NSTX

Fusion Energy Sciences

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Snowflake divertor configuration studies for NSTX-Upgrade

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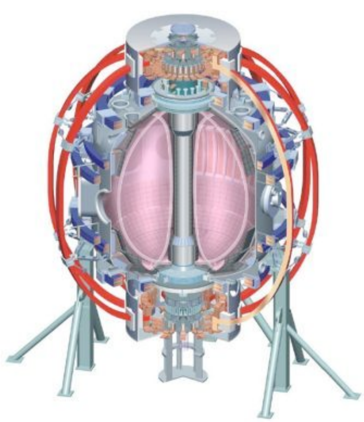

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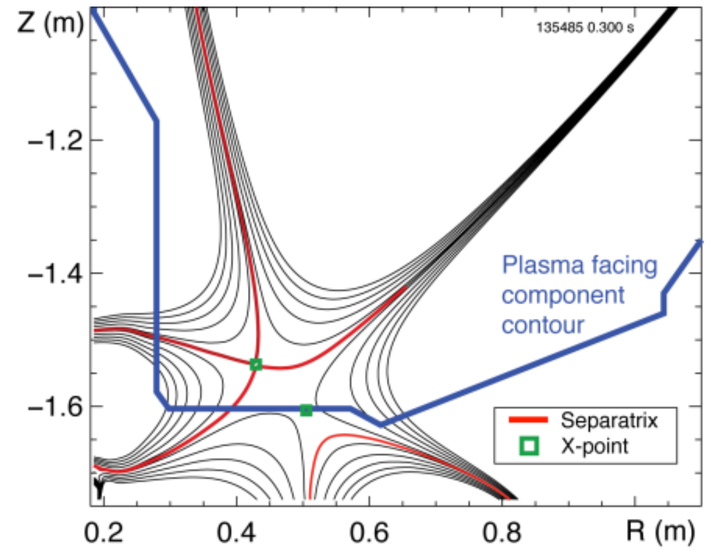
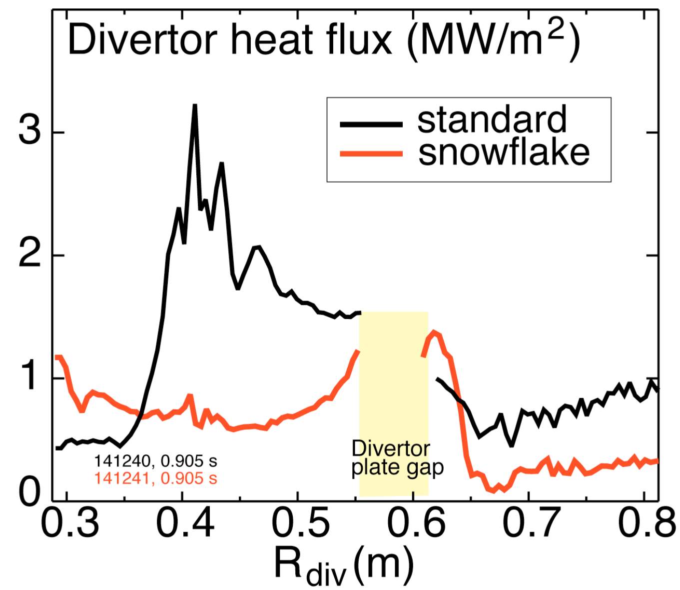
Snowflake divertor experiments in NSTX provide basis for PMI development toward NSTX-Upgrade

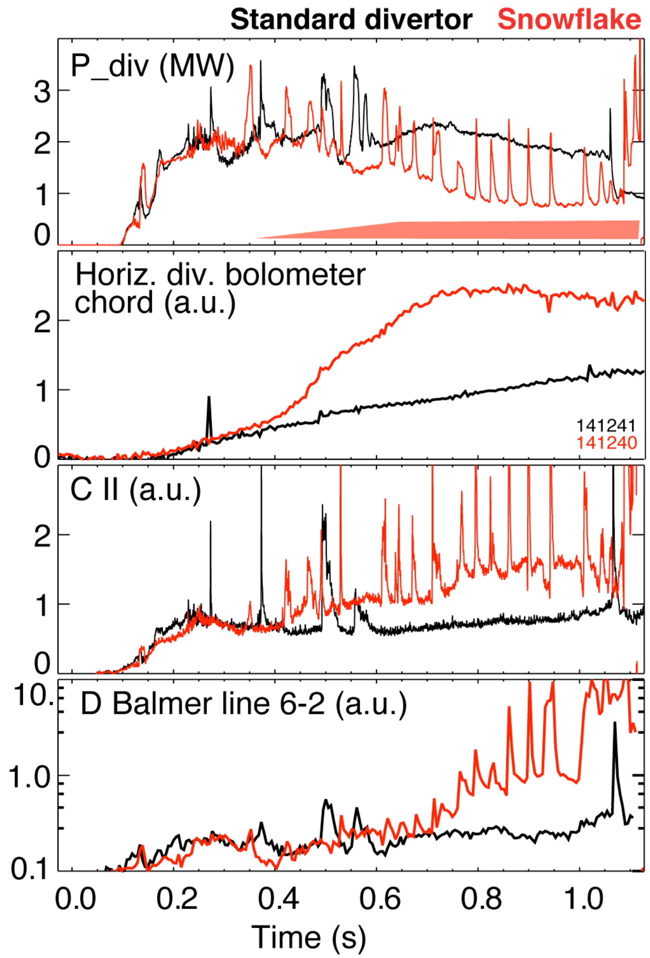
- **Snowflake divertor configuration in NSTX**
  - Three divertor coils, steady-state up to 600 ms
  - Core H-mode confinement unchanged
  - Core impurities reduced
  - Steady-state divertor peak heat flux significantly reduced
    - Due to geometry effects and radiative detachment

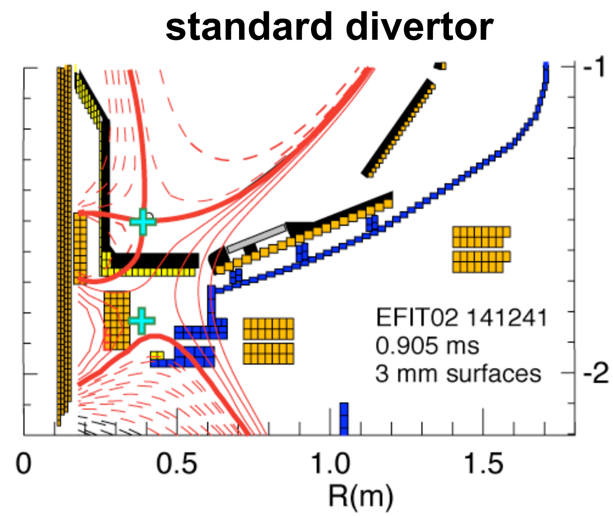


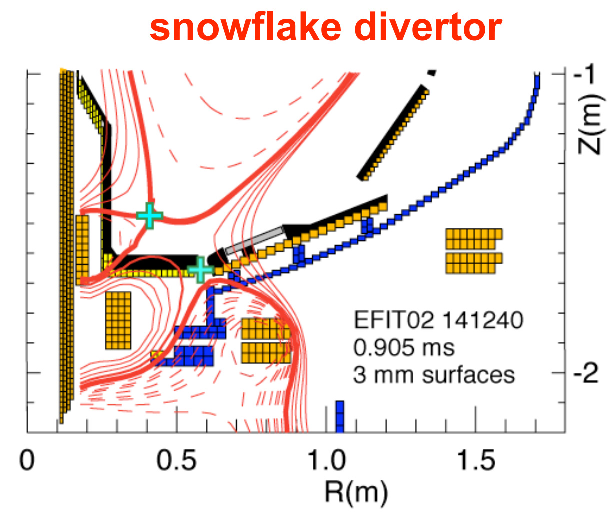
- **Development of snowflake divertor configuration for NSTX-U**
  - Steady-state and transient heat flux mitigation and detachment
  - Magnetic control and configuration development



