Advanced divertor configurations with large flux expansion

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NSTX-U and TCV Research Teams

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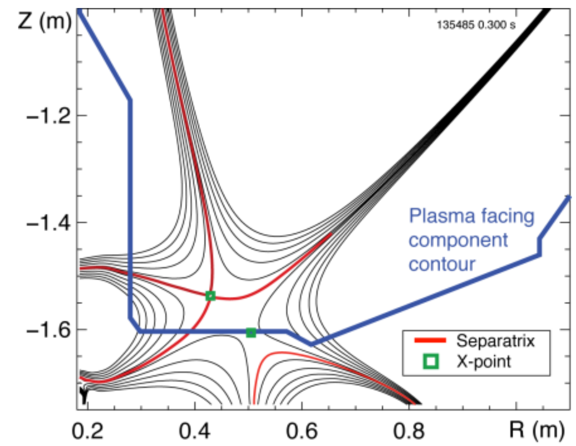
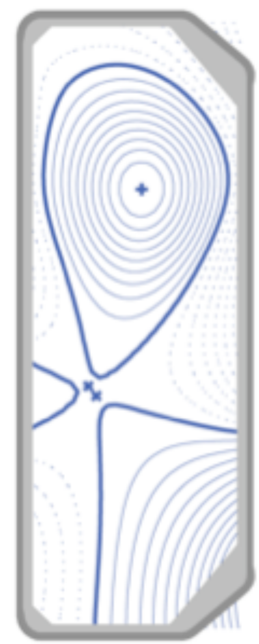
Outline: Experimental studies of snowflake divertor configuration in NSTX and TCV

- **Tokamak divertor challenge**
- **Snowflake divertor configuration**
- **Snowflake divertor in NSTX and TCV**
  - Magnetic properties and control
  - H-mode confinement and pedestal
  - Divertor heat flux mitigation and partitioning
  - Modeling
  - **Conclusions and outlook**





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

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

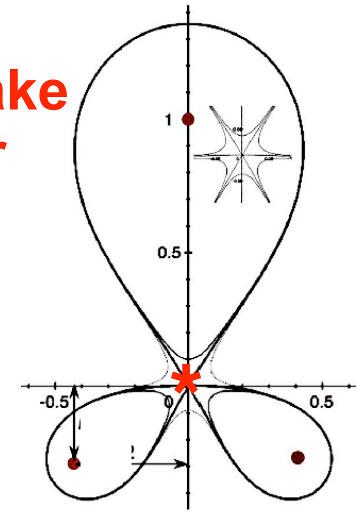
$$f_{exp} = \frac{(B_p/B_{tot})_{MP}}{(B_p/B_{tot})_{OSP}}$$

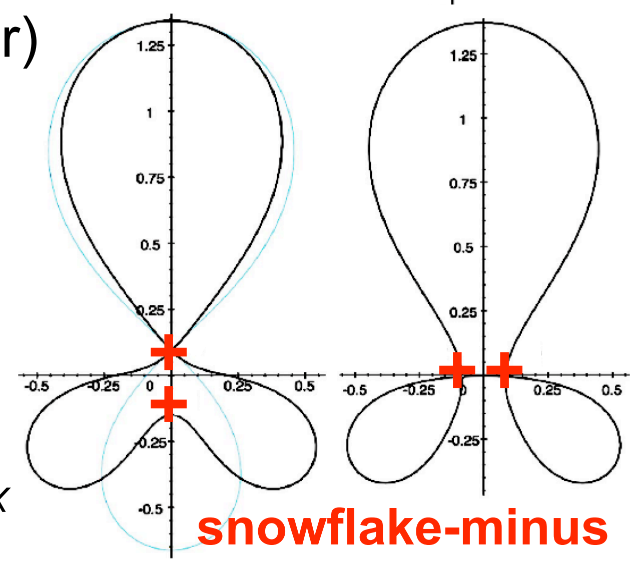
- Recent ideas to improve standard divertor geometry
  - Snowflake divertor (D. D. Ryutov, PoP 14, 064502 2007)
  - X-divertor (M. Kotschenreuther *et. al*, IC/P6-43, IAEA FEC 2004)
    - Local (strike point) flux expansion
  - Super-X divertor (M. Kotschenreuther *et. al*, IC/P4-7, IAEA FEC 2008)
    - Local (strike point) flux expansion at large R (major radius)
    - Being implemented in MAST Upgrade
    - See T. Petrie et al., Talk O36 on Friday, 25 May 2012

Snowflake divertor geometry is "advanced" w.r.t. standard X-point divertor

- 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
  - Deviation from ideal snowflake: $\sigma = d / a$
    - *d* – distance between nulls, *a* – plasma minor radius
- Predicted geometry properties (cf. standard divertor)
  - 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_{II}
  - Larger X-point connection length L_x : reduce q_{II}
  - Larger effective divertor volume V_{div} : incr. P_{rad} , P_{CX}
- Experiments: TCV and NSTX

Exact snowflake divertor





snowflake-minus

snowflake-plus

D. D. Ryutov, PoP 14, 064502 2007

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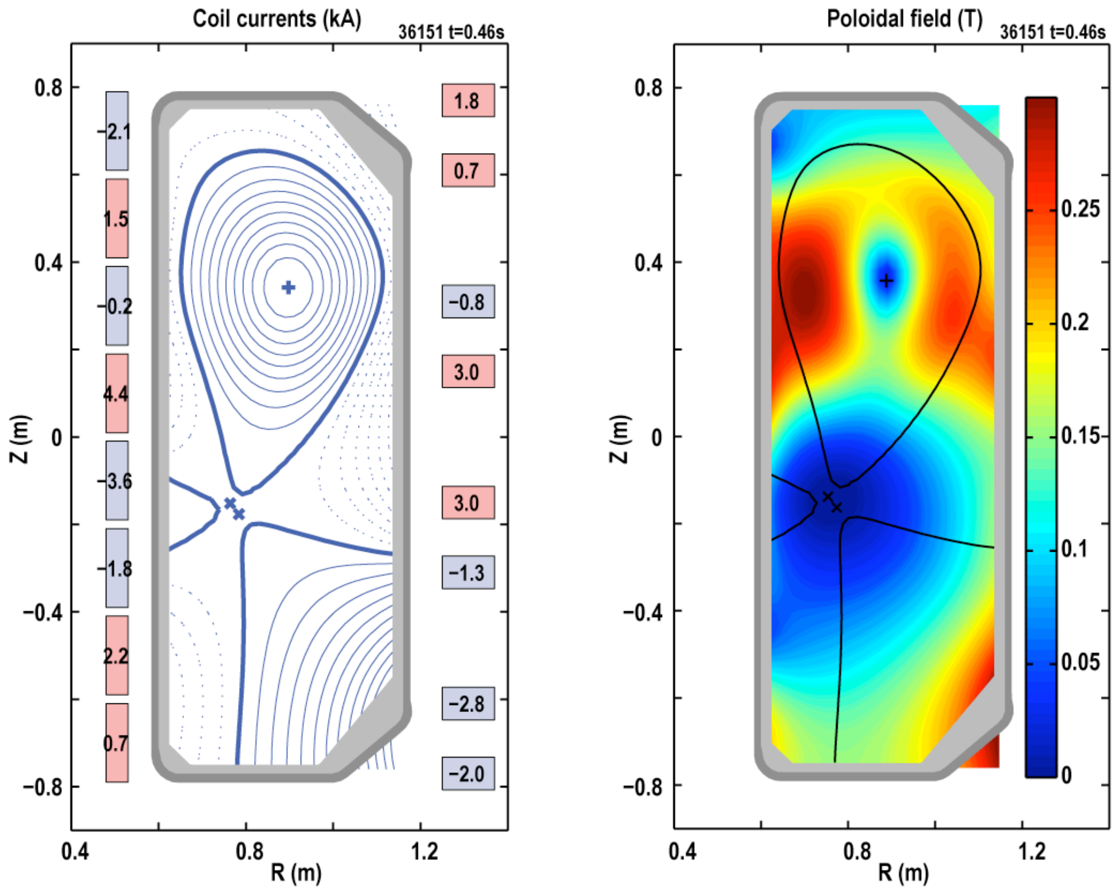
NSTX and TCV: Snowflake divertor configurations obtained with existing divertor coils

