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Snowflake Divertor Configuration Studies in DIII-D Tokamak.

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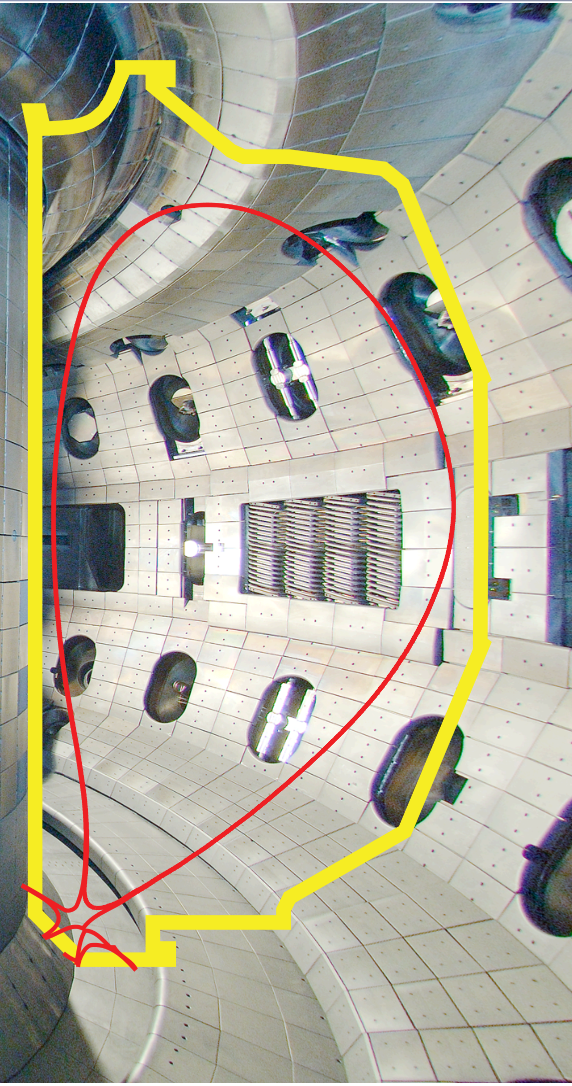

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DIII-D NATIONAL FUSION FACILITY

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Lawrence Livermore National Laboratory

Abstract

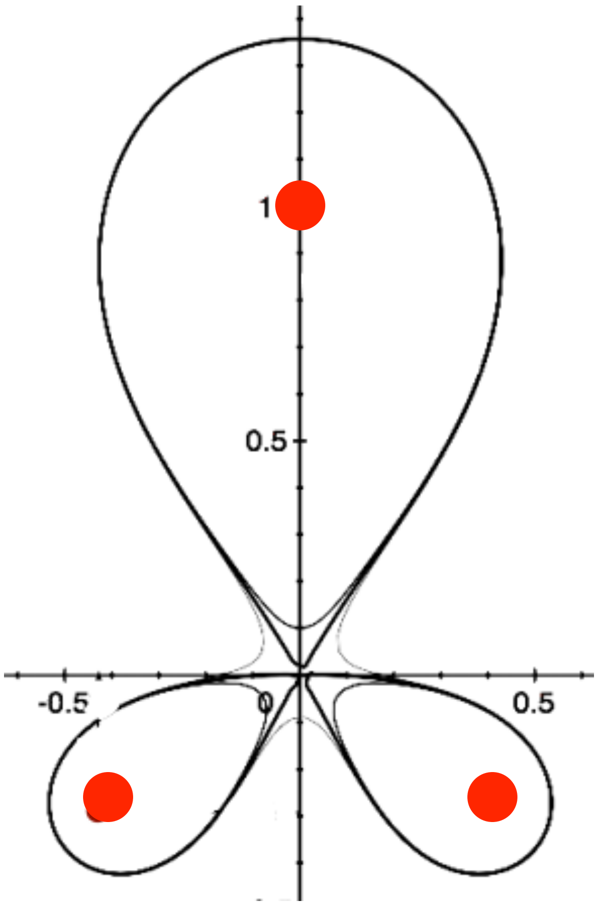
Recent DIII-D studies show the snowflake (SF) divertor enables significant manipulation of divertor heat transport for power spreading in attached and radiative divertor conditions, between and during edge localized modes (ELMs), while maintaining good H-mode confinement.
Results include: 1) Enhanced heat transport through the low poloidal field null-point region and divertor legs resulting in increased scrape-off layer (SOL) width;
2) Weak effect of the SF on pedestal profile and stability, and a reduction of Type-I ELM energy loss;
3) In radiative SF divertor regimes with D_2 seeding, a significant reduction of peak heat fluxes between and during ELMs compatible with H-mode;
4) Direct measurements of divertor null-region poloidal beta β_p>>1 in support of the theoretically proposed instability mechanism leading to fast convective heat redistribution between strike points, especially efficient during ELMs.
Work supported by the US Department of Energy under DE-AC52-07NA27344, DE-AC02-09CH11466, DE-FC02-04ER54698, and DE-AC04-94AL85000.

Outline and summary

- **Comparisons between snowflake and standard divertor encouraging**
  - Compatibility with good core and pedestal performance
  - Confirmed geometry properties A_{wet} and $L_{||}$
  - Initial confirmation of enhanced SOL transport
- **Broader divertor radiation distribution**
- **Reduced inter-ELM peak heat flux q_{peak}**
- **Reduced ELM energy, T_{peak} and q_{peak}**

Legend in this poster
Standard
Snowflake

Snowflake divertor configuration is studied in DIII-D as a tokamak divertor power exhaust concept

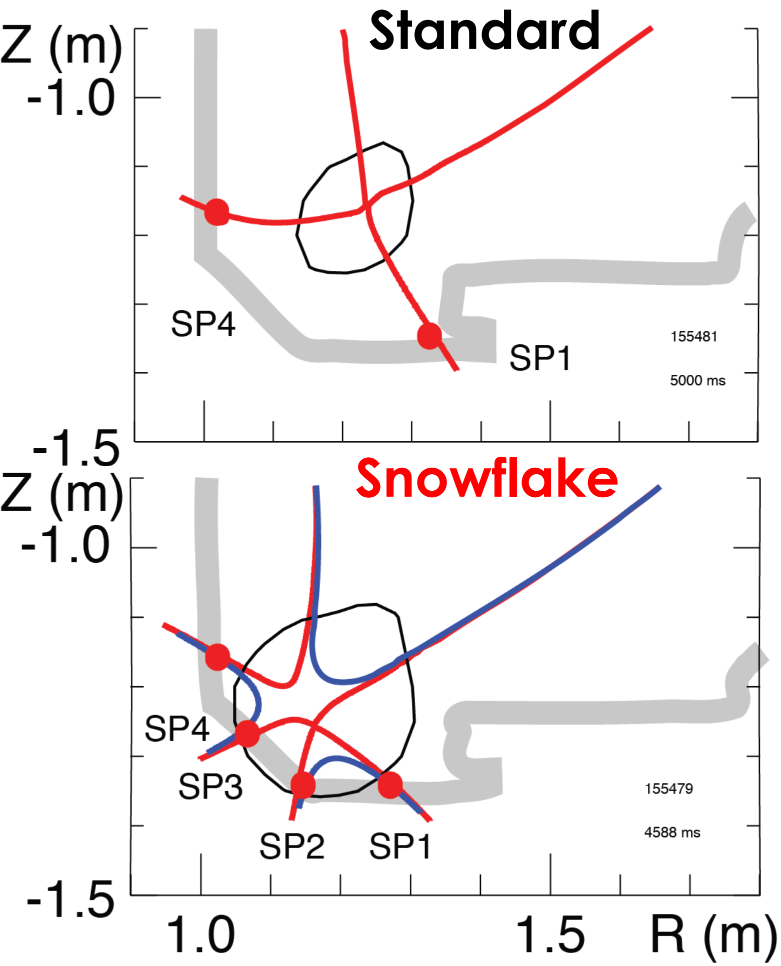


D. D. Ryutov, PoP 14, 064502 2007; PPCF 54, 124050 (2012)

$$q_{peak} = \frac{P_{div}}{A_{wet}} = \frac{P_{SOL}(1 - f_{rad}) f_{geo}}{2\pi R_{SP} f_{exp} \lambda_q}$$

- **Divertor power exhaust challenge**
  - Steady-state heat flux
    - Present limit $q_{peak} \leq$ 5-15 MW/m^2
    - DEMO: P_{SOL} ~150 MW, $q_{peak} \leq$ 150 MW/m^2
    - Narrow SOL width λ_q
  - ELM energy, target peak temperature
    - Present limit 0.1-0.5 MJ/m^2
- **Snowflake divertor with 2nd-order null**
  - $B_p \sim 0$, *grad* $B_p \sim 0$ (Cf. first-order null: $B_p \sim 0$)
  - $B_p(r) \sim r^2$ (Cf. first-order null: $B_p \sim r$)
- **Experiments in TCV, NSTX, DIII-D, EAST**

Larger region of low B_p around second-order null in snowflake divertor is predicted to modify power exhaust



Low B_p region: shown 0.1 B_p/B_p^{mid}

- **Geometry properties**

  Criterion: $d_{XX} \lesssim a\,(\lambda_q/a)^{1/3}$

  – Higher edge magnetic shear
  – Larger plasma wetted-area A_{wet} (f_{exp})
  – Larger parallel connection length $L_{||}$
  – Larger effective divertor volume V_{div}

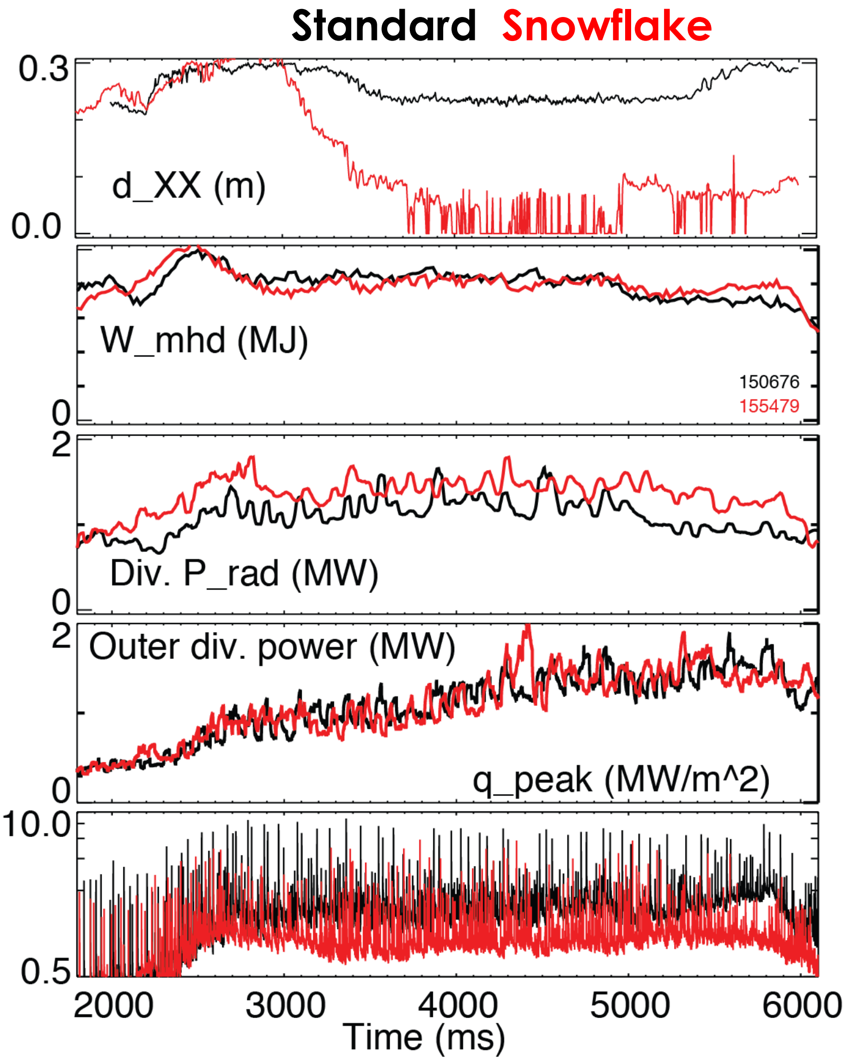
"Laboratory for divertor physics"

