Snowflake divertor configuration in NSTX

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Acknowledgements:
NSTX Team

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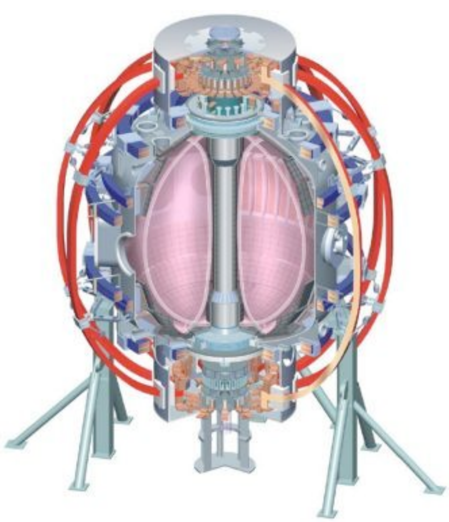

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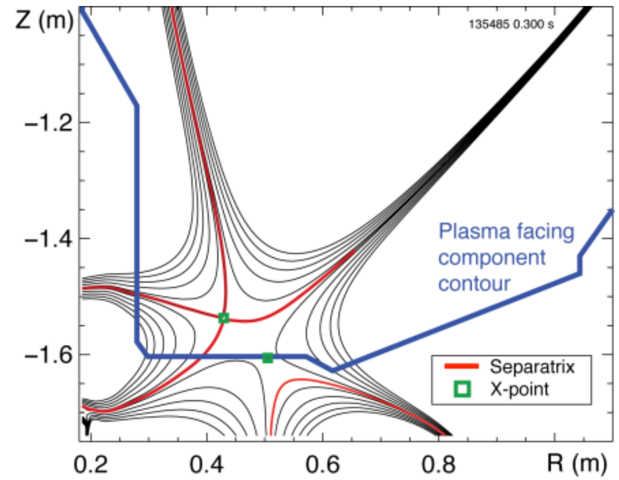
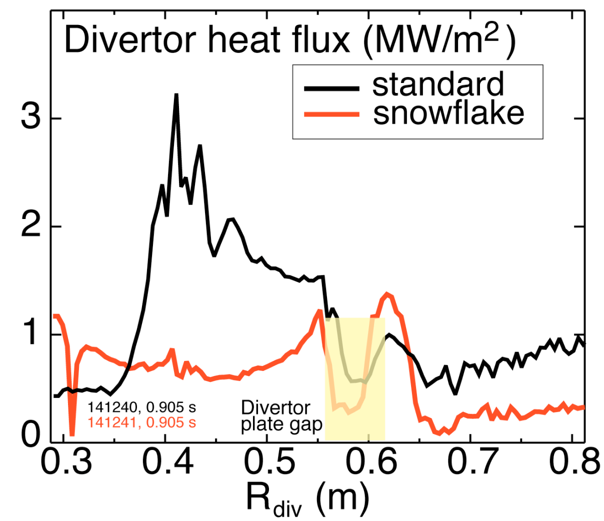
NSTX studies suggest the snowflake divertor configuration may be a viable divertor solution for present and future tokamaks

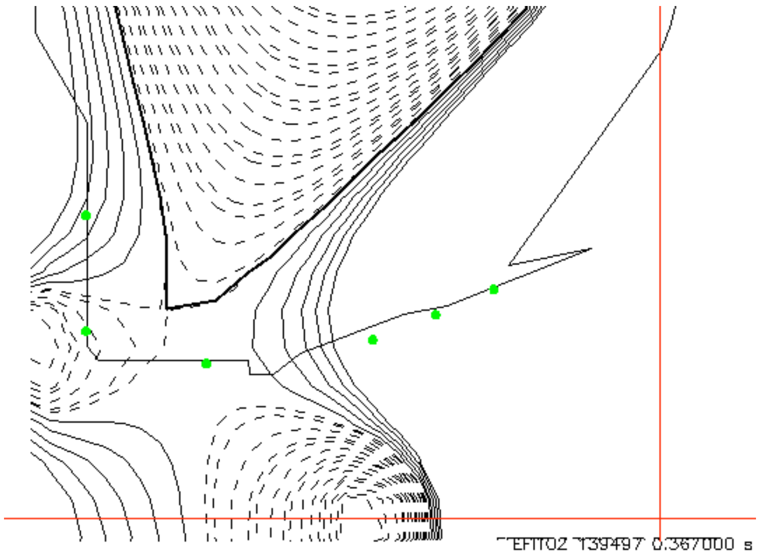
- Steady-state snowflake (up to 600 ms, many τ_E's)
- Good H-mode confinement
- Reduced core carbon concentration
- Significant reduction in peak divertor heat flux
- Potential to combine with radiative divertor for increased divertor radiation

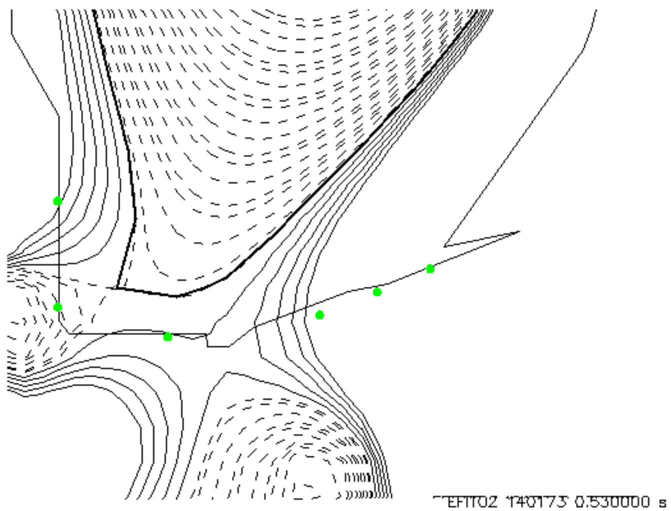
- Planned future efforts with the snowflake divertor:
  - Improved magnetic control
  - Pedestal peeling-balooning stability
  - ELM heat and particle deposition profiles
  - Divertor impurity source distribution
  - Divertor and upstream turbulence (blobs)

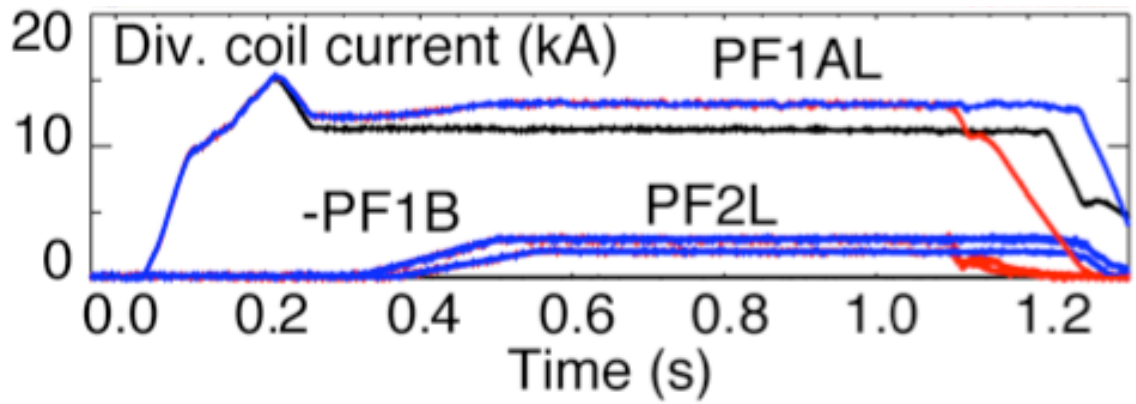




Standard divertor (medium and high-δ) is transformed into snowflake divertor using three divertor coils