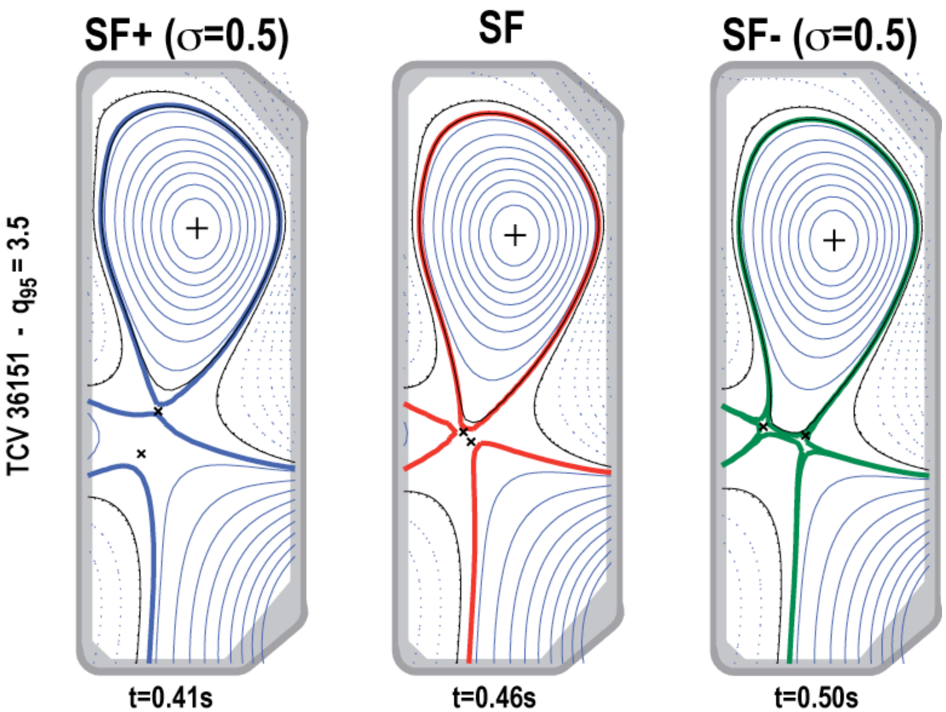


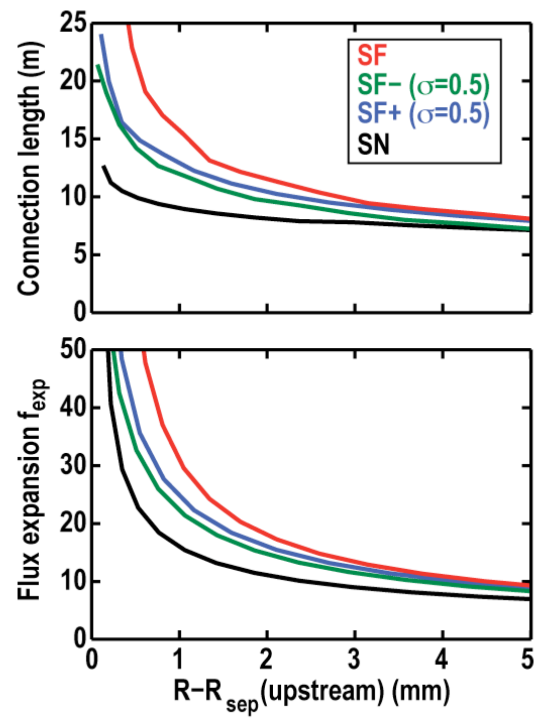
TCV

- Conventional aspect ratio A=3.5-3.7
- $I_p \leq 1.0$ MA, $B_T \leq 1.5$ T
- $P_{in} \leq 4.5$ MW (ECH)
- Graphite PFCs
- Open divertor (not optimized)
- Create magnetic configuration (SF, SF+, SF-) with shaping coils

TCV: Investigate the characteristics of the entire range of snowflake configurations

[F. Piras, et al., *Plasma Phys. Control. Fusion.* **51** (2009) 055009]





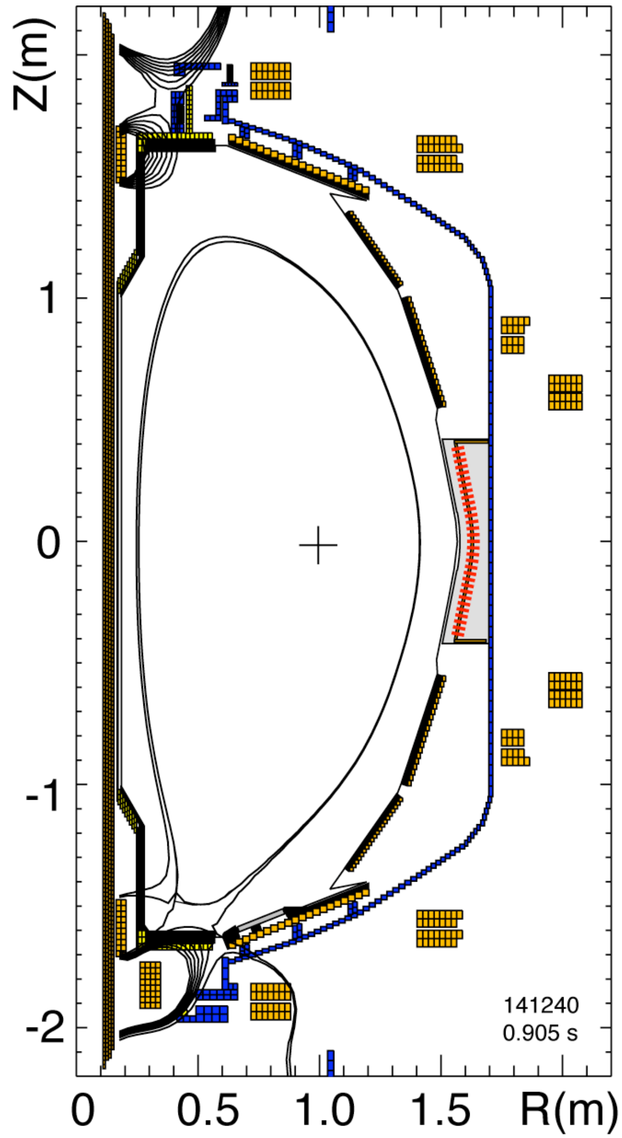
- Evaluate f_{exp} and CL at location of max. f_{exp}

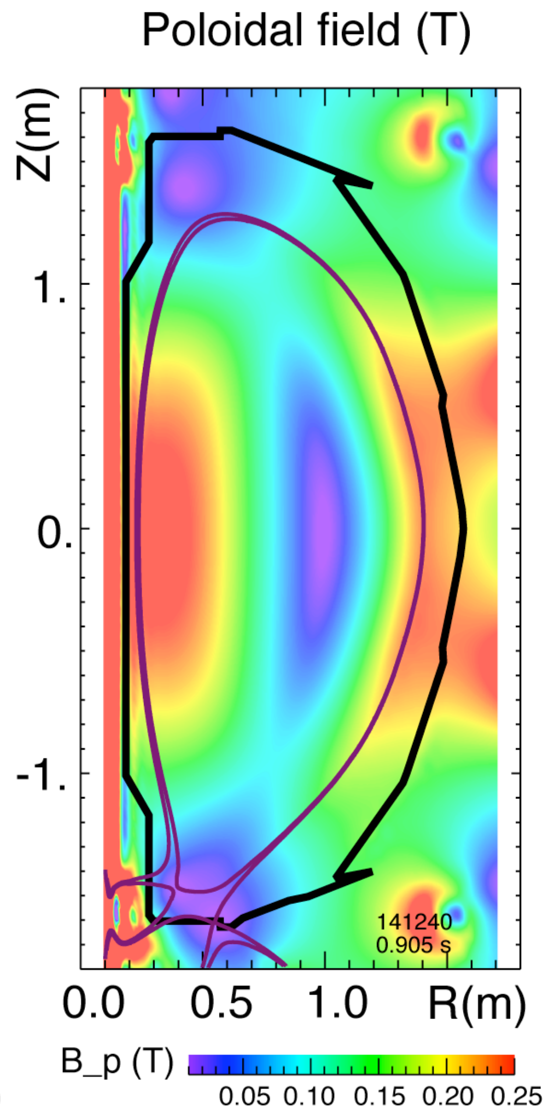
- Variable configuration: vary location of X-points over a wide range
  - All configurations are obtained under feed-forward control
  - Experiments have so far focused on SF+
- Investigate possibility to distribute exhaust power on more than the two strike points

