Resistive Wall Stabilization of High Beta Plasmas in DIII–D*

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Recent DIII–D experiments have demonstrated sustained stable operation well above the free-boundary stability limit (Fig. 1). The n=1 ideal kink mode is stabilized at high beta by a resistive wall and a combination of plasma rotation and active feedback, or by rotation alone, for durations up to 1.5 s. The key to this achievement has been to minimize resonant asymmetries of the magnetic field. Otherwise, a resonant plasma response to the static n=1 field asymmetry enhances the drag on plasma rotation at high beta, leading to loss of rotation followed by growth of an instability. A new technique makes use of this resonant plasma response to reduce the magnetic field asymmetry through feedback control. The ideal wall-stabilized beta limit has been reached (Fig. 2), at approximately twice the free-boundary limit [1].

Many "advanced tokamak" scenarios for steady-state operation at high beta rely on wall stabilization of the ideal kink mode. The broad current density profile associated with a large bootstrap current leads to a relatively low free-boundary kink mode limit, but also allows the possibility of stabilization by an ideally conducting wall. In the presence of a resistive wall, such as the DIII–D vacuum vessel, the kink mode is not completely stabilized but is converted to a slowly-growing resistive wall mode (RWM). Theory and numerical modeling predict that the RWM can be stabilized by feedback control [2] or plasma rotation [3]. However, DIII-D experiments have typically shown strong slowing of the rotation in the wall-stabilized regime [4].

The theoretically predicted "amplification" of magnetic field asymmetries by a marginally stable RWM [5], resulting in a strong drag on plasma rotation, has now been directly observed in DIII–D experiments. A six-section external coil set, located at the midplane, was used to apply a pulsed n=1 radial magnetic field perturbation in high beta

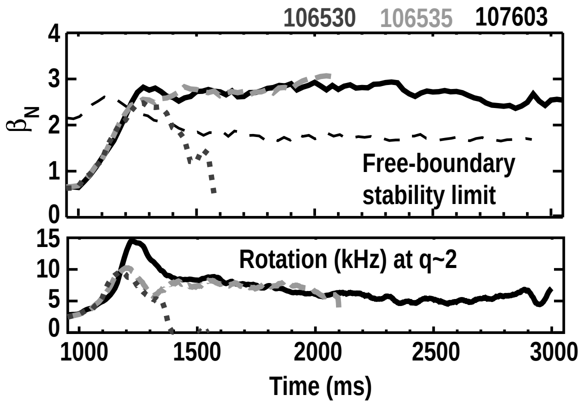

Fig. 1. Symmetrization of the external magnetic field allows the plasma to rotate, leading to sustained operation above the free-boundary stability limit (solid curves). A further increase in beta leads to a disruption at the calculated ideal-wall stability limit (dash curves). With uncorrected magnetic field asymmetry, plasma rotation and stabilization of the resistive wall mode are lost soon after the free-boundary beta limit is exceeded (dotted curves).

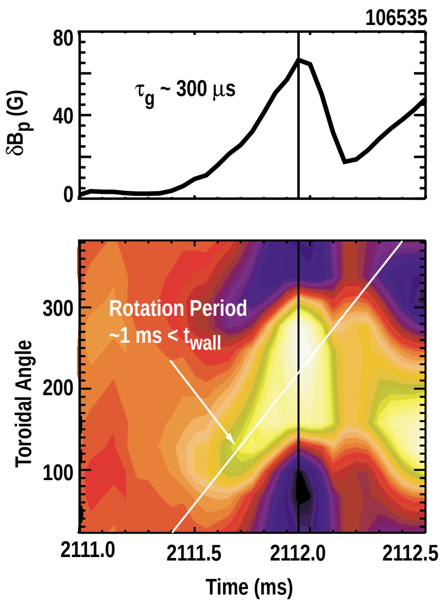

Fig. 2. Disruption precursor at the calculated ideal-wall beta limit grows in ~300 µs, consistent with an ideal MHD instability. The wall acts as a near-perfect conductor at the mode rotation rate of ~1 kHz.