Snowflake configuration formation was followed by radiative detachment

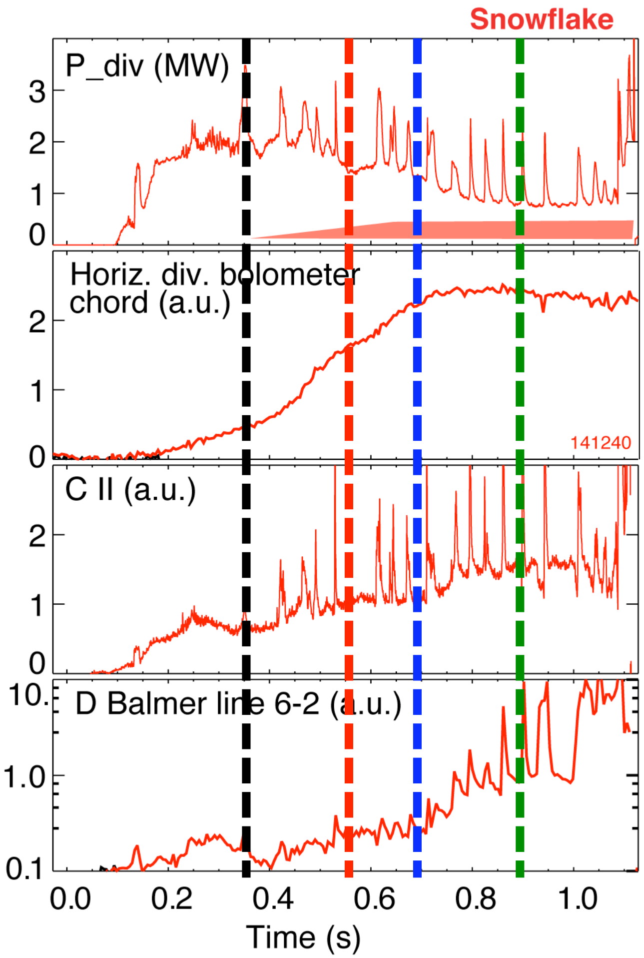


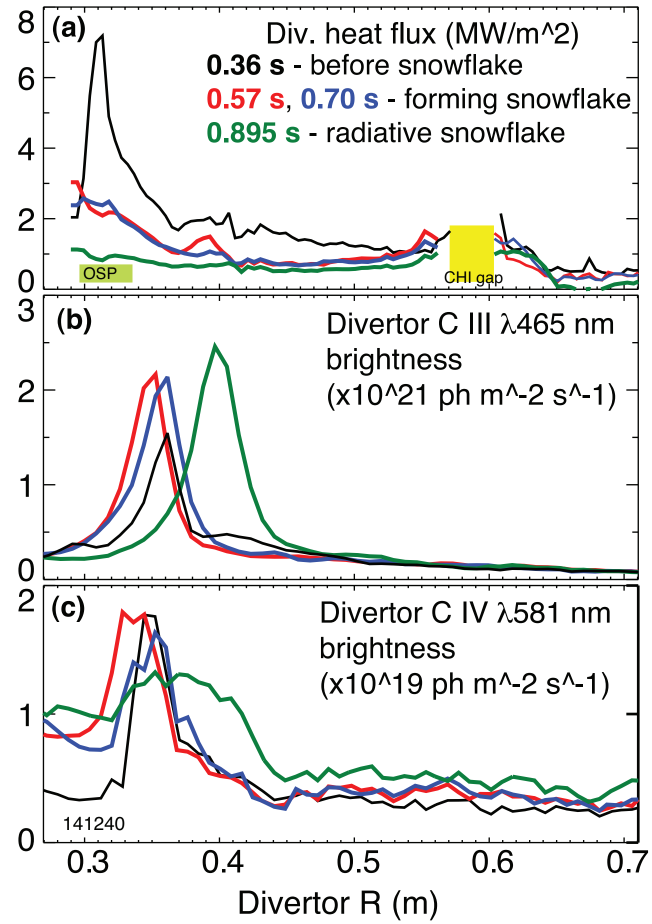




- P_{SOL} ~ 3 MW (P_{NBI} = 4 MW)
- Attached divertor -> snowflake transition (still attached) -> snowflake + detachment
- Q_{div} ~ 2 MW -> Q_{div} ~ 1-1.2 MW -> Q_{div} ~ 0.5-0.7 MW

Significant reduction of steady-state divertor heat flux observed in snowflake divertor

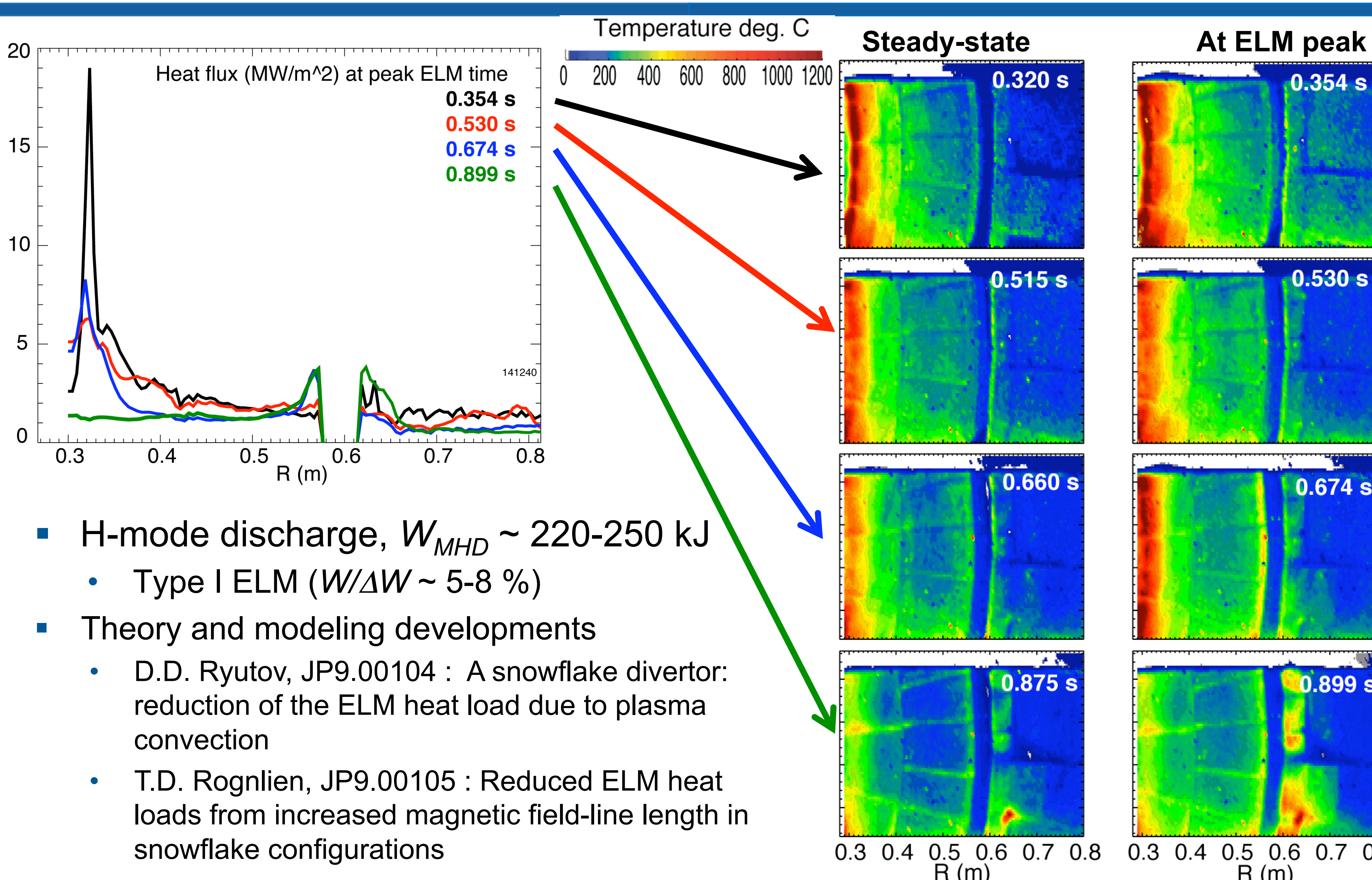




C III, CIV profiles courtesy of F. Scotti

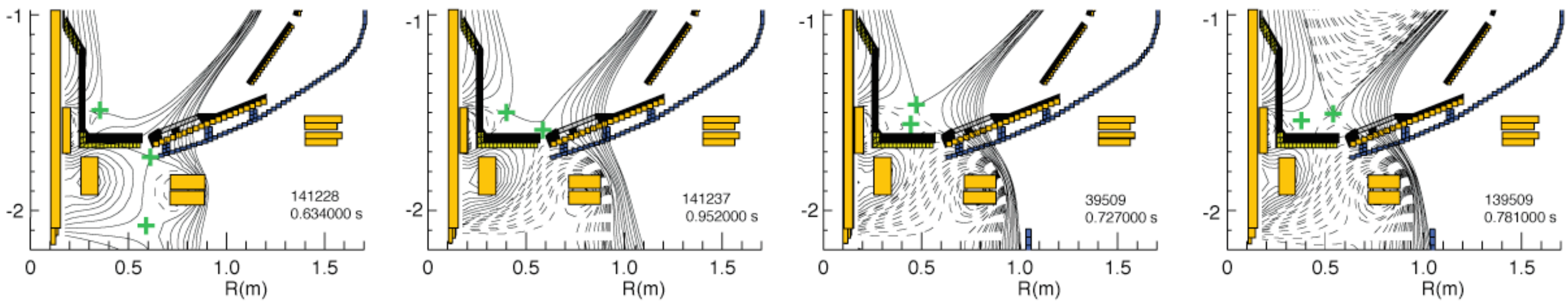
- **Attached standard divertor** -> **snowflake transition** -> **snowflake + detachment**
- More experiments and modeling needed to understand geometry vs radiative effects

