Topic: TH-D & EX-D

Modeling Divertor Concepts for Spherical Tokamaks NSTX, NSTX-U and ST-FNSF

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Experimentally constrained divertor modeling in the National Spherical Torus Experiment (NSTX) [1] is extrapolated to identify favorable divertor concepts for future spherical tokamak (ST) devices. Modeling of NSTX snowflake divertor experiments [2,3] demonstrates an ability to capture observed physics behavior, including partial detachment and several-fold heat flux reduction (Fig. 1). NSTX Upgrade (NSTX-U) [4] analysis shows that heat flux can be mitigated (to <10 MW/m^2, i.e., within present technological limits) using snowflake and standard divertor configurations with impurity seeding. For a notional Spherical-Tokamak-based Fusion Nuclear Science Facility (ST-FNSF) [5], divertor concepts are identified that provide heat flux mitigation (<10 MW/m^2) in up-down-symmetric double-null magnetic geometries with 40 MW input power and 100%-recycling metal targets. As fusion research progresses toward the reactor scale, increasingly intense power exhaust threatens the integrity of plasma facing components. The compact nature, i.e., small major radius (R), of the ST presents an economically attractive path to fusion commercialization [5], but magnifies the power exhaust challenge, because the plasma-wetted area is proportional to R. To address this challenge, a variety of heat flux mitigation techniques are tested, including the snowflake divertor, target tilting, and impurity seeding. Analysis is conducted with the multi-fluid edge transport code, UEDGE [6].

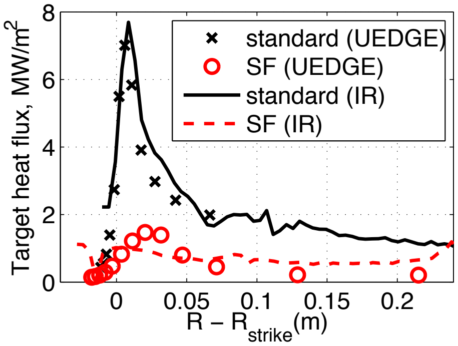

Fig. 1. Modeled and IR-thermography-based heat fluxes for NSTX standard and snowflake divertor configurations.

In NSTX modeling, radial variation of anomalous perpendicular diffusivities (assumed to be poloidally uniform) is constrained by requiring solutions to match measured radial profiles of ion and electron temperature and density at the outer midplane. Choices of divertor recycling and equilibrium separatrix location (which maps measured midplane profiles to the modeled flux surfaces) are constrained by matching simulated and measured Dα emission and heat flux at the outer target. Good agreement with heat flux data is achieved (Fig. 1), and partial detachment is captured in the snowflake case. Increased plasma-wetted area in the snowflake enhances neutral gas power loss to the outer divertor targets, enabling the partially detached state. A charge-state resolved carbon model, including physical and chemical carbon sputtering, shows that improved divertor impurity retention in the snowflake facilitates the observed reduction of core carbon concentration.

NSTX-U will have up to 12 MW neutral beam power and 2 MA plasma current [3], and the expected unmitigated divertor target heat fluxes are more than twice as high as observed in NSTX [7]. With pulse lengths up to 10 seconds (vs. ~1 second in NSTX), NSTX-U divertor operation must enable improved particle control. A divertor cryogenic pump system will be used for deuterium inventory control, and sputtering must be minimized by achieving low target temperatures – for carbon, <20 eV is desirable. Key UEDGE input parameters are scanned to explore the NSTX-U operating space. Neutral beam input powers between 9 and 15 MW are considered. Anomalous perpendicular thermal diffusivities are varied to study a range heat flux widths (λ_q), centered on λ_q = 3.0 mm, which is the expected width at 2 MA plasma current [7]. Divertor target recycling coefficients between 95% and 100% are used to model high-recycling scenarios and strong target pumping scenarios as expected with lithium conditioning. Divertor cryopumping, modeled by allowing 50% neutral transparency on the portion of the UEDGE boundary corresponding to the cyropump duct, typically provides 20% reduction of the separatrix deuterium density for both standard and snowflake configurations. Compared to the standard divertor, the particular snowflake divertor studied here strongly reduces outer target heat flux, but can lead to high target temperatures (>100 eV). This emphasizes the importance of optimizing the secondary snowflake X-point position. The majority of the analysis uses a fixed 5% carbon concentration, but seeding with neon and argon impurities is also considered. A broad range of neon concentrations – from 7 to 20% – provides effective heat flux mitigation without affecting core plasma properties, while argon can induce radiative collapse of the core plasma when concentration exceeds 3%. Snowflake divertor results with and without neon seeding are shown in Fig. 2; in this case, neon radiation prevents sheath-limiting in the near-SOL.