- **Transport properties**

  Criterion: $d_{XX} \lesssim D^{*} \sim a\,(a\,\beta_{pm}/R)^{1/3}$

  – High convection zone with radius D*
  – Power sharing over four strike points
  – Enhanced radial transport (larger λ_q)

Increased plasma-wetted area and connection length leads to q_{peak} reduction in snowflake divertor

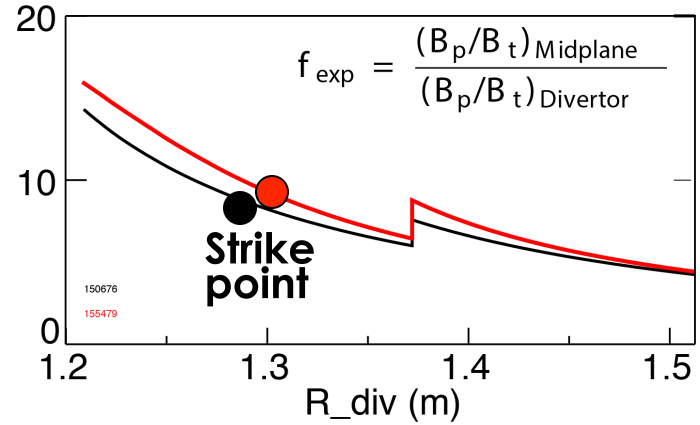


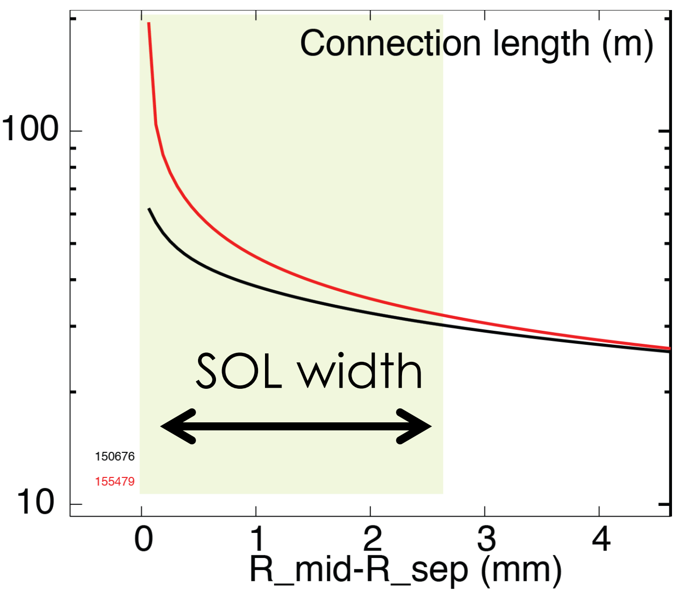
- **1.2 MA, 4-5 MW NBI H-mode**
  - Similar n_e, slightly higher div. P_{rad}
- **Snowflake with d_{XX} < 10 cm**
- **Similar P_{div}**
- **Inner divertor receives little power**
- **In outer divertor, q_{peak} reduced by 30%**

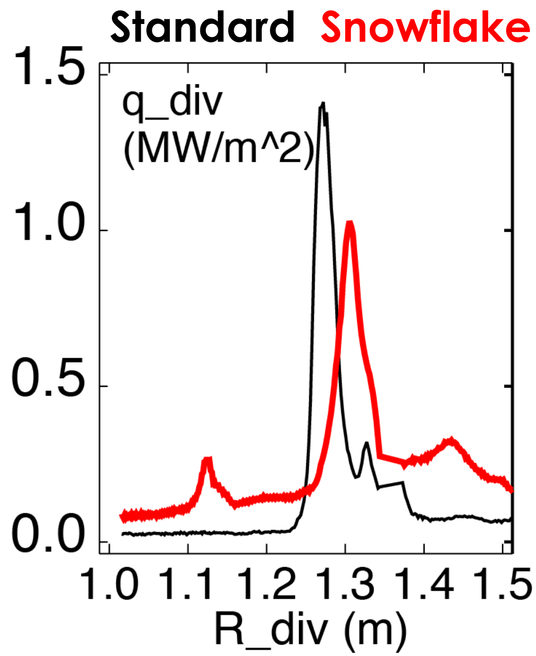
$$A_{wet} = 2\pi R \, f_{exp} \, \lambda_{q_{||}}$$

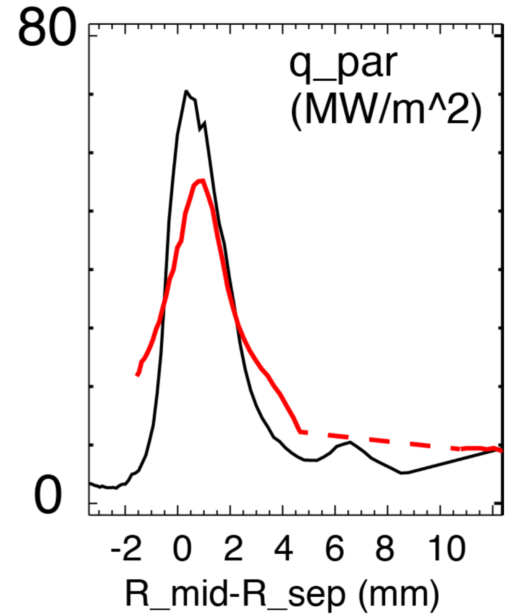
$$f_{exp} = \frac{(B_p/B_t)_{Midplane}}{(B_p/B_t)_{Divertor}}$$

q_{peak} reduction in snowflake divertor (cf standard divertor) partly due to increased f_{exp} and $L_{||}$







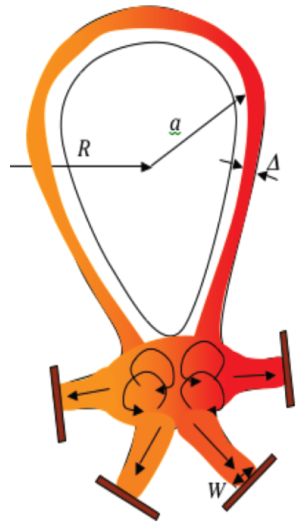


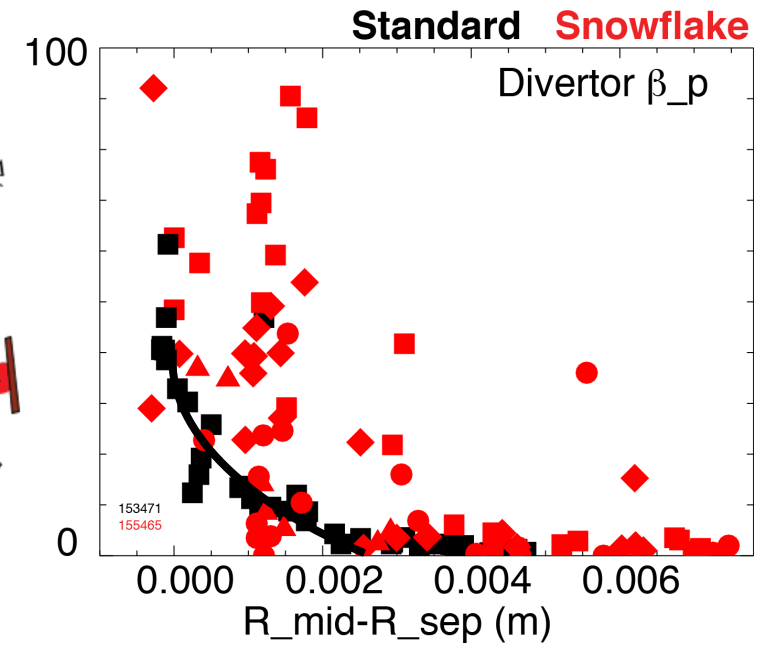
- **Flux expansion increased ~20%**
  - Depends on configuration, can be up to X3
- **$L_{||}$ increased by 20-60% over SOL width**
- **Divertor heat flux reduced ~30%**
- **Parallel heat flux reduced ~20%**

Convective plasma mixing driven by null-region instabilities may modify particle and heat transport

- **Flute-like, ballooning and electrostatic modes are predicted in the low B_p region**
  - $\beta_p = P_k/P_m = 8\pi\, P_k/B_p^2 \gg 1$
  - Loss of poloidal equilibrium
  - Fast convective plasma redistribution
  - Especially efficient during ELMs when P_k is large
- **Estimated size of convective zone**
  - Snowflake: 6-8 cm
  - Standard: 1cm

