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Developing snowflake divertor physics basis in the DIII-D and NSTX tokamaks aimed at the divertor power exhaust solution.

V. A. Soukhanovskii

September 24, 2015

First IAEA Technical Meeting on Divertor Concepts.
Vienna, Austria
September 29, 2015 through October 2, 2015

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Developing snowflake divertor physics basis in the DIII-D and NSTX tokamaks.

1st IAEA Technical Meeting on Divertor Concepts

Vlad Soukhanovskii and NSTX and DIII-D Research Teams

1 October 2015

LLNL-PRES-677496
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NSTX DIII-D NATIONAL FUSION FACILITY Fusion Energy Sciences Lawrence Livermore National Laboratory

Acknowledgements

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Divertor strike point heat flux mitigation using radiated power loss and magnetic / divertor 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}

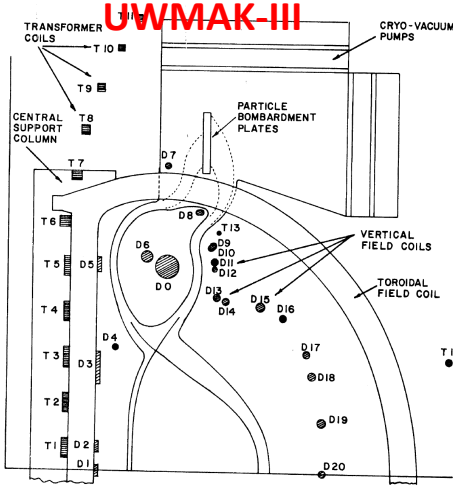
Increase λ_q via increased radial transport

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**

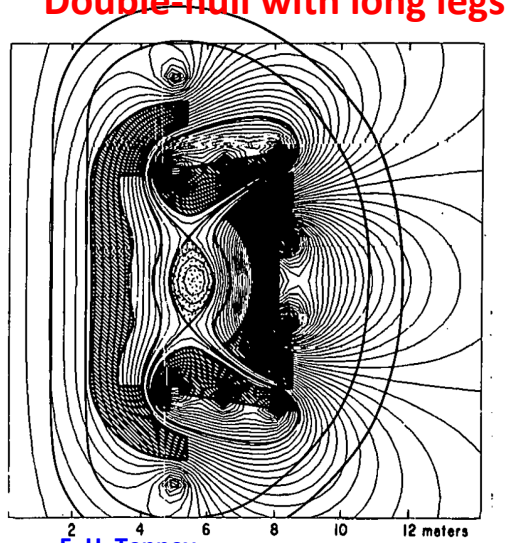
Focus on magnetic geometry since early days of tokamak studies. Some examples (R_{SP}, L_{II}, f_{exp}) …

UWMAK-III



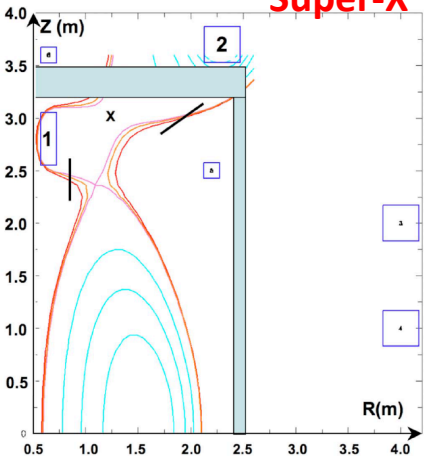
B. Badger et.al, U. Wisc. Report UWFDM-150, 1975

Double-null with long legs

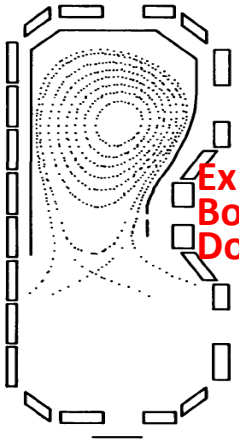


F. H. Tenney, PPPL Report 1284, 1976

Super-X



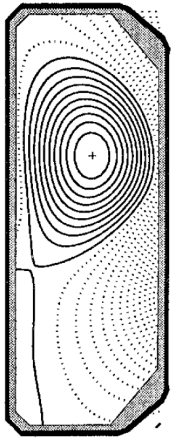
P. M. Valanju et.al, Phys. Plasmas 16, 056110 (2009)



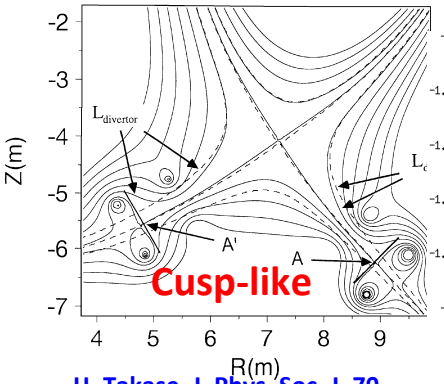
Expanded Boundary, Doublet III

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

TCV



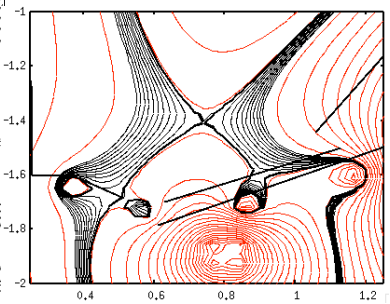
R. A. Pitts et. al, JNM 290-293, 2001, 940



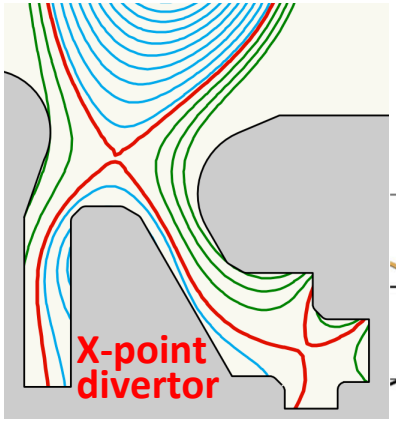
Cusp-like

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

X-divertor



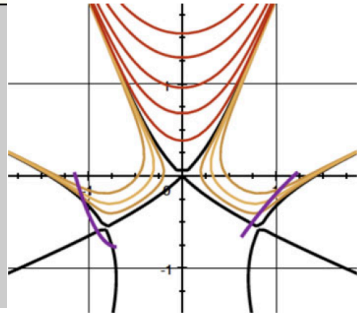
M. Kotschenreuther et. al, IAEA FEC 2004; Phys. Plasmas 14, 072502 (2007)



X-point divertor

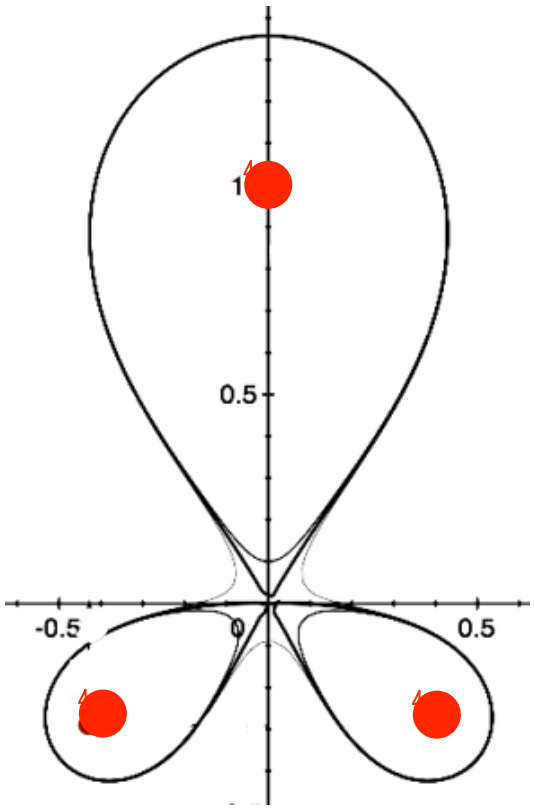
B. LaBombard et.al, NF 55 (2015) 053020

Super-cusp with Remote coils



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

Snowflake Divertor Configuration as a Tokamak Divertor Power Exhaust Concept



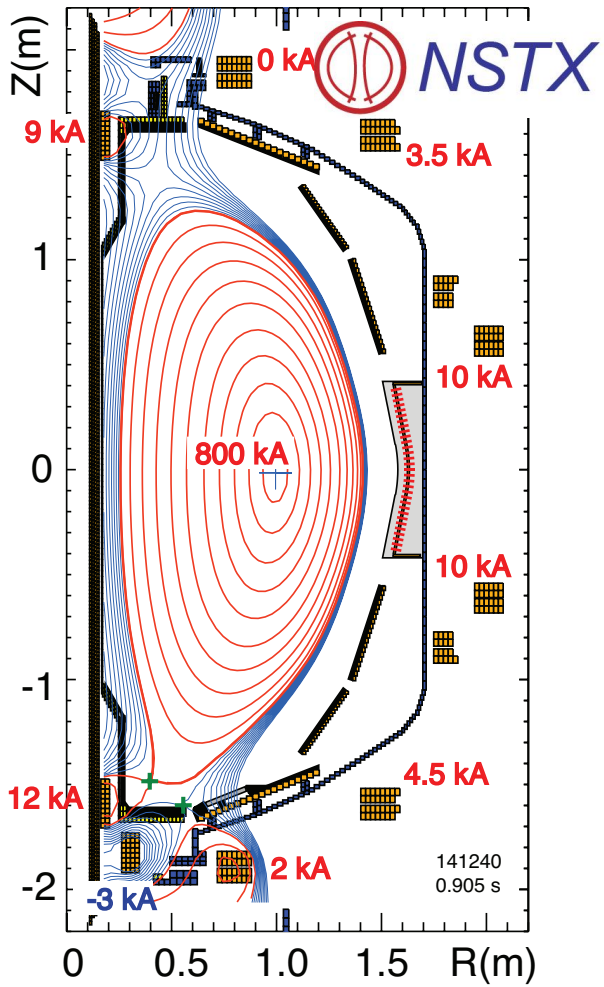
D. D. Ryutov, PoP 14, 064502 2007; PPCF 54, 124050 (2012)

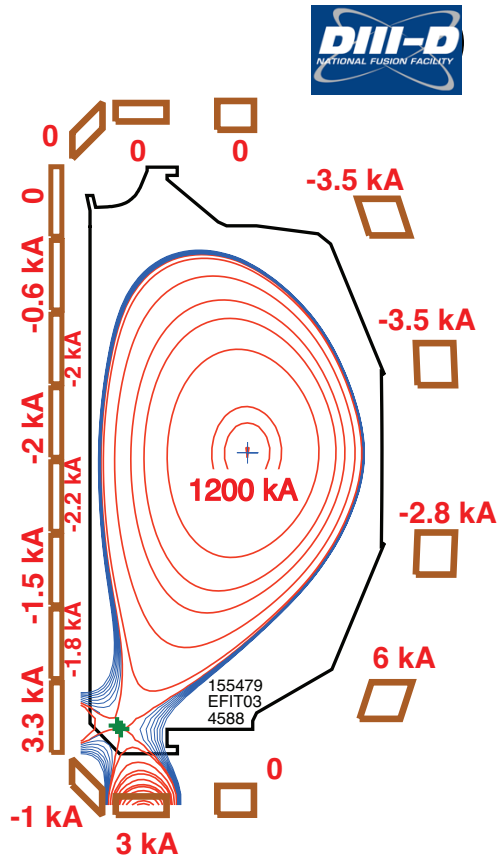
- **Snowflake, 2nd order null**
  - $B_p \sim 0$, *grad* $B_p \sim 0$
    (Cf. first-order null: $B_p \sim 0$)
  - $B_p(r) \sim r^2$ (Cf. first-order null: $B_p \sim r$)
  - Four divertor legs
- **Geometry benefits**
  - Higher edge magnetic shear
  - Larger plasma wetted-area A_{wet} (f_{exp})
  - Larger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

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

Snowflake configurations obtained in NSTX and DIII-D using existing PF coils for many energy confinement times

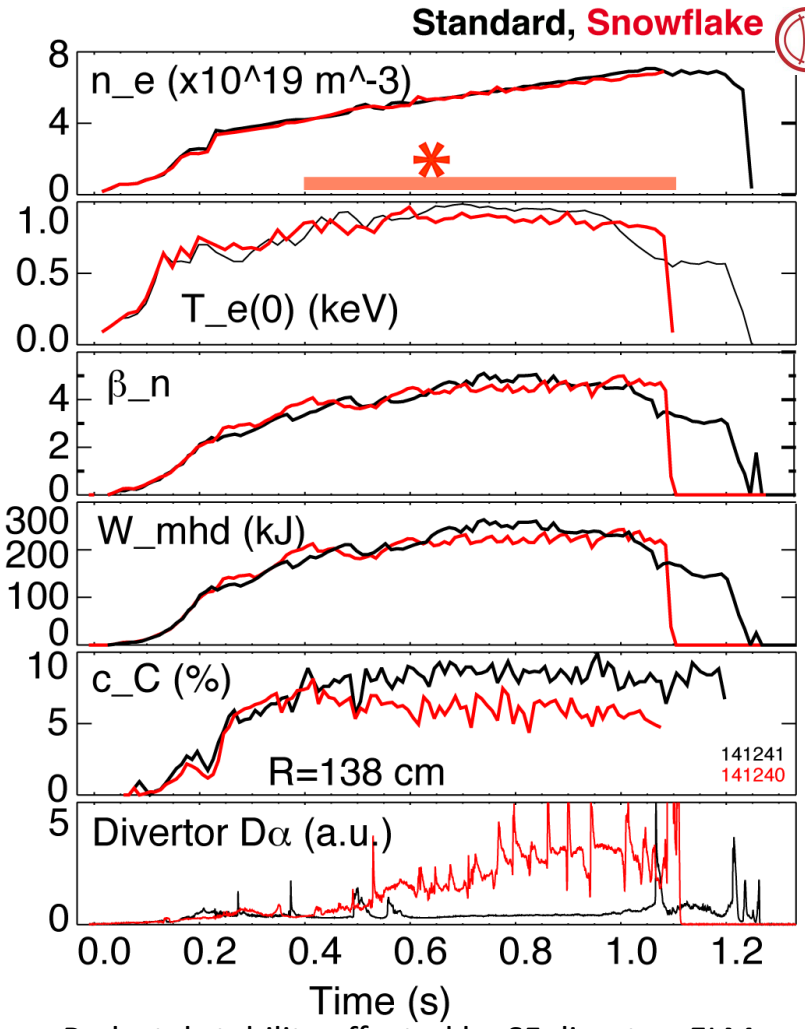


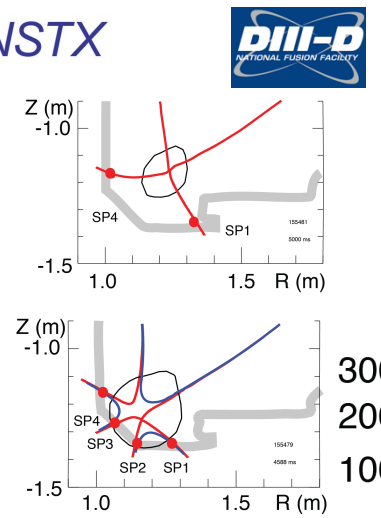


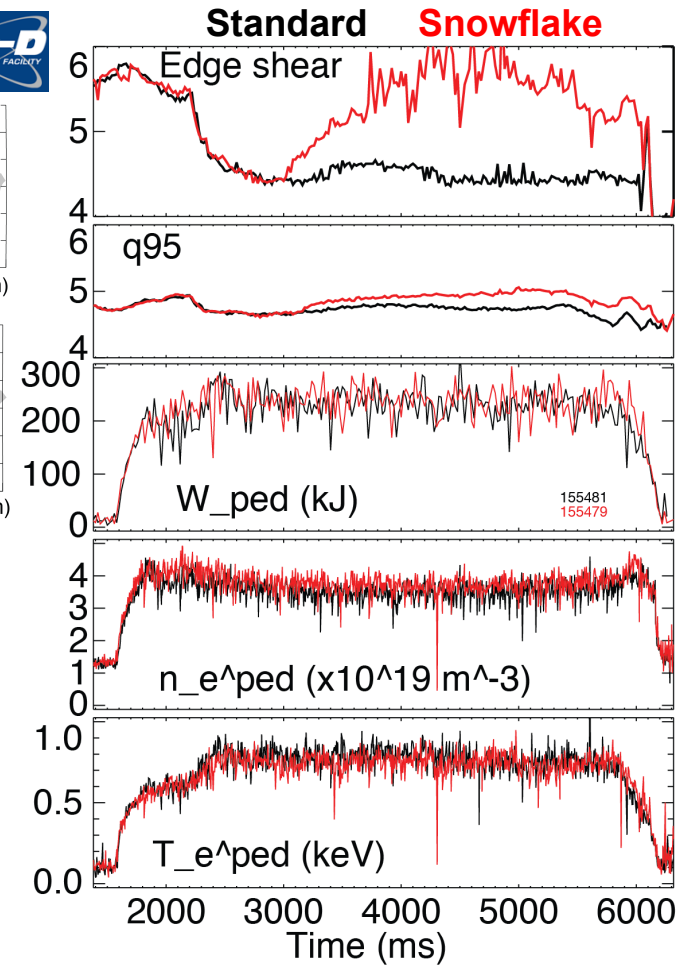
- NSTX
  - I_p=0.8-1.0 MA
  - $B_t \leq 0.45$ T
  - 3 divertor coils, pre-programmed currents
  - SF for 0.5 s
- DIII-D
  - I_p=0.8-1.0 MA
  - B_t=2 T
  - 3 divertor coils w/ control
  - SF for 2-3 s

Next slides: generalize snowflake divertor effects observed in NSTX and DIII-D

Snowflake divertor compatible with H-mode core and pedestal confinement, effect on ELMs vary

