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by

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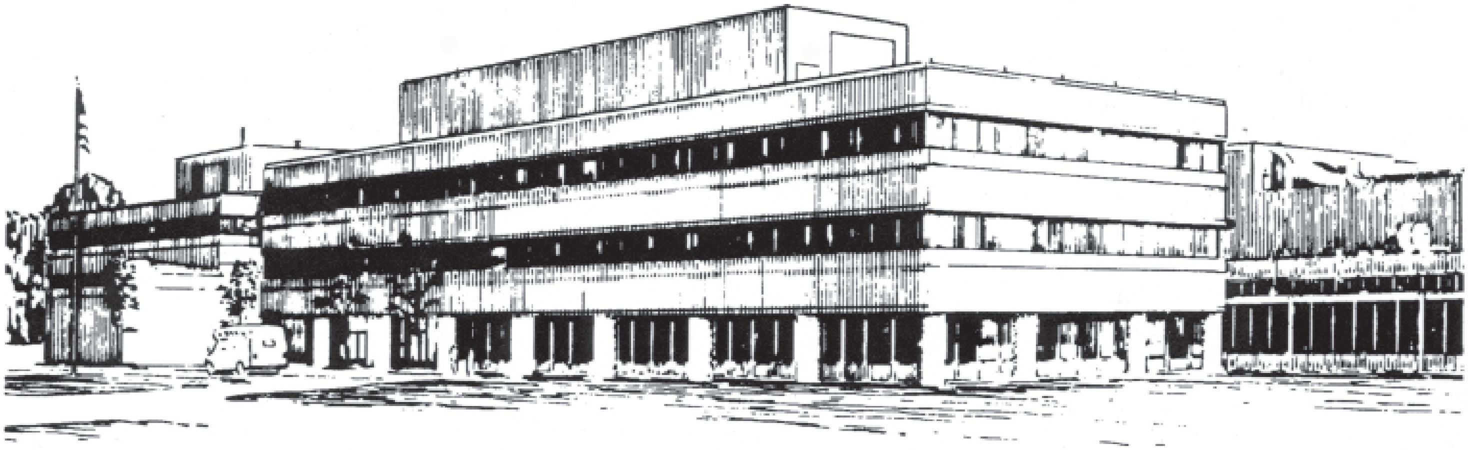

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Neutral Particle Analyzer Measurements of Ion Behavior in NSTX

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Abstract

Initial results obtained with the Neutral Particle Analyzer (NPA) diagnostic on the National Spherical Torus Experiment (NSTX) are presented. Magnetohydrodynamic activity and reconnection events cause depletion of the deuterium energetic ion distribution created by neutral beam injection. Adding High Harmonic Fast Wave Heating to neutral beam heated discharges results in the generation of an energetic ion tail above the beam injection energy. NPA measurements of the residual hydrogen ion temperature are in good agreement with those from recombination spectroscopy.

Introduction

The National Spherical Torus Experiment (NSTX) is a low aspect ratio (R/a ~ 1.3) device with auxiliary heating from Neutral Beam Injection (NBI) and High Harmonic Fast Wave (HHFW) heating. Typical NSTX parameters are R_0 = 85 cm, a = 67 cm, I_p = 0.7-1.4 MA, B_f = 0.25-0.45 T. Three co-directed deuterium neutral beam sources have injected $P_{NB} \leq 4.7$ MW. HHFW heating typically has delivered $P_{RF} \leq 3$ MW to D and He plasmas. Important to the understanding of ion behavior in NSTX are the Neutral Particle Analyzer (NPA) diagnostics and the Charge Exchange Recombination Spectroscopy (CHERS) system.

The NPA diagnostic utilizes a PPPL-designed E||B spectrometer [1] which measures the energy spectra of H^+ and D^+ ion species simultaneously with a time resolution of ~1 msec set by signal-to-noise levels. The calibrated energy range is E = 0.5 – 150 keV and the energy resolution varies from $\Delta E/E$ = 7% at low E to $\Delta E/E$ = 3% at high E.

