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The snowflake divertor: a game-changer for magnetic fusion devices ?

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Workshop on Innovation in Fusion Science and
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August 16-19, 2011
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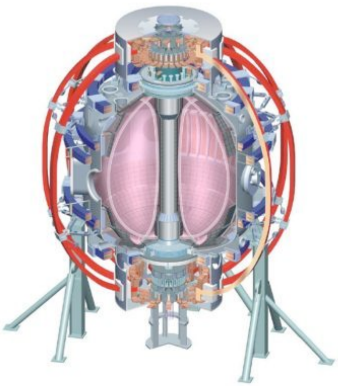

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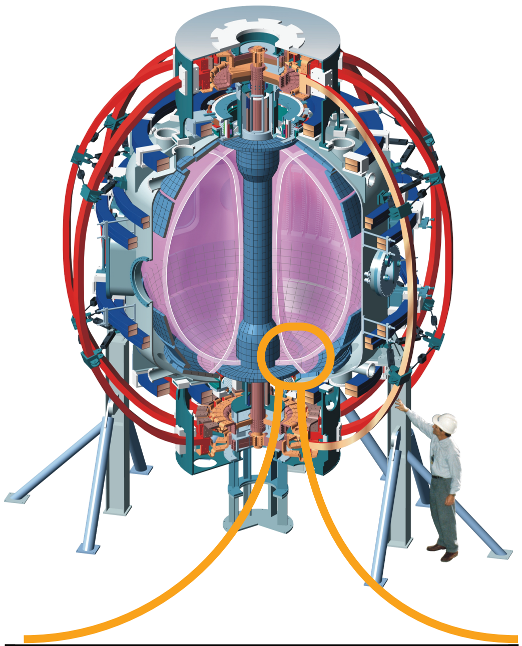
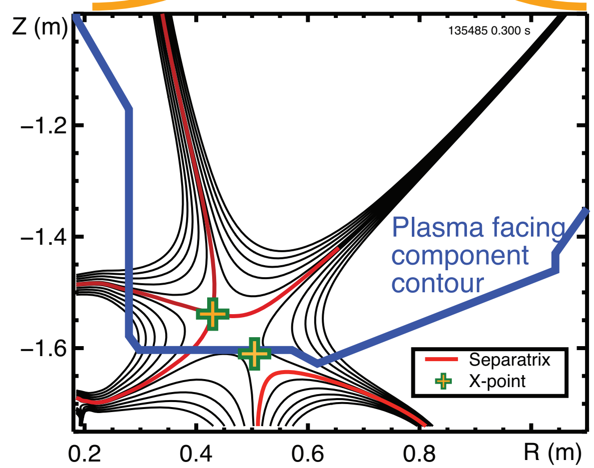
Outline: Experimental results from snowflake divertor experiments in NSTX are very encouraging

- **Tokamak divertor challenge**
- **Snowflake divertor configuration**
- **Snowflake divertor in NSTX**
  - Magnetic properties realized in steady-state
  - Core H-mode confinement unchanged
  - Core impurities reduced
  - Divertor heat flux significantly reduced
  - Consistent w/ 2D edge transport model
- **Conclusions and outlook**

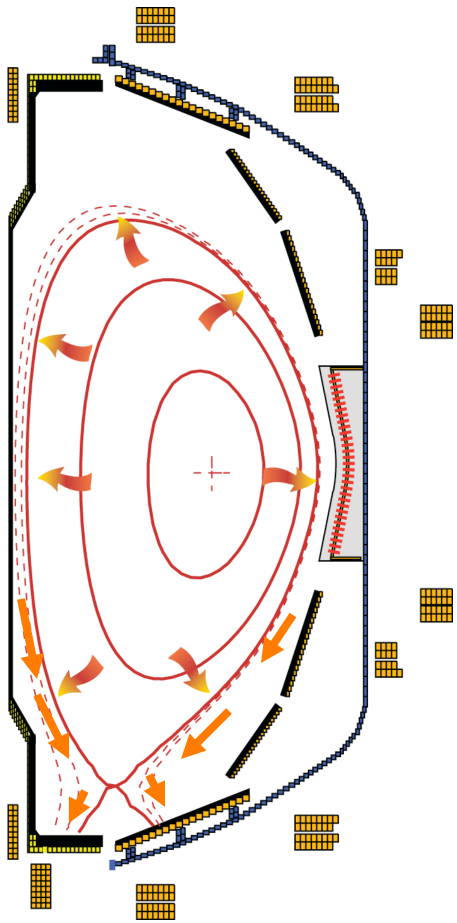




Poloidal divertor concept enabled progress in tokamak physics studies in the last 30 years

- Divertor challenge
  - Steady-state heat flux
    - present limit $q_{peak} \leq 10$ MW/m^2
    - projected to $q_{peak} \leq 80$ MW/m^2 for future devices
  - Density and impurity control
  - Impulsive heat and particle loads
  - Compatibility with good core plasma performance

- Spherical tokamak: additional challenge - compact divertor
- NSTX (Aspect ratio A=1.4-1.5)
  - $I_p \leq 1.4$ MA, $P_{in} \leq 7.4$ MW (NBI), P / R ~ 10
  - $q_{peak} \leq 15$ MW/m^2, $q_{||} \leq 200$ MW/m^2
  - Graphite PFCs with lithium coatings



National Spherical Torus Experiment

Various techniques developed for reduction of heat fluxes $q_{||}$ (divertor SOL) and q_{peak} (divertor target)

$$q_{peak} \simeq \frac{P_{SOL}(1-f_{rad})f_{geo}\sin\alpha}{2\pi R_{SP} f_{exp} \lambda_{q_{||}}}$$

$$A_{wet} = 2\pi R\, f_{exp}\, \lambda_{q_{||}}$$

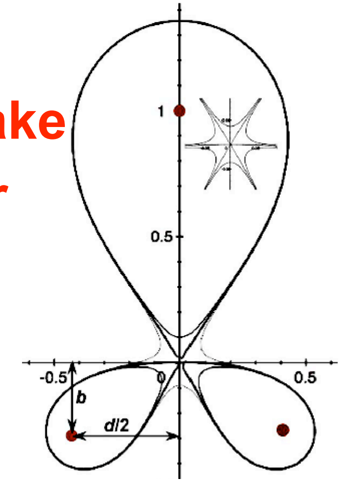
$$f_{exp} = \frac{(B_p/B_{tot})_{MP}}{(B_p/B_{tot})_{OSP}}$$

- Promising divertor peak heat flux mitigation solutions:
  - Divertor geometry
    - poloidal flux expansion
    - divertor plate tilt
    - magnetic balance
  - Radiative divertor
- Recent ideas to improve standard divertor geometry
  - X-divertor (M. Kotschenreuther *et. al*, IC/P6-43, IAEA FEC 2004)
  - Snowflake divertor (D. D. Ryutov, PoP 14, 064502 2007)
  - Super-X divertor (M. Kotschenreuther *et. al*, IC/P4-7, IAEA FEC 2008)

Snowflake divertor geometry attractive for heat flux mitigation

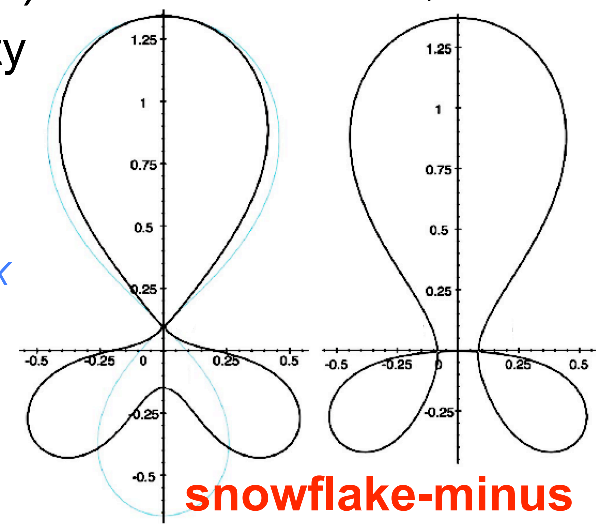
- Snowflake divertor
  - Second-order null
    - $B_p \sim 0$ and *grad* $B_p \sim 0$ (Cf. first-order null: $B_p \sim 0$)
  - Obtained with existing divertor coils (min. 2)
  - Exact snowflake topologically unstable

Exact snowflake divertor



- Predicted geometry properties (cf. standard divertor)
  - Larger region with low B_p around X-point: ped. stability
  - Larger plasma wetted-area A_{wet} : reduce q_{div}
  - Larger X-point connection length L_x : reduce $q_{||}$
  - Larger effective divertor volume V_{div} : incr. P_{rad} , P_{CX}

