Modeling NSTX Snowflake Divertor Experiments

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Abstract

Modeling NSTX Snowflake Divertor Experiments[1] E.T. MEIER, V.A. SOUKHANOVSKII, A.G. MCLEAN, T.D. ROGNLIEN, D.D. RYUTOV, LLNL, R.E. BELL, A. DIALLO, R. KAITA, B.P. LEBLANC, M. PODESTA, F. SCOTTI, PPPL, NSTX TEAM — Experiments on the National Spherical Torus Experiment (NSTX) have demonstrated the potential of the snowflake divertor to alleviate the tokamak power exhaust challenge. The NSTX snowflake configuration induced partial detachment and reduced heat flux approximately five-fold. To explore snowflake physics, the multi-fluid edge transport code, UEDGE, has been used to compare standard and snowflake configurations. Radial profiles of anomalous perpendicular transport coefficients (assumed to be poloidally uniform) are constrained by requiring solutions to match ion and electron temperature and density data at the outer midplane. Divertor recycling and separatrix location are constrained by matching D_α 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. Increased snowflake divertor volume and connection length result in higher radiation which, in tandem with direct flux-expansion profile broadening, leads to heat flux reduction.

Outline

- Motivation
  - Develop an understanding of snowflake performance in NSTX to help guide future divertor research.
- UEDGE modeling setup
  - Equilibria from LRDFIT capture changes to magnetic topology induced by snowflake divertor.
- Constraints on recycling (R_{div}), separatrix shift (δ_{eq}), and diffusivities
  - While adjusting diffusivities to fit midplane profiles, two-dimensional δ_{eq}-R_{div} space is scanned to find best agreement with experimental data.
  - Large increase in recombination rate needed to match snowflake data.
- Analysis of results
  - Snowflake electron thermal diffusivity twice as high at separatrix.
- Summary

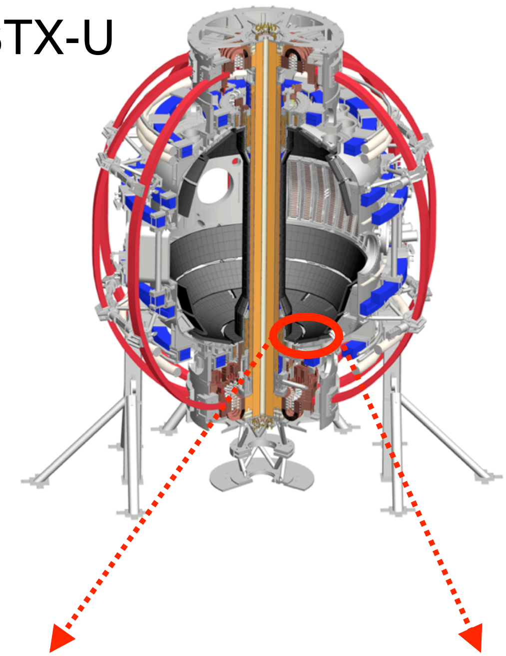
Motivation

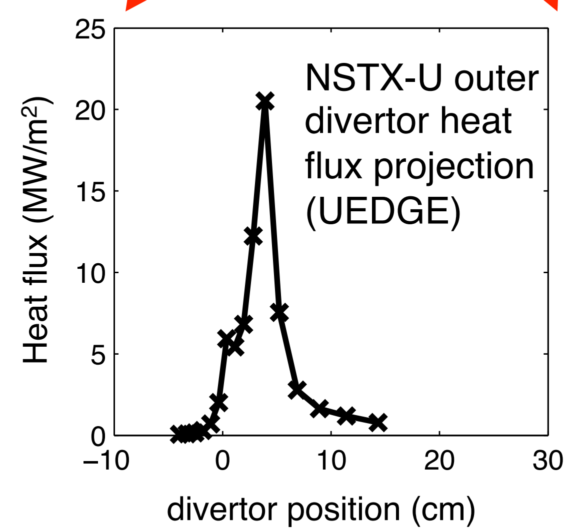
Divertor power-handling techniques are a focus of the NSTX-U program

- NSTX-U is a spherical tokamak (ST) due to come online in 2014.
- Divertor power handling is a challenge for future tokamaks.
  - Power input (P_{in}) will rise dramatically.
  - Heat flux width (λ_q) will probably shrink [Eich, PRL 2011].

  → Peak (unmitigated) heat flux will rise as P_{in}/λ_q!

NSTX-U



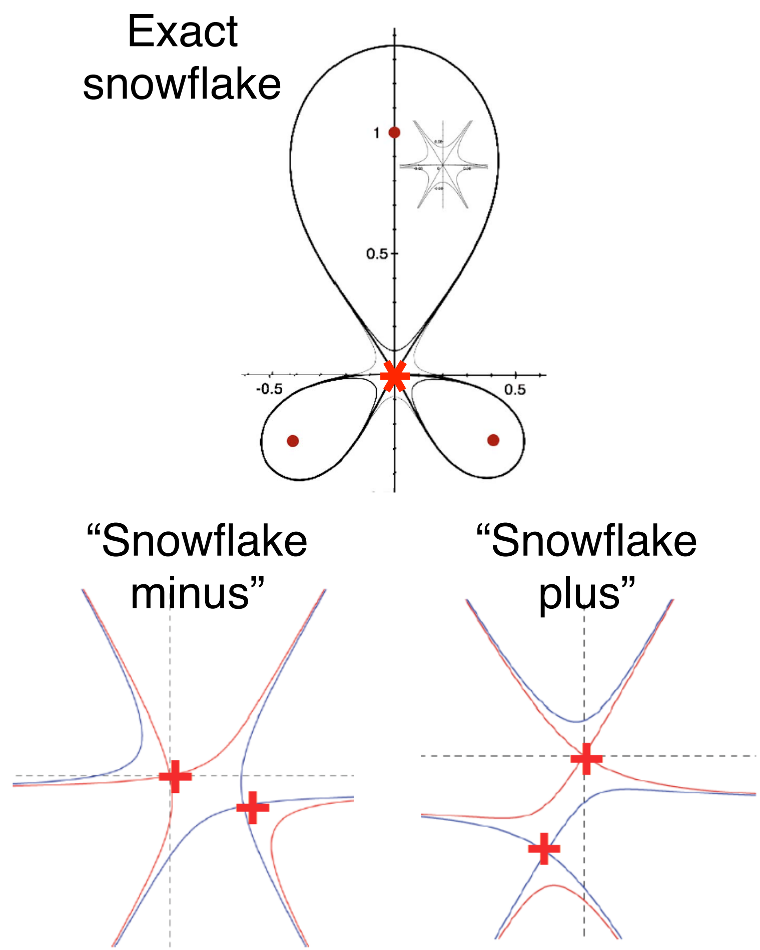


- In NSTX, λ_q depends inversely on plasma current (I_p): $\lambda_q \approx 0.91\, I_p^{-1.6}$ [Gray, JNM, 2011]
- NSTX-U I_p will reach 2 MA (vs. ~1 MA in NSTX).

  → $\lambda_q \approx 3$ mm (vs. $\lambda_q \approx 1$ cm in NSTX).

