Snowflake divertor configuration studies for NSTX-Upgrade

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Snowflake divertor configuration studies for NSTX-Upgrade

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Snowflake divertor experiments in NSTX provide basis for PMI development toward NSTX-Upgrade

- Snowflake divertor configuration in NSTX
  - Three divertor coils, steady-state up to 600 ms
  - Core H-mode confinement unchanged
  - Core impurities reduced
  - Steady-state divertor peak heat flux significantly reduced
    - Due to geometry effects and radiative detachment

- Development of snowflake divertor configuration for NSTX-U
  - Steady-state and transient heat flux mitigation and detachment
  - Magnetic control and configuration development
Snowflake configuration formation was followed by radiative detachment

- $P_{SOL} \sim 3$ MW ($P_{NBI} = 4$ MW)
- Attached divertor -> snowflake transition (still attached) -> snowflake + detachment
- $Q_{div} \sim 2$ MW $\rightarrow$ $Q_{div} \sim 1-1.2$ MW $\rightarrow$ $Q_{div} \sim 0.5-0.7$ MW
Significant reduction of steady-state divertor heat flux observed in snowflake divertor

- **Attached standard divertor -> snowflake transition -> snowflake + detachment**
- More experiments and modeling needed to understand geometry vs radiative effects

C III, C IV profiles courtesy of F. Scotti
Impulsive heat loads due to Type I ELMs are partially mitigated in snowflake divertor

- H-mode discharge, $W_{MHD} \sim 220-250$ kJ
  - Type I ELM ($W/\Delta W \sim 5-8\%$)
- Theory and modeling developments
  - D.D. Ryutov, JP9.00104 : A snowflake divertor: reduction of the ELM heat load due to plasma convection
  - T.D. Rognlien, JP9.00105 : Reduced ELM heat loads from increased magnetic field-line length in snowflake configurations
Magnetic control of snowflake divertor configuration is being developed

- Many ways for the open-loop snowflake configuration to fail - need close-loop feedback control of coil currents
- Testing X-point tracking algorithm
  - Locate X-points and snowflake centroid
  - E. Kolemen, PP9.00022 : Control Development for NSTX and the Effects of Strong Shaping
- Implementation of 2nd X-point position control in Plasma Control System being considered
  - Collaboration between PPPL, LLNL and GA

M.A. Makowski and D. Ryutov, “X-Point Tracking Algorithm for the Snowflake Divertor”
Plasma material interface development is critical for NSTX-U success

- NSTX-U mission elements:
  - Advance ST as candidate for Fusion Nuclear Science Facility
  - Develop solutions for PMI
  - Advance toroidal confinement physics for ITER and beyond
  - Develop ST as fusion energy system

- Challenge for NSTX-U divertor
  - 2-3 X higher input power
    - $P_{NBI} < 12$ MW, $I_p < 2$ MA
  - 30-50 % reduction in $n/n_G$
  - 3-5 X longer pulse duration

- Projected NSTX-U peak divertor heat fluxes up to 25-40 MW/m$^2$
  - Radiative divertor with impurity seeding, double null, high flux expansion (snowflake)
Four divertor coils should enable flexibility in boundary shaping and control in NSTX-U

- A variety of lower and both lower and upper divertor snowflake configurations are possible in NSTX-U with four coils per divertor
  - ISOLVER free-boundary Grad-Shafranov solver used
  - Four coils can be used to control up to four parameters (X-pts, OSP, etc)

- X 2 in plasma wetted surface area and connection length vs standard divertor
Snowflake divertor experiments in NSTX provide good basis for PMI development in NSTX-Upgrade

- **FY 2009-2010 snowflake divertor experiments in NSTX**
  - Helped understand control of magnetic properties
  - Core H-mode confinement unchanged
  - Core and edge carbon concentration reduced
  - Divertor heat flux significantly reduced
    - Steady-state reduction due to geometry and radiative detachment
    - Encouraging results for transient heat flux handling
    - Combined with impurity-seeded radiative divertor

