Observation and Analysis of Mercier Instabilities in C-Mod

R.J. Hastie, Y. In, J.J. Ramos, P.J. Catto[1], A.E. Hubbard, I.H. Hutchinson, E. Marmar, M. Porkolab, J. Snipes, S. Wolfe, G. Taylor[2], and A. Bondeson[3]

MIT Plasma Science and Fusion Center, Cambridge, MA 02139, U.S.A.
[1] Lodestar Research Corporation, Cambridge, MA 02139, U.S.A.
[2] Princeton Plasma Physics Laboratory, Princeton, NJ 08543, U.S.A.
[3] Chalmers University of Technology, Göteborg, Sweden

e-mail contact: hastie@psfc.mit.edu

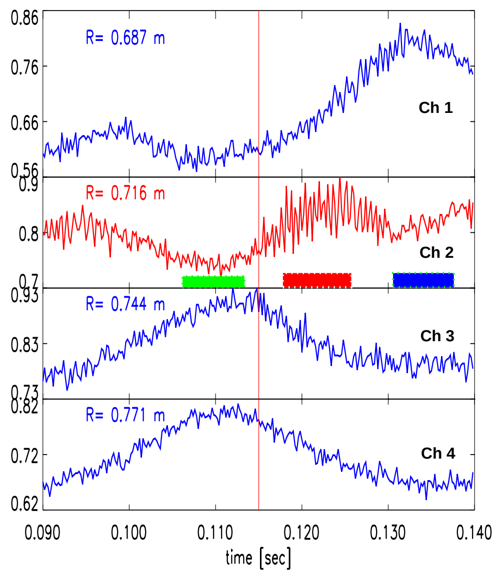
Abstract. During current ramp discharges, highly localized MHD fluctuations were observed on ECE diagnostics of Alcator C-Mod tokamak. The electron temperature profile was hollow, while the density profile was almost flat. Assuming that the equilibration time was short enough to quickly thermalize ions with $T_i/T_e \approx 0.9$, the pressure profile was also found to be hollow. Using the pressure profile as an additional constraint to the EFIT program, an equilibrium with reversed shear was constructed, whose q(0) $\gg$ 1. The localized MHD activity was observed near the inner q=5 rational surface in this reconstructed equilibrium. According to ideal MHD stability theory, it was found to be ideally unstable because of the reversed pressure gradient ($dp/dr > 0$), $q \gg 1$ and moderate shear. When kinetic effects are added, the ideal Mercier mode was finite ion Larmor radius (FLR) stabilized. However, considering that the ions are collisionless ($\nu_{ii} \ll \omega$), and the thermal ion transit frequency is comparable to the ion diamagnetic drift frequency ($\omega_{ti} \sim \omega_{*pi}$), ion Landau damping was found to be strong enough to drive kinetic Mercier instability. As a result, the localized fluctuations in C-Mod can be attributed to a FLR modified kinetic Mercier instability.

1. Introduction

During a recent experimental campaign on C-Mod a series of reversed shear (RS) discharges was investigated [1]. During the early phase of the current ramp in these discharges the electron temperature profile is observed to be hollow with an off-axis peak of around 0.9keV, and equilibrium reconstructions using EFIT indicate that the profile of the safety factor, $q(r)$, is also non-monotonic, with the axial value, $q(0) \gg 1$, and an off-axis minimum at $r/a \sim 0.6 - 0.8$.

These RS discharges displayed a variety of MHD activity, including global electron temperature fluctuations which can be explained in terms of double tearing modes[2]. In addition, however, in several discharges localized fluctuations were observed on one ECE channel, and magnetic data revealed a coherent oscillation at a frequency of a few kHz. At the time of observation these localized instabilities were the only ones present in the discharge and they continued for 10 - 15 msecs.

Figure 1 shows the Electron Cyclotron Emission (ECE) from several channels showing the presence of a localized fluctuation in electron temperature, most noticeable at R=0.716 m between 115 and 130 msec. Figure 2 shows the Fourier decomposition of the magnetic data with a coherent signal at $f \sim 3.2kHz$. In addition, it was possible, using this magnetic data, to determine the toroidal mode number of the instability as $n = 1$.