Snowflake configuration involves 2nd-order null in poloidal magnetic field

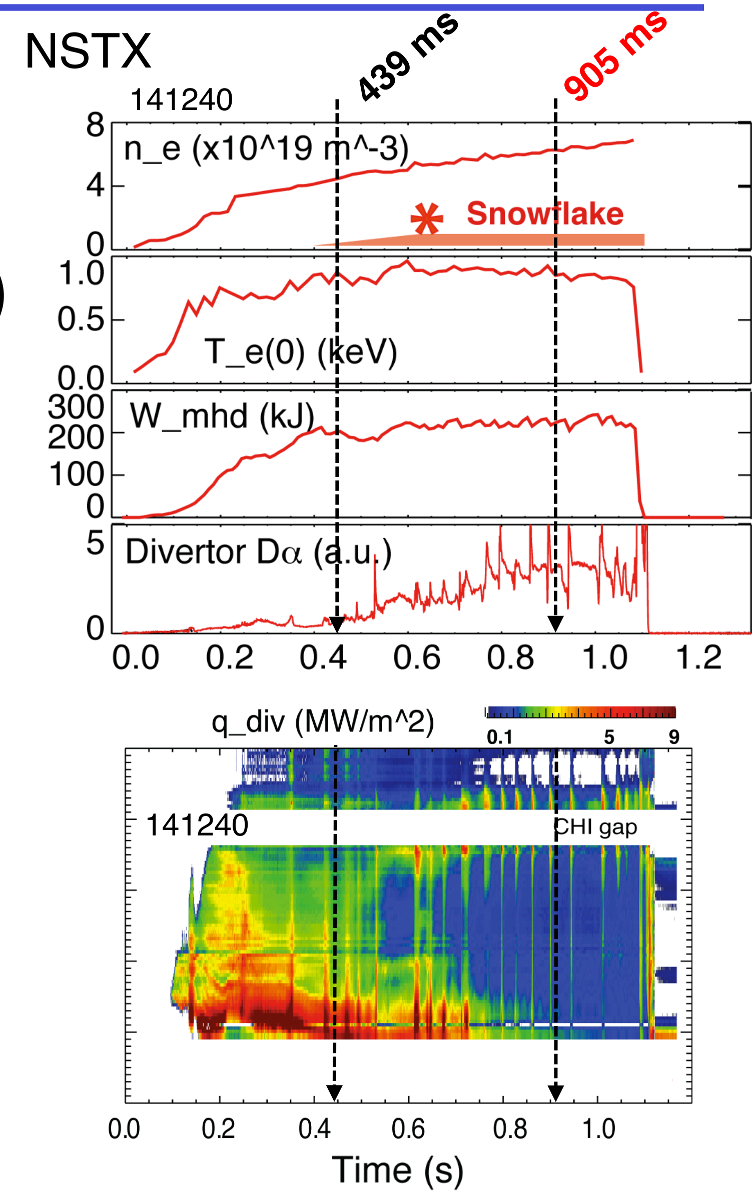
- In the snowflake [1]:
  - Greater wetted area → direct reduction of deposited heat flux.
  - Increased SOL volume → more radiated power.
  - Longer connection length → lower target temperature (→ detachment?).
- Snowflake experiments on NSTX, TCV, and DIII-D have shown effective heat flux mitigation [2-4].
- **This work aims to improve fundamental understanding of snowflake physics.**



[1] D.D. Ryutov, Phys. Plasmas **14**, 064502 (2007).
[2] F. Piras et al., Plasma Phys. Control. Fusion **51**, 055009 (2009).
[3] V.A. Soukhanovskii, et al., Nucl. Fusion **51**, 012001 (2011).
[4] S.L. Allen et al., IAEA Fusion Energy Conf., San Diego, USA, Oct. 2012, Paper PD/1-2.

In NSTX, snowflake divertor configuration yields partial detachment and large heat flux reduction

- Discharge is initialized with standard divertor (SD) configuration.
- Snowflake divertor configuration (SFD) is established at ~600 ms*.
  - Core plasma retains desirable properties.
  - Outer divertor partially detaches
  - ELMs are destabilized – snowflake effect on pedestal?.
  - Peak heat flux is reduced from ~8 MW/m^2 to ~1 MW/m^2.
- **Simulations are conducted for 439 ms (SD) and 905 ms (SFD).**



* Soukhanovskii et al., Phys. Plasmas, 2012

UEDGE modeling setup

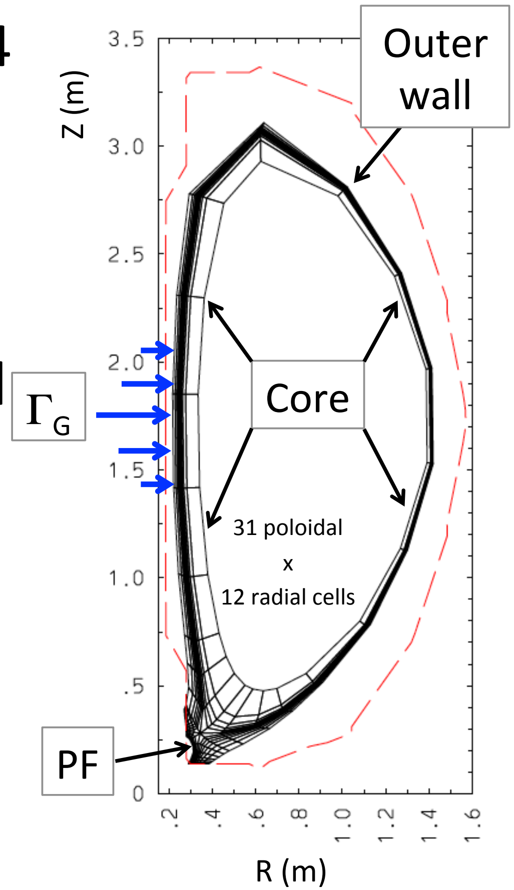
UEDGE is applied to interpret experimental results

- UEDGE provides a 2D laminar (vs. turbulent) fluid treatment of edge transport [Rognlien, JNM 1992].
  - Braginskii fluid equations plus anomalous (turbulent) radial transport.
  - Charge-state resolved carbon impurities are included in this work.
  - Fluid neutral treatment is used in this work.
- This work focuses on steady-state behavior
  - Transient behaviors, e.g., ELMs, are also important.
- Detailed settings and boundary conditions (BC):
  - Recycling:
    - 50% recycling at "walls"
    - Scan of recycling at targets
    - No neutral pumping anywhere
  - Core-edge BC:
    - n_D determined by particle input
    - $T_{i,e}$ determined by power input
    - n_{C6+} fixed
    - $n_{C1\text{-}5+}$ have 1-cm gradient length scale (decaying toward core)
    - Zero neutral flux
  - Outer wall BC:
    - $T_{i,e}$ fixed
    - n_D fixed
  - Private flux BC:
    - n_D has 5-cm gradient length scale
    - $T_{i,e}$ have 5-cm gradient length scale
  - Carbon sputtering model from DIVIMP
    - Reduced to 10% of nominal level at PF and outer walls (to account for unrealistically tight-fitting walls)
  - No drifts

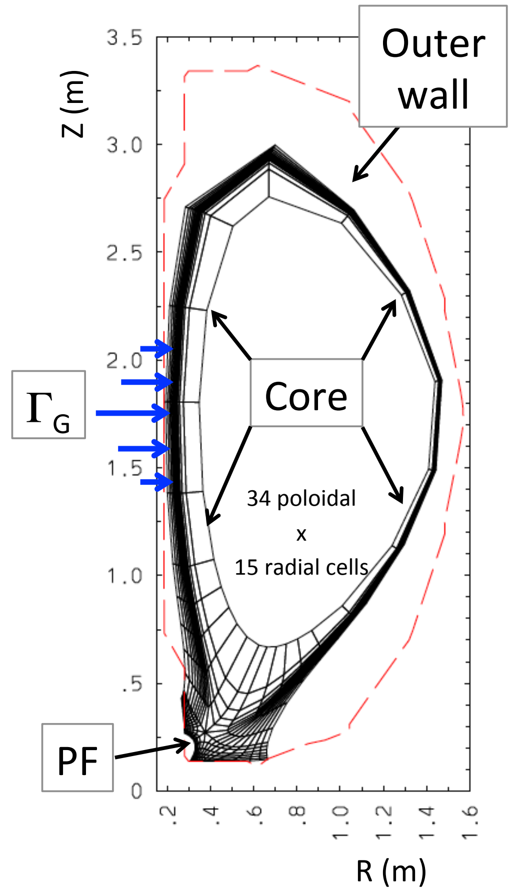
Magnetic flux-aligned grids are generated based on LRDFIT equilibria

- Equilibria are found with LRDFIT.
- Grids capture $0.9 < \psi_n < 1.04$
- High-field side gas injection (Γ_G=300 A) is included.
  - 10 A = 1 torr-liter = 7×10^{19} s^{-1}
- Power and particles injected through core boundary.
  - 3 MW neutral beam power is split evenly between ion and electron channels.
  - 20 A/MW is assumed for neutral beam injection.