- Experiments
  - TCV (F. Piras *et. al*, PRL 105, 155003 (2010))
  - NSTX



snowflake-minus

snowflake-plus

D. D. Ryutov, PoP 14, 064502 2007

Outline: Experimental studies of snowflake divertor in NSTX

- Tokamak divertor challenge
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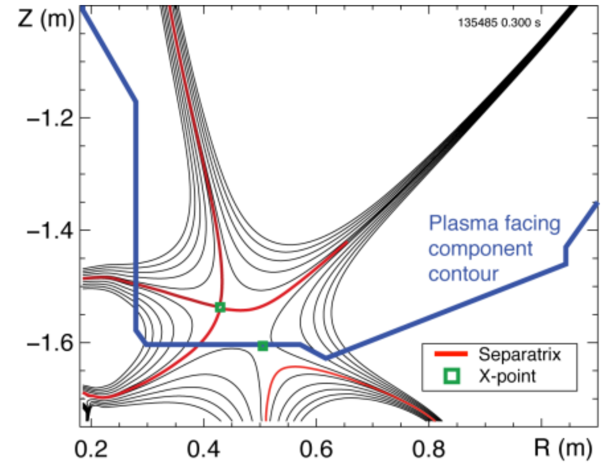
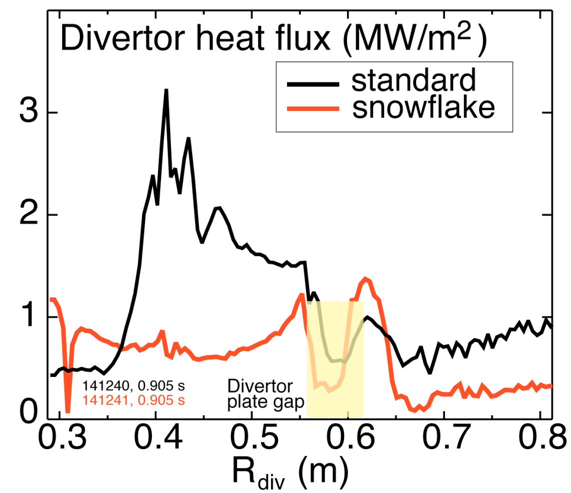


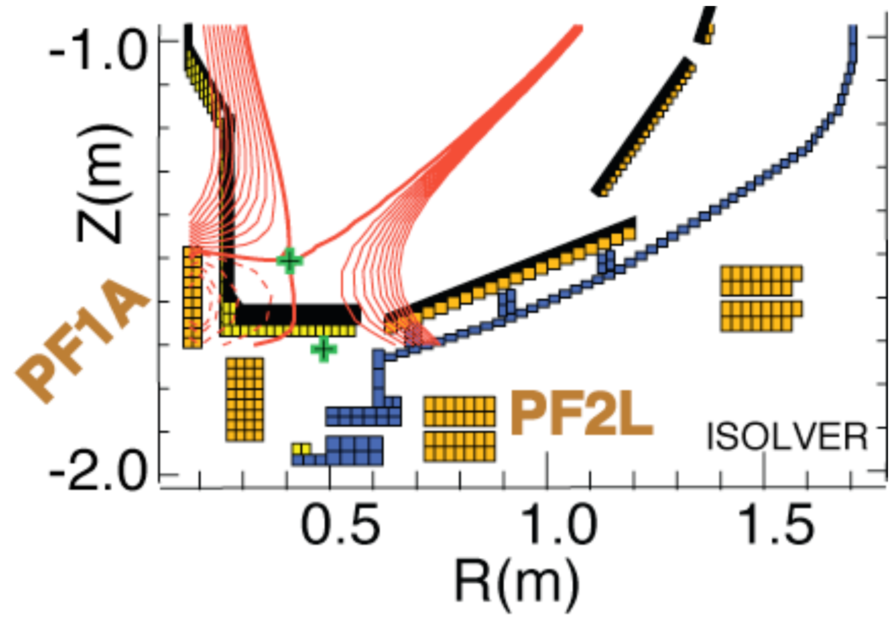


Possible snowflake divertor configurations were modeled with ISOLVER code

- ISOLVER - predictive free-boundary axisymmetric Grad-Shafranov equilibrium solver
  - Input: normalized profiles (P, I_p), boundary shape
  - Match a specified I_p and β
  - Output: magnetic coil currents

✓ Standard divertor discharge below:

B_t=0.4 T, I_p=0.8 MA, δ_{bot}~0.6, κ~2.1



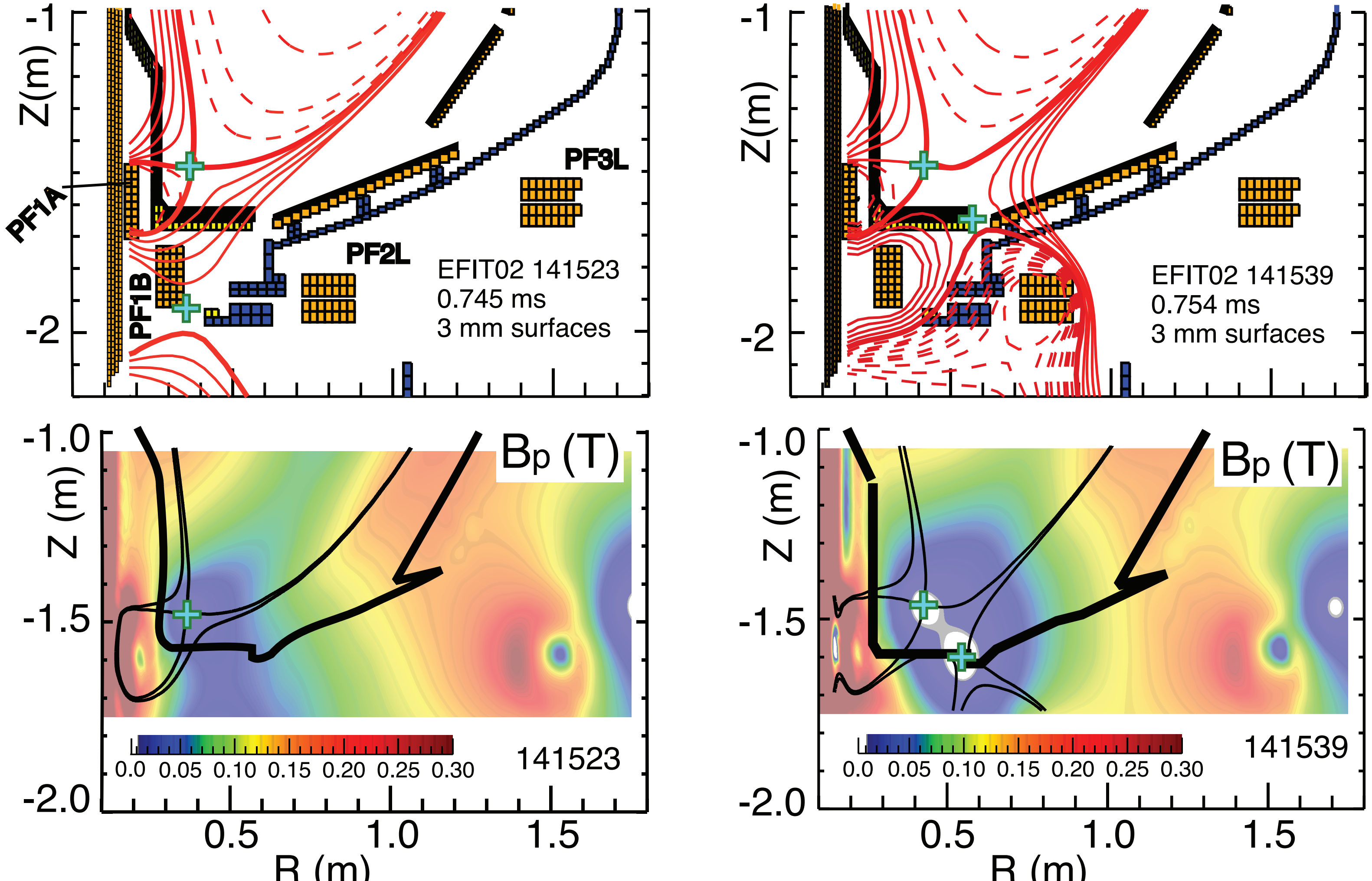
Quantity	Standard divertor	Simulated snowflake
X-point to target parallel length L_x (m)	**5-10**	**10**
Poloidal magnetic flux expansion f_{exp} at outer SP	**10-24**	**30-60**
Magnetic field angle at outer SP (deg.)	**1.5-5**	**~1-2**
Plasma-wetted area A_{wet} (m^2)	**≤ 0.4**	**0.95**

Snowflake divertor configurations obtained in NSTX with three existing divertor coils