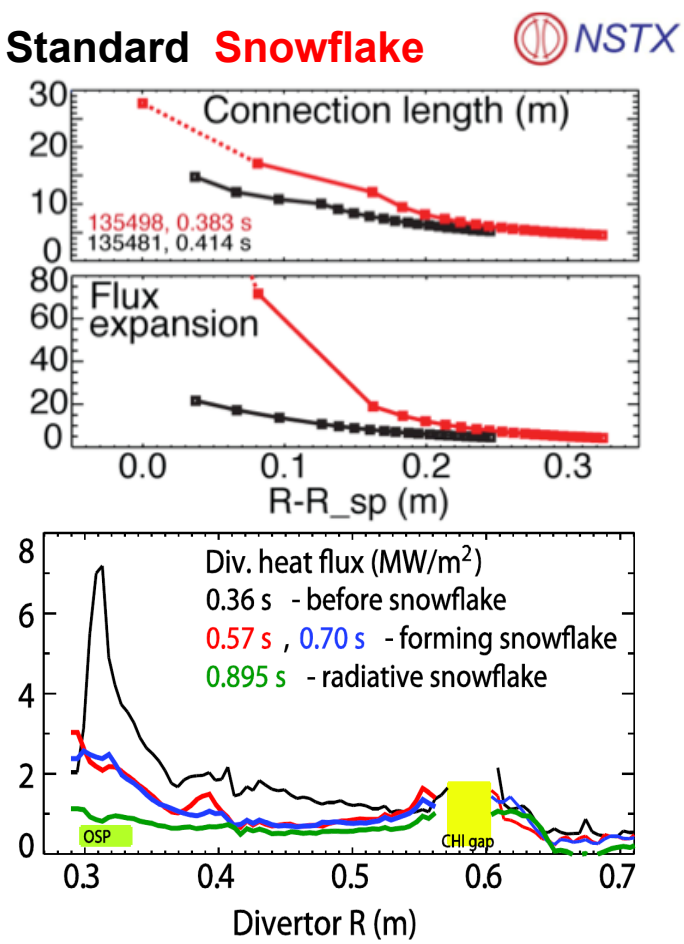




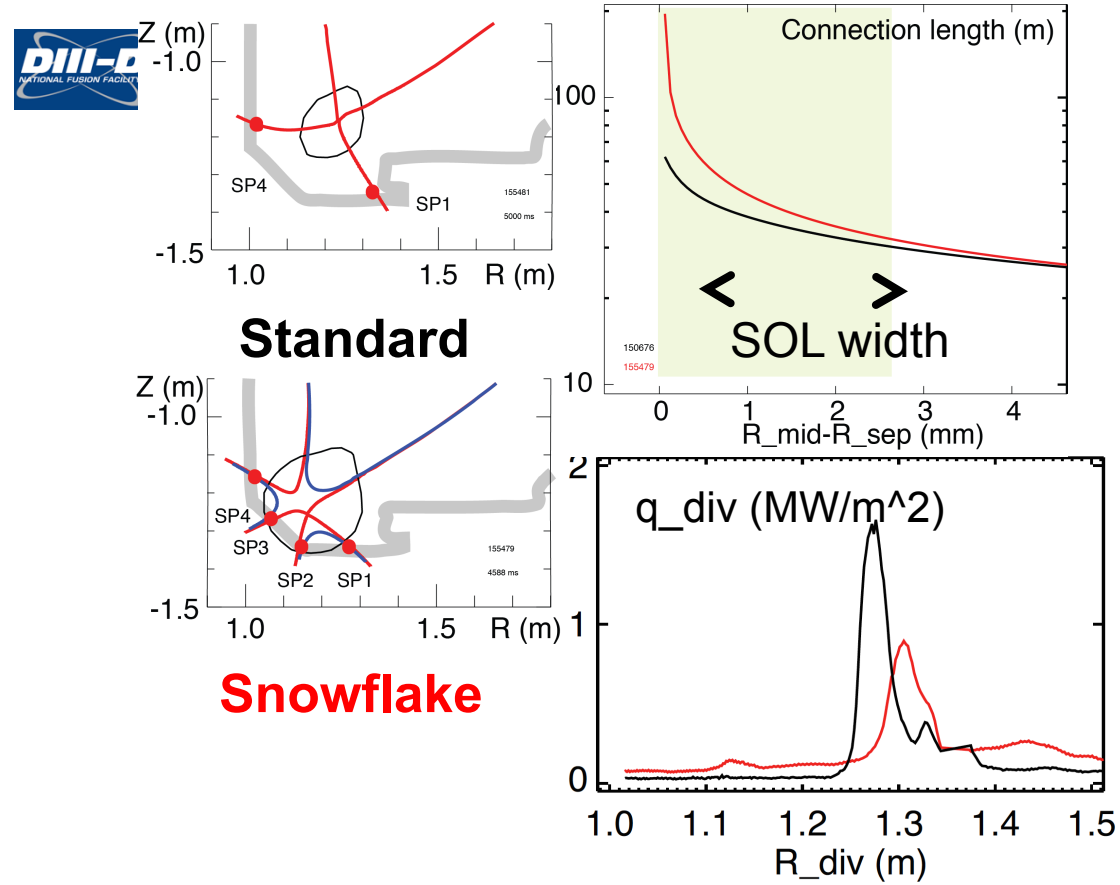


- Pedestal stability affected by SF divertor, ELMs destabilized
- H98(y,2) ~1.0-1.2, β_N~2. SF Divertor Weakly Affects Pedestal Magnetic and Kinetic Characteristics, Stability in DIII-D

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

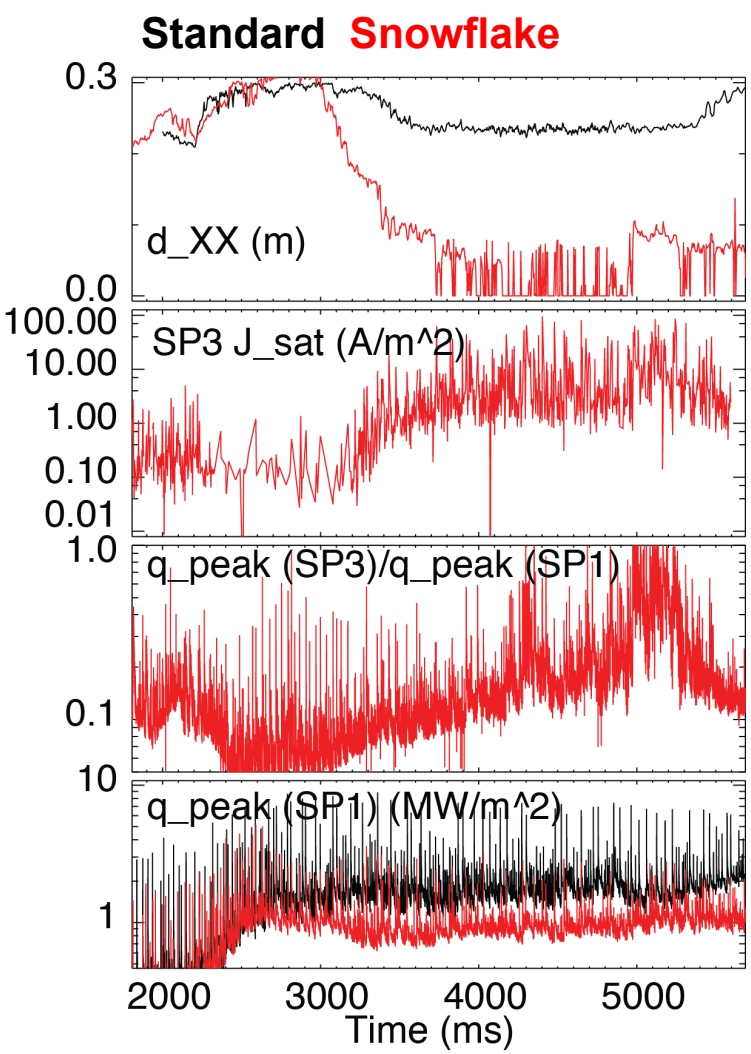


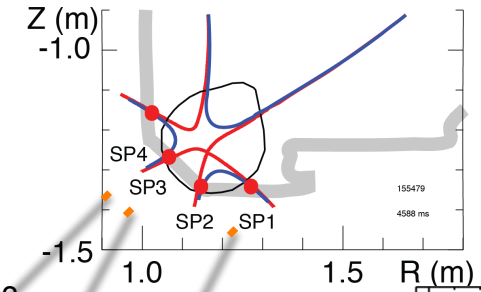
- Due to geometry and radiation



- Flux expansion increased ~20%
- $L_{||}$ increased by 20-60% over SOL width
- Divertor heat flux reduced ~50%

Snowflake divertor enables power and particle sharing over multiple strike points

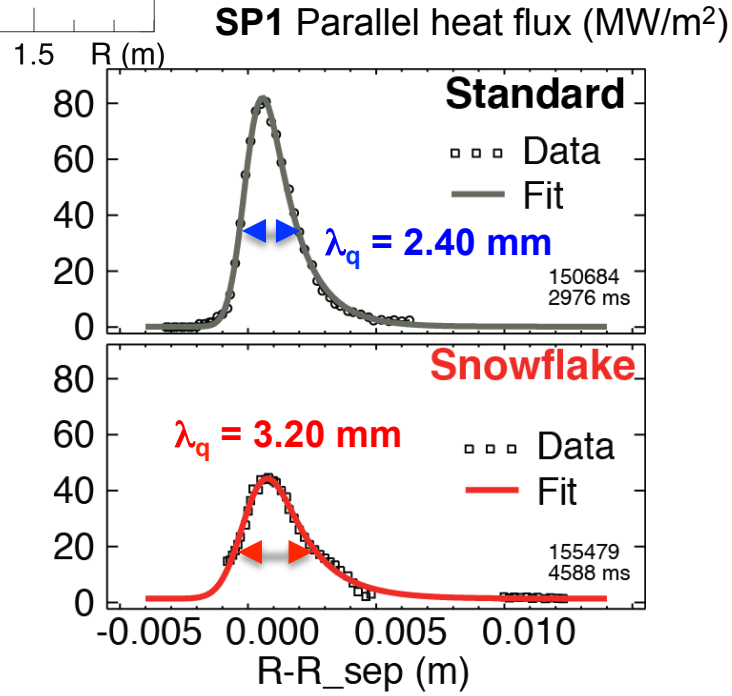




Γ_{SP3}

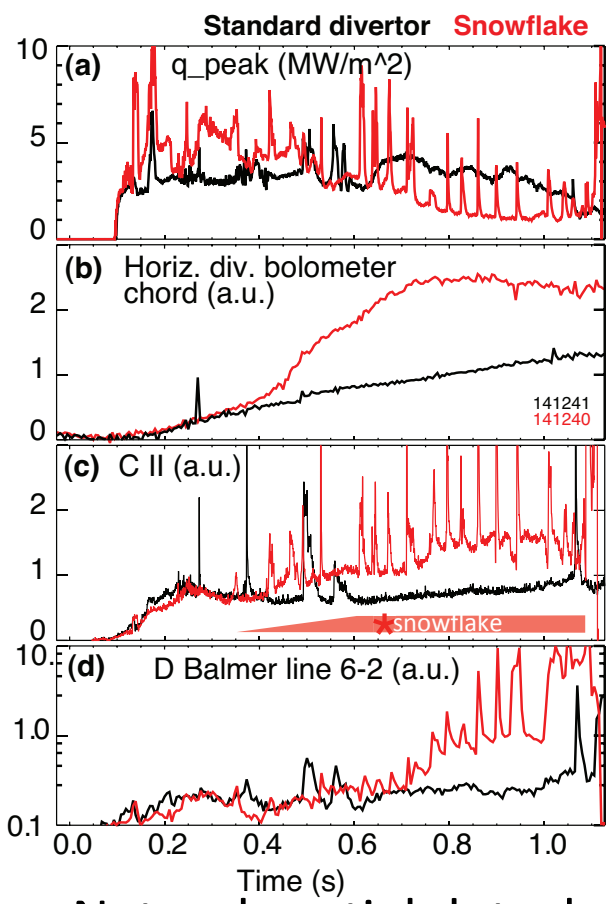
q_{SP3}

q_{SP1}



- Increased λ_q may imply increased transport

Snowflake configuration favorably affects radiative divertor and detachment



NSTX

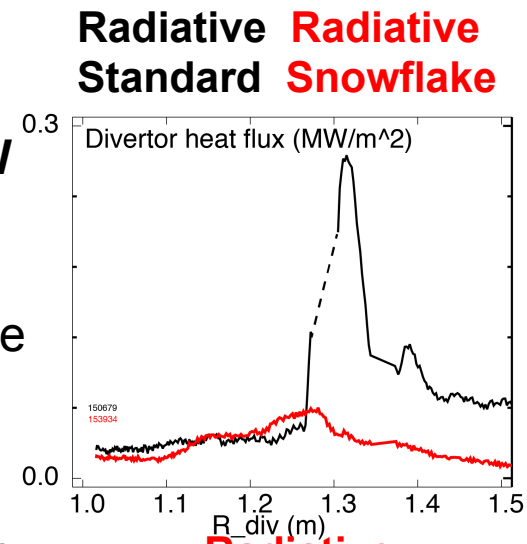
P_{SOL} = 2-3 MW

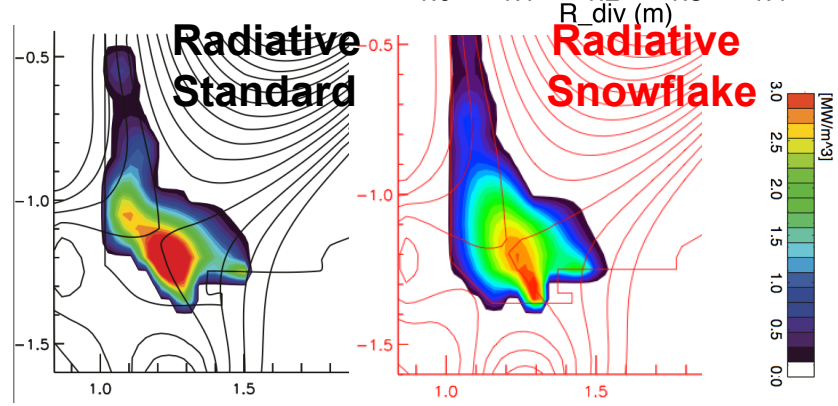
- Natural partial detachment in NSTX snowflake otherwise inaccessible with standard divertor

DIII-D NATIONAL FUSION FACILITY

P_{SOL} = 3-4 MW
f_rad ~ 0.50

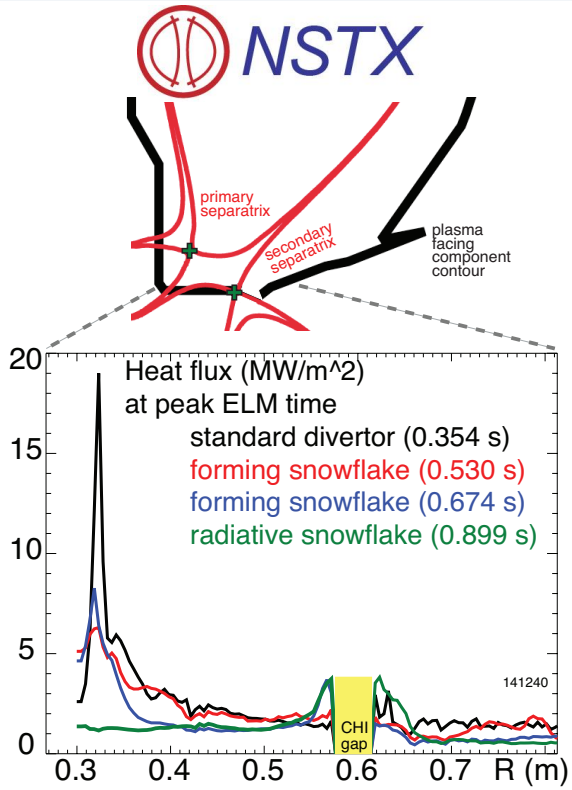
- Nearly complete power detachment



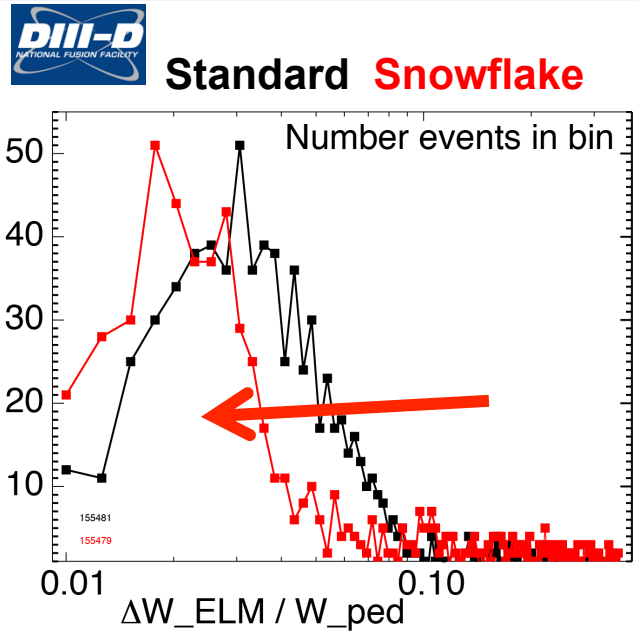


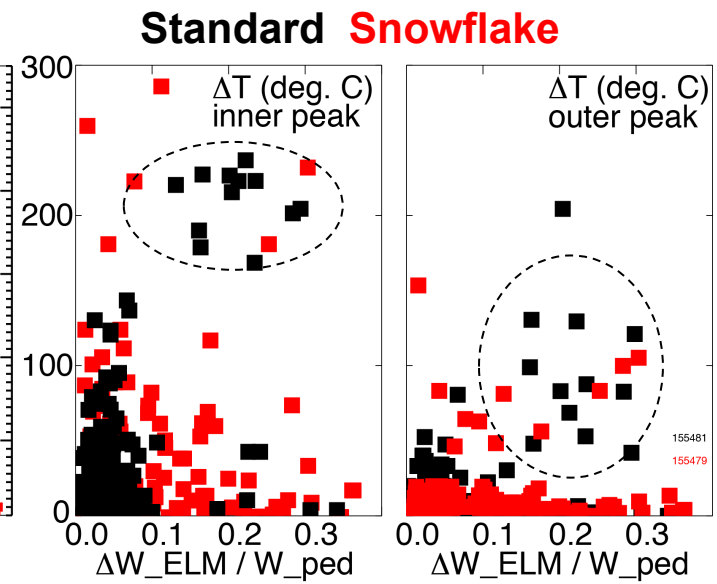
- Significant P_rad re-distribution
- Decreased near null, increased through leg

Snowflake divertor reduces ELM energy and divertor surface heating (peak heat flux)



- Divertor heat flux significantly reduced during Type-I ELMs ($\Delta W/W$ ~ 5-15 %)





- Both ΔW_{ELM} and $\Delta W_{ELM}/W_{ped}$ weakly reduced
- Mostly for $\Delta W_{ELM}/W_{ped} < 0.10$
- $\Delta T_{surf} \sim E_{ELM}/(A_{wet}\, \tau_{ELM})^{1/2}$
- Increased $\tau_{ELM}=L_{II}/c_{s,ped}$
  Weakly reduced E_{ELM}
  A_{wet}^{ELM} similar

