NSTX-U

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Divertor heat flux mitigation with impurity-seeded standard and snowflake divertors in NSTX.

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Stockholm, Sweden
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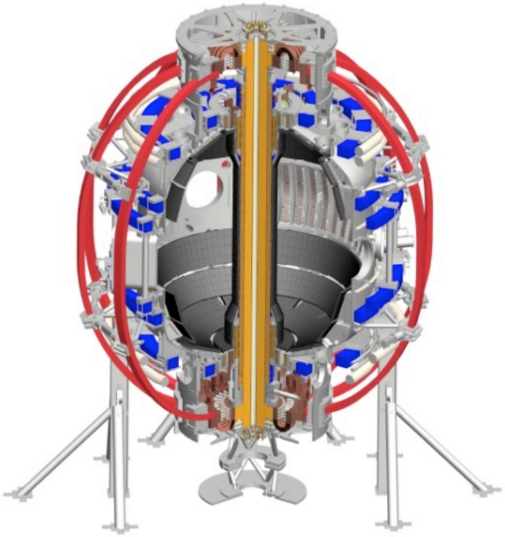

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Various techniques developed for reduction of heat fluxes $q_{||}$ (divertor SOL) and q_{peak} (divertor target)

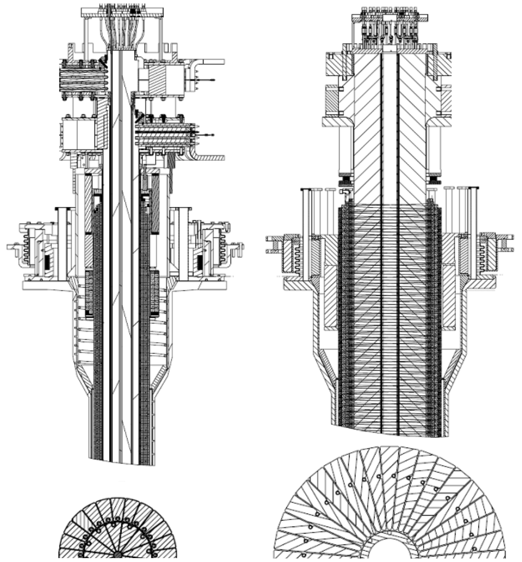
$$q_{pk} \simeq \frac{P_{heat}\,(1-f_{rad})f_{out/tot}f_{down/tot}(1-f_{pfr})\sin\alpha}{2\pi R_{SP}f_{exp}\lambda_{q_{||}}}$$

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

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

- Radiative divertor (partially detached strike point) is envisioned for present and future devices (e.g. ITER, ST-FNSF) as the steady-state heat flux mitigation solution
- Recent ideas to improve standard divertor geometry
  - Snowflake divertor (D. D. Ryutov, PoP 14, 064502 2007)
  - X-divertor (M. Kotschenreuther *et. al*, IC/P6-43, IAEA FEC 2004)
  - Super-X divertor (M. Kotschenreuther *et. al*, IC/P4-7, IAEA FEC 2008)

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

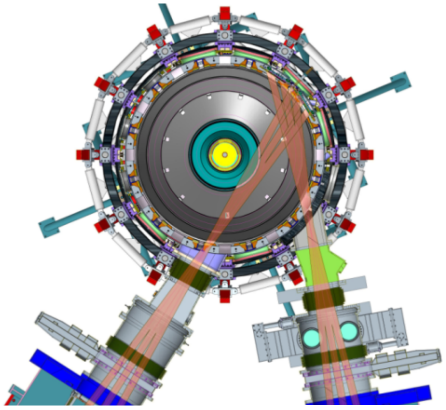


TF OD = 20cm
Previous center-stack

TF OD = 40cm
New center-stack

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



Present NBI

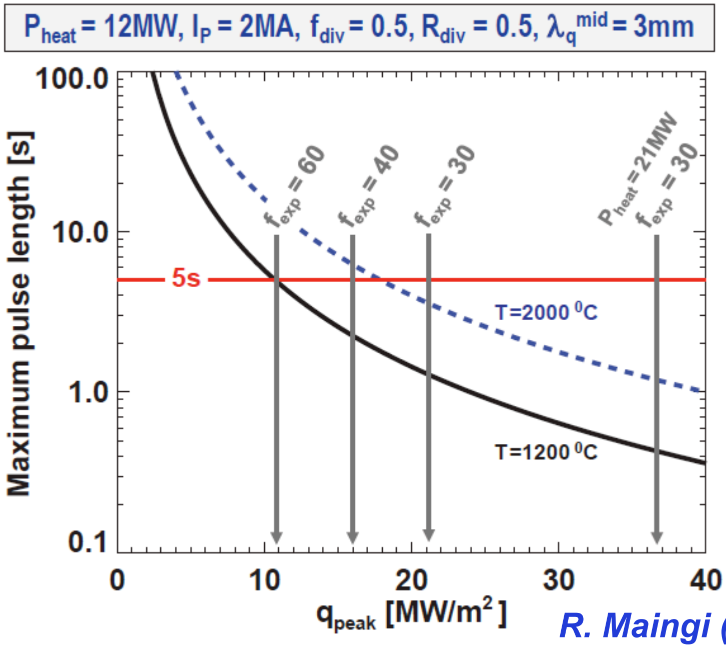
New 2nd NBI

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

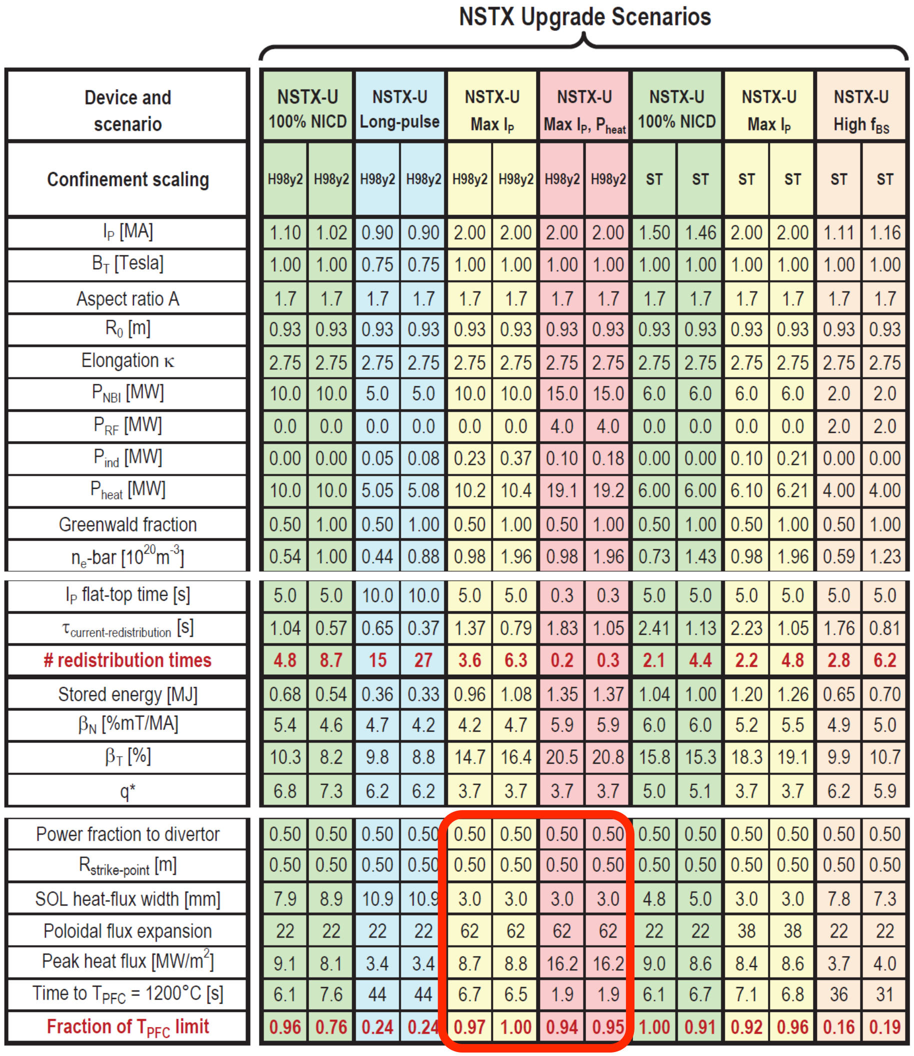
MENARD, J. et al., Proceedings of the 24th IEEE Symposium on Fusion Engineering (2011); Accepted to Nuclear Fusion (2012)

