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by

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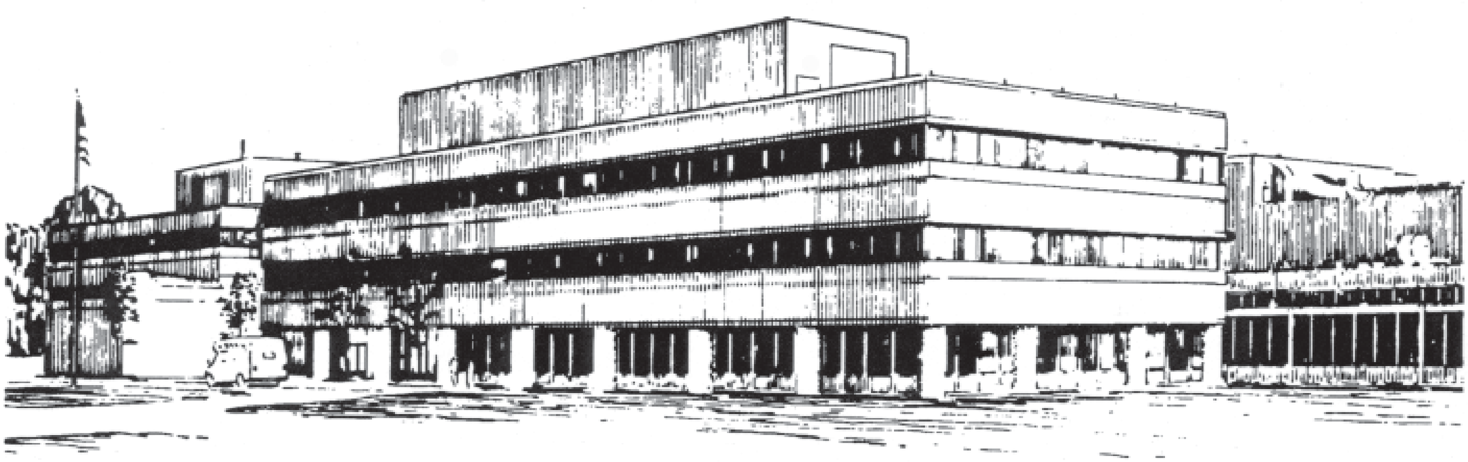

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Edge recycling and heat fluxes in L- and H-mode NSTX plasmas

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Introduction Edge characterization experiments have been conducted in NSTX to provide an initial survey of the edge particle and heat fluxes and their scaling with input power and electron density. The experiments also provided a database of conditions for the analyses of the NSTX global particle sources, core fueling, and divertor operating regimes. The pulse conditions comprised typical $I_p = 0.8 - 0.9$ MA, $B_t \simeq 0.4$ T, $\delta = 0.3 - 0.4$, $\kappa = 1.6 - 2.2$ plasmas of $t \simeq 0.6$ s duration, heated by 2 - 6 MW neutral beams. Both L-mode and H-mode plasmas were obtained, with $T_e(0) \simeq (0.8 - 1.0)$ keV, $\bar{n}_e \simeq (2 - 5) \times 10^{19}$ m^{-3}, and $Z_{eff}(0) < 2$. The outer midplane separatrix plasma parameters $T_e^{sep} \simeq 10 - 30$ eV and $n_e^{sep} \simeq 2 - 7 \times 10^{18}$ m^{-3}, measured by the Multi-point Thomson scattering system, show that the scrape-off layer (SOL) collisionality $\nu_e^* \geq 3$. The lower single null (LSN) magnetic configuration was utilized with the ion ∇B drift toward the lower X-point, the X-point height of 15 - 20 cm, and the flux expansion (evaluated at outer strike point) of 3 to 4. The deuterium plasmas are fueled by prefilling the vacuum vessel with gas and injecting gas from both a low field side (LFS) injector at about 120 Torr l/s from $t = 0$ s to $t = 0.1$ s, and a center-stack high field side (HFS) injector at the decreasing rate of 80 - 20 Torr l/s from $t = 0$ s to $t = 0.5$ s [1]. Whereas this fueling scheme allowed better access to H-modes, the $\bar{n}_e$ increased continuously and non-disruptively at a rate of $R \leq 20$ Torr l/s. For comparison, the fueling rate of one NBI source is about 2.5 Torr l/s, and the gas fueling efficiency is 0.1 - 0.2 [2], which implies that the plasmas are mainly fueled by other neutral recycling sources, e.g. the main chamber (MC) wall or divertor.

