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by

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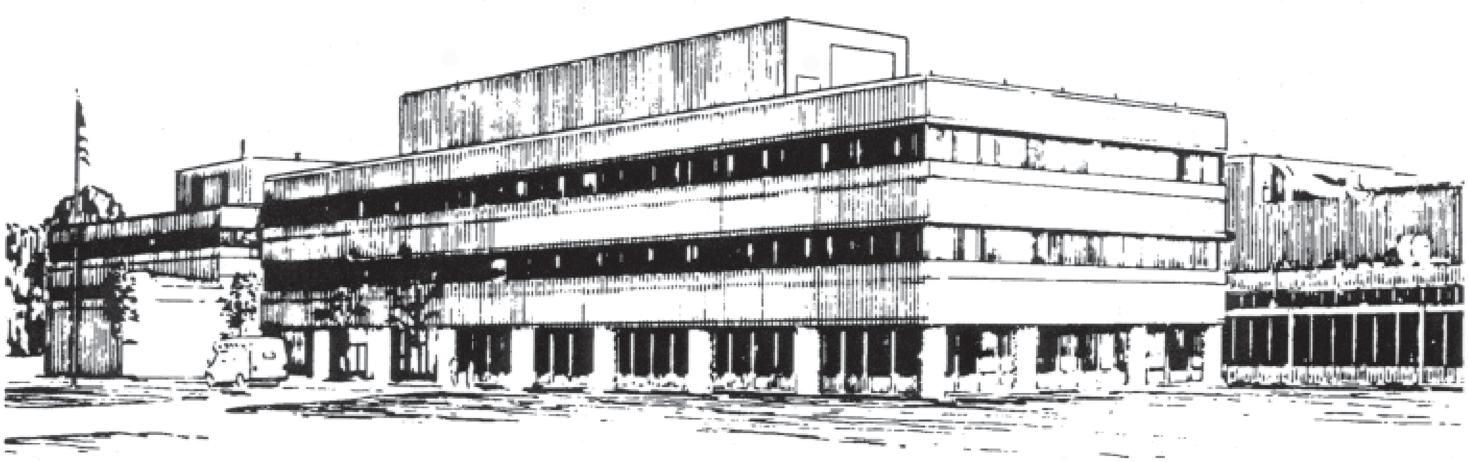

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Transport in Auxiliary Heated NSTX Discharges*

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The NSTX spherical torus (ST) provides a unique platform to investigate magnetic confinement in auxiliary heated plasmas at low aspect ratio. Auxiliary power is routinely coupled to ohmically heated plasmas by deuterium neutral beam injection (NBI) and by high-harmonic fast waves (HHFW) launch. While theory predicts both techniques to preferentially heat electrons, experiment reveals $T_e > T_i$ during HHFW, but $T_e < T_i$ during NBI. In the following we present the experimental data and the results of transport analyses.

Figure 1 displays four time evolution panels for a deuterium high power NBI heated discharge lasting beyond 0.55 s. In the top panel we see that the flattop of the 0.9 MA plasma current starts at 0.18 s. The plasma has a lower single null configuration (LSN) for the time of interest. Three neutral beam sources are staggered with respective onset times of 0.1, 0.2 and 0.25 s; NBI lasts until the end of the discharge. The injection energy ranges from 80 keV to 95 keV. β_T reaches 15% and the energy confinement time, τ_E, is ≈ 0.04 s.

