Modeling of NSTX and NSTX-U snowflake divertor configurations

Eric T. Meier[1]

V. A. Soukhanovskii[1], A. G. McLean[1], T. D. Rognlien[1], D. D. Ryutov[1], R. E. Bell[2], A. Diallo[2], S. Gerhardt[2], R. Kaita[2], B. P. LeBlanc[2], J. E. Menard[2], M. Podesta[2], F. Scotti[2], and the NSTX Research Team

[1]Lawrence Livermore National Laboratory

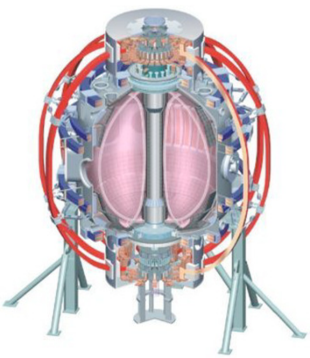
[2]Princeton Plasma Physics Laboratory

54th APS Division of Plasma Physics Meeting

Providence, RI

October 29 – November 2, 2012

Coll of Wm & Mary
Columbia U
CompX
General Atomics
FIU
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Lehigh U
Nova Photonics
ORNL
PPPL
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Illinois
U Maryland
U Rochester
U Tennessee
U Tulsa
U Washington
U Wisconsin
X Science LLC



Culham Sci Ctr
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Inst for Nucl Res, Kiev
Ioffe Inst
TRINITI
Chonbuk Natl U
NFRI
KAIST
POSTECH
Seoul Natl U
ASIPP
CIEMAT
FOM Inst DIFFER
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

This work was performed under the auspices of the U.S. Department of Energy under Contracts DE-AC52-07NA27344 and DE-AC02-09CH11466.

Outline

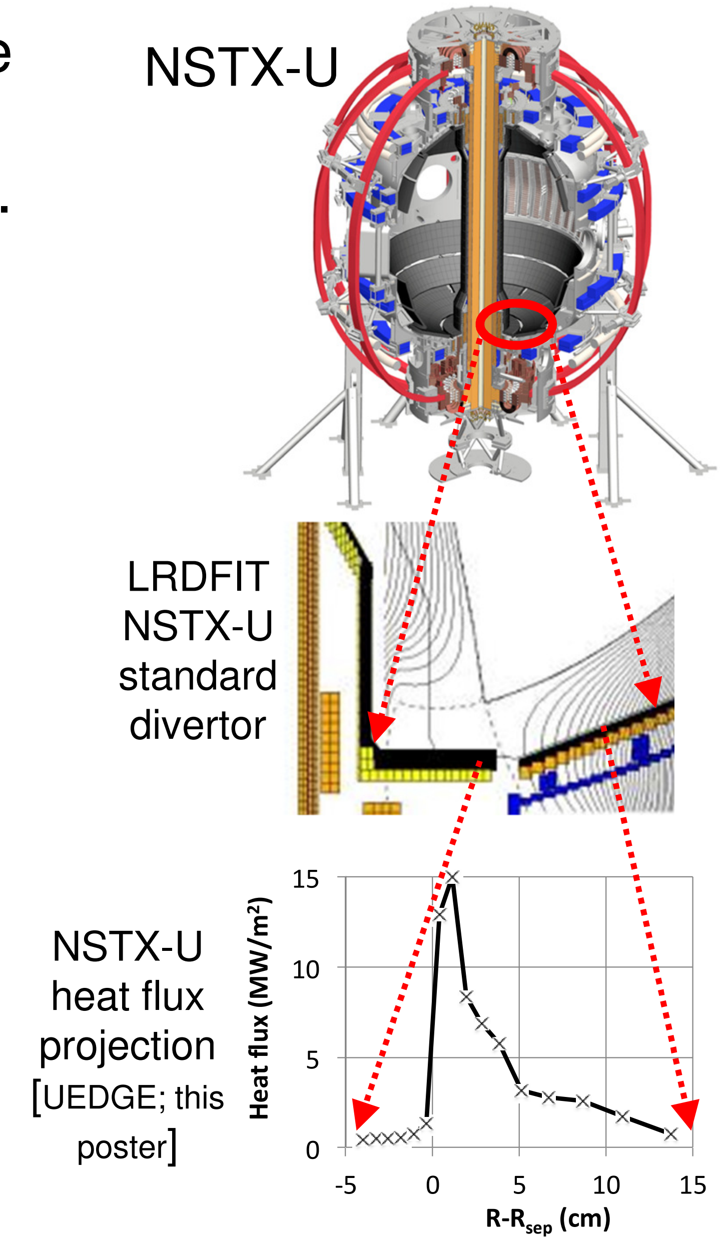
- Motivation for snowflake modeling
- UEDGE simulation setup
- NSTX modeling
  - NSTX discharge 141240 details
  - Comparison of modeling results to experiment
  - Analysis of results
- NSTX-U modeling
  - Core-edge interface condition for NSTX-U
  - Modeling results and analysis
- Summary

Motivation for snowflake modeling

Development of power-handling techniques is a strong component of the NSTX/NSTX-U program

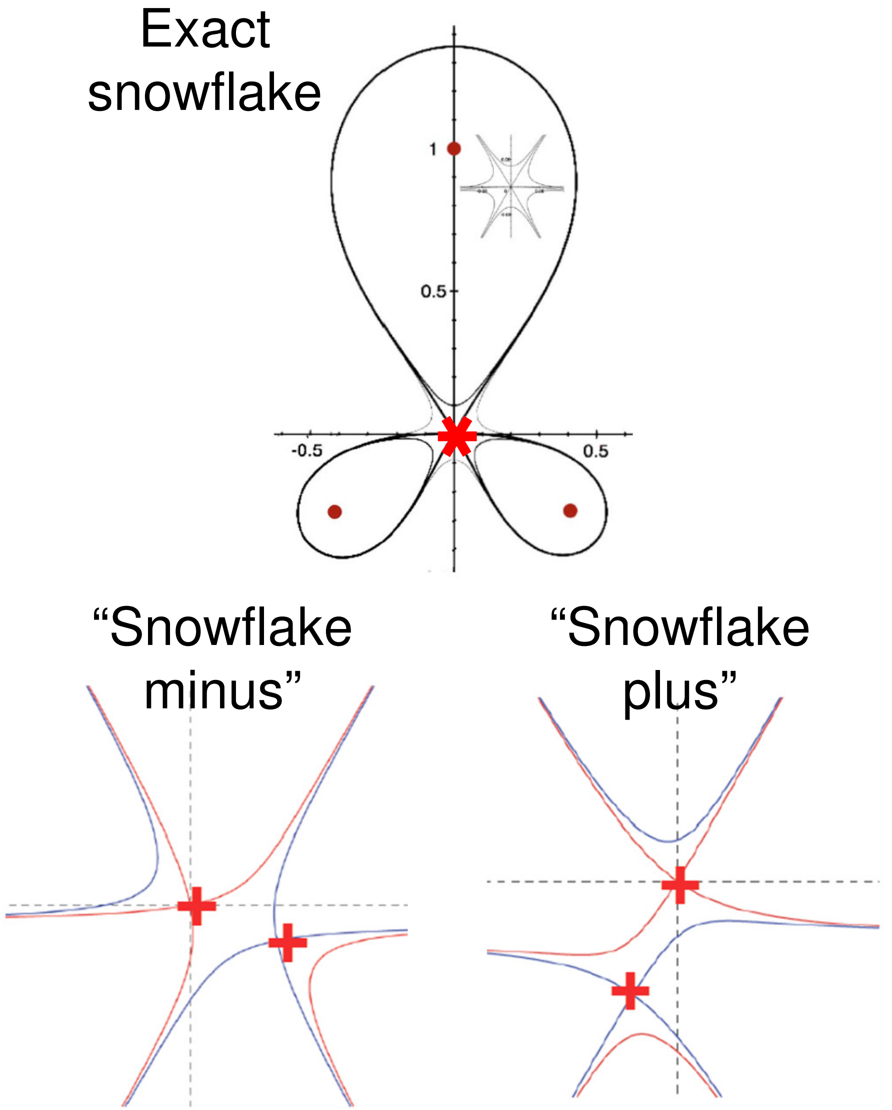
- Divertor power handling is a major challenge for future tokamak and spherical tokamak (ST) magnetic fusion energy (MFE) facilities.
- Because of their compact divertors, ST's offer exceptional divertor research environments [Menard, Nucl. Fusion, 2012].
- Heat flux width (λ_q) is an important characteristic of the the "exhaust" of MFE devices.
  - Small λ_q → threat to plasma-facing components.
- In NSTX, λ_q depends inversely on plasma current (I_p): $\lambda_q \sim I_p^{-1.6}$ [Gray, JNM, 2011]
- NSTX-U I_p will reach 2 MA (vs. ~1 MA in NSTX).

  λ_q as small as 2 mm are expected in NSTX-U standard divertor configurations!



Snowflake divertor configuration offers improved power handling

- The "snowflake" magnetic configuration leads to a second-order null.
  - Second-order null: both B_{pol} and grad(B_{pol}) are zero.
  - grad(B_{pol}) is non-zero in standard X-point.
  - → Large flux expansion near strike point.
  - → Longer connection lengths, etc.
  - → Improved power handling; increased λ_q.
- Exact snowflake is topologically unstable.
  - "Snowflake plus/minus" configurations are achievable.
  - The work presented here focuses on snowflake minus configurations.
- Snowflake is attainable with existing divertor coils.
- Snowflake experiments on NSTX have shown promising results [Soukhanovskii, Phys. Plasmas, 2012].