Divertor heat fluxes Divertor heat flux mitigation has been predicted to be of special importance to spherical tori, due to their compact design. Divertor infra-red emissivity profiles were recorded by an infra-red camera, and radial heat flux profiles were inferred using the one dimensional (1D) heat conduction model of ATJ graphite tiles [3]. The heat fluxes up to 10 MW/m^2 have been measured in NSTX, accounting for up to 70 % of the input power in most L- and H-mode plasmas. In one source NBI heated plasmas ($P_{NBI} \leq 2$ MW) divertor peak heat flux equilibrates in the I_p flat-top phase in $\tau_{eq} \simeq (2 - 3) \times \tau_E \simeq 100$ ms, and the in/out ratio remained constant in the 1.6 - 4 MW NBI power range. The average inboard heat flux is a factor of 2 - 3 lower than the outboard, mostly due to the higher flux expansion on the inboard side. Shown in Figure 1 (a) are the representative divertor heat flux profiles in an H-mode phase of LSN discharges with varying NBI input power. As the input power is changed from 2 MW to 4.9 MW the peak heat flux in both inner and outer strike points increases non-linearly, suggestive of divertor detachment. Figure 1 (b) compares peak heat fluxes in L- and H-mode phases of 2 MW NBI heated plasmas. As in conventional tokamaks higher outboard peak heat fluxes are measured in the L-mode, whereas the inboard target loads are similar. Inboard and outboard heat fluxes are found to be independent of the the gas fueling location suggesting that the NSTX divertor regime is not affected

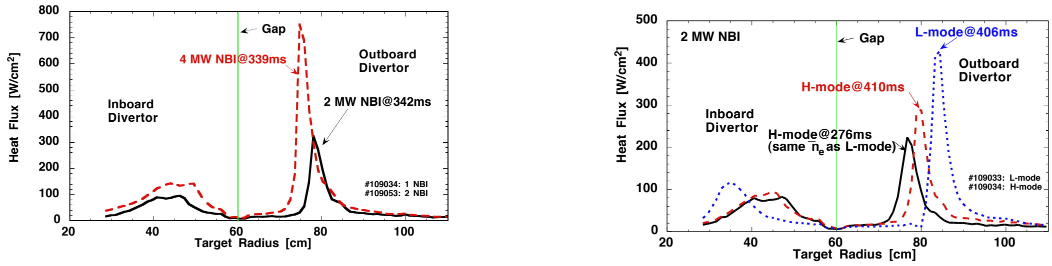

Figure 1: Divertor heat flux profiles in $P_{NBI} = 2 - 4$ MW L- and H-mode plasmas

by the present level of gas puffing.

