KINETIC PROFILES IN NSTX PLASMAS

R. E. Bell, B. P. LeBlanc, C. Bourdelle, D. R. Ernst, E. D. Fredrickson, D. A. Gates,
J. C. Hosea, D. W. Johnson, S. M. Kaye, R. Maingi,[a] S. Medley, J. E. Menard,
D. Mueller, M. Ono, F. Paoletti,[b] M. Peng,[a] S. A. Sabbagh,[b] D. Stutman,[c]
D. W. Swain[a], E. J. Synakowski, J. R. Wilson

Princeton Plasma Physics Laboratory, P. O. Box 451, Princeton, NJ 08543 USA
[a]Oak Ridge National Laboratory, Oak Ridge, TN 37831 USA
[b]Columbia University, New York, NY USA
[c]Johns Hopkins University, Baltimore, MD USA

1. 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 heating (HHFW). Typical NSTX parameters are R_0 = 85 cm, a = 67 cm, I_p = 0.7-1.4 MA, B_ϕ = 0.25-0.45 T. Three co-directed deuterium neutral beam sources have injected $P_{NB} \leq 4.7$ MW. HHFW plasmas typically have delivered $P_{RF} \leq 3$ MW. Important to the understanding of NSTX confinement are the new kinetic profile diagnostics: a multi-pulse Thomson scattering system (MPTS) and a charge exchange recombination spectroscopy (CHERS) system. The MPTS diagnostic currently measures electron density and temperature profiles at 30 Hz at ten spatial locations. The CHERS system has recently become available to measure carbon ion temperature, T_i, and toroidal flow, V_ϕ , at 17 radial positions spanning the outer half of the minor radius with 20 ms time resolution during NBI. Experiments conducted during the last year have produced a wide range of kinetic profiles in NSTX. Some interesting examples are presented below.

2. Peaked electron density and MHD in ohmic discharges

A broad range of electron density profiles has been observed to date. Peak central electron densities up to $n_e(0) = 8 \times 10^{19}$ m^{-3} have been measured in ohmic plasmas exhibiting little magnetohydrodynamic (MHD) activity. The appearance of MHD can have a pronounced effect on the electron density profile, in particular. By careful programming of the discharge, an MHD-quiescent plasma will result in a high centrally peaked n_e profile. Figure 1 shows the evolution of n_e and T_e profiles in a discharge that is initially MHD quiescent. The central electron density increases until the onset of an n=1 mode which appears at 0.27 seconds as the minimum q, as calculated by EFIT[1,2], drops below 1. In the presence of such MHD activity, the central peaking is usually lost and a much broader n_e profile results, as seen for the last profile at 0.297 seconds in Fig. 1; the T_e profile (Fig. 2b) remains unchanged.

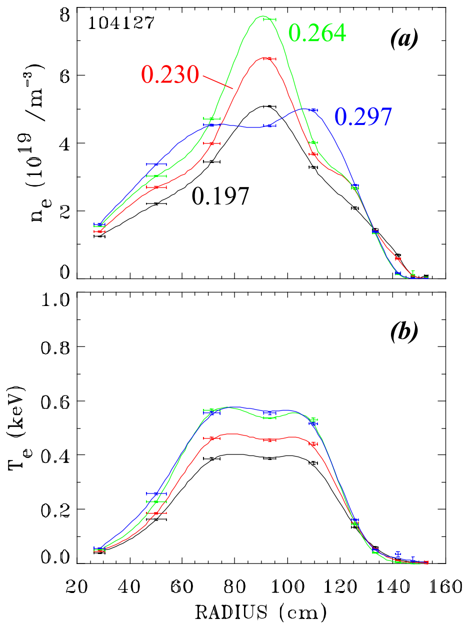

Figure 1. *n_e and T_e profiles during ohmic discharge. Strong central peaking of electron density is lost after onset of n=1 mode at 0.27 seconds.*

3. High Harmonic Fast Wave during I_p ramp

High harmonic fast wave yields effective electron heating[3,4]. HHFW power has also been applied during the ramp up of the plasma current, I_p, to slow current diffusion. This early application of HHFW power into a deuterium plasma resulted in a large density increase, leading to record central electron densities[2]. The initial n_e profile was hollow and filled in after about 0.15 seconds (see Fig. 2), producing a broad profile with $n_e(0) = 8 \times 10^{19}$ m^{-3} and steep edge density gradients. The density rise occurred without gas.

