Taming the Plasma-Material Interface with the Snowflake Divertor in NSTX

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- Colorado Sch Mines
- Columbia U
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V. A. Soukhanovskii

Lawrence Livermore National Laboratory

JI2.00002

52nd Annual Meeting of the APS DPP

Chicago, IL

Tuesday, November 9, 2010

- Culham Sci Ctr
- U St. Andrews
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- Chubu U
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- Hiroshima U
- Hyogo U
- Kyoto U
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- Kyushu Tokai U
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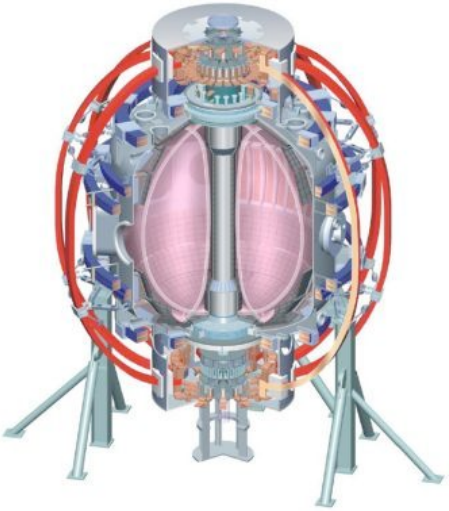

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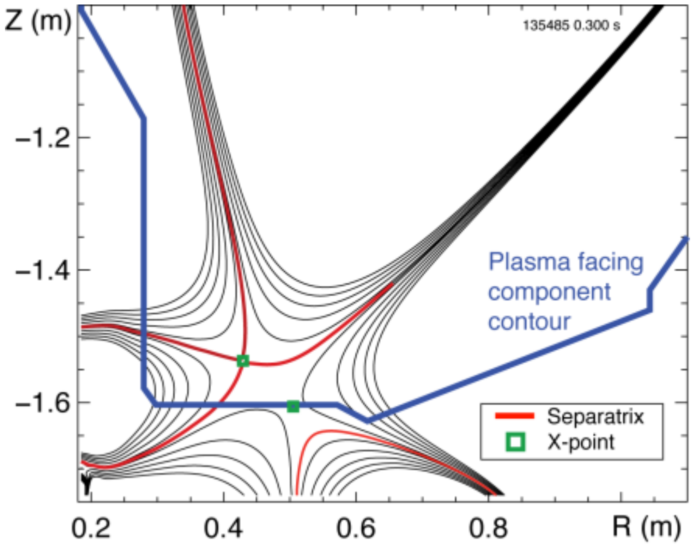
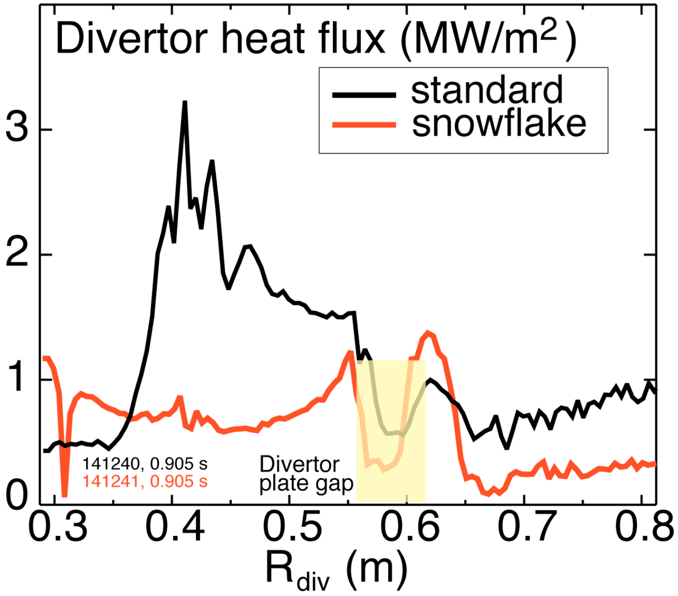
Outline: Experimental studies of snowflake divertor in NSTX

- **Tokamak divertor challenge**
- **Snowflake divertor configuration**
- **Snowflake divertor in NSTX**
  - Magnetic properties and control
  - Core and divertor plasma properties
  - Comparison with standard and radiative divertors
  - 2D transport model
- **Conclusions**

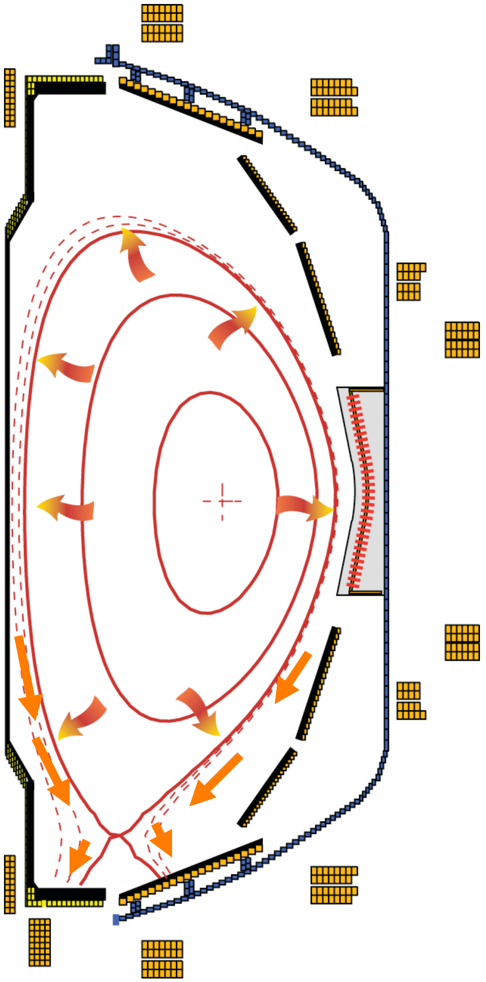




Poloidal divertor concept enabled progress in magnetic confinement fusion in the last 30 years

- 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)

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

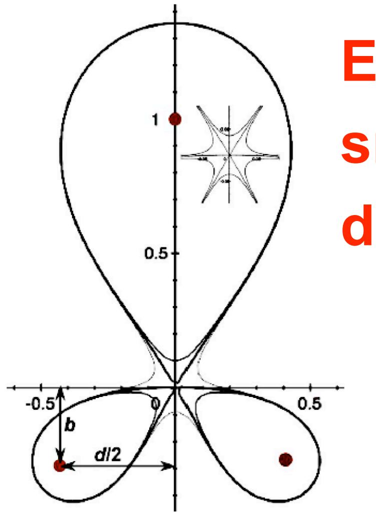
$$A_{wet} = 2\pi R\, f_{exp}\, \lambda_{q_{||}}$$

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

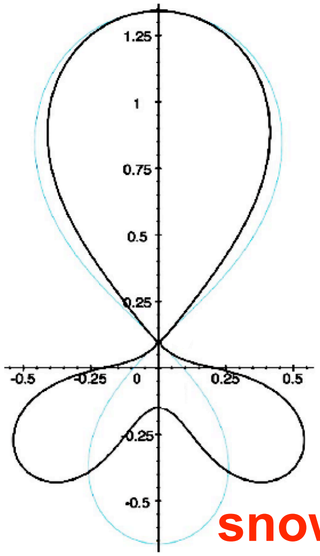
- Promising divertor peak heat flux mitigation solutions:
  - Divertor geometry
    - poloidal flux expansion
    - divertor plate tilt
    - magnetic balance
  - Radiative divertor
- Recent ideas to improve standard divertor geometry
  - X-divertor (M. Kotschenreuther *et. al*, IC/P6-43, IAEA FEC 2004)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

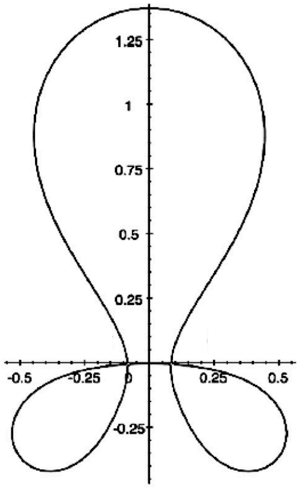
Attractive divertor geometry properties predicted by theory in snowflake divertor configuration

- 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))



