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Snowflake Divertor as Plasma-Material Interface for Future High Power Density Fusion Devices

V. A. Soukhanovskii, R. E. Bell, S. P. Gerhardt, S. Kaye, E. Kolemen, B. P. LeBlanc, E. T. Meier, J. E. Menard, A. G. McLean, T. D. Rognlien, D. D. Ryutov, F. Scotti, A. Diallo, R. Kaita, R. Maingi, M. Podesta, R. Raman, A. L. Roquemore

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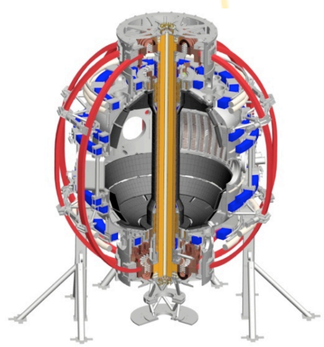
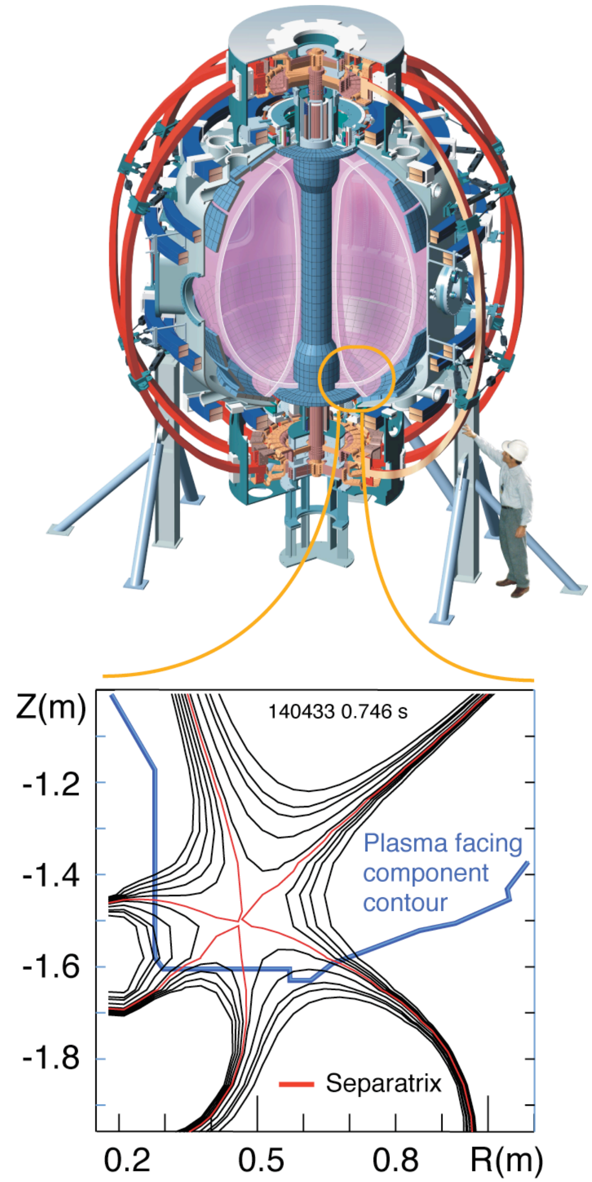


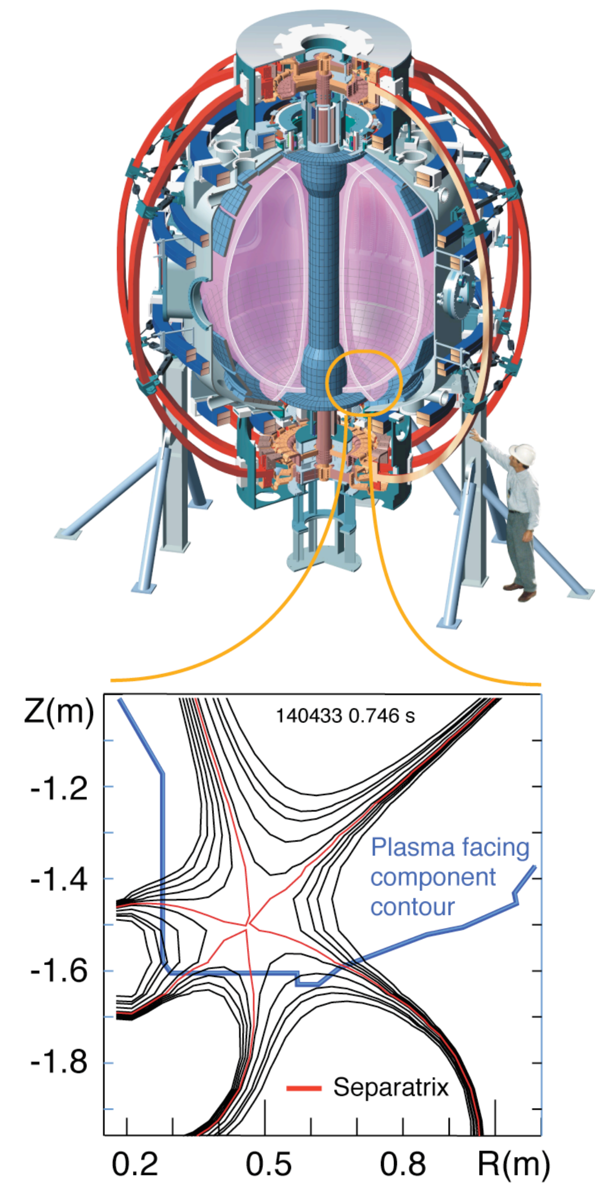
Snowflake divertor is a promising solution for mitigating divertor heat loads, and projects favorably to future fusion devices

Recent NSTX results demonstrate that the snowflake divertor (SFD) configuration may provide a promising solution for mitigating steady-state and transient divertor heat loads and target plate erosion, and project favorably to future fusion devices. In NSTX, a large spherical tokamak with high divertor heat flux $q_{peak} \leq 15$ MW/m^2, $q_{||} \leq 200$ MW/m^2, steady-state SFD configurations lasting up to 0.6 s (10 t_E) were obtained using the existing divertor poloidal field coils. The SFD geometry significantly increased the plasma-wetted area, the parallel connection length, and the divertor volumetric losses compared to the standard divertor configuration. The SFD formation led to a stable partial detachment of the outer strike point otherwise inaccessible in the standard divertor geometry at P_{SOL}=3 MW and n_e/n_G ~0.6-0.8 in NSTX. Peak divertor heat fluxes were reduced from 3-7 MW/m^2 to 0.5-1 MW/m^2 between ELMs, and from 5-20 MW/m^2 to 1-5 MW/m^2 at peak times of Type I ELMs (D W_{MHD} / W_{MHD}=7-15 %). H-mode core confinement was maintained albeit the radiative detachment, while core carbon concentration was reduced by up to 50 %. Additional divertor CD_4 seeding increased divertor radiation further. Based on the NSTX experiments, the SFD configuration is being developed as a leading heat flux mitigation technique for the NSTX Upgrade device. An edge transport model based on the two-dimensional multi-fluid code UEDGE favorably projects SFD properties to NSTX-U, showing a significant reduction of the steady-state peak divertor heat flux from 15 to about 3 MW/m^2 expected in 2 MA discharges with 12 MW NBI heating.



Snowflake divertor is a promising solution for mitigating divertor heat loads, and projects favorably to future fusion devices

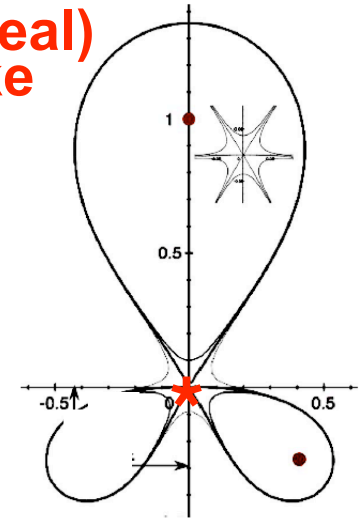
- Snowflake divertor configuration in NSTX
  - Core H-mode confinement unaffected, core carbon concentration reduced
  - Pedestal stability modified: suppressed Type I ELMs re-appeared
  - Divertor heat flux significantly reduced
    - Between-ELM reduction due to geometry and radiative detachment
    - ELM heat flux reduction due to power sharing between strike points, radiation and geometry
- Snowflake divertor is a leading candidate for NSTX-U
  - Divertor coils enable a variety of snowflakes
  - In 2 MA, 12 MW NBI-heated discharges
    - SOL power width λ_{SOL} = 3 mm projected
    - $q_{div} \leq$ 15 - 25 MW/m^2 projected in standard divertor
    - $q_{div} \leq$ 3 MW/m^2 projected in snowflake divertor



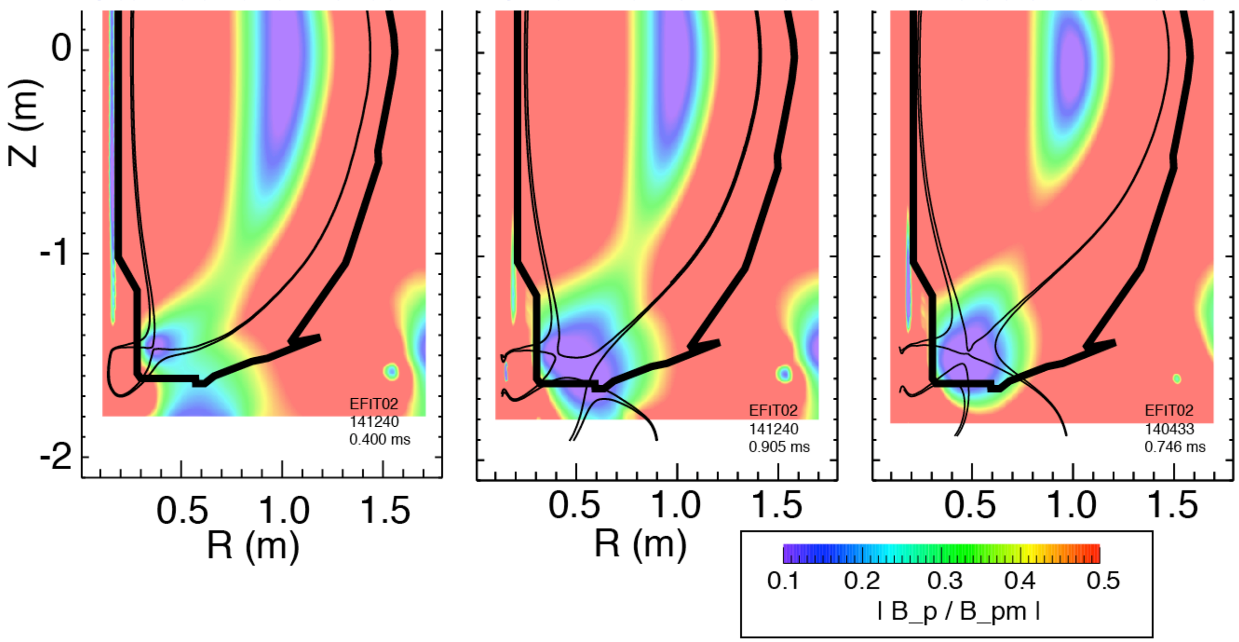
Snowflake divertor geometry takes advantage of second-order poloidal field null properties

