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

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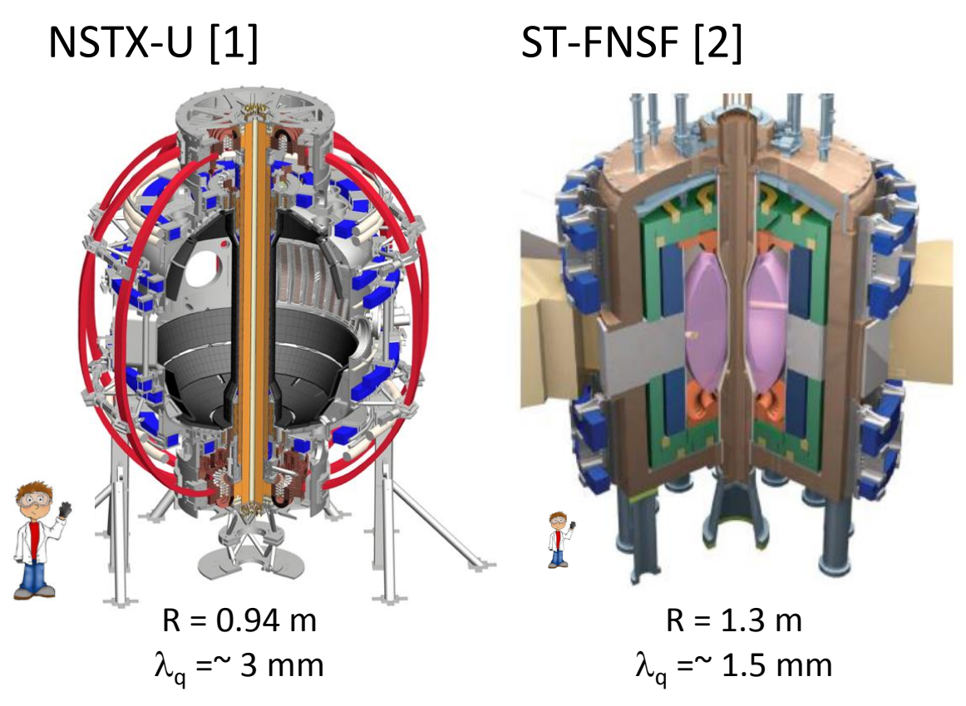
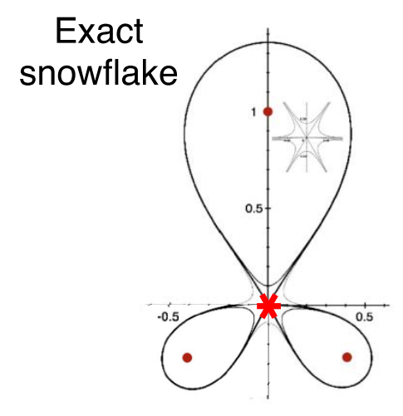
1. Motivation

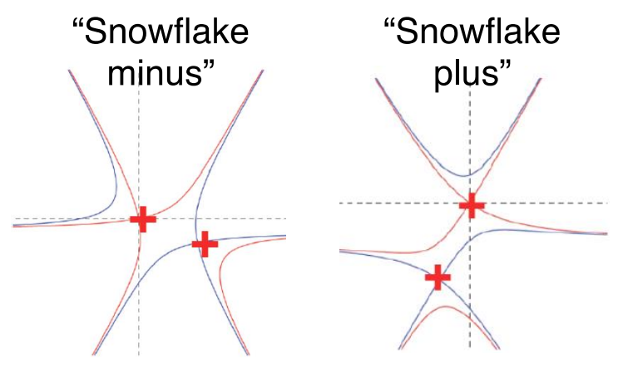
1.1 Divertor heat flux challenge

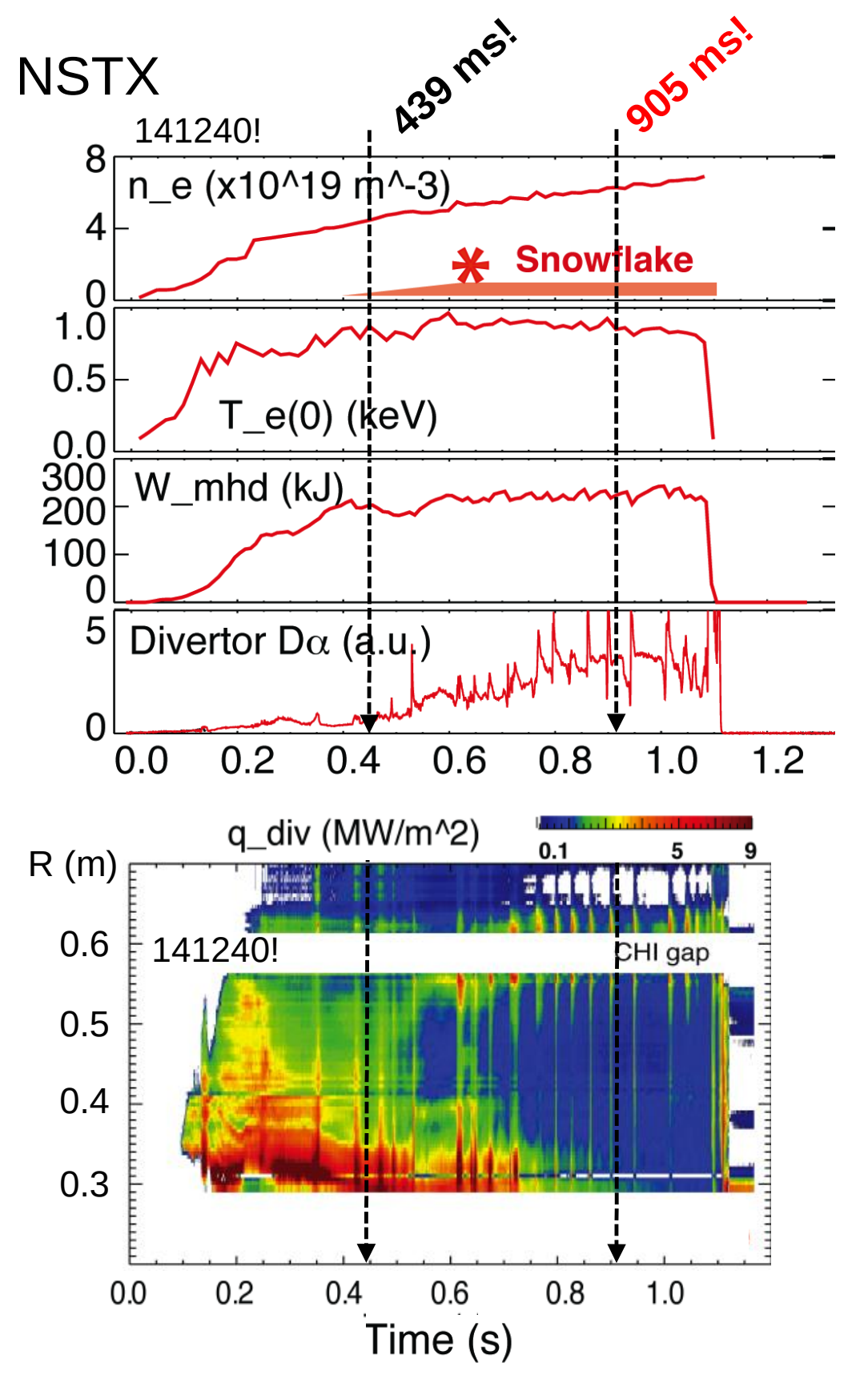
- Divertor power handling is a challenge for future tokamaks.
  - SOL power input (P_{SOL}) will rise.
  - Heat flux width (λ_q) is expected to shrink [3].
  - Peak (unmitigated) heat flux will rise as P_{SOL}/λ_q.
- Next-step spherical tokamaks (ST) have smaller major radii (R) than conventional tokamaks.
  - Compact → economically attractive.
  - But area wetted by SOL ($A_{wet} \sim 2\pi R\lambda_q$) is reduced, intensifying heat flux (for a given flux expansion).



