Conf-9406270-4

UCRL-JC-116862
PREPRINT

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This paper was submitted to
21st European Conference on Controlled
Fusion and Plasma Physics
Montpellier, France
June 27 - July 1, 1994

June 1994

Lawrence
Livermore
National
Laboratory

FLUCTUATIONS IN HIGH β_p PLASMAS IN DIII–D*

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In our investigation of improved confinement in high poloidal beta ($\beta_p = 2$ to 4) advanced tokamak experiments, coincident with q_0 rising above 2, we observe the internal MHD activity to evolve from an $m/n = 2/1$ to a 3/1 structure consistent with the GATO code stability analysis. The plasma eventually evolves to a quiescent state at which time the stored energy increases, mostly as a result of improved particle confinement. The measured plasma pressure profiles during this time are also calculated to be stable to high-n ballooning modes consistent with operation of the core in the second stable regime. The sustained improvement in confinement is ultimately limited by our ability to control the toroidal current profile of which the bootstrap current contributes a large fraction (up to 80%).

Introduction

We have operated DIII–D in a high β_p configuration with reduced fluctuations levels where both kink and ballooning mode activity are absent and the core ($r/a \lesssim 0.3$) operates in the second stable region. We are investigating the long temporal evolution of magnetohydrodynamic (MHD) stability in these double-null, diverted, H–mode discharges. We have observed improved confinement [1] in these advanced tokamak experiments with β_p up to 5 while operating at a toroidal field of 2 T with plasma currents of 0.4 to 0.8 MA and 8 MW of neutral beam power. At 0.4 MA, we observe highly peaked core density profiles with the central density increasing by a factor of 2 accompanied by a 20% increase in the central ion and electron temperatures. Coincident with this slow evolution, we observe a relaxation in the current profile which broadens to give an on-axis safety factor q_0 greater than two at which time the MHD fluctuation level drops and confinement improves.

However, confinement at low plasma current suffers from an anomalous fast-ion loss process which reduces the neutral-beam heating efficiency. In these experiments, the duration of high confinement is ultimately limited by the inductive response of the current profile to a rapid rise in core bootstrap current which provides a large fraction, up to 80%, of the total current. Future experiments are intended to explore operation at higher plasma current where fast ion losses are observed to decrease and confinement and beta limits increase. Active control of the current profile appears to be required to maintain stability while operating at high β_p with high bootstrap current fraction in steady state.

High β_p State

In these DIII–D experiments, high β_p conditions are achieved by a slow evolution on a resistive time scale which, for $I_p \sim 0.4$ MA, occurs after 3000 to 4000 ms into the discharge as shown in Fig. 1. From an initial ohmic equilibrium with $q_0 \sim 1$, we initiate neutral beam heating with a 200 ms ramp up in power to provide controlled heating of the plasma core providing a rapid rise in the stored energy. At 1250 ms into this discharge, we observe the onset of strong $m/n = 2/1$ MHD activity on the magnetic probe array accompanied by a drop in the stored

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*Work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-ENG-48 and by General Atomics under Contract DE-AC02-76-CHO-3073.

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energy and a rapid loss of hot, neutral beam injected ions as is indicated by a drop in the neutron flux detected with a (plastic) scintillator detector. This anomalous fast-ion loss remains for the duration of the discharge and represents typically a 50% reduction in the hot-ion population for the 0.4 MA operation when compared with predictions from the ONETWO code. These losses, however, are much less when operating at higher currents. As is evident in Fig. 1, this enhanced loss rate remains even as the strength of the MHD activity decreases in time.