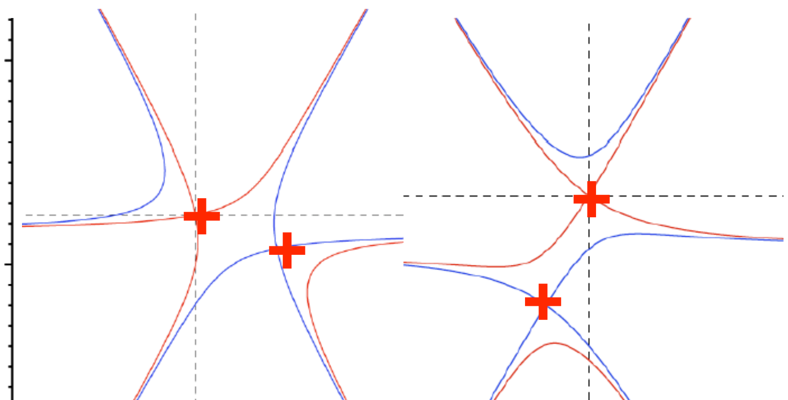
- Snowflake divertor configuration
  - Second-order null
    - $B_p \sim 0$ and *grad* $B_p \sim 0$ (Cf. first-order null: $B_p \sim 0$)
  - Obtained with existing divertor coils (min. 2)
  - Exact snowflake topologically unstable
  - Deviation from ideal snowflake: $\sigma = d / a$
    - *d* – distance between nulls, *a* – plasma minor radius

Exact (ideal) snowflake



Standard divertor **Snowflake-minus** **Exact snowflake**





snowflake-minus

snowflake-plus

D. D. Ryutov, PoP 14, 064502 2007
EPS 2012 Invited, subm. to PPCF

Snowflake divertor geometry has benefits over standard X-point divertor geometry

- Predicted geometry properties in snowflake divertor (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 $q_{||}$
  - Larger X-point connection length L_x : reduce $q_{||}$
  - Larger effective divertor volume V_{div} : incr. P_{rad} , P_{CX}

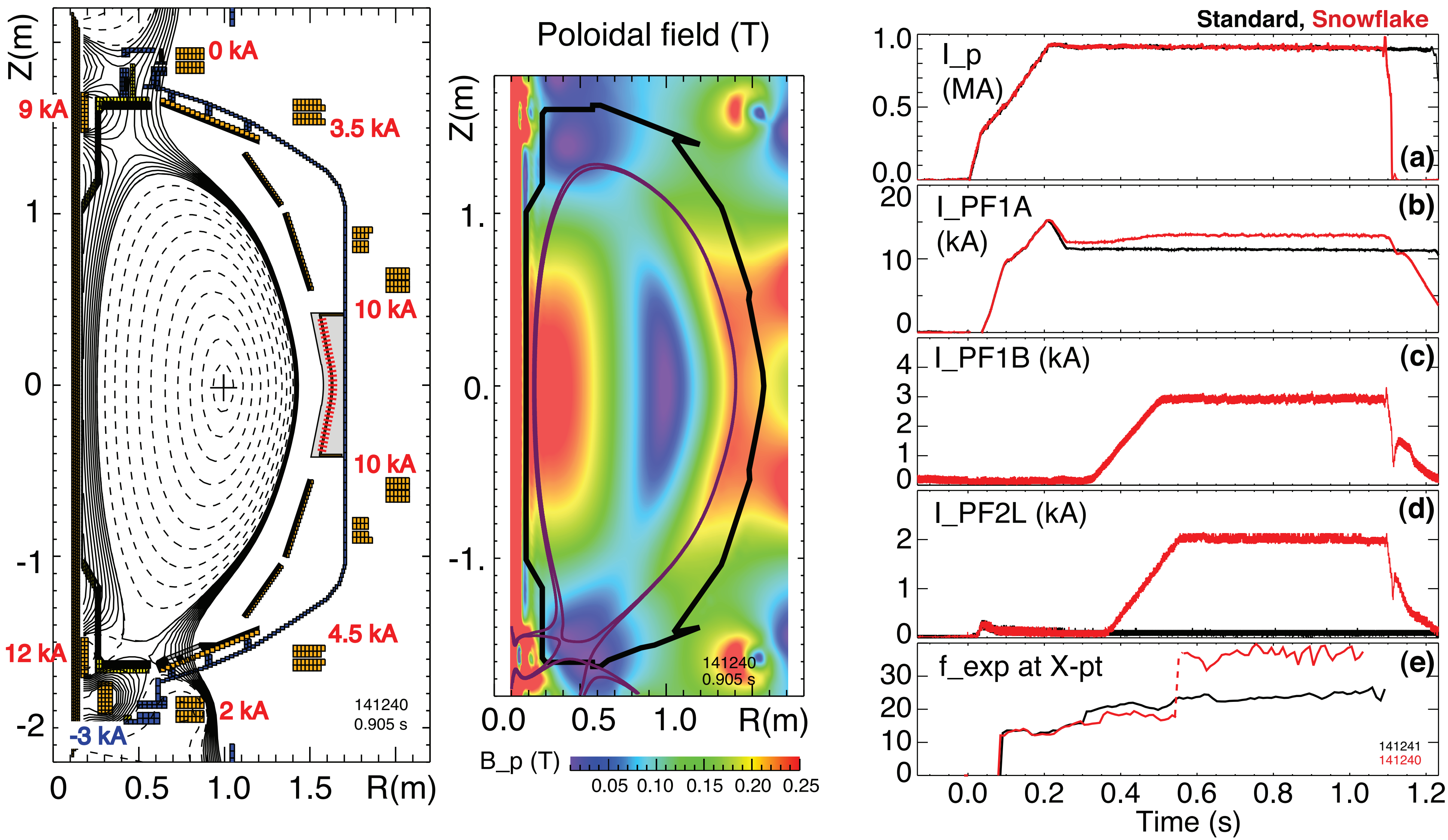
$$q_{pk} \simeq \frac{P_{heat}\,(1-f_{rad})f_{out/tot}f_{down/tot}(1-f_{pfr})\sin\alpha}{2\pi R_{SP} f_{exp} \lambda_{q_{||}}}$$

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

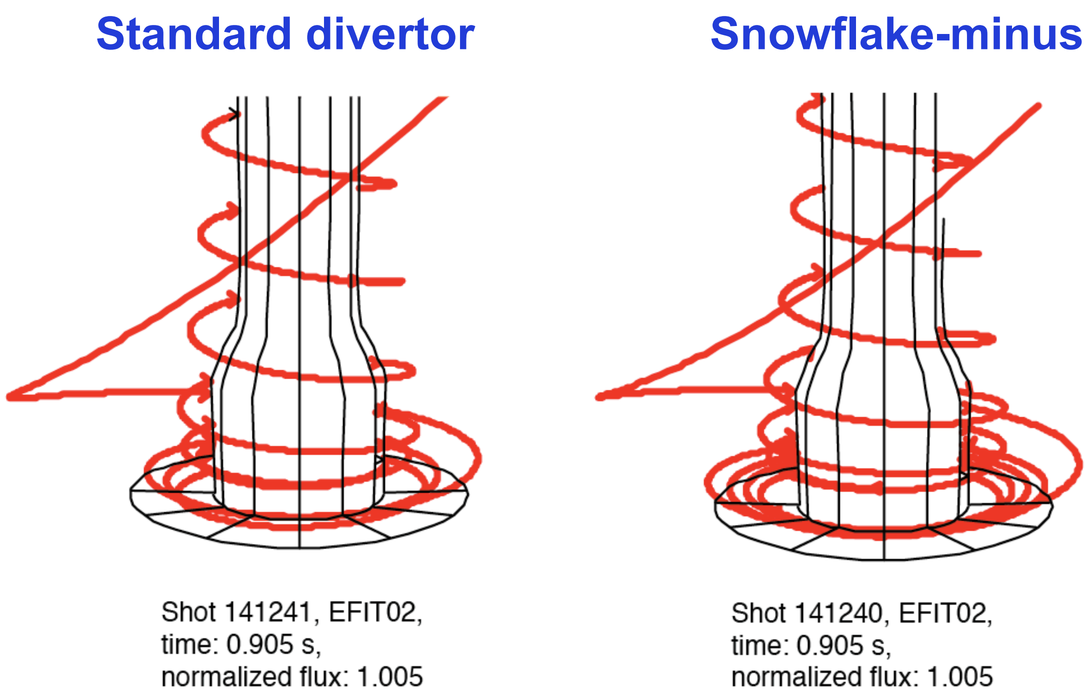
D. D. Ryutov, PoP 14, 064502 2007

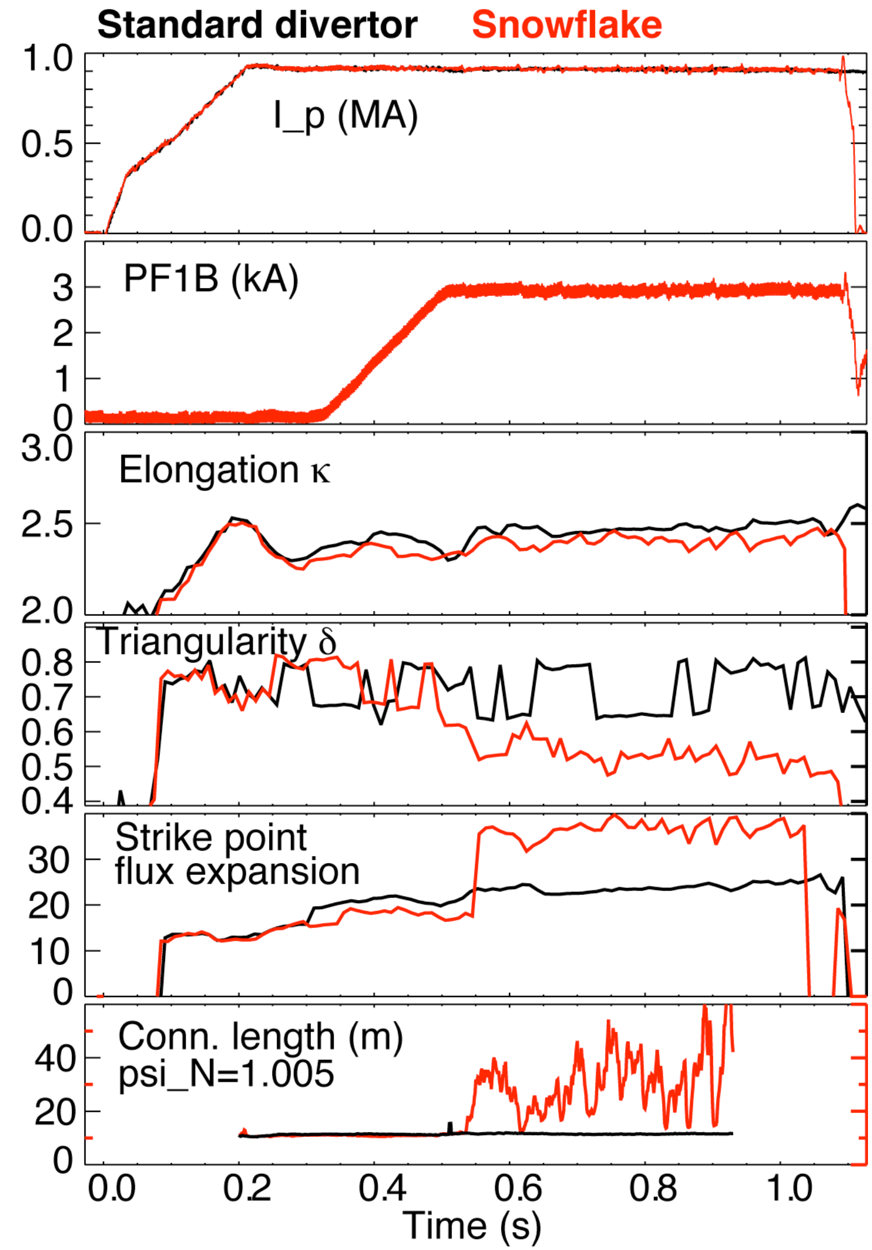
$$A_{wet} = 2\pi R\, f_{exp}\, \lambda_{q_{||}}$$

