Study of the Resistive Wall Mode in DIII–D*

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Reliable plasma operation at high beta, $\beta \equiv 2\mu_0\langle p\rangle/B^2$, and high normalized beta, $\beta_N \equiv \beta/(I/aB)$, is the key to developing more compact and economical energy producing tokamak designs. With this motivation, extensive theoretical and experimental work continues to be carried out on the problem of ameliorating the most dangerous beta limiting instability, the n=1 magnetohydrodynamic (MHD) external kink mode.

Recent MHD calculations [1] predict that, for a plasma with sufficient rotation, a resistive wall can provide stability up to the β_N limit predicted assuming the wall were ideal. In the region of β_N between the "wall-at -infinity" limit and the "ideal-wall" limit, an MHD instability branches into two modes: a *plasma mode*, that is nearly stationary with respect to the plasma at the resonant surface, and a *resistive wall mode* (RWM), that is nearly stationary with respect to the wall [2]. For a plasma rotation speed Ω_P » $1/\tau_W$ (where τ_W is the dominant wall time constant), the wall appears perfectly conducting to the plasma mode, and is therefore stabilizing. With the inclusion of plasma rotation and viscosity, the resistive wall mode also can rotate and be stabilized by the wall eddy currents, but there is considerable disagreement between several MHD theories on the magnitude of the plasma rotation required.

Experiments conducted in the DIII–D [3], PBX-M [4] and HBT-EP [5] tokamaks have demonstrated that plasmas with a nearby conducting wall can remain stable above the beta limit predicted with "wall-at-infinity," and have reported observations of instabilities with the characteristics of a resistive wall mode [6]. In the experiments described in this paper, improved diagnostic measurements and plasma operational techniques, giving broader current density profiles and high toroidal rotation, have provided direct identification of the resistive wall mode. These experiments were designed to ease the requirements on total beta in favor of maximizing the *wall stability enhancement factor*, E_w, ($E_w = \beta_N^{experimental}/\beta_N^{no\text{-}wall\ limit}$), increasing the duration of the wall-stabilized phase, and ensuring shot-to shot reproducibility with the available heating power.

Toward these goals, low internal inductance discharges ($\ell_i \approx 0.7$), with weak negative central magnetic shear and low edge safety factor ($q_{95} \sim 4.5$), were produced using early neutral beam injection and a fast positive current ramp during beam injection in the H–mode phase. This plasma formation technique reliably led to observation of the resistive wall mode in more than 50 discharges with toroidal field B_T=2.1 T and β_N values between 1.4 and 2.8.

Detailed analysis of these plasmas shows increases over previous DIII-D results [3] in both duration and magnitude of the wall-stabilization effect against the ideal external kink. For accurate MHD stability predictions, a careful determination of the plasma equilibrium profiles is essential. The equilibrium is reconstructed using measurements of the internal

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magnetic field pitch from a 35-channel motional Stark effect array, full kinetic profile data, and external magnetic field measurements.

The experimentally achieved beta values exceed the no-wall limit for a period of 200 ms and by up to a factor of ~1.4, as shown in Fig. 1. At the time this discharge reaches maximum beta, a global n=1 kink-ballooning mode is calculated to be strongly unstable with the wall at infinity, but near marginal stability with a perfectly conducting wall at the position of DIII–D's wall, as illustrated in Fig. 2. Figure 1(b) shows that the plasma remains stable until the plasma toroidal rotation, as determined from charge exchange recombination (CER) spectroscopy [7], decreases below ~2 kHz, allowing an n=1 RWM to become unstable.

The growth of the RWM causes a collapse of the stored energy, leading in some cases to a major disruption. Features common to all observations include the following. Mode destabilization follows the decrease of plasma toroidal rotation below a critical frequency of 2 to 7 kHz at the q=3 surface. Mode growth times are 3 to 8 ms, in agreement with measurements and numerical calculations, performed using the SPARK 3D electromagnetic code, of the dominant DIII–D vessel eigenmode time constants, τ_W's. The mode rotates toroidally in the direction of ω^*_e (counter to the beam injection) with slow frequency ≤ 60 Hz ~ $(2\pi\,\tau_W)^{-1}$ from the mode onset.

