PFC/JA-88-34

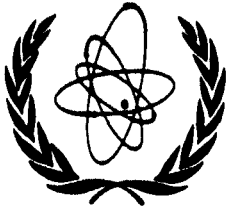# Stability Issues in the Tara Tandem Mirror Experiment

by

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G. Hallock, S. Horne, J. H. Irby, J. Kesner,
B. Lane, J. Machuzak, R. Myer, E. Sevillano,
D. K. Smith, J. D. Sullivan, R. Torti, X. Z. Yao,
and J. Zielinski

Plasma Fusion Center
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

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STABILITY ISSUES IN THE TARA TANDEM MIRROR EXPERIMENT

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E. Sevillano, D.K. Smith, J.D. Sullivan, R. Torti, X.Z. Yao, J. Zielinski

Plasma Fusion Center, Massachusetts Institute of Technology, Cambridge, Ma., USA

Abstract

Experimental studies were performed to understand the stability of the Tara tandem mirror. Central cell fluctuations are dominated by radially rigid, $m = 1$ flute modes in which the entire column oscillates about the machine axis. These modes can be stabilized by outboard quadrupole anchors, or by ponderomotive effects related to central cell ion cyclotron heating (ICH) power levels. A magnetic divertor installed at the central cell mid-plane has also significantly enlarged the stable operating parameter regime. Axially localized instabilities are clearly observed in the axicells during the application of axicell ICH. They also appear to exist during the application of axicell electron cyclotron heating (ECH) or neutral beams, and to limit the buildup of hot electrons and beam ions.

Introduction

The Tara tandem mirror configuration[1] consisted of a 10 m solenoidal central cell with a "magnetic plateau" at its center where the field rose to a mirror ratio of about two with respect to the "well" regions on either side. Atop the plateau was a "slot" antenna which launched radio frequency (RF) waves resonant with the ion cyclotron frequency at the bottoms of the adjacent wells. Also atop the magnetic plateau was a gas box[2] which was the primary fueling source for the plasma. Between these was mounted a magnetic divertor that diverted a fraction of the plasma around a coil and created an azimuthally symmetric null. This divertor was installed with the purpose of providing stability by enhanced electrical connection across field lines.[3] Using this configuration a stable central cell plasma ($T_{i,\perp} = 600$

- 1500 eV, $T_{i,\parallel} = 150 - 200$ eV, $T_e = 60 - 100$ eV, $n_e = 4 - 5 \times 10^{12} cm^{-3}$) could be created consistently.

The central cell region was terminated by high field (mirror ratio $R_c \leq 12$) coils, and flanked by axisymmetric plug cells (axicells) and outboard quadrupole minimum-B anchor cells. The axicells were designed to provide electrostatic plugging of the central cell endlosses through the use of neutral beams and gyrotrons[4] or, alternately, through the use of RF resonant with the ion cyclotron frequency at the mid-plane of the axicell.[5]

Interchange Modes

Early experiments in Tara showed that the central cell could be maintained stably by the central cell slot ICH.[6] This stability is attributed to ponderomotive effects from the RF heating.[7] However the introduction of auxiliary sources of power, such as beams or gyrotrons, during endloss reduction experiments caused the central cell to become unstable in the parameter regimes of interest.[10] It was found that these modes could be stabilized at moderate levels of axicell ECH and ICH power through the use of the outboard anchors as originally proposed for Tara, although the theoretically predicted enhancement of stability due to the presence of hot electrons in the anchors[8] was never observed.[9] The outboard anchors, however, did not provide sufficient stability during higher power ECH pulses. Furthermore, the cutoff of the plasma stream to the adjoining anchor during axicell plugging reduced the anchor ion beta, and a loss of MHD stability often ensued, particularly during ECH plugging.

This problem was ameliorated by the introduction of the magnetic divertor at the central cell mid-plane. The divertor allowed a significant enlargement of the parameter range in which the central cell could operate stably without anchors and allowed higher gyrotron powers to be employed in plugging experiments.[11]

Under unstable conditions the dominant characteristics of the coherent mode seen in Tara were: (a) low frequency 3-15 kHz; (b) axially flute-like; (c) radially coherent. We observed a sharp threshold behavior with respect to ECH power.

