is the first experimental verification of a theoretical result which is of general interest for the whole field of Hamiltonian dynamics [6].

While more work is still required in order to further lower the secondary mode amplitudes so as to enter a proper single helicity state, the experimental observation of the SHAx-RFP paves the way towards the achievement of even less chaotic RFP states, supporting the vision of a nonstochastic RFP plasma.

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