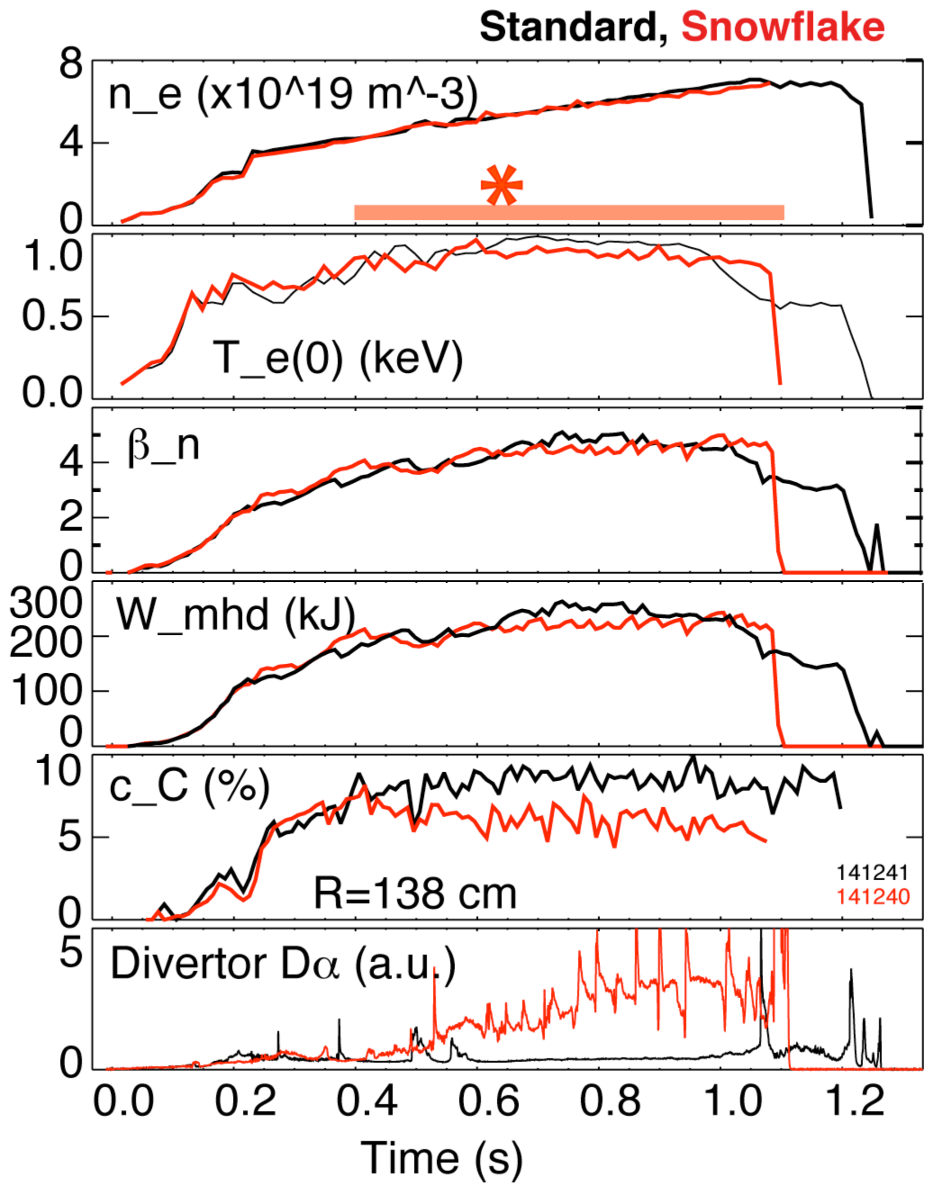






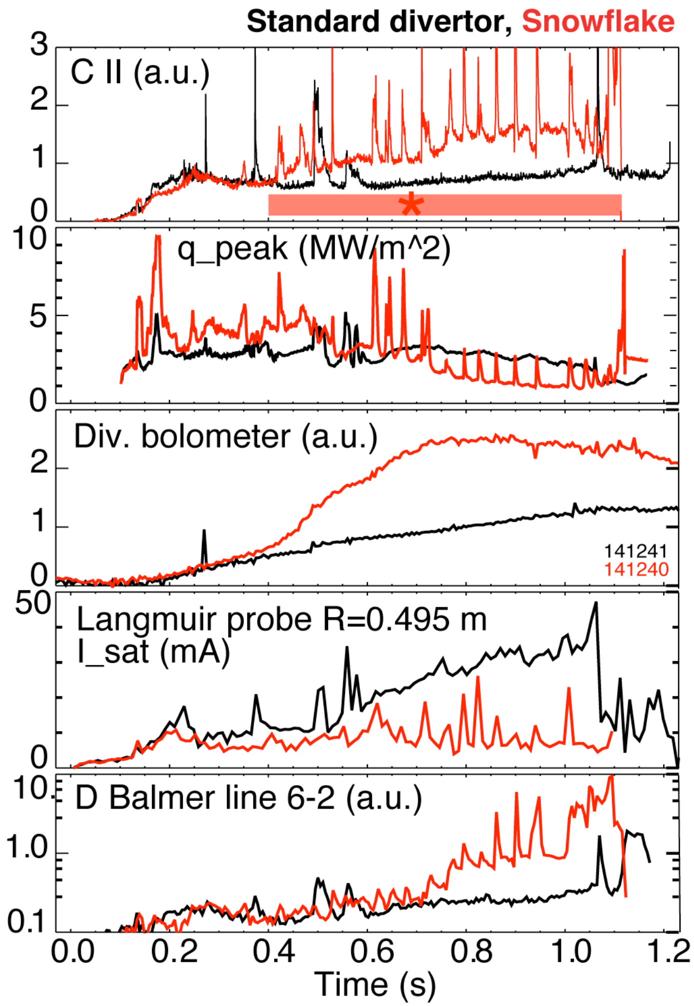
- Snowflake divertor with three coils (w/ reversed PF1B) from a medium-δ discharge
  - ELMy H-mode with steady-state snowflake
- Snowflake with three coils (w/ reversed PF1B) from a high-δ discharge
  - Best steady-state SFD, no OSP sweeping through CHI gap
  - Fiducial like-performance, basis for integration with advanced scenarios

