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First results from intelligent shell experiments with partial coil coverage in the EXTRAP T2R reversed field pinch

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Introduction

The conventional reversed-field pinch (RFP) plasma is enclosed in a thick conducting wall, or shell, in order to achieve the needed MHD mode stabilisation. If the shell is made thin, or resistive, the radial perturbation fields can diffuse through the wall. The required suppression of the radial field perturbation at the wall can then be supplemented with active magnetic feedback control using arrays of saddle coils, creating an "intelligent shell" [1]. A range of non-linearly saturated m= 1 tearing modes, resonant in the central plasma, are intrinsic to the RFP configuration. In the EXTRAP T2R thin shell RFP device the plasma and the modes are typically rotating at high angular frequencies compared to the inverse wall time [2, 3, 4]. As a result, the tearing modes are largely unaffected by the wall, and behave as if the wall were ideally conducting. On the other hand, a number of non-resonant m=1 kink modes that are stable with an ideally conducting wall become unstable when the wall resistivity is accounted for. These kink modes are converted to unstable resistive wall modes (RWM) that have growth times comparable to the wall magnetic flux penetration time [5].

EXTRAP T2R mode control system

The EXTRAP T2R device is a thin shell medium size RFP (R/a=1.24/0.183 m) [2]. The thin wall stainless steel corrugated vacuum chamber of the device is placed inside a closely fitting thin shell at a radius r/a=1.08, having a vertical field penetration time of τ_v=6.3 ms. In the present experiments, the plasma current is I_p=80 kA and the pulse length is 15-23 ms, equivalent to three to four times the shell time constant. The RWM feedback control system includes a large number of active saddle coils that are placed outside the shell at a radius r/a=1.28. The coils have angular extent 90° poloidally and 360/32=11.25° toroidally. The coverage in the poloidal direction is complete with M_c=4 coils, while the coverage in the toroidal direction is partial with N_c=16 equally spaced poloidal arrays that cover 50% of the toroidal circumference. The four coils at a toroidal position are connected (inboard-outboard and top-bottom) into m=1 cosine and sine coils forming 32 independent coils. Each saddle coil has 40 turns and the L/R time of the saddle coil pair is

τ_c= 1 ms. The current in each independent coil is produced by a high-bandwidth audio amplifier. The typical field produced is of the order of 1 mT, which is equivalent to about 1% of the equilibrium poloidal field at the wall. A sensor coil array is placed inside the shell, in the interspace between the shell and the vacuum vessel. The sensor coils are one-turn saddle coils with angular extent 90° poloidally and 5.625° toroidally. There are M_s=4 coils in the poloidal direction and N_s=32 equally spaced poloidal arrays in the toroidal direction. The sensor coils in a poloidal array are pair connected in the same way as the active coils into m=1 cosine and sine coils. The feedback control is implemented with a digital controller that has been developed for the RFX device [6, 7]. It uses the inputs from the 64 sensor signals and performs a toroidal Fourier decomposition of the radial field. For the present sensor array, m=1 modes with toroidal mode numbers in the range $-15 \leq n \leq +16$ are resolved. (The convention m=1,n<0 is used for modes that have the same helicity handedness as the equilibrium field in the central plasma.) An individual proportional gain is applied for each Fourier harmonic. The inverse Fourier transform is then performed and control signals for the 32 amplifiers are output.

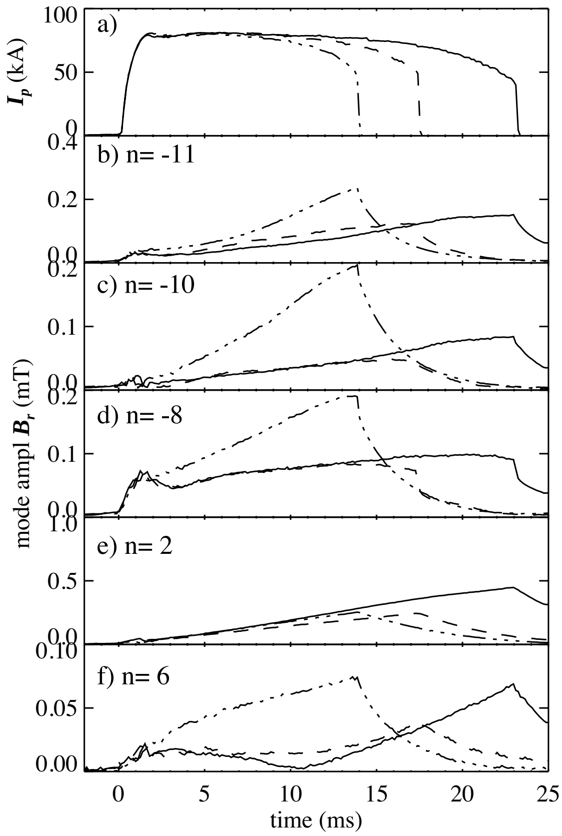

Fig. 1 Time evolution of radial magnetic field. a) plasma current, Amplitudes for different m=1 modes b) n=-11, c) n=-10, d) n=-8, e) n=+2, f) n=+6. Three cases are shown; shot 15863 without feedback (dot-dash), shot 15870 with feedback on all modes (dash) and shot 15867 with feedback on all modes except -2≤n≤+2 (full).