- **Outlook for snowflake divertor in NSTX-Upgrade**
  - 2D fluid modeling of snowflake divertor properties scaling
    - Edge and divertor transport, radiation, detachment threshold
    - Compatibility with cryo-pump and lithium conditioning
  - Magnetic control development
  - PFC development – PFC alignment and PFC material choice
Backup slides
Acknowledgements


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Radiative and geometric mitigation of divertor heat flux will be needed for high-power density NSTX-Upgrade discharges

\[ q_{pk} \approx \frac{P_{heat} (1 - f_{rad}) f_{out/tot} f_{down/tot} (1 - f_{pfr}) \sin \alpha}{2\pi R_{SP} f_{exp} \lambda_{q\|}} \]

\[ A_{wet} = 2\pi R f_{exp} \lambda_{q\|} \quad f_{exp} = \frac{(B_p/B_{tot})_{MP}}{(B_p/B_{tot})_{OSP}} \]

- Radiative divertor with impurity seeding
- Double null configurations
- Snowflake configuration as laboratory of divertor physics
Poloidal divertor concept enabled progress in tokamak physics studies in the last 30 years

- Divertor challenge
  - Steady-state heat flux
    - present limit $q_{peak} \leq 10 \text{ MW/m}^2$
    - projected to $q_{peak} \leq 80 \text{ MW/m}^2$ for future devices
  - Density and impurity control
  - Impulsive heat and particle loads
  - Compatibility with good core plasma performance

- Spherical tokamak: additional challenge - compact divertor

- NSTX (Aspect ratio A=1.4-1.5)
  - $I_p \leq 1.4 \text{ MA}, P_{in} \leq 7.4 \text{ MW (NBI)}, P / R \sim 10$
  - $q_{peak} \leq 15 \text{ MW/m}^2$, $q_{||} \leq 200 \text{ MW/m}^2$
  - Graphite PFCs with lithium coatings
Snowflake divertor geometry attractive for heat flux mitigation

- **Snowflake divertor**
  - Second-order null
    - $B_p \sim 0$ and $\nabla B_p \sim 0$ (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)
  - Larger region with low $B_p$ around X-point: ped. stability
  - Larger plasma wetted-area $A_{wet}$: reduce $q_{div}$
  - Larger X-point connection length $L_x$: reduce $q_{ll}$
  - Larger effective divertor volume $V_{div}$: incr. $P_{rad}$, $P_{CX}$

- **Experiments**
  - TCV (F. Piras *et. al*, PRL 105, 155003 (2010))
  - NSTX

\[\text{Exact snowflake divertor}\]
\[\text{snowflake-minus}\]
\[\text{snowflake-plus}\]

*D. D. Ryutov, PoP 14, 064502 2007*
Connection length is increased x 2-3 in snowflake divertor w.r.t. standard divertor

Shot 141240, EFIT02, time: 0.905s, normalized flux: 1.015

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

Shot 141240, EFIT02, time: 0.905s, normalized flux: 1.015
Plasma-wetted area and connection length are increased by 50-90% in NSTX snowflake divertor

- These properties observed in first 30-50% of SOL width
- \(B_{tot}\) angles in the strike point region: 1-2°, sometimes < 1°
  - Concern for hot-spot formation and sputtering from divertor tile edges
Good H-mode confinement properties and core impurity reduction obtained with snowflake divertor

- 0.8 MA, 4 MW H-mode
- $\kappa=2.1$, $\delta=0.8$
- Core $T_e \sim 0.8-1$ keV, $T_i \sim 1$ keV
- $\beta_N \sim 4-5$
- Plasma stored energy $\sim 250$ kJ
- H98(y,2) $\sim 1$ (from TRANSP)
- Core carbon reduction due to
  - Type I ELMs
  - Edge source reduction
    - Divertor sputtering rates reduced due to partial detachment
Snowflake divertor with CD$_4$ seeding leads to increased divertor carbon radiation

- $I_p=0.9$ MA, $P_{NBI}=4$ MW, $P_{SOL}=3$ MW

- Snowflake divertor (from 0.6 ms)
  - Peak divertor heat flux reduced from 4-6 MW/m$^2$ to 1 MW/m$^2$