T. D. Rognlien et. al, JNM 438, 2013, S418

Developing the Snowflake Divertor Physics Basis For High-power Density Tokamaks

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

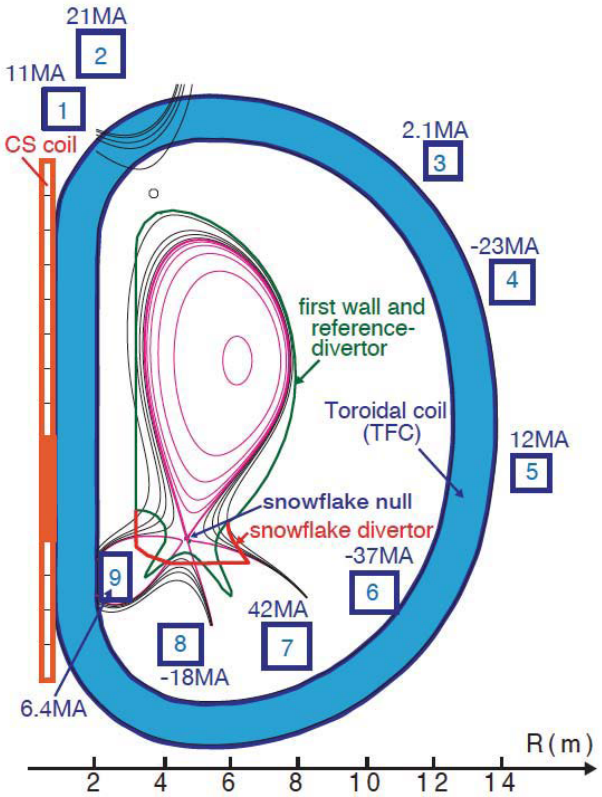
- Snowflake geometry may offer multiple benefits for inter-ELM and ELM heat flux mitigation
  - Geometry enables divertor inter-ELM heat flux spreading over larger plasma-wetted area, multiple strike points
  - Broader parallel heat fluxes may imply increased radial transport
  - ELM divertor peak target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

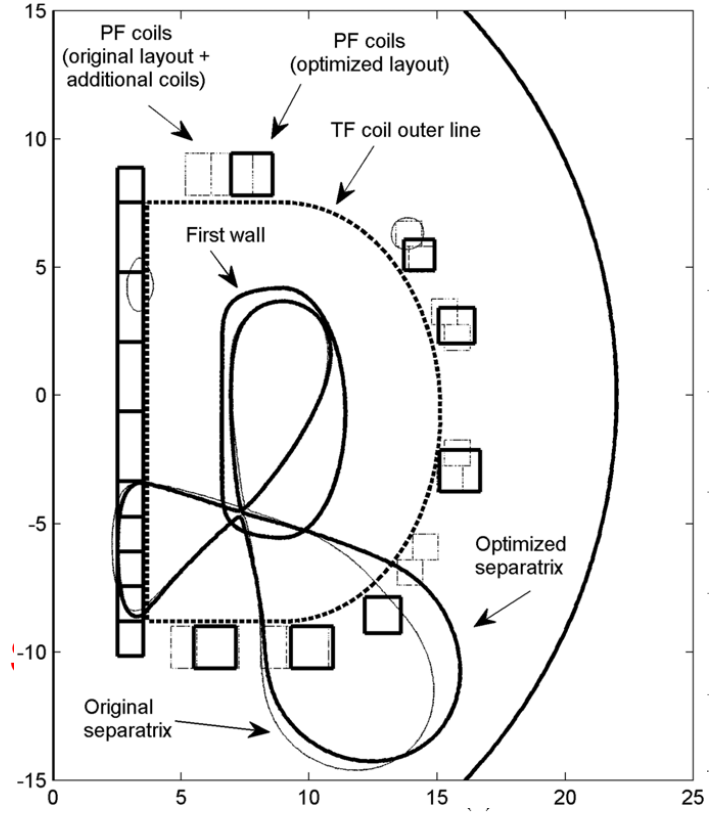
Outlook

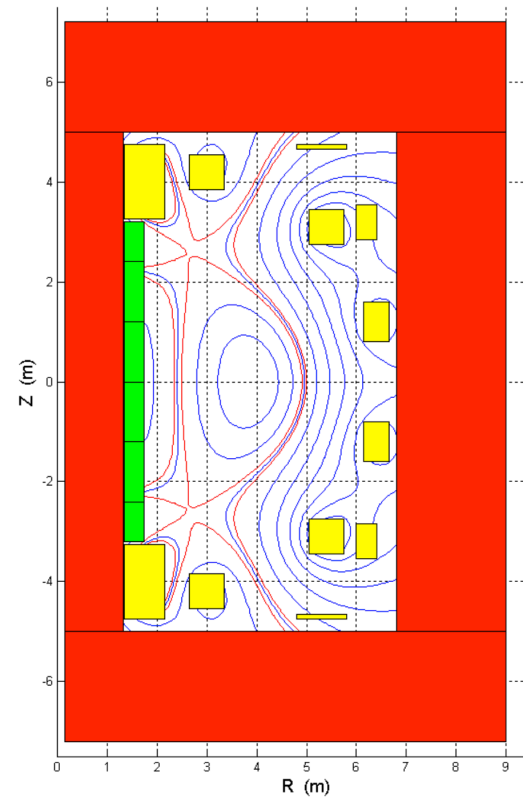
SF divertor experiments performed in TCV, NSTX, DIII-D, EAST

Near term future: NSTX-U, MAST-U and HL-2M

First pre-DEMO and DEMO device designs with snowflake divertor configurations







Snowflake for DEMO

N. Asakura et.al,
Trans. Fus. Sci. Tech. 63, 2013, 70.

Snowflake for DEMO

R. Albanese et. al,
PPCF, 56 (2014) 035008

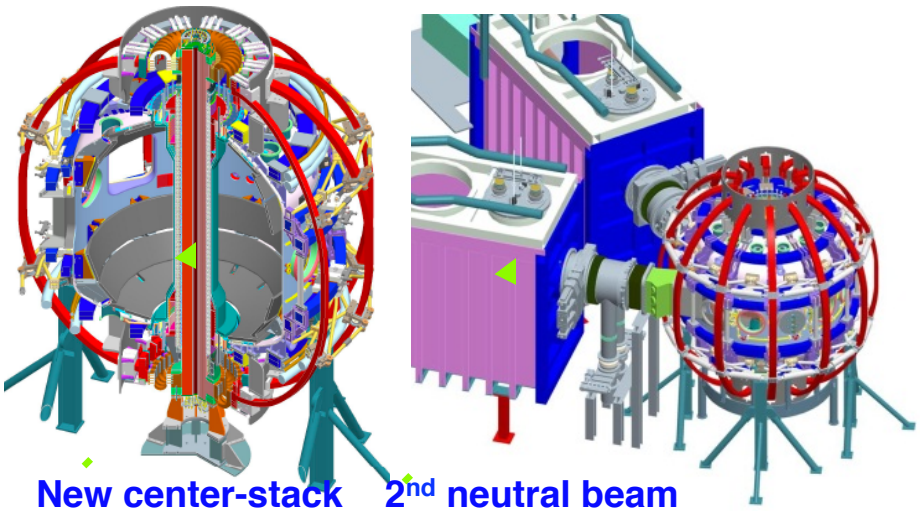
CFETR

Y. Wan, SOFE 2013

Z. Luo et.al, IEEE TRANSACTIONS ON PLASMA SCIENCE, V42, 2014, 1021

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

NSTX-U



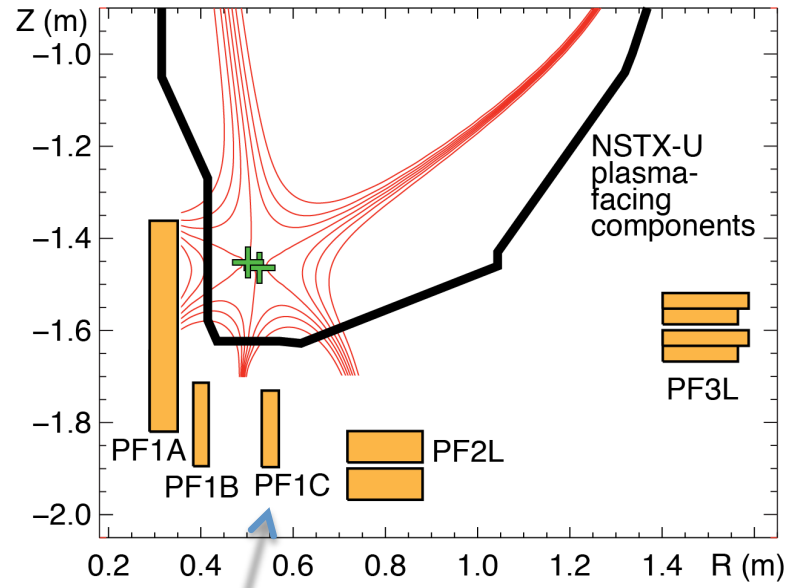
New center-stack

- B_T - > 1 T
- I_p - > 2 MA

2nd neutral beam

- P_{NBI} - > 12 MW
- pulse - > 5 s

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

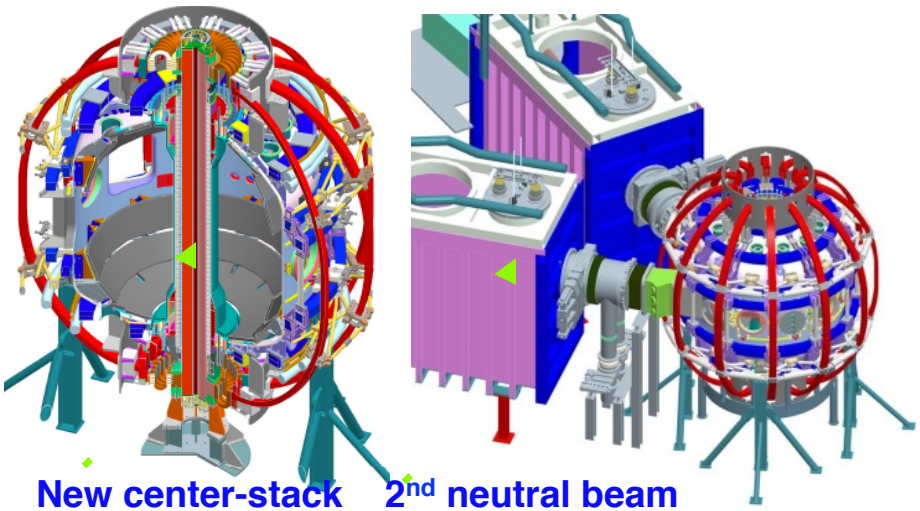


- NSTX-U Mission elements:
  - Advance ST as candidate for Fusion Nuclear Science Facility
  - **Develop solutions for the plasma-material interface challenge**
  - Explore unique ST parameter regimes to advance predictive capability for ITER
  - Develop ST as fusion energy system

- New divertor coil
- Upper-lower snowflake divertors
- Supported by NSTX-U divertor coils and compatible with coil current limits

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

NSTX-U



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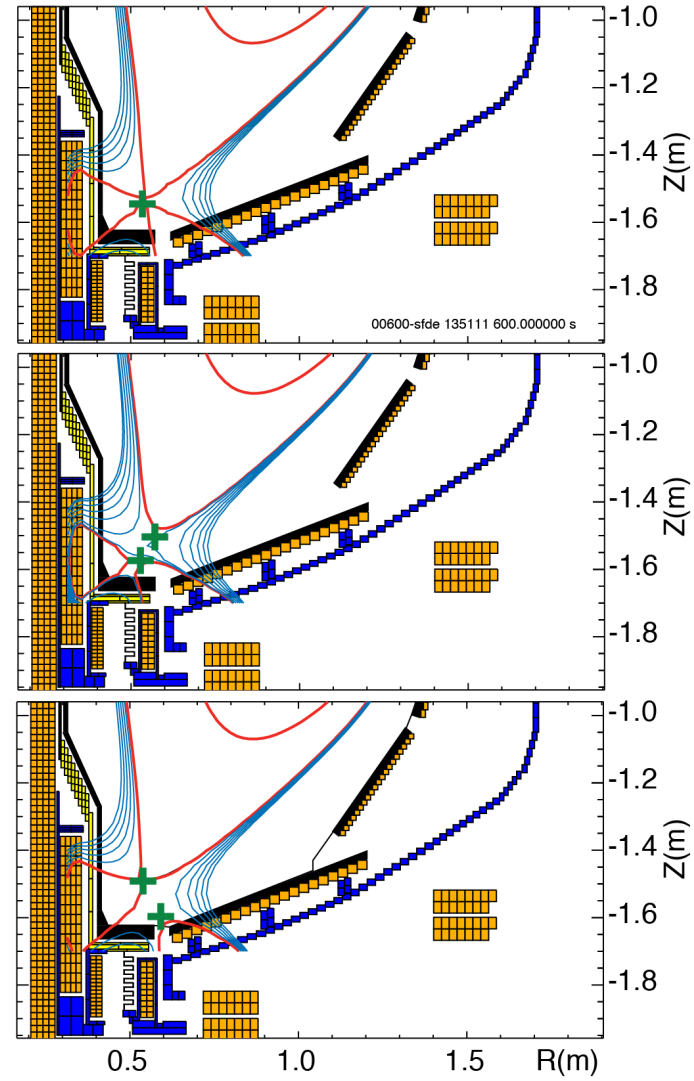
J. E. Menard et. al, Nucl. Fusion 52 (2012) 083015



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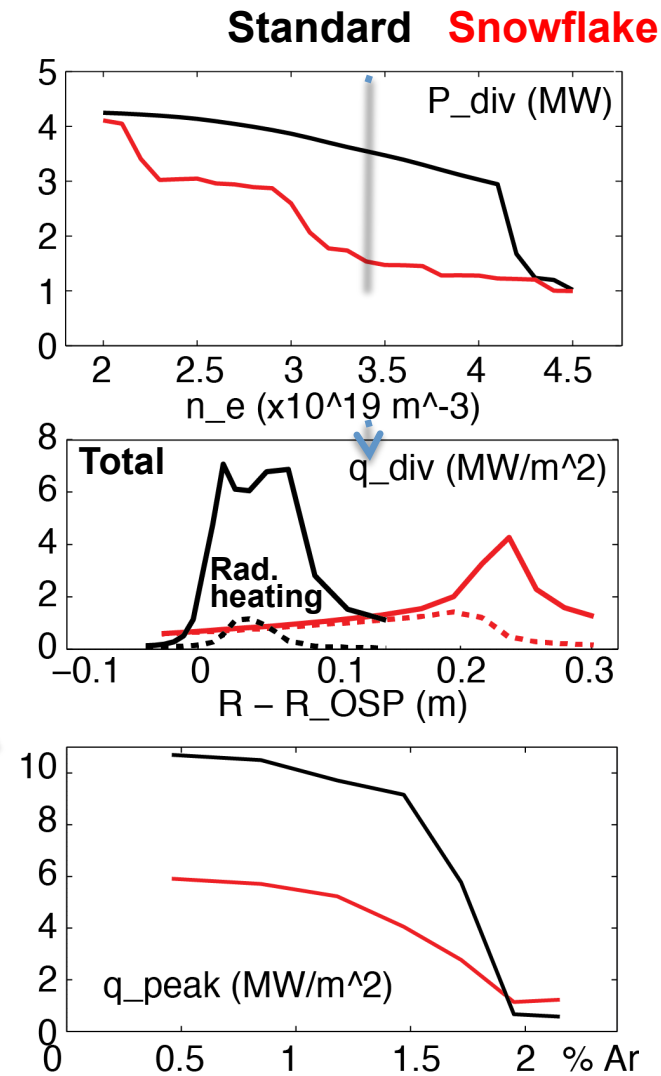
  - Explore unique ST parameter regimes to advance predictive capability for ITER
  - Develop ST as fusion energy system

Edge modeling predicts significant heat flux reduction with radiative snowflake divertor

NSTX-U

- Snowflake with 3% carbon
  - Wide density operational window as low as $n_e/n_G \leq 0.4$
  - Peak heat flux reduced up to 50% stronger (cf. standard radiative divertor) at lower n_e
- Less impurity seeding (argon or neon) needed for lower peak heat flux



- 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

E. T. Meier et. al, Nucl. Fusion (2015)

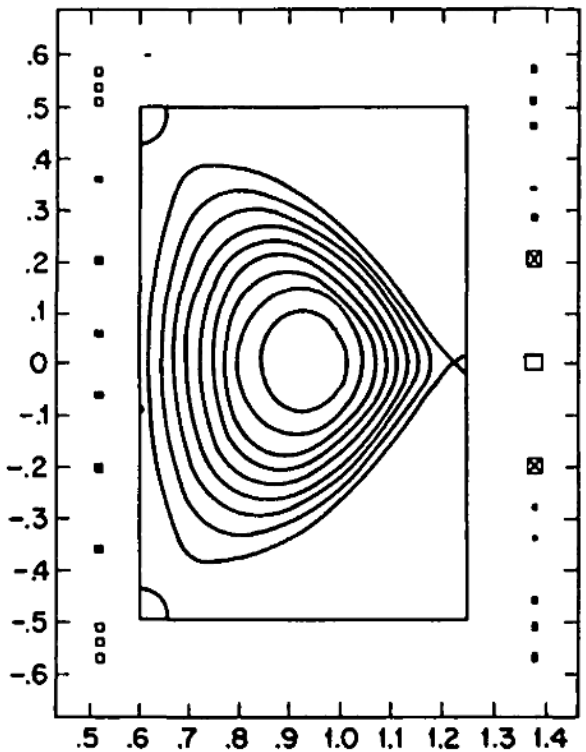
Backup

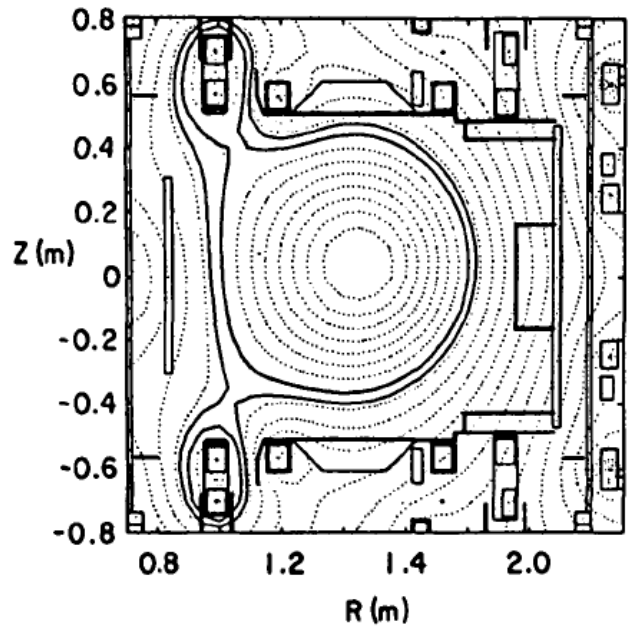
Advanced divertor magnetic configurations (classified by appearance)