Exact snowflake divertor





snowflake-minus

snowflake-plus

D. D. Ryutov, PoP 14, 064502 2007

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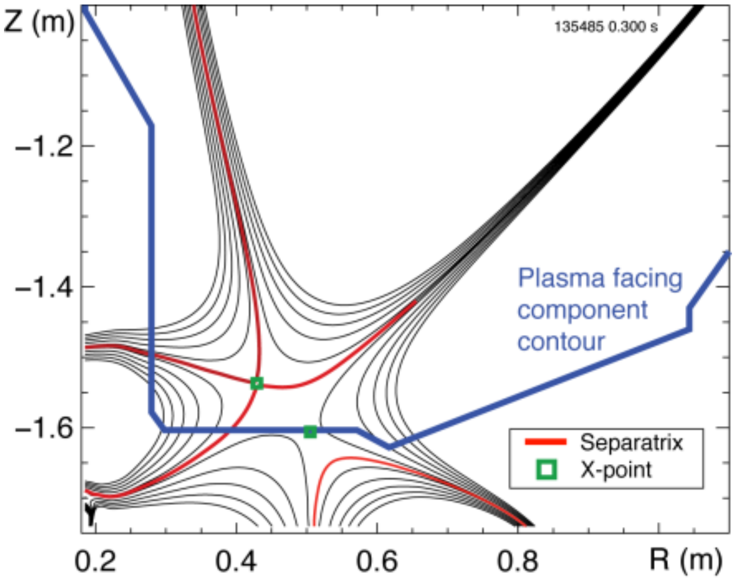
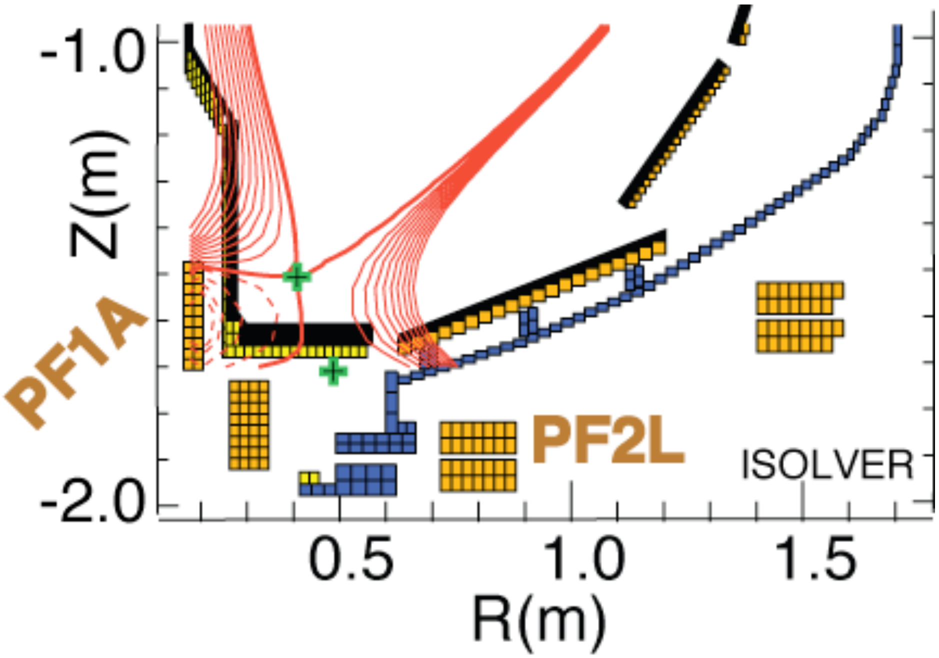


Possible snowflake divertor configurations were modeled with ISOLVER code

- 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



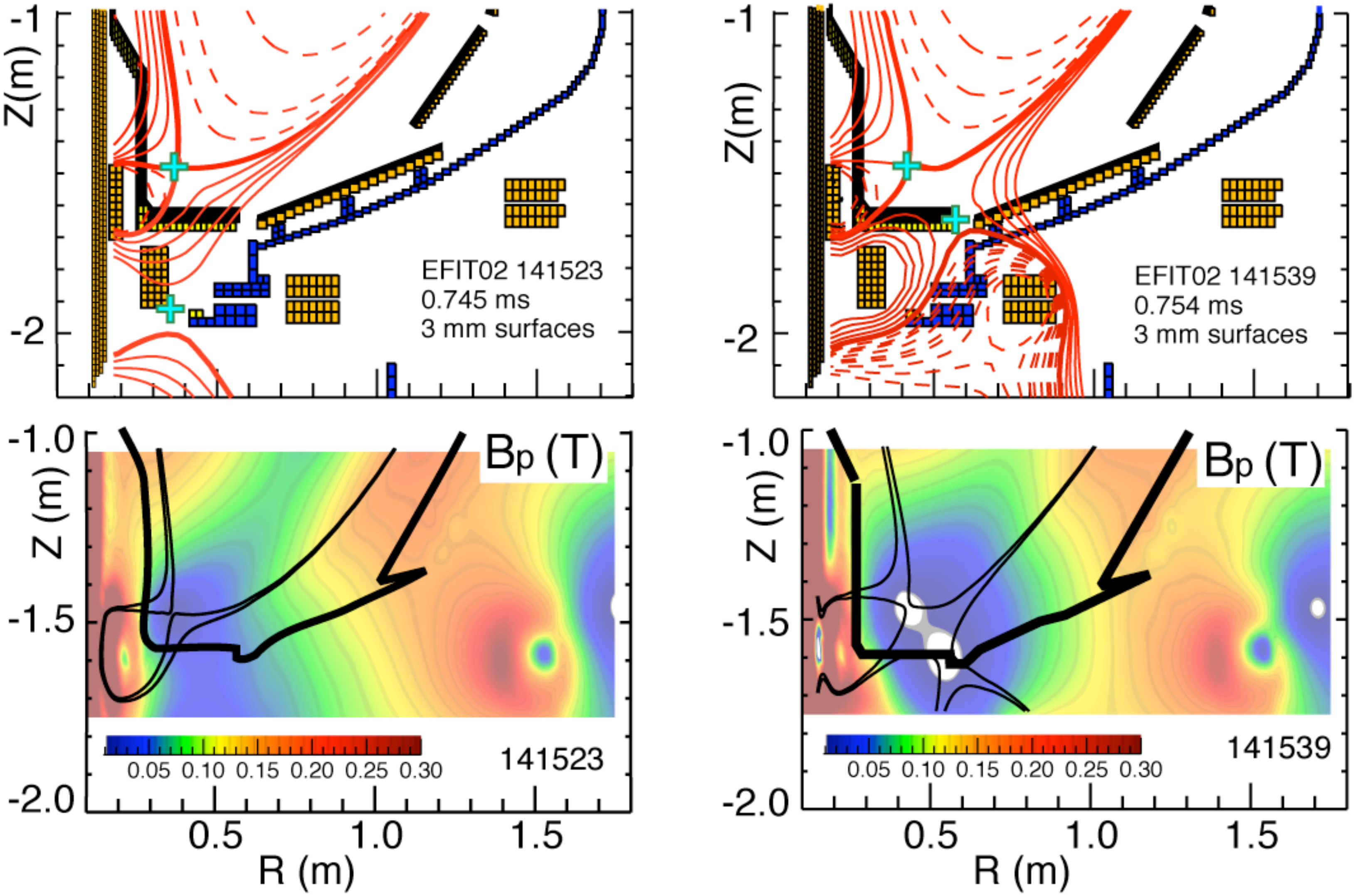
Quantity	Standard divertor	Simulated snowflake
X-point to target parallel length L_x (m)	**5-10**	**10**
Poloidal magnetic flux expansion f_{exp} at outer SP	**10-24**	**60**
Magnetic field angle at outer SP (deg.)	**1-2**	**~1**
Plasma-wetted area A_{wet} (m^2)	**≤ 0.4**	**0.95**

Snowflake divertor configurations obtained in NSTX confirm analytic theory and modeling

