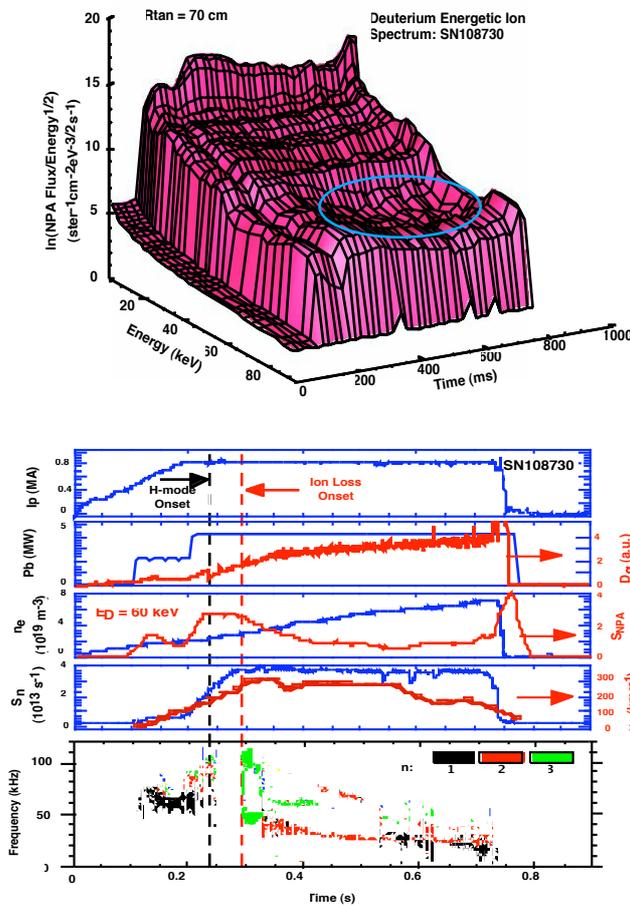# Measurement of MHD-induced Energetic Ion Loss during H-mode Discharges in the National Spherical Torus Experiment

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 $A = R_o/a \sim 1.3$, plasma current $I_p = 0.3 - 1.5$ MA and toroidal field $B_T = 0.3 - 0.6$ T. Three co-directed deuterium neutral beam sources have injected power up to $P_{NB} = 7$ MW at neutral energies up to $E_b = 100$ keV. HHFW heating at 30 MHz has delivered up to $P_{RF} \sim 5$

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]; $\beta_T = <p>/(B_0^2/2\mu_0)$ where $<p>$ 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, 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 shows the NPA spectrum of energetic NB deuterium ions as a function of energy and time. Following H-mode onset at 230 ms, the spectrum exhibits a significant loss of energetic ions only for $E > E_b/2$ (encircled region). Selected discharge waveforms are shown in the lower 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

neutron yield, S_n, the toroidal rotation velocity from the CHERS diagnostic, V_f, 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 dB ~ 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 ~ 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.

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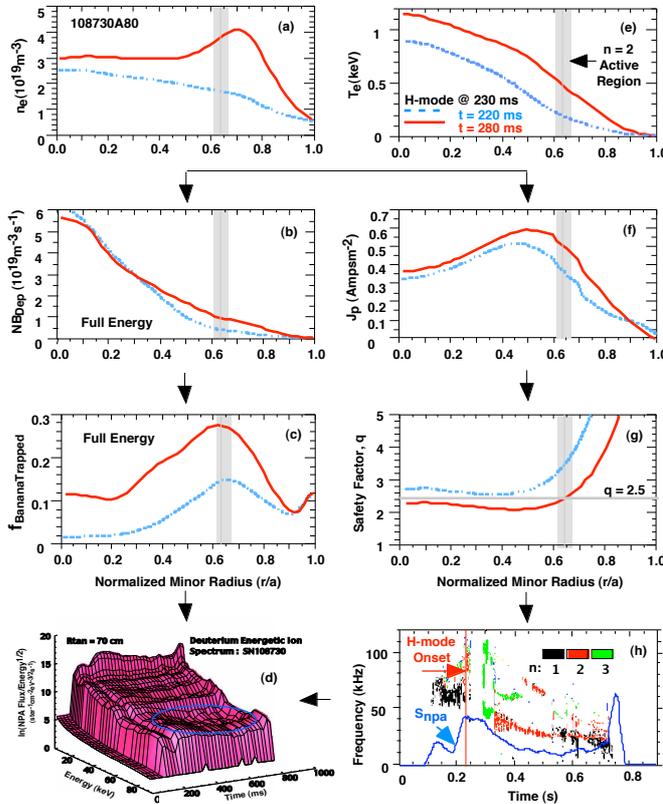
Figure 2. TRANSP analysis suggests that H-mode operation enhances MHD-induced energetic ion loss. The pressure profile generated by the H-mode evolves the q-profile to permit low-n MHD activity (right column) while shifting neutral beam deposition into the MHD active region (left column). This synergism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

