Divertor Heat Flux Reduction and Detachment in NSTX

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We report the first successful experiments at achieving outer divertor leg partial detachment with high auxiliary heating in a spherical torus. A dissipative divertor is an effective steady-state heat flux mitigation technique developed in large aspect ratio tokamaks. It is considered as a baseline operating scenario for ITER: heat flux at the divertor plate is reduced through volumetric momentum and energy dissipative processes - the ion-neutral elastic collisions, recombination and radiative cooling [1]. High steady-state divertor heat loads and material erosion, however, may still be a challenge for a high β reactor or a component testing facility based on a spherical torus geometry because of the compact divertor, and as a result, a small plasma-wetted surface and a small divertor plasma volume. Implications of the low aspect ratio magnetic geometry and plasma configurations for divertor regimes, divertor heat load mitigation and detachment threshold have been studied in an open lower single null divertor geometry in the National Spherical Torus Experiment in 1-6 MW NBI-heated L- and H-mode plasmas with elongation κ=1.8-2.4, triangularity δ =0.45-0.75, aspect ratio A = 1.27 and ion ∇ B drift direction towards the X-point.

Two approaches to high steady-state heat flux mitigation on the outer divertor plate were investigated in NSTX. In higher triangularity and elongation plasma shapes used for the extended pulse small ELM H-mode scenario [2] a natural reduction of the peak heat flux of 2-4 MW/m^2 due to high poloidal flux expansion (up to 20) at the outer strike point (OSP) was attained. A further reduction can be achieved by edge radiation using gas puffing or extrinsic impurities. Another approach - a dissipative divertor scenario with D_2 or impurity (e.g. CD_4, neon) puffing - was employed for plasma shapes with lower δ and κ where typical OSP steady-state peak heat flux was measured to be 4-6 MW/m^2. Without puffing, divertor regimes qualitatively similar to those of conventional tokamak divertors operating without active pumping, were observed. The inner divertor target heat flux q was dispersed over a broad region on the inner wall and divertor floor, with a peak steady-state value q_{in} = 0.5-1 MW/m^2. The inner leg naturally detached at n_e = 2-3 x 10^{19} m^{-3} and P_{NBI} = 0.8 MW and remained detached at higher density and input power throughout the operational space [3]. The existence of a cold dense strongly recombining region with a MARFE oscillating up and down the inner wall was inferred from spectroscopic D_γ, D_α profiles and divertor n_e=1-5 x 10^{20} m^{-3}, T_e = 0.4-1.3 eV. The latter were obtained from the measurements of Stark broadening and intensities of high-n Balmer (Fig. 1) and Paschen series lines, as well as recent astrophysical calculations [4]. The outer scrape-off layer (SOL) was in the linear and high-recycling regimes, the latter characterized by an upstream electron collisionality of 5-20 and a small parallel T_e gradient. The OSP remained attached even at densities approaching the Greenwald value. According to analytic criteria [5] and the two-point (2PM) SOL model [1], a relatively short connection length in NSTX $L_{||}$ = 4−8 m is marginal for the carbon impurity to radiate the energy necessary for detachment. Predictions of the multi-fluid edge code UEDGE for typical NSTX conditions are qualitatively consistent with the experimental trend [3].

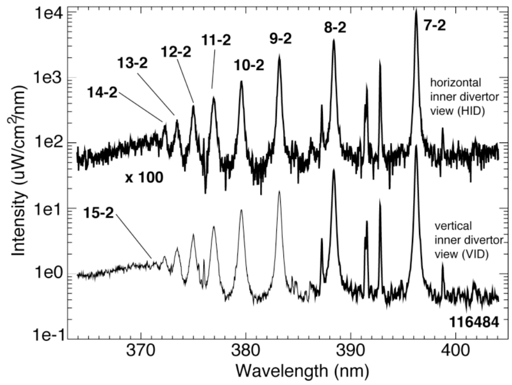

Figure 1. *Balmer series spectral lines with n < 15 observed in the inner divertor leg along a vertical and a horizontal lines of sight*

Dedicated experiments have been conducted in lower δ, κ plasmas with moderate (~ 3) poloidal flux expansion at the OSP using D_2 and neon puffing to study dissipative divertor heat flux reduction. Steady-state midplane deuterium puffing at R=3-7 x 10^{21} s^{-1} apparently lead to a radiative divertor operation with a two to four-fold reduction of the peak heat flux. However, no signs of volume recombination were observed at the OSP. Midplane neon puffing lead to a radiative layer power exhaust with total P_{rad} = 0.3 x P_{in} and a 50-75 % reduction of the OSP peak heat flux. The outer SOL, however, remained in the high-recycling regime and the H-mode confinement degraded by MHD instabilities. Deuterium injection into the lower divertor region resulted in an increase of the divertor neutral density and midplane SOL collisionality to 60 - 100, and lead to the OSP detachment. The extent of detachment appeared to be localized to a small radial region nearby the OSP. In this region the D_γ/D_α brightness ratio - a spectroscopic signature of volume recombination onset - increased two-fold and approached that of the detached inner divertor. An ~ 80 % reduction in the peak heat flux along with a shift of the peak location were also observed (Fig. 2). These results are satisfactorily explained by a power balance calculation based on the two point model with power and momentum losses: the short parallel connection length is a key factor limiting the radiative exhaust channel while a local steady-state neutral source provides the required momentum sink.

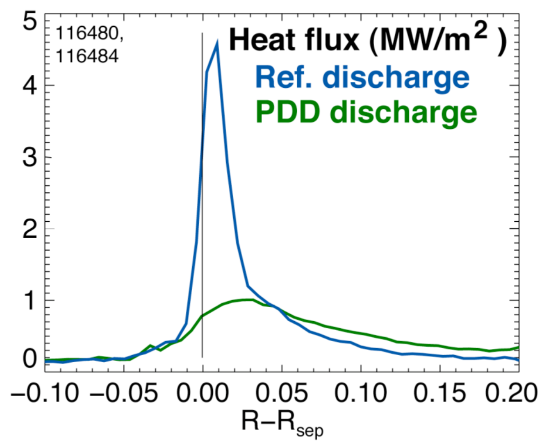

Figure 2. *Heat flux reduction at the outer strike point in a partially detached divertor (PDD) induced by D_2 puffing*

Evaporated lithium coatings, planned for the upcoming experimental campaign, may extend divertor operation into a pumped regime, providing a better control of the partially detached divertor density and recycling.

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