During neutral beam heating, the equilibrium relaxes slowly with a decrease in the internal inductance ℓ_i and an increase in q_0 as the current profile broadens. For these high β_p discharges, equilibria must be determined from a full kinetic fit using the EFIT code with measured pressure profiles adjusted to account for the fast ion losses and including the current profile measurements from a multichannel Motional Stark Effect diagnostic. In Fig. 2, we show the temporal variation of the magnetic field fluctuation spectrum for the discharge described above. The observed frequency in the laboratory frame is consistent with the toroidal rotation speed as measured with the Charge Exchange Recombination (CER) diagnostic. During the initial part of this relaxation (2000 to 2750 ms) MHD activity decreases and evolves from the predominantly 2/1 mode to a 2/2 mode as q_0 begins to rise. As q_0 approaches 2, MHD fluctuations are again strongly excited with higher order poloidal modes, *i.e.*, $m/n = 3/1$ for shot #77676 at $t = 2950$ ms. The MHD activity damps as q_0 passes through 2 with a decrease in fluctuation amplitude at which time we observe the evolution to the high β_p state. The equilibrium eventually evolves to a state where MHD fluctuations fall below the measurement sensitivity of the magnetic probe array at the vessel wall.

As the fluctuation amplitude drops, we observe the rise in β_p to ~ 3.8 for the discharge shown in Fig. 1 as the confinement improves with both the doubling and strong peaking in the central density as shown in Fig. 3 and a smaller increase in the ion and electron temperatures. Due to the rapid rise in the core pressure gradient, the bootstrap current rises to $J_{BS}/J_T \sim 0.8$. In high β_p discharges that exhibit improved confinement, this inductive plasma response limits the rise in q_0 which eventually relaxes back towards 2 with the reappearance of MHD activity. As we described previously for shot #77676, the mode structure was observed to change as a function of the q_0. In Fig. 4, we summarize the variation in fluctuation amplitude for several discharges which clearly indicates the sensitivity to the value of the q on axis.

Stability Analysis

Using the GATO [2] stability code, we have compared the kink mode theory with the measured fluctuation spectra. Using the experimentally measured kinetic profiles at 2950 ms into shot #77676, we show the Fourier components of the displacement versus poloidal flux in Fig. 5 for one such GATO code prediction of an unstable $n = 1$, $m = 3$ mode consistent with the measured fluctuations. We have found general agreement between the observed mode characteristics and GATO for this discharge with a prediction of stability during the quiescent period. In addition, the profile dependency of ballooning stability has been calculated from the CAMINO code [3]. As we show in a shear versus pressure gradient plot (Fig. 6) using experimentally measured pressure profiles at 3360 ms into the shot, CAMINO calculations indicate operation with the core $(0.2 < \psi < 0.5)$ accessible to the second stable regime during the time fluctuations are essentially nonexistent. Thus, we have observed DIII–D to operate in a high β_p configuration with >50% bootstrap current fraction for a duration which exceeds several confinement times ($\tau_E \sim 80$ ms), indicating the possibility for steady-state stable operation at high poloidal beta. Late in this shot, the bootstrap fraction rises to ~78% and weak MHD activity is again observed, thus indicating the possible need for active current profile control to sustain this advanced tokamak operation mode in steady state.

Issues

Successful evolution appears to depend sensitively on formation of an initial profile state which can evolve under controlled heating, consistent with access to second stability. Discharges forming at a moderately high ℓ_i state have the greatest chance of evolving to high β_p late in time, as the ℓ_i drops and q_0 rises above 2. However, a value of $q_0 > 2$ does not guarantee this evolution and other parameters, such as ℓ_i or details of the current profile, appear to be important with MHD stability responding to this evolution. We are presently investigating the role these different spectral characteristics play in predicting and understanding the evolution to high β_p.

A second critical issue is the confinement of hot ions. While these losses appear to be related to the larger banana orbits at the lower current (reduction is ~50% at 0.4 MA and only ~10% when operating at 1 MA), we have not isolated the drive. The presence of spectral characteristics consistent with the beta-induced Alfvén eigenmode [4] are present as coherent fluctuations in the 40 to 80 KHz range even during the nominally quiescent period. The rôle of such collective modes in the anomalous loss of fast ions is currently under investigation.

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Figure Captions

FIG. 1. Parameters for shot #77676 indicating onset of hot ion losses at 1250 ms and a transition to high β_p at 3500 ms.