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

profile which feeds beam ions into the region of low-n MHD activity in the region r/a ∼ 0.6, leading to depletion of the NPA energetic ion spectrum shown in panel (d).

It must be emphasized that MHD-induced energetic ion loss during H-modes is not a consequence of any H-mode characteristic other than the broad, high-density profiles that invariably occur. MHD-induced energetic ion loss has also been occasionally observed in L-mode discharges that have unusually high, broad electron density profiles.

The ORBIT code [10] was used to model the effect of MHD modes on the confinement of beam ions in NSTX. This work is presented in a companion paper [11], but the main results are as follows. MHD-induced ion loss was shown to be energy selective as in the observations. Only passing particles are affected and the loss can approach 15% for magnetic perturbation mode amplitudes, $\delta B/B$, consistent with those measured using the Mirnov coil arrays on NSTX.

4. Impact of Energetic Ion Loss on Neutron Yield and Transport Analysis

To palliate the lack of a physics-based model in TRANSP for MHD-induced loss of energetic ions, an existing capability to modify the fast ion diffusion in a manner that approximates MHD loss is invoked. Two criteria were employed for determining the fast ion diffusion parameters: the first was to obtain agreement between the measured neutron rate and that generated by the kinetically based TRANSP simulation, and the second was to simultaneously obtain agreement with the measured energetic ion distribution. The energetic ion diffusion model effecting this goal is as follows: (1) in time, the diffusivity was ramped up from a small value at the start of beam injection to χ_i^{Fast} = 3.8 m^2/s at t = 300 ms and thereafter increased gradually to a value of χ_i^{Fast} = 5.0 m^2/s at t = 600 ms; (2) in energy, the diffusivity multiplier was increased from zero at E_D = 45 keV to unity at E_D = 50 keV where it remained constant until E_D = 75 keV and was then decreased to zero at E_D = 80 keV and remained so up to the injection energy of E_D = 90 keV; (3) in space, the diffusivity was constant across the plasma minor radius. In all simulations, Z_{eff} = 2.5 over the minor radius and D/(H + D) = 0.9, constant in time.

The effect of fast ion diffusion on the energetic ion distribution at t = 400 ms is show in Fig. 3 along with the neutron rate. As can be seen, an excellent match exists simultaneously between the neutron yield and energetic ion distribution measurements and the TRANSP simulation with fast ion diffusion.