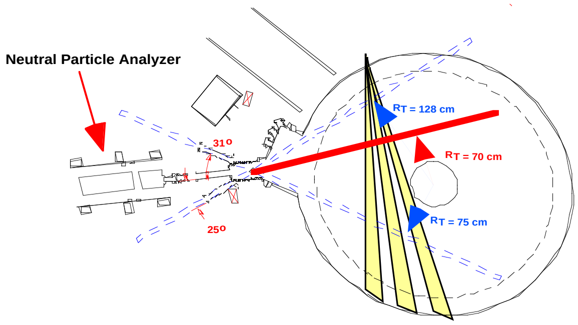

Figure 1. Neutral Particle Analyzer layout on NSTX.

The detector consists of a large area microchannel plate (MCP) which is provided with two rectangular, semi-continuous active area strips, one coinciding with each of the mass rows for detection of H^+ and D^+ and each mass row has 39 energy channels. The NPA measures Maxwellian spectra of residual H^+ to obtain ion temperatures, T_i, and D^+ energetic ion spectra produced by injection of 80 keV D neutral beams into a D plasma. The CHERS system [2] measures carbon ion temperature, T_i, and toroidal flow, V_f, at 17 radial positions spanning the outer half of the minor radius with 20 ms time resolution during NBI.

The three neutral beam lines on NSTX inject at R_{tan} of 50 cm (source A), 60 cm (source B) and 70 cm (source C). Initially, the NPA was installed with a fixed sightline having R_{tan} = 70 cm which views across the neutral beam lines at co-directed ions as shown by the solid chord in Figure 1. At present, the NPA is being upgraded to provide horizontal scanning as shown by the dashed chords as well as vertical scanning to view below the plasma midplane.

A rich variety of energetic ion behavior resulting from MHD activity has been observed in NSTX during experiments conducted during the last year and some interesting examples are presented in this paper.

Effect of MHD Activity on NPA Energetic Ion Measurements

The appearance of magnetohydrodynamic (MHD) activity can have a pronounced effect on both the 'thermal' (E ~ 0.5–5 keV) and 'energetic' (E ~ 5–80 keV) ion populations in

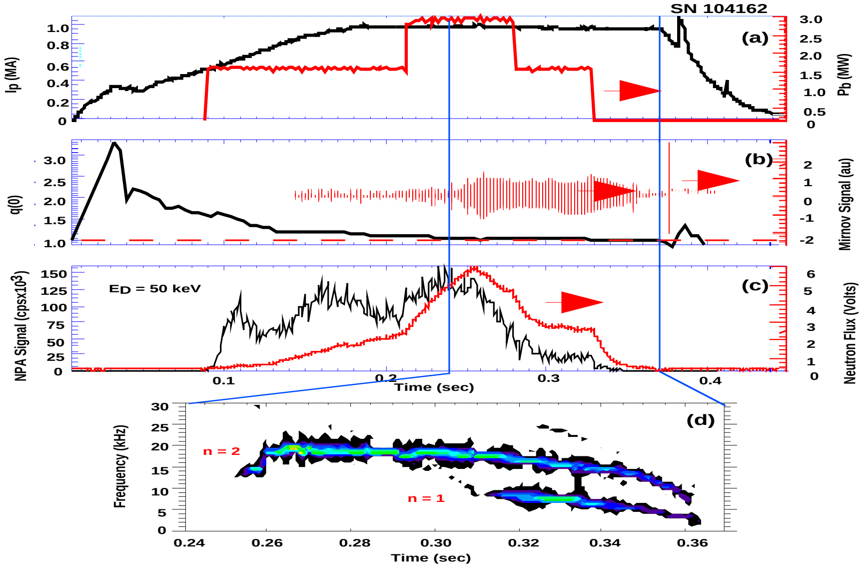

Figure 2. MHD activity (panels b,d) causes losses in neutron yield and energetic deuterium ion confinement (panel c) in NSTX

