

Dependence of electron transport on heating power and q-profile in NSTX

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Motivation. Electron transport dominates thermal losses in high performance, beam heated NSTX H-modes [1]. Studying the dependence of this loss on discharge parameters is important for predicting the performance of future devices, such as a ST based CTF [2]. Recent experiments have shown for instance a decrease in the electron heat diffusivity χ_e , with toroidal magnetic field [1]. Another important trend to study is the dependence of electron transport on the heating power and T_e gradients. A large body of evidence in conventional tokamaks indicates the existence of a threshold in $\nabla T_e/T_e$ for the onset of turbulent electron transport [3]. In NSTX an unusual effect is observed, consisting in the broadening of the T_e profiles with increasing beam power, P_{NB} in H-mode plasmas. The TRANSP power balance calculations indicate that this is due to a large χ_e increase in the central plasma, coupled with a decrease in the outer plasma. This situation is illustrated in Fig. 1, which shows the T_e and χ_e profiles for 1 MA, 4.5 kG discharges heated by 2, 4 and 6 MW beams. χ_i is computed to be in the neoclassical range for all power levels.

An important question here is if the power balance assumptions are correct. For instance, it was shown that low and high frequency MHD activity can have a significant impact on the energetic ion distribution in NSTX [4]. While at low frequency only low amplitude, peripheral perturbations are observed in the discharges in Fig. 1, the intensity of high frequency (CAE range) MHD activity is increasing with power [5]. If these modes

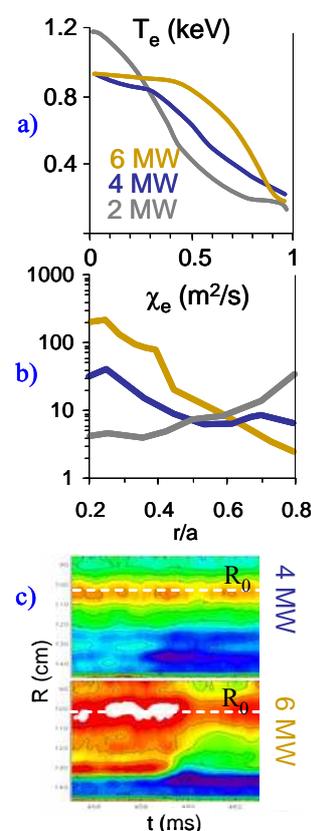


Fig. 1 a) T_e change with P_{NB}
b) TRANSP computed χ_e
c) T_e sensitive SXR emission during pellet cold pulse

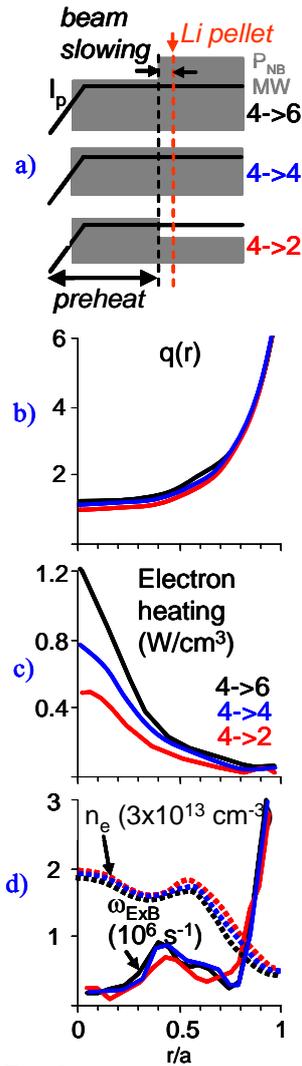


Fig. 2
 a) P_{NB} change at fixed- q
 b) q -profile change
 c) Electron heating change
 d) ω_{ExB} and n_e change

redistribute the beam ions which heat the electrons in NSTX, the T_e profile could change without a change in electron transport.