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



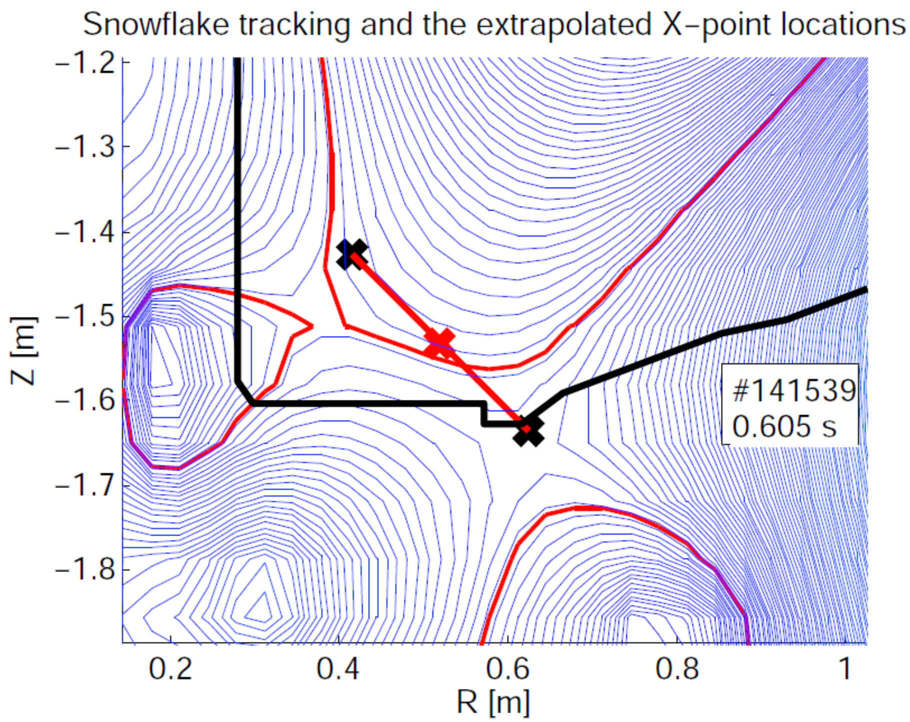
Plasma-wetted area and connection length are increased by 50-90 % in snowflake divertor





- These properties observed in first 30-50 % of SOL width
- B_{tot} angles in the strike point region: 1-2°, sometimes < 1°

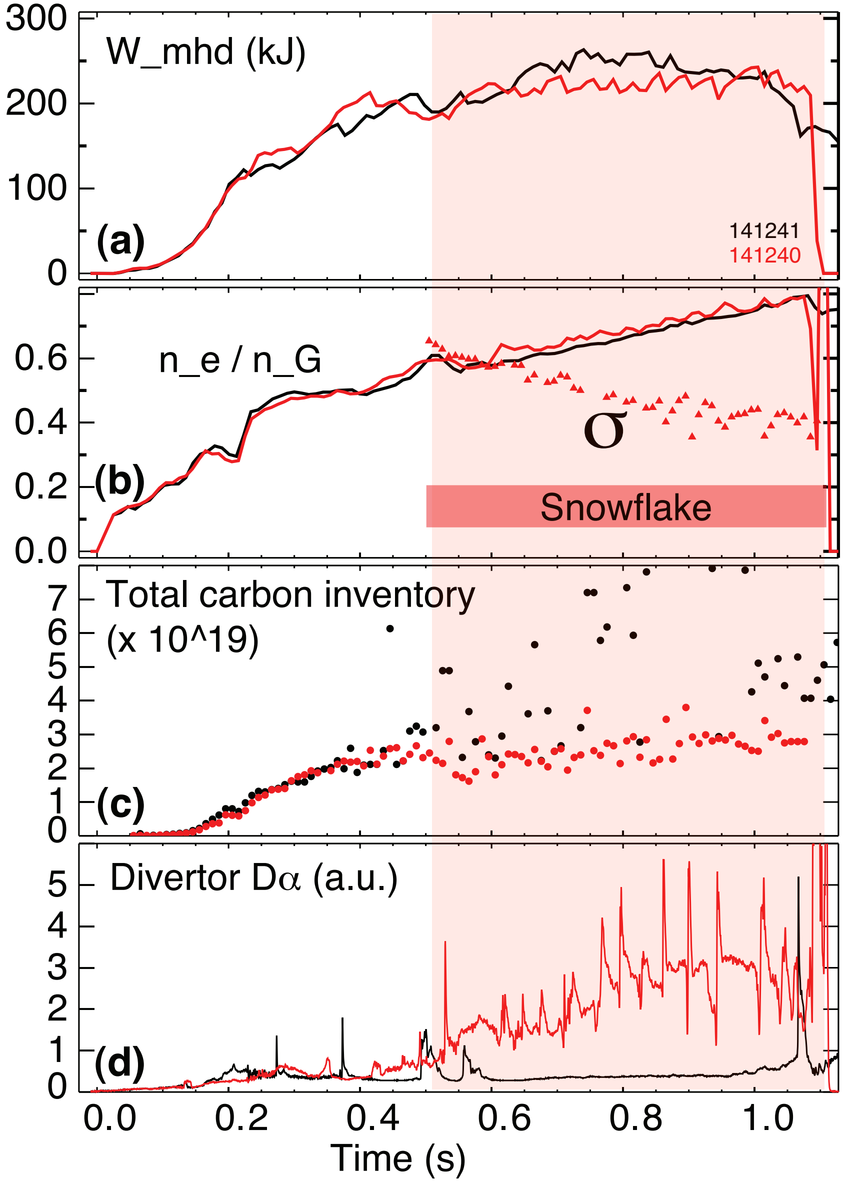
Close-loop feedback control of divertor coil currents is desirable for steady-state snowflake



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

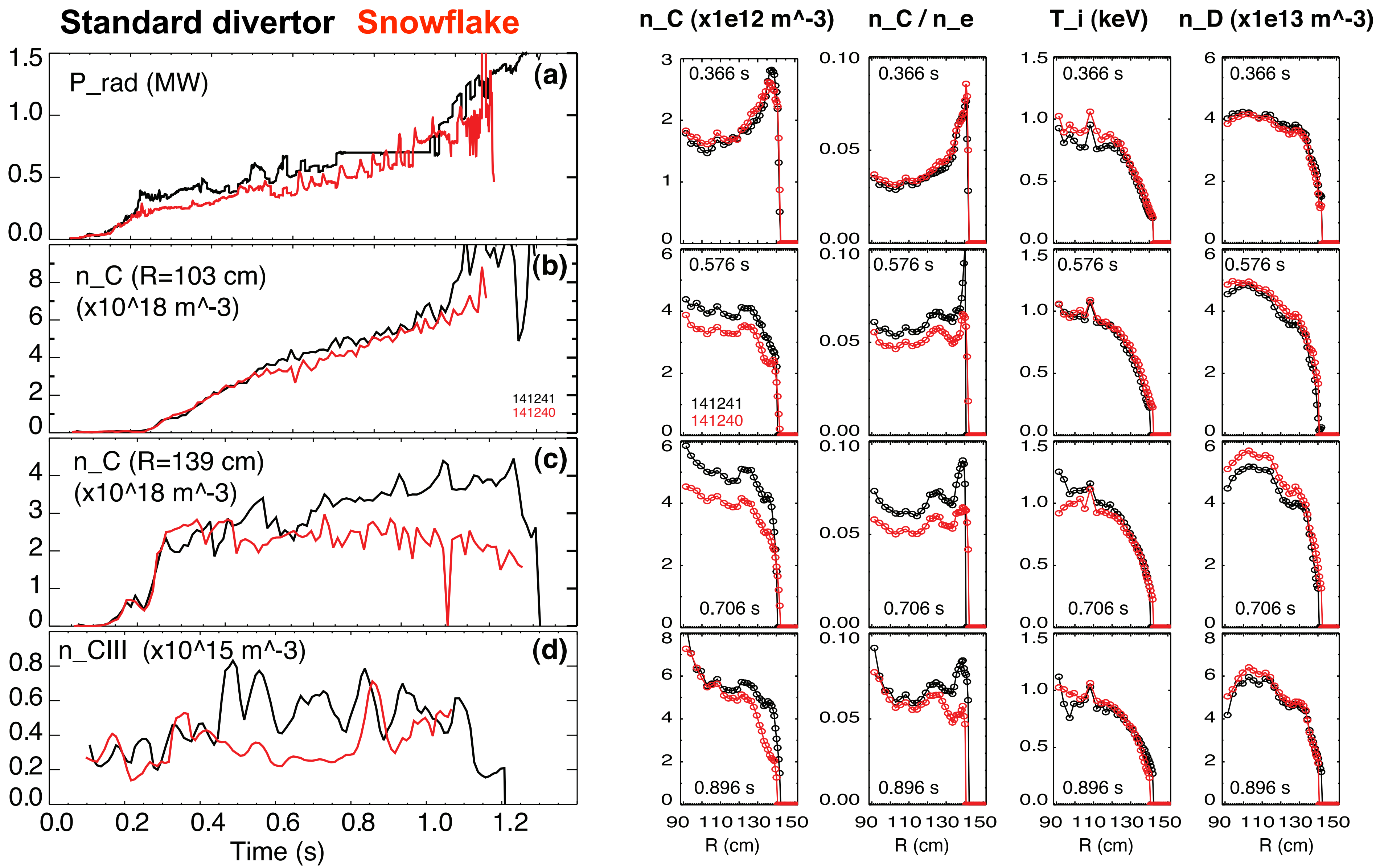
- All configurations are obtained reproducibly under feed-forward control in NSTX
- In NSTX
  - Developed X-point tracking algorithm that locates nulls and centroid
  - Algorithm tested on NSTX snowflakes successfully
  - Implementing snowflake control in digital plasma control system

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



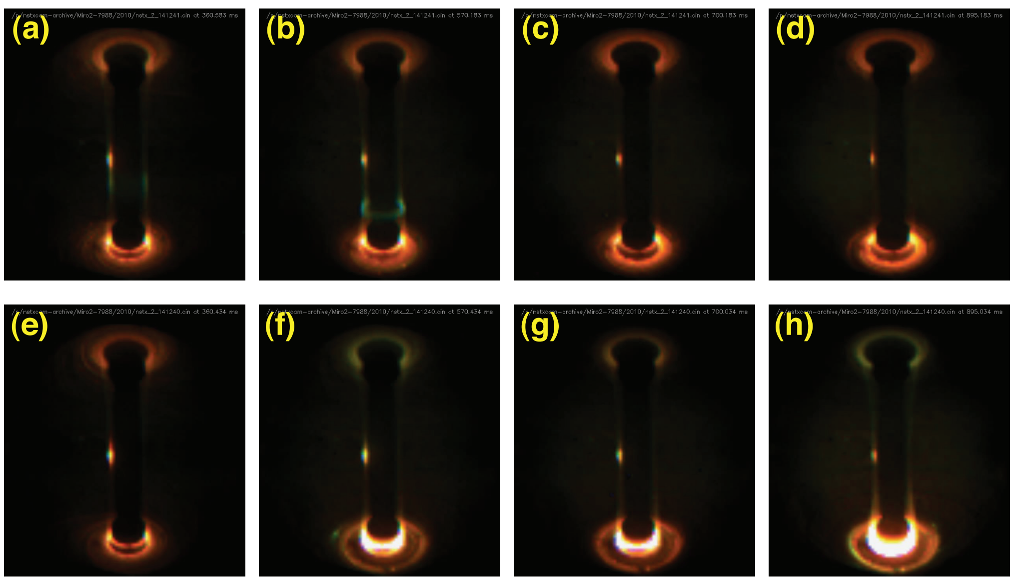
- 0.8 MA, 4 MW H-mode
- κ=2.1, δ=0.8
- Core T_e ~ 0.8-1 keV, T_i ~ 1 keV
- β_N ~ 4-5
- Plasma stored energy ~ 250 kJ
- H98(y,2) ~ 1 (from TRANSP)
- ELMs
  - Suppressed in standard divertor H-mode via lithium conditioning
  - Re-appeared in snowflake H-mode
- Core carbon reduction due to
  - Type I ELMs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

