Active-Feedback Control of the Magnetic Boundary for Magnetohydrodynamic Stabilization of a Fusion Plasma

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Stable operation with control on magnetohydrodynamic modes has been obtained in the modified reversed field experiment employing a set of 192 feedback controlled saddle coils. Improvements of plasma temperature, confinement (twofold), and pulse length (threefold) and, as a consequence of the magnetic fluctuation reduction, strong mitigation of plasma-wall interaction and mode locking are reported.

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In tokamak research, it has been recognized that one of the major obstacles to reaching enhanced plasma performances is represented by the unstable magnetohydrodynamic (MHD) modes known as resistive wall modes (RWMs). The RWMs are relatively slow modes which grow on a time scale of the order of the magnetic field penetration time of the metal wall surrounding the plasma. In future devices, such as ITER (International Thermonuclear Experimental Reactor), the RWM control will be a major issue to reach the so-called ‘‘advanced scenarios’’ (AS). The RWMs can be stabilized either by plasma rotation [1] or by external control using active coils [2]. Successful experiments on RWM stabilization have been performed in the presence of a substantial plasma flow [3]. In ITER plasmas, the predicted rotation (induced by neutral beam injection) will be low [4], and the possibility of operating ITER in the AS will strongly rely on the effectiveness of magnetic active control.

In the reversed field pinch (RFP), the important role of a ‘‘magnetically’’ thick wall surrounding the plasma has been recognized for stability [5], as a key feature of the plasma relaxation [6], and also as a means to reduce the amplitude of the dominant MHD modes [7]. RWM nonresonant instabilities exist in the RFPs [8], not influenced by plasma rotation below the Alfvén speed (sub-Alfvénic). Hence, RFPs can test the stabilization of the RWMs by a pure magnetic field control. Encouraging experiments of this kind have been already realized [9]. In order to experimentally address these issues, the RFP experiment [10] has been modified (RFX-mod) by replacing a thick (450 ms for vertical field penetration) with a thinner (50 ms) wall and by adding a set of 4 (poloidally) × 48 (toroidally) equally spaced saddle coils (and independent power supplies) [11]. The main parameters characterizing the RFX-mod device are major radius $R = 2$ m, minor radius $a = 0.459$ m, shell proximity $b/a = 1.11$, and plasma current up to 2 MA.

The idea of a ‘‘net’’ of coils which can mimic an ideally conducting wall by locally opposing the radial field [‘‘intelligent’’ or ‘‘virtual shell’’ (VS)] was theoretically proposed [12]. The concept has been realized practically in RFX-mod.

In a RFP, the spectrum of unstable Fourier modes is dominated by the $m = 1$ poloidal harmonic in a wide range of n values (n is the toroidal mode number). In Fig. 1, the spectrum is calculated using a cylindrical resistive code with a resistive wall [13]. The modes with $n \leq -7$ are the so-called ‘‘internal resonant’’ modes; these are resistive modes and are responsible for the dynamo sustainment of

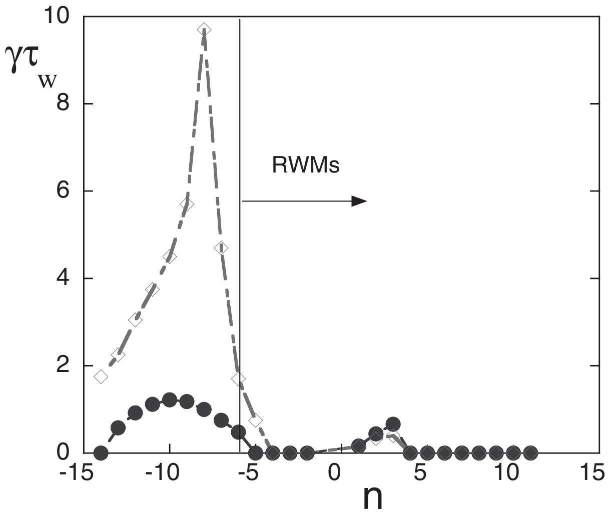

FIG. 1. Linear $m = 1$ growth rates normalized to the wall time vs n. The equilibrium parallel current is defined as: $\mu = \mu(o) \times (1 - r^\alpha)$. Empty diamonds correspond to $\mu(o) = 3.42$, $\alpha = 3$ and black circles to $\mu(o) = 3$, $\alpha = 5.8$.