- A proposed technique to control heat flux is the snowflake divertor (SFD) [4], which has:
  - Greater wetted area (A_{wet})
  - Increased divertor volume (V_{div})
  - Longer connection length (L_{con})
- Other techniques include extended outer divertor leg (e.g., Super-X [5]), seeded impurity radiation, and target tilt.



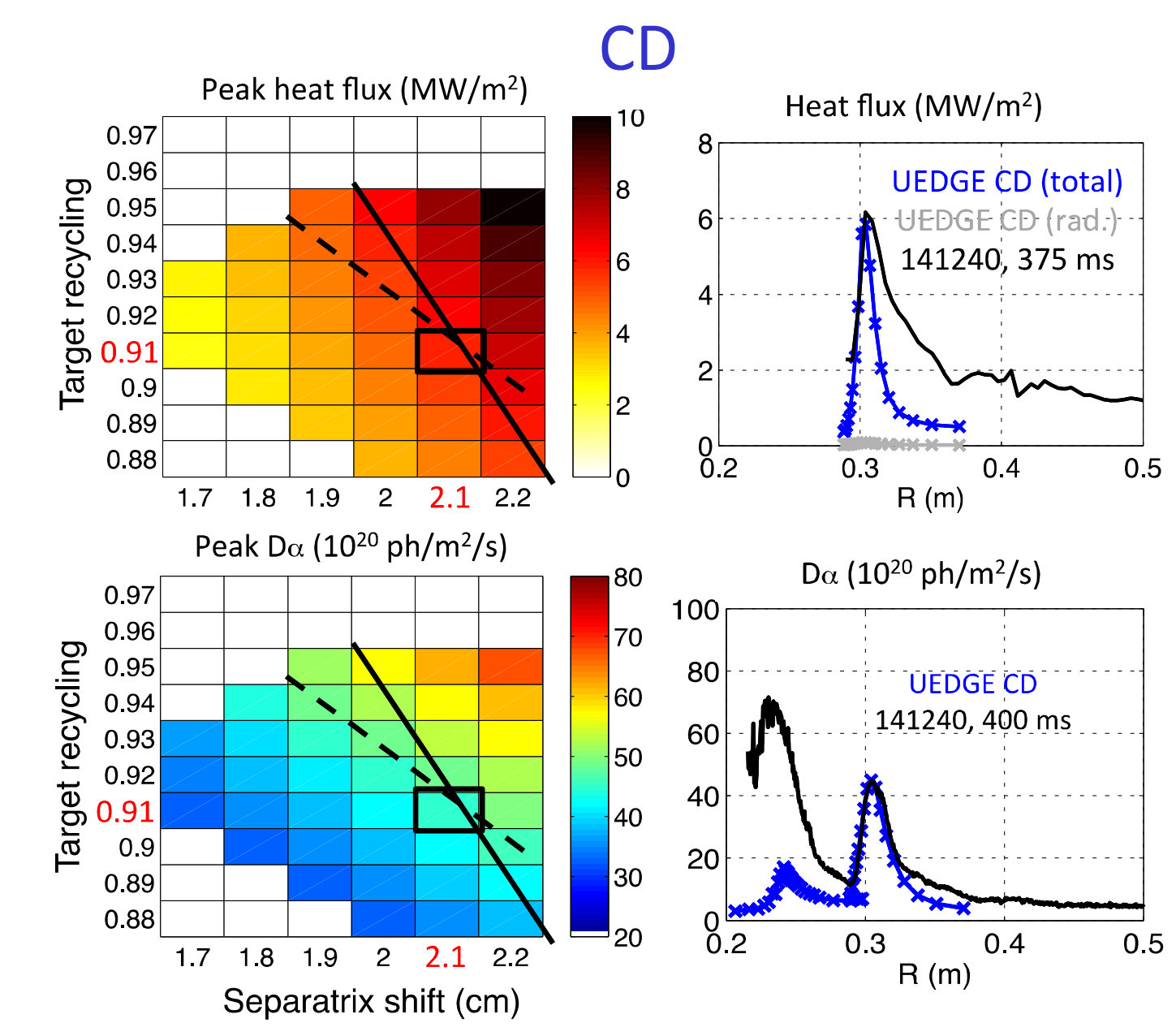


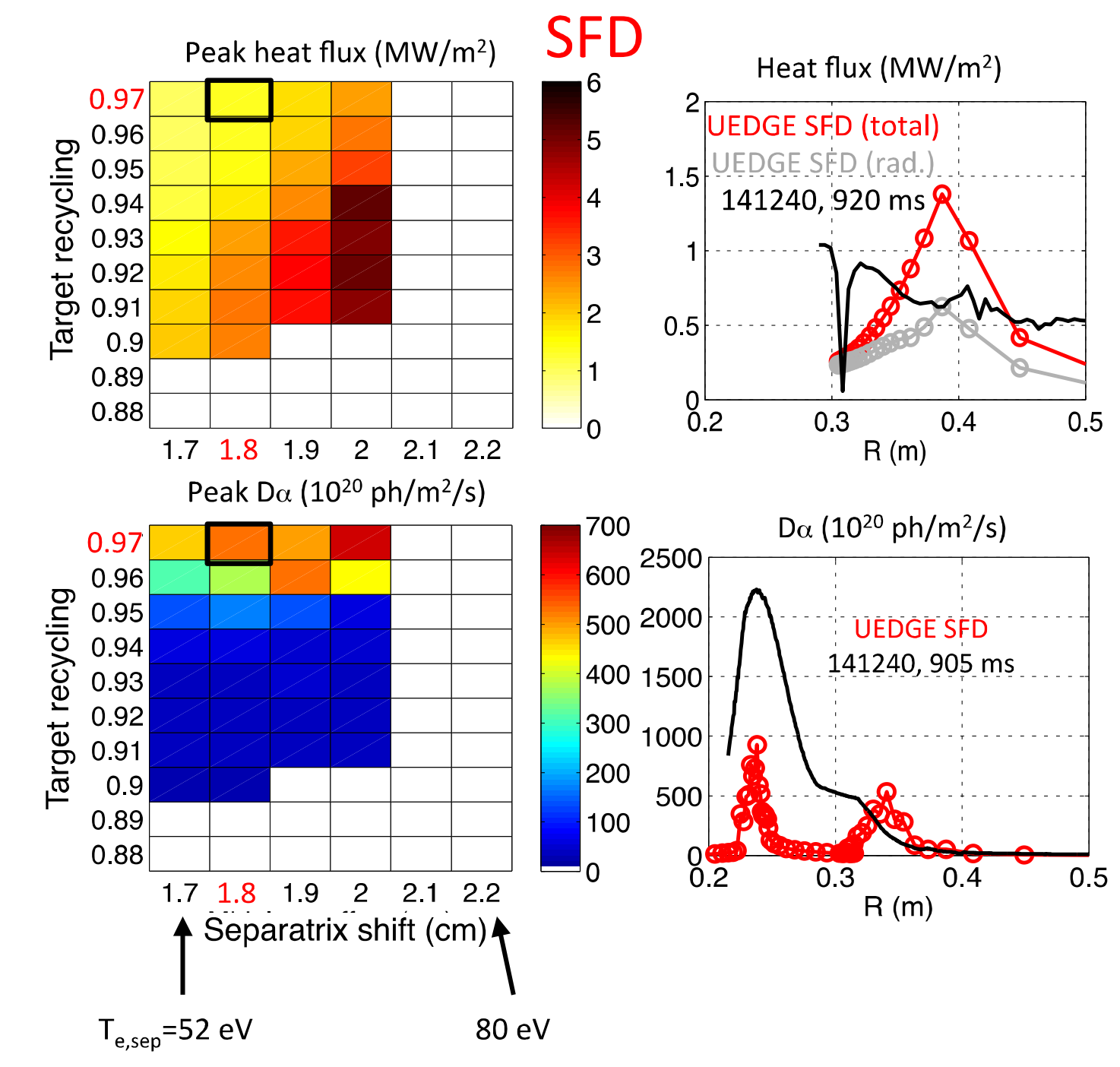


1.2 NSTX snowflake divertor experimental results

- NSTX snowflake divertor (SFD) experiments consistently produced detachment [6].
- Discharge 141240 was initialized with a conventional divertor (CD).
- SFD was established at ~600 ms.
  - Core plasma retained desirable properties.
  - Outer divertor partially detached.
  - ELMs were destabilized – snowflake effect on pedestal?
  - Peak heat flux was reduced from ~6 MW/m² to ~1 MW/m².
- Validation simulations (see section 2) are conducted at 439 and 905 ms.
- P_{SOL} =~ 3 MW (P_{NBI} = 4 MW), B_t = 0.5 T, I_p = 0.9 MA.

2. UEDGE analysis of NSTX SFD



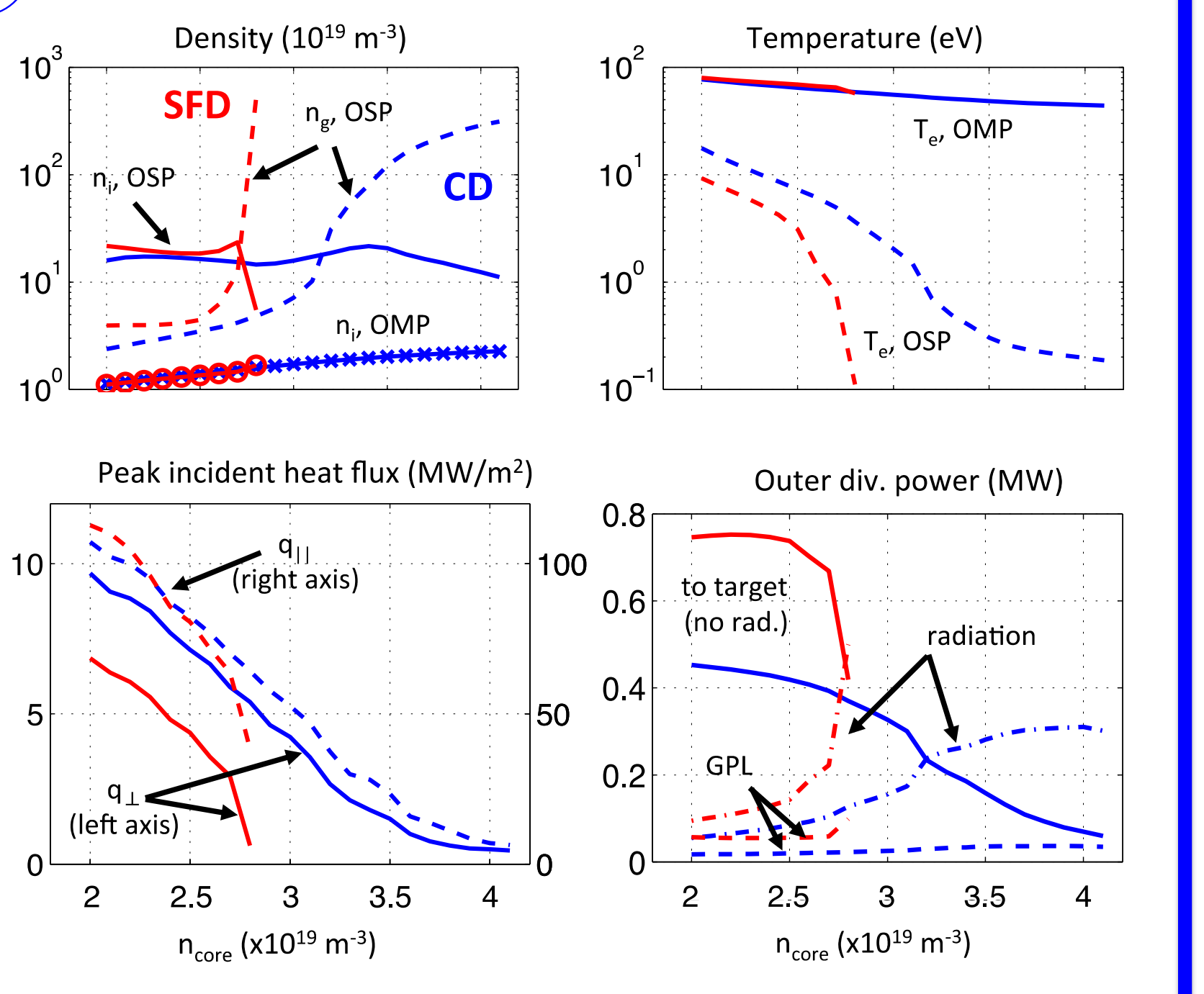


2.1 UEDGE validation

- Goal: By fitting key diagnostic data, demonstrate the ability of UEDGE [7] to capture relevant physics.
- Diagnostics:
  - Outer midplane (OMP) n_e and T_e from Thomson scattering.
  - OMP n_{C6+} and T_{C6+} from CHERS.
  - n_{D+} is derived ($n_{D+} = n_e - 6n_{C6+}$) and $T_{D+} = T_{C6+}$ is assumed.
  - Divertor heat flux profiles from IR thermography.
  - Line-integrated divertor Dα data.
- Separatrix location (w.r.t. measured OMP profiles) and target recycling are treated as unknowns; simulations explore the resulting 2D space.
- For each simulation, diffusivities are adjusted to match OMP data.
- Best fit SFD solution has higher recycling than CD (0.97 vs. 0.91).
  - Saturation of lithium-based pumping mechanism in high-fluence detached conditions is not unexpected [8].
- Neutral gas power loss (GPL) to targets is required to reproduce the observed high Dα brightness.
  - Outer divertor Dα (at R=~0.33) is closely matched; without GPL, there is a 10x shortfall.
- 3% fixed carbon concentration is assumed.