NSTX-U scenarios with high I_p and P_{NBI} are projected to challenge passive cooling limits of graphite divertor PFCs



R. Maingi (ORNL)

- High I_P scenarios projected to have narrow λ_q^{mid} → ~3mm
  - At high power, peak heat flux ≥ 9MW/m^2 even with high flux expansion ~60 with U/L snowflake
  - Numbers shown ignore radiation, plate tilt, strike-point sweeping



NSTX Upgrade Scenarios

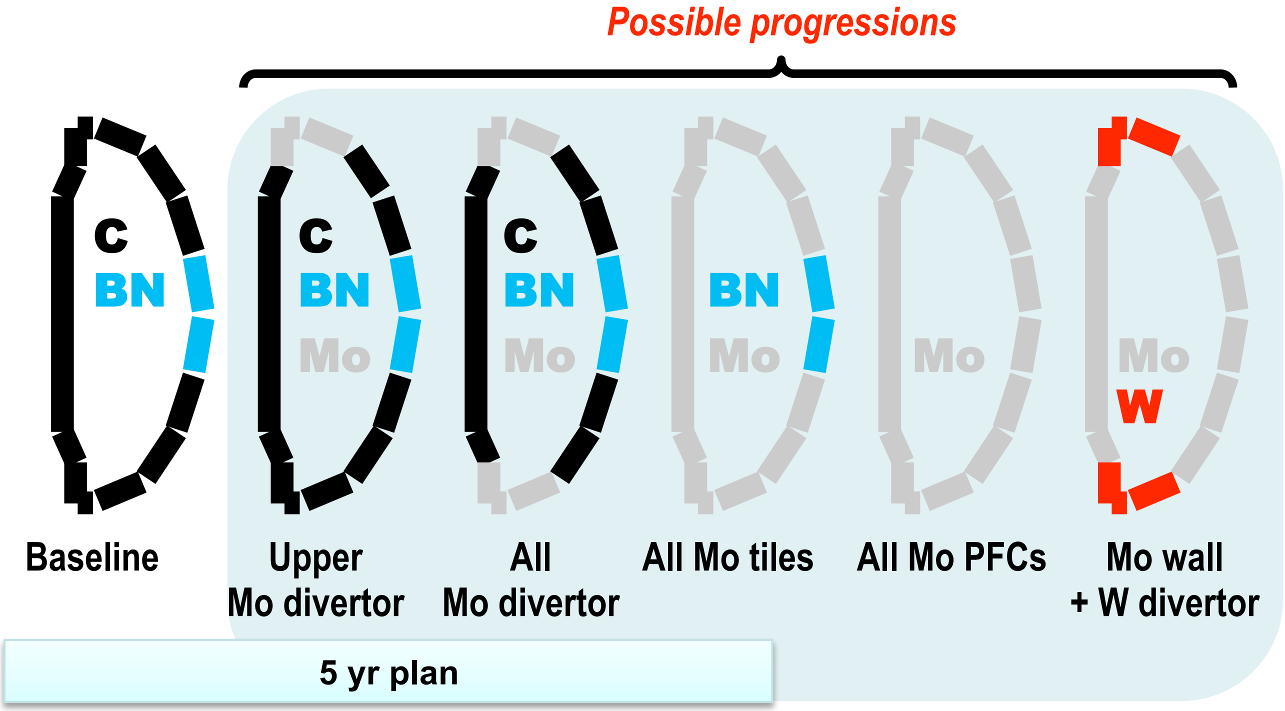
Device and scenario	NSTX-U 100% NICD		NSTX-U Long-pulse		NSTX-U Max I_P		NSTX-U Max I_P, P_{heat}		NSTX-U 100% NICD		NSTX-U Max I_P		NSTX-U High f_{BS}	
Confinement scaling	H98y2	H98y2	H98y2	H98y2	H98y2	H98y2	H98y2	H98y2	ST	ST	ST	ST	ST	ST
I_P [MA]	1.10	1.02	0.90	0.90	2.00	2.00	2.00	2.00	1.50	1.46	2.00	2.00	1.11	1.16
B_T [Tesla]	1.00	1.00	0.75	0.75	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Aspect ratio A	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7
R_0 [m]	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93
Elongation κ	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75
P_{NBI} [MW]	10.0	10.0	5.0	5.0	10.0	10.0	15.0	15.0	6.0	6.0	6.0	6.0	2.0	2.0
P_{RF} [MW]	0.0	0.0	0.0	0.0	0.0	0.0	4.0	4.0	0.0	0.0	0.0	0.0	2.0	2.0
P_{ind} [MW]	0.00	0.00	0.05	0.08	0.23	0.37	0.10	0.18	0.00	0.00	0.10	0.21	0.00	0.00
P_{heat} [MW]	10.0	10.0	5.05	5.08	10.2	10.4	19.1	19.2	6.00	6.00	6.10	6.21	4.00	4.00
Greenwald fraction	0.50	1.00	0.50	1.00	0.50	1.00	0.50	1.00	0.50	1.00	0.50	1.00	0.50	1.00
n_e-bar [$10^{20}m^{-3}$]	0.54	1.00	0.44	0.88	0.98	1.96	0.98	1.96	0.73	1.43	0.98	1.96	0.59	1.23
I_P flat-top time [s]	5.0	5.0	10.0	10.0	5.0	5.0	0.3	0.3	5.0	5.0	5.0	5.0	5.0	5.0
$\tau_{current\text{-}redistribution}$ [s]	1.04	0.57	0.65	0.37	1.37	0.79	1.83	1.05	2.41	1.13	2.23	1.05	1.76	0.81
# redistribution times	**4.8**	**8.7**	**15**	**27**	**3.6**	**6.3**	**0.2**	**0.3**	**2.1**	**4.4**	**2.2**	**4.8**	**2.8**	**6.2**
Stored energy [MJ]	0.68	0.54	0.36	0.33	0.96	1.08	1.35	1.37	1.04	1.00	1.20	1.26	0.65	0.70
β_N [%mT/MA]	5.4	4.6	4.7	4.2	4.2	4.7	5.9	5.9	6.0	6.0	5.2	5.5	4.9	5.0
β_T [%]	10.3	8.2	9.8	8.8	14.7	16.4	20.5	20.8	15.8	15.3	18.3	19.1	9.9	10.7
q*	6.8	7.3	6.2	6.2	3.7	3.7	3.7	3.7	5.0	5.1	3.7	3.7	6.2	5.9
Power fraction to divertor	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
$R_{strike\text{-}point}$ [m]	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
SOL heat-flux width [mm]	7.9	8.9	10.9	10.9	3.0	3.0	3.0	3.0	4.8	5.0	3.0	3.0	7.8	7.3
Poloidal flux expansion	22	22	22	22	62	62	62	62	22	22	38	38	22	22
Peak heat flux [MW/m^2]	9.1	8.1	3.4	3.4	8.7	8.8	16.2	16.2	9.0	8.6	8.4	8.6	3.7	4.0
Time to T_{PFC} = 1200°C [s]	6.1	7.6	44	44	6.7	6.5	1.9	1.9	6.1	6.7	7.1	6.8	36	31
Fraction of T_{PFC} limit	**0.96**	**0.76**	**0.24**	**0.24**	**0.97**	**1.00**	**0.94**	**0.95**	**1.00**	**0.91**	**0.92**	**0.96**	**0.16**	**0.19**

MENARD, J. et al., Proceedings of the 24th IEEE Symposium on Fusion Engineering (2011).

