NSTX

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

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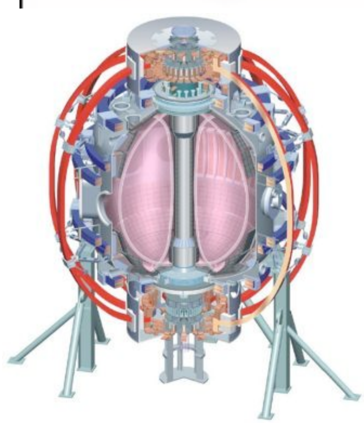

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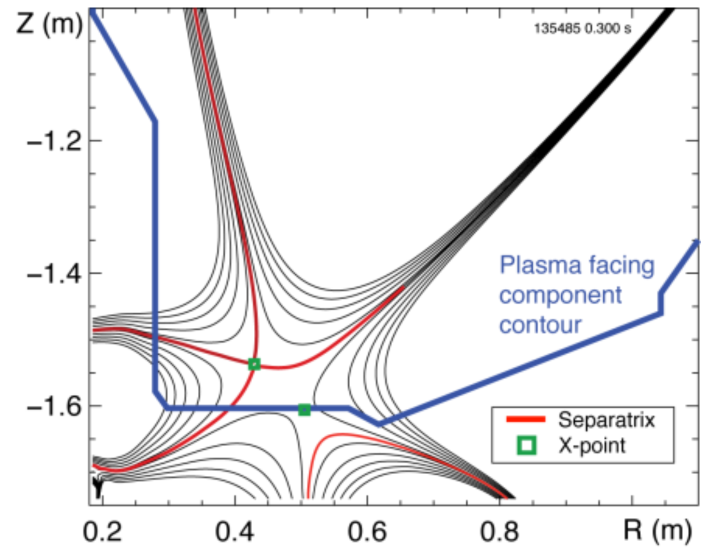
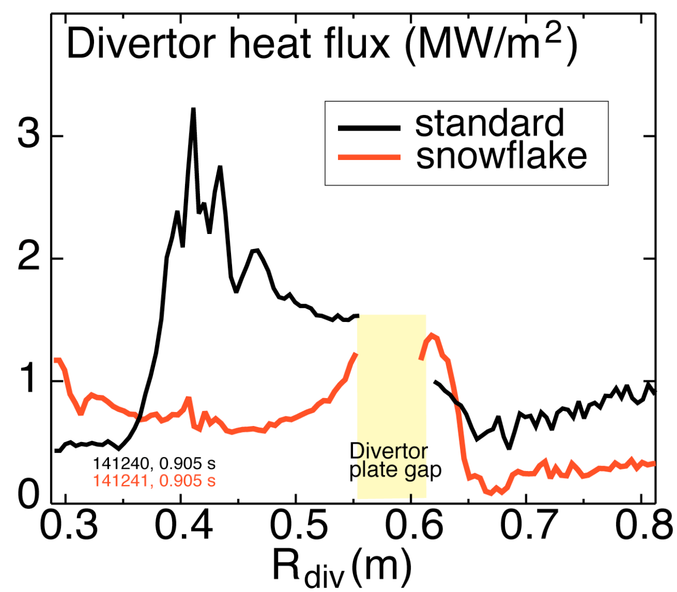
Outline: Experimental results from snowflake divertor in NSTX very encouraging

- **Snowflake divertor geometry attractive for heat flux management**
- **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**





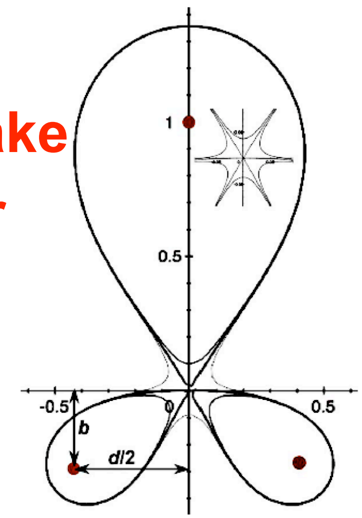
Snowflake divertor geometry attractive for heat flux mitigation

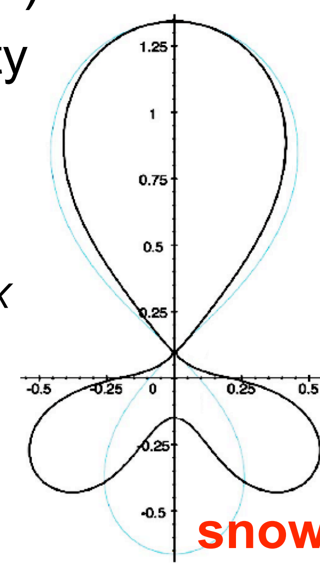
- Snowflake divertor
  - Second-order null
    - $B_p \sim 0$ and *grad* $B_p \sim 0$ (Cf. first-order null: $B_p \sim 0$)
  - Obtained with existing divertor coils (min. 2)
  - Exact snowflake topologically unstable

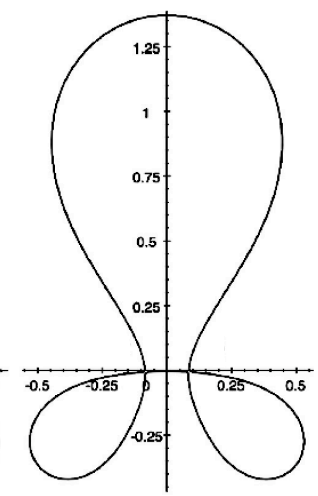
- Predicted geometry properties (cf. standard divertor)
  - Larger region with low B_p around X-point: ped. stability
  - Larger plasma wetted-area A_{wet} : reduce q_{div}
  - Larger X-point connection length L_x : reduce q_{II}
  - Larger effective divertor volume V_{div} : incr. P_{rad} , P_{CX}