Below a particular power the plasma was quiescent and the fluctuation level was independent of ECH power. Above this level fluctuations were large, but again the power dependence was weak. We interpret this behavior as evidence of a stability boundary.

In Figure 1 we show the stability boundary relative to the divertor null radius and ICH power level for several power levels of ECH heating in the axicell. We note that higher ICH power and smaller divertor null radius were stabilizing, while higher ECH power was destabilizing. Figure 1 demonstrates the interplay of divertor and ICH stabilization on two widely separated run days. The scaling of these stability boundaries with divertor current and ICH power was reproducible. More detailed description of the ponderomotive stabilization appears elsewhere.[7]
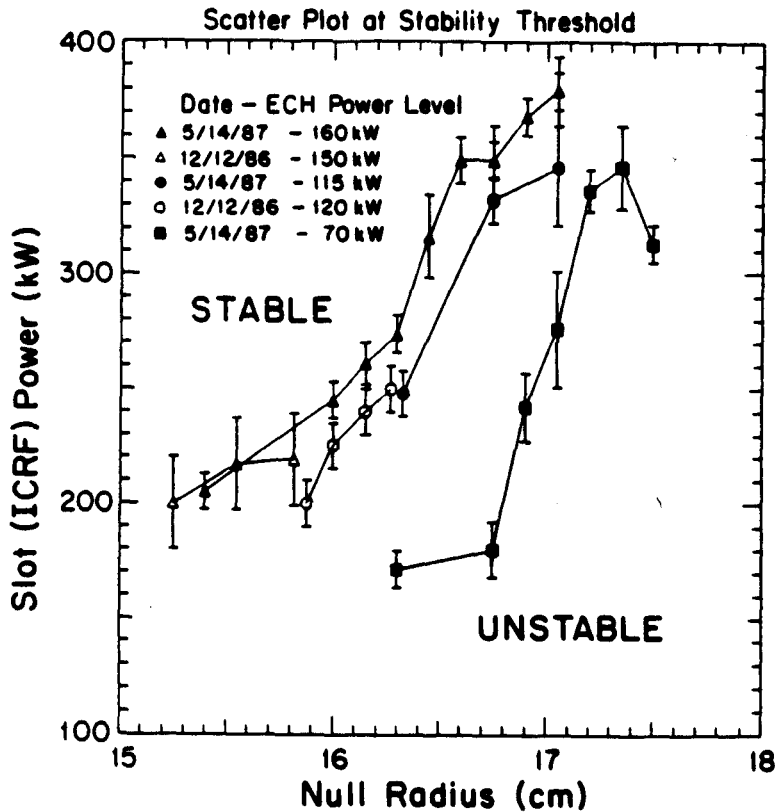

Figure 1. The multi-parameter nature of the stability boundary is shown at constant fueling rate. Plug ECH drives the plasma unstable. Enhanced stability is achieved by mapping the null deeper into the plasma, raising the central cell ICH power level, or both.
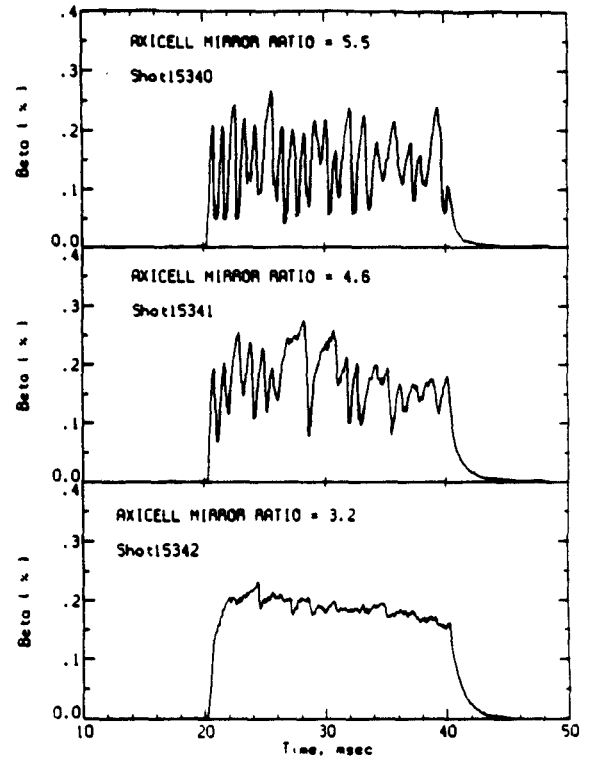
Figure 2. Series of shots exhibiting the damping of the north axicell sawteeth as the central cell mirror ratio R_c, is decreased.

