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LLNL-CONF-707157

Progress in snowflake divertor research in DIII-D, NSTX and NSTX-U.

V. A. Soukhanovskii

October 27, 2016

58th Annual Meeting of the APS Division of Plasma Physics
San Jose, CA, United States
October 31, 2016 through November 4, 2016

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Poster TP10.00068
58th Annual Meeting of the APS Division of Plasma Physics
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LLNL-CONF-707157
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

NSTX-U DIII-D Lawrence Livermore National Laboratory

Co-authors and Acknowledgements

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R. E. Bell, A. Diallo, S. P. Gerhardt, S. Kaye, B. P. LeBlanc, J. E. Menard, M. Podesta, *PPPL*

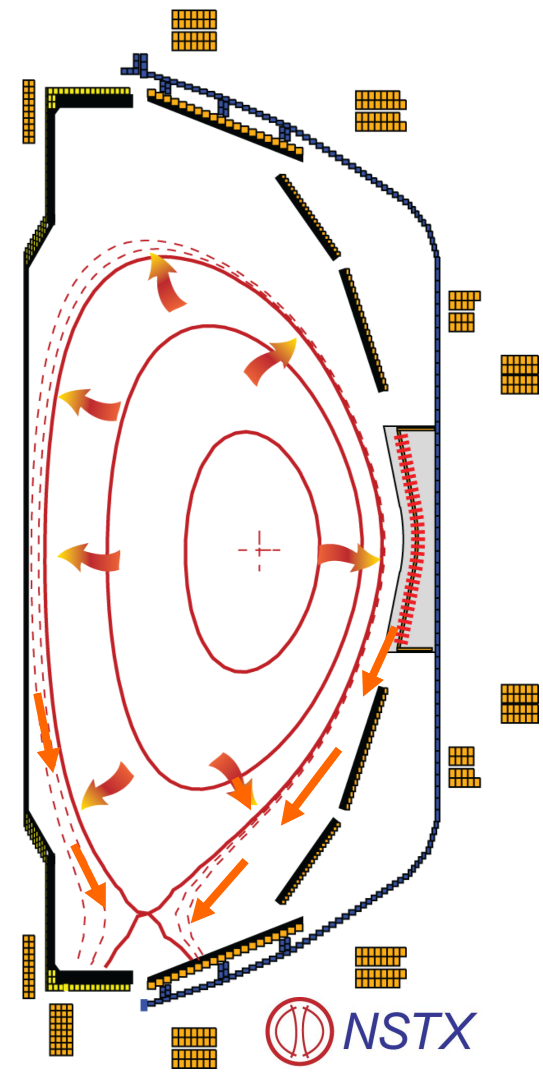
This work is supported by the US DOE under DE-AC52-07NA27344, DE-AC02-09CH11466, DE-FC02-04ER54698.

Outline

1. Introduction and previous results
2. Magnetic feedback control developments
3. Core and pedestal analysis of H-mode plasmas with the snowflake divertor
4. Edge localized modes with the snowflake divertor
5. Radiative snowflake divertor studies with CD_4 injection
6. Preparation for NSTX-U experiments

Significant gaps exist between present divertor solutions and future device requirements

- **Critical divertor tasks**
  - Power exhaust
  - D/T and He pumping
  - Impurity source reduction
  - Impurity screening
- **Outstanding issues**
  - Steady-state heat flux
    - Technological limit $q_{peak} \leq$ 5-15 MW/m^2
    - ITER: $q_{peak} \leq$ 10 MW/m^2 (Mitigated)
    - DEMO: $q_{peak} \leq$ 150 MW/m^2 (Unmitigated)
  - ELM energy, target peak temperature
    - Melting limit 0.1-0.5 MJ/m^2
    - DEMO: Unmitigated, $\geq$ 10 MJ/m^2
  - Impurity erosion
    - Divertor target T_e < 5-10 eV



Divertor strike point heat flux mitigation using radiated power loss and magnetic / PFC geometry

Radiated power loss
Increase via V_{div}, $L_{||}$

Poloidal target inclination, up-down, in-out fractions, N divertors

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

Increase plasma-wetted area

Increase divertor area at large R_{SP}

Increase λ_q via increased radial transport

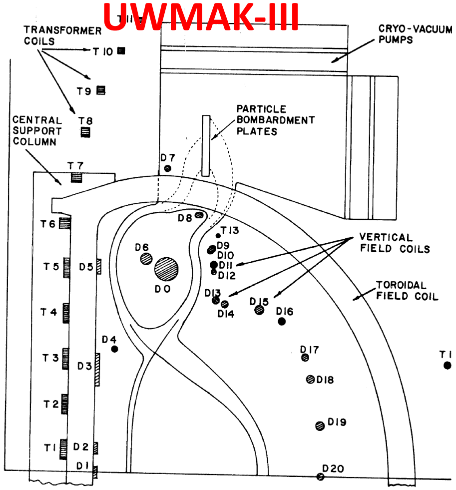
Increase plasma-wetted area via increasing f_{exp}

- **Divertor physics is inherently 2D or even 3D**
  - Parallel / cross-field transport and turbulence
  - Radiation front (detachment) stability
  - Neutral pressure / density distribution

- **Important engineering aspect – divertor coil layout**

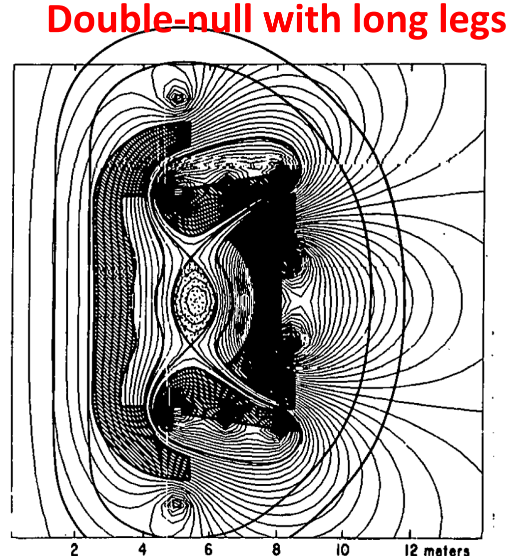
Focus on magnetic geometry since early days of tokamak studies. Some examples (R_{SP}, $L_{||}$, f_{exp}) …

UWMAK-III



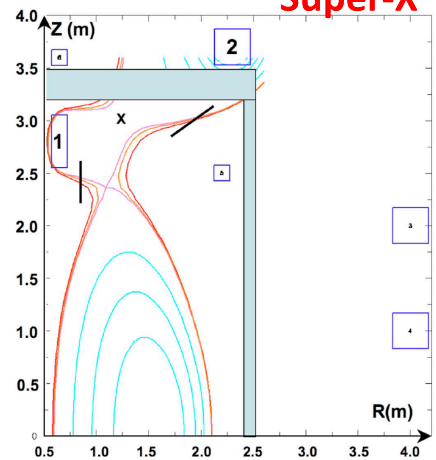
B. Badger et.al, U. Wisc. Report UWFDM-150, 1975

Double-null with long legs



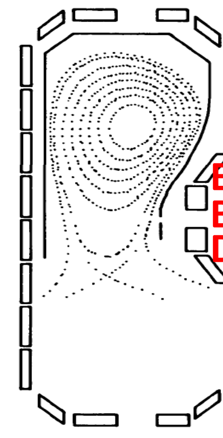
F. H. Tenney, PPPL Report 1284, 1976

Super-X



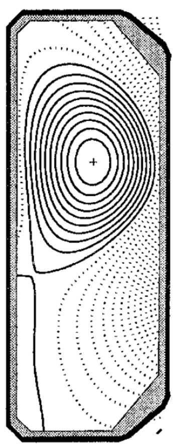
P. M. Valanju et.al, Phys. Plasmas 16, 056110 (2009)

Expanded Boundary, Doublet III

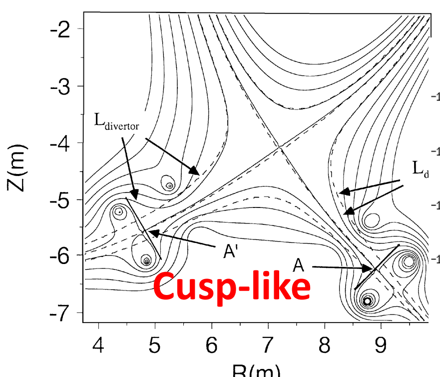


N. Ohyabu et. al, Nucl. Fusion 5 519 (1981)

TCV

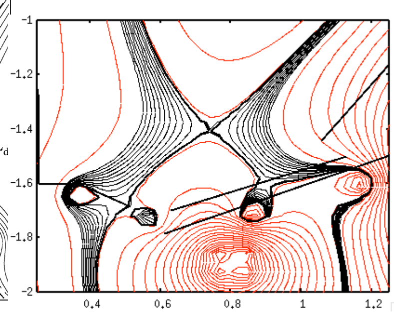


R. A. Pitts et. al, JNM 290-293, 2001, 940

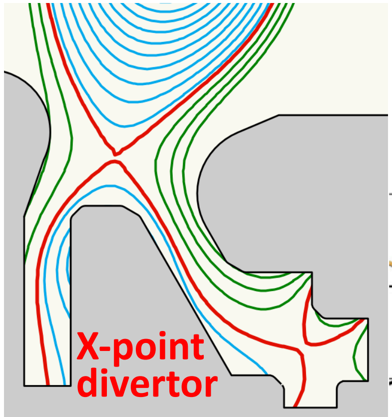


H. Takase, J. Phys. Soc. J. 70, 609, 2001

X-divertor

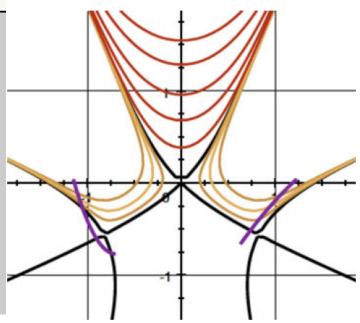


M. Kotschenreuther et. al, IAEA FEC 2004; Phys. Plasmas 14, 072502 (2007)



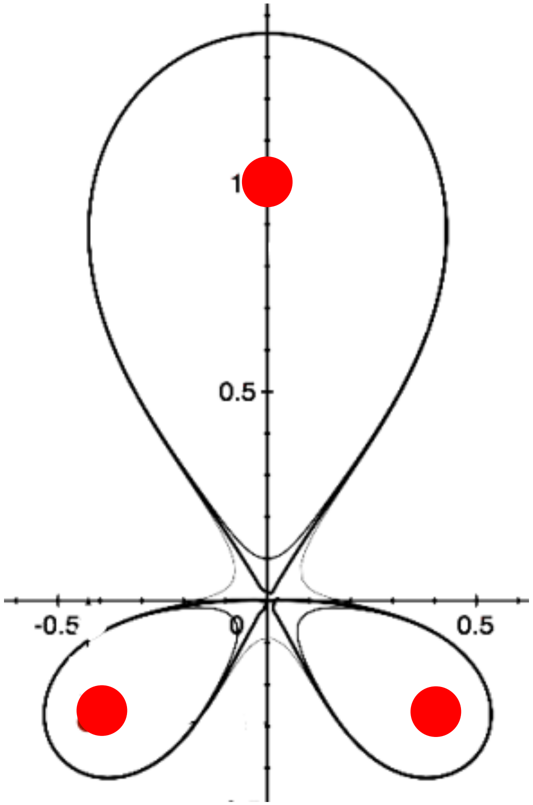
B. LaBombard et.al, NF 55 (2015) 053020

Super-cusp with Remote coils



D. D. Ryutov, J. Plasma Phys. 2015, 81, 495810516

Snowflake divertor configuration as a tokamak divertor power exhaust concept



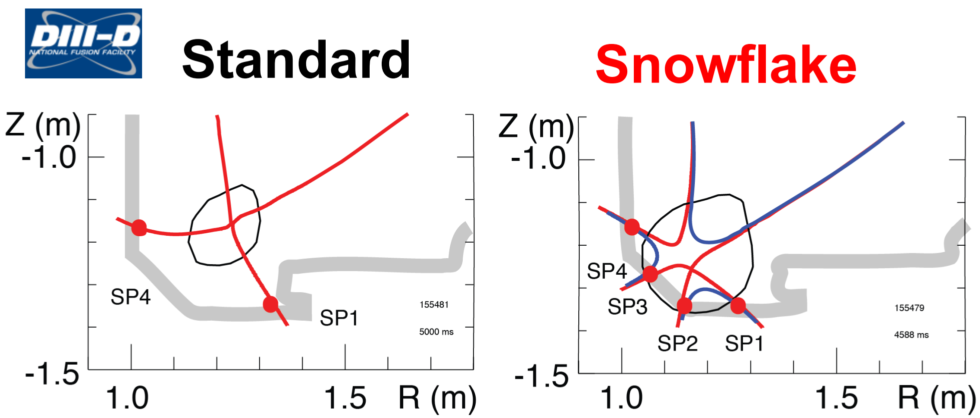
- **Snowflake, 2^{nd} order null**
  - $B_p \sim 0$, $grad\ B_p \sim 0$
    (Cf. first-order null: $B_p \sim 0$)
  - $B_p(r) \sim r^2$ (Cf. first-order null: $B_p \sim r$)
  - Four divertor legs
- **Geometry benefits**
  - Higher edge magnetic shear
  - Larger plasma wetted-area A_{wet} (f_{exp})
  - Larger parallel connection length $L_{||}$
  - Larger effective divertor volume V_{div}

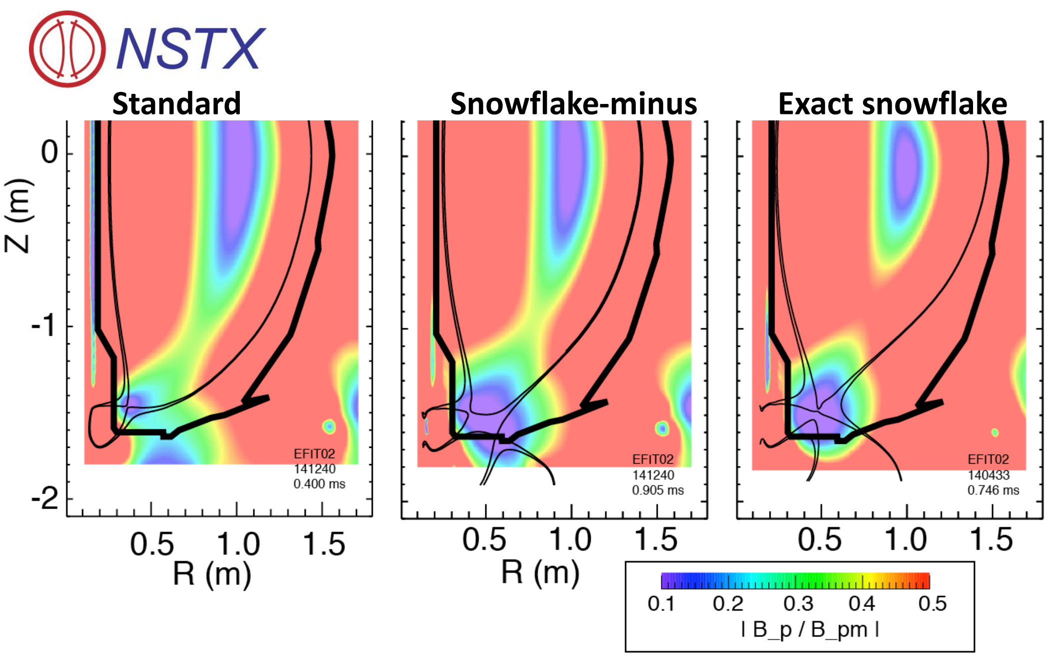
  To maximize geometry benefits: $d_{XX} \leq a\ (\lambda_q\ /a)^{1/3}$
- **Transport benefits**
  - High convection zone with radius D*
  - Power sharing over four strike points
  - Enhanced radial transport (larger l_q)

  To maximize sharing: $d_{XX} \leq D^* \sim a\ (a\ \beta_{pm}\ /\ R)^{1/3}$

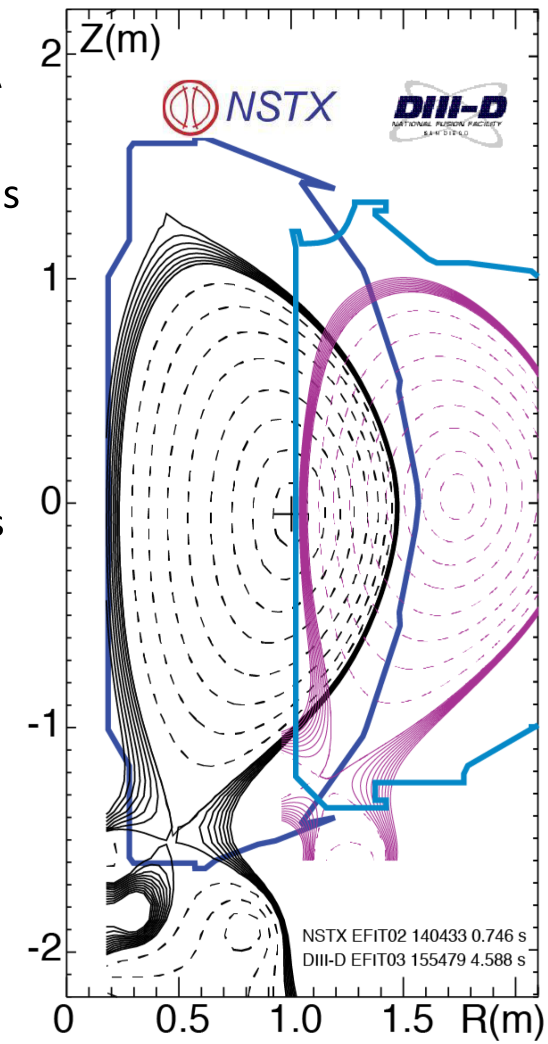
D. D. Ryutov, PoP 14, 064502 2007;
PPCF 54, 124050 (2012)

Snowflake configurations obtained in NSTX and DIII-D using existing PF coils





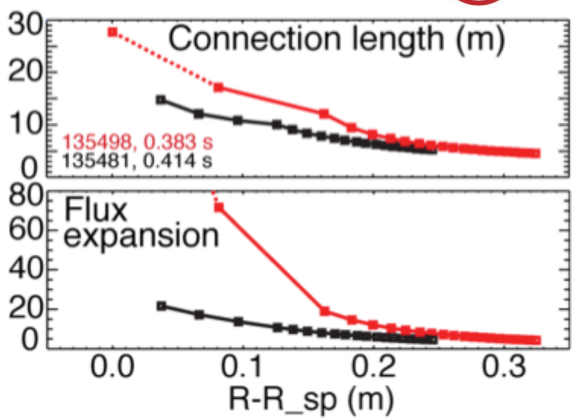
- NSTX
  - I_p=0.8-1.0 MA
  - B_t≤0.45 T
  - 3 divertor coils
  - SF for 0.5 s
- DIII-D
  - I_p=0.8-1.0 MA
  - B_t=2 T
  - 3 divertor coils
  - SF for 2-3 s