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

Exact snowflake divertor







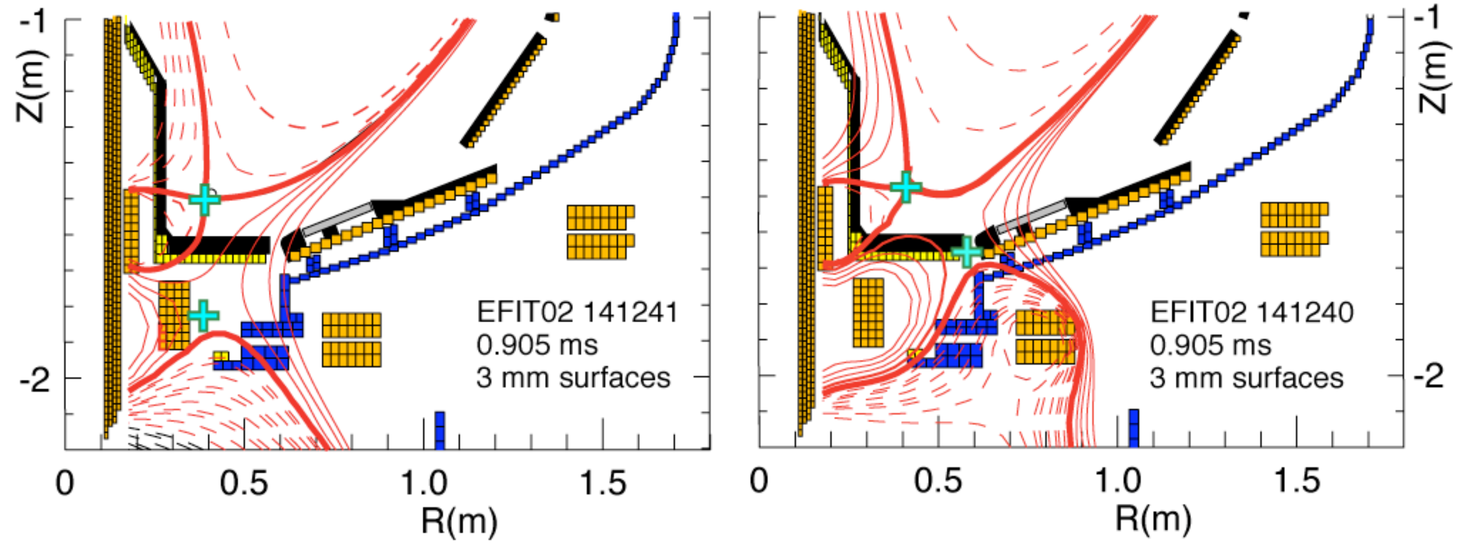
snowflake-minus

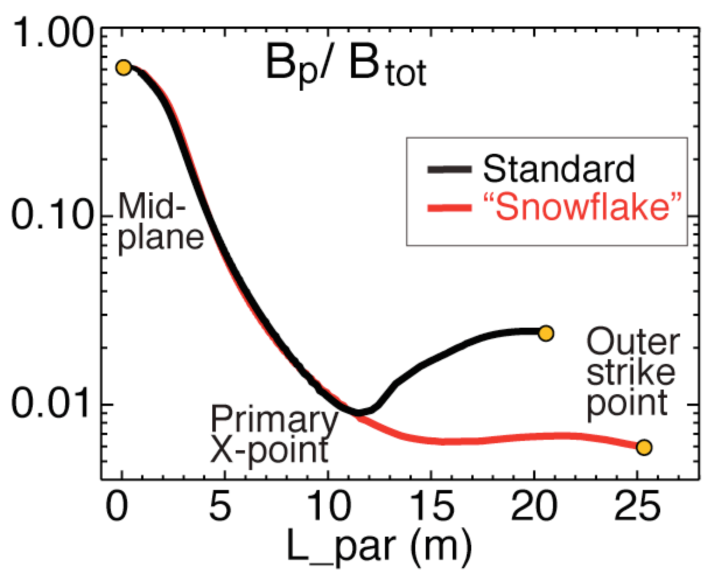
snowflake-plus

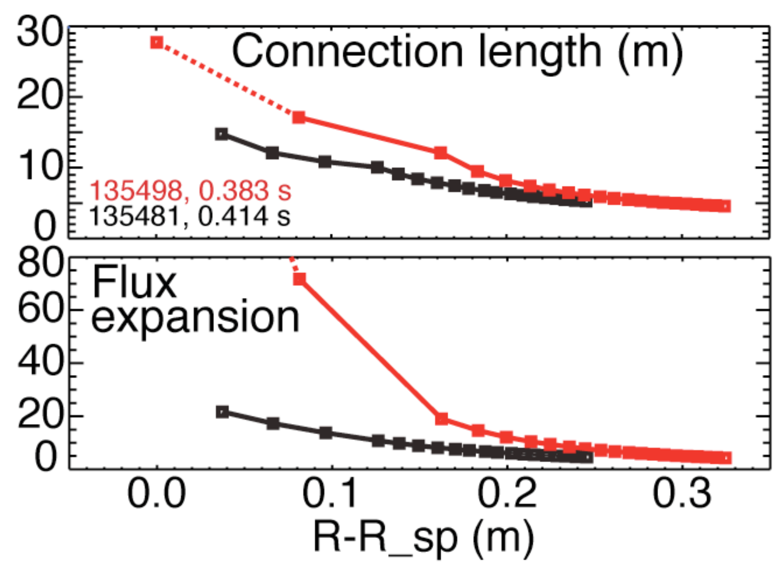
D. D. Ryutov, PoP 14, 064502 2007

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

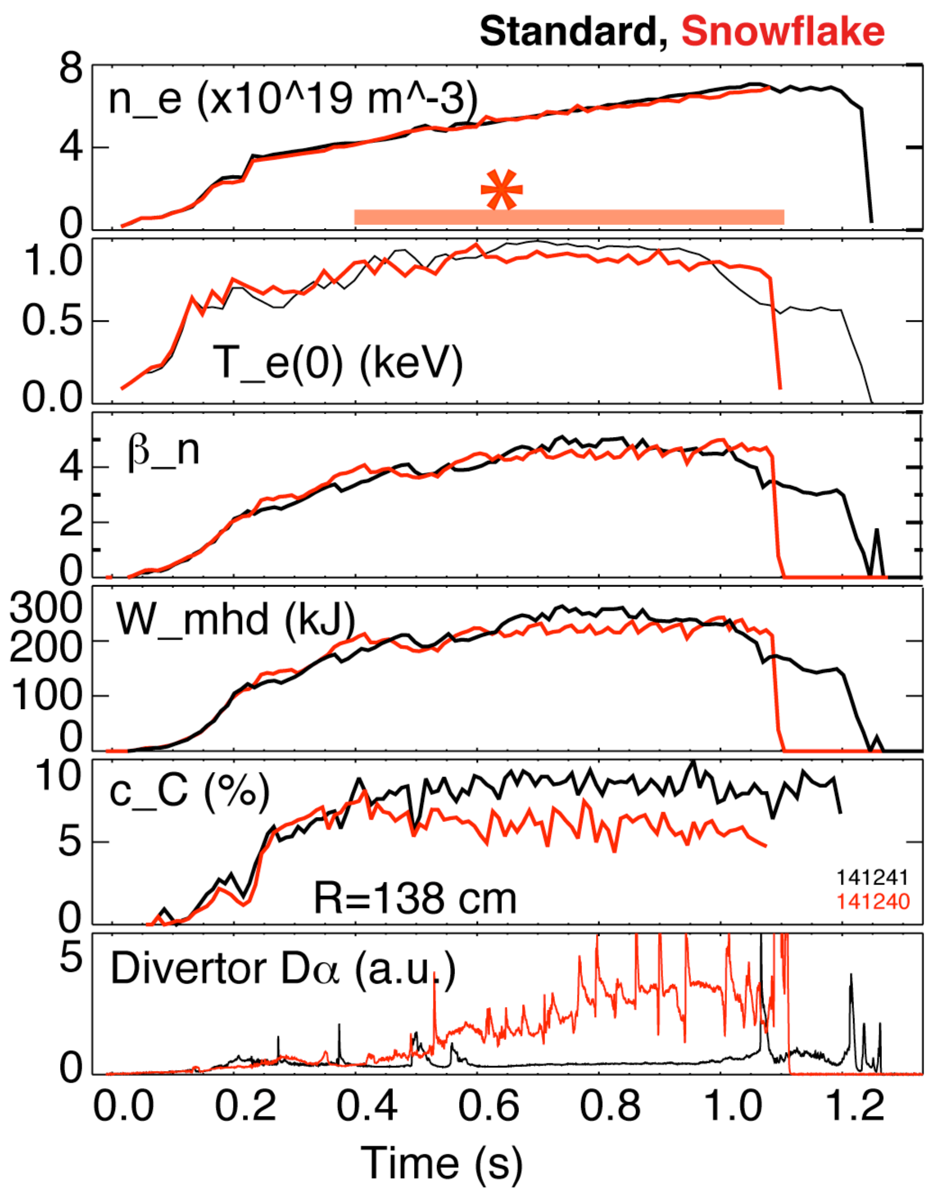
- These properties observed in first 30-50 % of SOL width
- B_{tot} angles in the strike point region: 1-2°, sometimes < 1°





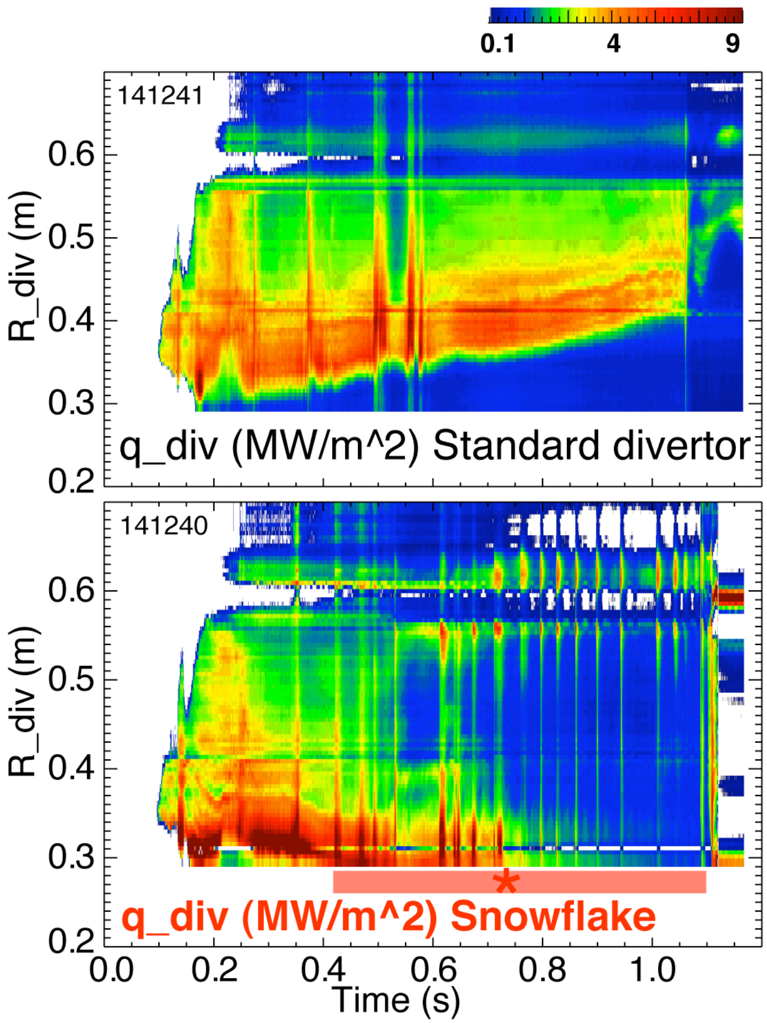


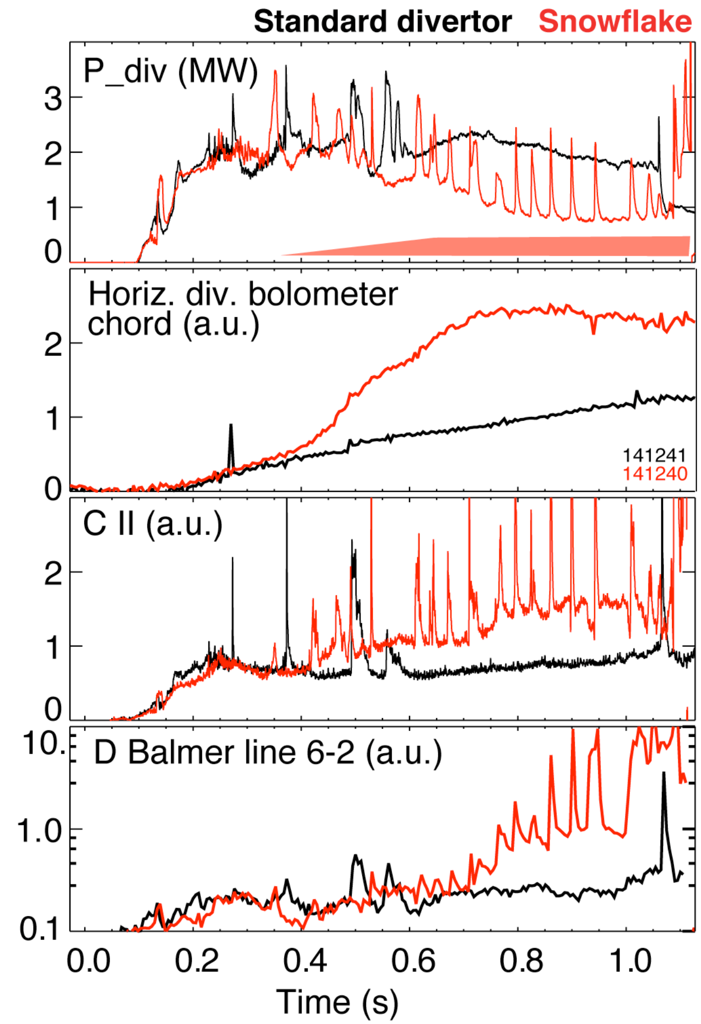
Good H-mode confinement properties and core impurity reduction obtained with snowflake divertor