NSTX. An example is presented in Figure 2 where panel (a) shows injection of a peak NB power of 3 MW during the 1 MA flat top of a deuterium discharge. Panel (b) shows the onset of large scale MHD activity at t ~ 0.26 sec as indicated by the Mirnov coil measurements. Note that q(0) > 1 during this MHD activity. As shown in panel (d), this activity is identified as a large n = 2 mode with frequency ~ 20 kHz arising at 0.26 sec followed by an additional n = 1 mode with frequency ~ 10 kHz at 0.32 sec. For both modes the frequency downshifts during the period of activity. Onset of the n = 2 mode leads to rollover and relatively slow decay of the energetic ion population and consequently the neutron yield as shown in panel (c). Although not shown here, thermal ions are also lost during MHD activity which results in a collapse in the ion temperature.

Effect of Reconnection Events on Thermal and Energetic Ion Distributions

The effects of reconnection events and sawteeth on the thermal and energetic ion distributions in NSTX differ from that observed for MHD activity. In this case, prompt loss of the energetic ions occurs on a fast time scale of ≤ 2 msec while the thermal ions remain confined but are redistributed outboard from the plasma core to a region of higher neutral

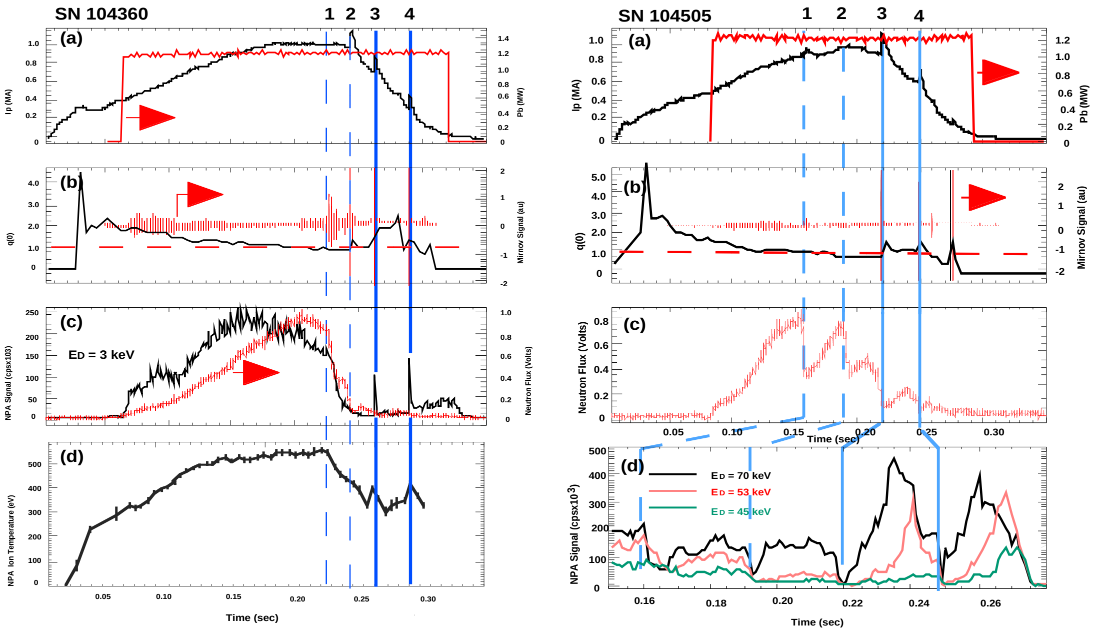

Figure 3. Illustration of the effect of reconnection events on thermal (left) and energetic ion (right) ion distributions measured by the NPA diagnostic in NSTX

