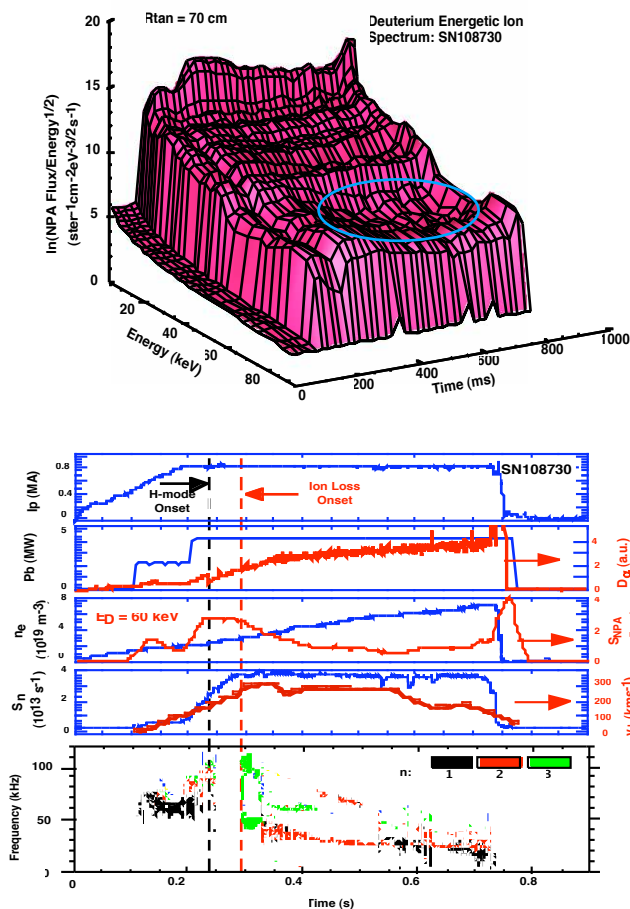


Measurement of MHD-induced Energetic Ion Loss during H-mode Discharges in the National Spherical Torus Experiment

S. S. Medley, N. N. Gorelenkov, R. Andre and A. L. Roquemore
Princeton Plasma Physics Laboratory, Princeton, New Jersey, 08543, USA

1. Introduction

The National Spherical Torus Experiment (NSTX) [1] is a midsize low aspect ratio fusion research facility with auxiliary heating from Neutral Beam Injection (NBI) and High Harmonic Fast Wave (HHFW) launch. Typical NSTX parameters are major radius $R_0 = 0.85 - 0.9$ m, minor radius $a = 0.67$ m resulting in an aspect ratio of $A = R_0/a \sim 1.3$, plasma current $I_p \approx 0.3 - 1.5$ MA and toroidal field $B_T \approx 0.3 - 0.6$ T. Three co-directed deuterium neutral beam sources have injected power up to $P_{NB} \approx 7$ MW at neutral energies up to $E_b \approx 100$ keV. HHFW heating at 30 MHz has delivered up to $P_{RF} \approx 5$



although this loss occasionally extends to lower energy [6]. An example of MHD-induced energetic ion loss during an H-mode for NSTX discharge SN108730 is presented in Fig. 1. The upper panel

Figure 1. Following onset of the H-mode at 230 ms, the NPA spectrum (top panel) shows significant ion loss only for energies $E_b/2 < E \leq E_b$ (encircled region) starting at $t = 280$ ms concurrently with onset of $n = 2$ mode activity (lower panels).

From the top, this is an $I_p = 0.8$ MA discharge with sources A and B injecting a total of $P_{NB} = 4.2$ MW of power with an injection energy of $E_b = 90$ keV. At the onset of the H-mode marked by the black dashed line passing through the drop in the D_a signal, little change is observed in the evolution of the

MW to deuterium and helium plasmas. The performance achieved to date in NSTX has been reported elsewhere [2]. H-modes triggered by NBI heating are routinely obtained in NSTX and have become a standard operational scenario [3]. L-H transitions triggered by NBI heating have been obtained over a wide parameter range in I_p , B_T and n_e in either lower-single-null or double-null diverted discharges with elongation κ up to 2.4, triangularity δ up to 0.8 and plasma pulse length approaching 1 s. To date NSTX has achieved, non-simultaneously, stored energies up to 0.39 MJ, energy confinement times $\tau_E < 0.12$ s and $\beta_T \leq 35\%$ [4]; $\beta_T = \langle p \rangle / (B_0^2 / 2\mu_0)$ where $\langle p \rangle$ is the volume averaged total pressure and B_0 is the vacuum magnetic field at R_0 . MHD-induced energetic ion loss in neutral beam heated H-mode discharges in NSTX is the subject of this paper.

