Control of the Resistive Wall Mode With Internal Coils in the DIII–D Tokamak*

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New internal control coils, which produce non-axisymmetric magnetic fields, have been installed inside the vacuum vessel on the DIII-D tokamak for stabilizing the resistive wall mode (RWM) branch of the external kink modes. Recent experimental results have clearly demonstrated advantages of the internal coils with respect to RWM stabilization. The poloidal field structure provided by the internal coils is a superior match to the RWM eigenmode structure, as illustrated in the reduction of the coil current optimized for dynamically correcting the error field (Fig. 1), the stabilization of the RWM at rotation velocities below the critical velocity (Fig. 2) and the suppression of the RWM to a larger growth rate (Fig. 3). The ultimate objective of this research is to develop a robust and economical control scheme for the RWM aimed at the practical application to commercially-oriented reactors.

A steady-state power plant with a high fusion power density, utilizing a high fraction of bootstrap current, is a viable ultimate goal of tokamak fusion research. It was experimentally demonstrated that the vulnerability of this self-sustained tokamak configuration to the long-wavelength ideal external kink can be overcome by plasma rotation [1] and/or magnetic feedback with external coils [2] combined with the presence of a nearby conducting wall with low resistivity, as predicted by theory [3,4]. It was also shown that the external coils stabilize these external kinks by a combination of sustained high plasma rotation frequency ($\Omega > \Omega_{crit}$) with dynamic error field correction and direct feedback process [5].

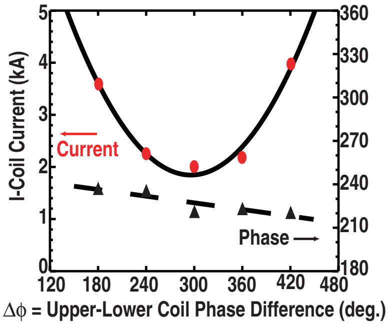

Fig. 1. Amplitude and phase of error field correction with various I-coil upper/lower connection angles determined by dynamic error field correction process.

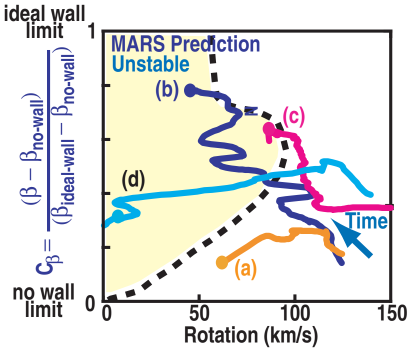

Fig. 2. Trajectories of discharges without feedback (a), with feedback using internal (b) and external coils (c) and magnetic braking (d). The dotted line indicates the critical β calculated with MARS.

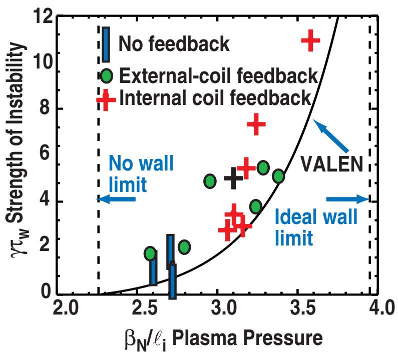

Fig. 3. The observed growth rates of unstable RWM after the feedback system exhausted the available current.

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Recent experiments have demonstrated several advantages of the internal coils. For dynamic error field correction, the dependence of the internal coil current on the applied field pitch agrees with a model prediction based on the mode structure of an ideal MHD external kink mode, Fig. 1. With the optimized pitch connection (≈300 deg.), the applied average magnetic field normal to the plasma surface using the internal coils is ≈20% of the average field using the external coils — showing that unnecessary harmonic components have been greatly reduced. The stored magnetic energy of the internal coils is <10% of the stored energy with external coils due to the much smaller total self-inductance of the internal coils and the lower required currents, indicating definite engineering advantages of internal coils.

Advantages of the internal coils are their proximity to the plasma surface and the more flexible poloidal field structure — providing a better coupling to the RWM. Feedback using internal coils largely eliminates the time delay due to the finite impedance of the resistive wall, resulting in overall faster feedback time response. According to the VALEN code [6], feedback utilizing the internal coils can stabilize the plasma β_N to within $C_\beta \approx 0.9$, almost to the ideal wall beta limit [C_β is a measure of achievable beta above no-wall limit defined as $(\beta - \beta_{no\text{-}wall})/(\beta_{ideal\ wall} - \beta_{no\text{-}wall})$], whereas for the case of feedback with the external coils, the achievable beta value is predicted to be limited to $C_\beta \approx 0.5$.

Feedback with the internal coils is indeed more efficient compared to feedback with the external coils. The achievable β_N in relation to the plasma rotation near the q = 2 surface is shown in Fig. 2 by trajectories of several discharges in which unstable RWMs were observed. Theoretical estimates with the MARS code [8] along with experimental results suggest that the critical rotation velocity, Ω_{crit}, for the path to high beta without feedback is around 95 km/s. This corresponds to $\Omega_{crit}/\Omega_A = 2.8\%$, which is consistent with Ref. [8].

Without feedback, a discharge is terminated near the estimated critical velocity, Fig. 2 trajectory (a). In Fig. 2(b), the plasma β_N is raised to $C_\beta \approx 0.7$ by using internal coils with a proper choice of feedback gains. The beneficial action of the feedback is inferred from the observation that during this period, the plasma rotation is gradually reduced to well below the critical rotation predicted by the MARS code for RWM stabilization. Feedback using internal coils also allows the plasma to reach higher pressure than feedback using the external coils, Fig. 2(c), even though the plasma rotation was significantly reduced. It should be cautioned that the non-zero plasma rotation may have an additional stabilization effect in these discharges. By using the experimental technique of resonant magnetic braking, the plasma rotation has been reduced to nearly zero outside the q=2 region. Nonetheless, as shown in Fig. 2(d), feedback with the internal coils can sustain the plasma to $C_\beta \approx 0.3$ above the no-wall limit for more than 100 ms (which is more than 20 times the wall time constant of 5 ms).

Figure 3 shows the growth rates when the RWM becomes unstable at the highest beta limit and the feedback system has exhausted the available current. At that moment, the plasma rotation is reduced to nearly zero due to the strong viscous effect of the uncontrolled growth of the RWM amplitude. The growth rates therefore correspond to that without any stabilization effect. The solid line is the growth rate calculated with the VALEN code with no feedback [6]. The observed growth rates are in good agreement with the model prediction regardless of feedback using external coils or internal coils. The results suggest that the feedback system with internal coils can suppress the intrinsic RWM growth rate up to $\gamma\tau_w \approx 10$ (τ_w is the wall time constant).

The implication for RWM stabilization in ITER has been studied using the DIII-D experimental rotational profiles applied to the ITER-AT equilibrium [9]. The critical rotation velocity Ω_{crit}/Ω_A is 5% at the magnetic axis, suggesting that the high beta operation regime could be severely limited without the use of an auxiliary momentum input system or direct magnetic feedback stabilization. The DIII-D results are encouraging for the feasibility of magnetic feedback control.

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