When the feedback gains are set equal for all modes, the feedback system attempts to maintain zero flux through all sensor coils, analogous to the intelligent shell scheme [1]. With a toroidal array of saddle coils, a number of radial field harmonics are produced for a given Fourier harmonic n_c of the coil current. The field harmonics n_f are given by the relation $n_f=n_c+iN_c$, where i=...-2,-1,0,1,2,...., and N_c is the number of coils in the toroidal direction. This gives rise to a linear coupling of different unstable modes through the feedback action which is expected to limit the effectiveness of the feedback system [8].

Feedback suppression of RWMs

The magnetic equilibrium is mainly characterised by the parameter $\Theta=B_\theta(a)/<B_\phi>$, where $B_\theta(a)$ is the poloidal field at the edge and $<B_\phi>$ is the average toroidal field. For the present equilibrium with Θ=1.65, the resonant *m*=1 tearing modes in EXTRAP T2R have toroidal mode numbers *n*≤-12. The non-resonant unstable RWMs are -11≤*n*≤-3 (internally non-resonant) and +1≤*n*≤+*7* (externally non-resonant). The fastest growing unstable modes are the internally non-resonant modes -11≤*n*≤-8. The RWMs predicted by linear MHD theory are experimentally observed in EXTRAP T2R. The growth rates are in quantitative agreement with theory [9]. Experimentally, some low-|*n*| modes are observed with higher growth rates than predicted by theory. These modes, with toroidal mode number -2≤*n*≤+2, are believed to be driven by field errors due to machine asymmetries.

The time evolution of the main non-resonant modes is shown in Fig. 1. Two cases with, and one case without feedback control are compared. Without feedback, the mode amplitudes increase with time corresponding to growth rates comparable to the inverse shell time constant. In the first case, all modes are targeted for feedback, and the proportional controller feedback gains are set equal for all modes, corresponding to intelligent shell operation. It is clear from Fig. 1 that the growth of the internally non-resonant modes (*n*=-11,-10,-8) is partially suppressed. The amplitude of the external non-resonant mode shown (*n*=+6) is initially strongly decreasing, but later in the discharge, the mode phase changes and the mode becomes in anti-phase with the coupled internally non-resonant mode (*n*=-10*)* and it starts to grow. The observed behaviour of the modes is in qualitative agreement with theory [8].

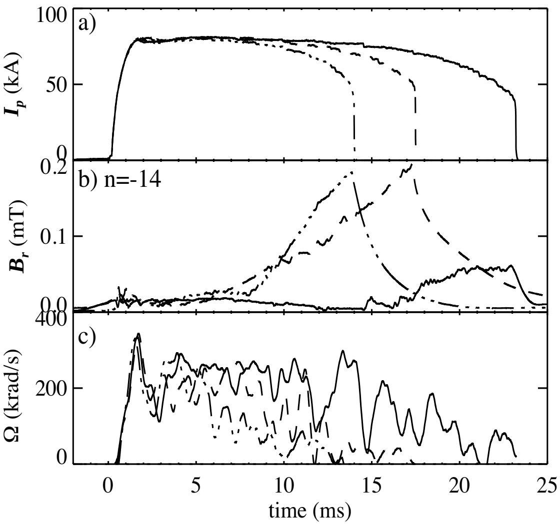

Fig.2 Amplitude and angular phase velocity for resonant tearing mode m=1, n=-14. a) plasma current, b) mode amplitude, c) mode angular phase velocity. Three cases are shown; shot 15863 without feedback (dot-dash), shot 15870 with feedback on all modes (dash) and shot 15867 with feedback action on all modes except -2≤n≤+2 (full).

Effect of RWM feedback on tearing mode rotation

The coil array also couples non-resonant and resonant modes such as modes *n*=(-14,+2). The field error driven mode *n*=+2 has a large amplitude. The growth of this mode is somewhat reduced with feedback. Feedback suppression of the large amplitude *n*=+2 mode produces a static resonant *n*=-14 field component that tends to wall lock the saturated rotating tearing mode with the same mode number [10]. In the second feedback case, shown in Fig. 1, the feedback action has been removed for modes $-2 \le n \le +2$. The suppression of the main modes is similar as in the first case, but the discharge duration is increased. With this feedback scheme, a significant extension of the pulse length is achieved, in the present example from 14 ms to 23 ms, equivalent to a 60% increase. The amplitude of the coupled mode (n=-14) is shown in Fig. 2, for cases with and without feedback. The n=-14 tearing mode rotation frequency, shown also in Fig. 2, is initially high, but decreases toward the end of the discharge. As the mode brakes, the mode radial field at the wall increases approximately linearly. This rapid growth of the resonant mode amplitude is coincident with an increase in the plasma resistance, which in this device leads to discharge termination. The mode braking is clearly delayed in the second feedback case (not targeting the low-$|n|$ modes $-2 \le n \le +2$), indicating that the suppression of RWM growth is effective to sustain the plasma and tearing mode rotation. This suggests the existence of a coupling between the growth of the non-resonant RWMs and braking of the mode rotation.

Summary

Significant suppression of RWMs is observed in a reversed field pinch plasma using an intelligent shell type feedback system with partial coil coverage. Coupling of modes due to the limited number of active coils is observed. The suppression of non-resonant RWMs has also an effect on resonant rotating saturated tearing modes. An improved sustainment of the tearing mode rotation is observed with feedback, resulting in an increase of the discharge pulse length.

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