Developing Physics Basis for the Radiative Snowflake Divertor at DIII-D

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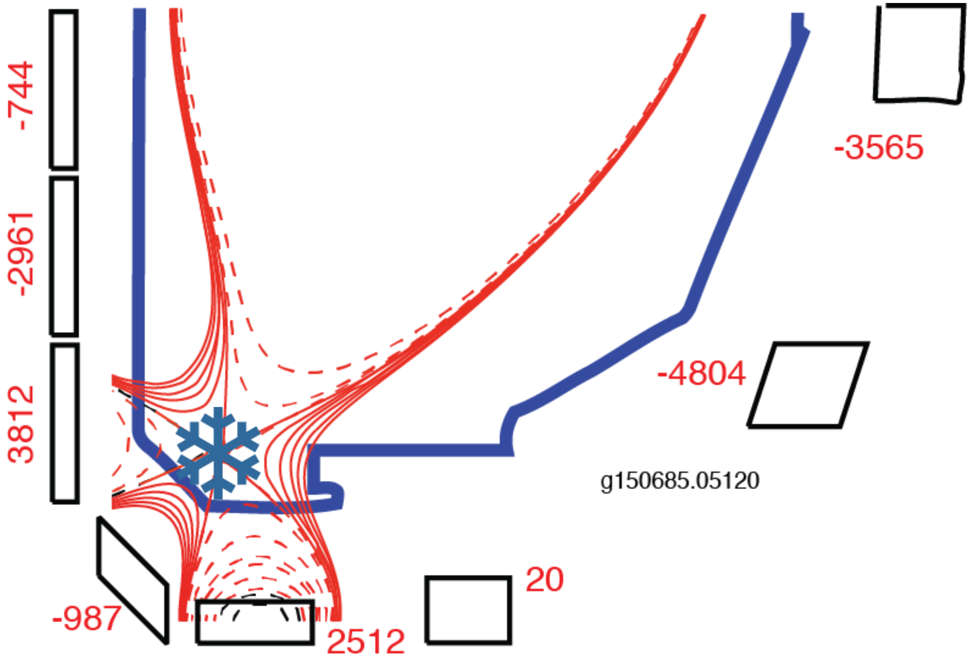

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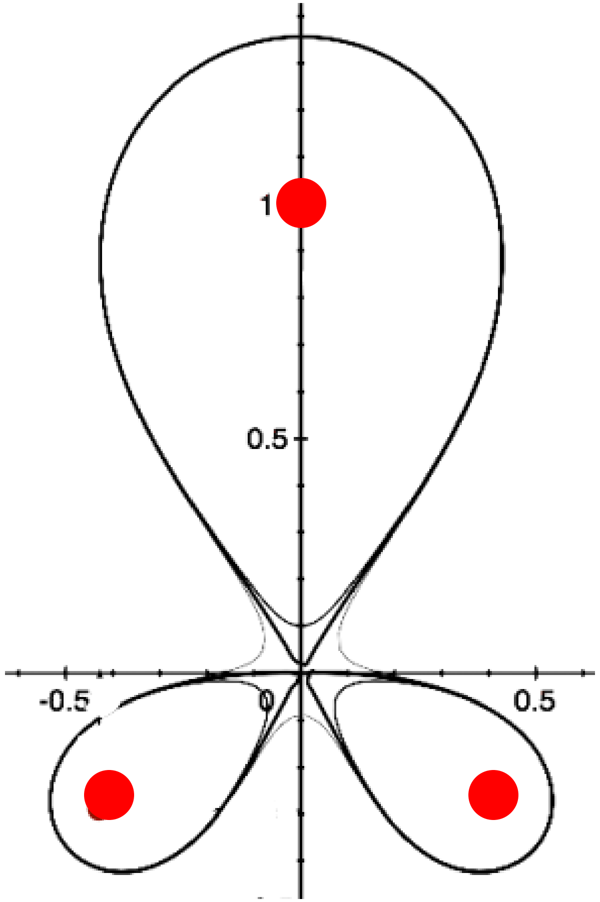
Snowflake Divertor Configuration is Studied in DIII-D as a Tokamak Divertor Power Exhaust Concept