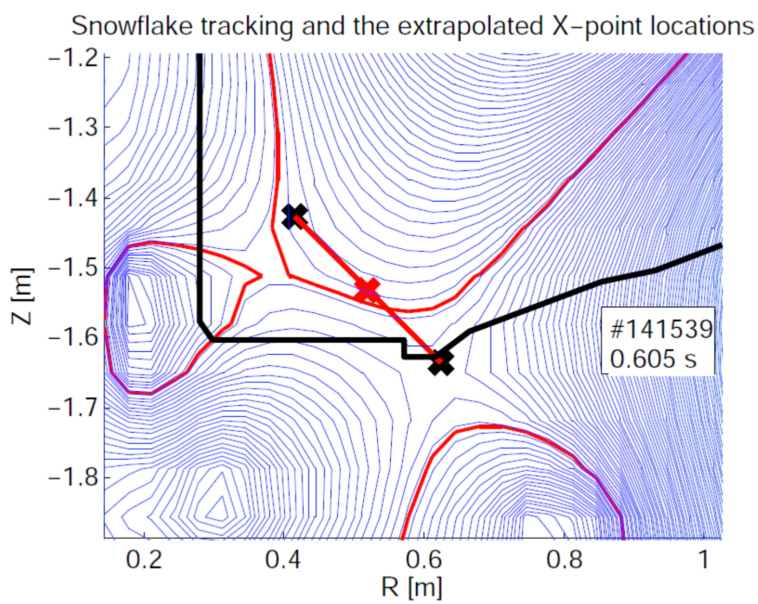
Impulsive heat loads due to Type I ELMs are partially mitigated in snowflake divertor



- H-mode discharge, W_{MHD} ~ 220-250 kJ
  - Type I ELM ($W/\Delta W$ ~ 5-8 %)
- Theory and modeling developments
  - D.D. Ryutov, JP9.00104 : A snowflake divertor: reduction of the ELM heat load due to plasma convection
  - T.D. Rognlien, JP9.00105 : Reduced ELM heat loads from increased magnetic field-line length in snowflake configurations

Magnetic control of snowflake divertor configuration is being developed



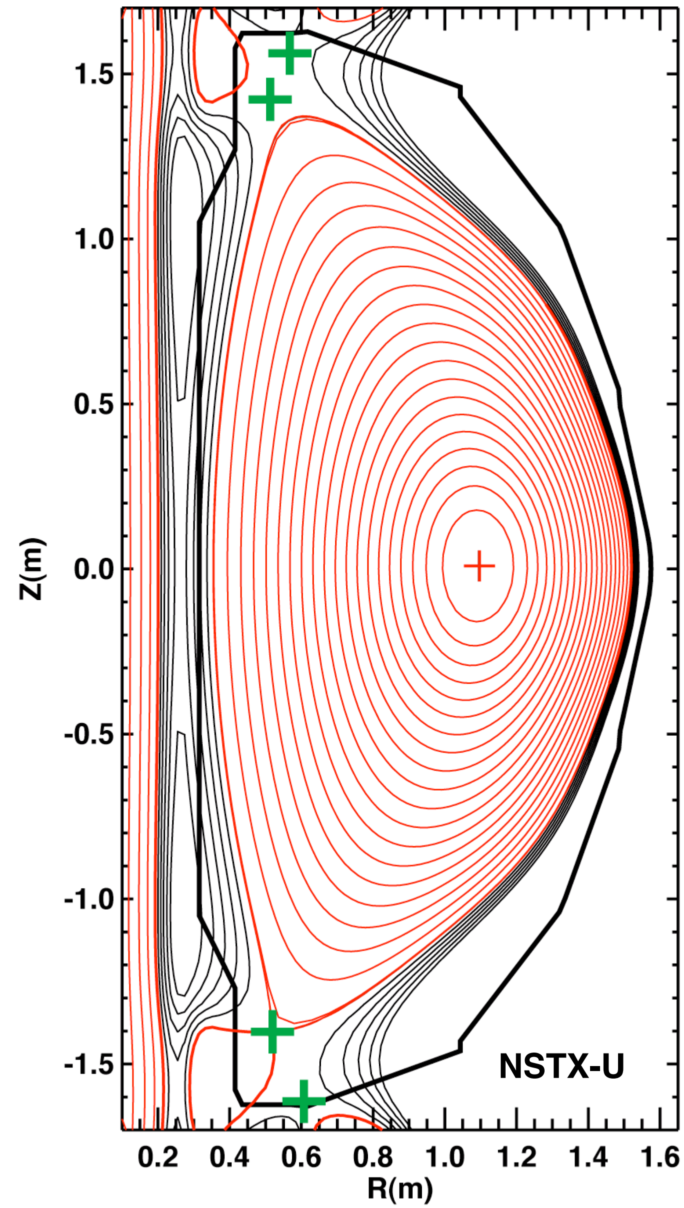


M.A. Makowski and D. Ryutov, “X-Point Tracking Algorithm for the Snowflake Divertor”

- Many ways for the open-loop snowflake configuration to fail - need close-loop feedback control of coil currents
- Testing X-point tracking algorithm
  - Locate X-points and snowflake centroid
  - E. Kolemen, PP9.00022 : Control Development for NSTX and the Effects of Strong Shaping
- Implementation of 2nd X-point position control in Plasma Control System being considered
  - Collaboration between PPPL, LLNL and GA

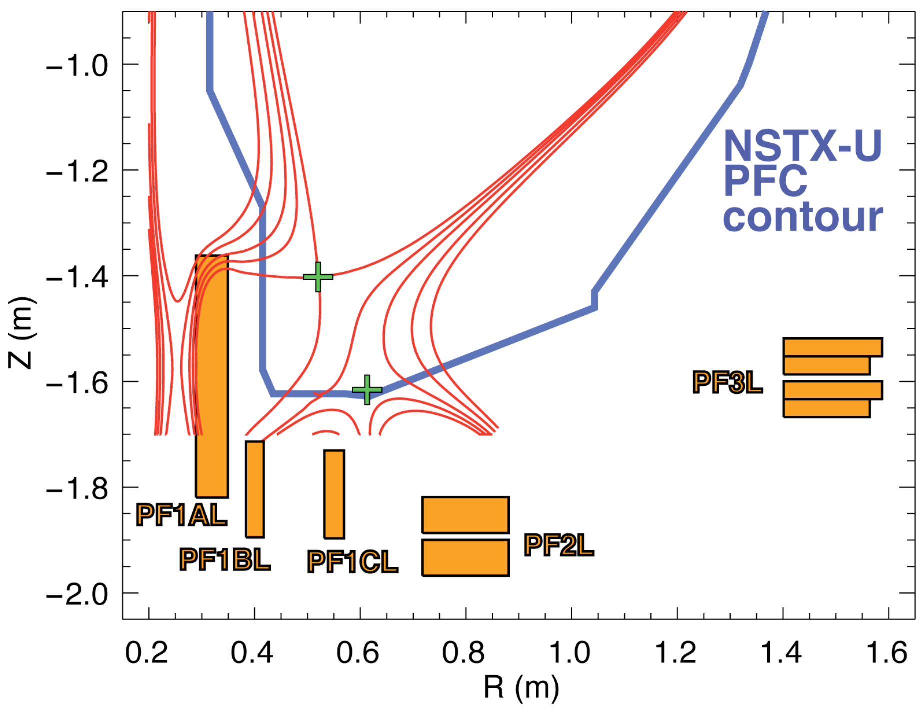
Plasma material interface development is critical for NSTX-U success

- NSTX-U mission elements:
  - Advance ST as candidate for Fusion Nuclear Science Facility
  - Develop solutions for PMI
  - Advance toroidal confinement physics for ITER and beyond
  - Develop ST as fusion energy system
- 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
  - ➢ Radiative divertor with impurity seeding, double null, high flux expansion (snowflake)



Four divertor coils should enable flexibility in boundary shaping and control in NSTX-U

- A variety of lower and both lower and upper divertor snowflake configurations are possible in NSTX-U with four coils per divertor
  - ISOLVER free-boundary Grad-Shafranov solver used
  - Four coils can be used to control up to four parameters (X-pts, OSP, etc)



Midplane flux surface	0.0	1.5 mm	3.0 mm	6.0 mm	9.0 mm
L_{tot} (m)	38.3	20.4	13.9	9.9	8.3
L_X (m)	16.5	4.0	2.2	1.6	1.5
Angle (deg.)	1.6	0.8	0.99	3.0	3.9