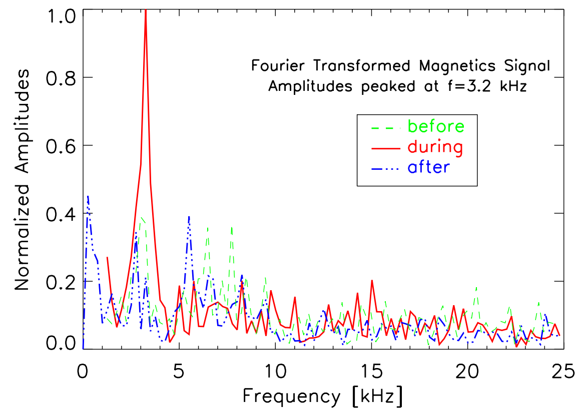
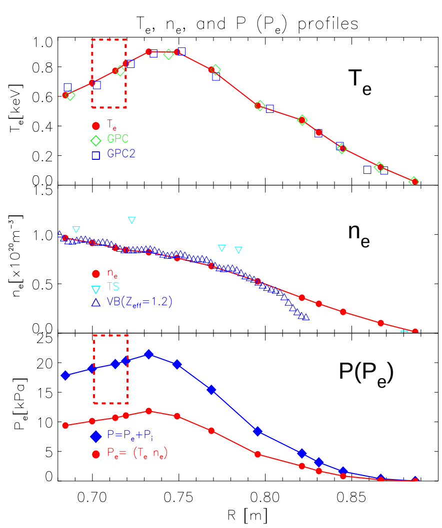


Figure 1 (Left) Highly localized MHD activity on the innermost four grating polychromator (GPC) channels.
Figure 2 (Right) Fourier-transformed magnetic signals before, during and after the MHD activity.

This paper gives an account of the theoretical analysis of these fluctuations and their identification as kinetic Mercier instabilities. In Sec.2 we present the results of MHD stability calculations, with the MARS code[3]. These predict Mercier instability. In Sec.3 we discuss finite Larmor radius stabilization and show that the ideal Mercier[4] modes found in Sec.2 are FLR stabilized. The dominant dissipative effect for these modes is identified as ion Landau damping, and in Sec.4 solutions of a kinetic dispersion relation, which includes ion Landau damping, are presented. These results show that a kinetic Mercier mode is predicted to be unstable in the reverse shear core of C-Mod. Section 5 presents a summary and discussion.

2. 2-D Toroidal Ideal and Resistive MHD Simulations



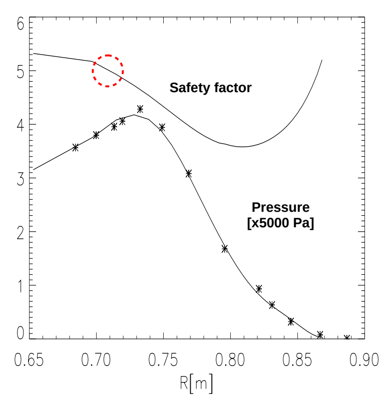


Figure 3 (Left) Electron temperature (T_e), density (n_e), pressure (p_e) and total pressure profiles.
Figure 4 (Right) $q(r)$ and pressure profiles.

Reconstruction (with the aid of EFIT) of the equilibrium in shot 990526029 indicates that $q(0) > 5$, and that $q(r) = 5$ at the location ($r/a \sim 0.25$) of the observed temperature fluctuations. The reverse shear $q(r)$ profile, and the hollow temperature profile are shown

in Figs.3 and 4 respectively. Instability studies using the MARS code[3] (with toroidal mode number, $n = 1$) predict the presence of a localised ideal MHD instability with growth rate $\gamma \sim 10^{-3}\omega_A$, where $\omega_A = B_0/R\mu_0\rho^{1/2}$.
Figure 5 shows the scaling of γ as the magnetic Reynolds number, S, is increased from the relevant C-Mod value of $S \sim 10^7$ to infinity. Figure 5 also shows the growth rate (solid circles) of a weakly unstable global tearing mode, predicted by the MARS code, but not observed in this experiment. Such global double tearing modes have indeed been observed in other current ramp discharges [2]. Figure 6 shows the pressure perturbation and its poloidal harmonic content. Evaluation of the exact Mercier[4] stability criterion, $1/4 - D_M > 0$ reveals that this criterion is violated across a substantial region of the plasma core where the electron temperature gradient is reversed ($dT_e/dr > 0$). Near the magnetic axis, if the magnetic surfaces are approximately circular, D_M takes the form:

$$D_M = \frac{-2\mu_0 r p'(1-q^2)}{B^2 s^2} \tag{1}$$

with the shear $s \equiv rq'/q$ and primes representing radial derivatives. The key factors contributing to violation of the Mercier criterion in the core of C-Mod are the large values of q ($q^2 > 20$), the moderate shear, and the reverse pressure gradient. It is therefore natural to identify the observed fluctuations with an $n = 1$ and dominantly $m = 5$ Mercier instability.