- 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

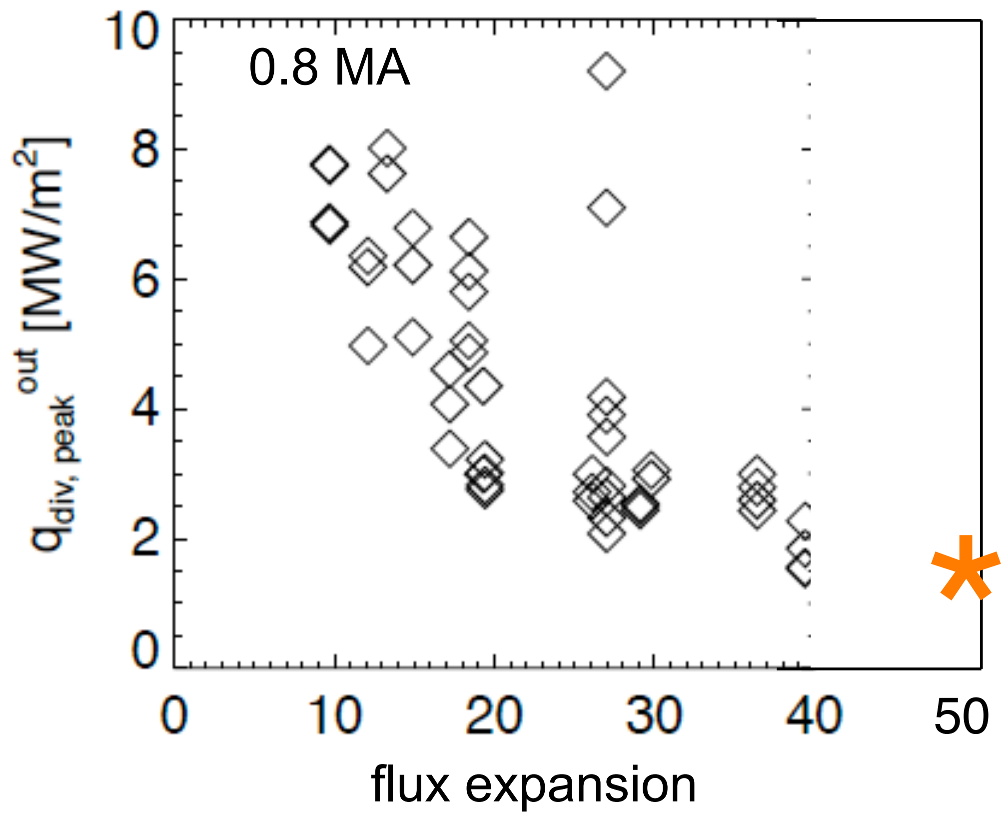
Significant reduction of steady-state divertor heat flux observed in snowflake divertor (at P_{SOL}~ 3 MW)

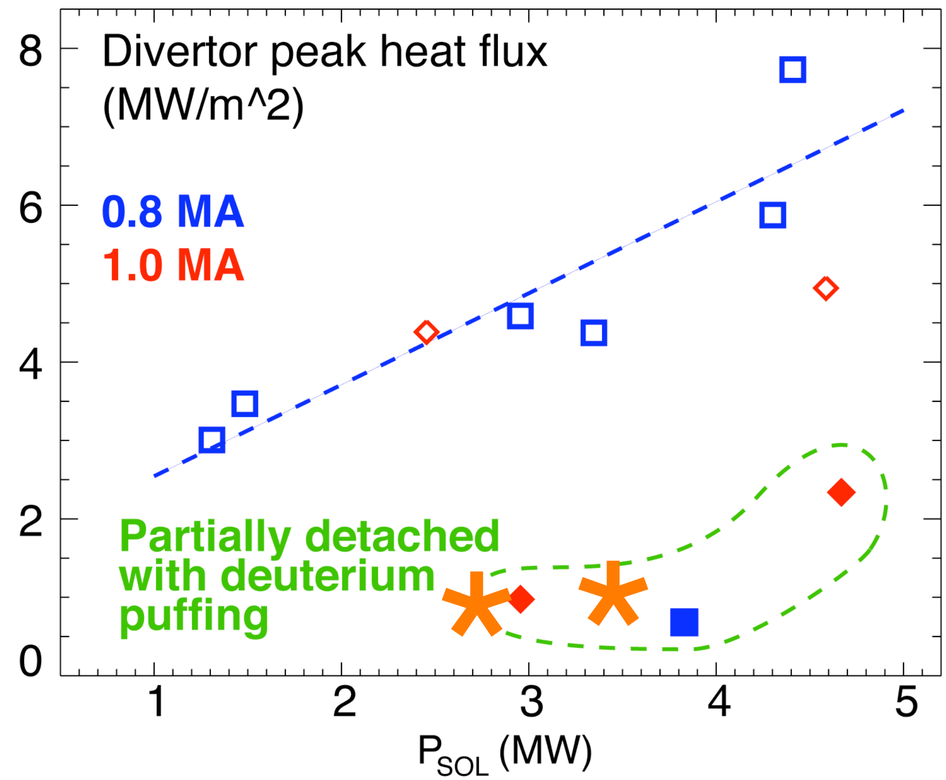




- Partial detachment at or after snowflake formation time
  - Heat and ion fluxes in the outer strike point region decreased
  - Divertor recombination rate and radiated power are increased

Snowflake divertor heat flux consistent with NSTX divertor heat flux scalings





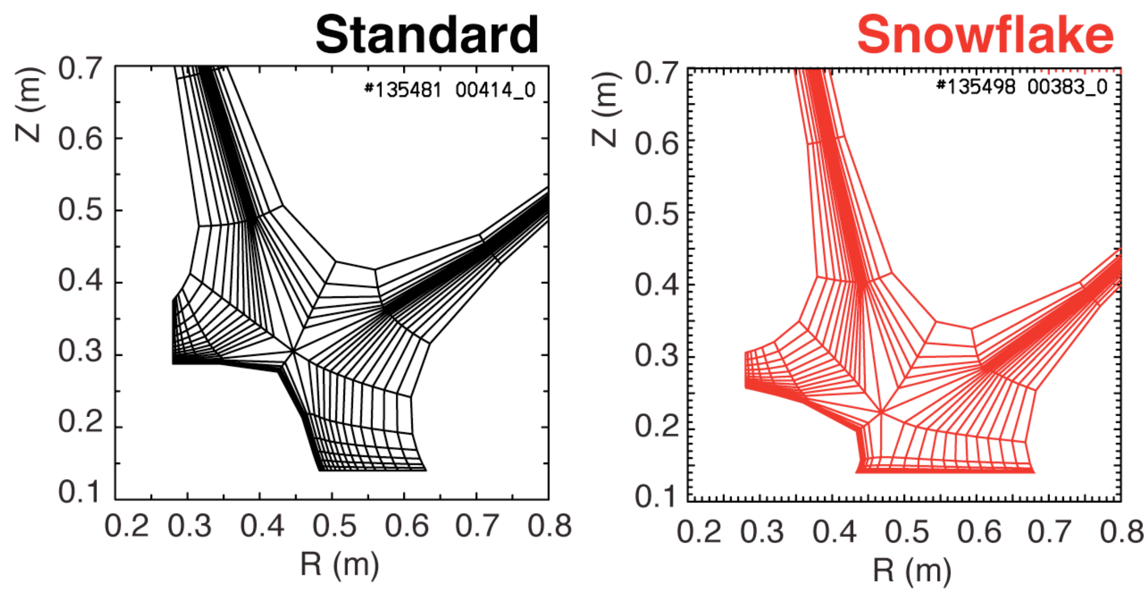
- Snowflake divertor (*): P_{SOL}~3-4 MW, f_{exp}~40-60, q_{peak}~0.5-1.5 MW/m^2

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

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

Modeling shows a trend toward reduced temperature, heat and particle fluxes in the snowflake divertor