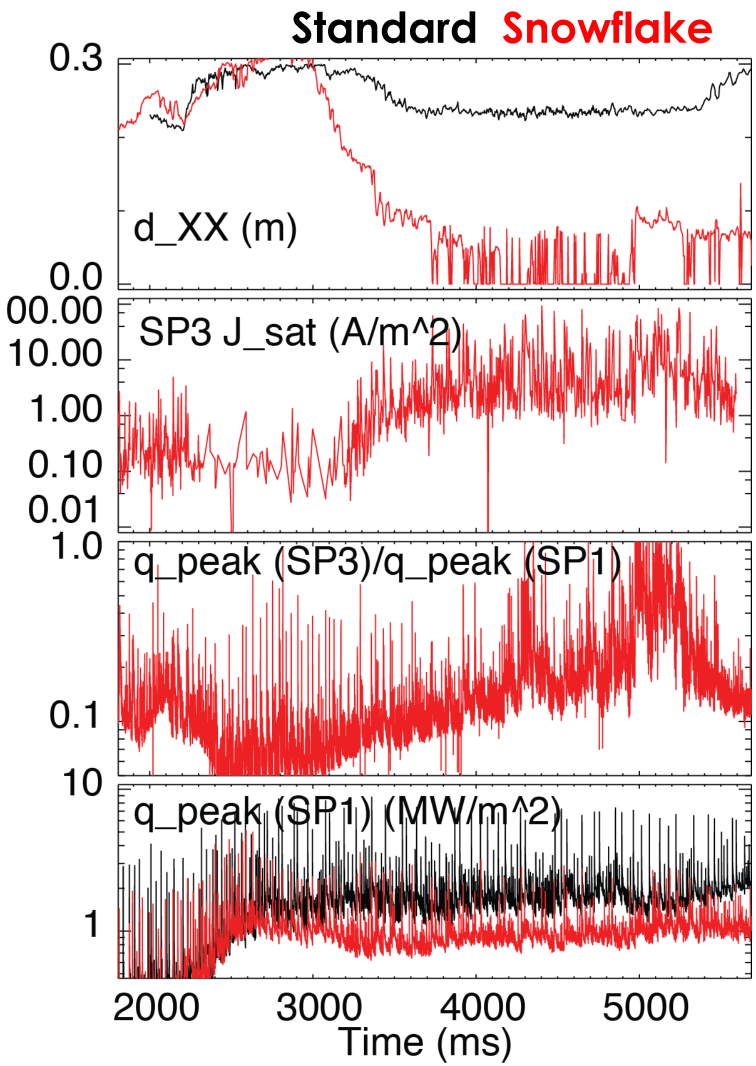
D. D. Ryutov et. al, IAEA 2012; Phys. Scripta 89 (2014) 088002.

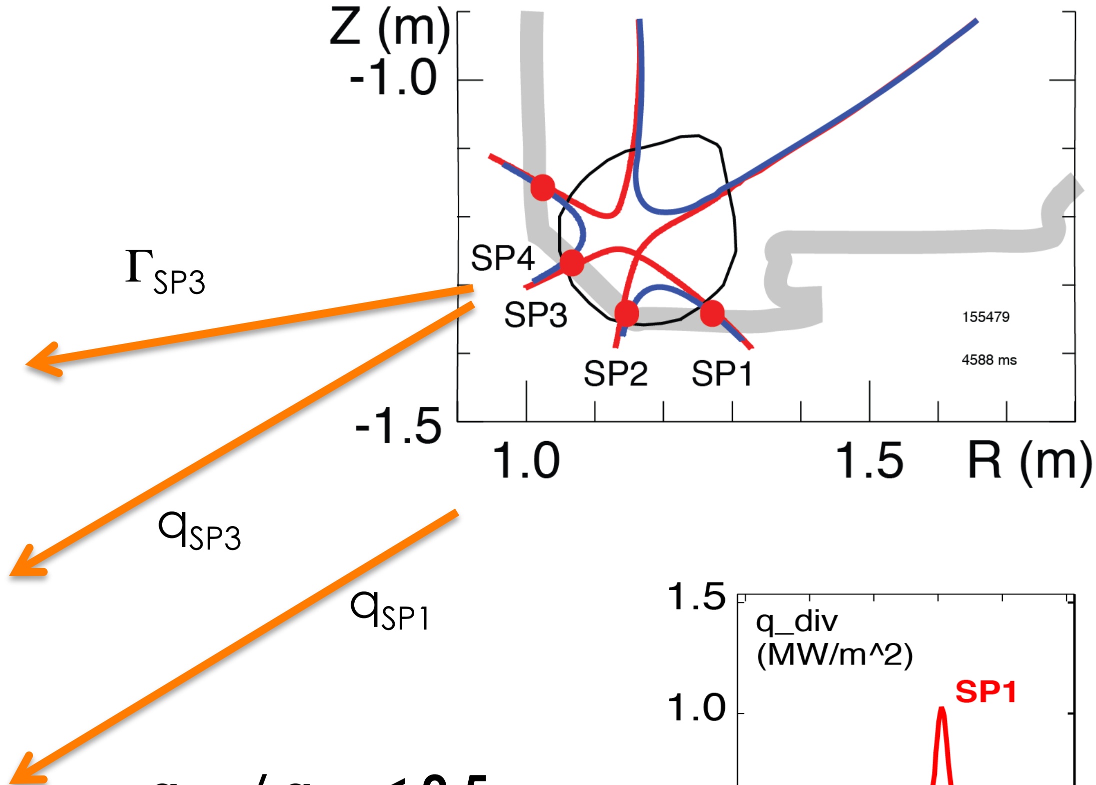




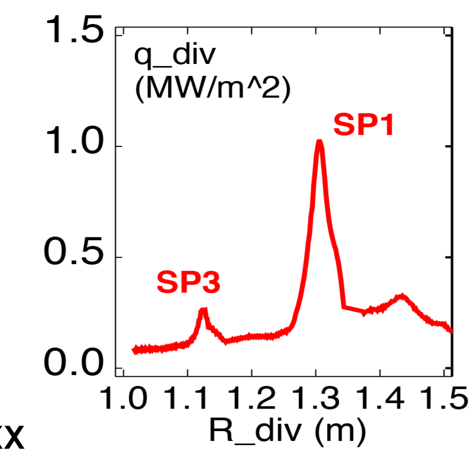
- **Divertor null-region β_p measured in DIII-D divertor**
  - In snowflake, broader region of higher $\beta_p \gg 1$
  - Cf. SOL $\beta_p \sim 0.01$
  - Higher X10 during ELMs

Heat and particle fluxes shared among strike points in snowlfake divertor

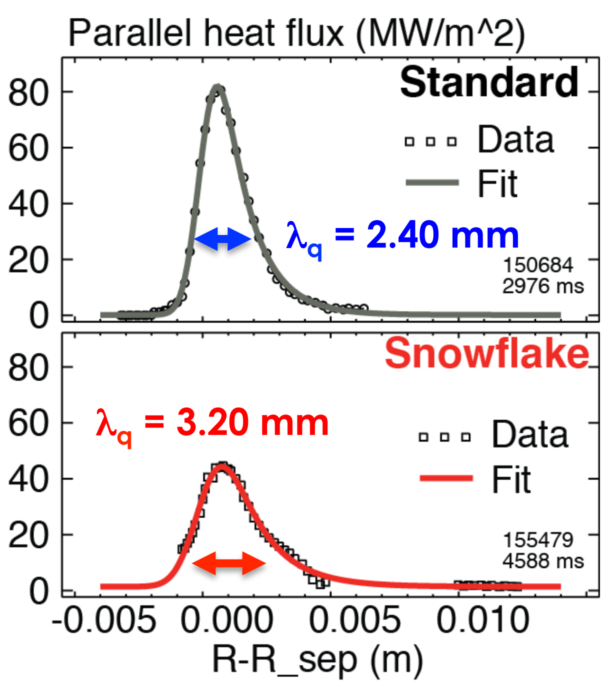


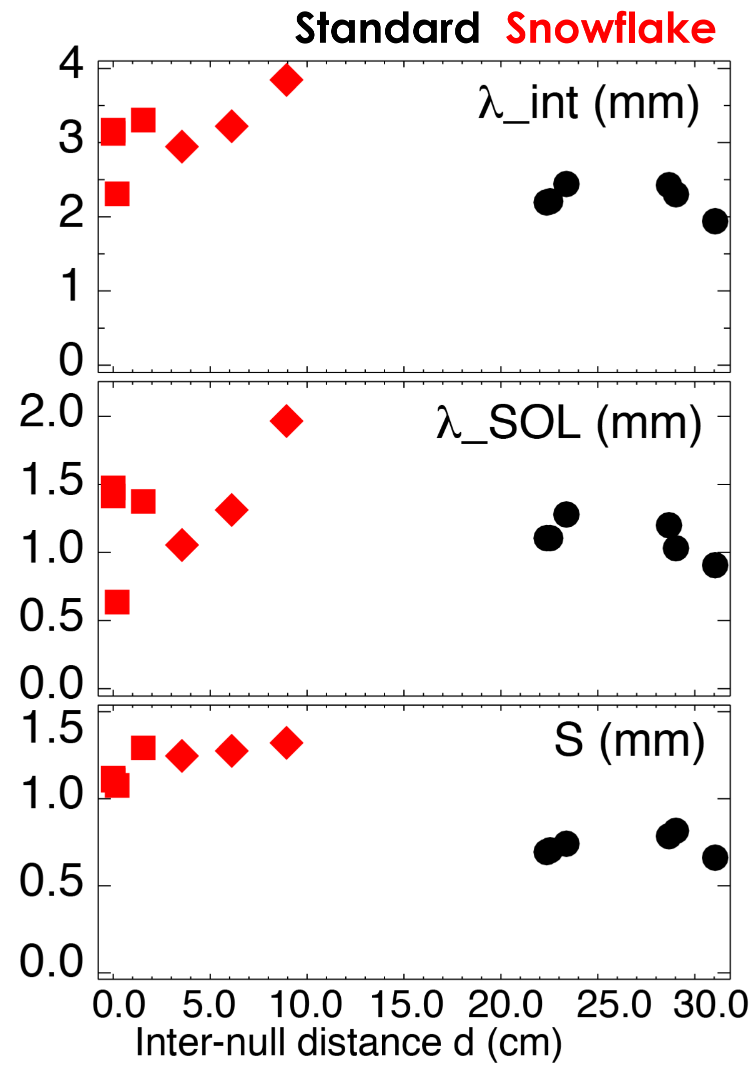


- q_{SP3} / q_{SP1} < 0.5
- P_{SP3} / P_{SP1} < 0.3
- **Sharing fraction maximized at low d_{XX}**



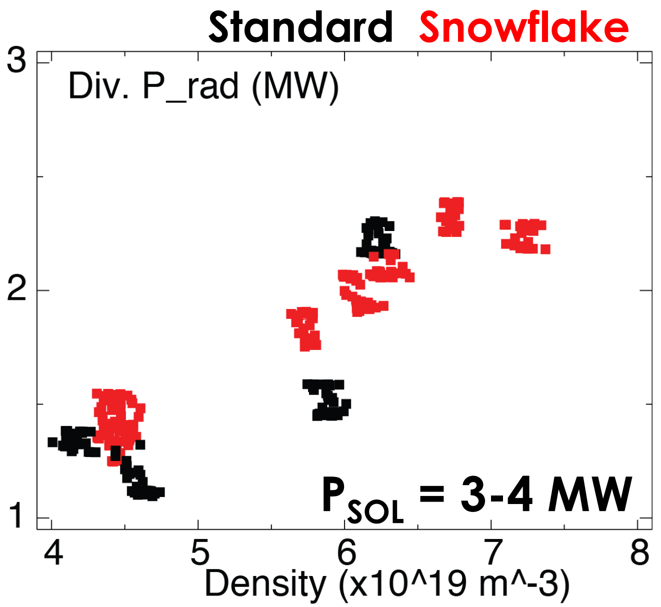
Broader $q_{||}$ profiles in snowflake divertor may imply increased radial transport