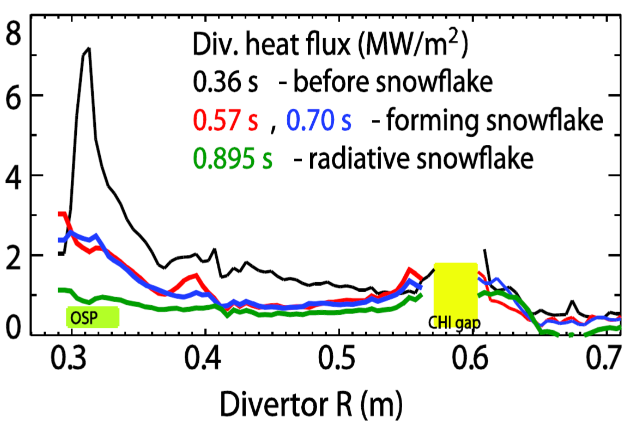


Peak divertor heat flux significantly reduced due to snowflake divertor geometry effects

Standard **Snowflake**

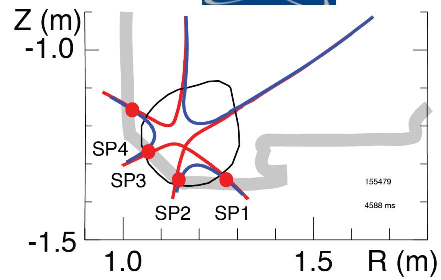
NSTX

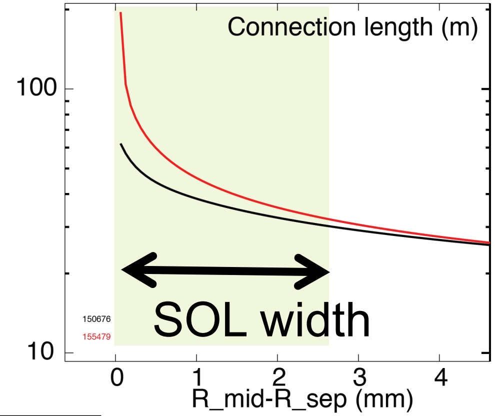




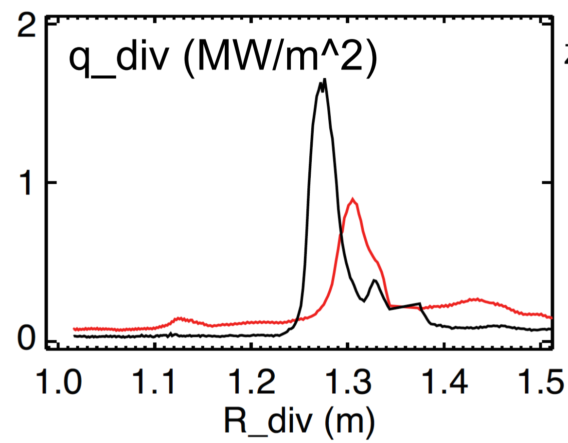
- Due to geometry and radiation

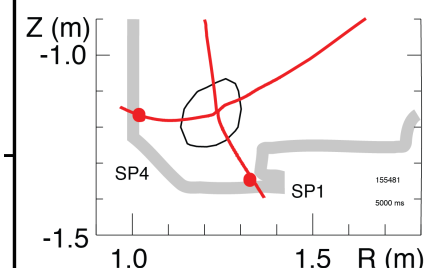
DIII-D





Snowflake

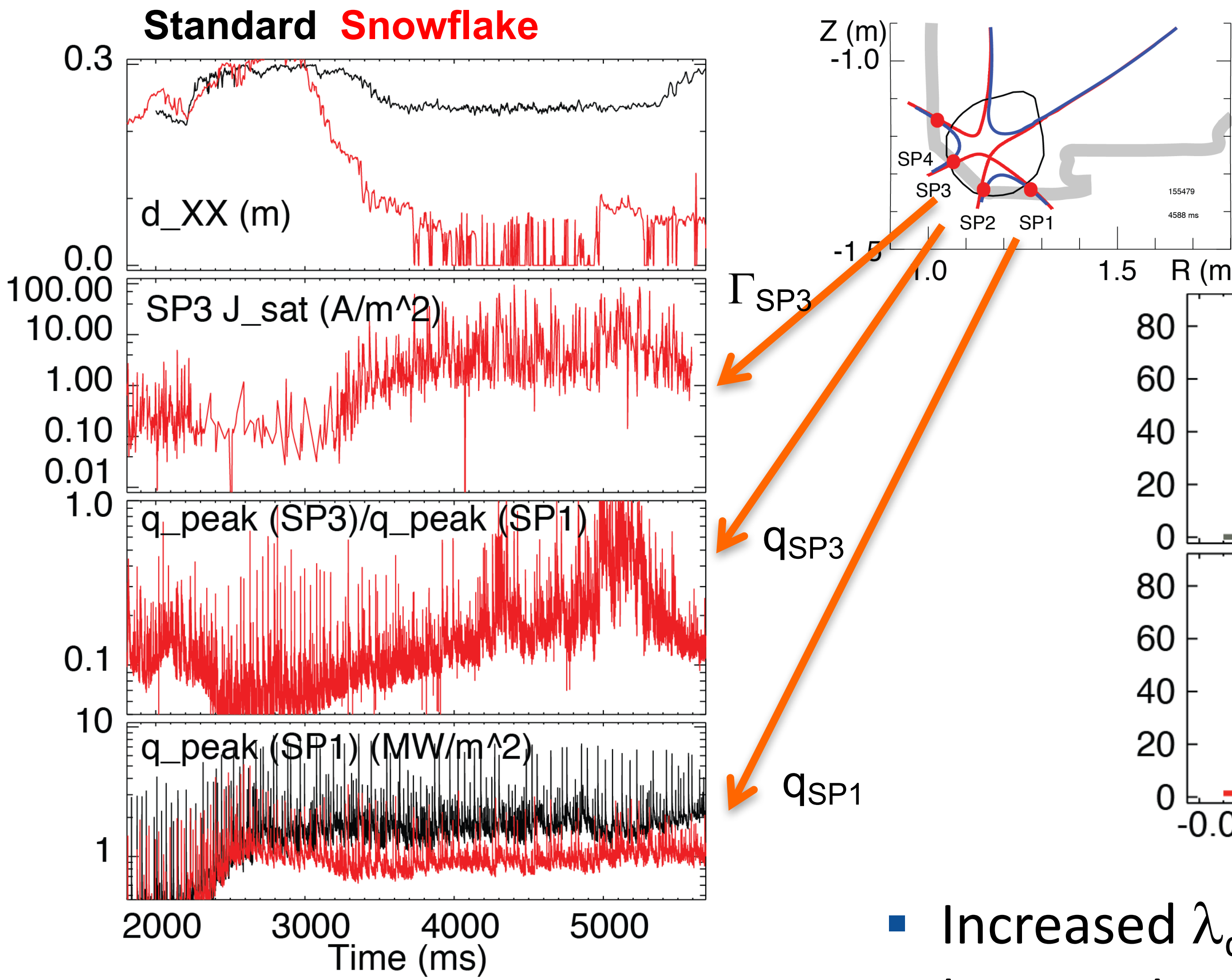


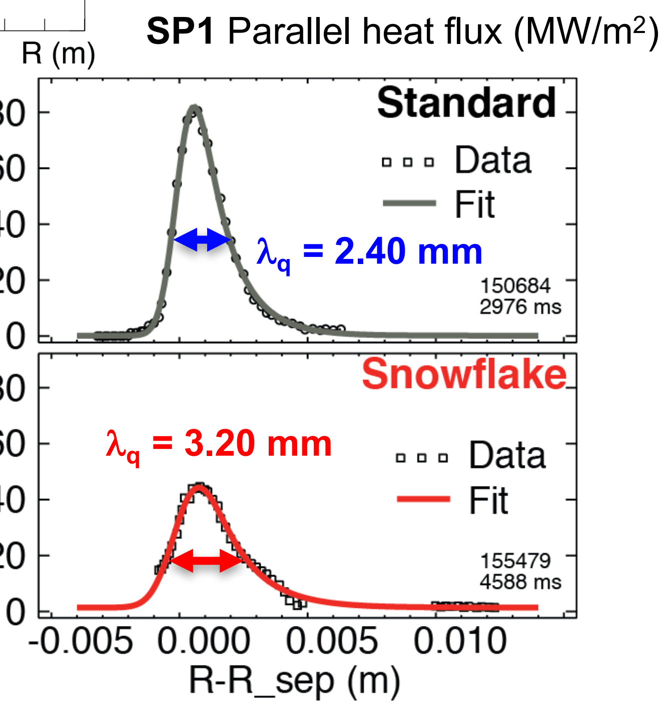


Standard

- Flux expansion increased ~20%
- $L_{||}$ increased by 20-60% over SOL width
- Divertor heat flux reduced ~40%

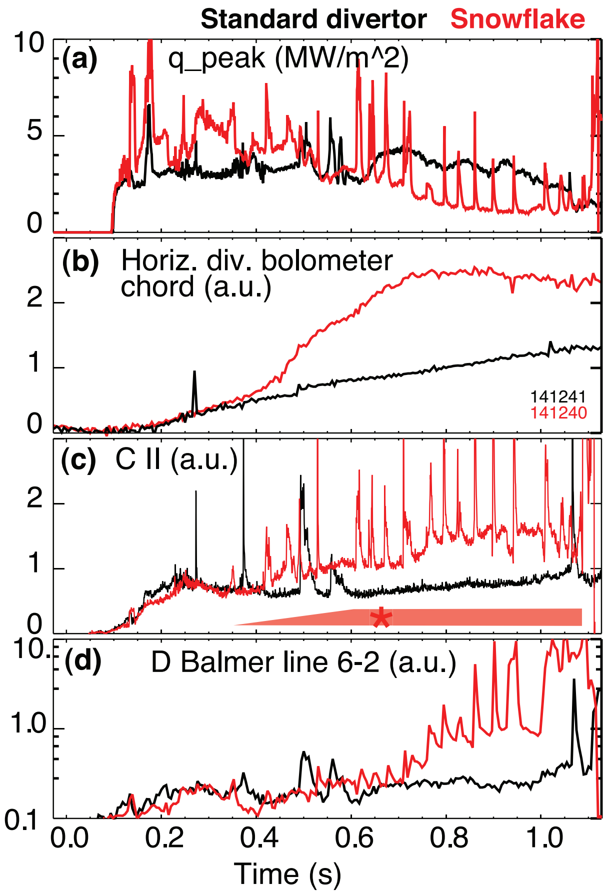
Snowflake divertor enables power and particle sharing over multiple strike points





- Increased λ_q may imply increased transport

Snowflake configuration favorably affects divertor radiation and detachment

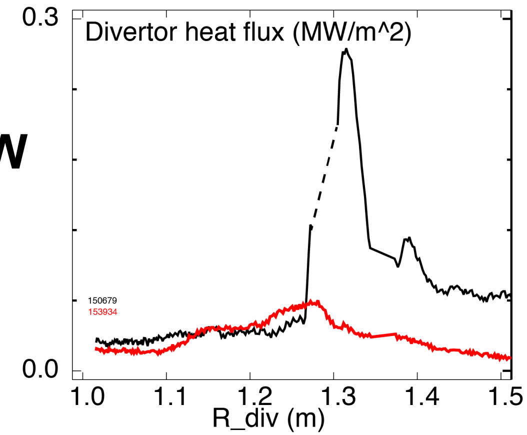


NSTX

P_{SOL} = 2-3 MW

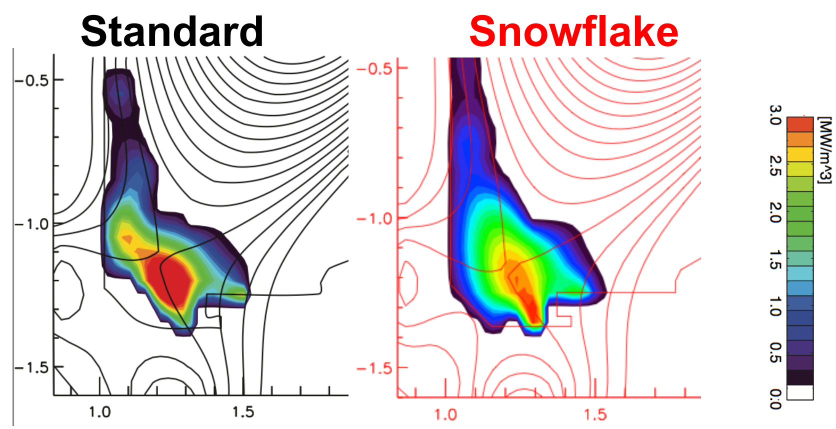
DIII-D

P_{SOL} = 3-4 MW



Radiative Standard

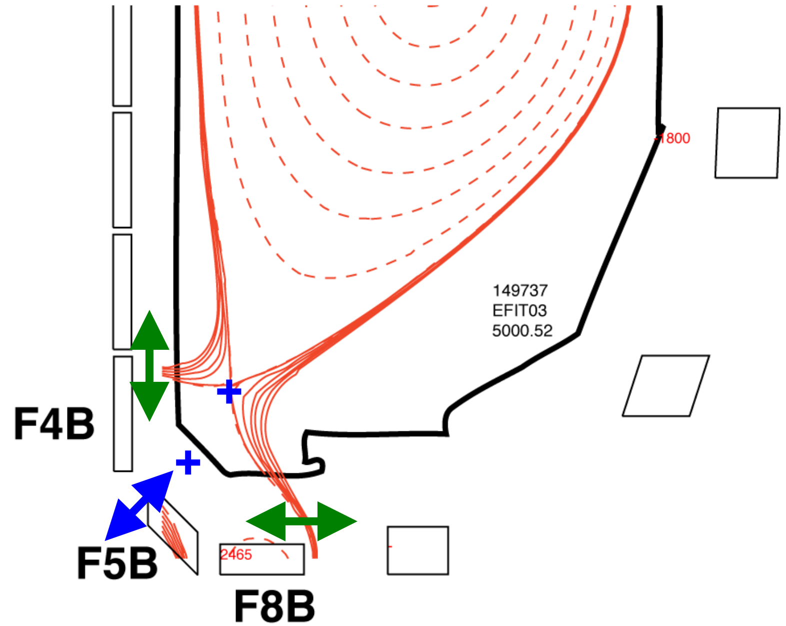
Radiative Snowflake



- Natural partial detachment in NSTX snowflake otherwise inaccessible with standard divertor
- Broader radiated power distribution, nearly complete power detachment in DIII-D

Continuing development of real-time snowflake configuration control

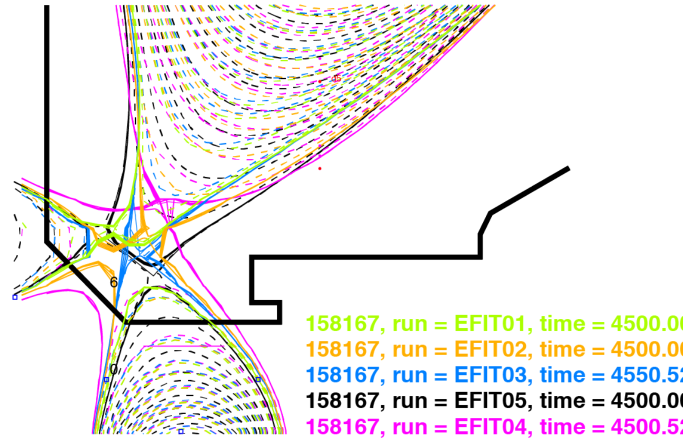
- Statement of problem - need to control
  - positions and orientation of two nulls
  - general null and strike point positions
- Grad-Shafranov equilibria modeling of possible configurations
- Present approach
  - Use rtEFIT for B_r and B_z (limited spatial resolution 65x65 grid)
  - Use B_r and B_z with Makowski's algorithm to infer null positions
  - Problem may be underdetermined
  - Limited success at DIII-D with small inter-null distances
- Inner and outer strike point positions controlled by PCS using F4B and F8B coils
- Secondary null-point formed and pushed in using F5B

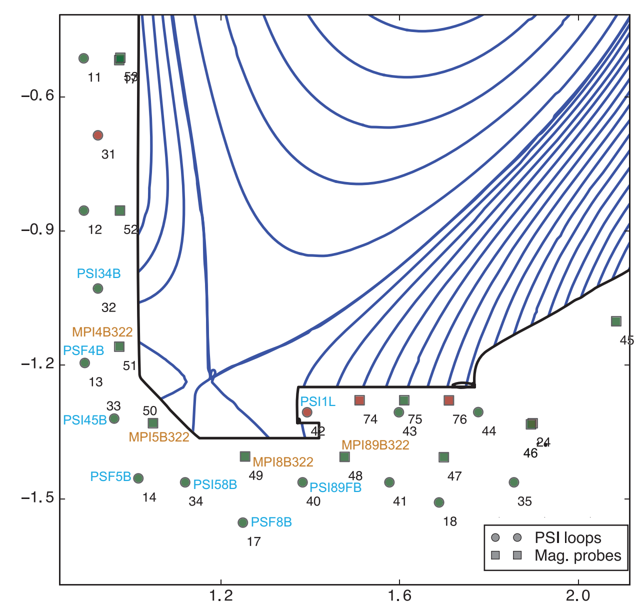


P. Vail, NP10.00008

Progress made in real-time control but several issues are still outstanding

- Often heat flux footprint and divertor impurity emission distribution from cameras differ from expectations from equilibria
- Often EFIT01, EFIT02 and kinetic EFIT show different equilibria
  - JT (magnetics) vs MSE (q-profile)
  - q profile affected by SF configuration
- rtEFIT is presently 65x65
  - Additional magnetic sensors for additional divertor flux constraints ?
- Near-term plan – rtEFIT
  - Consider improvements to Makowski's algorithm
  - Study how EFIT constraints affect equilibria and snowflakes
- Consider direct sensor-based control
  - Additional magnetic sensors for additional divertor flux constraints ?