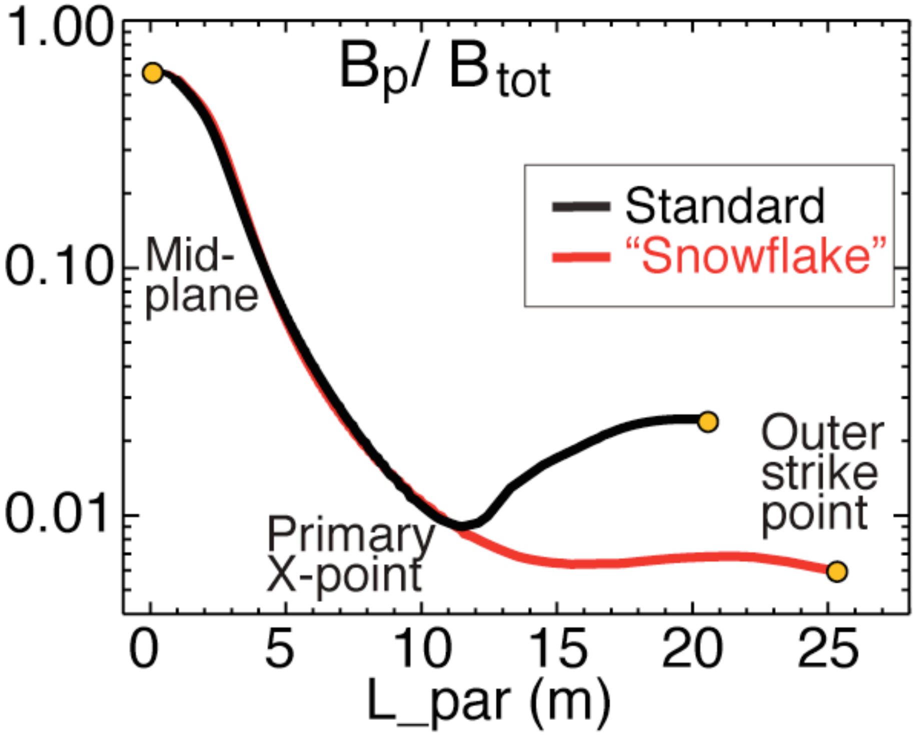
Standard **Snowflake**

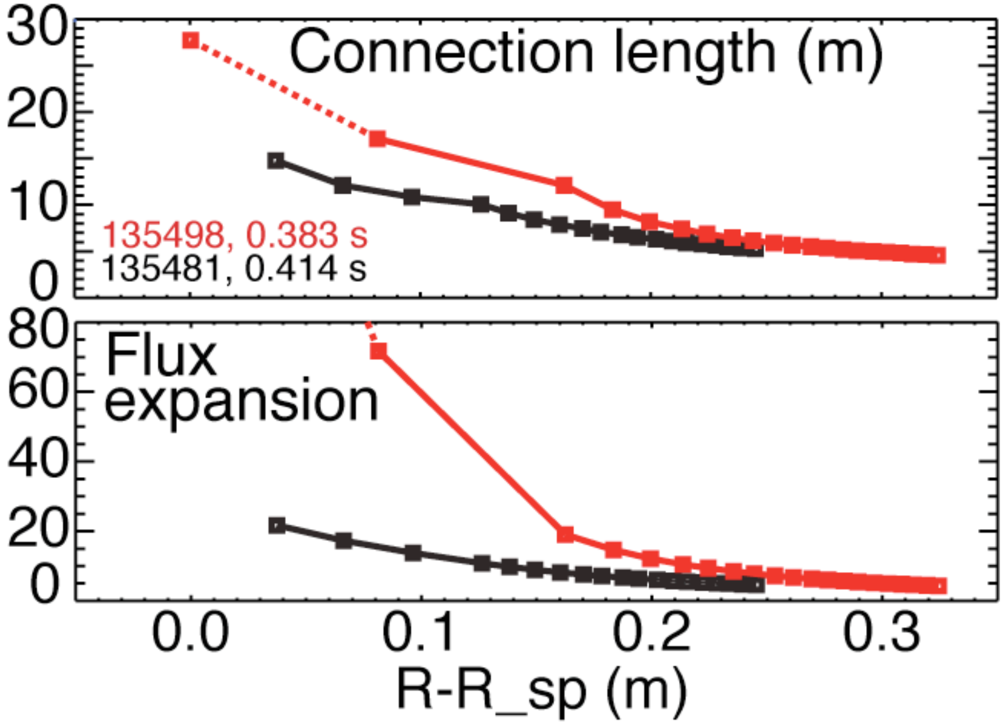
f_{exp}

B_p



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





- These properties observed in first 2-3 mm of SOL λ_q ~ 6-7 mm when mapped to midplane
- Magnetic characteristics derived from EFIT and LRDFIT equilibria

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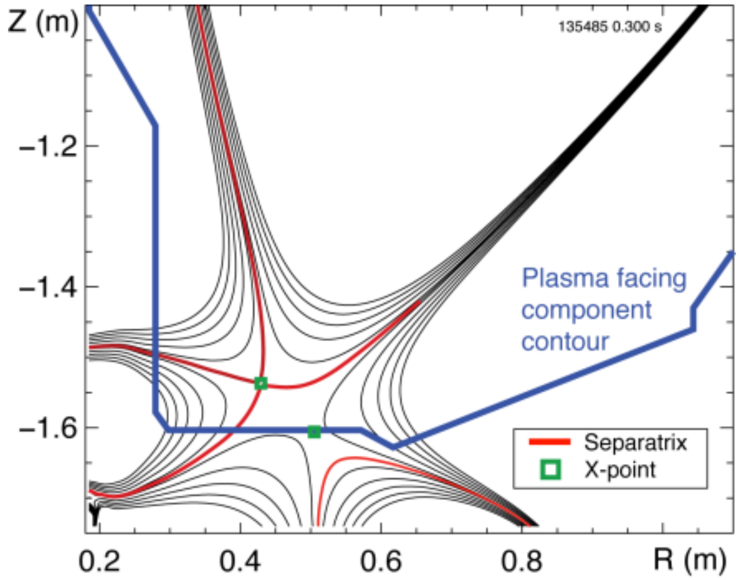
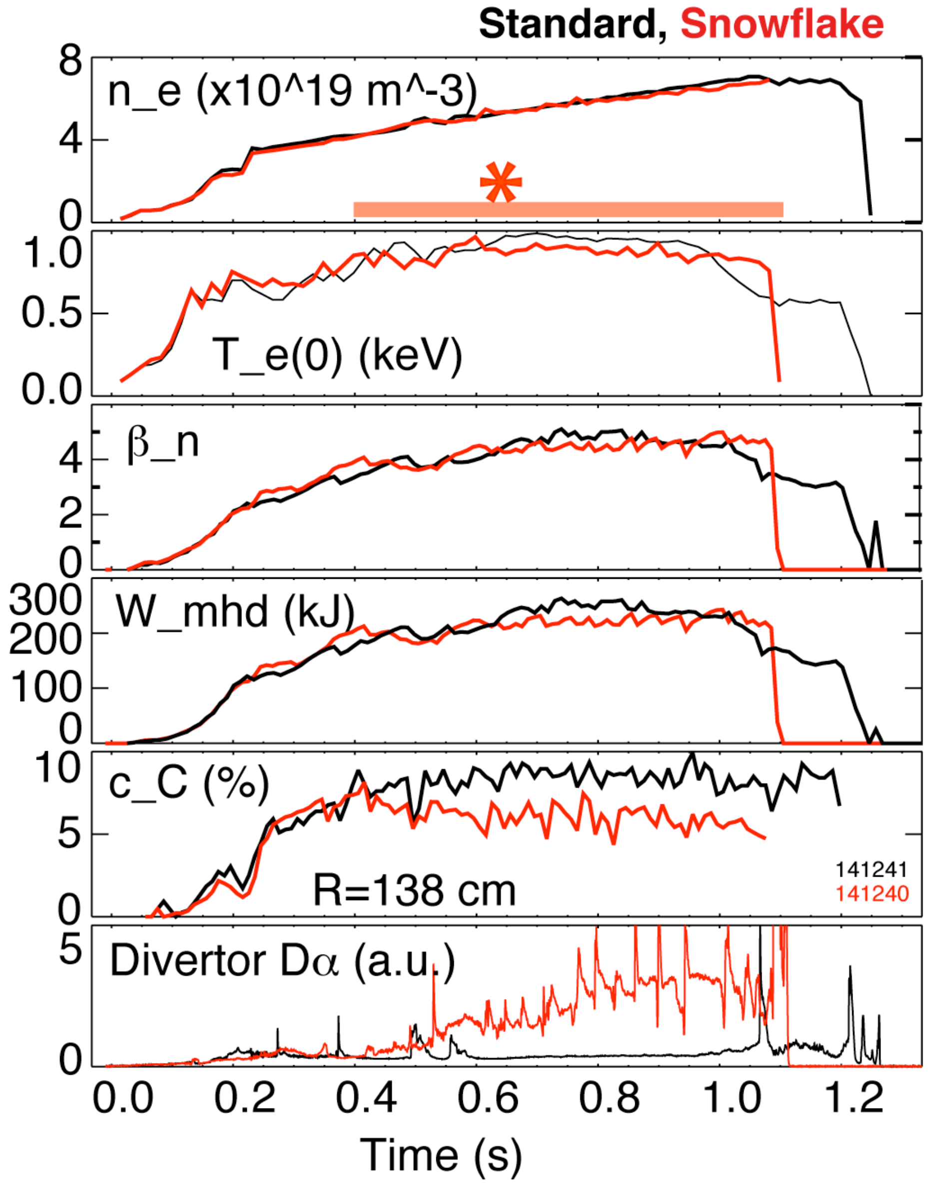
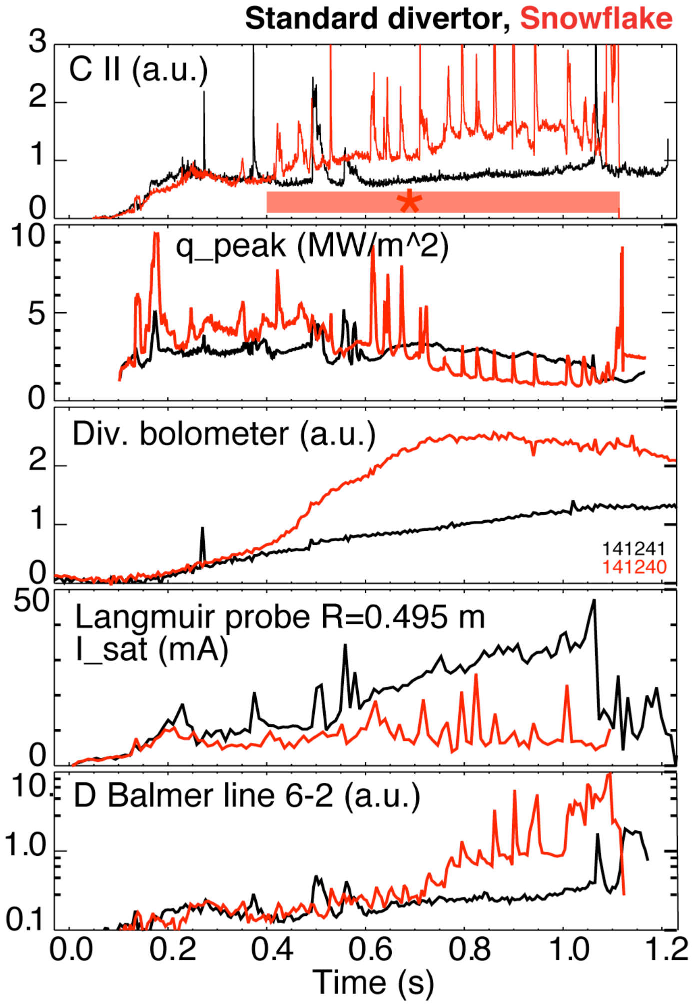