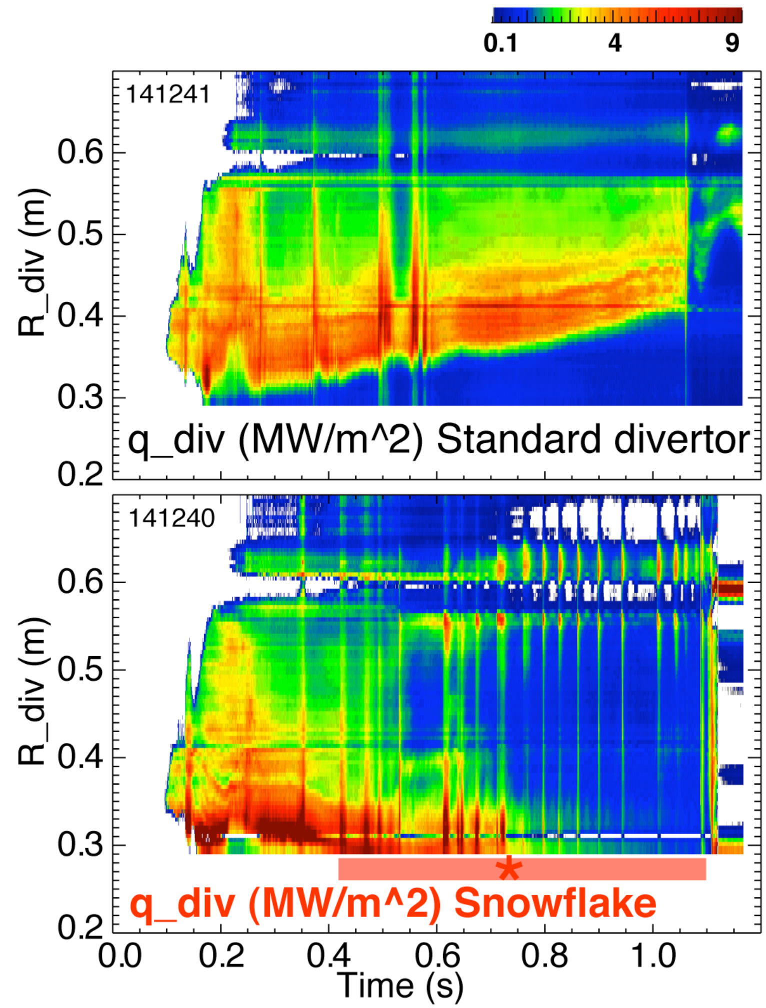
Significant core impurity reduction and good H-mode confinement properties with snowflake divertor



- 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
  - Medium-size Type I ELMs
  - Edge source reduction
- In ELM-free discharges with snowflake divertor, carbon concentration reduction also observed and attributed to edge source reduction

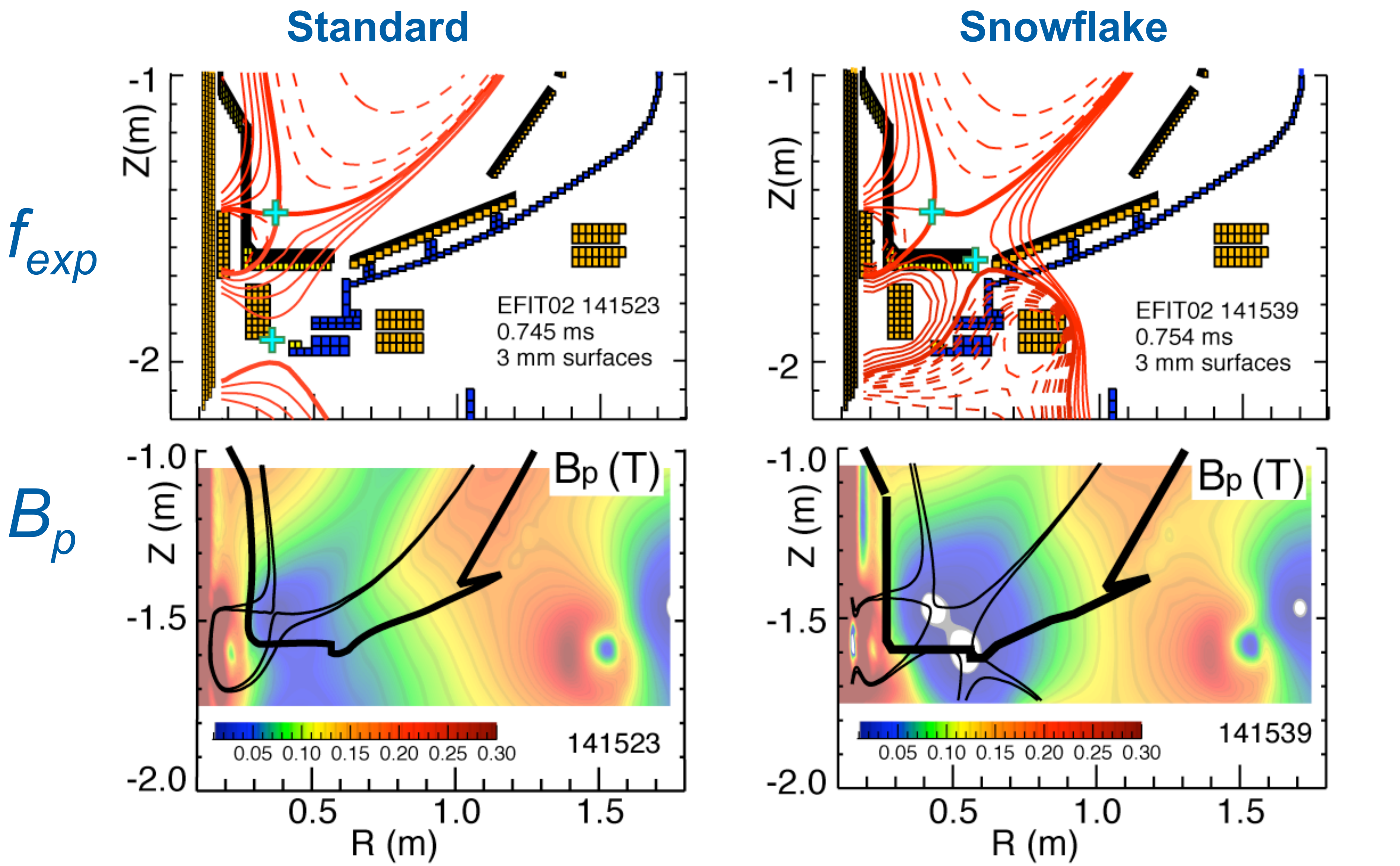
Strong signs of partial strike point detachment are observed in snowflake divertor





- Heat and ion fluxes in the outer SP region decreased
- Divertor recombination rate and radiated power are increased

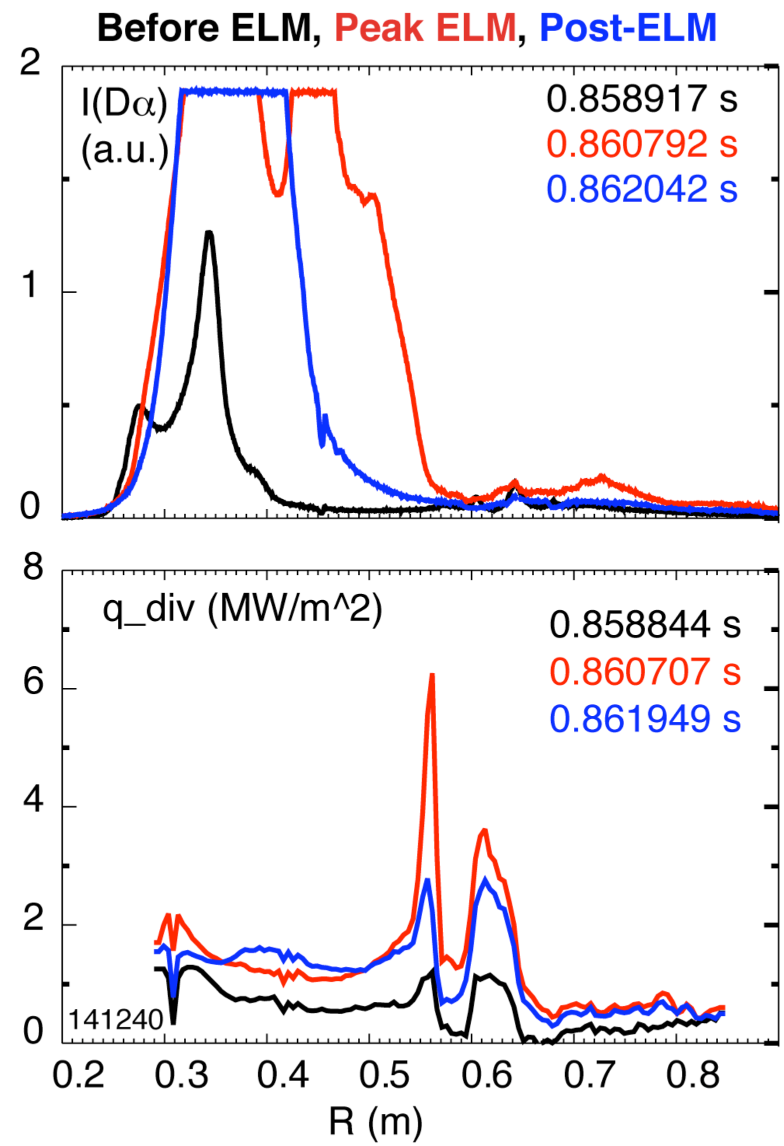
Snowflake divertor configurations obtained in NSTX confirm analytic theory and modeling