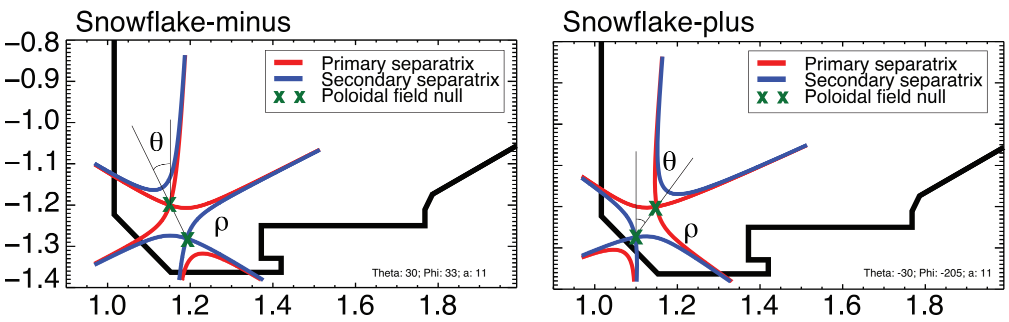


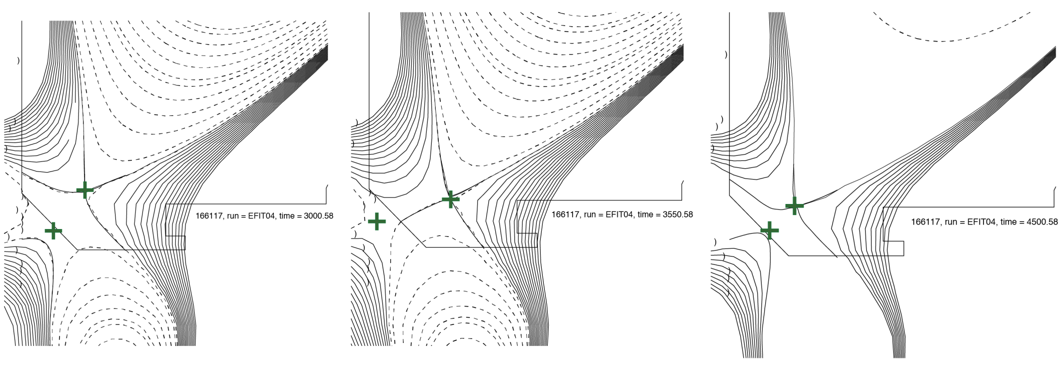


Progress made in real-time control but several issues are still outstanding

- Inter-null distance control works
- Angle control does not work

P. Vail, NP10.00008

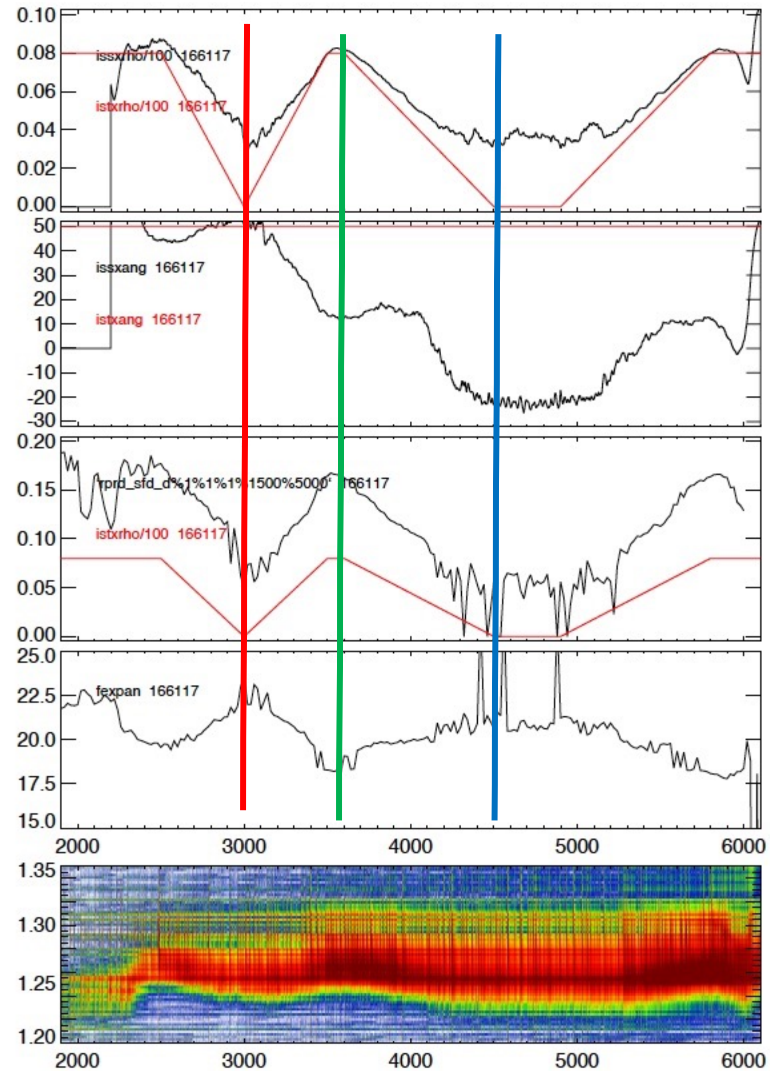




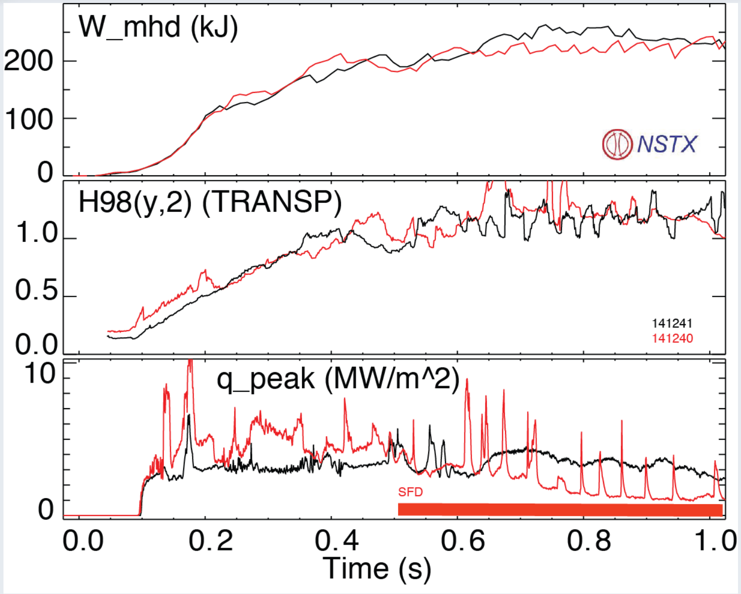
3000 ms

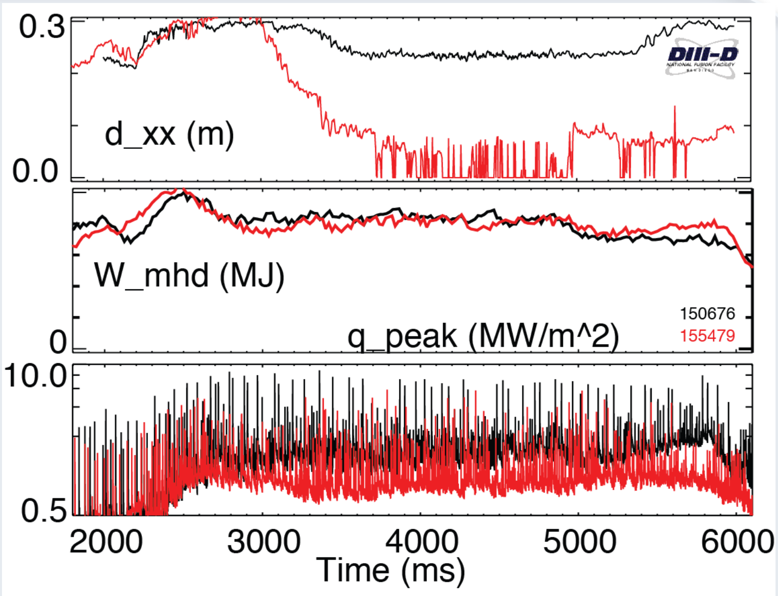
3550 ms

4500 ms



Spatially extended region of very low B_p may affect pedestal stability, transport and ELMs



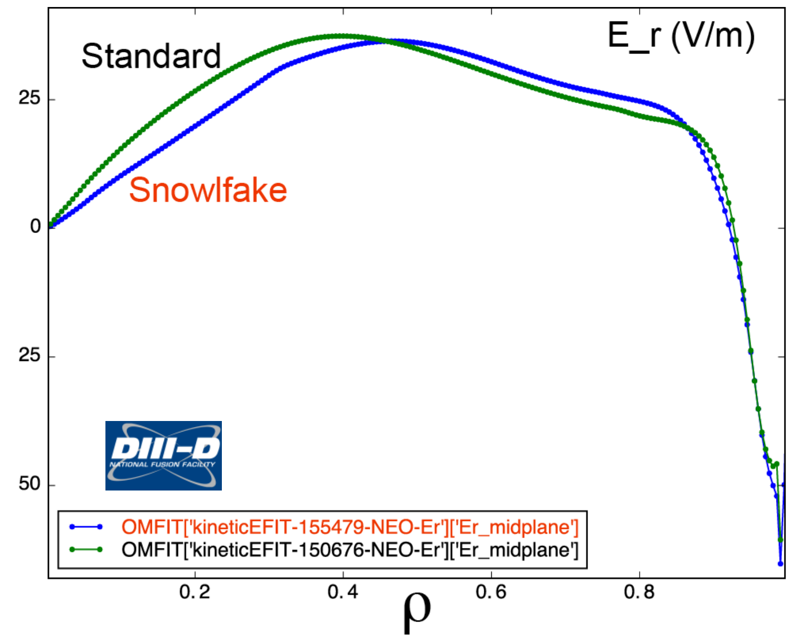


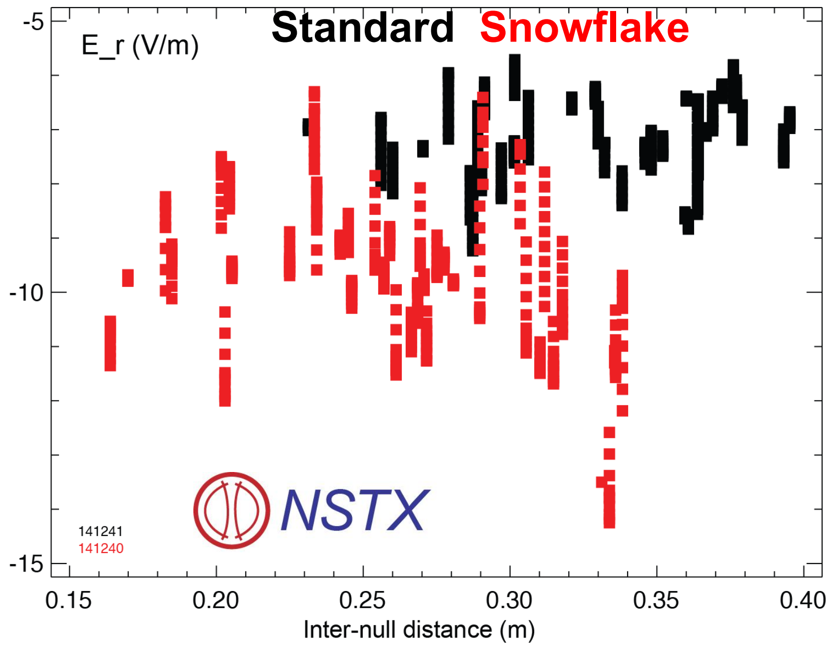
- H98(y,2) ~1.0-1.2, β_N~2
- Pedestal weakly affected

- Partial outer strike point detachment
- Destabilization of large Type I ELMs

- ELM stability can be affected by snowflake divertor configuration
  - Peeling (kink) modes driven by edge (bootstrap) current
  - Ballooning modes driven by edge pressure gradient
- Edge E_r in SF can be affected by enhanced X-transport (ion loss in divertor region)
- Collisionality and shaping are affected by snowflake configuration

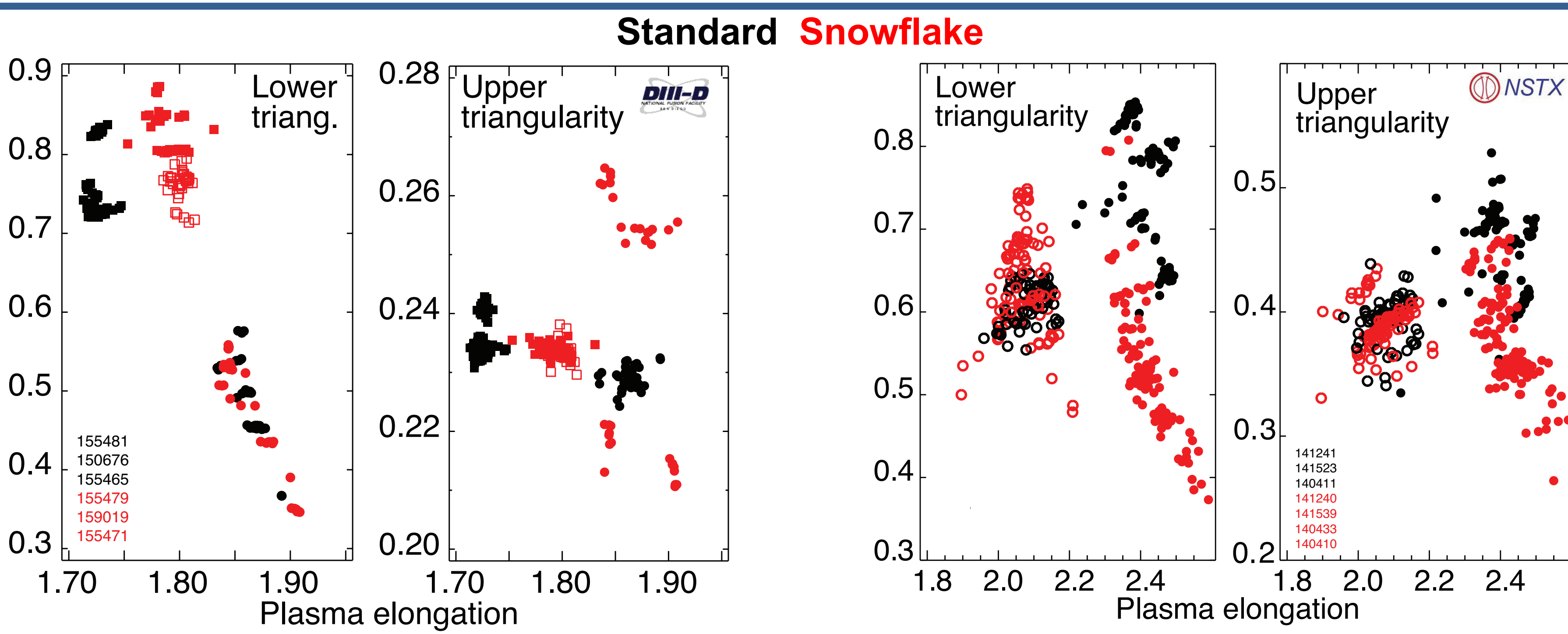
Edge radial electric field weakly affected by snowflake divertor in NSTX and DIII-D



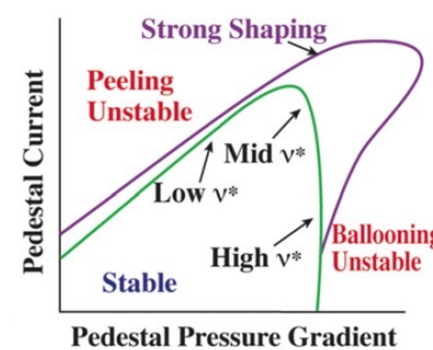


- E_r well depth and location may affect shear flow -> L-H transition
- In DIII-D, E_r well ~10% deeper (from profile analysis and NEO)
- In NSTX, edge E_r (as function of d_xx) also greater by 10-20 %
  - From edge force balance E_r=-$(vxB)_r$+grad p / Zen and v, p measurements

Plasma shaping enhanced as a result of transition from standard to snowflake divertor

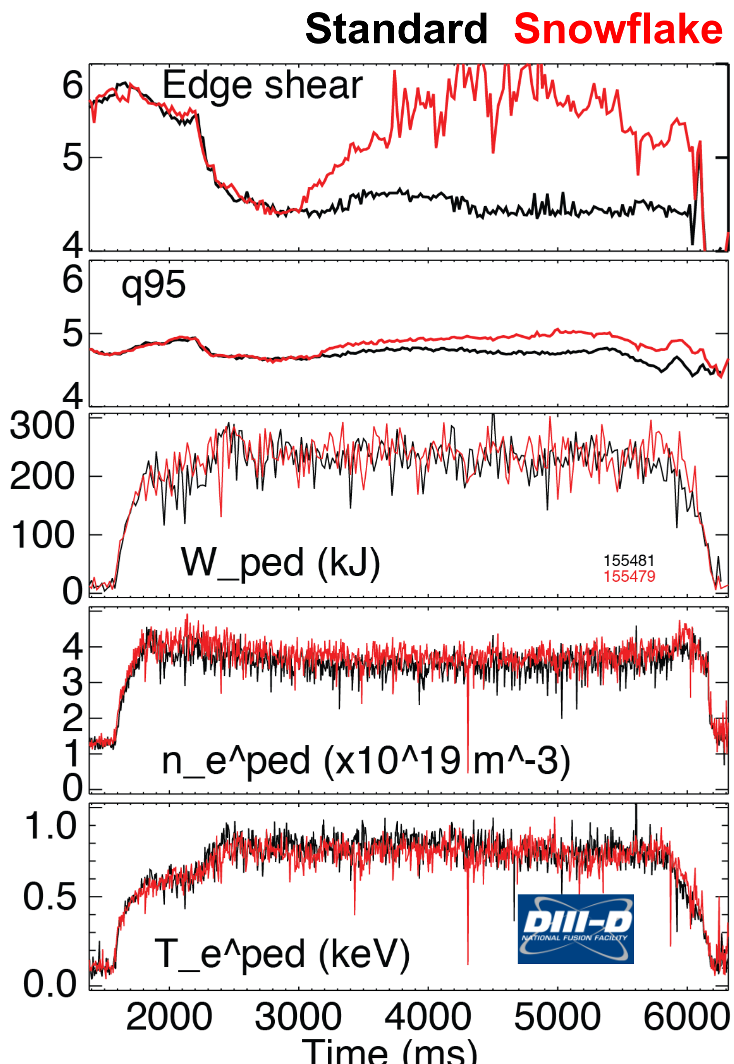


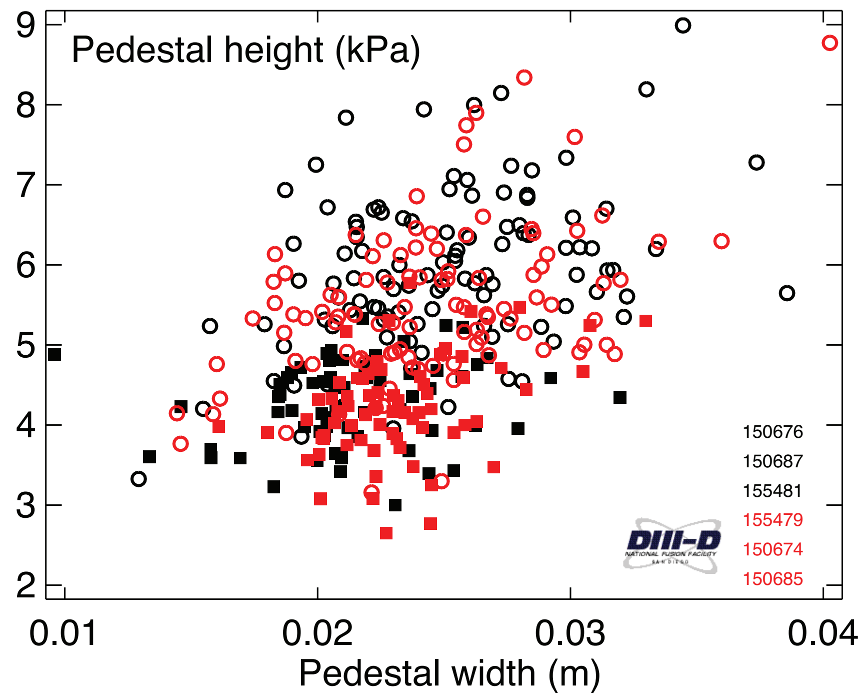
- DIII-D and NSTX: stronger shaping with SF (higher κ, δ)
- Stronger shaping could contribute to stabilizing certain modes
  - E.g., higher pedestal pressure – stabilizing effect on ideal ballooning modes