Neutral and ion fluxes The signs of divertor detachment are also apparent in the spectroscopic measurements. Divertor and midplane neutral deuterium Balmer-alpha (D_α) profiles were recorded by two photometrically calibrated spectrally filtered 1D CCD arrays [4]. Shown in Fig. 2 (a) are representative divertor L- and H-mode D_α brightness profiles. The data are summarized in Fig. 2 (b). The D_α brightness in the inner and outer divertor increases with power in L- and H-mode plasmas. The divertor D_α brightness is almost always higher in L-mode vs H-mode plasmas, although the inner divertor brightness is comparable at $\bar{n}_e \geq 3 \times 10^{19}$ m^{-3}. The lower divertor in/out D_α brightness asymmetry $A_{D_\alpha} = B_{in}/B_{out}$ develops due to a faster rise of the inboard emission with $\bar{n}_e$. The asymmetry is 4 - 6 in the L-mode, and 7 - 12 in the H-mode plasmas. It is, however, smaller than 1 at low densities, and greater than 1 at $\bar{n}_e \simeq 2.5 \times 10^{19}$ m^{-3} in the L-mode, and at slightly higher $\bar{n}_e$ in the H-mode (Fig.3 (a). This behavior is consistent with the divertor being detached on the inboard side and being attached on the outboard side. Three divertor operating regimes have been found in tokamaks based on the ability of a divertor to sustain a parallel temperature gradient and effectively dissipate the heat load: a sheath-limited, a high-recycling and a detached regime. Lacking direct divertor measurements, we use the two point (2PM) model of the SOL transport [5] to interpret the experimental results. The 2PM relates the plasma parameters at the divertor target T_t, n_t, Γ_t to the "upstream" parameters through the Spitzer heat conduction equation, the pressure balance in a flux tube, and the sheath condition at the target surface. Using the measured heat flux density q_t, and n_u, T_u (measured at separatrix) as inputs, the target temperature and density are estimated as shown in Fig. 3 (b). The inner and outer target temperatures are estimated to be $T_t^{in} \leq 5$ eV and $T_t^{out} \leq 20$ eV, respectively, suggesting that the inner target may be detached, whereas the outer target operates in the flux limited (high-recycling) regime. Peak D_α behavior and the divertor D_α in/out asymmetry also support this notion, as $n_t \sim n_u^3$, $T_t \sim n_u^{-2}$ in the high-recycling regime, and both n_t, T_t decrease as the detachment occurs, increasing the D_α intensity.

The relative fueling strength of the recycling outboard divertor and the MC walls can be estimated using the Johnson-Hinnov factor of 30 ionizations/photon. The outer divertor plate of area $A_{out} \simeq 2$ m^2 produces $\Gamma^i_{out} \leq 5 \times 10^{21}$ ion/s. The main chamber plasma surface of area $A_{MC} \simeq 26$ m^2 produces $\Gamma^i_{MC} \leq 10^{20}$ ion/s, comparable or slightly lower than the inboard gas injector flux, however much lower than the divertor source. The inner and outer midplane brightness shows little correlation with the density (Fig. 4 (a)) and inner gap, also suggesting that the MC recycling is not a major core fueling source. Further support to the notion of the reduced importance of the MC recycling sources in the L- and H-mode plasmas come from the fast neutral pressure measurements. The measurements are performed in the lower and upper divertor ports and in two toroidally separated midplane ports ("Bay E" and "Bay H") by calibrated Penning and micro-ion gauges, respectively [6]. The midplane gauge at Bay E is not shielded: it is likely that its measurements, systematically higher than those at Bay H done by a shielded gauge, are affected by ultraviolet emission and fast neutral particles from the plasma. Shown in Fig. 4 (b) are the midplane neutral pressure measurements. The lower and upper divertor port neutral pressure measurements are shown in Fig. 5 (a). The midplane pressure is practically independent of discharge density $\bar{n}_e$ and input power P_{NBI}, and is always slightly higher in the L-mode than in the H-mode. The lower divertor pressure shows a weak linear dependence on $\bar{n}_e$ and input power. The upper divertor, which can be regarded as a part of MC in these LSN pulses, measures a much higher pressure at low $\bar{n}_e$ in the L-modes, and at higher $\bar{n}_e$ in the H-modes. This may be due to gas injections and neutral leakage through parts of the vessel. The divertor compression P_{mid}/P_{div} correlates little with the inner gap, typically held at 3 - 9 cm (Fig. 5). The outboard density scale length is between 2 and 3 cm [7]. Neutral compression is similar in the L- and H-modes and does not depend on the input power.

In summary, the analyses of heat and recycling fluxes in the LFS-fueled L- and H-mode plasmas suggest that the divertor operates in a partially detached state, consistent with the target temperature estimates from the analitic two point model of the divertor. The outboard attached target is the dominant source of recycling, and its ionization flux exceeds the MC flux by over an order of magnitude. The notion of reduced importance of the MC sources is supported by the midplane D_α and neutral pressure measurements. Heat flux densities up to 10 MW/m^2 have been measured in NSTX divertor, indicating that specific heat flux mitigation plans ought to be developed for $t_{pulse} \geq 3$ s operation.