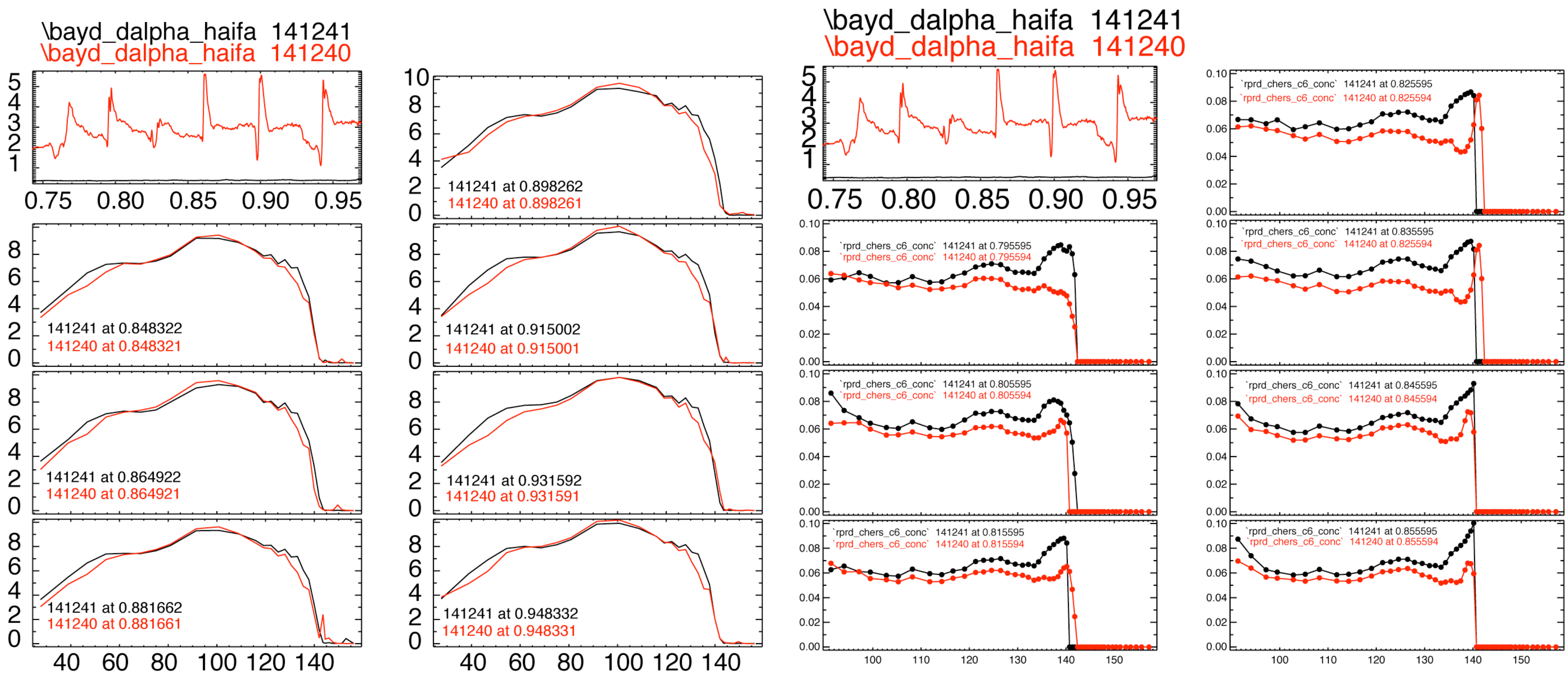
Snowflake divertor appears to alter pedestal stability and impulsive divertor heat loads due to ELMs

- Increased magnetic shear predicted in snowflake divertor
- In NSTX
  - Snowflake sometimes does not survive ELMs
  - Convective ELM heat flux follows magnetic surfaces, peak still reduced
  - Snowflake divertor triggered ELMs from a suppressed ELM state (lithium)

- Snowflake divertor effect on ELMs in TCV (F. Piras et al., PRL 2010)
  - Type I ELMs in snowflake divertor
    - increased size
    - decreased frequency