- **Passive cooling ok for low-I_P scenarios**
- **Long-pulse + high I_P and power may ultimately require active divertor cooling**

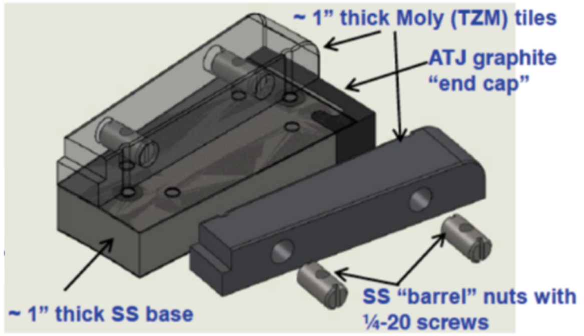
Radiative divertor control options are affected by NSTX-U plasma-facing component development plan

- Developing PFC plan to transition to full metal coverage for FNSF-relevant PMI development
- Wall conditioning: GDC, lithium and / or boron coatings
- PFC bake-out at 300-350°C



- Radiative divertor elements affected by PFC choice:
  - Divertor impurity gas handling and injection system
    - D_2, CD_4, Ar with graphite PFCs and lithium coatings
    - D_2, N_2, CD_4, Ar with refractory metal PFCs
  - Diagnostic sensors for control
  - Plasma Control System development

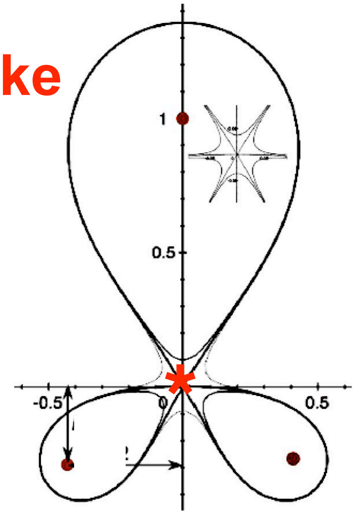
Mo tiles

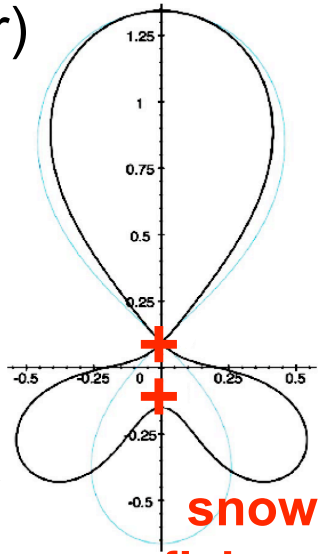


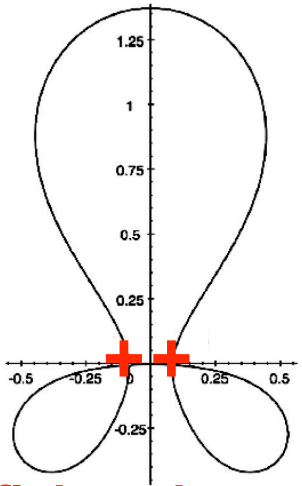
Snowflake divertor geometry has benefits over standard X-point divertor geometry

- 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
  - Deviation from ideal snowflake: $\sigma = d / a$
    - *d* – distance between nulls, *a* – plasma minor radius
- Predicted geometry properties (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}
- Experiments: TCV and NSTX

Exact snowflake divertor





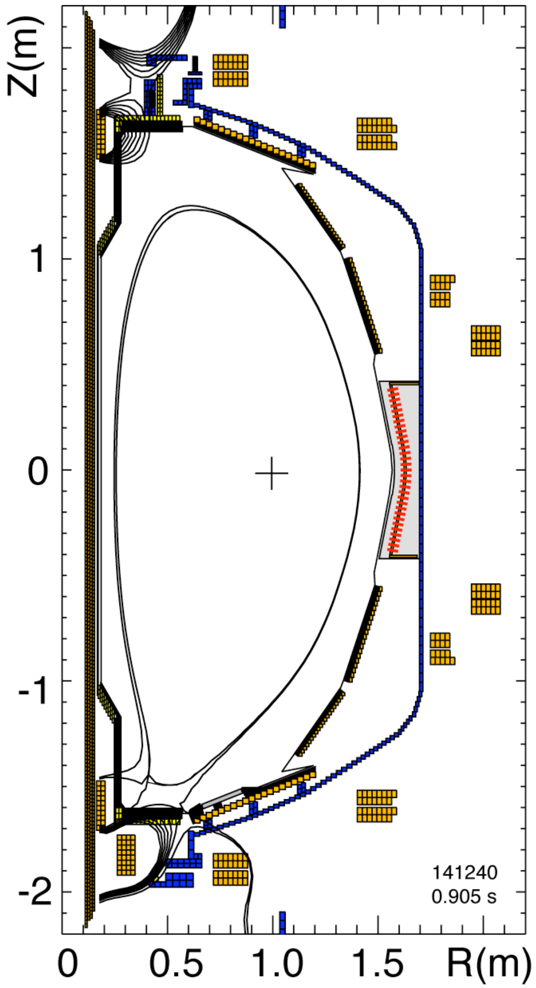


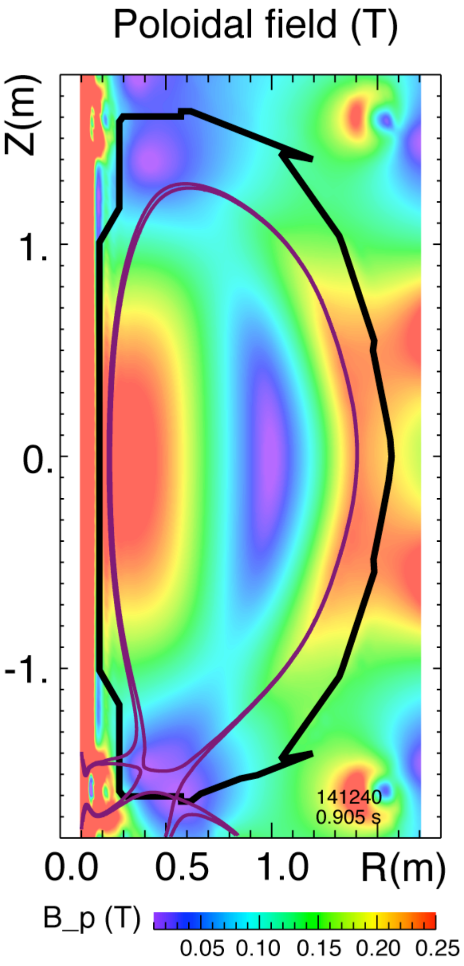
snowflake-minus

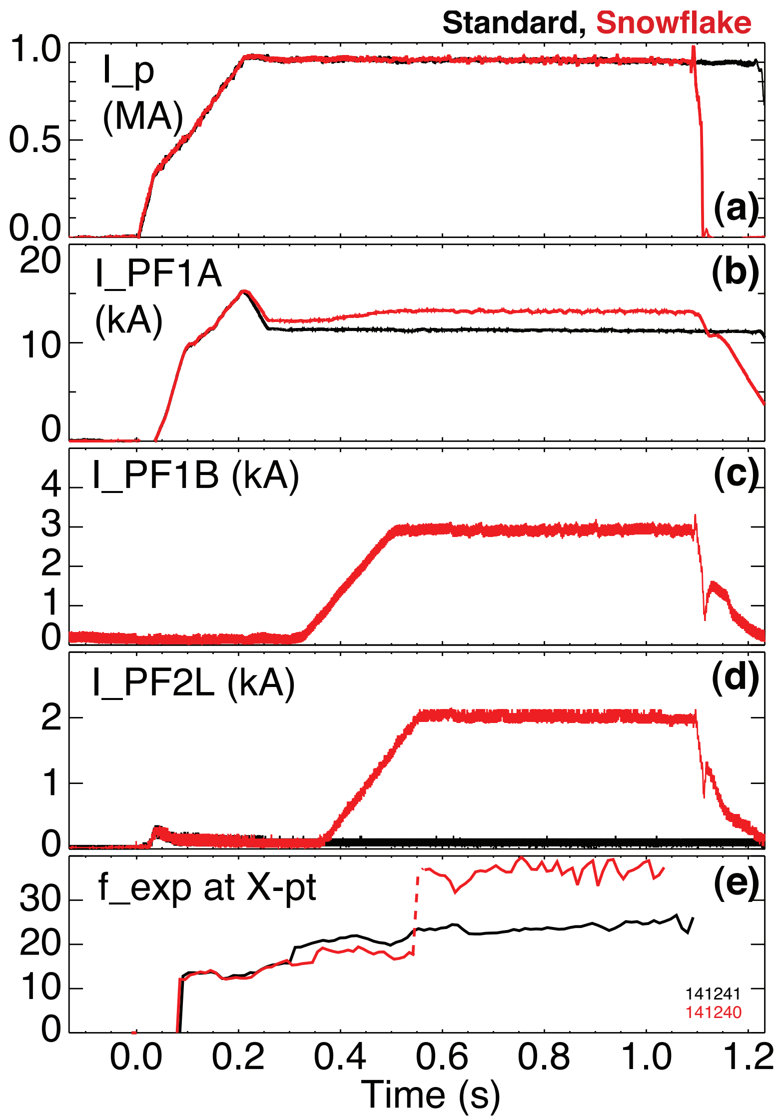
snowflake-plus

D. D. Ryutov, PoP 14, 064502 2007

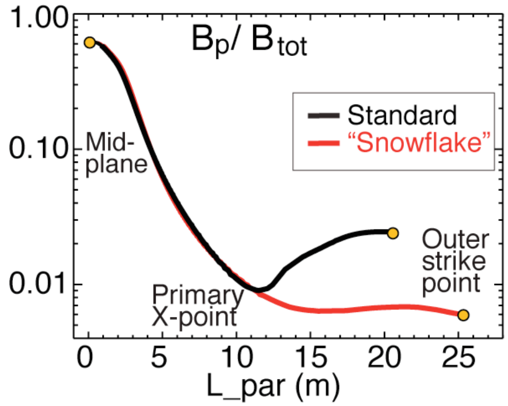
NSTX: Snowflake divertor configurations obtained with existing divertor coils