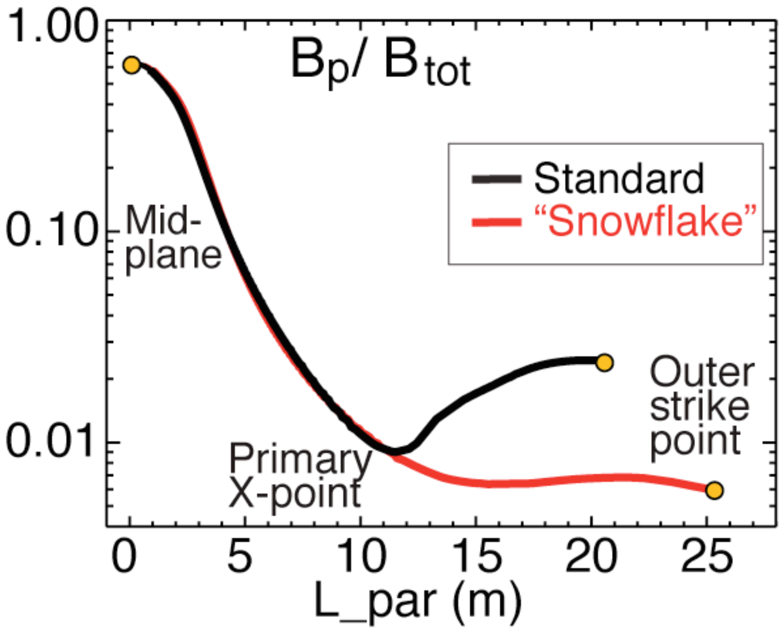
Standard | Snowflake

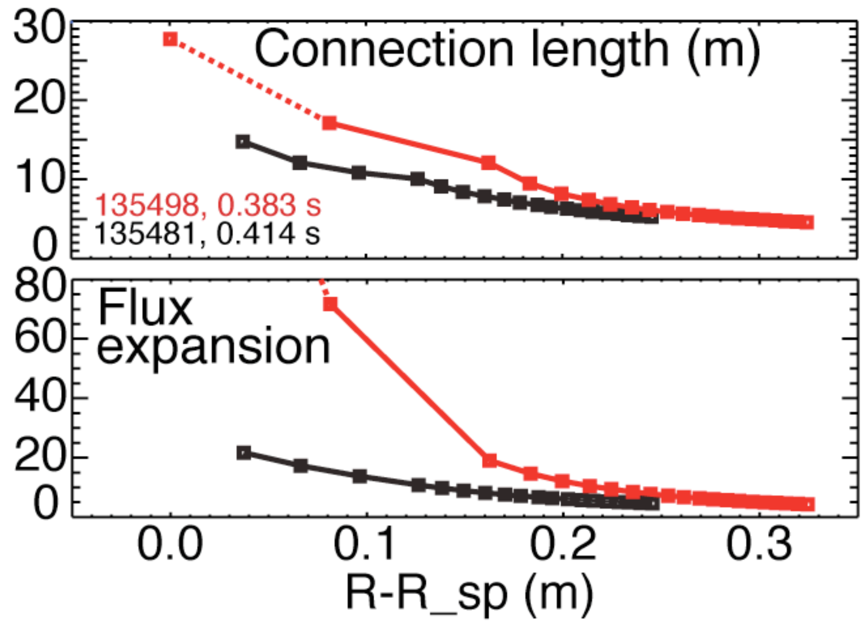
f_{exp}

B_p



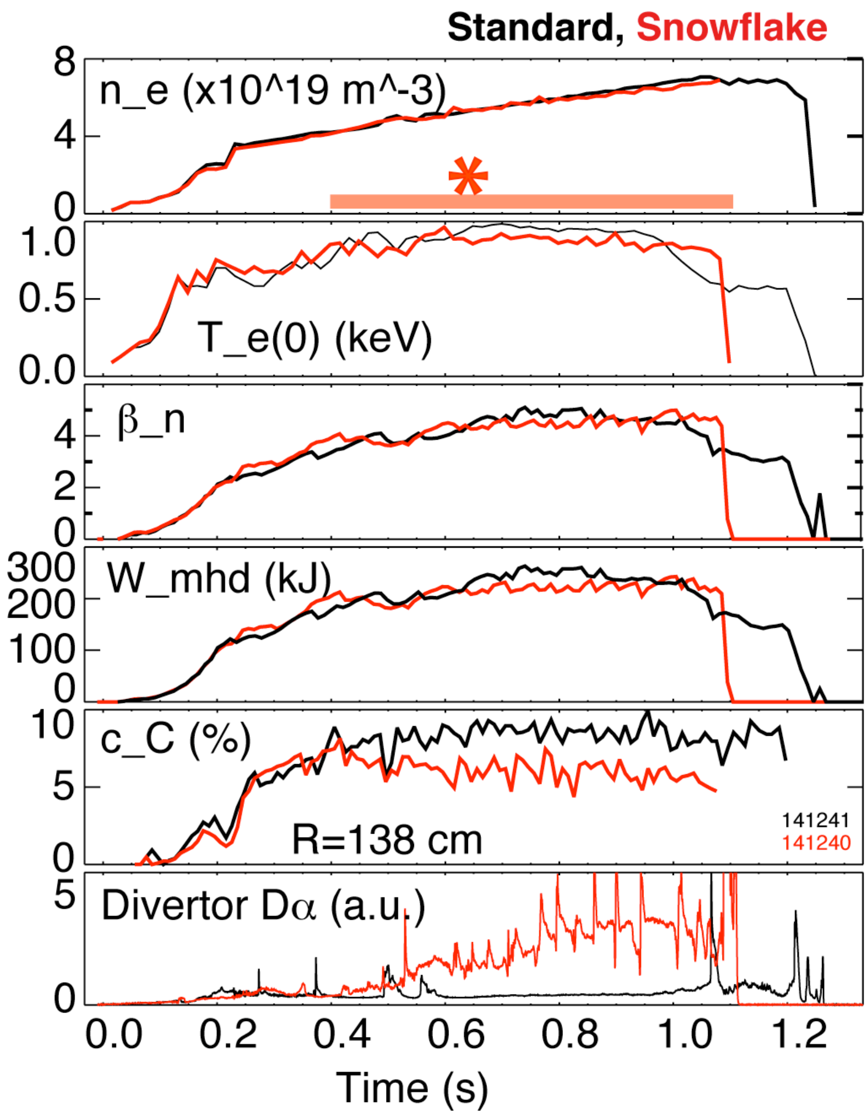
Plasma-wetted area and connection length are increased by 50-90 % in NSTX snowflake divertor





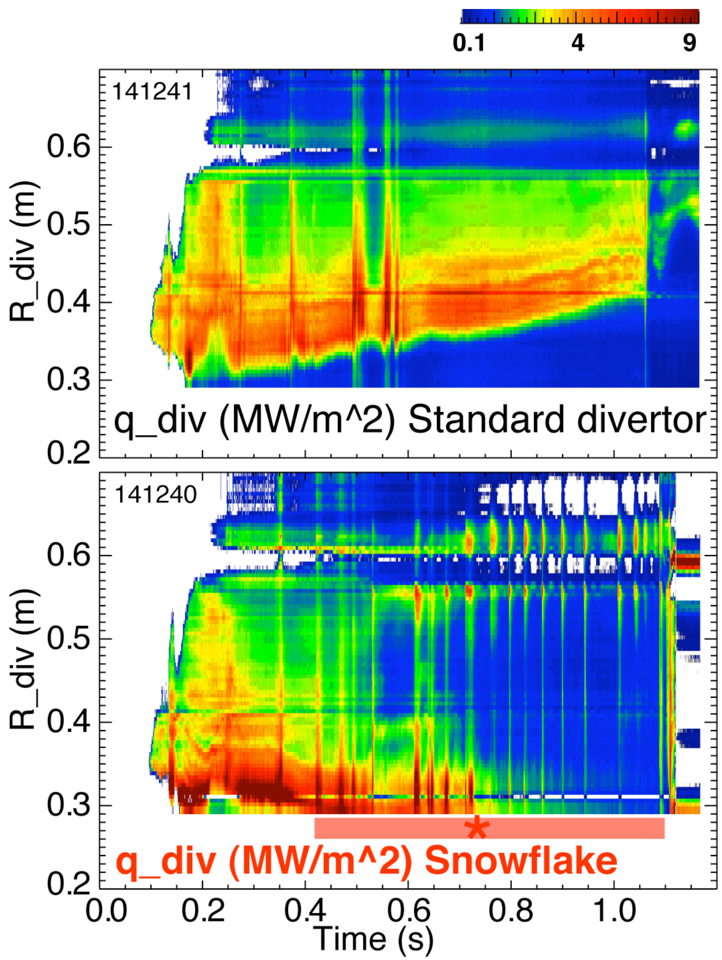
- These properties observed in first 30-50 % of SOL width
- B_{tot} angles in the strike point region: 1-2°, sometimes < 1°
  - Concern for hot-spot formation and sputtering from divertor tile edges

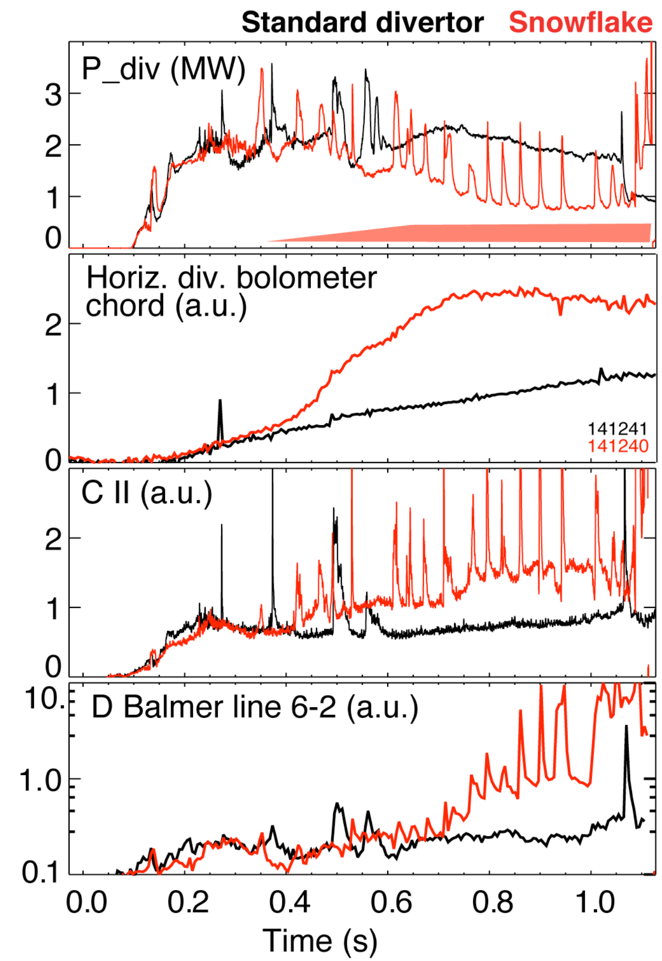
Good H-mode confinement properties and core impurity reduction obtained with snowflake divertor