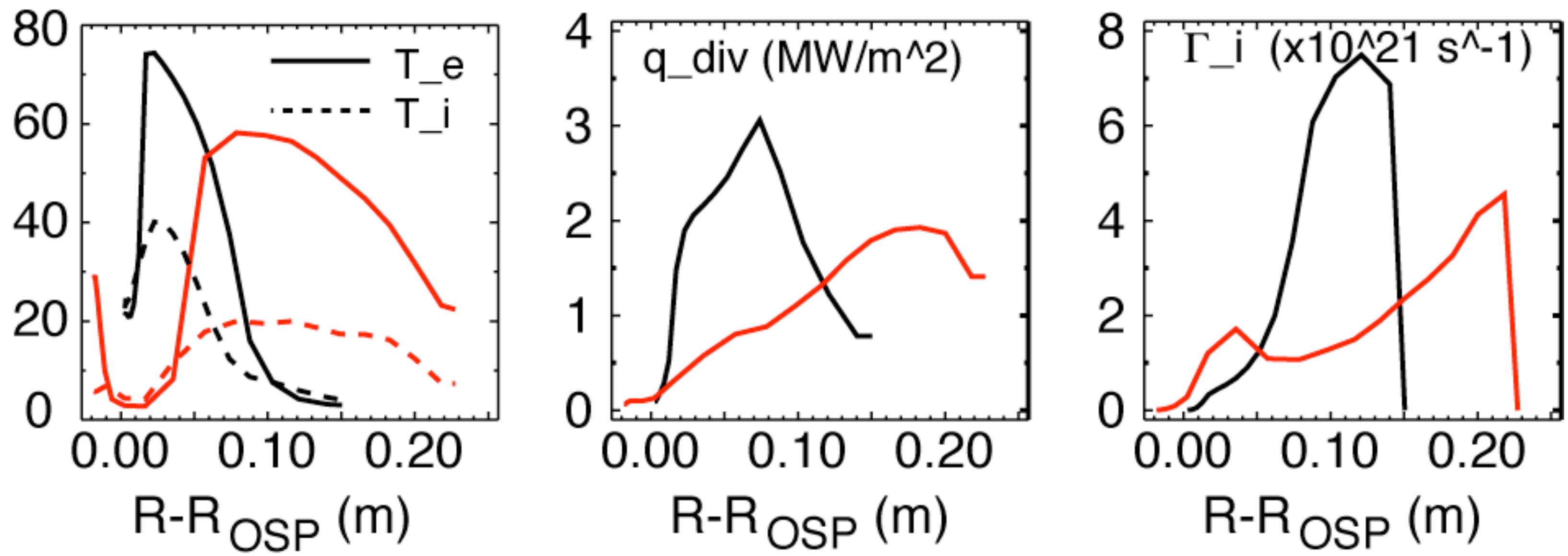
- 2D multi-fluid code UEDGE
  - Fluid (Braginskii) model for ions and electrons
  - Fluid for neutrals
  - Classical parallel transport, anomalous radial transport
    - $D = 0.25\ m^2/s$
    - $\chi_{e,i} = 0.5\ m^2/s$



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

R_{recy} = 0.95

Carbon 3 %



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 heat flux
- Potential to combine with radiative divertor for increased divertor radiation

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

- This talk focused on divertor results. Planned research on NSTX:
  - Improved magnetic control
  - Pedestal peeling-balooning stability
  - Snowflake at low SOL collisionality with lithium
  - Divertor and upstream turbulence (blobs)

NSTX presentations at 38th EPS Conference

D. Kumar: Modeling of space resolved impurity emission in the EUV range using a transmission grating based imaging spectrometer at NSTX

D. Stutman: Multi-energy SXR imaging diagnostics for fusion experiments

D.J. Clayton: Edge transport measurements with the new multi-energy soft-x-ray diagnostic on NSTX

J.C. Hosea: Properties of HHFW electron heating generated H-modes in NSTX

R.J. La Haye: Aspect ratio effects on neoclassical tearing modes from comparison between DIII-D and NSTX

J.W. Berkery: Resistive wall mode kinetic stability advancements for refined comparison with experiments

S.A. Sabbagh: Advances in resistive wall mode stabilization to maintain high beta, low internal inductance plasmas in NSTX

G. Taylor: High-harmonic fast wave heating and current drive results for deuterium H-mode plasmas in the National Spherical Torus Experiment

W. Guttenfelder: Nonlinear gyrokinetic simulations of microtearing mode turbulence

E. Fredrickson: Internal amplitude measurements of CAE and GAE

Ya.I. Kolesnichenko: Formation of a non-monotonic energy distribution of energetic ions in NSTX

J.W. Ahn: Effect of 3-D fields on divertor detachment and associated pedestal profiles in NSTX H-mode plasmas

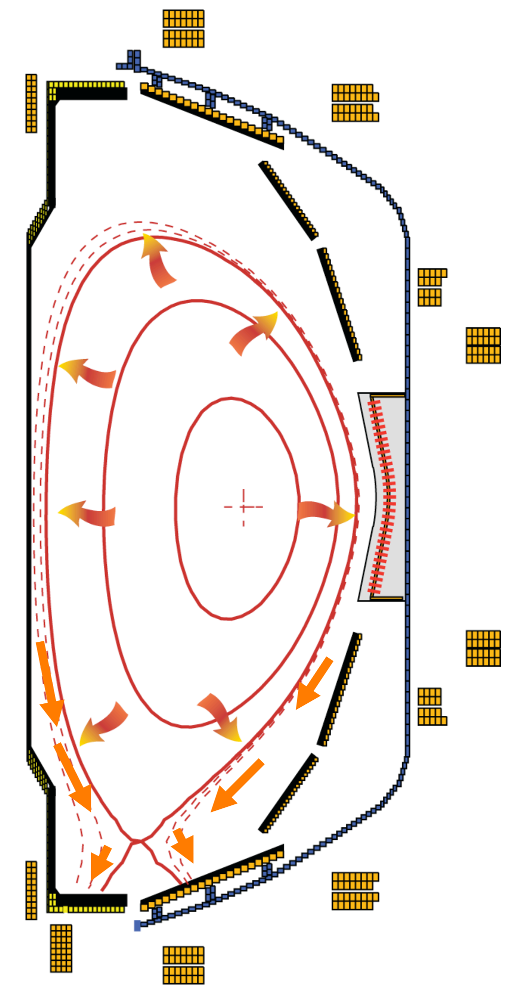
R. Maingi: Density Profile and Particle Transport Control as the Critical Ingredients for ELM Suppression in Tokamaks

Backup slides

Poloidal divertor concept enabled progress in magnetic confinement fusion 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)

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

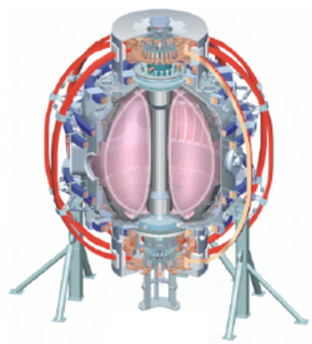
$$A_{wet} = 2\pi R \, f_{exp} \, \lambda_{q_{||}}$$

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

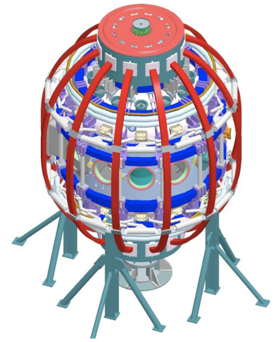
- Promising divertor peak heat flux mitigation solutions:
  - Divertor geometry
    - poloidal flux expansion
    - divertor plate tilt
    - magnetic balance
  - Radiative divertor
- Recent ideas to improve standard divertor geometry
  - X-divertor (M. Kotschenreuther *et. al*, IC/P6-43, IAEA FEC 2004)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

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

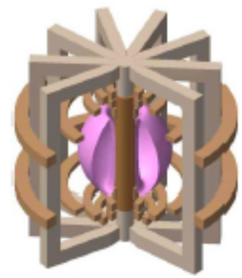
- ST / NSTX goals:
  - Study high beta plasmas at reduced collisionality
  - Access full non-inductive start-up, ramp-up, sustainment
  - Prototype solutions for mitigating high heat & particle flux
- In an ST, modest $q_{||}$ can yield high divertor q_{pk}
  - in NSTX, $q_{||}$= 50-100 MW/m^2 and q_{pk}=6-15 MW/m^2
  - Large radiated power and momentum losses are needed to reduce $q_{||}$
- In NSTX, partially detached divertor regime is accessible only
  - in highly-shaped plasma configuration with high flux expansion divertor (high plasma plugging efficiency, reduced $q_{||}$)
  - modest divertor D_2 injection still needed