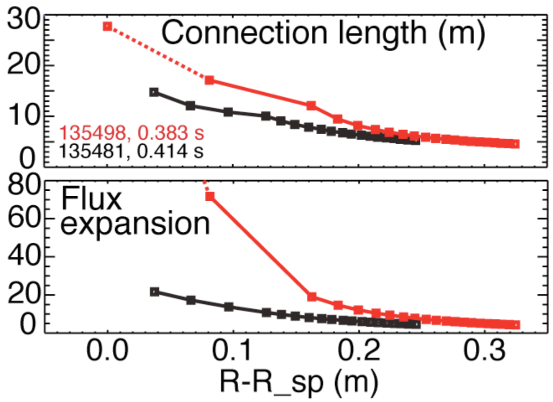


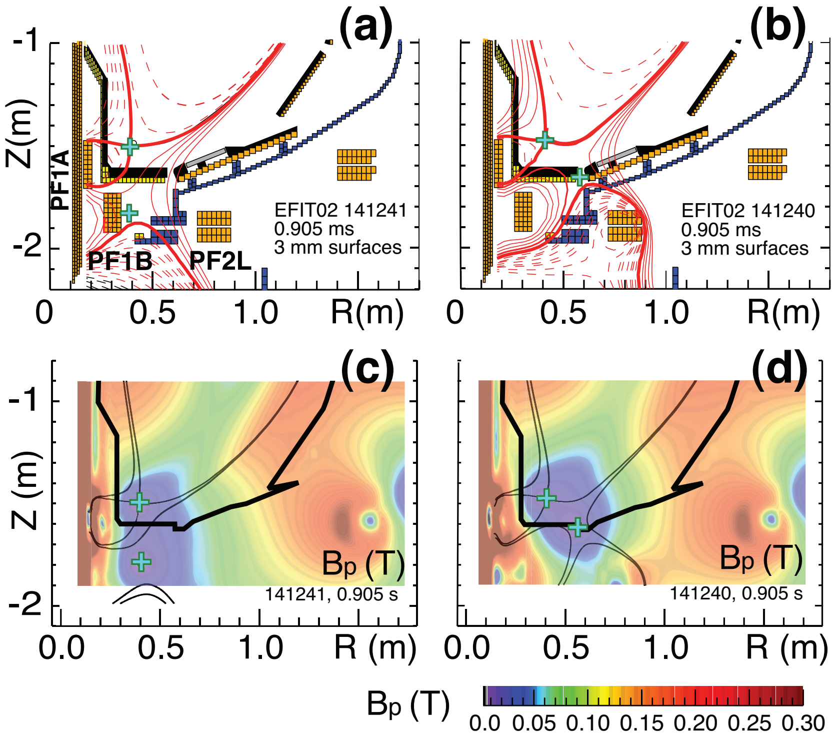




Plasma-wetted area and connection length are increased by 50-90 % in snowflake divertor

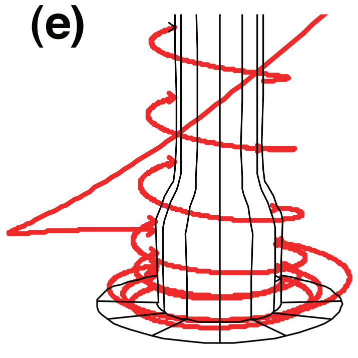




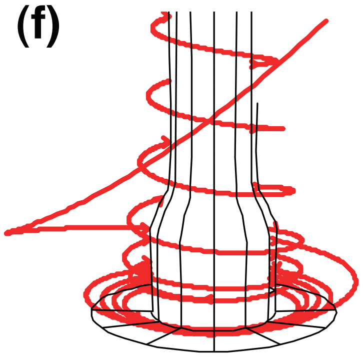


- These properties observed in first 30-50 % of SOL width

- B_{tot} angles in the strike point region: 1-2°, sometimes < 1°

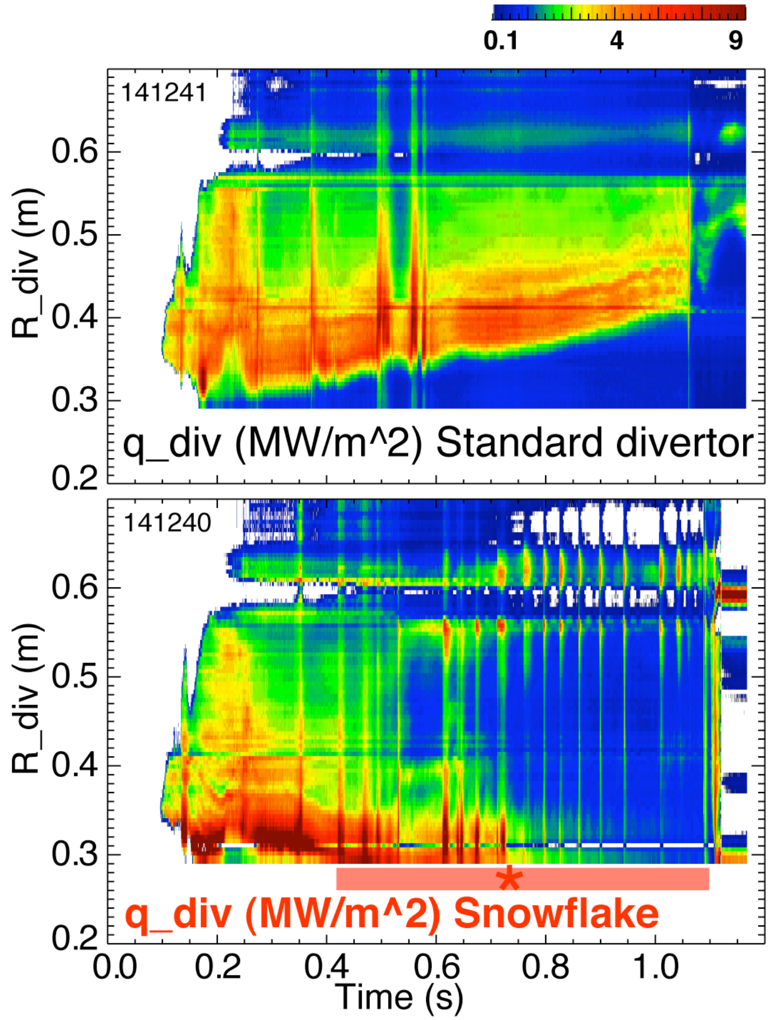


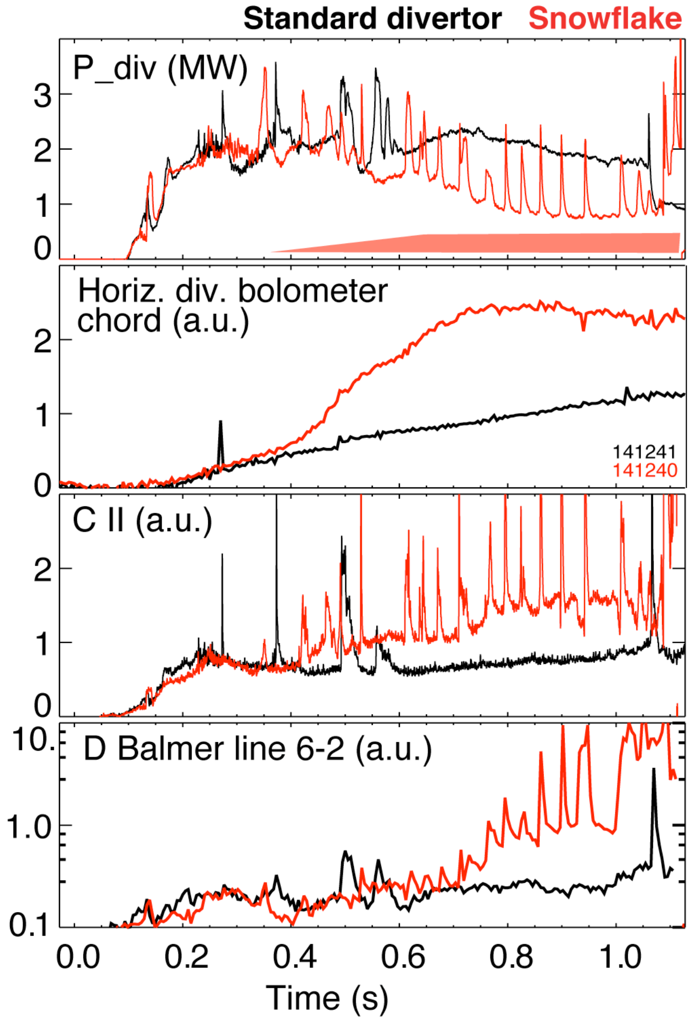
Shot 141241, EFIT02,
time: 0.905 s,
normalized flux: 1.005