- 0.8 MA, 4 MW H-mode
- κ=2.1, δ=0.8
- Core T_e ~ 0.8-1 keV, T_i ~ 1 keV
- β_N ~ 4-5
- Plasma stored energy ~ 250 kJ
- H98(y,2) ~ 1 (from TRANSP)
- Core carbon reduction due to
  - Type I ELMs
  - Edge source reduction
    - Divertor sputtering rates reduced due to partial detachment

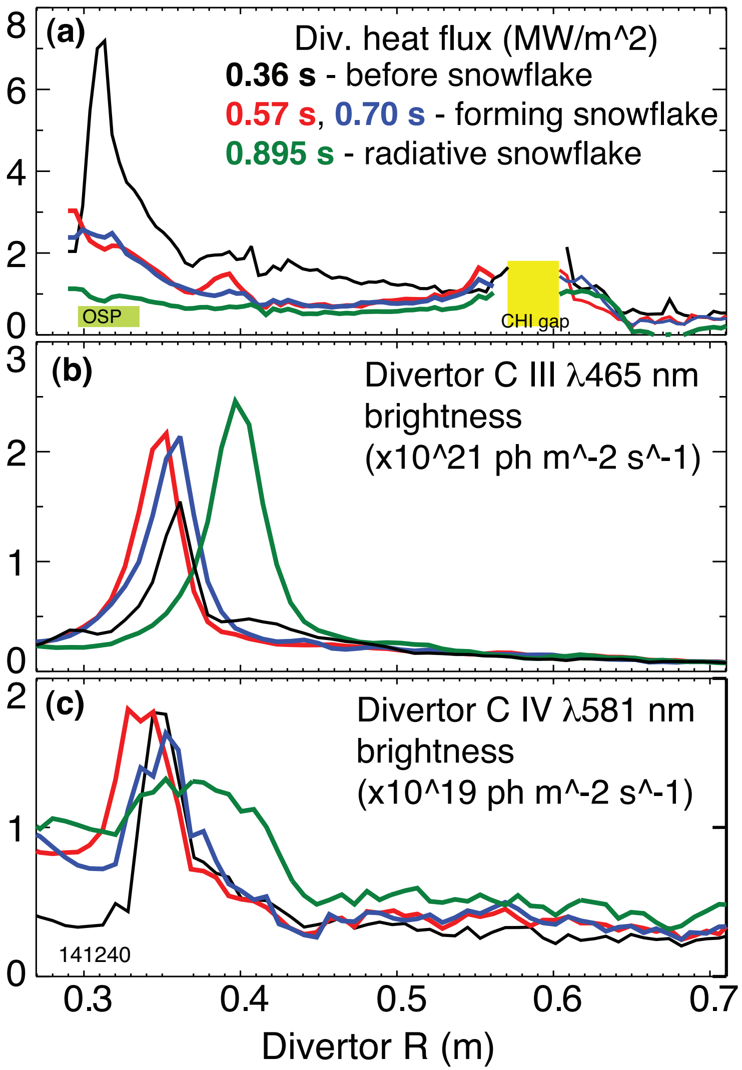
Significant reduction of steady-state divertor heat flux observed in snowflake divertor (at P_{SOL}~ 3 MW)



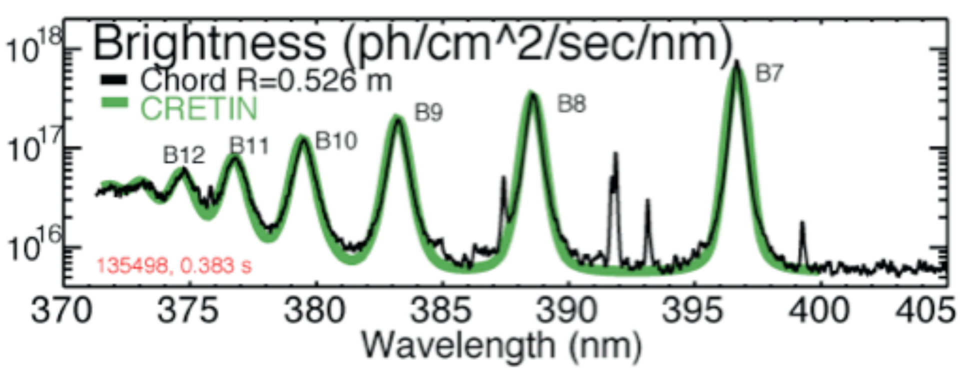


- Partial detachment at or after snowflake formation time
  - Heat and ion fluxes in the outer strike point region decreased
  - Divertor recombination rate and radiated power are increased

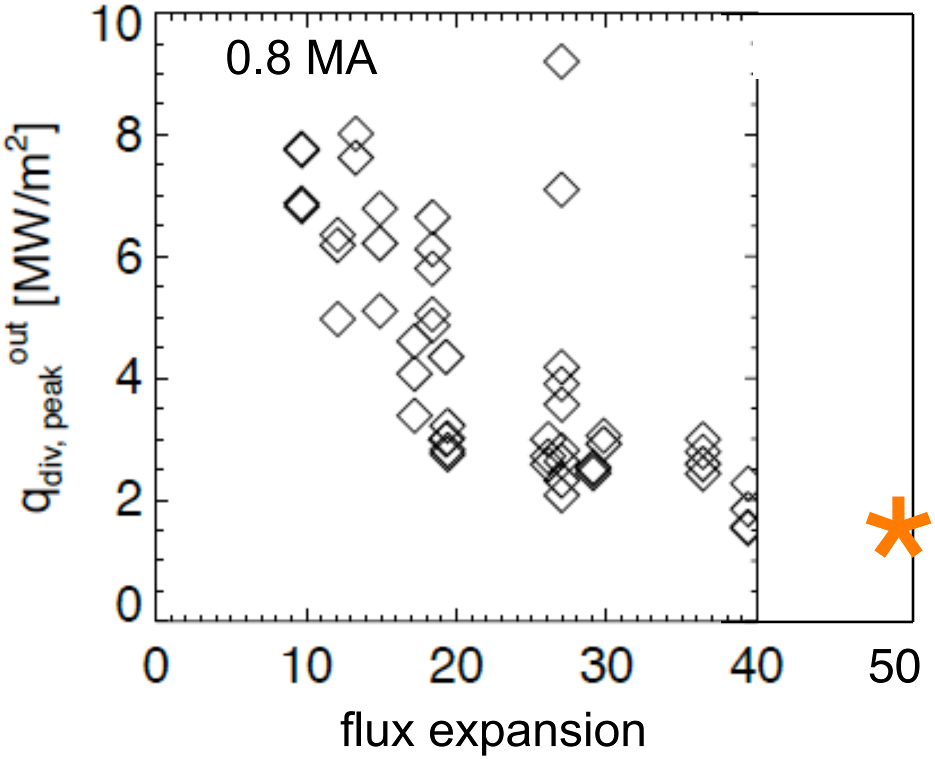
Divertor profiles show low heat flux, broadened C III and C IV radiation zones in the snowflake divertor phase

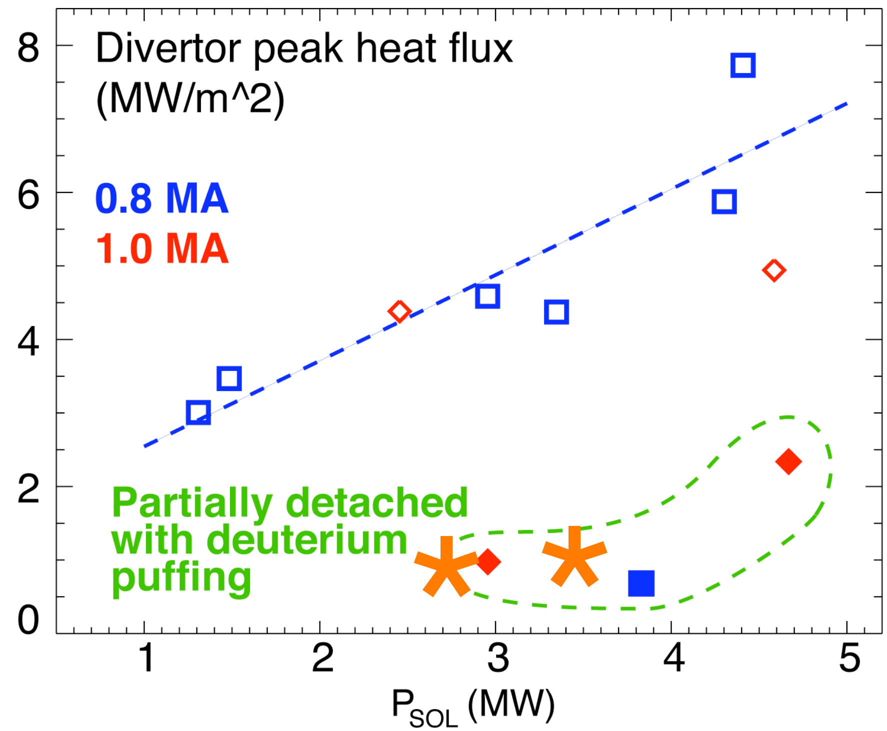


- Heat flux profiles reduced to nearly flat low levels, characteristic of radiative heating
- Divertor C III and C IV brightness profiles broaden
- High-*n* Balmer line spectroscopy and CRETIN code modeling confirm outer SP detachment with $T_e \leq 1.5$ eV, $n_e \leq 5 \times 10^{20}$ m^{-3}
  - Also suggests a reduction of carbon physical and chemical sputtering rates