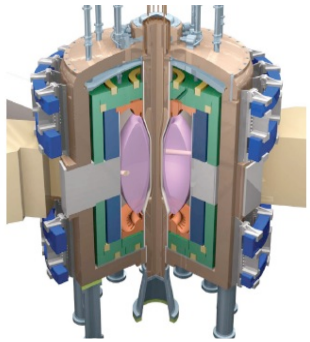
NSTX



NSTX-U



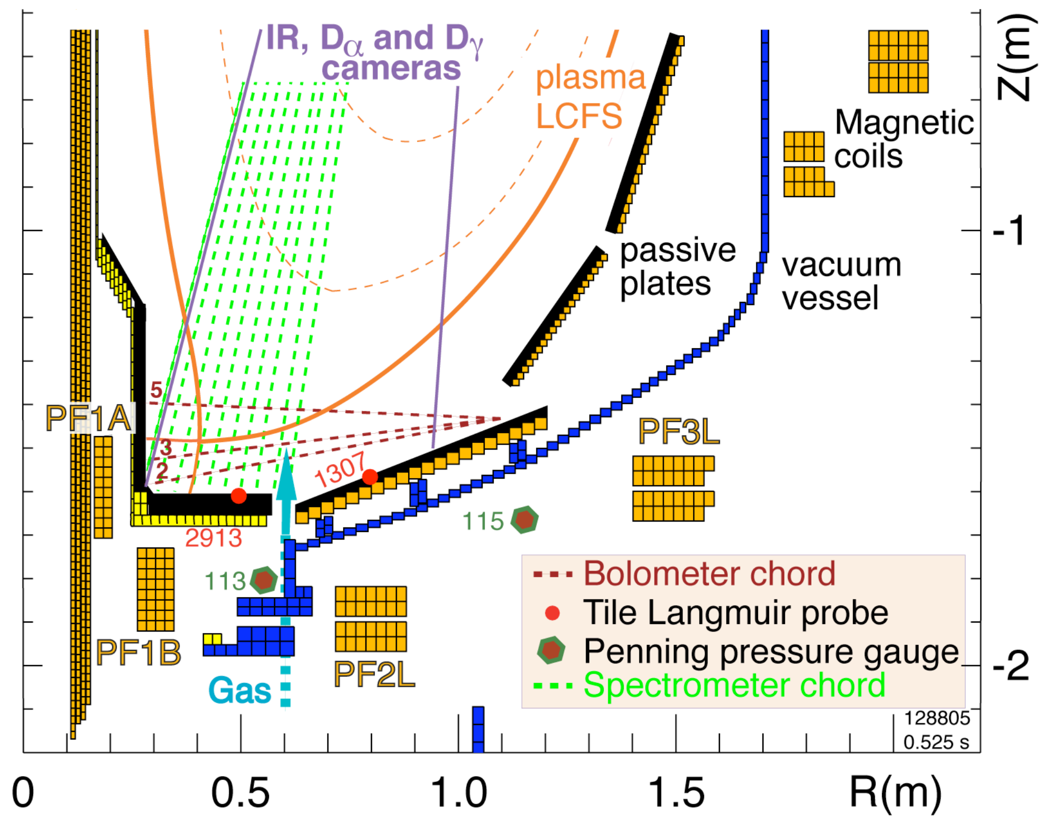
ST-based Plasma Material Interface (PMI) Science Facility



ST-based Fusion Nuclear Science (FNS) Facility

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} ≤ 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

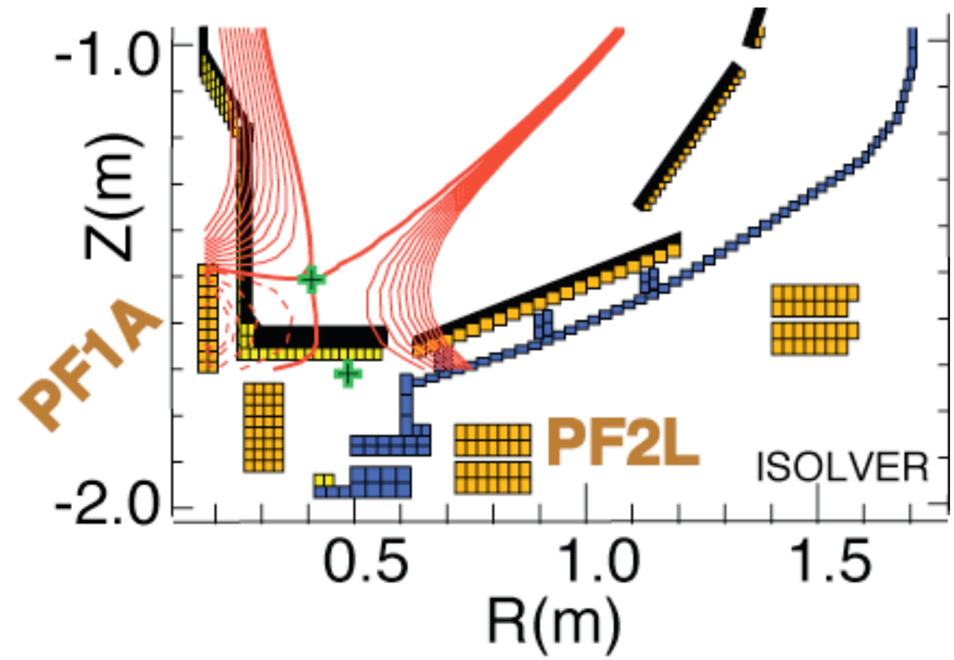


Possible snowflake divertor configurations were modeled with ISOLVER code

- 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



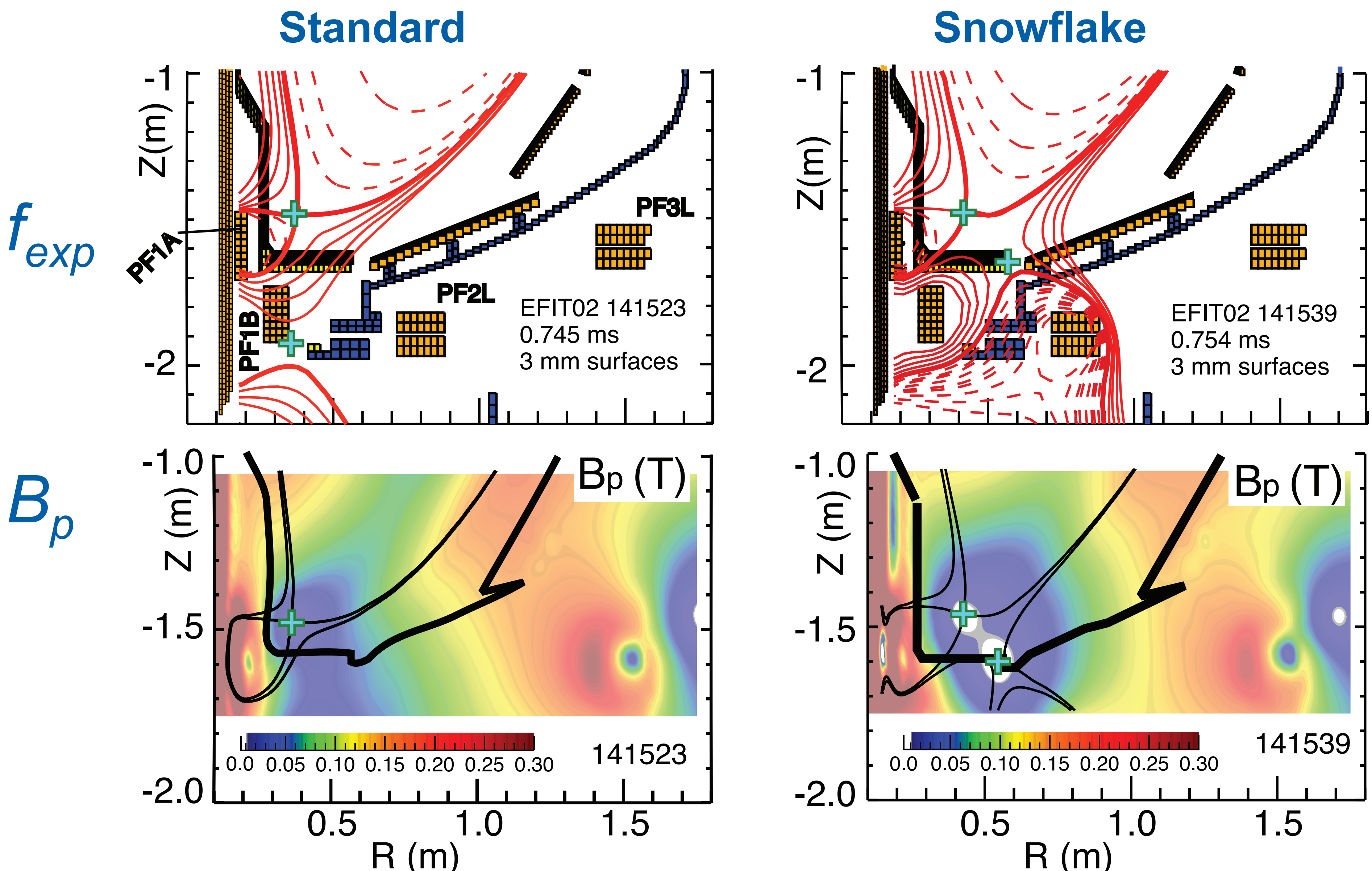
Quantity	Standard divertor	Simulated snowflake
X-point to target parallel length L_x (m)	**5-10**	**10**
Poloidal magnetic flux expansion f_{exp} at outer SP	**10-24**	**60**
Magnetic field angle at outer SP (deg.)	**1.5-3**	**~1**
Plasma-wetted area A_{wet} (m^2)	**≤ 0.4**	**0.95**

