Snowflake Divertor Studies in DIII-D and NSTX Aimed at the Power Exhaust Solution for the Tokamak

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for the NSTX-U and DIII-D Research Teams

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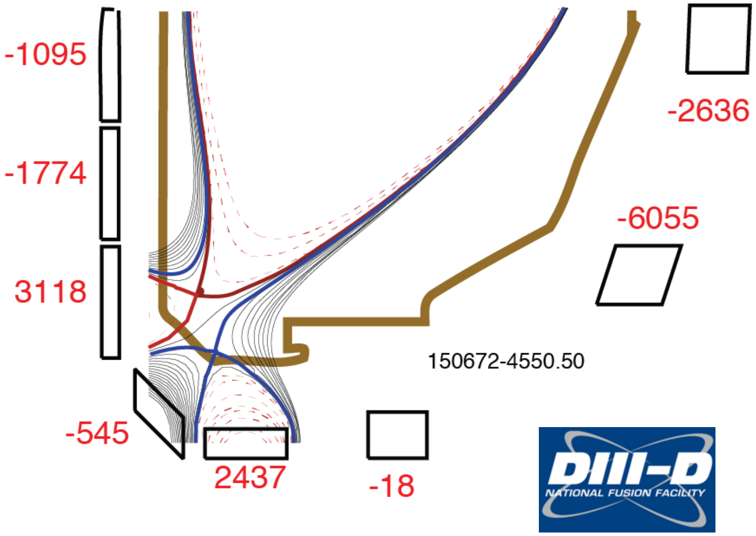
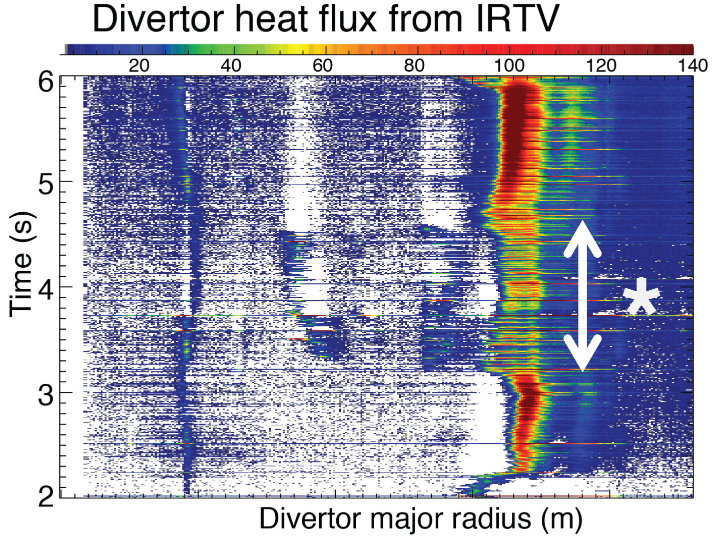
Significant heat flux reduction between and during ELMs observed in NSTX and DIII-D snowflake divertors

Outline of talk

- Snowflake divertor configuration
- Snowflake divertor in NSTX
  - Facilitated access to detachment
  - Heat flux reduction compatible with H-mode
- Snowflake divertor in DIII-D
  - Heat flux reduction compatible with H-mode
  - Cryopump density control within $n_e/n_G = 0.4\text{-}0.75$
  - Detachment and ELM heat flux
- Projections for NSTX-Upgrade
- Conclusions

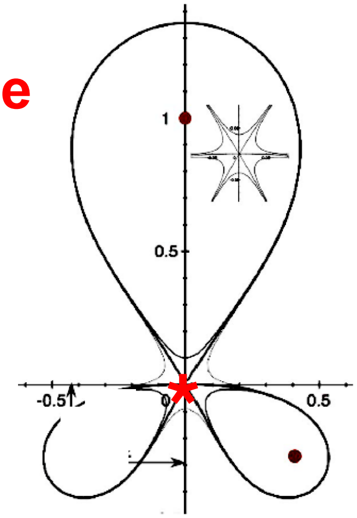




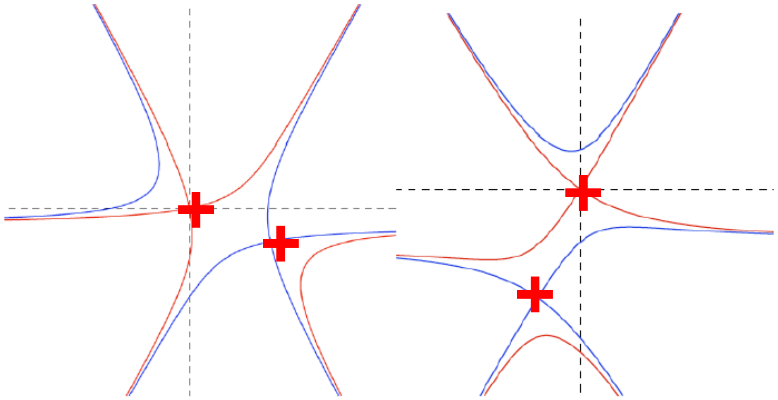
Snowflake divertor geometry takes advantage of B_p structure in second-order null region

- **Snowflake divertor configuration**
  - Second-order null
    - $B_p \sim 0$ and *grad* $B_p \sim 0$ (Cf. first-order null: $B_p \sim 0$)
  - Exact snowflake topologically unstable
  - Deviation from exact snowflake
    - $d \leq a\ (\lambda_q / a)^{1/3}$ where *d* – distance between nulls, *a* – plasma minor radius, λ_q – SOL width

Exact snowflake



- **Predicted properties**
  - Increased edge shear: ped. stability
  - Add'l null: H-mode power threshold, ion loss
  - Larger plasma wetted-area A_{wet} : reduce q_{div}
  - Four strike points : share $q_{||}$
  - Larger X-point connection length L_x : reduce $q_{||}$
  - Larger effective divertor volume V_{div} : incr. P_{rad}
  - High β_p convective zone $D^* \leq a\ (a\ \beta_{pm} / R)^{1/4}$

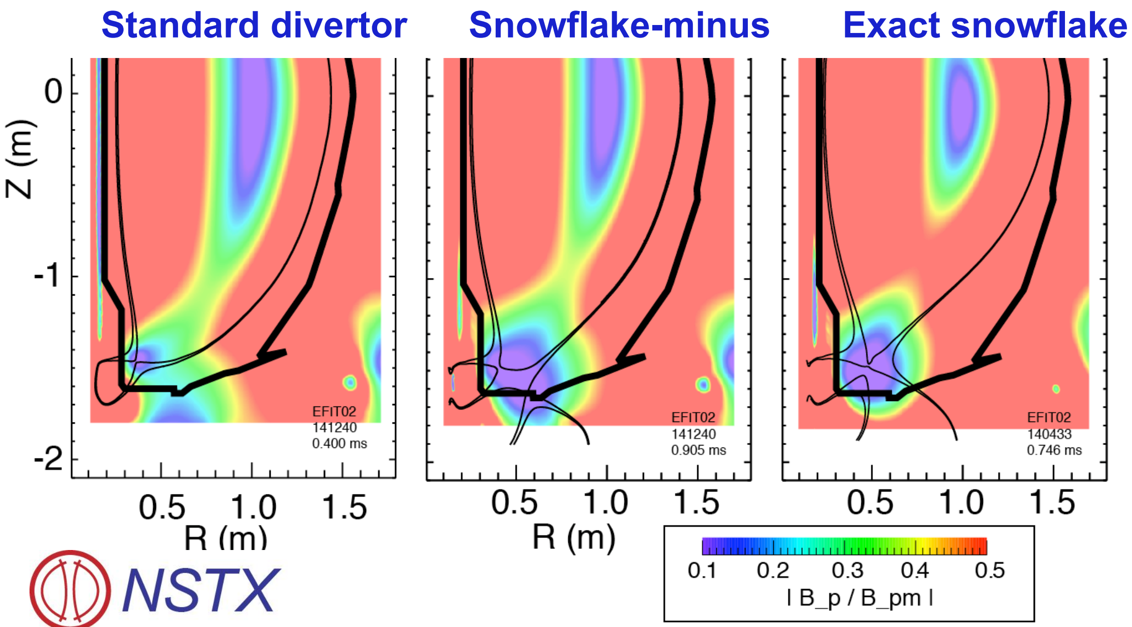


Snowflake-minus

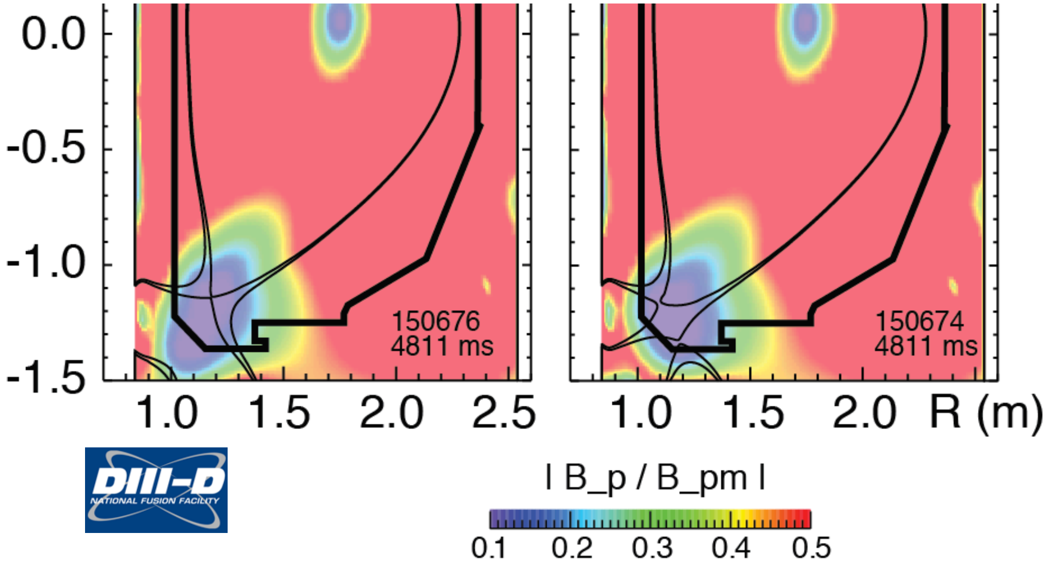
Snowflake-plus

D. D. Ryutov, PoP 14, 064502 2007;
EPS 2012 Invited, PPCF 54, 124050 (2012)

Snowflake configurations sustained in NSTX and DIII-D for many τ_E's with divertor coil currents within safety margins



- Divertor coil currents 0.5-4 kA within safety margins
- Steady-state snowflake configurations
  - NSTX: 0.5 s
  - DIII-D: 3 s

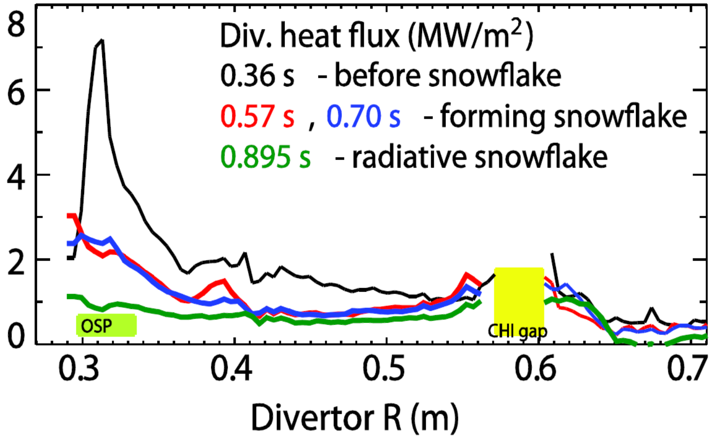


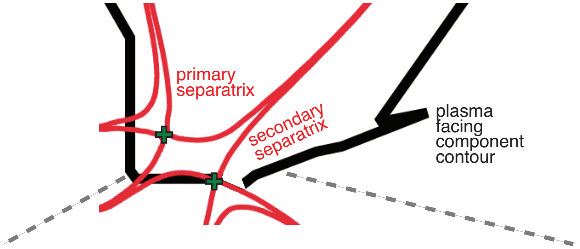
Snowflake divertor in NSTX compatible with H-mode confinement, facilitated access to partial detachment