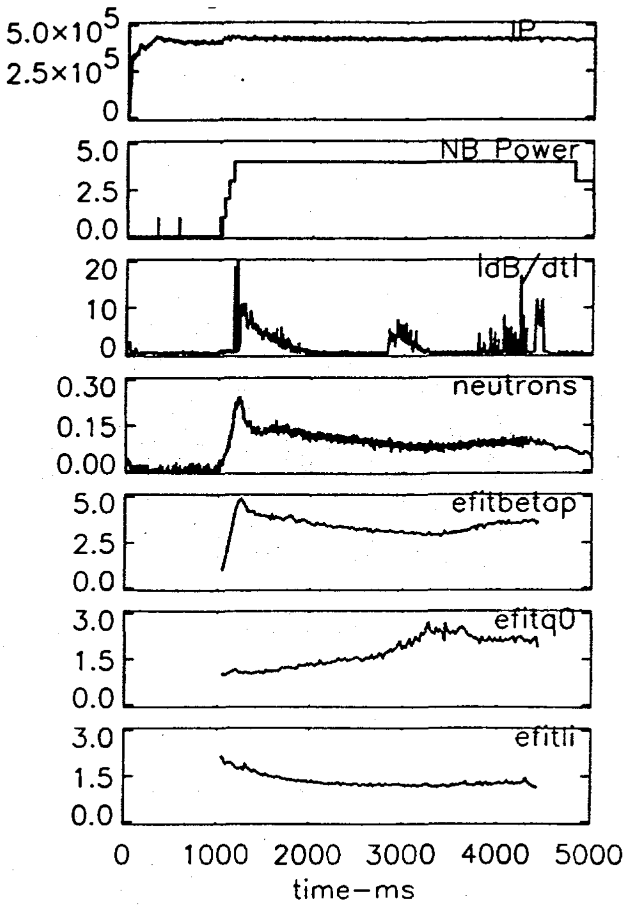
FIG. 2. Temporal variation of magnetic fluctuation spectrum for shot #77676 showing the evolution of fluctuations and the quiescent period from 3300 to 4000 ms.

FIG. 3. Thomson density profile showing improved core confinement after 3500 ms in shot #77676.

FIG. 4. $|dB/dt|$ fluctuation amplitude variation on axis q for four high β_p shots.

FIG. 5. GATO displacement versus poloidal flux using shot #7767 profiles measured at 2950 ms indicating $m = 3$ is predicted.

FIG. 6. CAMINO result using shot #77676 profiles measured at 3360 ms (quiescent period) indicating $0.2 < \psi < 0.5$ is in second stable region.



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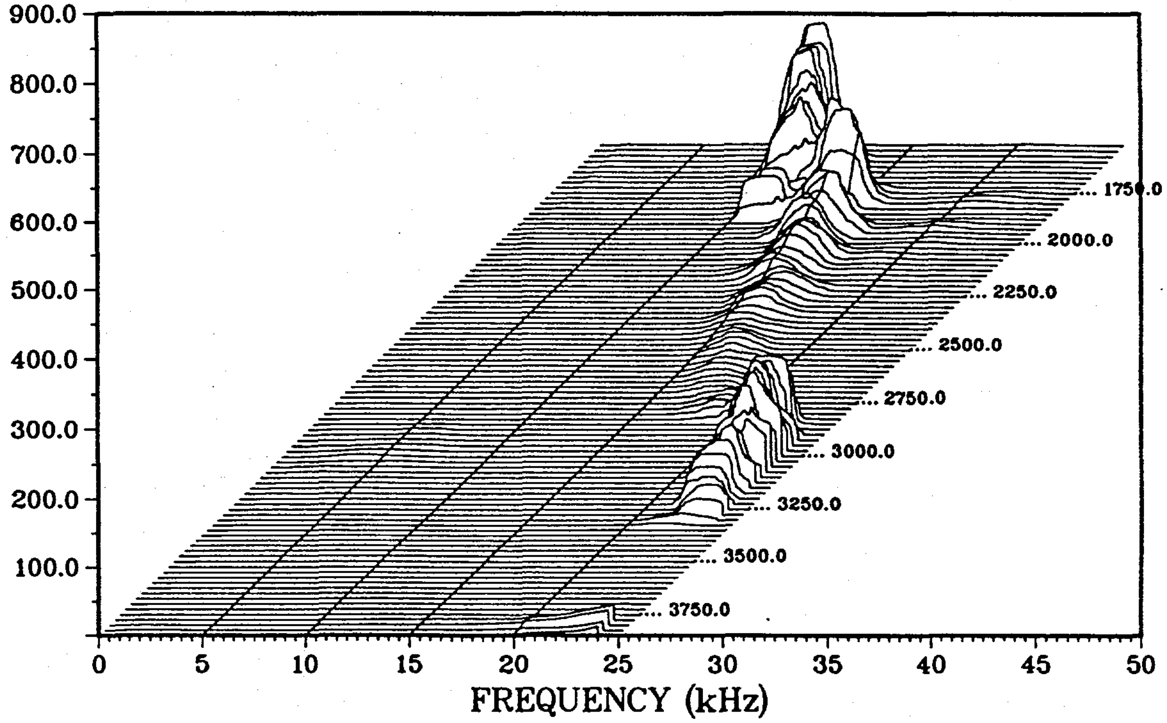