Ryutov, Phys. Plasmas, 2007

UEDGE provides insight into snowflake physics

- UEDGE is a 2D multi-fluid edge transport code [Rognlien, JNM, 1992; Rognlien, Rensink, FED, 2002].
  - Braginskii fluid equations plus anomalous perpendicular transport.
  - Impurities treatments:
    - Fixed fraction of the plasma density (this work); not practical to capture non-coronal effects.
    - Charge-state resolved (future work); non-coronal effects captured.
  - Fluid neutral treatment is used in this work; Monte Carlo neutral treatment is available.
  - Non-orthogonal grid generation based on EFIT-like equilibria.
- UEDGE provides insight into snowflake physics
  - Synthetic diagnostics help disentangle contributions of geometric effects (e.g., flux expansion) from volumetric effects (e.g., radiation).

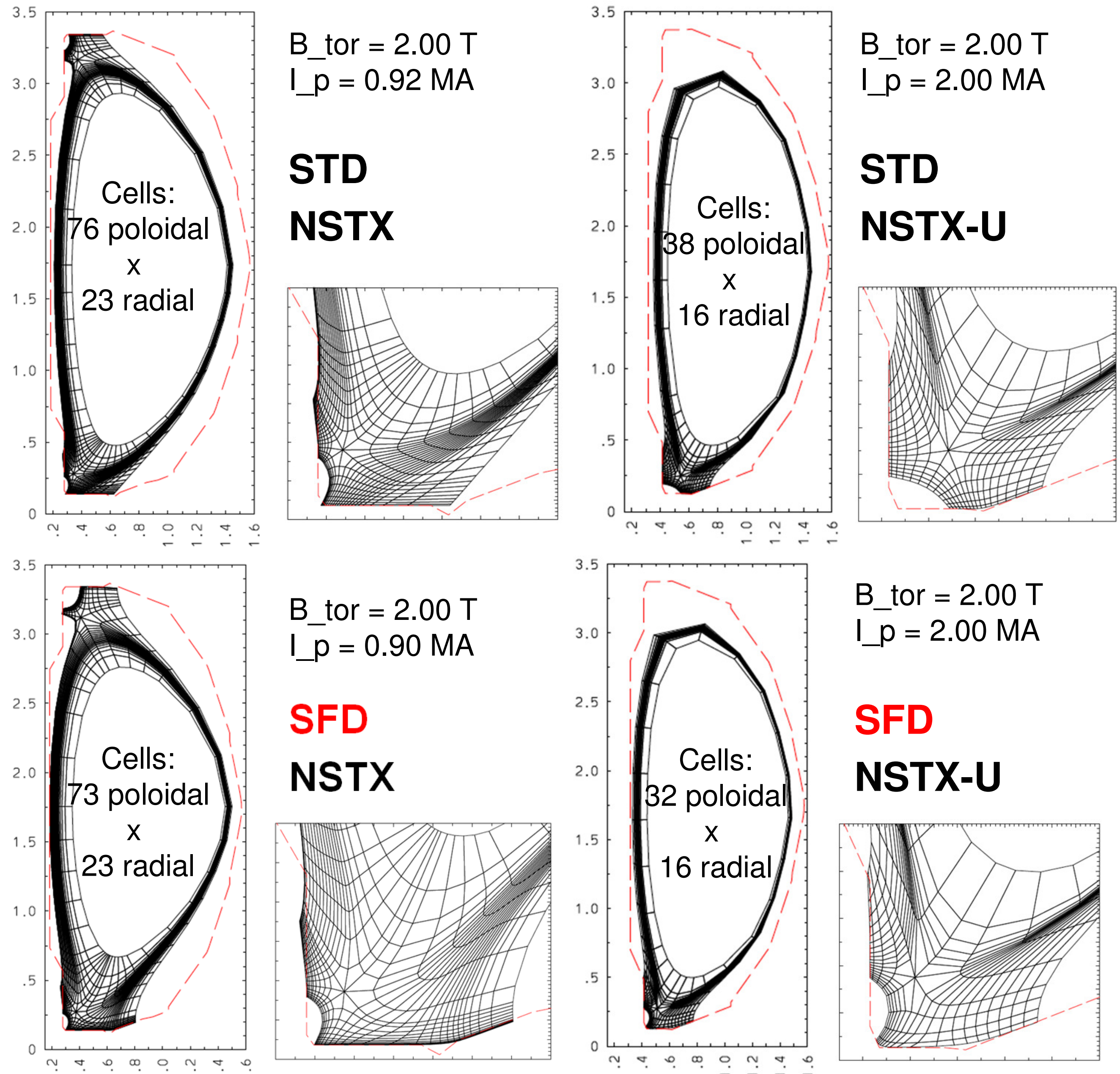
UEDGE simulation setup

UEDGE is used to compare snowflake divertor (SFD) and standard divertor (STD) physics in NSTX and NSTX-U

UEDGE Setting	NSTX	NSTX-U
Carbon impurity	Fixed fraction, 7% (essentially non-coronal)	Fixed fraction, 4% (essentially non-coronal)
Anomalous perpendicular transport	Constrained by outer midplane data • Thomson: T_e, n_e • Charge-exchange recombination spectroscopy: n_{C6+}, T_{C6+}	Same
Target recycling	97% • Some pumping to model Li coatings	99% • Less pumping to model uncoated C tiles
Scrape-off-layer power	3 MW • Discharge 141240 has 4 MW neutral beam power • Assume 25% fast ion + radiation losses.	9 MW • Corresponds to 12 MW neutral beam power minus 25% losses
n_{D+} BC at core-edge interface	Fixed D^+ flux • 60 atom amps (3.7e20 s^{-1}) for STD simulation corresp. to particle injection from 4 MW neutral beam. • 90 atom amps (5.6e20 s^{-1} for SNF simulation	Fixed D^+ flux • 180 atom amps (5.6e20 s^{-1} for SNF simulation
Drift effects	No	No

To capture 1+ cm SOL, double-null grids are used for NSTX modeling; for NSTX-U, single-null grids capture ~1 cm SOL

- NSTX grids are based on LRDFIT equilibria at 439 ms (**STD**), and 905 ms (**SNF**).
  - Both grids capture psi=0.9 to 1.1.
  - Outer midplane SOL thicknesses are 2.03 cm and 2.44 cm for the standard and snowflake grids, resp.
- NSTX-U grids are based on (predicted) LRDFIT equilibria
  - Both grids capture psi=0.9 to 1.055.
  - Outer midplane SOL thicknesses are 0.84 and 0.92 cm for the standard and snowflake grids, resp.



SFD heat flux reduction is enabled by increased wetted area and greater connection lengths

- SFD configurations benefit from an greater plasma wetted area and longer midplane-to-target connection lengths.
  - Increased wetted area allows a geometric reduction of heat flux.
  - Longer connection lengths ($L_{conn.}$) lead to reduced target temperatures [Stangeby, 2000]:

$$T_t \propto q_{\|}^{10/7} / L^{4/7} n_u^2$$ (assuming conduction only)

- The geometric profile broadening (i.e., the increase of plasma wetted area) is

  $f_{geo} = f_{exp}/\sin(\alpha)$

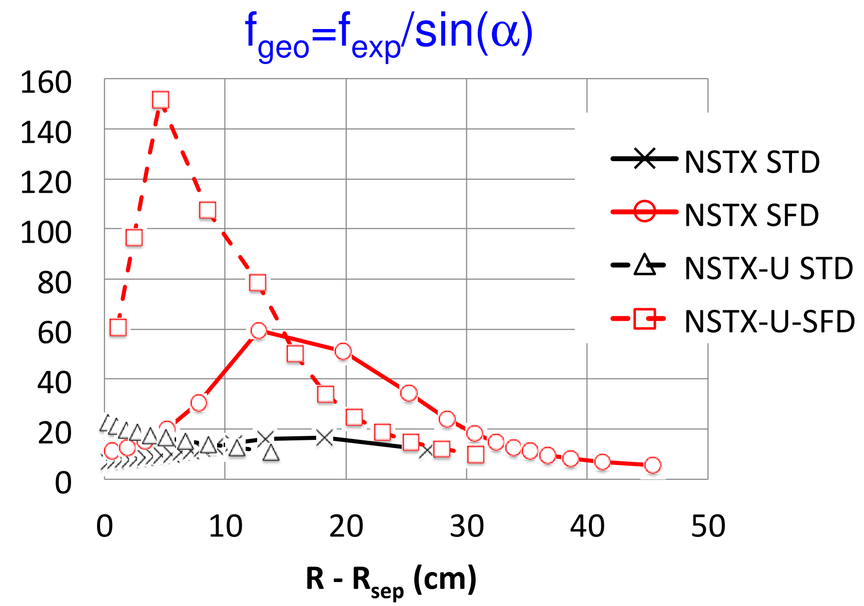
  where

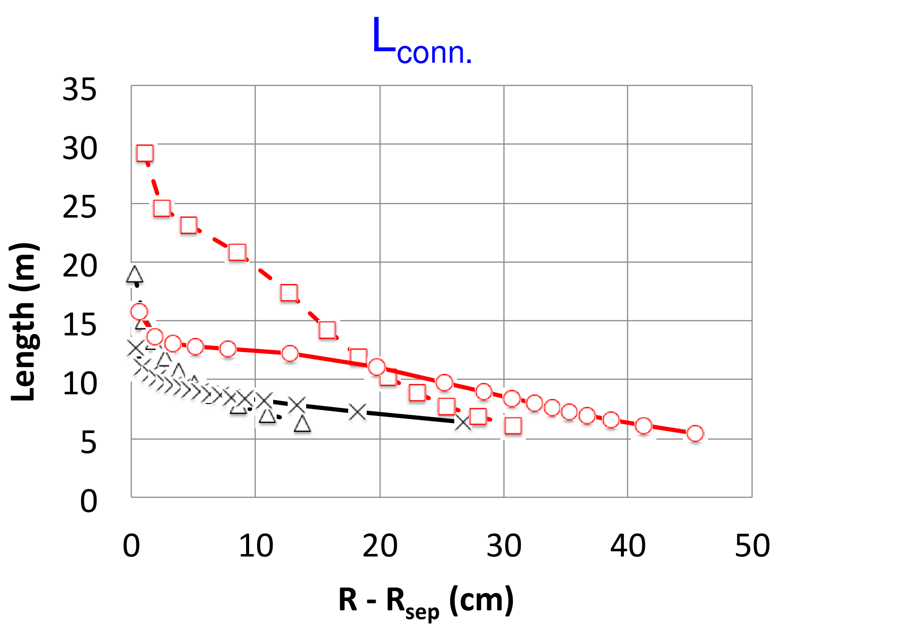
  $f_{exp} = (B_{tot}/B_{pol})_{target}/(B_{tot}/B_{pol})_{midplane}$

  is the flux expansion, and

  α = angle ***in the poloidal plane*** of field lines w.r.t. target.