Standard divertor configuration



Snowflake divertor configuration



Secondary X-point of snowflake within one heat flux width of strike point

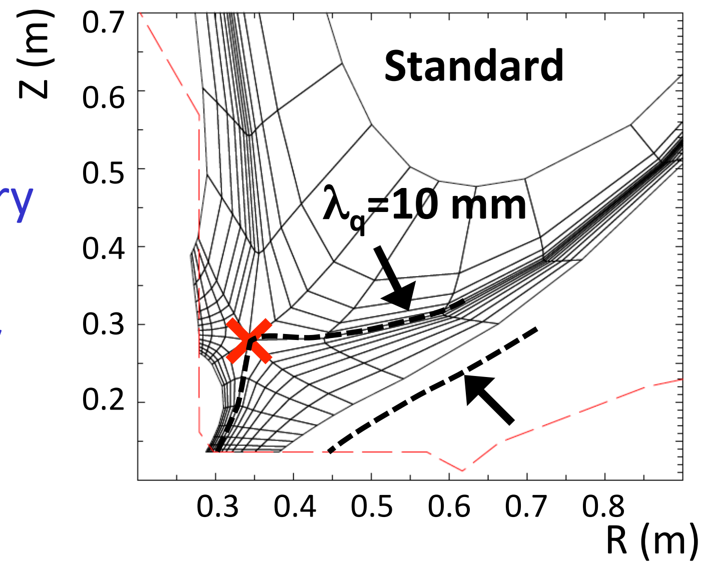
- Criterion for a snowflake:

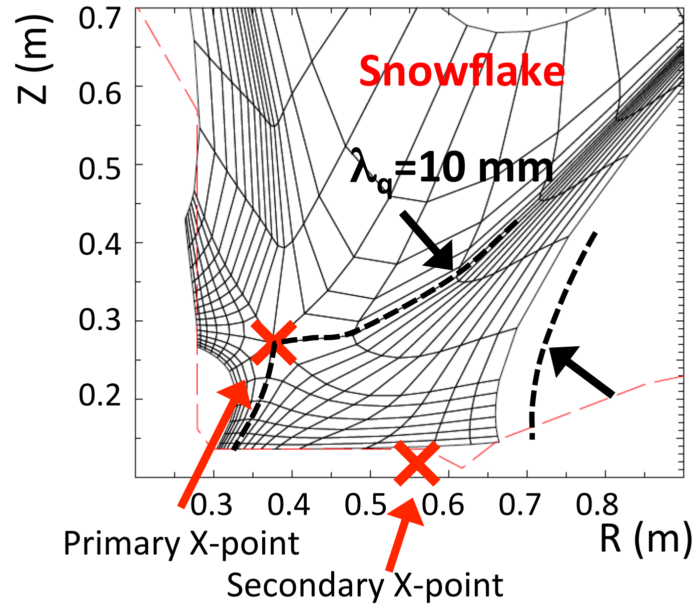
$$d_{sf} / \lambda_{q,X} \lesssim 1,$$

  - d_{sf} : distance between primary and secondary X-points.
  - $\lambda_{q,X}$: heat flux width mapped to the primary X-point.

  [Ryutov, PPCF 2012]

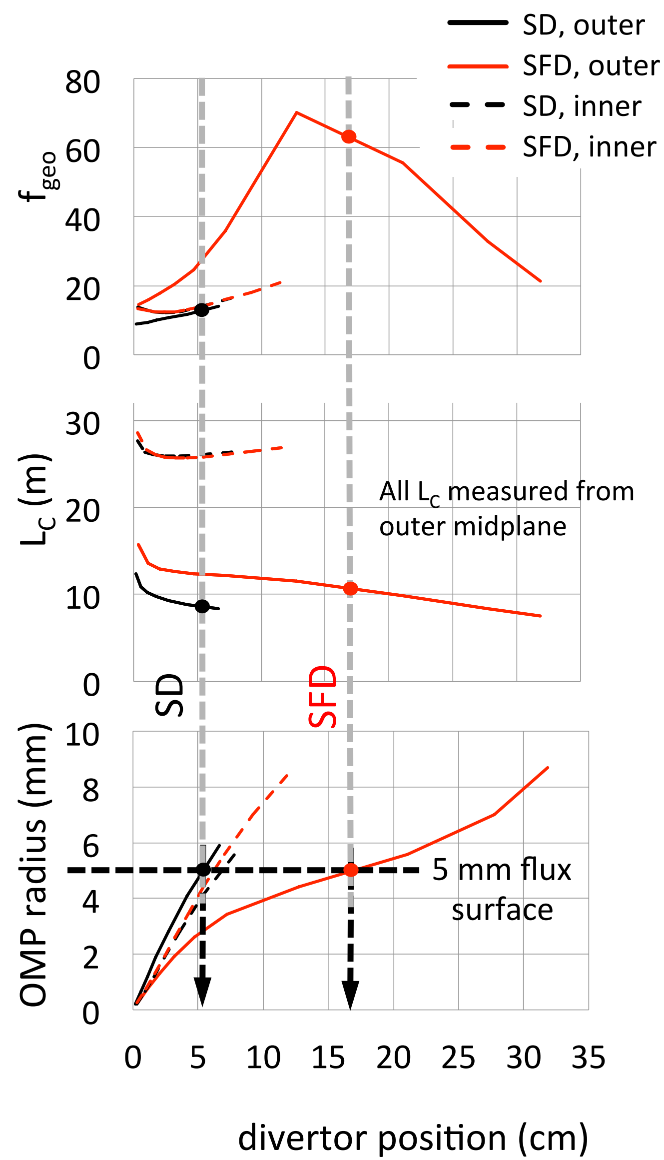
- For this snowflake, $d_{sf} / \lambda_{q,X} = 0.75$
  - Significant snowflake X-point interaction expected.





Snowflake increases wetted area by up to 4x

- Outer target geometric expansion is 2-4 times higher in the snowflake.
  - f_{geo} is the footprint area of a flux tube relative to its midplane area.
- Midplane-to-divertor connection length is ~50% longer in the snowflake (within the 5 mm flux surface).
  - Assuming conduction-limited plasma, $T_{target} \sim L_C^{-4/7}$. [Stangeby 2000]
  - For this SFD vs. SD, only 20% reduction of T_{target} is expected ($1.5^{-4/7} = 0.8$).
- Inner divertors of snowflake and standard configurations are nearly identical in terms of f_{geo} and L_C.



Constraints

Diffusivities, separatrix offset (δ_{eq}), and divertor target recycling (R_{div}) must be constrained

- Modeling depends on determining separatrix shift (δ_{eq}) and recycling coefficient (R_{div}).

→ In UEDGE, scan δ_{eq} and R_{div} to find the point in δ_{eq}-R_{div} space that yields the best match to heat flux data (inferred from infrared thermography), and divertor spectroscopy (typically D_α light).

- It is critical to automate determination of diffusivities – see next slide.
  - Diffusivities must be determined at each point in the two-dimensional δ_{eq}-R_{div} space!
  - Diffusivities should yield temperature and density profiles that match midplane data (at least approximately).

δ_{eq}:
The separatrix location found by equilibrium fitting codes (e.g., EFIT, LRDFIT) typically requires a slight shift (of order 1 cm) for consistency with the midplane diagnostics. Without the shift, 2D fluid codes show unrealistic target heat fluxes.

R_{div}:
Recycling is less than unity due to lithium conditioning, but the exact value is unknown.

Diffusivities are determined using iterative fitting method

Procedure closely follows Canik [Canik, JNM 2011]:

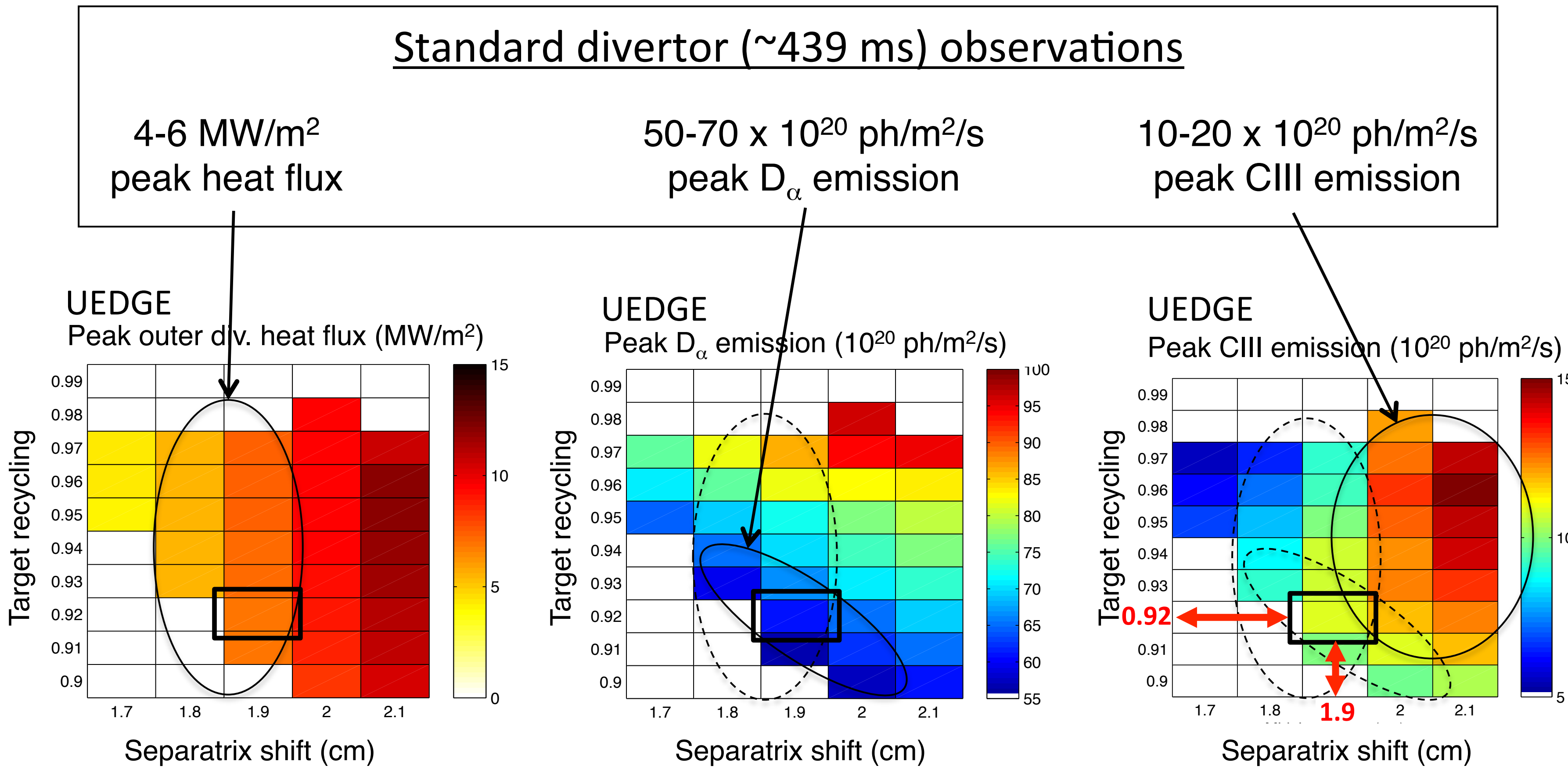
- Establish hyperbolic tangent fits to outer midplane data, including T_e and n_e from multi-point Thomson scattering, and T_i and n_{C6+} from CHERS.
- Begin with steady-state solution using approximate diffusivities. Then set new diffusivities (χ^{n+1}, D^{n+1}) as

$$D^{n+1}_{D,C} = D^{n}_{D,C} + f_{fit}\left(D^{fit}_{D,C} - D^{n}_{D,C}\right); \quad D^{fit}_{D,C} = -\Gamma^{\text{UEDGE}}_{D,C^{6+}} / \nabla n^{exp}_{D,C^{6+}}$$

$$\chi^{n+1}_{i,e} = \chi^{n}_{i,e} + f_{fit}\left(\chi^{fit}_{i,e} - \chi^{n}_{i,e}\right); \quad \chi^{fit}_{i,e} = -\left(q_{i,e} - \tfrac{5}{2}\Gamma_D T_{i,e}\right)^{\text{UEDGE}} / (n\nabla T_{i,e})^{exp}$$

  - Same diffusivity is used for all C charge states.
  - To speed convergence, the factor f_{fit} is varied from ~0.01 in early iterations to ~0.1 in later iterations.
- In an outer iterative loop, carbon pinch velocity is increased/ decreased as required to give zero net flux through core boundary.

With UEDGE, scan separatrix shift and divertor recycling to find match to experimental data



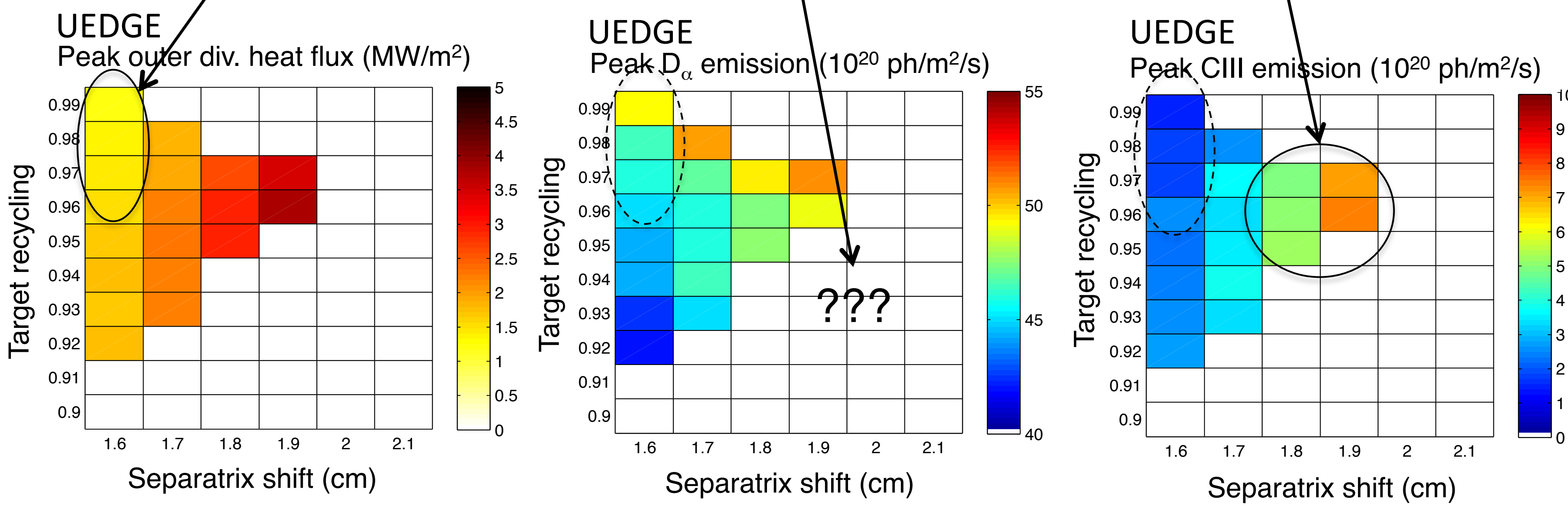
→ To match experiment, divertor recycling and separatrix shift are:

R_{div}=0.92 and separatrix shift **δ_{eq}=1.9 cm**

For snowflake divertor, match to experimental data proves to be challenging

Snowflake divertor (~905 ms) observations

<1.5 MW/m^2 peak heat flux	500-1200 x 10^{20} $ph/m^2/s$ peak D_α emission	5-20 x 10^{20} $ph/m^2/s$ peak CIII emission

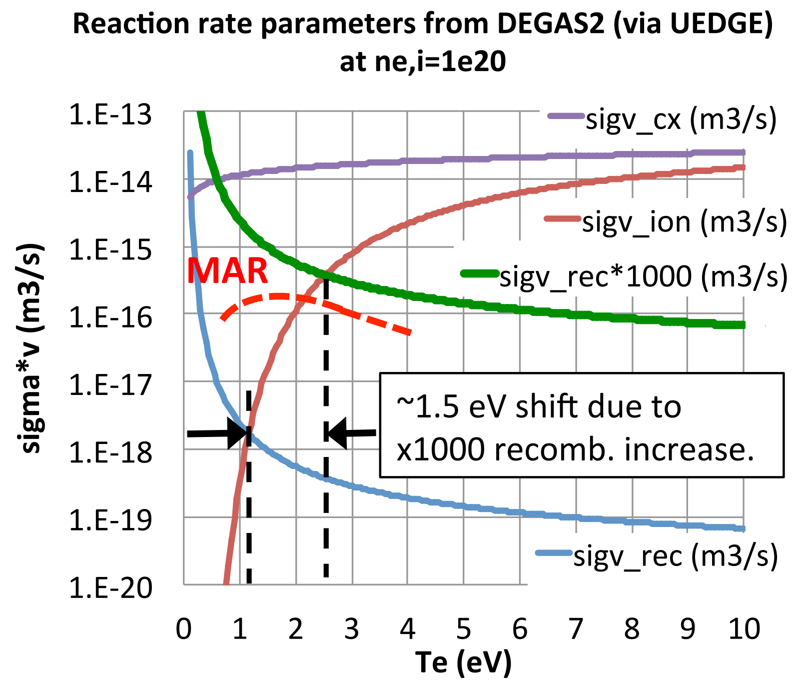


→ Match to experimental data proves to be challenging.

- Need enhanced recombination to yield large (~10^{23} $ph/m^2/s$) D_α emission; Recombination increases dramatically at lower T_e.
- T_e in UEDGE too high? Missing physics?

If recombination rates are artificially boosted, solution is found

- Multiplying recombination by 1000 shifts the ionization/recombination parity temperature by ~1.5 eV.
- Justification for x1000 increase?
  - Molecular activated recombination (MAR) [Krasheninikov, JNM 1997] can be ~1000 times stronger than standard recombination processes.