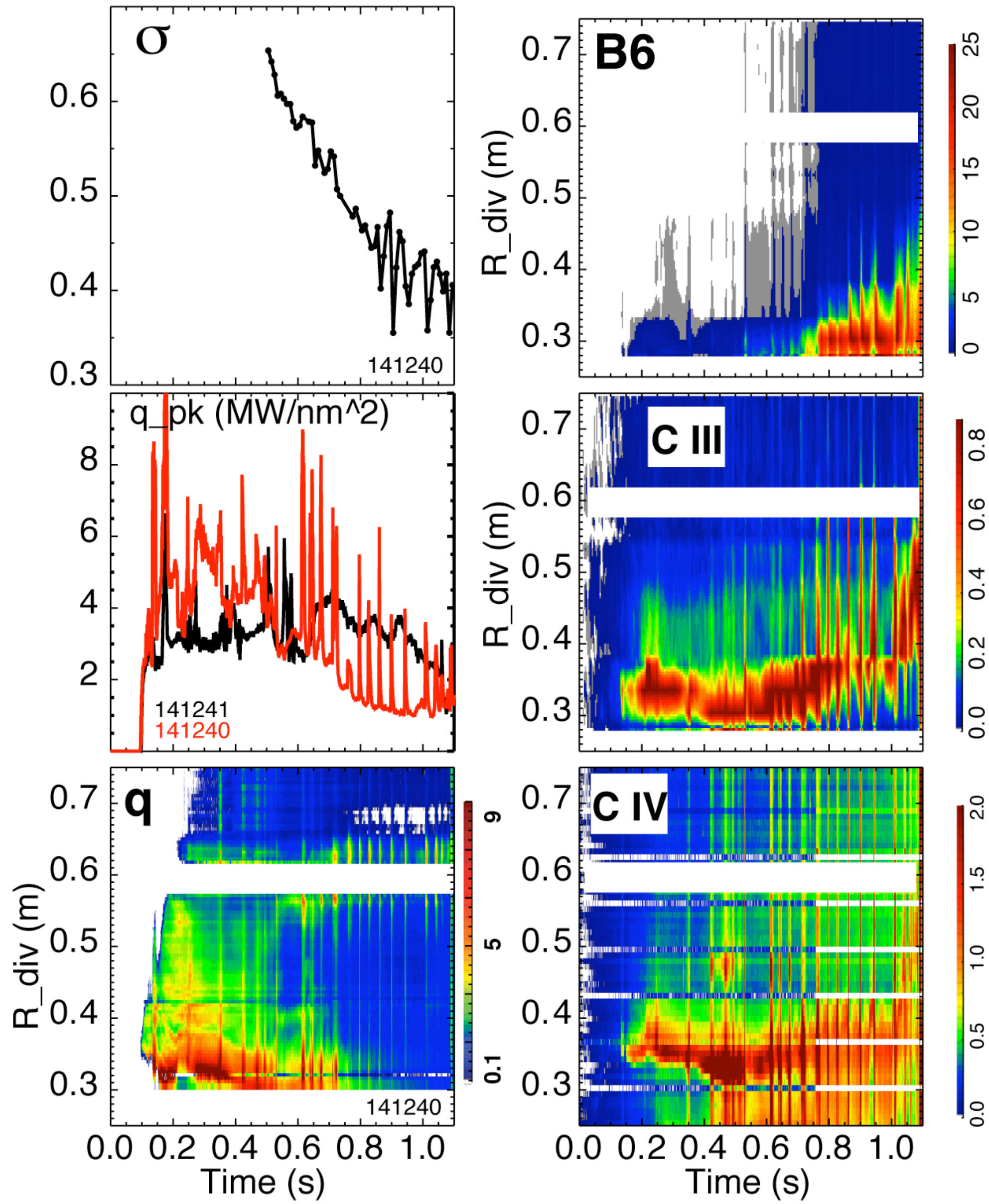
Core carbon density significantly reduced with snowflake divertor



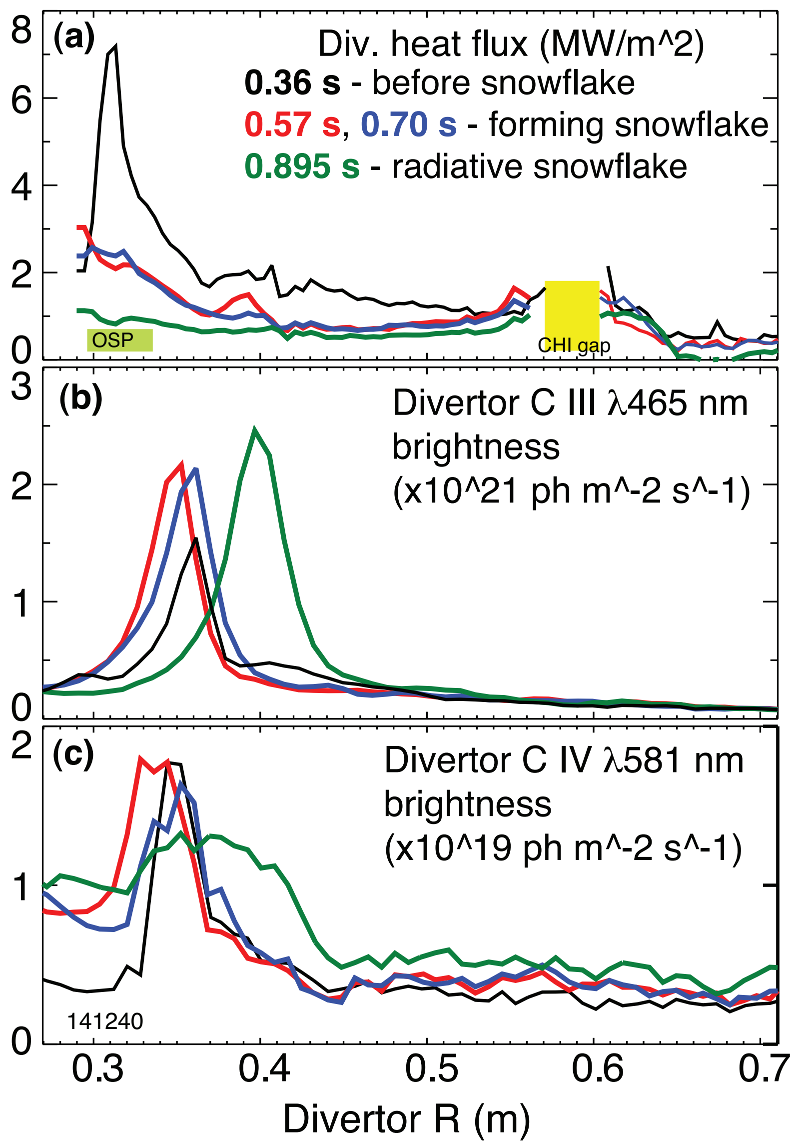
Radiative detachment with strong recombination and high radiated power observed in snowflake divertor

- 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

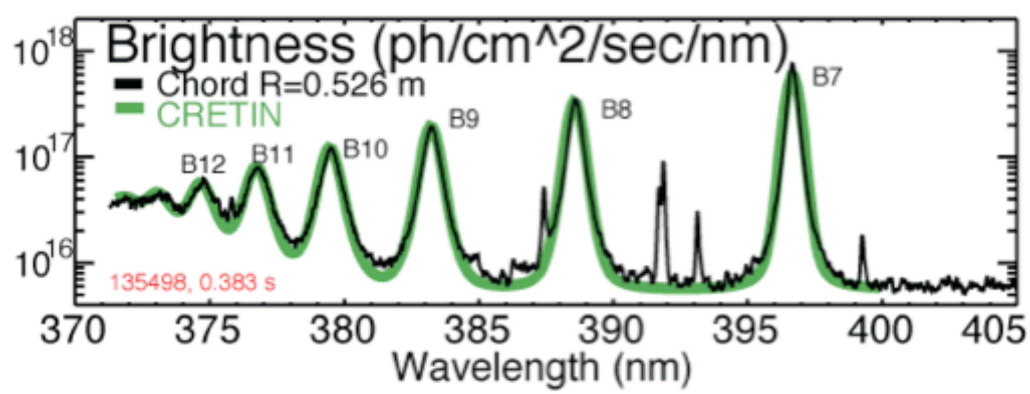




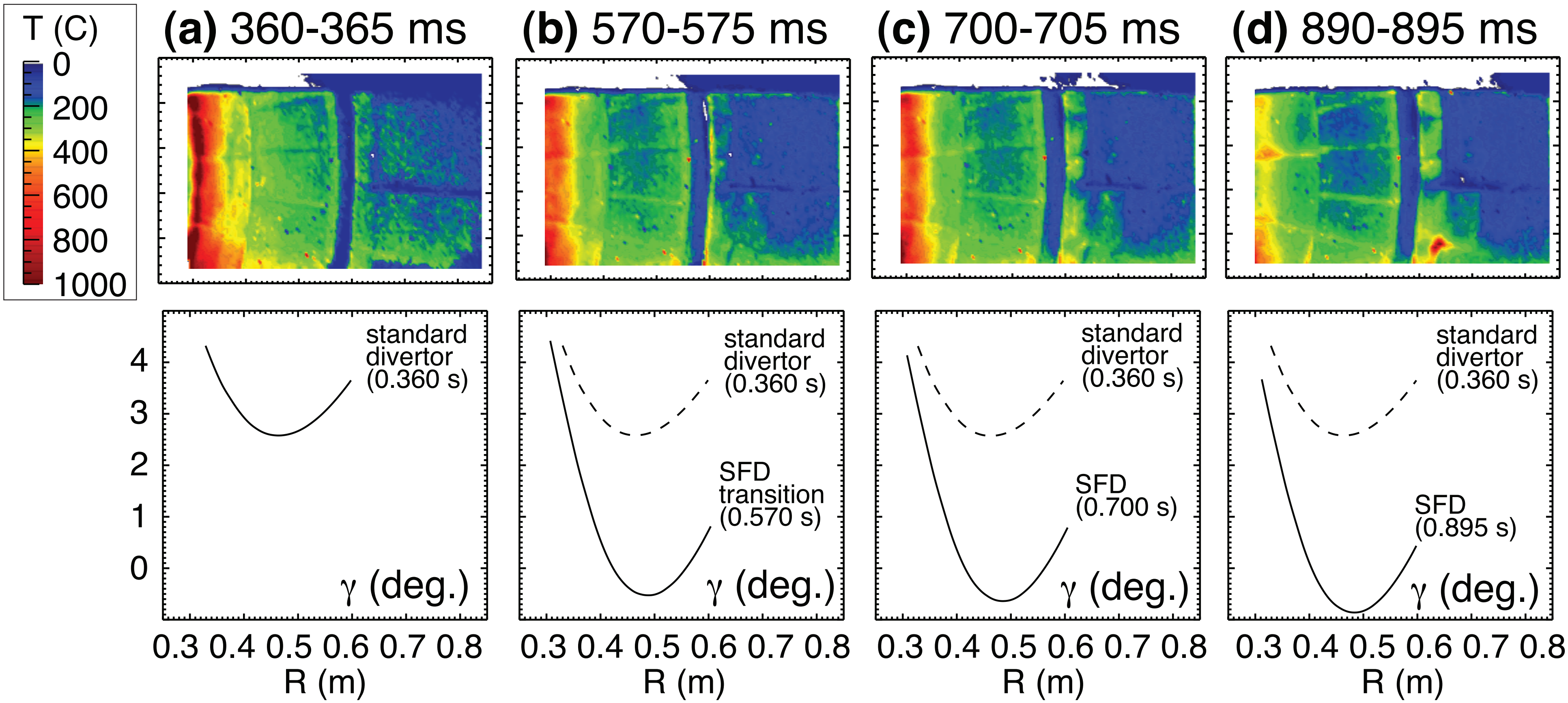
Divertor profiles show low heat flux, broadened C III and C IV radiation zones in the snowflake divertor phase



- 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



No leading edge PFC tile heating observed at shallow magnetic field incidence angles