Figure 2. Temporal variation of |dB/dt| spectrum for shot #77676 showing the evolution of fluctuations and the quiescent period from 3300 to 4000ms

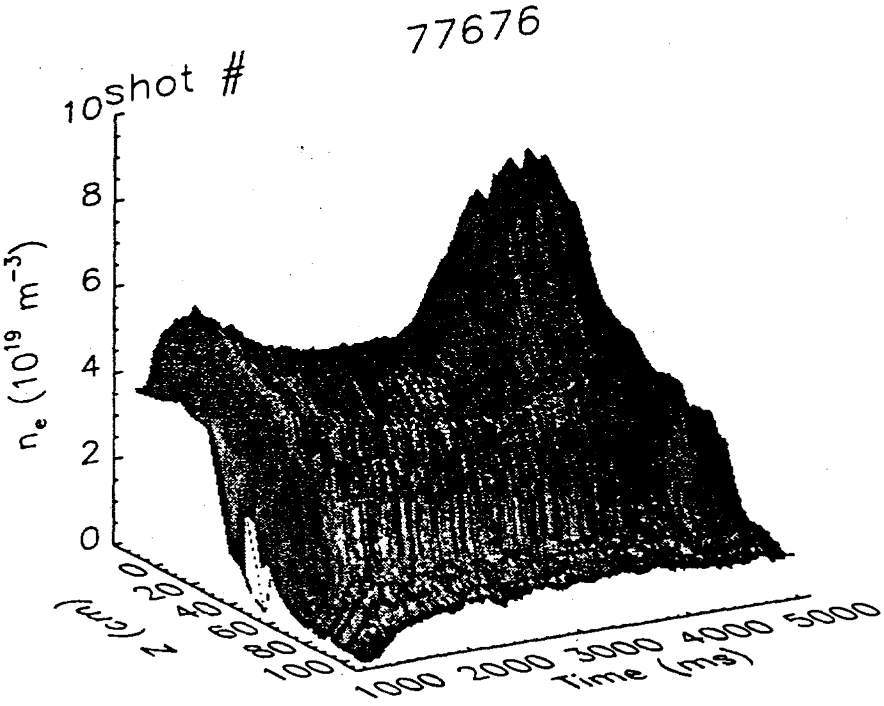

Figure 3. Thomson density profile showing improved core confinement after 3500ms in shot #77676