density which leads to a burst in the neutral particle flux and the apparent ion temperature measured by the NPA. These effects are illustrated in Figure 3 which shows the case for the 'thermal' ions on the left and 'energetic' ion on the right. Panels (a) give waveforms for the plasma current and total injected beam power. Reconnection events (REs) are signatured by sharp upticks on the plasma current waveform which are flagged by the solid vertical lines in both plots. Panels (b) show representative Mirnov coil traces in which an RE is identified by a sharp signal burst while other activity exhibits more continuous signal fluctuations. In both plots, strong REs are preceded by sawteeh or other MHD activity flagged by the dashed vertical lines. While this preceding activity does influence neutron and ion behavior, attention will be focused on the strong REs marked by the solid vertical lines. In the case of the thermal ions (left), an RE produces a sharp burst in the NPA signal [panel (c)] while having little or no affect on the neutron yield. A small increase in the apparent ion temperature can be seen in panel (d). These observations are indicative of a redistribution of core ions to the plasma periphery where the neutral density is higher, thus producing the spike in the NPA flux and measured T_i. On the other hand, an RE causes a prompt depletion of the NPA energetic ion distribution [right, panel (d)] without the redistribution signature seen in the thermal energy range. The ion loss caused by the RE results in a prompt drop in the neutron yield as seen in panel (c). As neutral beam injection continues following the REs, the energetic ion distribution recovers as does the neutron yield. The NPA signal becomes larger during I_p rampdown due to the increasing charge exchange neutral target density.

NPA Measurements of HHFW Energetic Tail Formation

High Harmonic Fast Wave (HHFW) heating at 30 MHz, $P_{RF} \leq 3$ MW has been applied to NSTX plasmas with and without the presence of NB heating. When HHFW is combined with NB heating, an energetic tail up to 140 keV is formed above the D neutral beam injection energy which is typically ~ 80 keV. An example of this behavior is shown in Figure 4. From the top, the waveforms on the right show the plasma current with a flattop of 550 kA, injection of three 1.5 MW, 80 keV D beam blips of 20 msec width, HHFW injection of 2.5 MW power, the neutron yield and the NPA signal at E_D = 100keV. At bottom left is shown the NPA measurement of the 3-D energetic ion spectra extending out to 140 keV corresponding to the three NB blips. The top left panel shows a time slice of the HHFW energetic tail spectrum extending from 80 – 140 keV overlaid with 80 keV NB slowing down spectrum in the absence of HHFW. The HHFW energetic tail forms in 5 – 10 msec, saturates in time during HHFW and appears to decay classically after HHFW turn off with a decay time of ~ 20 msec, similar to the decay of the NB slowing down distribution. As the HHFW injection power decreases, an energetic tail out to 140 keV still forms but the time required for the tail to grow increases.

