Results From Initial Snowflake Divertor Physics Studies on DIII-D

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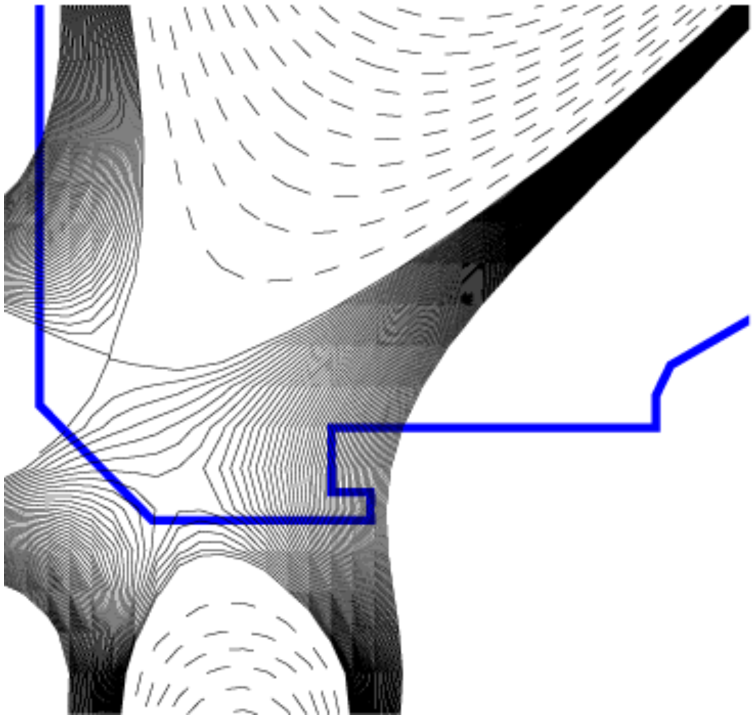

IAEA Fusion Energy Conference, San Diego, CA

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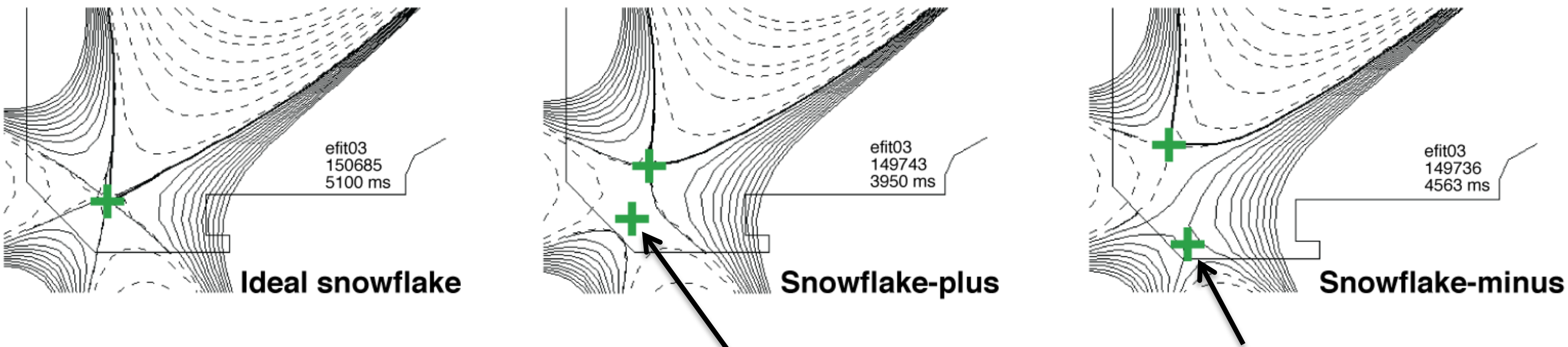
DIII-D Experiments focus on SF(-) configuration

- **Theory[1] predicts second order null of SF Divertor ($\nabla B_P \sim 0$)**
  - Multiple strike points, increased volume and connection lengths
  - Increased edge shear, influencing pedestal stability
- **Experiments[2] have made progress on comparisons**
- **DIII-D adds new data: Focus on SF(-) configuration**



2nd X-Point in Private Flux

2nd X-Point in SOL

[1]D. D. Ryutov, PoP 14, 064502 2007, TH/P4-18
[2]Vijvers EX/P5-22, [3]Soukhanovskii EX/P5-21

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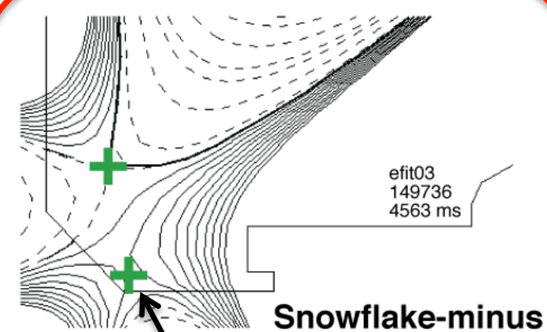
  - Experience on NSTX
- **Possible heat flux control for future compact machines**



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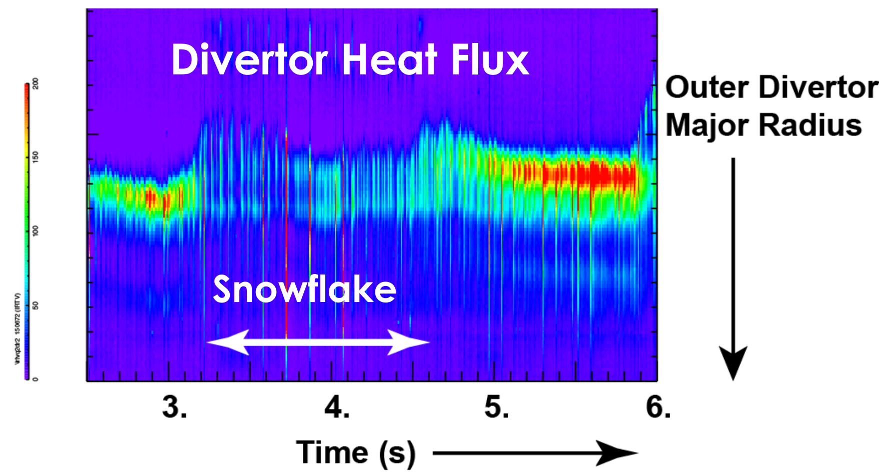

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DIII-D
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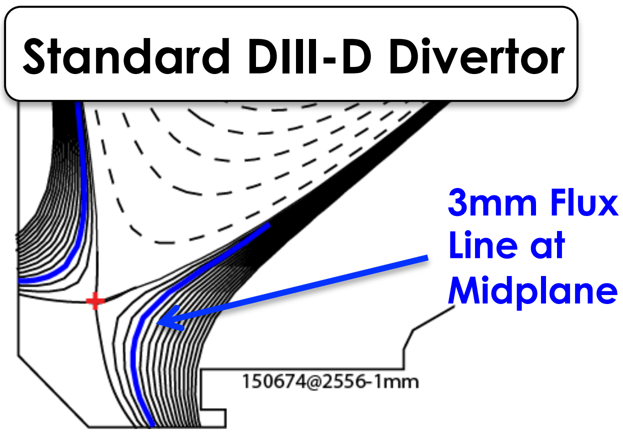
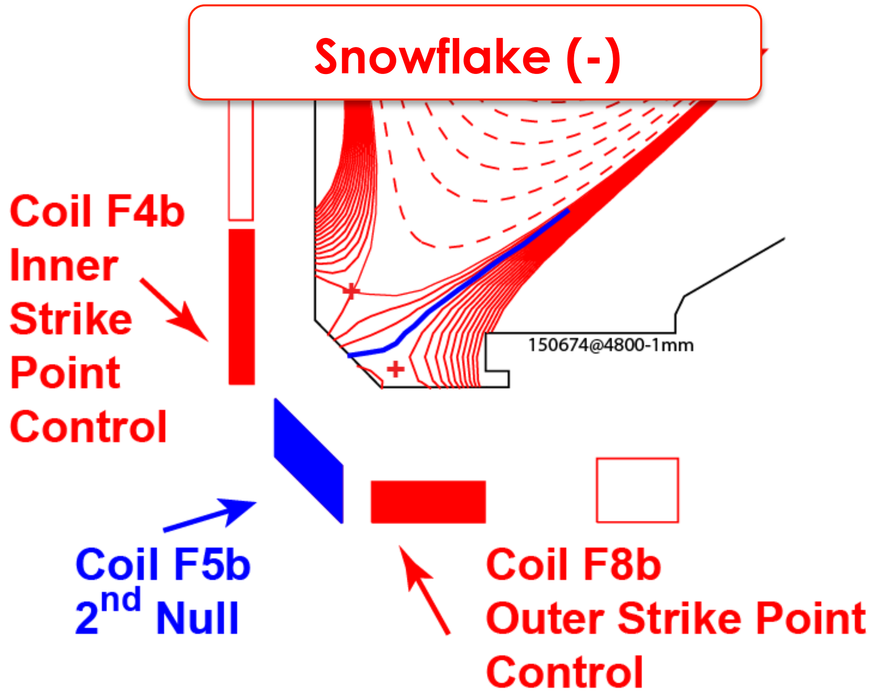
Compare DIII-D Normal Divertor with SF(-)