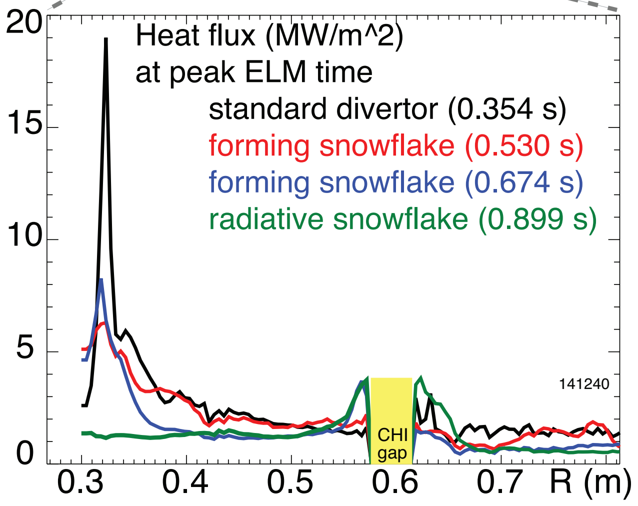
- Graphite PFCs with lithium coatings
- I_p = 0.9 MA, P_{NBI} = 4 MW, P_{SOL} ~ 3 MW
- $q_{peak} \leq 8$ MW/m^2, $q_{||} \leq 100$ MW/m^2

With snowflake divertor

- H-mode confinement unchanged
  - W_{MHD}~250 kJ, H98(y,2)~ 1, β_N~5
- Core impurity reduced by up to 50 %
- Suppressed ELMs re-appeared
- Divertor heat flux significantly reduced
  - Between ELMs
  - During Type-I ELMs ($\Delta W/W$ ~ 5-15 %)





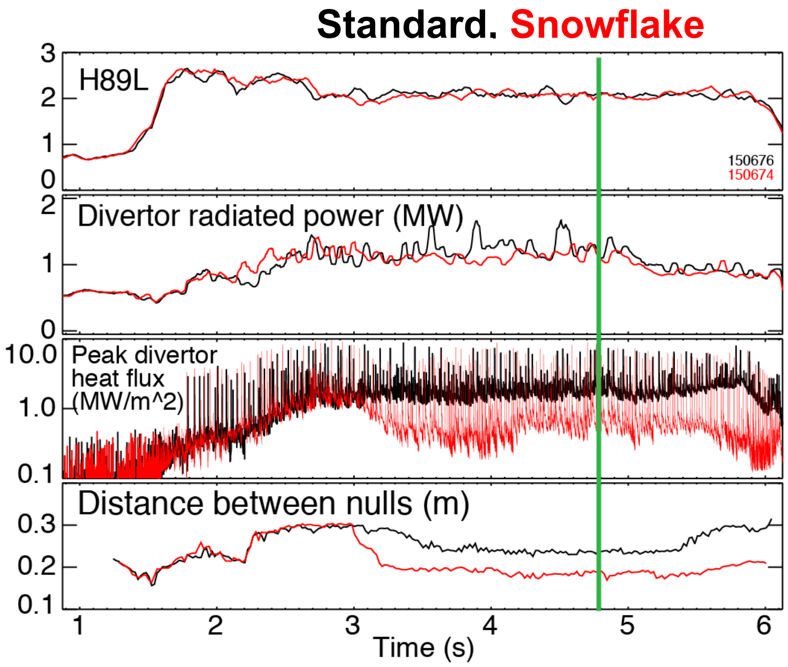


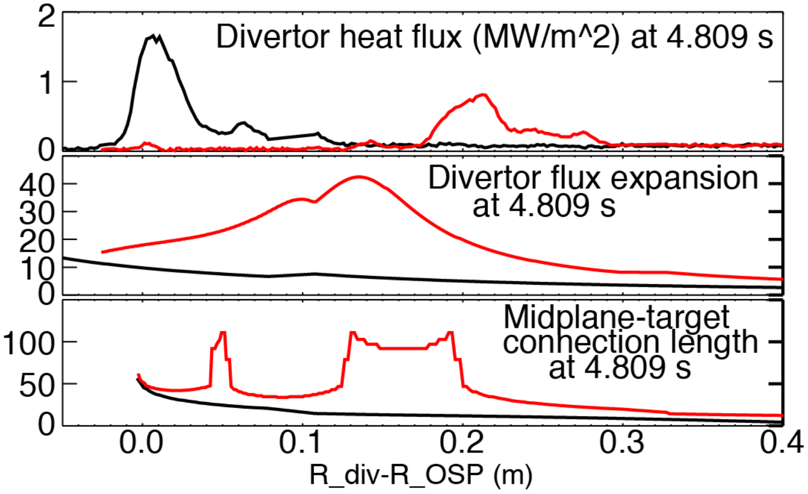
In DIII-D, peak divertor heat flux reduction by 50-60 % between ELMs due to geometry

- Graphite PFCs
- $I_p = 1.2$ MA, $P_{NBI} = 5$ MW, $P_{SOL} \sim 3$ MW
- $q_{peak} \leq 2$ MW/m^2, $q_{||} \leq 100$ MW/m^2

- Obtained snowflake-minus for up to 3 s duration over $n_e/n_G = 0.4 – 0.75$ using cryo-pump for density control

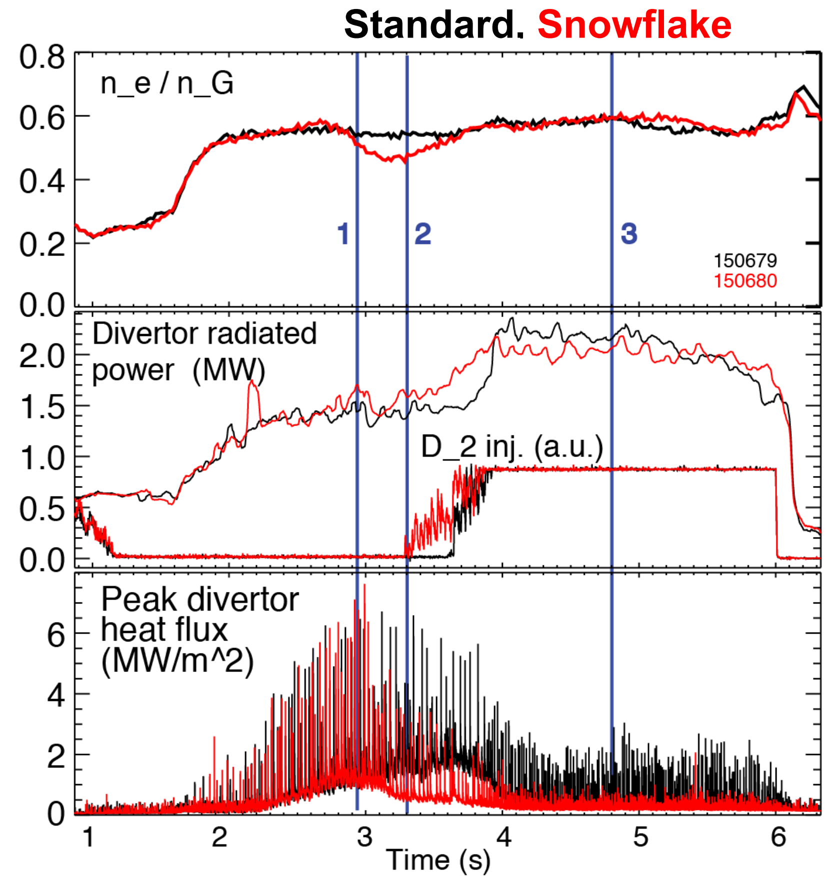
- In lower-density snowflake H-mode
  - Confinement unaffected
  - Divertor attached
    - Divertor P_{rad} similar to standard div.
  - Divertor heat flux reduced
    - Plasma-wetted area increased up to 80 %
    - Connection length increased up to 75 %

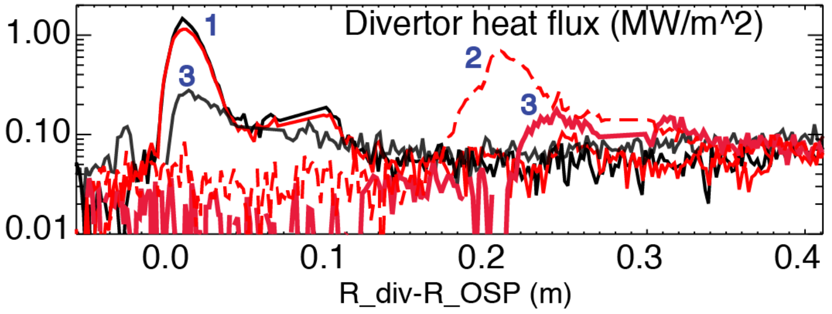


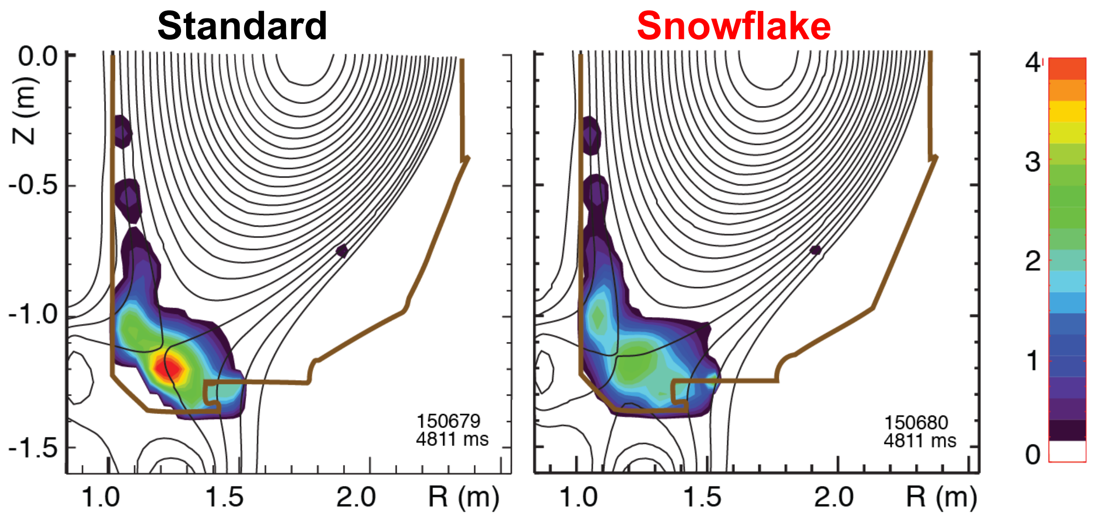


Heat flux in snowflake divertor is further reduced during partial detachment in DIII-D

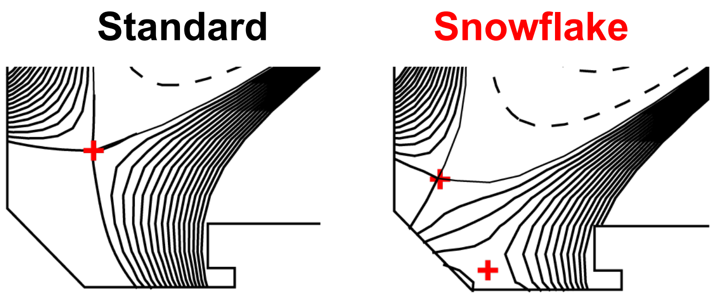
- In higher-density snowflake H-mode
  - Density n_e/n_G = 0.55-0.75
  - Partial detachment onset (n_e) similar in standard and snowflake (preliminary)
  - Peak heat flux is up to 50 % lower in partially detached snowflake vs partially detached standard divertor
  - Lower divertor rad. power broadly distributed in partially detached snowflake
  - No MARFEs