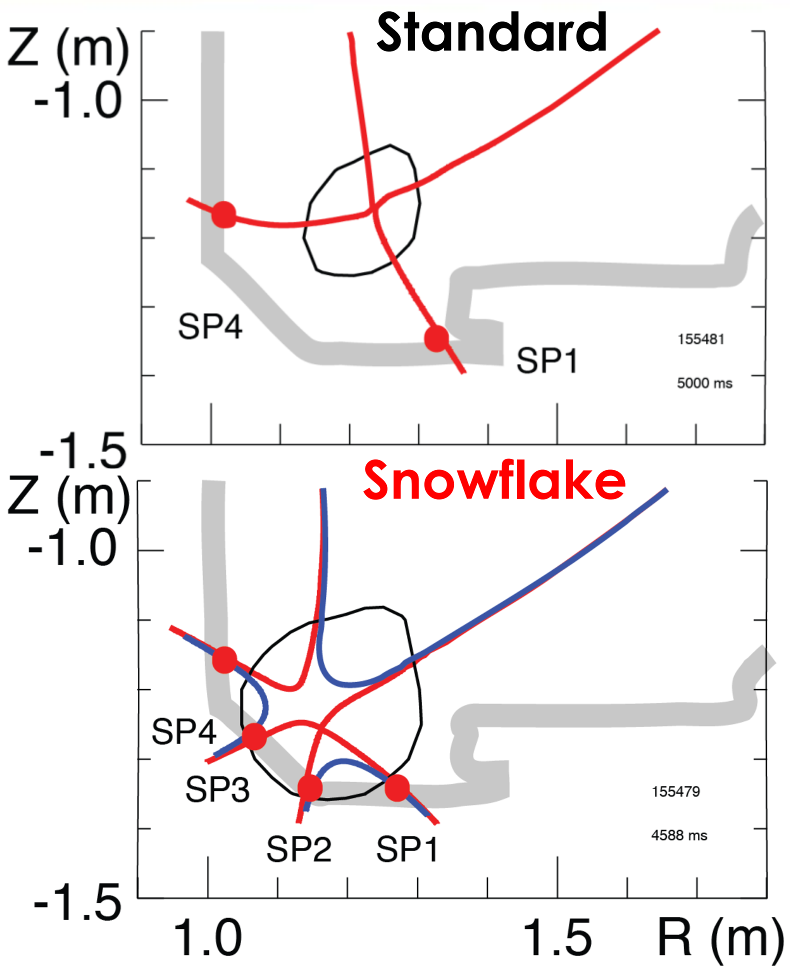


D. D. Ryutov, PoP 14, 064502 2007; PPCF 54, 124050 (2012)

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

- **Divertor power exhaust challenge**
  - Steady-state heat flux
    - Technological limit $q_{peak} \leq$ 5-15 MW/m^2
    - DEMO: Unmitigated, $q_{peak} \leq$ 150 MW/m^2
  - ELM energy, target peak temperature
    - Melting limit 0.1-0.5 MJ/m^2
    - DEMO: Unmitigated, $\geq$ 10 MJ/m^2
- **Snowflake divertor with 2nd-order null**
  - $\nabla B_p \sim 0 \Rightarrow$ Large region of low B_p
  - Very large A_{wet} possibility
- **Experiments in TCV, NSTX, EAST, DIII-D**

Large Region of Low B_p Around Second-order Null in Snowflake Divertor is Predicted to Modify Power Exhaust



Low B_p contour: 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}

- **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)

"Laboratory for divertor physics"

Radiative Snowflake Divertor Experiments in DIII-D Suggest Strong Effects on Power Exhaust

Outline of talk

- **Comparisons between snowflake and standard divertor encouraging**
  - Compatibility with good core and pedestal performance
  - Confirmed geometry properties A_{wet} and L_{II}
  - Initial confirmation of transport properties

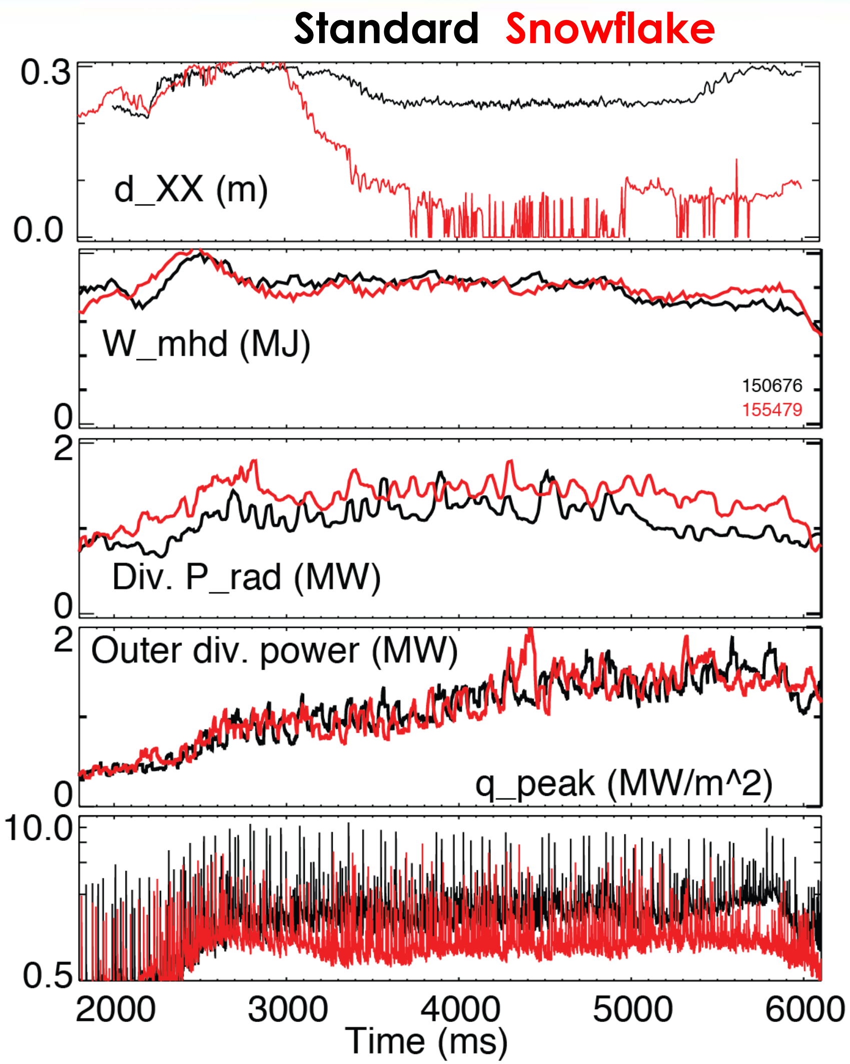
Standard
Snowflake

- **Broader divertor radiation distribution**
- **Reduced inter-ELM peak heat flux q_{peak}**
- **Reduced ELM energy, T_{peak} and q_{peak}**