- The connection length is measured parallel to the magnetic field from the outer midplane.

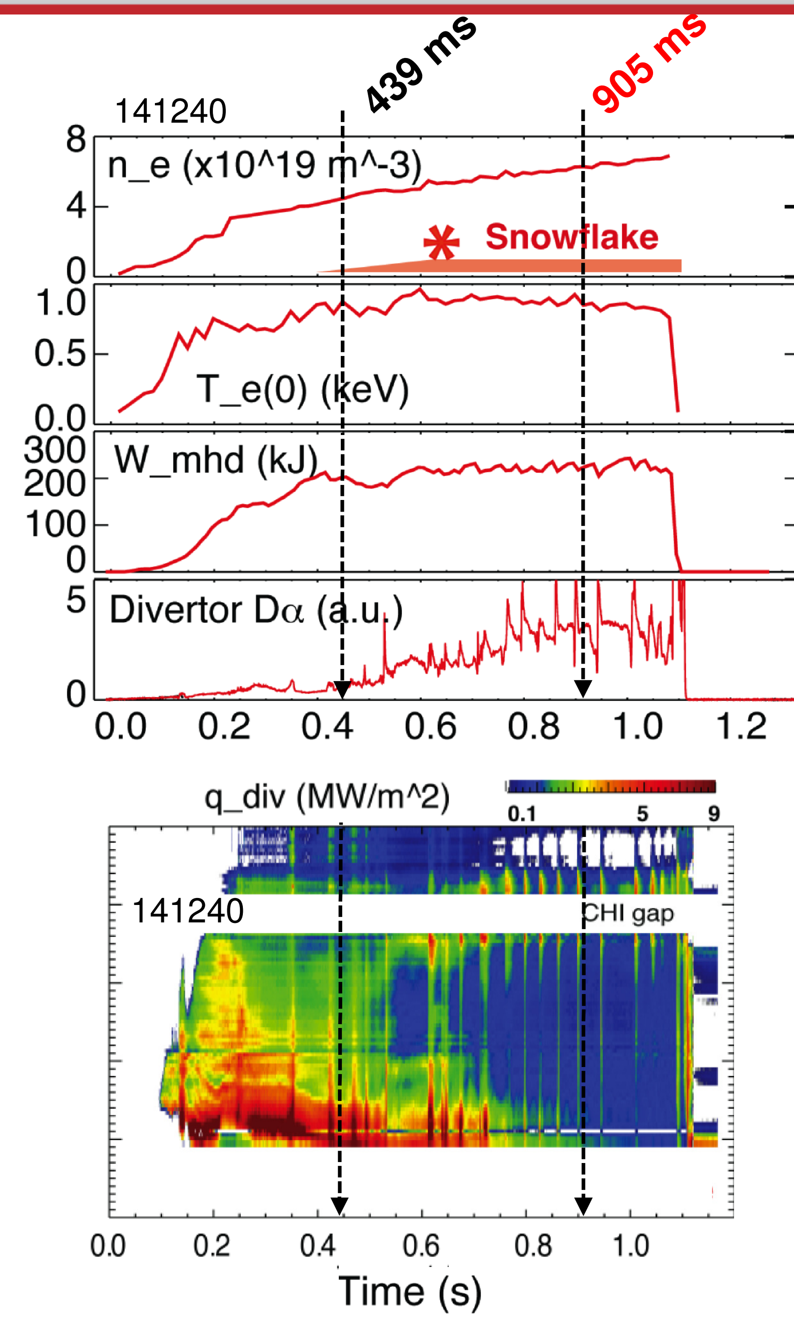




NSTX modeling

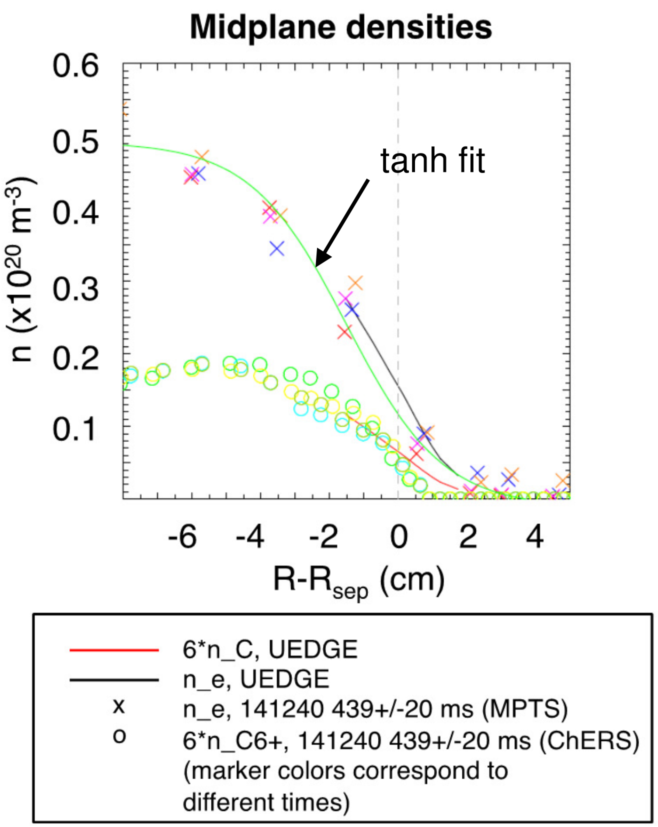
Snowflake divertor (SFD) configuration yields partial detachment and large heat flux reduction

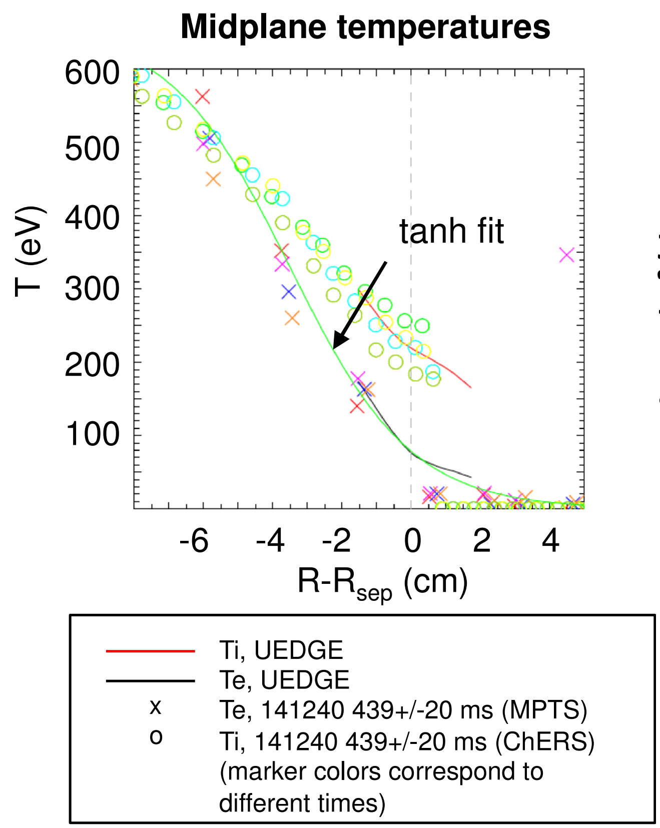
- SFD is established at ~600 ms*.
  - Core plasma retains desirable properties.
  - Outer divertor partially detaches, and ELMs are present.
  - Peak heat flux is reduced from ~8 MW/m^2 to ~1 MW/m^2.
- **Simulations are conducted for 439 ms (STD) and 905 ms (SFD).**