- With enhanced recombination:

(At R_{div}=0.92 and δ_{eq}=1.6 cm)

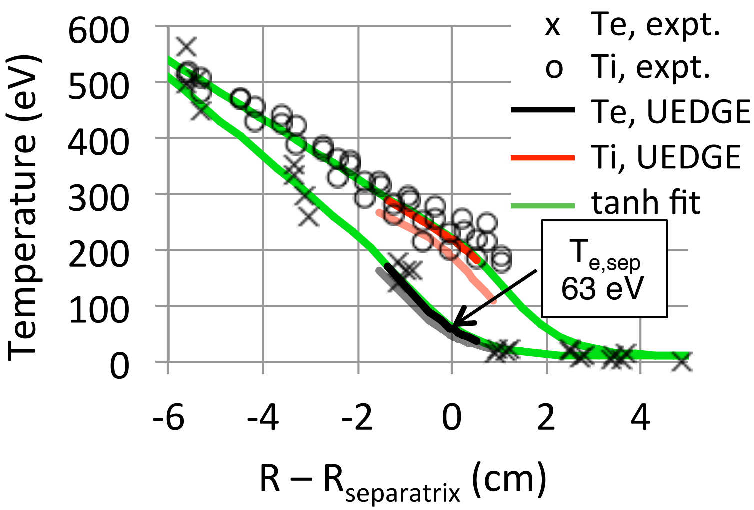
	UEDGE results	Snowflake divertor observations
Peak outer div. heat flux:	1.5 MW/m^2	<1.5 MW/m^2
Peak outer div. D_α:	250 x 10^{20} ph/m^2/s	500-1200 x 10^{20} ph/m^2/s
Peak outer div. CIII:	2.3 x 10^{20} ph/m^2/s	5-20 x 10^{20} ph/m^2/s

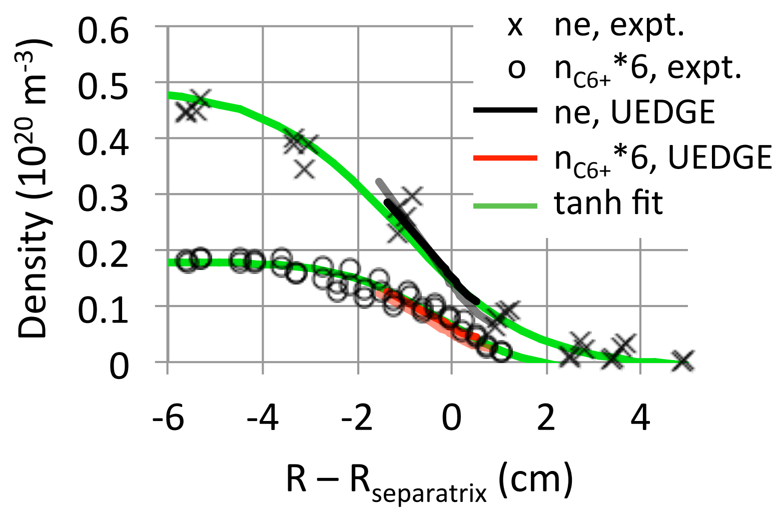
→ Match is within a factor of 2.

Analysis of results

Separatrix T_e is 15 eV lower in snowflake (48 vs. 63 eV)

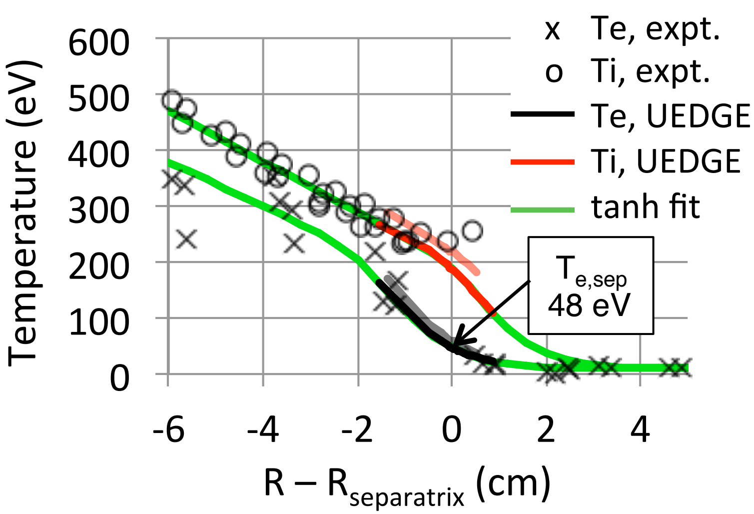
$(q_{||} \sim T_{sep}^{7/2} \rightarrow q_{||,snowflake} \sim 0.4\, q_{||,standard})$

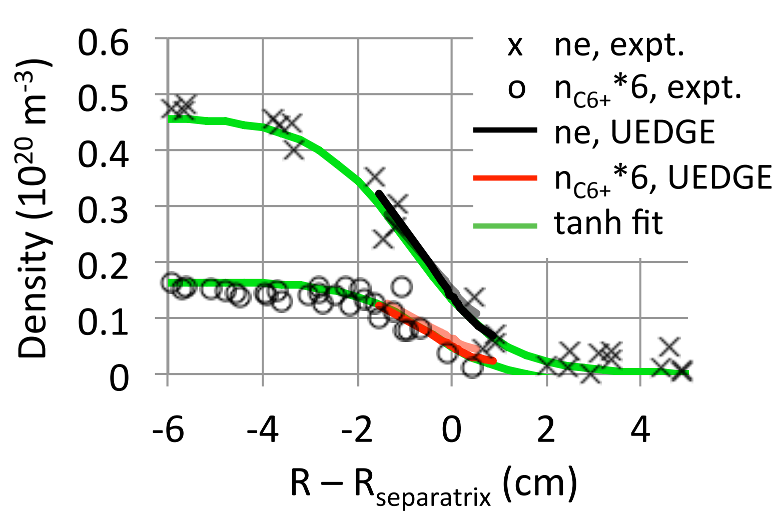




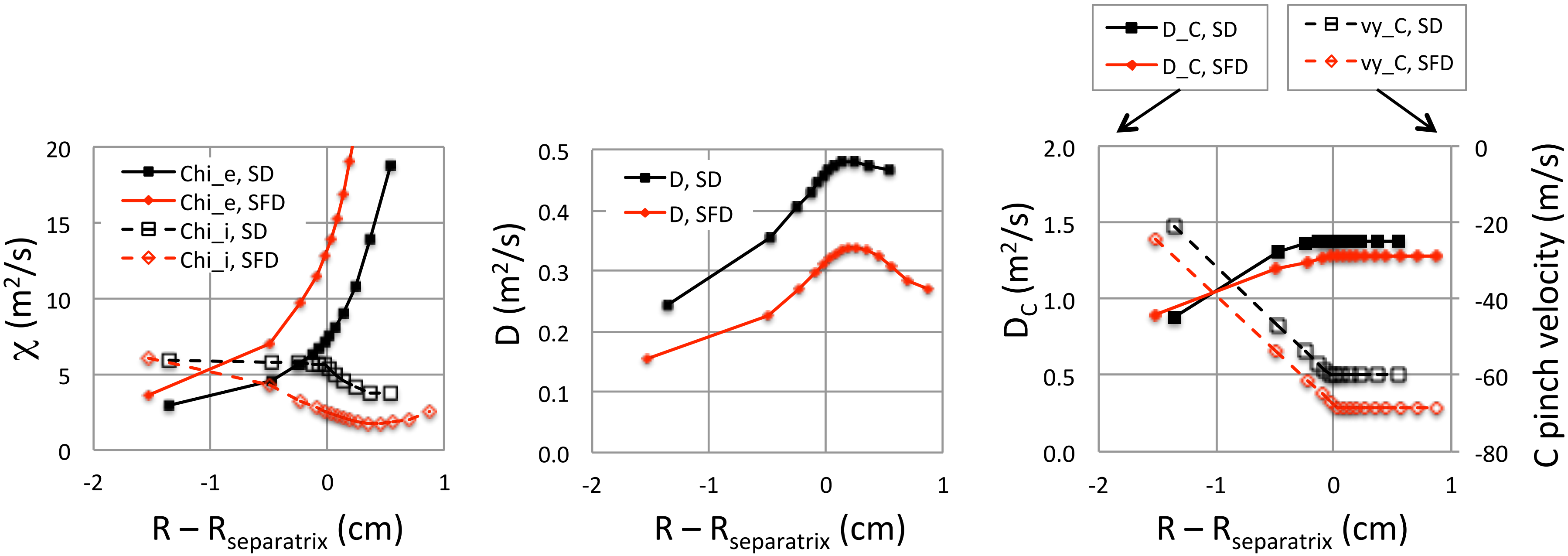
Standard (Snowflake solutions shown with semi-transparent lines)