the RFP configuration. The $-7 < n < 0$ and $n > 0$ modes are instead the nonresonant (internal and external, respectively) RWMs. Being nonresonant, these modes are not influenced by the plasma sub-Alfvénic motion. Because of the presence of multiple unstable high n modes, the number of active coils (and sensors) in the toroidal direction should be large enough to avoid the coupling, through the sidebands generated by the active control system, of two (or more) unstable plasma modes [14,15]. The coils surround the thin copper shell, and, under each of them, a saddle radial field sensor of the same area is mounted on the internal part of the shell, in such a way that the flux at the sensor can be exactly balanced by a suitable current in the active coil. Each coil is individually fed with a maximum current of 400 A, which generates a radial field of about 50 mT [11]. The bandwidth of the power supplies is of the order of 1 kHz, while the L/R time of each coil is about 6 ms. The system of saddle coils, sensors, and power supplies can be controlled by different schemes [16]. In particular, a real-time fast Fourier transform (FFT) allows control of individual modes. During VS operation, the FFT is used to exclude from feedback the equilibrium field ($m = 1$, $n = 0$), while all the other measured modes ($m = 0$ with $0 \leq n < 24$ and $m = 1$ with $-23 \leq n \leq 24$) are controlled.

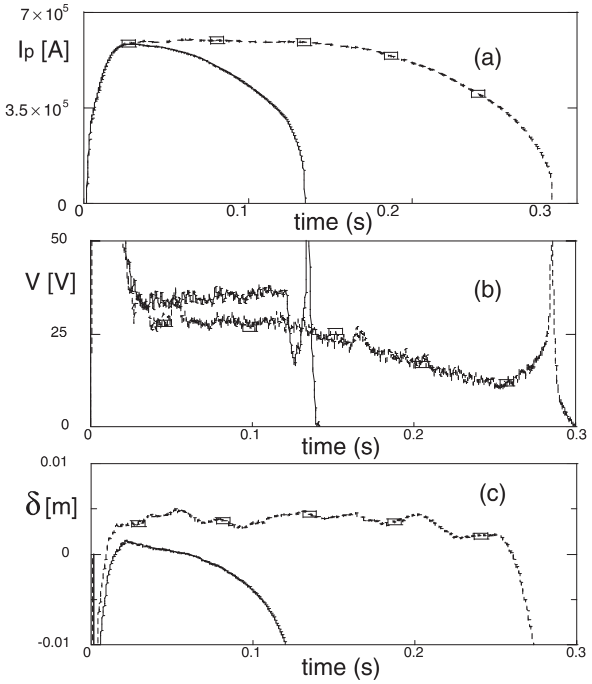

FIG. 2. RFX-mod standard and VS (squares) discharges: (a) plasma current; (b) toroidal loop voltage; (c) equilibrium axisymmetric shift.

Results at plasma currents between 550 and 650 kA without active control and comparison with the old RFX have been already reported [17]: Similar plasma conditions, in terms of pulse duration, current, density, and temperature, have been obtained in this case. As in RFX, also in RFX-mod without active control, a strong, stationary deformation of the plasma boundary has been detected. This toroidally localized deformation causes a direct loss of plasma particles and energy to the wall with a degradation of plasma performance and enhanced plasma-wall interaction [18]. The wall locking is the result of the nonlinear mode coupling in the plasma, combined with the interaction with external stationary error fields and/or braking effects due to the resistive wall [19,20]. Locked discharges are hardly reproducible and pulse duration never exceeds 120–140 ms, preventing observation of the RWM's growth.

To reduce field errors and control mode amplitudes at the boundary, the full set of RFX-mod coils is employed in the VS operation mode. The effect (see Fig. 2) is very clear: The discharge is prolonged in time, the loop voltage is lowered, while the horizontal equilibrium is maintained throughout the discharge. Note that the controlled discharge terminates due to transport effects and insufficient loop voltage and not because of a lack of control. Improvements on the electron and ion temperatures are also observed: Figure 3(a) shows time evolution of the electron temperature measured by a soft x-ray (SXR) double filter technique and of the ion temperature deduced from the Doppler broadening of an O VII line. A significant increase of both temperatures is observed for the VS operation, and, taking into account the different emission zones, Te ≈ Ti can be estimated. In Fig. 3(b), the comparison of the electron temperature profiles measured by a Thomson scattering system is shown. Because of the