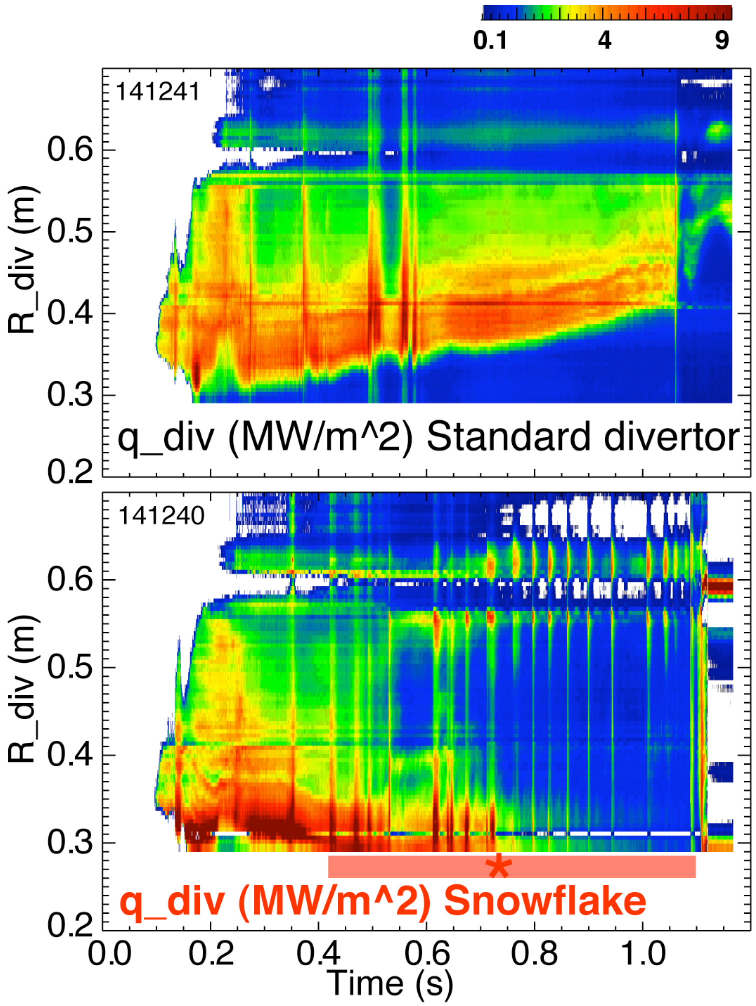
Significant core impurity reduction and good H-mode confinement properties with snowflake divertor



- 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

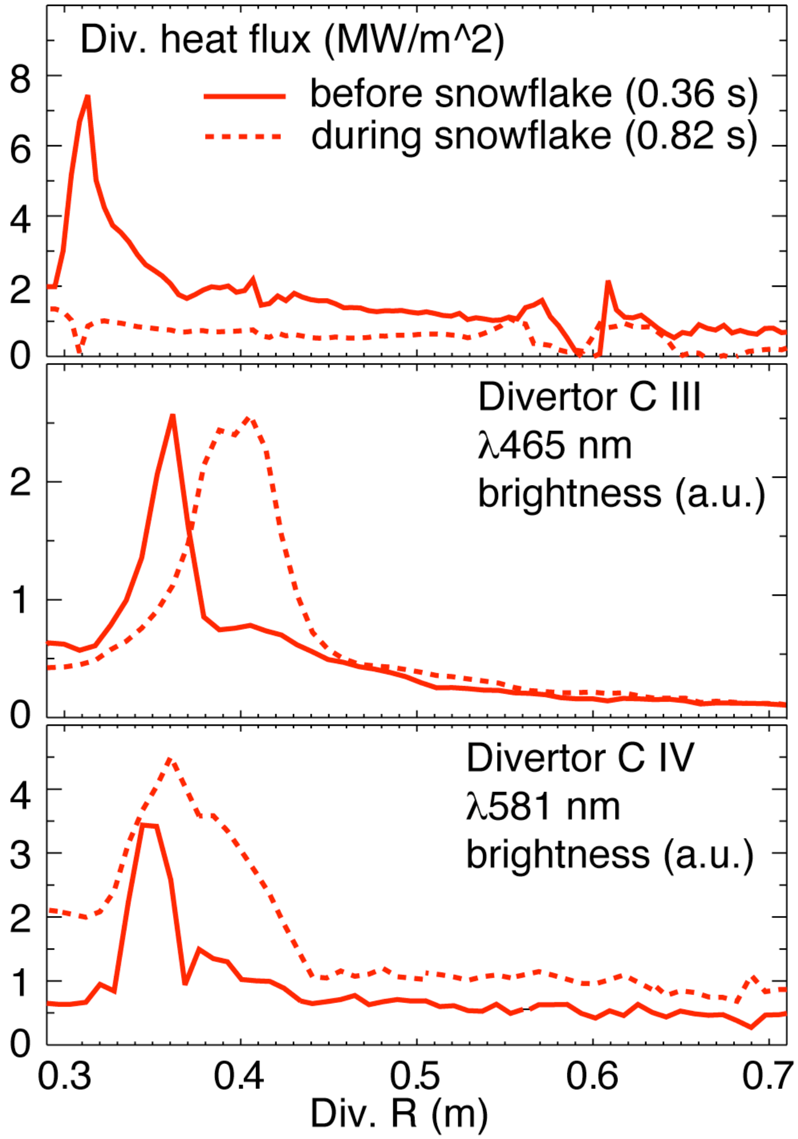
Strong signs of partial strike point detachment are observed in snowflake divertor





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

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 a reduction of carbon physical and chemical sputtering rates

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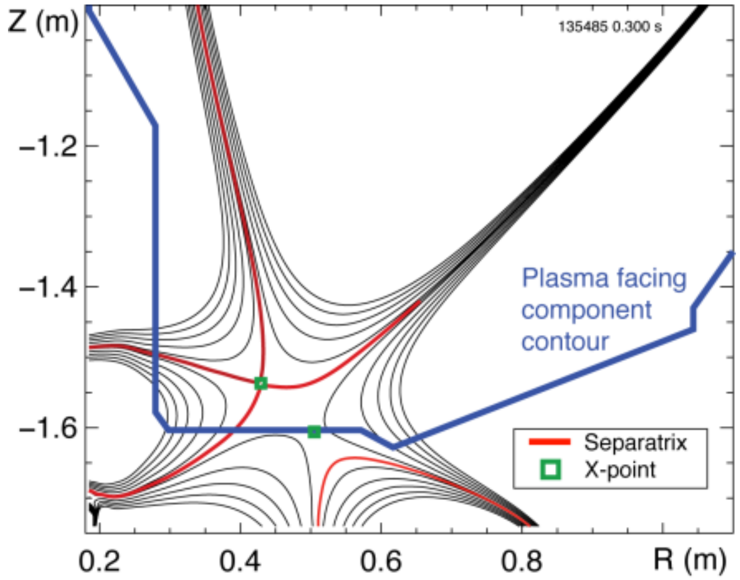
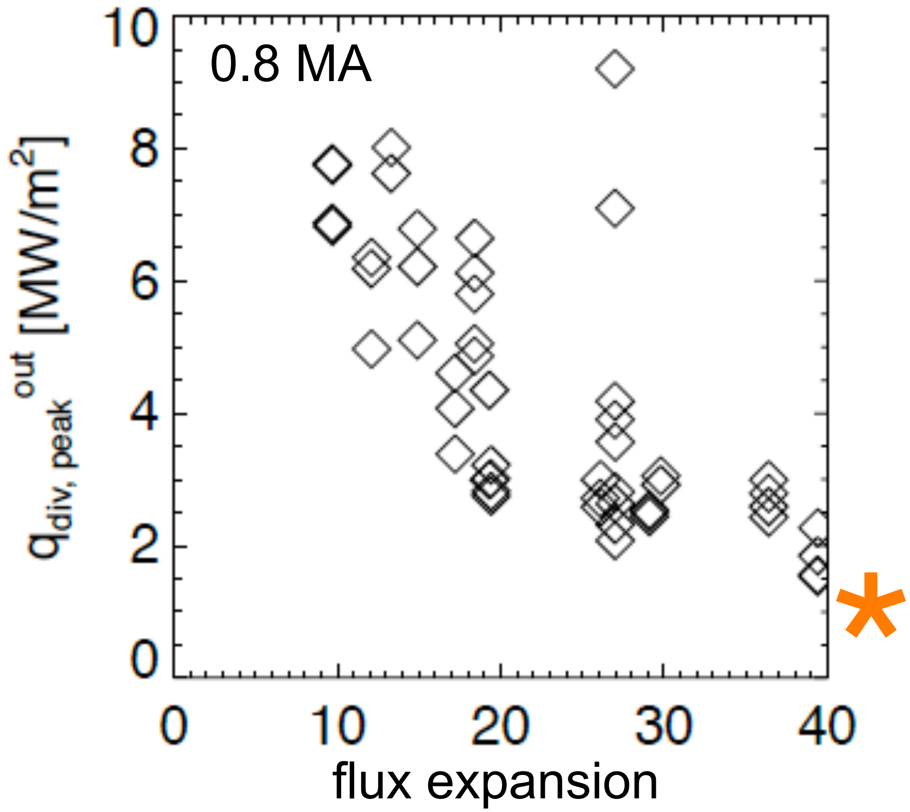
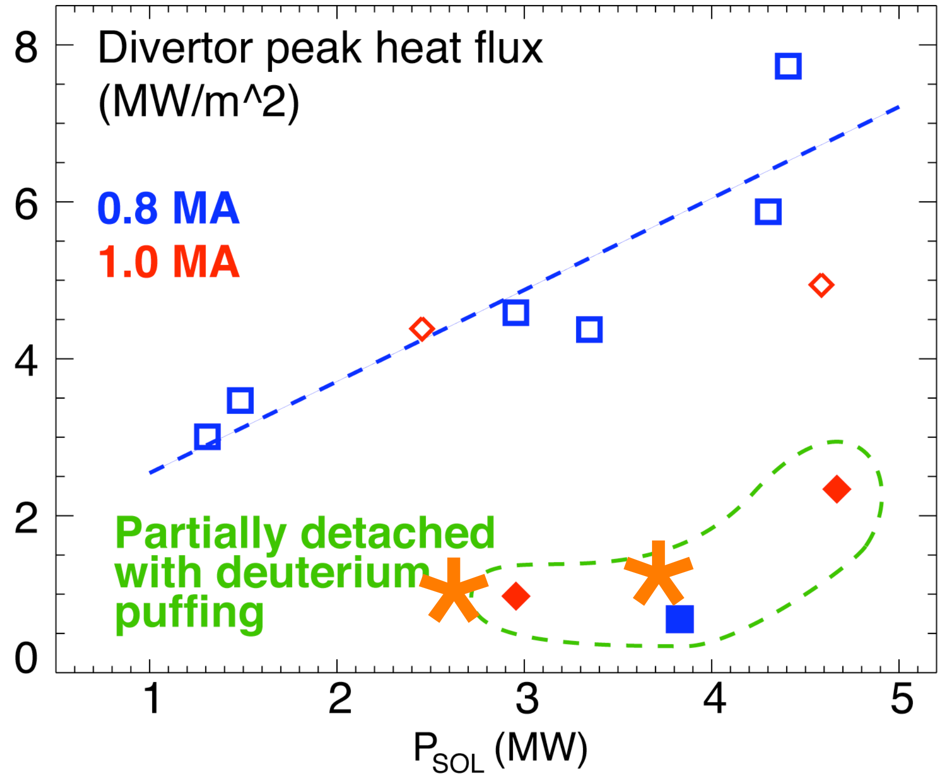