Control of steady-state snowflake configurations in DIII-D with existing coils

- **E. Kolemen et.al., next talk**

Increased Plasma-wetted Area Leads to q_{peak} Reduction In Snowflake Divertor



- **Snowflake with d_{XX} < 10 cm**
- **Core plasma unaffected**
  - 5 MW NBI H-mode
  - Stored energy and density constant
- **Divertor power balance unaffected**
- **In outer divertor, q_{peak} reduced by 30%**

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

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

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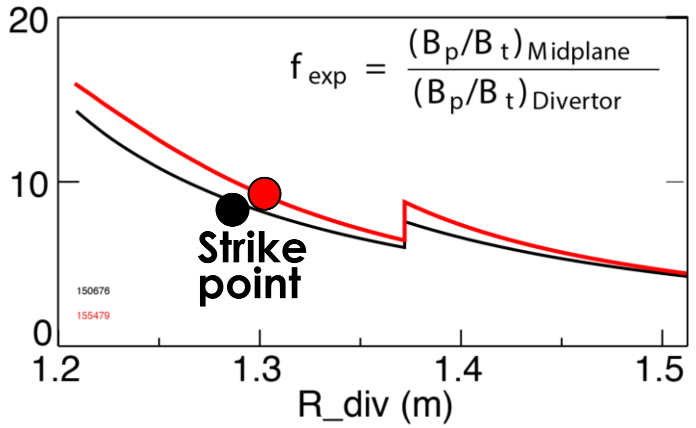
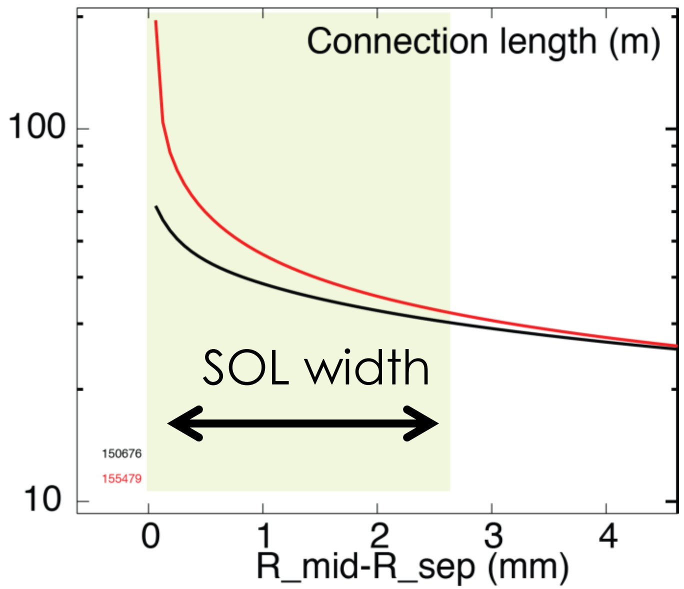
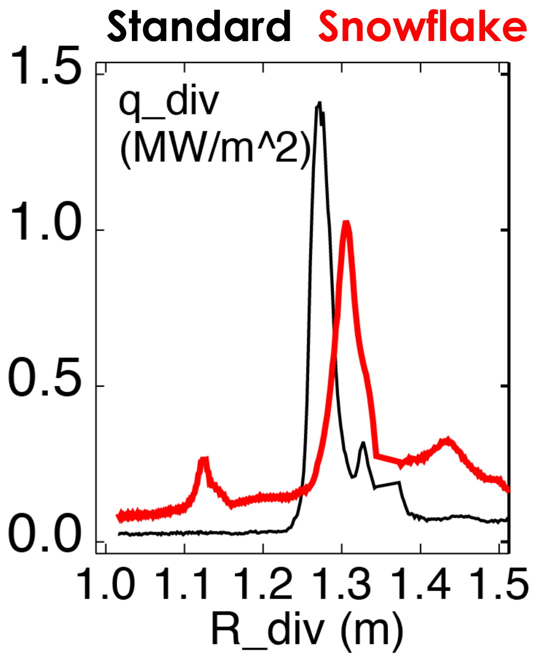
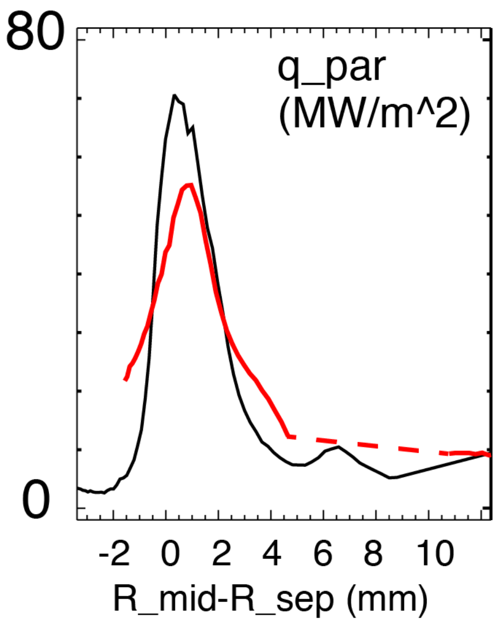
q_{peak} Reduction in Snowflake Divertor Partly Due to Increased A_{wet} and $L_{||}$