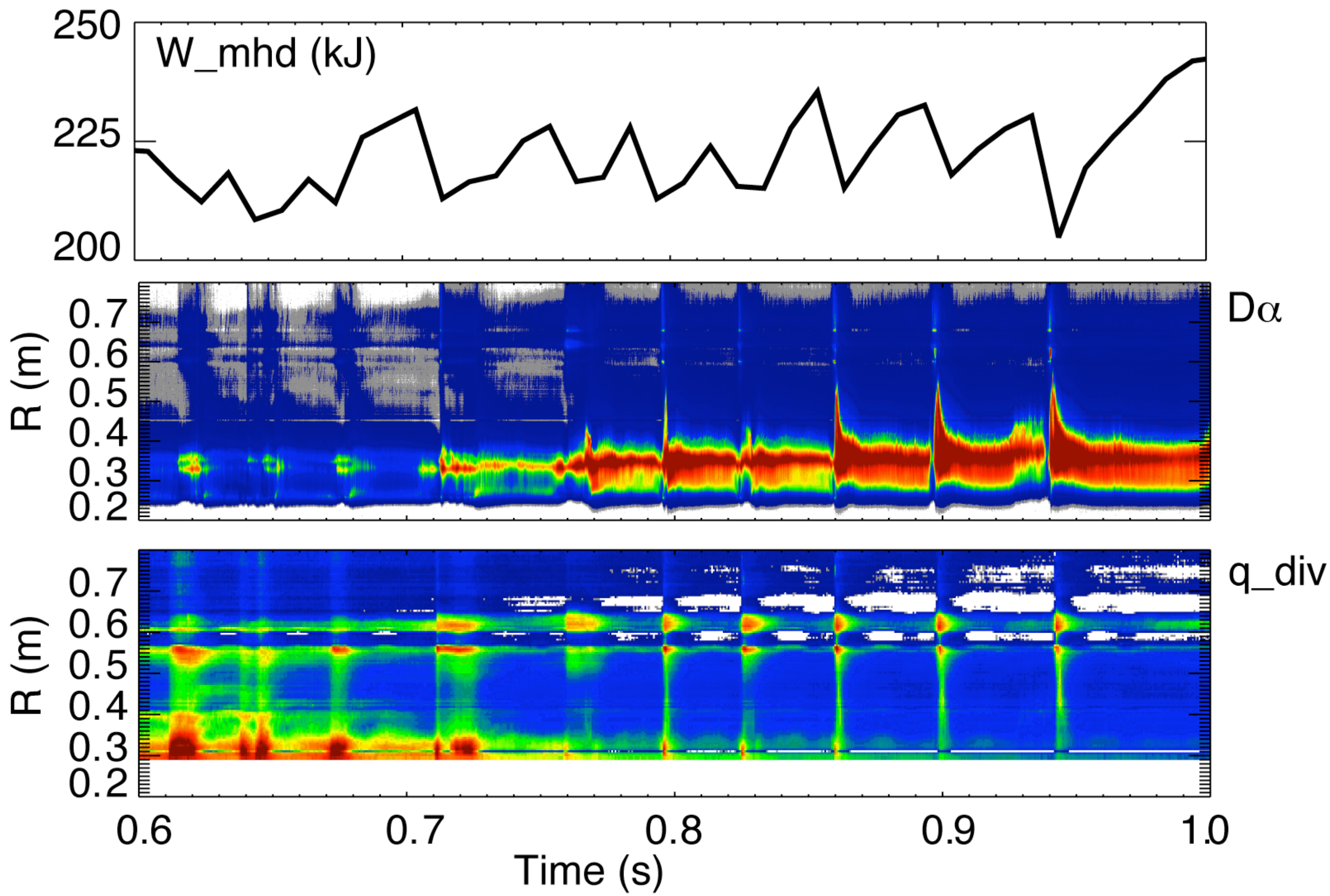


Different edge profiles are measured during the ELMy snowflake phase

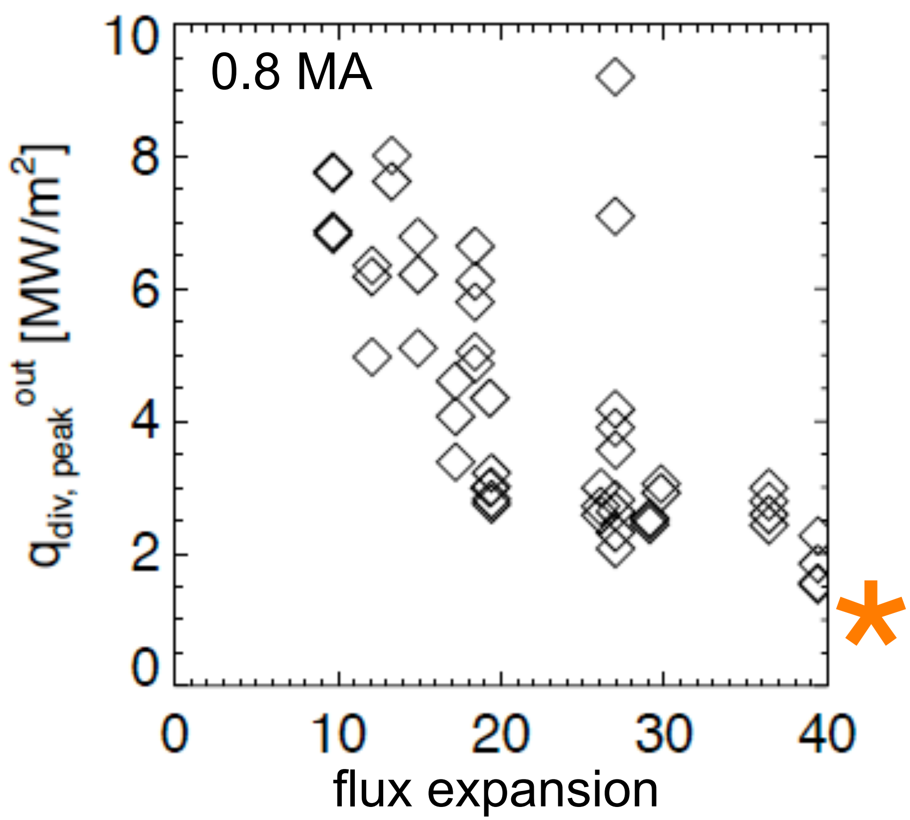


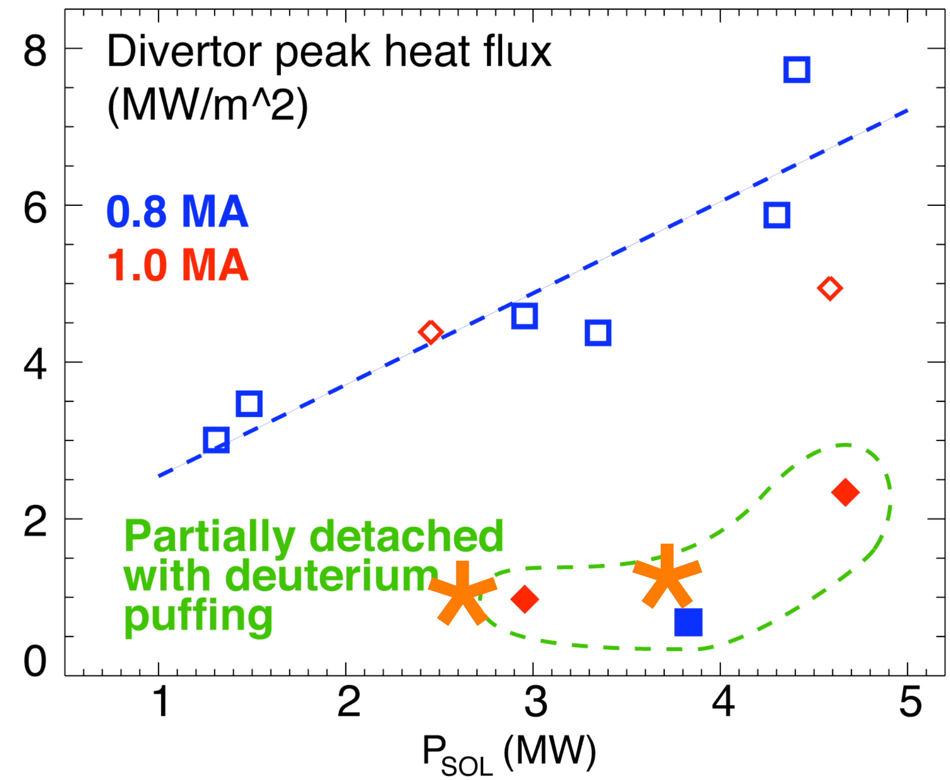
- Carbon concentration reducedby 10-20 % in the pedestal region
- n_e reduced in top pedestal region (due to carbon reduction?)