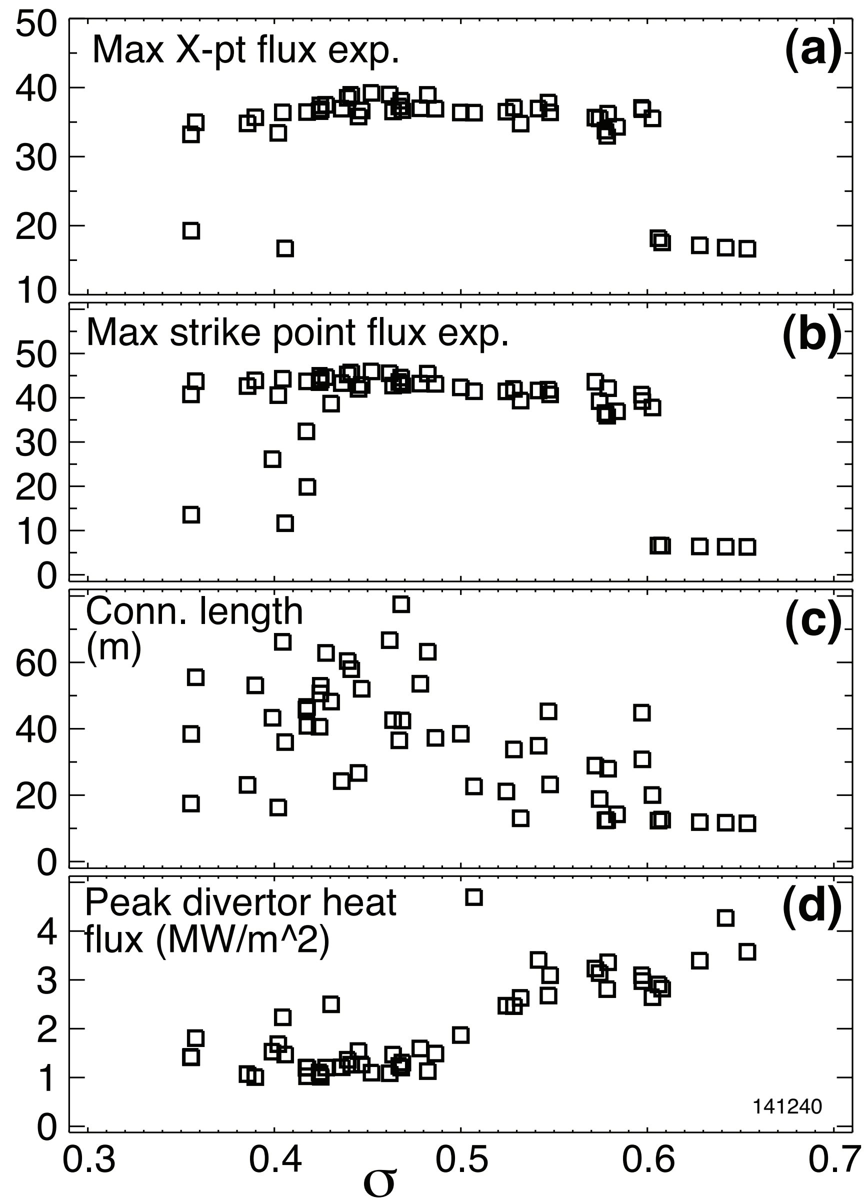


- Reduction of $q_{||}$ due to radiative detachment is considered

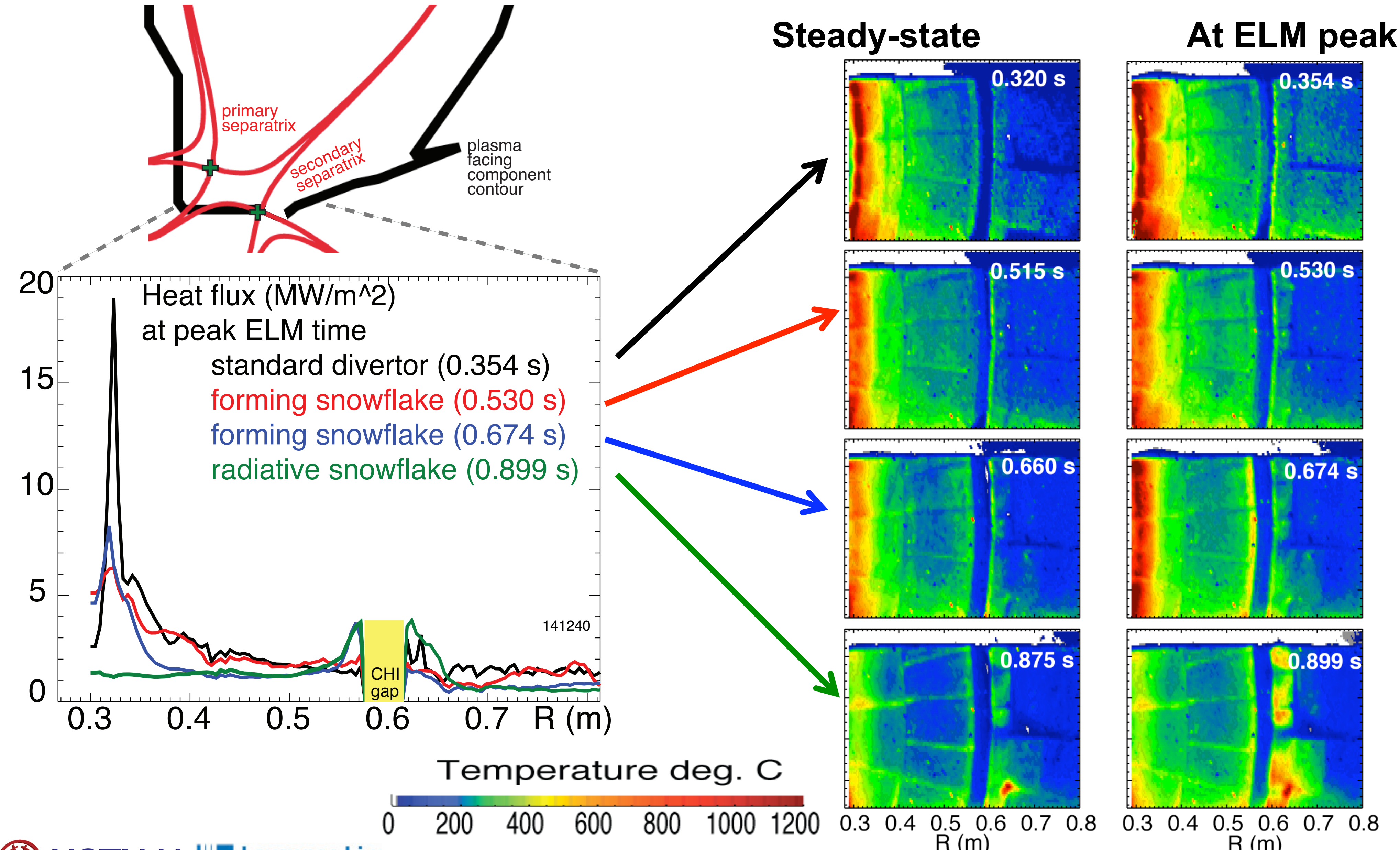
Peak divertor heat flux decreases with stronger snowflake effects (lower σ)

- Deviation from ideal snowflake: $\sigma = d / a$
  - d – distance between nulls, a – plasma minor radius

- Clear trends of flux expansion, connection length, and peak heat flux with σ observed

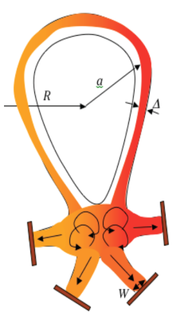


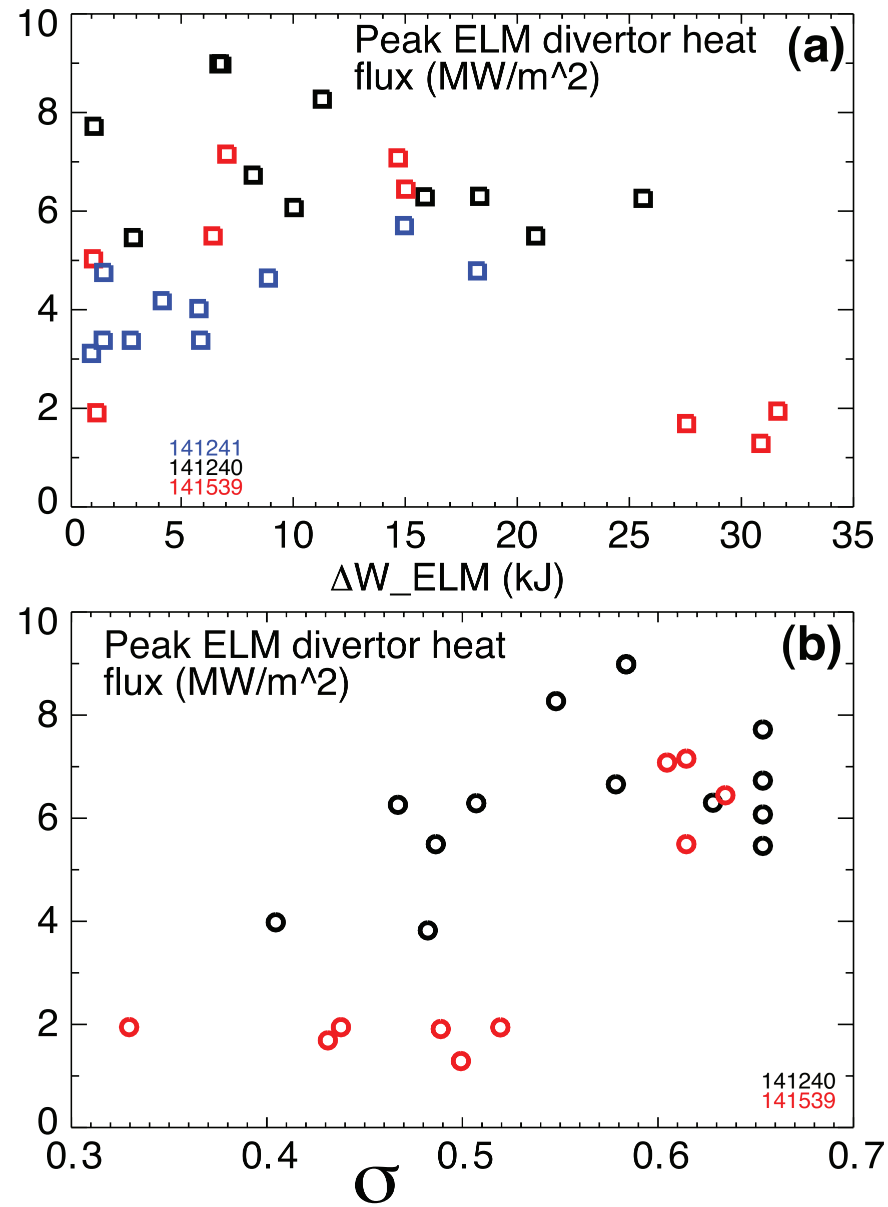
Impulsive heat loads due to Type I ELMs are mitigated in snowflake divertor