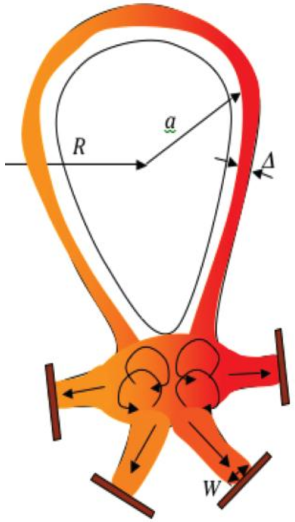


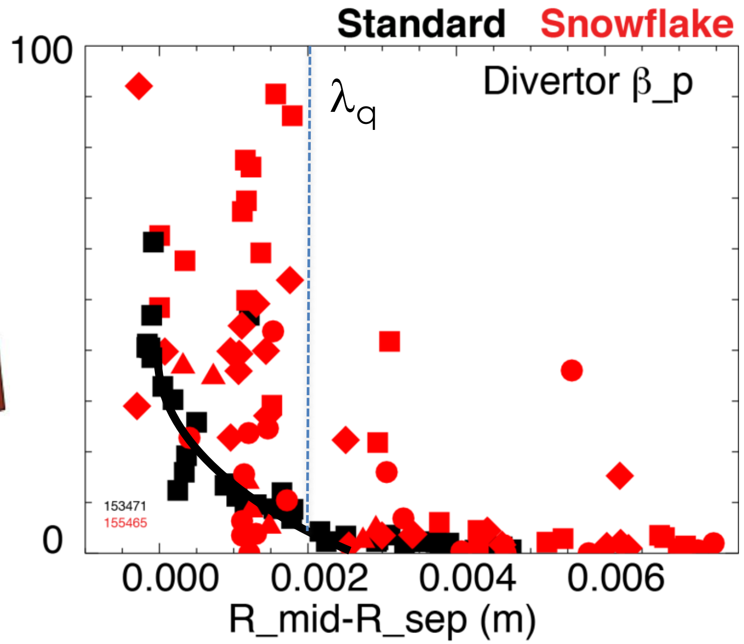


- **Flux expansion increased ~20%**
  - Depends on configuration, can be up to X3
- **$L_{||}$ increased by 20-60% over SOL width**
- **Divertor heat flux reduced ~30%**
- **Parallel heat flux reduced ~20%**

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**
  - Standard: 1cm
  - Snowflake: 6-8 cm

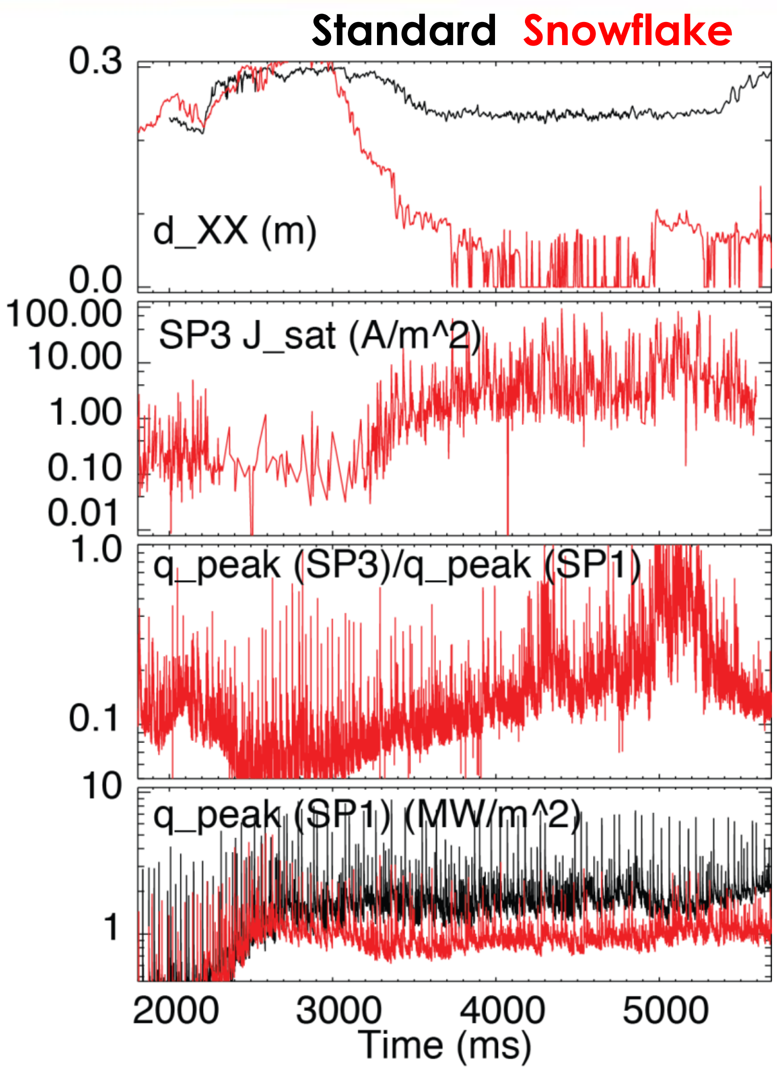




- **Divertor null-region β_p measured by divertor Thomson Scattering**
  - In snowflake, broad region of higher $\beta_p \gg 1$
  - Higher X10 during ELMs