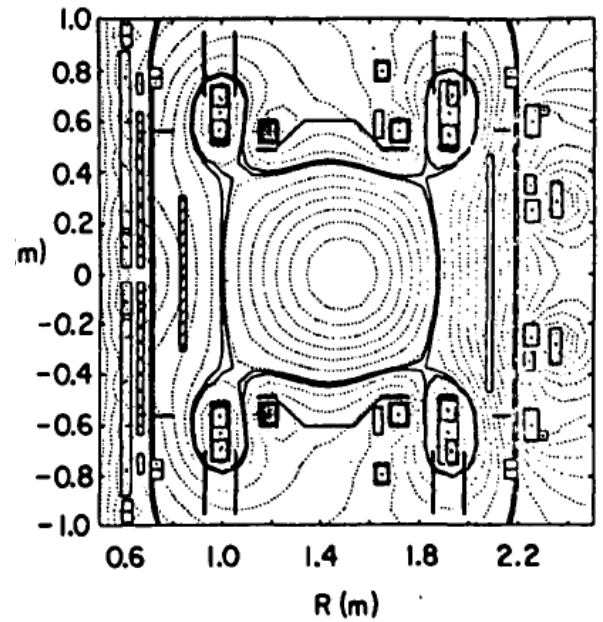
1. **Multiple divertors, each with one X-point**
2. **Higher order (2nd, 3rd) null divertors**
3. **Divertor with multiple X-points**
4. **Long-legged divertors with multiple X-points**

- Note on early concepts
  - Envisioned before H-mode discovery (1982)
  - Some concepts envisioned divertor for particle and impurity control **only**

1. Multiple divertors: triple-null, quadruple-null to share heat and particle fluxes







- D-shaped plasma, high triangularity
- Increased local shear
- Enhanced kink stbility

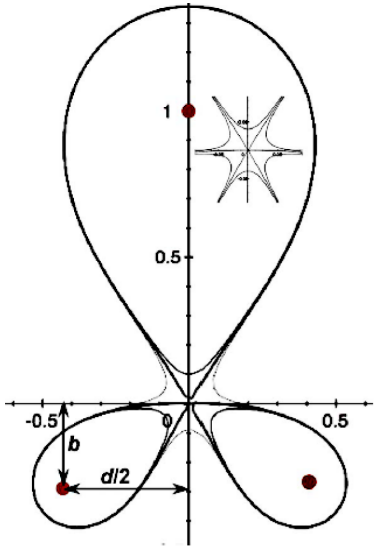
J. Kesner, Nucl. Fusion 30, 548 (1990)

- Poloidal Divertor Experiment tokamak at PPPL (1979 – 1983)
- Significant contribution to divertor physics with double-null configuration

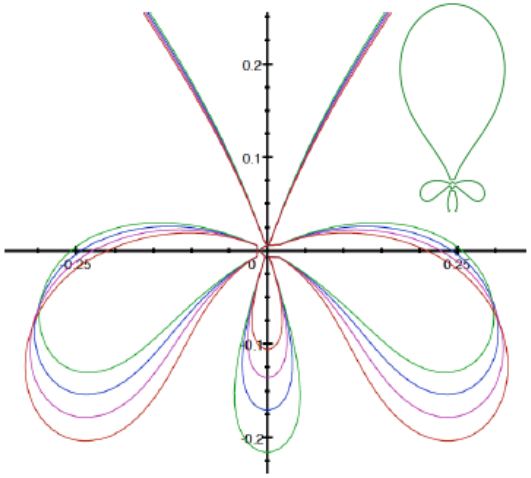
K. Bol et.al, Nucl. Fusion 25, 1149 (1985)

2. Higher order null divertors : larger region of very low B_p to affect geometry and transport

- Snowflake, 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: $B_p \sim r$)
  - Four divertor legs
- Cloverleaf, 3rd order null
  - $B_p(r) \sim r^3$
  - Six divertor legs
- Strong plasma convection

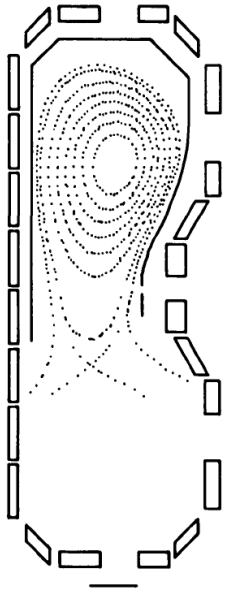


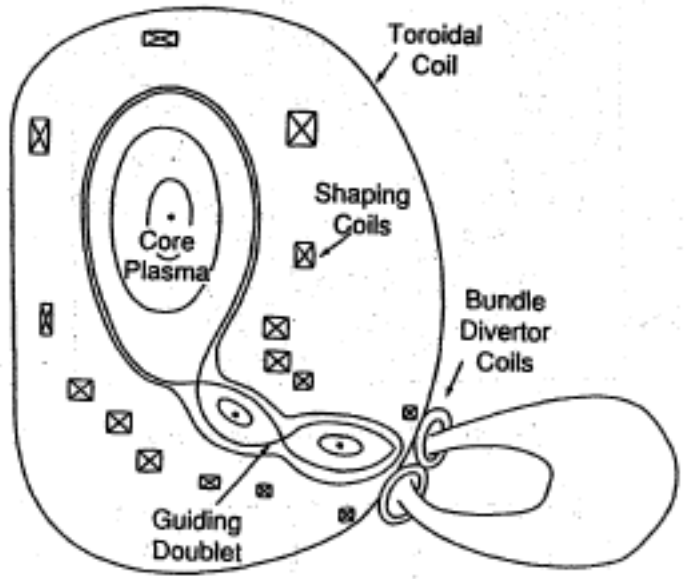
D. D. Ryutov, Phys. Plasmas 14 (2007), 064502



D. D. Ryutov et. al, Phys. Plasmas 20 (2013), 092509

3. Divertor with multiple X-points: expand SOL in the divertor region





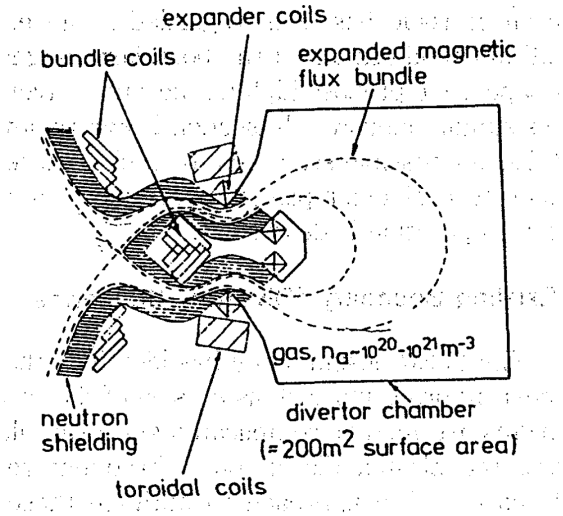


Fig. 3. Bundle divertor proposed for INTOR (M. F. A. Harrison *et al.* : J. Nucl. Mater. 93&94 (1980) 454).

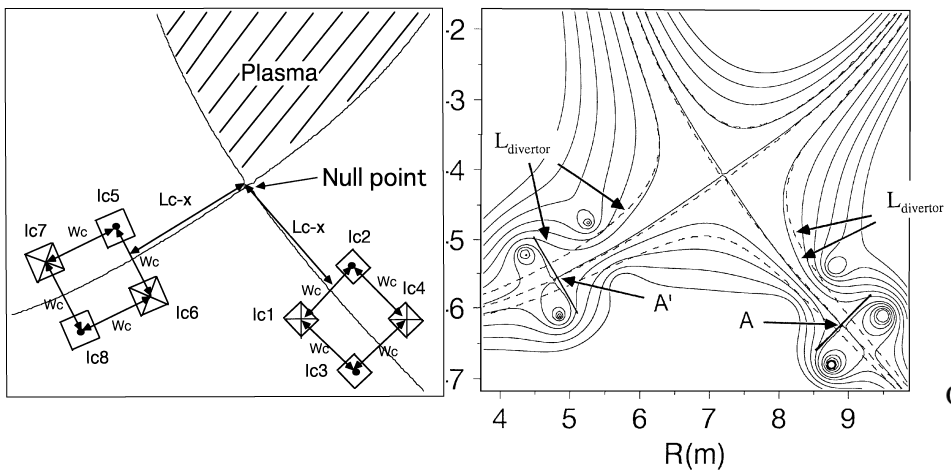
N. Ohyabu et. al, Nucl. Fusion 5 519 (1981)

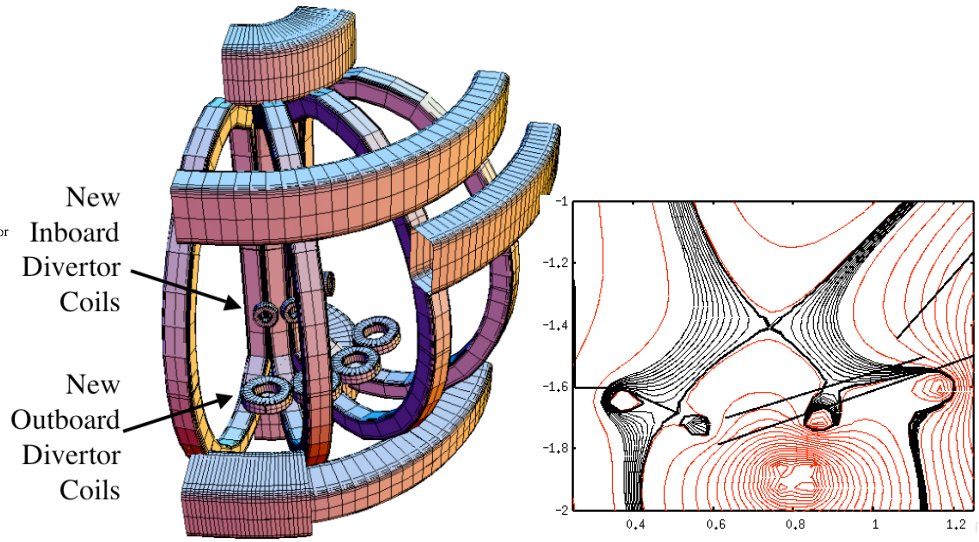
- Doublet III
  Expanded Boundary

N. Ohyabu, J. Plasma Fus. Res. 5 525 (1991)

- Poloidal Bundle + Expanded Boundary
- Analysis of radiation, H-mode compatibility, neutron shielding, coil currents

3. Divertor with multiple X-points: expand SOL in the divertor region





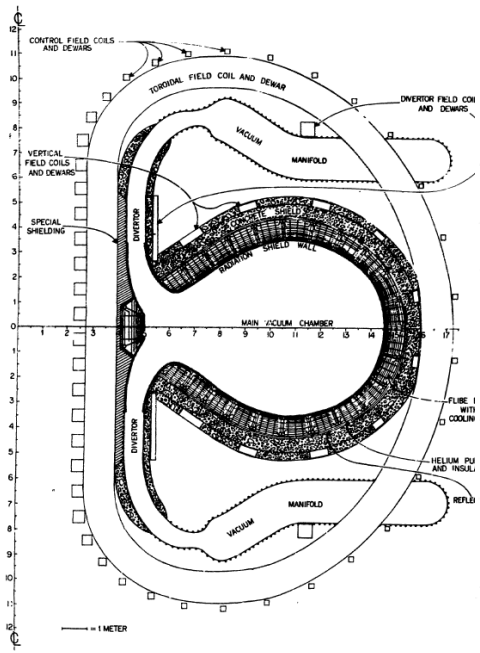
H. Takase, J. Phys. Soc. J. 70, 609, 2001

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

- Cusp-like divertor configuration
  - Coil currents acceptable for ITER-like parameters

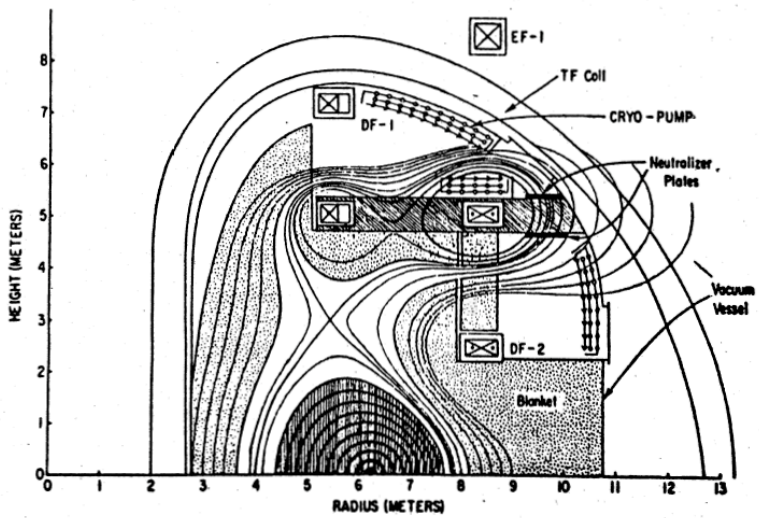
- X-Divertor
  - Small dipole coils under each divertor leg, inside the TF
  - Potential to stabilize rad. front

4. Long-legged divertors with multiple X-points: increase connection length, expand SOL



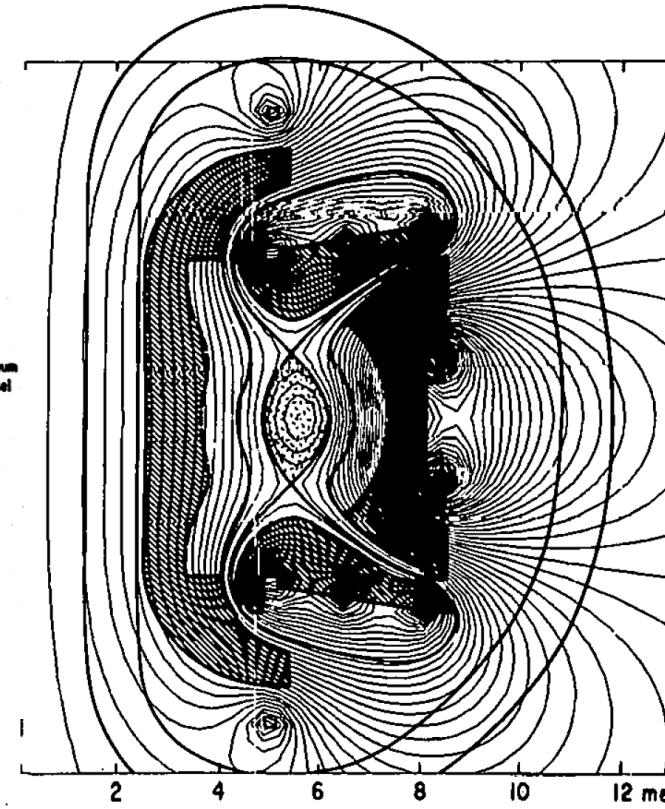
F. H. Tenney et.al,
J. Nucl. Mater. 53 43 (1974)

Conceptual divertor design for Princeton Reference Design Reactor.



A.V. Georgievsky et.al, 6th Symp Eng Prob of Fus Energy, p 583, 1975, IEEE 75CH1097-5-NPS, Copyright 1976

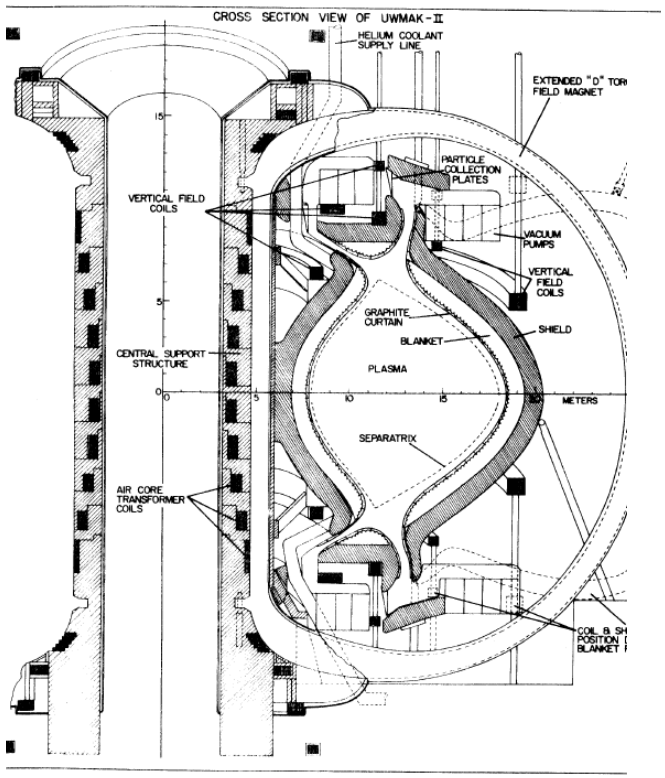
Long-legged high flux expansion poloidal divertor