NSTX and TCV: Snowflake divertor configurations obtained with existing divertor coils

NSTX

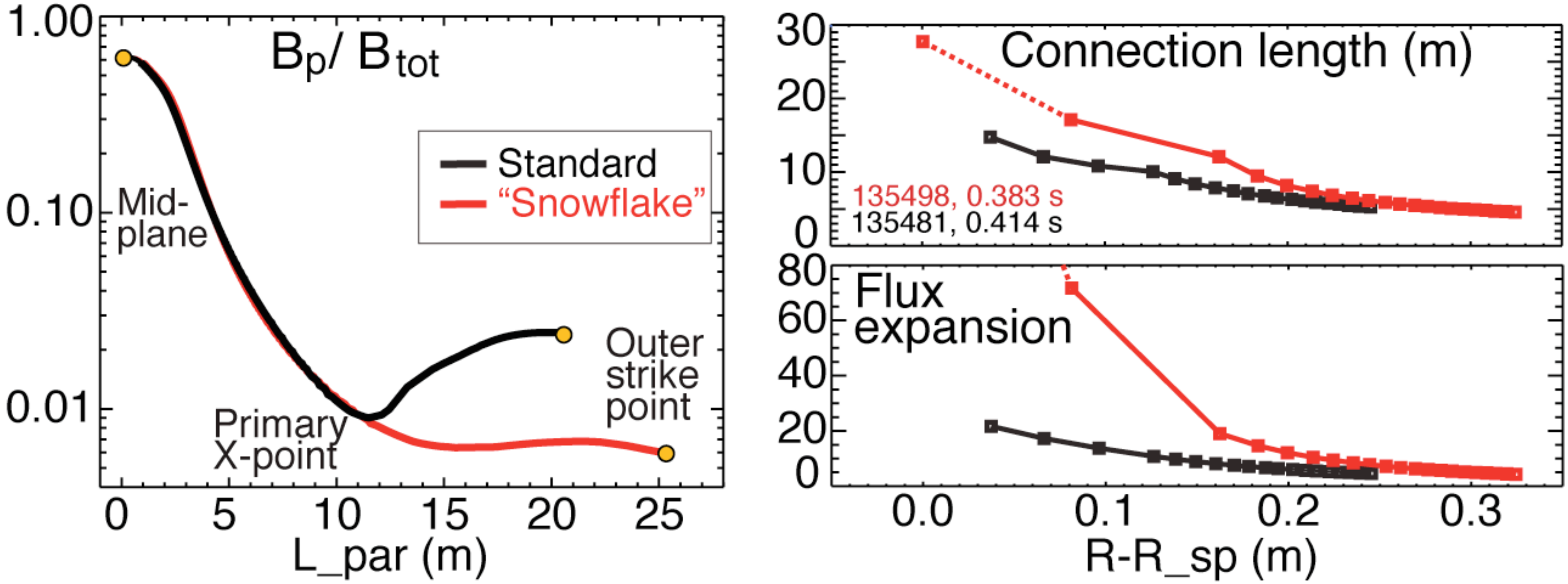
- Aspect ratio A=1.4-1.5
- $I_p \leq$ 1.4 MA, B_T= 0.45 T
- $P_{in} \leq$ 7.4 MW (NBI)
- λ_q = 5-10 mm
- High divertor heat flux
  - $q_{peak} \leq$ 15 MW/m^2
  - $q_{||} \leq$ 200 MW/m^2
- Open divertor
- Graphite PFCs with lithium coatings
- Asymmetric snowflake-minus σ = 0.4-0.5





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

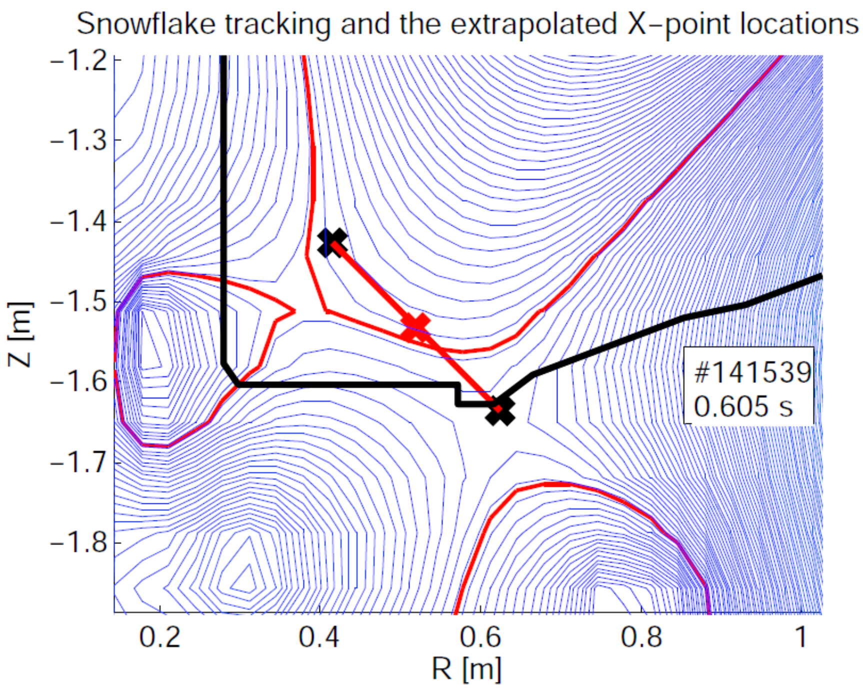
NSTX



- 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

Close-loop feedback control of divertor coil currents is desirable for steady-state snowflake

NSTX



M.A. Makowski & D. Ryutov, "X-Point Tracking Algorithm for the Snowflake Divertor"

- All configurations are obtained reproducibly under feed-forward control in TCV and NSTX
- In NSTX
  - Developed X-point tracking algorithm that locates nulls and centroid
  - Algorithm tested on NSTX snowflakes successfully
  - Implementing snowflake control in digital plasma control system
    - Collaboration between NSTX-U and DIII-D

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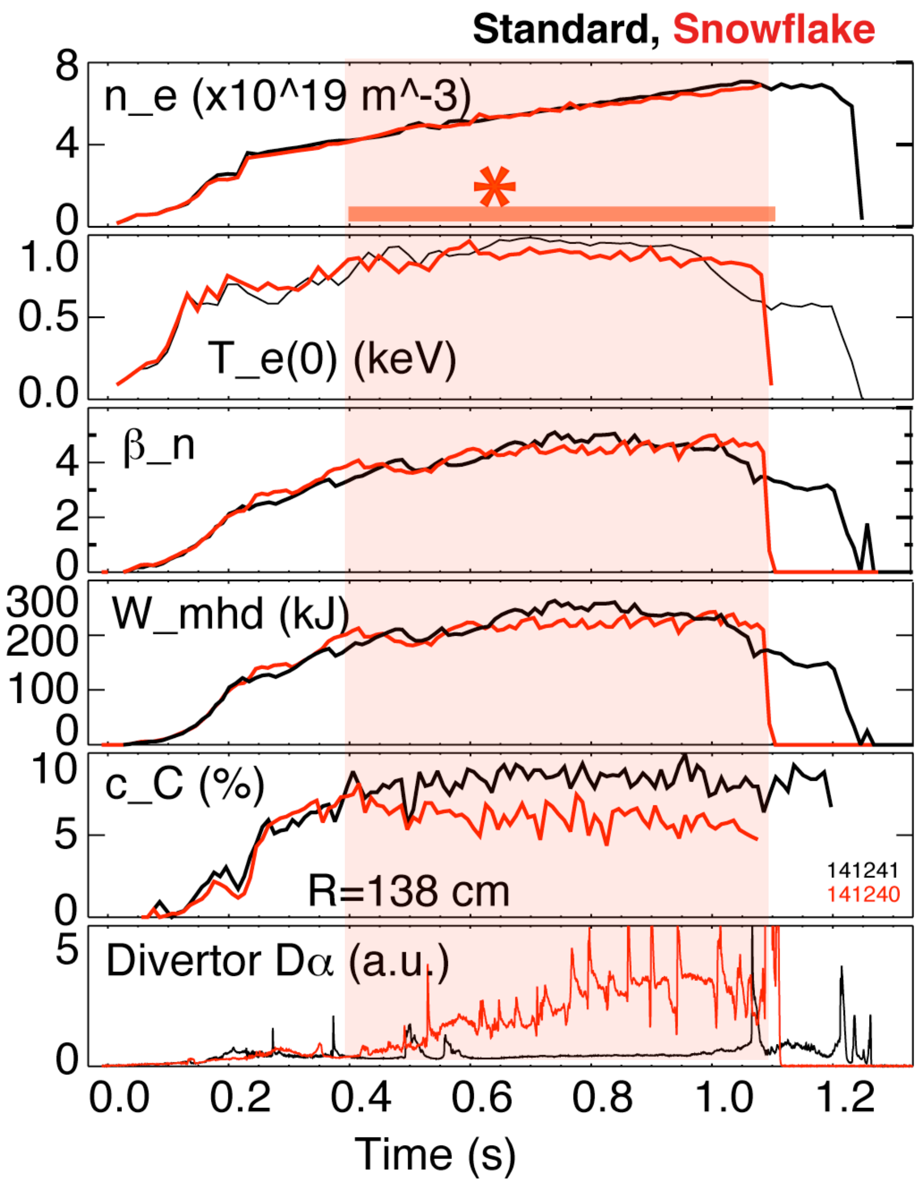
NSTX: good H-mode confinement properties and core impurity reduction obtained with snowflake divertor