2. Energetic Ion Loss Observations

After H-mode onset, the energy spectrum measured by the Neutral Particle Analyzer (NPA) diagnostic [5] on NSTX usually exhibits a significant loss of energetic ions mainly for $E > E_b/2$ where E_b is the beam injection energy, (encircled region). Selected discharge waveforms are shown in the lower panel.

neutron yield, S_n , the toroidal rotation velocity from the CHERS diagnostic, V_t , or the NPA signal, S_{NPA} , shown here for 60 keV deuterium neutrals just above the beam half energy $E_b/2 = 45$ keV. Shortly afterwards around 280 ms as marked by the red dashed line, however, the neutron yield and toroidal rotation velocity clamp concurrently with onset of decay in the NPA signal. The last panel shows the Mirnov spectrogram identifying the MHD mode activity. In the first ~ 50 ms of the H-mode, MHD activity vanishes to give a quiescent phase where S_{NPA} remains relatively constant. At ~ 280 ms, strong $n = 3, 2$ activity arises with mode amplitude $\text{dB} \sim 0.5$ Gauss and simultaneously S_{NPA} begins to decay and the neutron yield clamps. In the time interval from 280 – 400 ms, S_{NPA} diminishes by $\sim 75\%$. Depletion of energetic ions with $E > E_b/2$ ‘saturates’ and persists until termination of the H-mode by a reconnection event.

The magnitude of the energetic ion loss (decrease of S_{NPA} in the region $E > E_b/2$) was observed to diminish with increasing tangency radius, R_{tan} , of the NPA sightline and with increasing NB injection energy, E_b . In addition, the loss diminishes with increasing toroidal field B_T .

3. TRANSP Analysis of the Energetic Ion Loss Mechanism

The TRANSP code [7] is capable of simulating the NPA neutral flux measurements including horizontal scanning of the sightline and modeling suggests a possible mechanism causing the enhancement of MHD-induced ion loss observed during H-mode operation as illustrated in Fig. 2.

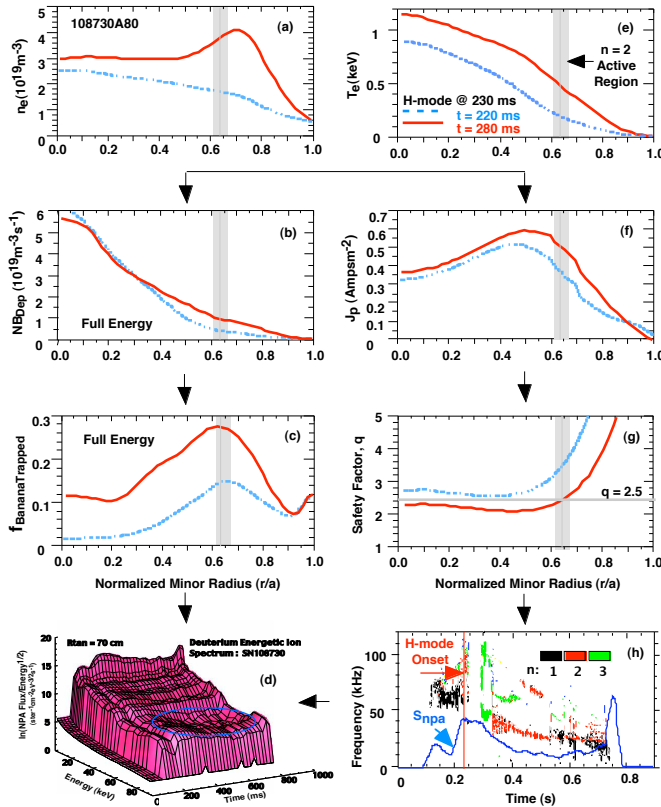


Figure 2. TRANSP analysis suggests that H-mode operation enhances MHD-induced energetic ion loss. The pressure profile generated by the H-mode evolves the q -profile to permit low- n MHD activity (right column) while shifting neutral beam deposition into the MHD active region (left column). This synergism between MHD activity and outward shift of the neutral beam deposition leads to enhanced energetic ion loss observed in H-mode discharges.