Snowflake divertor heat flux consistent with NSTX divertor heat flux scalings





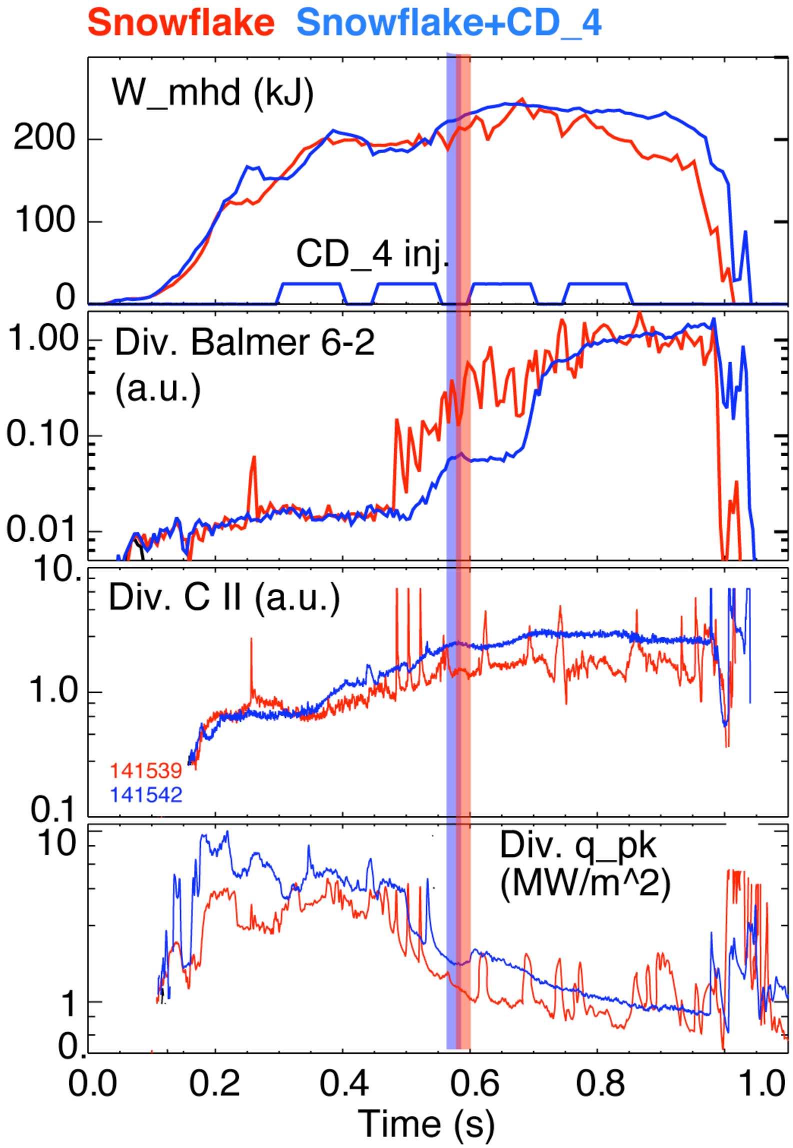
- Snowflake divertor (*): P_{SOL}~3-4 MW, f_{exp}~40-80, q_{peak}~0.5-1.5 MW/m^2

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

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

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/m² to 1 MW/m²
- Snowflake divertor (from 0.6 ms) + CD_4
  - Peak divertor heat flux reduced from 4-6 MW/m² to 1-2 MW/m²
  - Divertor radiation increased further



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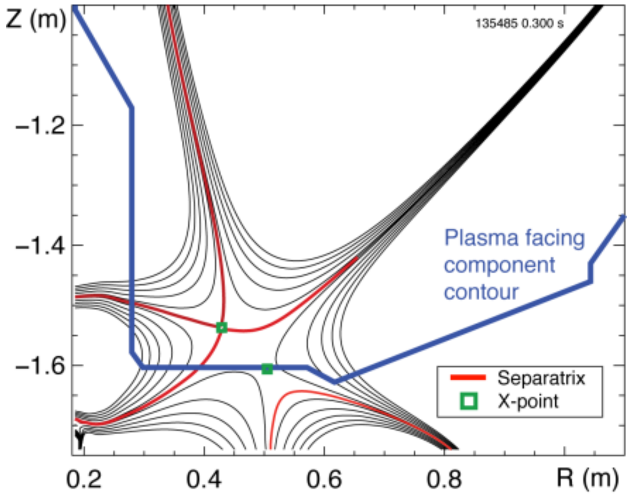
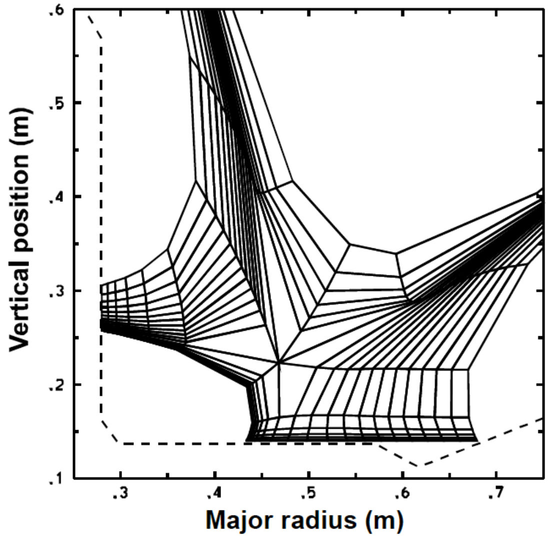
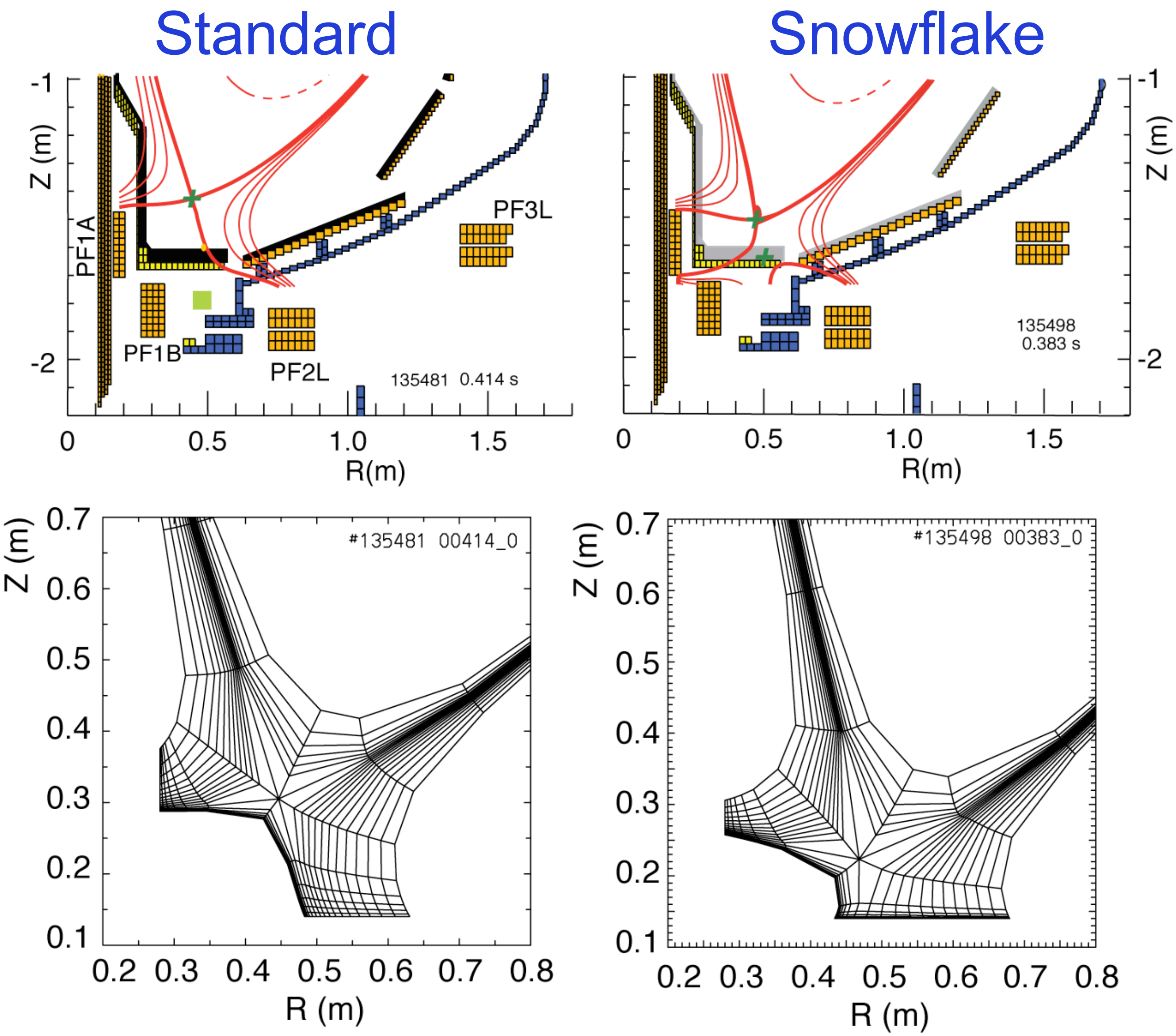