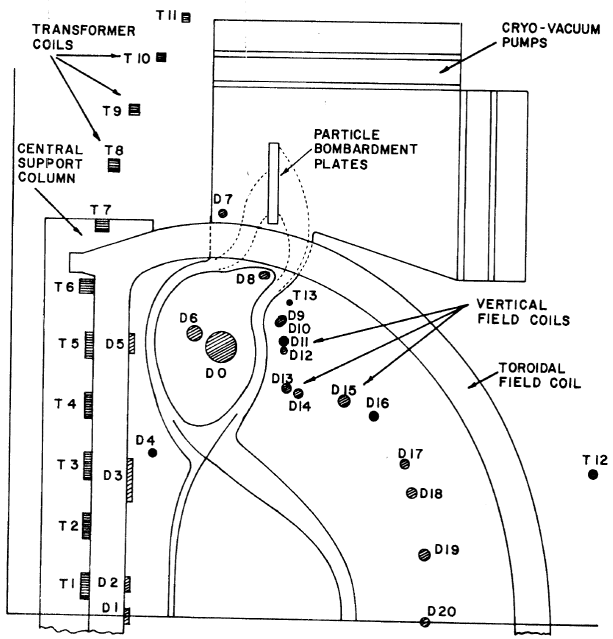


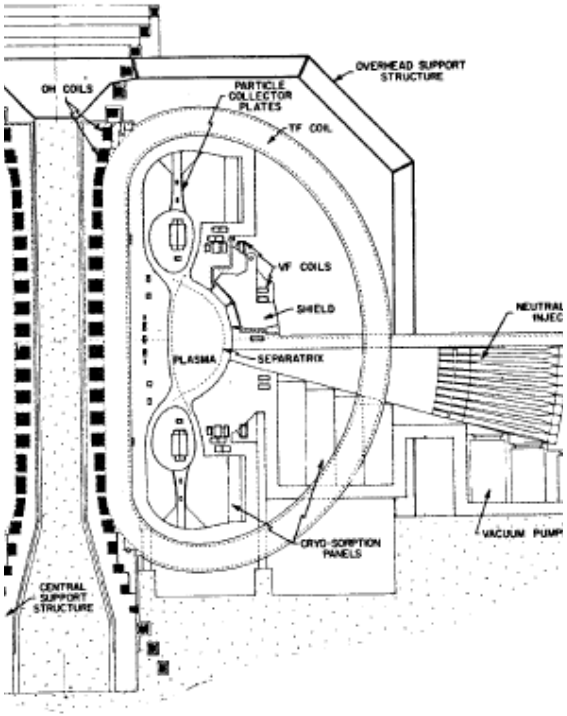
F. H. Tenney,
PPPL Report 1284, 1976

Long-legged double null poloidal divertor

Long-legged divertors with multiple X-points







R. W. Conn et.al, U. Wisc. Report UWFDM-114, 1974

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

G. L. Kulcinski et.al, U. Wisc. Report UWFDM-173, 1976

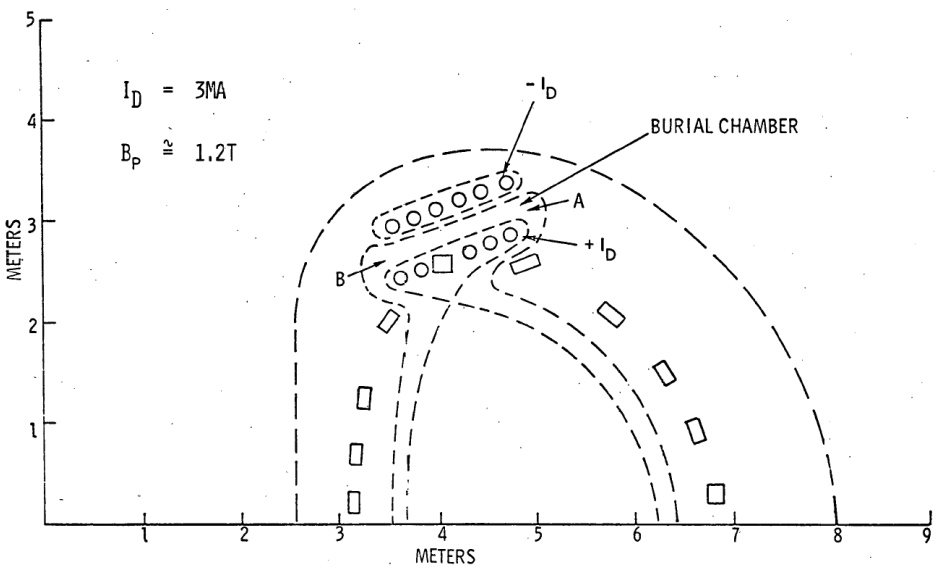
UWMAK-II

UWMAK-III

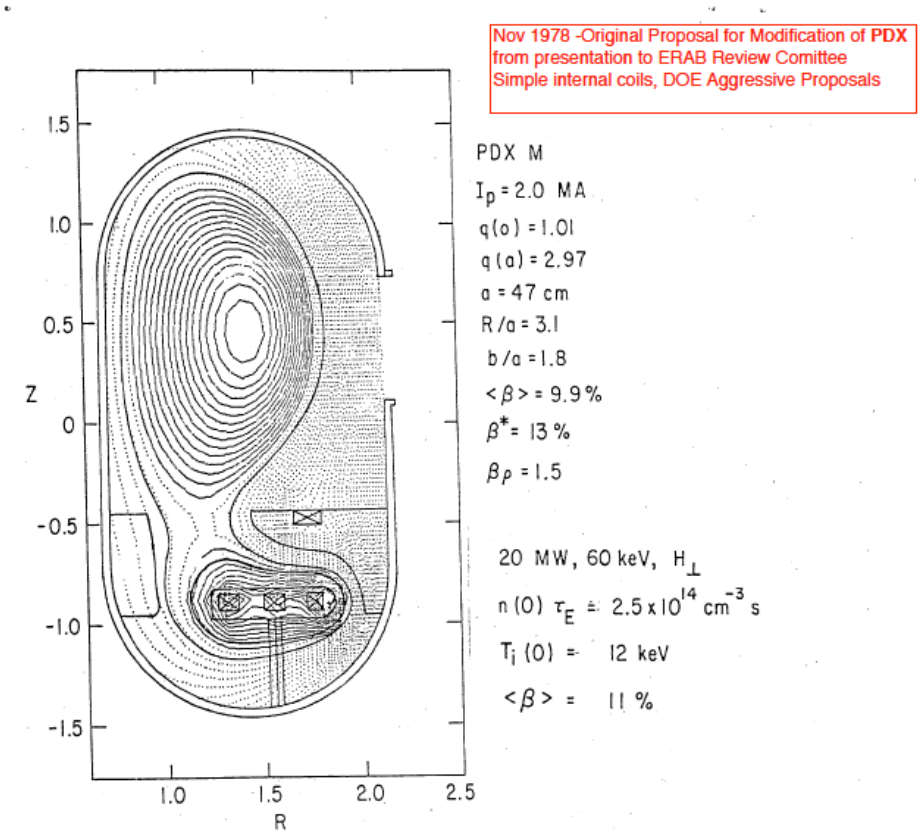
Tokamak Enginering Test Reactor

UW Fusion Technology Institute conceptual reactor systems studies

4. Long-legged divertors with multiple X-points



T. F. Yang et.al, Westinghouse Corp. WFPS-TME-055 1977



TNS reactor (w/ ORNL)

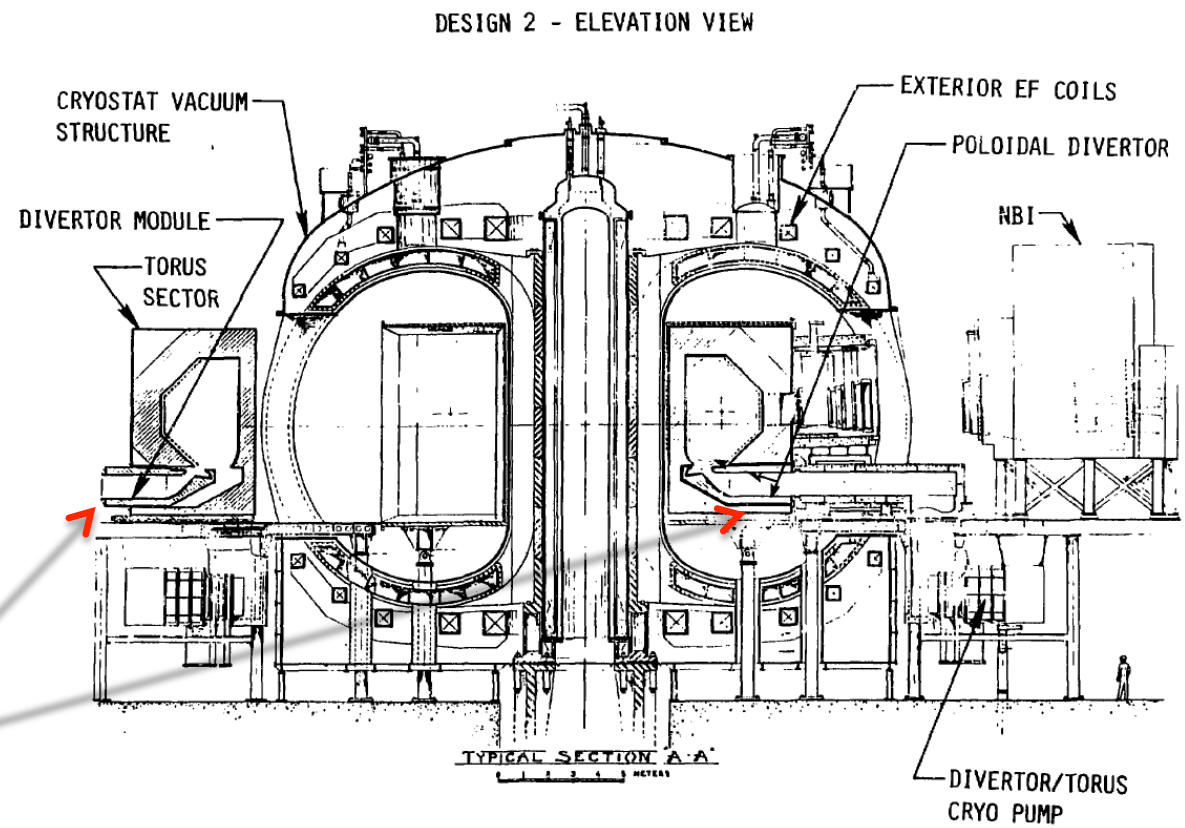
- Divertor heat flux 1-3 MW/m^2
- Flowing liquid lithium targets for heat and particle removal

D. Meade, Private Communication

PDX Modification proposal

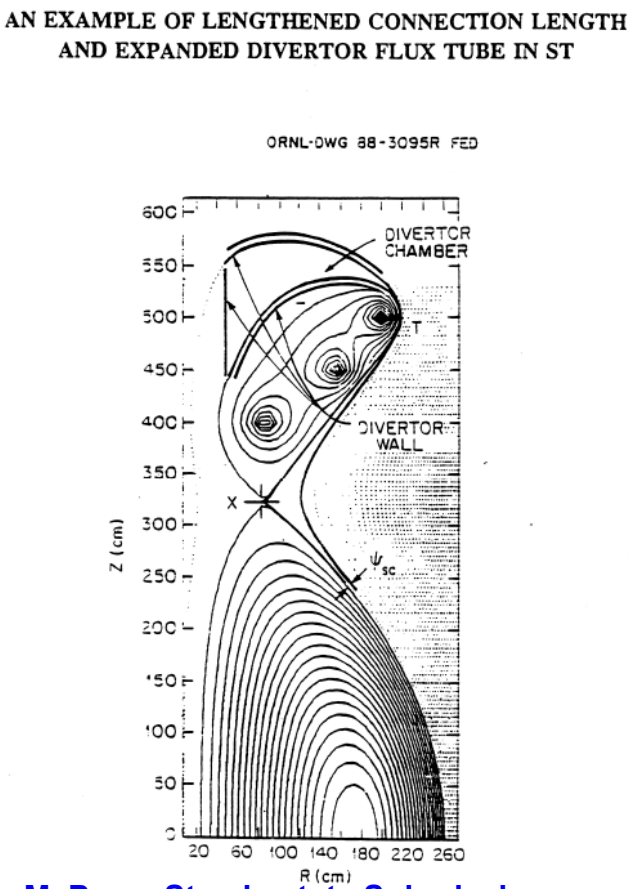
4. Long-legged divertors remove interaction zone away from plasma

- Conceptual design Engineering Test Facility
- R=5.6 m
- a=1.3 m
- B_t=5.5 T
- I_p=6.1 MA
- P_{NBI}=60 MW
- Poloidal divertor
  - W target plates
  - Cryo-panels for particle control

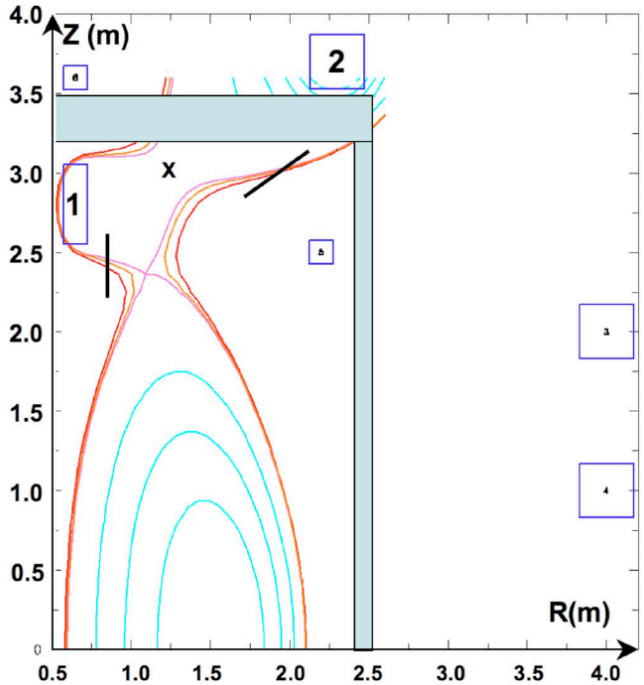


P. H. Sager et. al, J. Vac. Sci. Tech. 18, 1081 (1981)

4. Long-legged divertors with multiple X-points

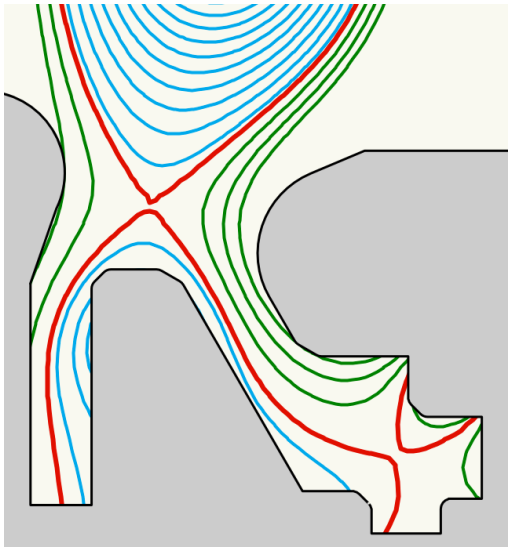


M. Peng, Steady-state Spherical tokamak TST,
Workshop on Edge Plasma for BPX and ITER, 1991



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

Super-X divertor



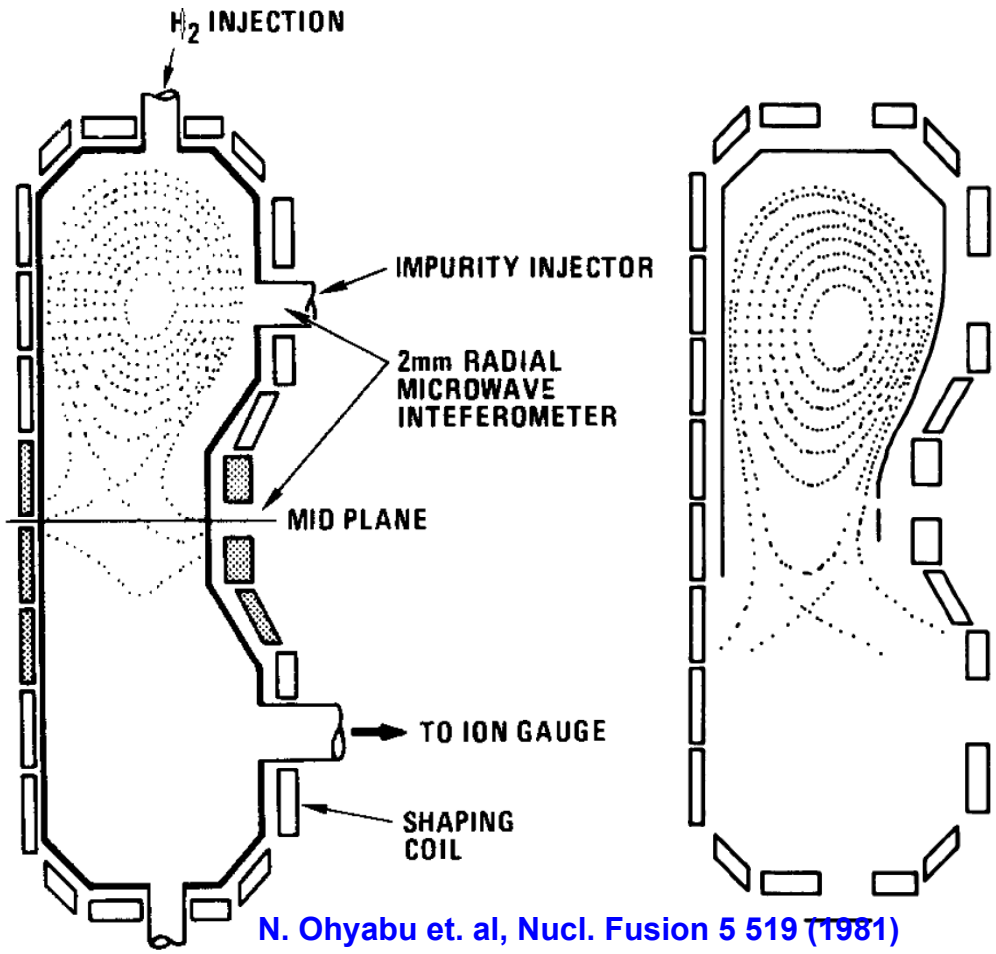
B. LaBombard et.al, APS 2013, IAEA 2014

X-point target divertor
ADX tokamak proposal

Advanced magnetic divertor configurations: status of experiments

1. **Dedicated experimental devices (1979-1986)**
   - PDX
   - Doublet III Expanded boundary
2. **Snowflake divertor configuration (existing devices with existing coils, 2008-present)**
   - TCV, 2008
   - NSTX, 2009
   - DIII-D, 2012
   - EAST, 2014
3. **Long leg divertor physics (2010-present)**

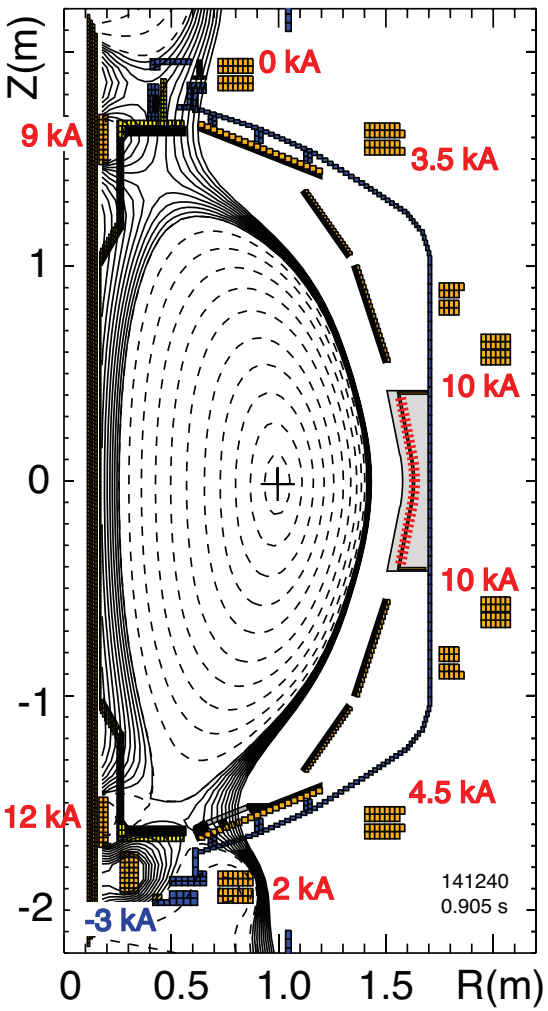
1. Doublet III Expanded Boundary was the first advanced magnetic divertor configuration experiment