- Use NSTX control algorithm
- 2- External coils control strike points (F4B and F8B)
- 1- External coil moves 2nd null point (F5B)
- DIII-D and NSTX use similar Plasma Control Systems (PCS)





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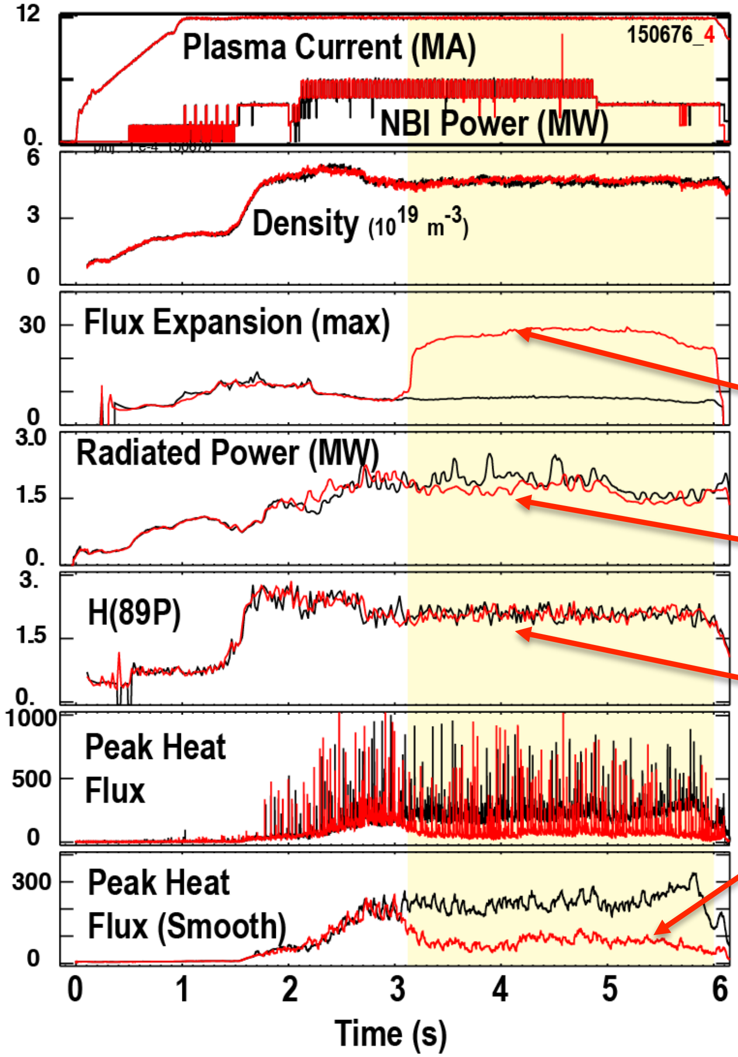
2.5X Divertor Heat Flux Reduction due to geometry



- I_p=1.2 MA, B_t=2 T
- P_{NBI}= 3-5 MW
- SF(-) maintained for → 3s
- Flux expansion ↑ 2.5X
- Radiated Power → similar
- Confinement → similar
- Heat Flux reduced ↓ 2.5X

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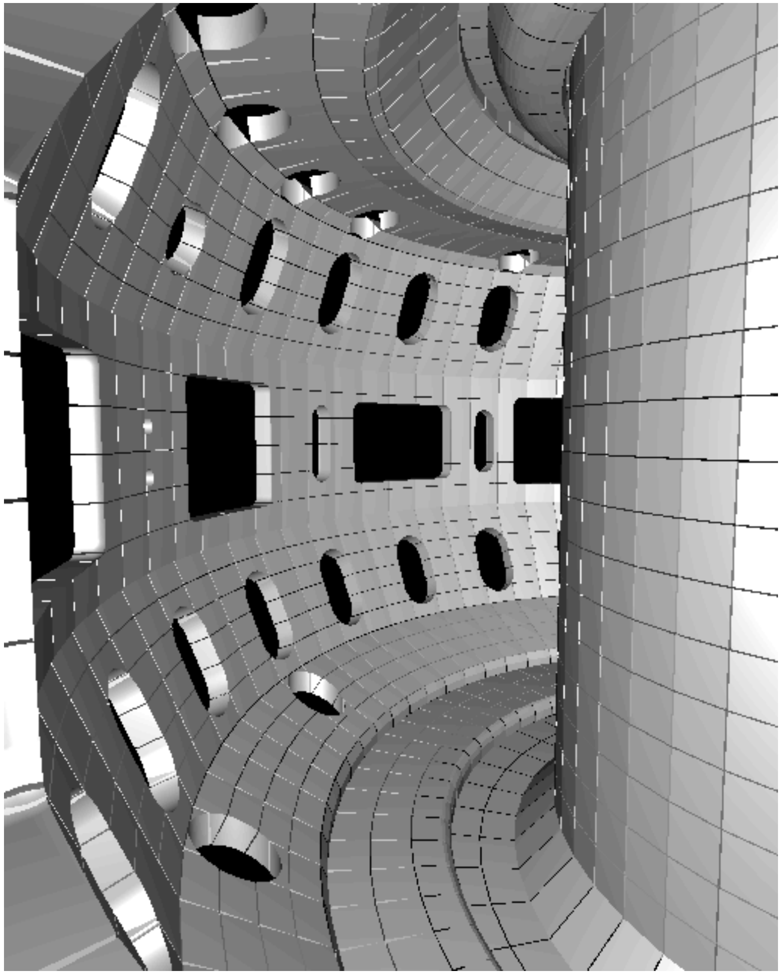
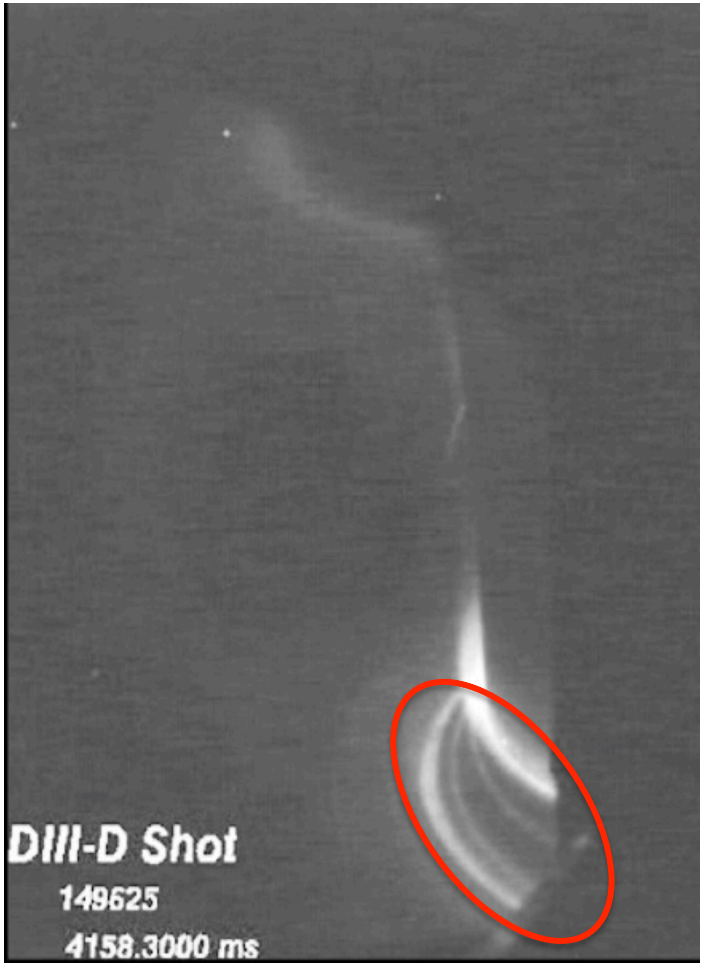
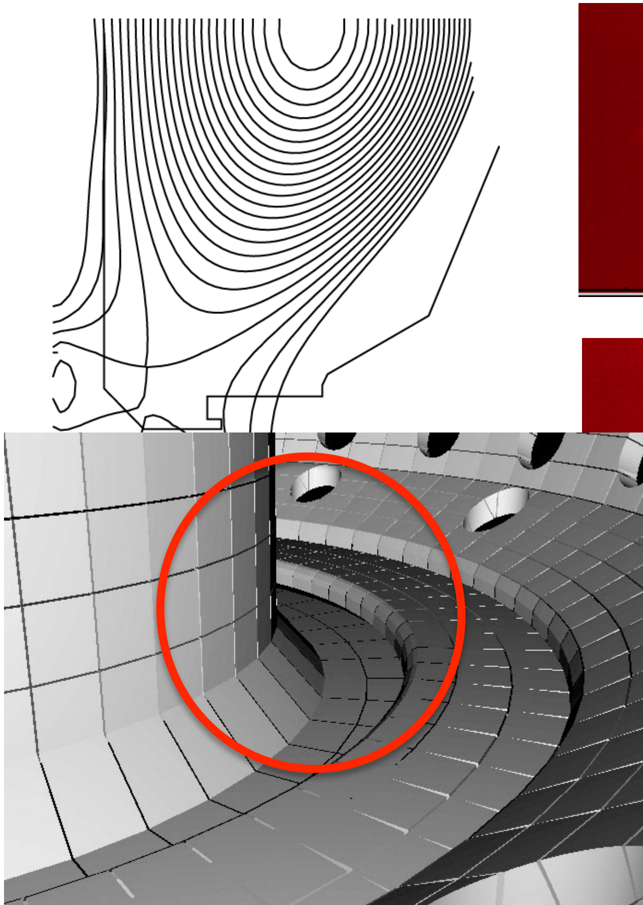
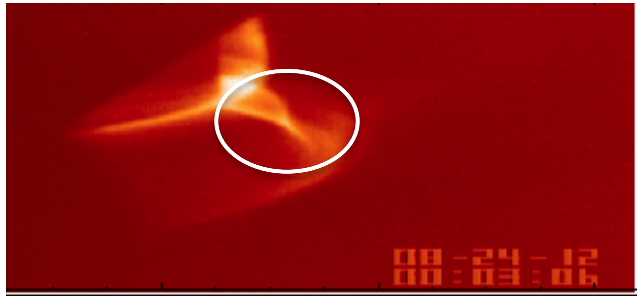
New LLNL Periscope: IR image shows 3-D features of SF(-) operation on DIII-D



