GA–A26683

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MAY 2010

GENERAL ATOMICS

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This is a preprint of a paper to be presented at the 23rd IAEA Fusion Energy Conference, October 11–16, 2010 in Daejon, Republic of Korea and to be published in Proceedings.

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Work supported in part by
the U.S. Department of Energy
under DE-FG02-89ER53297, DE-FC02-04ER54698
and DE-AC02-09CH11466

GENERAL ATOMICS ATOMICS PROJECT 30200
MAY 2010

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Recent DIII-D experiments deliver strong evidence for the importance of kinetic modifications of ideal MHD 3D equilibrium and resistive wall mode (RWM) stability models. At high plasma pressure, the observed stability of the RWM over a wide range of plasma rotation profiles and the measured dependence of the plasma response to externally applied non-axisymmetric fields on plasma pressure and rotation can both be explained by wave-particle resonances due to the quasi-static perturbation of the equilibrium field. The DIII-D results highlight the necessity to extend the kinetic RWM stability model originally developed by Bondeson and Chu [1] by including the precession motion of trapped particles [2] as well as the effect of trapped energetic ions [3]. Experimental tests of these kinetic models are essential in developing confidence in predictions for reactor scenarios that rely on wall-stabilization, such as the steady-state scenario in ITER.

Deviations from ideal MHD already become apparent in magnetic measurements of the plasma response to externally applied non-axisymmetric magnetic fields even before the normalized plasma pressure β exceeds the ideal MHD no-wall stability limit [4]. While the ideal MHD model implemented in the MARS-F code [5] is in good agreement with the *n*=1 plasma response measured with poloidal field sensors outside the plasma for values of β up to 80% of the no-wall limit, the model starts to overestimate the response at higher values of β and predicts instability above the no-wall limit, Fig. 1. The non-ideal effects that limit the plasma perturbation in the presence of externally applied fields at high β, also modify the RWM stability, since 3D equilibria and RWMs both constitute a similar quasi-static (when compared to plasma rotation or particle motion) 3D perturbation of the 2D plasma equilibrium.

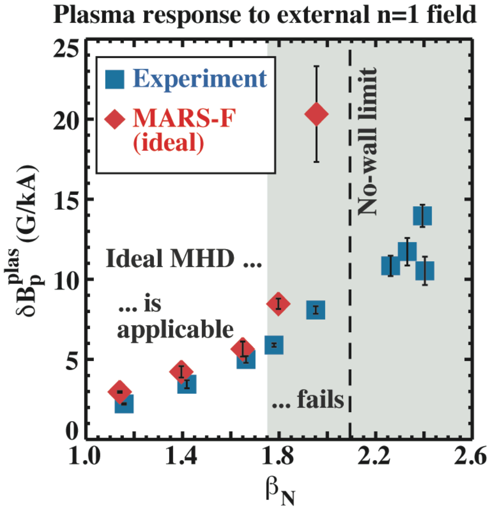

Fig. 1. Measured (squares) and modeled (diamonds) beta dependence of the plasma response to externally applied *n*=1 fields using DIII-D's I-coil.

A detailed comparison of experimental observations with modeling shows that kinetic RWM stability models can explain the wide range of stable rotation profiles in DIII-D, Fig. 2(a), but indicates that the effect of energetic ions must be included. Taking into account only thermal particles the kinetic RWM stability model implemented in the MISK code [3] leads to stability at low plasma rotation [$\Omega\tau_A(q=2)$ <1%], when precessing trapped ions resonate in the perturbed magnetic field, and at higher rotation [$\Omega\tau_A(q=2)$>1%], when the bounce motion of trapped particles resonate with the perturbation, but is not sufficient to explain the observed stability over the entire range of rotation profiles, Fig. 2(b). Adding the contribution of trapped energetic ions, which originate from the neutral beam injection (NBI) heating and constitute up to 35% of the kinetic energy of the plasma, stabilizes the RWM over the entire range of rotation profiles [$\Omega\tau_A(q=2)$~0-2%], Fig. 2(b), consistent with DIII-D observations. The importance of energetic ions for RWM stability is further supported by the observation that fishbone like modes, which quickly redistribute energetic ions, can trigger RWMs [6].