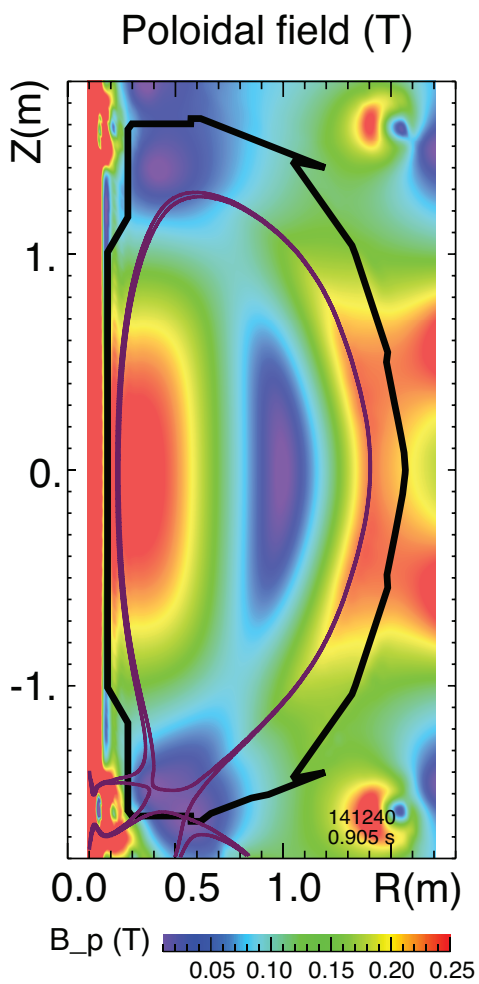


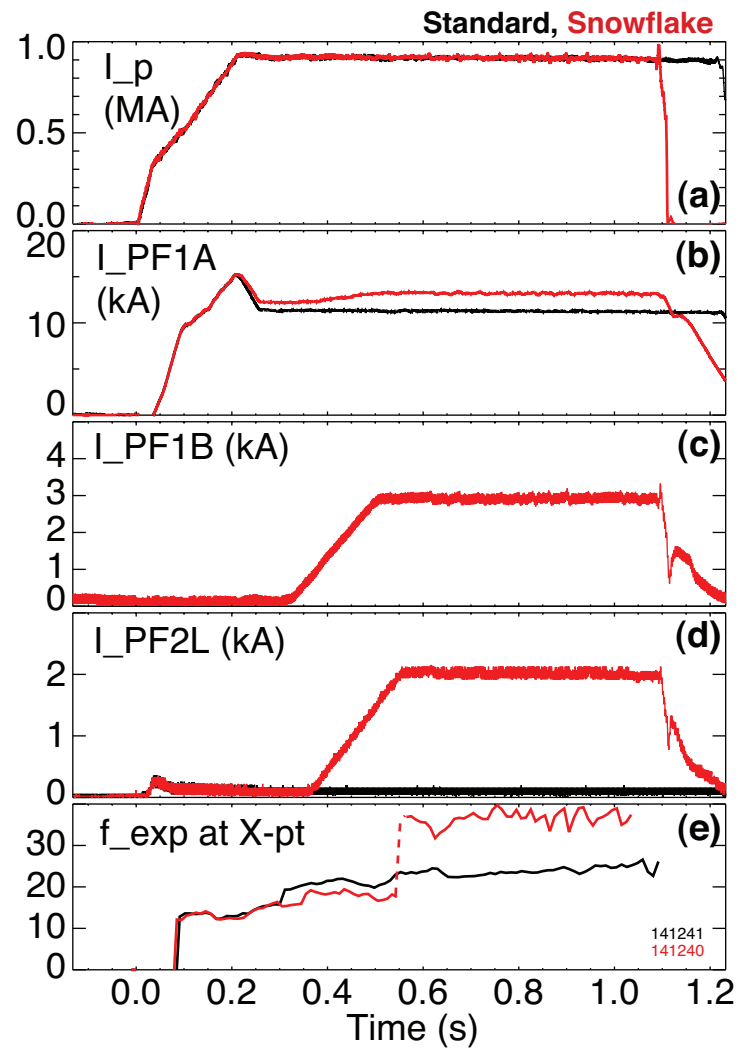
N. Ohyabu et. al, Nucl. Fusion 5 519 (1981)
A. Mahdavi et. al, J. Nuc. Mater. 111 (1982) 355

- Stability of divertor configuration with outside PF coils
- Integrated power and particle exhaust
  - Reduction of intrinsic impurities in the core
  - Radiative divertor plasma cooling with seeded argon
  - Argon screening from main plasma
- Compatibility with core confinement

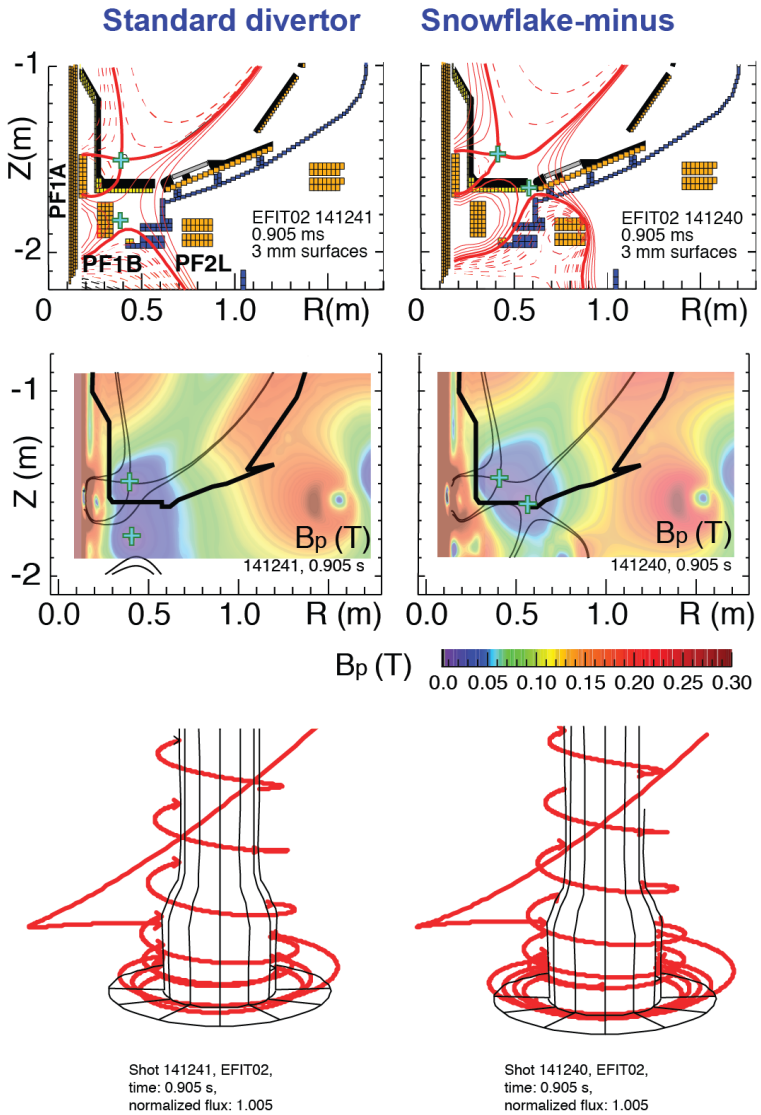
Snowflake divertor configurations obtained with existing divertor coils, maintained for up to 10 τ_E

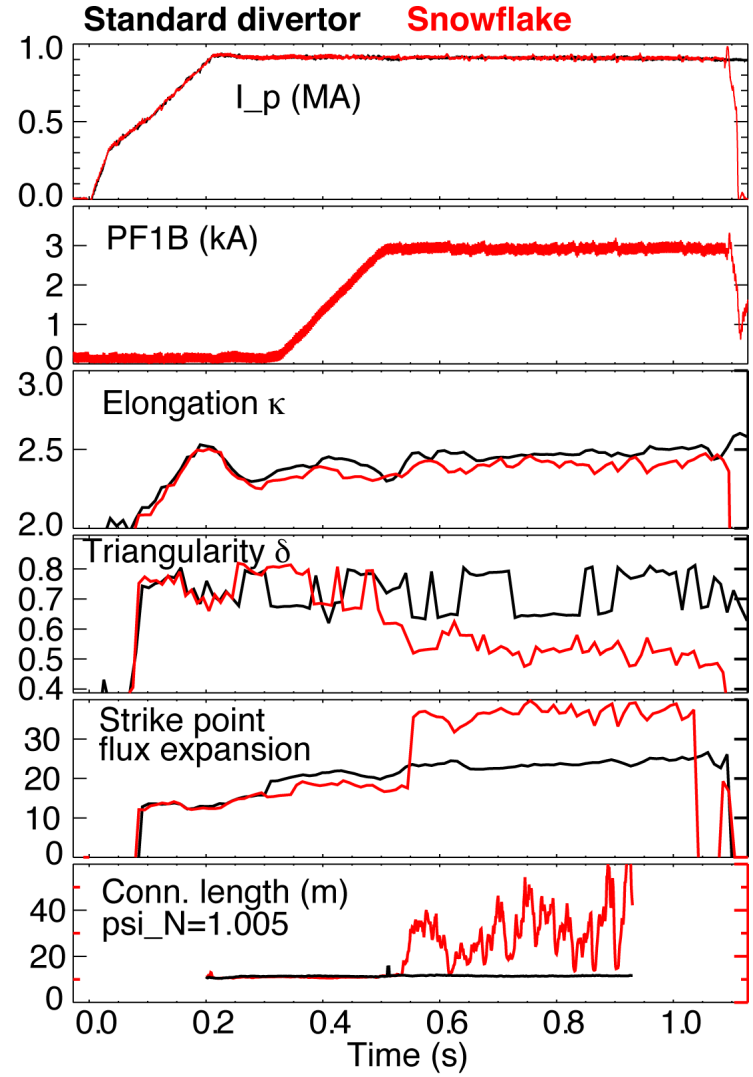






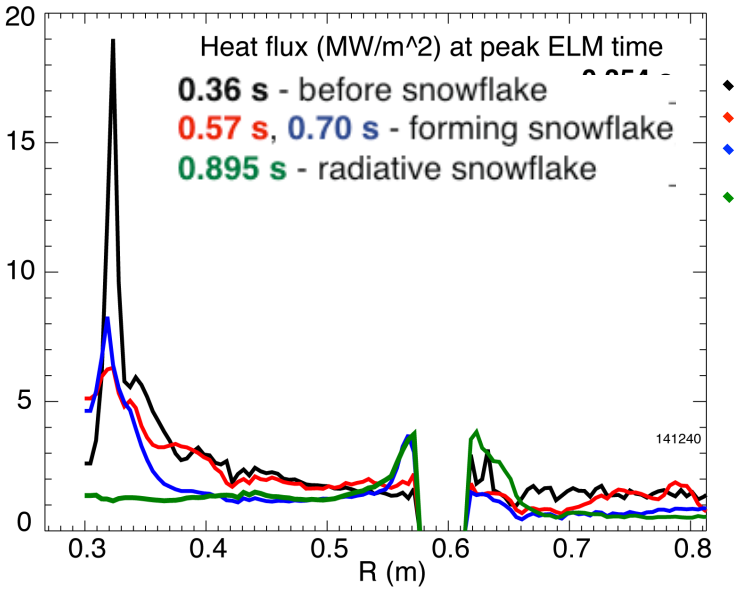
Snowflake divertor configurations obtained with existing divertor coils in NSTX



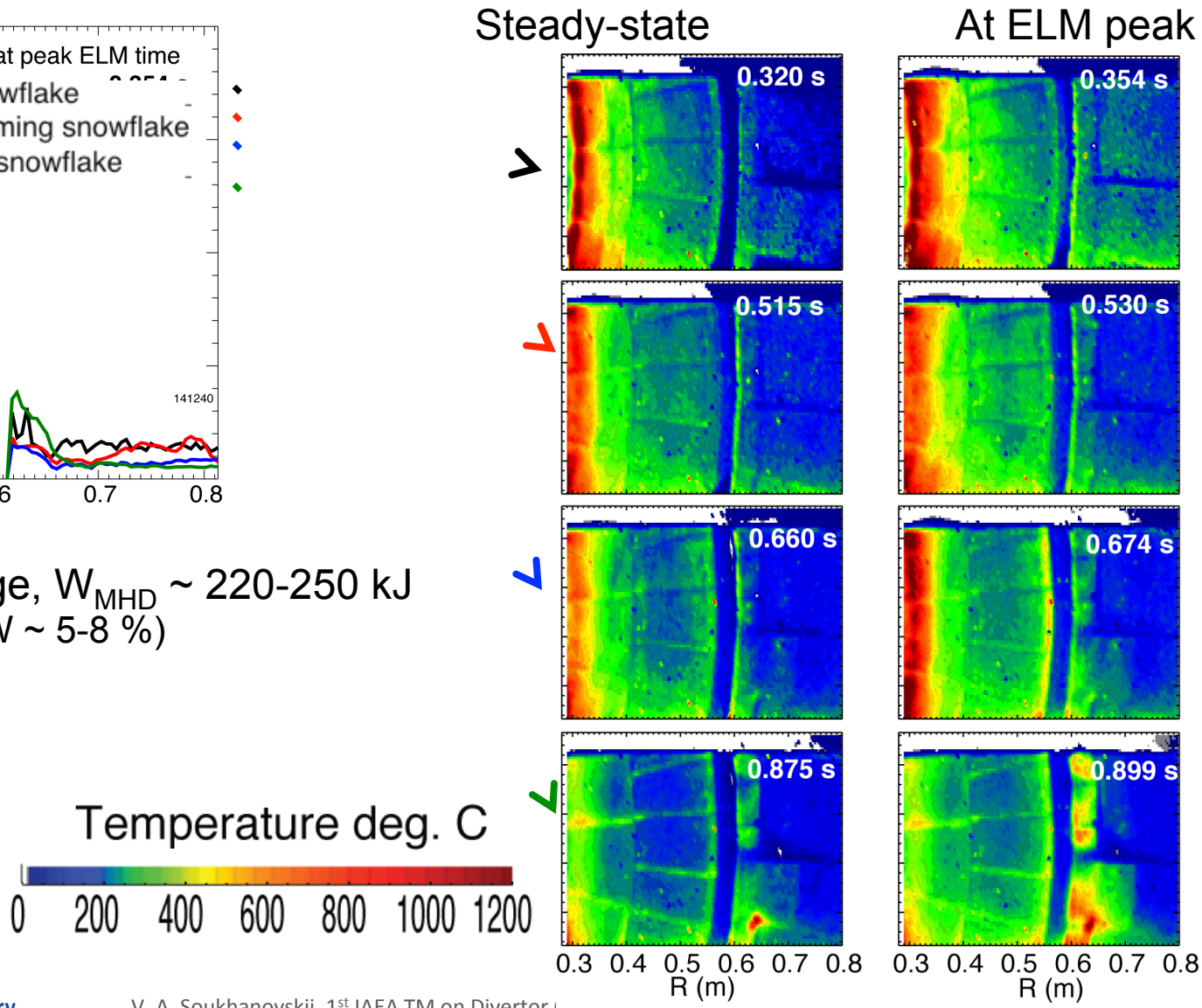


Impulsive heat loads due to Type I ELMs are mitigated in snowflake divertor

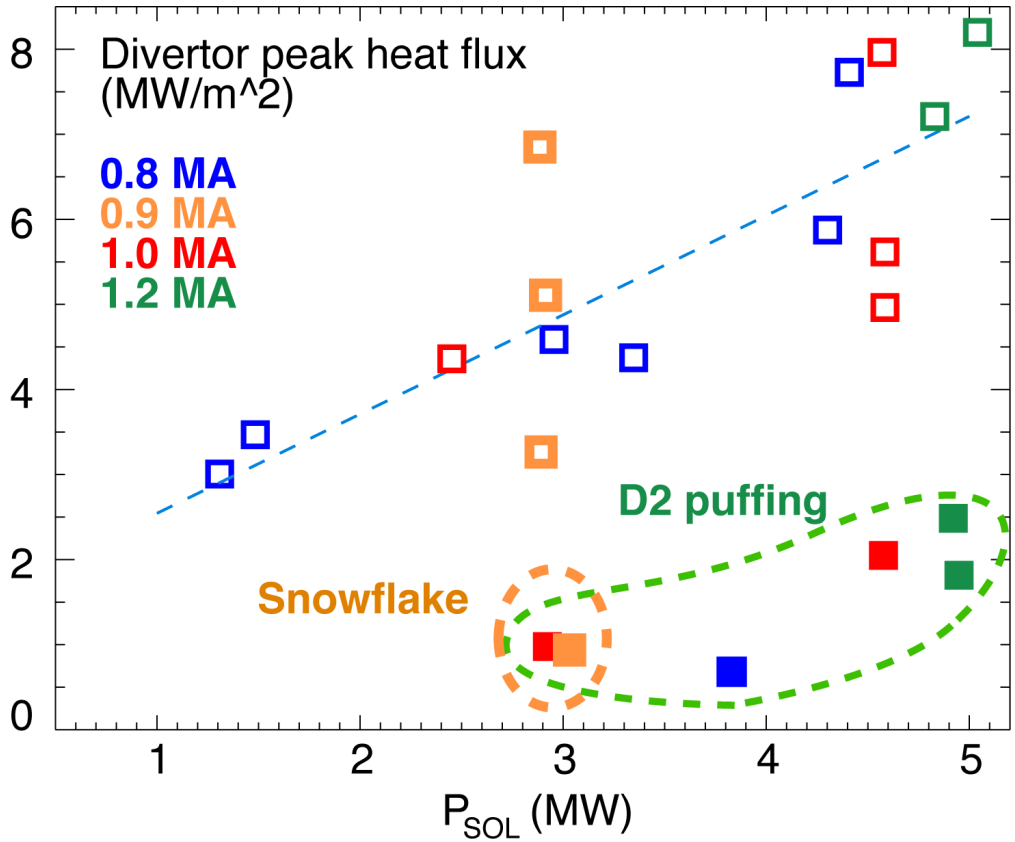
NSTX



- H-mode discharge, W_{MHD} ~ 220-250 kJ
  Type I ELM ($W/\Delta W$ ~ 5-8 %)

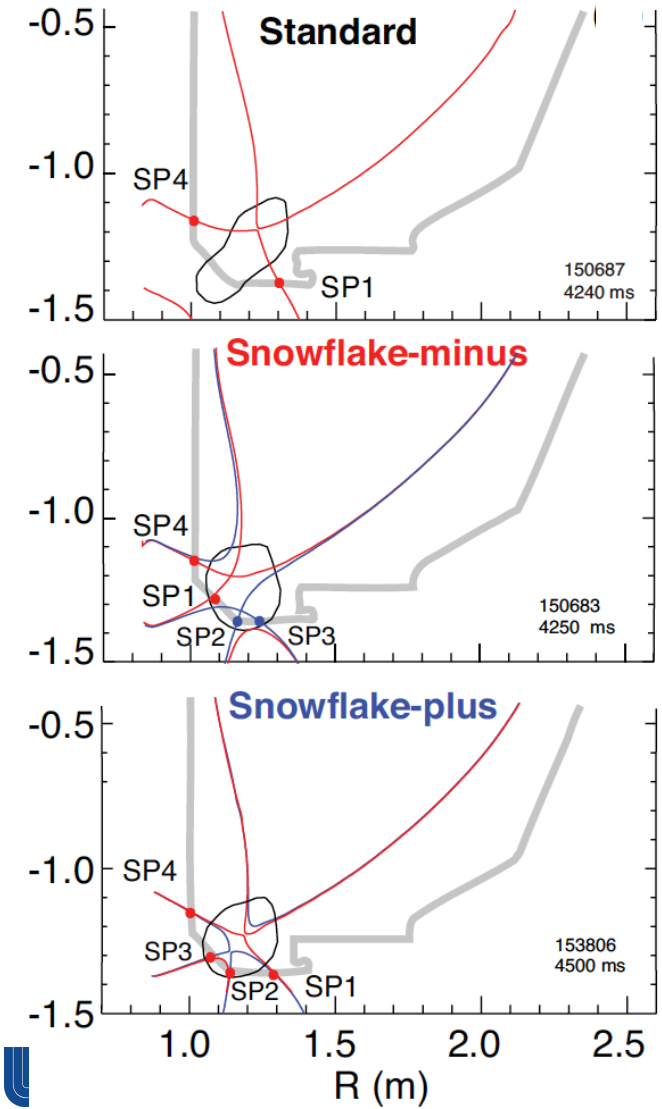


NSTX: Access to radiative detachment with intrinsic carbon in snowflake divertor facilitated