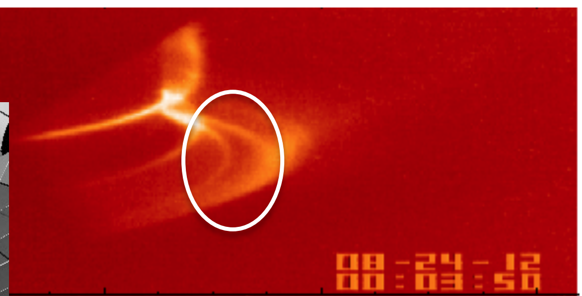


Lower Divertor C III Shows Attached SF Divertor

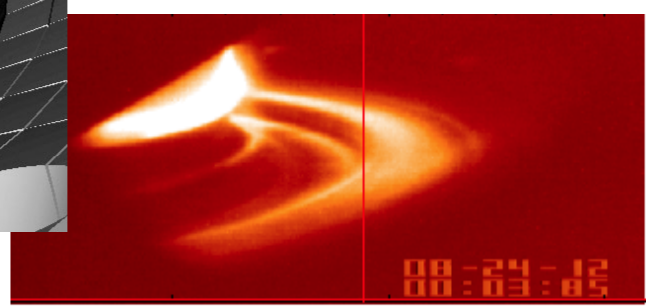




Before SF(-): CIII extends to outer strike point (attached divertor)



SF(-): Between ELMs, Additional Strike Point

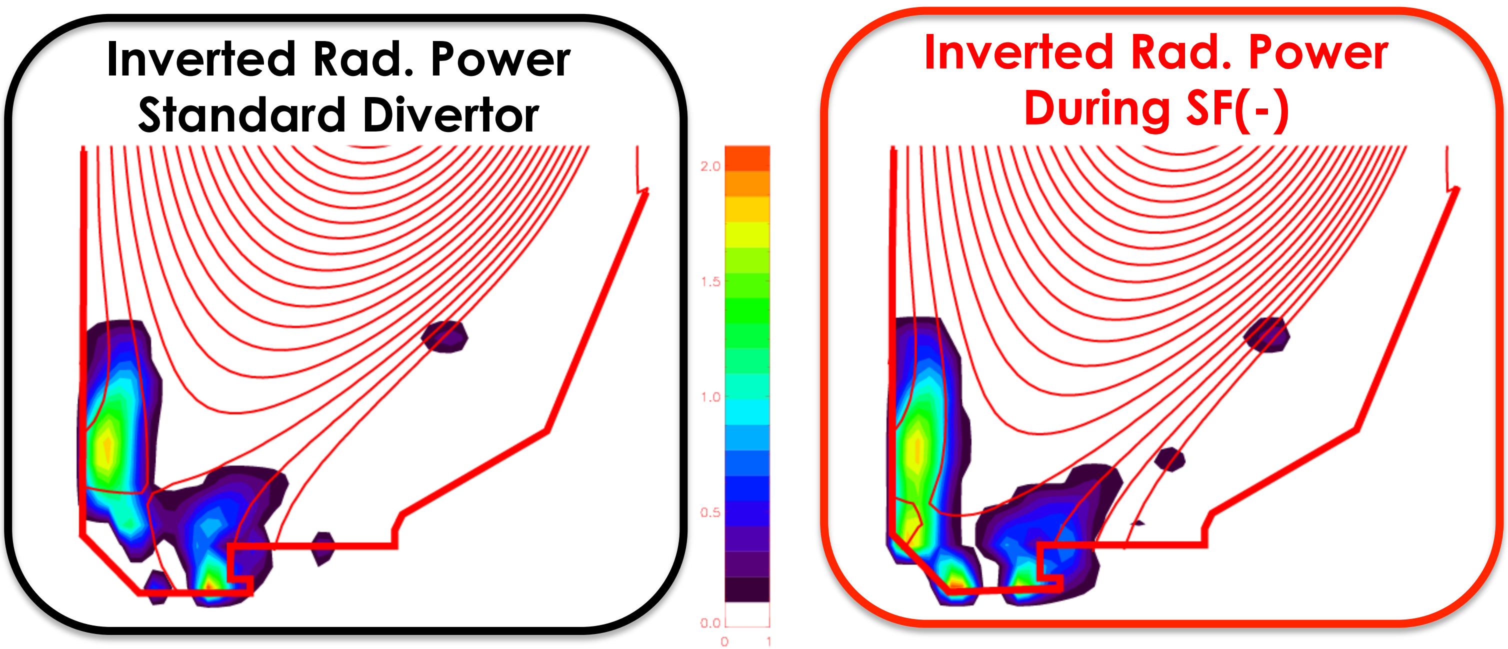


SF(-): During ELM, profile broadens

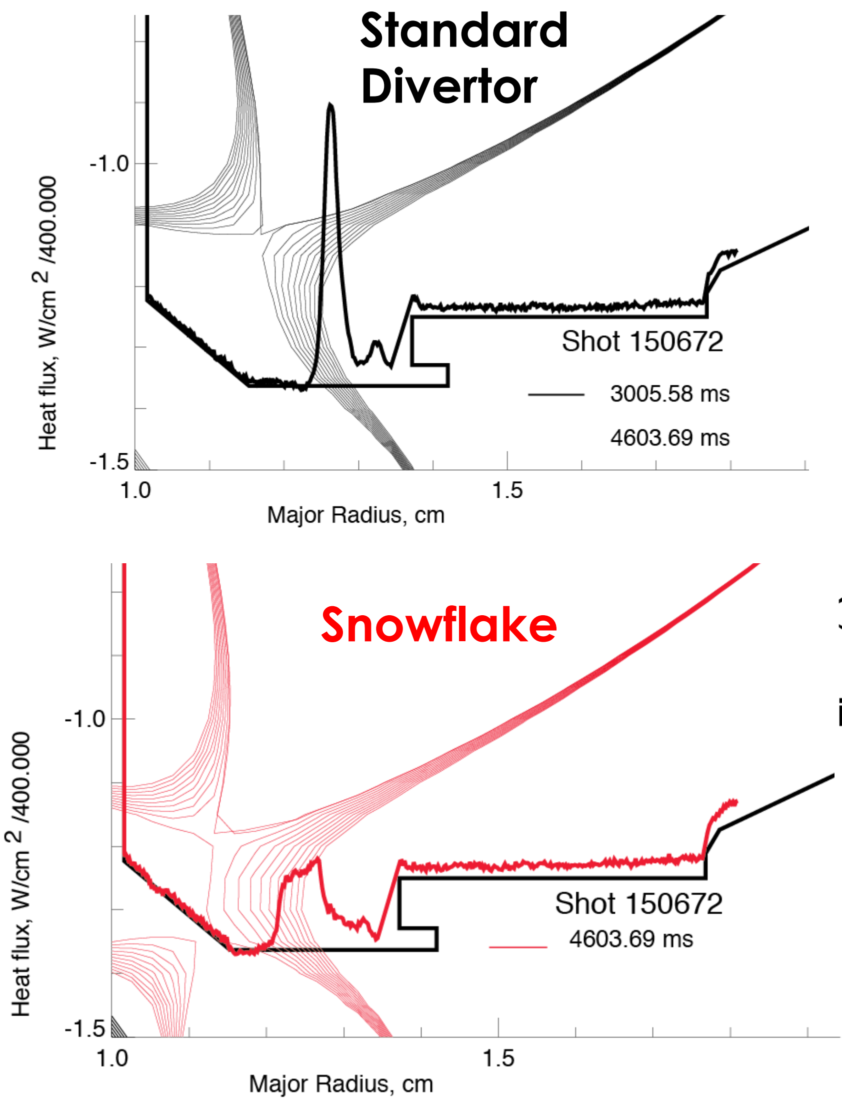
Shot 150673, 3056-3654ms, CIII (465nm)

