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Divertor heat flux reduction and detachment experiments in NSTX

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Abstract

We report the first successful experiments at achieving significant outer divertor peak heat flux reduction, from 4–7 $\mathrm{MW/m^2}$ to 1–2 $\mathrm{MW/m^2}$, in 4 MW NBI-heated H-mode plasmas in NSTX. Steady-state divertor deuterium puffing at $\Gamma \leqslant 1.1 \times 10^{22}\ \mathrm{s^{-1}}$ resulted in a high-recycling radiative divertor regime with a 50–80% reduction of the outer strike point (OSP) peak heat flux, without a loss of H-mode confinement or degradation of core plasma parameters. At higher D_2 injection rate, $\Gamma = 1.12\text{–}2.80 \times 10^{22}\ \mathrm{s^{-1}}$ up to 80% reduction in the peak heat flux and spectroscopic signatures of volume recombination have been observed, suggesting the OSP partial detachment. Radiative mantle plasmas were obtained by neon injection. The OSP peak heat flux decreased by 50–75% as the scrape-off layer power was reduced through the main plasma radiation which was about 30% of the input power. The results suggest that while an H-mode compatible radiative divertor can be obtained in NSTX, the realization of a partially detached divertor regime may be hindered by divertor properties specific to a spherical torus and NSTX.

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Keywords: Divertor detachment; Target profiles; Recombination; NSTX

1. Introduction

Radiative and dissipative divertor regimes compatible with H-mode confinement have been developed in large aspect ratio tokamaks to ameliorate otherwise high, up to 10 $\mathrm{MW/m^2}$, peak heat fluxes [1]. Divertor heat load mitigation is achieved in these regimes by volumetric momentum and energy dissipative processes – the ion-neutral elastic collisions, recombination and radiative cooling. Whereas an H-mode scenario with medium-to-small ELMs and a partially detached divertor satisfies the

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steady-state divertor requirements for an ITER-like tokamak, a solution for a spherical torus (ST) based device, such as the Component Test Facility [2] may be challenging, because of the compact divertor, and as a result, a small plasma-wetted surface, and a small divertor plasma volume. Peak heat fluxes up to 10 MW/m^2 have been measured at the outer strike point (OSP) in 6 MW NBI-heated H-mode plasmas in the National Spherical Torus Experiment (NSTX) [3]. The inner divertor leg detachment occurs naturally in NSTX at $\bar{n}_e \simeq 2$–3×10^{19} m^{-3} and input power $0.8 \geqslant P_{in} \leqslant 6$ MW [4] as in conventional tokamaks operating without actively pumped divertors. The outer scrape-off layer (SOL), however, remains in the high-recycling regime even at densities approaching the Greenwald values. We report on the first successful experiments at achieving significant steady-state outer divertor peak heat flux reduction in the NSTX high auxiliary heating H-mode plasmas. A radiative high-recycling divertor (RD), a partially detached divertor (PDD), and a radiative mantle (RM) regimes have been established using deuterium and neon injections.

2. Experiment

The experiments used a 4 MW NBI-heated H-mode target plasma with the following parameters: $B_t = 0.45$ T, $I_p = 0.7$ MA, $T_e(0) \simeq (0.8$–$1.0)$ keV, $\bar{n}_e \simeq (3$–$5) \times 10^{19}$ m^{-3} ($n_G \simeq 5.5 \times 10^{19}$ m^{-3}), $Z_{eff}(0) \leqslant 1.2$–1.4, $\tau_E \simeq 40$ ms, and the ITER 89P scaling factor 1.3–2.0. An L-H power threshold at these conditions was about 2.0–2.5 MW. Small, type *V* [5], and occasional large ($\Delta W/W \simeq 0.10$), type I, ELMs were observed. A lower single null (LSN) magnetic configuration was utilized with the *drsep* parameter of -1.5 cm, the ion ∇B drift toward the lower *X*-point, the elongation of $\kappa \simeq 2$, triangularity of $\delta \simeq 0.4$, $q_{95} \simeq 6$–7, the *X*-point height of 15–20 cm, and the OSP flux expansion $f_{exp} = 3$–4. The layout and description of NSTX edge and divertor diagnostics are given in Refs. [4,6,7]. The plasmas were fueled by deuterium from a high field side injector at a rate of $\Gamma \leqslant 3.8 \times 10^{21}$ s^{-1}.