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

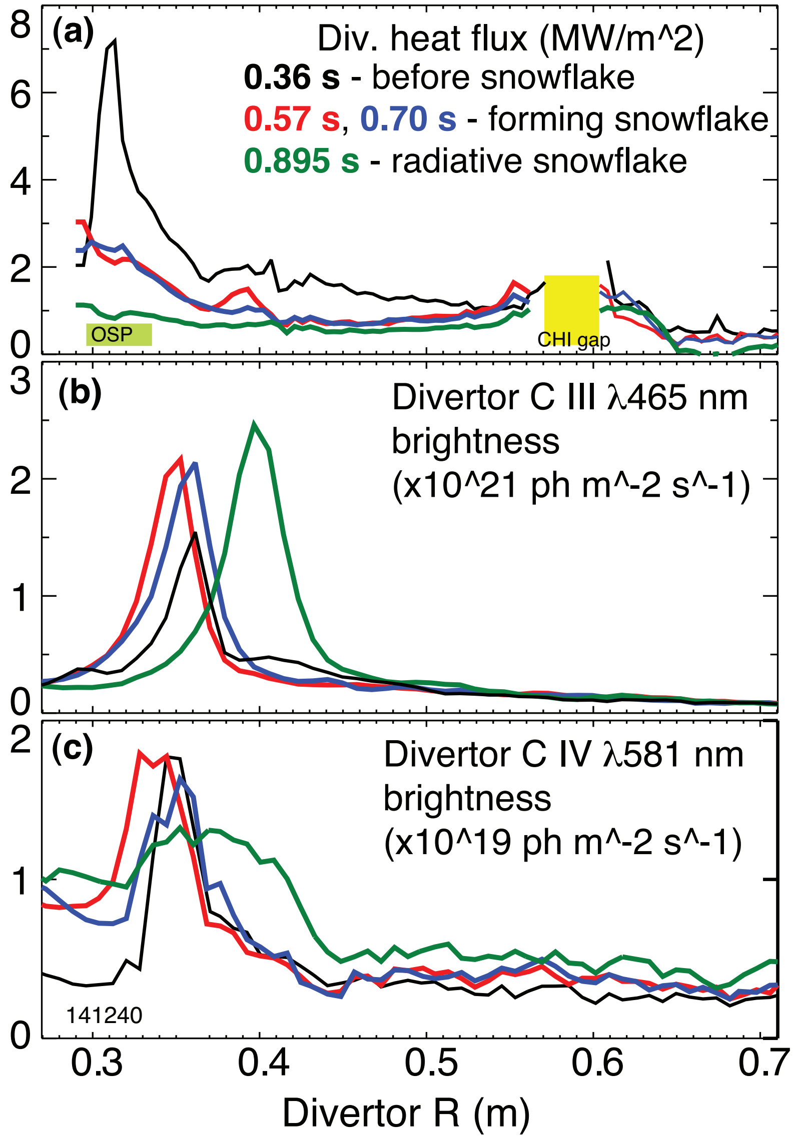
Significant reduction of steady-state divertor heat flux observed in snowflake divertor (at P_{SOL}~ 3 MW)





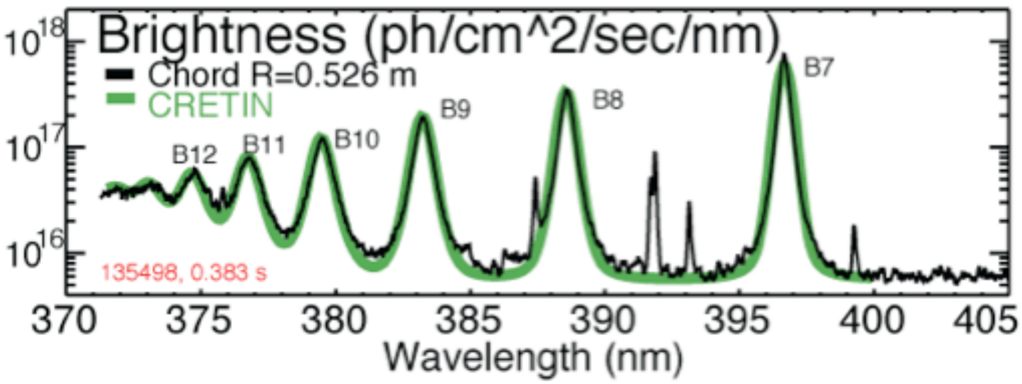
- Partial detachment at or after snowflake formation time
  - Heat and ion fluxes in the outer strike point region decreased
  - Divertor recombination rate and radiated power are increased

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

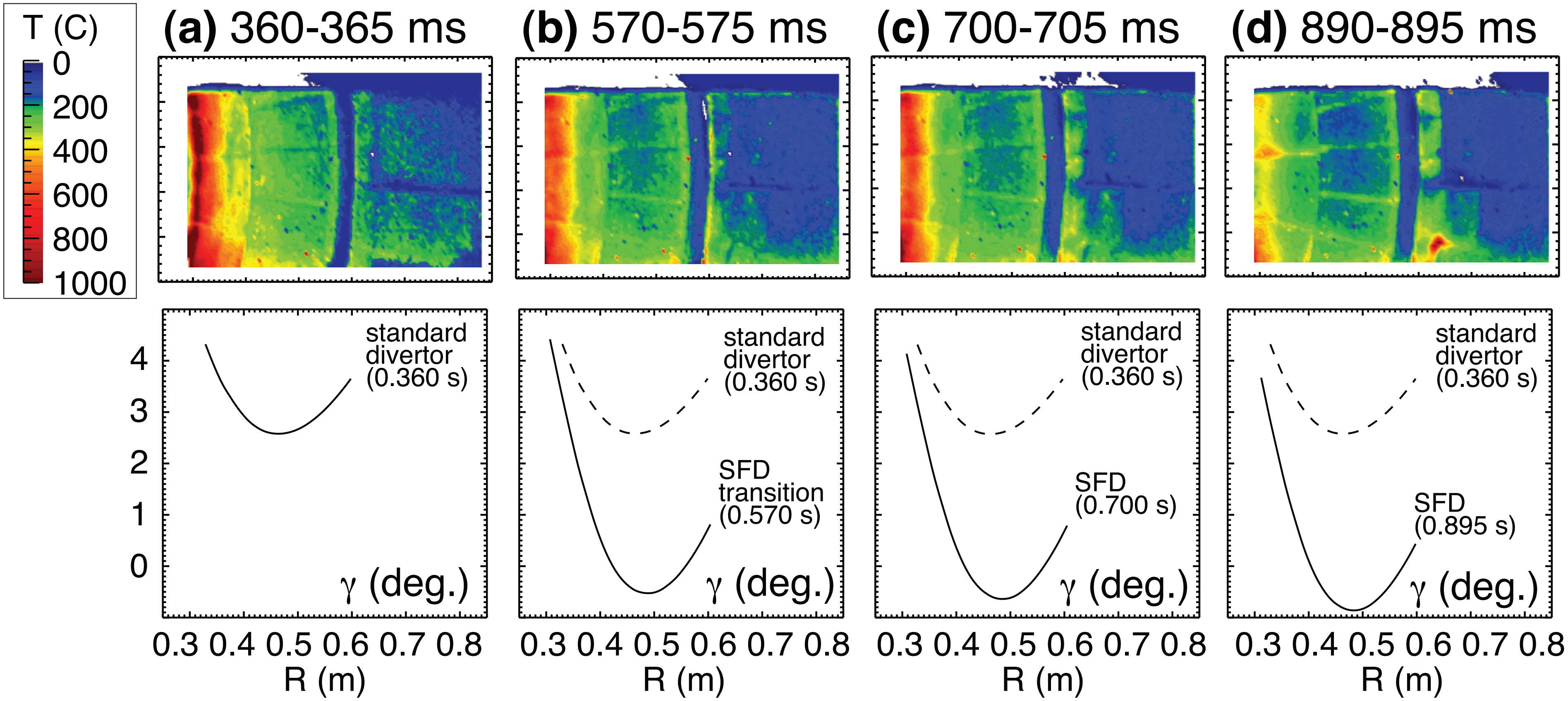


- Heat flux profiles reduced to nearly flat low levels, characteristic of radiative heating
- Divertor C III and C IV brightness profiles broaden
- High-*n* Balmer line spectroscopy and CRETIN code modeling confirm outer SP detachment with $T_e \leq 1.5$ eV, $n_e \leq 5 \times 10^{20}$ m^{-3}