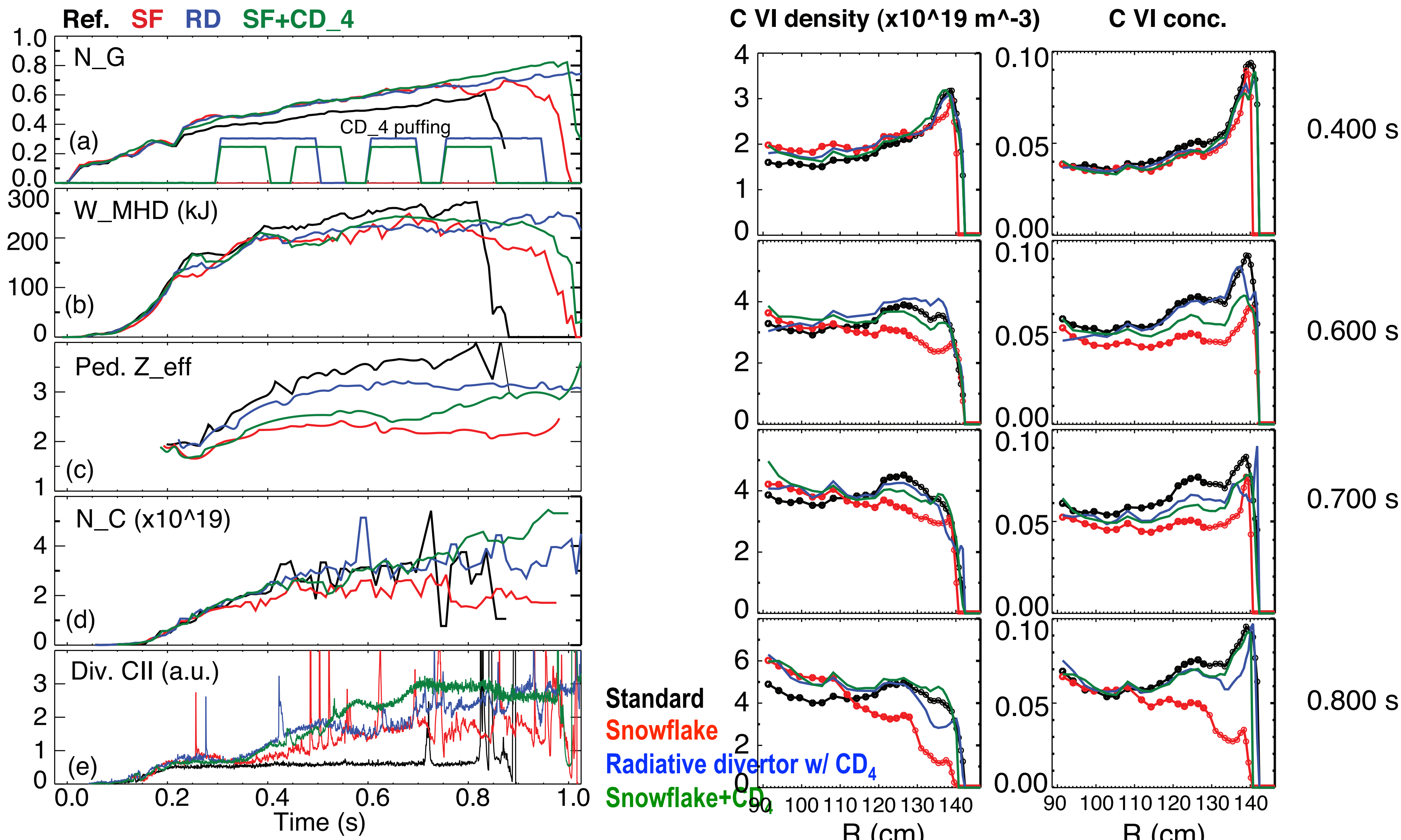
ELM peak heat flux strongly decreases with stronger snowflake effects (lower σ)

- H-mode standard divertor discharge
  - W_{MHD} ~ 220-250 kJ
  - Type I ELMs suppressed by lithium conditioning
  - Occasional ELMs occur
- In the snowflake phase
  - Type I ELM (*ΔW/W* ~ 5-15 %) re-appeared
  - ELM peak heat flux lower
- Theory (D. Ryutov, TH/ P4-18)
  - 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

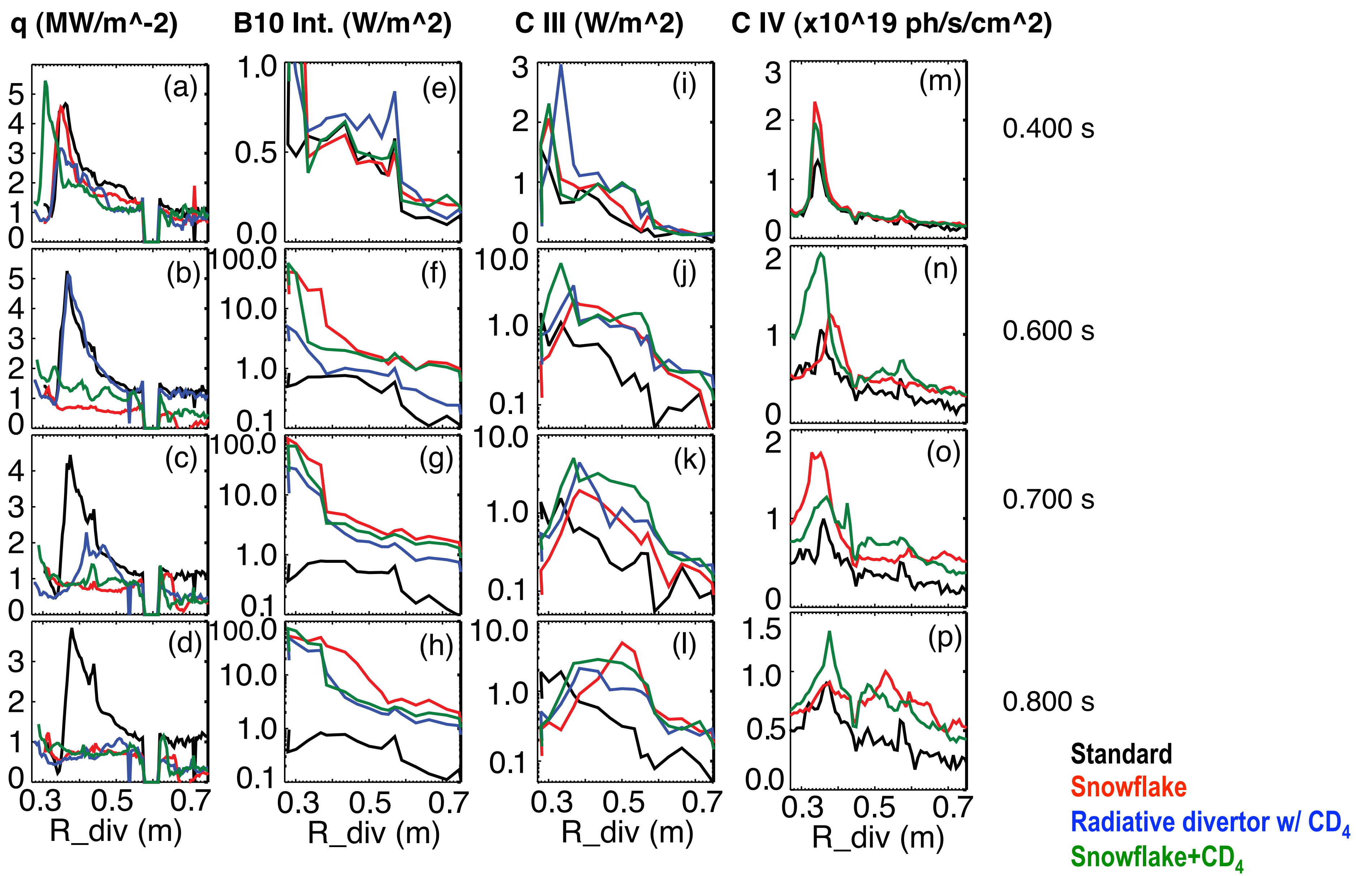




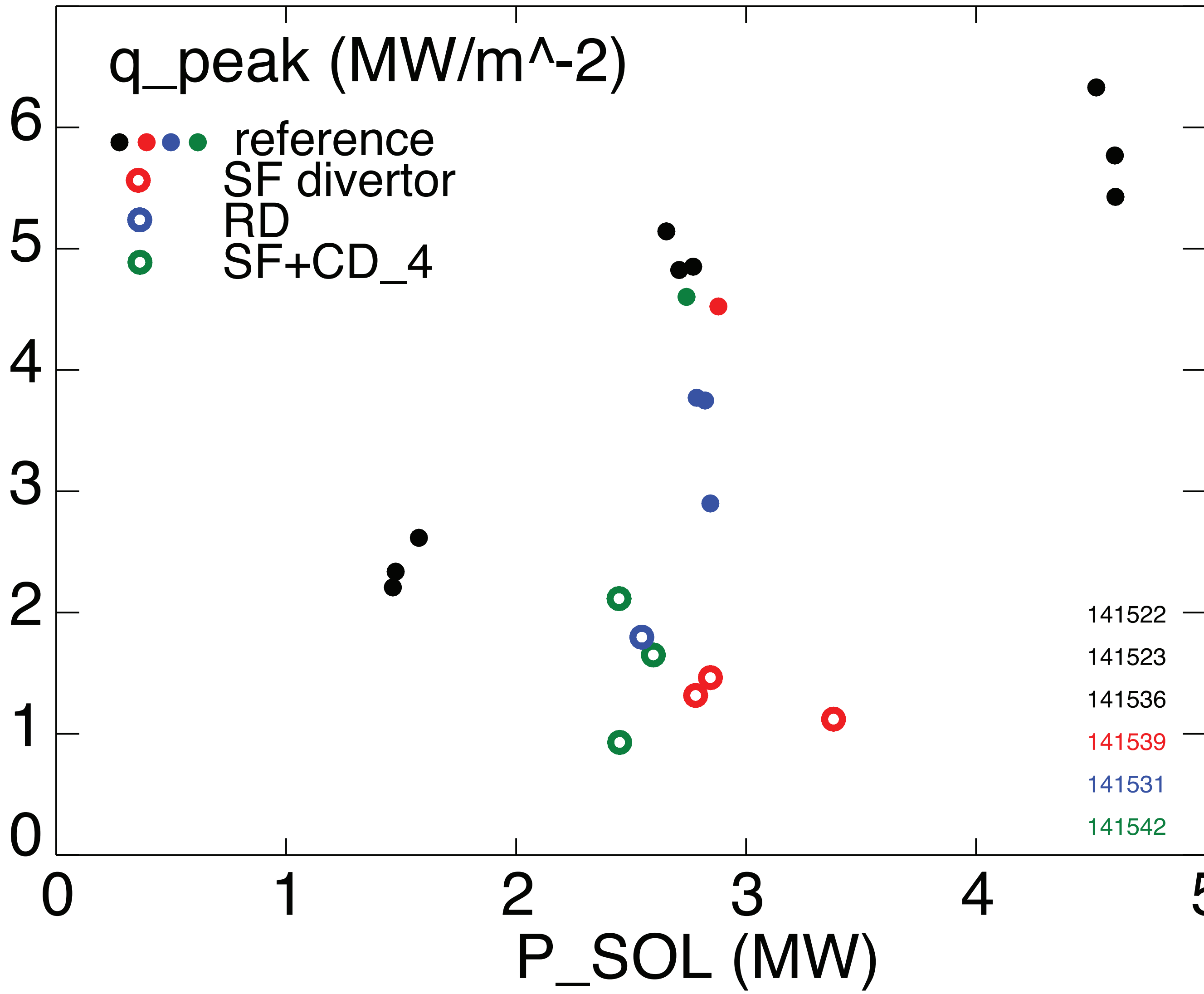
Good H-mode confinement properties retained or slightly reduced with CD_4-seeded snowflake divertor



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

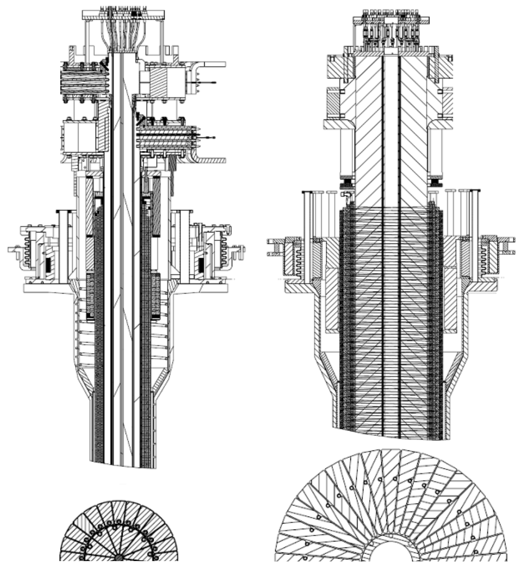


Divertor heat flux reduced by radiation and/or geometry in radiative and snowflake divertors