3. Results

Deuterium gas injection in the lower divertor region was used to investigate the operating space and effectiveness of this technique for divertor heat load reduction. The RD and PDD regimes were obtained at different levels of deuterium puffing. In both regimes, a 50–80% peak OSP heat flux reduction was measured. Various properties have been used in tokamak experiments to identify these regimes [8]. The heat flux and deuterium emission profile measurements from the infrared and spectrally filtered cameras [4,7] are the main focus of the discussion below. Divertor tile Langmuir probe, bolometer and neutral pressure gauge data will be presented elsewhere [9]. Despite the low spatial resolution of these diagnostics in NSTX the data contribute to the physical picture of NSTX divertor regimes inferred from the high resolution cameras.

3.1. Partially detached divertor regime

The PDD regime obtained in NSTX demonstrated the following features: peak OSP heat flux reduction, heat flux peak radial shift and broadening, and volume recombination in a narrow radial region localized in the OSP vicinity. These characteristic properties have been previously observed in tokamak PDD discharges [10–12]. The PDD regime was established transiently by puffing D_2 in the divertor region at a high gas injection rate $(1.1$–$2.8) \times 10^{22}$ s^{-1}. Deuterium was puffed either in a sequence of four 10–20 ms pulses from the divertor gas ports located 1–10 cm away from the inner strike point of the LSN configuration, or continuously into the private flux region (PFR), as shown in Fig. 1. Shown in Fig. 2 are the time traces of a reference H-mode plasma discharge and a PDD discharge. The gas flow started at 0.250 s. Gas

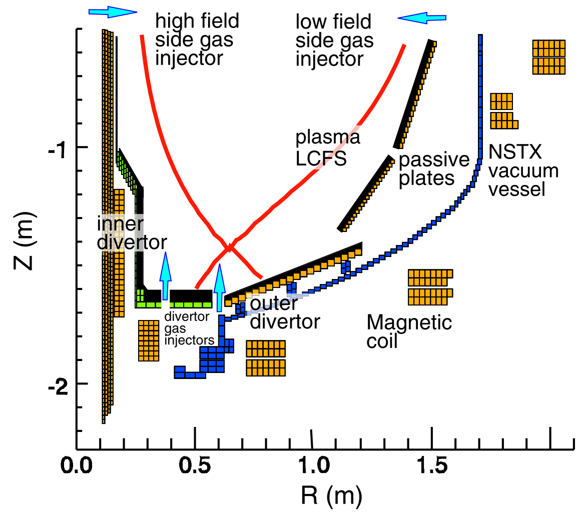

Fig. 1. Gas injector locations in NSTX.

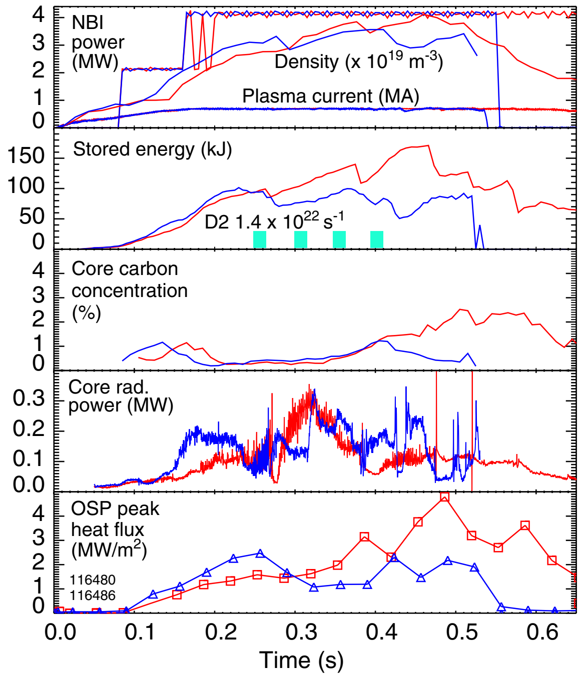

Fig. 2. Time traces of a partially detached divertor discharge (in blue) and a reference discharge (in red). (For interpretation of the references in colour in this figure legend, the reader is referred to the web version of this article.)