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

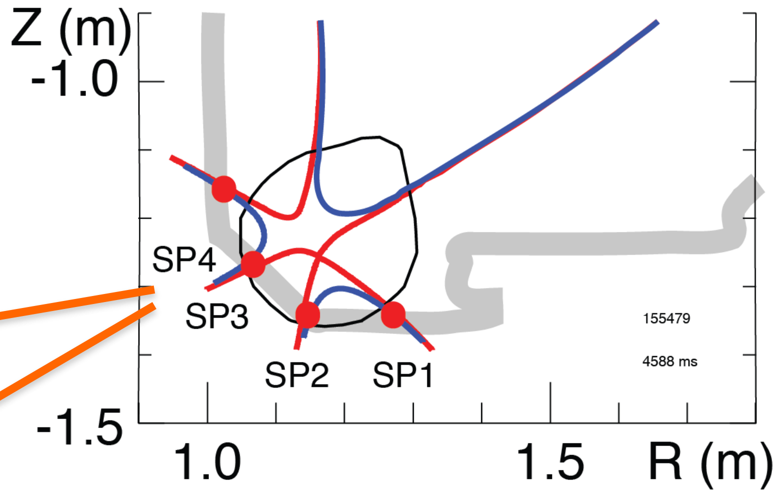
Heat and Particle Fluxes Shared Among Strike Points in Snowflake Divertor



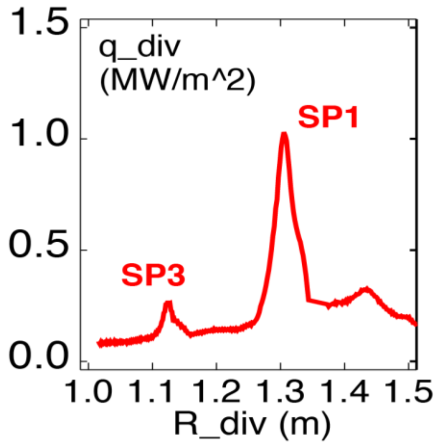
Γ_{SP3}

q_{SP3}

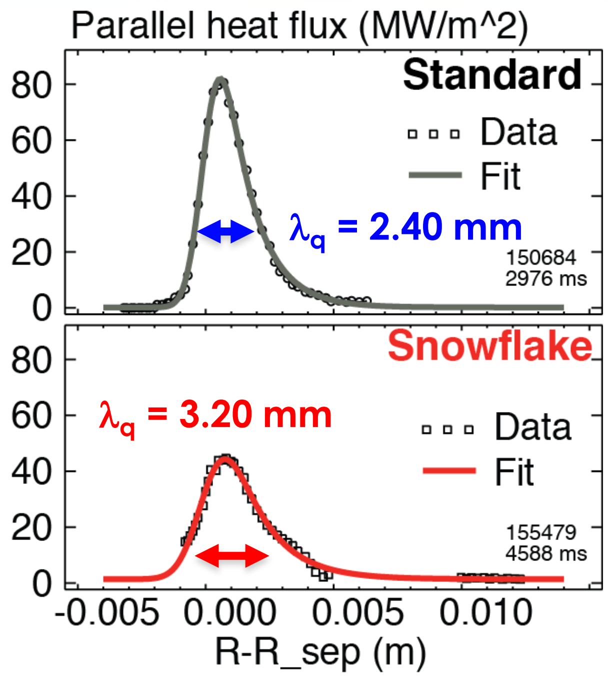
q_{SP1}

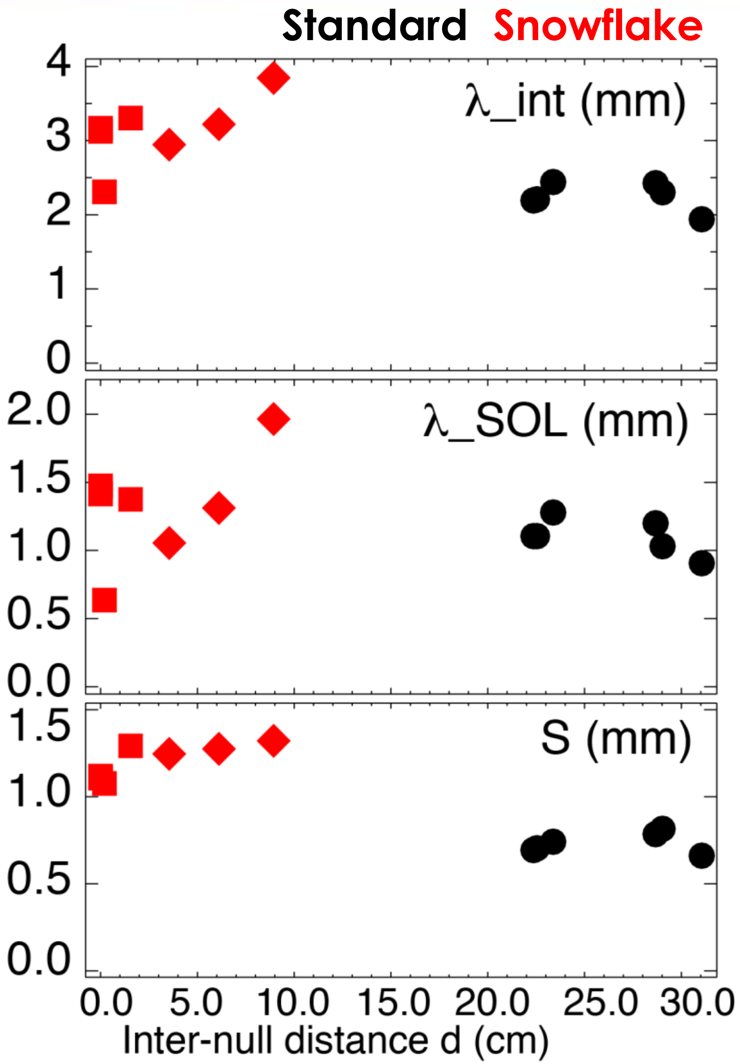


- $q_{SP3} / q_{SP1} < 0.5$
- $P_{SP3} / P_{SP1} < 0.3$
- **Sharing fraction maximized at low d_{XX}**



