Snowflake divertor – a possible power exhaust solution for magnetic fusion

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FUSION POWER ASSOCIATES

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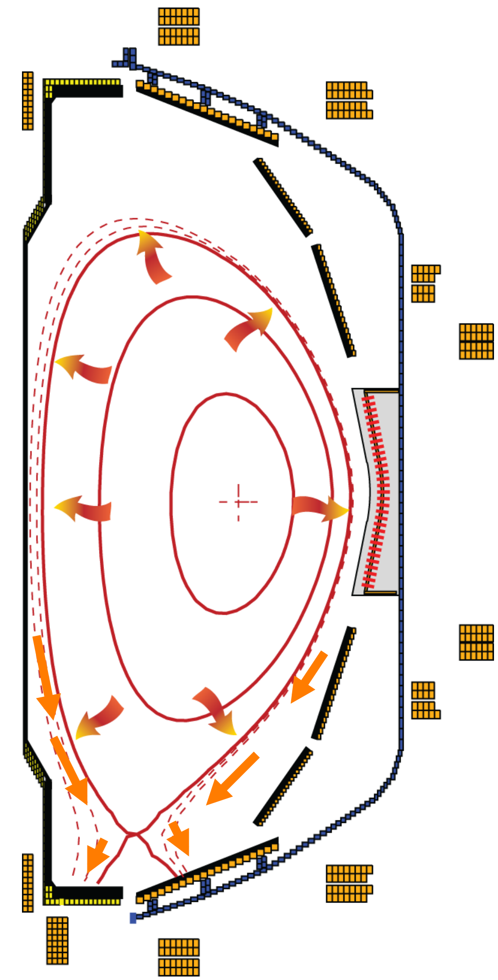
Poloidal divertor concept enabled progress in tokamak physics studies in the last 30 years

- Divertor challenge
  - Steady-state heat flux
    - present limit $q_{peak} \leq 10$ MW/m^2
    - projected to $q_{peak} \leq 80$ MW/m^2 for future devices
  - Density and impurity control (low T_e)
  - Impulsive heat and particle loads
  - Compatibility with good core plasma performance
- NSTX (Spherical Tokamak, aspect ratio A=1.4-1.5)
  - $I_p \leq 1.4$ MA, $P_{in} \leq 7.4$ MW (NBI)
  - $q_{peak} \leq 15$ MW/m^2, $q_{||} \leq 200$ MW/m^2
  - Graphite PFCs with lithium coatings
- DIII-D (Conventional tokamak, aspect ratio A~2.7)
  - $I_p \leq 1.5$ MA, $P_{in} \leq 20$ MW NBI + 3.6 MW ECH
  - $q_{peak} \leq 10$ MW/m^2
  - Graphite PFCs



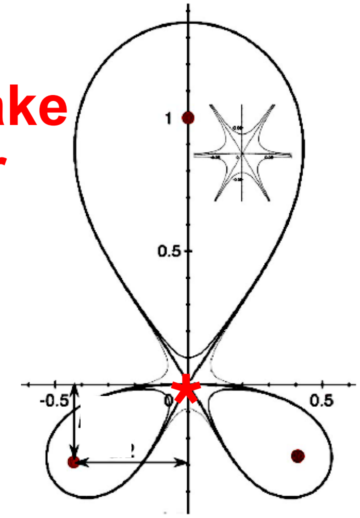
National Spherical Torus Experiment at PPPL

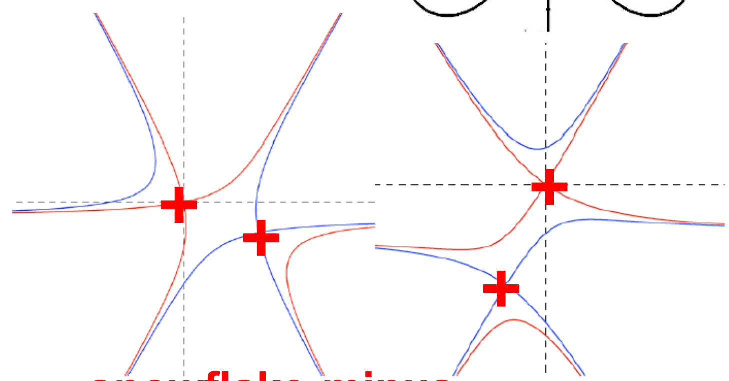
Snowflake divertor configuration predicted to have significant benefits over standard X-point divertor

- Snowflake divertor
  - Second-order null
    - $B_p \sim 0$ and grad $B_p \sim 0$ (Cf. first-order null: $B_p \sim 0$)
  - Obtained with existing divertor coils (min. 2)
  - Exact snowflake topologically unstable

- Predicted geometry properties (cf. standard divertor)
  - Increased edge shear: ped. stability
  - Add'l null: H-mode power threshold, ion loss
  - Larger plasma wetted-area A_{wet} : reduce q_{div}
  - Four strike points : share q_{II}
  - Larger X-point connection length L_x : reduce q_{II}
  - Larger effective divertor volume V_{div} : incr. P_{rad} , P_{CX}