2D multi-fluid edge transport code UEDGE is used to study snowflake divertor properties

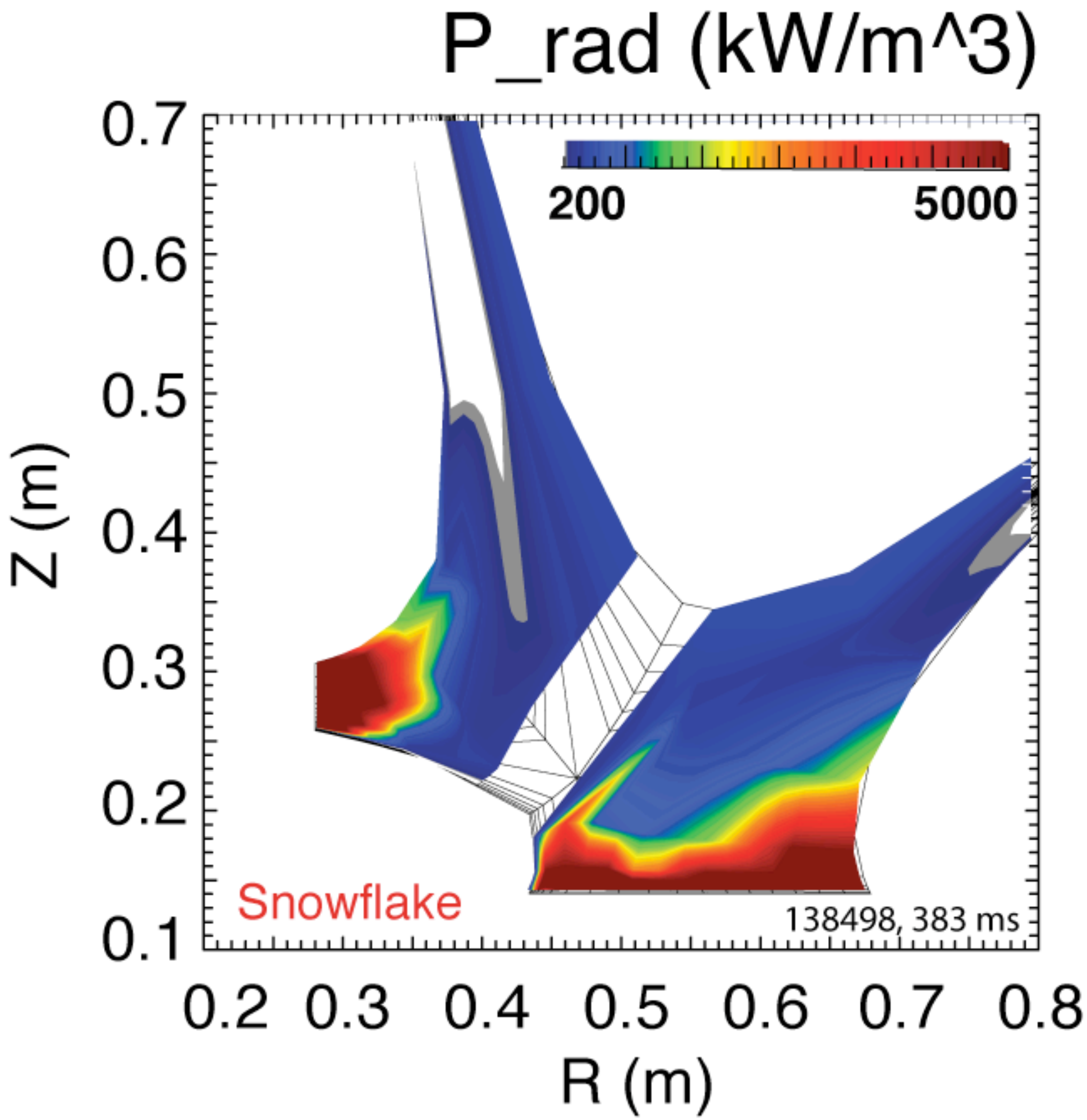
- Fluid (Braginskii) model for ions and electrons
- Fluid for neutrals
- Classical parallel transport, anomalous radial transport
- Core interface:
  - T_e = 120 eV
  - T_i = 120 eV
  - $n_e = 4.5 \times 10^{19}$
- $D = 0.25$ m^2/s
- $\chi_{e,i} = 0.5$ m^2/s
- $R_{recy} = 0.95$
- Carbon 3 %



Standard

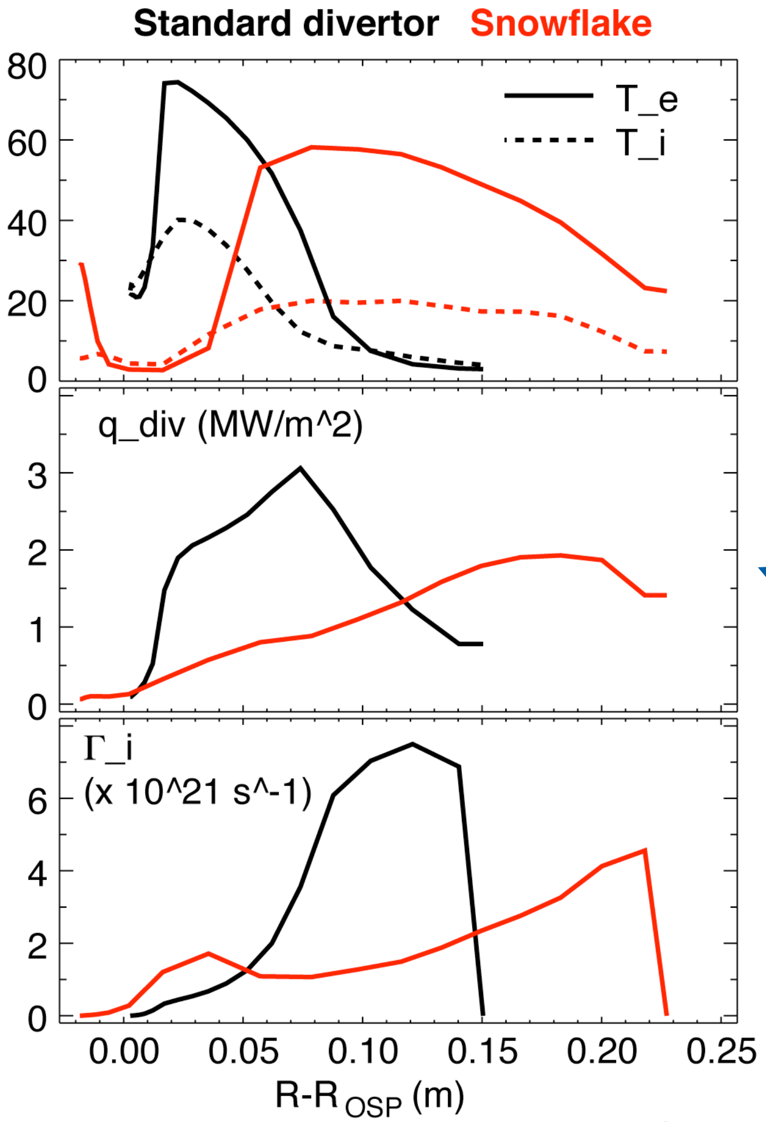
Snowflake

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



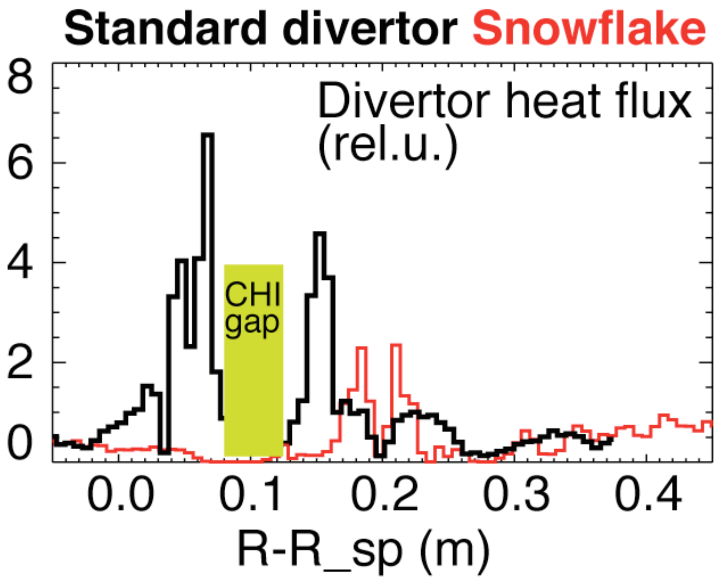
UEDGE model

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



In the snowflake divertor outer strike point region:

