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AVOIDANCE OF TEARING MODE LOCKING AND DISRUPTION WITH ELECTRO-MAGNETIC TORQUE INTRODUCED BY FEEDBACK-BASED MODE ROTATION CONTROL IN DIII-D AND RFX-MOD

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Avoidance of Tearing Mode Locking and Disruption with Electro-Magnetic Torque Introduced by Feedback-based Mode Rotation Control in DIII-D and RFX-mod

EX-S

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We have demonstrated an innovative scheme to avoid the tearing mode (TM) locking and its associated disruptions in tokamaks by utilizing the electromagnetic (EM) torque produced by 3D coils. In this scheme, the EM torque to the modes is created by a toroidal phase shift between the externally-applied n=1 field and the excited TM fields, compensating the mode momentum loss due to the interaction with the resistive wall and error field. Fine control of the toroidal phase of the 3D field relative to the TM is provided by feedback providing the stability of torque balance. We have carried out proof-of-principle experiments in DIII-D and RFX-mod and established common basic physics understanding with independently-developed modeling efforts. Magnetic control of tearing mode was initiated more than two decades ago and have received revived attention recently in combination with electron cyclotron current drive [1]. Recent concerns about ITER operational limits due to disruptions have resurrected the interest in this subject.

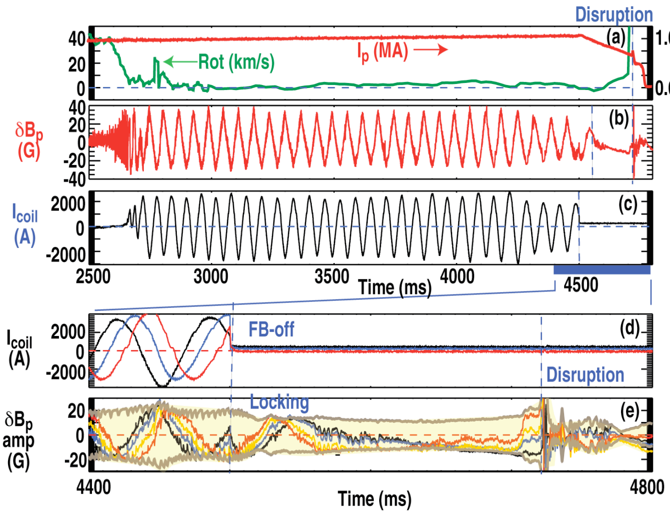

Fig. 1. DIII-D. The NTM locking avoidance, (a) I_p, plasma rotation at q~2 surface, (b) a sensor signal, (c) a coil current. The locking and disruption after feedback termination are shown by (d) individual coil currents and (e) the sensor signals.

In high beta poloidal β_p discharges of DIII-D, by applying sufficiently high gain, a large amplitude m/n=2/1 TM propagating initially with the plasma rotation is successfully slowed down, in a controlled manner to very low frequency, i.e. of the order of the inverse of resistive wall time as shown in Fig. 1. This quasi-steady helical equilibrium was sustained over several seconds. Upon termination of feedback, the mode survived only a few tenths of a second and locking occurred leading to disruption, demonstrating clearly the advantage of feedback-driven mode rotation control.

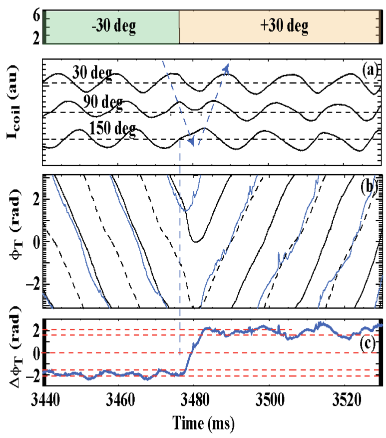

Fig. 2. DIII-D. (a) Feedback coil currents, (b) the toroidal phase of applied field $B_{r.ext}$ (at max, solid), $B_{r.ext}$ (at min. dot) and TM δB_p (at max, blue), and (c) the phase difference $\Delta\phi_T$ between the $B_{r.ext}$ and δB_p mode.