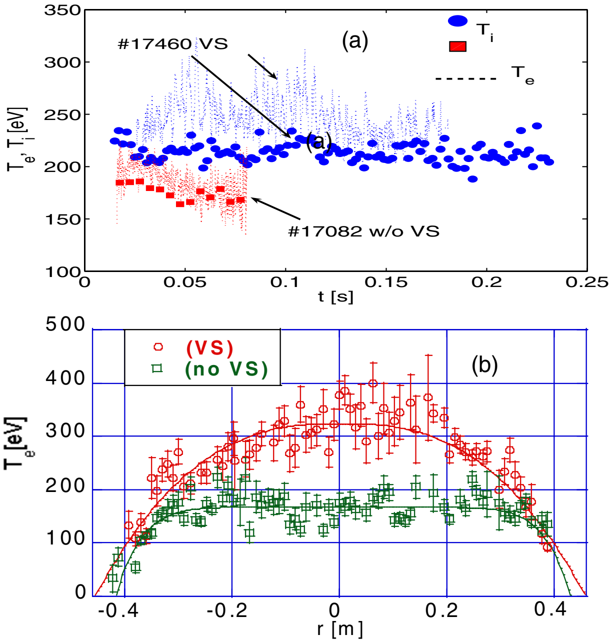

FIG. 3 (color online). (a) Ion (squares and circles) and electron temperature (lines); (b) electron temperature profiles.

higher ion and electron temperatures, the more peaked electron temperature profile, and the lower loop voltage, the energy confinement time in VS discharges is at least twice that in reference uncontrolled discharges. This improvement can be explained by the reduction of the mode amplitudes in the plasma during VS operation.

In Fig. 4, the comparison between the standard and VS $m = 1$ reconstructed spectrum [21] is shown for a set of selected discharges, both at the edge [Fig. 4(a)] and in the core [Fig. 4(b)]. Nonlinear saturation effects are certainly present; nevertheless, the linear dominant modes predictions (Fig. 1) are confirmed by the experimental spectrum in standard discharges [Fig. 4(a)]. Taking into account the equilibrium reconstruction, the edge radial and toroidal field measurements, and Newcomb's equation describing the perturbed fields in the plasma [22], it is possible to infer the harmonic amplitudes in the plasma core [Fig. 4(b)]. The plot shows the maximum radial field amplitude for each harmonic. This maximum corresponds to the on-axis value of the eigenfunction for the nonresonant modes, while it is representative of a value close to the resonance surface for resonant modes. The on-axis resonant $n = -7$ mode is not shown due to difficulties in its reconstruction. The use of Newcomb's equation is justified since the linear and nonlinear eigenfunctions (both for RWMs and tearings) show, in numerical simulations, similar radial profiles [23]. Hence, the mode amplitudes are reduced by the VS for all ns, both at the sensors position and in the core. Experiments confirm also that, if the VS is made not to react to some specific RWM, the mode grows with the predicted linear rate, as seen in simulations [23]. Hence, it can be concluded that, on one hand, the RWMs are stabilized, and, on the other hand, the resonant tearing mode amplitudes are significantly reduced by the VS operation. The average radial perturbation (over all ns) is lowered by a factor of about 3 in the plasma region. The reduction of the tearings is due to the fact that the VS mimics an ideally conducting wall, having a stabilizing influence on the whole spectrum of unstable modes [7]. This explains the improved confinement in controlled discharges, since stochastic transport, which critically depends on the resonant magnetic perturbation amplitudes [24], plays an important role in the core of RFP devices.

Following the mode amplitude reduction, the locking phenomenon (for the $m = 1$ modes) is also mitigated. A residual toroidally localized structure is still present, but it corresponds to a radial shift of the last closed surface lower than 0.5 cm for the $m = 1$ (3–4 cm in the absence of control). A 1–2 cm $m = 0$ local deformation (as in the noncontrolled cases) is also detected.

The VS affects also the error fields. This can be seen in Fig. 4(a), where the modes with $-4 \leq n \leq 2$, which are linearly stable and can be identified as error fields, are effectively reduced.

The VS operation offers the conditions for interesting internal plasma dynamics, i.e., an oscillatory behavior of the $(1/-7)$ on-axis (or near axis) resonant mode. During the "sawtooth," it is also possible to observe a simultaneous (in phase) oscillation of the soft x-ray signals, corresponding to a clear increase of the electron temperature, while both the $m = 0$ and the $m = 1$, $-13 \leq n \leq -8$ modes show antiphase correlation (see Fig. 5 for some $m = 1$). At the peak of the $(1/-7)$ oscillation, a very clean quasi-single-helicity [25,26] state is transiently achieved. In Fig. 6, the spectrogram measured by edge fast (200 kHz bandwidth) magnetic probes shows a richer frequency content at the peaks of the $m = 0$ activity, i.e., at the crash time of the dominant $m = 1$ mode, implying that a broadband turbulence is generated. The oscillations show