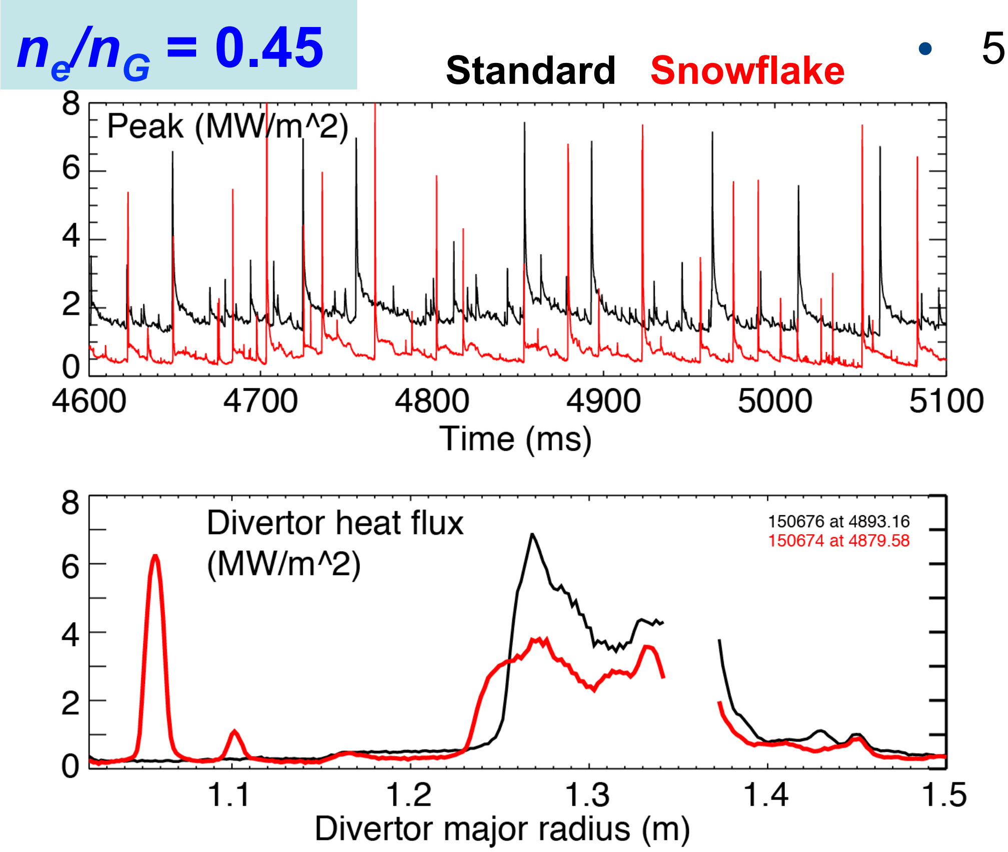


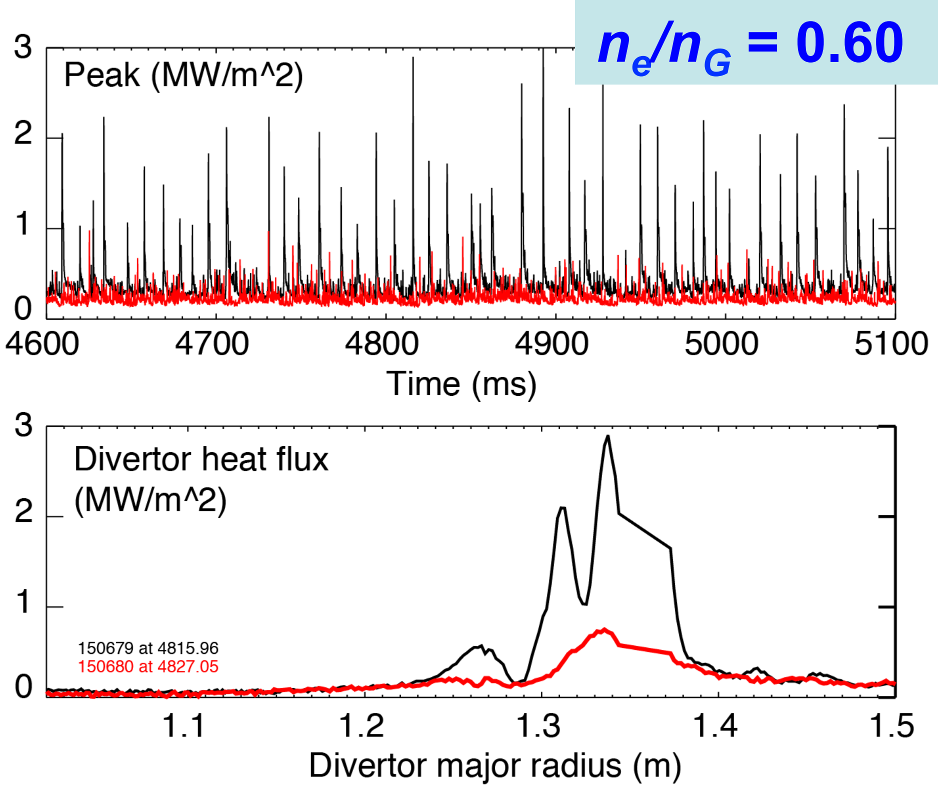


In DIII-D, Type-I ELM heat loads reduced in D_2-seeded (partially detached) snowflake divertor

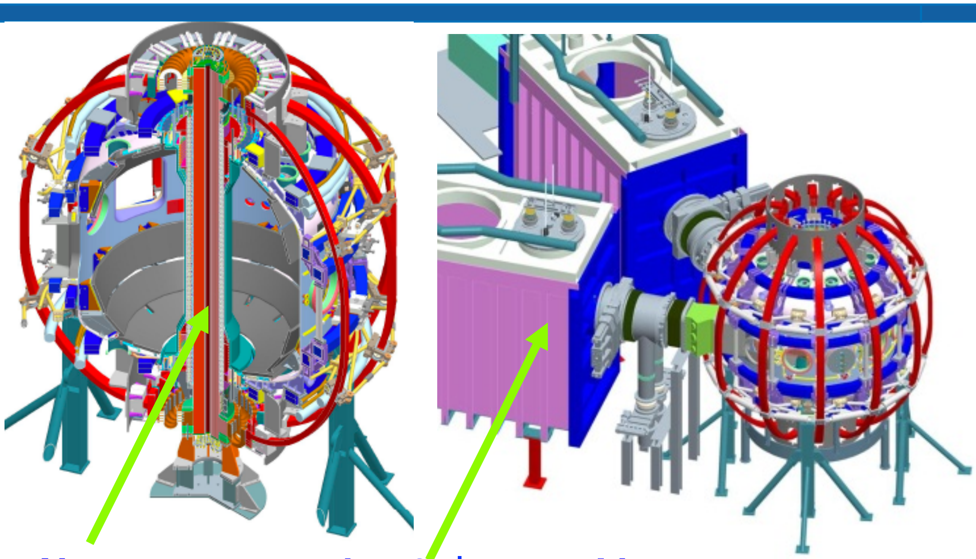


- At lower density, heat flux channels close to primary and second separatrices during ELMs
  - Additional strike points
- At high density (partial detachment), ELM heat flux significantly reduced
  - 50-75 % lower than in standard partially detached





Snowflake divertor is a leading heat flux mitigation candidate for NSTX-Upgrade

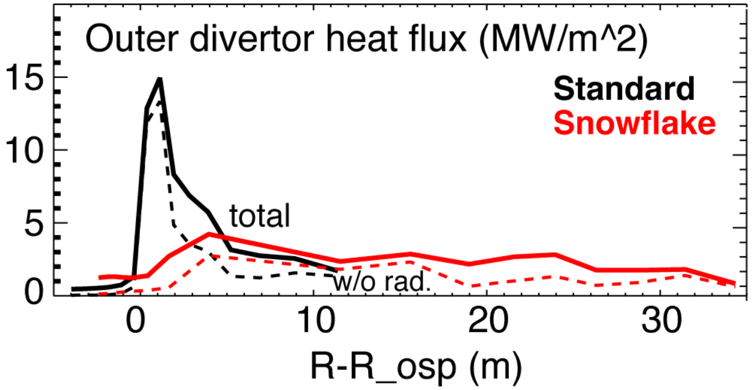


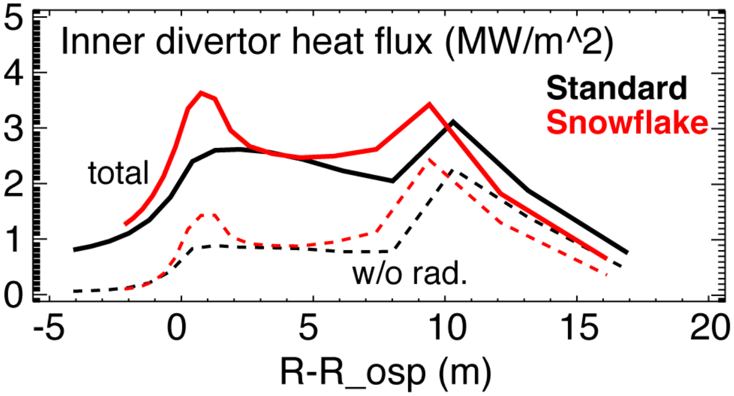
New center-stack **2^{nd} neutral beam**

$B_T \longrightarrow$ 1 T $P_{NBI} \longrightarrow$ 12 MW
$I_p \longrightarrow$ 2 MA pulse $\longrightarrow$ 5 s

- **NSTX-U Mission elements:**
  - Advance ST as candidate for Fusion Nuclear Science Facility
  - Develop solutions for the plasma-material interface challenge
  - Explore unique ST parameter regimes to advance predictive capability for ITER
  - Develop ST as fusion energy system

- Predictions for 12 MW NBI
  - 2D multifluid code UEDGE
  - P_{SOL}=9 MW, 4 % carbon
  - D, χ to match λ_q
  - Outer divertor attached
    - T_e, $T_i \leq$ 80 eV





Developing the Power Exhaust Solution for the Tokamak with the Snowflake Divertor in NSTX and DIII-D

- Large zone of low poloidal field in divertor resulting in significant geometry benefits for heat exhaust
- Steady-state configurations with existing divertor coils
- Significant peak divertor heat flux reduction between and during Type I ELMs compatible with high H-mode confinement
- Initial confirmation of compatibility with cryo-pump density control
- Potential to combine with radiative divertor solution
- Favorable projections for NSTX-Upgrade with 12 MW NBI power

Backup slides

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Theory

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DIII-D

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NSTX

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

$$q_{pk} \simeq \frac{P_{heat}\,(1-f_{rad})f_{out/tot}f_{down/tot}(1-f_{pfr})\sin\alpha}{2\pi R_{SP} f_{exp} \lambda_{q_{||}}}$$

$$A_{wet} = 2\pi R\, f_{exp}\, \lambda_{q_{||}} \qquad f_{exp} = \frac{(B_p/B_{tot})_{MP}}{(B_p/B_{tot})_{OSP}}$$

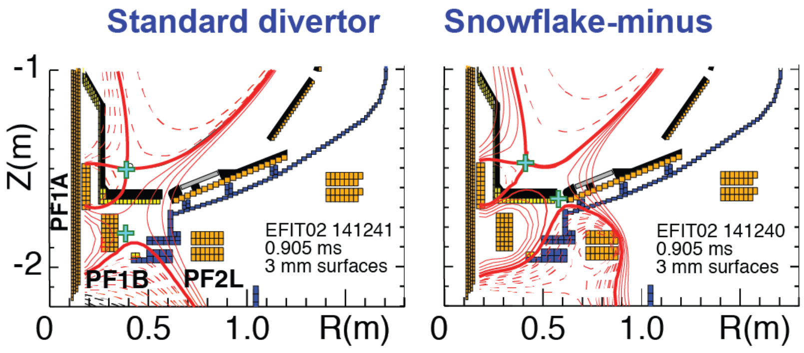
- Recent ideas to improve standard divertor geometry
  - Snowflake divertor (D. D. Ryutov, PoP 14, 064502 2007)
  - X-divertor (M. Kotschenreuther *et. al*, IC/P6-43, IAEA FEC 2004)
  - Super-X divertor (M. Kotschenreuther *et. al*, IC/P4-7, IAEA FEC 2008)

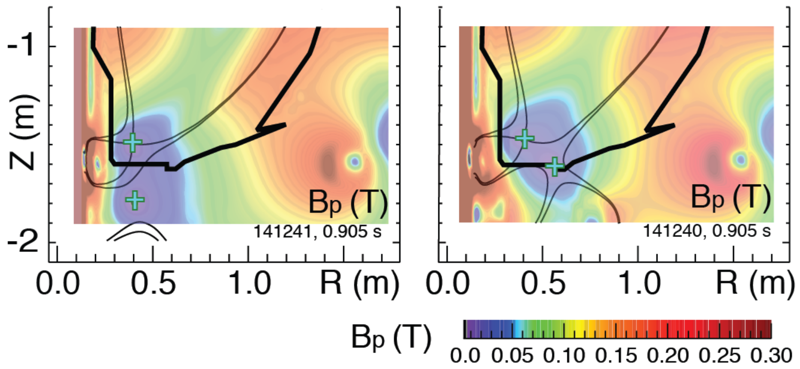
Heat flux mitigation is more challenging in compact divertor of spherical torus