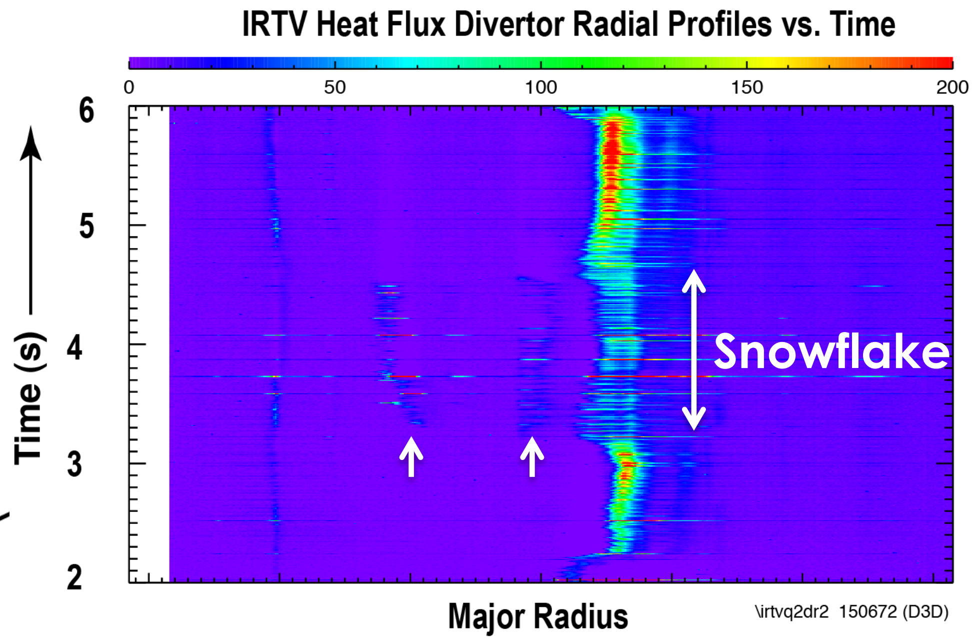
SF(-) divertor conditions similar to “attached” divertor

- No significant change in divertor bolometer radiation
- Small recombination (Balmer n= 7-2 line)
- Tangential divertor Dα and C III cameras show no detachment
- In contrast with NSTX where SF(-) detaches



Divertor Peak Heat Flux Reduced 2.5X in SF due to changes in divertor geometry

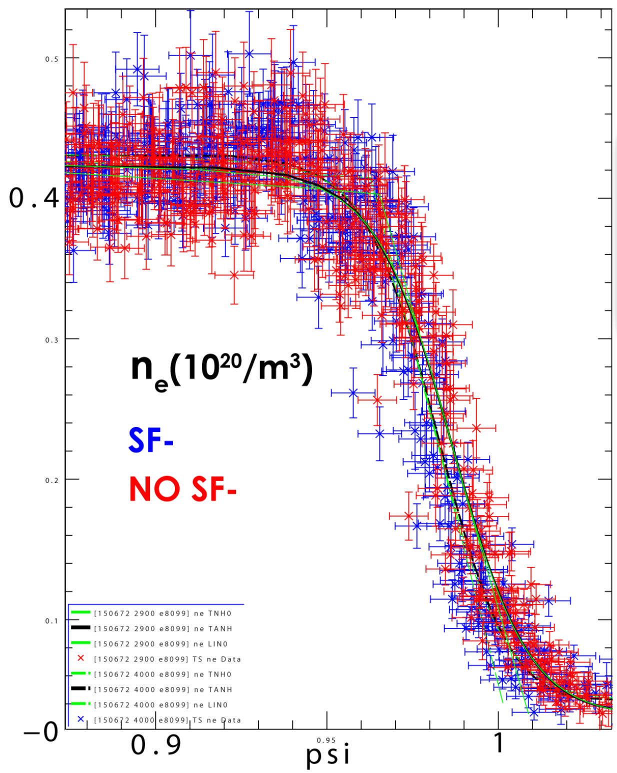




Pedestal profiles between ELMs very similar with and without SF(-)

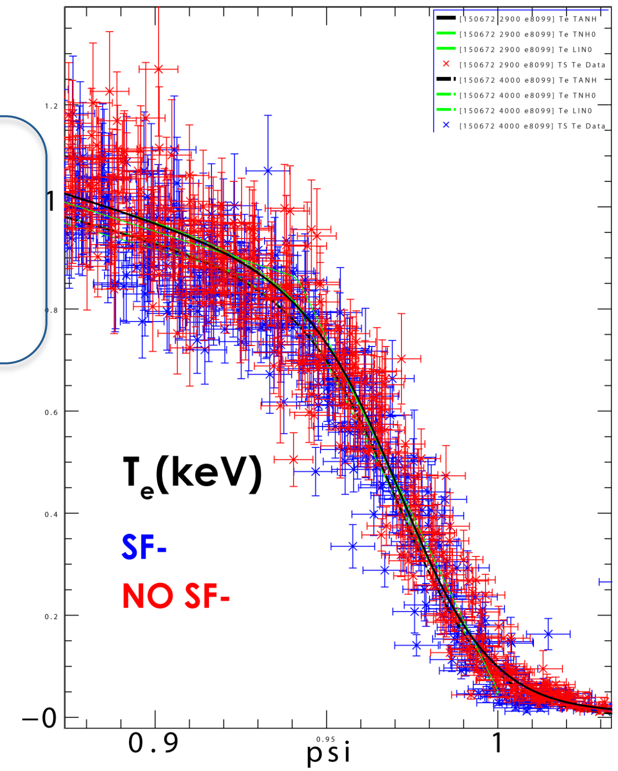
- **Slightly steeper and higher n_e, lower and flatter T_e with SF-**

Electron Density n_e

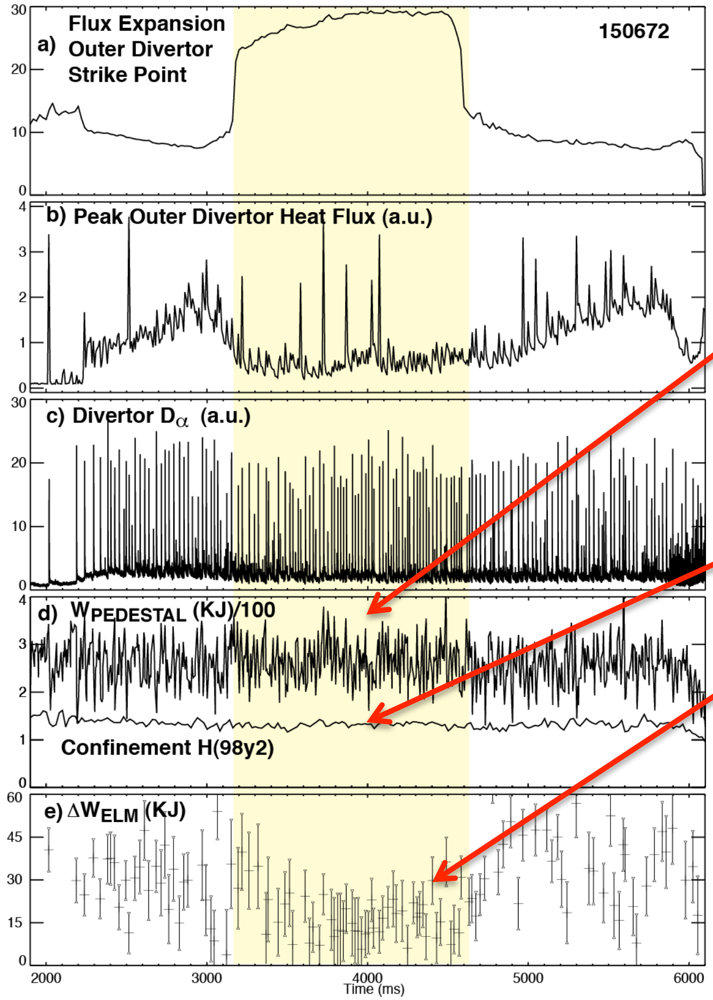


Note: BLUE is SF

Electron Temperature T_e



Detailed ELM Analysis: ΔW(ELM) decreased, W pedestal constant in SF



Detailed ELM analysis before/during SF shows:

- Pedestal Energy ($W_{PEDESTAL}$) Constant
- Confinement Constant
- Change in stored energy lost per ELM (ΔW_{ELM}) is reduced
- Consistent with Loarte connection length scaling

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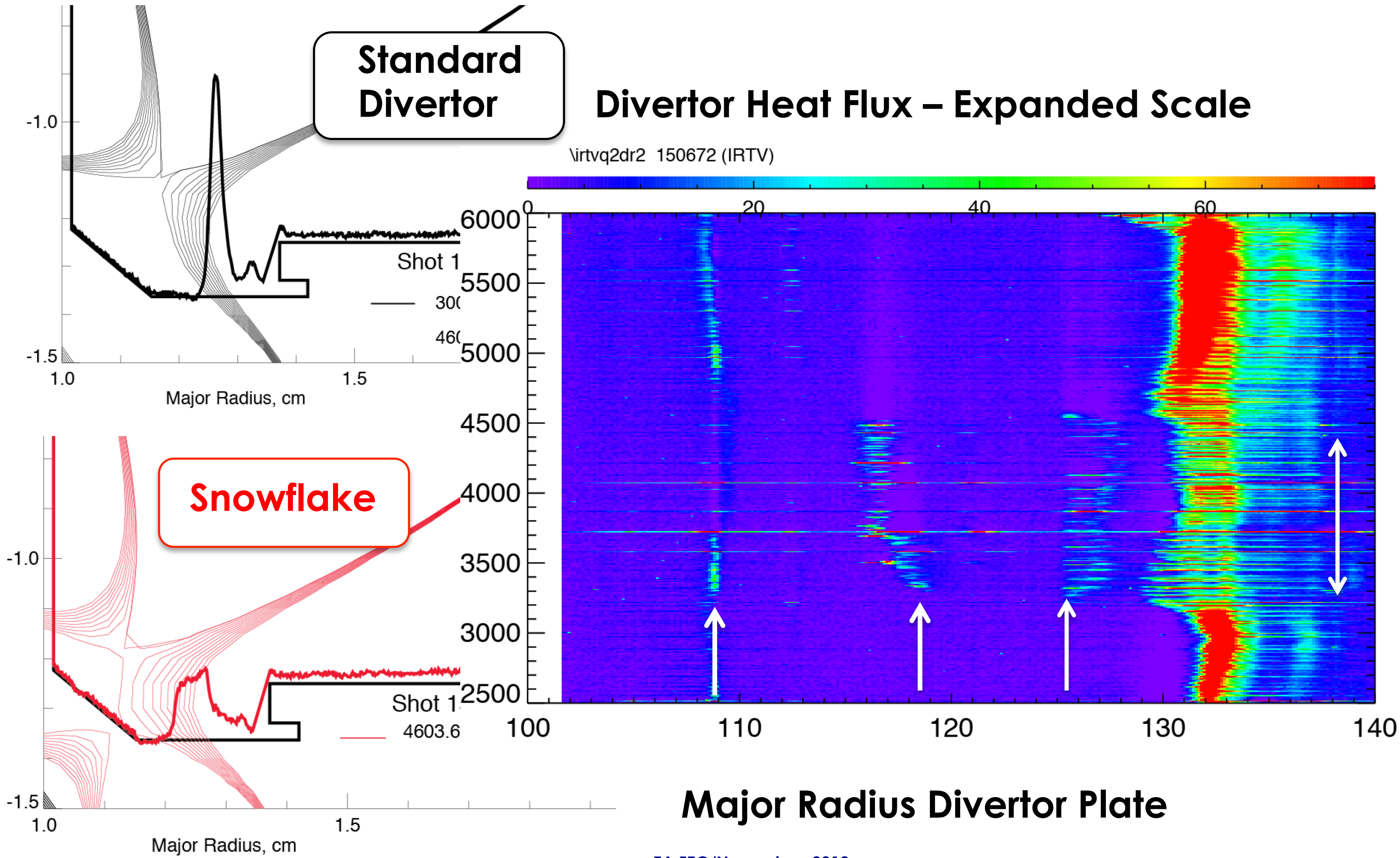
New opportunity to study details of SOL transport in attached SF divertor; study ELMs