Snowflake (Standard solutions shown with semi-transparent lines)



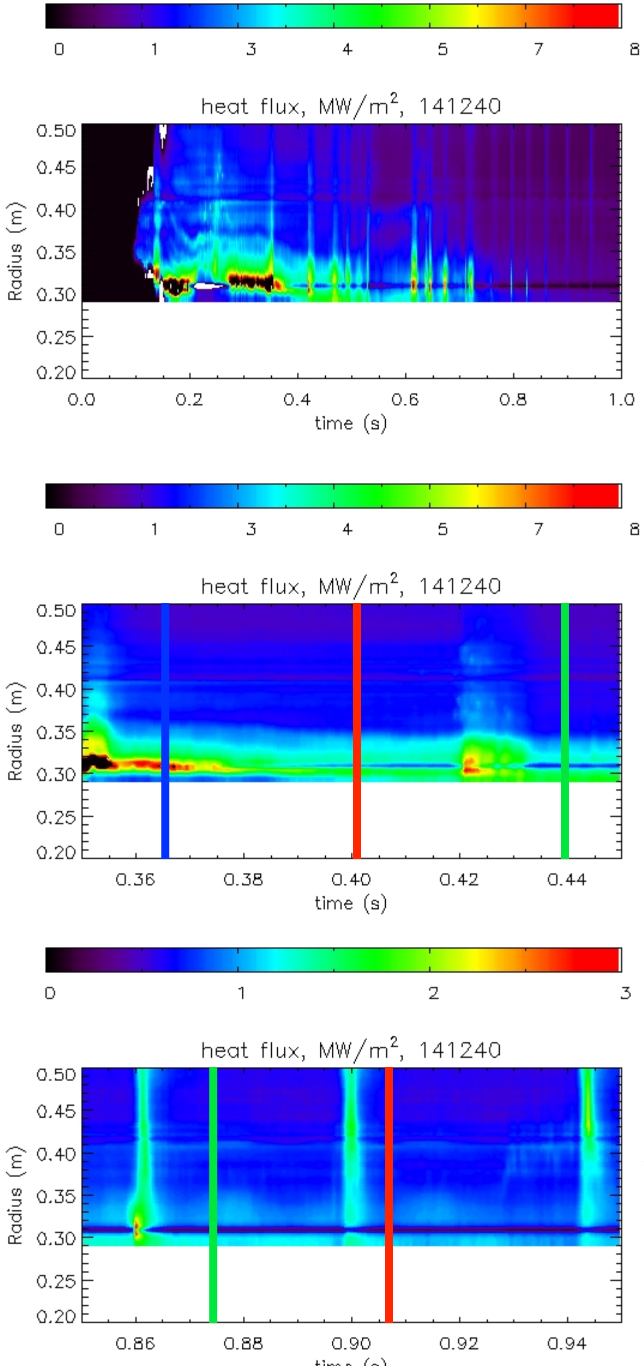


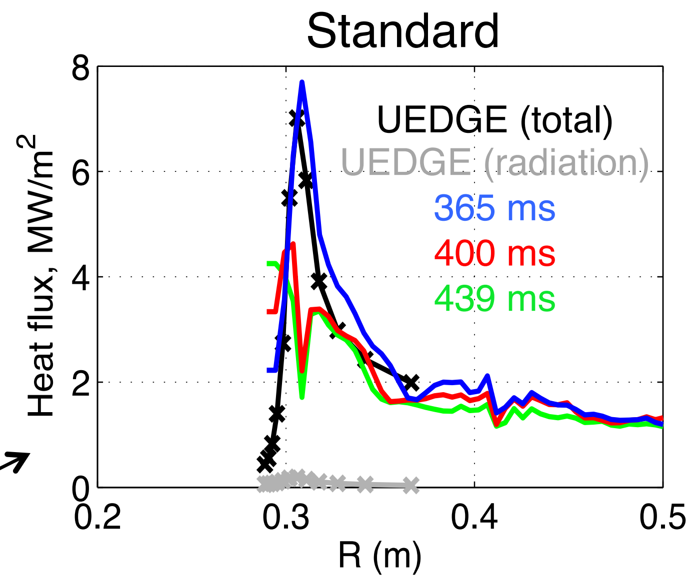
Snowflake solutions have higher electron thermal diffusivity



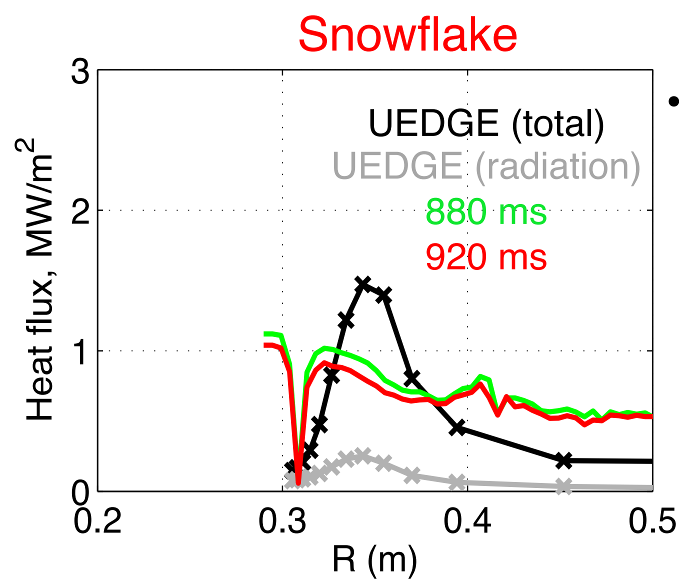
- Compared to the standard case, the snowflake electron thermal diffusivity (χ_e) is 1.9x higher at the separatrix (13 vs. 7 m^2/s).
  - The primary effect of higher χ_e is to reduce the separatrix T_e.
- No obvious reason that snowflake would give higher diffusivity!
  - UEDGE seems to require low separatrix T_e; perhaps a different physical mechanism (besides higher diffusivity) leads to low separatrix T_e.

Divertor heat flux is well matched





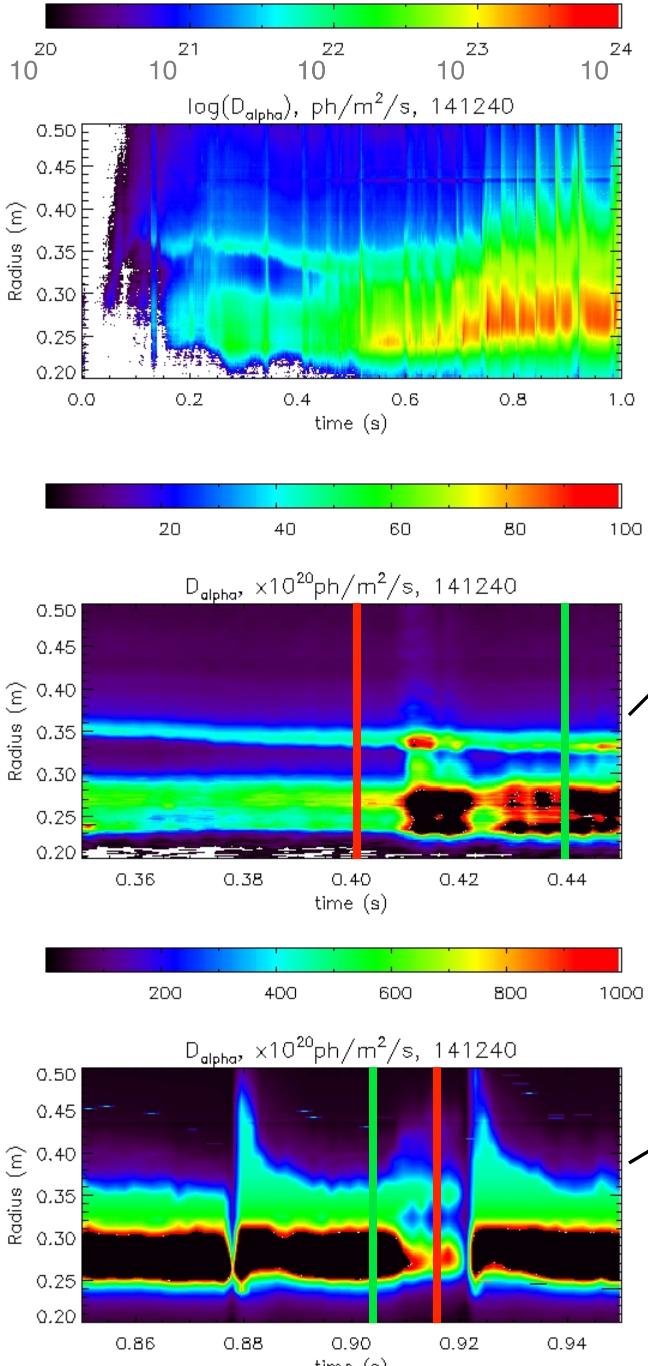
Experimental heat flux data available only for outer divertor.