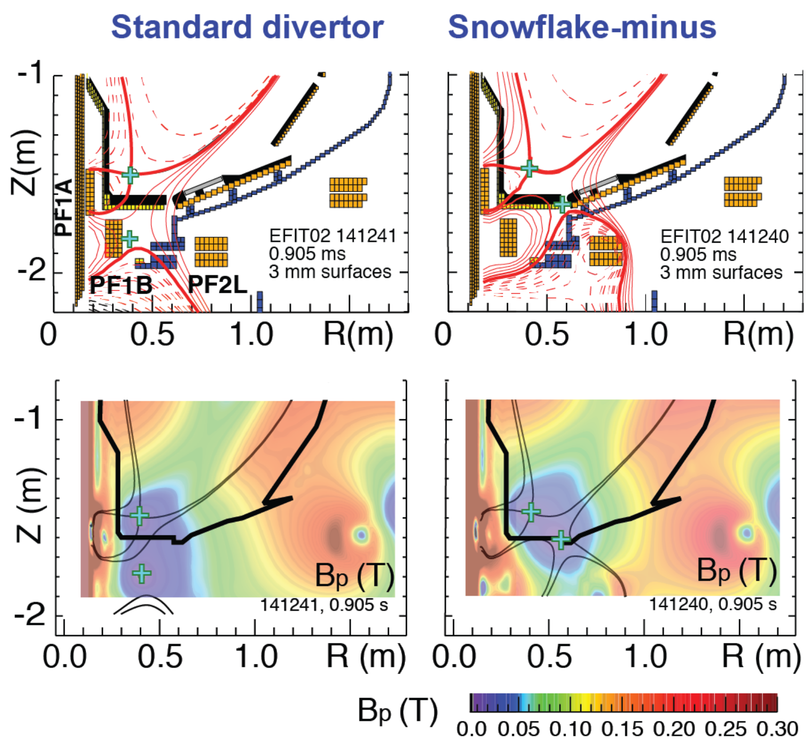
- Experiments: TCV, NSTX, DIII-D

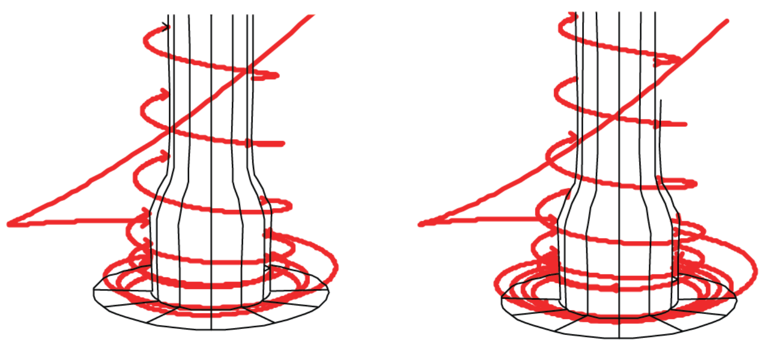




D. D. Ryutov, PoP 14 (2007), 064502;
Plasma Phys. Control. Fusion 54 (2012) 124050

Snowflake divertor configurations obtained with existing divertor coils in NSTX and DIII-D

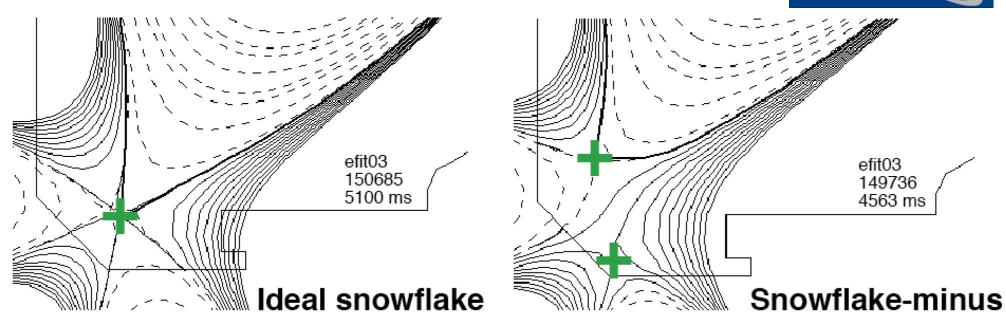




Shot 141241, EFIT02,
time: 0.905 s,
normalized flux: 1.005

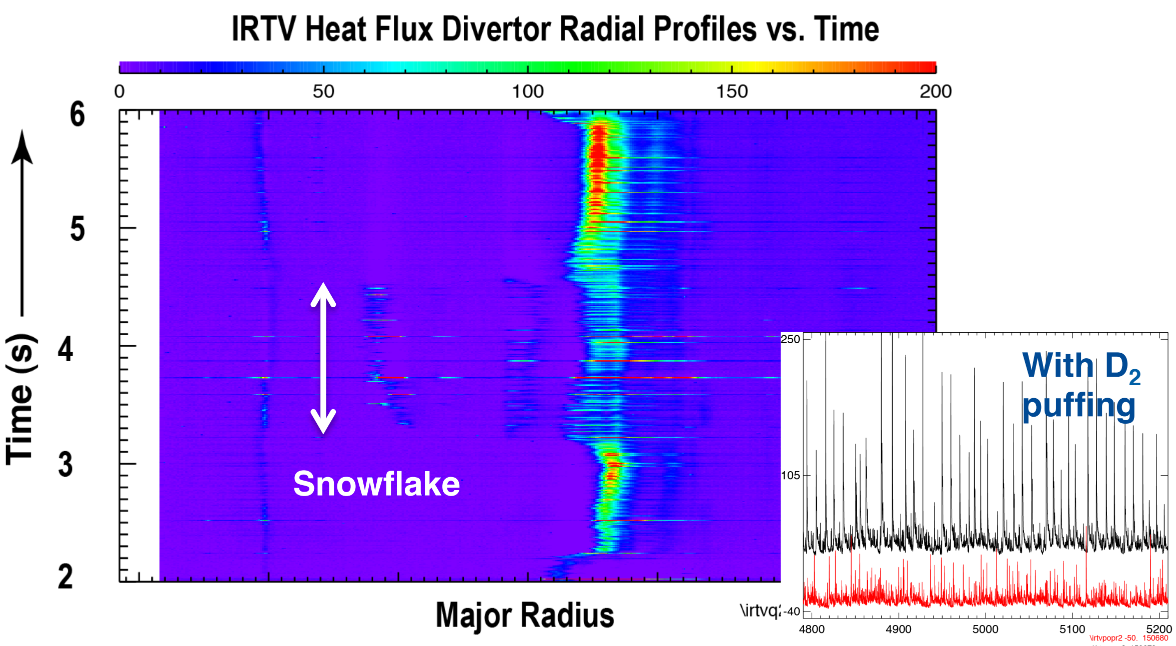
Shot 141240, EFIT02,
time: 0.905 s,
normalized flux: 1.005