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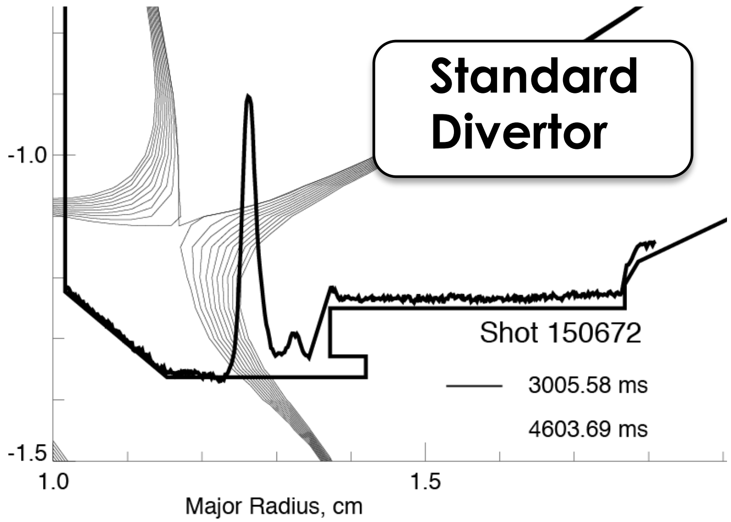
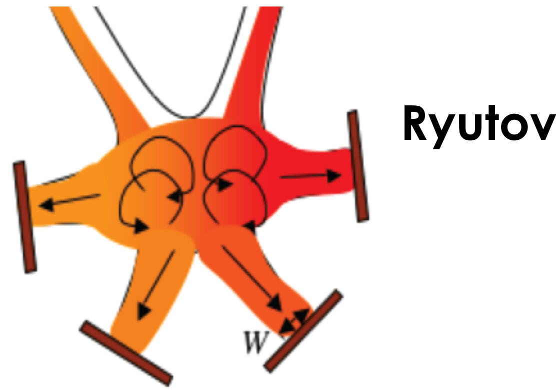
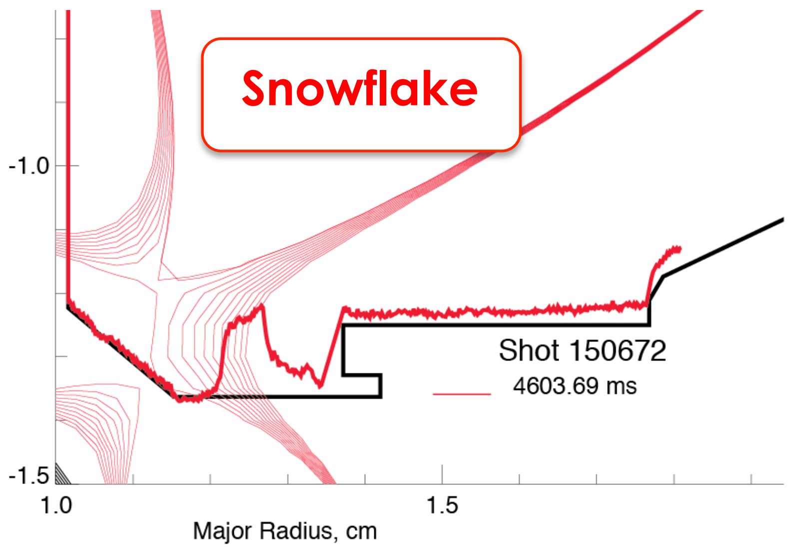
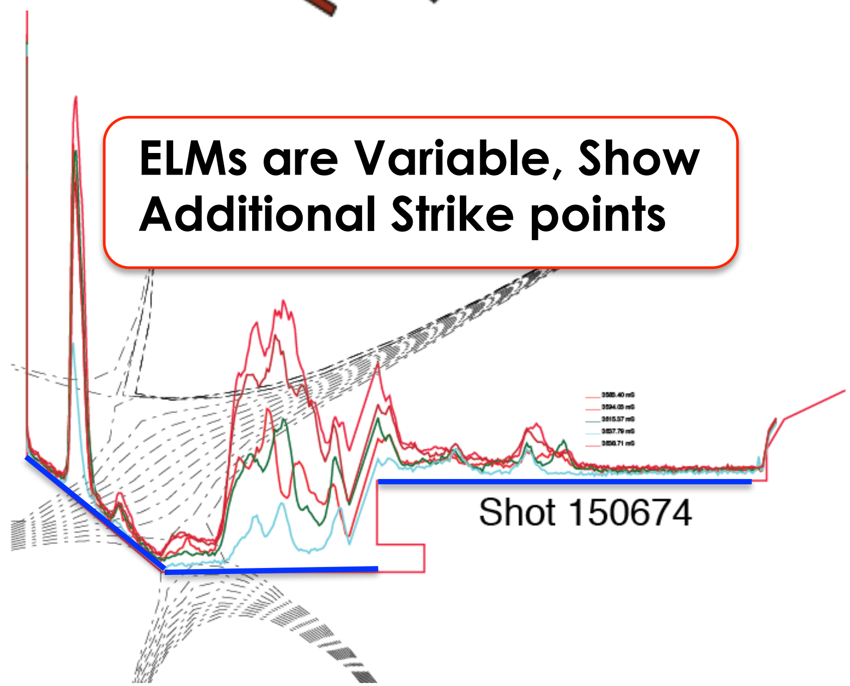
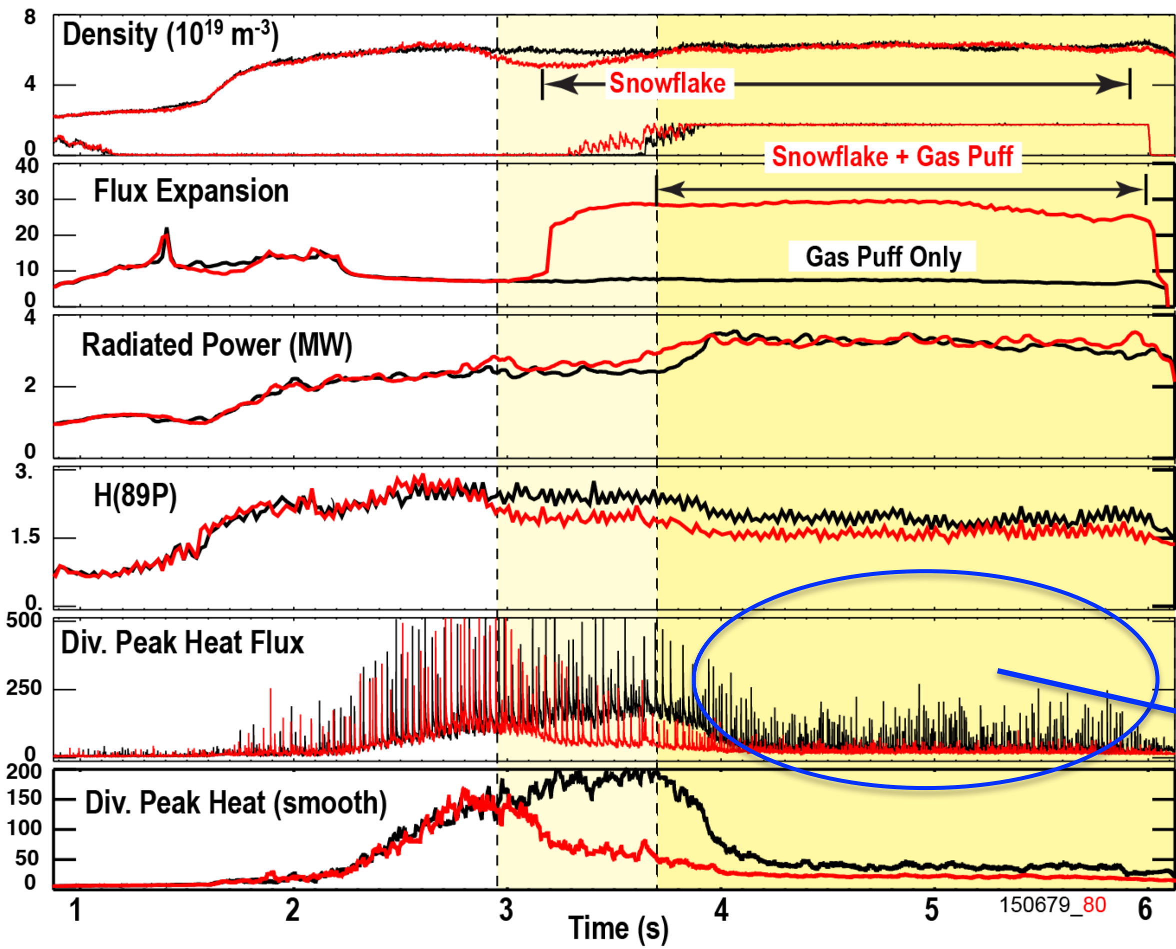




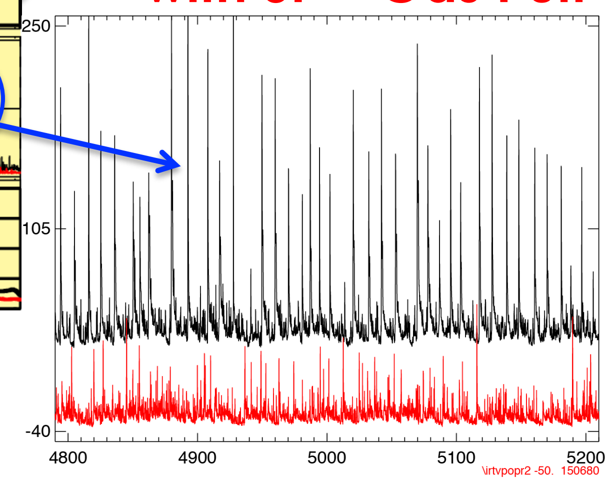




SF + gas puffing reduces divertor ELM peak heat load



- **Shot with gas puffing only (black lines)**
- **Compared with:**
  - SF
  - SF + Gas puff
- **Reduced ELM peak heat load with SF + Gas Puff**



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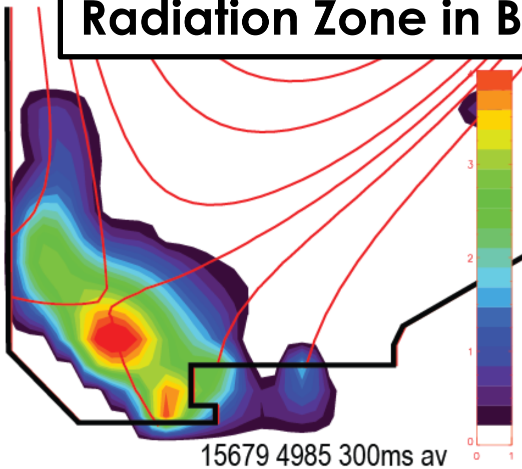
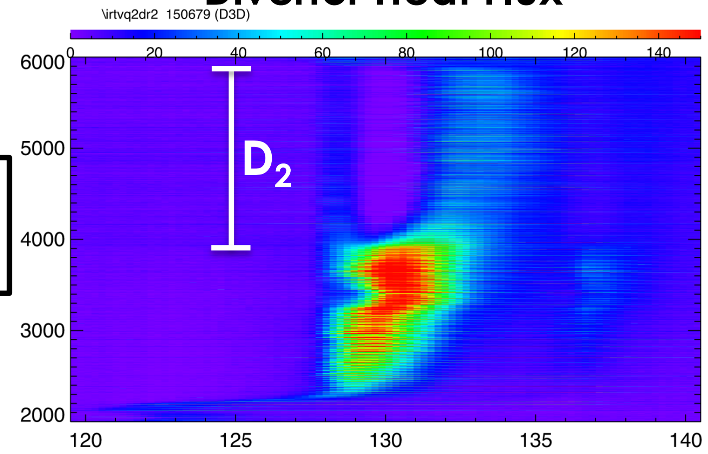
SF + Gas Puff Reduced ELM divertor heat flux over GP alone

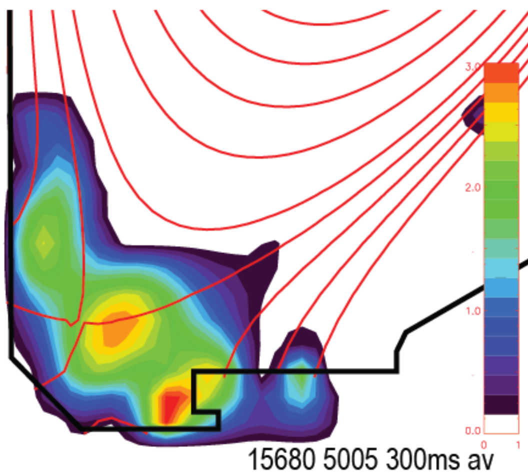
Expanded Divertor Radiation Zone in Both Cases