- X 2 in plasma wetted surface area and connection length vs standard divertor

Snowflake divertor experiments in NSTX provide good basis for PMI development in NSTX-Upgrade

- **FY 2009-2010 snowflake divertor experiments in NSTX**
  - Helped understand control of magnetic properties
  - Core H-mode confinement unchanged
  - Core and edge carbon concentration reduced
  - Divertor heat flux significantly reduced
    - Steady-state reduction due to geometry and radiative detachment
    - Encouraging results for transient heat flux handling
    - Combined with impurity-seeded radiative divertor

- **Outlook for snowflake divertor in NSTX-Upgrade**
  - 2D fluid modeling of snowflake divertor properties scaling
    - Edge and divertor transport, radiation, detachment threshold
    - Compatibility with cryo-pump and lithium conditioning
  - Magnetic control development
  - PFC development – PFC alignment and PFC material choice

Backup slides

Acknowledgements

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Radiative and geometric mitigation of divertor heat flux will be needed for high-power density NSTX-Upgrade discharges

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

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

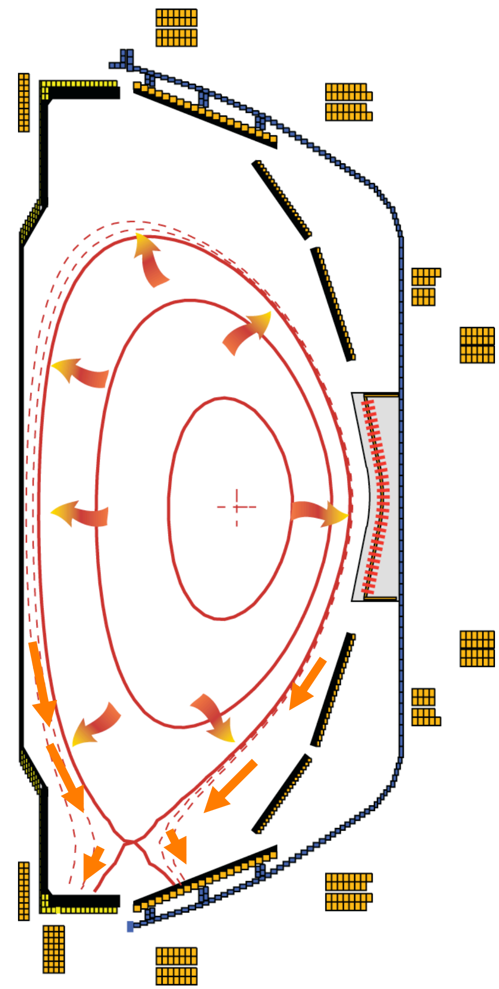
$$f_{exp} = \frac{(B_p/B_{tot})_{MP}}{(B_p/B_{tot})_{OSP}}$$

- Radiative divertor with impurity seeding
- Double null configurations
- Snowflake configuration as laboratory of divertor physics

Poloidal divertor concept enabled progress in tokamak physics studies 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

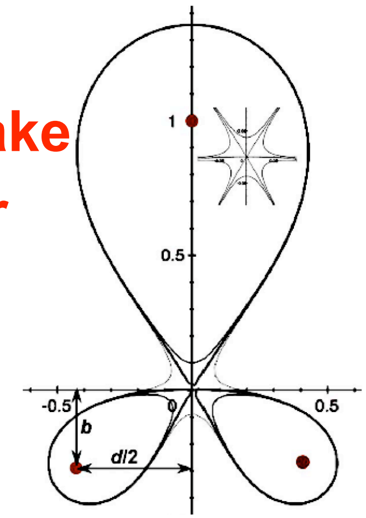


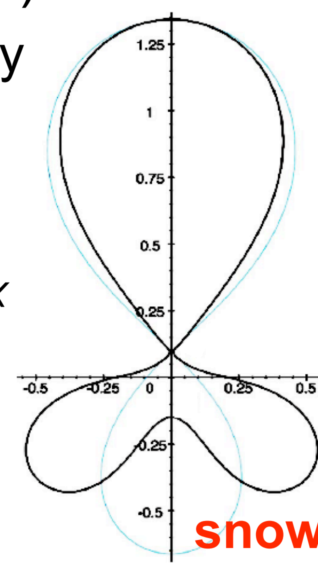
National Spherical Torus Experiment

Snowflake divertor geometry attractive for heat flux mitigation

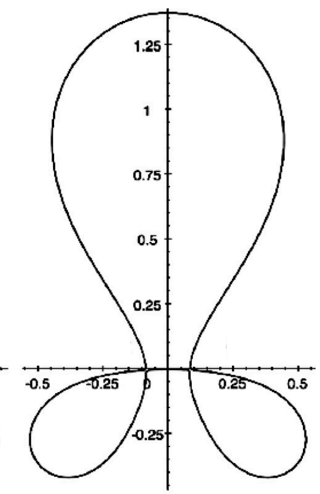
- Snowflake divertor
  - Second-order null
    - $B_p \sim 0$ and *grad* $B_p \sim 0$ (Cf. first-order null: $B_p \sim 0$)
  - Obtained with existing divertor coils (min. 2)
  - Exact snowflake topologically unstable
- Predicted geometry properties (cf. standard divertor)
  - Larger region with low B_p 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





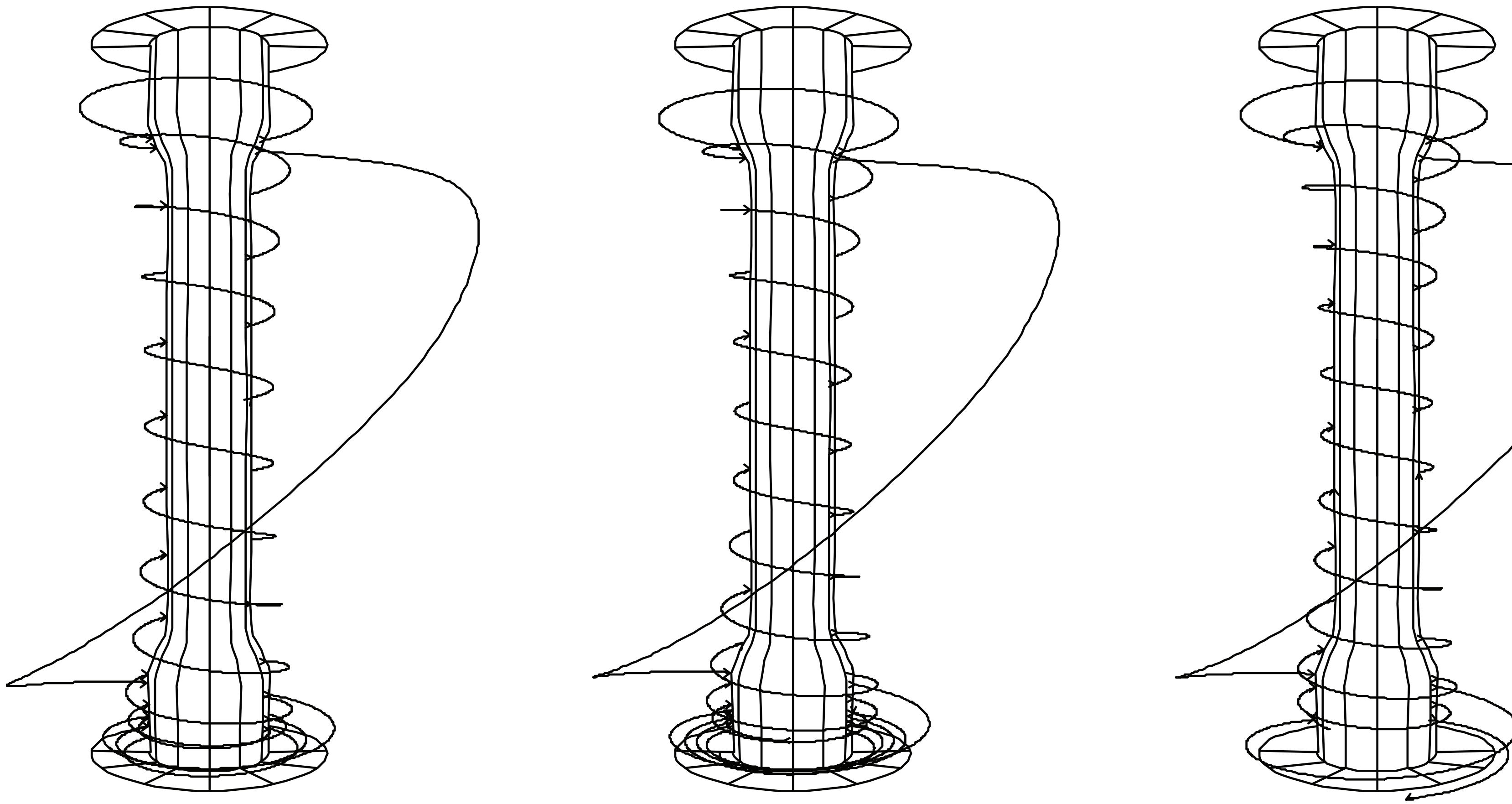
snowflake-plus



snowflake-minus

D. D. Ryutov, PoP 14, 064502 2007

Connection length is increased x 2-3 in snowflake divertor w.r.t. standard divertor