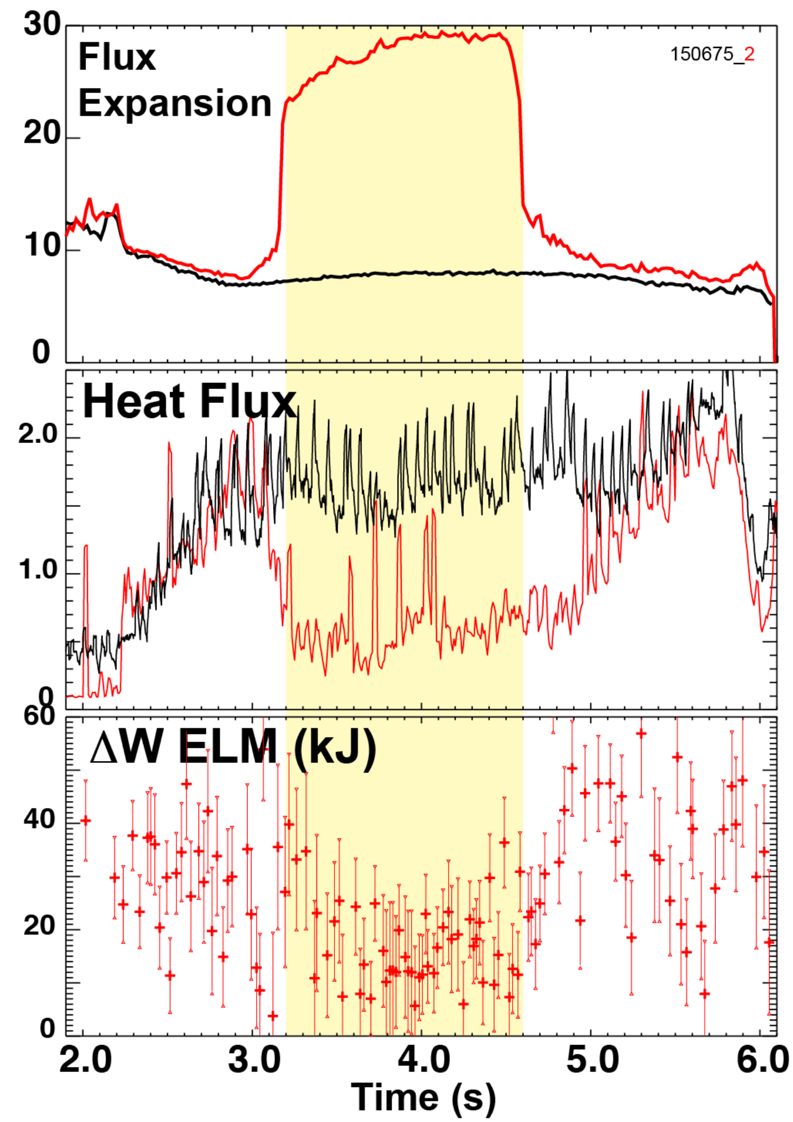
- Significant increase in the snowflake divertor (cf. standard divertor)
  - Plasma-wetted area (flux expansion)
  - Region of low B_p field in divertor
  - Magnetic field line length
- Divertor coil currents 0.5-4 kA within safety margins
- Steady-state snowflake configurations sustained for many energy confinement times τ_E
  - NSTX: 0.5 s
  - DIII-D: 3 s



DIII-D snowflake: good H-mode confinement maintained, heat flux reduction, ELM reduction

- Core confinement (H89P > 2) and pedestal constant
- Divertor heat flux reduced 2-3X
- ΔW(ELM) reduced
- ELM heat flux reduced dramatically with deuterium puffing