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

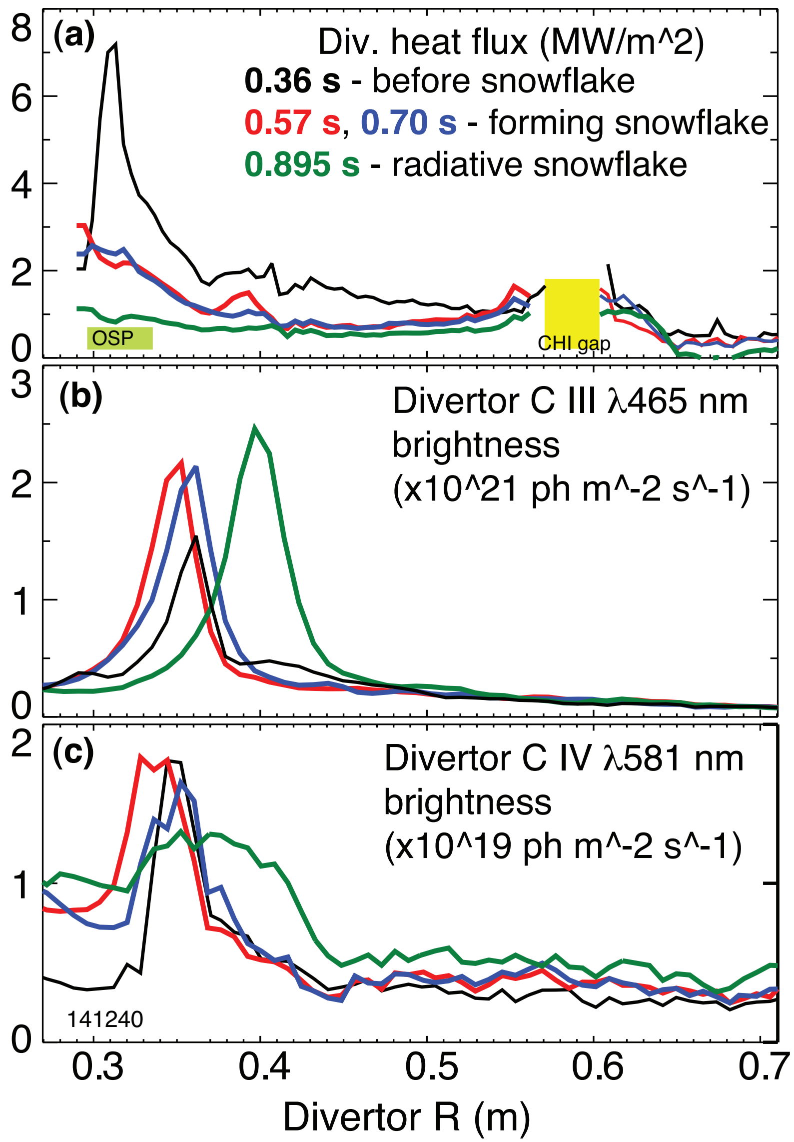
- NSTX
  - I_p = 0.7-1.4 MA, t_{pulse} < 1.5 s, $P_{in} \leq$ 7.4 MW (NBI)
  - ATJ and CFC graphite PFCs
  - P / R ~ 10
  - $q_{pk} \leq$ 15 MW/m^2
  - $q_{||} \leq$ 200 MW/m^2

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 in NSTX confirm analytic theory and modeling



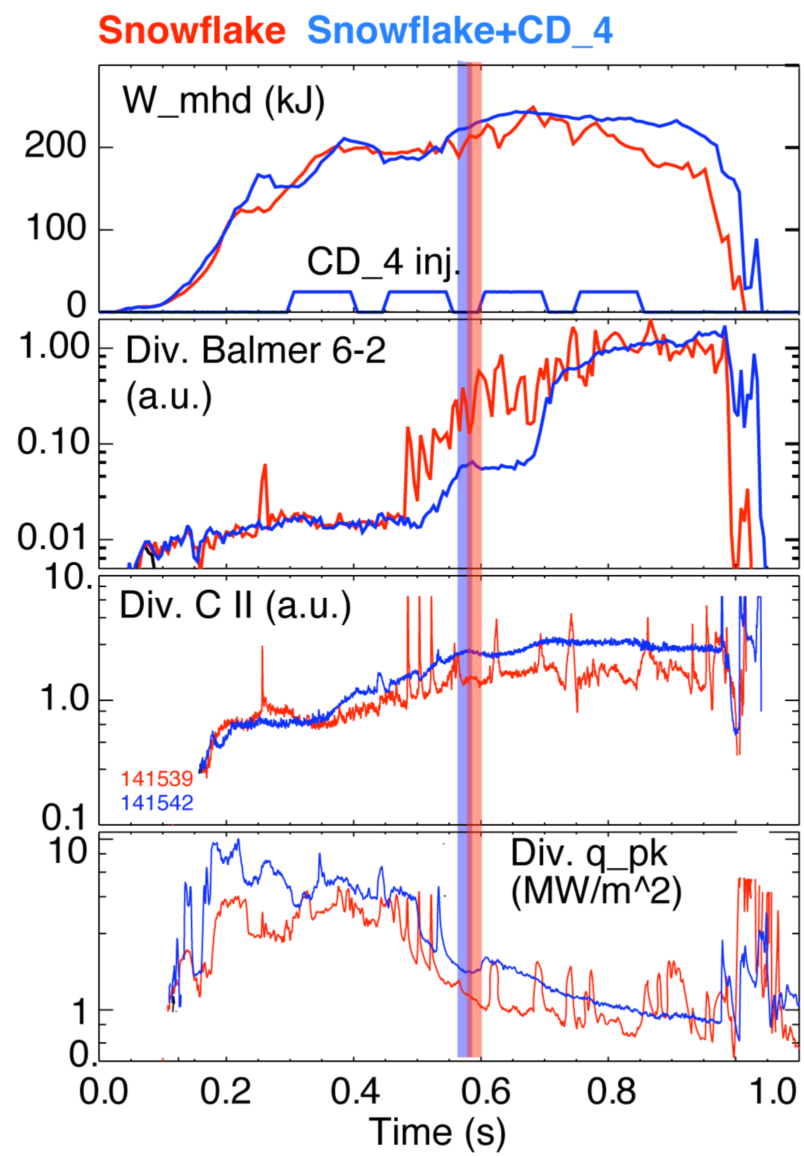
Divertor profiles show low heat flux, broadened C III and C IV radiation zones in the snowflake divertor phase



- 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

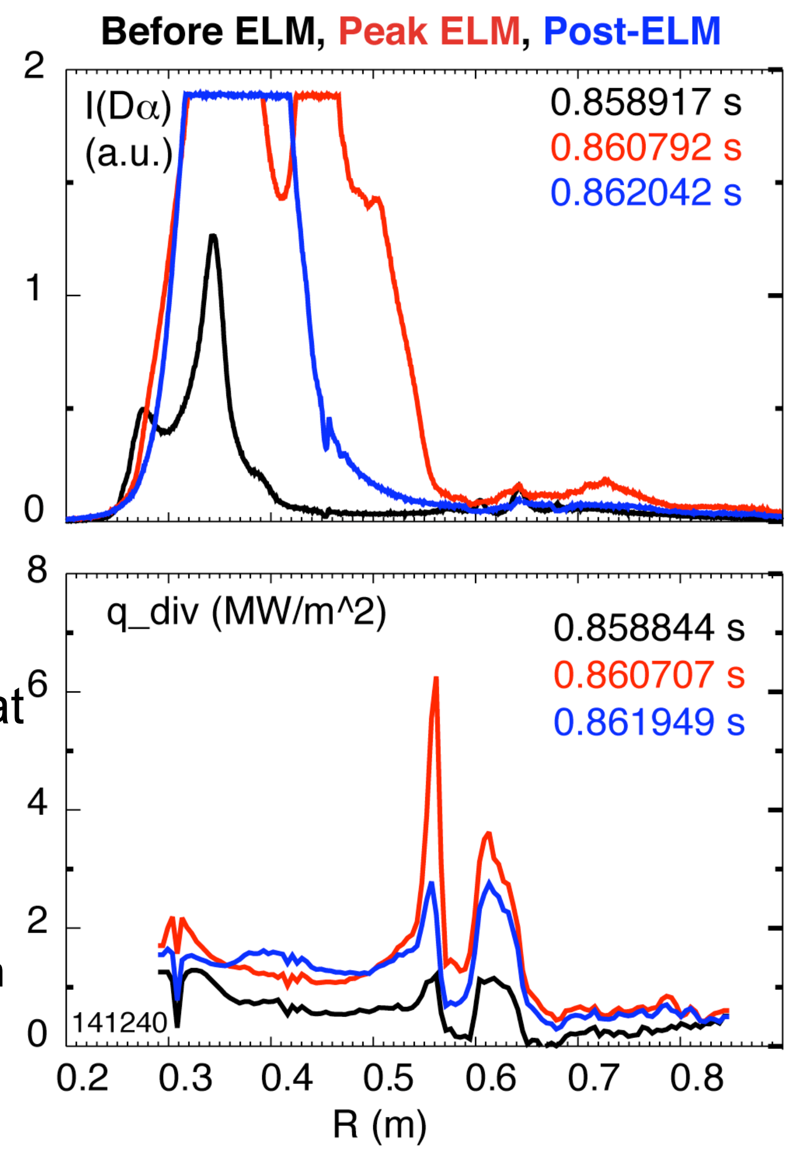
Snowflake divertor with CD_4 seeding leads to increased divertor carbon radiation

- I_p=0.9 MA, P_{NBI}=4 MW, P_{SOL}=3 MW
- Snowflake divertor (from 0.6 ms)
  - Peak divertor heat flux reduced from 4-6 MW/m^2 to 1 MW/m^2
- Snowflake divertor (from 0.6 ms) + CD_4
  - Peak divertor heat flux reduced from 4-6 MW/m^2 to 1-2 MW/m^2
  - Divertor radiation increased further
  - Divertor heat flux not as low due to additional radiative heating