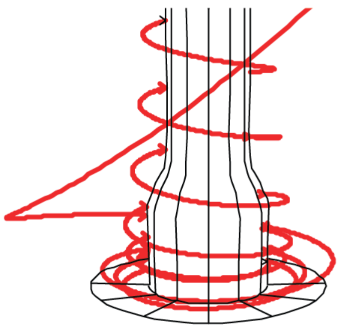
- NSTX
  - I_p = 0.7-1.4 MA, $t_{pulse} < 1.5$ s, $P_{in} \leq 7.4$ MW (NBI)
  - ATJ and CFC graphite PFCs
  - P / R ~ 10
  - $q_{pk} \leq 15$ MW/m^2
  - $q_{||} \leq 200$ MW/m^2

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

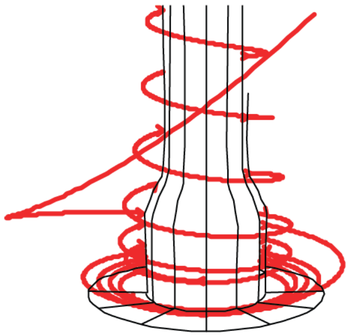
Snowflake divertor configurations obtained with existing divertor coils in NSTX







Shot 141241, EFIT02,
time: 0.905 s,
normalized flux: 1.005



Shot 141240, EFIT02,
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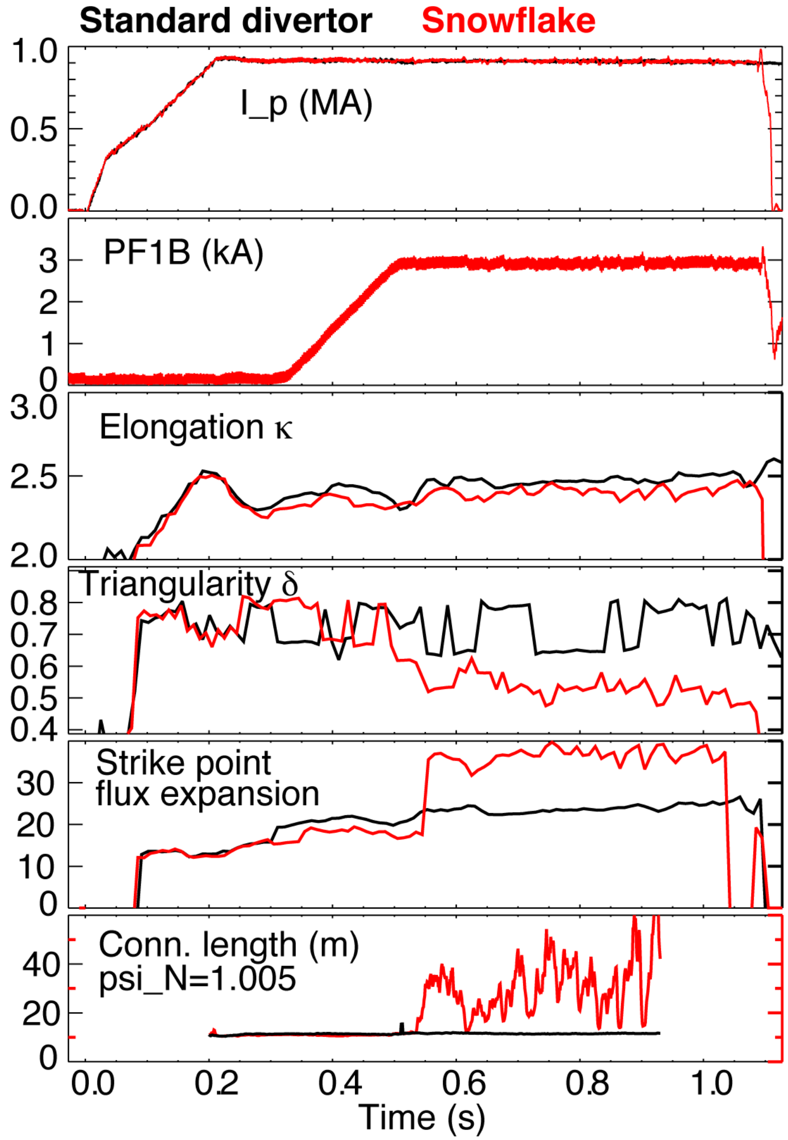
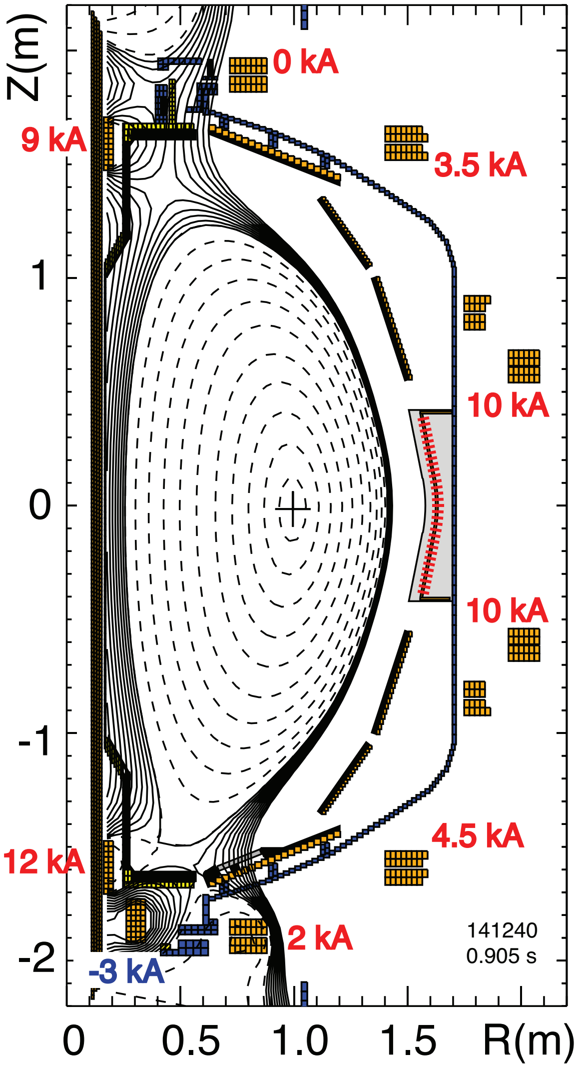
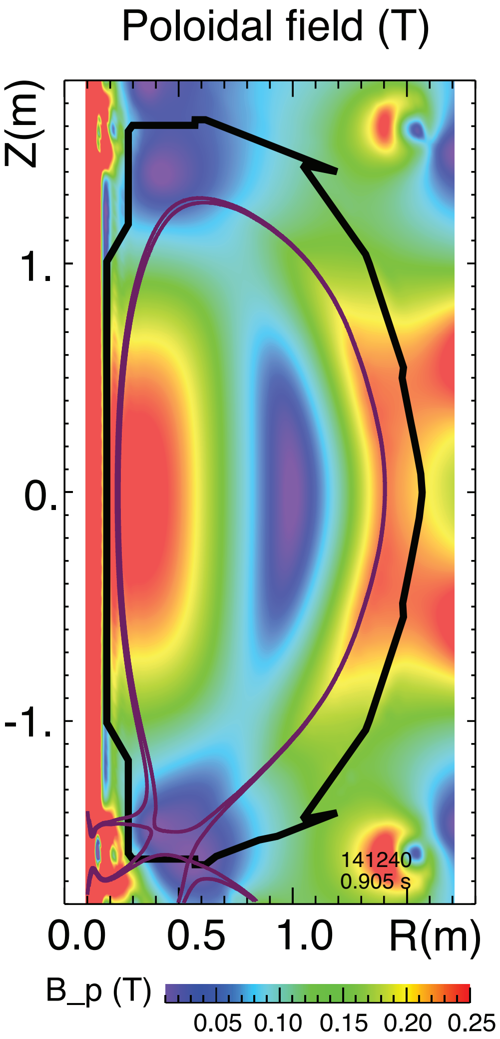
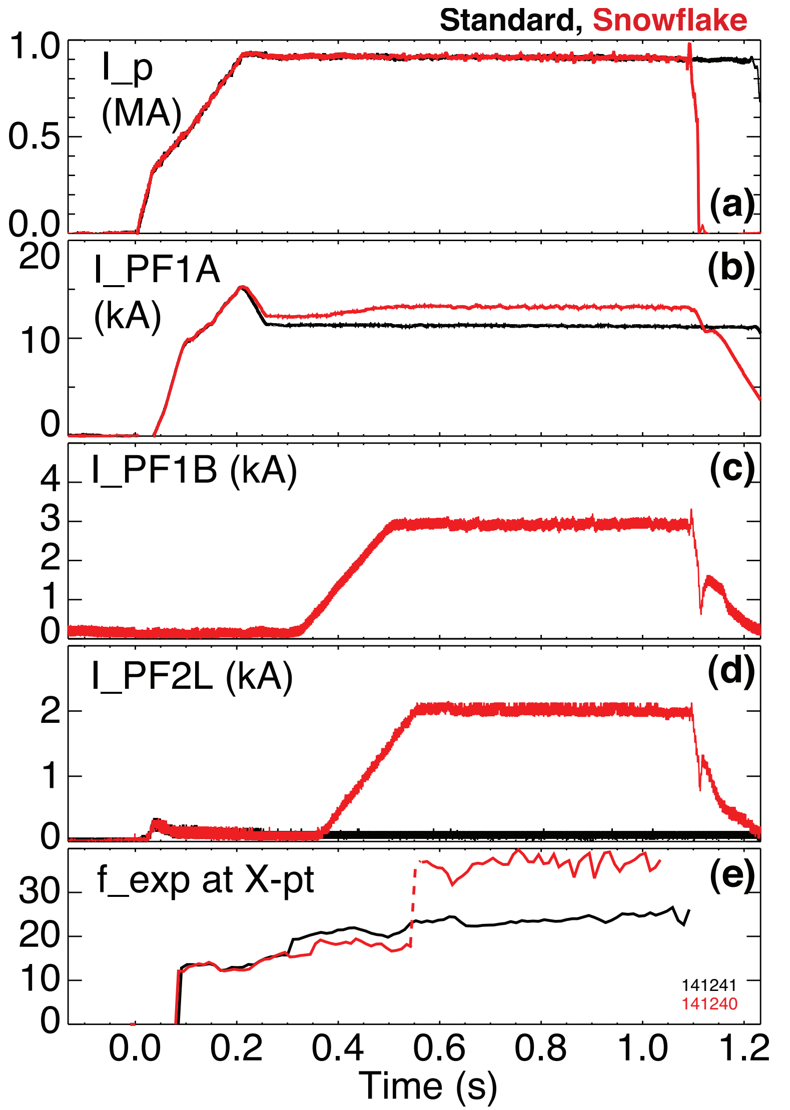
normalized flux: 1.005



Snowflake divertor configurations obtained with existing divertor coils, maintained for up to 10 τ_E