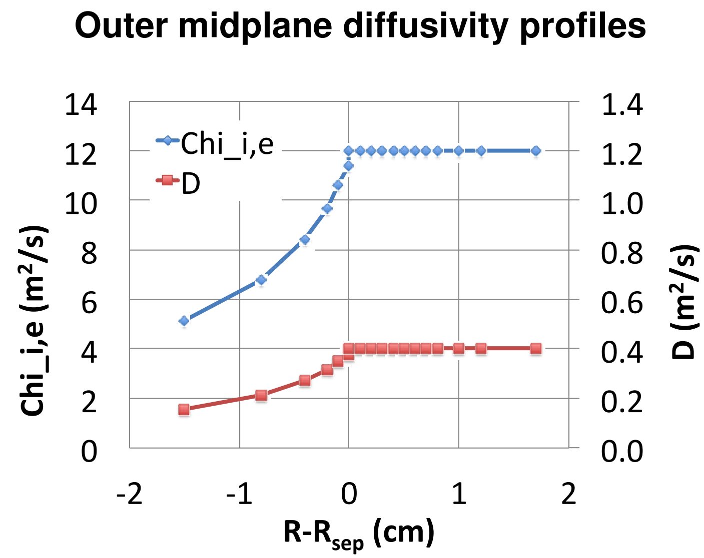


* Soukhanovskii et al., Phys. Plasmas, 2012

STD simulation matches midplane MPTS and ChERS data…





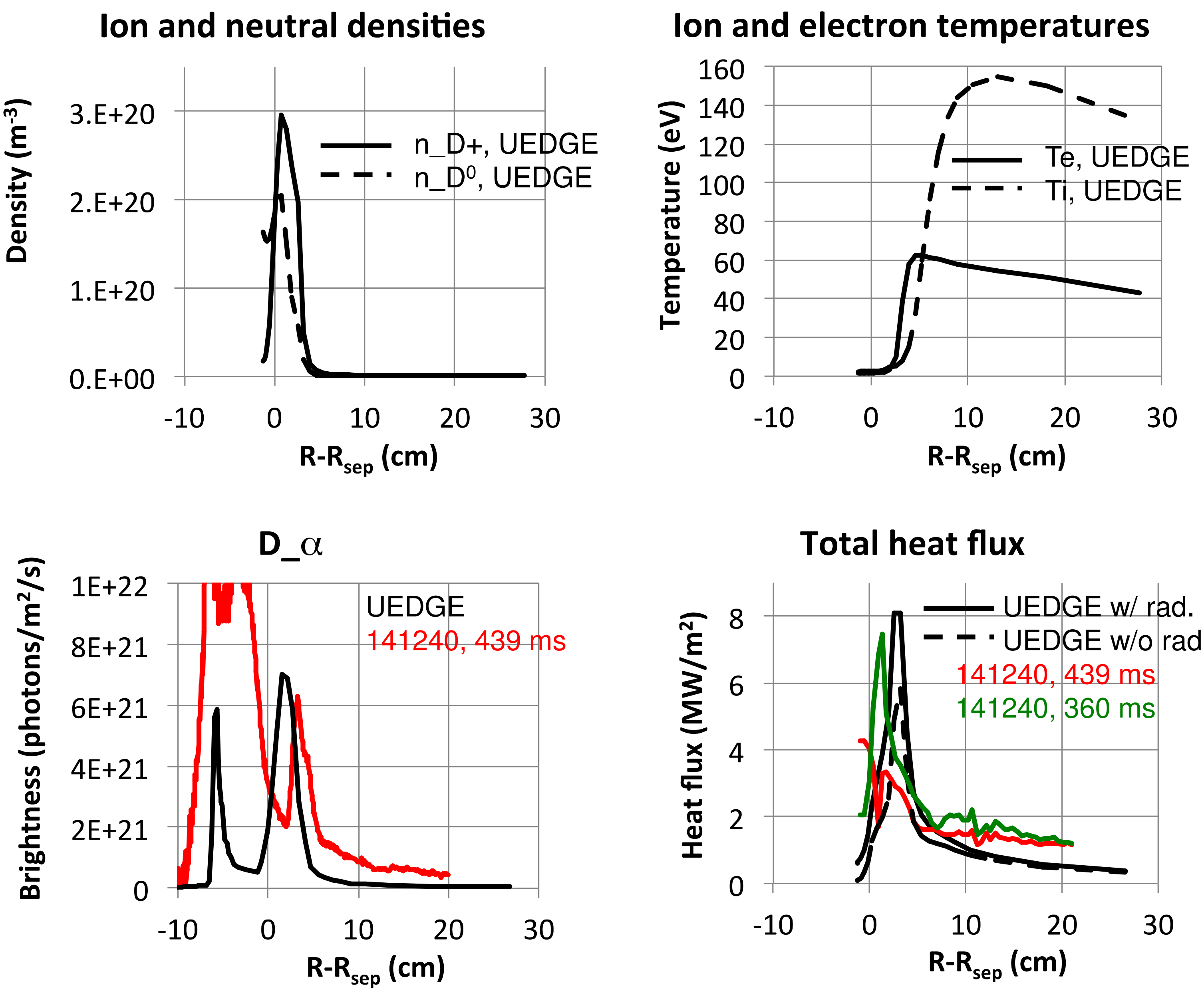


- Diffusivities in the core region vary as radius cubed and are uniform in the SOL and PF regions.
- Diffusivites are uniform in the SOL and PF regions.

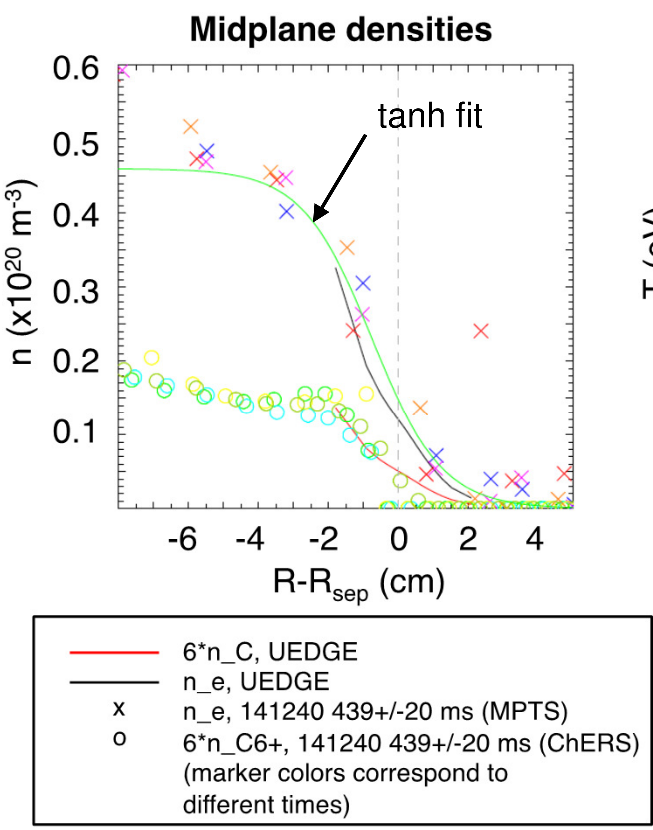
- Hyperbolic tangent functions are generated following Porter [G.D. Porter et al., PoP, 1998].
- The experimental data is shifted outboard 1.5 cm with respect to the LRDFIT equilibrium.

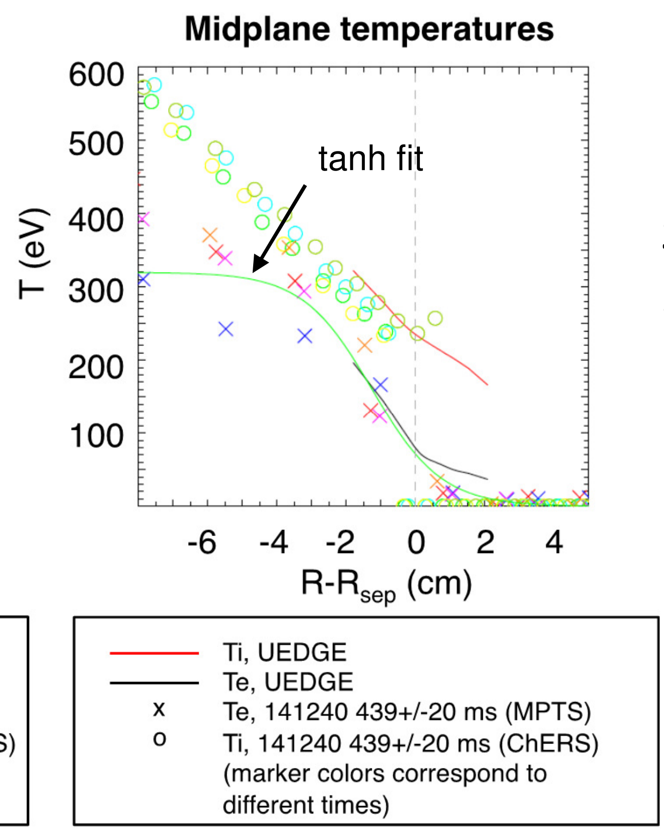
…and the lower/outer divertor heat flux and D_α data

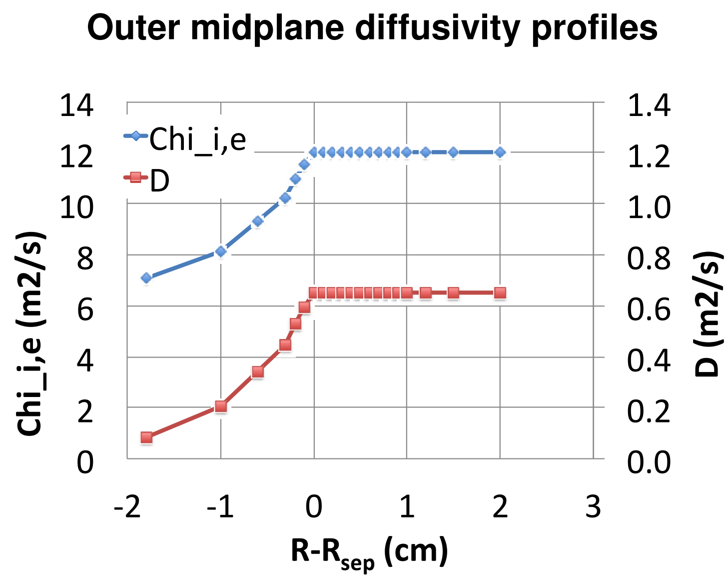
- D_α measurements are from filtered cameras.
- Heat flux is based on dual-band IR thermography.