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plasmas. Although the applied n=1 field has equal right- and left-handed helical components, the measured plasma response has a left-handed helical structure consistent with excitation of a resonant mode. As beta is raised above the free-boundary stability limit, the amplitude of the plasma response increases rapidly and the measured damping rate decreases. The applied n=1 perturbation has little effect on the plasma at low beta, but causes a strong slowing of plasma rotation at beta above the free-boundary stability limit, as expected.

Several independent techniques using the system of six external control coils have been shown to symmetrize the external magnetic field, and thereby to sustain the plasma rotation. Feedback control of the coils is designed to minimize the resonant n=1 plasma response, and thus minimizes the field asymmetries that drive that response. Pre-programming the same coil currents without feedback yields similar results with respect to plasma stability, showing that the system is primarily responding to static field asymmetries and not an unstable plasma mode. Discharge-to-discharge adjustment of the coil currents to maximize plasma rotation converges on the same current distribution found with magnetic field symmetrization by the feedback system.

The stability of DIII–D plasmas has been significantly improved through these techniques. Operation above the free-boundary stability limit has been sustained for as long as 1.5 s, about 300 times the characteristic wall penetration time for n=1 fields (Fig. 1) and limited in this case only by a power supply fault. A further increase in beta up to about twice the free-boundary limit results in a disruption with a fast-growing precursor, consistent with calculations showing that the wall-stabilized kink mode limit has been reached (Fig. 2). In other discharges, rotation has allowed stable operation at normalized beta ($\beta_N = \beta(aB/I)^{-1}$) up to 4.2, well above the free-boundary limit of about 2.8 for these discharges (Fig. 3).

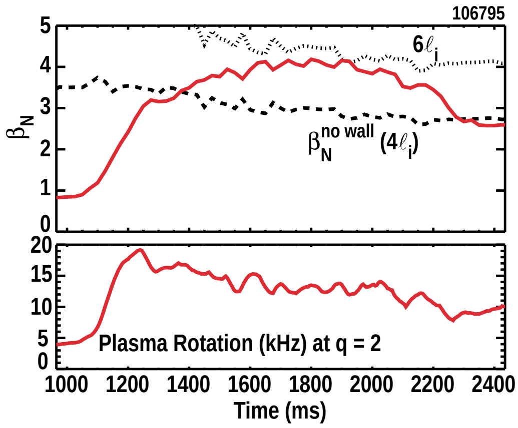

Fig. 3. Sustained operation above the free-boundary limit in a high-beta plasma: β_T (%) ≈ β_N ≈ 4.2. Here the free-boundary β_N limit is approximated by 4 ℓi (internal inductance), a typical value for DIII–D. The high-beta duration is limited by the onset of an m=2/n=1 tearing mode.

Direct feedback control of the RWM using the six external control coils can also improve plasma stability in DIII–D [6]. In these experiments, the rotation is allowed to decay to the threshold of rotational stabilization. Feedback control prolongs the stable duration as the plasma continues to become more unstable. Briefly switching off the feedback during this time leads to a growing mode, showing that feedback is indeed controlling an unstable mode. Experimental results are in good qualitative agreement with modeling predictions [6,7] that RWM stabilization is improved with radial field sensors inside the wall as compared to radial field sensors outside the wall, and further improved with poloidal field sensors, which do not couple to the applied radial field. A new set of twelve control coils inside the vacuum vessel, planned for installation in 2003, is predicted to allow feedback stabilization up to essentially the ideal wall-stabilized limit even in the absence of rotation.

These results open a new regime of tokamak operation above the free-boundary stability limit, accessible by a combination of plasma rotation and feedback control. This regime is favorable for steady-state plasma with high fusion gain and a high fraction of bootstrap current.

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