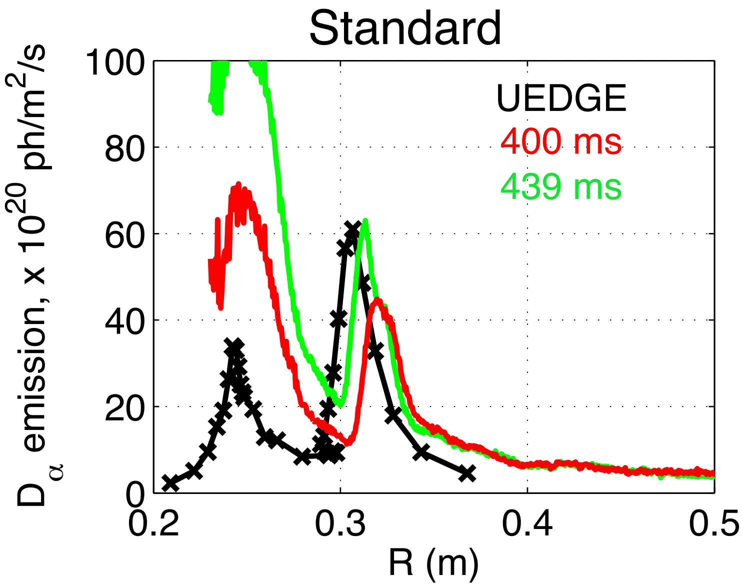


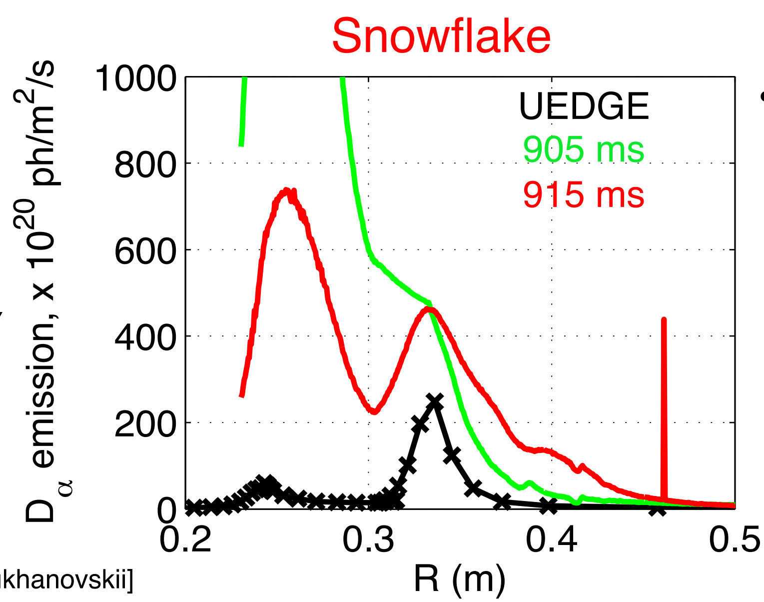
- Snowflake heat flux match not as good as standard.

[Experimental data: McLean]

Outer target D_α is well matched; inner target discrepancy exists



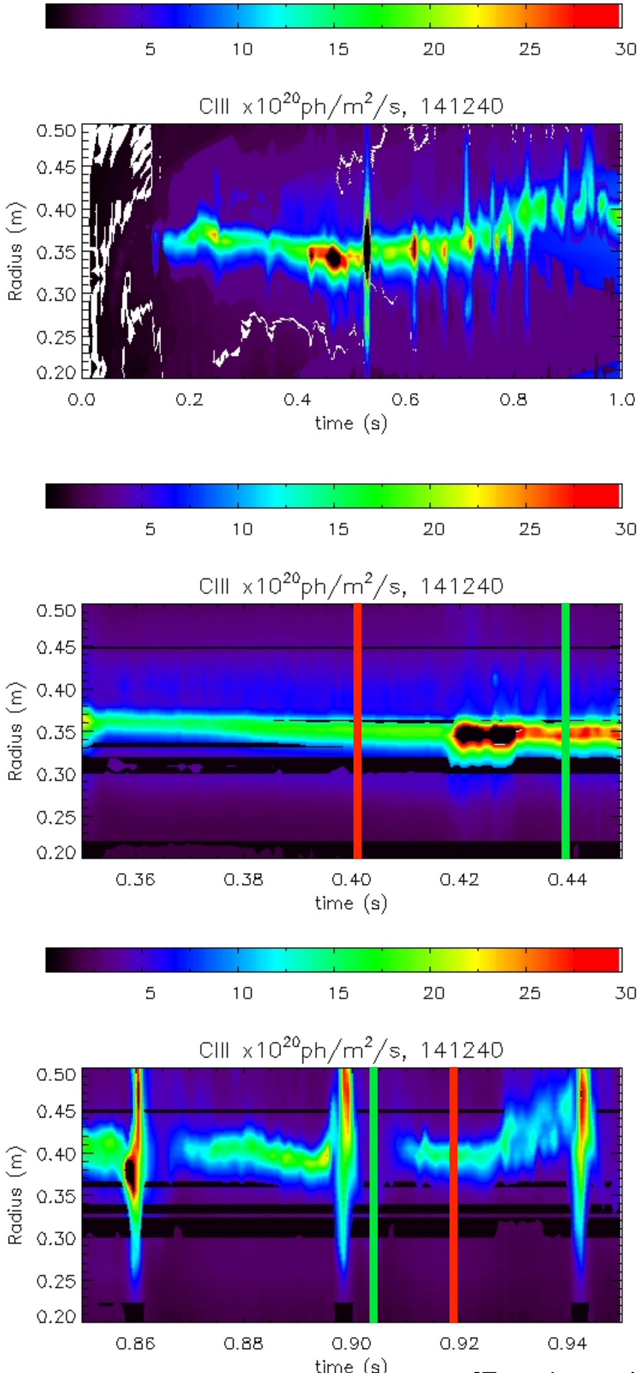


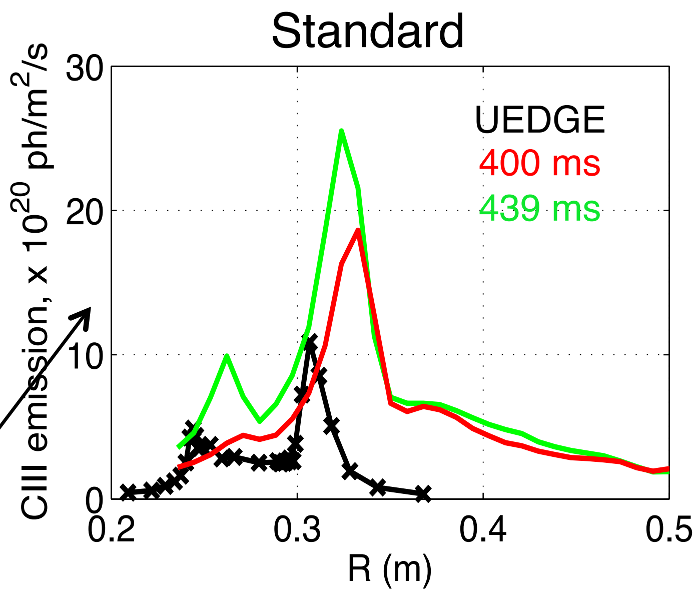


- As for heat flux, snowflake D_α match not as good as standard.