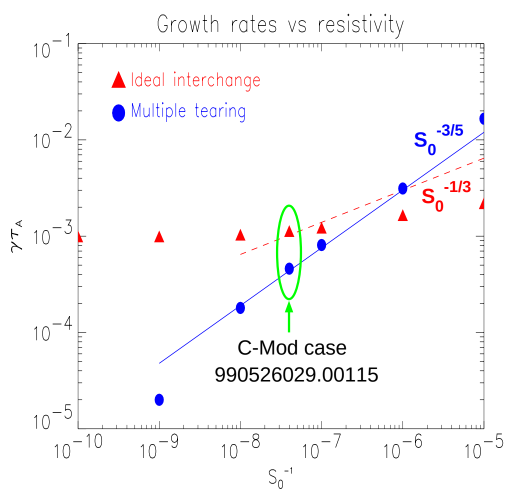


Figure 5 Growth rates vs resistivity using MARS code.

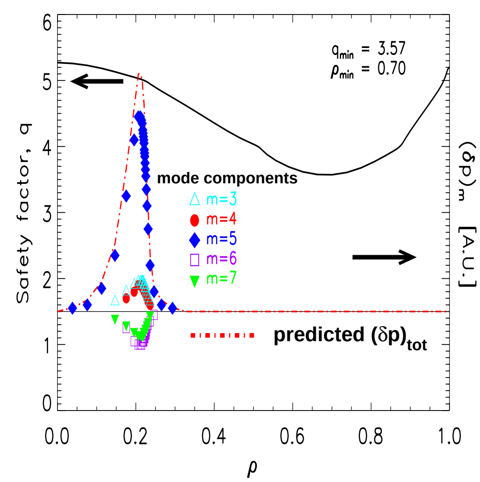


Figure 6 n=1 ideal interchange mode.

3. The Effect of Finite Ion Larmor Radius (FLR) Stabilization

The FLR [6,7] modified eigenvalue can immediately be obtained from the ideal MHD growth rate, γ_I, calculated by e.g. the MARS code, by solving the dispersion relation, $\omega(\omega - \omega_{*pi}) + \gamma_I^2 = 0$, where γ_I is the ideal MHD growth rate, ω is the complex eigenvalue and $\omega_{*pi} = \frac{m}{neBr}\frac{dp_i}{dr}$. For a weak instability, inertia is only important close to the resonant magnetic surface so that only $\omega_{*pi}(r = r_s)$ is required. The result is a pair of modes with $\omega = \omega_\pm$ where,

$$\omega_\pm = \frac{\omega_{*pi}}{2} \pm \sqrt{\frac{\omega_{*pi}^2}{4} - \gamma_I^2} \tag{2}$$

Thus, when

$$\gamma_I < \frac{\omega_{*pi}}{2} \tag{3}$$

the ideal MHD solutions are replaced by a pair of, marginally stable, oscillatory modes with frequencies in the range $[0, \omega_{*pi}]$, ie within the diamagnetic gap in the Alfven continuum. Surprisingly, for an $n = 1$ ideal mode, when we evaluate ω_{*pi} for the core plasma conditions in these Alcator C-Mod discharges, we find that inequality (3) is satisfied and that the ideal $n = 1$ Mercier mode is FLR stabilized. In fact $\omega_{*pi}/2 \sim 2.9 \times 10^4$, while $\gamma_I \sim 1.3 \times 10^4$.

It is, however, well known that FLR stabilization is not robust. Addition of any plasma dissipation to the equations results in destabilization of one of the oscillatory modes and damping of the other. Which mode is damped and which destabilized depends on the the precise nature of the dissipation. The task is therefore to identify which dissipative effect is dominant in any given situation. For the conditions of the C-Mod discharges under consideration we have evaluated the following characteristic frequencies: electron collision frequency, ν_e; ion collision frequency, ν_{ii}; ion diamagnetic frequency, ω_{*pi}, which we take to be equivalent to the mode frequency ω_+; ion transit frequency, $\omega_{ti} = \sqrt{2T_i/m_i}/Rq$; Alfven transit frequency, ω_A/q. These are $\omega_A/q = 2.5 \times 10^6$, $\gamma_I = 1.3 \times 10^4$, $\omega_{*pi} = 5.8 \times 10^4$, $\omega_{ti} = 8.2 \times 10^4$, $\nu_{ii} = 2.7 \times 10^3$, $\nu_e = 2.3 \times 10^5$, in units of rad/sec.