  Also suggests a reduction of carbon physical and chemical sputtering rates



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

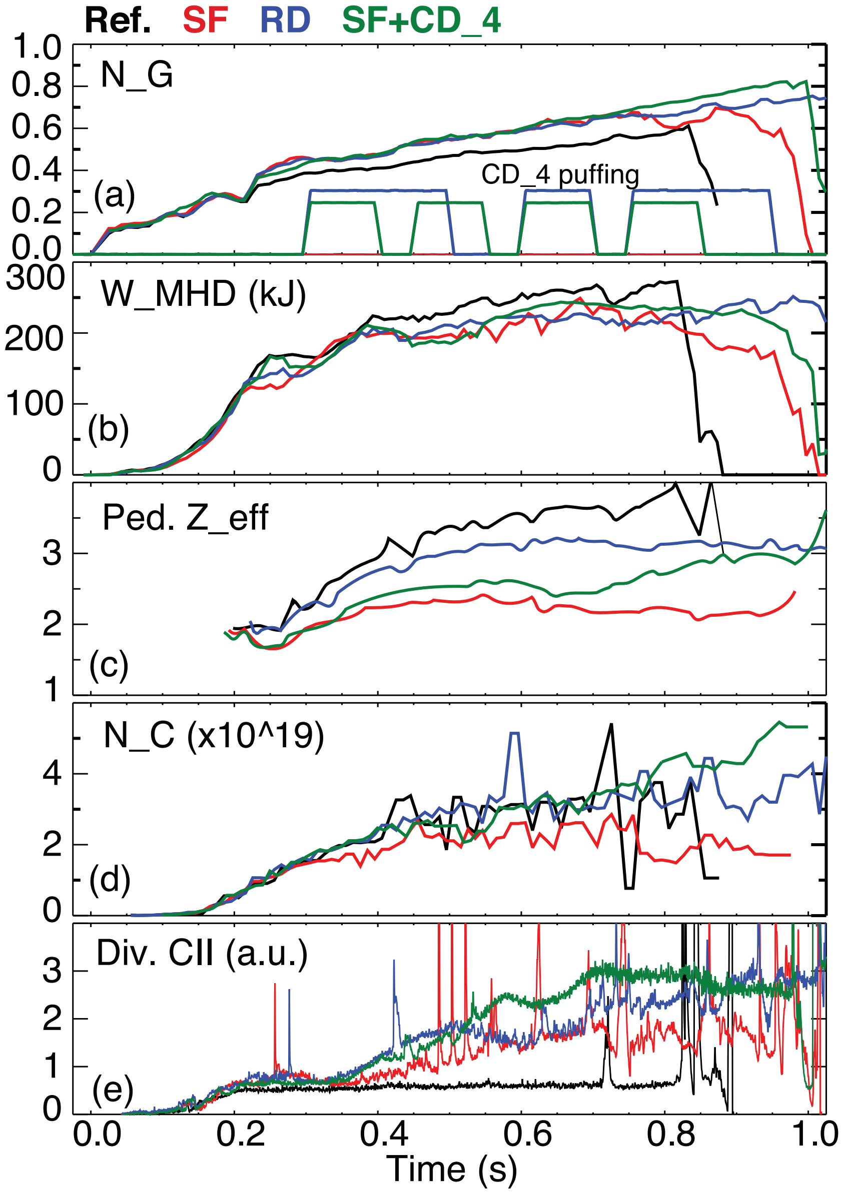


- Reduction of $q_{||}$ due to radiative detachment is considered

NSTX experiments compared standard and snowflake divertors with and without extrinsic CD_4 seeding

- Goal of the experiment – develop high-performance H-mode discharge with reduced divertor heat flux
  - Use highly-shaped configuration
    - κ=2.1, δ=0.8, drsep=6-7 mm (similar to λ_{SOL})
  - *B x grad B* toward lower divertor
  - 4 MW NBI, I_p=0.9 MA
    - **Reference** (attached standard divertor)
    - **Snowflake divertor** (partially detached divertor due to intrinsic carbon radiation)
    - **Radiative divertor in standard geometry with CD_4 seeding** (partially detached divertor due to enhanced divertor density and carbon concentration)
    - **Snowflake divertor with CD_4 seeding** (partially detached divertor due to enhanced carbon radiation in low T_e snowflake divertor)

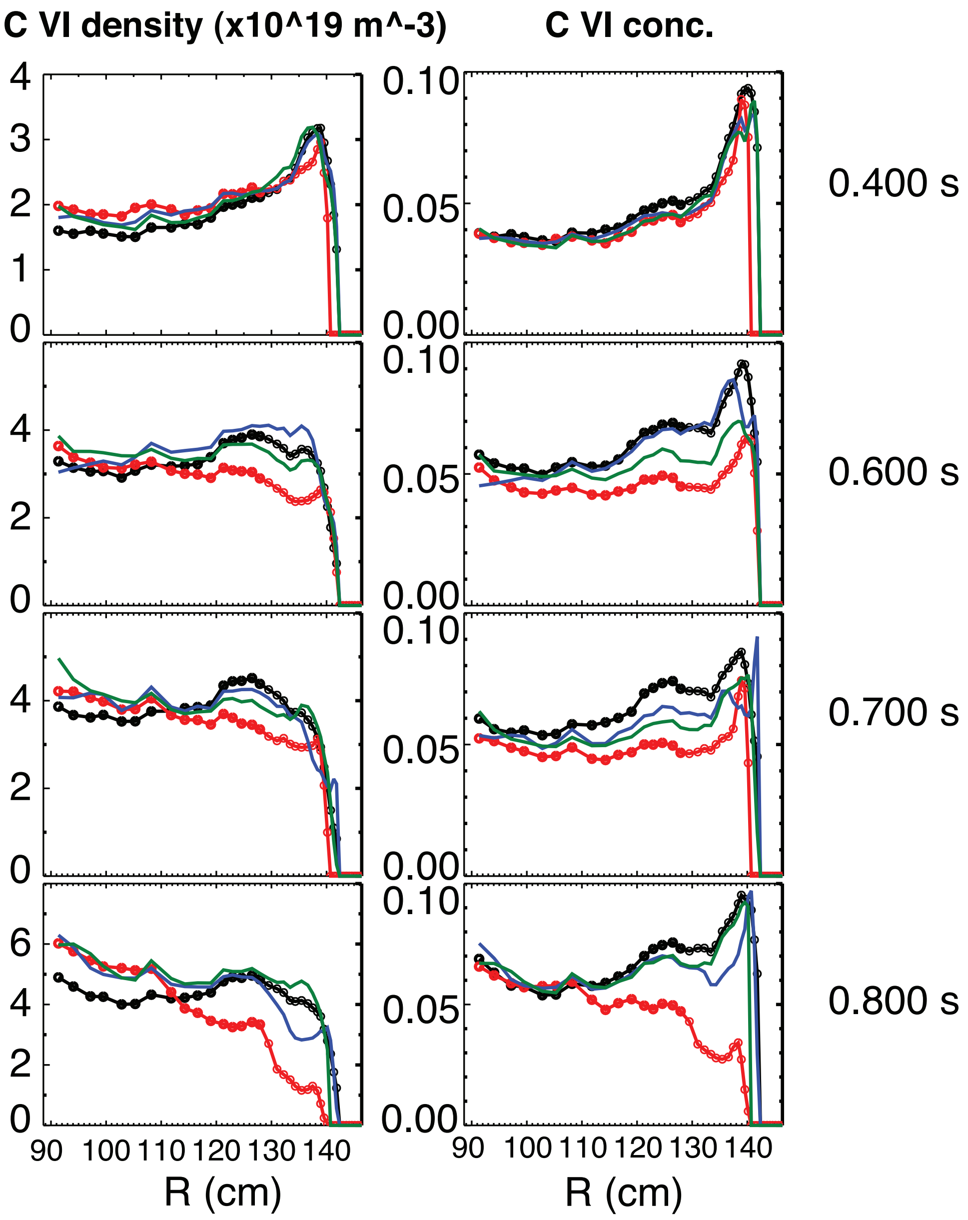
Good H-mode confinement properties retained or slightly reduced with radiative divertor and snowflake divertor