SFD simulation also matches midplane data…





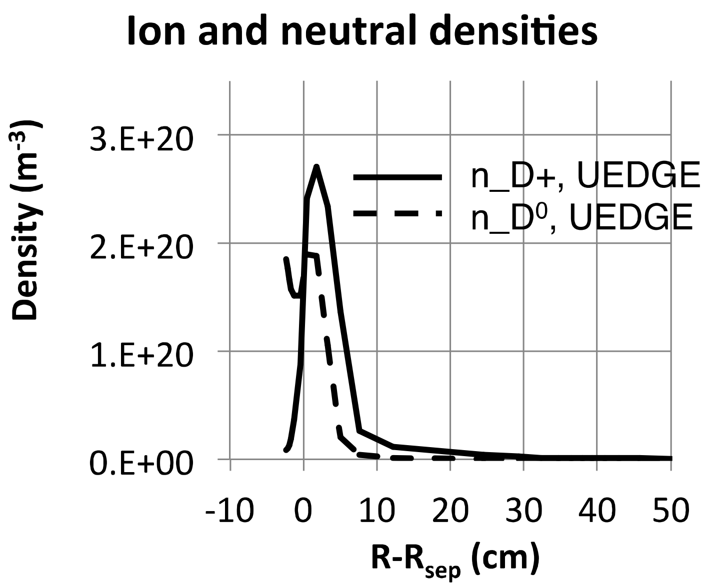


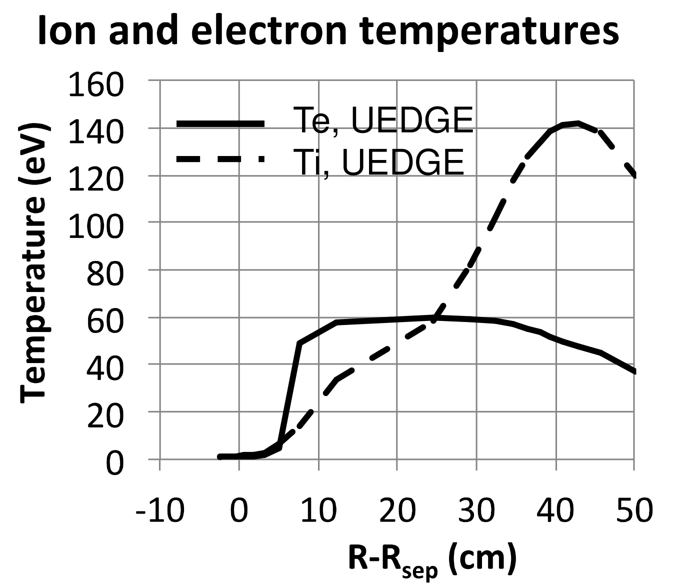
- Diffusivities in the core region vary as radius cubed and are uniform in the SOL and PF regions

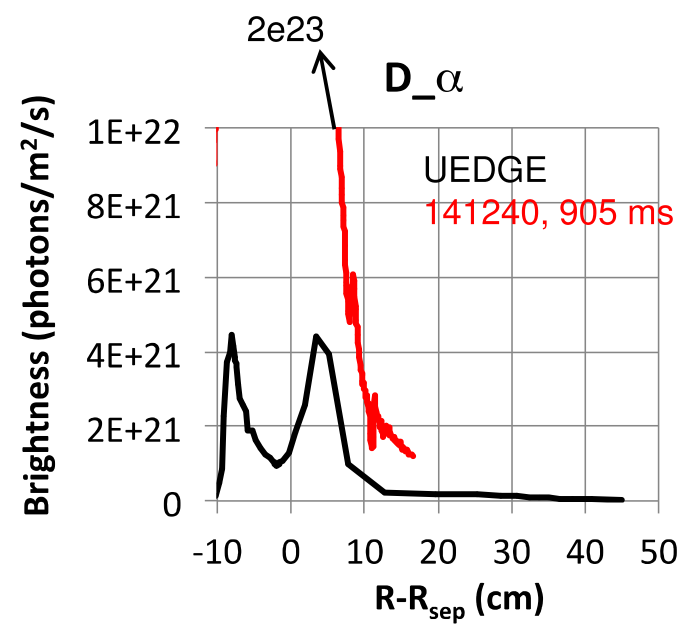
- Hyperbolic tangent functions are generated following Porter [G.D. Porter et al., PoP, 1998].
- The experimental data is shifted outboard 1.75 cm with respect to the LRDFIT equilibrium.

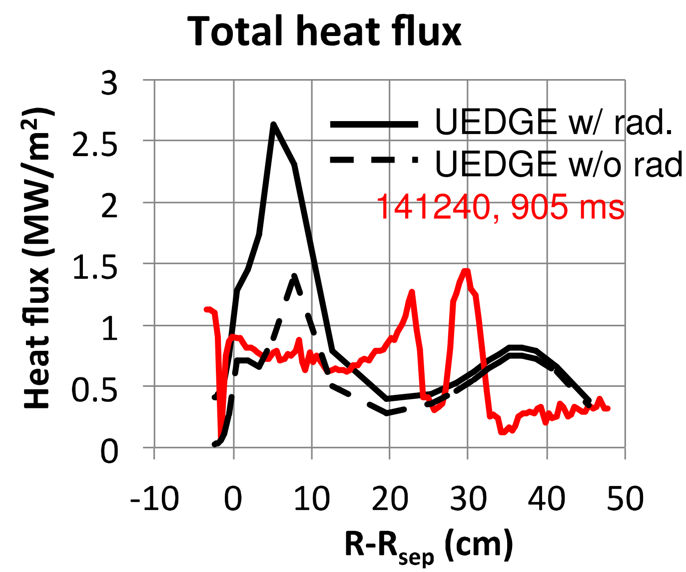
...but deviates from lower/outer divertor data, especially D_α light

- Simulated heat flux is reduced as in the experiment, but detailed profile is not captured.
- D_α discrepancy is significant.
  - Cause of discrepancy is unclear.
- Partially detached divertor solution is found.
  - Te and Ti are ~1.5 eV from 0 to 7 cm from the SP.









STD heat flux width (λ_q) found by UEDGE agrees with experimental values

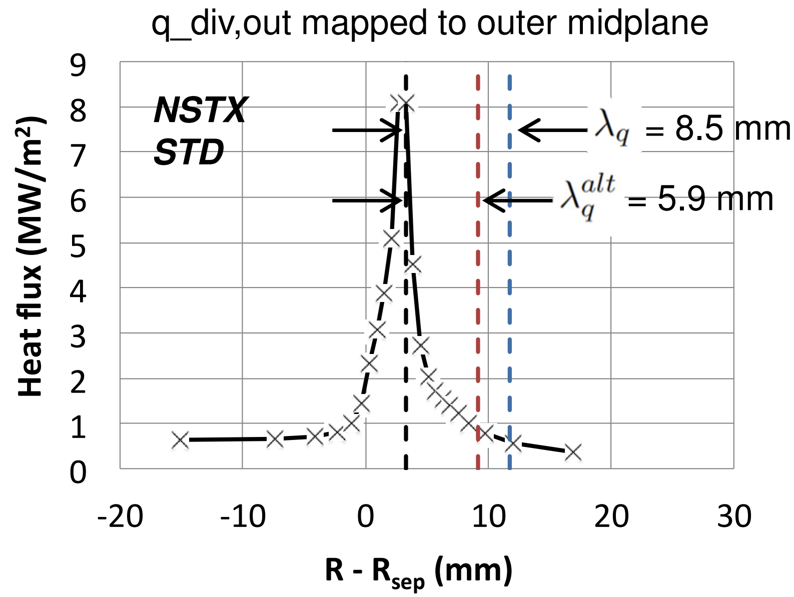
- Gray et al. [T.K. Gray et al., JNM, 2011] found λ_q ~= 10 +/- 3 mm; UEDGE STD value is 8.5 mm.
- Following Gray et al., the midplane heat flux width is found as

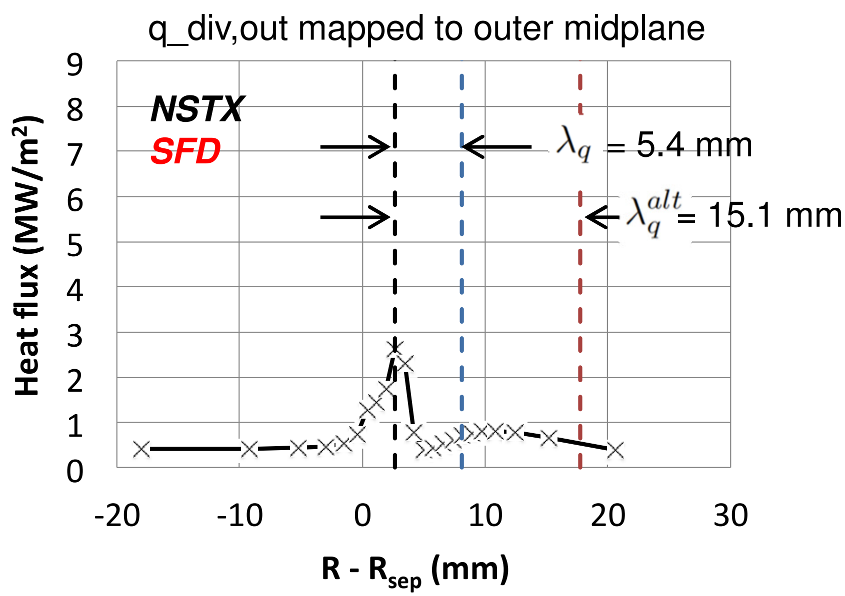
$$\lambda_q = \frac{\int_{div} [2\pi r q_{div}^{out}] dr_{div}}{2\pi R_{div,peak}^{out} q_{div,peak}^{out} f_{exp}(r = 5\ mm)}$$

- An alternate definition is

$$\lambda_q^{alt} = \frac{\int_{R_{sep}}^{R_{max}} [2\pi r q_{div}^{out} / f_{exp}(r)] dr_{div}}{2\pi R_{div,peak}^{out} q_{div,peak}^{out}}$$