4. Ion temperature and velocity during neutral beam injection

The addition of neutral beam injection in NSTX has allowed the measurement of carbon impurity temperature using charge exchange recombination spectroscopy. The neutral beam sources can be used to heat the plasma or, using a brief pulse of NBI, act as probes of T_i and V_ϕ during ohmic or HHFW experiments. At present, analysis of CHERS data is limited to times when there is a step in the NB power. The application of short neutral beam pulses into ohmic plasmas shows profiles with $T_i \sim T_e$. During HHFW heating experiments, $T_e(0) > T_i(0)$ is measured under conditions of strong electron heating.

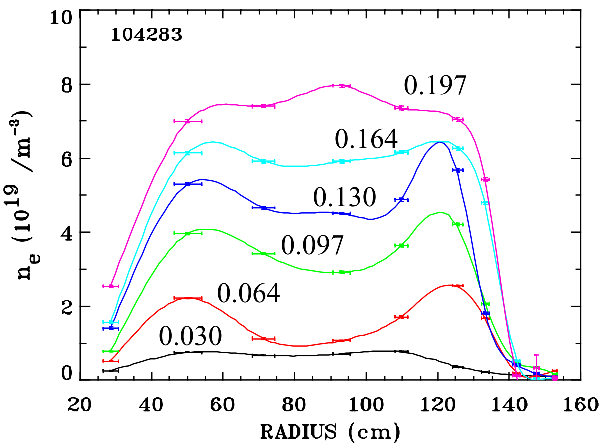

Figure 2. *Evolution of the n_e profile with the application of HHFW during I_p ramp. Time of successive profiles are indicated.*

The initial analysis of CHERS profiles during NB heating shows T_i profiles that are typically hotter and broader than T_e profiles. Ion temperatures up to 2 keV have been measured. Shown in Figure 3 are the T_i and V_ϕ profiles for a plasma with a step in the NB power as I_p is being ramped up to 1.2 MA. The toroidal impurity velocity during this discharge is the highest measured to date, $V_\phi \leq 240$ km/s. This carbon velocity is a significant fraction of the deuterium thermal and Alfvén velocities, $V_\phi = 0.26\ V_A^{deuterium}$ and $V_\phi = 0.6\ V_{th}^{deuterium}$.

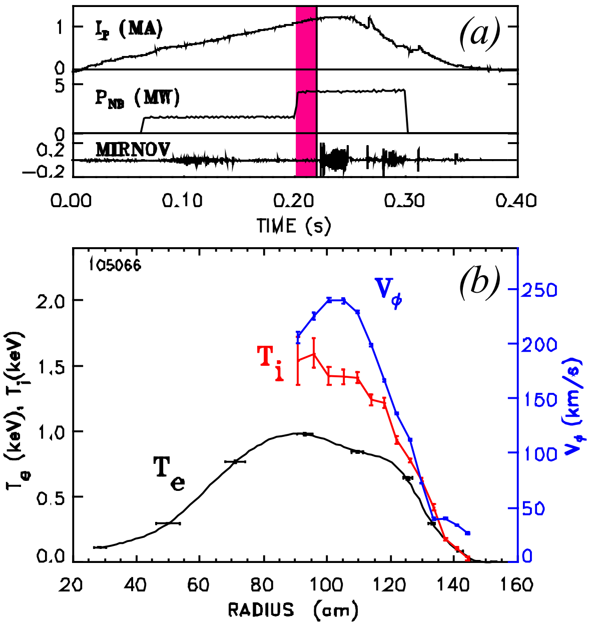

Figure 3. *(a) Time of CHERS measurement (shaded) at step in NB power. (b) Profiles showing* $T_I > T_e$ *and high* V_ϕ.

Figure 4 shows kinetic profiles measured during a high β discharge ($\beta_T \sim 20\%$ from EFIT based on magnetics only) when a large m/n=1/1 mode was present, just before the β collapse. In Fig. 4a, T_i is flat in the center and broader than T_e (T_i was measured at 0.215 seconds, compared to T_e at 0.197 seconds). The toroidal velocity within a few centimeters of the low field edge is also remarkably high, $V_\phi = 50$ km/s. In Fig. 4c, V_ϕ peaks off axis. In similar discharges, prior to the strong 1/1 mode, the central values of T_i and V_ϕ are more peaked, such as seen in Fig. 3. In Fig. 4d, the flow measurements are plotted in terms of the rotational frequency, $f_\phi = V_\phi / 2\pi R$ where R is the major radius. A hollow f_ϕ profile results. Isobars from the electron pressure profile were used to map the low field side to the high field. This mapping of f_ϕ is shown as a dashed line in Fig. 4d, which retraces the measured values that extend inside the magnetic axis. The dashed line in Fig. 4c are the analog linear velocities on the high field side of the magnetic axis which are not