P. Snyder NF 2009

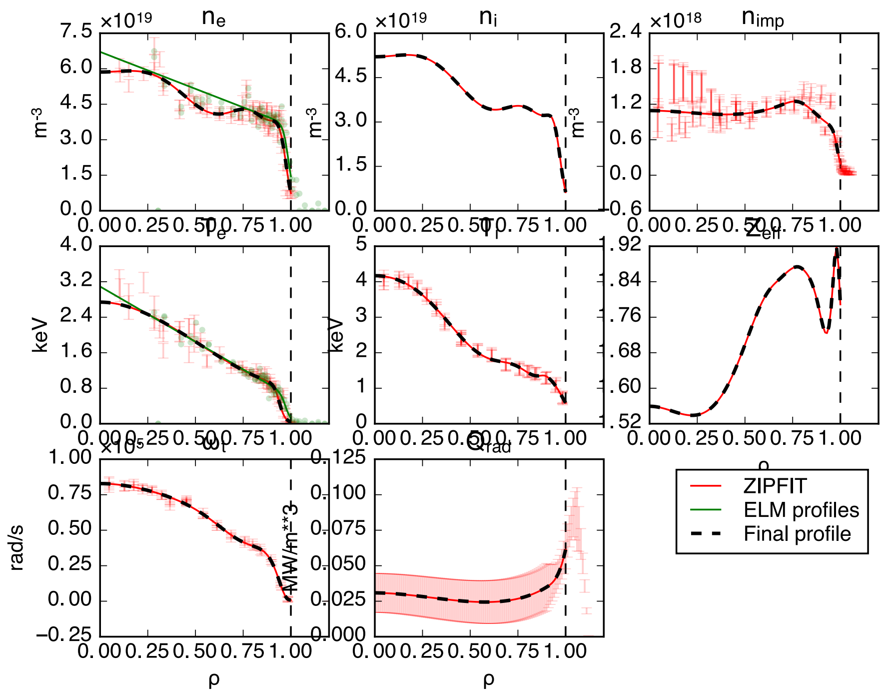
Pedestal kinetic profiles and structure are practically unaffected in DIII-D with snowflake divertor



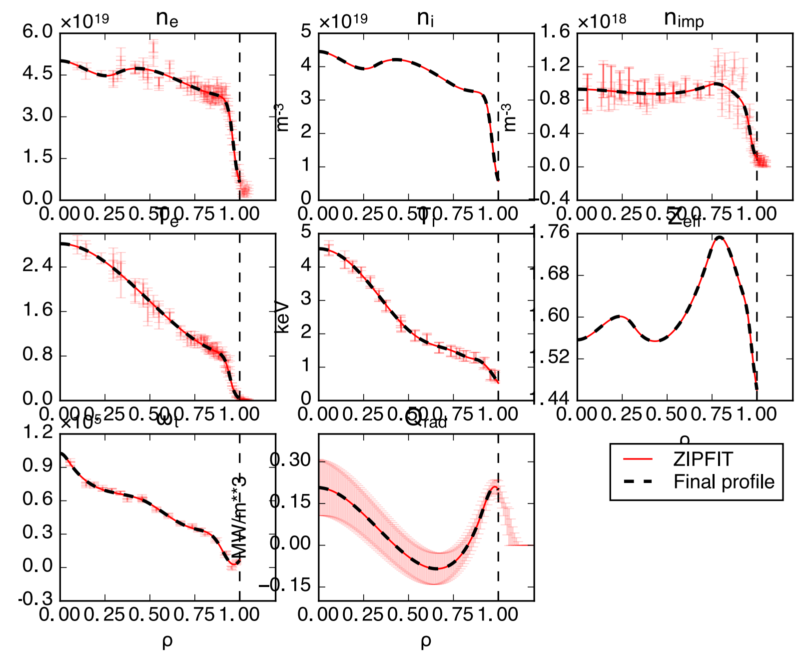


- Shear95, q95 increased by up to 30%
- Medium-size type I ELMs
- Pedestal height ~ W_{ped}, W_{MHD}
- Pedestal width ~ β_p^{ped}

DIII-D profiles



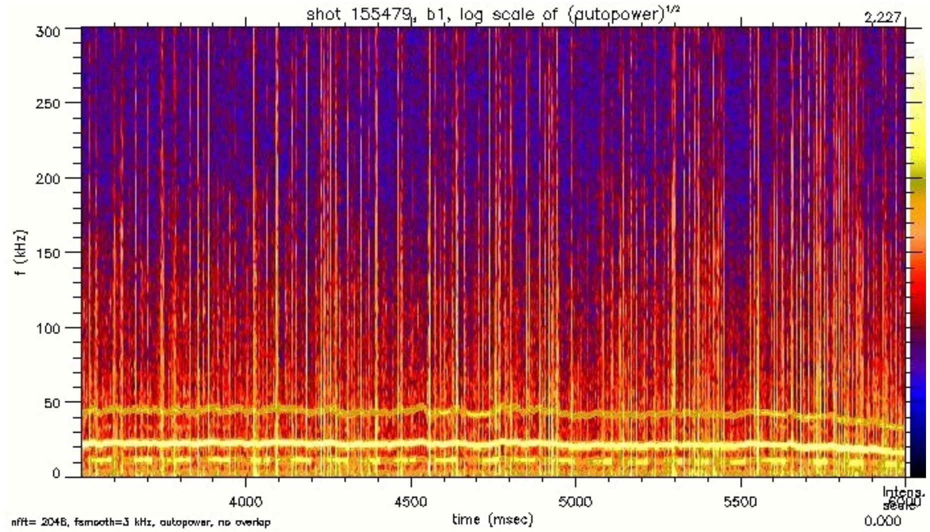
Standard

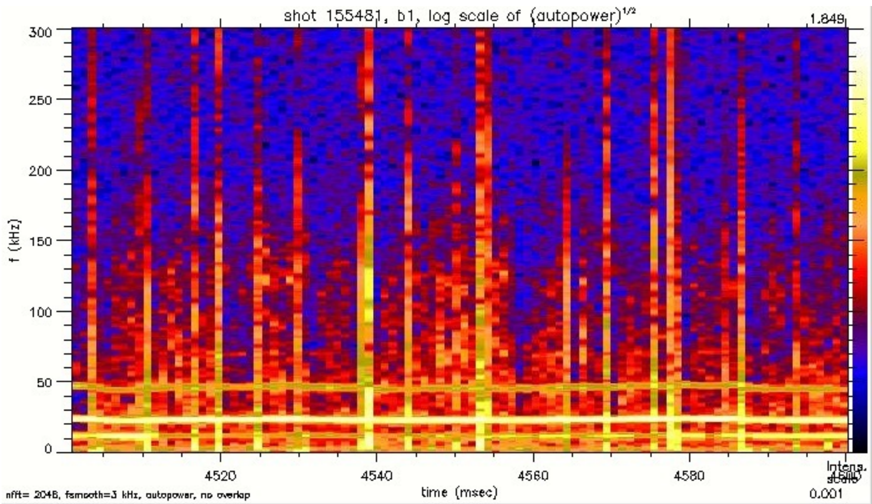


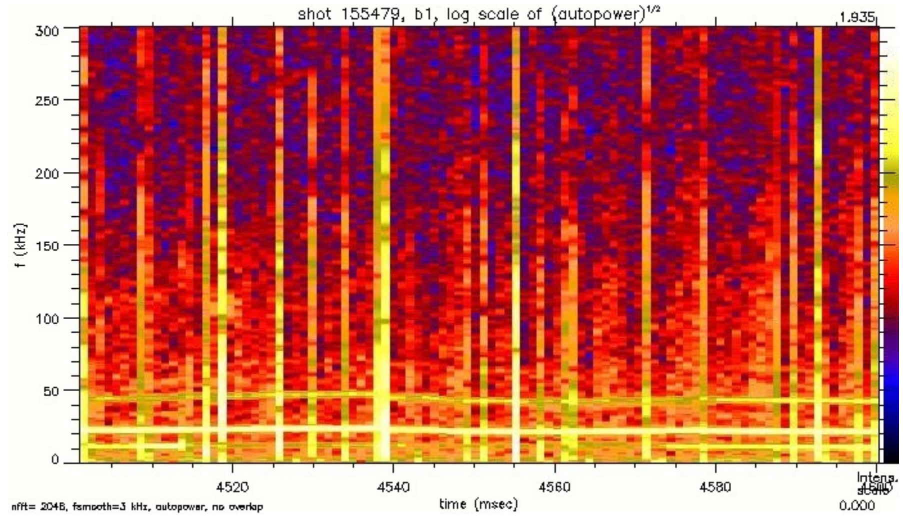
Snowflake

No significant difference in midplane between-ELM magnetic fluctuations between standard and snowflake configuration H-modes

- Mirnov probe at R=167 cm, z=0 cm
- FFT autopower spectrograms
- Slightly higher level of broadband magnetic fluctuations with snowflake

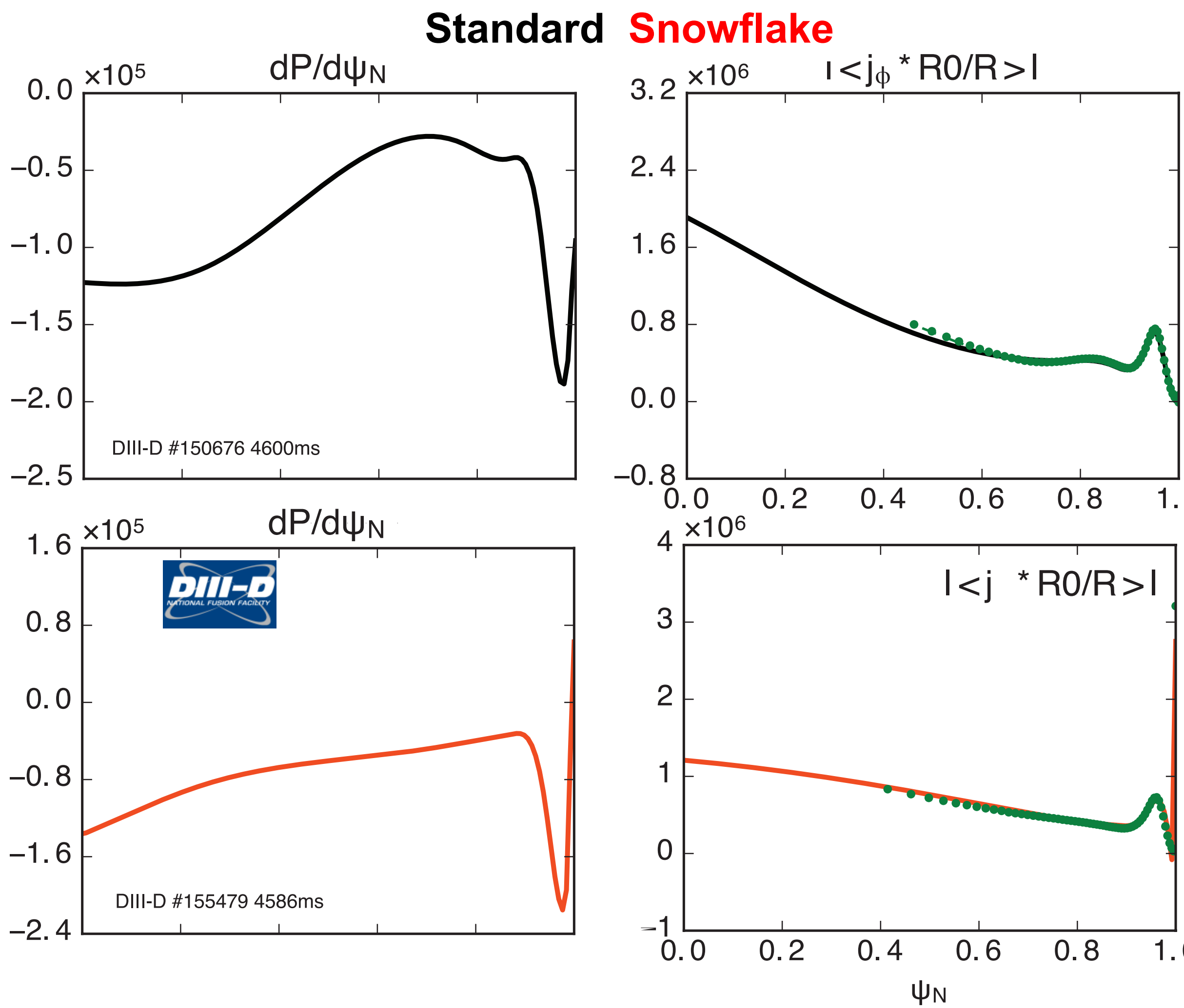






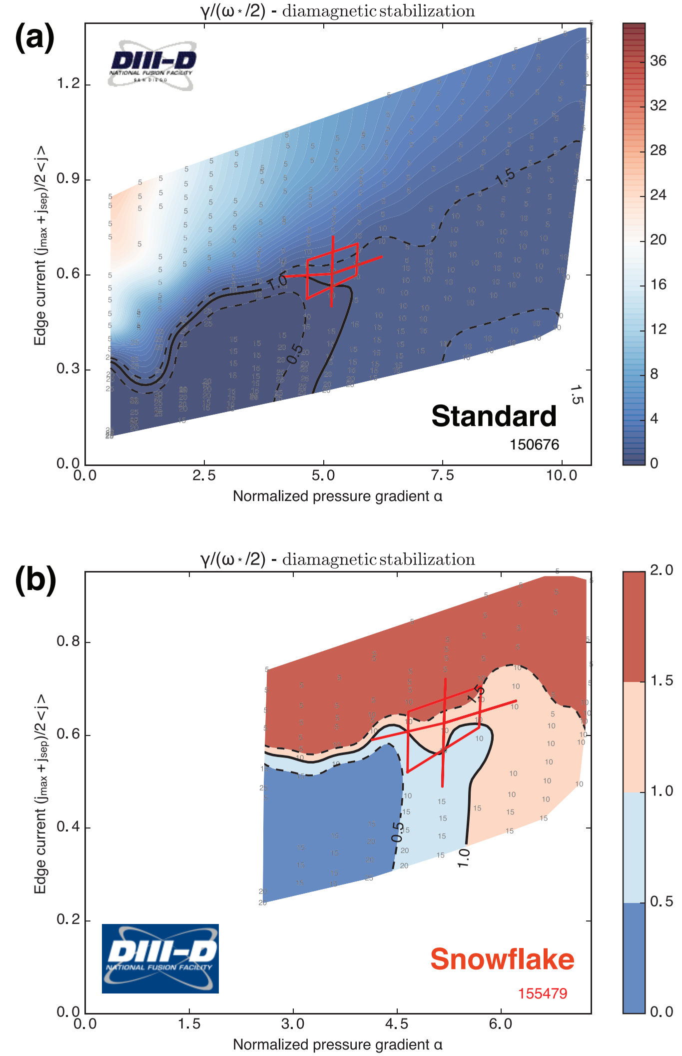
Snowflake divertor weakly affects edge pressure gradient and edge current in DIII-D

- Profiles analyzed with OMFIT
- Kinetic EFITs obtained
  - E_r self-consistently calculated by NEO
  - Fast ion pressure included from ONETWO
  - Edge current density also includes bootstrap current from NEO