Snowflake divertor heat flux consistent with NSTX divertor heat flux scalings





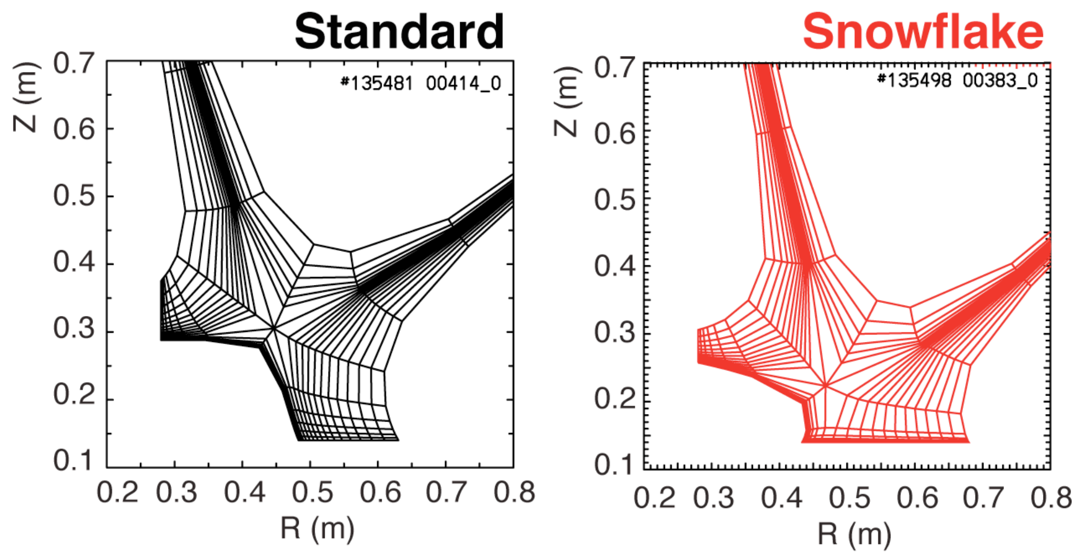
- Snowflake divertor (*): P_{SOL}~3-4 MW, f_{exp}~40-60, q_{peak}~0.5-1.5 MW/m^2
  - Low detachment threshold

T. K. Gray et. al, EX/D P3-13, IAEA FEC 2010

V. A. Soukhanovskii et. al, PoP 16, 022501 (2009)

2D modeling shows a trend toward reduced temperature, heat and particle fluxes in the snowflake divertor

- 2D multi-fluid code UEDGE
  - Fluid (Braginskii) model for ions and electrons
  - Fluid for neutrals
  - Classical parallel transport, anomalous radial transport
    - $D = 0.25\ m^2/s$
    - $\chi_{e,i} = 0.5\ m^2/s$

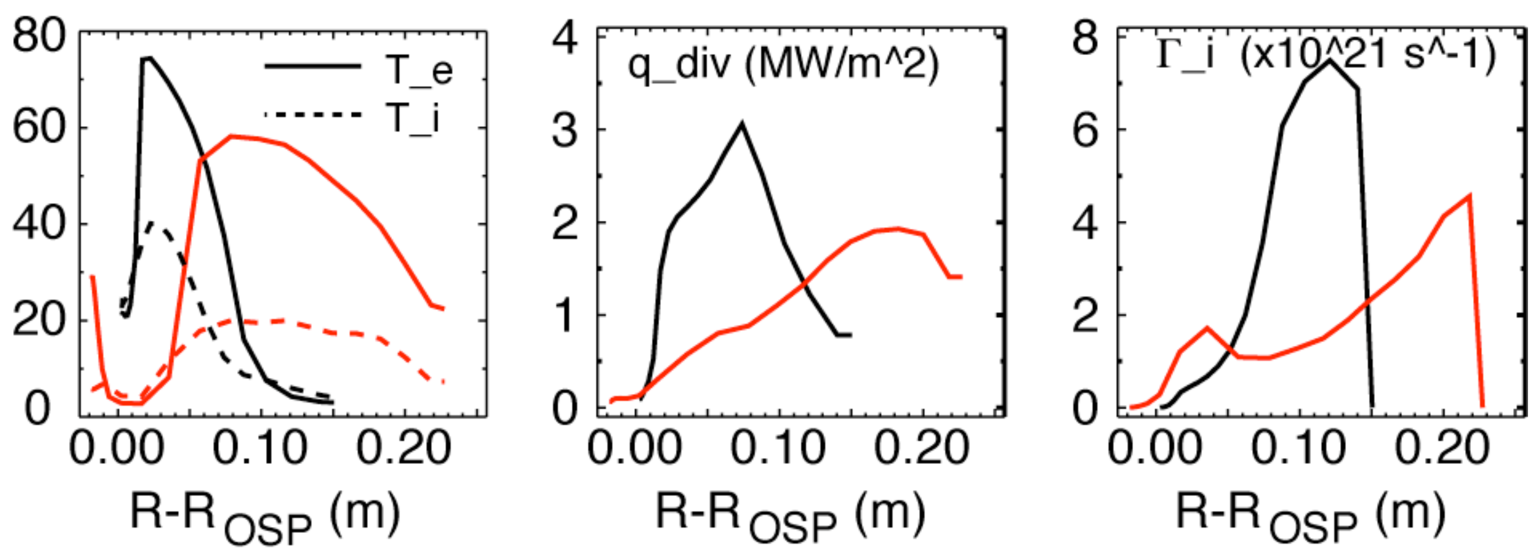


Core interface:

- $T_{e,i}$ = 120 eV
- $n_e = 4.5 \times 10^{19}$

R_{recy} = 0.95

Carbon 3 %



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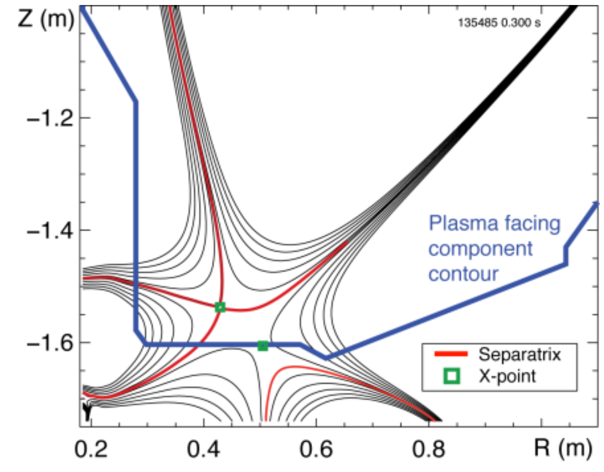
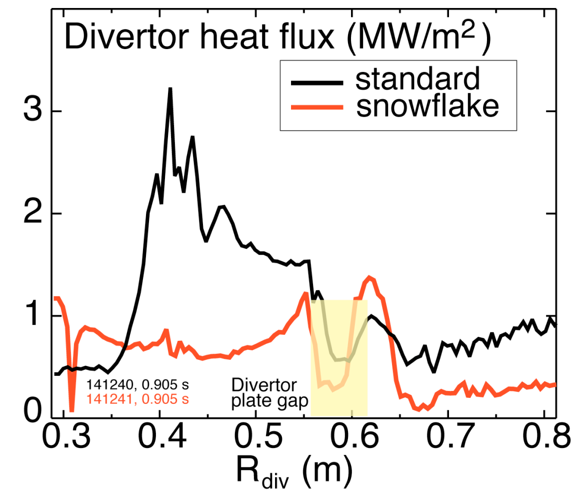
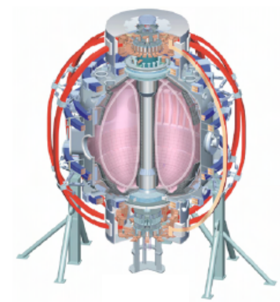


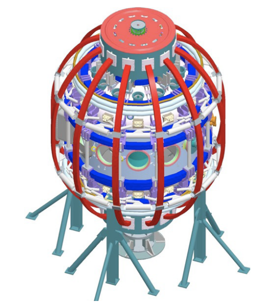


Divertor heat flux mitigation is key for present and future fusion plasma devices