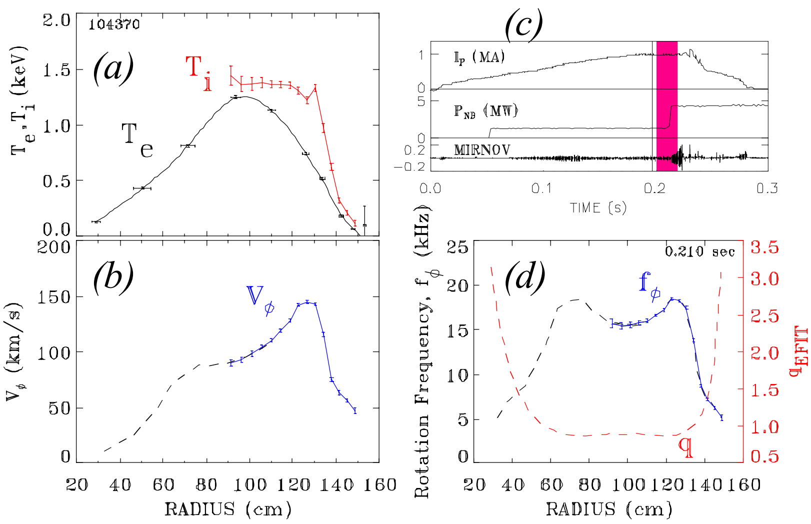

Figure 4. *(a) Temperature profiles (b) Toroidal velocity proifle (blue) with inferred values (dashed) assuming* f_ϕ *constant on flux surface. (c) Time of CHERS measurements (shaded) at step in* P_{NB}. *(d) Rotational frequency profile with q profile from EFIT.*

directly measured. Under the above assumptions, the high measured edge velocity at the outer radii are mapped to velocities which are an order of magnitude lower near the central column of NSTX.

Quite recently, a neutral particle analyzer (NPA) became operational, yielding the first time histories of $T_i(0)$ on NSTX. Measurements taken during a 1.4 MA discharge are shown in Fig. 5b along with $T_e(0)$ from MPTS. Good agreement is found between the $T_i(0)$ from the CHERS profile (Fig. 5c) and T_i from NPA taken at the same time.

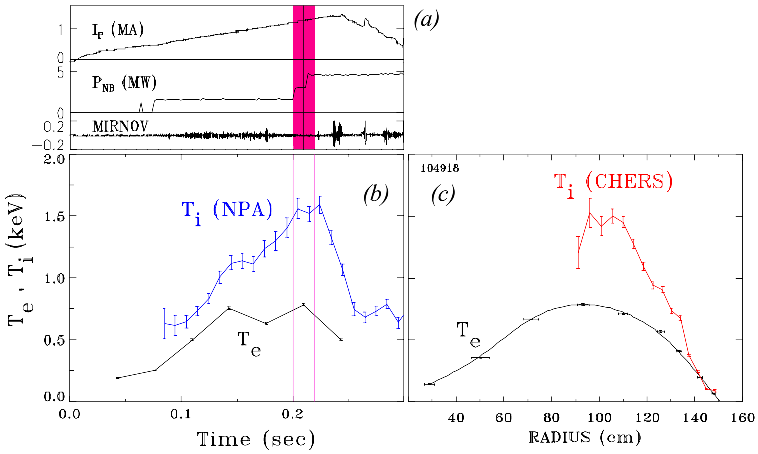

Figure 5. *Comparison of temperature measurements from NPA, CHERS, and MPTS.*

The measured temperature and velocity profiles during NBI present several puzzles. The difference between T_i and T_e at some radii is sufficiently large to challenge our understanding of the power balance in terms of classical collisional processes. Electron ion coupling is expected to be strong. Most of the neutral beam power is expected to be delivered to the electrons. However, a power balance calculation indicates that the power flow from ions to electrons exceeds the power delivered to the ions by NBI. Efficient coupling of beam ion energy to thermal ions by stochastic heating from MHD may account for some of the calculated deficit [5]. This could imply a small, but positive, ion thermal conduction and large electron thermal conduction, consistent with recent microstability analyses of these discharges.

Acknowledgements

This work was supported by the United States Department of Energy under contract number DE-AC02-76CH03073.

[1] Lao, L. L. , *et al.*, Nucl. Fusion **25**, 1611 (1985).

[2] Sabbagh, S. A., *et al.*, Nucl. Fusion (2001), accepted for publication.

[3] Wilson, J. R., *et al*, Proc. 18th IAEA Fusion Energy Conf. (Sorento 2000) EXP 4/08

[4]LeBlanc, B. P., *et al*, Proc. 14th Conf. RF Power in Plasmas (Oxnard 2001) Invited

[5] Gates, D. A., Gorlenkov, N., White, R. B., submitted to Phys. Rev. Lett. (2001).