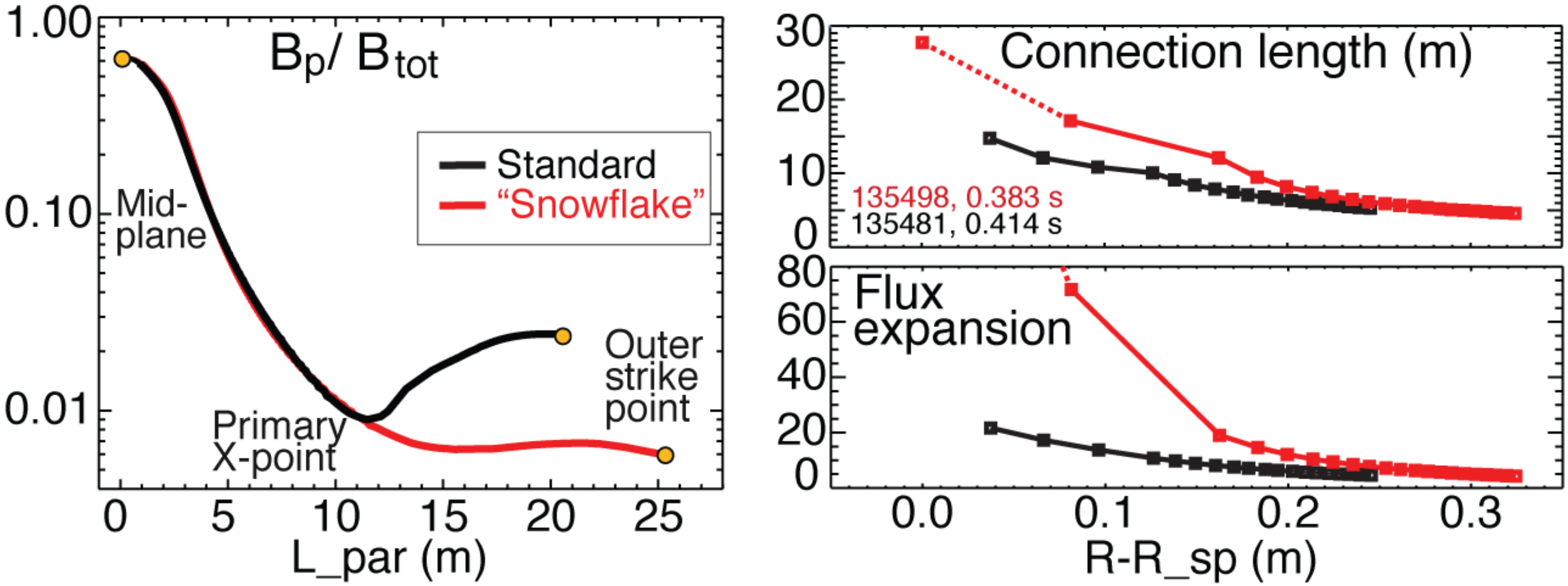






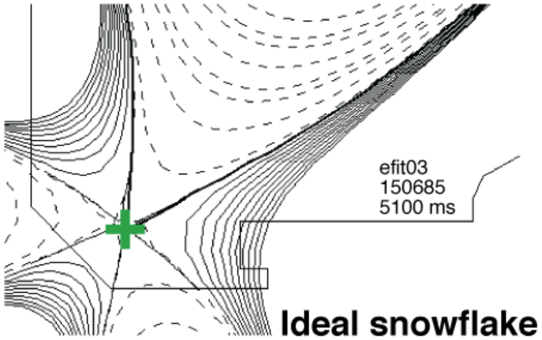
NSTX: Plasma-wetted area and connection length are increased by 50-90 % in snowflake divertor

NSTX

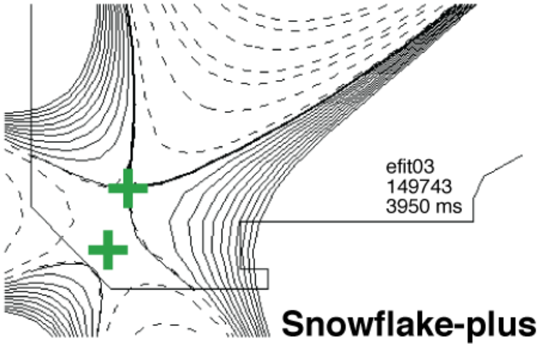


- These properties observed in first 30-50 % of SOL width (λ_q~6 mm)
- B_{tot} angles in the strike point region: 1-2^o, sometimes < 1^o
    - Concern for hot-spot formation and sputtering from divertor tile edges
    - Can be alleviated by $q_{||}$ reduction due to radiative detachment and power partitioning between strike points

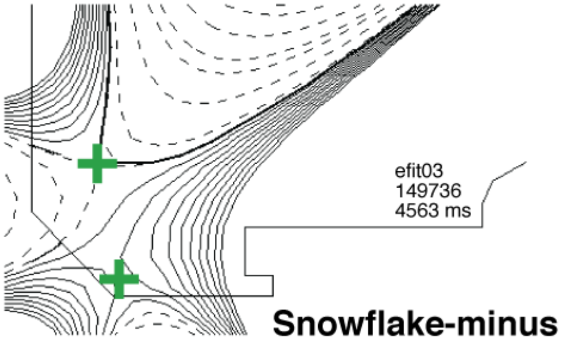
Snowflake divertor configurations obtained with existing divertor coils in DIII-D



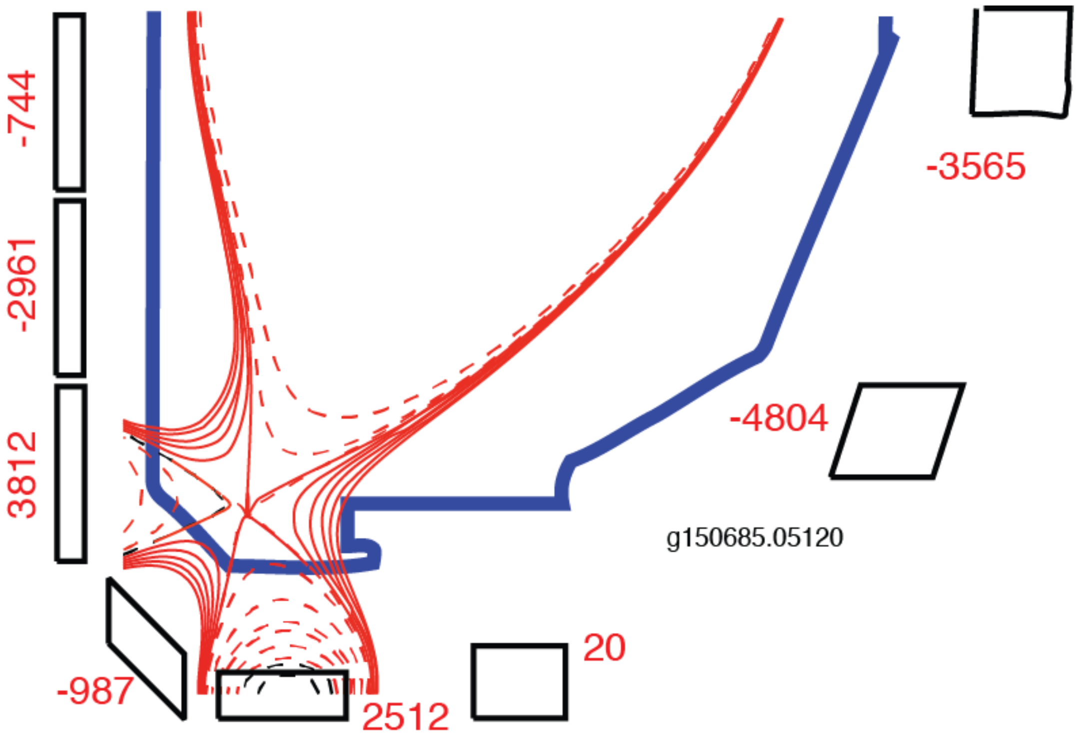
Ideal snowflake



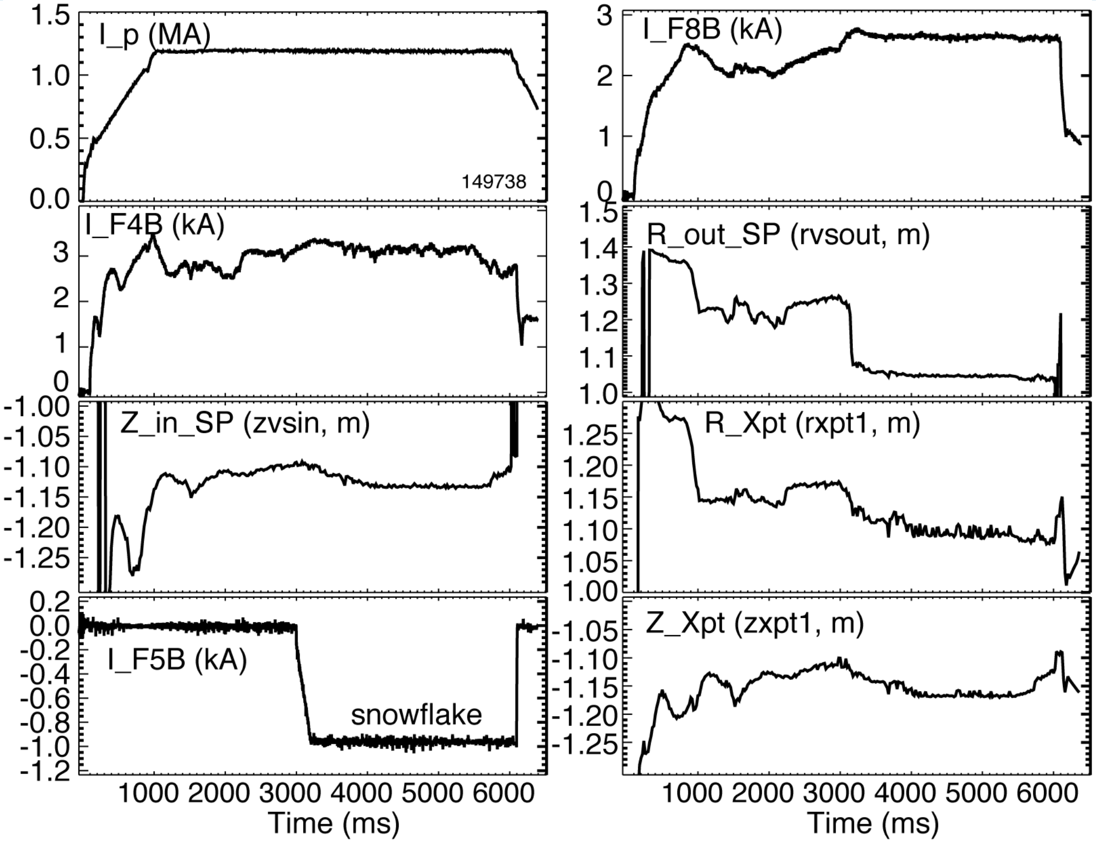
Snowflake-plus

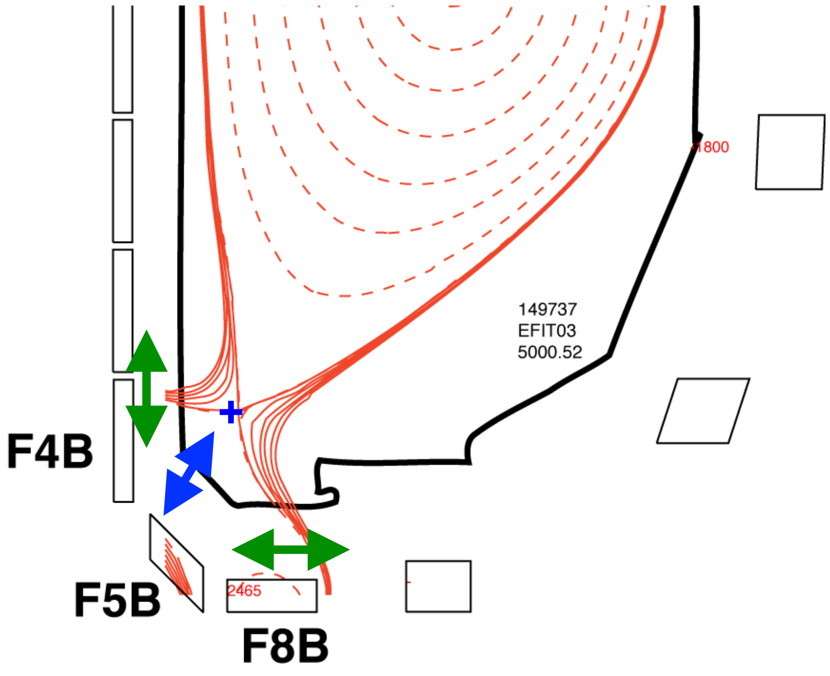


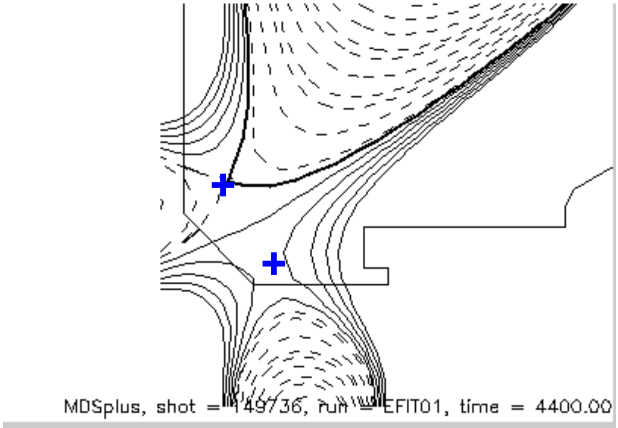
Snowflake-minus



Snowflake configurations obtained from the standard divertor using an algorithm developed at NSTX