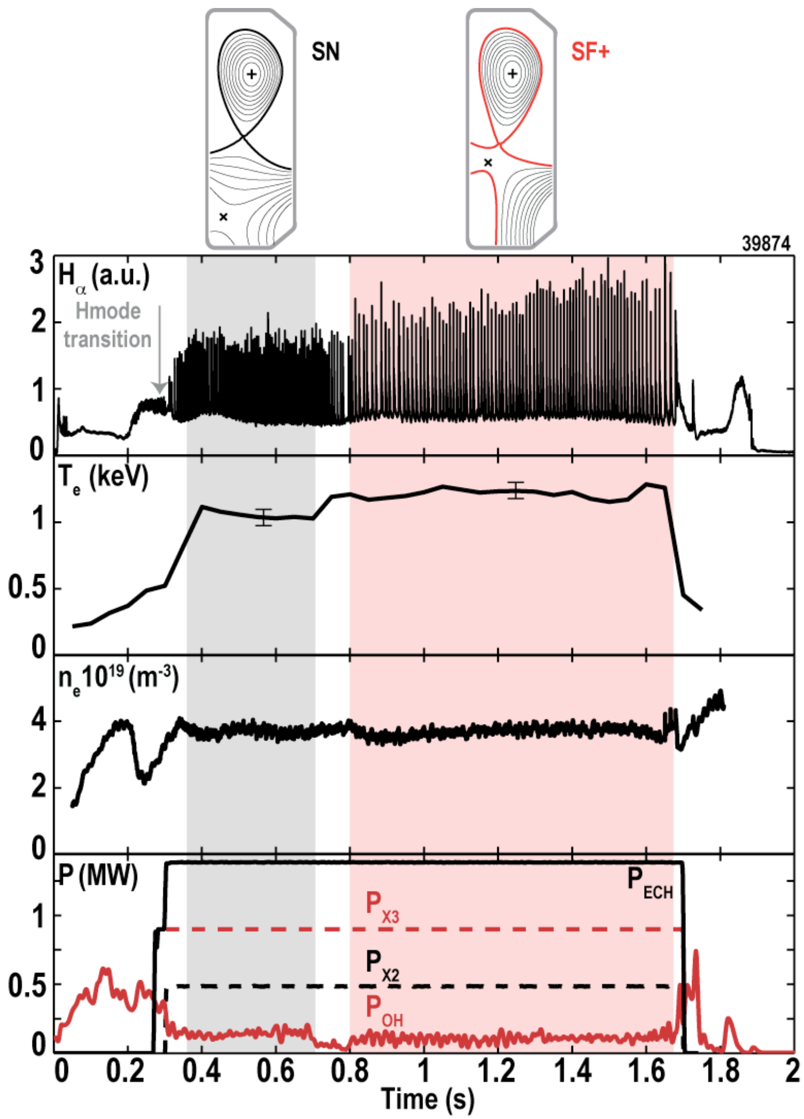


NSTX

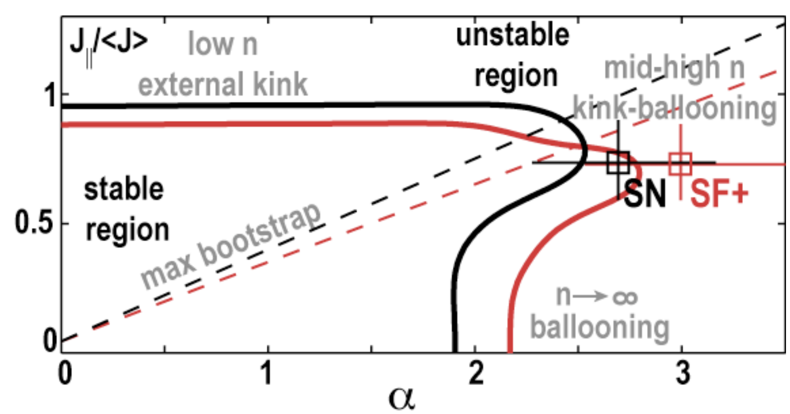
- 0.8 MA, 4 MW H-mode
- κ=2.1, δ=0.8
- Core T_e ~ 0.8-1 keV, T_i ~ 1 keV
- β_N ~ 4-5
- Plasma stored energy ~ 250 kJ
- H98(y,2) ~ 1 (from TRANSP)
- ELMs
  - Suppressed in standard divertor H-mode via lithium conditioning
  - Re-appeared in snowflake H-mode
- Core carbon reduction due to
  - Type I ELMs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

TCV: Snowflake configuration leads to an improved kink-ballooning stability

[F. Piras, et al., *Phys. Rev. Lett.* **105** (2010) 155003]



- H-mode threshold unchanged (power and density dependence)
- Modest confinement improvement (may be due to increased core shaping)
- Frequency of type-I ELMs decreases
  - Experiment consistent with improved kink-ballooning stability
  - Even though energy loss per ELM increase, the average energy lost through ELMs decreases significantly