Broader $q_{||}$ Profiles in Snowflake Divertor May Imply Increased Radial Transport





- **Fit $q_{||}$ profile with Gaussian (S) and Exp. (λ_{SOL}) functions** (Eich PRL 107 (2011) 215001)
- **Increased λ_q may imply increased transport**
  - Increased radial spreading due to $L_{||}$
  - SOL transport affected by null-region mixing
  - Enhanced dissipation may also play role

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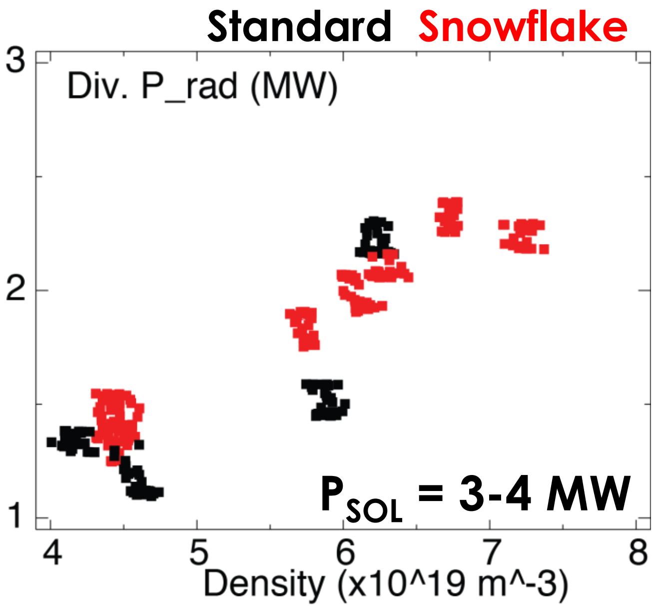
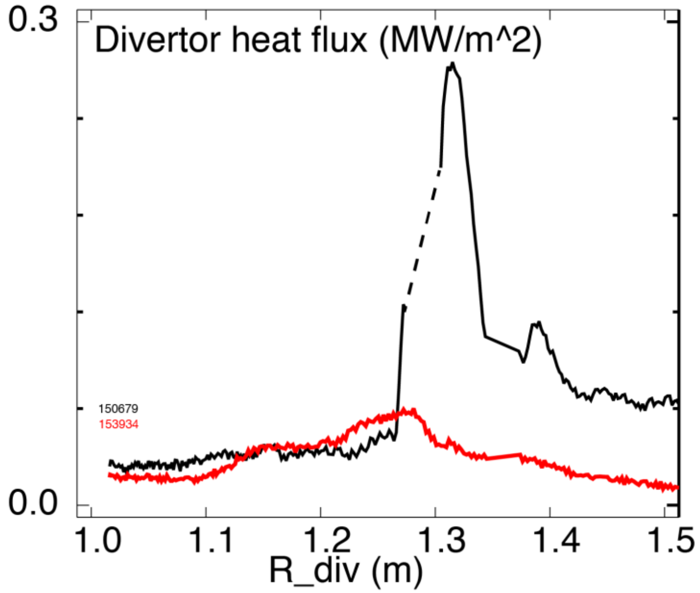
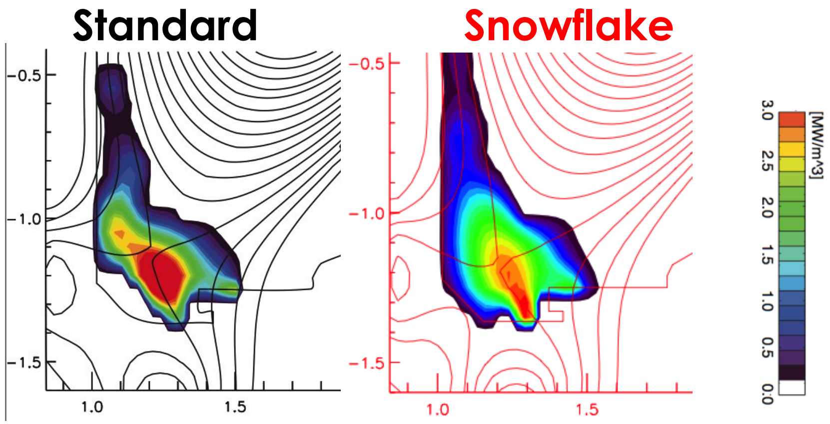
Divertor Radiation More Broadly Distributed in Snowflake for Radiative Divertor, q_{peak} Reduced by x5