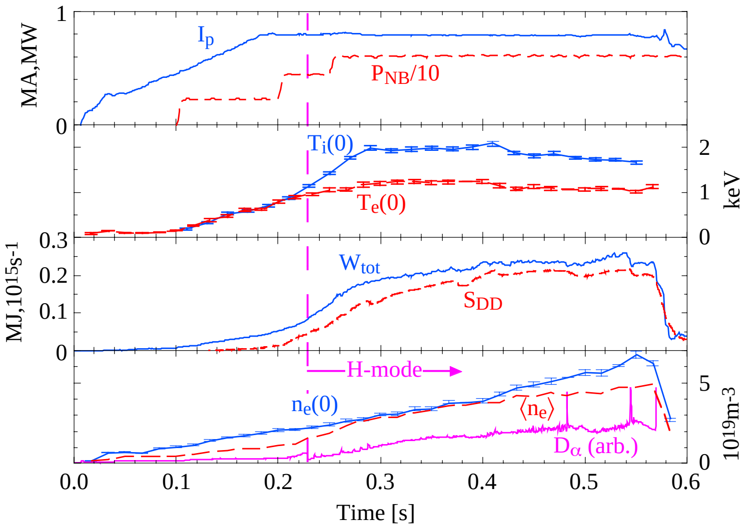

Figure 1: Time evolution of a high power NBI heated plasmas. H-mode transition marked with a dotted line.

A vertical dotted line marks the H-mode transition time, which can be seen on the D_α trace

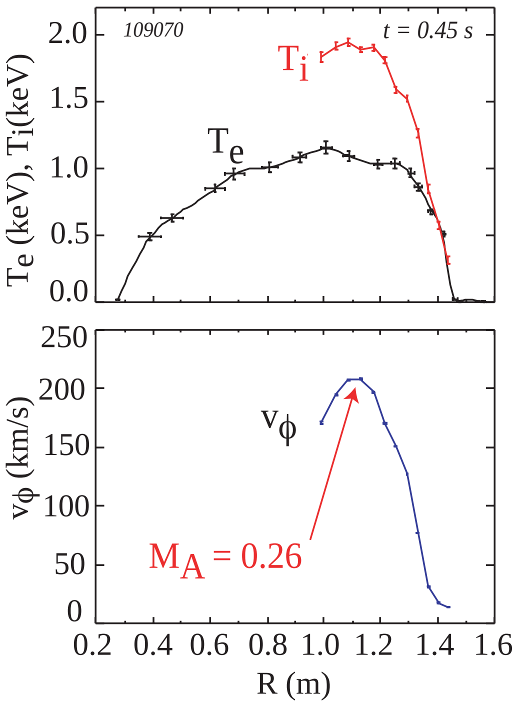

Figure 2: Kinetic profile during NBI. (a) Overlay of T_e and T_i profile s. (b) Profile of v_ϕ . The the Alfvén Mach number reaches M_A = 0.26 in the plasma core.

(bottom panel). The central ion temperature, T_{i0}, and electron temperature,T_{e0}, are equal during the early phase of auxiliary heating. But for times greater than 0.22 s, T_{i0} increases over T_{e0} and remains greater until the end of the discharge. A small drop of T_{i0} at ≈ 0.42 s is echoed by T_{e0}. The T_i *(R)*, T_e*(R)* and toroidal velocity $v_\phi(R)$ profiles shown in Fig.2 correspond to t = 0.45 s of this discharge. While there is good agreement between T_e and T_i at the edge, we see that $T_i > T_e$ over a wide section of the plasma column. Since the beam energy is typically many times larger than the 1-2 keV electron temperature, one would expect from classical slowing down physics of fast particles that most (≈ 2/3) of the neutral beam power be deposited into the electron population. The experimental observation that T_i is greater than T_e during NBI despite the expected preferential electron heating suggests that the ion confinement is much better than that of the electrons. The third panel shows global measurements stored energy and neutron production rate, which are well reproduced in TRANSP analyses. The effects of the H mode are seen in the bottom panel where the central density, n_{e0} and the volume average density $\langle n_e \rangle$ are displayed. One sees that $n_{e0} \approx \langle n_e \rangle$ from 0.25s to 0.40 s, corresponding to a phase where n_e*(R)* profile builds up “ears” in the edge regions. Later on n_{e0} becomes greater than $\langle n_e \rangle$ as the center of the density profile fills in. More details about H-mode plasmas in NSTX can be found elsewhere [1]. Figure 3 shows profiles of the power and momentum balance diffusivities extracted from TRANSP analysis at t = 0.45 s.