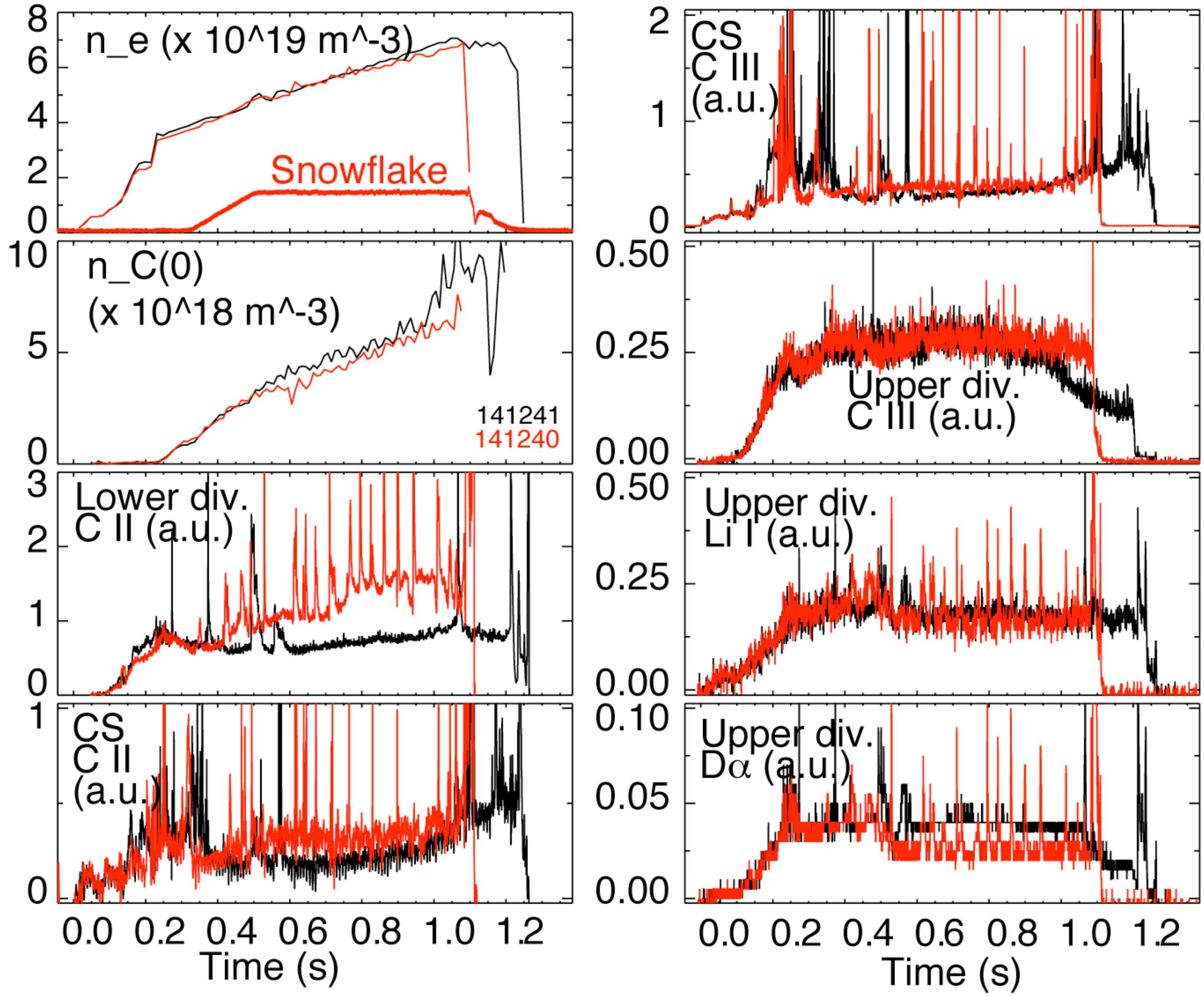


Preliminary indications that ELM heat flux is effectively dissipated in snowflake divertor

- 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
    - Energy diffusion over longer conn. Length
    - Field line mixing in null-point region
    - Radiative / collisional dissipation
    - Plasma-wetted area effect

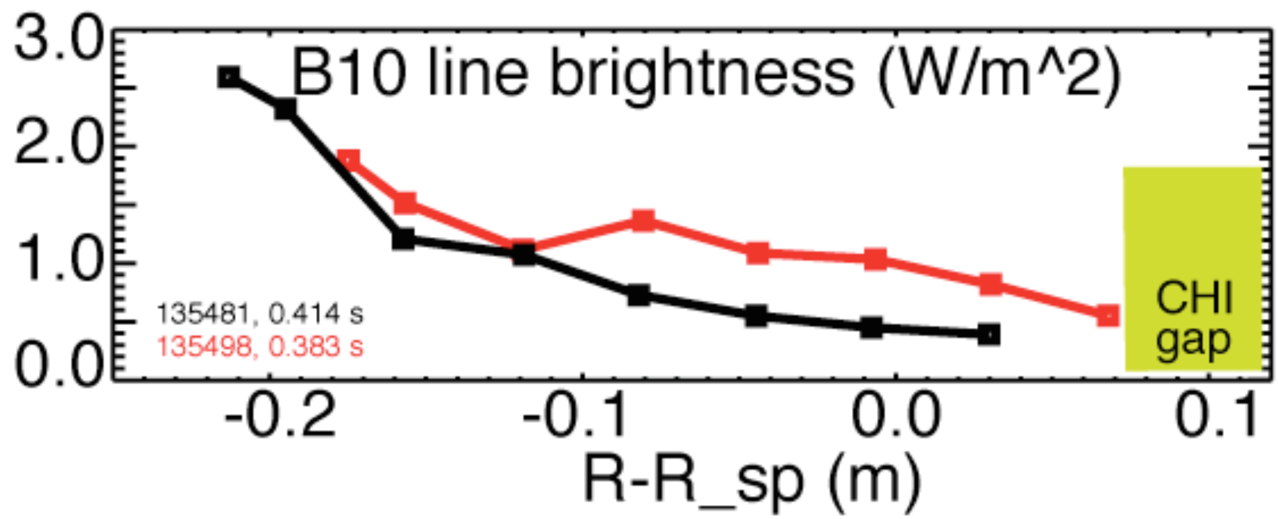


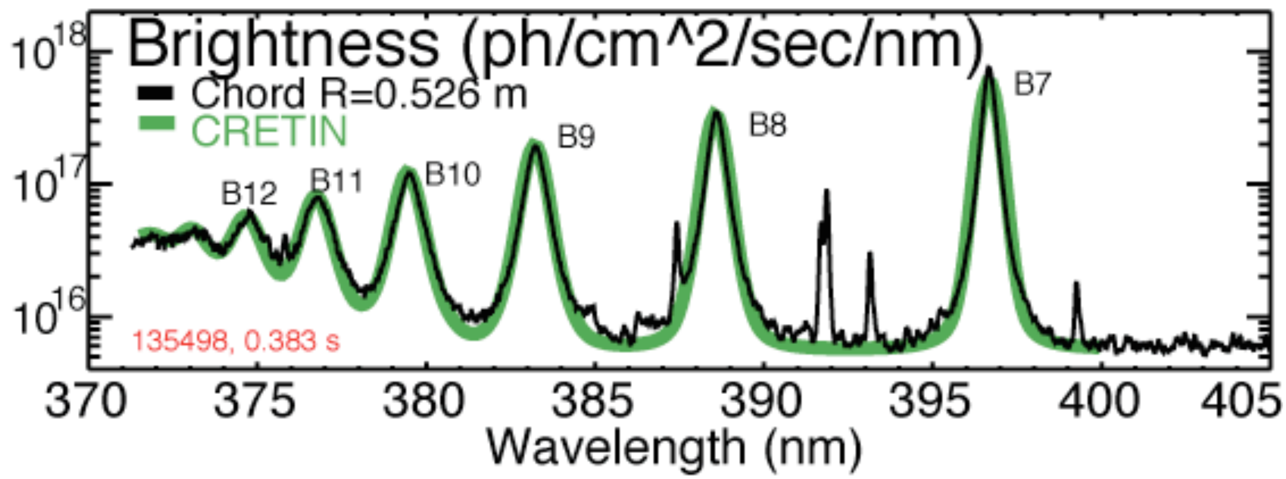
Upper divertor is unaffected by lower divertor snowflake configuration



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





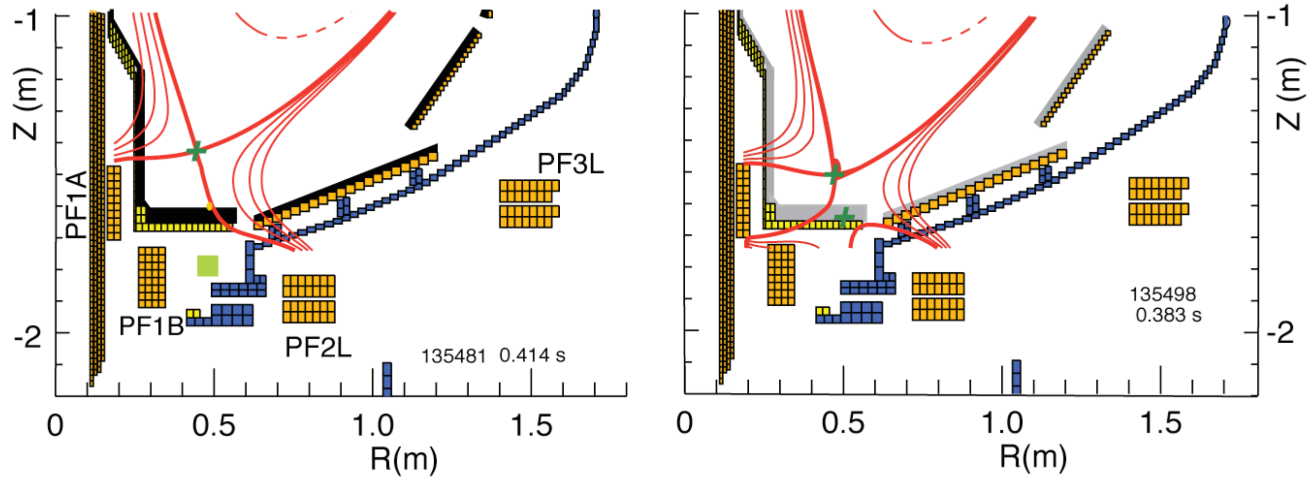
- T_e=0.8-1.2 eV, n_e=2-7 x 10^{20} m^{-3} inferred from modeling

