Modeling divertor concepts for spherical tokamaks NSTX, NSTX-U and ST-FNSF

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Experimentally constrained modeling of the National Spherical Torus Experiment (NSTX) [1] divertor configurations is extrapolated to identify scenarios for NSTX Upgrade (NSTX-U) [2] and the Spherical-Tokamak-based Fusion Nuclear Science Facility (ST-FNSF) [3] with divertor target heat loads <10 MW/m^2, and target temperatures <50 eV, compatible with low sputtering. A variety of mitigation techniques are tested including the snowflake divertor [4], target tilting, and impurity seeding. Modeling is carried out with the multi-fluid edge transport code, UEDGE [5]. 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 spherical tokamak (ST), suggests an economically attractive path to fusion commercialization [3], but magnifies the power exhaust challenge, because heat flux intensity varies as 1/R. This research represents a computational evaluation of divertor concepts that could blunt this challenge, and enable the ST platform for next-step fusion development.

Modeling of NSTX snowflake experiments [6] demonstrates an ability to capture the key physics behavior in the snowflake divertor, including partial detachment and several-fold heat flux reduction (Fig. 1). 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. Divertor recycling and the location of the equilibrium separatrix (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, and partial detachment is captured in the snowflake case, with neutral power loss to divertor targets playing a key role. A charge-state resolved carbon model, with physical and chemical carbon sputtering rates adapted from DIVIMP, shows that improved divertor impurity retention facilitates the reduction of carbon concentration seen in the snowflake.

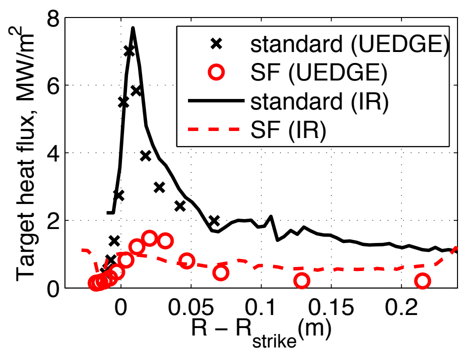

Fig. 1. Modeled and IR-thermography-based heat fluxes for NSTX standard and snowflake divertor configurations.

In NSTX-U modeling, heat flux mitigation and low target temperatures are achieved via snowflake and standard divertor configurations with impurity seeding. With up to 12 MW neutral beam power and 2 MA plasma current, the expected unmitigated divertor target heat fluxes are more than twice as high as observed in NSTX [7]. With a 5-second pulse length (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 – to prevent core carbon build-up. (Note that additional impurity control techniques, e.g., ELM flushing, may also be necessary.) The majority of the analysis uses a fixed 5% carbon concentration. Several 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 explore a range heat flux widths (λ_q), centered on λ_q = 3.0 mm, the value expected from the NSTX scaling, $\lambda_q = 0.91\ I_p^{-1.6}$ [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. 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. Seeding with neon and argon impurities is studied. A broad range of neon concentrations – from 7 to 20% – provides effective heat flux mitigation without radiative deterioration of core plasma temperatures. Argon can induce radiative core plasma collapse 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. Divertor cryopumping is found to be effective for both snowflake and standard configurations, typically allowing 20% reduction of the separatrix deuterium density.

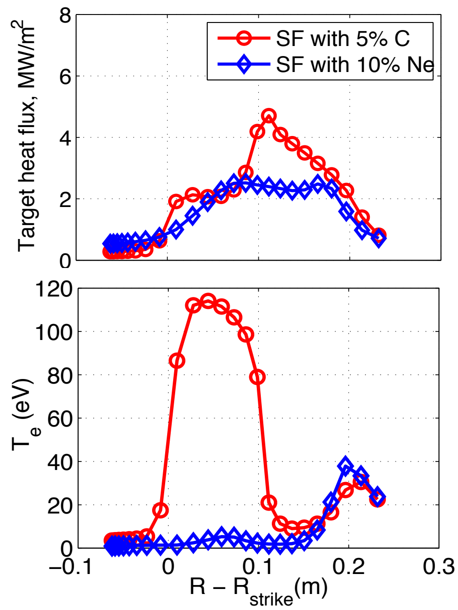

Fig. 2. Heat flux and temperature profiles for NSTX-U snowflake divertor with 5% carbon, and with 10% neon.

Modeling of divertor concepts for a notional ST-FNSF [3], has identified configurations (Fig. 3) that mitigate heat fluxes in up-down-symmetric double-null magnetic geometries with 40 MW input power and 100%-recycling metal targets. Nitrogen is included at fixed 4% concentration. Standard, snowflake, and "super-snowflake" divertor configurations have been analyzed. (Here, "super-snowflake" refers to a snowflake with the outer divertor leg extended to a large major radius as in, e.g., the Super-X divertor [8].) Simulations indicate that control of neutral behavior through plate tilt and/or cryopump location and duct geometry 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). In the "super-snowflake," complete detachment is seen, with the upstream location of detachment set by the position of the cryopump duct.

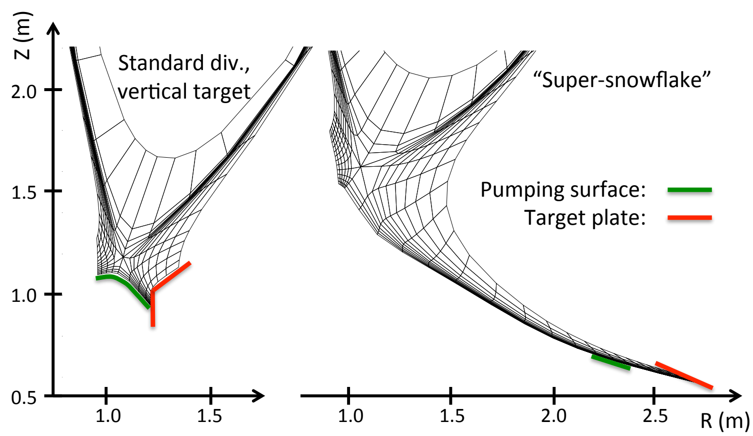

Fig. 3. Computational domains for ST-FNSF standard and "super-snowflake" scenarios showing target and cryopump duct positions.

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