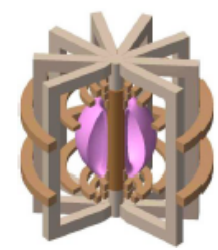
- ST / NSTX goals:
  - Study high beta plasmas at reduced collisionality
  - Access full non-inductive start-up, ramp-up, sustainment
  - Prototype solutions for mitigating high heat & particle flux
- NSTX-Upgrade
  - Development of divertor solutions to address
    - 2-3x higher input power
    - Projected peak divertor heat fluxes up to 24 MW/m^2
    - Up to 30 % reduction in Greenwald fraction
    - 3-5 x longer pulse duration
  - Additional divertor coil PF1C
    - Flux expansion variation with fixed X-point height



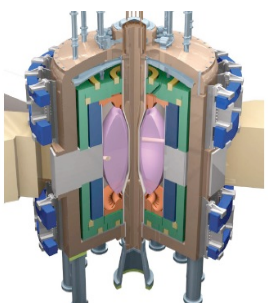
NSTX



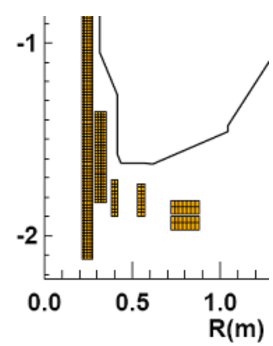
NSTX-U

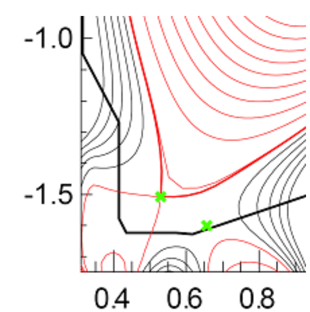


ST-based Plasma Material Interface (PMI) Science Facility



ST-based Fusion Nuclear Science (FNS) Facility





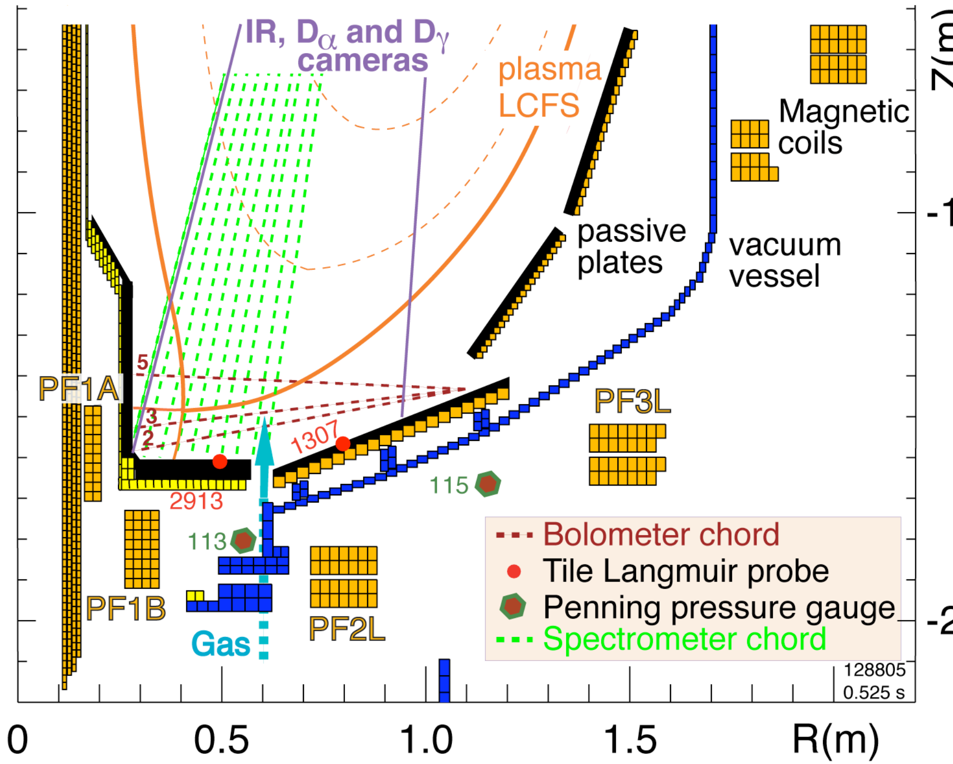
NSTX studies suggest the snowflake divertor configuration may be a viable divertor solution for present and future tokamaks

- Steady-state snowflake (up to 600 ms, many τ_E's)
- Good H-mode confinement (τ_E, $T_{e,i}(0)$, β_N, H98(y,2))
- Reduced core carbon concentration
- Significant reduction in divertor steady-state heat flux
- Potential to combine with radiative divertor for increased divertor radiation

Backup slides

Open divertor geometry, three existing divertor coils and a good set of diagnostics enable divertor geometry studies in NSTX

- I_p = 0.7-1.4 MA
- $P_{in} \leq$ 7.4 MW (NBI)
- ATJ and CFC graphite PFCs
- Lithium coatings from lithium evaporators
- Three lower divertor coils with currents 1-5, 1-25 kA-turns
- Divertor gas injectors (D_2, CD_4)
- Extensive diagnostic set

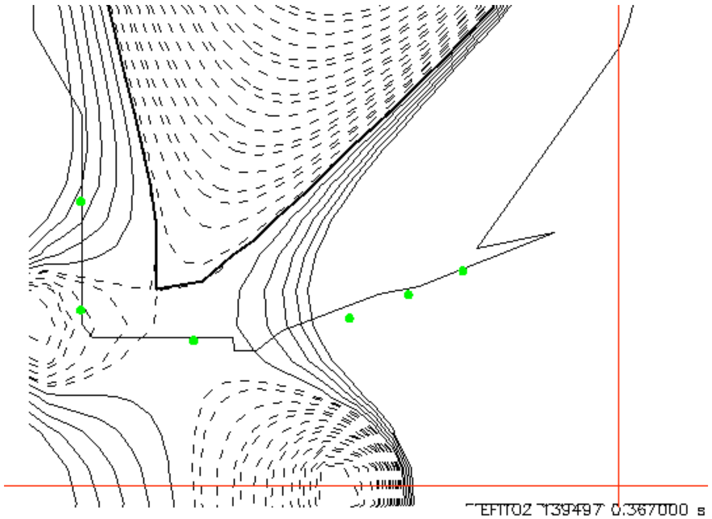


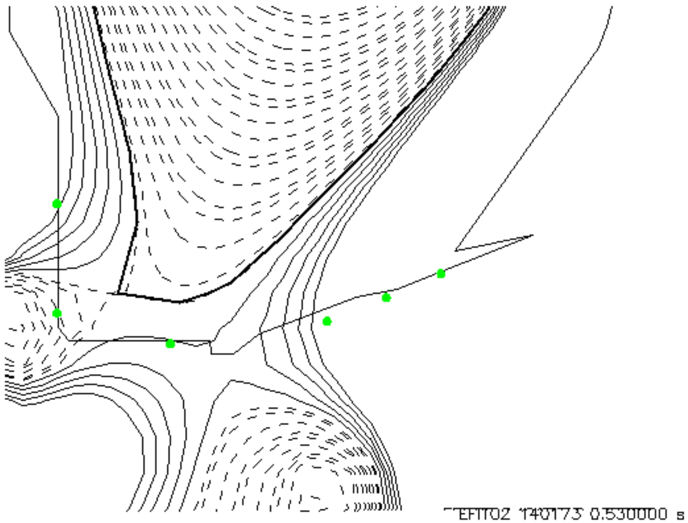
Heat flux mitigation is more challenging in compact divertor of spherical torus

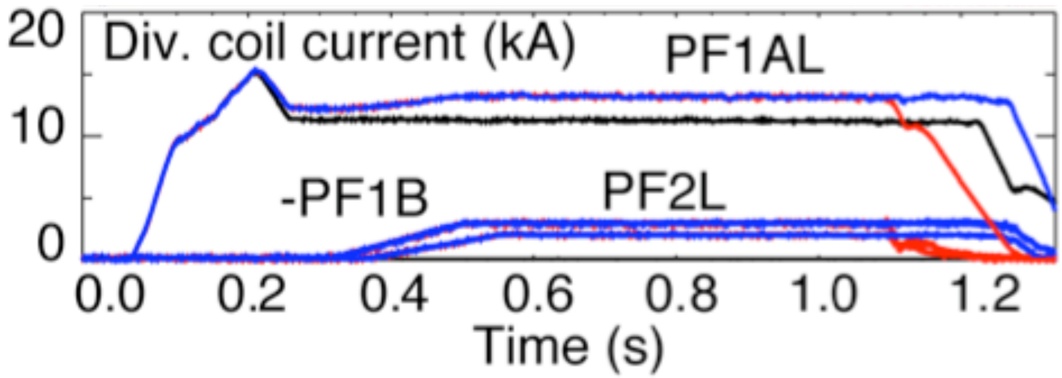
- NSTX
  - I_p = 0.7-1.4 MA, t_{pulse} < 1.5 s, P_{in} ≤ 7.4 MW (NBI)
  - ATJ and CFC graphite PFCs
  - P / R ~ 10
  - q_{pk} ≤ 15 MW/m^2
  - $q_{||}$ ≤ 200 MW/m^2

Quantity	NSTX	DIII-D
Aspect ratio	1.4-1.5	2.7
In-out plasma boundary area ratio	1:3	2:3
X-point to target parallel length L_x (m)	5-10	10-20
Poloidal magnetic flux expansion f_{exp} at outer SP	5-30	3-15
Magnetic field angle at outer SP (deg.)	1-10	1-2

