Topic: TH-S

Modeling of Feedback and Rotation Stabilization of the Resistive Wall Mode in Tokamaks*

M.S. Chu,[1] M.S. Chance,[2] A.H. Glasser,[3] M. Okabayashi,[2] V.S .Chan,[1] S.C. Guo,[4]
D.A. Humphreys,[1] T.H. Jensen,[1] L.L. Lao,[1] F.W. Perkins,[2] H.E. St.John,[1] E. Soon,[5]
A.D. Turnbull,[1] M.L. Walker,[1] and S.K. Wong[1]

[1]General Atomics, P.O.Box 85608, San Diego, California 92186-5608 USA
email: chum@fusion.gat.com
[2]Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, New Jersey 08543 USA
[3]Los Alamos National Laboratory, Los Alamos, New Mexico 87545 USA
[4]Consorzio RFX, Corso Stati Unit 4, Padova 35127, Italy
[5]Univeristy of California, San Diego, 9500 Gilman Drive, La Jolla, California 92093 USA

A practical tokamak fusion reactor must have a beta normal (β_N) of at least 3.5 at high current [1]. This requires steady-state operation of the tokamak above the no wall β_N limit ($\leq$2.8) with sustained stabilization of the resistive wall mode (RWM) [2].

The paper describes modeling and validation of feedback control and rotational stabilization of the RWM in tokamaks. Normal mode [3,4] analysis and time dependent simulations [5] have been compared with experiment to validate the various mechanisms invoked in the model and to anticipate the performance of the feedback system in coming experiments.

The normal mode approach has been found to be particularly useful for studying the feedback stabilization of the RWM for plasmas with negligible toroidal rotation. In this approach, the open loop system dynamics are described by a set of normal modes. Only one of which, (the RWM) can be unstable. The rest are stable (damped) modes in which the resistive wall provides the dissipation. The magnetic signals from the plasma instability and that from the external feedback coils are decomposed into the normal modes of the open loop system. These results are then coupled with the characteristics of the feedback circuits to determine the closed loop behavior.

This approach has been applied to the DIII–D geometry shown in Fig. 1, with up to three bands (central mid-plane, upper, and lower) of external feedback coils. As shown in Fig. 2, the strength of the RWM (growth rate normalizes by the resistive wall time, $\gamma\tau_W$) in

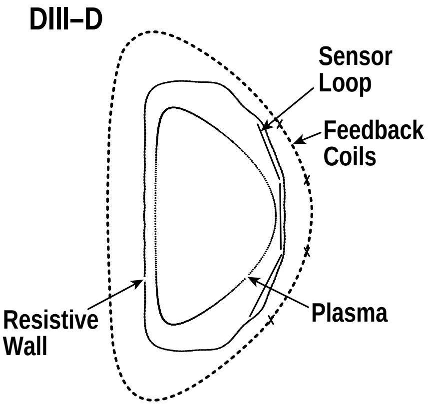

Fig. 1. Schematic of plasma, resistive wall, sensor loops and external feedback coil location in the poloidal cross-section.

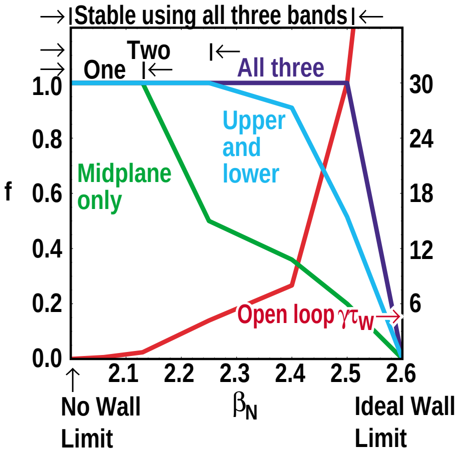

Fig. 2. Effectiveness, f, of different feedback coil arrangements in stabilizing the plasma versus β; f is a measure of the completeness of suppression of the RWM normalized between f=0 (no suppression) and f=1 (complete suppression).

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absence of feedback) has been found to be a strongly increasing function of plasma β. It is found that using the upper and lower bands of feedback coils can provide a substantial additional stabilization effect to the RWM. Using the central midplane band only, the strength of the RWM that can be stabilized is computed to be around $\gamma\tau_W$=1. Together with the two upper and lower off-mid-plane bands, the strength of the RWM that can be stabilized is up to a factor of 30 stronger. On the other hand, using the upper and lower bands only without the central band will limit the strength of the RWM that can still be stabilized to $\gamma\tau_W$=5. The effect of variation in the geometry of the various elements is also studied. The sensor loops have been varied from sensing radial field to poloidal field. The feedback coils have been varied from providing radial field to providing poloidal field. Various forms of feedback logic including “Smart Shell” and “Mode Control” [5] are also studied.

Plasma rotation has been found to stabilize the RWM even in the absence of feedback. The linear dispersion relation for general plasma geometry indicates that, aside from the plasma potential energy with and without the external resistive wall, the crucial parameter that determines the rotational stabilization is the dissipation associated with plasma rotation. Different models of angular momentum exchange between a rotating plasma and the RWM are examined theoretically. These include the sound wave damping model, plasma viscosity model, the induction motor model and the transit time magnetic pumping model. They are used in assessing the stability of the plasma during its evolution and the effect on the plasma rotation profile. These angular momentum exchanges cause the RWM to be stabilized through the combined effect of feedback and plasma rotation. In the limit without feedback, a toroidal rotation rate of 1% of the Alfvén frequency has been found to be sufficient to stabilize the n=1 resistive wall mode with a favorable plasma equilibrium profile.

The presence of a sufficiently large external error field causes the plasma to lose angular momentum and slow down. The strength of these interactions is calculated from experiment in order to perform realistic simulations of the development of the RWM. For instance, the uncorrected external error field has been found to cause anomalous angular momentum loss to the plasma at a rate exceeding 3500 times the neoclassical value. The amplitude of the field and the phase response of the plasma to the external imposed error field are obtained when the plasma β increases through the marginal stability [6] point.

The presence of the RWM in the DIII–D experiment is identified through detailed comparison of the observed signals from the experiment with that anticipated from theory. These comparisons in turn validate and reduce uncertainties in the plasma model. The validated model is used to investigate the characteristics of the feedback circuits necessary for controlling the instability for future experiments.

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