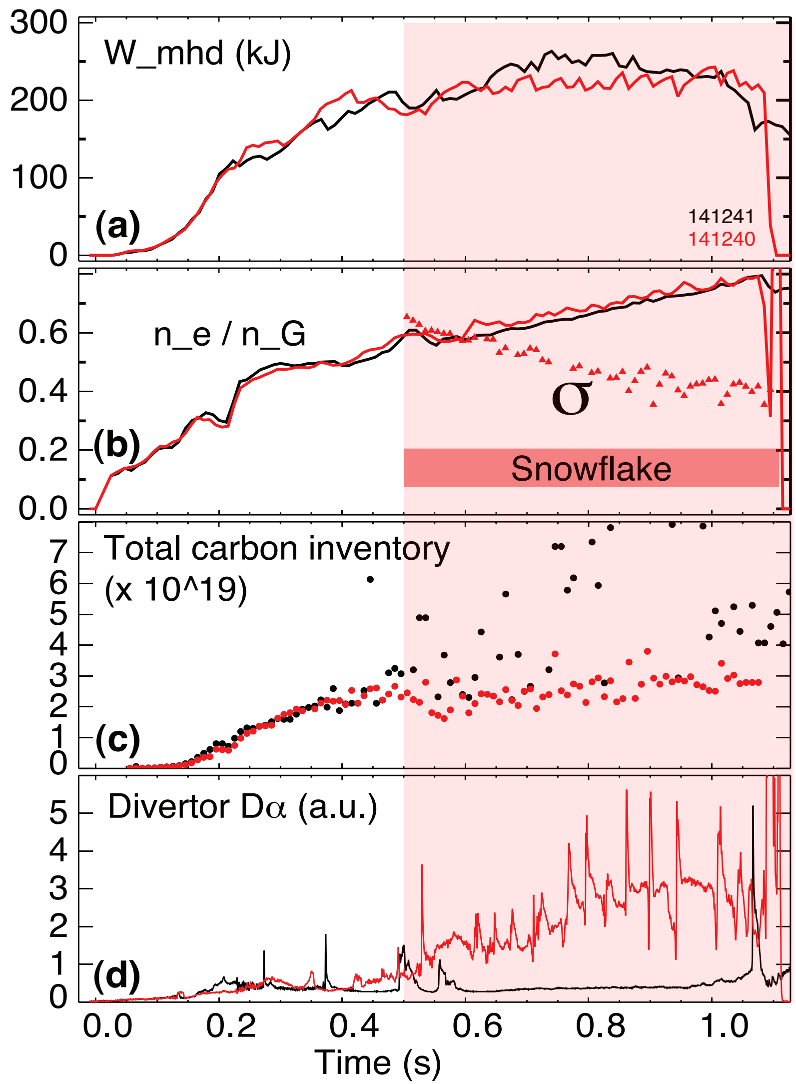


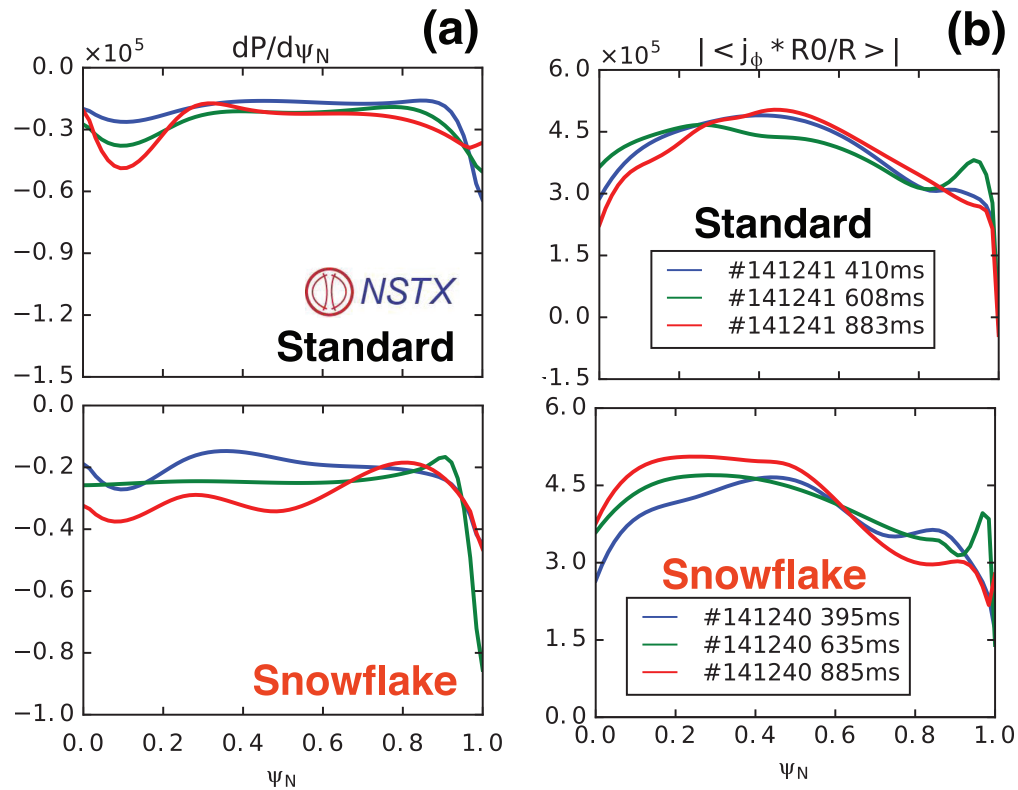
Weak changes in ELM regime with SF are consistent with ELITE calculations in DIII-D

- With both Standard and SF divertors, pedestal at the current-limiting side of stability boundary
  - Most unstable modes n=10, 15
- Stability calculated by ELITE
  - SNYDER, P. B. et al., Phys. Plasmas 9 (2002) 2037.
  - WILSON, H. R. et al., Phys. Plasmas 9 (2002) 1277.
- Pedestal current and pressure gradient operating space by VARYPED



In NSTX, large ELMs destabilized with snowflake formation

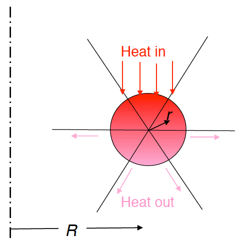


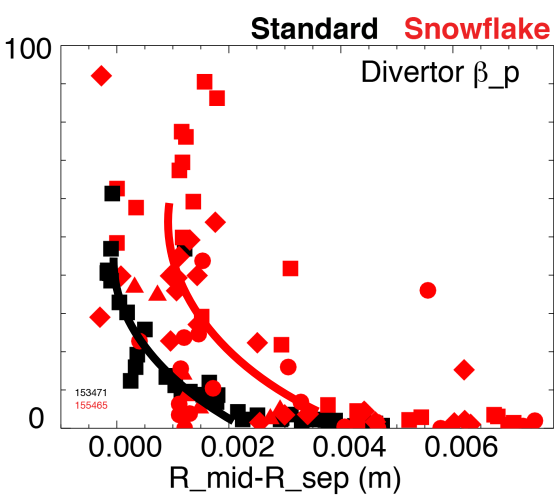


- With SF formation both dP/dψ and J(psi) first increase, then relax in radiative SF phase

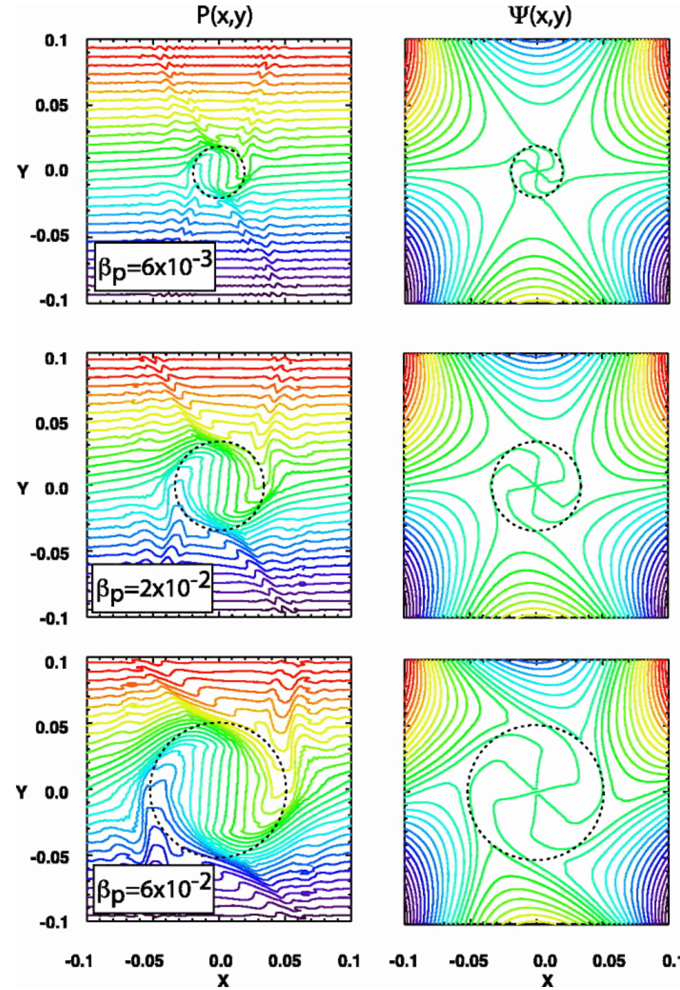
Convective plasma mixing driven by null-region instabilities may modify particle and heat transport in snowflake especially during ELMs

- Flute-like, ballooning and electrostatic modes are predicted in the low B_p region
  - $\beta_p = P_k/P_m = 8\pi P_k/B_p^2 >> 1$
  - Loss of poloidal equilibrium
  - Fast convective plasma redistribution
  - Especially efficient during ELMs when P_k is large



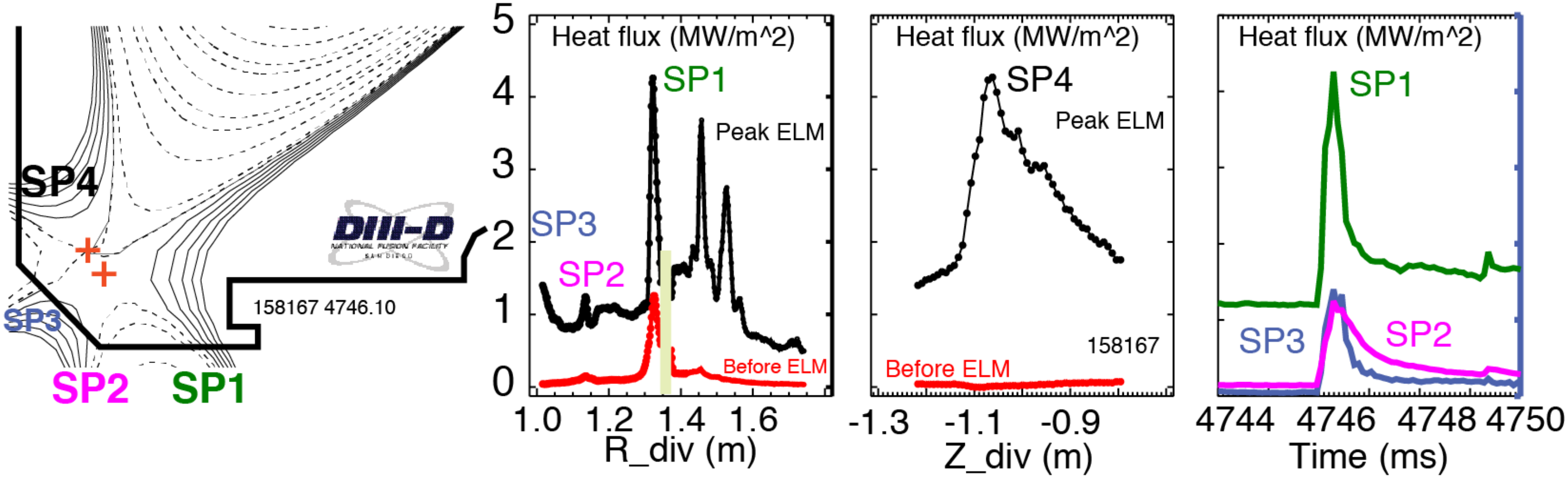


- Divertor null-region β_p measured in DIII-D divertor
  - In snowflake, broader region of higher β_p>>1
  - Cf. SOL β_p~0.01
  - Higher X10 during ELMs

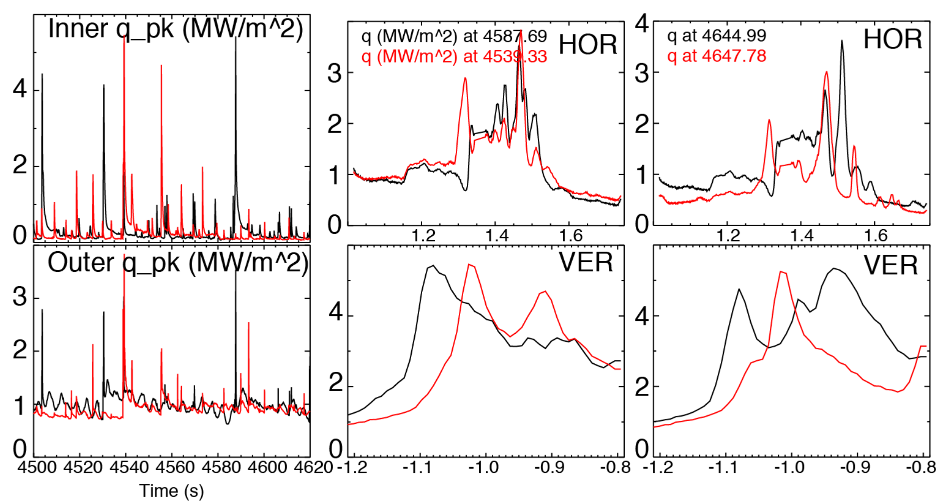


D. D. Ryutov et. al, IAEA 2012; Phys. Scripta 89 (2014) 088002
M. V. Umansky and D. D. Ryutov, Phys. Plasmas 23, 030701 (2016)

In DIII-D snowflake divertor, ELM heat is shared over additional strike points, peaks less (cf. st.div.)

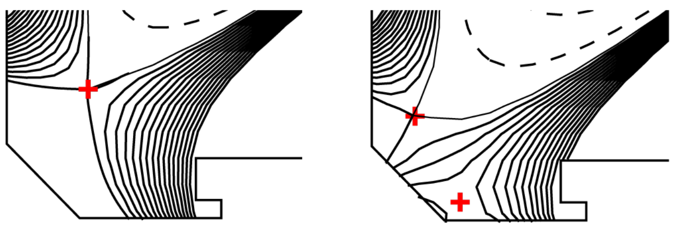


- In standard divertor, inner divertor receives less or equal heat than the outer divertor (cf. JET, ASDEX)
- In both standard and SF divertors, a large fraction of ELM heat is deposited outside of divertor SOL and not affected by divertor magnetic configuration



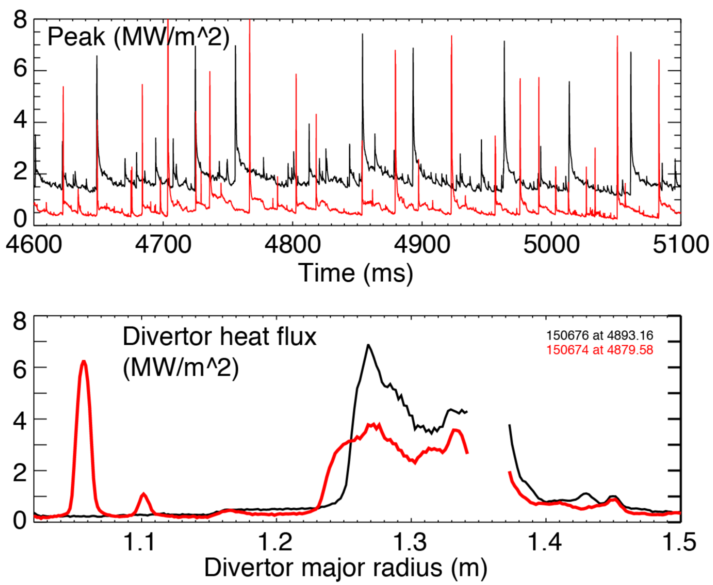
In DIII-D, Type-I ELM heat loads reduced in D_2-seeded (partially detached) snowflake divertor

Standard Snowflake

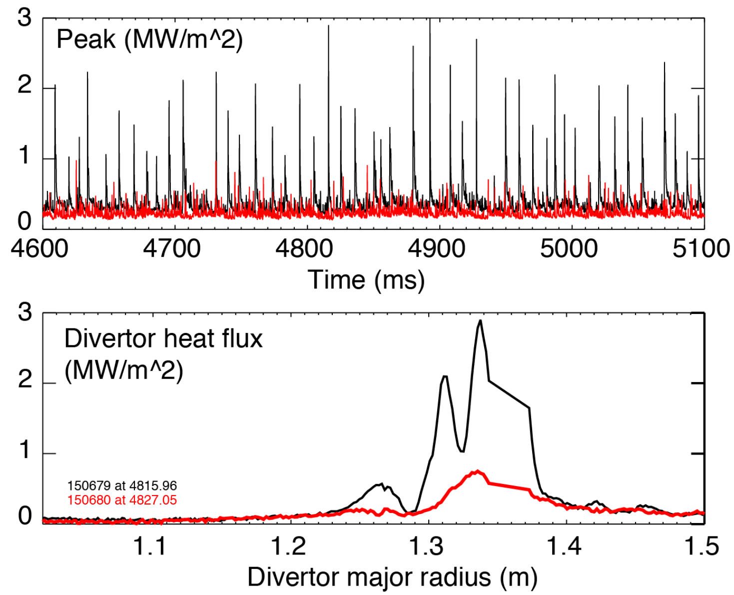


- At lower density, heat flux channels close to primary and second separatrices during ELMs
  - Additional strike points
- At high density (partial detachment), ELM heat flux significantly reduced
  - 50-75 % lower than in standard partially detached

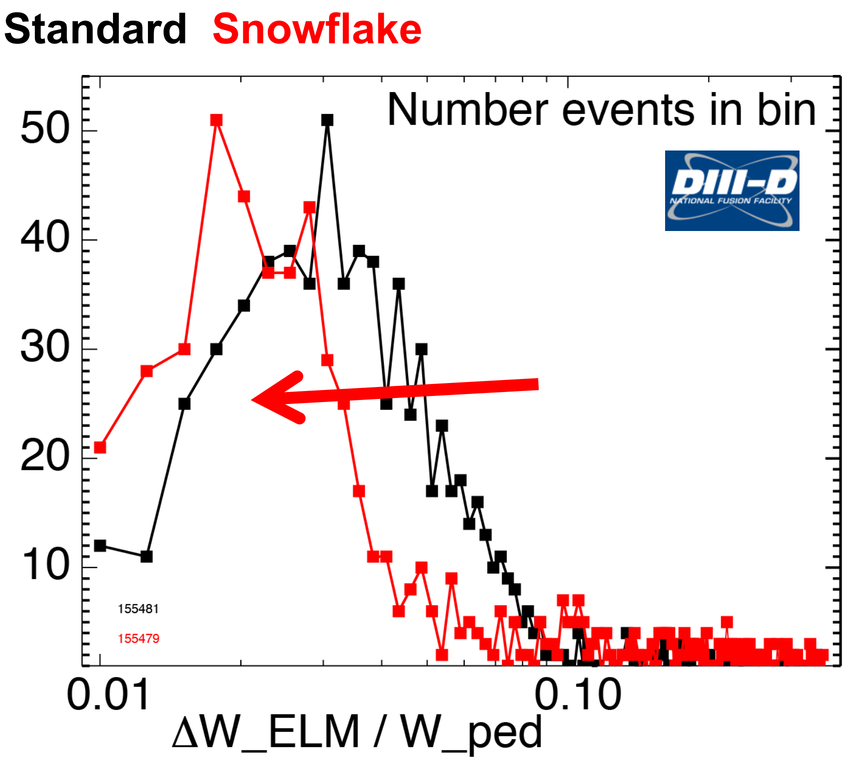
$n_e/n_G = 0.45$ **Standard** **Snowflake**

