TOPIC: EX-D

Snowflake Divertor as Plasma-Material Interface for Future High Power Density Fusion Devices.

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Recent National Spherical Torus Experiment (NSTX) results demonstrate that the snowflake divertor configuration [1] may provide a promising solution for mitigating steady-state and transient divertor heat loads and target plate erosion. The present vision of the tokamak plasma-material interface is an axisymmetric magnetic X-point divertor that enables access to high confinement core and pedestal plasma performance metrics while keeping divertor heat load and plate erosion within the operating margins of plasma-facing component (PFC) cooling technology and target materials. Based on divertor designs tested in large tokamak experiments, a closed divertor with tilted vertical targets and partial radiative detachment of strike points is planned for ITER [2]. However, for much higher heat fluxes expected in fusion nuclear science facilities (FNSF) and DEMO, the standard radiative divertor solution is inadequate. The snowflake divertor configuration, as predicted by theory [1], potentially reduces heat flux density and plasma temperature at the target by enabling the divertor plasma-wetted area, effective connection length and divertor volumetric power loss to increase beyond those in the standard divertor. In NSTX, a medium-size spherical tokamak (ST) with lithium-coated graphite PFCs and high divertor heat flux ($q_{pk} \leq 15$ MW/m^2, $q_{||} \leq 200$ MW/m^2 [3]), snowflake divertor experiments have demonstrated a significant reduction of steady-state [4] and ELM divertor heat fluxes, compatibility with high core plasma confinement, reduction in core impurity concentration, and a stable operation with additional impurity seeding that could increase divertor radiation further.

The snowflake divertor concept uses a second-order null-point created by bringing close two first-order null-points of the standard divertor [1]. In recent NSTX experiments, three divertor coils were used to obtain steady-state snowflake configurations for up to 600 ms in 4 MW NBI-heated H-mode discharges of 1.0-1.2 s duration (Fig. 1). The snowflake geometry increased the plasma-wetted area A_{wet} by 100-200 %; the X-point connection length L_x by 50-100%; and the divertor volume V_{div} by up to 60 % [4]. Analysis of the experimental snowflake equilibria and their failure modes, in combination with a one-parameter analytic description of the configurations [5] provided guidelines for the design of a real-time feedback control algorithm, which is presently being implemented on NSTX [6].

The snowflake configuration formation led to a stable partial detachment of the outer strike point otherwise inaccessible in the standard divertor at P_{SOL}=3 MW in NSTX [7]. During the transition from the standard configuration to the snowflake, magnetic geometry parameters A_{wet}, L_x, and V_{div} increased continuously until the onset of detachment, resulting in additional volumetric power and momentum losses. Divertor radiation increased by up to 50 %, as did recombination rate, while peak divertor heat flux was reduced from 3-7 MW/m^2 to 0.5-1 MW/m^2. Additional CD_4 seeding increased divertor radiation further, thus showing the potential to enhance non-coronal impurity radiation in the snowflake configuration due to its already reduced T_e regime. H-mode core confinement with τ_E~50-60 ms, W_{MHD} =200-250 kJ, and H98(y,2)~1 (from TRANSP), was maintained albeit the detachment. Core carbon concentration was reduced by up to 50 % due to the edge source reduction.

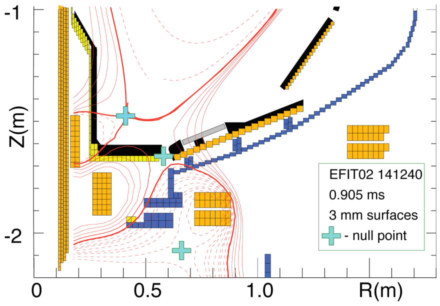

Fig. 1. Asymmetric snowflake-minus divertor configuration realized in NSTX

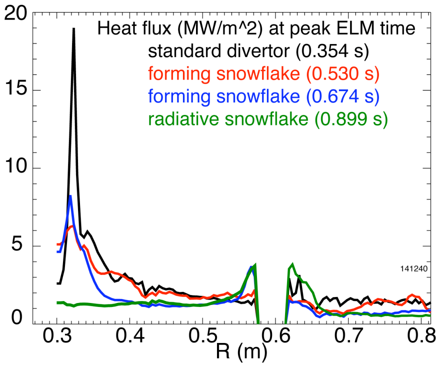

Fig. 2. Divertor heat flux profiles measured in the standard and snowflake divertor configuration at peak Type I ELM times.

Transient heat and particle fluxes from large Type I ELMs remain an unresolved issue for future divertor designs. ELM elimination techniques are explored, as radiative buffering of ELMs has been found ineffective [2]. NSTX experiments indicated that in the snowflake geometry, heat fluxes from Type I ELMs ($\Delta W/W$=7-10 %) were significantly dissipated (Fig. 2). Peak target temperatures (measured by fast infrared thermography) at peak ELM times reached 1000-1200 ^{o}C in the standard divertor phase and only 300-500 ^{o}C in the snowflake phase. This was consistent with the lower surface temperature rise due to the longer convective heat deposition time because of the longer L_x in the snowflake divertor, and the convective heat redistribution mechanism in the null-point region proposed theoretically. The snowflake configuration was maintained during the ELMs. Additional measurements are needed to elucidate on the conductive and convective ion heat flux components in the inner and outer divertor legs.

To project snowflake divertor properties to future devices, e.g., NSTX Upgrade [8] and ST-based FNSF, a two-dimensional multi-fluid edge transport model based on the UEDGE code [9] is developed. Initial simulations that used NSTX magnetic equilibria and a fixed carbon impurity fraction indicated large reductions in T_e , T_i, particle and heat fluxes due to the geometric effects.

Experimental results from NSTX, as well as from TCV tokamak [10], favorably project the snowflake divertor properties to future high-power density devices. In the NSTX Upgrade [8], two up-down symmetric sets of four divertor coils will be used to test snowflake divertors for handling the projected steady-state 20-30 MW/m^2 peak divertor heat fluxes [3] in 2 MA discharges up to 5 s long with up to 12 MW NBI heating. NSTX Upgrade magnetic equilibria with snowflake configurations have been modeled using the predictive free-boundary Grad-Shafranov code ISOLVER. Results suggest that a robust snowflake control can be maintained even when time-dependent electromagnetic effects are included [8].

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