Snowflake divertor alters divertor heat load deposition profile due to ELMs



Snowflake divertor heat flux consistent with NSTX divertor heat flux scalings





- Snowflake divertor (*): P_{SOL}~3-4 MW, f_{exp}~40-80, q_{peak}~0.5-1.5 MW/m^2

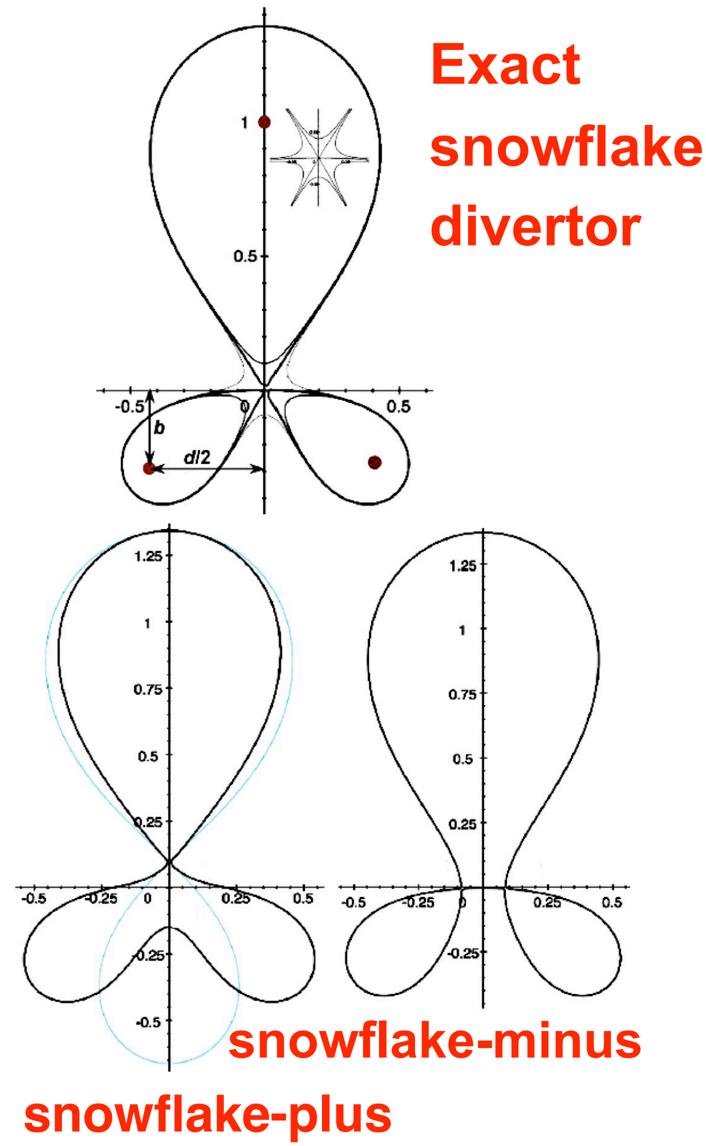
T. K. Gray et. al, EX/D P3-13, IAEA FEC 2010

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

Backup

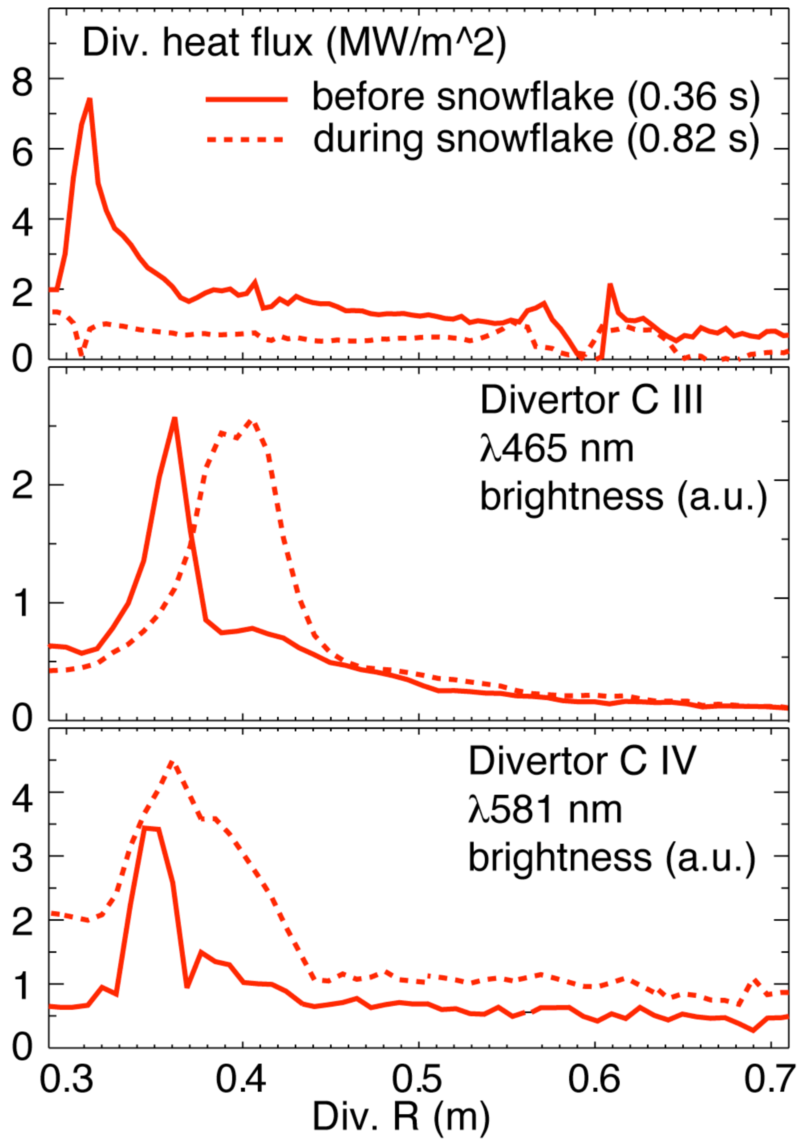
Attractive divertor geometry properties predicted by theory in snowflake divertor configuration

- Snowflake divertor
  - Second-order null
    - $B_p \sim 0$ and $grad\ B_p \sim 0$; $B_p \sim r^2$
      (Cf. first-order null: $B_p \sim 0$; $B_p \sim r$)
  - Obtained with existing divertor coils (min. 2)
  - Exact snowflake topologically unstable
- Predicted properties (cf. standard divertor)
  - Larger low B_p region around X-point
  - Larger plasma wetted-area A_{wet} (flux expansion f_{exp})
  - Larger X-point connection length L_x
  - Larger effective divertor volume V_{div}
  - Increased edge magnetic shear
- Experiments
  - TCV (F. Piras *et. al*, PRL 105, 155003 (2010))