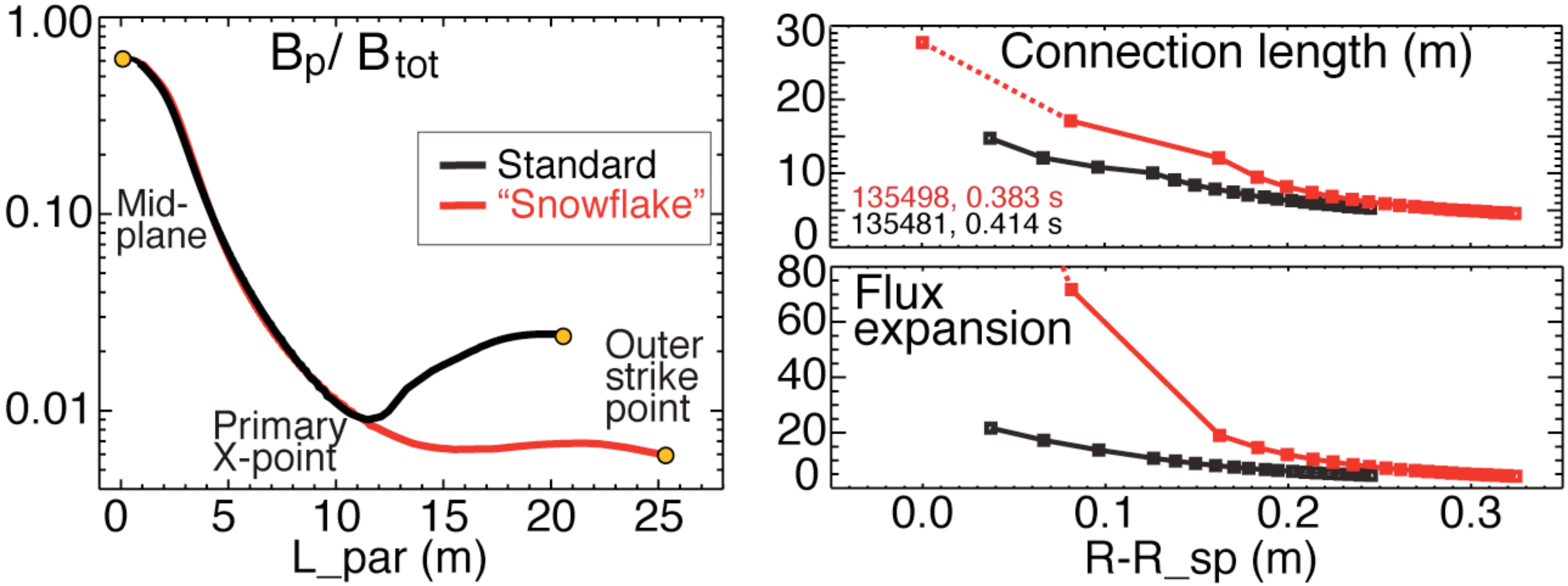


Shot 141241,
EFIT02,
time: 0.905s,
normalized flux: 1.005

Shot 141240,
EFIT02,
time: 0.905s,
normalized flux: 1.005

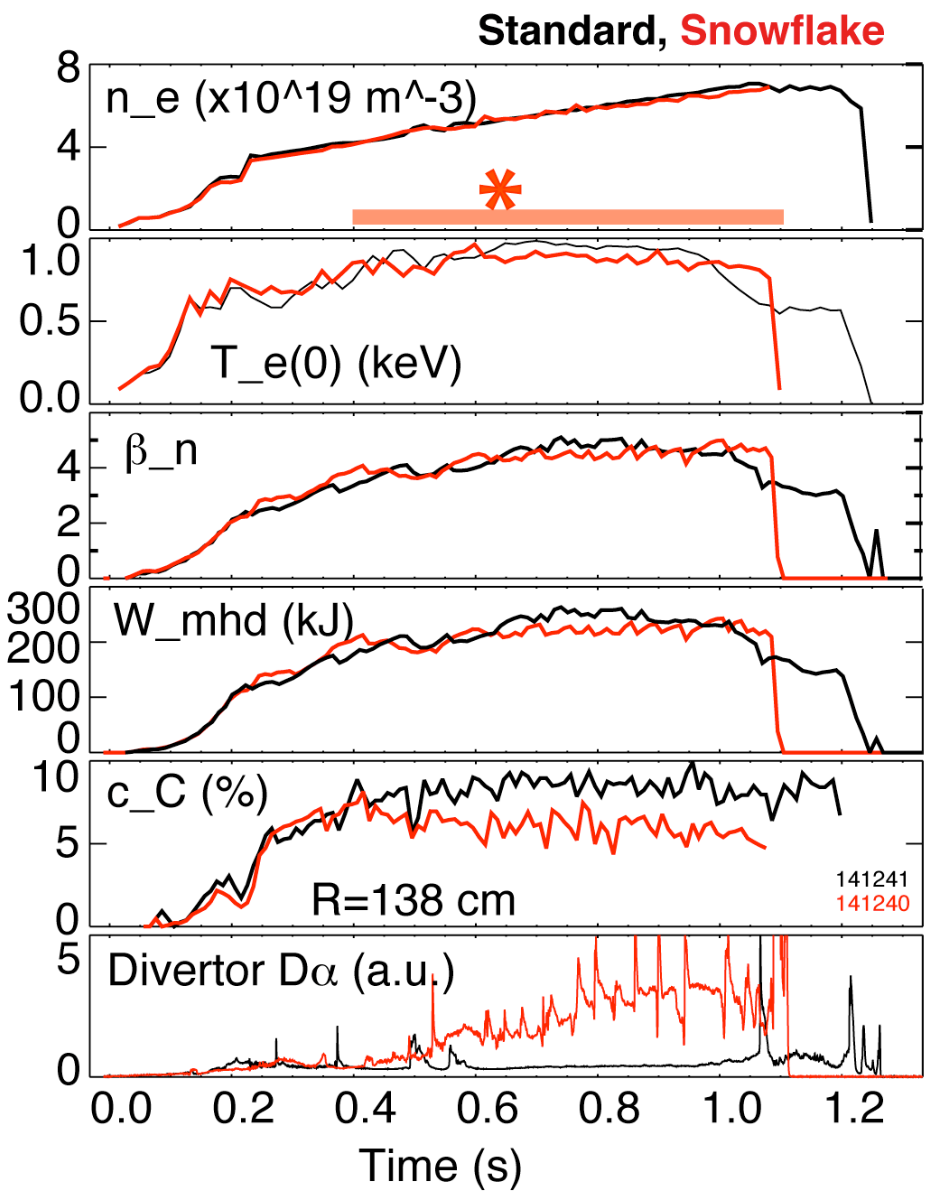
Shot 141240,
EFIT02,
time: 0.905s,
normalized flux: 1.015

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



- These properties observed in first 30-50 % of SOL width
- B_{tot} angles in the strike point region: 1-2°, sometimes < 1°
  - Concern for hot-spot formation and sputtering from divertor tile edges