puffing did not change the core radiated power and core carbon concentration. The OSP peak heat flux remained at 1–2 MW/m^2 throughout the discharge. During the gas injections the plasma stored energy and confinement degraded by about 15–25%, and the discharge back-transitioned to an L-mode within (2–7) $\times\ \tau_E$. Shown in Fig. 3 are the divertor heat flux and deuterium emission profiles. The peak heat flux decreased, the peak moved outward by up to 5 cm, and the profile broadened. Plasma detachment from the divertor target plate is often accompanied by the volume recombination process. As an ion recombines, the excess energy is radiated as high-n hydrogenic emission lines, which can be detected spectroscopically. Transient onset of volume recombination, as evident from the increase in the D_γ/D_α ratio, was detected in the OSP region in the PDD discharges. Atomic physics calculations from the ADAS database ([13] and references therein) predict the ratio to be 0.1–0.2 in purely recombining plasmas, and 0.010–0.025 in purely ionizing plasmas where the electron excitation populating mechanism prevails. The ratio is also highly dependent on electron density, being about 0.1 below 10^{18} m^{-3} in ionizing plasmas and approaching 0.01 at 10^{20} m^{-3}. As deuterium was injected at the ISP or in PFR, a region of volume recombination expanded outward and reached the OSP region as evidenced by a twofold D_γ/D_α ratio increase. The low absolute values measured in these transient PDD plasmas could be caused by a systematic error in camera photometric calibrations, and/or by high spatial plasma electron temperature and density gradients and a complex two dimensional plasma structure. An ongoing two dimensional modeling effort is aimed at resolving this issue. Data from other diagnostics were also consistent with the PDD picture. The ISP region injection resulted in a large increase in the PFR neutral pressure from about 0.1 mTorr to 2 mTorr, from which an estimate of atomic neutral density of 3.5–70 $\times$ 10^{18} m^{-3} was obtained. At such densities ion momentum loss due to charge exchange and elastic collisions becomes appreciable. Because of inadequate bolometric coverage of the outer divertor leg the total divertor radiated power could not be fully measured. It was estimated to be in the range 10–15% of the total input power.

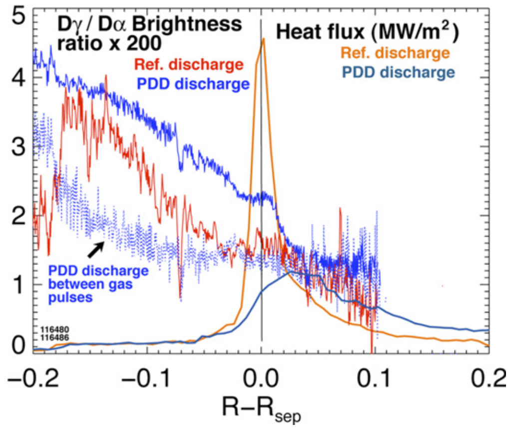

Fig. 3. Heat flux and D_γ/D_α ratio profiles in partially detached divertor and reference discharges.

3.2. High-recycling radiative divertor regime

In an attempt to obtain a controlled steady-state heat flux mitigation scenario, deuterium was injected continuously using the same gas ports as shown in Fig. 1 at rates (0.3–1.12) $\times$ 10^{22} s^{-1}. The rate of the continuous injection was limited by the gas system throughput. Shown in Fig. 4 are typical time traces of a discharge obtained with the PFR puffing, and a reference plasma. Fig. 5 shows the heat flux and deuterium emission profiles. The peak