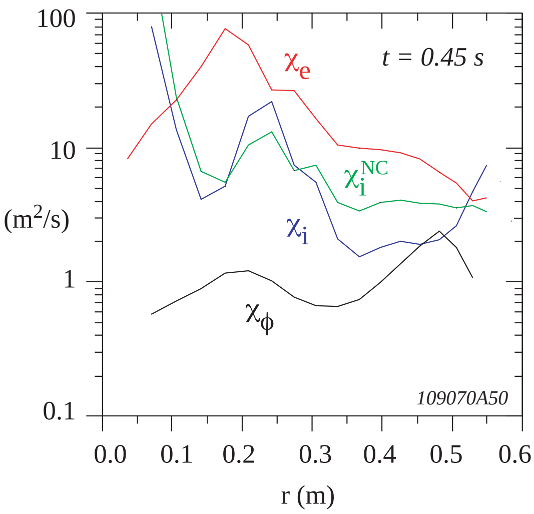

Figure 3: Experimental diffusivities during high power NBI heating: electron thermal, χ_e, ion thermal, χ_i, and momentum, χ_ϕ. Neoclassical calculation of ion thermal diffusivity, χ_i^{NC}.

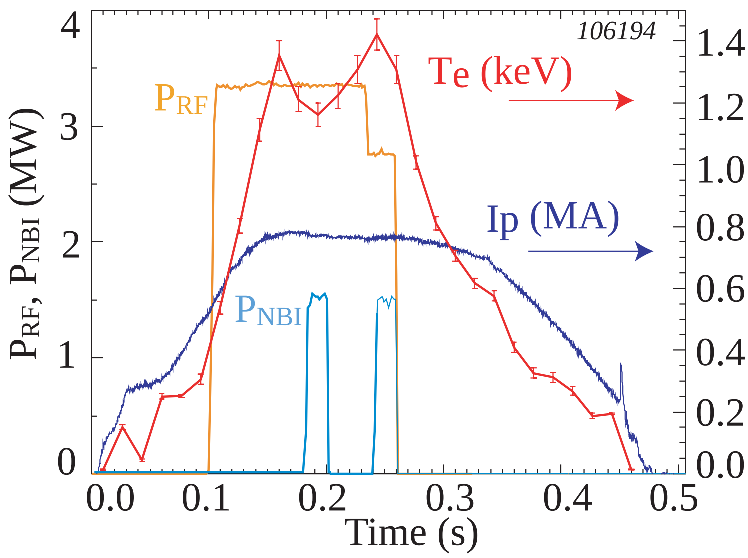

Figure 4: HHFW heating in 0.5 MA, 0.45 T, He plasma. T_{e0} rises rapidly 1o 1.3 keV in response to HHFW power onset. Two short NBI pulse are use for T_i measurement.

The momentum diffusivity χ_ϕ is the lowest in magnitude, hovering slightly below 1 m^2/s in the core region and increases towards the edge up to slightly higher than 2 m^2/s. The χ_i profile has a different behavior, being the largest in the core region and lowest in the edge region. The neoclassical χ_i^{NC} prediction from the NCLASS code [2] follows the shape of χ_i over the whole profile. This is partially due to the fact that χ_i^{NC} is computed using the neoclassical ion thermal flux from NCLASS and the measured local gradient and density. One notes that $\chi_i \approx \chi_i^{NC}$ in the core region, while $\chi_i < \chi_i^{NC}$ in the outer region. The electron thermal confinement is poor, with large χ_e values reflecting the flattening of the core T_e profile seen in Fig. 2. The overall $\chi_e(R)$ shape is also unusual, being lower at the edge than at in the core. These results support the inference that the ion confinement is superior to that of the electrons in NSTX NBI discharges. A micro-stability analysis can be found elsewhere [3].