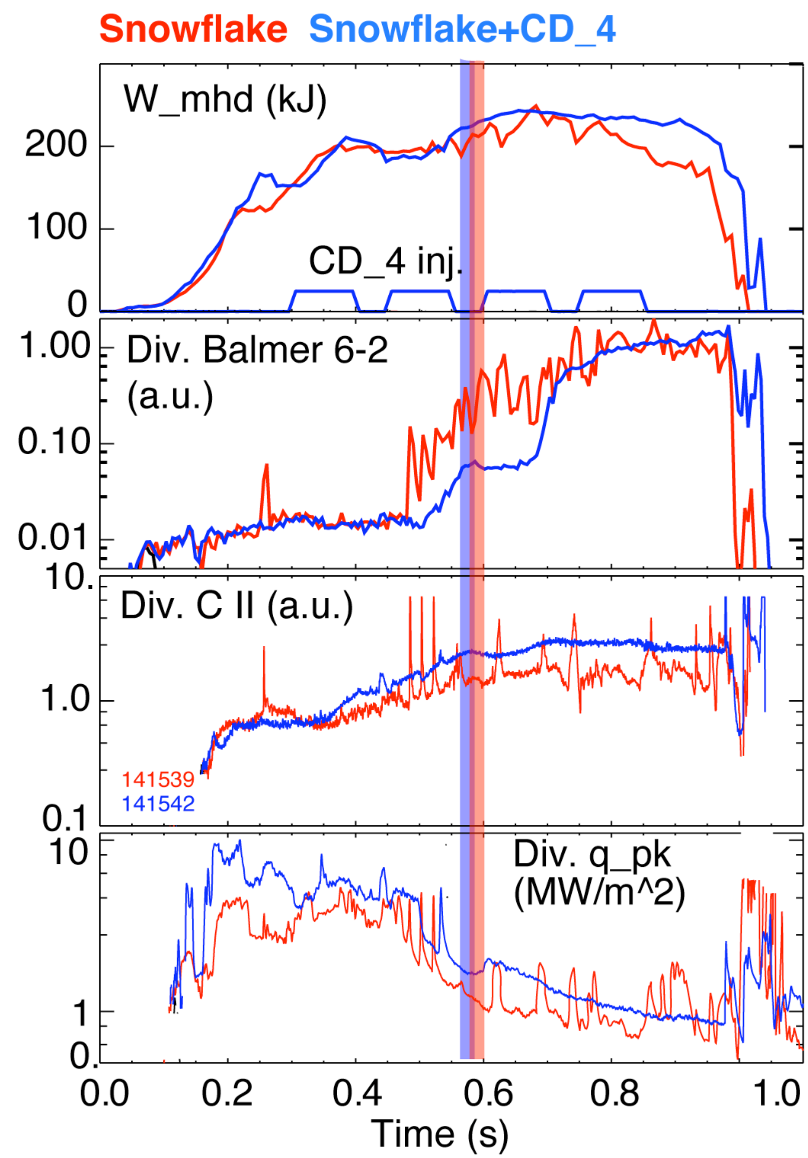
Good H-mode confinement properties and core impurity reduction obtained with snowflake divertor



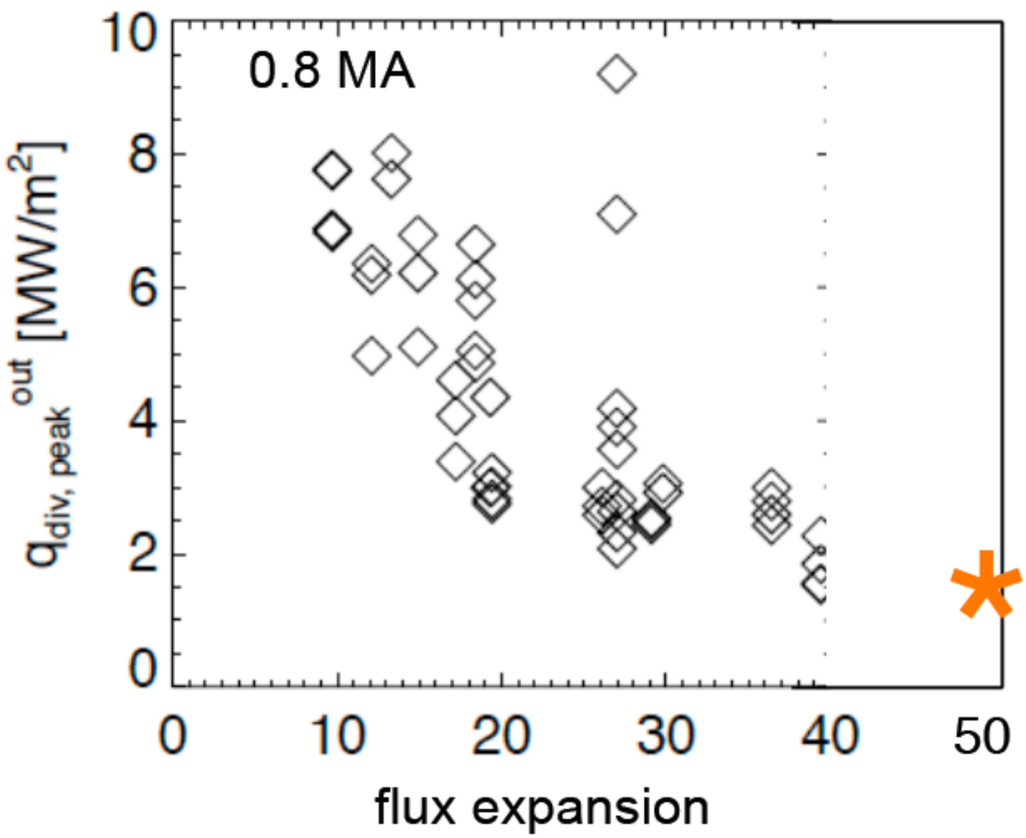
- 0.8 MA, 4 MW H-mode
- κ=2.1, δ=0.8
- Core T_e ~ 0.8-1 keV, T_i ~ 1 keV
- β_N ~ 4-5
- Plasma stored energy ~ 250 kJ
- H98(y,2) ~ 1 (from TRANSP)
- Core carbon reduction due to
  - Type I ELMs
  - Edge source reduction
    - Divertor sputtering rates reduced due to partial detachment

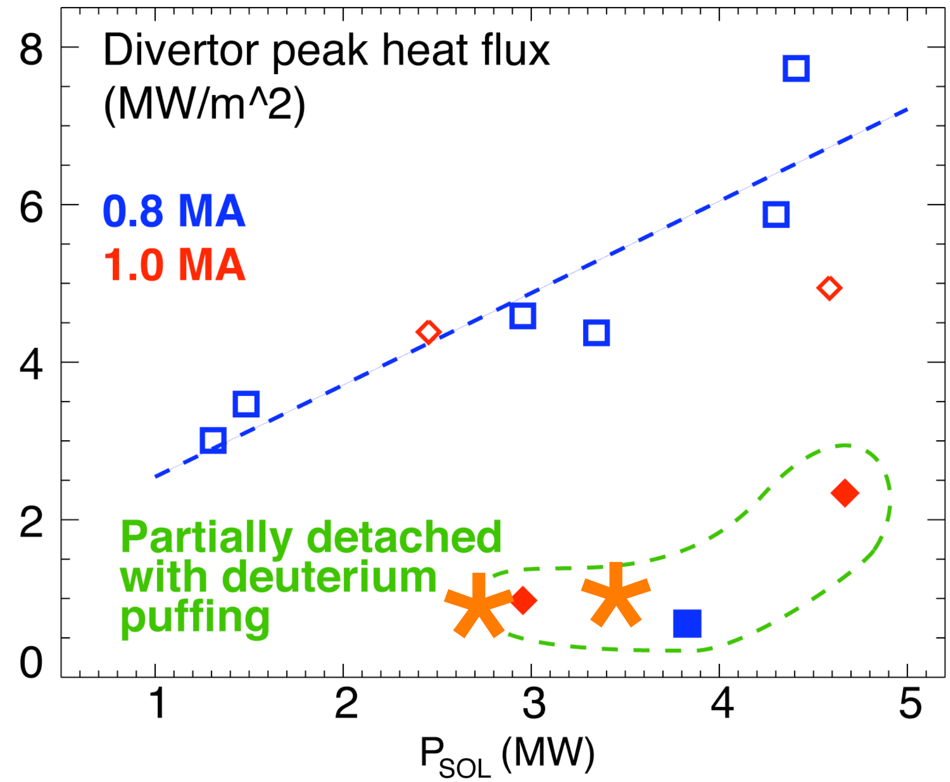
Snowflake divertor with CD_4 seeding leads to increased divertor carbon radiation