2.2 Core density scan

- Scan core density to identify key physics.
  - 95% target recycling.
  - Uniform perp. diffusivities D=0.4 m²/s and $\chi_{i,e}$=10 m²/s (similar to separatrix values found in Sect. 2.1); same D/χ for CD and SFD.
- Density scan shows:
  - Radiation associated with increased V_{div} provides most of the $q_{||}$ reduction.
  - Similar $q_{||}$ prior to detachment suggests minimal role of increased L_{con}.
  - GPL reduces T_e, triggering recombination and high n_g.

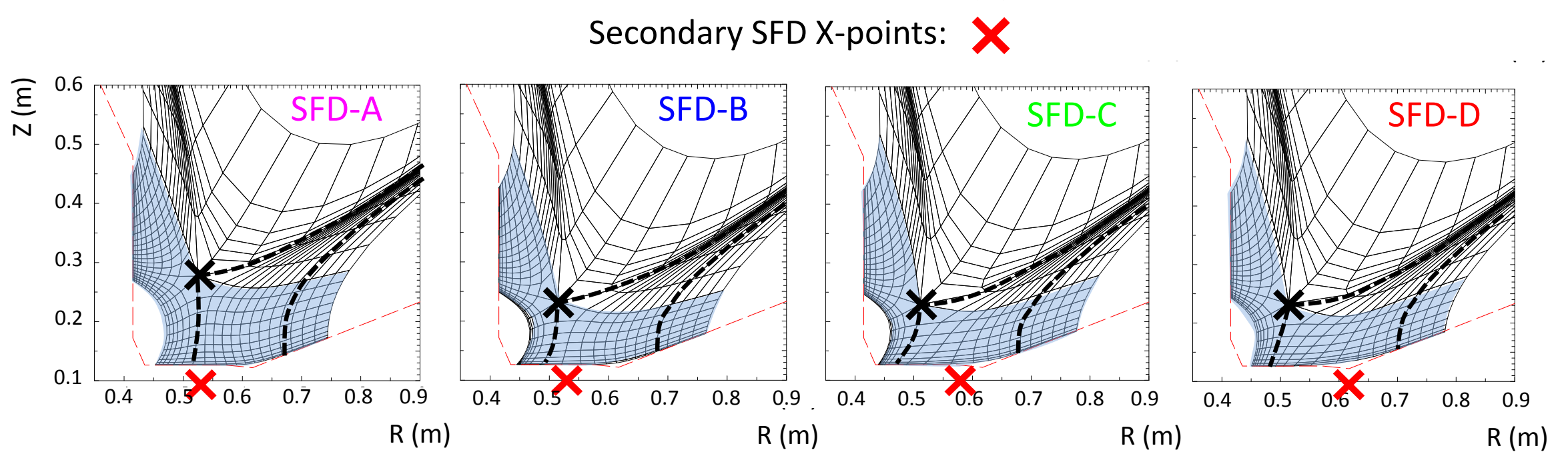


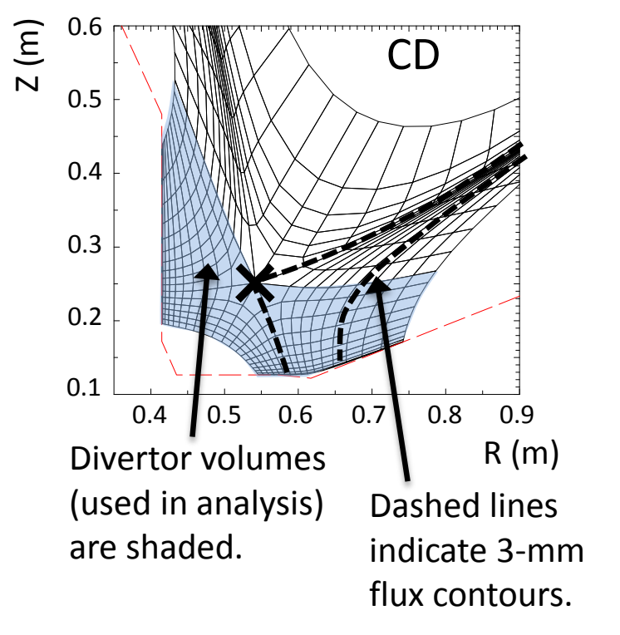
Though it does not provide formal validation, this modeling provides evidence that UEDGE can be used to qualitatively predict divertor behavior including detachment.

See [9] for details.