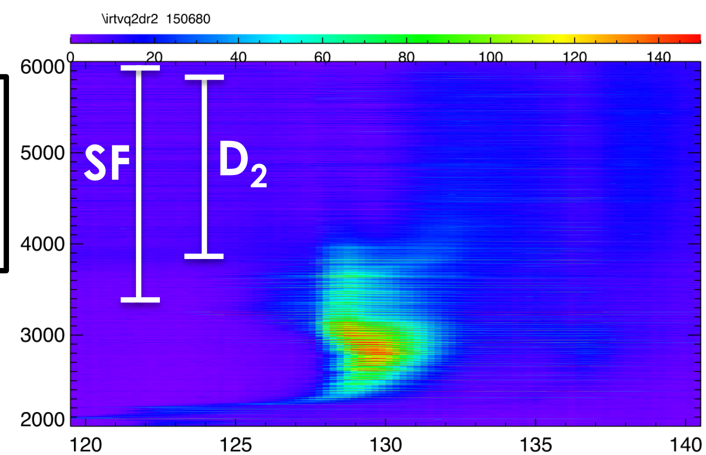
Gas Puff

Divertor Heat Flux





Gas Puff & SF



Major Radius

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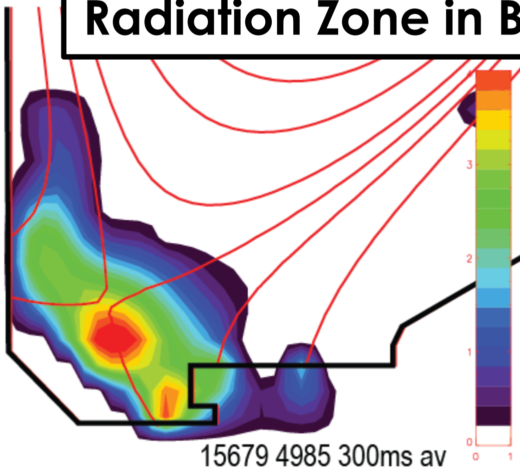
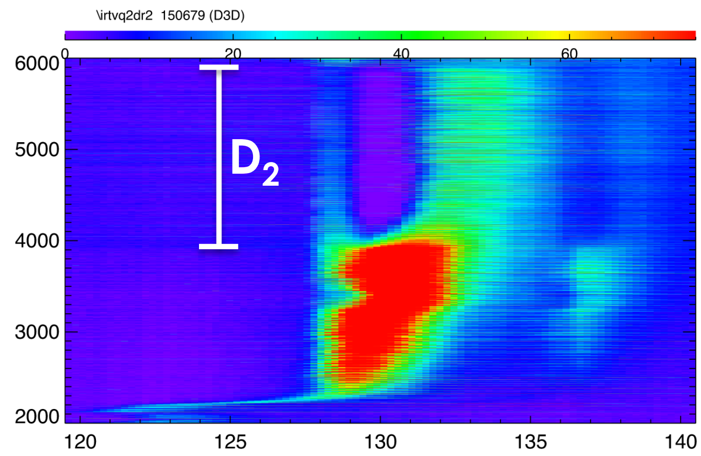
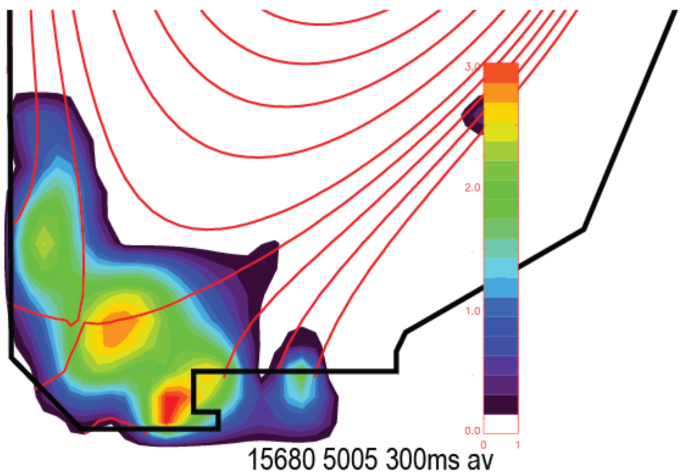
SF + Gas Puff (expanded scale)

Expanded Divertor Radiation Zone in Both Cases

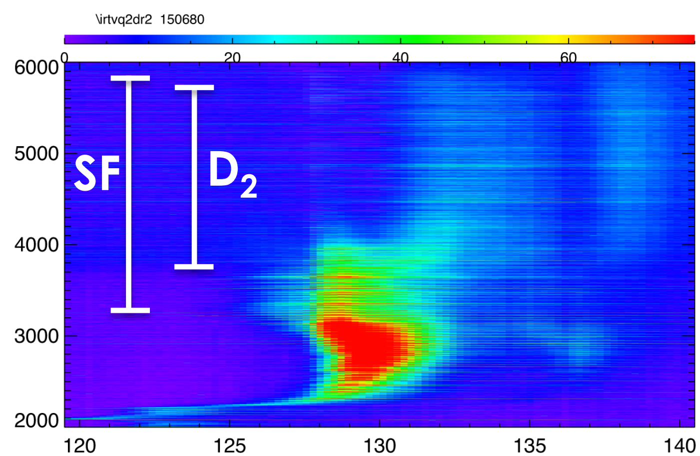


Gas Puff





Gas Puff & SF



Major Radius

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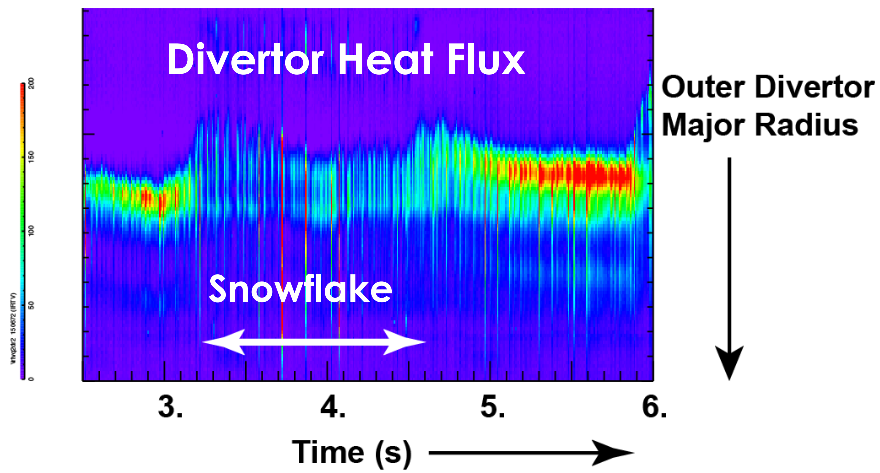

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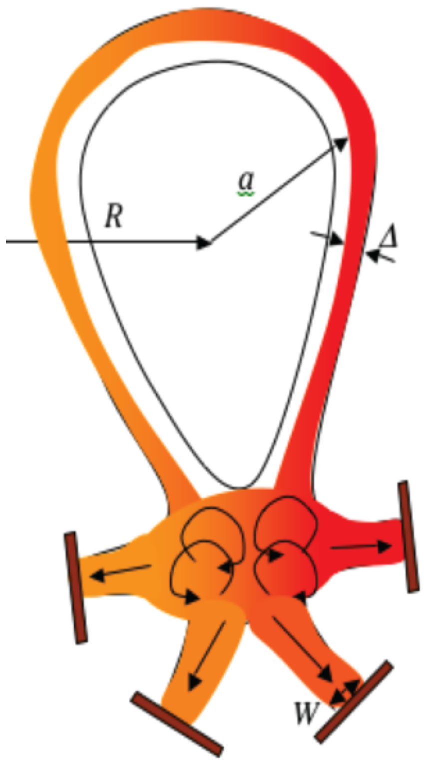
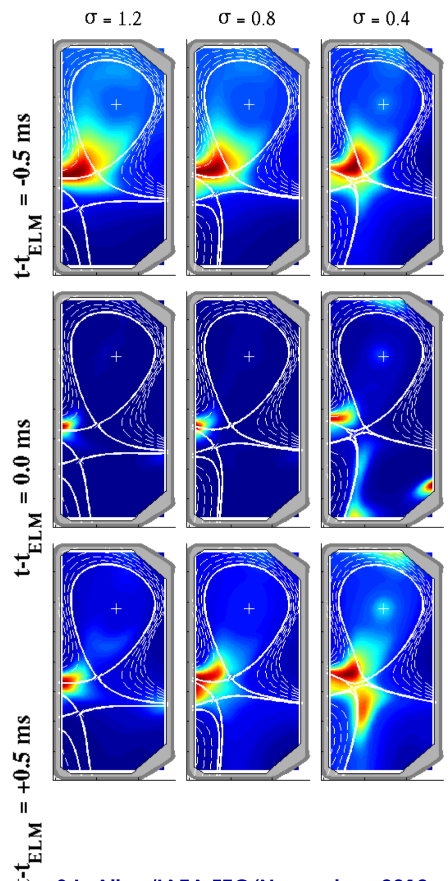
- **Future snowflake studies:**
  - Integration with high-δ Advanced Tokamak Scenarios
  - Clarification of detachment threshold w.r.t. standard divertor
  - Study of parallel versus perpendicular SOL transport – SOL Physics
  - Heat flux control in compact machines, new regimes