- 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



Snowflake divertor heat flux consistent with NSTX divertor heat flux scalings



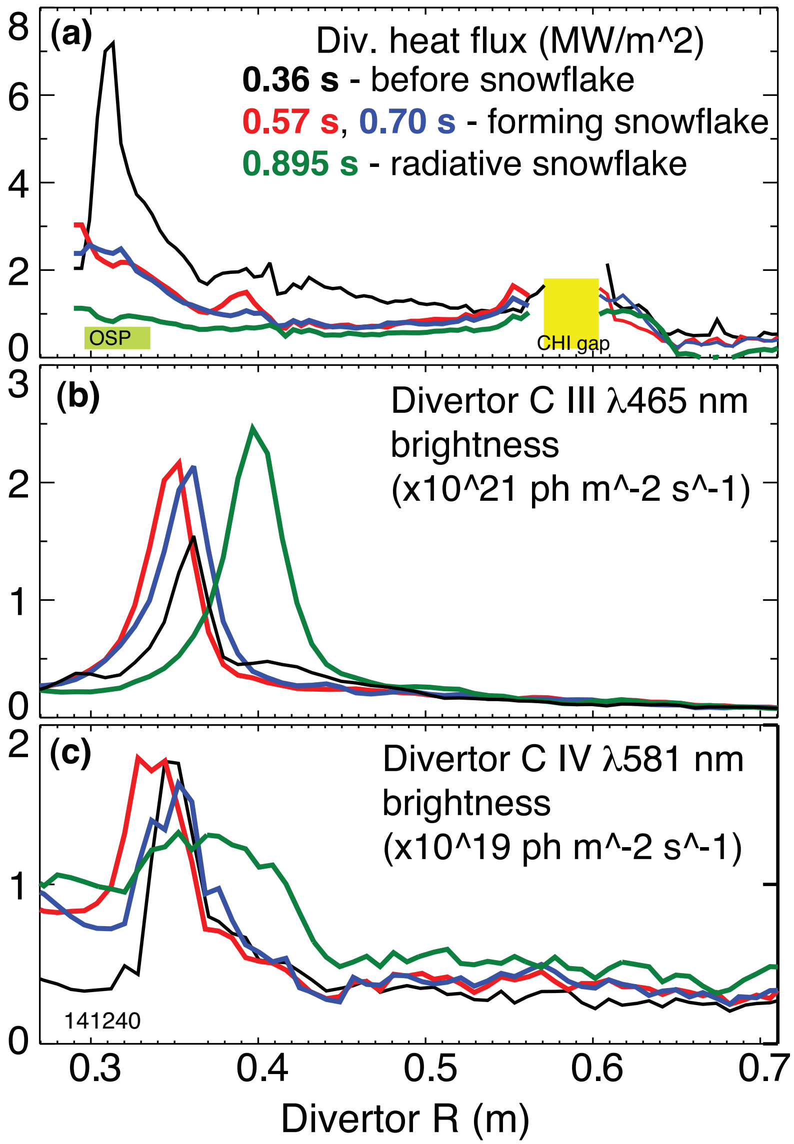


- Snowflake divertor (*): P_{SOL}~3-4 MW, f_{exp}~40-60, q_{peak}~0.5-1.5 MW/m^2
  - Low detachment threshold

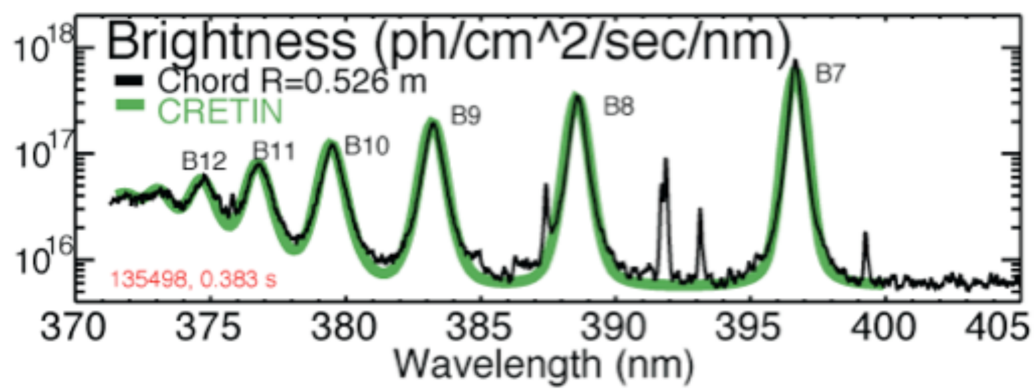
T. K. Gray et. al, EX/D P3-13, IAEA FEC 2010

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

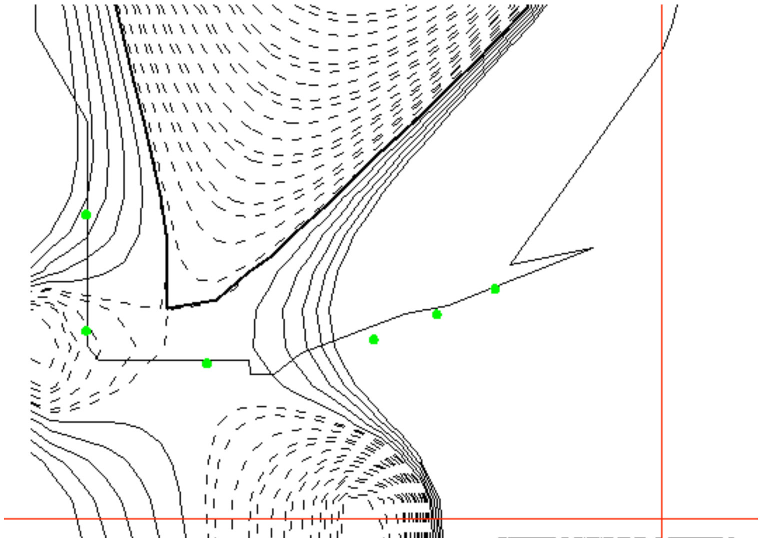
Divertor profiles show low heat flux, broadened C III and C IV radiation zones in the snowflake divertor phase

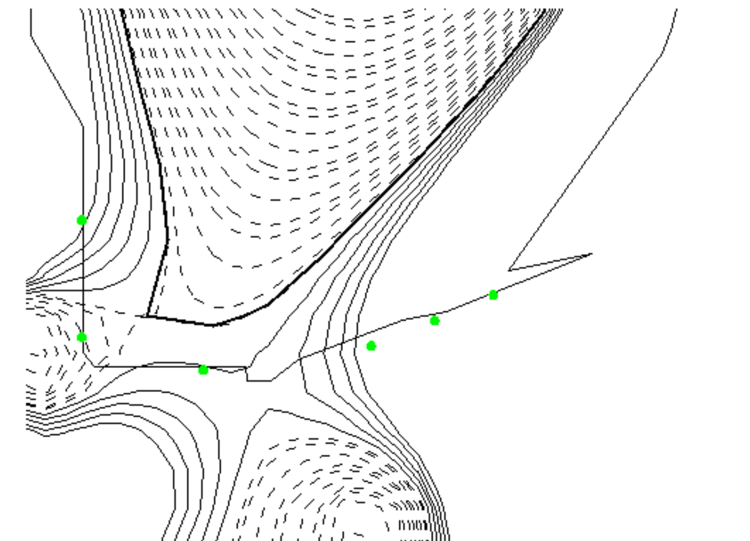


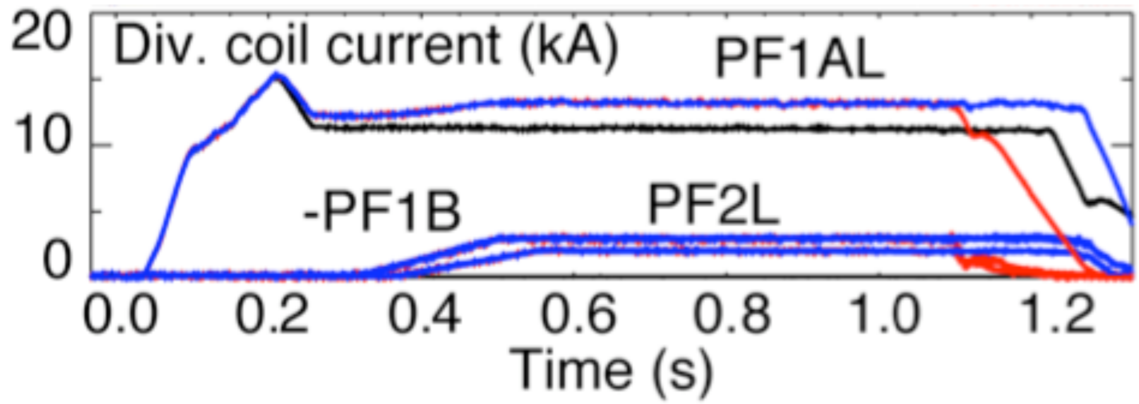
- Heat flux profiles reduced to nearly flat low levels, characteristic of radiative heating
- Divertor C III and C IV brightness profiles broaden
- High-*n* Balmer line spectroscopy and CRETIN code modeling confirm outer SP detachment with $T_e \leq 1.5$ eV, $n_e \leq 5 \times 10^{20}$ m^{-3}
  - Also suggests a reduction of carbon physical and chemical sputtering rates



Steady-state asymmetric snowflake-minus configuration has been obtained in FY2010 experiments in NSTX