The indications are however that the electron power balance is reasonably accurate. First, the measured and TRANSP computed neutron rates agree within 5-10% these plasmas. Artificially broadening the fast ion distribution in TRANSP by assuming an anomalous fast ion diffusivity, shows that it takes an order of magnitude diffusivity increase (from 1 m²/s to 10 m²/s) to change χ_e by a factor of two. In this case however the neutron rate decreases far below the experimental value, suggesting that the TRANSP computation in Fig. 1b must be correct. Finally, support for a change in electron transport with P_{NB} comes also from perturbative electron transport experiments [6]. As shown by the SXR data in Fig. 1c, high P_{NB} cases exhibit a stronger T_e perturbation than low P_{NB} ones.

Since together with P_{NB} , $q(r)$ and ω_{ExB} also significantly change in the plasmas in Fig. 1, in order to study the broadening effect we designed a simple experiment aimed at separating the dependence of χ_e on P_{NB} at fixed $q(r)$ and ω_{ExB} , as well as its dependence on $q(r)$ at fixed P_{NB} and ω_{ExB} .

Experiment. The principle of the experiment is depicted in Fig. 2a. The plasma is preheated at fixed power for duration of the order of the current diffusion time (0.42s), in order to ‘freeze-in’ the q -profile and also to allow the rotation and thermal profiles to reach equilibrium. After this state is reached, P_{NB} is varied to change the electron heating. Transport is then assessed at about one beam slowing down time after the P_{NB} change ($t=0.45s$), in order to allow the fast ion distribution to reach its new equilibrium. The results of this technique are illustrated in Fig. 2b to 2d. As seen, a large change in electron heating is obtained in conditions of nearly identical q -profiles, ω_{ExB} and density profiles.

The T_e profiles at $t \approx 0.45$ s are shown in Fig. 3a and exhibit the same trend as in those in Fig. 1. At high power the profile broadens, while at low power it narrows. The effect is now directly attributable to the change in electron heating. The change in electron transport is

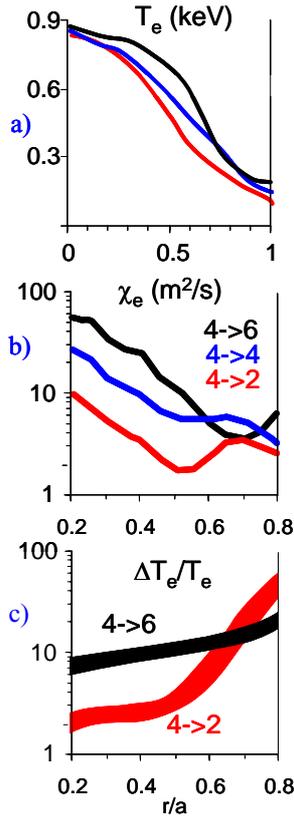


Fig. 3 a) T_e change with P_{NB} at fixed-q
 b) χ_e change
 c) Cold pulse amplitude

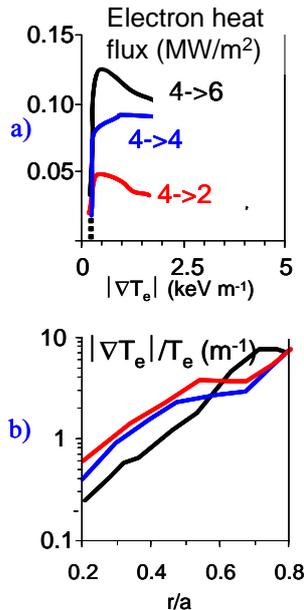


Fig. 4 a) TRANSP electron heat flux vs. T_e gradient
 b) normalized T_e gradient in the three P_{NB} cases

assessed in two ways. First, the power balance shows a large increase in the core χ_e ($r/a < 0.6$) with increasing P_{NB} . Second, as in Ref. 6, the T_e profiles are perturbed using shallow pellet injection and the ‘cold pulse’ propagation followed with a multi-energy SXR system [7]. The results (Fig. 3c) show that at high power the pellet produces a global, rapid (≈ 2 ms) T_e perturbation, while at low power the T_e perturbation is strongly damped inside $r/a < 0.6$, qualitatively consistent with the power balance result.