Acknowledgments

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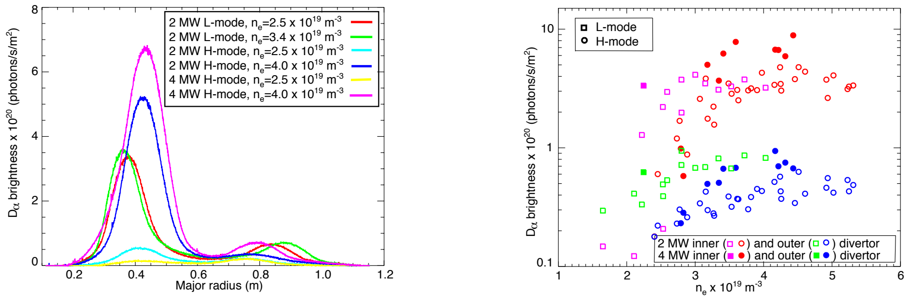

Figure 2: (a) Divertor D_α brightness profiles in L- and H-mode plasmas. (b) Divertor peak D_α brightness as a function of $\bar{n}_e$, P_{NBI}

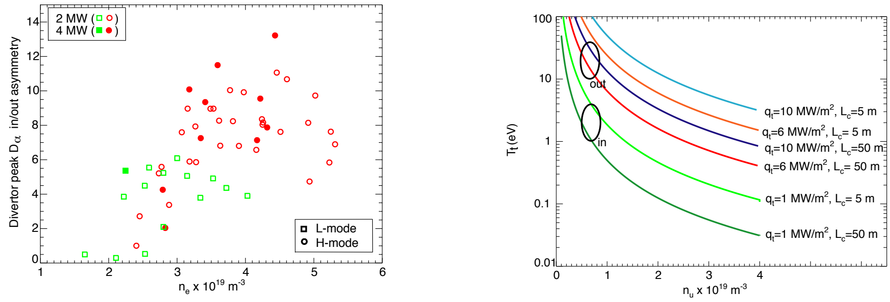

Figure 3: (a) Divertor D_α brightness asymmetry as a function of $\bar{n}_e$, P_{NBI}. (b) 2PM prediction of T_t as a function of n_u for various connection lengths L_c and q_t

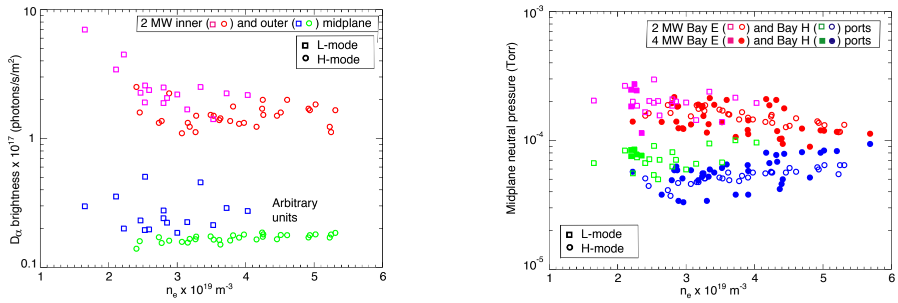

Figure 4: (a) Inboard and outboard midplane D_α brightness and (b) midplane neutral pressure as a function of $\bar{n}_e$, P_{NBI}

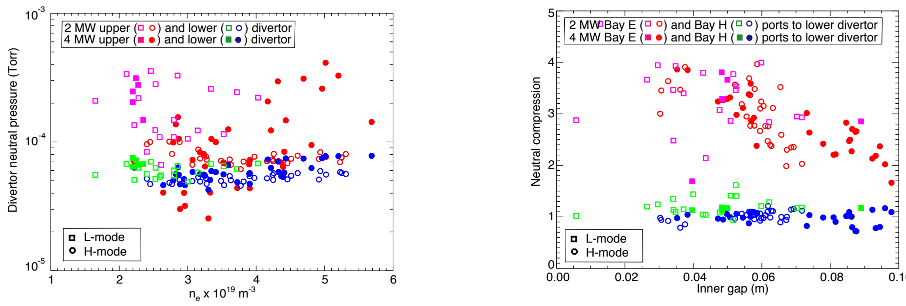

Figure 5: (a) Lower and upper divertor neutral pressure as a function of $\bar{n}_e$, P_{NBI} and (b) neutral compression as a function of inner gap

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