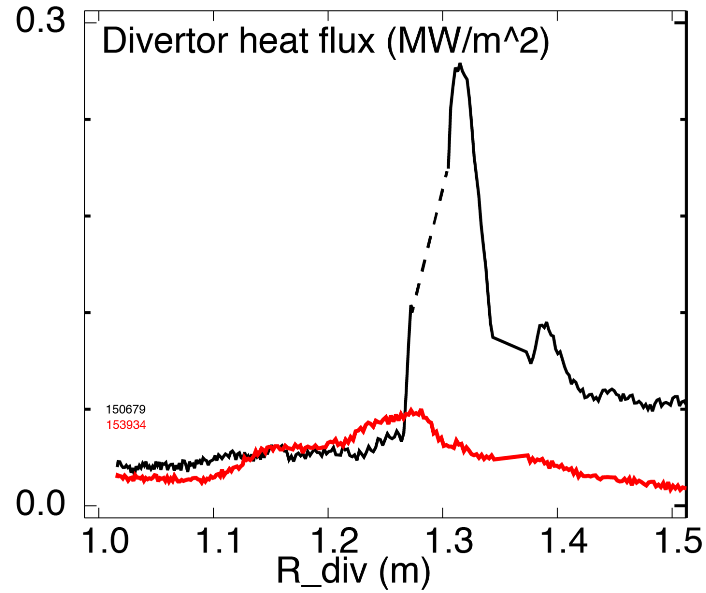


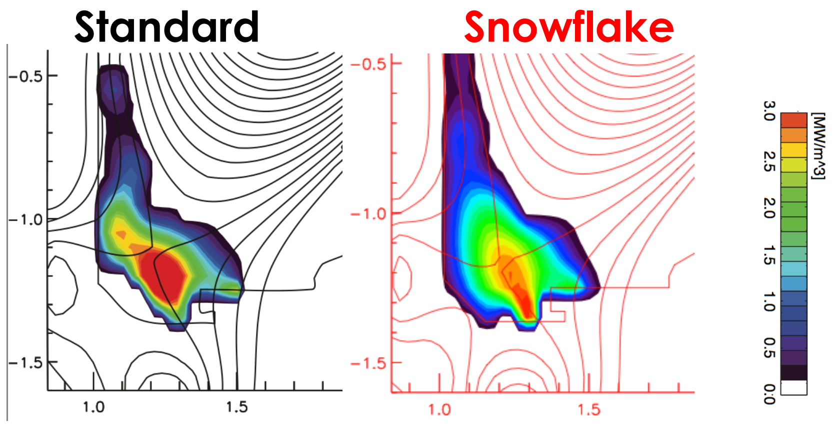


- **Fit $q_{||}$ profile with Gaussian (S) and Expon. (λ_{SOL}) functions** (Eich PRL 107 (2011) 215001)
- **Neglect dissipative losses in null region**
- **Increased λ_q may imply increased transport**
  - Increased radial spreading due to $L_{||}$
  - SOL transport affected by null-region mixing

Divertor radiation broader distributed in snowflake divertor (cf. standard divertor), q_{peak} reduced by X5

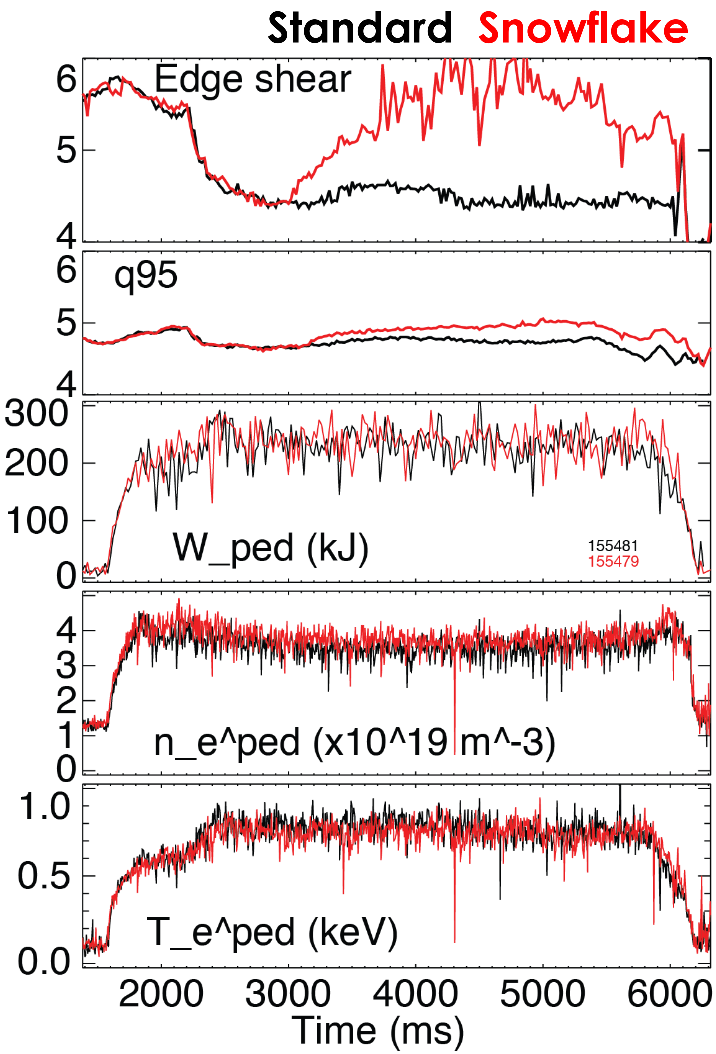






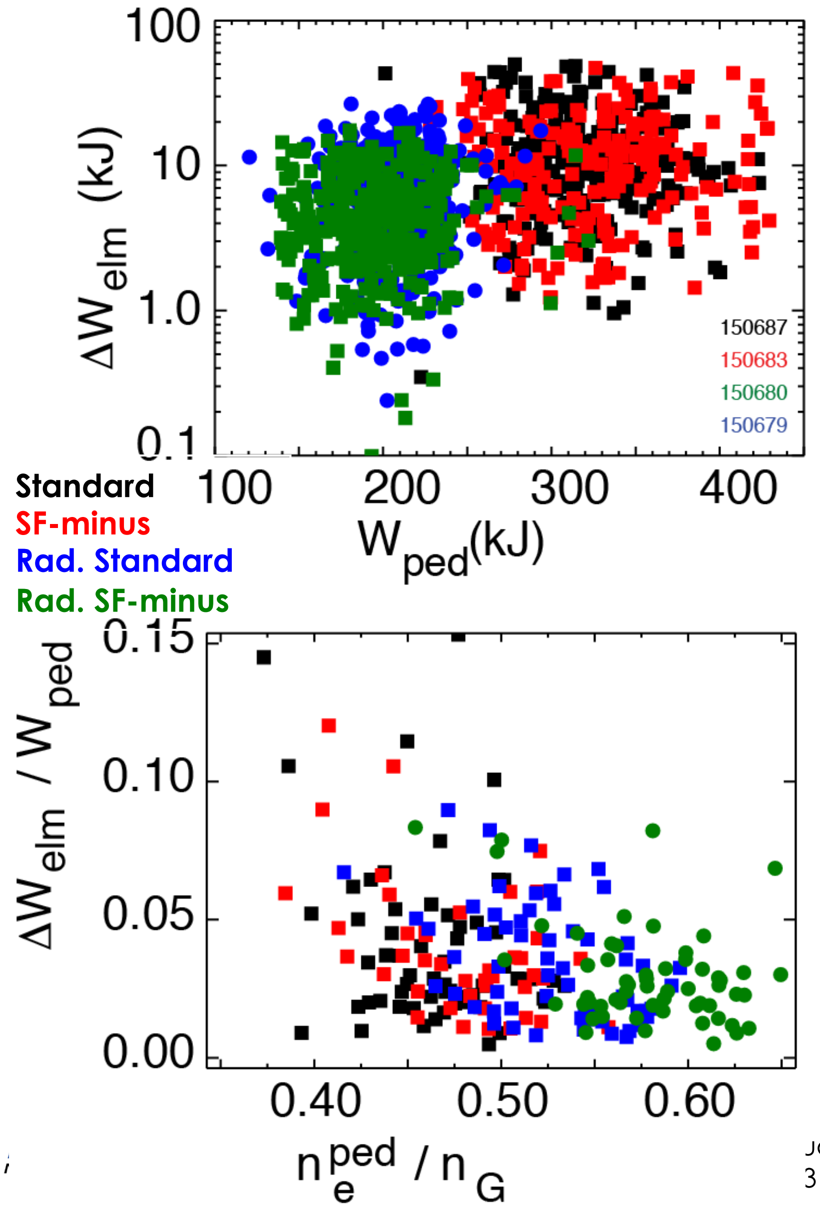
- **Radiative divertor at higher n_e**
- **Divertor carbon and deuterium radiation, $P_{rad} \lesssim 0.6\ P_{in}$**
- **In radiative snowflake (cf. standard radiative) nearly complete power detachment at P_{SOL}~3 MW**
- **V_{div}~L_{II}**

SF divertor weakly affected pedestal magnetic and kinetic characteristics, peeling-balooning stability in DIII-D



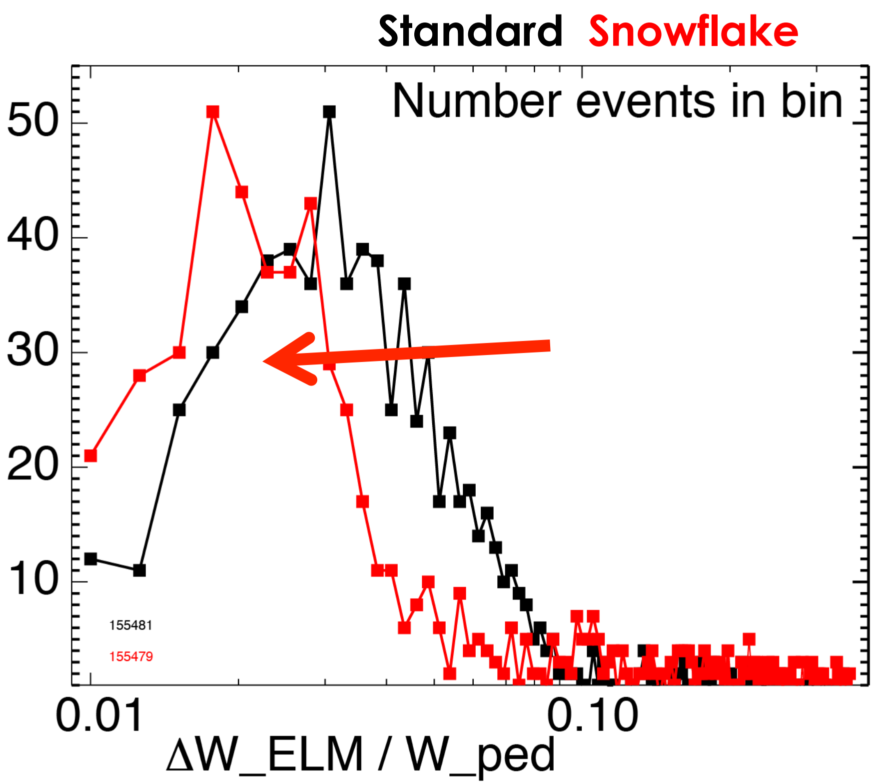
- **At lower n_e, in H-modes with snowflake divertor (cf. standard divertor)**
  - Similar P_{ped}, W_{ped}
  - H98(y,2)~1.0-1.2, β_N~2
  - Plasma profiles weakly affected
- **Peeling-ballooning stability unaffected**
  - Shear95, q95 increased by up to 30%
  - Medium-size type I ELMs
  - ELM frequency weakly reduced
  - ELM size weakly reduced