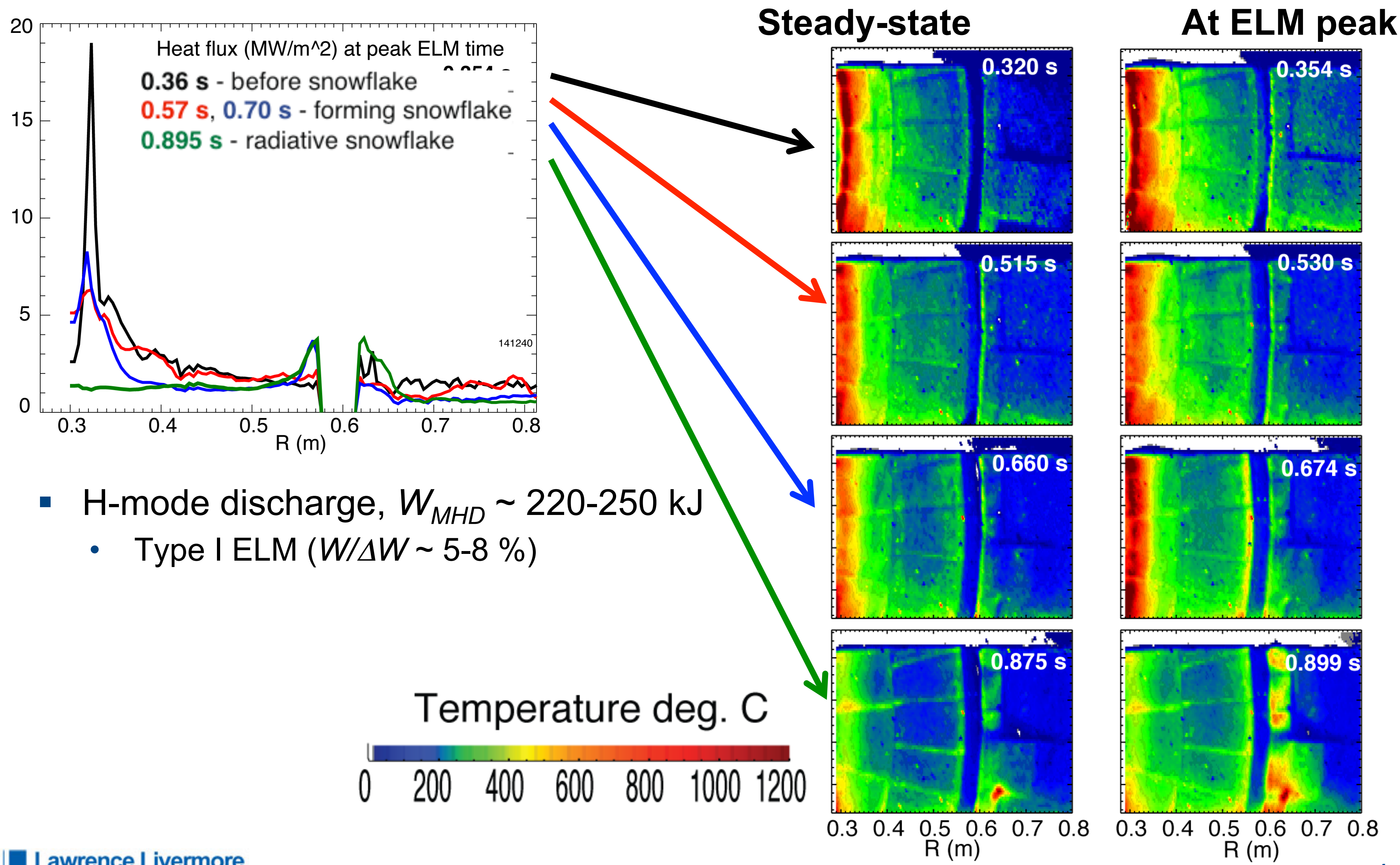






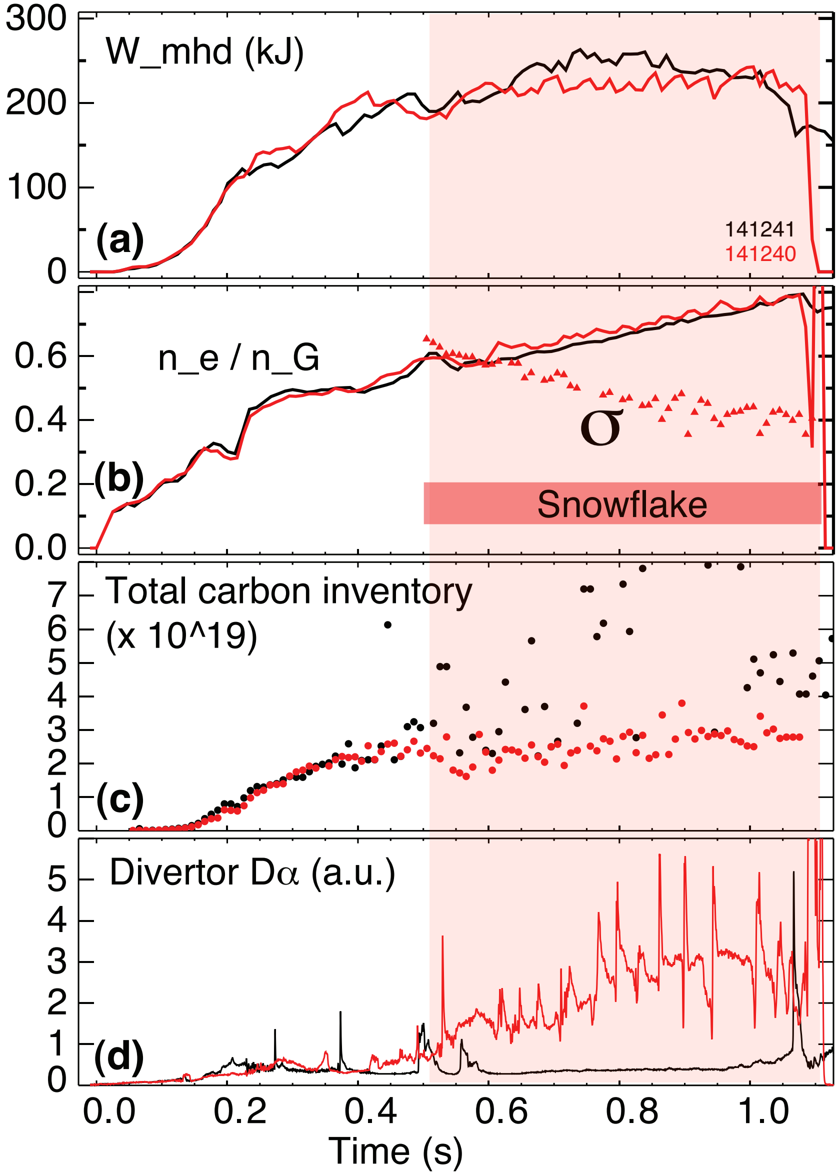
- Grad-Shafranov equilibria modeling of possible configurations
- Inner and outer strike point positions controlled by PCS using F4B and F8B coils
- Secondary null-point formed and pushed in using F5B

Impulsive heat loads due to Type I ELMs are mitigated in snowflake divertor



- H-mode discharge, W_{MHD} ~ 220-250 kJ
  - Type I ELM ($W/\Delta W$ ~ 5-8 %)

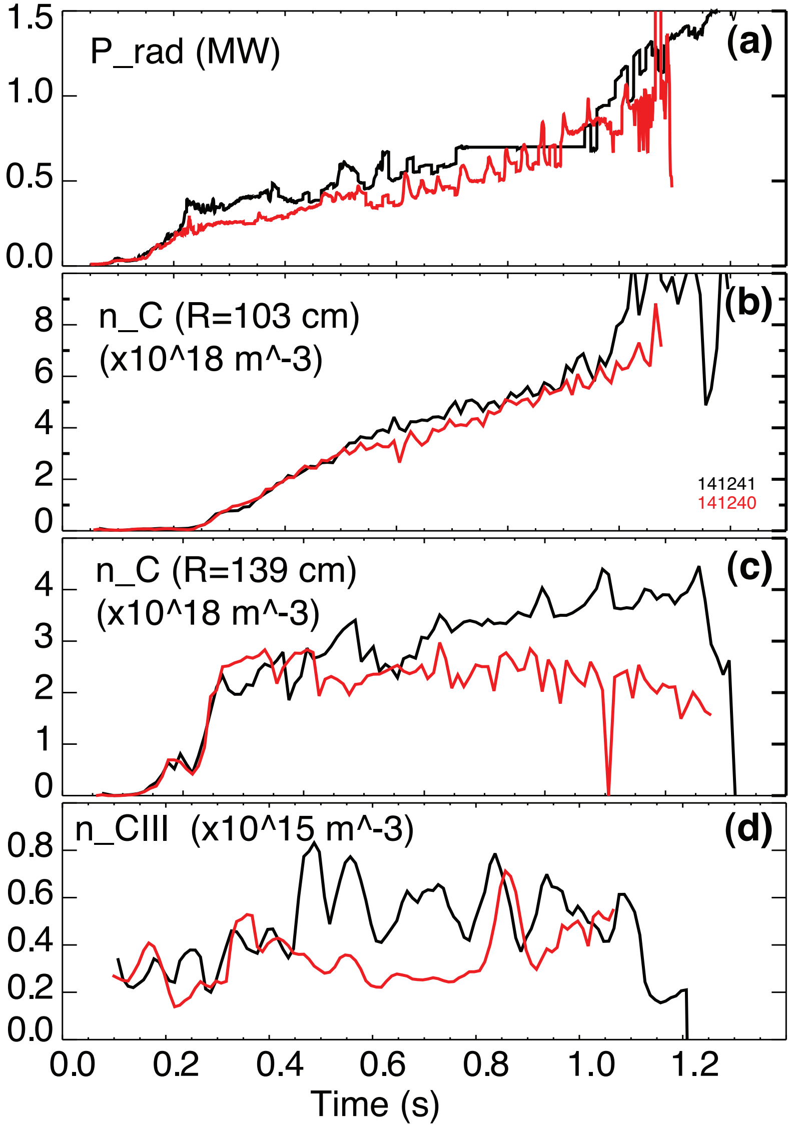
Good H-mode confinement properties and core impurity reduction obtained with snowflake divertor