3. NSTX-U predictive modeling

3.1 UEDGE setup



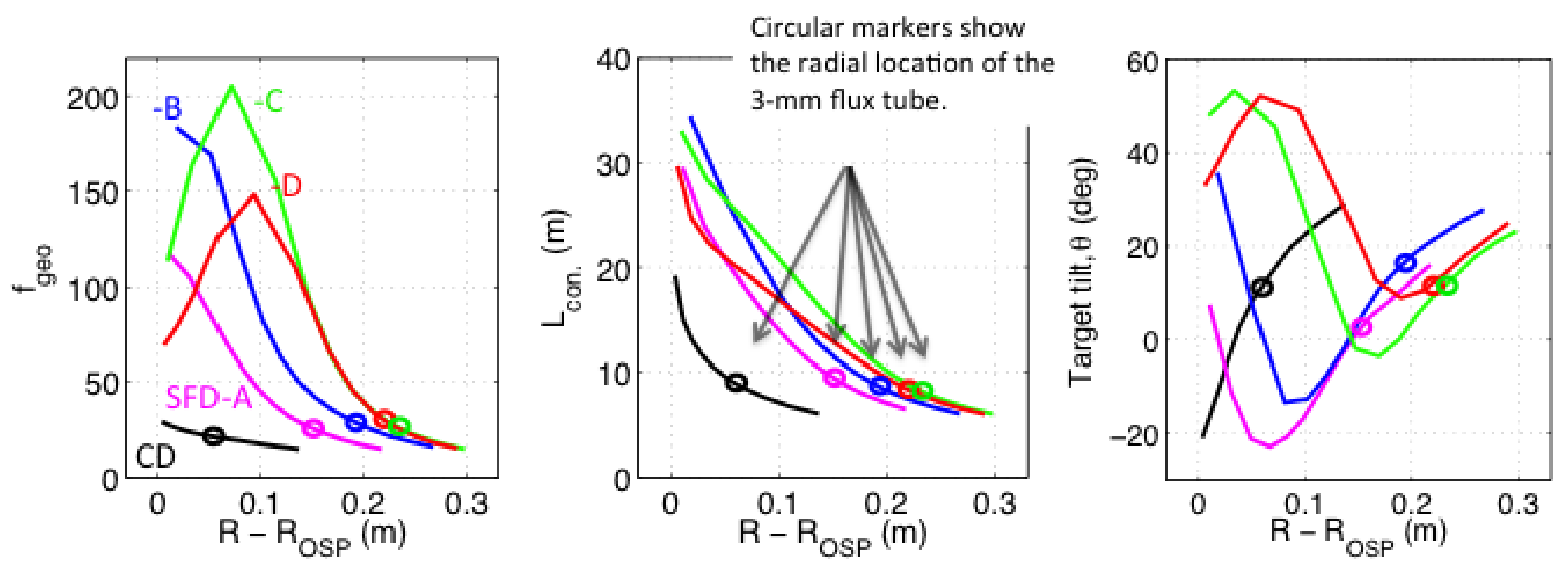


Divertor volumes (used in analysis) are shaded.

Dashed lines indicate 3-mm flux contours.

- Grids are based on ISOLVER-generated equilibria.
- Equilibria for CD and SFD-A grids are from [1].
- UEDGE analysis of CD and SFD-A (see [10]) found limited benefit from snowflake effects, apparently due to unfavorable neutral trapping in SFD-A.
- By studying SFD-B, -C- and -D, optimization is sought.
- B_t = 1.0 T and I_p = 2 MA, P_{SOL} = 9 MW.
- 3% fixed carbon concentration is assumed.

3.2 Magnetic geometries

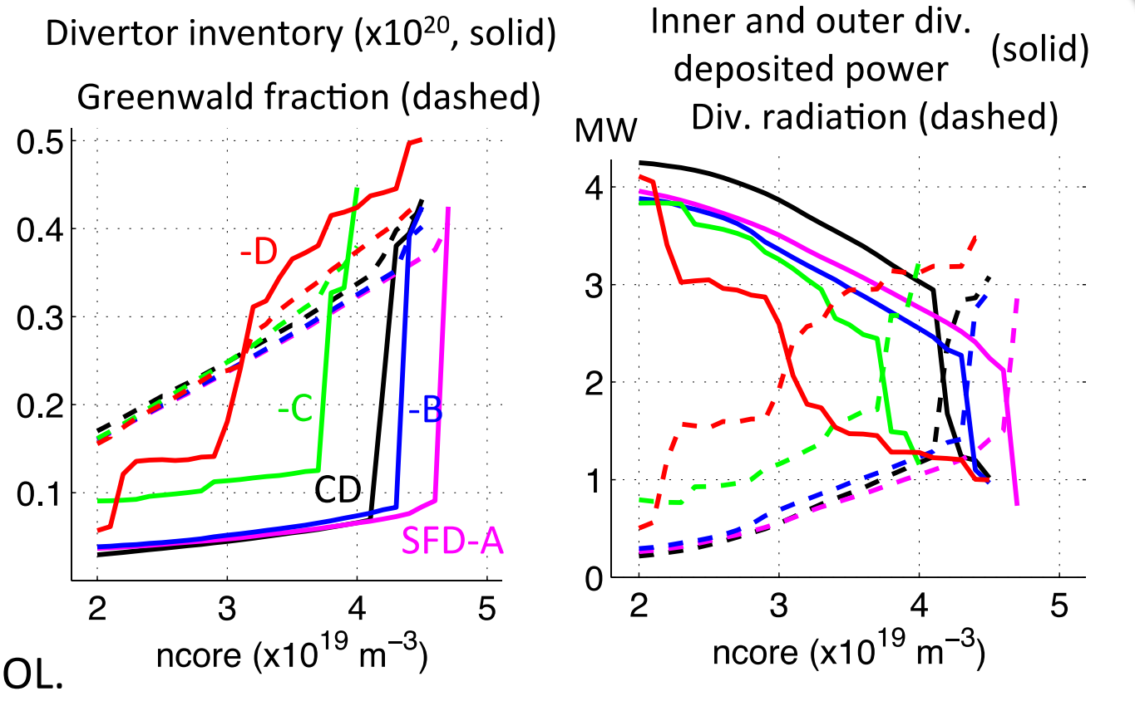


Circular markers show the radial location of the 3-mm flux tube.

- Geometric flux expansion (f_{geo}) peaks near the secondary SFD X-point.
  - $f_{geo} = f_{exp}/\cos(\theta)$, where f_{exp} is the poloidal flux expansion and θ is "target tilt" (defined below).
- Midplane-to-target connection lengths (L_{con}) are typically 50% larger for SFD configurations.
- Positive target tilt (θ) near the outer strike point (OSP) in SFD-C and -D provides favorable neutral retention.
  - θ is the angular deviation from normal incidence of flux surfaces on the target.