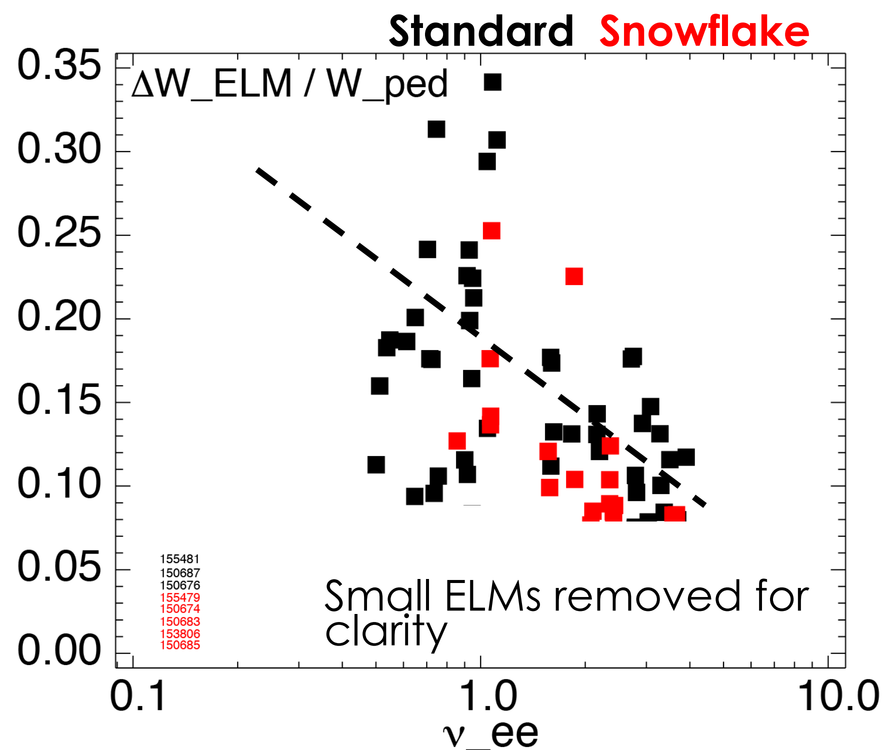
SF divertor compatible with pedestal, leads to ELM energy reduction, radiative SF needs optimization



- **At lower n_e**
  - **Confinement unaffected by SF**
  - H98(y,2)~1.0-1.2, β_N~2
  - Similar P_{ped}, W_{ped}
  - Kinetic profiles weakly affected
- **Shear95, q95 increased in SF by up to 20-30%**
- **ELM frequency weakly affected**
- **ΔW_{ELM} reduced 5-15 %, in some discharges by up to 30 %**
  - Loarte's ΔW_{ELM} scaling with ν_{ee}
    - Increased $\nu^*_{ped}=\pi R q_{95}/\lambda_{ee}$
    - Increased $\tau^{ELM}=2\pi R q_{95}/c_{s,ped}$
- **Add'l reduction in ΔW_{ELM} in radiative SF**
  - Needs optimization as W_{ped} reduced

ELM power loss scales with collisionality, reduced in H-modes with snowflake divertor (cf. standard divertor)

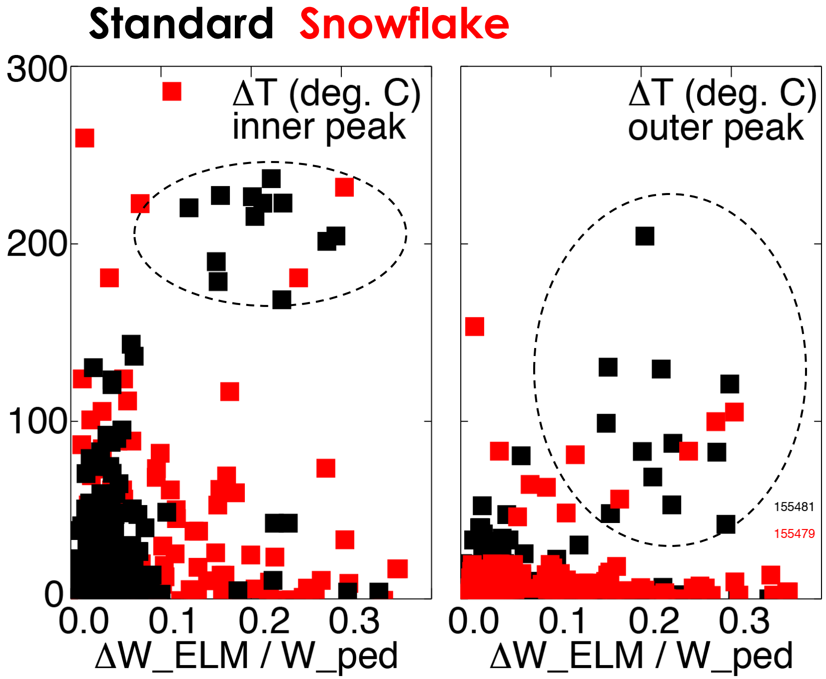


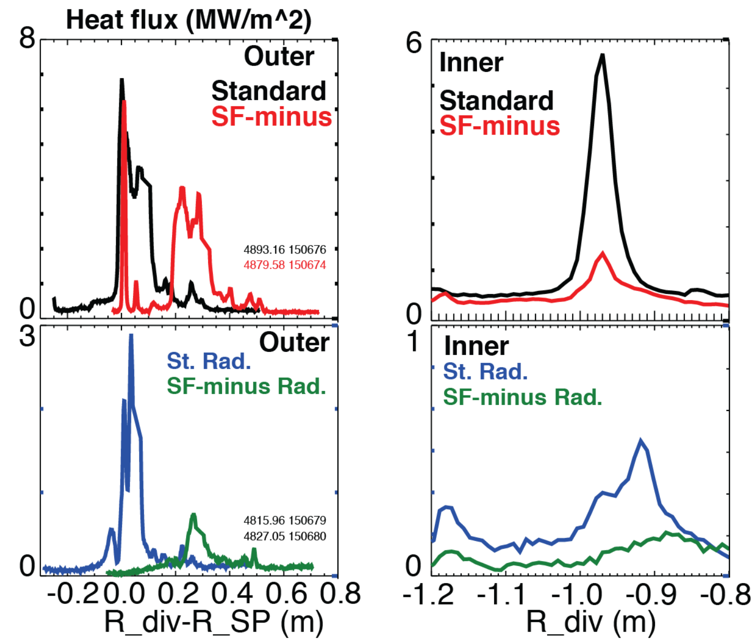


- Both ΔW_{ELM} and $\Delta W_{ELM}/W_{ped}$ weakly reduced
- Mostly for $\Delta W_{ELM}/W_{ped} < 0.10$

- Increased collisionality with snowflake $\nu^*_{ped}=\pi R q_{95}/\lambda_{ee}$

Peak ELM target temperature and ELM heat flux reduced in snowflake divertor



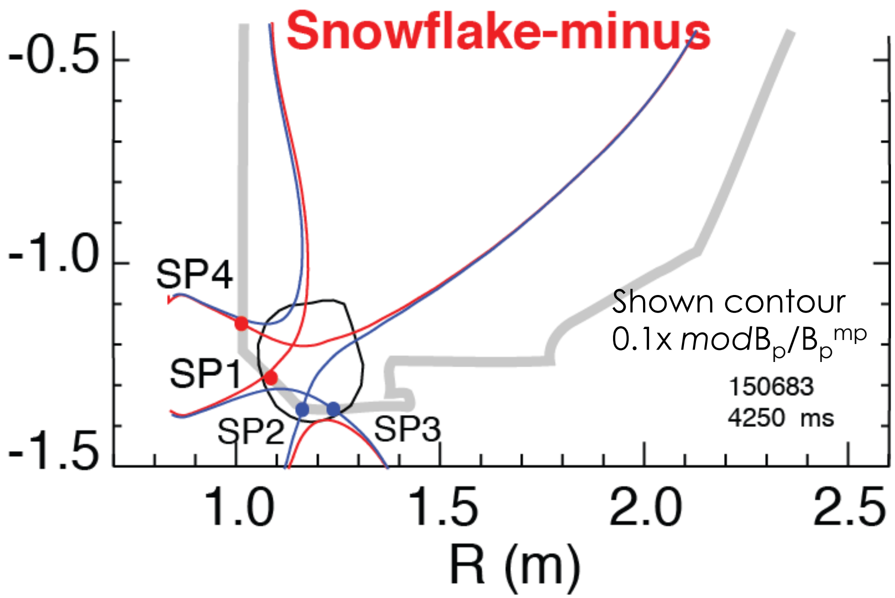


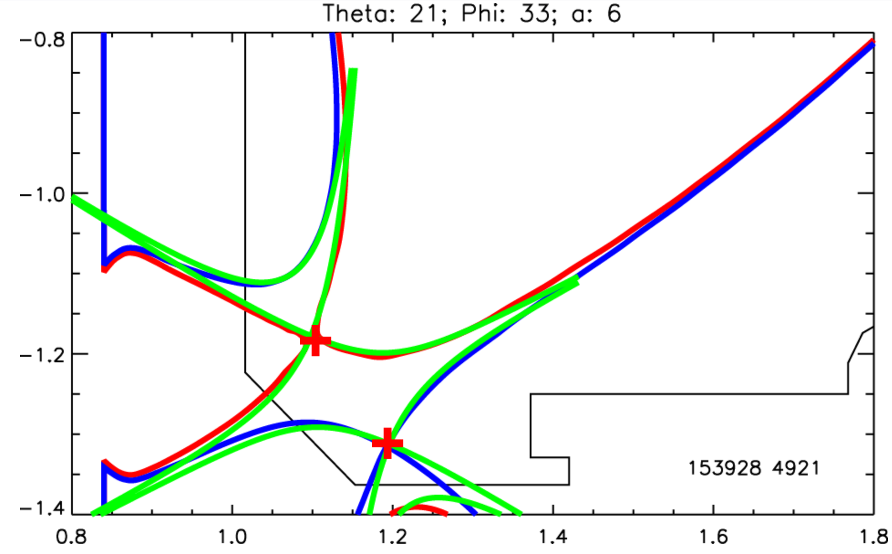
- **In snowflake divertor**
  - $\Delta T_{surf} \sim E_{ELM}/(A_{wet}\,\tau_{ELM})^{1/2}$
  - Increased $\tau_{ELM}=L_{II}/c_{s,ped}$
  - Weakly reduced E_{ELM}
  - A_{wet}^{ELM} similar

