Developing Physics Basis for the Radiative Snowflake Divertor at DIII-D

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Snowflake Divertor Configuration is Studied in DIII-D as a Tokamak Divertor Power Exhaust Concept

\[ q_{\text{peak}} = \frac{P_{\text{div}}}{A_{\text{wet}}} = \frac{P_{\text{SOL}}(1 - f_{\text{rad}}) f_{\text{geo}}}{2\pi R_{SP} f_{\exp} \lambda_q} \]

- **Divertor power exhaust challenge**
  - Steady-state heat flux
    - Technological limit \( q_{\text{peak}} \leq 5-15 \text{ MW/m}^2 \)
    - DEMO: Unmitigated, \( q_{\text{peak}} \leq 150 \text{ MW/m}^2 \)
  - ELM energy, target peak temperature
    - Melting limit 0.1-0.5 MJ/m^2
    - DEMO: Unmitigated, \( \geq 10 \text{ MJ/m}^2 \)
- **Snowflake divertor with 2nd-order null**
  - \( \nabla B_p \sim 0 \Rightarrow \text{Large region of low } B_p \)
  - Very large \( A_{\text{wet}} \) possibility
- **Experiments in TCV, NSTX, EAST, DIII-D**

Large Region of Low $B_p$ Around Second-order Null in Snowflake Divertor is Predicted to Modify Power Exhaust

- **Geometry properties**
  - Criteria: $d_{xx} \leq a \left( \frac{\lambda_q}{a} \right)^{1/3}$
    - Higher edge magnetic shear
    - Larger plasma wetted-area $A_{wet} (f_{exp})$
    - Larger parallel connection length $L_{||}$
    - Larger effective divertor volume $V_{div}$

- **Transport properties**
  - Criteria: $d_{xx} \leq D^* a \left( \frac{a \beta_{pm}}{R} \right)^{1/3}$
    - High convection zone with radius $D^*$
    - Power sharing over four strike points
    - Enhanced radial transport (larger $\lambda_q$)

"Laboratory for divertor physics"
Outline of talk

• Comparisons between **snowflake** and standard divertor encouraging
  – Compatibility with good core and pedestal performance
  – Confirmed geometry properties $A_{\text{wet}}$ and $L_{\text{II}}$
  – Initial confirmation of transport properties

• Broader divertor radiation distribution
• Reduced inter-ELM peak heat flux $q_{\text{peak}}$
• Reduced ELM energy, $T_{\text{peak}}$ and $q_{\text{peak}}$

Control of steady-state snowflake configurations in DIII-D with existing coils
• E. Kolemen et.al., next talk
Increased Plasma-wetted Area Leads to $q_{\text{peak}}$ Reduction In Snowflake Divertor

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

\[
A_{\text{wet}} = 2\pi R f_{\text{exp}} \lambda_{q_{\|}}
\]

\[
f_{\text{exp}} = \frac{(B_p/B_t)_{\text{Midplane}}}{(B_p/B_t)_{\text{Divertor}}}
\]
Reduction in Snowflake Divertor Partly Due to Increased $A_{\text{wet}}$ and $L_{\|}$

- Flux expansion increased $\sim 20\%$
  - Depends on configuration, can be up to $X3$
- $L_{\|}$ increased by 20-60\% over SOL width
- Divertor heat flux reduced $\sim 30\%$
- Parallel heat flux reduced $\sim 20\%$
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**
  - $\beta_p = \frac{P_k}{P_m} = 8\pi \frac{P_k}{B_p^2} \gg 1$
  - Loss of poloidal equilibrium
  - Fast convective plasma redistribution
  - Especially efficient during ELMs when $P_k$ is large

- **Estimated size of convective zone**
  - Standard: 1cm
  - Snowflake: 6-8 cm

- **Divertor null-region $\beta_p$ measured by divertor Thomson Scattering**
  - In snowflake, broad region of higher $\beta_p \gg 1$
  - Higher X10 during ELMs

Heat and Particle Fluxes Shared Among Strike Points in Snowflake Divertor

\[ \frac{q_{SP3}}{q_{SP1}} < 0.5 \]
\[ \frac{P_{SP3}}{P_{SP1}} < 0.3 \]

Sharing fraction maximized at low \( d_{XX} \)
Broader $q_{\parallel}$ Profiles in Snowflake Divertor May Imply Increased Radial Transport

- **Fit $q_{\parallel}$ profile with Gaussian ($S$) and Exp. ($\lambda_{\text{SOL}}$) functions** (Eich PRL 107 (2011) 215001)
- **Increased $\lambda_q$ may imply increased transport**
  - Increased radial spreading due to $L_{\parallel}$
  - SOL transport affected by null-region mixing
  - Enhanced dissipation may also play role
Divertor Radiation More Broadly Distributed in Snowflake for Radiative Divertor, $q_{\text{peak}}$ Reduced by $x5$

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

$P_{\text{SOL}} = 3-4$ MW

$R_{\text{div}}$ (m) vs. Divertor heat flux (MW/m$^2$)

$P_{\text{SOL}} = 3-4$ MW
SF Divertor Weakly Affects Pedestal Magnetic and Kinetic Characteristics, Peeling-ballooning Stability in DIII-D

- At lower $n_e$, H-mode performance unchanged with snowflake divertor
  - Similar $P_{ped}$, $W_{ped}$
  - $H98(y,2) \sim 1.0$-1.2, $\beta_N \sim 2$
  - Plasma profiles only weakly affected

- Peeling-ballooning stability unaffected
  - $\text{Shear}_{95}$, $q_{95}$ 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 $\Delta W_{\text{ELM}}$ and $\Delta W_{\text{ELM}}/W_{\text{ped}}$ weakly reduced
- Mostly for $\Delta W_{\text{ELM}}/W_{\text{ped}} < 0.10$

- Increased collisionality with snowflake $\nu_{\text{ped}}^* = \pi Q_{95}/\lambda_{ee}$
Peak ELM Target Temperature and ELM Heat Flux Reduced in Snowflake Divertor

**In snowflake divertor**
- $\Delta T_{\text{surf}} \sim E_{\text{ELM}}/(A_{\text{wet}} \tau_{\text{ELM}})^{1/2}$
- Increased $\tau_{\text{ELM}} = L_{\text{II}}/C_{s,\text{ped}}$
- Weakly reduced $E_{\text{ELM}}$
- $A_{\text{wet}}^{\text{ELM}}$ similar

**Type I ELM power deposition correlates with $\tau_{\text{ELM}}$**
- In radiative snowflake, ELM peak heat flux reduced by 50-75 %
- Similar effect in NSTX

S. L. Allen et. al., IAEA 2012
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