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



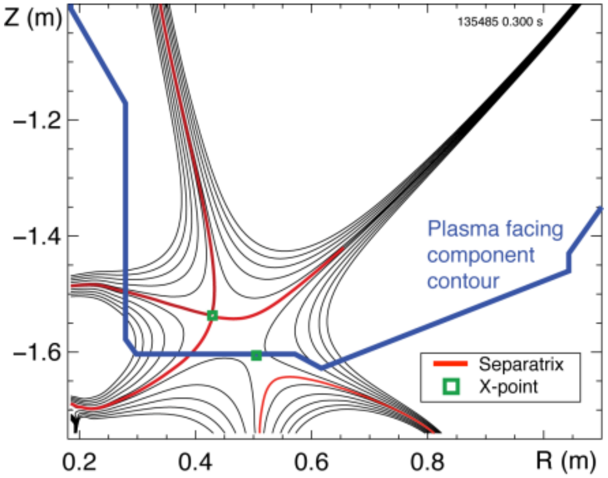
UEDGE model

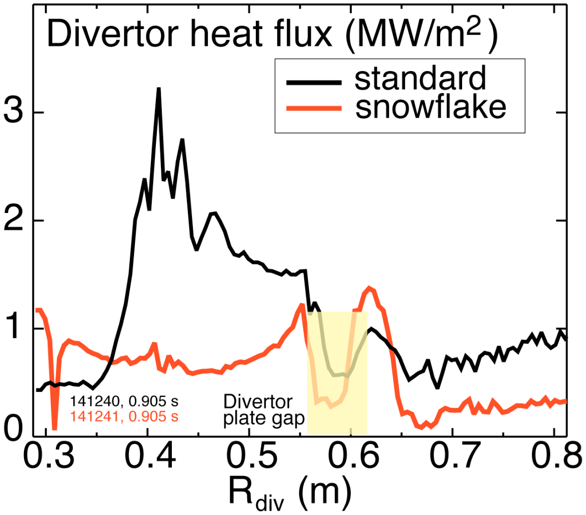
Experiment

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

- This talk focused on divertor results. 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)





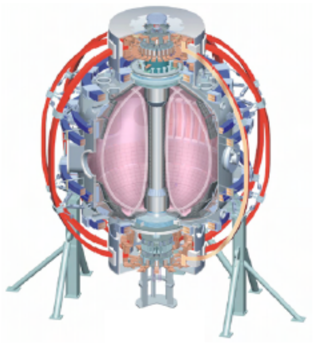
Session PP9: Poster Session VI, 10 November, Wednesday PM - Snowflake divertor presentations

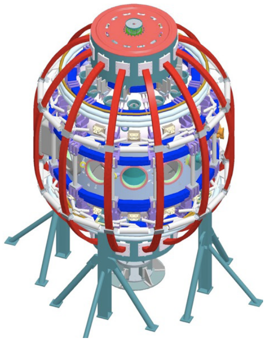
- PP9.00149 : D. D. Ryutov et. al, General properties of the magnetic field in a snowflake divertor
- PP9.00152 : M. V. Umansky et. al, Ion orbit loss effects on radial electric field in tokamak edge for standard and snowflake divertor configurations
- PP9.00136 : F. Piras et. al, H-mode Snowflake Divertor Plasmas on TCV

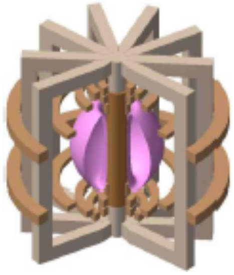
Backup slides

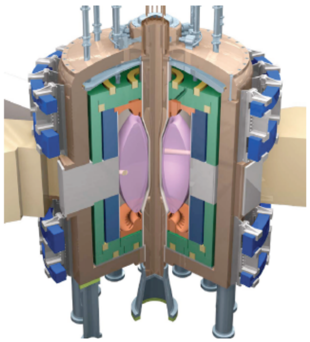
Divertor heat flux mitigation is key for present and future fusion plasma devices

- 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

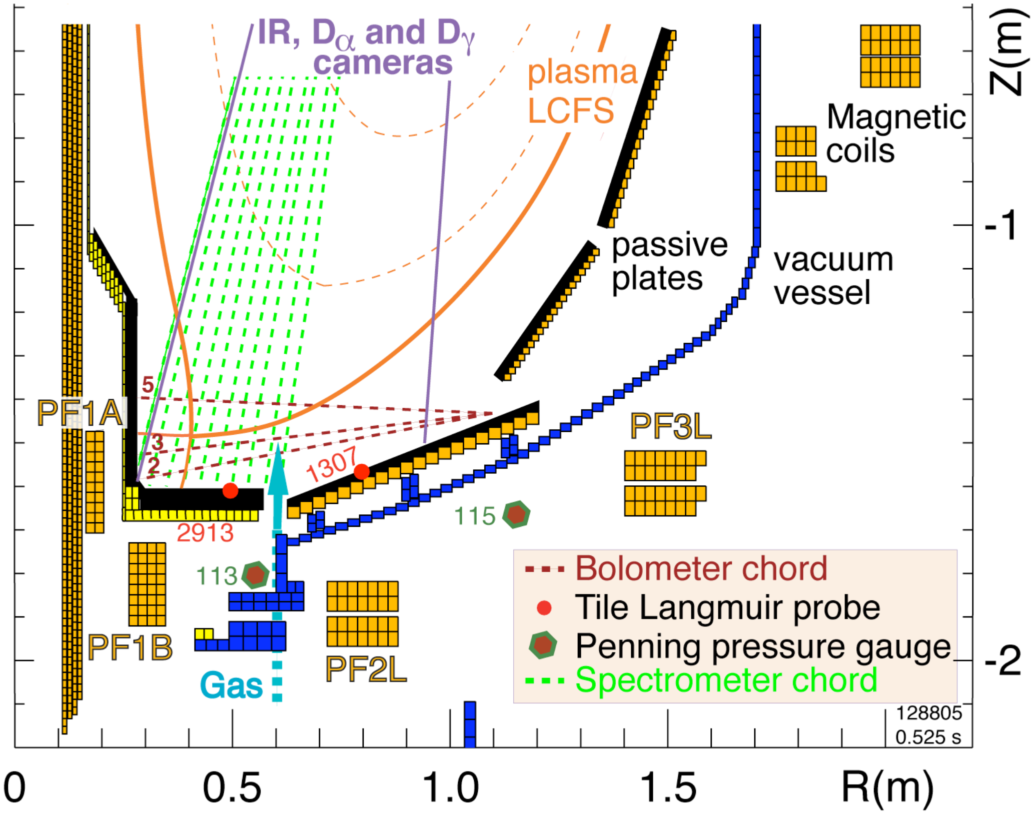
Heat flux mitigation is more challenging in compact divertor of spherical torus