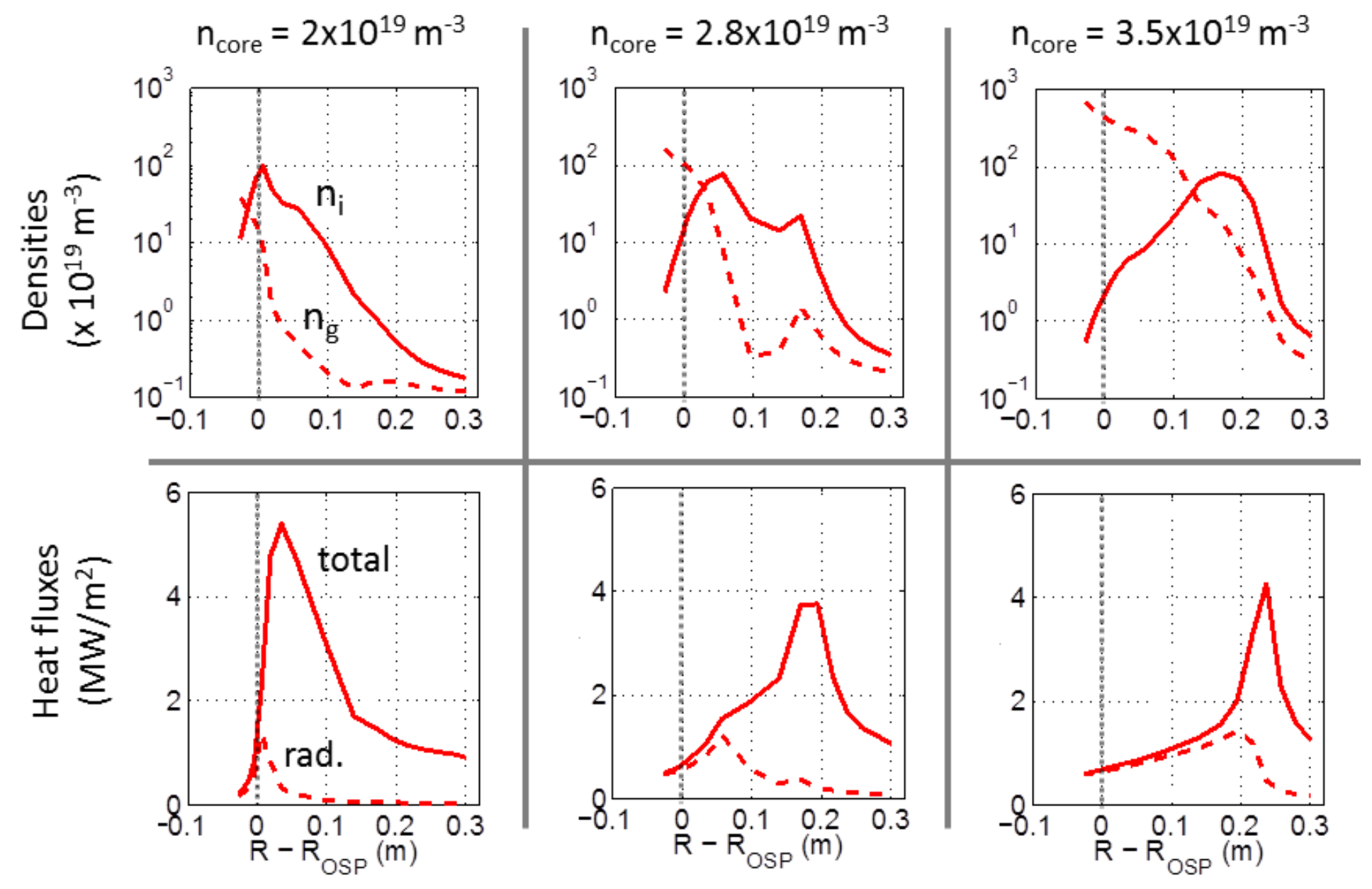
3.3 Core density scan

- UEDGE settings:
  - 99% target recycling
  - Perpendicular diffusivities vary radially from D=0.1 m²/s and $\chi_{i,e}$=2 m²/s at the core-edge interface to D=0.5 m²/s and $\chi_{i,e}$=4 m²/s at the separatrix; diffusivities are uniform in the SOL.



- Divertor particle inventory rises gradually for SFD-C and -D, indicating stable detachment.
  - Stable detachment is enabled by neutral transport physics associated with target tilt (θ).
  - Radial neutral particle transport is proportional to $\nabla p_g \sin(\theta)$; positive θ causes transport toward the strike point.
- Detachment occurs at Greenwald fractions f_{GW} <~ 0.4, which is appropriate for NSTX-U.
  - f_{GW} is calculated as $3n_{OMP}/n_{GW}$, where $3n_{OMP}$ is an estimate of line-averaged density, consistent with NSTX data.
- Total power to the divertor targets falls as total divertor radiation rises.

3.4 SFD-D divertor profiles

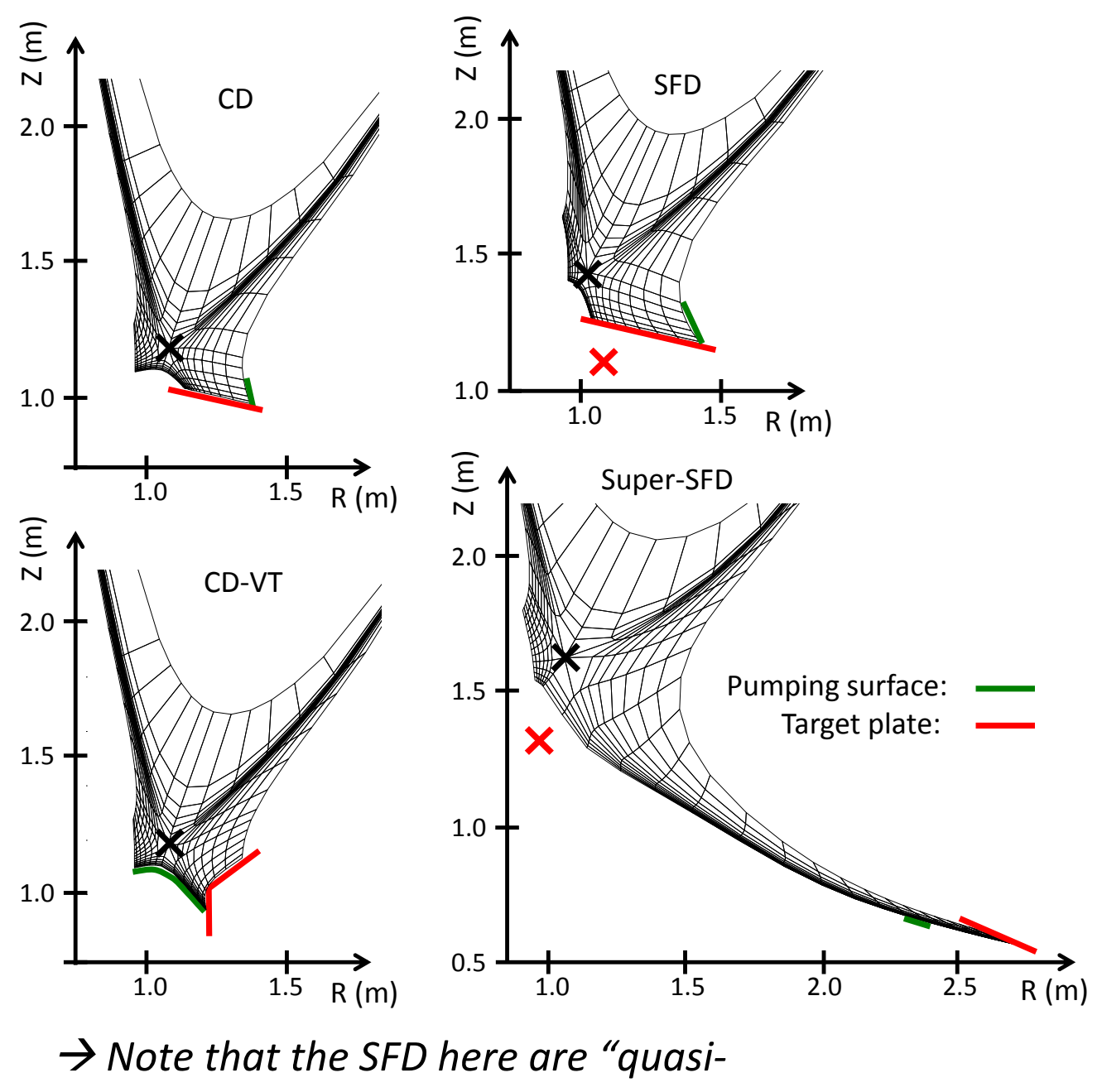


- The detached portion of the SOL expands radially as n_{core} is increased.
  - $n_g > n_i$ is used as a proxy for detachment.
- Decreasing θ (and associated degradation of neutral confinement) at larger radii acts as a brake on detachment.
- At n_{core}=3.5x10¹⁹ m⁻³, T_e < 10 eV throughout the 3-mm flux tube, compatible with low-sputtering operation.