Figure 3 shows an example of a disruption induced by a RWM. The mode onset is most clearly detected by an array of saddle loops mounted outside the vessel at the outer midplane, which measure an n=1 radial magnetic field nearly stationary with respect to the vessel and slowly growing through the wall. At the time when the n=1 radial field starts to grow, the rotation of the plasma, as determined by CER, is ≥ 5 kHz for all the relevant resonant surfaces (q_{95}=4.4). Mirnov loop signals and electron temperature fluctuations measured by an electron cyclotron emission (ECE) radiometer do not show rotating precursors of the stationary mode; the mode arises locked to the wall, while the plasma is rapidly rotating. However, at the

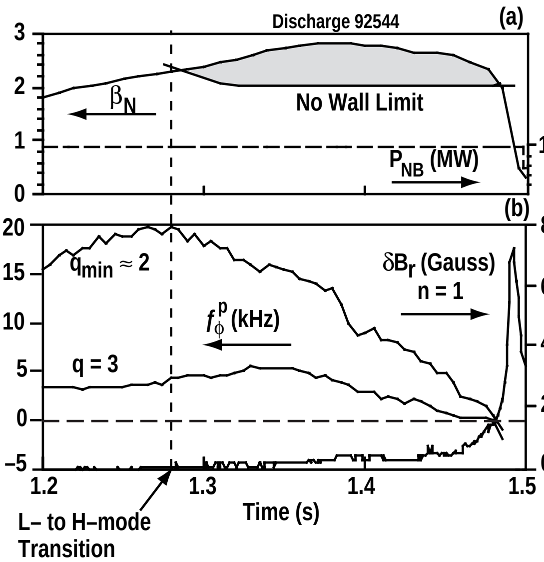

Fig. 1. Time evolution of discharge 92544, showing (a) normalized beta β_N and neutral beam power, and (b) plasma toroidal rotation frequency f_ϕ^p at the location of the q_{min} and q=3 surfaces, and perturbed radial magnetic field δB_r measured outside the vessel at the outer midplane.

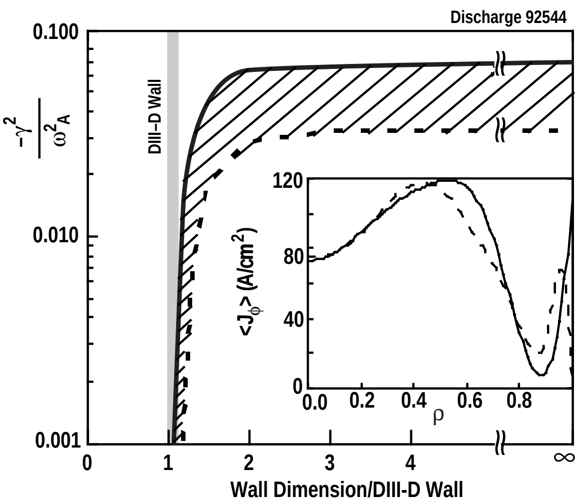

Fig. 2. Calculated growth rate of the n=1 ideal kink mode normalized to the Alfven frequency for discharge 92544 at the time of maximum beta (t=1.37 s). Solid curve shows results for an equilibrium reconstruction allowing finite flux averaged toroidal current density, $\langle J_\phi \rangle$, at the edge. Dashed curve is for case with $\langle J_\phi \rangle$=0 at the edge. Inset shows the profiles of $\langle J_\phi \rangle$ for the two cases.

RWM onset, the profile of the plasma toroidal rotation changes sharply. A rapid reduction in rotation begins at the q=3 resonant surface and, with a small time delay, propagates through the rest of the plasma. A few milliseconds later other signs of the RWM growth can be seen in an increase in the D_α light emission, and a decrease of the electron temperature, which is largest near the plasma edge.

In most cases, the time evolution of the electron temperature profile shows no evidence for the formation of magnetic islands, as expected for an ideal kink instability (resistive wall kink mode, RWKM). However, some discharges were limited to a lower β_N by the onset of a tearing instability, also with the characteristics of a wall mode (resistive wall tearing mode, RWTM) [8]. In these cases, the time evolution of the electron temperature shows the formation of a flat spot in the profile at the location of the resonant surface.