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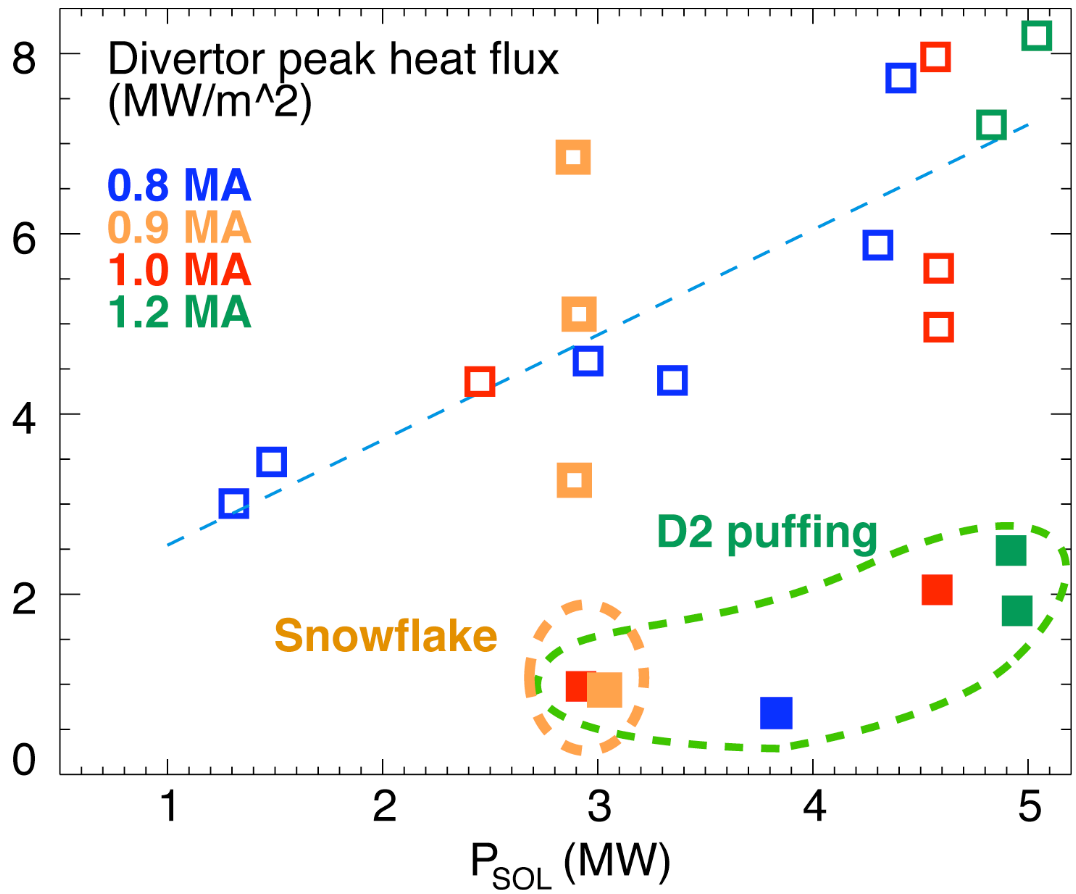
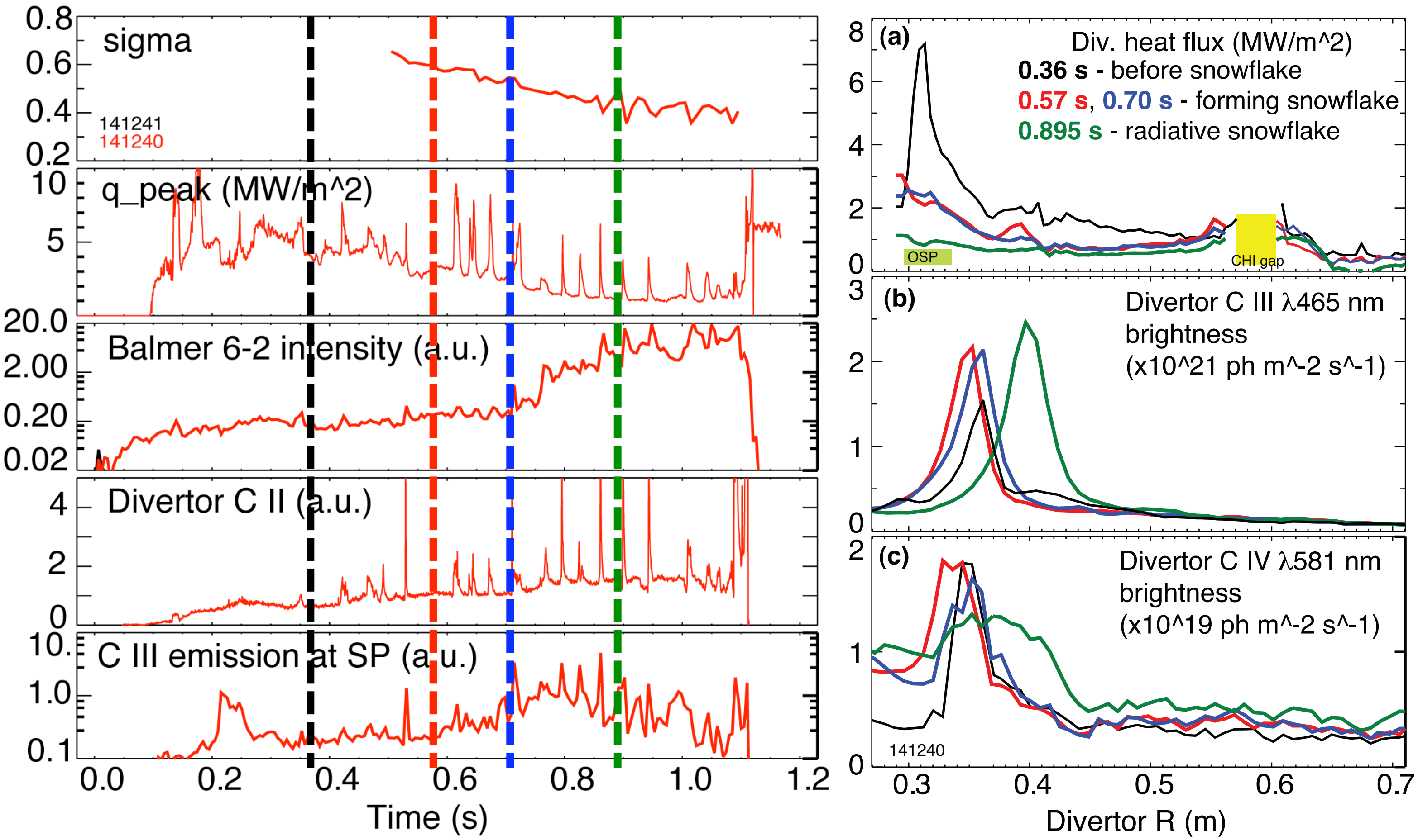
NSTX: Access to radiative detachment with intrinsic carbon in snowflake divertor facilitated



NSTX

- 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

NSTX: Significant reduction of divertor heat flux observed between ELMs in snowflake divertor



NSTX

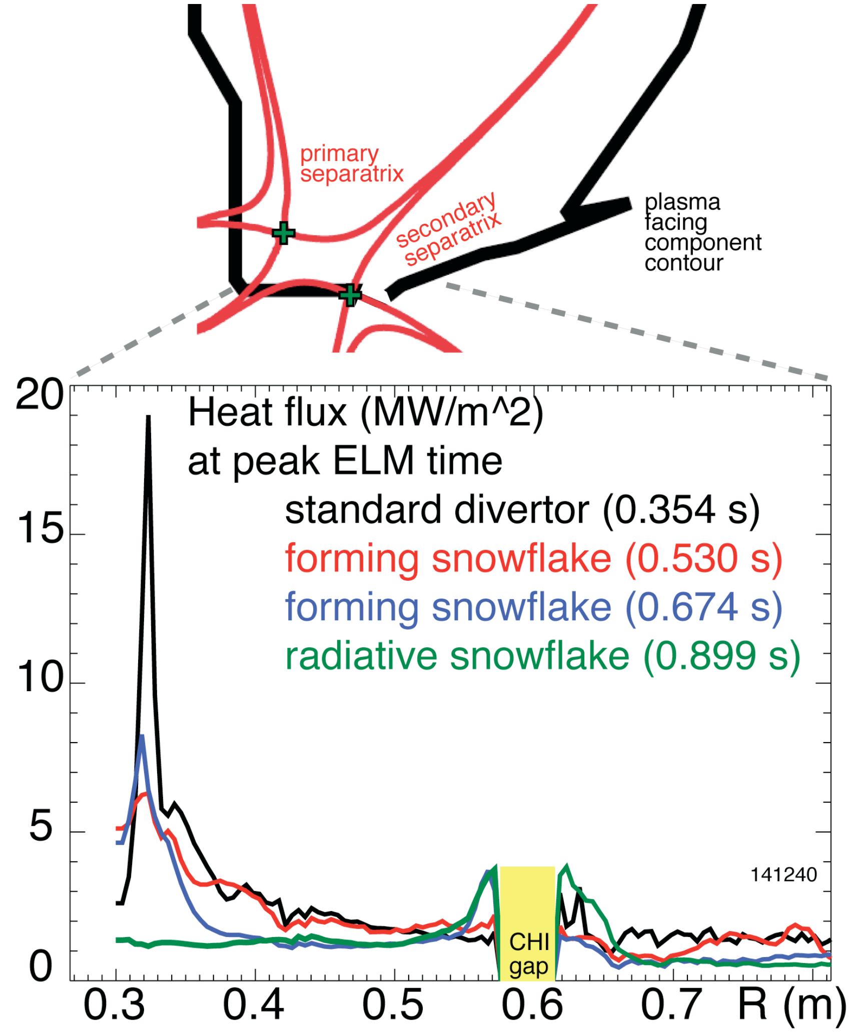
- Divertor C III and C IV brightness profiles broaden