4. ST-FNSF predictive modeling

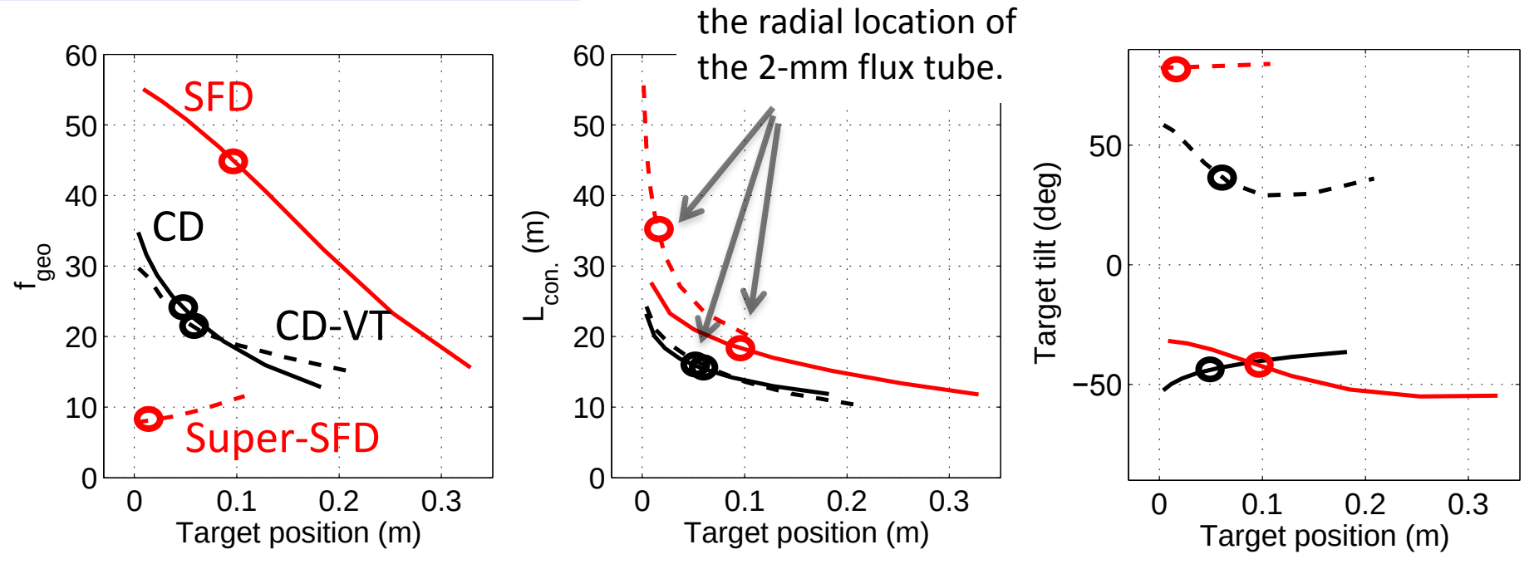
4.1 UEDGE setup

- Preliminary simulations are conducted for four configurations:
  - CD
  - SFD
  - Conventional divertor with vertical target (CD-VT)
  - Snowflake divertor with extended leg (super-SFD).
- Cryopumping is simulated by allowing transmission of neutral particles through the cryopump surfaces.
  - Transmission is 50% in the CD, SFD, and super-SFD, and 5% in the CD-VT.
- B_t = 2.4 T, I_p = 12 MA, P_{SOL} = 30 MW.
- 4% fixed nitrogen concentration is assumed (i.e., N seeding).



→ *Note that the SFD here are "quasi-snowflakes" in the sense that the inter-X-point distance exceeds the heat flux width mapped to the X-point.*

4.2 Magnetic geometries

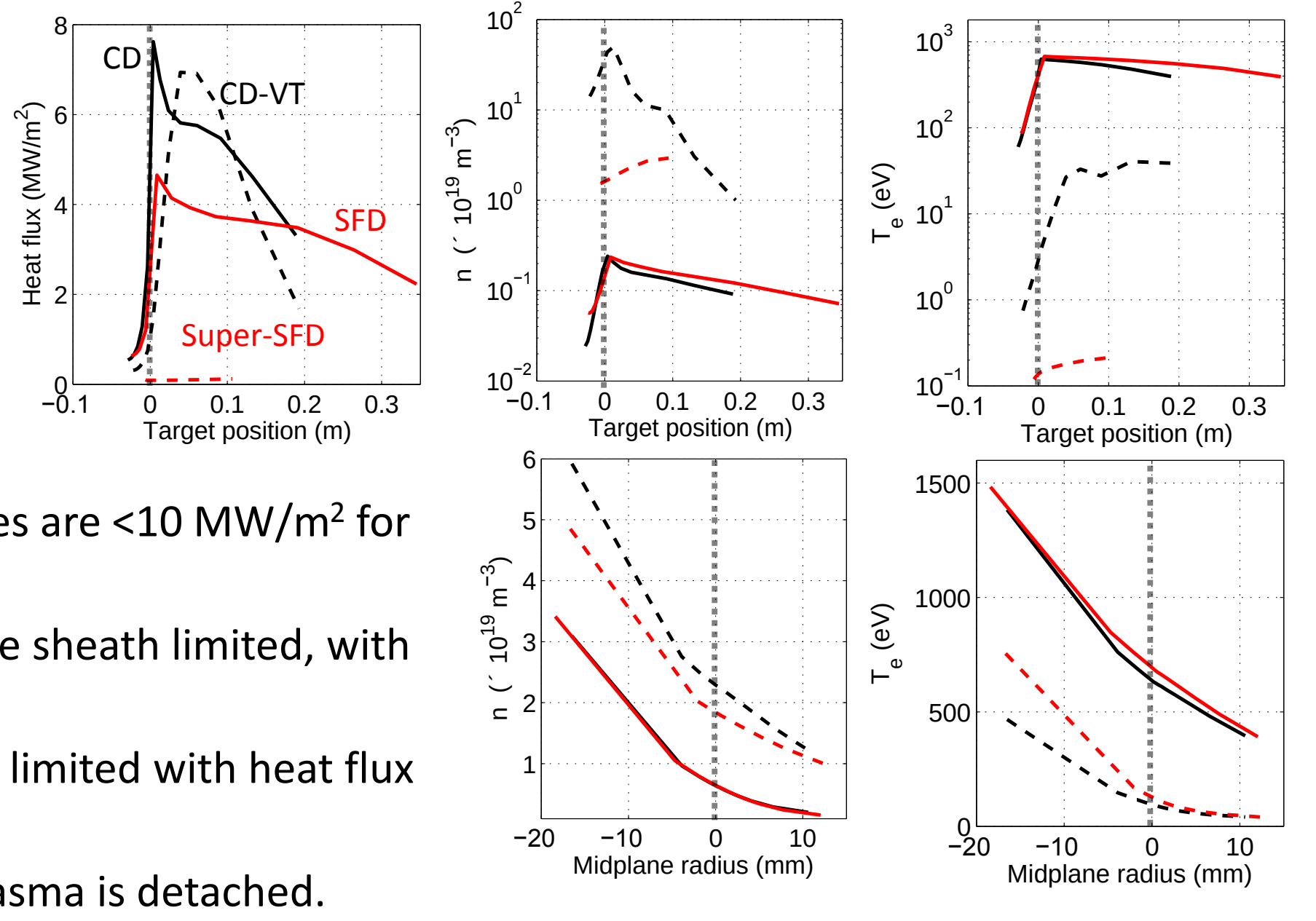


Circular markers show the radial location of the 2-mm flux tube.