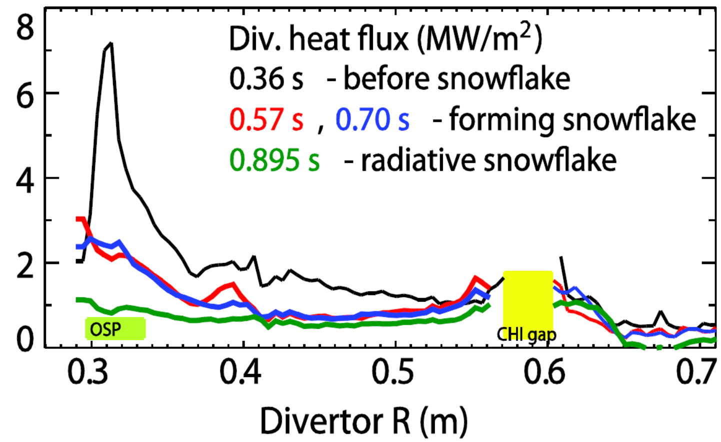


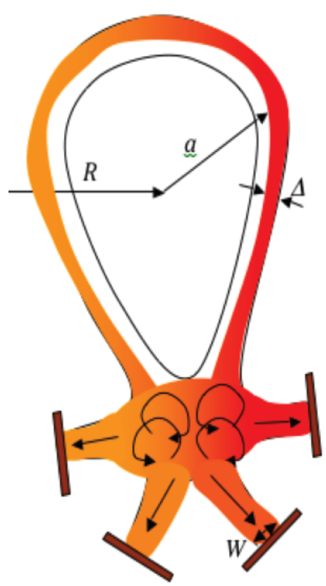


S. L. Allen et al., Paper PD/1-2, IAEA FEC 2012.

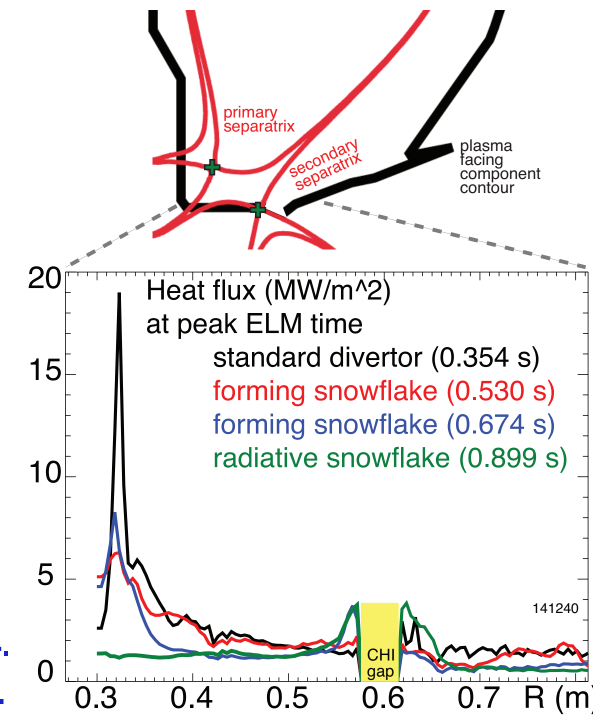
NSTX studies demonstrated compatibility of snowflake divertor with H-mode confinement, heat flux reduction

- NSTX snowflake divertor experiments
  - H-mode confinement unchanged
    - W_{MHD}~250 kJ, H98(y,2)~ 1, β_N~5
  - Core impurity reduced by up to 50 %
  - Pedestal stability and ELMs affected
  - Divertor heat flux significantly reduced
    - By up to 80 % between ELMs (from 5-7 to ~1 MW/m^2)
    - By up to 70 % at peak ELM





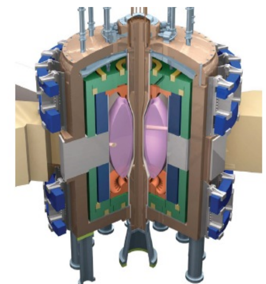
- ELM heat transport theory
  - Reduced surface heating due to increased ELM energy deposition time
  - Convective mixing of ELM heat in null-point region -> heat flux partitioning between separatrix branches (strike points)



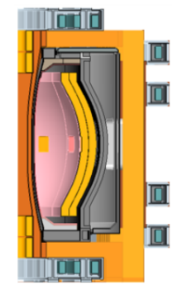
V. A. Soukhanovskii et al., Nucl. Fusion 51 (2011) 012001.
V. A. Soukhanovskii et al., Phys. Plasmas 19 (2012) 082504.
V. A. Soukhanovskii et al., Paper EX/P5-21, IAEA FEC 2012.
D. D. Ryutov et al., Paper TH/P4-18, IAEA FEC 2012

NSTX-U research aims at predictive understanding needed for fusion energy development facilities

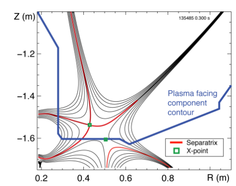
- Advance ST as candidate for Fusion Nuclear Science Facility (FNSF)
- Develop solutions for plasma-material interface
- Advance toroidal confinement physics predictive capability for ITER and beyond
- Develop ST as fusion energy system



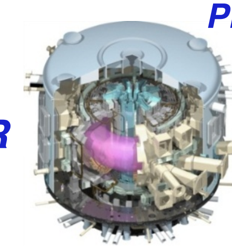
Fusion Nuclear Science Facility (FNSF)