Axially Localized Modes

Tara was seen to exhibit modes of instability which were axially localized.[13] At the highest divertor currents and at high R_c, ICRF heating in the north axicell was observed to drive only the axicell unstable. A buildup and dump in density and diamagnetism (β) was observed to occur with 1 to 2 ms periodicity. During each dump the neutral density increased in the axicell indicating that the plasma was scraping off in the axicell. These "sawteeth" and the increases in neutral density were *not* observed in the central cell.

The sawteeth were accompanied by increased low frequency noise detected by the gyrotron scattering diagnostic[14] and by Langmuir probes. We observed from the gyrotron scattering signal that the axicell diamagnetism rise triggered a coherent low frequency burst ($\approx$ 30 kHz) which built up until the dump. A correlated burst could be detected by the central cell heavy ion beam probe only in shots where the instability was strongest. The 30 kHz signal was generally *not* seen on the axicell light detector array, a line integrated diagnostic that should be insensitive to high m modes. Since the axicell light detector did pick up $m = 1$ and $m = 2$ flutelike modes, this suggests that the 30 kHz mode had $m \geq 3$. Double-tipped Langmuir probes, used in some shots, showed 30-100 kHz modes with $m =$3-10.

Figure 2 shows that the sawteeth decreased in amplitude and frequency as the mirror ratio between the central cell and axicell was decreased. Variation of the outer axicell high field coils did not affect the appearance of the sawteeth, supporting the view that it was the connection to the central cell that was important, not the axicell mirror ratio.

The relatively small axicell beta (less than 1%) precludes MHD ballooning as an explanation for the instability, and the passing fraction dependence implies that we were observing a trapped particle mode. Theoretically,[12]cancellation between the ion finite Larmor radius (FLR) stabilization term and the collisionless trapped particle mode charge separation term should lead to an unstable band of modes for azimuthal mode numbers $m \approx 4$ to 5, similar to what was observed. The data in Fig. 2 shows that the sawteeth decreased in amplitude when the passing fraction

n_{pass}/n_e was increased (by decreasing the mirror ratio between the central cell and axicell). This data is consistent with theory, which predicts that the azimuthal mode number m at which trapped particle modes are unstable is an increasing function of passing fraction. Modes with higher m should cause less rapid radial transport, since the radial loss rate is probably roughly γ/m^2 (where γ is the linear growth rate). Although the mechanism causing sawteeth is not fully understood, it appears to be related to the release of gas when plasma scrapes off, so we expect that the sawtooth amplitude will decrease when the radial loss rate decreases.