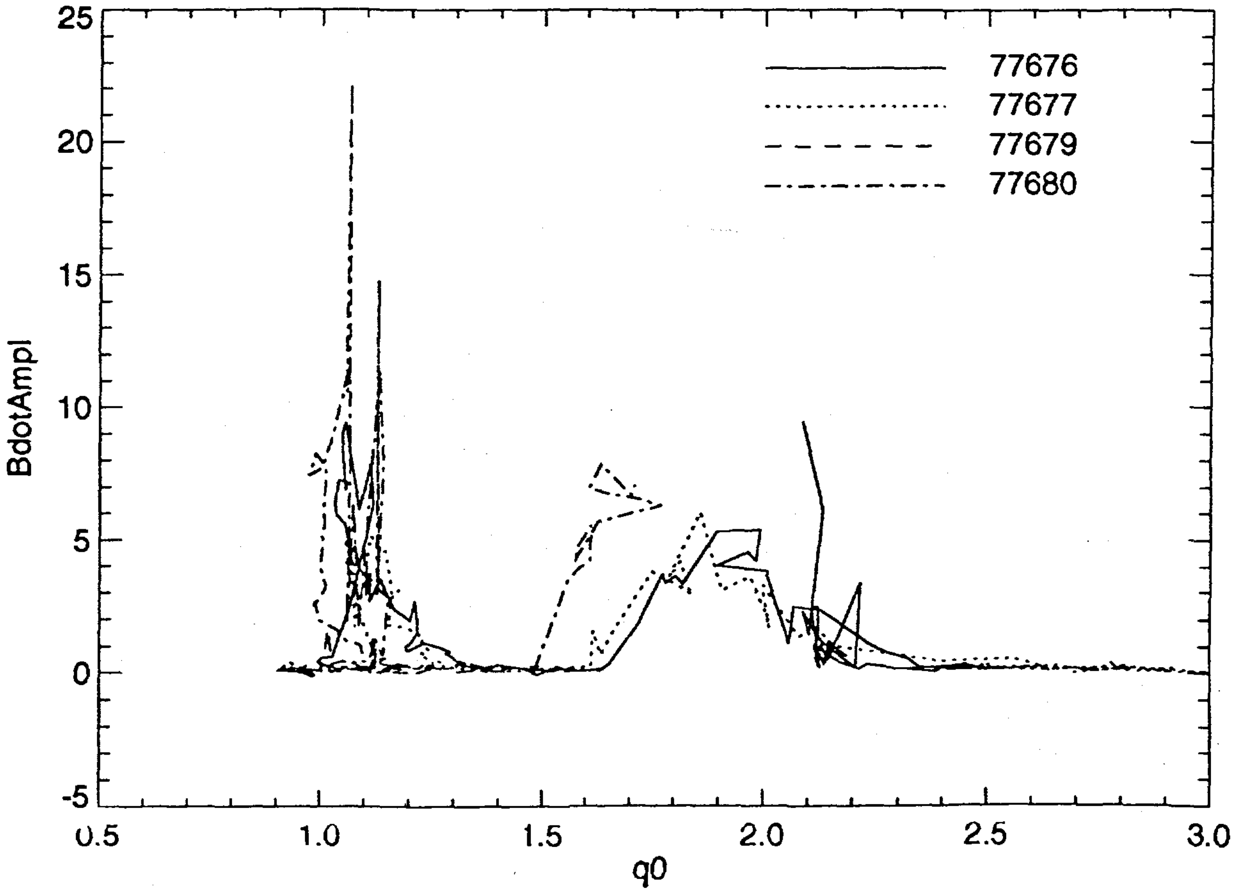

Figure 4. |dB/dt| fluctuation amplitude variation with on axis q for four high β_p shots.