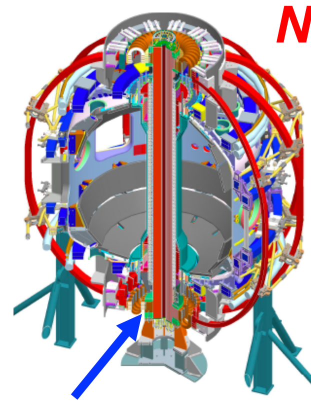
ST Pilot Plant



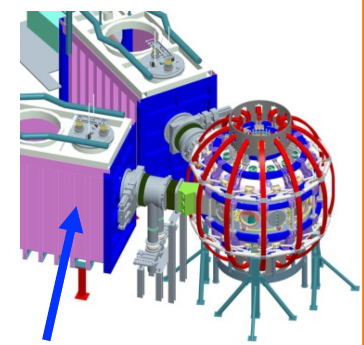
ITER



NSTX-U



New center-stack

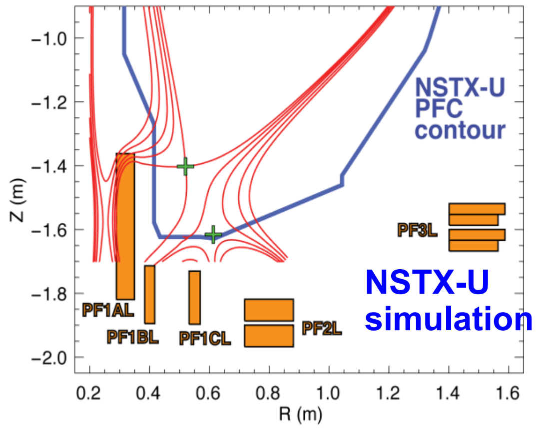


2nd neutral beam

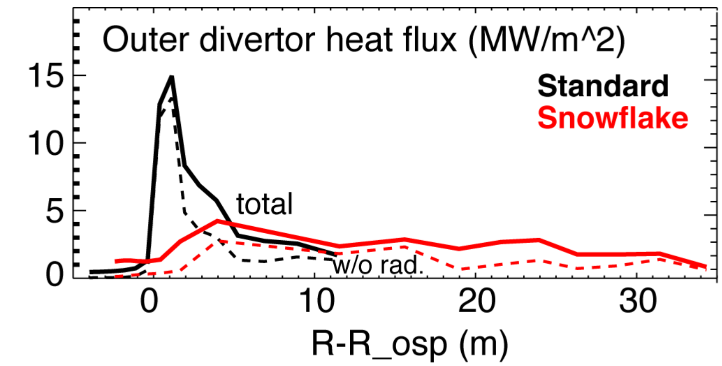
$B_T \rightarrow$	1 T	$P_{NBI} \rightarrow$	12 MW
$I_p \rightarrow$	2 MA	pulse $\rightarrow$	5 s

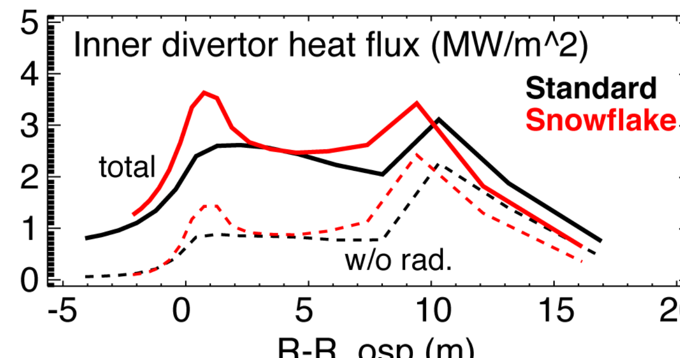
Snowflake divertor is a leading divertor power exhaust candidate for NSTX-U, modeling projections optimistic

- NSTX-U divertor coils designed to support a variety of snowflake configurations
  - Up-down symmetric possible

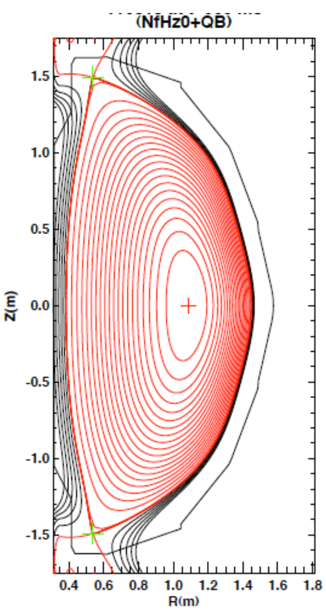


- Predictions for 12 MW NBI case with UEDGE code
  - P_{SOL}=9 MW
  - Standard div. heat flux 15-20 MW/m²
  - Snowflake 2-4 MW/m²