Measurements of the plasma response in plasmas above the ideal MHD no-wall stability limit also yield more direct evidence for the importance of the precession and bounce frequencies of trapped ions. Varying the NBI torque in otherwise similar plasmas yields the largest plasma response to an externally applied *n*=1 field, indicating weaker damping of the RWM, when $\Omega\tau_A(q=2)\approx 1\%$, Fig. 3. The weakest damping, thereby, occurs in the rotation gap

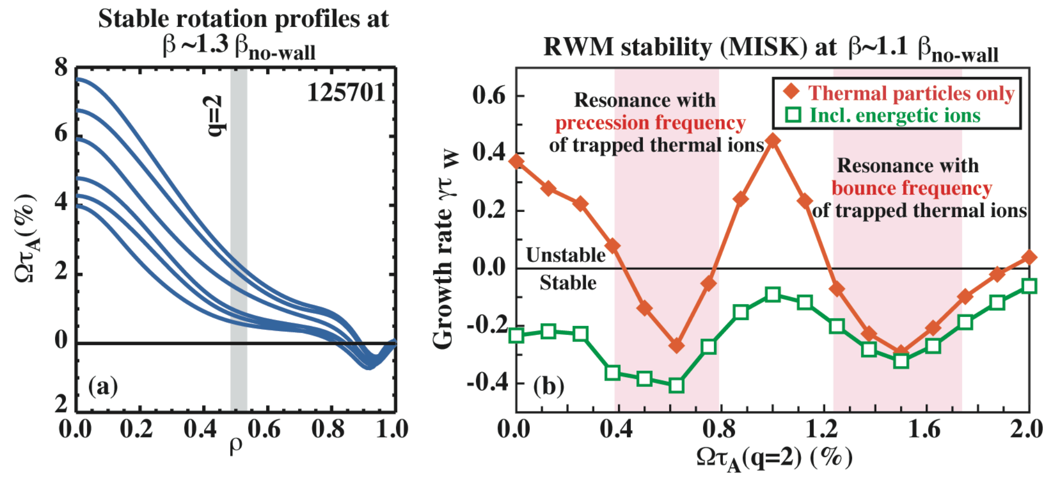

Fig. 2. (a) Stable rotation profiles and (b) kinetic calculations of stability with and without energetic ions using the MISK code. $\Omega\tau_A$ is the toroidal plasma rotation normalized to the Alfvén time.

between the precession and bounce frequencies of the trapped thermal particles, qualitatively consistent with the kinetic calculations shown in Fig. 2(b). The importance of these two wave-particle resonances is also exposed by the measured toroidal phase shift between the plasma response and the externally applied field.

Modifications of ideal MHD are the physics basis for passive RWM stabilization, which is very attractive for a reactor since it increases the attainable β_N, and thereby fusion performance, without the need for a complex magnetic feedback system. In order to extrapolate the potential of passive RWM stabilization with confidence from today's NBI heating dominated experiments to a burning plasma, the role of rotation and energetic ions has to be understood. The present DIII-D experiments are an important step towards this understanding.

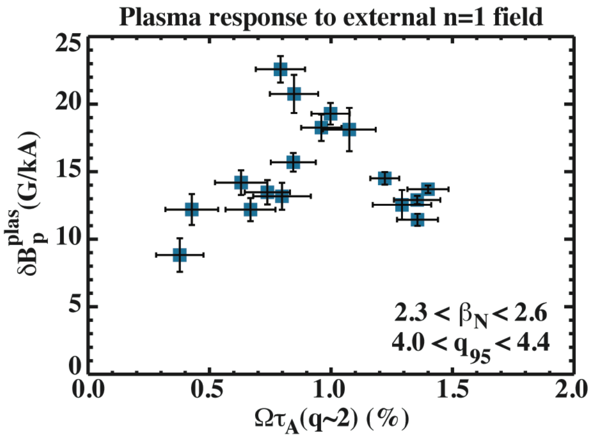

Fig. 3. Rotation dependence of the plasma response to externally applied *n*=1 fields in wall-stabilized discharges.

This work was supported in part by the US Department of Energy under DE-FG02-89ER53297, DE-FC02-04ER54698, and DE-AC02-09CH11466.

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