The controllability of torque balance in DIII-D is illustrated in Fig. 2. The nearly-in-phase relation between the mode δB_p and the $B_{r.ext}$ can produce the maximum torque for the given coil current and mode amplitude. When the feedback preset phase shift, ϕ_0 between the observed toroidal phase and the applied n=1 field, was shifted from -30° to +30°, the mode direction was reversed. The phase relation still sustains nearly-maximum torque.

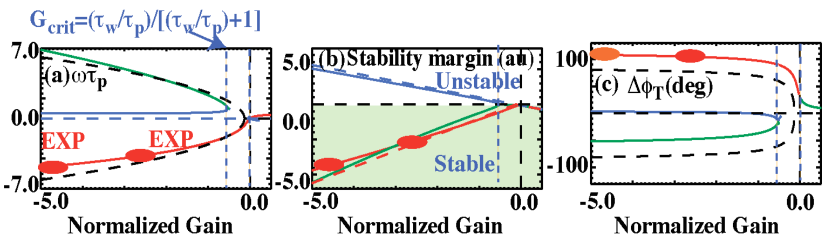

Fig. 3. The predictions by a cylindrical model: (a) the ωτp dependence on gain, (b) the margin of torque-balanced stability, and (c) the phase difference between the applied field and the mode.

Figure 3 shows the model prediction of torque balance stability and the experimental observation in DIII-D. The parameters in the experiment are consistent with the model predictions for the normalized gain *G* of 2.5–5. The model also predicts that changing the polarity of the preset phase shift reverses the mode rotation as shown in Fig. 2.

RFX-mod has independently demonstrated m/n=2/1 tearing mode controllability in a tokamak configuration [2]. DIII-D and RFX-mod are significantly different devices; DIII-D is a non-circular divertor configuration, while the RFX-mod operated as a tokamak [2] is a circular limiter device with active coils located outside the resistive wall in a geometry completely different from the internal coils in DIII-D [3]. The fundamental approach for tearing mode control is similar as in DIII-D, but its details are different since the system was originally developed for the RFP configuration with accommodation of various unique features including 192 3D coils located outside the resistive wall [4]. The controllability of mode rotation has been demonstrated at moderate plasma density (n/n_G<0.5 where n_G is the Greenwald limit) and low q(a) [q(a)<2.5]. The key element for sustaining a mode, whose amplitude is above the wall-locking threshold [5] into slow rotation frequency (the order of a few inverse shell time constant) is the minimization of coil-sideband pollution in the feed-back variable, rather than the application of a phase shift. The use of complex gains, which introduce the phase shift, allows selecting the mode rotation direction, but requires more current in the active coils. As shown in Fig. 4, the observed dependence of mode parameters vs gain K_p are well consistent with predictions by a MHD model (RFX Locking) which has been developed independently, but with principles similar to that in DIII-D.

In summary, a scheme of avoidance of tearing mode locking and its associated disruption with 3D coils has been proposed and its applicability has been demonstrated in completely different devices and plasmas in DIII-D and RFX-mod. Thus, this approach is robust and promising. Currently, ITER is considering the use of internal coils for ELM control. Proactive TM rotation control would expand the horizon of the ITER operational regime.

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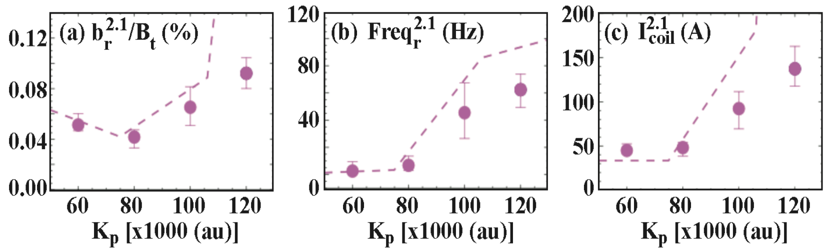

Fig. 4. RFX-Mod tokamak. Experimental data (symbols) and simulated trend (dashed line) for the 2/1 control. The abscissa is the proportional gain applied to the measured radial field.

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