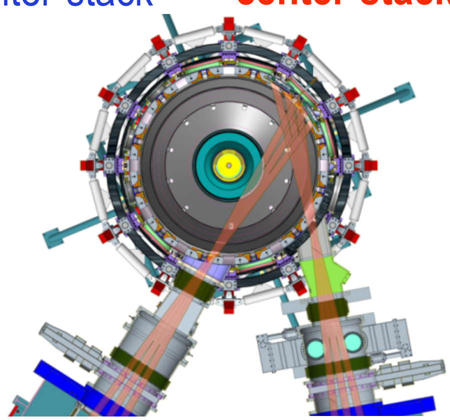
Stnadard
Snowflake
Radiative divertor w/ CD_4
Snowflake+CD_4

NSTX Upgrade will address critical plasma confinement and sustainment questions by exploiting 2 new capabilities



TF OD = 20cm
Previous center-stack

TF OD = 40cm
New center-stack



Present NBI

New 2nd NBI

New center-stack

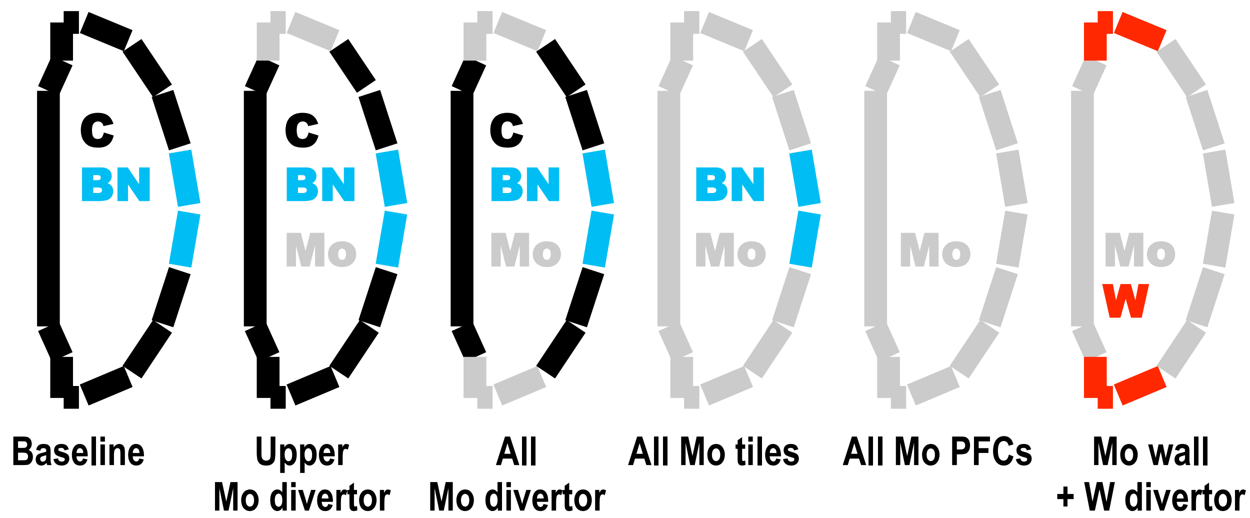
- Reduces ν^* → ST-FNSF values to understand ST confinement
  - Expect 2x higher T by doubling B_T, I_P, and NBI heating power
- Provides 5x longer pulse-length
  - q(r,t) profile equilibration
  - Tests of NBI + BS non-inductive ramp-up and sustainment

New 2nd NBI

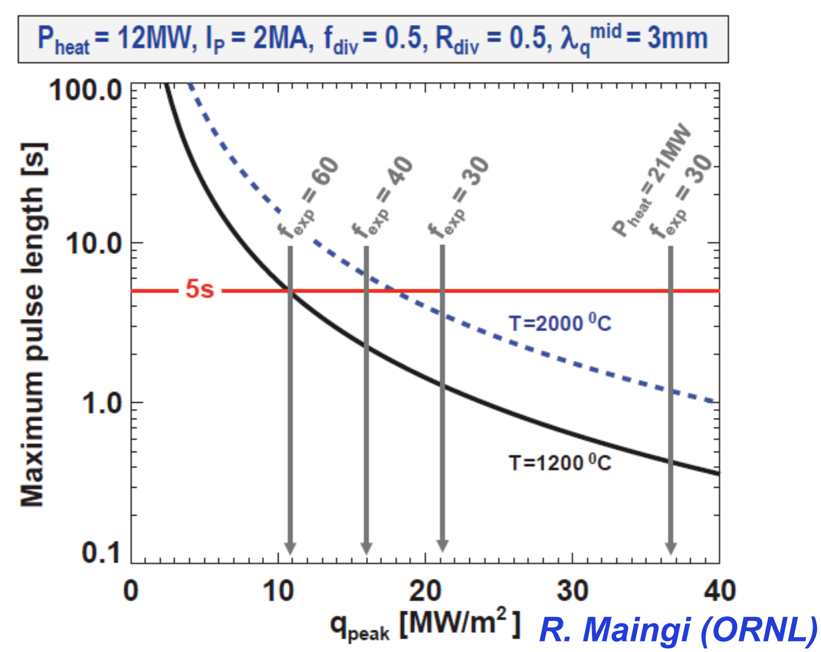
- 2x higher CD efficiency from larger tangency radius R_{TAN}
- 100% non-inductive CD with q(r) profile controllable by:
  - NBI tangency radius
  - Plasma density
  - Plasma position

Divertor heat flux mitigation options are affected by NSTX-U plasma-facing component development plan

- Developing PFC plan to transition to full metal coverage for FNSF-relevant PMI development
- Wall conditioning: GDC, lithium and / or boron
- PFC bake-out at 300-350°C
- Divertor impurity seeding:
  - D_2, CD_4, Ne, Ar with graphite PFCs
  - N_2 with molybdenum PFCs



- High I_P = 2 MA scenarios projected to have narrow λ_q^{mid} ~ 3mm
- Scenarios with high I_p and P_{NBI} are projected to challenge passive cooling limits of graphite divertor PFCs

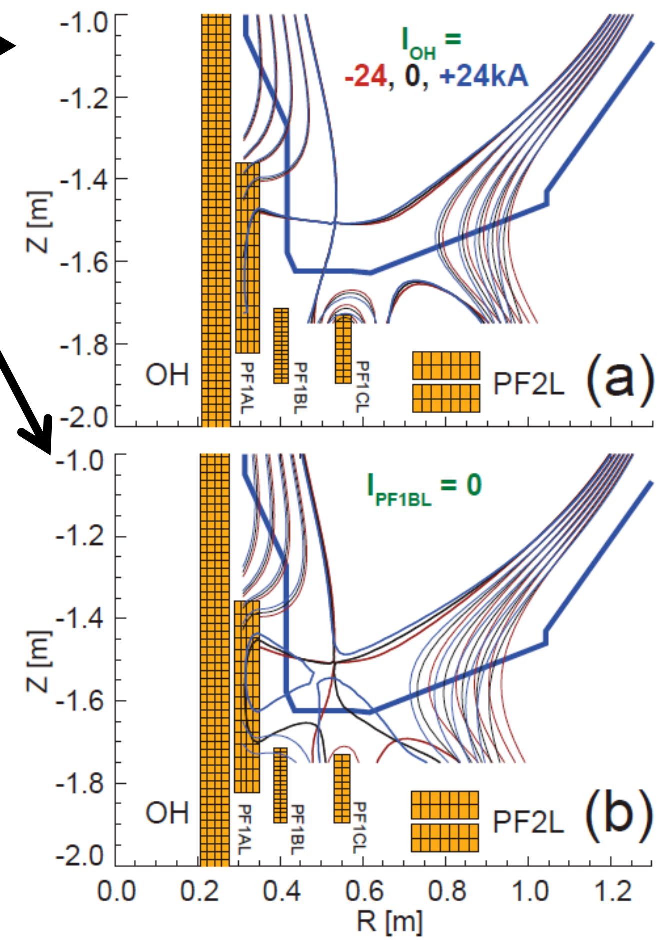


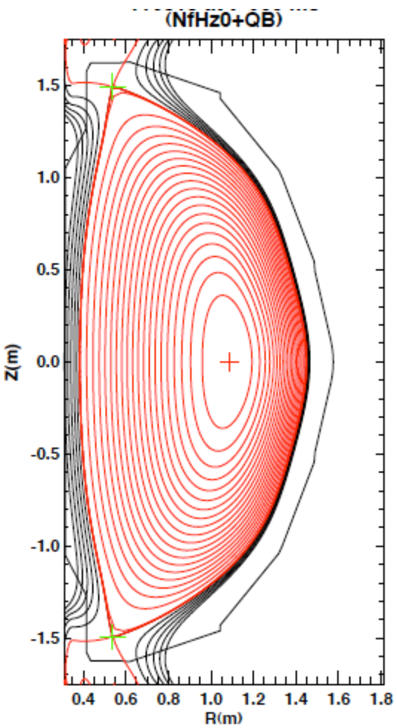
R. Maingi (ORNL)

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

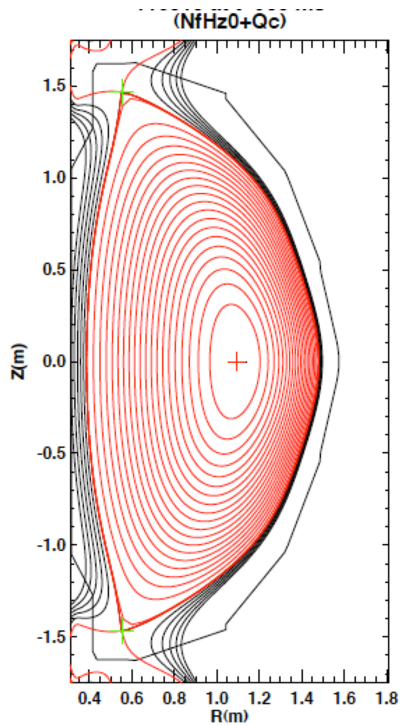
- Single and double-null radiative divertors and upper-lower snowflake configurations considered
  - Supported by NSTX-U divertor coils and compatible with coil current limits
  - ISOLVER modeling shows many possible equilibria
    - Impact of changing I_{OH} on snowflake minimal
    - Reduced divertor coil set can be used for snowflakes