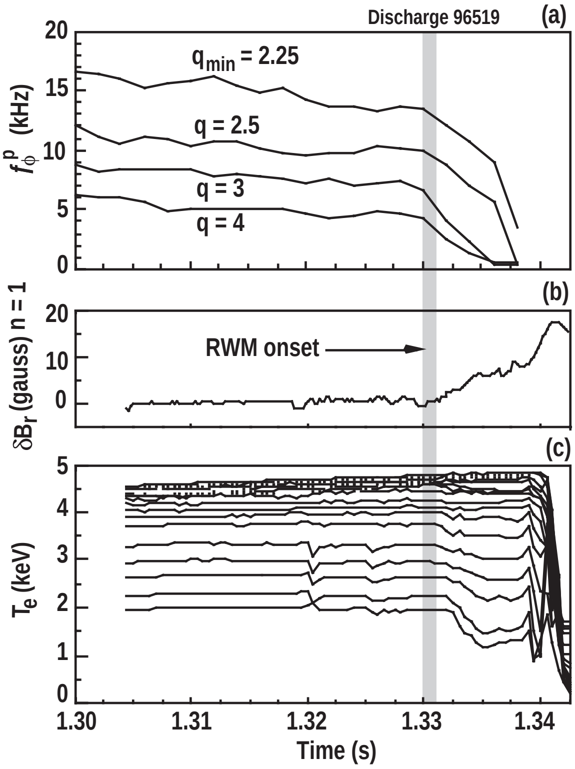

Fig.3. Time evolution of (a) plasma toroidal rotation f_ϕ^p (b) n=1 radial magnetic field δB_r from midplane saddle loops; and (c) electron temperature from ECE (measurements spaced 2.5 cm apart in major radius). The measurements show the onset of the resistive wall mode at t=1.33 s in discharge 96519.

An important distinction between the usual tearing locked mode [9] and the onset of a resistive wall mode (RWKM or RWTM) is that the locking process of a tearing mode involves an instability that begins nearly stationary with respect to the plasma. If at mode onset the plasma is rotating, then $f_{\text{mode}} \sim f_{\text{plasma}}$ until an increasingly rapid transfer of momentum between the plasma and the wall eventually brings both the plasma and the mode to rest. In contrast, the experiments described here clearly show an instability that begins nearly stationary with respect to the wall, while the plasma is rotating past it ($f_{\text{mode}} \ll f_{\text{plasma}}$ at mode onset), therefore the instability observed in these experiments is a resistive wall mode.

Figure 4 shows the result of a braking experiment, where the plasma rotation is systematically decreased using a static n=1 poloidal magnetic field perturbation applied from an external coil (C-coil) [10]. The n=1 perturbation is non-resonant; its dominant poloidal harmonics are m=1 and m=2, but there is no q=1 or q=2 surface in the plasma. The three representative cases illustrate the correlation between the time of the RWM disruption and the magnitude of the braking field. As the coil current and braking increases, the rotation decreases more rapidly, reaching a critical value of ~6 kHz earlier, when the RWM onset is detected in all cases.

At the time of the RWM onset, the discharges of this sequence have a β_N value ~2, and are predicted just above the β_N limit with a wall at infinity. No RWM rotation was detected. In comparison, the higher β_N plasma of Fig. 1 becomes unstable at a lower plasma rotation threshold, and a RWM rotation ~60 Hz was measured. These observations are in qualitative agreement with predicted relationships between plasma β_N, RWM rotation, and plasma rotation required for stability of the RWM [2].

The direct and reproducible observation of the RWM, increased duration of wall stabilized plasmas, and the observation of a critical rotation rate needed for stabilization, have begun to yield physics understanding needed to predict with confidence the requirements for wall stabilization in future devices. Future experiments will focus on the implementation on DIII-D of the "smart shell" [11] concept for active feedback control of the RWM: the feedback loop is designed to make the resistive wall appear perfectly conducting using coils outside the vessel to maintain a net zero radial magnetic field at the wall. Preliminary open-loop tests of this scheme have been carried out, with encouraging results.

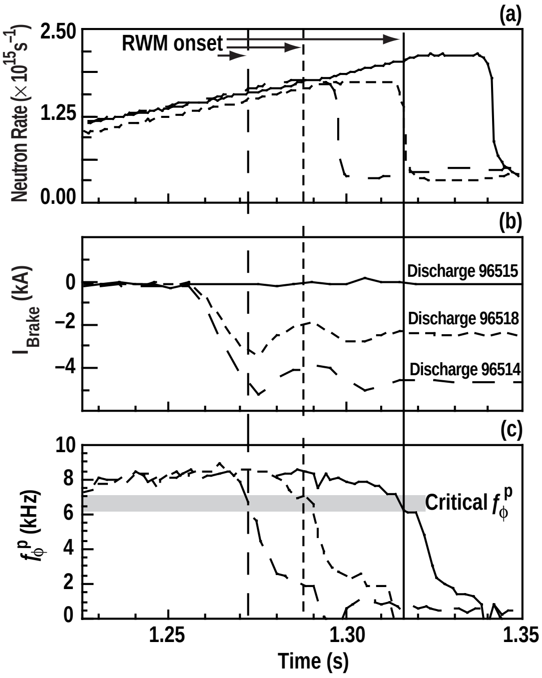

Fig.4. Controlled variation of the RWM onset through C-coil braking of the plasma rotation in similar discharges. Time evolution of (a) neutron rate; (b) C-coil current, proportional to the magnetic braking field; and (c) plasma rotation f_ϕ^p at the q=3 surface.

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