- Comparing the SFD and CD:
  - More geometric profile broadening in SFD by ~2x.
  - 20-30% increase in connection length.
- Super-SFD has much longer (2x) connection length at the outer strike point.
- Target tilt is favorable in CD-VT and super-SFD.

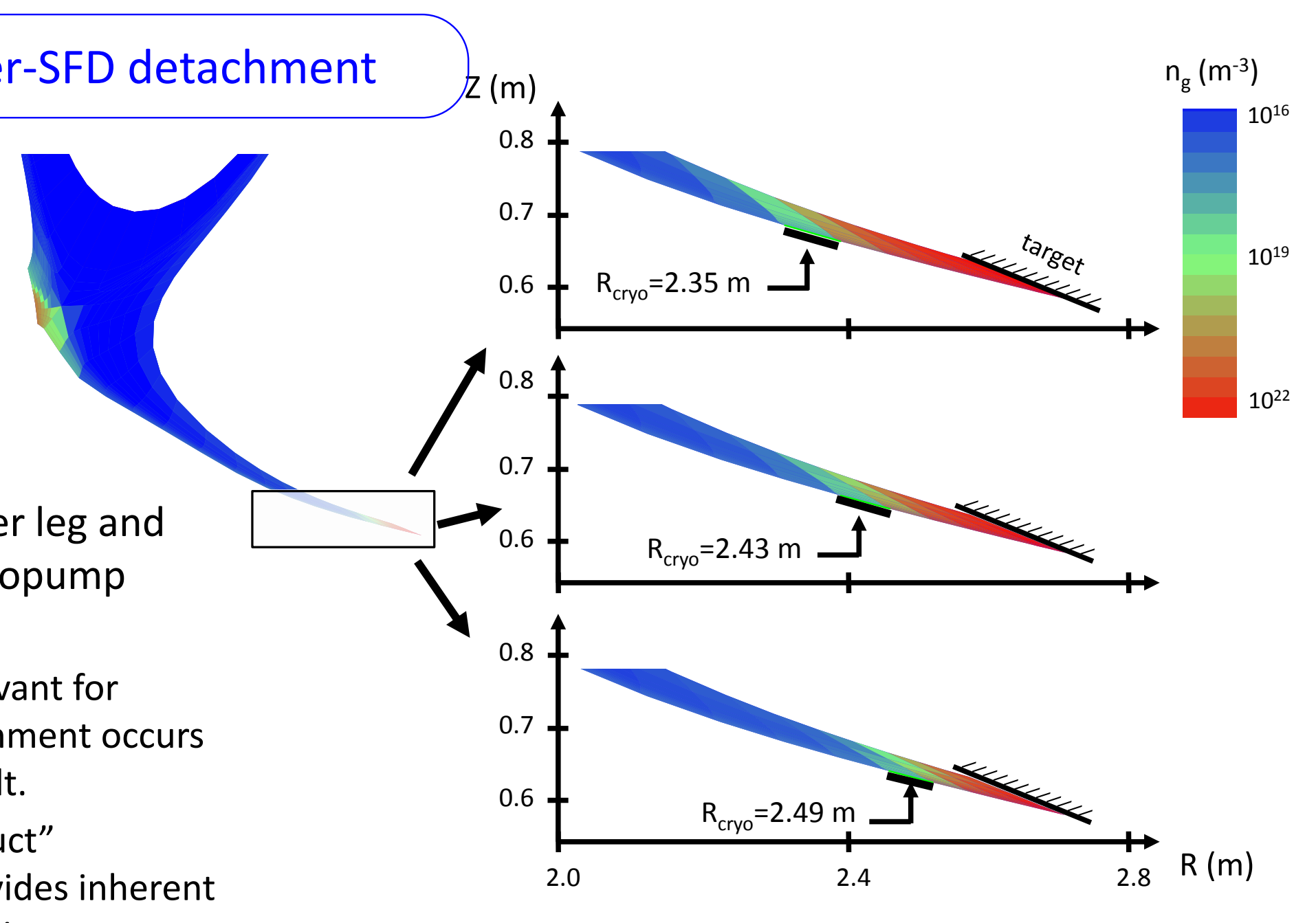
4.3 Divertor and midplane profiles

- UEDGE settings:
  - 100% target recycling
  - D same as NSTX-U; $\chi_{i,e}$ 2x lower than NSTX-U.
- Deposited heat fluxes are <10 MW/m² for all cases.
- SFD and CD cases are sheath limited, with target T_e > 500 eV!
- CD-VT is conduction limited with heat flux < 7 MW/m².
- Super-SFD target plasma is detached.



4.4 Super-SFD detachment

- 100% neutral recycling at walls for R > 2.0 m (99% elsewhere).
- Cryopump duct location is varied.
- Neutral gas fills outer leg and "overflows" into cryopump duct.
  - Target tilt is irrelevant for super-SFD; detachment occurs with or without tilt.
  - This "upstream duct" arrangement provides inherent detachment stability.



5. Conclusions

- The ability of UEDGE to simulate partially detached snowflake divertor (SFD) plasmas in NSTX has been demonstrated.
- In NSTX-U, the SFD can be harnessed to provide effective heat flux mitigation; attention should be given to flux surface tilting with respect to the target.
  - Analysis of a series of modeled NSTX-U SFD show that favorable flux surface tilting produces favorable neutral trapping, facilitates detachment, and enables gradual detachment onset.
- In ST-FNSF, two viable heat flux mitigation techniques are identified: a conventional divertor with vertical target (CD-VT), and a "super-snowflake" (super-SFD) configuration.
  - In the CD-VT, target tilt provides neutral trapping as expected (see, e.g, the ITER vertical target design).
  - In the super-SFD, scenarios with full detachment are found, with the detachment front position determined by the cryopump duct location.
- In future work, this modeling can be extended in many ways. For example:
  - It may be insightful to capture realistic geometry (e.g., baffling), detailed molecular and kinetic neutral effects, charge-state resolved impurity behavior, and plasma drift physics.
  - Additional snowflake effects [11] can be considered, e.g., ELM mitigation via turbulent mixing in low B_{pol} zone, and pedestal stability modifications.

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