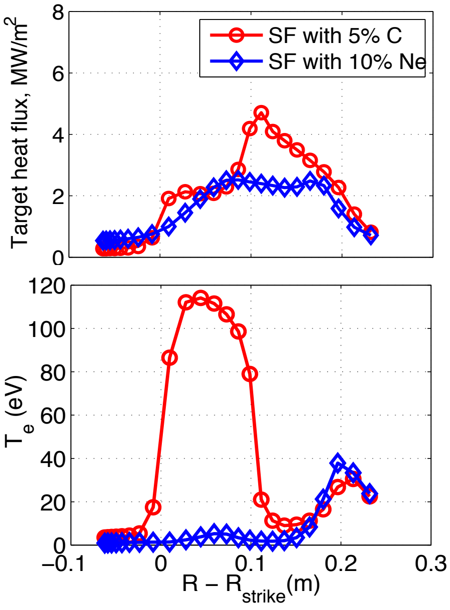

Fig. 2. Heat flux and temperature profiles for NSTX-U snowflake divertor with 5% carbon (blue), and with 10% neon (red).

Standard, snowflake, and "super-snowflake" divertor configurations have been analyzed for ST-FNSF [5]. (Here, "super-snowflake" refers to a snowflake with the outer divertor leg extended to large major radius as in the Super-X divertor [8].) Example computational domains are shown in Fig. 3. Recycling is assumed to be 100%, corresponding to metal targets. Nitrogen is included at fixed 4% concentration. Simulations indicate that control of neutral behavior through plate tilt and/or cryopump location is crucial to achieving low target temperature compatible with low sputtering yields. The vertical target configuration shown in Fig. 3 directs neutrals toward the strike point, maintaining high density and low temperature there. By managing neutral behavior with target tilt, partially detached scenarios are found, with acceptable target temperature (<50 eV) and heat flux (<10 MW/m^2). Complete detachment is seen in the "super-snowflake," with the upstream location of detachment set by the position of the cryopump duct.

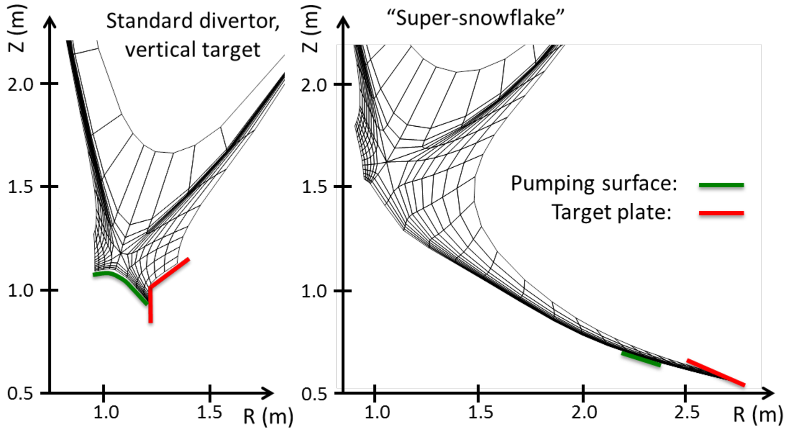

Fig. 3. Computational domains for ST-FNSF standard and "super-snowflake" divertor scenarios showing positions of targets and cryopump ducts.

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