- 0.9 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
  - Disappeared again in snowflake with CD_4 seeding

Reference
Snowflake
Radiative divertor w/ CD_4
Snowflake+CD_4

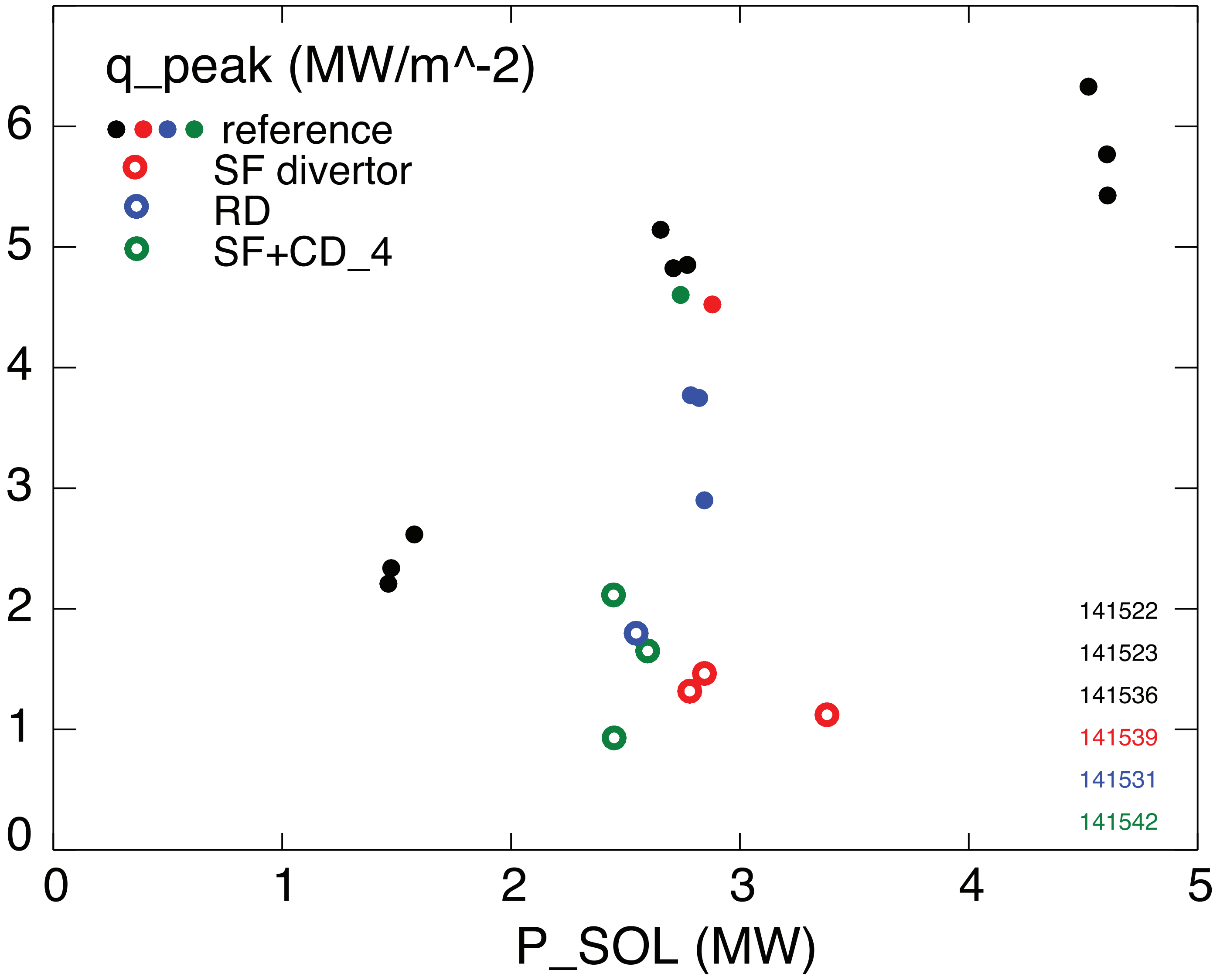
Core carbon reduction obtained with snowflake divertor



- Core carbon reduction due to
  - Type I ELMs
  - Edge source reduction
    - Divertor sputtering rates reduced due to partial detachment
- Good divertor screening for puffed CD_4

Reference
Snowflake
Radiative divertor w/ CD_4
Snowflake+CD_4

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



Reference

Snowflake

Radiative divertor w/ CD_4

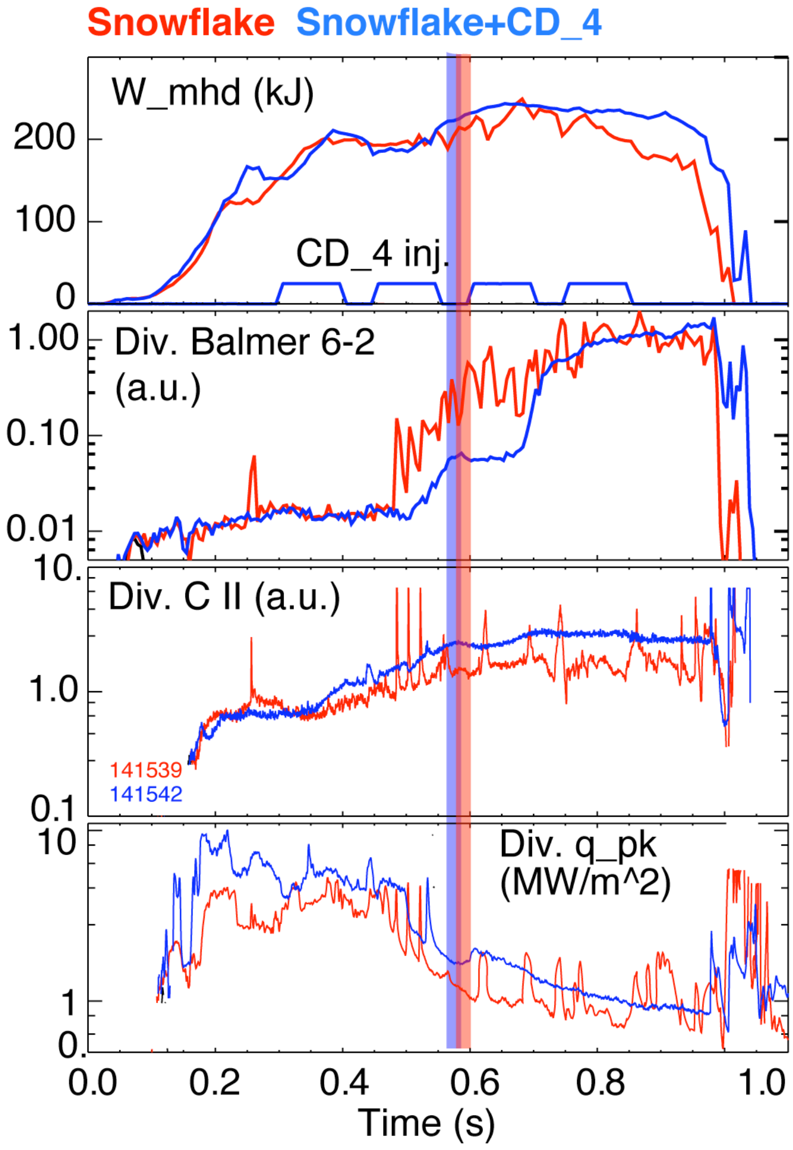
Snowflake+CD_4

Snowflake divertor with CD$_4$ seeding leads to increased divertor carbon radiation