- Type I ELM power deposition correlates with τ_{ELM}
- In radiative snowflake, ELM peak heat flux reduced by 50-75 %
- Similar effect in NSTX

S. L. Allen et. al., IAEA 2012

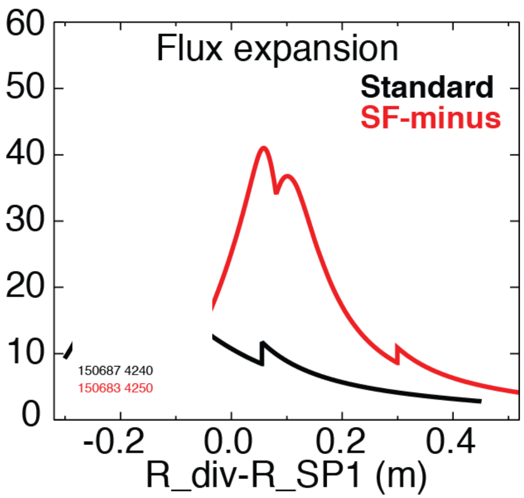
Snowflake-minus connects outer SOL to two strike points

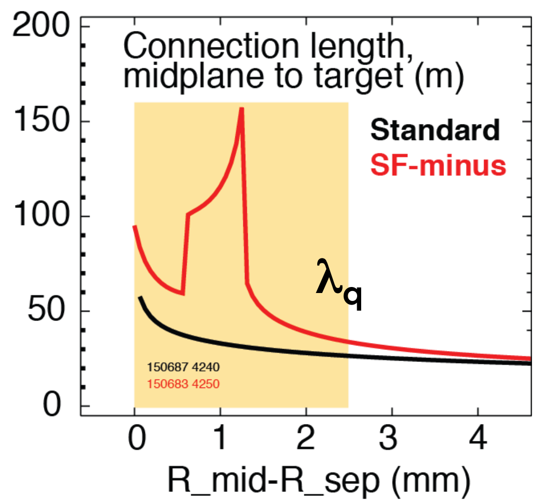


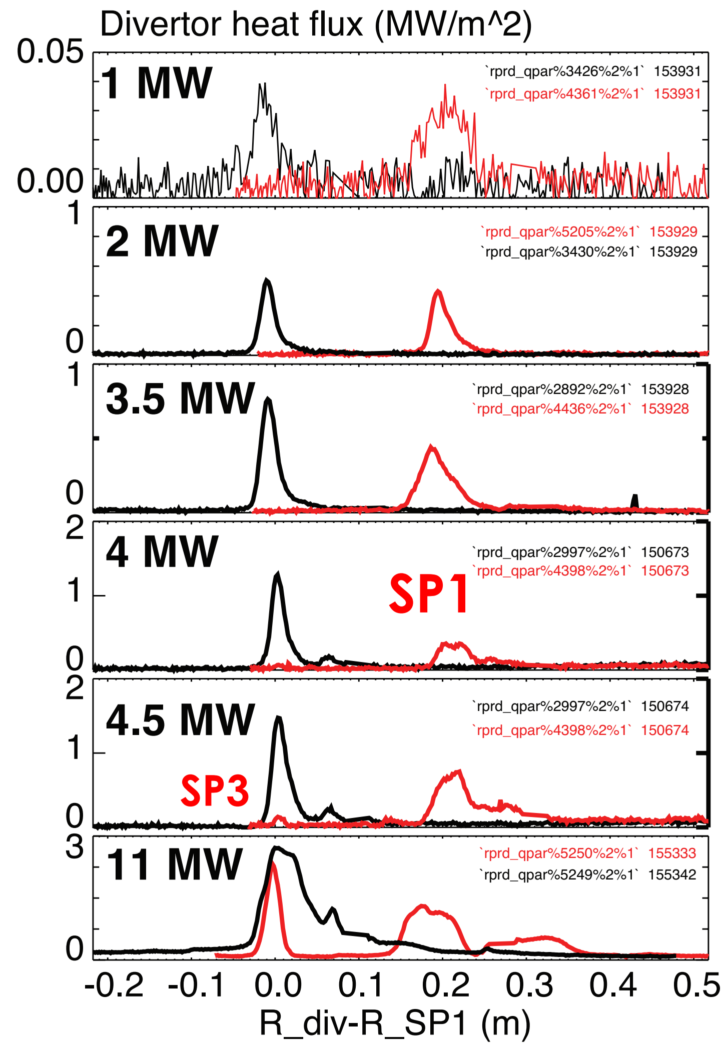


- **Acceptable deviation from exact snowflake $d_{SF} \leq a\,(\lambda_q\,/a)^{1/3}$**
  - $d_{XX} \leq 0.11$ m in SF-minus, Cf. $d_{XX} = 0.25$-0.30 m in standard divertor
  - $\sigma = d_{xx}/a \leq 0.20$
- **Main outer SOL directly connected to SP3 and SP1**
- **EFIT poloidal flux surfaces overlay with analytic 2-null expansion (D. D. Ryutov et al., PPCF 52 (2010) 105001)**

Inter-ELM divertor heat flux significantly reduced due to snowflake geometry (A_{wet}, $L_{||}$ greater)

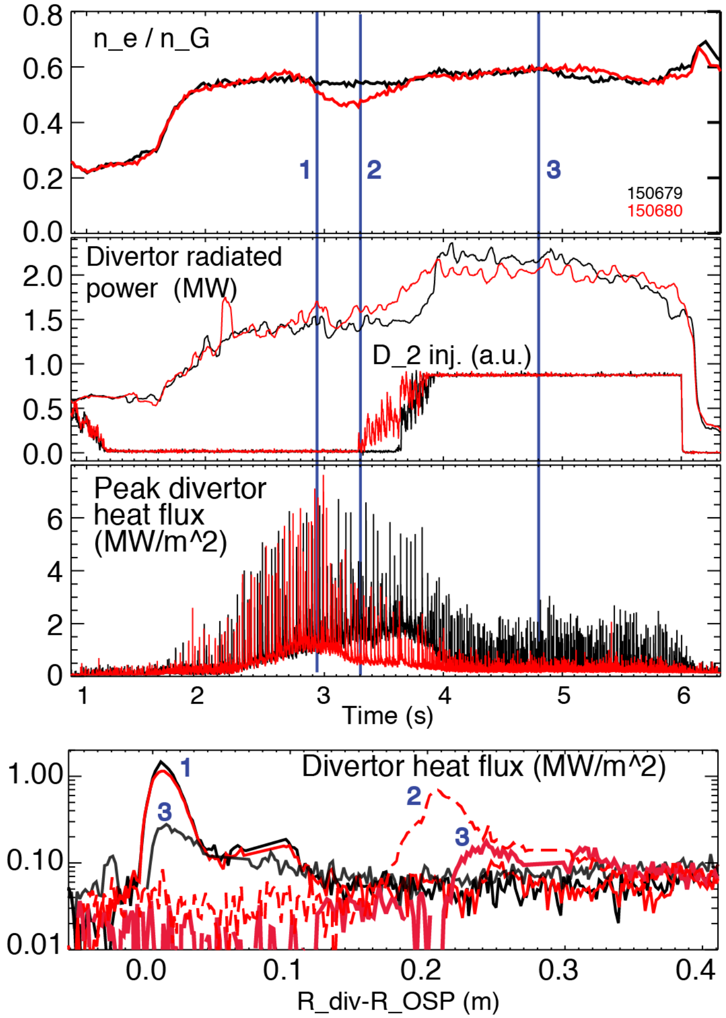






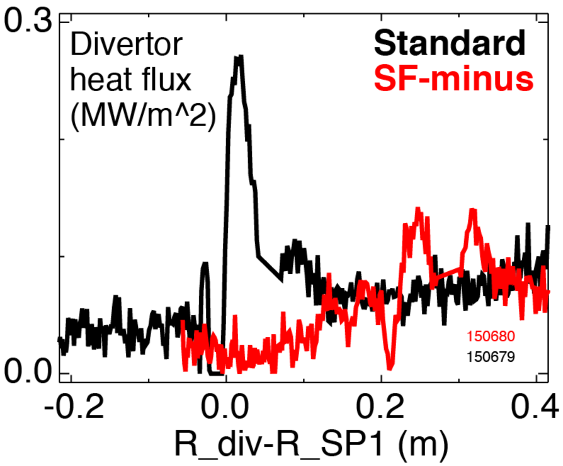
- **Poloidal flux expansion increase significantly for SP3 and less for SP1**
- **Connection length increased up to X3 for SP3 and less for SP1**
- **Peak heat flux reduced significantly in SP3 and less in SP1**

Additional inter-ELM q_{peak} reduction at higher n_e with D_2 seeding due to radiation in snowflake