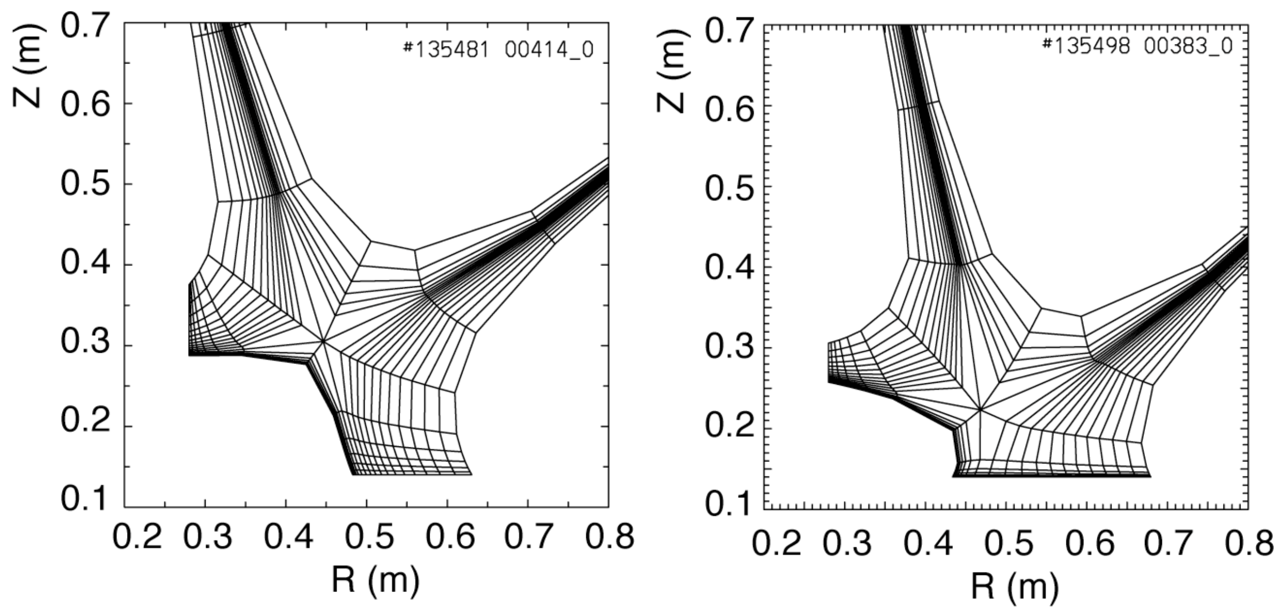
2D multi-fluid edge transport code UEDGE is used to study snowflake divertor properties

- 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 %

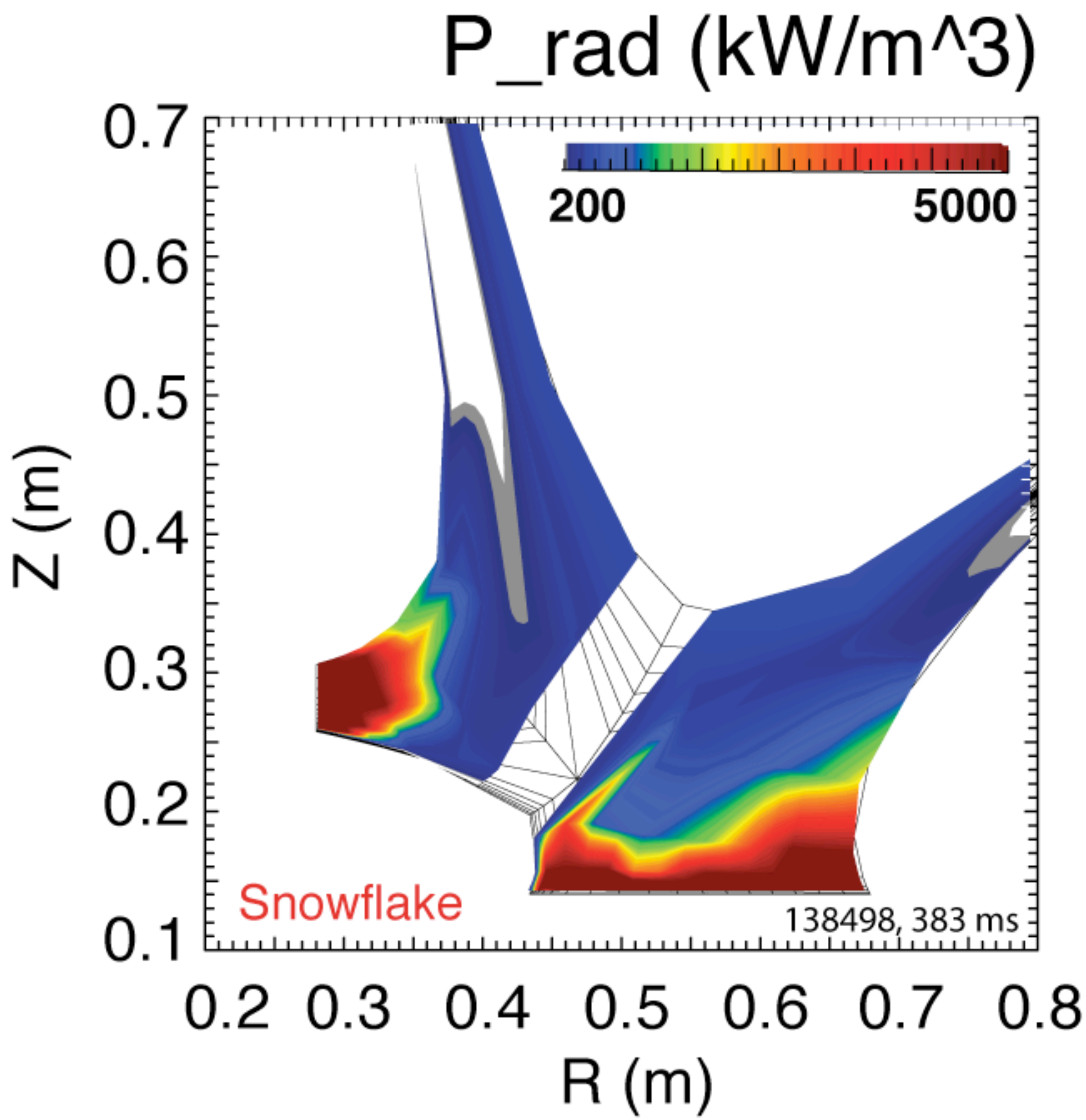
Standard

Snowflake





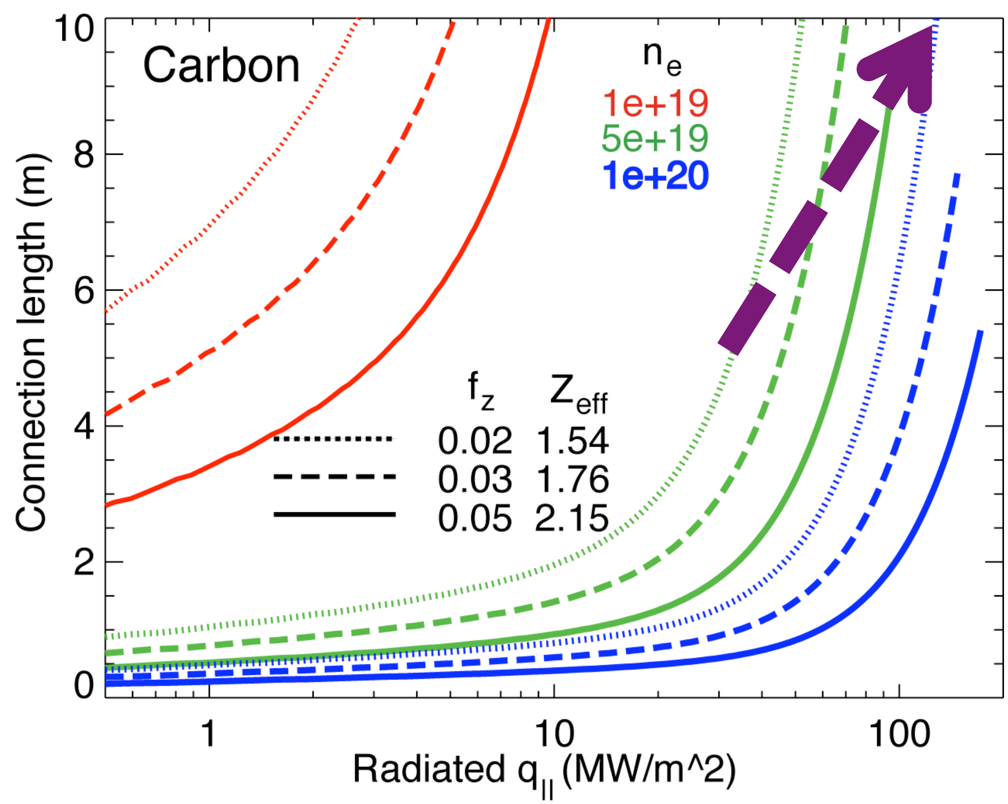
Radiated power is broadly distributed in the outer leg of snowflake divertor



UEDGE model

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
- Three-body electron-ion recombination rate depends on divertor ion residence time
  - Ion recombination time: $\tau_{ion}\sim$ 1−10 ms at T_e =1.3 eV
  - Ion residence time: $\tau_{ion} \leq$ 3-6 ms in standard divertor, x 2 in snowflake



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

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