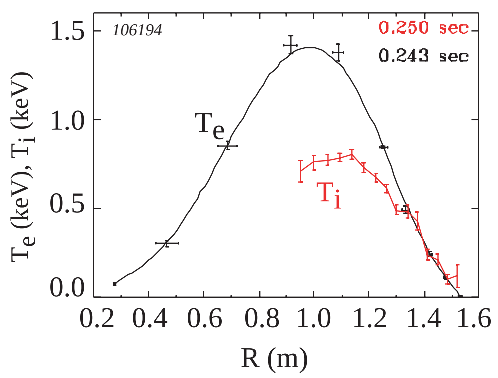

Figure 5: Measured T_e and T_i profiles during second NBI diagnostic pulse. T_e is roughly twice T_i in core region. $T_e \approx T_i$ in edge region.

HHFW heating is an important auxiliary heating system that complements NBI. The antenna array comprises 12 current carrying elements driven by transmitters operating at 30 MHz. In the present case the launch spectrum is undirected and characterized by $k_{//}$ = 14 m^{-1}. The application of HHFW power is an effective means of bulk electron heating. One can see in Fig. 4 the temporal evolution of relevant plasma parameters of a LSN helium discharge undergoing HHFW heating. The toroidal field is 0.45 T and the

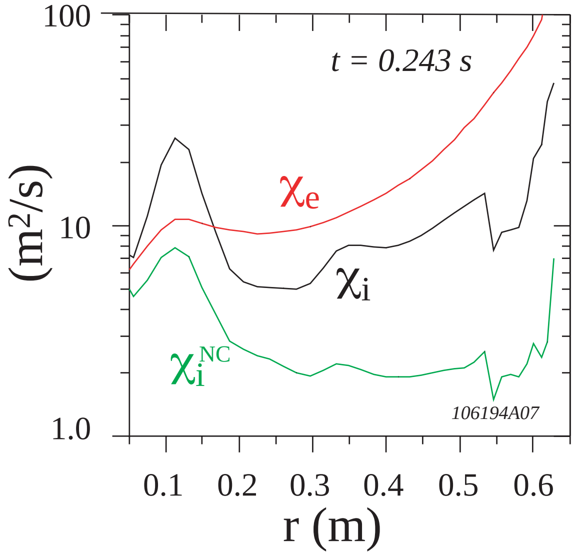

Figure 6: Experimental thermal diffusivity profiles against minor radius *r* during HHFW heating: electron thermal, χ_e, and ion thermal, χ_i . Neoclassical calculation of ion thermal diffusivity, χ_i^{NC} .

plasma current 0.8 MA. HHFW power reaching 3.3 MW is applied during the 0.1-0.26 s time interval. Following the HHFW power onset, a rapid increase of the central electron temperature, T_{e0}, rising from 0.3 keV to 1.3 keV in 0.06 s. β_T reaches 4.5% and $\tau_E \approx 0.014$ s. The low T_{e0} seen at $t \approx 0.045$ s is caused by a radial shift of the plasma column. Two NBI short pulses were injected to measure the T_i profile by charge exchange recombination spectroscopy. Figure 5 shows an overlay of the T_i and T_e profiles corresponding to the second beam blip. We find again good agreement between T_i and T_e in the edge region. In the central region, T_e reaches 1.4 keV, while T_i remains at 0.8 keV, as one would expect under this condition of electron heating. A TRANSP analysis can be made by making use of the HPRT[4] code for the computation of the HHFW power deposition by ray tracing. Such a calculation was made for a time within the second NBI diagnostic pulse. Most of the HHFW power is absorbed by the electrons, over a wide profile that peaks in the center. Only a very small amount of power is absorbed by the thermal ions, but some power is absorbed by the fast ions during NBI. For the purpose of this analysis, the power absorbed by the fast ions is divided evenly between thermal ions and electrons. In absence of NBI, the electrons absorb essentially all the HHFW power. One can see in Fig. 6 profiles of the thermal diffusivities at $t = 0.243$ s corresponding to the time shown in Fig. 5. Contrary to what was seen in the high-power NBI case shown earlier, one sees that $\chi_i > \chi_i^{NC}$. Electron thermal transport remains the leading loss mechanism. The thermal diffusivities χ_i and χ_e bare profiles that are lower at the center and larger near the edge.

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