Snowflake Divertor Results at the IAEA Conference: DIII-D adds recent new data

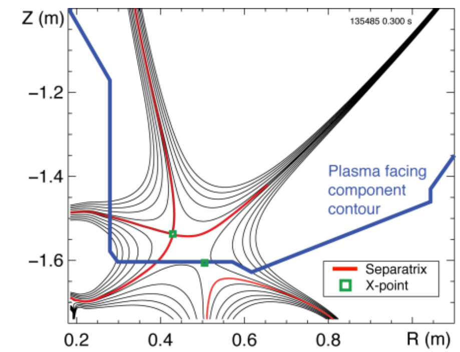
Ryutov – Original Theory TH/P4-18

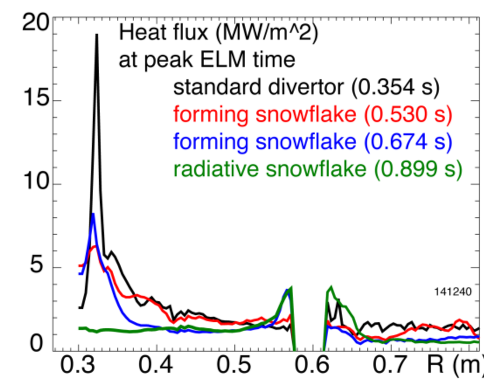


TCV Heat Flux Reduction – Vijvers EX/P5-22



NSTX Heat Flux Reduction – Soukhanovskii EX/P5-21



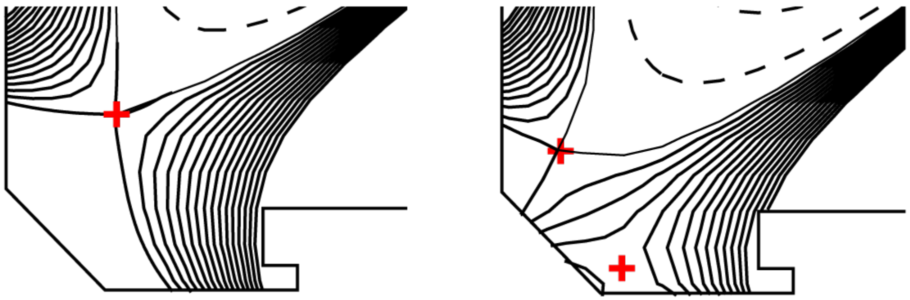


Backup Slides

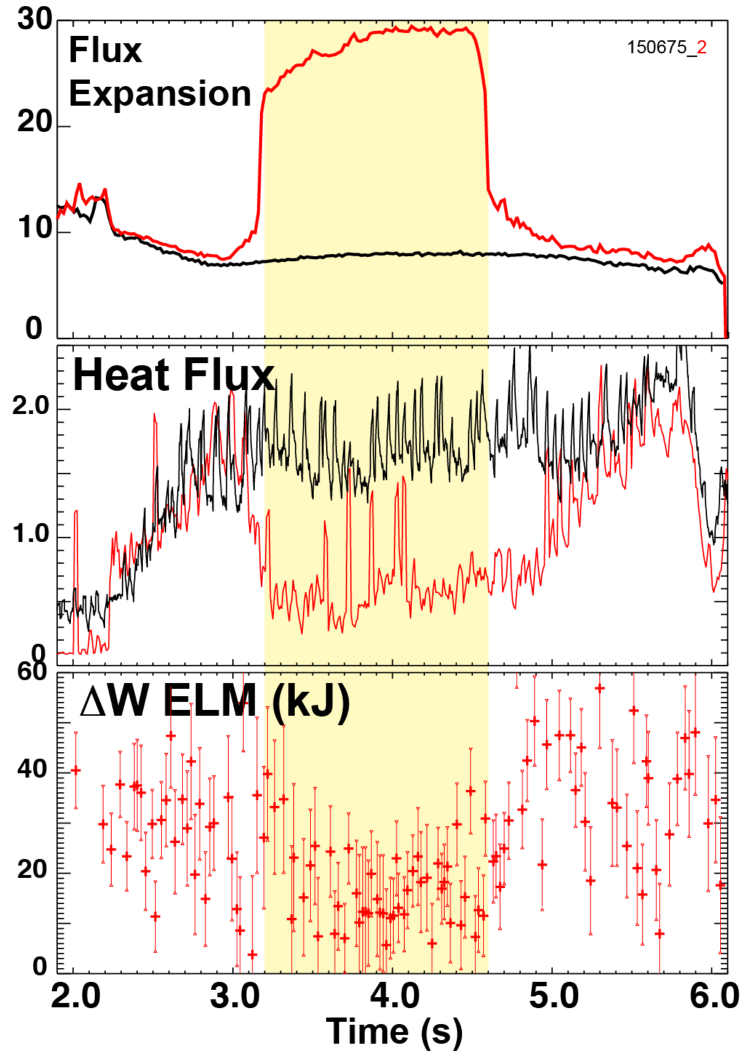
Initial DIII-D snowflake divertor results very encouraging and motivate further studies

- ✓ **Demonstrated steady-state (2 s) snowflake-minus and plus configurations at $\sigma = d_{X\text{-}X}/a_{minor}$=0.15-0.20**
  - Optimized divertor geometry and plasma shape for pedestal profile measurements, analysis commencing
- ✓ **Demonstrated beneficial magnetic geometry properties**
- ✓ **Demonstrated between-ELM peak divertor heat flux reduction via geometry**
  - ✓ Favorable comparison with standard divertor geometry
  - ✓ Snowflake divertor attached at P_{NBI}=3-5 MW , 0.5 x n/n_G
  - ✓ High confinement maintained (HL89~2.1, H98(y,2)~1.2-1.3)
- ✓ **Demonstrated radiative detachment at 0.55-0.75 x n/n_G**
  - ✓ Density scan using D_2 puffing
  - ✓ Significant reduction of peak divertor heat flux, $P_{div\text{-}rad} \leq 0.75\ P_{tot}$
  - ✓ Formation of MARFE-like X-point region outside of separatrix (?)
  - ✓ Up to 20 % confinement degradation at higher densities

Snowflake divertor configuration reduces ELM and steady state heat flux



- SF configuration reduces heat flux 2-3X by flux expansion
- Divertor heat flux reduced
- ΔW(ELM) reduced
- Core confinement (H98 > 2) and pedestal constant



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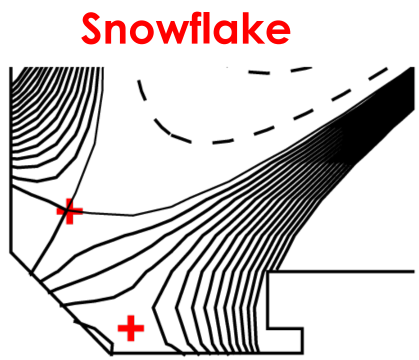
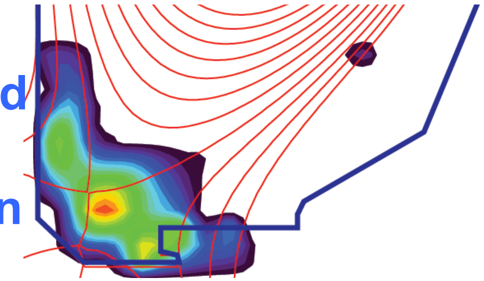
Recent DIII-D Snowflake divertor experiments show heat flux reduction by flux expansion, ELM reduction



Increased Divertor Radiation



- SF configuration reduces heat flux 2-3X by flux expansion
- Divertor heat flux reduced
- ΔW(ELM) reduced
- Core confinement (H98 > 2) and pedestal constant
- ELM heat flux reduced dramatically with gas puffing

Reduced Divertor Heat Flux