ECH Plugging

In the original Tara operating scenario,[1] plugging would be achieved by neutral beams which produce a density that peaks at the 10 kG point, and by ECH at both the barrier (5 kG) and plug (10 kG) points which would create a thermal barrier to further enhance the potential at the peak density point. In the experiment the neutral beams were never able to build up a density of greater than $4 \times 10^{11} \text{cm}^{-3}$ at the 10kG point (as inferred from the diamagnetism), and the population of hot electrons ($E_e > 100$ keV) that were localized to the barrier region never built up to more than 2% of the total density, although a large population of warm nonlocalized electrons ($E_e \approx$ 2-8 keV) was observed. These components were theoretically insufficient to produce a plugging potential. Nevertheless, ECH often produced a reduction in end loss, even without neutral beams, and even with only barrier ECH, in apparent contradiction to plugging theory. This is illustrated in Figure 3 which shows data from a discharge in which only the south barrier gyrotron was used. This data resembles plugging since the south endloss was cut off entirely. However there was no increase in north end loss, and the central cell density rise (corresponding to a trapping rate of 2A) cannot account for the 25A reduction in south end loss. We conclude that the reduction in south end loss was due not to plugging, but to enhanced ambipolar radial losses in the south axicell. Furthermore in discharges where the end loss was not cut off completely, potential peak measurements made by gridded end loss analyzers showed an overall rise in potential when ECH was
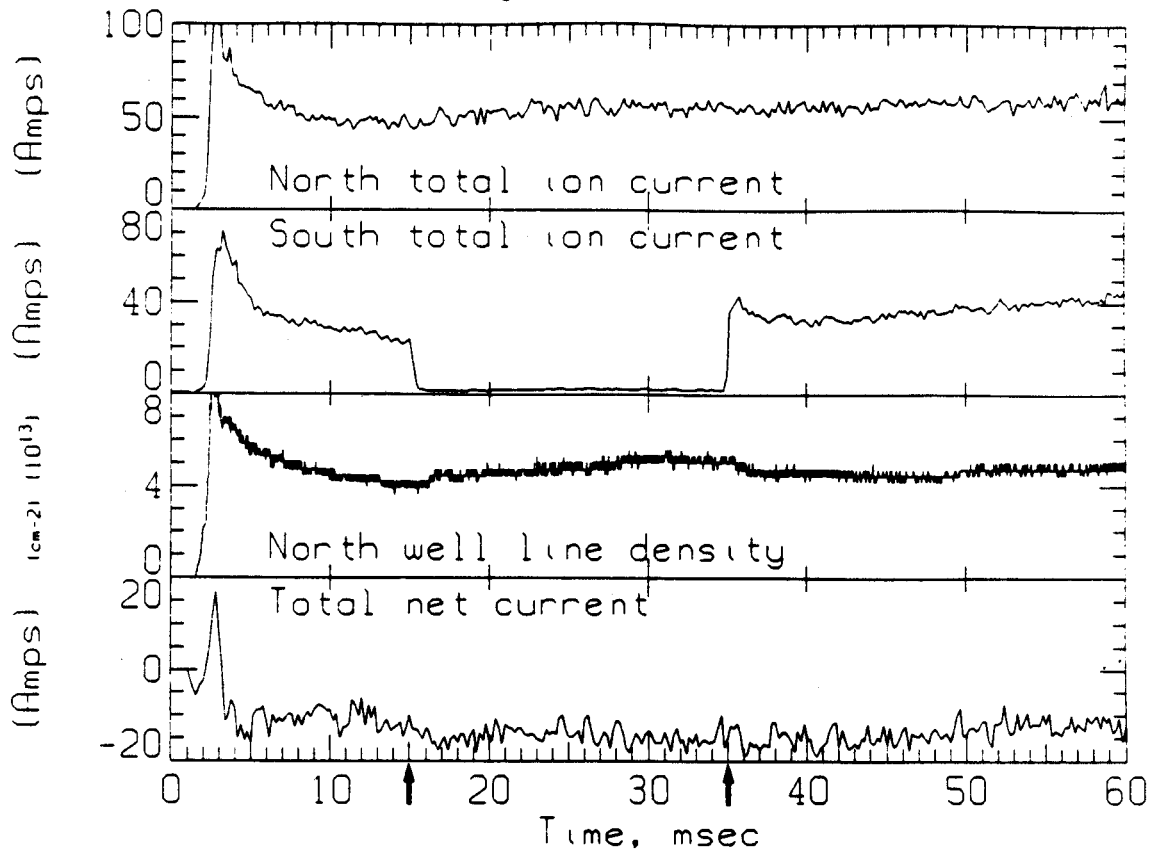
Figure 3. Time histories during an ECH plugging discharge (#13092) in the south plug. Note that although the endloss is entirely cut off in the south, no reflected stream appears in the north and no density increases are seen in the central cell. Gyrotron timing is indicated by the arrows.

applied to one axicell, but no significant potential difference between the two ends, again showing that the reduction in end loss was not due to plugging.

The same radial loss rate can account for poor buildup of neutral beam ions, and of hot electrons. The anomalous electron and ion loss rates are comparable to both the theoretical and observed γ/m^2 for trapped particle modes. The observed γ/m^2 is based on the measured correlation time and m for the 30-100 kHz modes seen by Langmuir probes in the axicells during ECH or neutral beam injection.[13](These modes apparently saturated before the plasma scraped off and did not cause sawteeth, as similar modes did during axicell ICH.) High frequency (6-30 MHz) ion microinstabilities have also been observed by Langmuir probes in the plug during neutral beam injection, but only at very low amplitudes, far too low to account for the lack of buildup of neutral beams. The failure of Tara to achieve plugging (and

central cell buildup) may thus be a consequence of the bad curvature of the plug cells.

Acknowledgments:

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