Steady-state asymmetric snowflake-minus configuration has been obtained in FY2010 experiments in NSTX



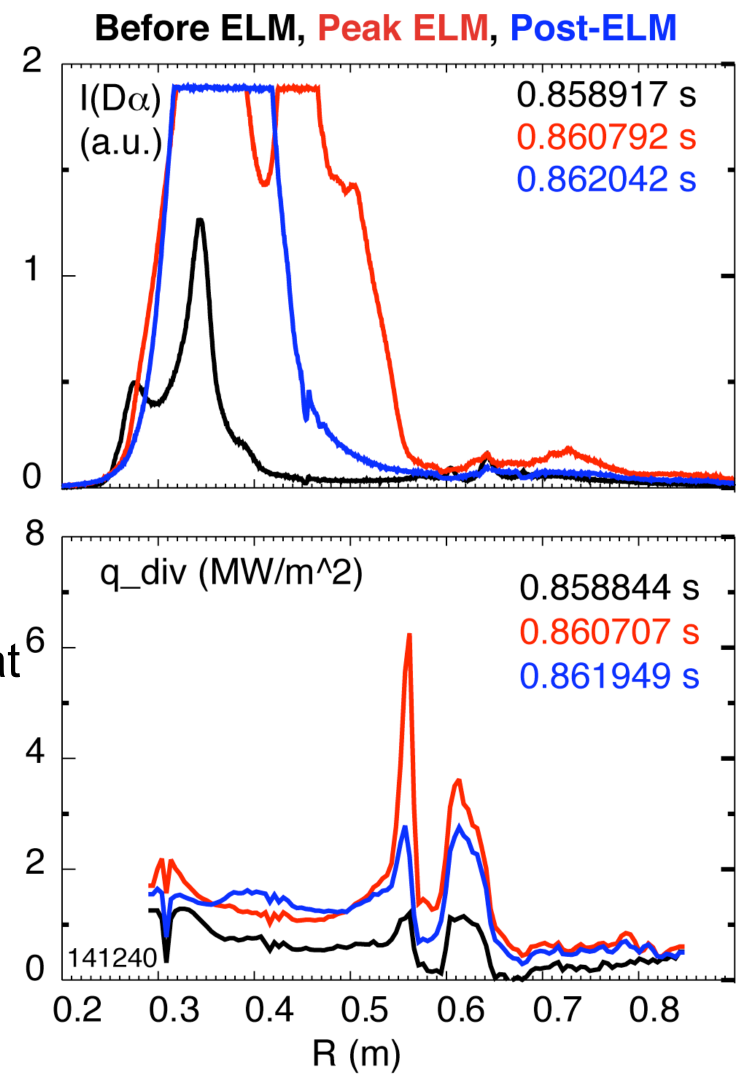




- Snowflake-minus with three coils (w/ reversed PF1B) transformed from a standard medium-δ LSN at ~ 500 ms
- Snowflake with three coils (w/ reversed PF1B) transformed from a standard high-δ LSN at ~ 500 ms

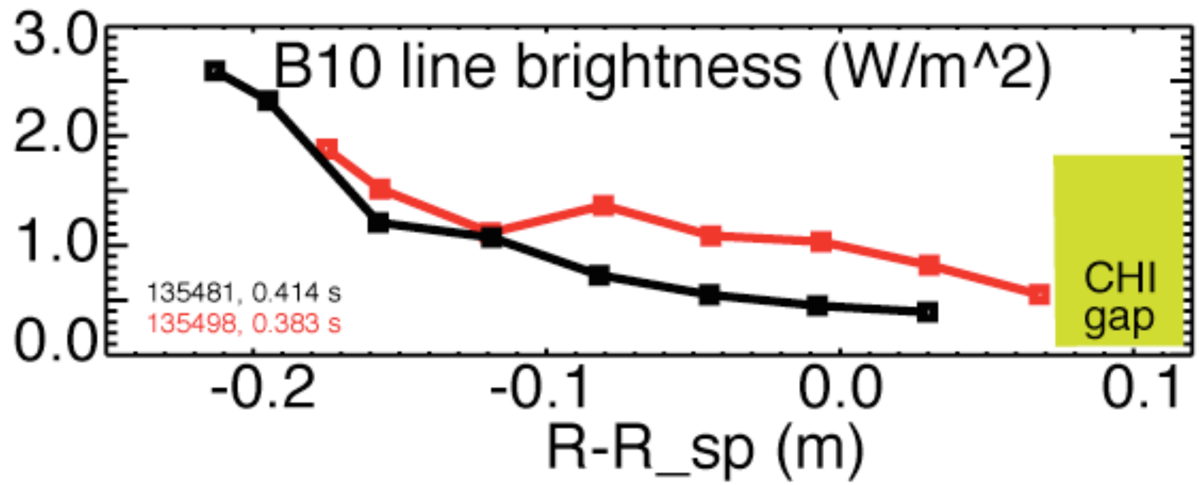
Preliminary indications that ELM heat flux is effectively dissipated in snowflake divertor

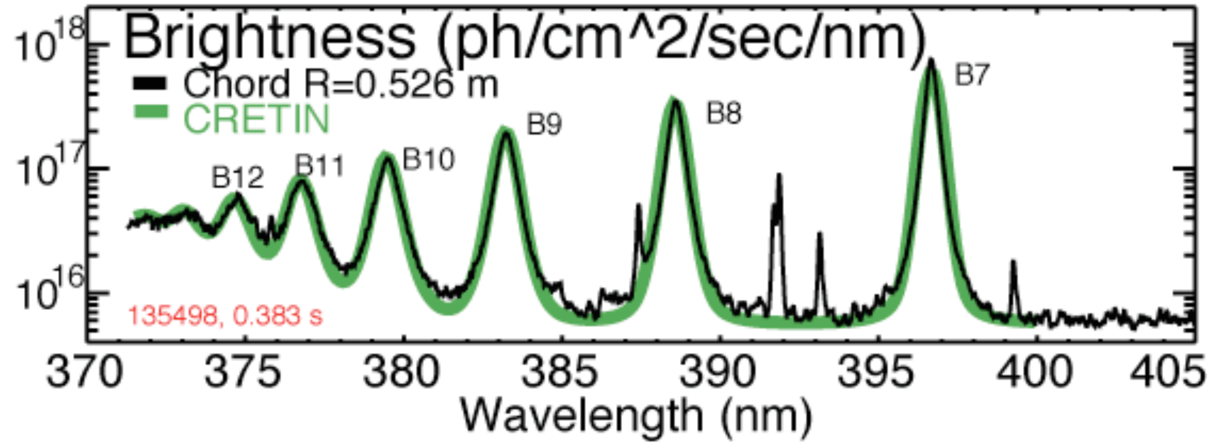
- Type I ELMs is a concern for divertor lifetime
  - Erosion
  - Evaporation, melting
- Radiative buffering of ELMs ineffective
- In NSTX snowflake divertor
  - Type I ELMs 5-12 % $\Delta W/W$
  - Significant dissipation of ELM energy in strike point region
  - Reduction in low flux expansion region (at larger R_{div})
  - Need more data to analyze mechanisms and trends
    - Heat diffusion over longer conn. length
    - Field line mixing in null-point region
    - Radiative / collisional dissipation
    - Plasma-wetted area effect



High-*n* Balmer line emission measurements suggest high divertor recombination rate, low T_e and high n_e

- Balmer series spectra modeled with CRETIN; Spectra sensitive to
  - Line intensity <-> Recombination rate
  - T_e <-> Boltzman population distribution
  - n_e <-> Line broadening due to linear Stark effect from ion and electron microfield

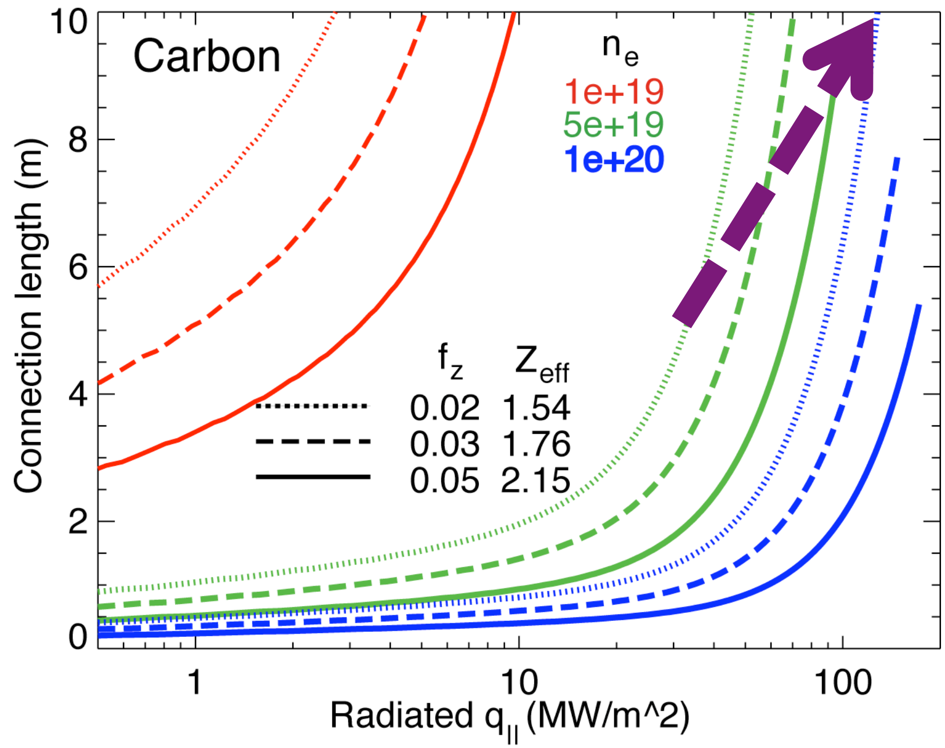




- T_e=0.8-1.2 eV, n_e=2-7 x 10^{20} m^{-3} inferred from modeling

1D estimates indicate power and momentum losses are increased in snowflake divertor