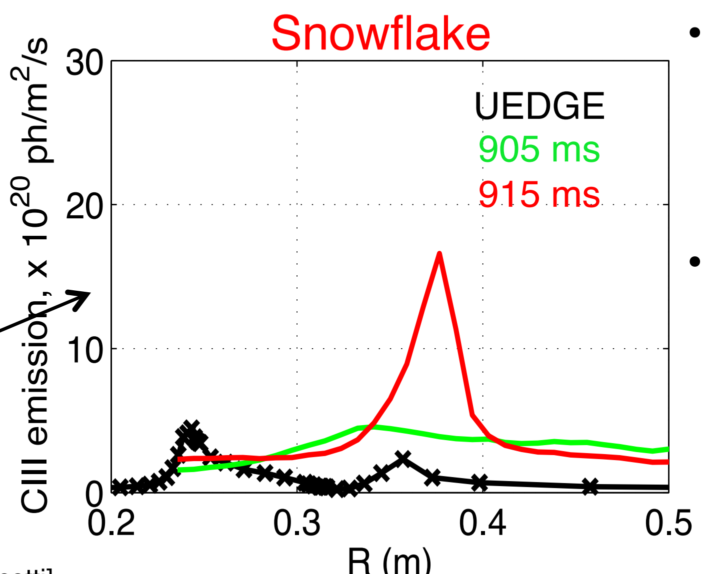
[Experimental data: Soukhanovskii]

Divertor CIII is too low, but some features captured





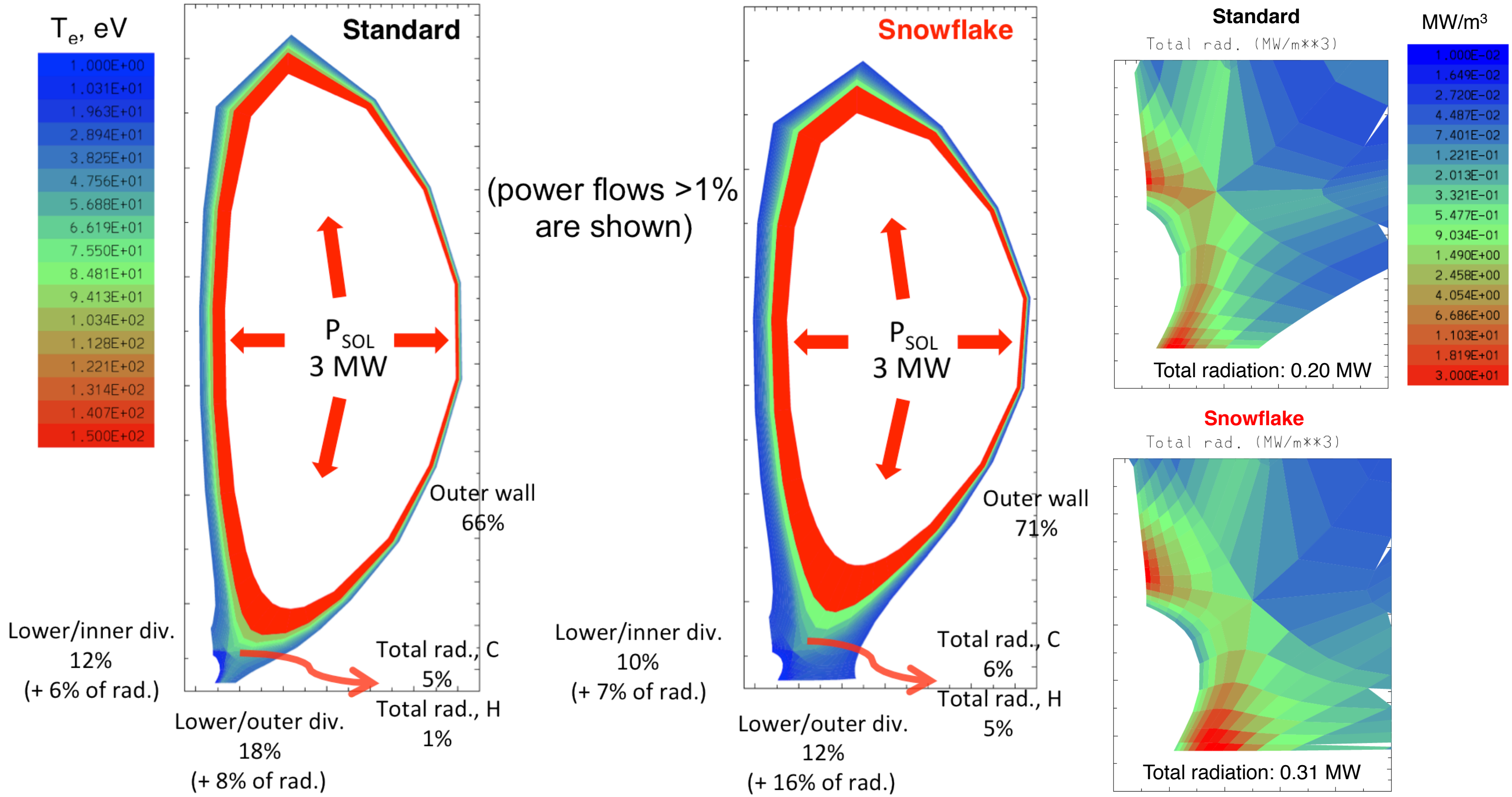
Because of calibration issues, experimental data is considered "upper limit."



- Snowflake CIII match not as good as standard.
- UEDGE CIII peak shifted outward with respect to D_α peak as seen in experiment.

[Experimental data: Scotti]

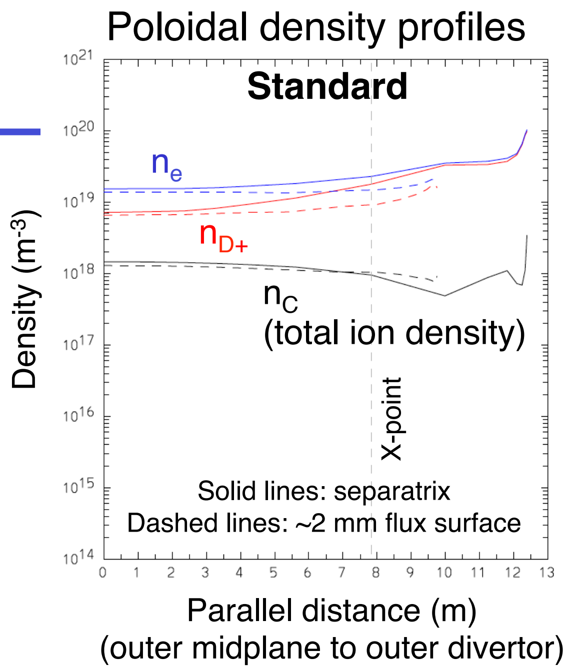
In snowflake, total radiation is increased 50%

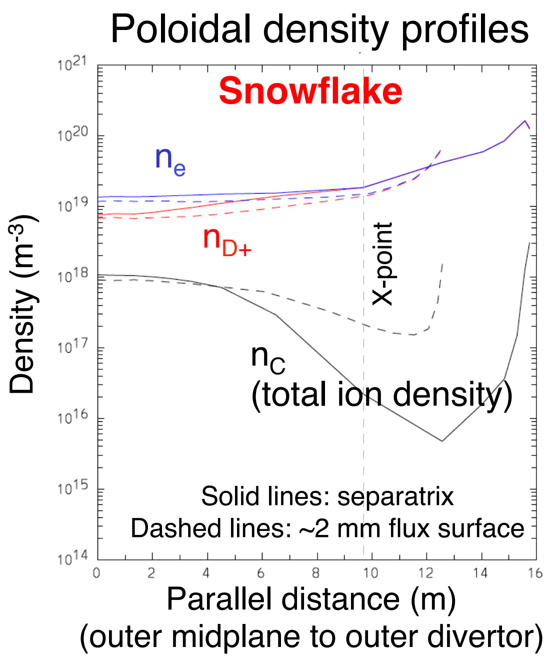


- In snowflake, hydrogenic radiation is 5x higher.
- In snowflake, total power to the divertor targets is reduced 31%.

Snowflake dramatically changes the poloidal carbon density profile

- UEDGE C^{6+} density at outer midplane is fitted to experimental data.
  - With snowflake, carbon concentration at the outer midplane separatrix drops from 9.6% to 8.0% (15% relative reduction).
- UEDGE snowflake simulation shows much stronger divertor trapping than standard.
  - Further research required to better understand snowflake effects on carbon transport.





Summary

Summary

- Separatrix shift and recycling coefficient in UEDGE are constrained with heat flux measurements and divertor spectroscopy.
- Experimental snowflake D_α emission is matched by adding a large multiplier on the recombination rate in UEDGE.
- Electron thermal diffusivity in UEDGE snowflake simulation is a factor of two higher than in the standard simulation.
  - But is the higher χ_e "real"? Snowflake certainly affects pedestal stability (destabilizes ELMs).
- Future work:
  - Consider modeling changes to capture experimentally-relevant (<0.5 eV) Te in NSTX snowflake.
  - Double-null simulations with more SOL coverage.
  - In NSTX-U, look for experimental evidence of signatures of molecular assisted recombination in D2 emission.