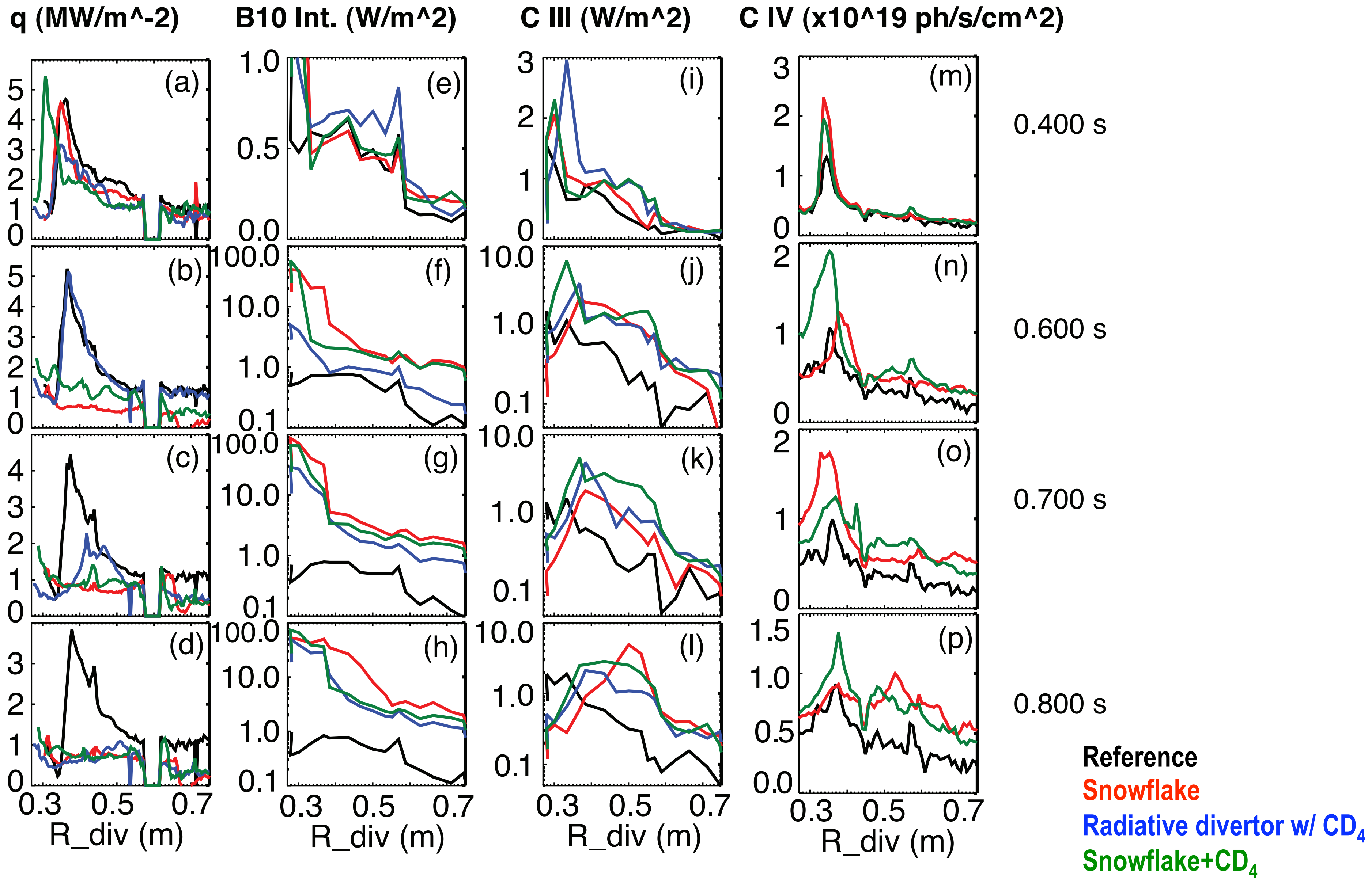
- I_p=0.9 MA, P_{NBI}=4 MW, P_{SOL}=3 MW

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



q (MW/m^-2)

B10 Int. (W/m^2)

C III (W/m^2)

C IV (x10^19 ph/s/cm^2)

0.400 s

0.600 s

0.700 s

0.800 s

Reference

Snowflake

Radiative divertor w/ CD_4

Snowflake+CD_4

Summary of divertor profiles

- Divertor heat flux
  - In snowflake divertor, flat ~ 1-2 MW/m^2 profiles due to geometry and radiative heating
  - In radiative divertor, peak reduction in strike point region only

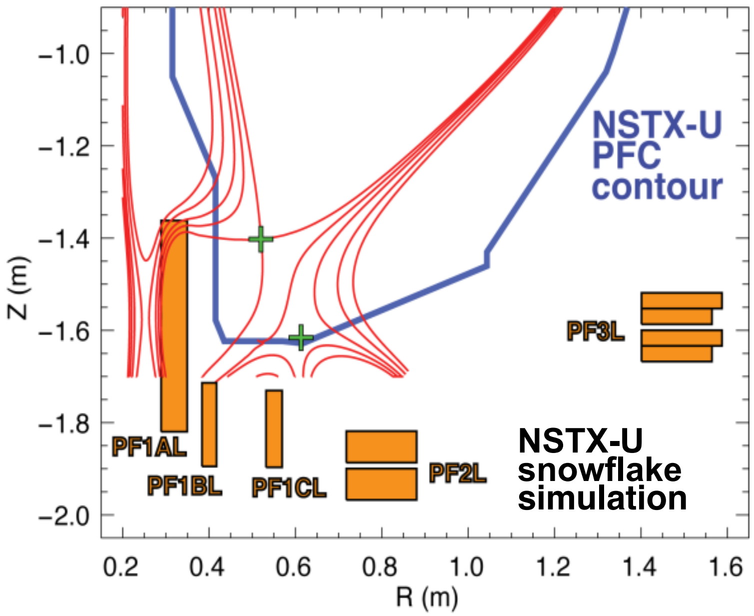
- Volumetric recombination
  - Large ion sink in both radiative and snowflake discharges
  - Larger in snowflake due to higher Lx (higher ion residence time)
    - ✓ Ion recombination time: τ_{ion}~ 1−10 ms at T_e =1.3 eV
    - ✓ Ion residence time: $\tau_{ion} \leq$ 3-6 ms in standard divertor, x 2 in snowflake

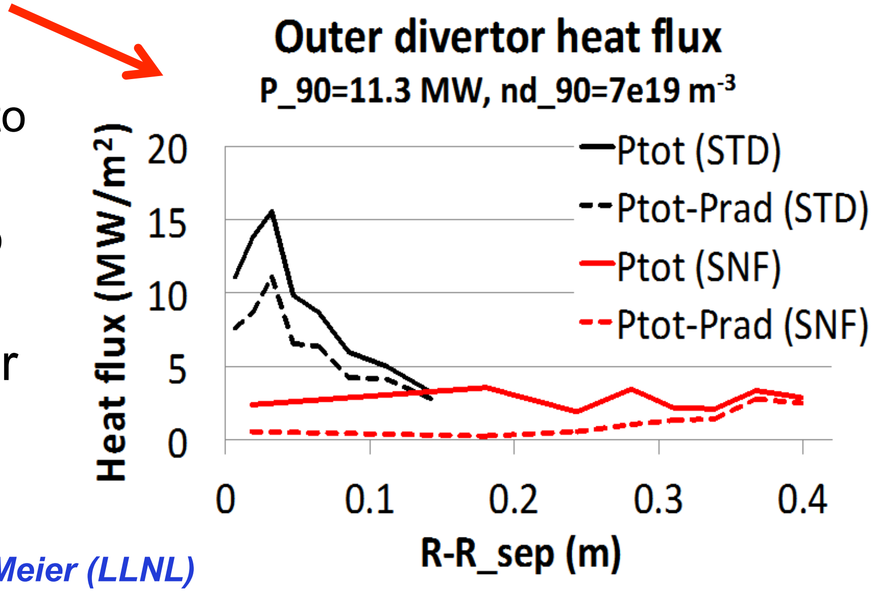
- Divertor carbon radiation
  - C III and C IV are main radiators
  - Both C III and C IV radiation enhanced in snowflake geometry due to low T_e and larger volume

Reference
Snowflake
Radiative divertor w/ CD$_4$
Snowflake+CD$_4$

Impurity-seeded radiative divertor with feedback and snowflake geometry are the leading NSTX-U heat flux mitigation candidates

- NSTX-U scenarios with high I_p and P_{in} projected to challenge thermal limits of graphite divertor PFCs
- Single and double-null radiative divertors and upper-lower snowflake configurations considered
  - Supported by NSTX-U divertor coils and compatible with coil current limits
- Snowflake divertor projections to NSTX-U optimistic
  - UEDGE modeling shows radiative detachment of all snowflake cases with 3% carbon and up to P_{SOL}~11 MW
    - q_{peak} reduced from ~15 MW/m^2 (standard) to 0.5-3 MW/m^2 (snowflake)
- Snowflake divertor with impurity seeding for P_{SOL} ~ 20 MW under study





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