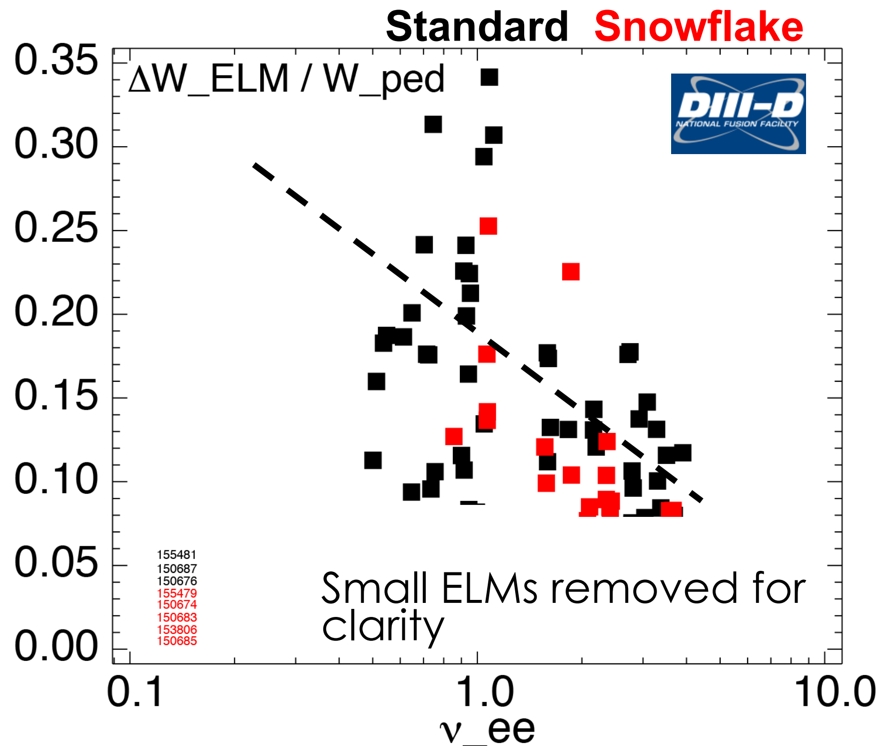


$n_e/n_G = 0.60$



Snowflake divertor reduces ELM energy, ELM power loss scales with collisionality (also reduced)

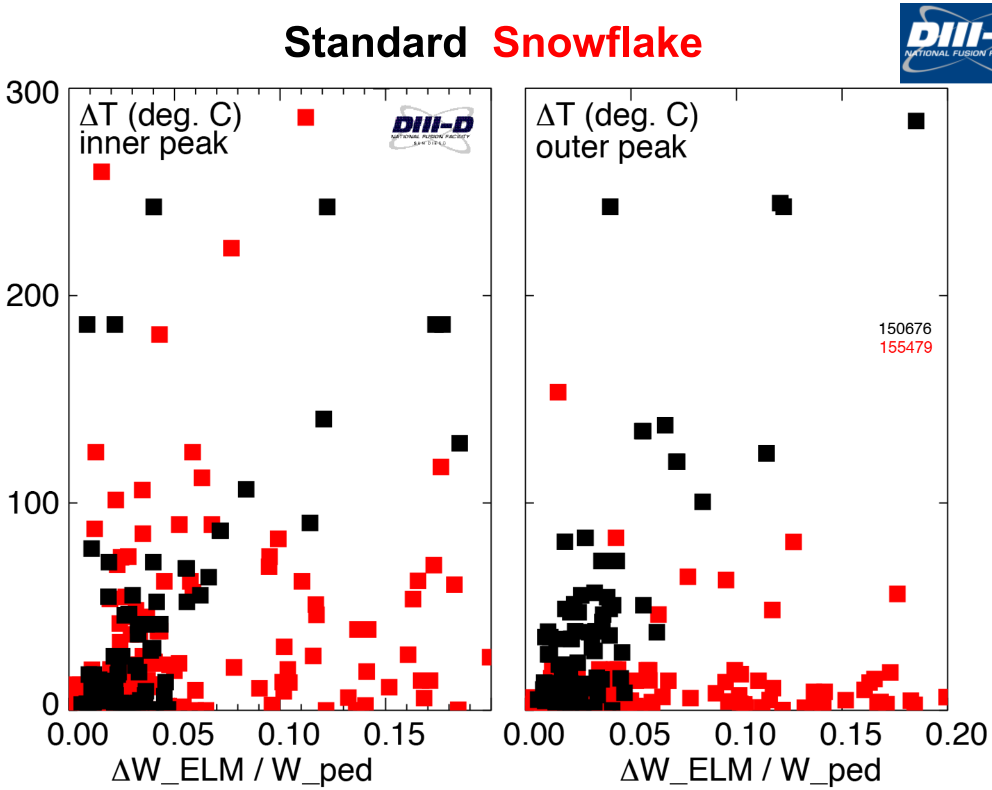


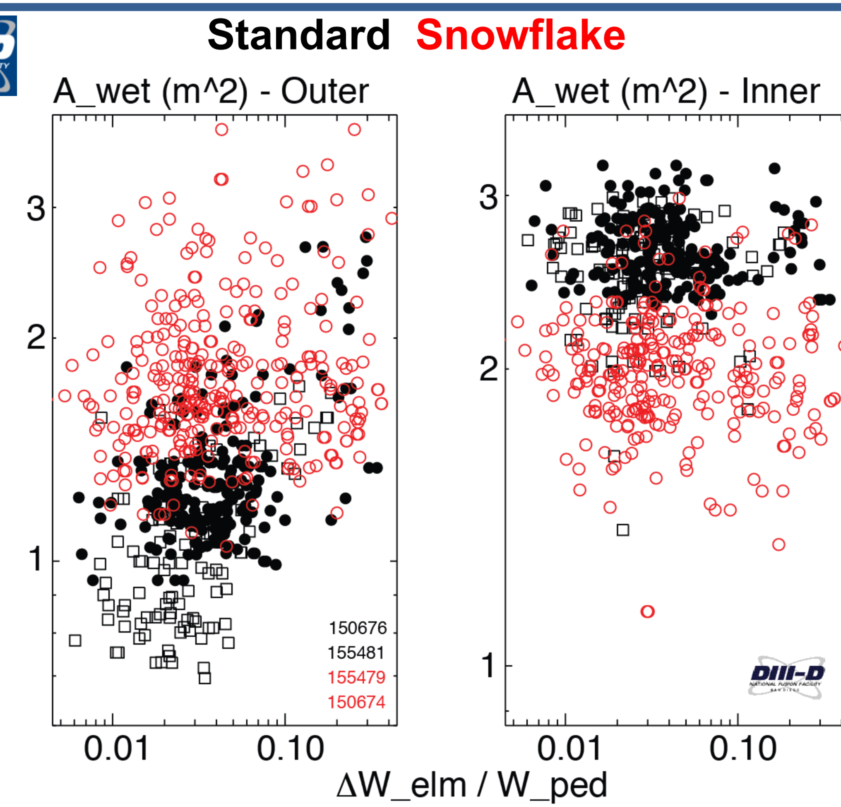


- Both ΔW_{ELM} and $\Delta W_{ELM}/W_{ped}$ weakly reduced
- Mostly for $\Delta W_{ELM}/W_{ped} < 0.10$

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

Snowflake divertor reduces ELM divertor surface heating (peak heat flux), increases ELM wetted area

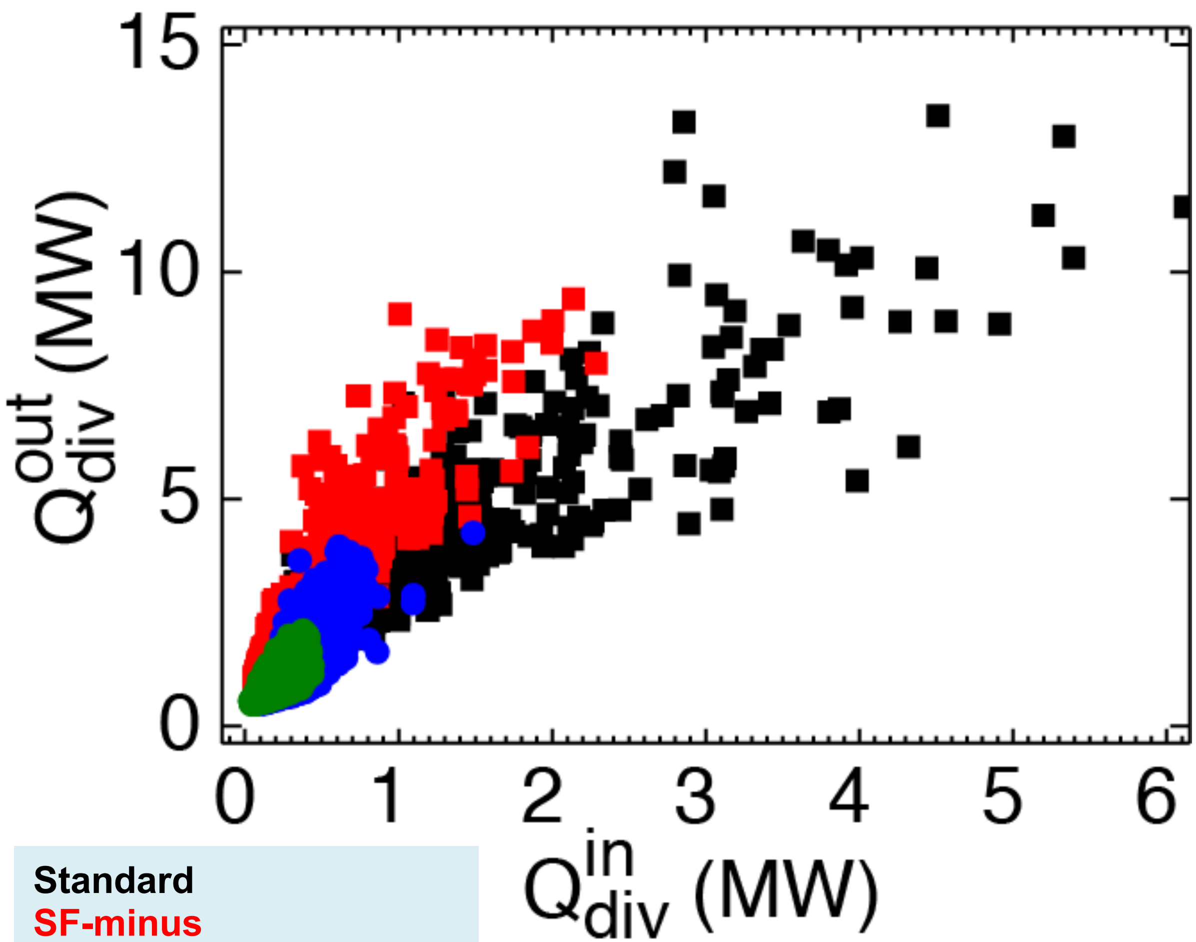




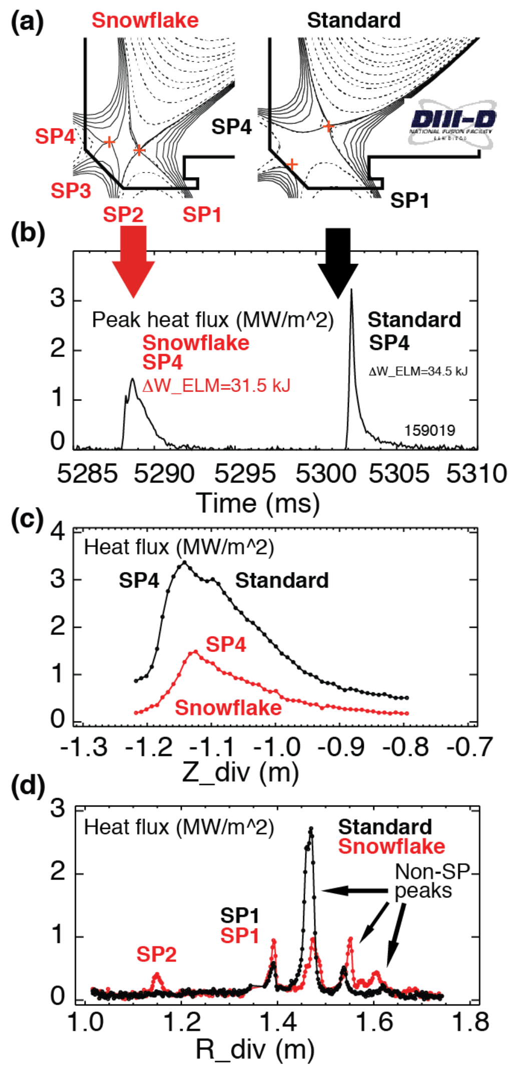
- $\Delta t_{surf} \sim E_{ELM}/(A_{wet}\ \tau_{heat})^{1/2}$
- Increased $\tau_{ELM}=L_{II}/c_{s,ped}$, τ_{heat}
- Reduction of ΔT and q_{peak} from larger ΔW_{ELM} ELMs (higher ion dynamic pressure) may suggest SF null-region convection

- $A_{wet}=P_{div} / q_{peak}$
- Outer divertor A_{wet} increased (due to spreading over add'l strike points)
- Inner divertor A_{wet} decrteased

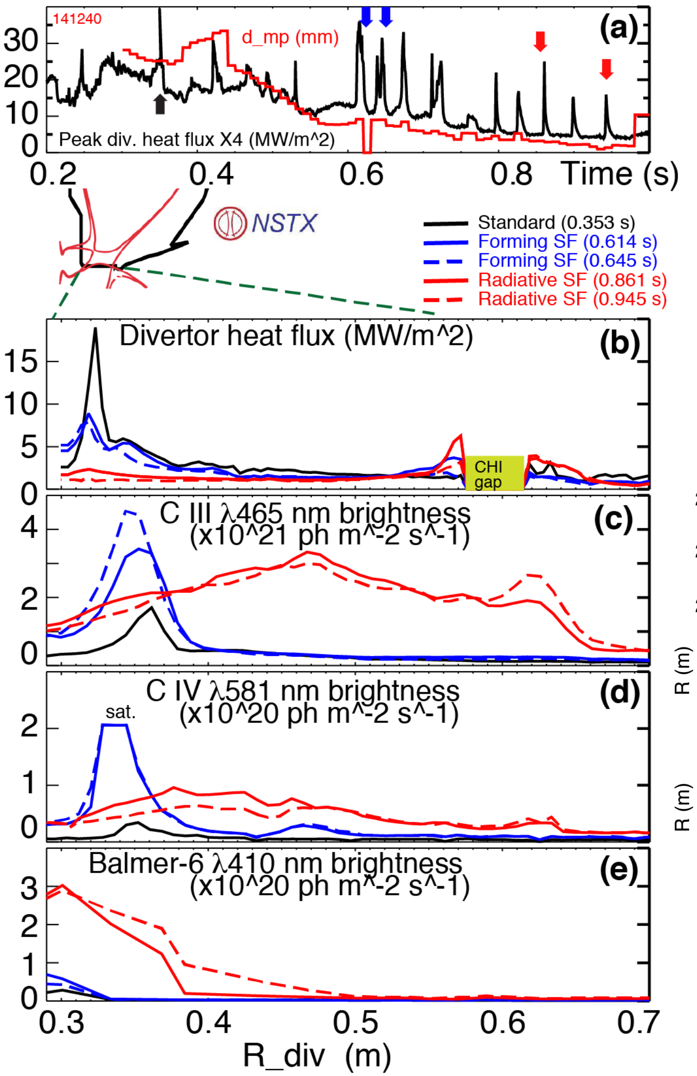
High-field-side snowflake-minus can be effectively used to mitigate inner divertor heat

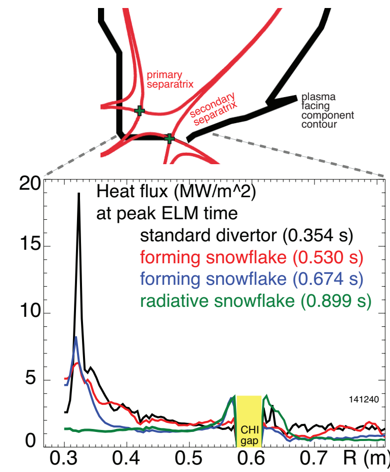


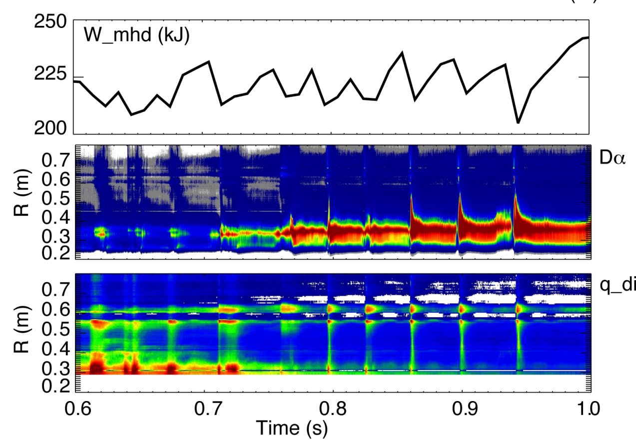
Standard
SF-minus
Rad. Standard
Rad. SF-minus

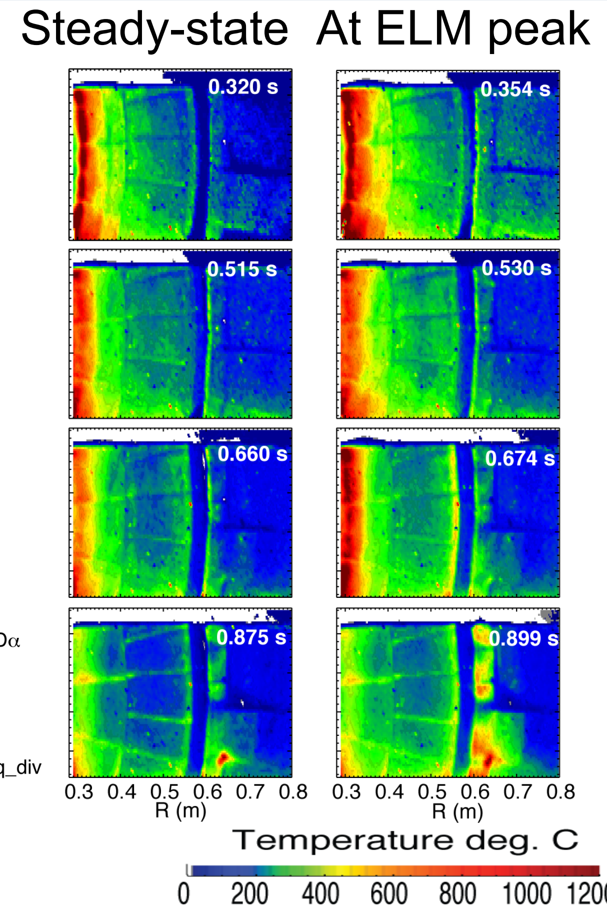


Radiative snowflake divertor effectively buffers ELMs in NSTX, no excessive tile leading edge heating due to shallow angles ($q_{||}$)