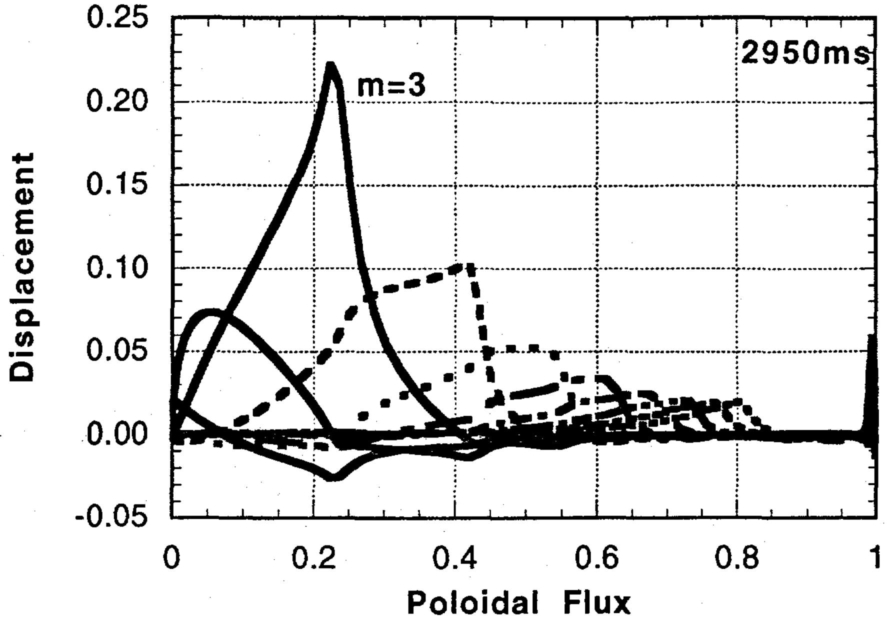

Figure 5. GATO displacement versus poloidal flux using shot #77676 measured profiles at 2950ms indicating m=3 is predicted.

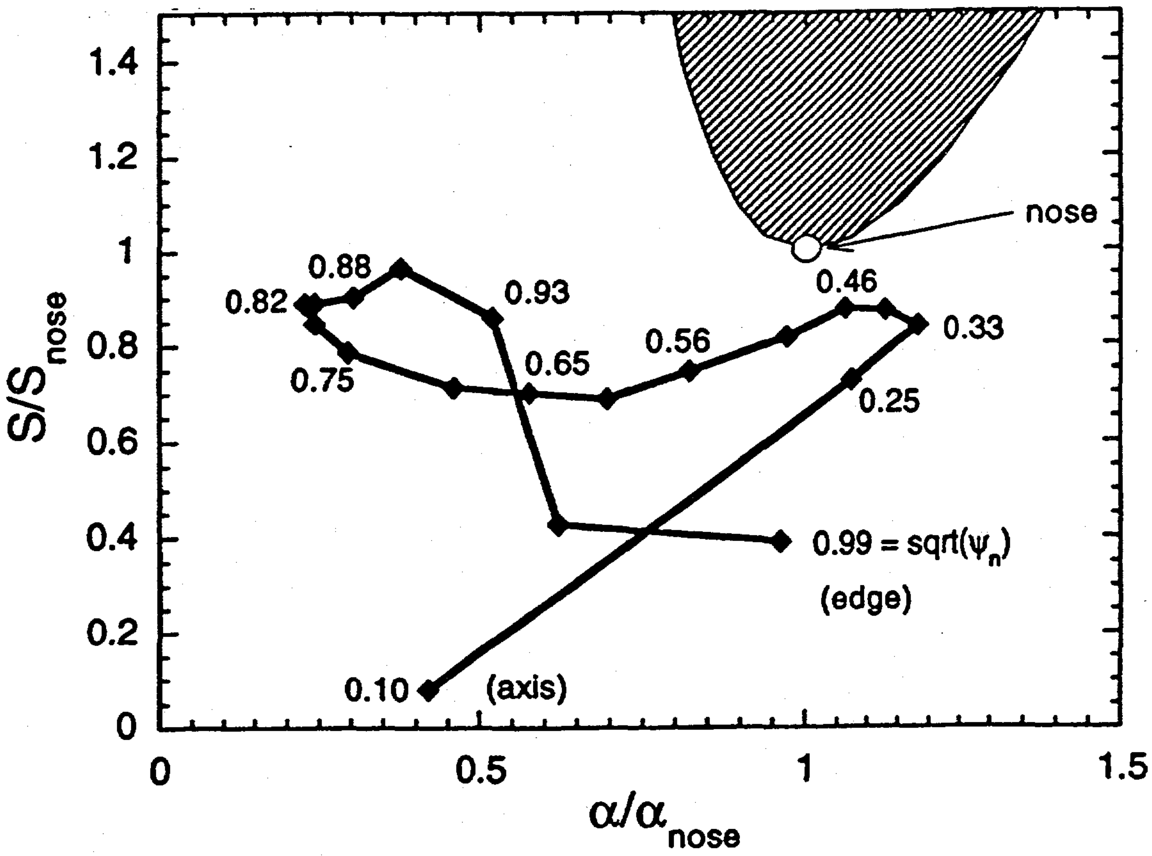

Figure 6. CAMINO result using shot #77676 measured profiles at 3360ms (quiescent period) indicating $0.2 < \psi < 0.5$. is in second stable region