D. D. Ryutov, PoP 14, 064502 2007

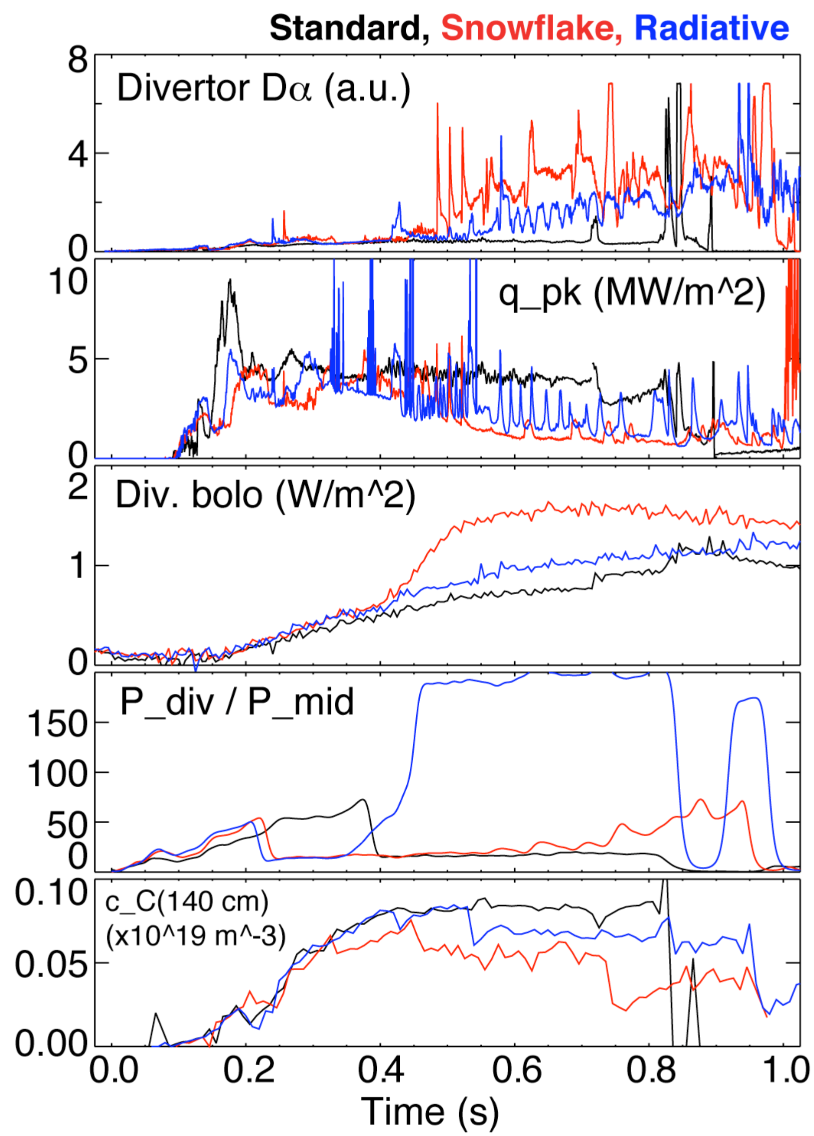
Divertor profiles show low heat flux, broadened C III and C IV radiation zones in the snowflake divertor phase



- Heat flux profiles reduced to nearly flat low levels, characteristic of radiative heating
- C III and C IV emission 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 large reduction of carbon physical and chemical sputtering rates

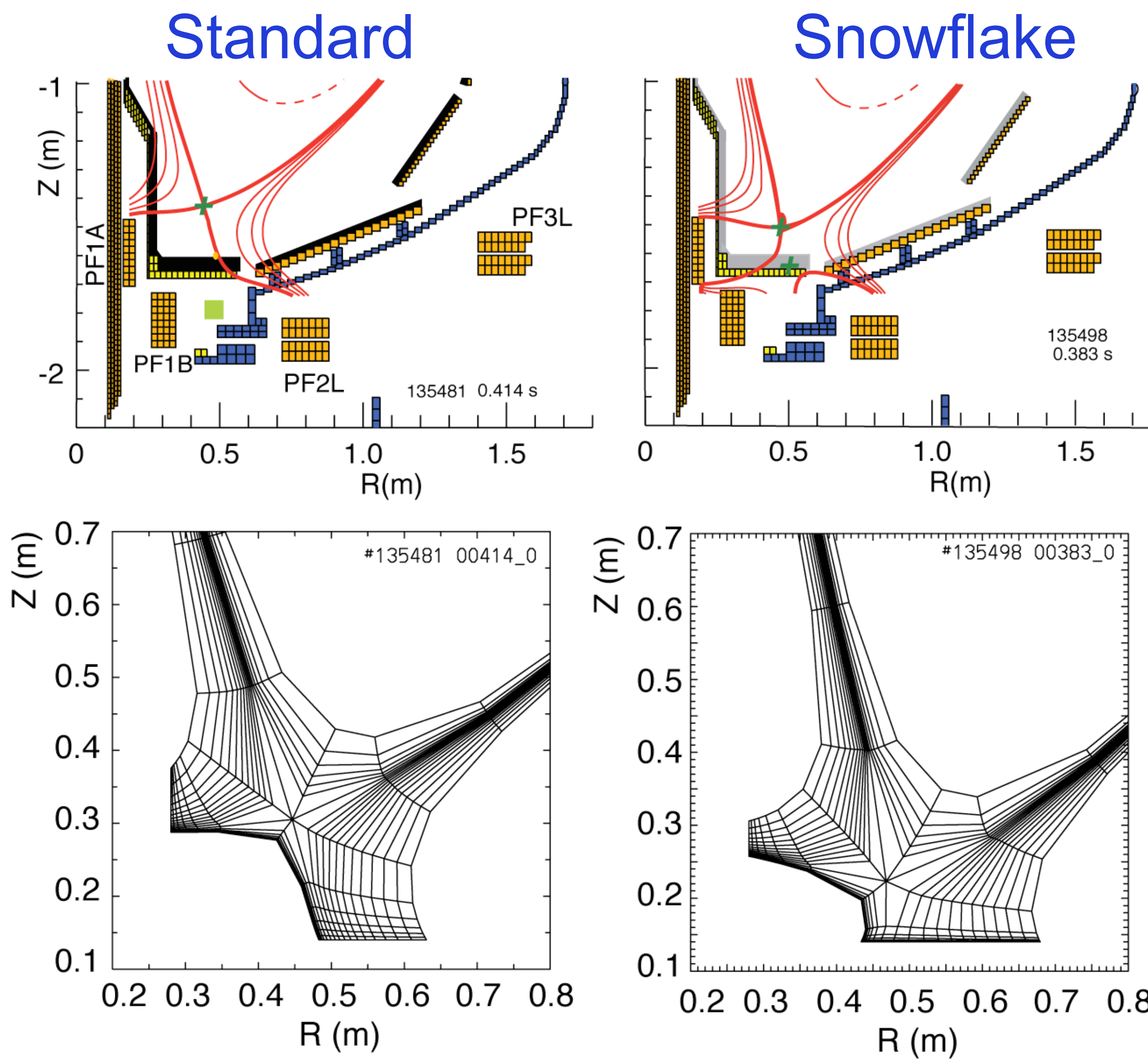
Snowflake divertor reduces heat flux and screens impurities as good as radiative divertor

- I_p=0.9 MA, P_{NBI} = 4 MW, P_{SOL} = 3 MW
- Comparison of **standard divertor**, snowflake divertor, and radiative divertor with CD_4 puffing (onset at 0.5 s)
- Peak heat flux reduced by 60-75 % by radiative divertor and snowflake divertor
- Divertor P_{rad} increased by up to 50 % in snowflake divertor, less in radiative divertor
- Neutral compression (P_{div} / P_{mid}) higher in snowflake and radiative divertors
- Pedestal impurity concentration reduced in snowflake and radiative divertors