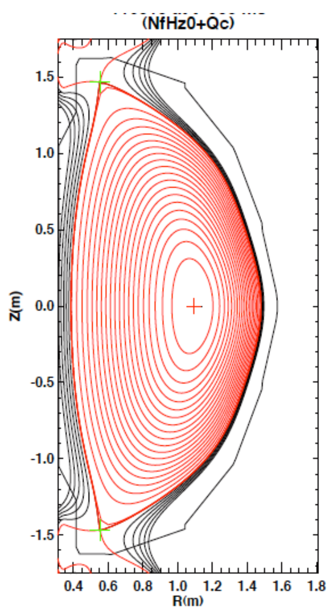




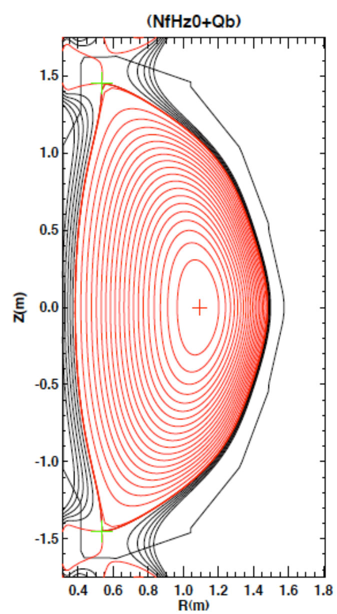
NSTX-U simulation



NSTX-U standard double-null divertor



NSTX-U double-snowflake-plus

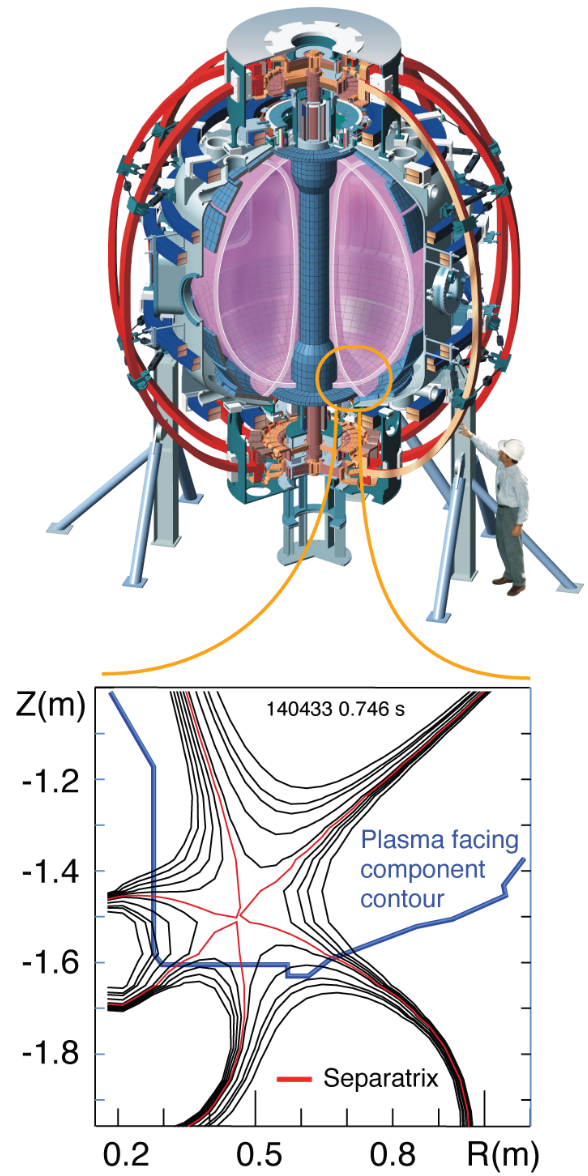


NSTX-U double-snowflake-minus

V. A. Soukhanovskii et al., Paper EX/P5-21, IAEA FEC 2012.

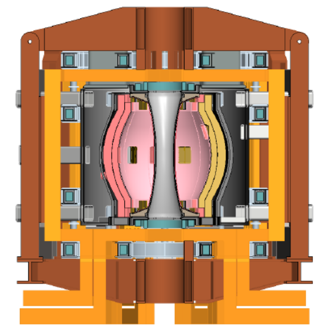
Experiments suggest the snowflake divertor configuration may be a viable divertor power exhaust solution

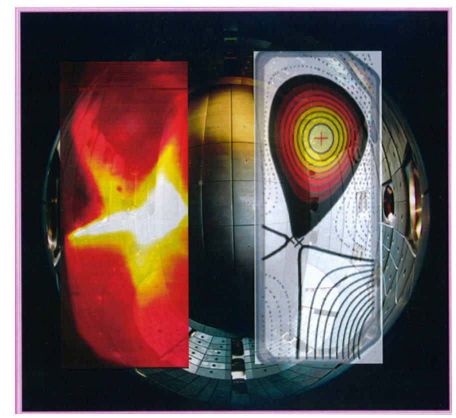
- Results from DIII-D and NSTX:
  - Steady-state snowflake configuration compatible with good H-mode confinement
  - All predicted magnetic geometry properties realized
    - Plasma-wetted area, connection length much higher than in the standard divertor
  - Effects on H-mode pedestal stability and ELM energy
  - Significant reduction of steady-state and ELM peak divertor heat flux
  - Potential to combine with radiative divertor solution



- Future plans:
  - Proposing new experiments in DIII-D in 2013-2014
  - Preparations for experiments in NSTX-U
    - Synergistic effects of snowflake and lithium plasma-facing components
  - Concept development for FNSF and DEMO
    - ST-FNSF planning activity at PPPL

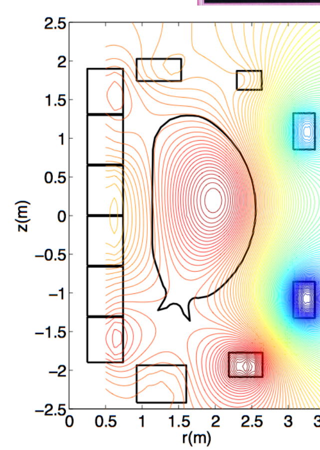
Snowflake divertor concept rapidly developing into mainstream fusion research direction

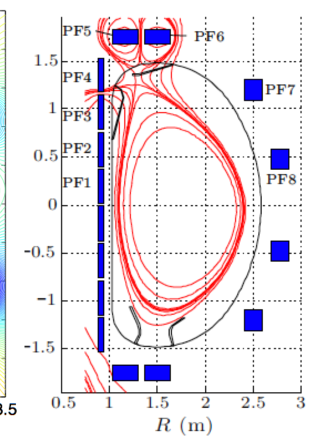




- Snowflake divertor concept development by LLNL
  - Theory – D. D. Ryutov et al., 2007 - present
  - Experiment
    - NSTX tokamak, 2009 - 2011
    - DIII-D tokamak, 2012 - present
  - 6 Invited and Oral talks – IEAE FEC, PSI, APS, EPS, ICC conferences
  - R&D 100 Award 2012