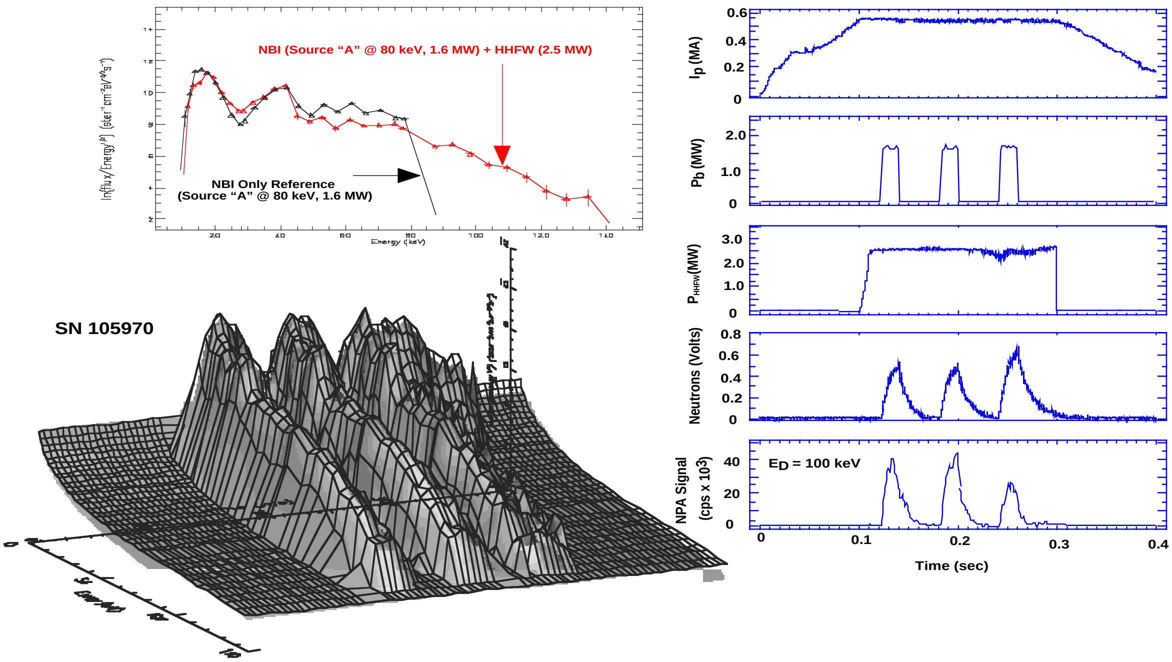

Figure 4. NPA Measurements of HHFW energetic ion tail formation in NSTX

The growth rate, amplitude and decay rate of the neutron yield all increase with application of HHFW during NBI which is consistent with the existence of the energetic ion tail observed. The tail is attributed to HHFW plus NBI fast ion interactions at $\omega/\Omega_D \sim 9$.

NPA Measurement of Ion Temperature

Since NSTX uses deuterium for both the neutral beams and the plasma discharge, it is necessary to measure the spectra of the residual H^+ ions in order to obtain NPA ion temperature measurements. Quite recently, the NPA yielded the first time histories of T_i on NSTX, an example of which is shown in Figure 5. The top panel shows the NPA fitted Maxwellian spectra for two times corresponding to the $T_i(t)$ measurements in the center panel obtained with a time resolution of 5 msec. The bottom panel shows waveforms for electron temperature and density from the multi-pulse Thomson scattering (MPTS) system as well as the injected neutral beam power, plasma current and a Mirnov coil trace. It can be seen that the ion and electron temperatures roll over at ~ 0.22 sec due to the onset of large MHD activity indicated by the Mirnov signal.