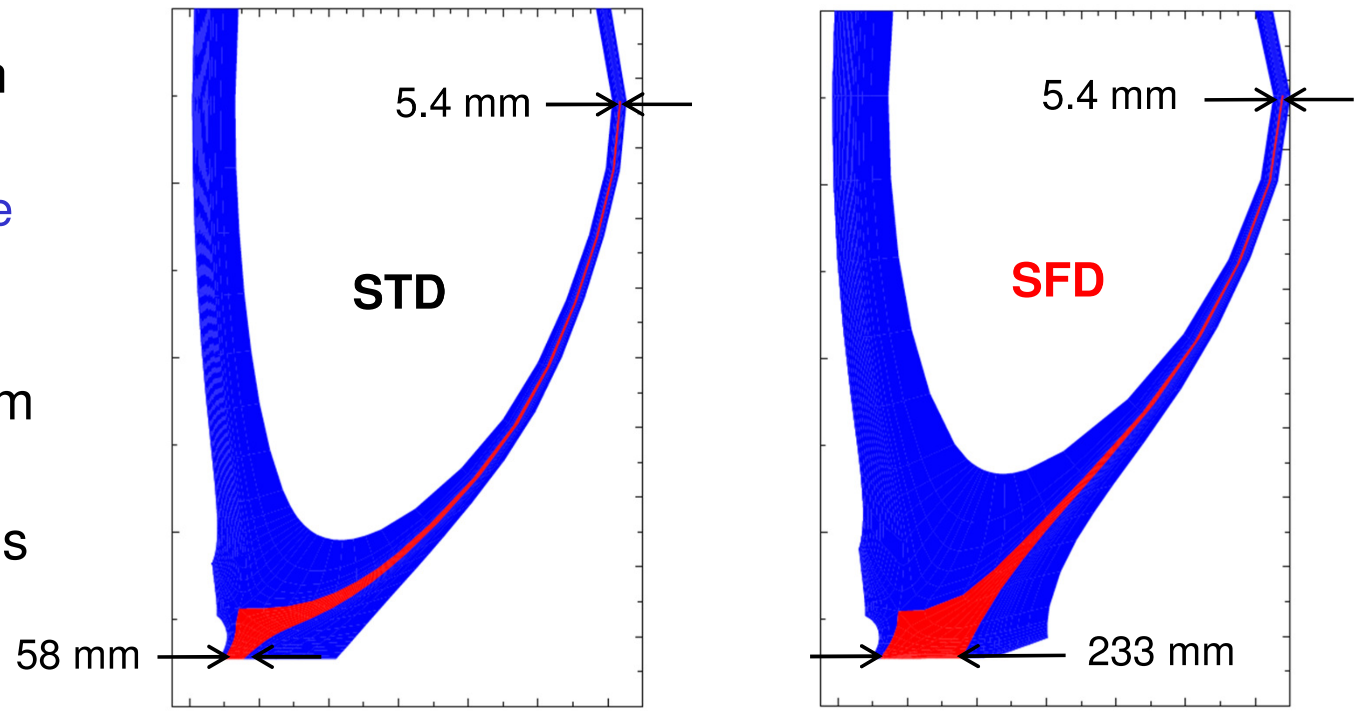
  – This definition is arguably more meaningful when f_{exp} varies significantly across the target.

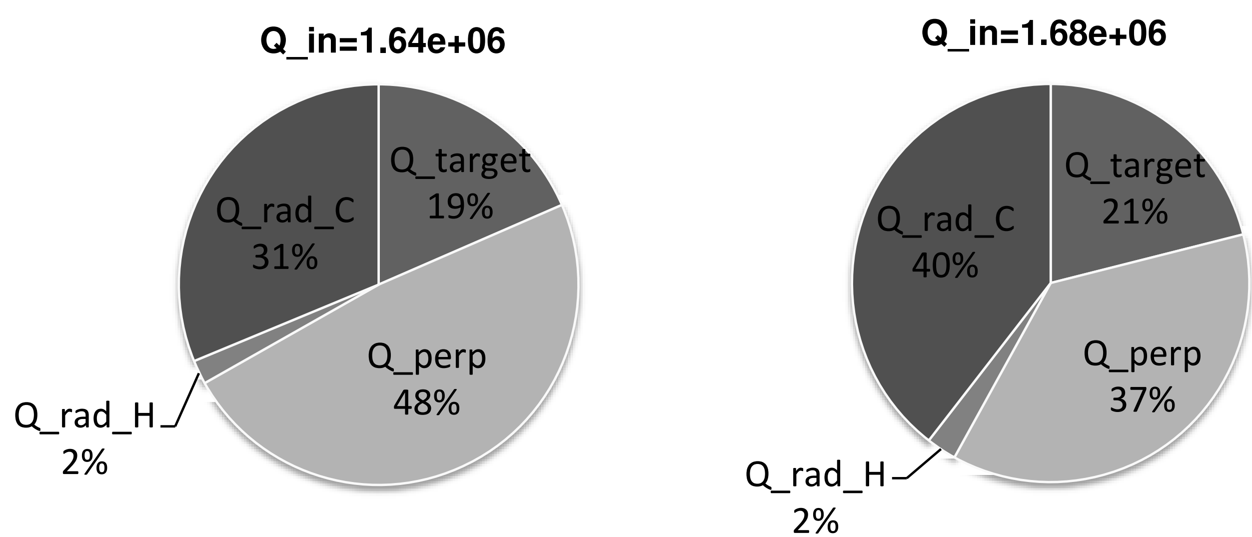




Radiation is stronger in NSTX SFD, but primary heat flux reduction is due to geometric profile broadening

- Consider power balance in the red-shaded flux tubes.
  - At the outer midplane, the tubes enclose ~5 mm.
- Power enters primarily by perpendicular diffusion from the core (Q_in).
- Power leaves the flux tubes through four channels:
  - Convected+conducted power to target (Q_target)
  - Perpendicular diffusion (Q_perp)
  - Carbon radiation (Q_rad_C)
  - Hydrogenic radiation (Q_rad_H)

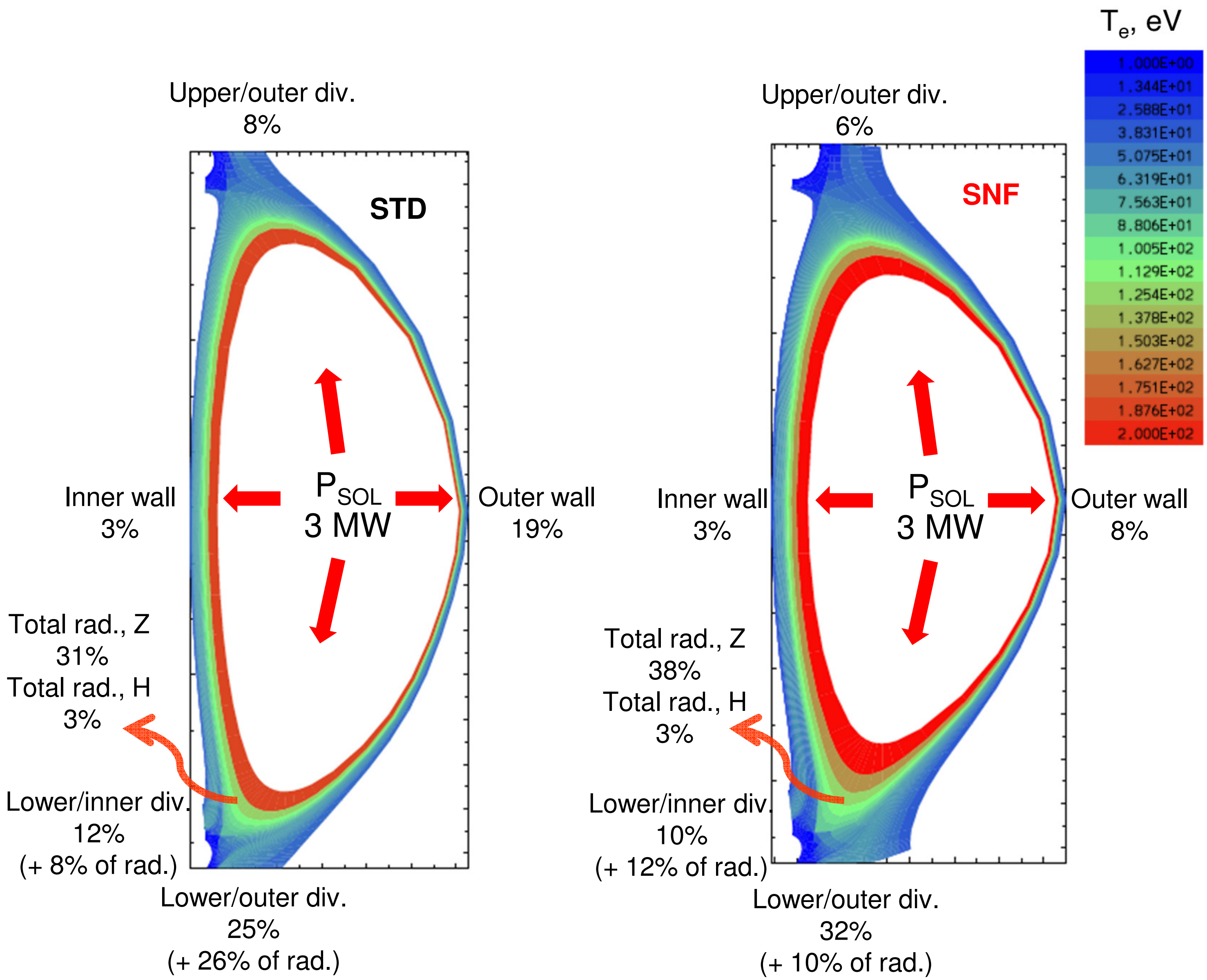




~20% more radiated power is seen in NSTX SFD vs. STD (41% of total vs. 34% of total)

- SNF lower/outer divertor actually sees higher total power flux.
- The greater perpendicular power flow is seen in the increased power to the outer wall in the STD (19% vs. 8%).
- Radiated power in SNF is 41% of total vs. 34% in STD.