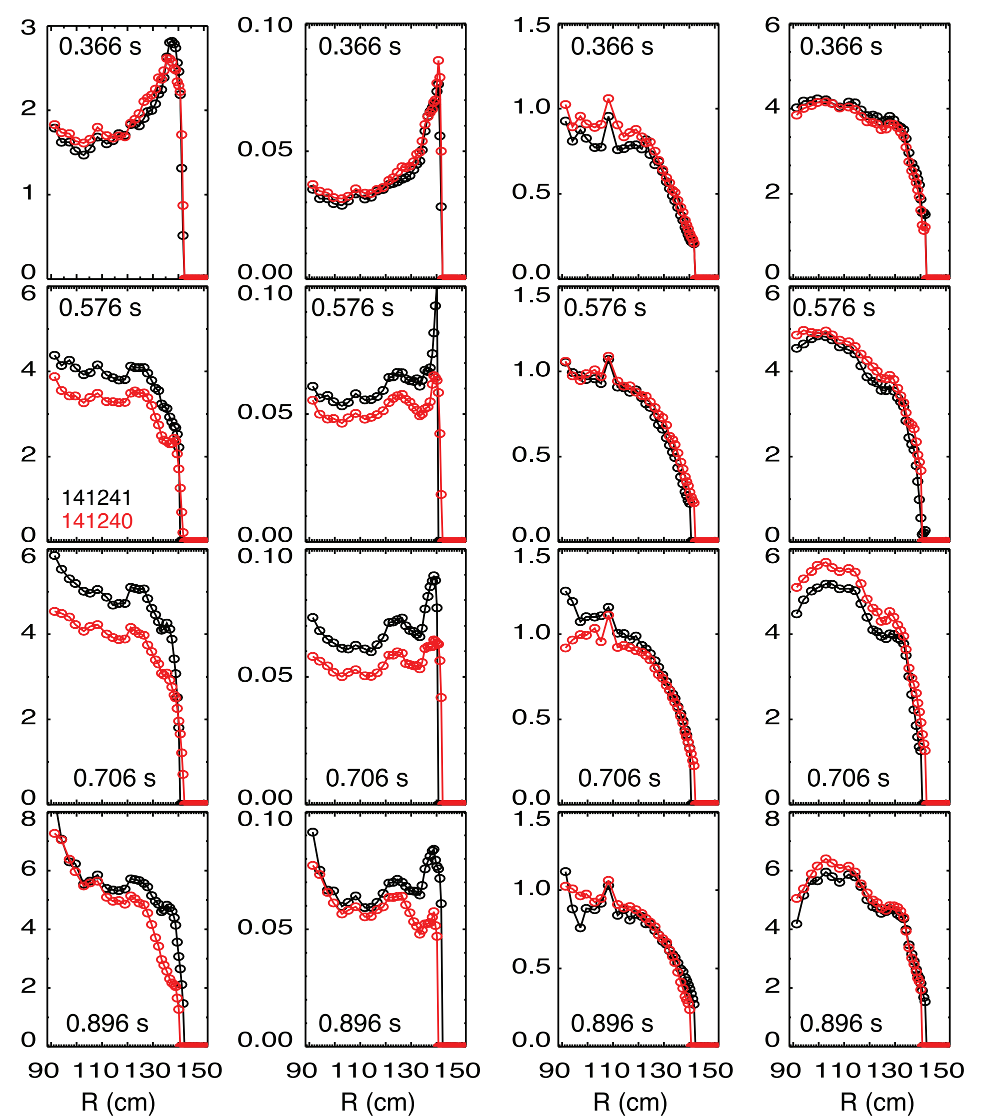


- 0.9 MA, 4 MW H-mode
- κ=2.1, δ=0.8
- Core T_e ~ 0.8-1 keV, T_i ~ 1 keV
- β_N ~ 4-5
- Plasma stored energy ~ 250 kJ
- H98(y,2) ~ 1 (from TRANSP)
- ELMs
  - Suppressed in standard divertor H-mode via lithium conditioning
  - Re-appeared in snowflake H-mode
- Core carbon reduction due to
  - Type I ELMs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

Core carbon density significantly reduced with snowflake divertor

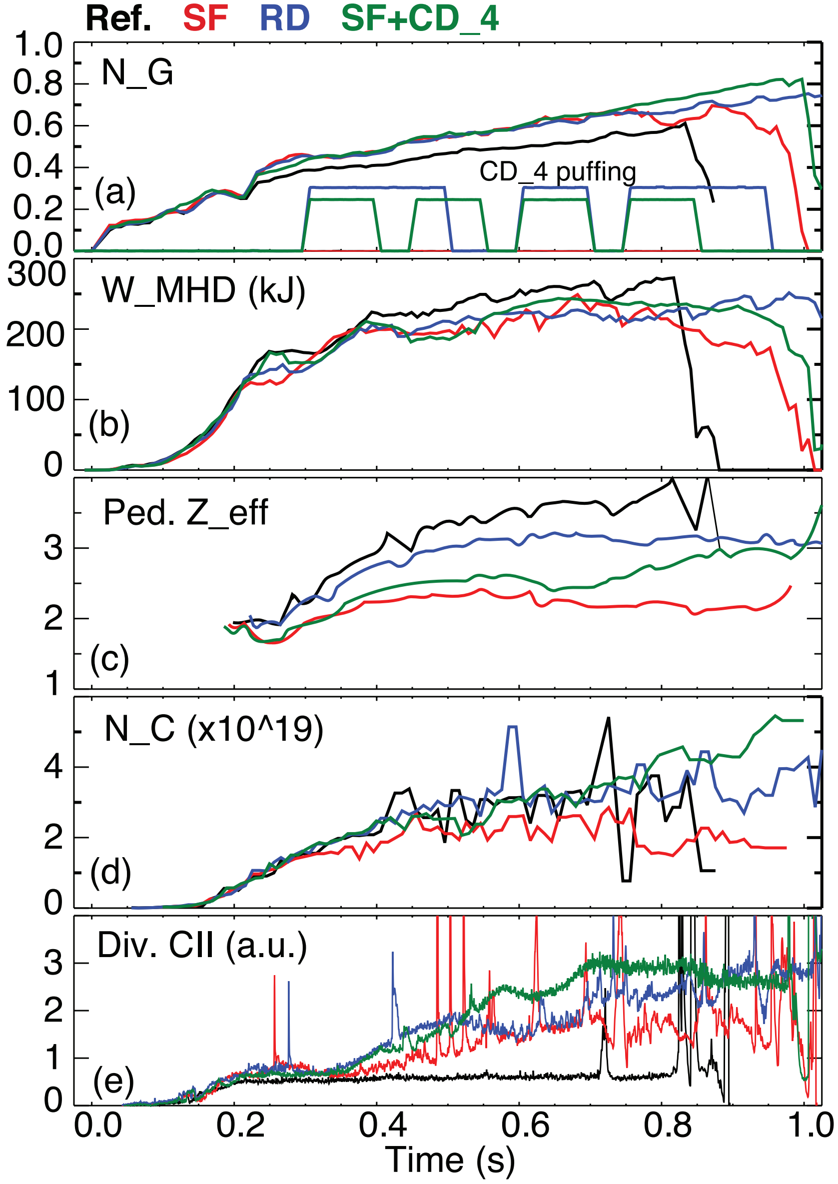
- **Standard divertor** **Snowflake**

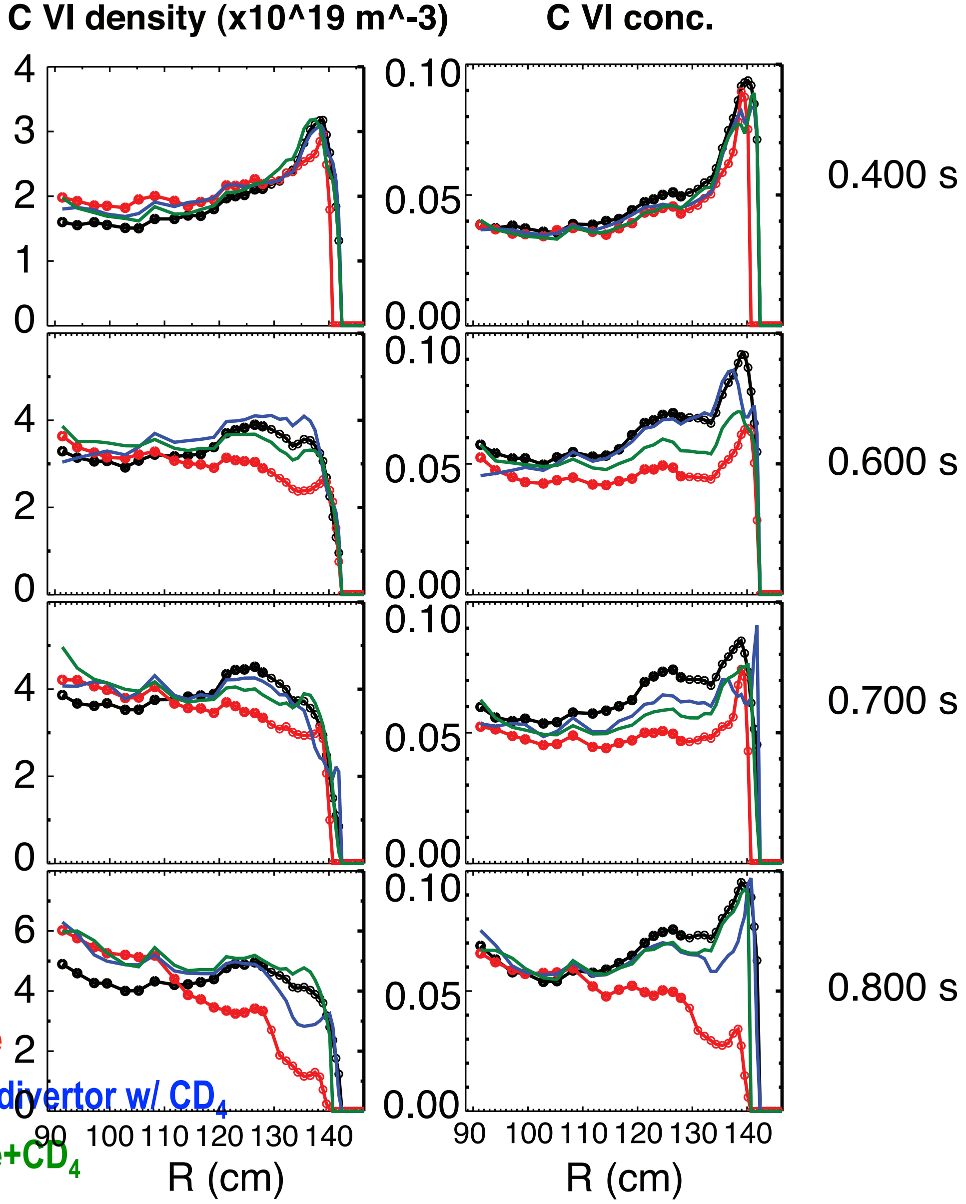




Good H-mode confinement properties retained or slightly reduced with CD_4-seeded snowflake divertor