NSTX-U simulation

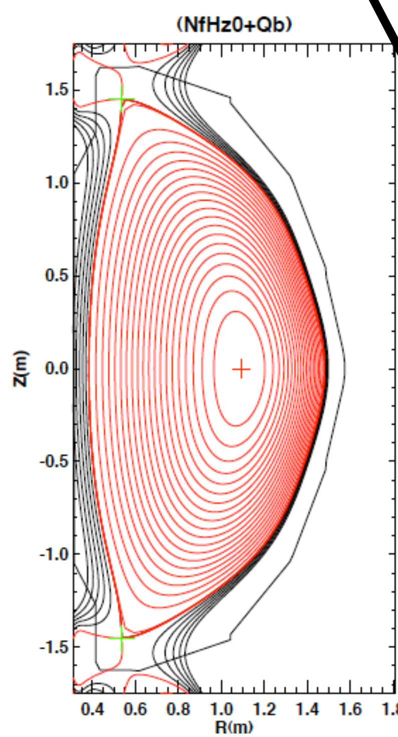




NSTX-U double-null

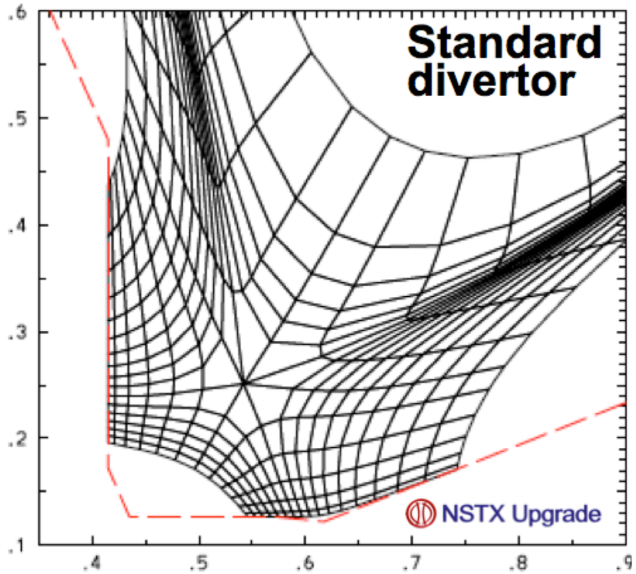


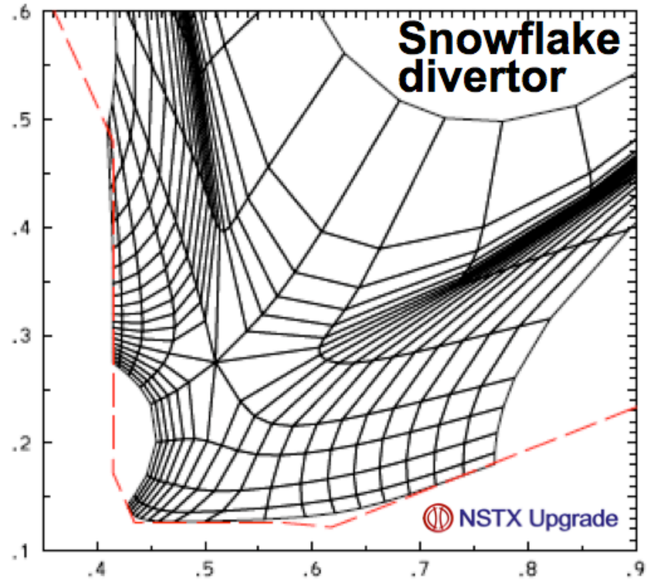
NSTX-U double-snowflake-plus



NSTX-U double-snowflake-minus

Projections with UEDGE edge multi-fluid model for NSTX-U are optimistic

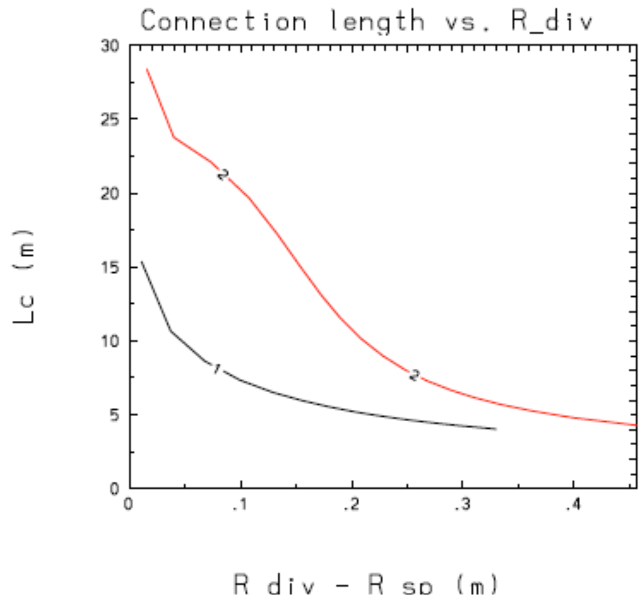


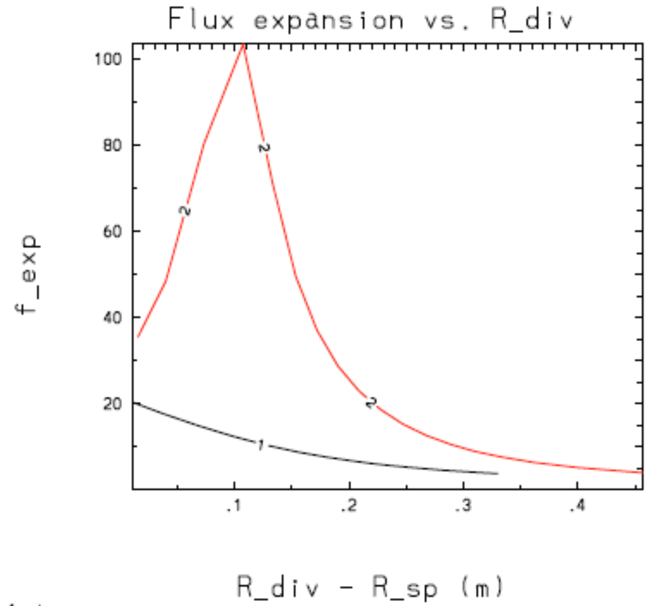


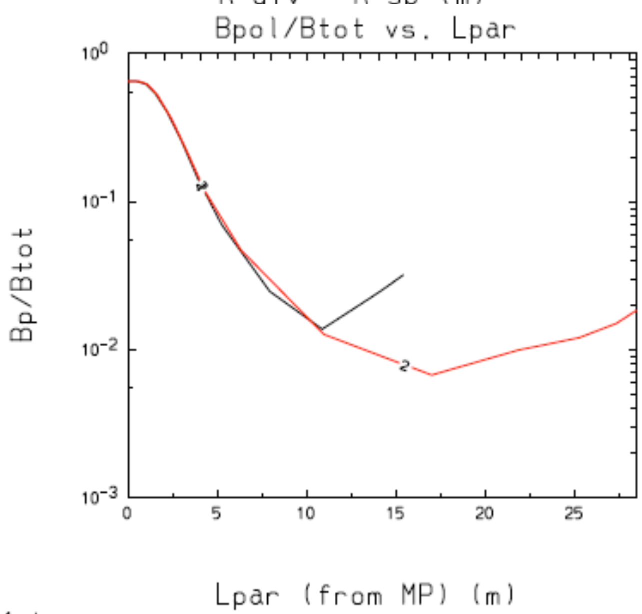
- Fluid (Braginskii) model for ions and electrons
- Fluid for neutrals
- Classical parallel transport, anomalous radial transport
- Core interface:
  - P_{SOL90} = 5; 7; 9 MW
- D = 0.1-0.5 m^2/s
- $\chi_{e,i}$ = 1-2 m^2/s
- R_{recy} = 0.99
- Carbon 5 %

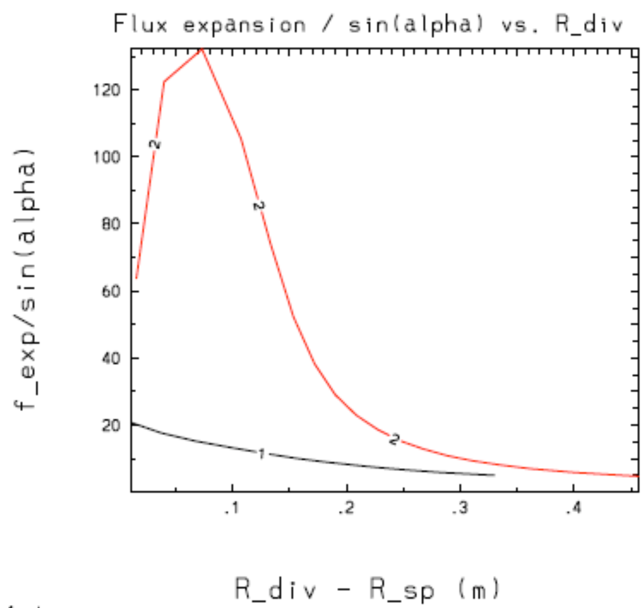
- Grids extend from psi=0.9 to psi=1.2
- STD grid covers 3.1 cm outside the separatrix at the outer MP
- SNF grid covers 3.4 cm outside the separatrix at the outer MP.

In modeled NSTX-U snowflake configuration magnetic geometry shows clear benefits (cf. standard divertor)

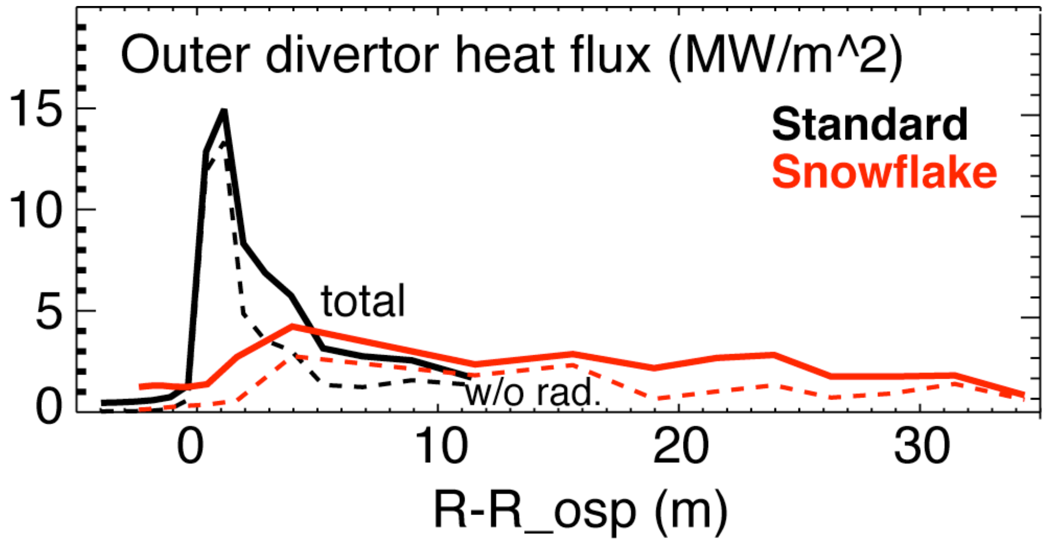


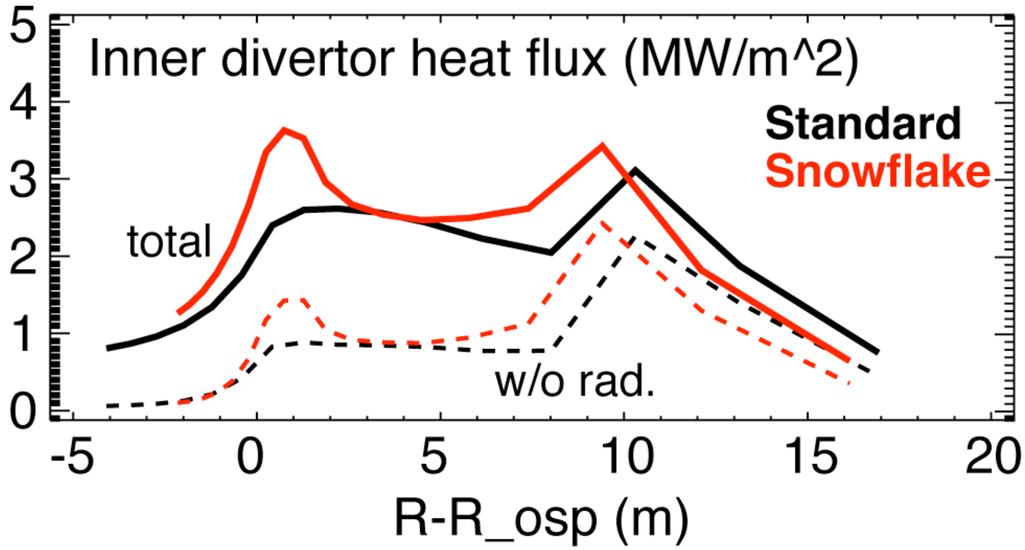






UEDGE predicts significant divertor heat flux reduction and attached conditions in NSTX-U at 12 MW NBI heating





- Predictions for 12 MW NBI case
  - P_{SOL}=9 MW
  - Outer divertor attached
    - T_e, $T_i \leq 80$ eV
  - Inner divertor detached