- 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

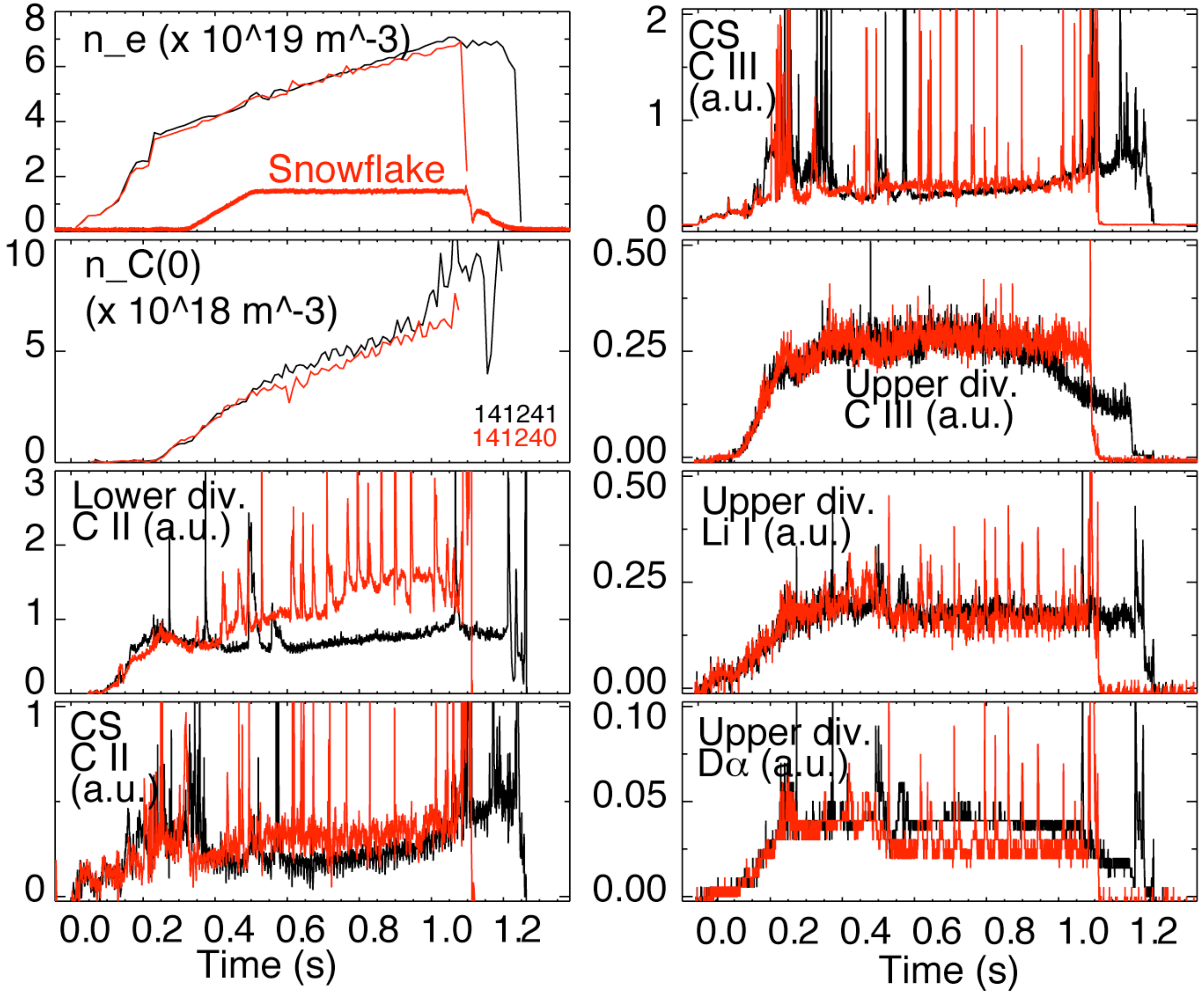
Quantity	NSTX	DIII-D
Aspect ratio	1.4-1.5	2.7
In-out plasma boundary area ratio	1:3	2:3
X-point to target parallel length L_x (m)	5-10	10-20
Poloidal magnetic flux expansion f_{exp} at outer SP	5-30	3-15
Magnetic field angle at outer SP (deg.)	1-10	1-2

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
- $P_{in} \leq$ 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

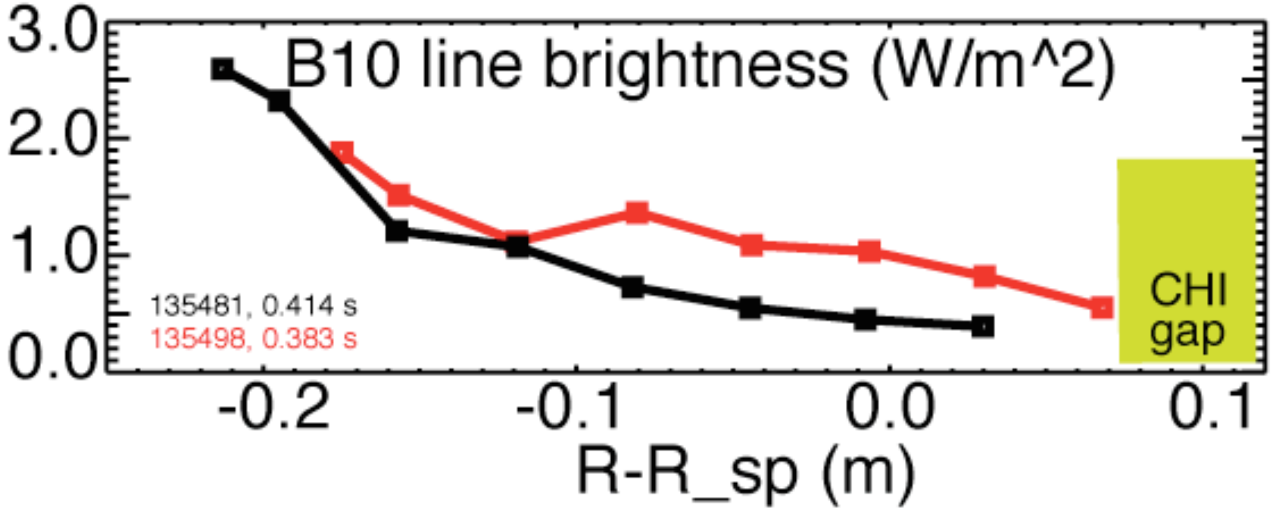


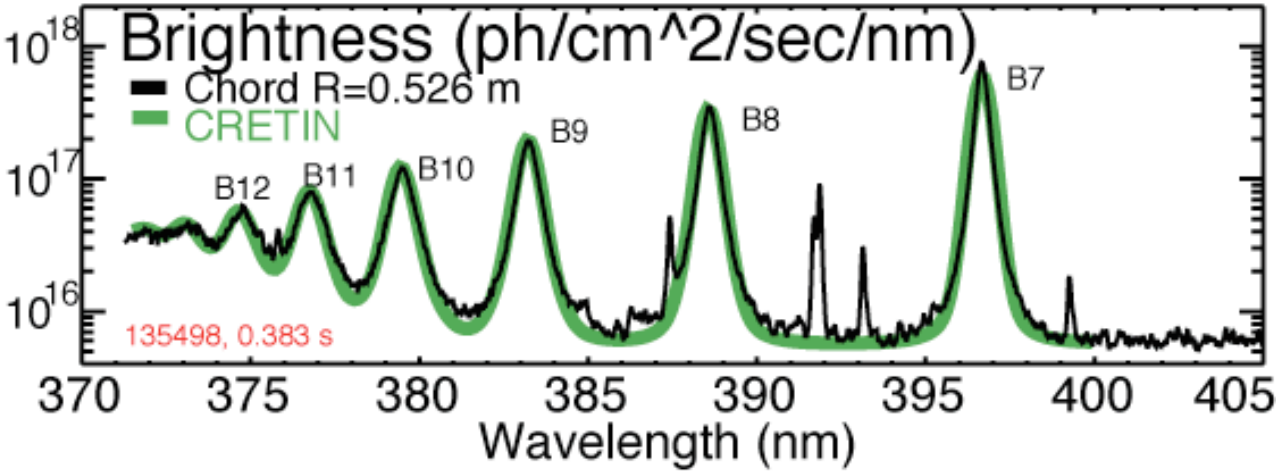
Upper divertor is unaffected by lower divertor snowflake configuration



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



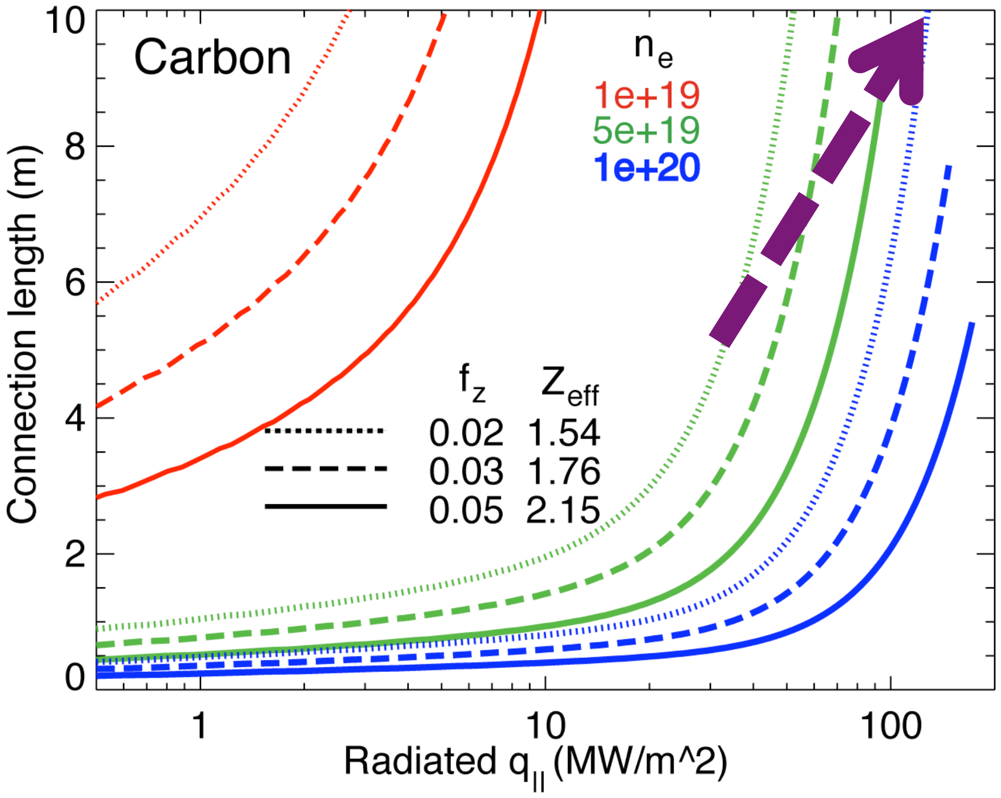


- T_e=0.8-1.2 eV, n_e=2-7 x 10^{20} m^{-3} inferred from modeling

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



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

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