- Snowflake divertor (from 0.6 ms) + CD$_4$
  - Peak divertor heat flux reduced from 4-6 MW/m$^2$ to 1-2 MW/m$^2$
  - Divertor radiation increased further
Snowflake divertor heat flux consistent with NSTX divertor heat flux scalings

- Snowflake divertor (\(^*\)): \(P_{\text{SOL}} \sim 3-4 \text{ MW}, f_{\text{exp}} \sim 40-60, q_{\text{peak}} \sim 0.5-1.5 \text{ MW/m}^2\)
  - Low detachment threshold

**T. K. Gray et. al, EX/D P3-13, IAEA FEC 2010**
**V. A. Soukhanovskii et. al, PoP 16, 022501 (2009)**
Divertor profiles show low heat flux, broadened C III and C IV radiation zones in the snowflake divertor phase

- Heat flux profiles reduced to nearly flat low levels, characteristic of radiative heating
- Divertor C III and C IV brightness profiles broaden
- High-$n$ Balmer line spectroscopy and CRETIN code modeling confirm outer SP detachment with $T_e \leq 1.5$ eV, $n_e \leq 5 \times 10^{20}$ m$^{-3}$
  - Also suggests a reduction of carbon physical and chemical sputtering rates
Steady-state asymmetric snowflake-minus configuration has been obtained in FY2010 experiments in NSTX

- Snowflake-minus with three coils (w/ reversed PF1B) transformed from a standard medium-δ LSN at ~ 500 ms
- Snowflake with three coils (w/ reversed PF1B) transformed from a standard high-δ LSN at ~ 500 ms
1D estimates indicate power and momentum losses are increased in snowflake divertor

- 1D divertor detachment model by Post
  - Electron conduction with non-coronal carbon radiation
  - Max $q_\parallel$ that can be radiated as function of connection length for range of $f_z$ and $n_e$
  - $\Rightarrow$ Greater fraction of $q_\parallel$ is radiated with increased $L_x$

- Three-body electron-ion recombination rate depends on divertor ion residence time
  - Ion recombination time: $\tau_{ion} \sim 1\text{–}10$ ms at $T_e = 1.3$ eV
  - Ion residence time: $\tau_{ion} \leq 3\text{–}6$ ms in standard divertor, x 2 in snowflake
  - $\Rightarrow$ Greater parallel momentum sink

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

$$\frac{\partial q_\parallel}{\partial x} = -n_e n_z L Z(T_e)$$
2D multi-fluid edge transport code UEDGE is used to study snowflake divertor properties

- Fluid (Braginskii) model for ions and electrons
- Fluid for neutrals
- Classical parallel transport, anomalous radial transport
- Core interface:
  - $T_e = 120 \text{ eV}$
  - $T_i = 120 \text{ eV}$
  - $n_e = 4.5 \times 10^{19}$
- $D = 0.25 \text{ m}^2/\text{s}$
- $\chi_{e,i} = 0.5 \text{ m}^2/\text{s}$
- $R_{\text{recy}} = 0.95$
- Carbon 3 %
2D modeling shows a trend toward reduced temperature, heat and particle fluxes in the snowflake divertor

- 2D multi-fluid code UEDGE
  - Fluid (Braginskii) model for ions and electrons
  - Fluid for neutrals
  - Classical parallel transport, anomalous radial transport
    - \( D = 0.25 \text{ m}^2/\text{s} \)
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Core interface:
- \( T_{e,i} = 120 \text{ eV} \)
- \( n_e = 4.5 \times 10^{19} \)
- \( R_{\text{recy}} = 0.95 \)
- Carbon 3%

\[ Z \text{(m)} \]
\[ R \text{(m)} \]

\[ T_e \quad T_i \]

\[ q_{\text{div}} \text{ (MW/m}^2\text{)} \]

\[ \Gamma_i \text{ (x10}^{21} \text{ s}^{-1}) \]