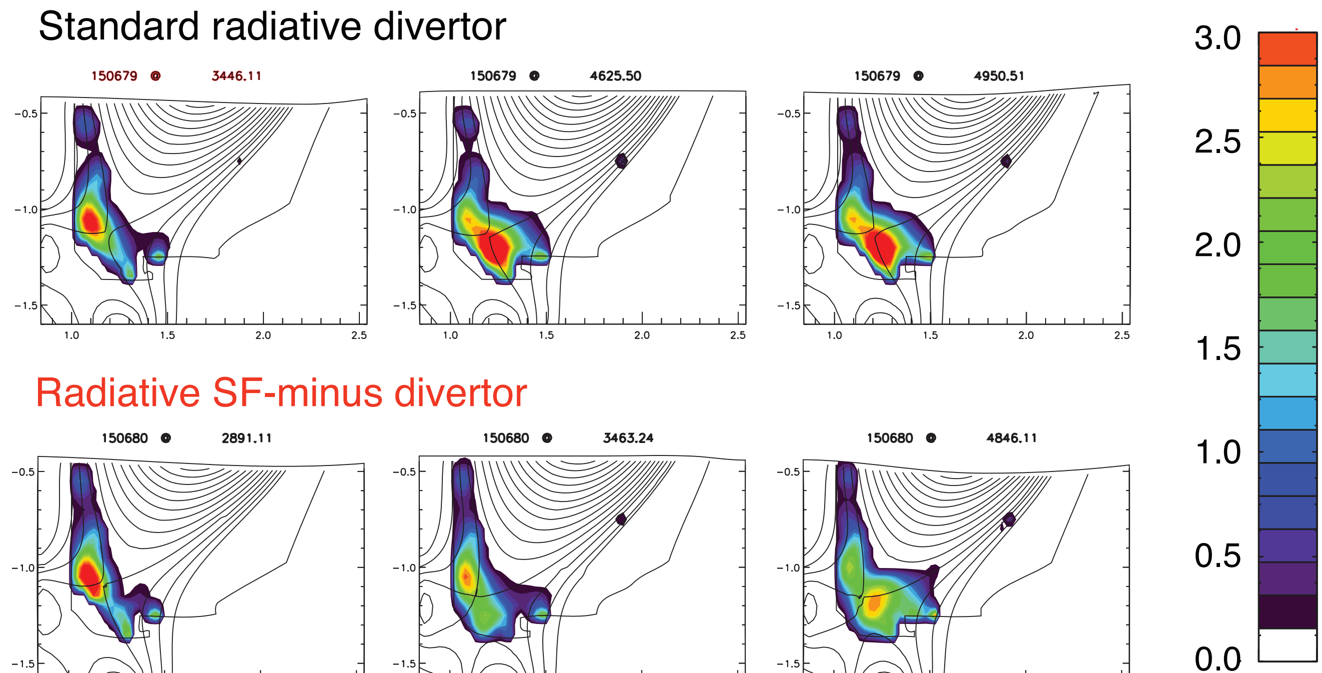
- In higher-density snowflake H-mode
  - D_2 puffing
  - Density n_e/n_G = 0.55-0.75
  - Peak heat flux is up to 50 % lower in partially detached snowflake vs partially detached standard divertor
  - Confinement degraded in standard radiative by 10-20 % and additional 10-20 % in radiative snowflake

Heat flux is further reduced in SF-minus with deuterium seeding, divertor radiation broadly distributed



- **Radiative SF-minus vs Standard Radiative**
  - Density at detachment n_e/n_G = 0.60-0.65
  - Radiative phase onset (n_e) similar
  - Lower divertor rad. power broadly distributed, rad. zone stabilized between nulls
  - Similar reduction in $q_{||}$

P_{NBI}=4 MW
$n_e \sim 6.5 \times 10^{19}$ m^{-3}
P_{SOL}~3.5 MW
P_{rad}(div)~2 MW



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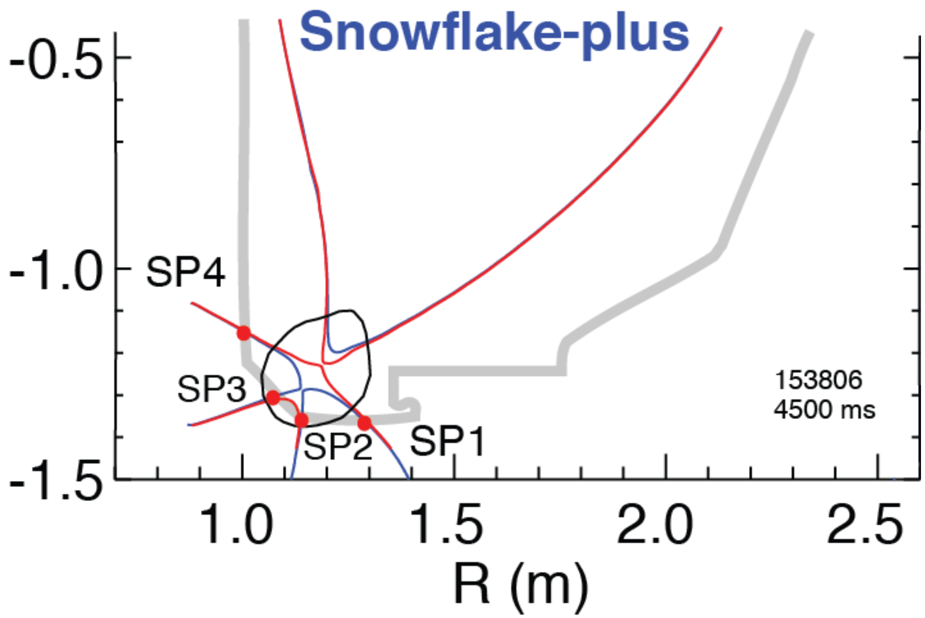
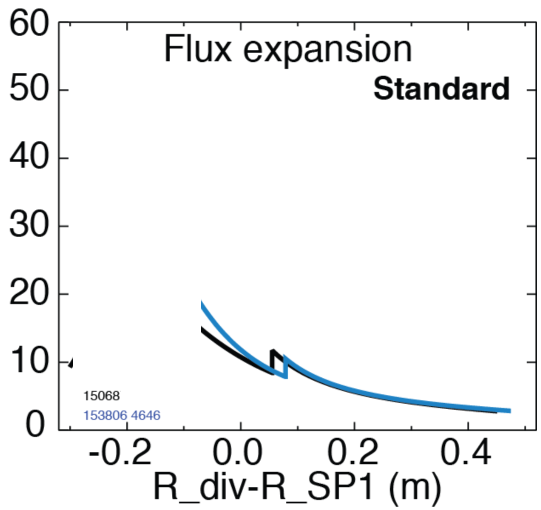
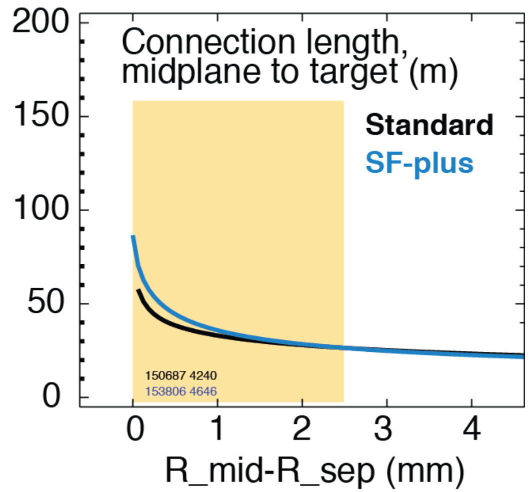
Snowflake-plus configuration

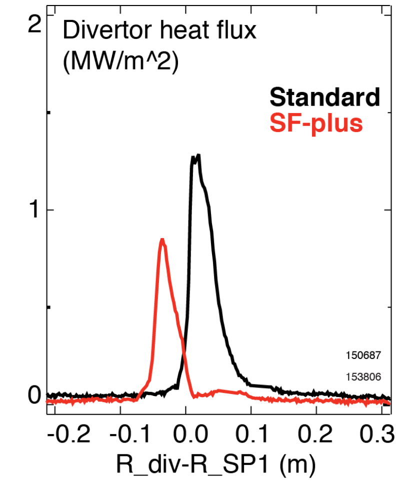


- **Acceptable deviation from exact snowflake $d_{SF} \leq a\,(\lambda_q\,/a)^{1/3}$**
  - $d_{XX} \leq$ 0.1 m in SF-plus
  - Cf. d_{XX}= 0.25-0.30 m in standard divertor
- **Additional strike points not connected to main SOL**

Inter-ELM divertor heat flux significantly reduced due to snowflake-plus geometry (A_{wet}, $L_{||}$ greater)

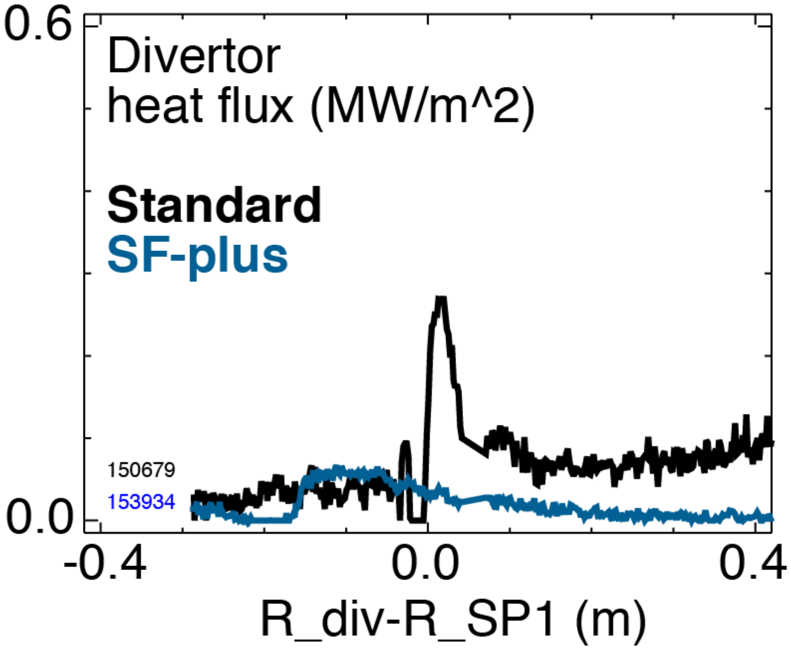


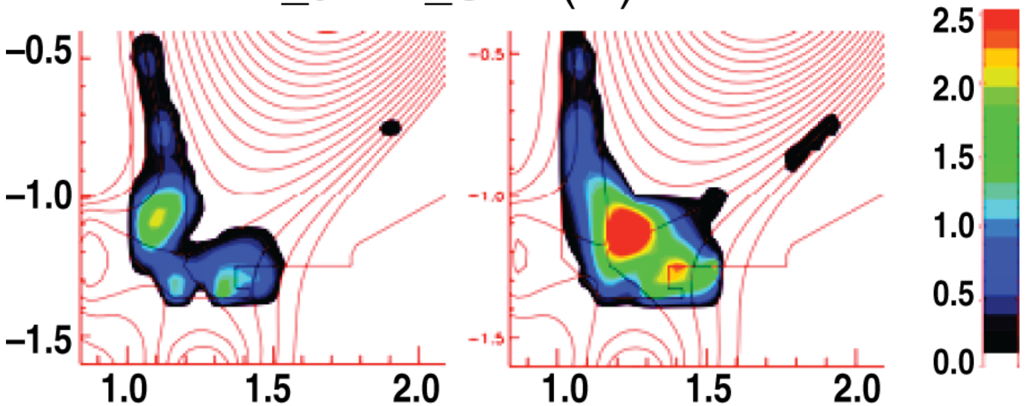




- **Poloidal flux expansion increase modestly**
  - Plasma-wetted area $A_{wet}=2\pi R f_{exp} \lambda_q$
- **Connection length increased up to X2**
  - Only in the first 30% of SOL
- **Peak heat flux reduced**

In radiative SF-plus, increased dissipation of heat flux (cf. standard radiative divertor)