From these results we conclude that: (i) electrons are collisional ($\nu_e >> \omega_\pm$); (ii) ions are collisionless, ($\nu_{ii} << \omega_+$); and (iii) an oscillatory mode for which $\omega \sim \omega_{*pi}$ is strongly resonant with passing ions of thermal energy, $\omega \sim \omega_{ti}$. Ion Landau damping is, therefore, likely to be the dominant form of dissipation for the upper of the two FLR stabilised gap modes, so we examine the relevant kinetic theory in the next section.

4. Kinetic Theory of Mercier modes and the effect of Ion Landau Damping

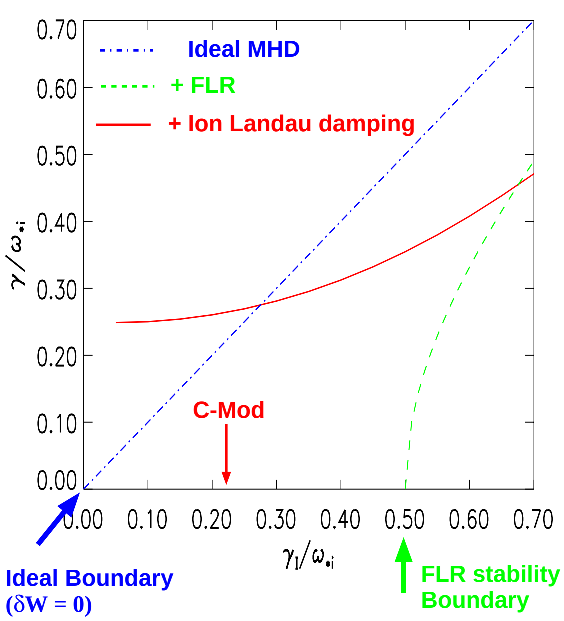


Figure 7 Growth rates.

The relevant 'inertial layer' theory for low frequency modes in the presence of ion Landau damping has been developed in a number of papers [7,8]. Solving the drift kinetic equation for the perturbed ion distribution function one finds that this contains the two sideband harmonics with $m' = m \pm 1$, which are strongly Landau resonant. Parallel ion dynamics is also affected by an electrostatic component in $E_\parallel$, so the analysis requires a consistent solution of the quasi-neutrality condition to determine this electric field. The resulting dispersion relation, Eq. (21) of Ref.[8], can be written in the form:

$$\omega(\omega - \omega_{*pi}) + q^2\omega\omega_{ti}[(1 - \frac{\omega_{*i}}{\omega})F(\frac{\omega}{\omega_{ti}}) - \frac{\omega_{*i}\eta_i}{\omega}G(\frac{\omega}{\omega_{ti}}) - \frac{N^2(\frac{\omega}{\omega_{ti}})}{D(\frac{\omega}{\omega_{ti}})}] + \gamma_I^2(1 + 2q^2) = 0 \quad (4)$$

where the functions F, G, N and D contain the plasma dispersion function and are defined in Ref. [8], $\omega_{*i} = \frac{mT_i}{neBr}\frac{dn}{dr}$ and $\eta_i = dLn(T_i)/dLn(n)$.

Equation (4) has been solved with parameter values representing C-Mod conditions $(\omega_{*pi}/\omega_{ti}) \sim 0.7$, $\eta_i \sim -2$ and by varying the ideal MHD growth rate (γ_I/ω_{*pi}) over the range $[0, 0.7]$, which spans the typical value found by the MARS code, $\gamma_I/\omega_{*pi} \sim 0.22$. An unstable, kinetic Mercier, mode is found throughout this range. Figure 7 shows the growth rate, γ/ω_{*pi}, in this range.

In the foregoing analysis the ion temperature was estimated from a close coupling approximation $(T_i(r) \sim T_e(r))$, which relied on the fact that the electron-ion equilibration time is short compared to the energy confinement time. As an alternative we have solved a time dependent thermal equation in which neoclassical thermal conduction[9] and classical electron-ion equilibration determine $T_i(r)$ when $T_e(r,t)$ is ramped up on the experimental time scale of about 100 msec. The result is a weakly non-monotonic $T_i(r)$, with a more weakly unstable Mercier instability predicted by MARS in the modified EFIT equilibrium. The ideal mode is again FLR stabilized, but ion Landau resonance and resistivity both drive a residual instability at finite frequency, $\omega_+ \sim \omega_{*pi}$.

5. Discussion and Conclusions

Detailed theoretical studies, with both the MARS MHD code and a collisionless kinetic analysis, have led to the identification of the localized temperature fluctuations in some RS discharges in Alcator C-Mod as FLR modified Mercier instabilities with n=1. The C-Mod observations may therefore be the first observation of Mercier instability in tokamaks. They indicate that, at least for m=5, the instability seems to be of a relatively benign nature, possibly because it is so localized.

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