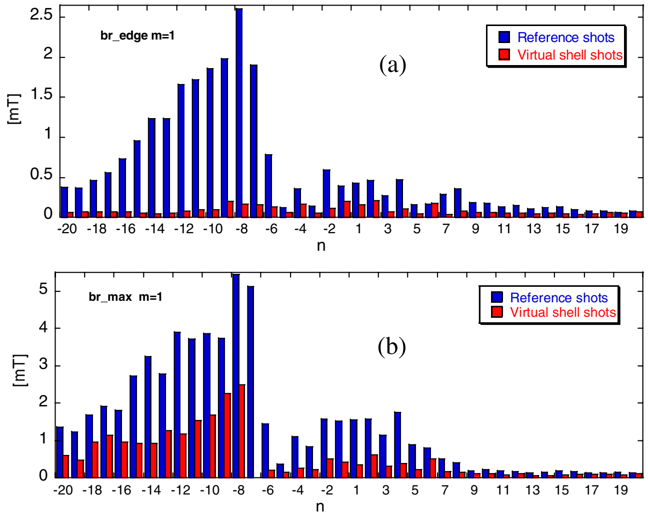

FIG. 4 (color online). Mode amplitudes (radial magnetic field) vs n (a) at the edge and (b) in the core.

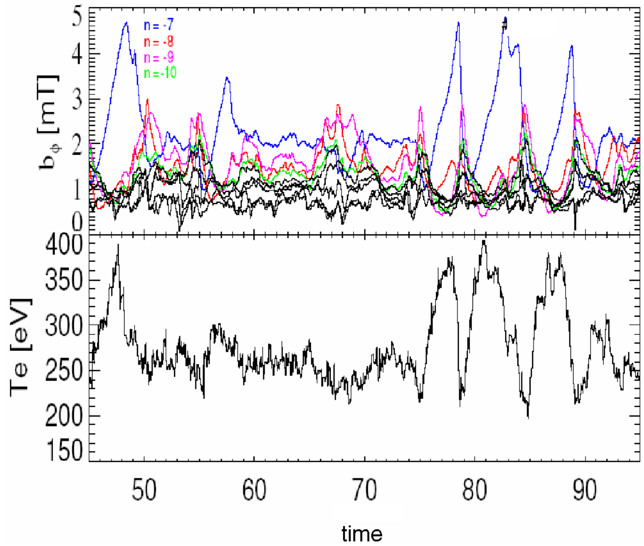

FIG. 5 (color online). Mode amplitudes ($m = 1$ toroidal magnetic field) and electron temperature (SXR double filter) vs time (ms) during "sawtoothlike" oscillations with VS operation.

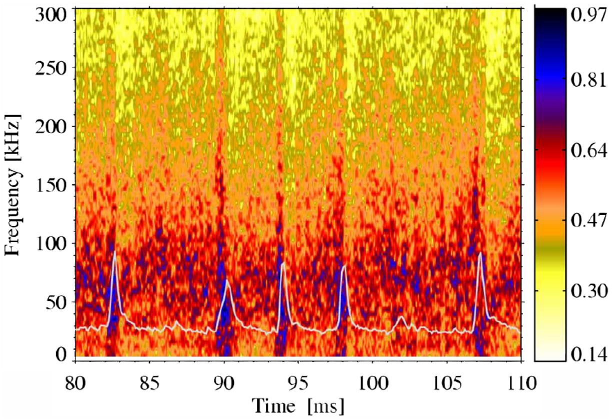

FIG. 6 (color online). Frequency vs time as measured by fast magnetic probes at the plasma edge. The $m = 0$ mode activity is given by the superimposed white line.

similarities with the $m = 1$, $n = 1$ sawtooth in tokamaks with strong effects on the electron temperature. The measured increase of the temperature in the island region can be attributed to a local improved confinement, but the overall reduction of the transport due to the suppression of the higher n modes and reduction of the core field line stochasticity [24] can also play a key role. The dynamics also has similarities to that detected in other RFPs operating with a thick ideal wall [27,28]. Stationary single-helical states are observed in numerical simulations [29–31]. The study of these phenomena is very important both from a basic plasma physics point of view (reconnection theory, plasma dissipation effects, etc.) but also for the fusion perspective of the RFP device.

In this Letter, experimental results on a novel technique of MHD mode control using the VS concept have been reported. Strong reduction of the magnetic fluctuations both at the wall and in the plasma and an increase of confinement have been obtained.

Our results demonstrate that successful active control on the multiple RWMs is possible in the absence of plasma rotation effects. This fact has positive implications for ITER. Finally, these experiments show also that a thick passive conductive shell is not necessary for the RFP operation.

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