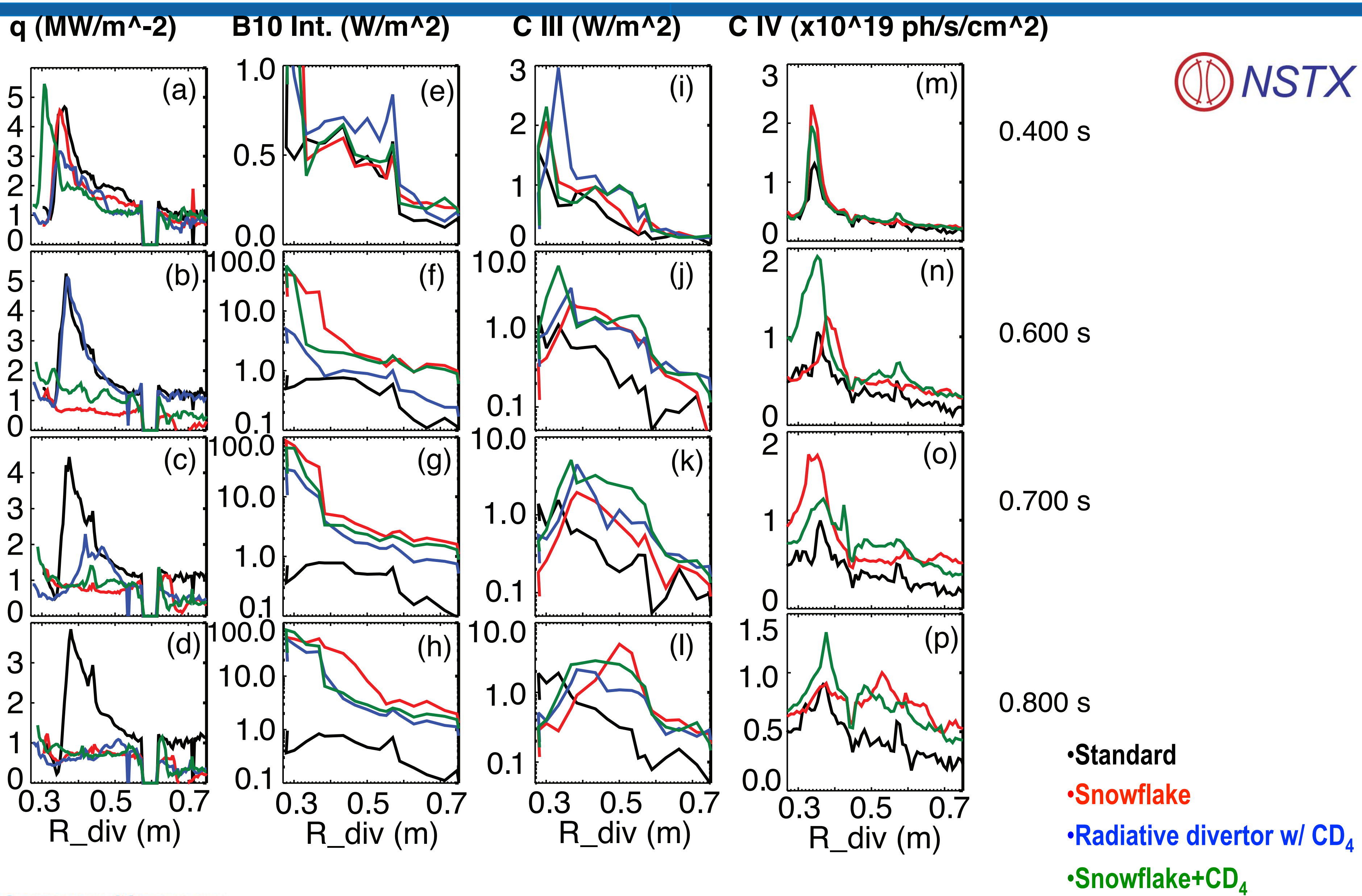
NSTX





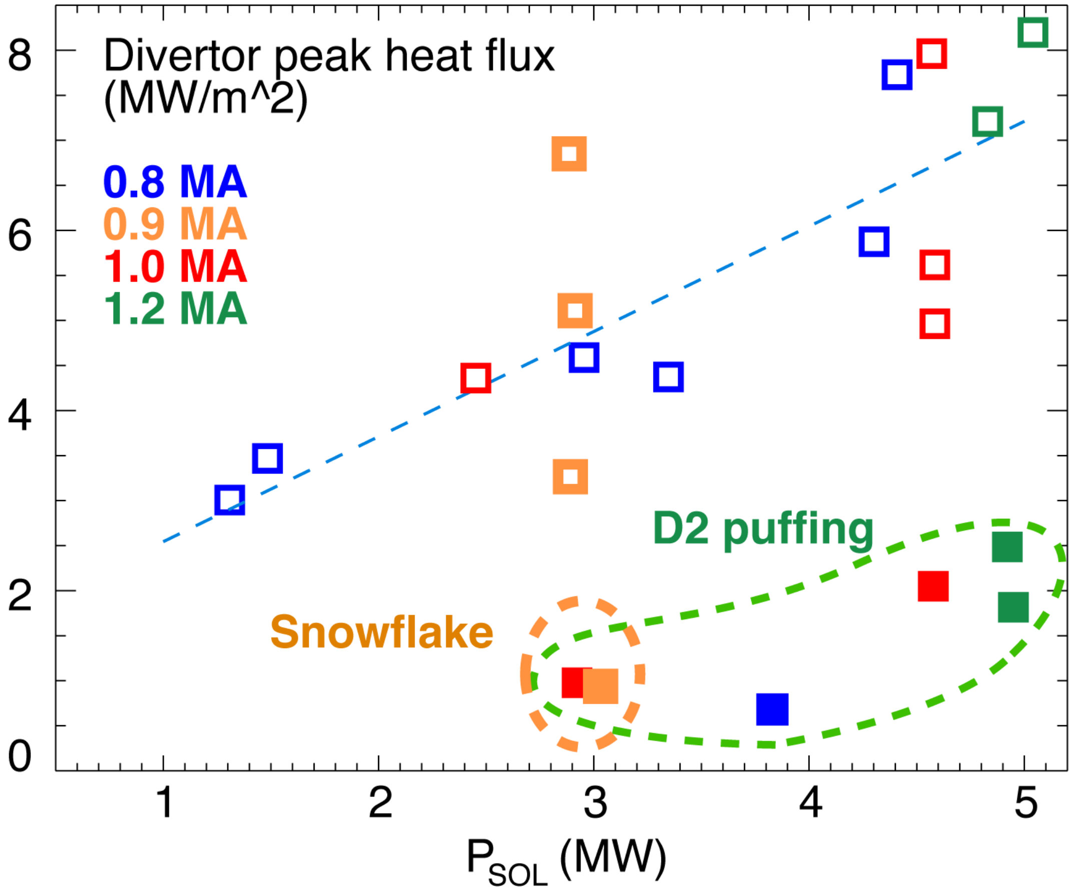
- **Standard**
- **Snowflake**
- **Radiative divertor w/ CD_4**
- **Snowflake+CD_4**

Divertor profiles show enhanced radiation and recombination zone in snowflake divertor w/ and w/o CD_4



NSTX

NSTX: Access to radiative detachment with intrinsic carbon in snowflake divertor facilitated

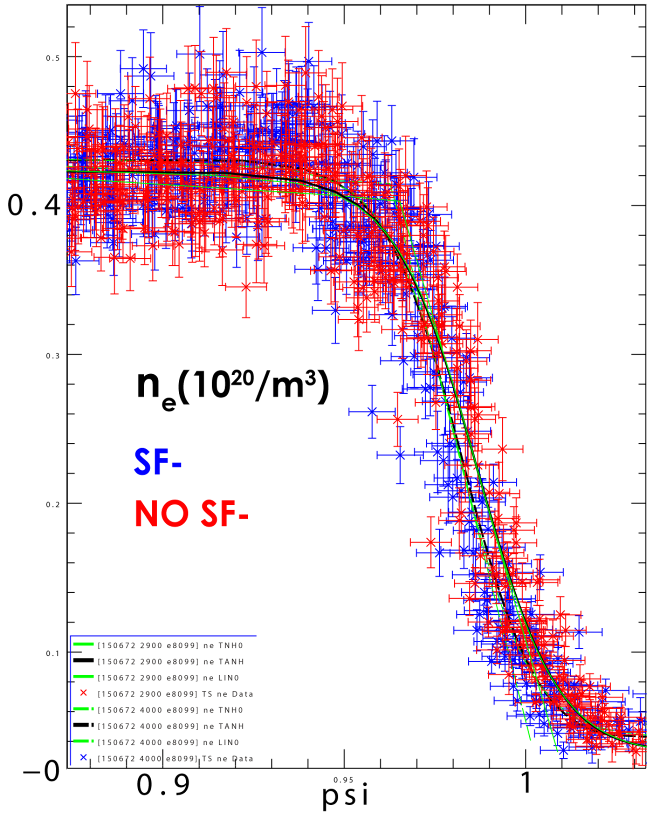


- Snowflake divertor (*): P_{SOL}~3-4 MW, f_{exp}~40-60, q_{peak}~0.5-1.5 MW/m^2
  - Low detachment threshold
  - Detachment characteristics comparable to PDD with D_2 or CD_4 puffing

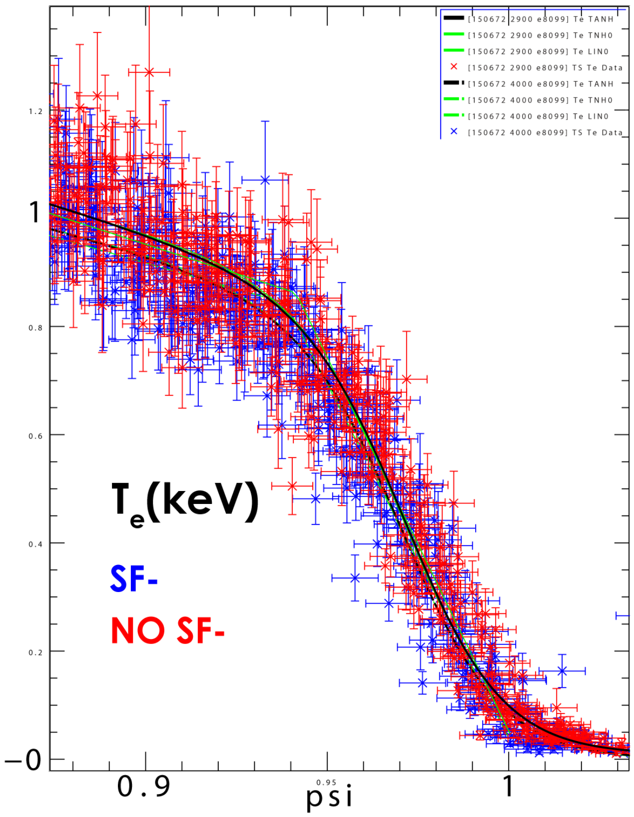
Pedestal profiles very similar with and without SF(-)

- Slightly steeper and higher n_e, lower and flatter T_e with SF-

Electron Density n_e

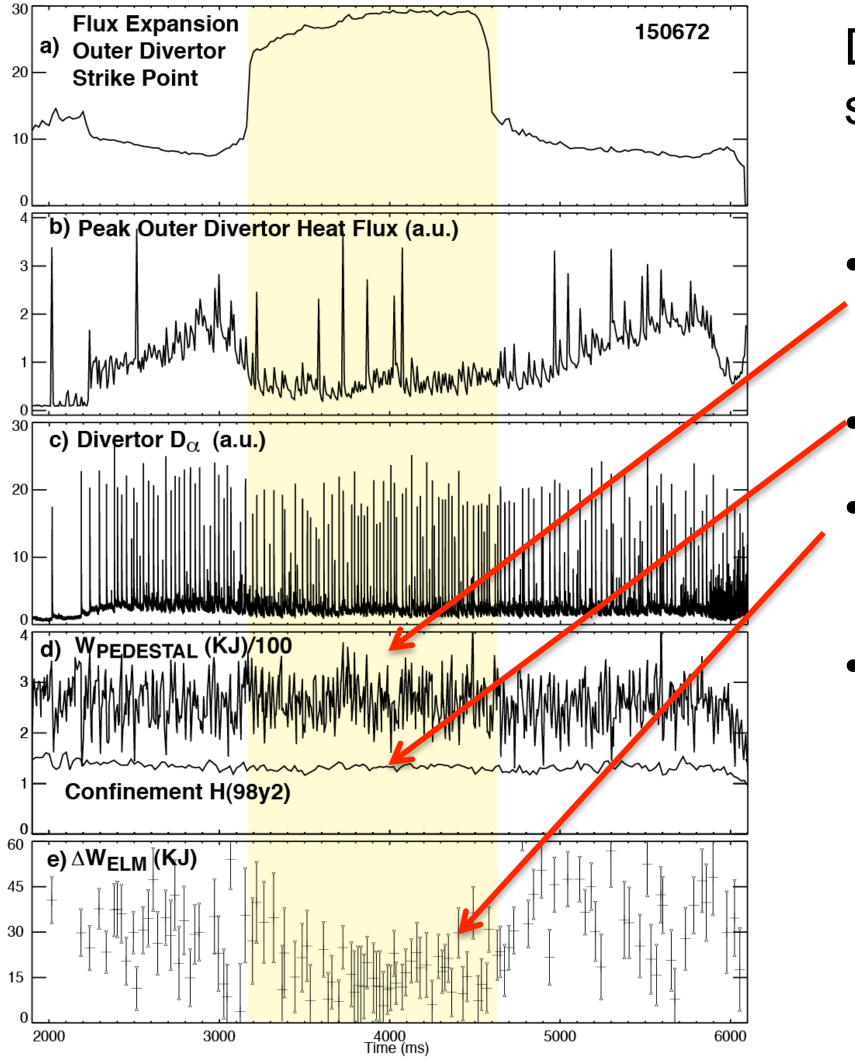


Electron Temperature T_e



S. L. Allen et al., Paper PD/1-2, IAEA FEC 2012.

Detailed ELM Analysis: ΔW(ELM) decreased, W pedestal constant in SF



Detailed ELM analysis before/during SF shows:

- **Pedestal Energy ($W_{PEDESTAL}$) Constant**
- **Confinement Constant**
- Change in stored energy lost per ELM (ΔW_{ELM}) is reduced
- Consistent with Loarte connection length scaling

S. L. Allen et al., Paper PD/1-2, IAEA FEC 2012.