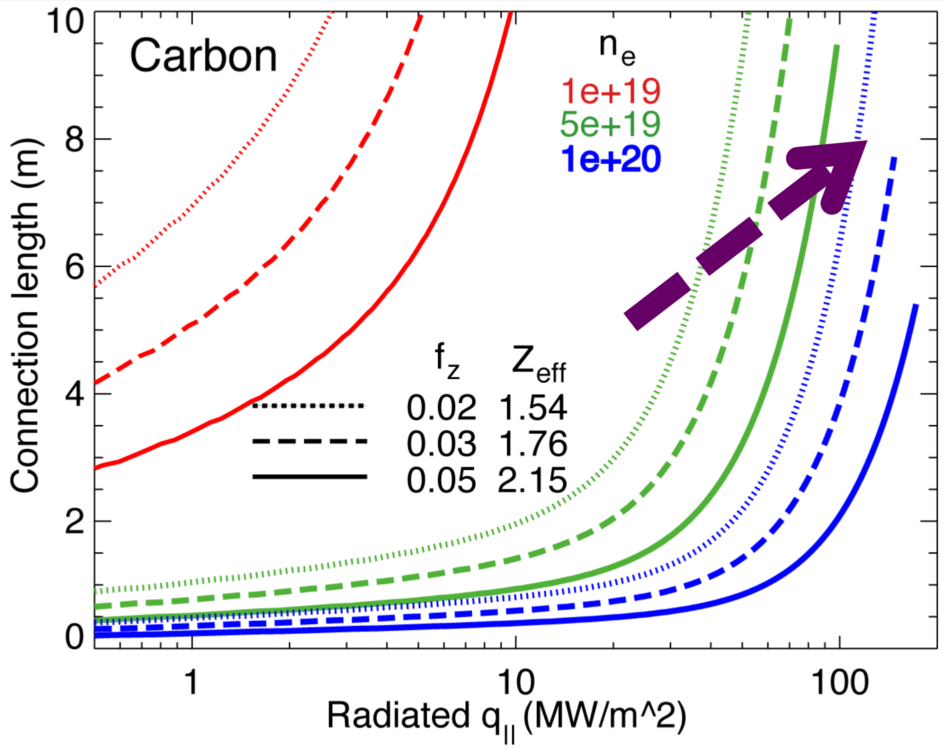




- Three phases: standard divertor, forming SF (q reduction), Radiative SF (q buffering)

1D modeling indicates power and momentum losses are increased in snowflake divertor

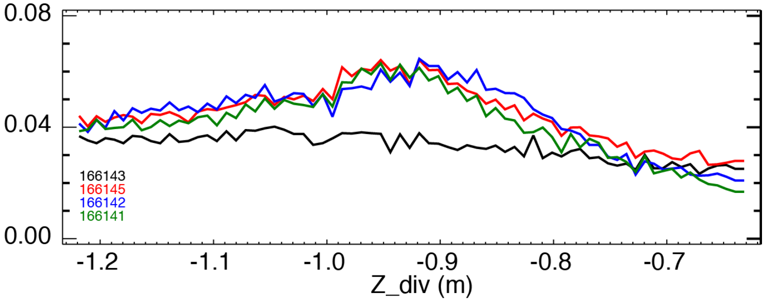
- 1D divertor detachment model by Post
  - Electron conduction with non-coronal carbon radiation
  - Max $q_{//}$ that can be radiated as function of connection length for range of f_z *and* n_e
- Three-body electron-ion recombination rate depends on divertor ion residence time
  - Ion recombination 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

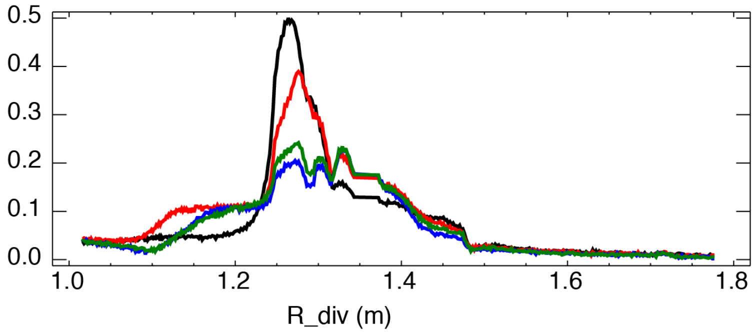


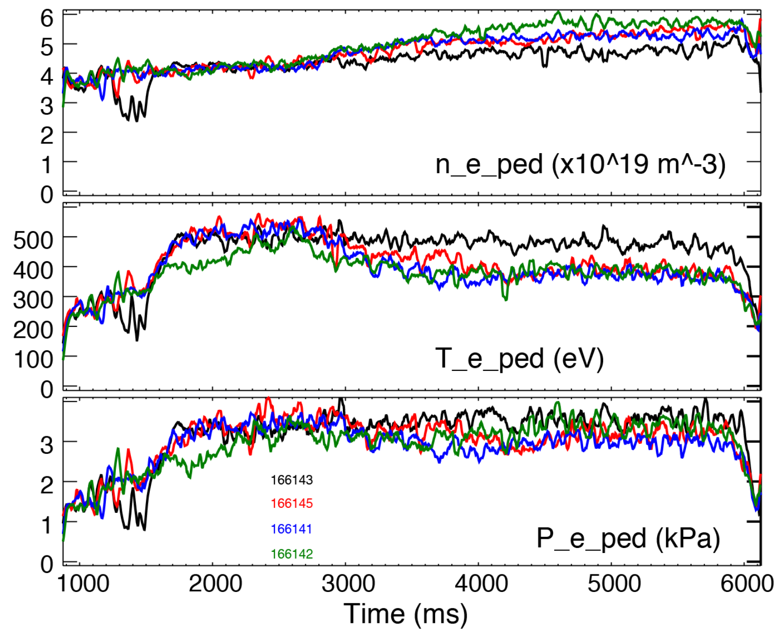
$$q_{\|} = -\kappa_0 T_e^{5/2} \frac{\partial T_e}{\partial x}$$

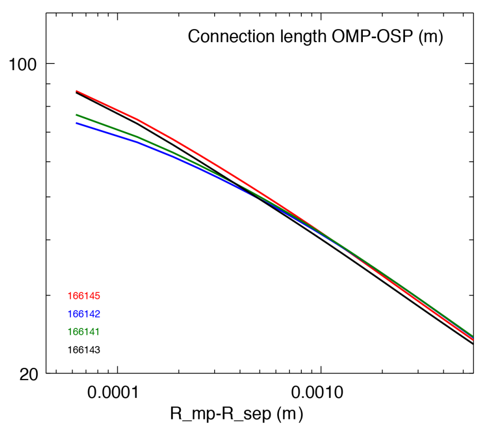
$$\frac{\partial q_{\|}}{\partial x} = -n_e n_z L_Z(T_e)$$

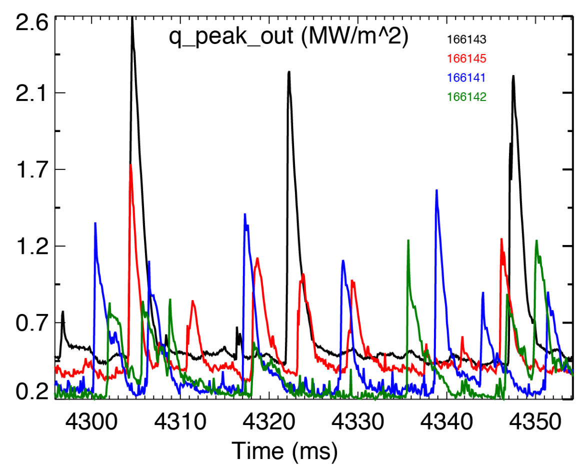
CD_4-seeded snowflake divertor development at DIII-D



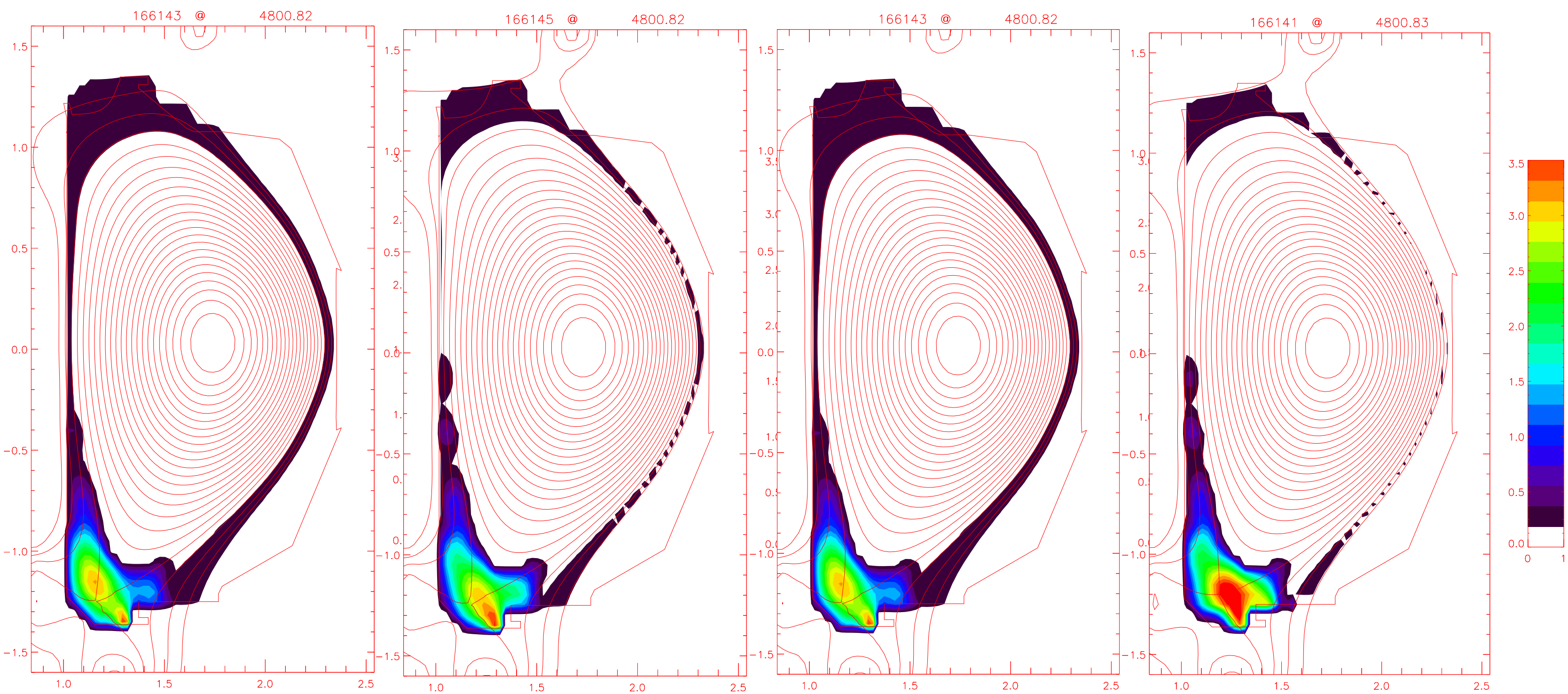






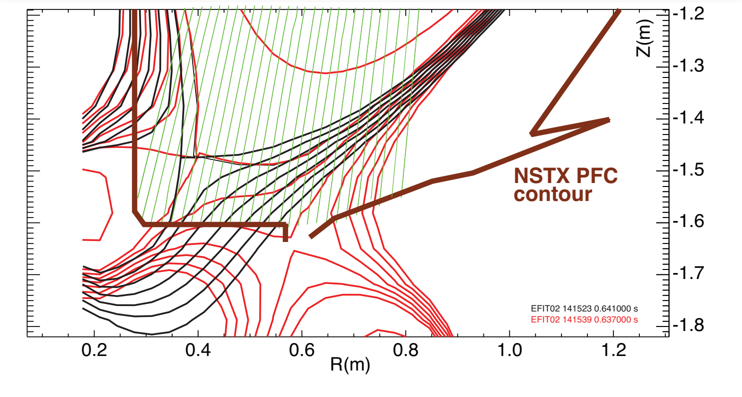


CD_4-seeded snowflake divertor development at DIII-D



- 1.2 MA, 5 MW NBI heated H-mode discharges

Different ELM and impurity regimes due to divertor geometry and CD_4

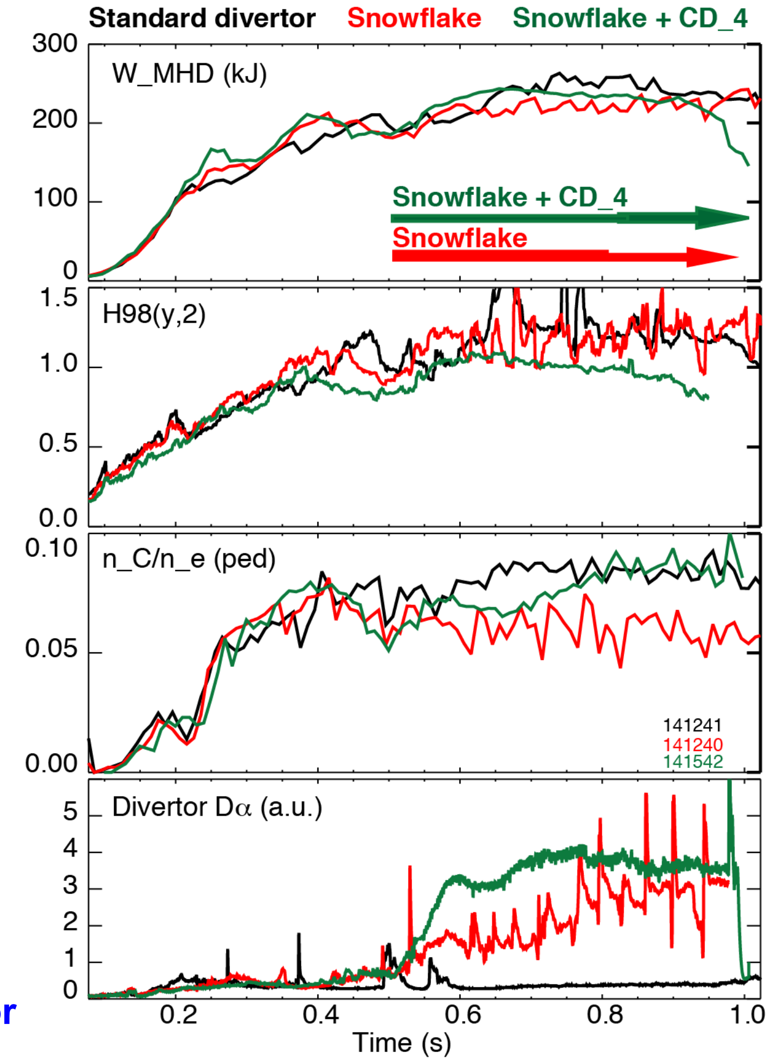


- High-performance H-mode with reduced divertor heat flux
- ELM and impurity control

	Lithium conditioning, no CD_4,	Lithium conditioning, divertor CD_4 inj.	Lithium conditioning, midplane CD_4 inj. from SGI
Standard divertor	ELMs stabilized, Impurity accumulation 141523, 141524, 141537	Singular ELMs, Impurity accumulation 141532	ELMs stabilized 141534, 141535
Snowflake-minus divertor	Type I ELMs, f_{ELM}=12-35 Hz, $\Delta W_{MHD}/W_{MHD}$~0.05-0.1 141240, 141539	Singular ELMs, then ELMs stabilized 141542	

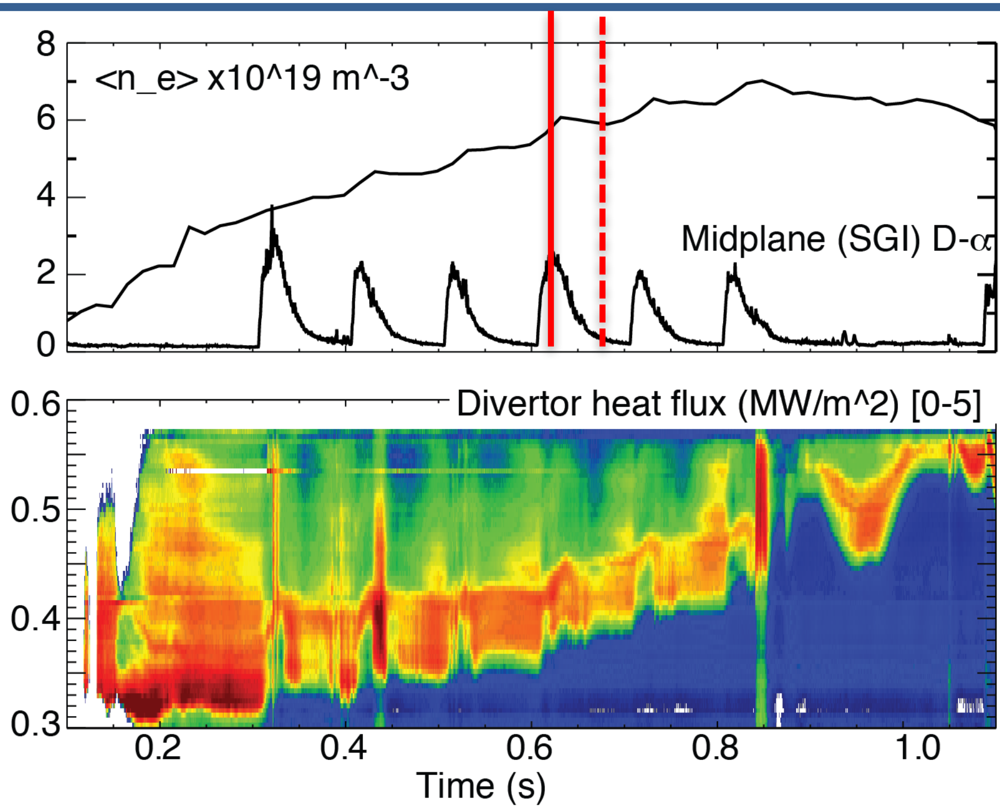
10-20% reduction in confinement (H98 and W_{MHD}) in H-mode with CD_4-seeded snowflake divertor