- International snowflake divertor research on the rise:
  - Switzerland: TCV tokamak – ongoing experiments
  - China: modeling configurations for HL-2M and CFETR tokamak proposals
  - Italy: snowflake configurations developed for FAST satellite tokamak proposal
  - Britain: planning snowflake configurations for MAST-U tokamak (2015)
  - France: WEST tokamak – planning divertor coils





Backup slides

Various techniques developed for reduction of heat fluxes $q_{||}$ (divertor SOL) and q_{peak} (divertor target)

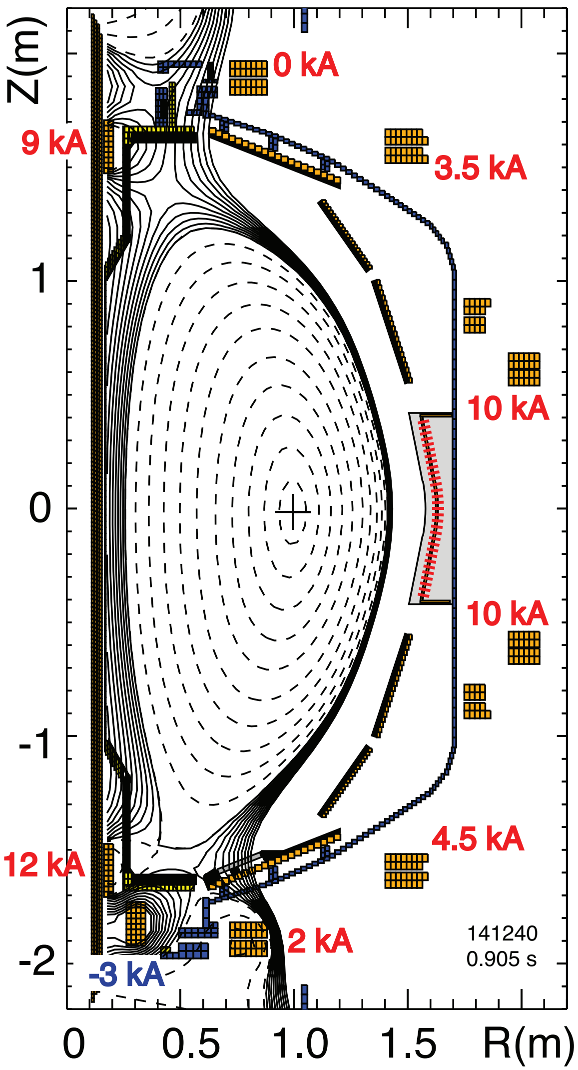
$$q_{peak} \simeq \frac{P_{SOL}(1 - f_{rad}) f_{geo} \sin\alpha}{2\pi R_{SP} f_{exp} \lambda_{q_{||}}}$$

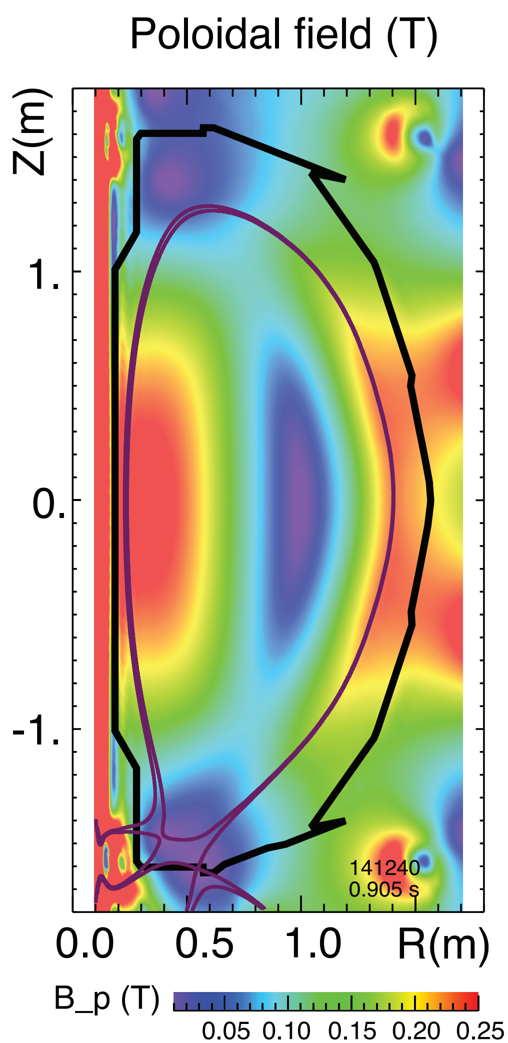
$$A_{wet} = 2\pi R \, f_{exp} \, \lambda_{q_{||}}$$