- Snowflake divertor (*): P_{SOL}~3-4 MW, f_{exp}~40-60, q_{peak}~0.5-1.5 MW/m^2
  - Low detachment threshold
  - Detachment characteristics comparable to PDD with D_2 or CD_4 puffing

Snowflake-minus and snowflake-plus configurations maintained for 2-3 seconds in H-mode discharges



- Acceptable deviation from exact snowflake $\mathbf{d_{SF} \leq a\,(\lambda_q\,/a)^{1/3}}$

  where *d* – distance between nulls, *a* – plasma minor radius, λ_q – SOL width

  — $d_{XX} \leq 0.1$ m in SF-minus and SF-plus

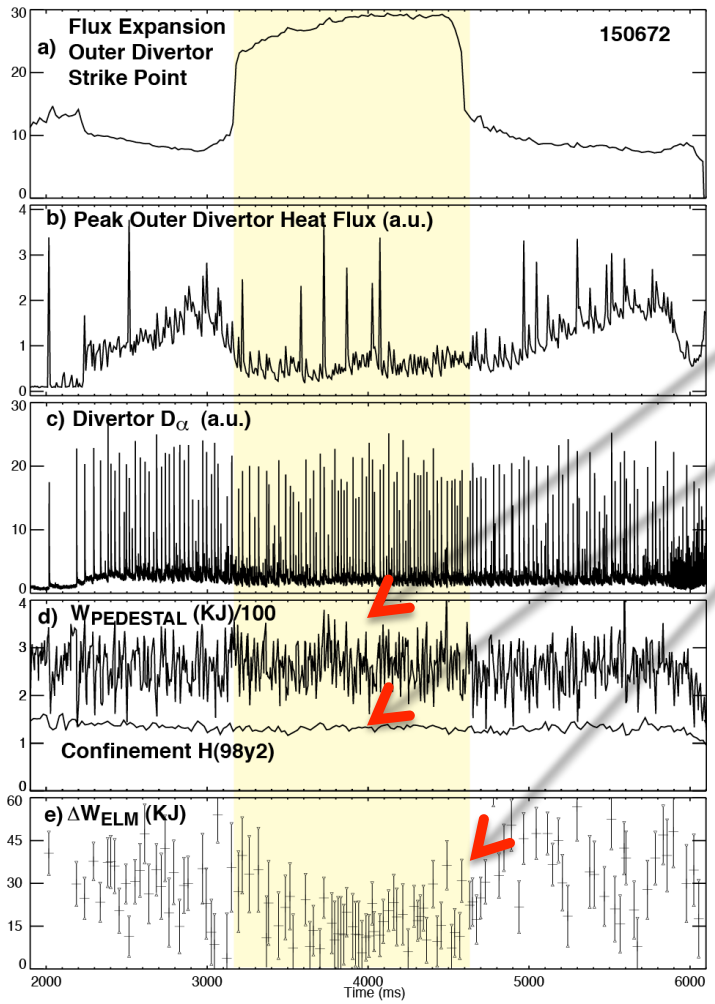
  — Cf. $d_{XX} = 0.25$-0.30 m in standard divertor

- Additional strike points

- Large region of low B_p

  — Shown contour $0.1\times\,|B_p|/B_p^{mp}$

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

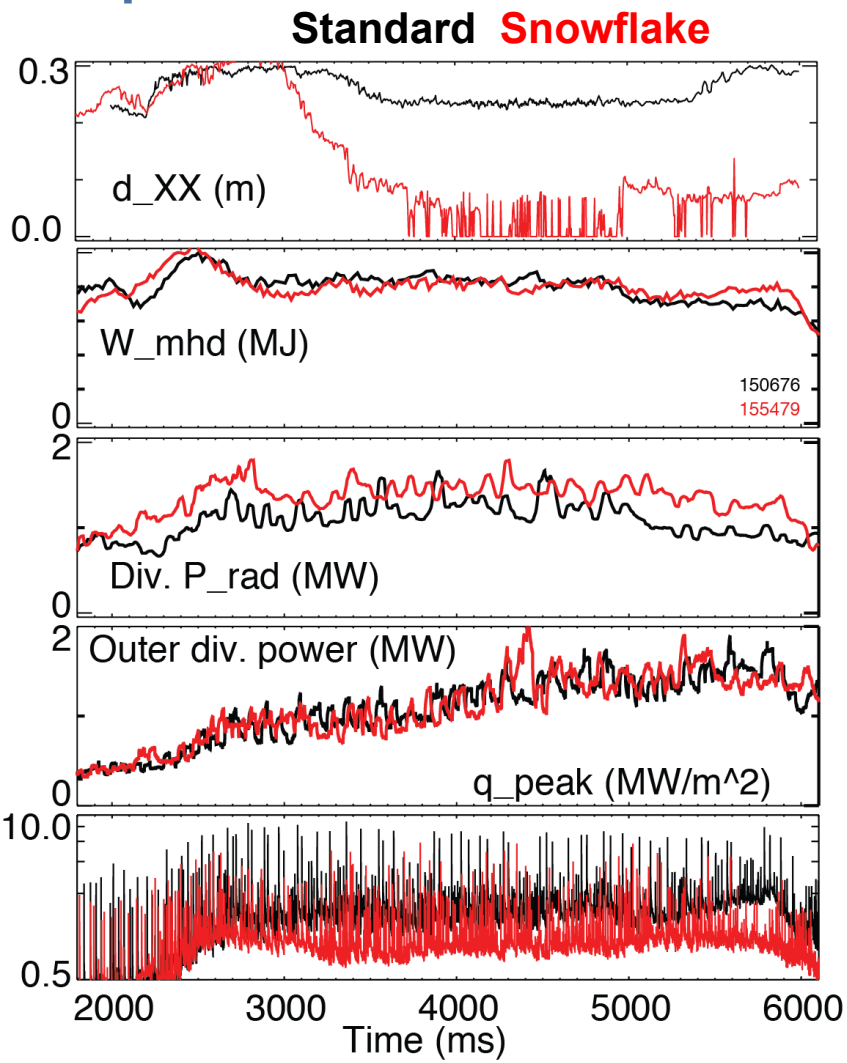


Detailed ELM analysis before/during SF shows:

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

S. L. Allen et al., Paper PD/1-2, IAEA FEC 2012.

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

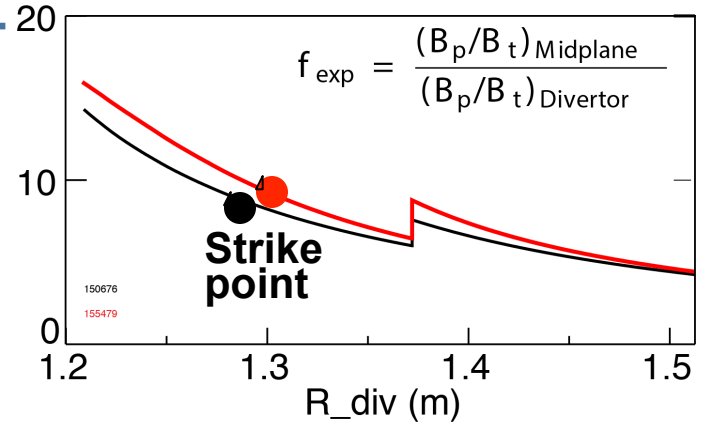


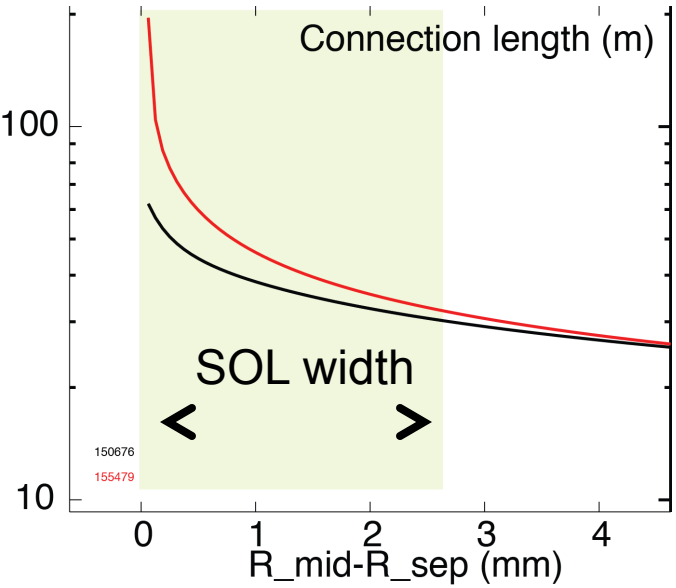
- Snowflake with d_{XX} < 10 cm
- Core plasma unaffected
  - 5 MW NBI H-mode
  - Stored energy and density constant
- Divertor power balance unaffected
- In outer divertor, q_{peak} reduced by 30%

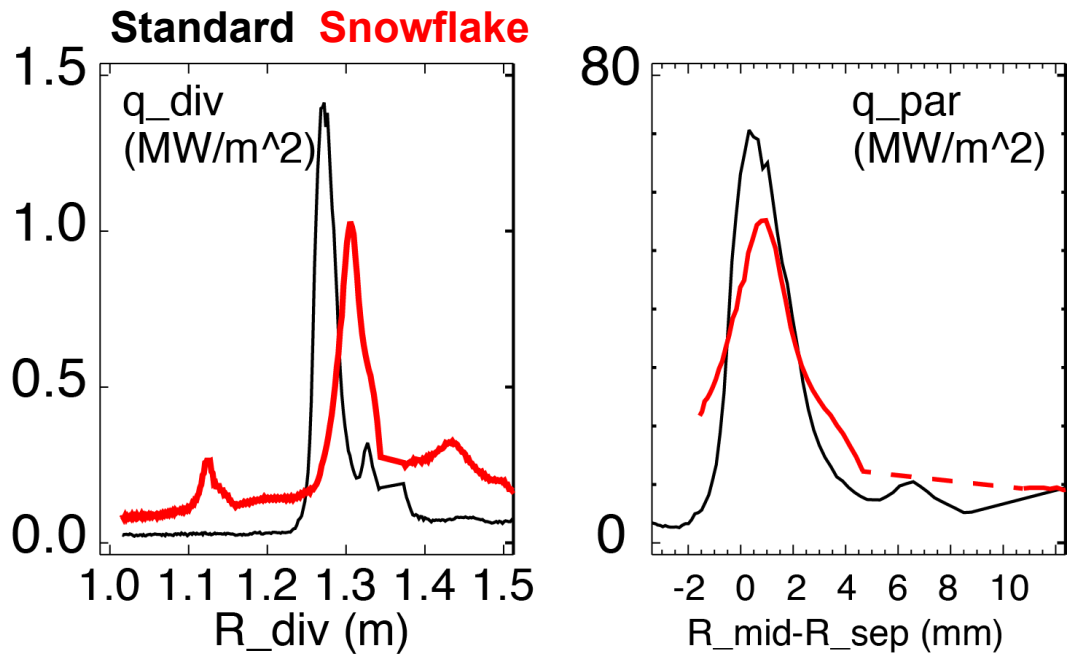
$$A_{wet} = 2\pi R\, f_{exp}\, \lambda_{q_{||}}$$

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

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



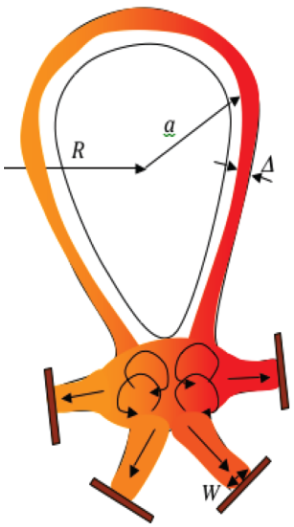


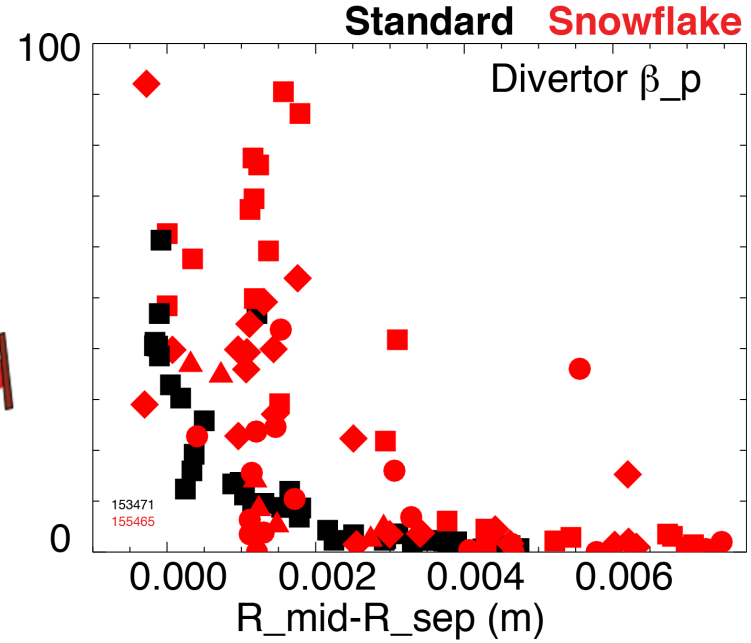


- Flux expansion increased ~20%
  - Depends on configuration, can be up to X3
- $L_{||}$ increased by 20-60% over SOL width
- Divertor heat flux reduced ~30%
- Parallel heat flux reduced ~20%

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**
  - $\beta_p = P_k/P_m = 8\pi P_k/B_p^2 >> 1$
  - Loss of poloidal equilibrium
  - Fast convective plasma redistribution
  - Especially efficient during ELMs when P_k is large
- **Estimated size of convective zone**
  - Standard: 1 cm
  - Snowflake: 6-8 cm

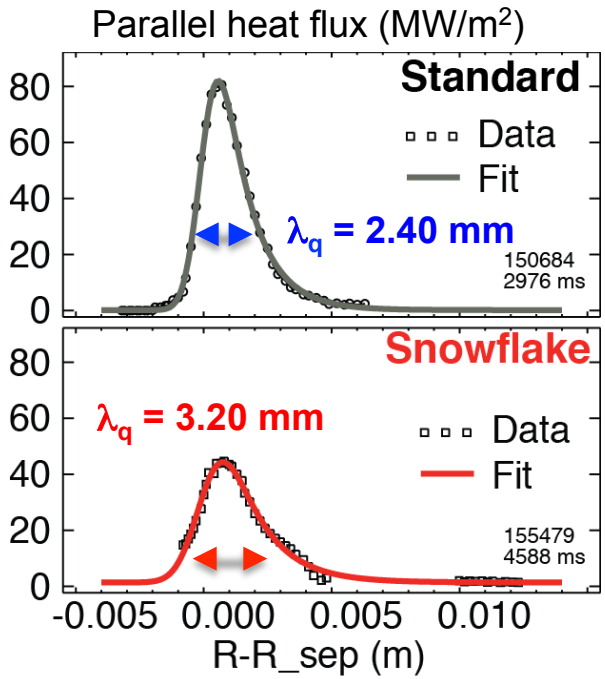


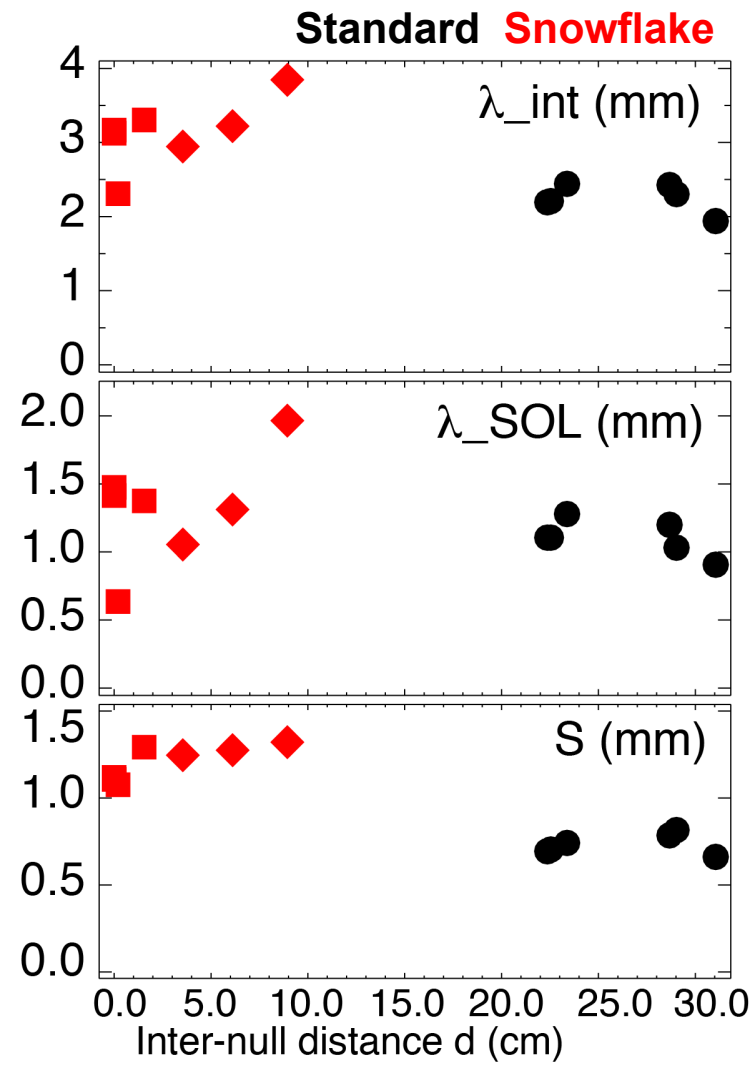


- Divertor null-region β_p measured by divertor Thomson Scattering
  - In snowflake, broad region of higher β_p>>1
  - Higher X10 during ELMs