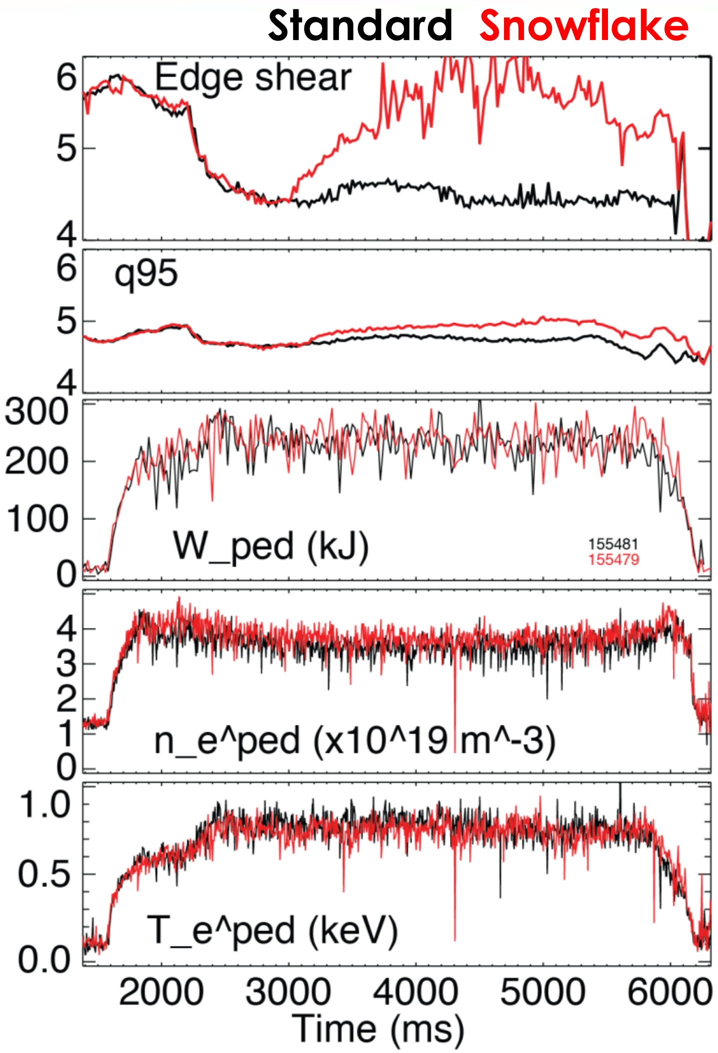






- Detached radiative divertor produced by D_2 injection with intrinsic carbon radiation
- In radiative snowflake nearly complete power detachment at P_{SOL}~3 MW

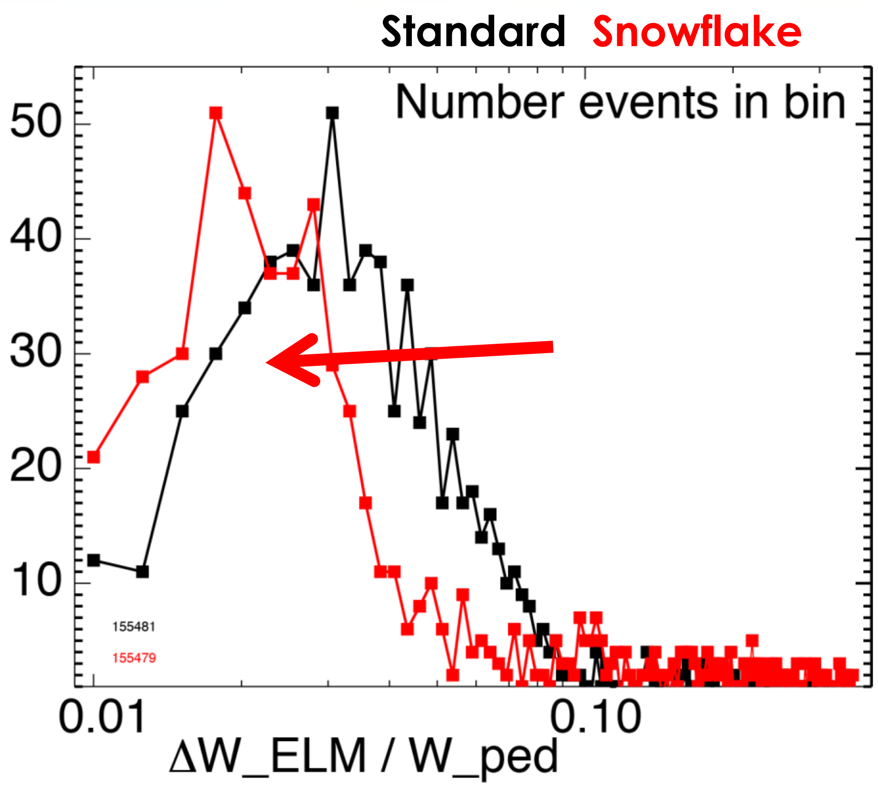
SF Divertor Weakly Affects Pedestal Magnetic and Kinetic Characteristics, Peeling-balooning Stability in DIII-D