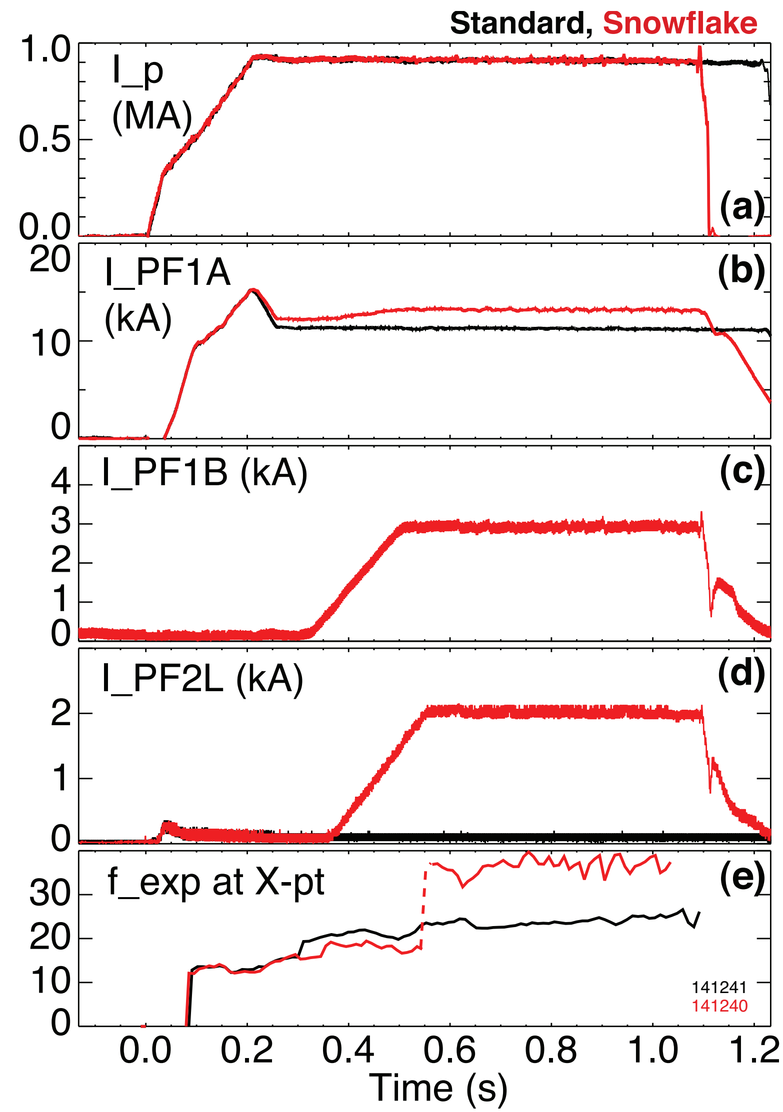
$$f_{exp} = \frac{(B_p/B_{tot})_{MP}}{(B_p/B_{tot})_{OSP}}$$

- Promising divertor peak heat flux mitigation solutions:
  - Divertor geometry
    - poloidal flux expansion
    - divertor plate tilt
    - magnetic balance
  - Radiative divertor
- Recent ideas to improve standard divertor geometry
  - X-divertor (M. Kotschenreuther *et. al*, IC/P6-43, IAEA FEC 2004)
  - Snowflake divertor (D. D. Ryutov, PoP 14, 064502 2007)
  - Super-X divertor (M. Kotschenreuther *et. al*, IC/P4-7, IAEA FEC 2008)

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

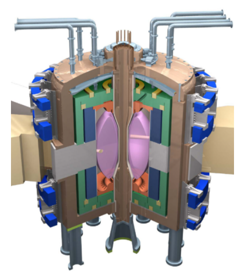


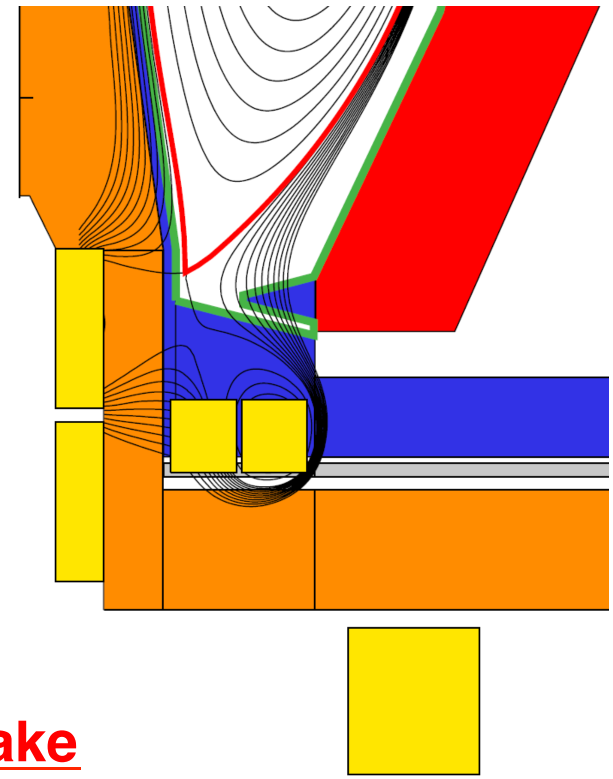




Snowflake divertor designs are studied for next-step spherical tokamak based divices

- ST-FNSF development studies are quantifying performance dependence on size
- Building on achieved/projected NSTX/NSTX-U performance and design
- Divertor PF coil configurations identified to achieve high δ while maintaining peak divertor heat flux < $10 MW/m^2$





Parameter	Fusion Nuclear Science Facility
Major Radius R_0 [m]	1.3
Aspect Ratio R_0 / a	≥ 1.5
Plasma Current [MA]	4 – 10
Toroidal Field [T]	2 – 3
Auxiliary Power [MW]	22 – 45
P/R [MW/m]	30 – 60
P/S [MW/m^2]	0.6 – 1.2
Fusion Gain Q	1 – 2

Snowflake

- **Flux expansion = 40-60, δ_x ~ 0.62**
- **$1/\sin(\theta_{plate})$ = 1-1.5**
- **Good detachment (NSTX data) and cryo-pumping (NSTX-U modeling)**

J. Menard et. al., Paper FTP/3-4, IAEA FEC 2012