- **Attached standard divertor** -> **snowflake transition** -> **snowflake + detachment**
- P_{SOL} ~ 3 MW (P_{NBI} = 4 MW)
- Q_{div} ~ 2 MW -> Q_{div} ~ 1.2 MW -> Q_{div} ~ 0.5-0.7 MW

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

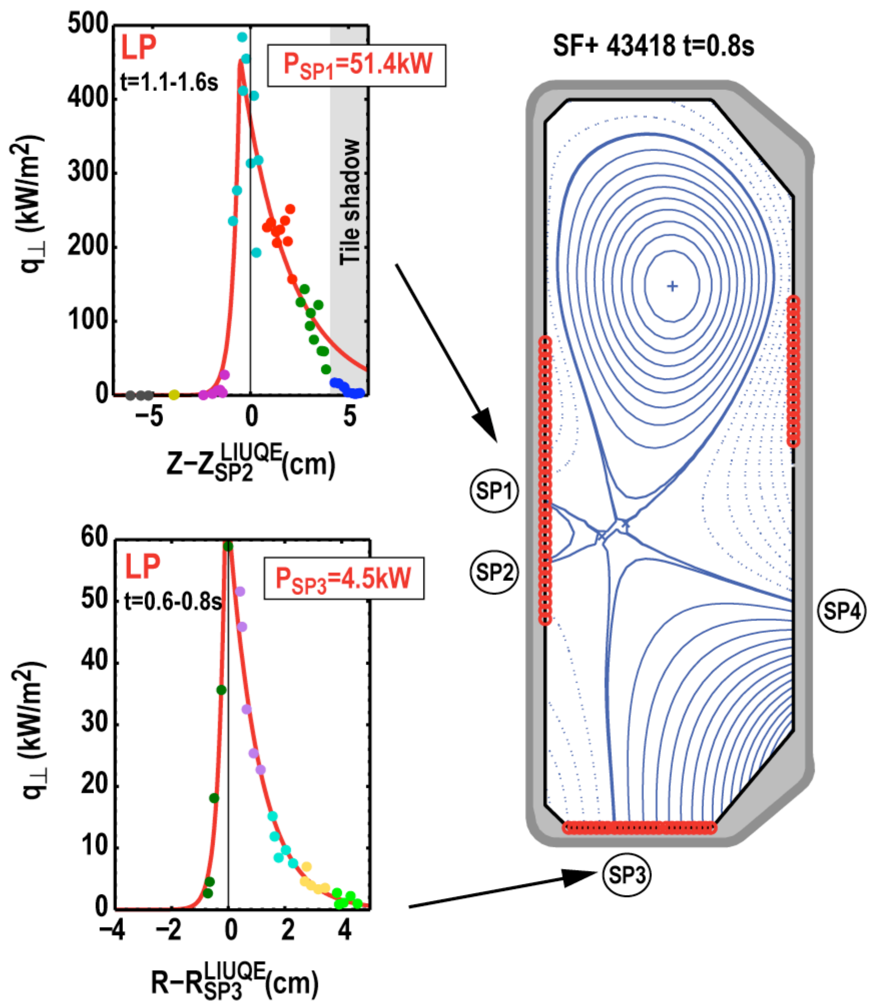
NSTX

- H-mode discharge, W_{MHD} ~ 220-250 kJ
  - Type I ELM ($\Delta W/W$ ~ 5-8 %) re-appeared
- ELM peak heat flux decreased
- Theory and modeling highlight (T. D. Rognlien *et al.*, P1-031)
  - Reduced surface heating due to increased ELM energy deposition time
  - Convective mixing of ELM heat flux in null-point region -> heat flux partitioning between separatrix branches

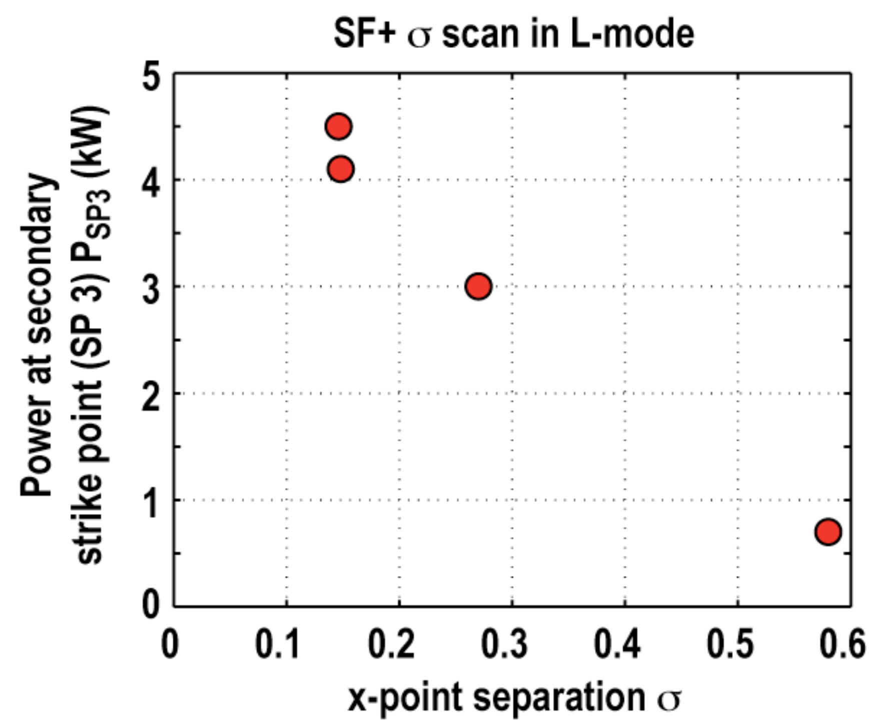


TCV: In L-mode σ has to be small to activate a secondary strike point

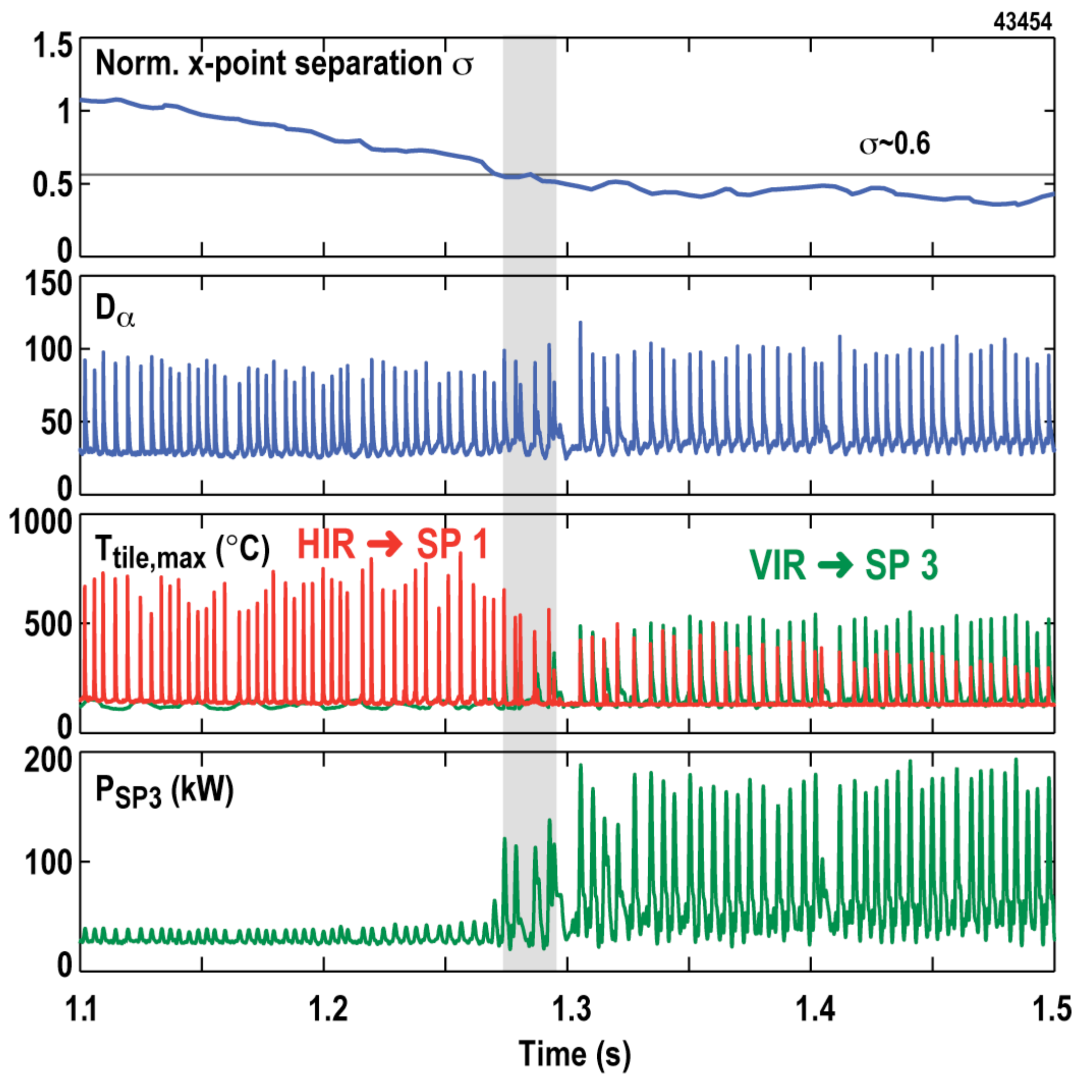
- Heat flux estimate from Langmuir probes (LP)