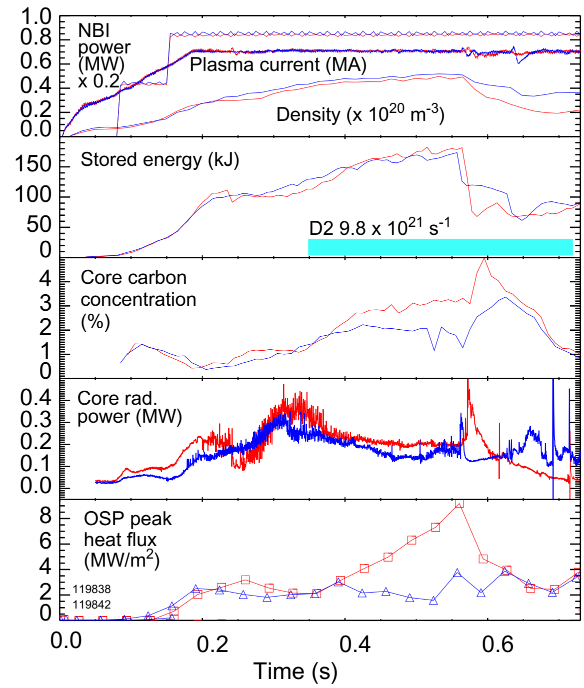

Fig. 4. Time traces of a radiative divertor discharge (in blue) and a reference discharge (in red). (For interpretation of the references in colour in this figure legend, the reader is referred to the web version of this article.)

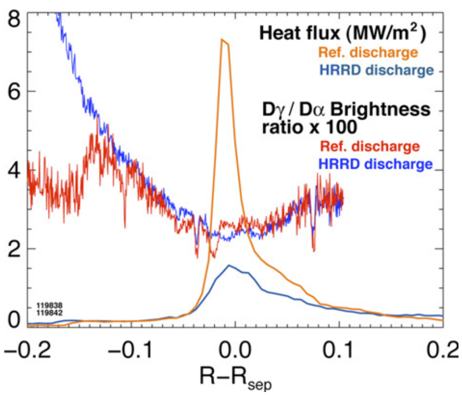

Fig. 5. Heat flux and D_γ/D_α ratio profiles in radiative divertor and reference discharges.

OSP heat flux was reduced to 1–2 MW/m^2, however, in contrast to the PDD regime, it remained peaked and shifted only as a result of the strike point drift. No increase in the D_γ/D_α brightness ratio was observed at lower gas puffing rates. At the highest rate intermittent increases up to three-fold were observed in the OSP region suggestive of the transition from a high recycling divertor regime to the PDD regime. H-mode confinement was retained for a much longer period, without degradation of the core plasma parameters (W_p, n_C). The RD regime appears to be a promising scenario for long-pulse H-mode NSTX discharges.

3.3. Radiative mantle regime

Divertor heat flux reduction by means of radiated power loss was investigated using neon injection. H-mode plasmas with a highly radiative edge and a reduced divertor heat flux were produced, however, the duration of an H-mode radiative phase was limited to $5\times\tau_E$. Neon was injected at a mid-plane location at a rate $(3\text{–}15)\times10^{19}\ s^{-1}$. In previous NSTX L-mode transport experiments with trace neon injection [3] it was found that neon did not penetrate in the core because of a diffusive transport barrier at $r/a = 0.6$. A 4 MW NBI-heated H-mode plasma with the core P_{rad} fraction exceeding 30% of the input power and core $Z_{eff} = 1.7\text{–}2.2$ was obtained, as shown in Fig. 6. The core radiated power profiles were hollow, with a significant P_{rad} increase at the edge $r/a \geqslant 0.6$. The divertor radiated power increase was estimated to be 10–20%. Following the power accounting procedures outlined in Ref. [6] the power flowing into the SOL P_{SOL} was estimated to be about 3 MW, which was about 25% lower than P_{SOL} in reference discharges. This had a profound effect on the divertor: the peak heat flux at the outer target was reduced by a factor of four, while the inner divertor peak heat flux decreased by 20%. These results suggest that the divertor heat flux is largely reduced due to the