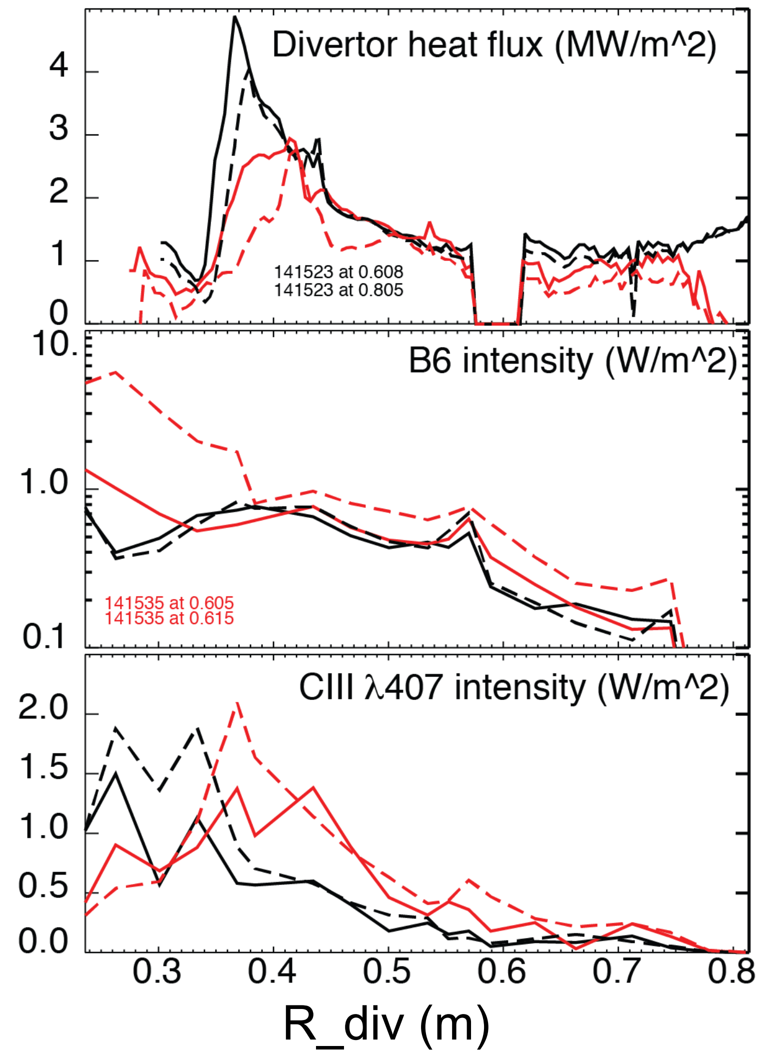
- 0.45 T, 0.9 MA, 4 MW H-mode
- Shaping: κ=2.1, δ=0.8
- Core temperature:
  - T_e ~ 0.8-1 keV
  - T_i ~ 1 keV
- β_N ~ 4-5
- H98(y,2) ~ 1 (from TRANSP)
- P_{SOL}=3 MW
- Magn. Balance: drsep=6-7 mm (cf. λ_{SOL}~6 mm)
- B x grad B toward lower divertor



Reference
Snowflake
Radiative divertor
Snowflake+CD_4

CD_4 puffing from midplane SGI produces dynamic partial detachment only during SGI pulses

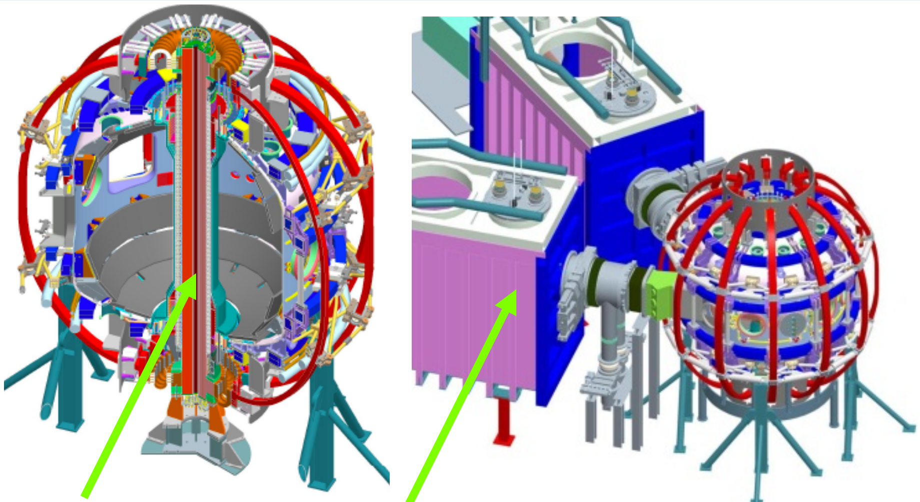




- SGI produced intense CD_4 pulses resulting in pulsed upstream density

Snowflake divertor is a leading heat flux mitigation candidate for NSTX Upgrade

NSTX-U

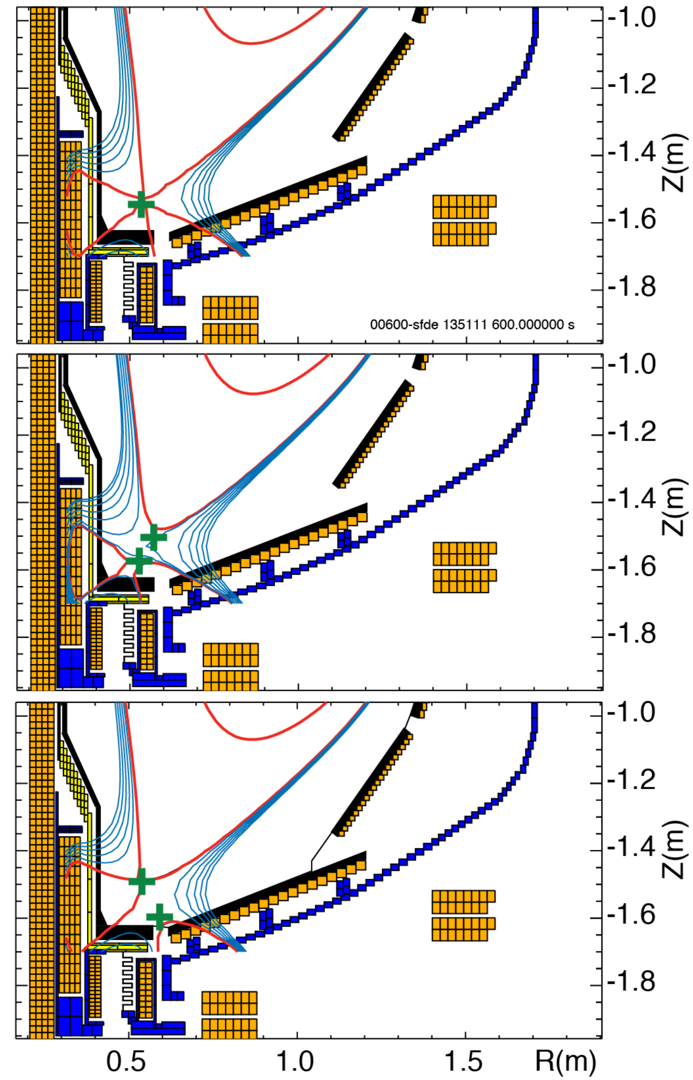


New center-stack **2^{nd} neutral beam**

B_T → 1 T		P_{NBI} → 12 MW	
I_p → 2 MA		pulse → 5 s	

J. E. Menard et. al, Nucl. Fusion 52 (2012) 083015

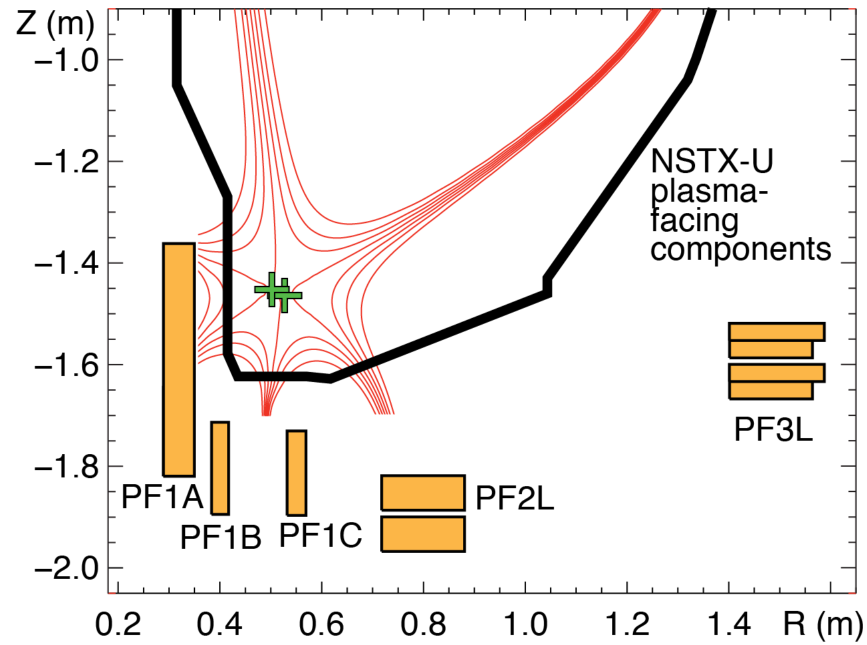
- NSTX-U Mission elements:
  - Advance ST as candidate for Fusion Nuclear Science Facility
  - **Develop solutions for the plasma-material interface challenge**
  - Explore unique ST parameter regimes to advance predictive capability for ITER
  - Develop ST as fusion energy system



Snowflake divertor equilibria obtained with ISOLVER and realistic divertor coil currents

NSTX-U

- Four divertor coils in NSTX-U
  - Only three coils in initial years
- ISOLVER used for equilibria
  - Predictive free-boundary axisymmetric Grad-Shafranov equilibrium solver
  - Input: normalized profiles (P, I_p), boundary shape
  - Match a specified I_p and β from an NSTX shot
  - Output: magnetic coil currents



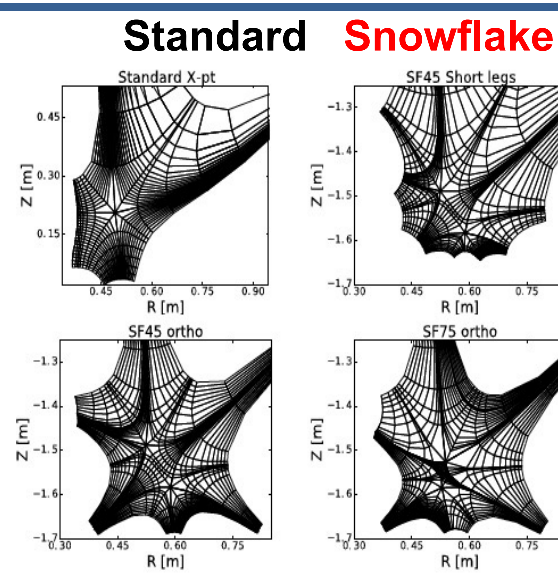
Divertor coil	Current limits (kA)	Standard configuration currents (kA)	Near-exact SF configuration currents (kA)	SF-plus configuration currents (kA)	SF-minus configuration currents (kA)
PF1A	19	2.3	3.1	2.8	3.2
PF1B	13	0	0	0	0
PF1C	-8 / + 16	0.4	-1.4	-0.97	-1.3
PF2L	15	1.0	6.6	5.4	6.2

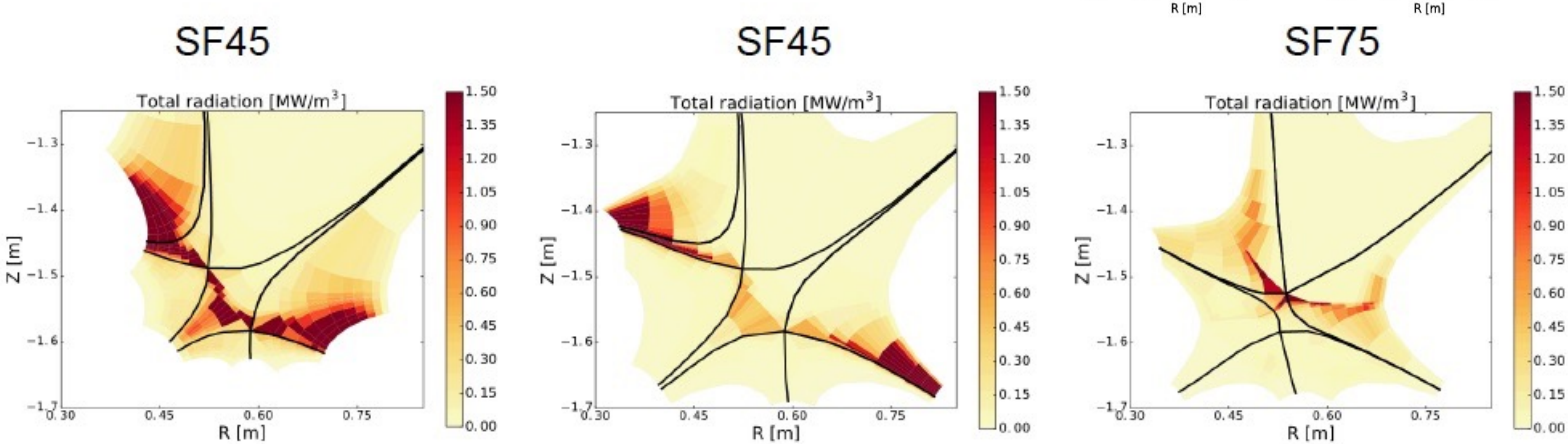
Edge modeling predicts significant heat flux reduction with radiative snowflake divertor

NSTX-U

- New UEDGE grid generator for nearly-arbitrary divertor configuration
- Multi-fluid code UEDGE
  - B_t = 1.0 T, I_p = 2 MA, P_{SOL} = 9 MW
  - NSTX-like transport $\chi_{i,e}$=2-4 m^2/s, D=0.5 m^2/s

O. Izacard, NP10.00010

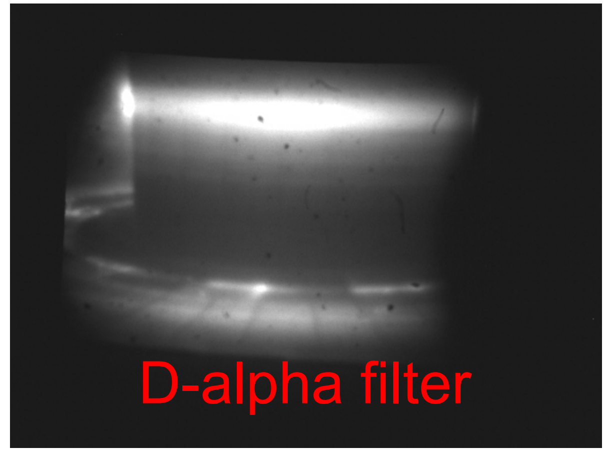


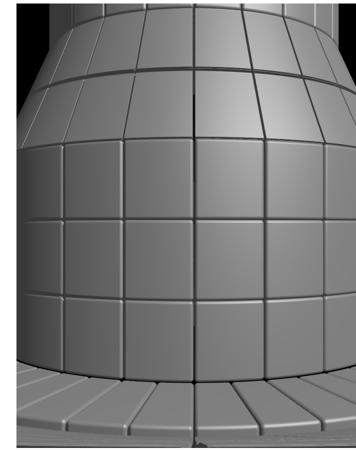


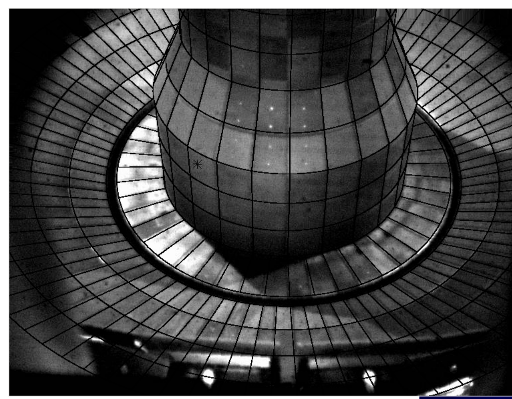
Fast filtered visible camera will enable divertor emission distribution and turbulence imaging in NSTX-U

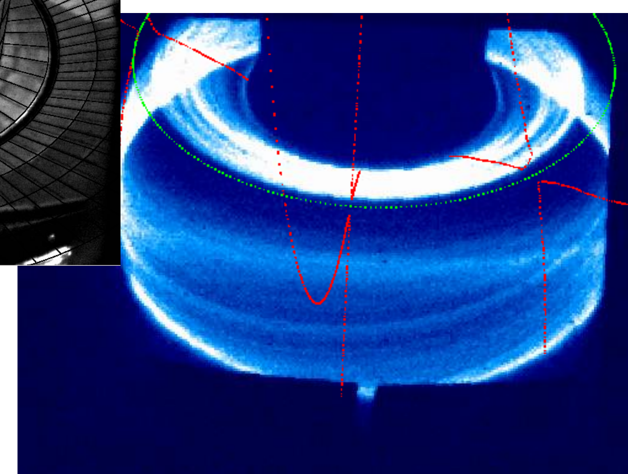
NSTX-U

- Vision Research Phantom camera v1211
- 1280x800 pixels
- Pixel size 28x28 micron
- Chip size 35.8 x 22.4 mm
- Planned divertor turbulence studies
  - Filament imaging
  - Turbulence metrics







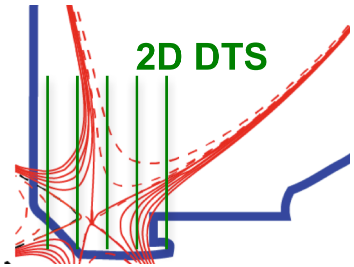


Resolution	Max kfps	Max rec time (s)
1280x800	12.6	1.3
256x256	103.4	2.42
128x128	240.3	3.85
128x64	415.1	4.06
128x32	571.0	5.0

F. Scotti, NP10.00028

Outstanding questions

- Develop real-time near-exact snowflake configuration feedback control
- Identify transport mechanisms
  - For heat and particle flux sharing between multiple strike points (inter-ELM and ELM)
  - For SOL broadening
- Identify radiation limits at high density and with seeded impurities
- Confirm particle control via cryo-pumps
- Investigate pedestal MHD stability control



Proposed DIII-D experiments with new DTS