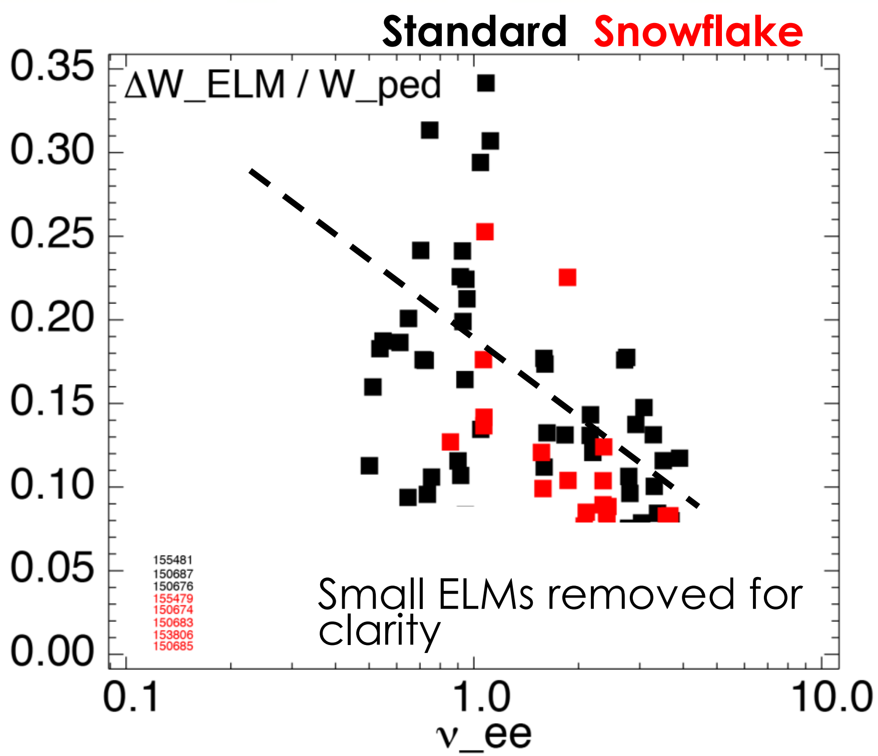


- **At lower n_e, H-mode performance unchanged with snowflake divertor**
  - Similar P_{ped}, W_{ped}
  - H98(y,2) ~1.0-1.2, β_N~2
  - Plasma profiles only weakly affected

- **Peeling-ballooning stability unaffected**
  - $Shear_{95}$, q_{95} increased by up to 30%
  - Medium-size type I ELMs
  - ELM frequency weakly reduced
  - ELM size weakly reduced

ELM Power Loss Scales with Collisionality, Reduced in H-modes with Snowflake 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 $\nu^*_{ped}=\pi R q_{95}/\lambda_{ee}$**

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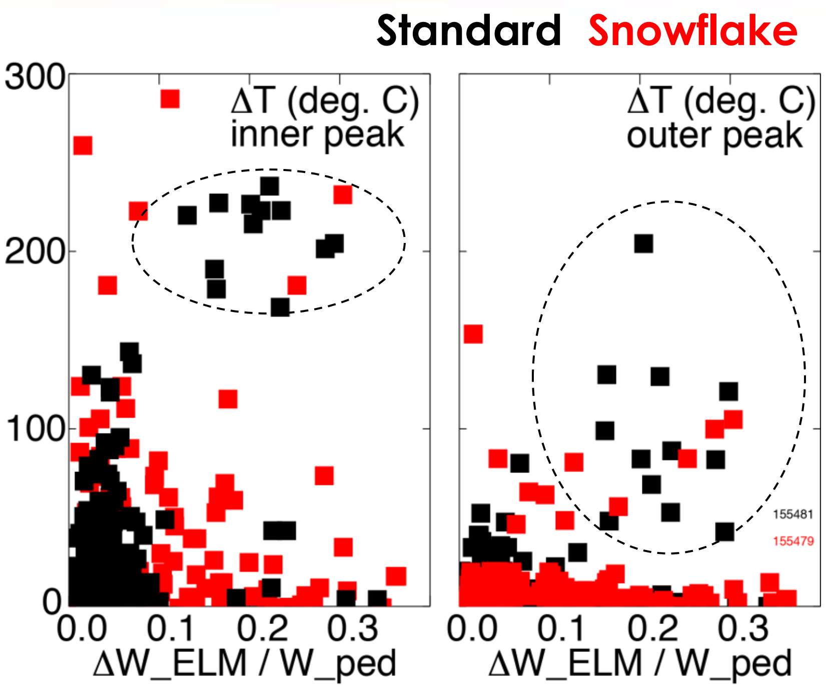
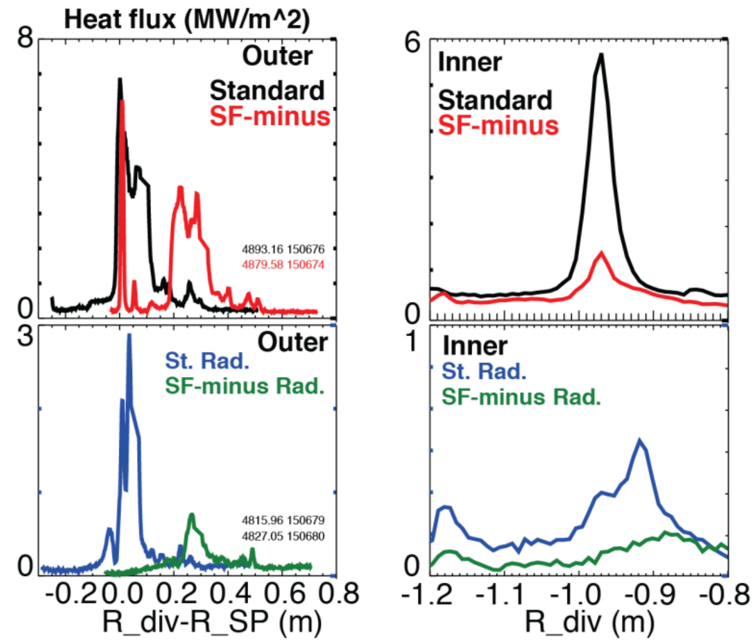
Peak ELM Target Temperature and ELM Heat Flux Reduced in Snowflake Divertor





- **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

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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