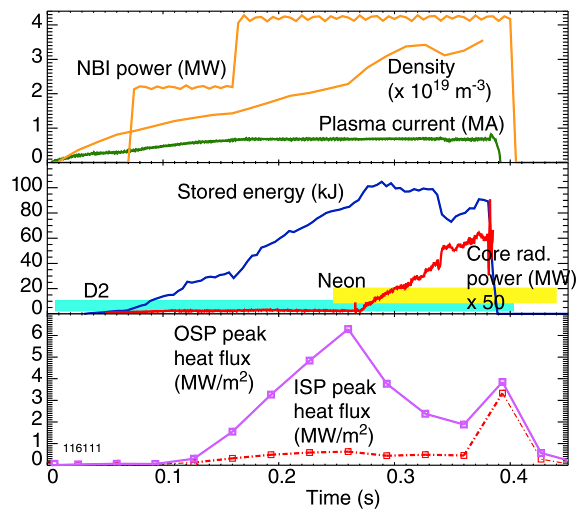

Fig. 6. Time traces of a radiative mantle discharge.

reduced P_{SOL}. The SOL and divertor temperatures of $T_e \sim 10$–50 eV are not sufficient for neon to radiate efficiently as the neon radiative cooling curve peaks at 80 eV.

4. Discussion

We have demonstrated that conventional tokamak divertor heat flux mitigation solutions, such as the radiative and dissipative divertors and radiative mantle, are applicable to ST-based devices. However, the present NSTX results obtained in a lower single null low δ,κ configuration point to several challenging issues which we discuss below using simple two point SOL model (2PM) [8] arguments. The PDD regime is established in NSTX only at high SOL collisionalities $\nu_e^* \simeq 40$–80. The collisionality was a result of a high rate divertor deuterium injection the separatrix density increased with each gas pulse to $n_u \simeq 10^{-19}\ \mathrm{m}^{-3}$ – a factor of 2–5 higher than n_{sep} obtained during midplane or PFR injections at a lower gas flow rate. In the reference discharges, typical SOL collisionalities evaluated from the Thomson scattering data at separatrix are in the range 5–40. Second, the divertor neutral pressure P_{div}, as well as the neutral compression $\eta \sim P_{div}/P_{mid}$, being measures of the power and momentum loss involving neutrals, are typically low in NSTX because of an open divertor geometry, a high conductance of the vacuum vessel wall structures and a reduced plasma plugging effect. This may explain the appearance of volume recombination only during the gas pulses. Finally, according to analytic 2PM-based criteria [8,14] a relatively short connection length in NSTX $L_{\parallel} = 4$–8 m is marginal for the carbon impurity to radiate the energy necessary to detach the plasma from the outer target plate. These factors help explain why the outer SOL in NSTX usually does not detach even when plasma densities approach the Greenwald values. The reported experimental results suggest that a radiative divertor regime may be a more viable option for divertor heat flux reduction in NSTX. The radiative divertor is generally compatible with the H-mode operation and can be obtained with a modest rate of deuterium puffing.

Future work will focus on a detailed characterization of radiative and detached divertor conditions and a further development of the heat flux mitigation scenarios in higher δ,κ configurations.

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References

[1] R. Stambaugh et al., Nucl. Fusion 39 (12) (1999) 2391.
[2] Y.-K. Peng et al., Plasma Phys. Control. Fus. 47 (12B) (2005) 263.
[3] R. Maingi et al., Plasma Phys. Control. Fus. 45 (5) (2003) 657.
[4] V. Soukhanovskii et al., J. Nucl. Mater. 337–339 (1–3) (2005) 475.
[5] R. Maingi et al., Nucl. Fusion 45 (4) (2005) 264.
[6] S. Paul et al., J. Nucl. Mater. 337–339 (1–3) (2005) 251.
[7] R. Maingi, J. Nucl. Mater., these Proceedings, doi:10.1016/j.jnucmat.2007.01.063.
[8] P.C. Stangeby, The Plasma Boundary of Magnetic Fusion Devices, IoP, Bristol, 2000.
[9] V.A. Soukhanovskii et al., Paper EX-4/28, in: Proceedings of IAEA FEC, Chengdu, China, 2006.
[10] T.W. Petrie et al., Nucl. Fusion 37 (3) (1997) 321.
[11] B. Lipschultz et al., J. Nucl. Mater. 220–222 (1995) 50.
[12] M. Fenstermacher et al., J. Nucl. Mater. 266 (1999) 348.
[13] G.M. McCracken et al., Nucl. Fusion 38 (4) (1998) 619.
[14] D. Post et al., J. Nucl. Mater. 220–222 (1995) 1014.