- SF+ configuration: secondary strike points are in the private flux region of the primary separatrix
- Sigma scan in Ohmic L-mode shows activation of the secondary strike points (P_{SP3}/P_{SP1}~10%) only for small values of sigma (σ<0.2)



TCV: ELMs activate secondary strike points at larger values of σ



- Measure transient heat fluxes during ELMs in ECH H-modes with fast infra-red (IR) cameras
  - Sampling time ≥ 40μs
- Secondary strike point (SP3) receives significant power at relatively large values of sigma
- Power redistribution during ELMs consistent with poloidal beta-driven convection around the null-point

  [D.D. Ryutov, et al., APS DPP 2011]

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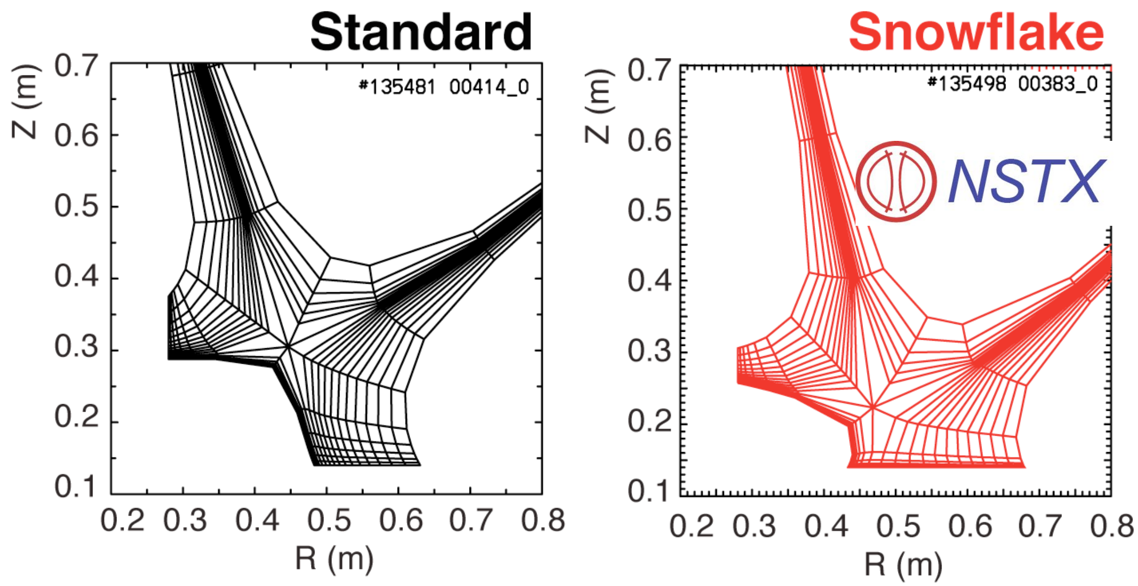
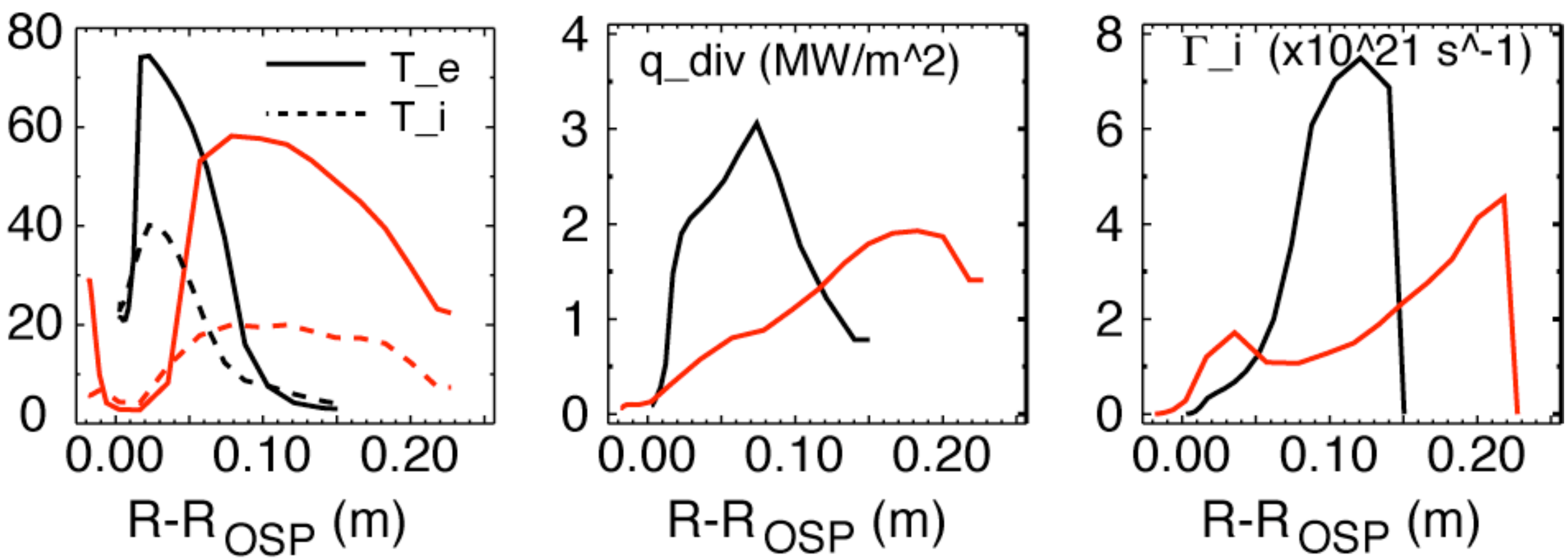
UEDGE modeling shows a trend toward reduced temperatures, heat and particle fluxes in snowflake divertor

- 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
- $n_e = 4.5 \times 10^{19}$