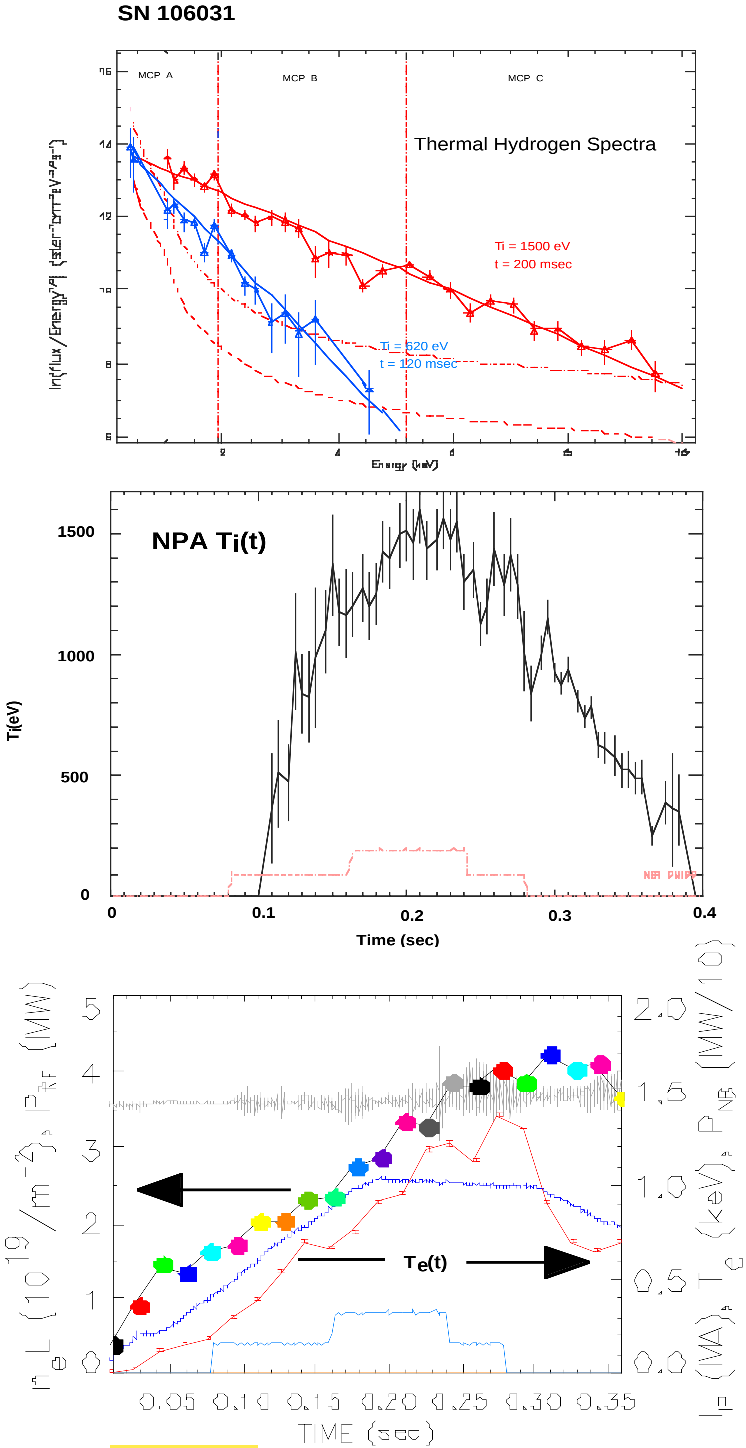

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Figure 5.Typical NPA thermal hydrogen spectra (top panel) and ion temperature evolution (center panel).

The initial analysis of CHERS profiles during NB heating shows T_i profiles that are typically hotter and broader than T_e profiles [2]. Figure 6a shows the plasma current , NB power and a Mirnov coil trace. The vertical bar indicates the time of the CHERS measurement. NPA measurements are shown in Figure 6b along with $T_e(0)$ from MPTS. Good agreement is found between the $T_i(0)$ from the CHERS profile (Figure 6c) and T_i from NPA taken at the same time. This agreement of the line-integral NPA measurements with the localized CHERS data is no doubt abetted by the broadness of the T_i profiles. Further analysis is in progress to see if this agreement persists over a wide range of electron temperature and density profiles.

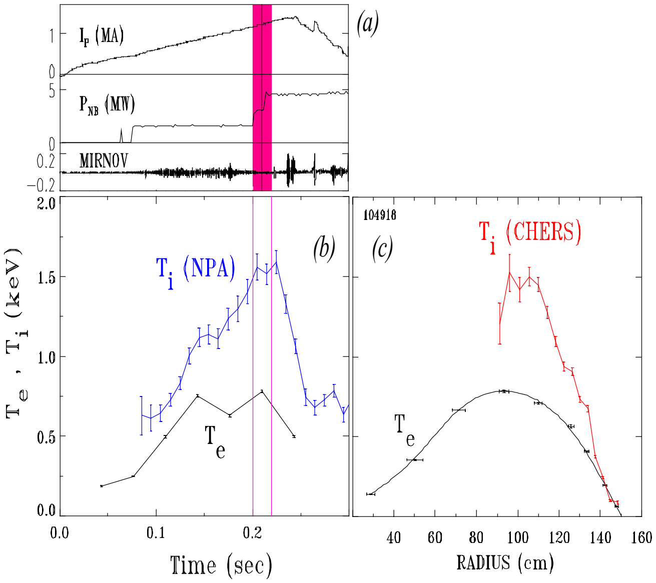

Figure 6. Comparison of temperature measurements from NPA, CHERS, and MPTS.

Acknowledgements

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[1] S. S. Medley, *et al. Rev. Sci. Instrum*. **69**, 2651 (1998).

[2] R. E. Bell, et al. PPPL Report, PPPL-3591 (1998).

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