- 1D divertor detachment model by Post
  - Electron conduction with non-coronal carbon radiation
  - Max $q_{||}$ that can be radiated as function of connection length for range of f_z *and* n_e
  - -> Greater fraction of $q_{||}$ is radiated with increased L_x
- Three-body electron-ion recombination rate depends on divertor ion residence time
  - Ion recombination time: τ_{ion}~ 1−10 ms at T_e =1.3 eV
  - Ion residence time: τ_{ion} ≤ 3-6 ms in standard divertor, x 2 in snowflake
  - -> Greater parallel momentum sink

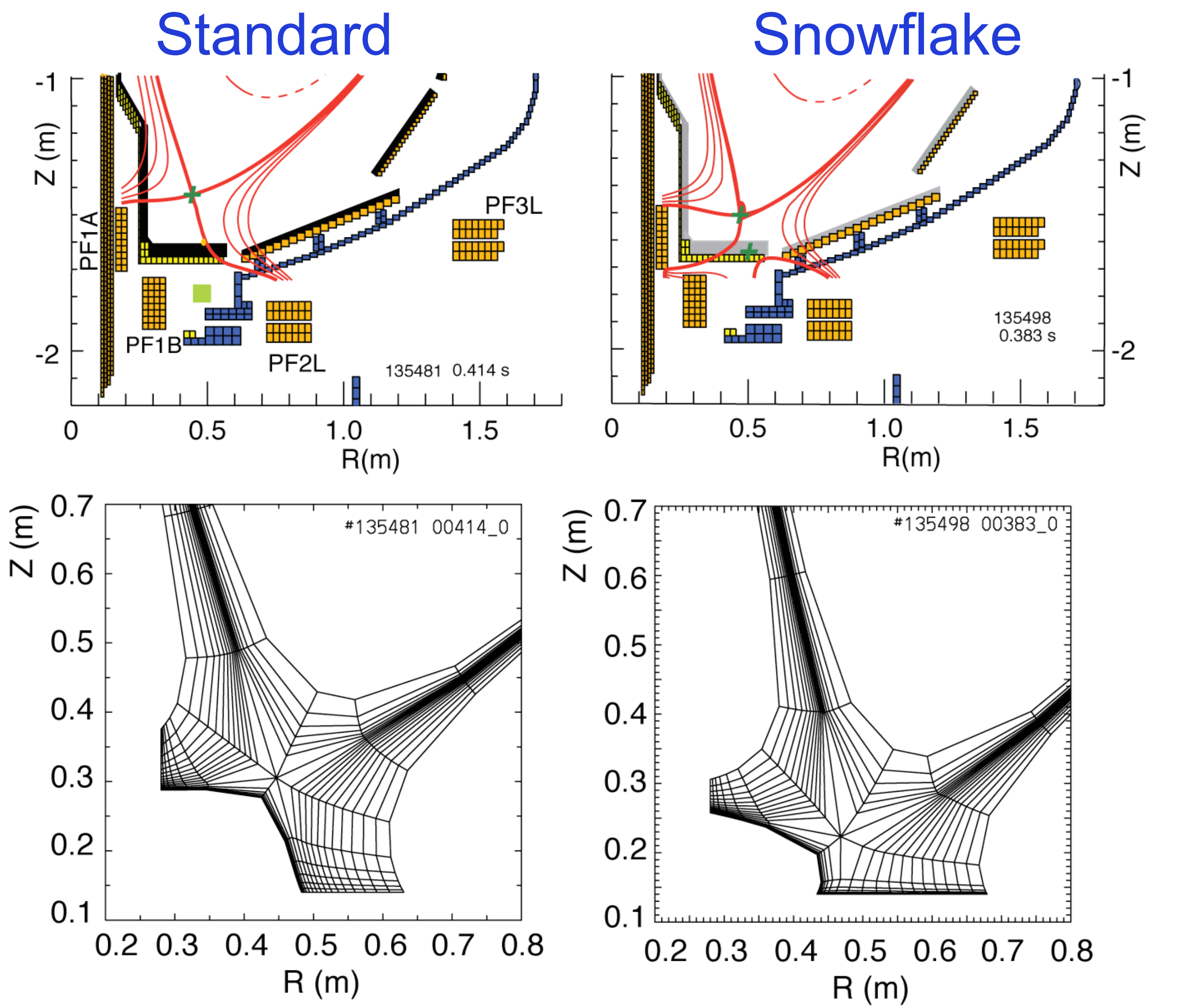


$$q_{||} = -\kappa_0 T_e^{5/2} \frac{\partial T_e}{\partial x}$$

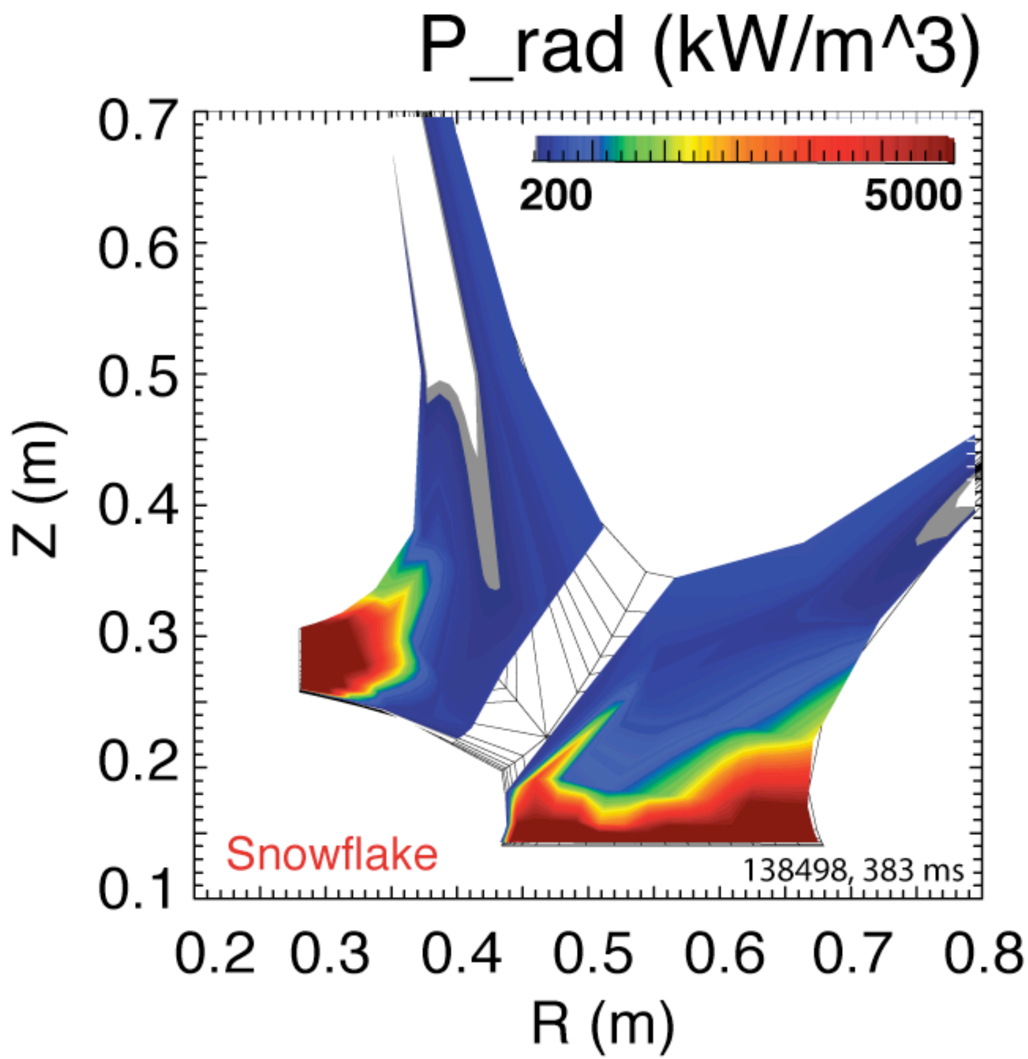
$$\frac{\partial q_{||}}{\partial x} = -n_e n_z L_Z(T_e)$$

2D multi-fluid edge transport code UEDGE is used to study snowflake divertor properties

- Fluid (Braginskii) model for ions and electrons
- Fluid for neutrals
- Classical parallel transport, anomalous radial transport
- Core interface:
  - T_e = 120 eV
  - T_i = 120 eV
  - $n_e = 4.5 \times 10^{19}$
- D = 0.25 m^2/s
- $\chi_{e,i}$ = 0.5 m^2/s
- R_{recy} = 0.95
- Carbon 3 %



Radiated power is broadly distributed in the outer leg of snowflake divertor



UEDGE model