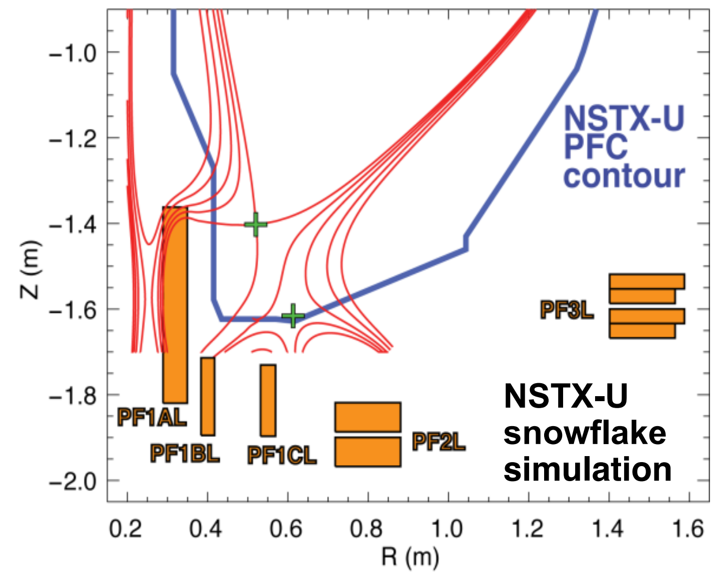
R_{recy} = 0.95
Carbon 3 %

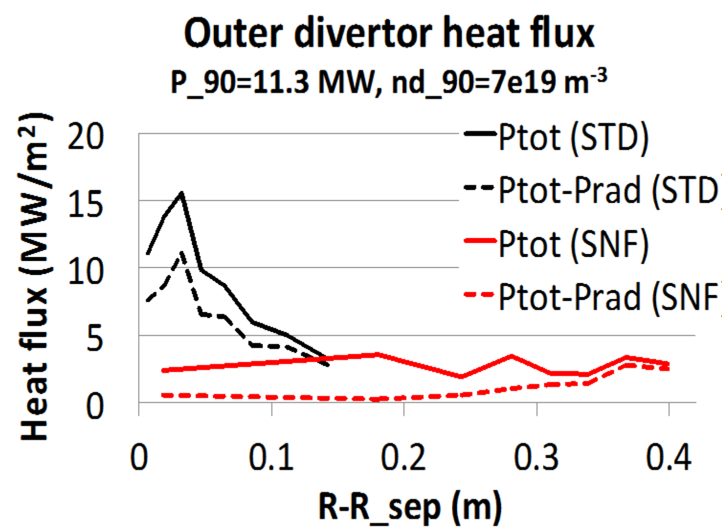


Snowflake geometry is a leading heat flux mitigation candidate for NSTX-U

NSTX-U

- Challenge for NSTX-U divertor
  - 2-3 X higher input power (P_{NBI} < 12 MW, I_p < 2 MA
  - 30-50 % reduction in n/n_G
  - 3-5 X longer pulse duration
- Projected NSTX-U peak divertor heat fluxes up to 25-40 MW/m^2
- Snowflake divertor projections to NSTX-U optimistic
  - UEDGE modeling shows radiative detachment of all snowflake cases with 3% carbon and up to P_{SOL}~11 MW
  - q_{peak} reduced from ~15 MW/m^2 (standard) to 0.5-3 MW/m^2 (snowflake)





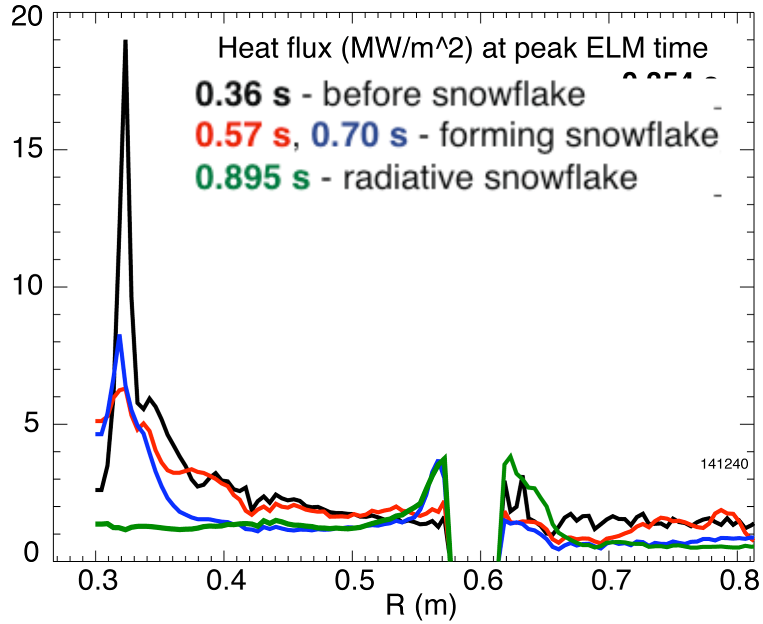
TCV and NSTX studies suggest the snowflake divertor configuration may be a viable divertor solution for present and future tokamaks

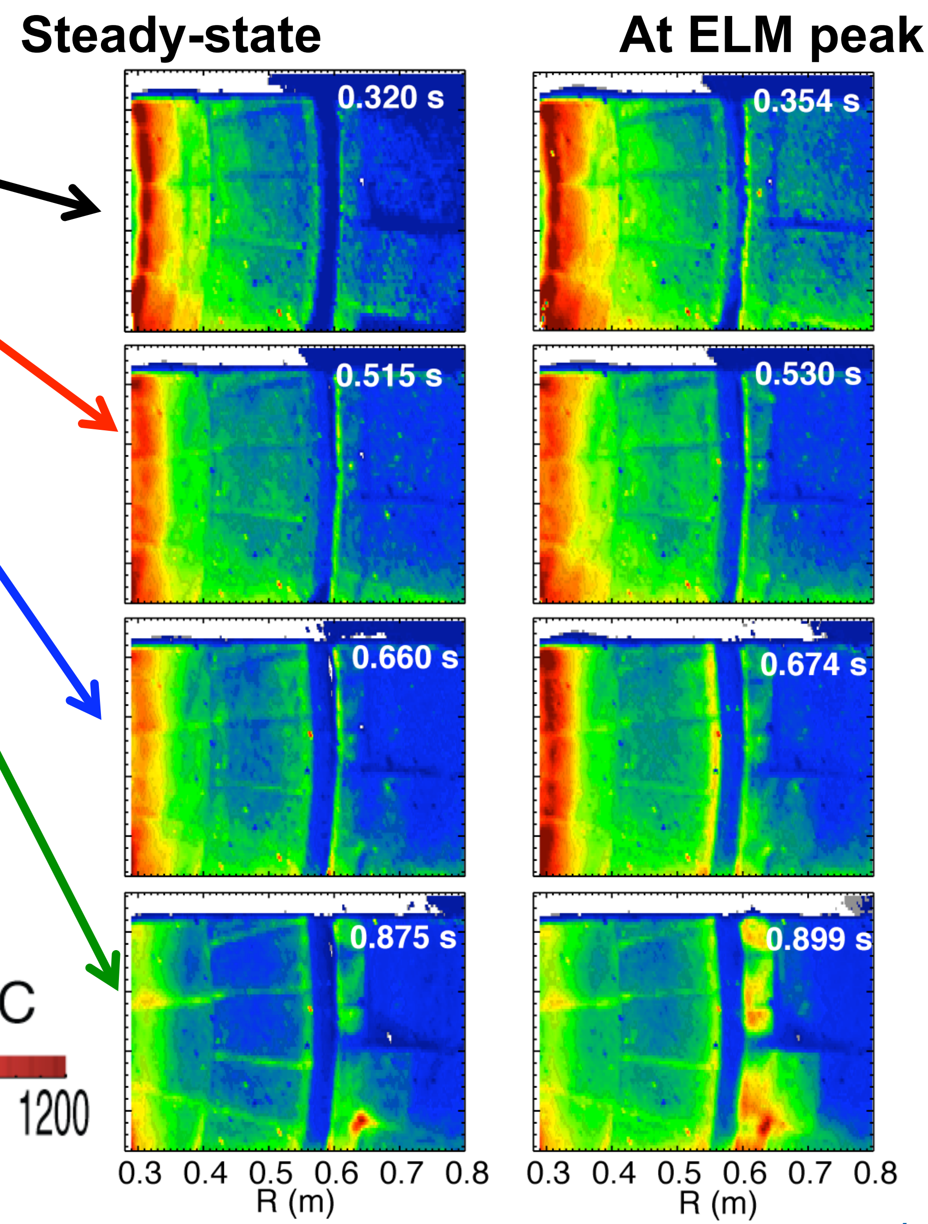
- **NSTX**
  - Core H-mode confinement unaffected, core carbon reduced
  - Pedestal stability modified: Type I ELMs re-appeared
  - Divertor heat flux significantly reduced
    - » Steady-state reduction due to geometry and radiative detachment
    - » ELM heat flux reduction due to power sharing, radiation and geometry
  - Proposing experiments and control development at DIII-D, planning snowflake divertor for NSTX-U
- **TCV**
  - Can create a wide range of snowflake configurations
  - Heat flux at a secondary strike point increases with decreasing σ
  - ELMs activate secondary strike point at larger values of σ
  - Improved edge stability leading to less frequent Type I ELMs
  - Current upgrades will improve heat flux measurements at the target
    - Additional Langmuir probe array will also cover LFS strike point
    - Improved IR system will allow ELM resolved measurements

Backup slides

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

NSTX





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