(power flows >1% are shown)



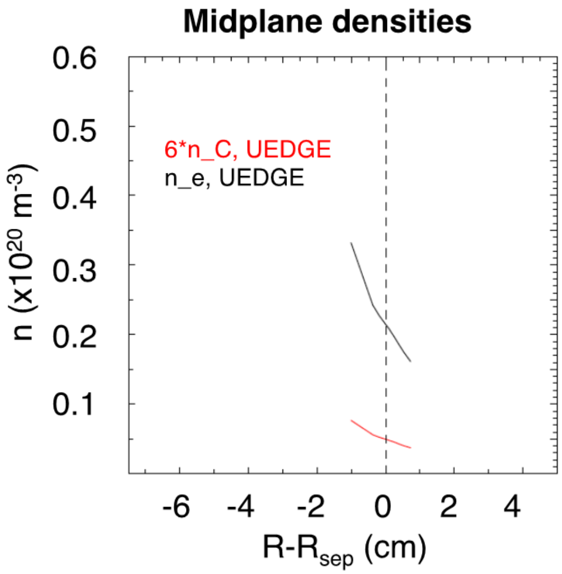
NSTX-U modeling

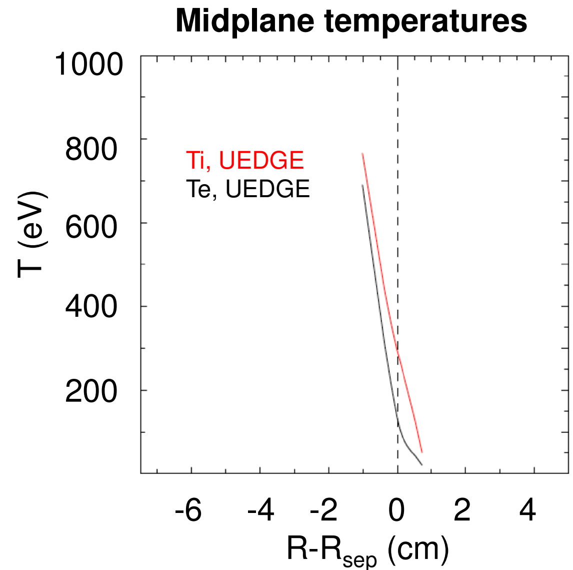
Integrated core-edge modeling could solidify expectations of NSTX-U separatrix conditions (T_i, T_e, n_i, n_e, …)

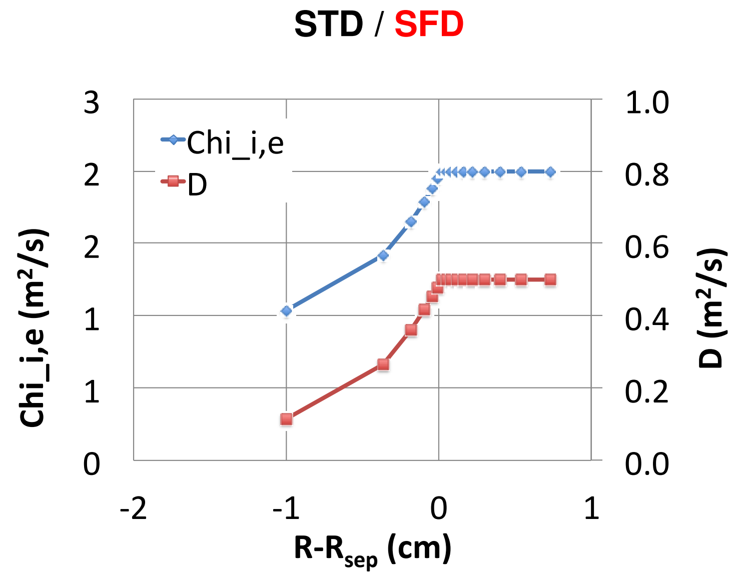
- TRANSP modeling of NSTX-U yields information about the core plasma; solutions are not sensitive separatrix conditions, and rough approximations are made.
- UEDGE modeling depends strongly on conditions at the core-edge interface (ψ=0.90 in this case).
  - E.g., given a core power, knowledge of $T_{i/e}$ helps identify meaningful anomalous transport values.
- In the absence of expected ψ=0.90 conditions, assumptions are made about anomalous transport as shown on the following slides.
- Accurate predictions of separatrix conditions (and ψ=0.90 conditions) might be possible by coupling an edge plasma transport code to a core code.

Lower anomalous transport is assumed for NSTX-U; temperatures are higher at core-edge interface

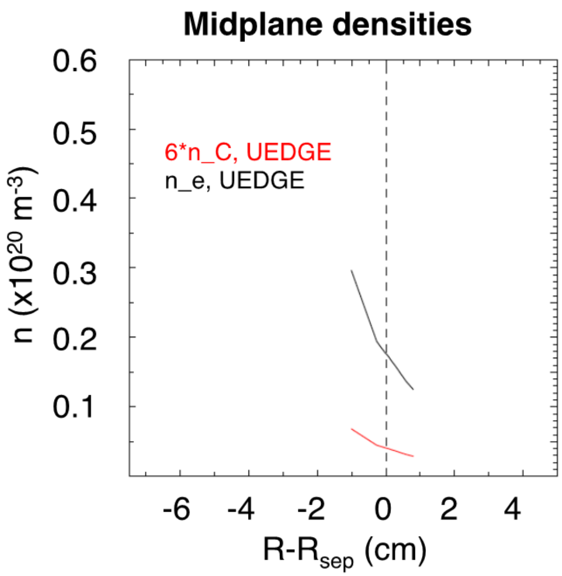
STD

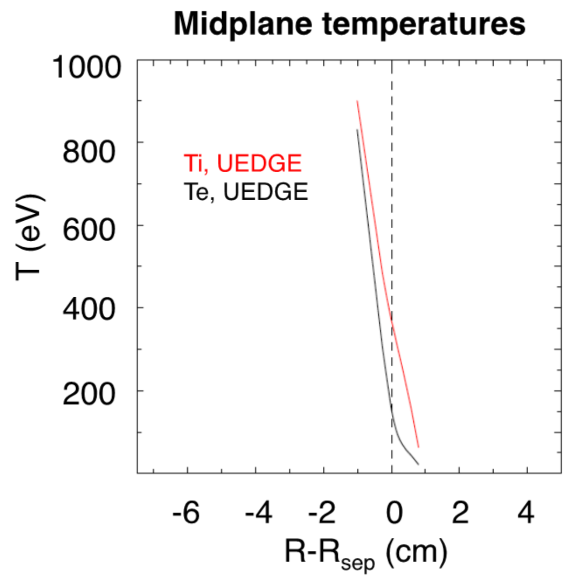






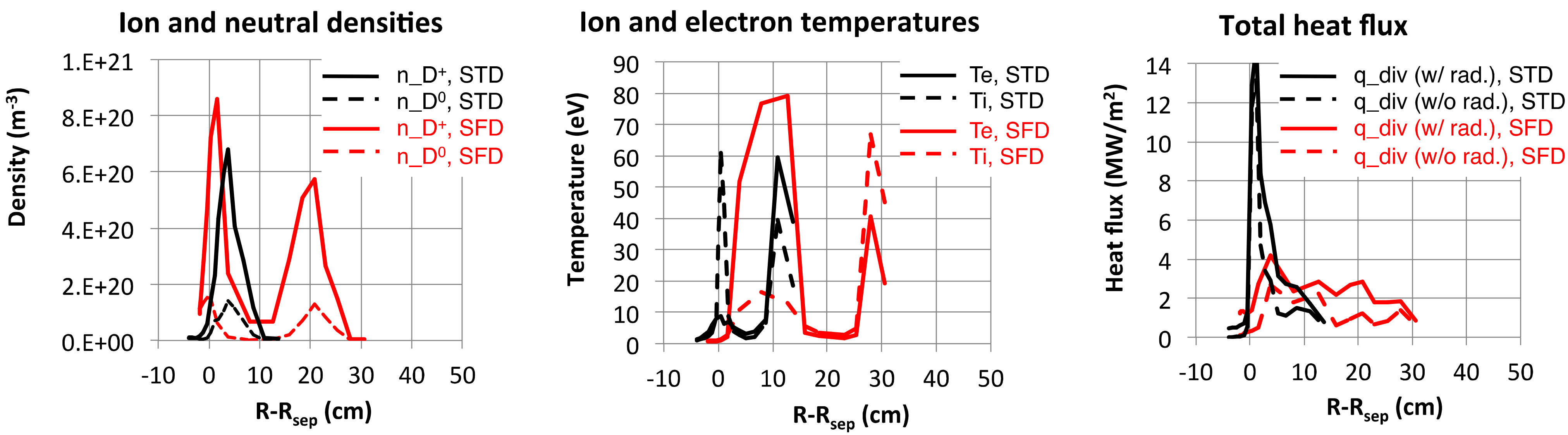
SFD





- Diffusivities in the core region vary as radius cubed and are uniform in the SOL and PF regions.
- Diffusivites are uniform in the SOL and PF regions.

Peak heat flux is reduced by 3x in the SFD vs. STD.



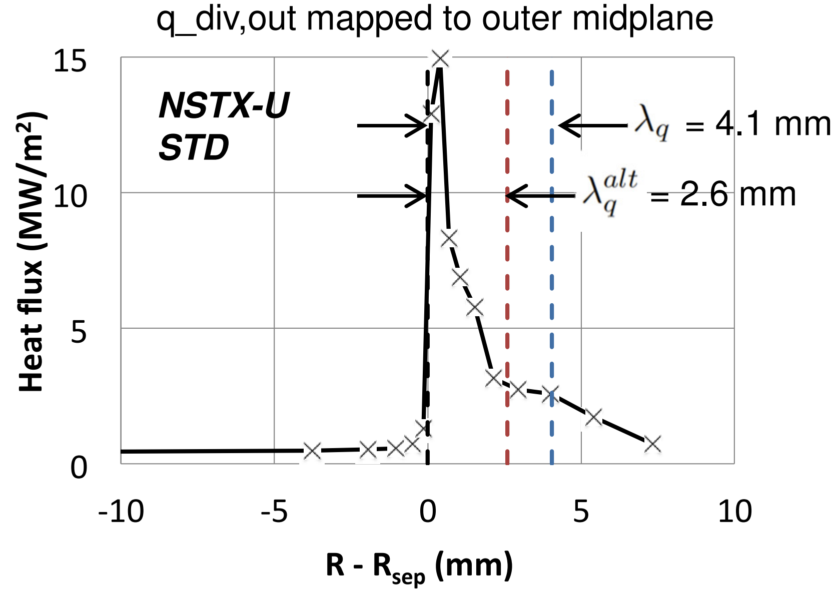
- Minimum in SFD densities, and associated maximum in SFD temperatures, corresponds to maximum flux expansion at ~5-10 cm.
  - Some of the plasma appears to be “shunted” radially past the region of maximum expansion. This might be related to the rapid escape (via diffusion) of hot neutral gas from the hot, expanded region.