Shown are TRANSP outputs for $t = 220$ ms prior to the H-mode (dashed blue curves) and $t = 280$ ms during the H-mode (solid red curves) corresponding to onset of the NPA signal decay (see Fig. 1). The shaded bar near $r/a \sim 0.6$ denotes the predominant region of MHD activity detected by the ultra soft x-ray diagnostic arrays. Multi-pulse Thomson Scattering (MPTS) [8] input profiles are shown for the electron density and temperature in panels (a) and (e), respectively. Following the transition to the H-mode, the evolution of these profiles drives a broadening and edge-gradient steepening of the pressure profile that in turn evolves the plasma current density profile as shown in panel (f), this change being largely due to bootstrap driven current. As a result, the q -profile evolves so as to introduce a $q = 2.5$ surface in the shaded region where MHD activity was identified as noted earlier. (There is as yet no direct measurement of the q profile on NSTX; it is inferred via fitting of the magnetics data with the code EFIT [9].) Thus low- n MHD activity arises as shown in the Mirnov spectrogram in panel (h). Concurrently, the broad density profile shifts a significant fraction of core-weighted beam deposition to the MHD-active region as shown in panel (b). Volume

integration of the beam deposition over the region $0.3 < r/a < 0.9$ and conversion to power gives $P_{dep} = 1.0$ MW at $t = 0.220$ s and $P_{dep} = 1.5$ MW at $t = 0.280$ s. An increased fraction of this out-shifted power, $\Delta P_{dep} = 0.5$ MW, is deposited on trapped banana orbits as shown in panel (c). From this we infer that MHD-induced ion loss is enhanced during H-mode operation due to a congruous evolution of the q profile and beam deposition

diffusivity, $\chi_i^{\text{Fast}} \sim 4 \text{ m}^2/\text{s}$ (green line), modestly exceeds χ_i^{NC} outside the core region and $\chi_i^{\text{Fast}} \gg \chi_i$. Inclusion of fast ion diffusion also reduces the inferred momentum diffusivity, χ_ϕ , drastically as TRANSP responds to maintaining the measured input toroidal rotation in the face of $\sim 20\%$ reduction of the NB drive. As a result, the momentum confinement time increases from $\sim 80 \text{ ms}$ without fast ion diffusion to $\sim 160 \text{ ms}$ with fast ion diffusion.

Fig. 5 shows the thermal energy confinement time, τ_{E_i} , in panel (a) and the toroidal beta, β_T , in panel (b) with and without fast ion diffusion. Of note here is that the confinement time with fast ion diffusion (red curve) is 15% larger than without fast ion diffusion (blue curve). This is understandable,

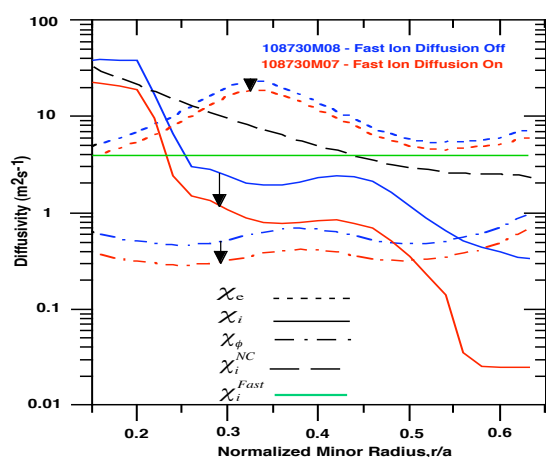


Figure 4. TRANSP calculation of power balance diffusivities at $t = 400 \text{ ms}$ with (red curves) and without (blue curves) fast ion diffusion is shown.

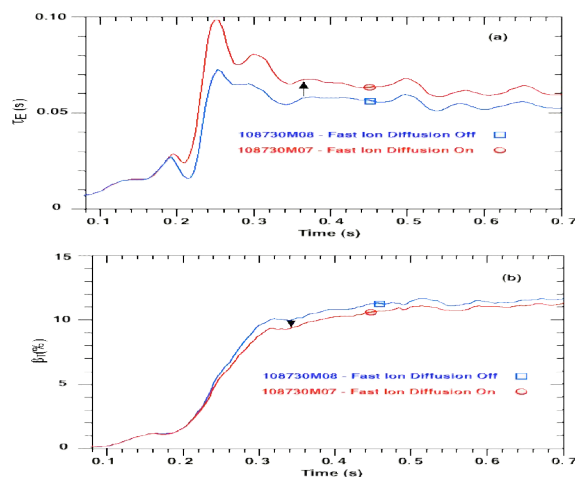


Figure 5. TRANSP calculation of thermal energy confinement time (a) and toroidal beta (b) with and without fast ion diffusion is shown.

since loss of neutral beam heating power as a result of MHD-induced energetic ion loss naturally requires improved energy confinement to realize the measured input values for T_e and T_i . On the other hand, toroidal beta decreases by 7% with the inclusion of fast ion diffusion. This is due to the fact that fast ion diffusion reduces both the parallel and perpendicular energetic ion betas by $\sim 25\%$ due to a reduction in the energetic ion pressure profile. (Note that non-thermal ions usually contribute $\sim 25\text{-}30\%$ to the stored energy and toroidal beta in NSTX.) A proper accounting of energetic ion loss is therefore important for accurate analysis of power balance and transport in plasmas exhibiting MHD-induced energetic ion loss.

Acknowledgement

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