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

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

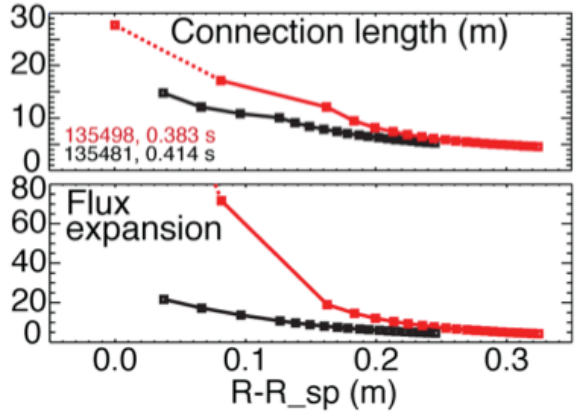


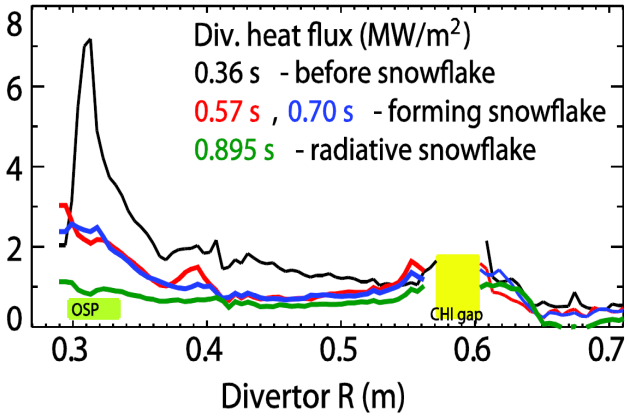


- Fit $q_{||}$ profile with Gaussian (S) and Exp. (λ_{SOL}) functions (Eich PRL 107 (2011) 215001)
- Increased λ_q may imply increased transport
  - Increased radial spreading due to $L_{||}$
  - SOL transport affected by null-region mixing
  - Enhanced dissipation may also play role

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

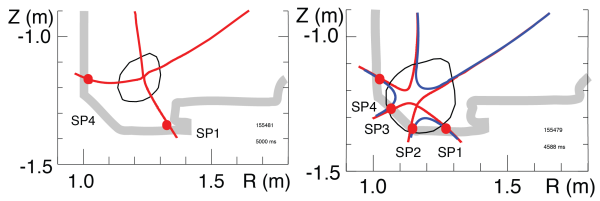
Standard **Snowflake** NSTX

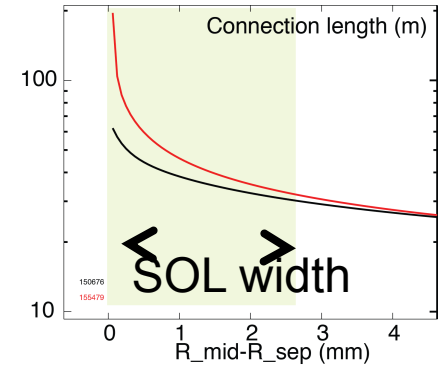




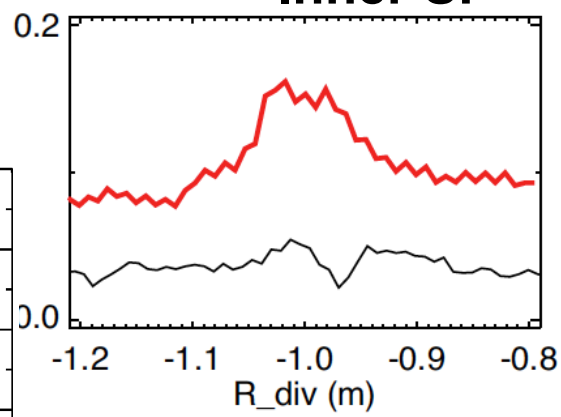
- Geometry and radiation

Standard **Snowflake**

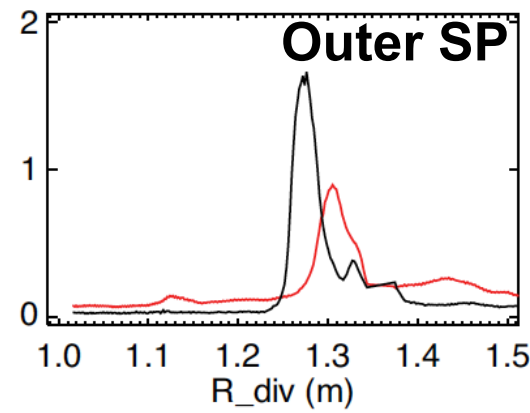




Inner SP

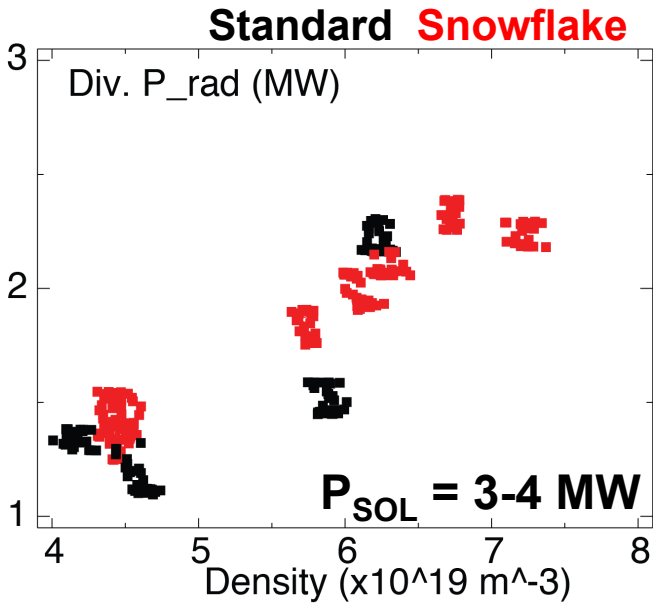


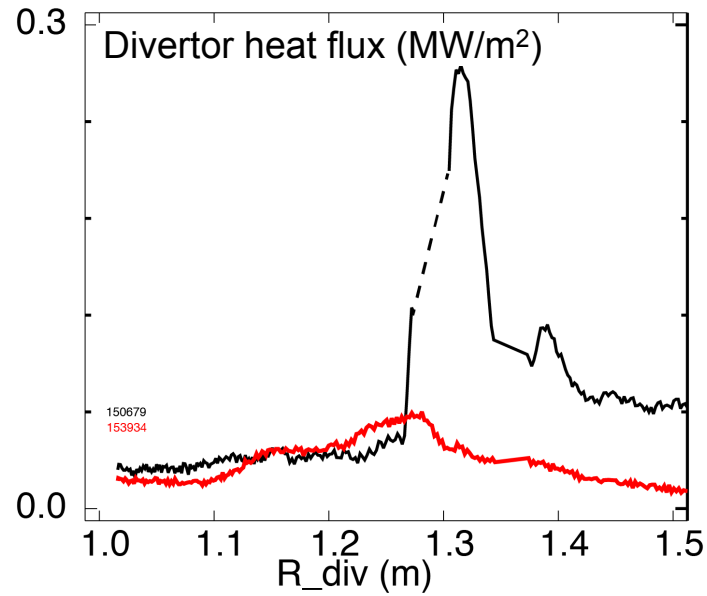
Outer SP

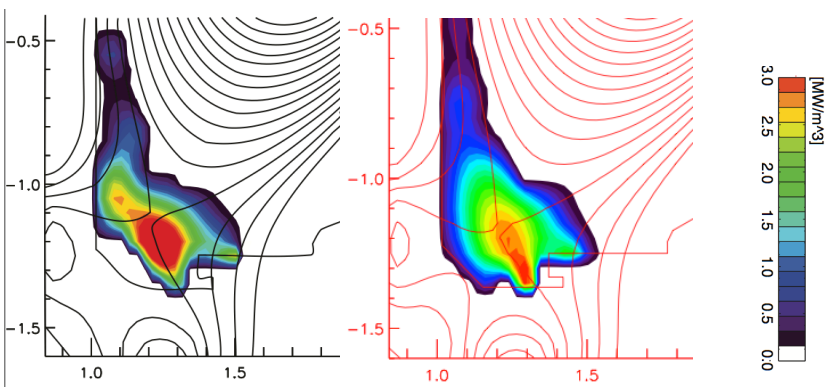


- Flux expansion increased ~20%
- $L_{||}$ increased by 20-60% over SOL width
- Divertor heat flux reduced ~40%

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

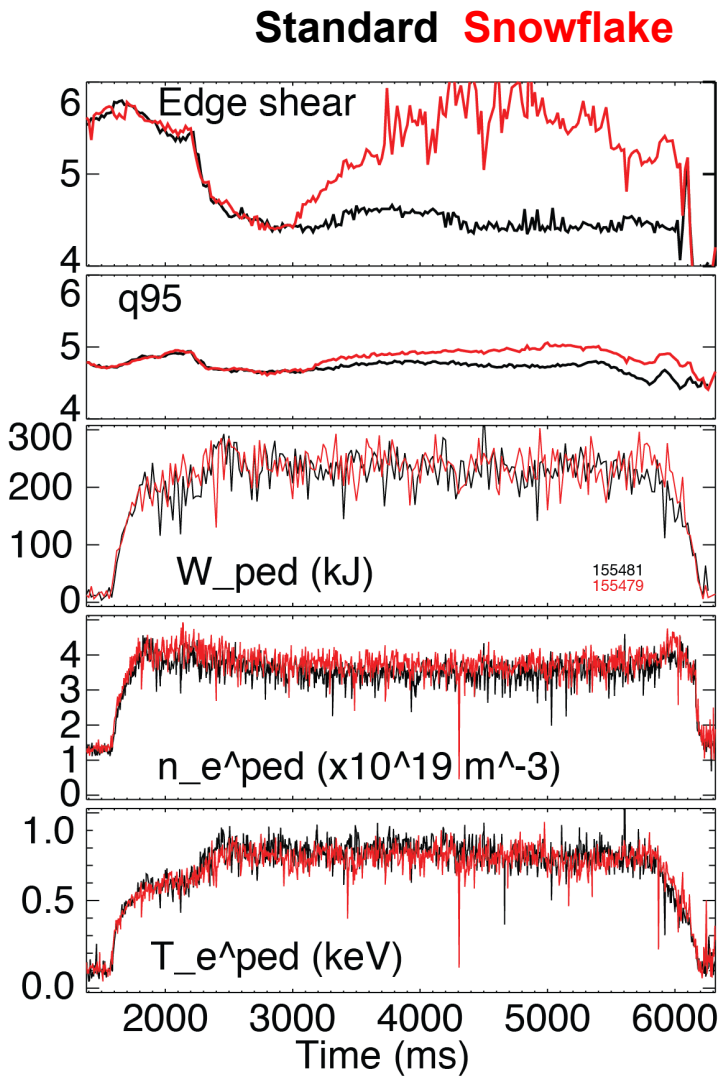






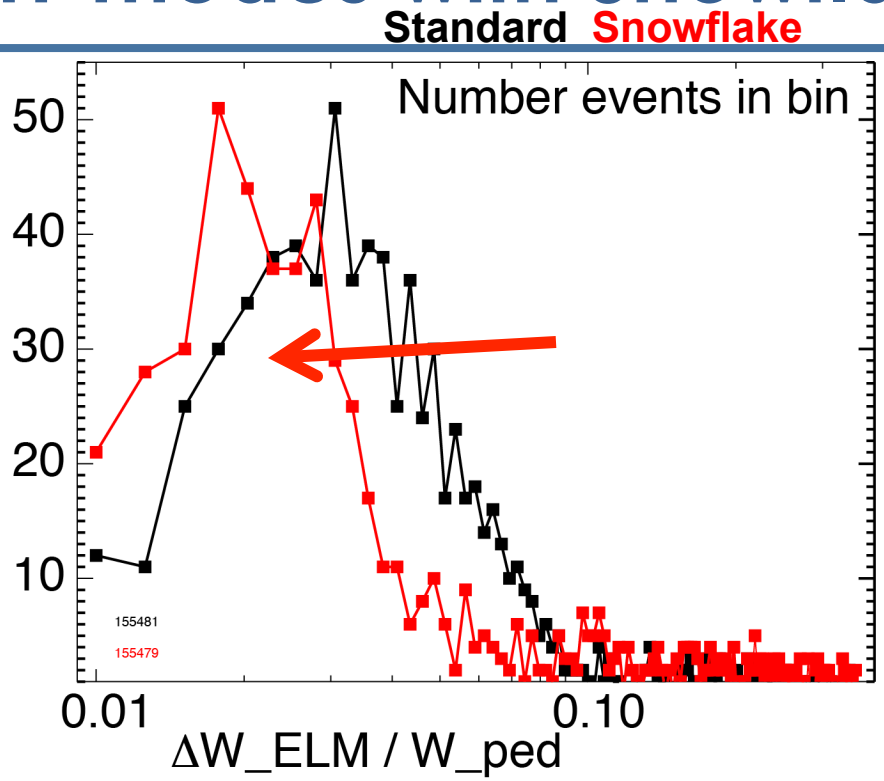
- **Detached radiative divertor produced by D_2 injection with intrinsic carbon radiation**
- **In radiative snowflake nearly complete power detachment at P_{SOL}~3 MW**

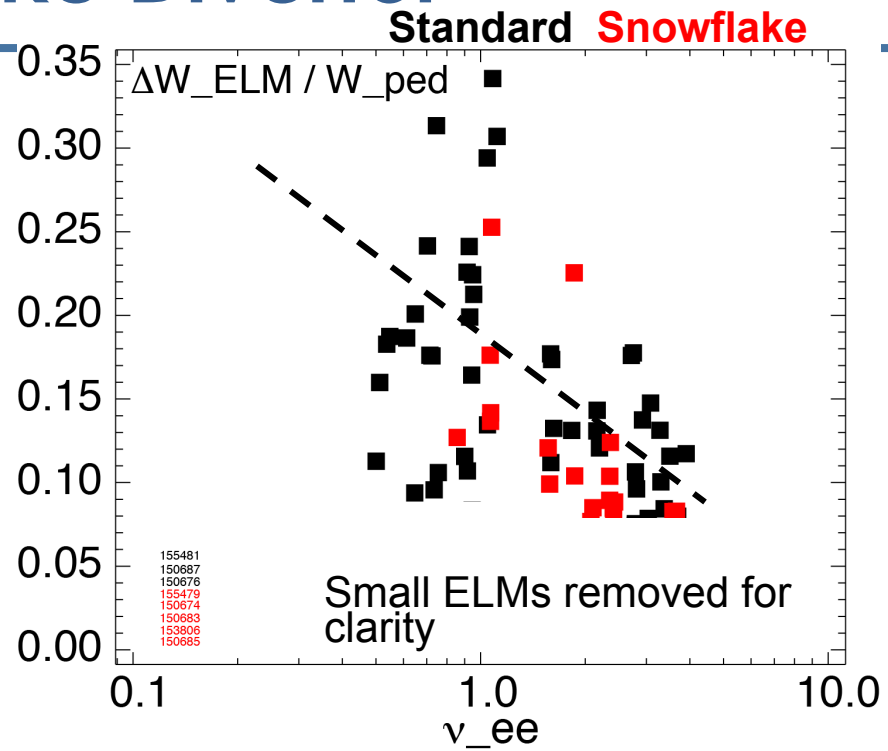
SF Divertor Weakly Affects Pedestal Magnetic and Kinetic Characteristics, Peeling-balooning Stability in DIII-D



- **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

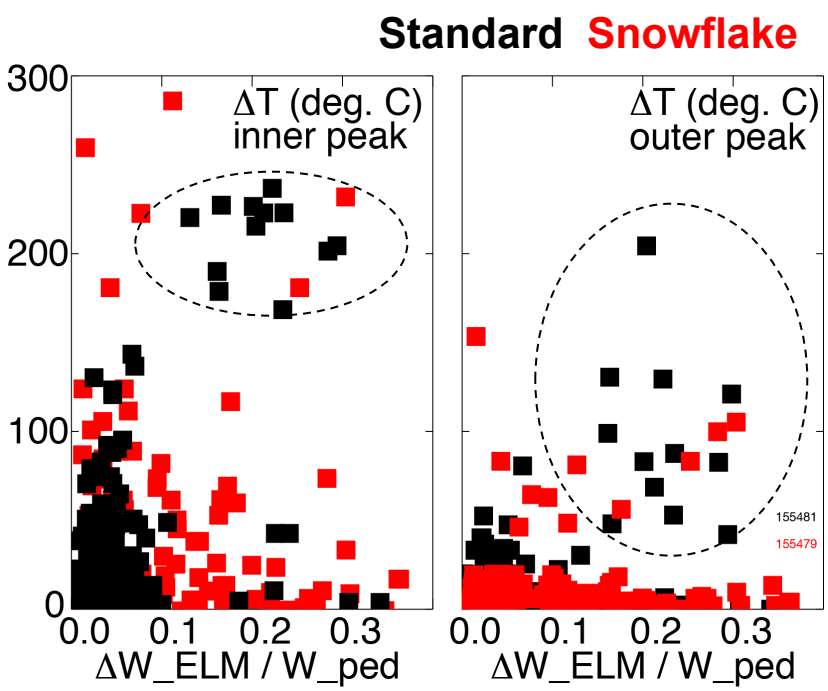


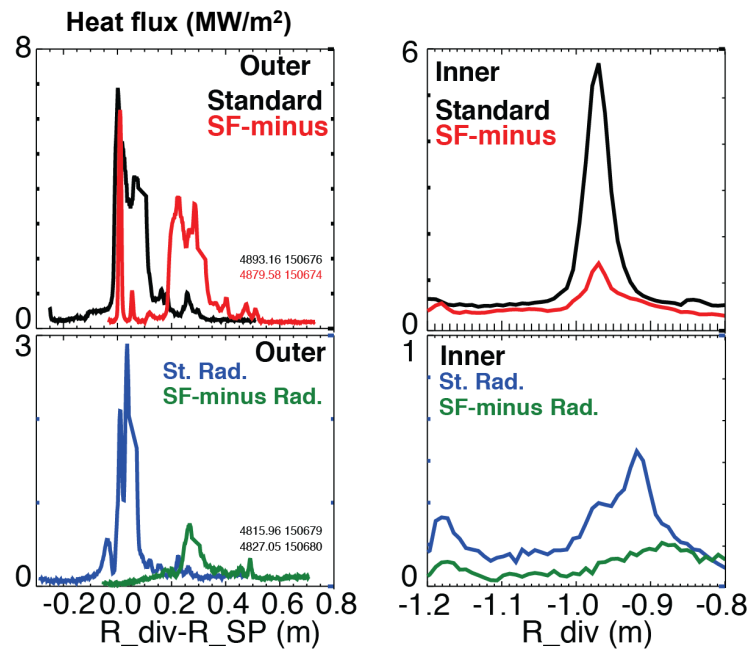


- **Both ΔW_{ELM} and $\Delta W_{ELM}/W_{ped}$ weakly reduced**
- **Mostly for $\Delta W_{ELM}/W_{ped} < 0.10$**

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

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 $\tau_{ELM}=L_{||}/c_{s,ped}$
  - 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