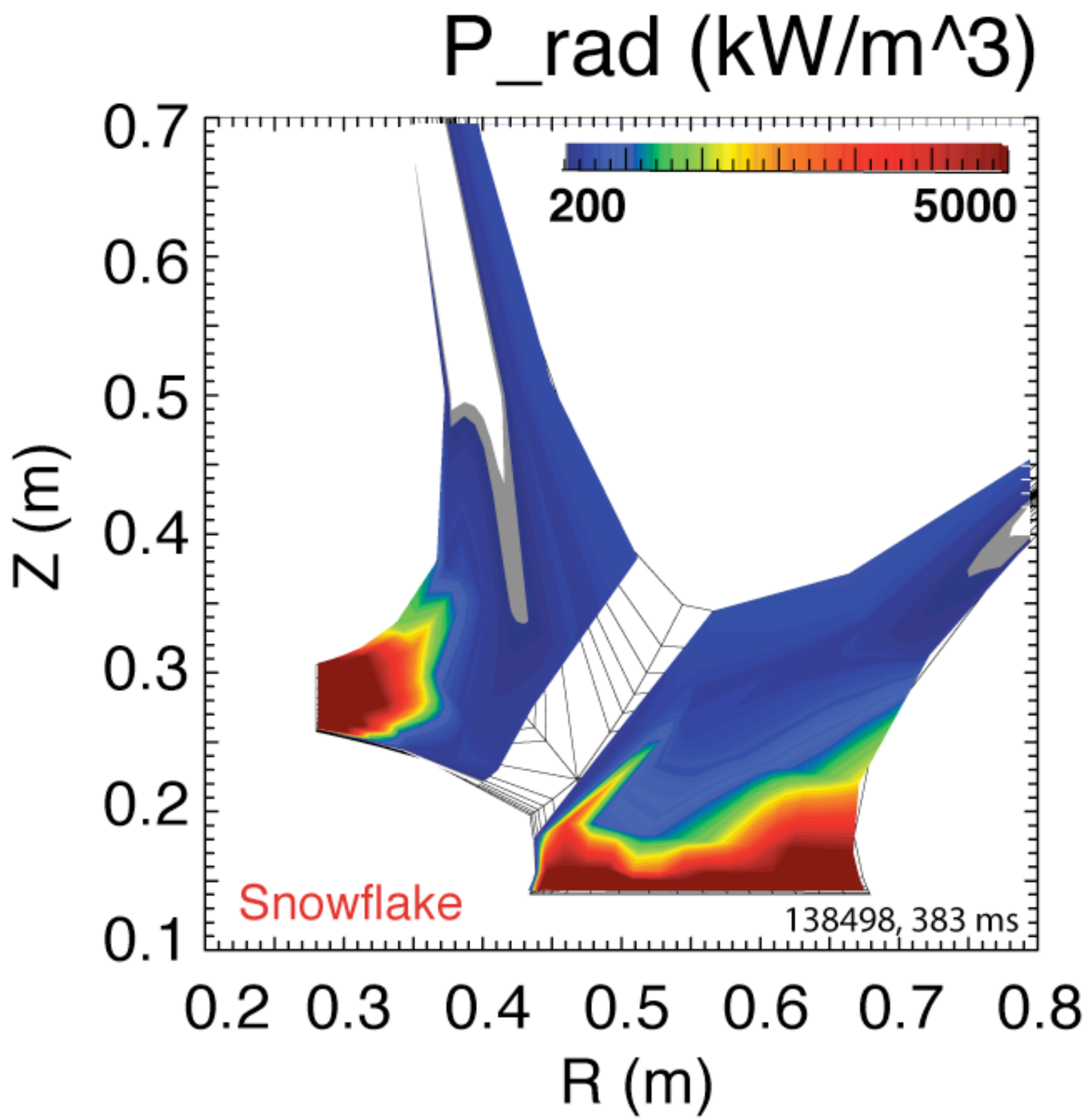


2D multi-fluid edge transport code UEDGE is used to study snowflake divertor properties

- 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 %

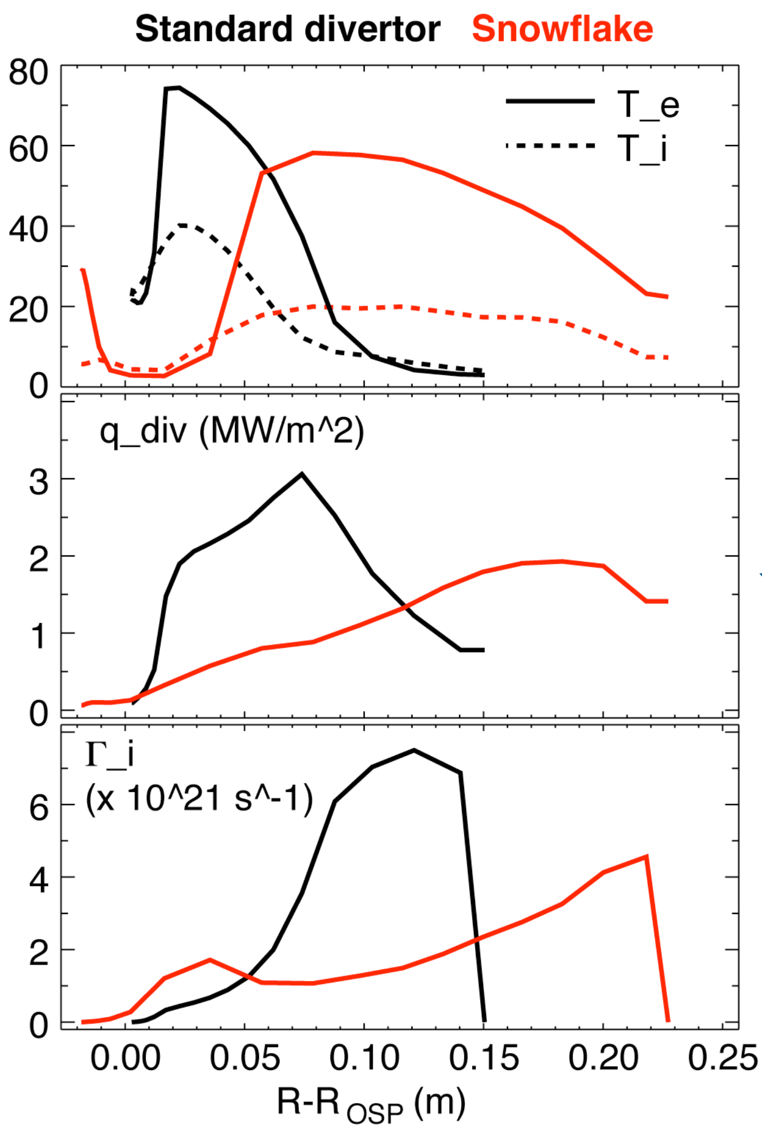


Radiated power is broadly distributed in the outer leg of snowflake divertor



UEDGE model

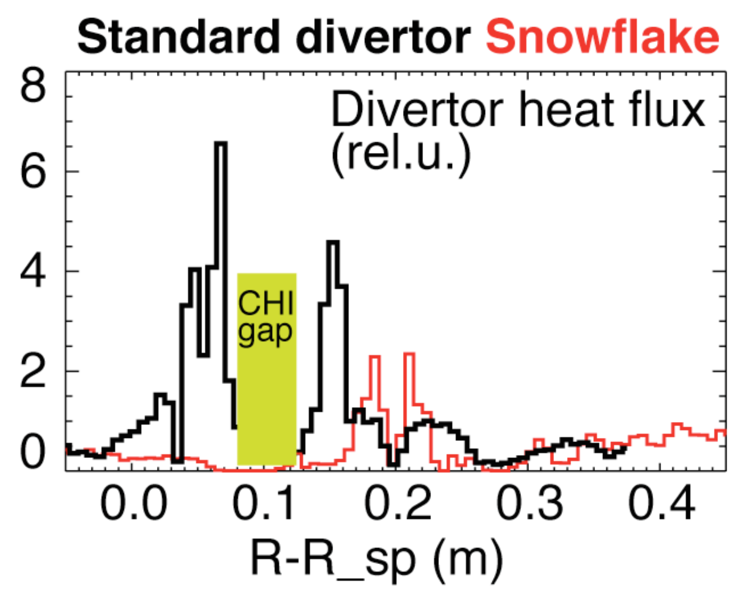
UEDGE model shows a trend toward detachment in snowflake divertor outer leg (cf. standard divertor)



UEDGE model

In the snowflake divertor outer strike point region:

- T_e and T_i reduced
- Divertor peak heat flux reduced
- Particle flux low



Experiment