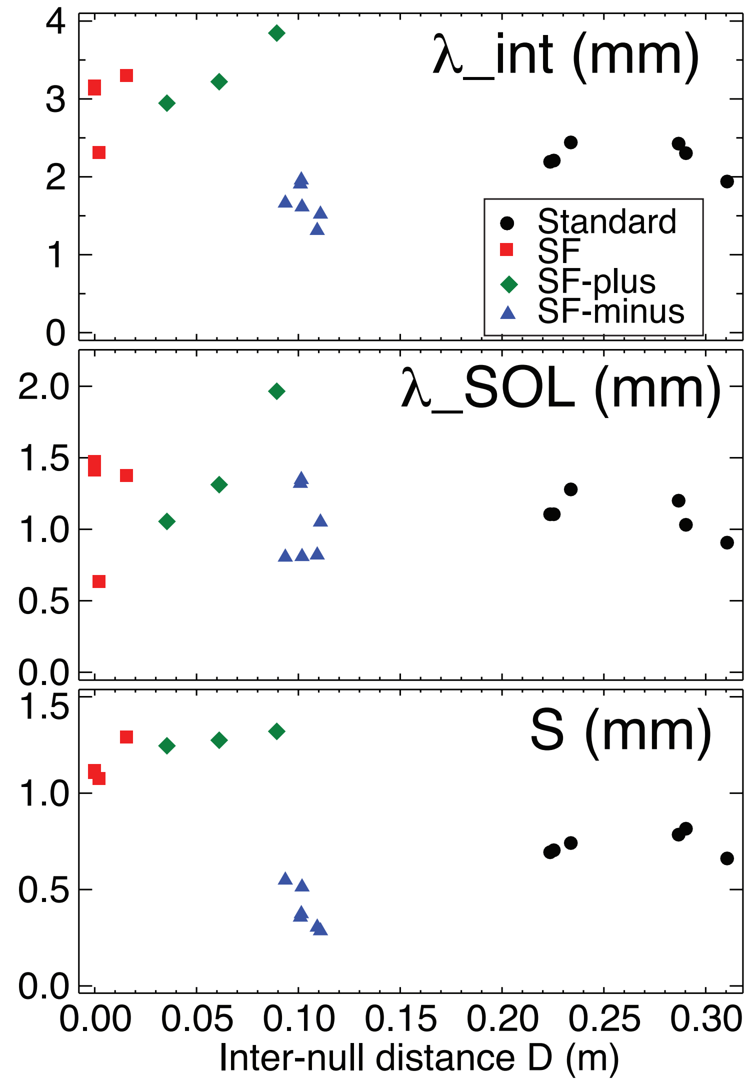


- **In SF-plus, near complete power detachment**
- **q_{peak} reduction much greater than A_{wet} increase**
- **Radiation front moves along legs and stabilizes between null points**

P_{NBI}=4 MW
n_e ~ 6-7 x 10^{19} m^{-3}
P_{SOL}~3.5 MW
P_{rad}(div)~2 MW

SOL width scales differently in the snowflake-plus and snowflake-minus divertor configurations

- SF-minus
  - the secondary null separates the SOL into two manifolds
  - λ_{SP1} reduced
  - In SP3, little heat, Gaussian profile
- SF-plus (and SF-nearly-exact)
  - Broder λ_{int}, higher S and λ_{SOL}
- Present data does not allow to separate the effect of the increased diffusive spreading due to the higher $L_{||}$ and transport.
- $\tau_{||}=L_{||}/v_{th}$ if $\nu<v_{th}/L_{||}$ (low ν_{ei})
- $\tau_{||}=L_{||}^2/v_{th}\lambda_{mfp}$ if $\nu>v_{th}/L_{||}$ (high ν_{ei})
- $\lambda \sim (D_{perp}\,\tau_{||})^{1/2}$ i.e. $\lambda_q \sim (\chi_{perp}\,\tau_E^{SOL})^{1/2}$

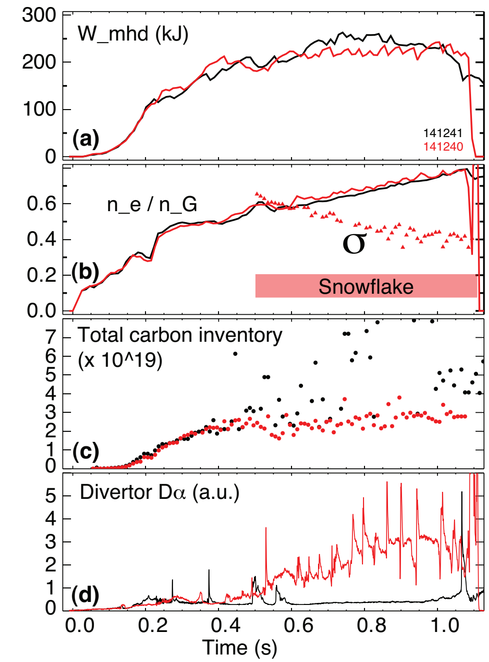


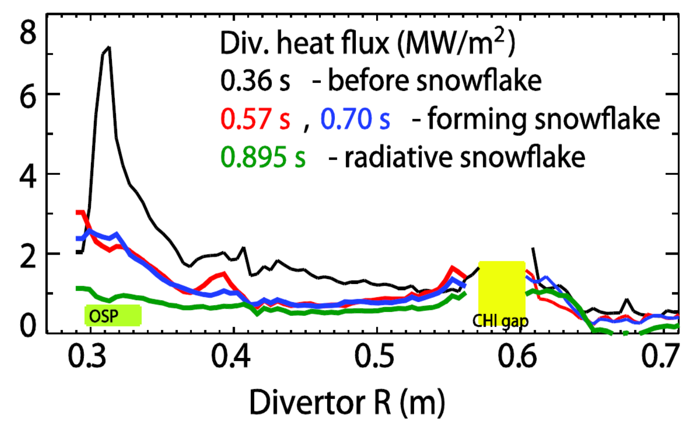
Snowflake divertor experimental results consistent in DIII-D and NSTX

- Graphite PFCs with lithium coatings
- I_p = 0.9 MA, P_{NBI} = 4 MW, P_{SOL} ~ 3 MW
- $q_{peak} \leq$ 8 MW/m^2, $q_{||} \leq$ 100 MW/m^2

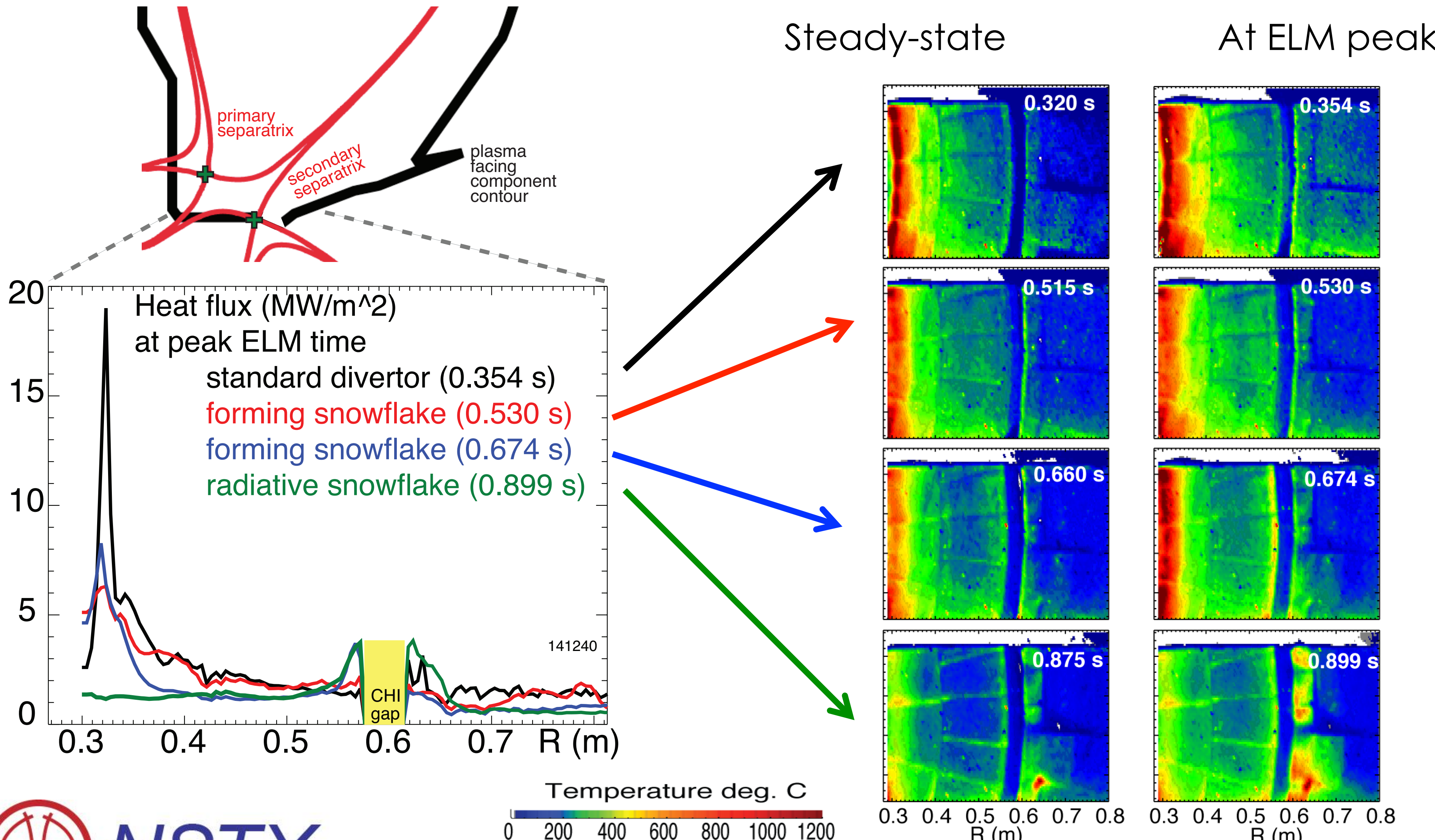
With snowflake divertor

- H-mode confinement unchanged
  - W_{MHD}~250 kJ, H98(y,2)~ 1, β_N~5
- Core impurity reduced by up to 50 %
- ELMs, previously suppressed, re-appeared
- Partial outer strike point detachment on-set (unlike standard divertor)
- Divertor heat flux significantly reduced
  - Between ELMs
  - During Type-I ELMs (ΔW/W ~ 5-15 %)





Shallow field angle not a problem for steady-state and impulsive heat loads in NSTX snowflake divertor



Developing the snowflake divertor physics basis for high-power density tokamaks

- **SF divertor configurations compatible with high H-mode confinement and high pressure pedestal**

- **Snowflake geometry may offer multiple benefits for inter-ELM and ELM heat flux mitigation**
  - Geometry enables divertor inter-ELM heat flux spreading over larger plasma-wetted area, multiple strike points
  - Broader parallel heat fluxes may imply increased radial transport
  - ELM divertor peak target temperature and heat flux reduction, especially in radiative snowflake configurations