Fig. 4 shows profiles of the flux surface average thermal diffusivities extracted from TRANSP power and momentum balance analysis plotted against normalized minor radius for the time of interest. It can be seen that the diminished power input to ions and electrons causes TRANSP to reduce the ion and electron diffusivities in order to preserve the match with the measured ion and electron temperatures used as input to the calculation. A neoclassical prediction of the ion diffusivity, χ_i^{NC}, obtained from the NCLASS code [12] follows more or less the shape of the χ_i profile and is unchanged with the inclusion of fast ion diffusion. This is due to the fact that χ_i^{NC} is computed
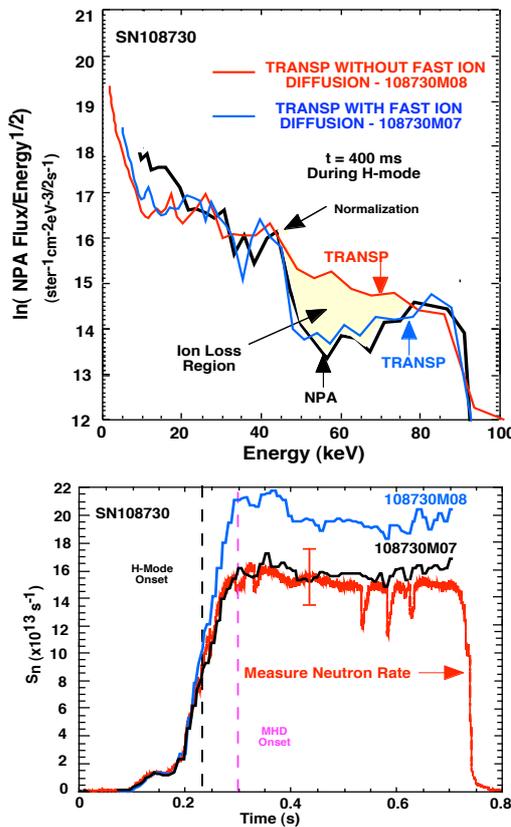

Figure 3. Comparison of TRANSP simulations with and without fast ion diffusion against the NPA spectrum (top panel) and measured neutron rate (lower panel) for SN108730.

using the neoclassical ion thermal flux from NCLASS and the measured local gradient and density, ignoring energetic ions. Without fast ion diffusion, one sees that $\chi_i \sim \chi_i^{NC}$ in the core region, but that $\chi_i < \chi_i^{NC}$ in the edge region. A similar trend is observed with fast ion diffusion, but including fast ion diffusion causes χ_i to plummet drastically in the outer region to $\chi_i << \chi_i^{NC}$. The energetic ion

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diffusivity, $\chi_i^{Fast} \sim 4$ m^2/s (green line), modestly exceeds χ_i^{NC} outside the core region and $\chi_i^{Fast} \gg \chi_i$. 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 ~ 80 ms without fast ion diffusion to ~ 160 ms with fast ion diffusion.

Fig. 5 shows the thermal energy confinement time, τ_E, 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,
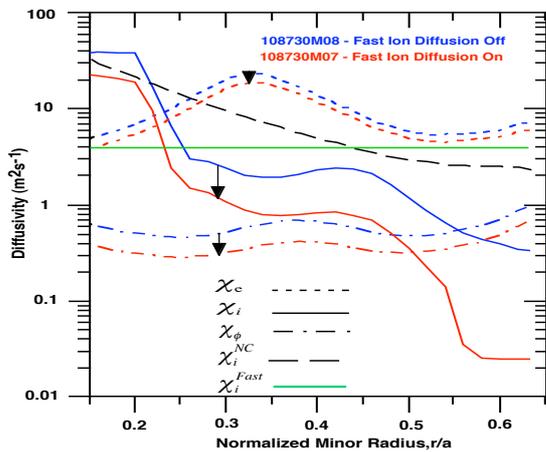

Figure 4. TRANSP calculation of power balance diffusivities at t = 400 ms with (red curves) and without (blue curves) fast ion diffusion is shown.
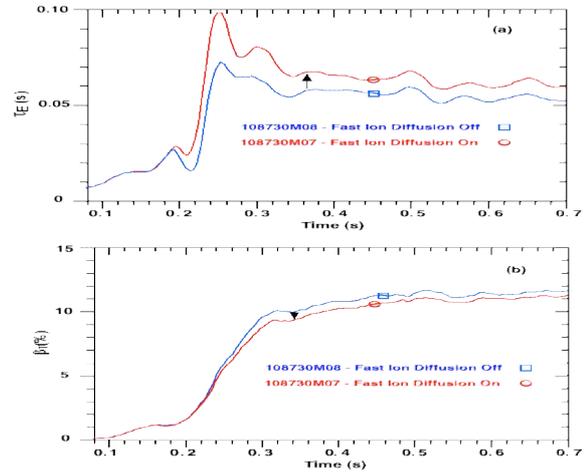
Figure 5. TRANSP calculation of thermal energy confinement time (a) and toroidal beta (b) with and without fast ion diffusion is shown.

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 ~ 25-30% 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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