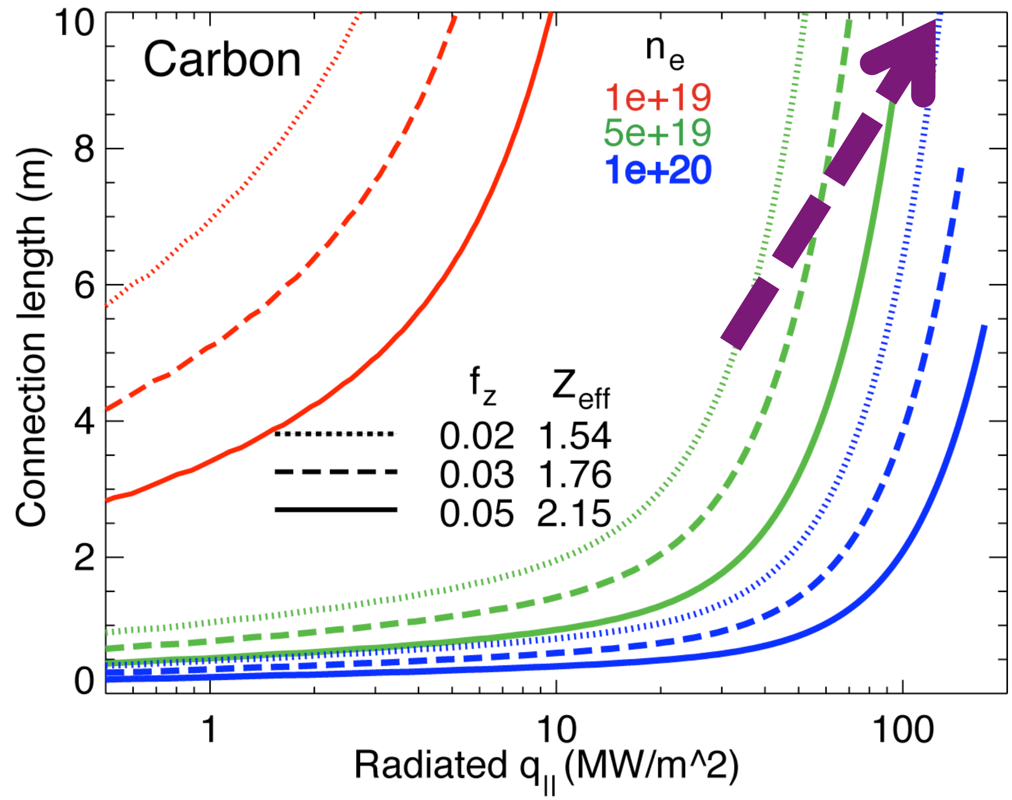




- Snowflake-minus with three coils (w/ reversed PF1B) transformed from a standard medium-δ LSN at ~ 500 ms
- Snowflake with three coils (w/ reversed PF1B) transformed from a standard high-δ LSN at ~ 500 ms

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
  - -> Greater fraction of $q_{||}$ is radiated with increased L_x
- Three-body electron-ion recombination rate depends on divertor ion residence time
  - Ion recombination time: τ_{ion}~ 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
  - -> Greater parallel momentum sink

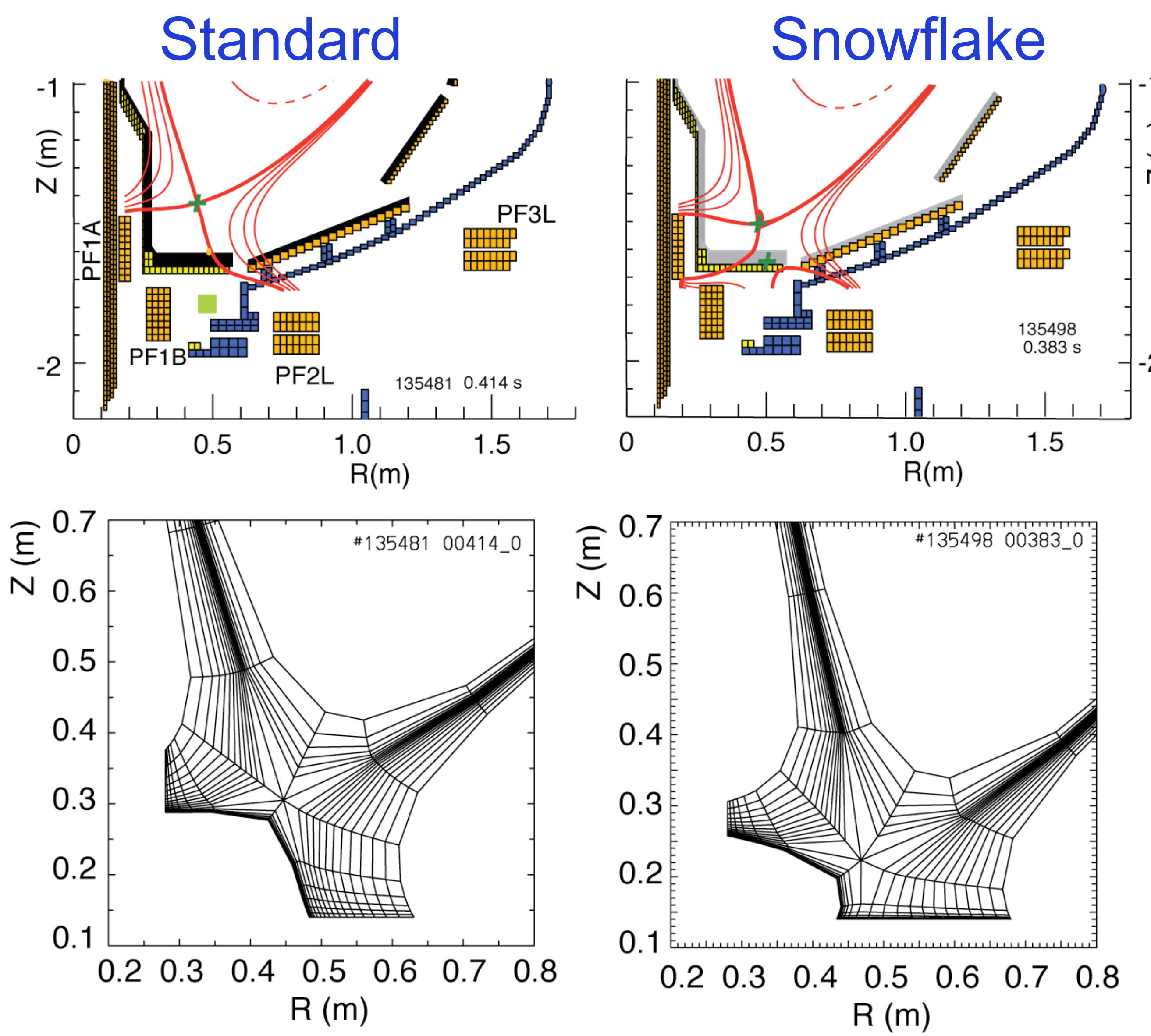


$$q_{||} = -\kappa_0 T_e^{5/2} \frac{\partial T_e}{\partial x}$$

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

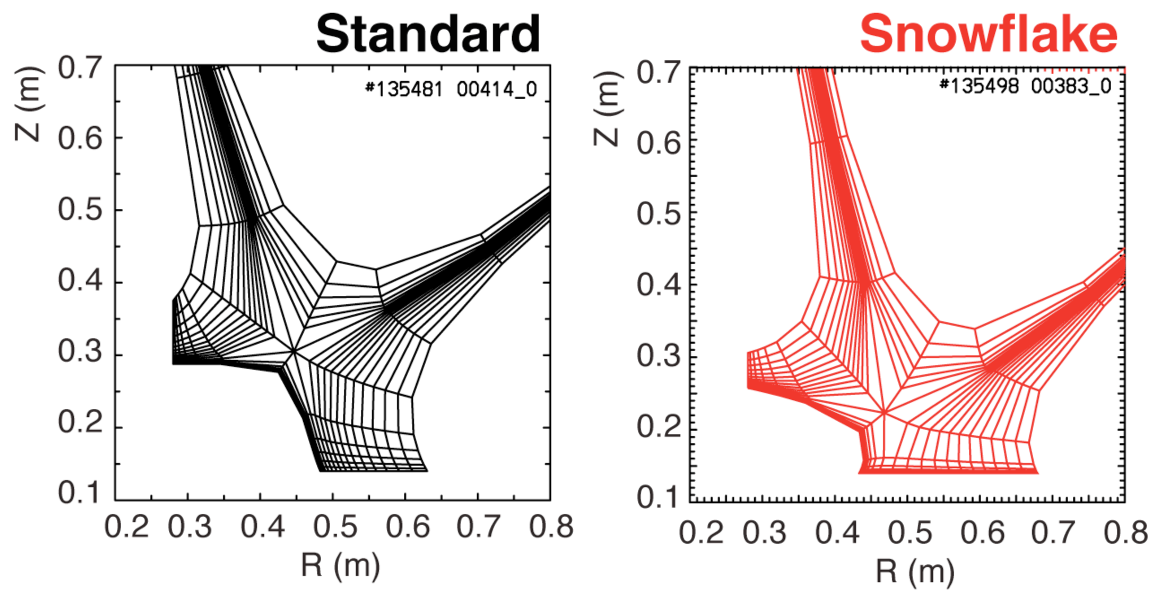
2D multi-fluid edge transport code UEDGE is used to study snowflake divertor properties

- 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 %



2D 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 x 10^{19}

R_{recy} = 0.95
Carbon 3 %