Two interesting observations arise from this experiment. First, the large increase in χ_e at $P_{NB} > 2$ MW indicates a low critical T_e gradient in the central NSTX plasma. To quantify this gradient, we plot as in Ref. 8 the electron heat flux versus the T_e gradient (Fig. 4a). As seen, for all cases the extrapolation to zero heat flux indicates a critical gradient near $\nabla T_e = 0$. For comparison, the critical gradient in Tore Supra is 2.5 keV/m [8].

A second observation is that, as shown in Fig. 4b, the 4->2 discharge has substantially larger normalized T_e gradient at $r/a < 0.6$ than the 4->6 one. Since the electron transport is much faster in the 4->6 case, the inference is that it is not the T_e gradient driving electron transport in the core of these plasmas, but rather the heat flux itself. This can occur through avalanche mechanisms [9] and might explain rapid transport in regions with little thermal gradients, such as central NSTX plasma, or ‘box-like’ ITB plasmas [3].

Further on, we began studying also the effects of changes in the q-profile at fixed P_{NB} . The experiment consisted in pre-heating the plasma at different power levels in order to change the ‘frozen-in’ q-profile, and then bringing the power to a fixed level of 4 MW (Fig. 5a). A substantial difference in the q-profiles at fixed power (and also ω_{EXB}) is achieved, as shown in Fig. 5b. The change in q-profile has a large effect on the T_e

profiles, as shown in Fig. 6a. TRANSP computes this is associated with a large difference in the χ_e profiles in the two plasmas, with the 2->4 case having much reduced electron transport inside $r/a \approx 0.6$ ($q \approx 2$ radius). This trend is also supported by the perturbative experiments, which show slowing down of the cold pulse inside $q=2$ and ‘polarity reversal’ inside $q=1$. A role for low order rational surfaces in NSTX transport is also suggested by reversed shear, low n_e L-modes, which show transient T_e increases when rational surfaces enter the plasma.

Lastly, the particle diffusivity was also measured in the 6->4 case and found to be around neoclassical ($< 1 \text{ m}^2/\text{s}$ for $r/a < 0.8$), suggesting suppression of low-k turbulent transport [10]. To explain the large gap between the particle diffusivity and the central χ_e in Fig. 6b, one can invoke high-k electrostatic turbulence, or magnetic (stochastic) electron transport. Micro-tearing modes have indeed been predicted to be active in the ST [11].

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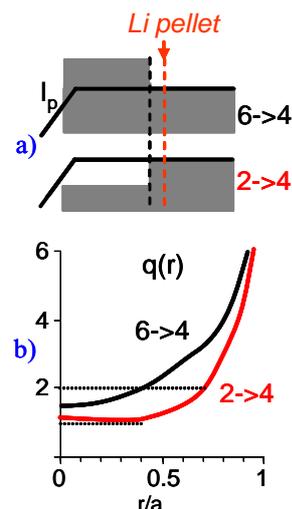


Fig. 5 a) Scheme for q-profile change at fixed P_{NB}
b) q-profile change obtained

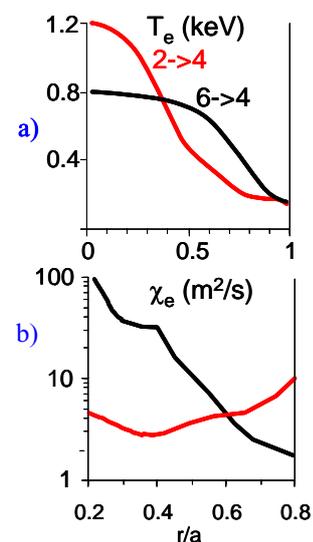


Fig. 6 a) T_e profiles at different q and fixed P_{NB}
b) χ_e change with q