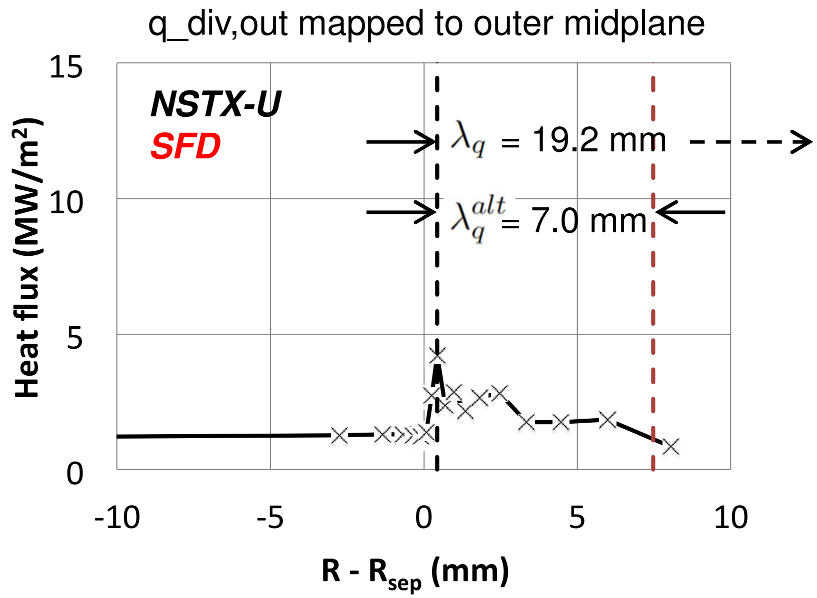
UEDGE NSTX-U heat flux width are reduced by approximately the expected $I_p^{-1.6}$ scaling

- Gray et al. [T.K. Gray et al., JNM, 2011] found a heat flux width scaling,

  $\lambda_q \sim I_p^{-1.6}$

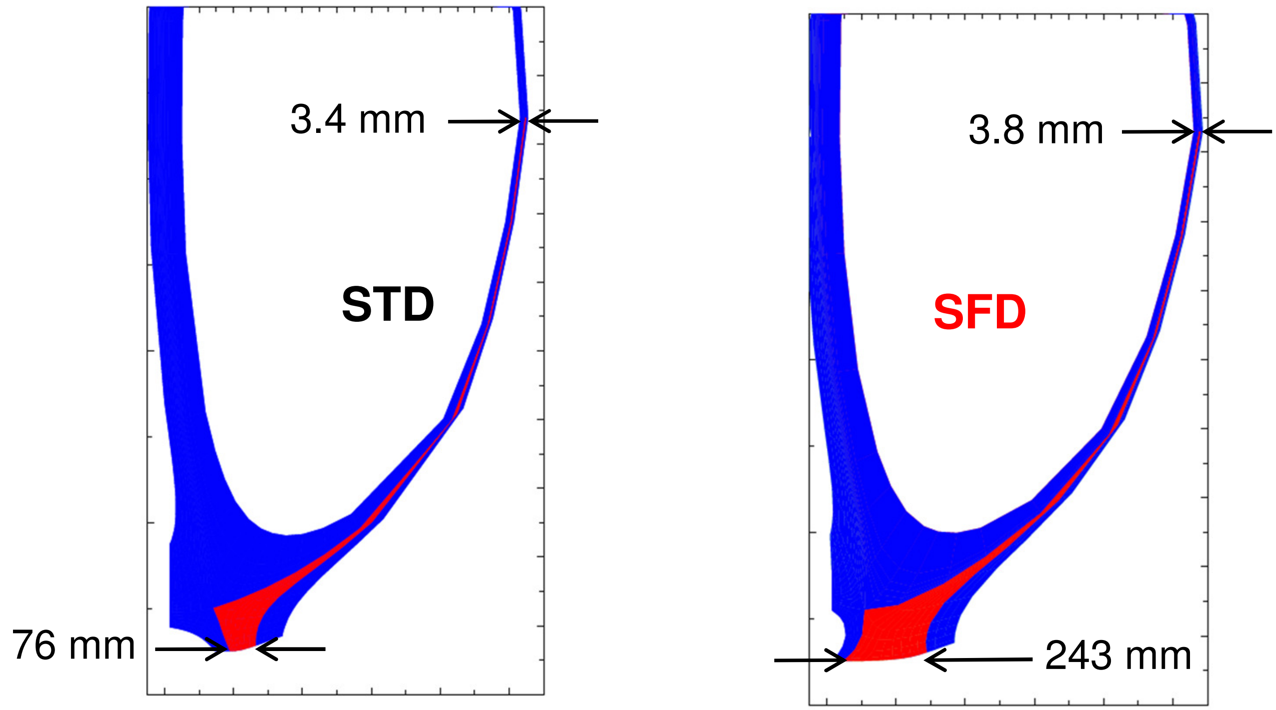
- Using $I_{p,NSTX\text{-}U} = I_{p,NSTX}*2$, expected λ_q is $\lambda_q^{NSTX\text{-}U,STD} = (\lambda_q^{NSTX,STD})*2^{-1.6}$
  - Using the λ_q^{alt} definition (5.9 mm for NSTX STD), this gives $\lambda_q^{NSTX\text{-}U,STD}$=1.9 mm.
  - This is close to the UEDGE value of 2.6 mm.
    - By adjusting anomalous perpendicular diffusivities, the UEDGE λ_q for NSTX-U could be "dialed" to the projected heat flux width.
- The SFD case has a much larger heat flux width as in NSTX
  - This is not a surprise: an exponential heat flux fall-off is not expected for partially-detached (or detached) conditions.

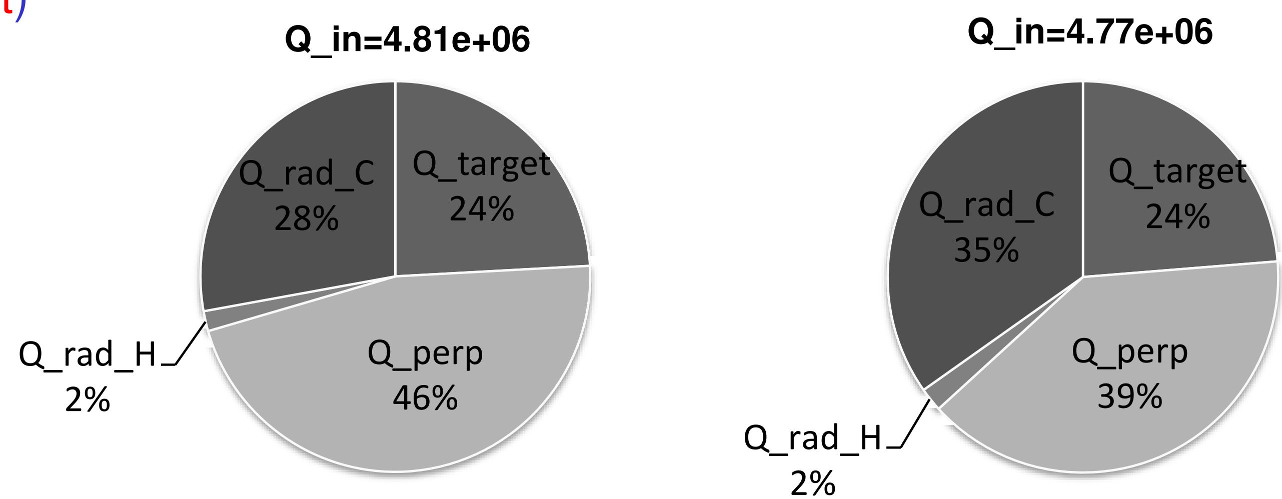




As in NSTX simulations, primary NSTX-U SFD heat flux reduction is due to geometric profile broadening

- Consider power balance in the red-shaded flux tubes.
  - At the outer midplane, the tubes enclose ~3.5 mm.
- Power enters primarily by perpendicular diffusion from the core (Q_in).
- Power leaves the flux tubes through four channels:
  - Convected+conducted power to target (Q_target)
  - Perpendicular diffusion (Q_perp)
  - Carbon radiation (Q_rad_C)
  - Hydrogenic radiation (Q_rad_H)





Conclusions

- NSTX modeling of discharge 141240:
  - Anomalous perpendicular transport is found to be similar in the STD and SFD phases of the discharge.
  - Total power to the outer divertor target is similar in STD and SFD; peak heat flux reduction is enabled by geometric profile broadening.
  - Simulation of snowflake phase does not recreate the strong (highly radiative) detachment seen in the experiment.
- NSTX-U predictive modeling:
  - SFD shows promise for achieving partial detachment and low peak heat fluxes (<5 MW/m^2) even in high-power (9 MW neutral beam power) scenarios.

Future work

- NSTX
  - Conduct multi-charge-state simulations of discharge 141240 and analyze changes in carbon source and transport.
    - Inclusion of non-coronal impurity radiation might lead to more realistic detachment in snowflake case.
- NSTX-U
  - Evaluate SFD performance as a function of perpendicular transport, and recycling.
  - Study feasibility of cryopumping in SFD configuration.
  - Analyze methods of increasing radiation.
    - Impurity seeding, D_2 gas puffing.

Reprint Sign-up

- Email me at emeier(at)pppl.gov with any questions
- Print your name below to be sent a reprint of this poster

Name	Email