Why investigating alternative divertor concepts?

• Power exhaust is an issue for a reactor
• There is a strong risk that the Single-Null Divertor cannot be extrapolated to DEMO [R. Neu, this conference]
• Investigates alternatives divertor configurations such as the snowflake divertor as backup plans for a reactor
• Improve our understanding of the divertor physics, which will be beneficial to SND
Snowflake divertor (SFD) proposed as an exhaust solution for DEMO [D.D. Ryutov, PHP (2007)]

• SFD ≡ 2nd order null-point: \( B_p = 0 \wedge \nabla B_p = 0 \)
  - In practice always two first order x-points
  - Large region of low \( B_p \) near the null point
    + Increases connection length \( L_{||} \)
    + Increase divertor volume \( V_{\text{div}} \)

• Potential advantages
  - Greater \( L \) decreases target temperature
  - Greater \( V_{\text{div}} \) may increase power and momentum losses
  - Greater \( L \) may broaden the SOL
  - Lower \( B_p \) may increase cross field transport and broaden SOL
  - Facilitate access to detachment/widens operating regime
  - Decrease peak target heat flux

• Possible disadvantages
  - Radiation in null point region may lead to excessive confinement degradation
  - Requires at least two divertor coils and higher current
TCV tokamak well suited for studies of alternative divertor configurations

- "Medium-size" tokamak
  - Toroidal field $B_T < 1.5$ T
  - Plasma current $I_P < 1$ MA

- 16 independently controlled poloidal field coils
  - Unique flexibility to shape plasma

- Electron cyclotron heating system
  - 2$^{nd}$ harmonic $P_{X2} < 3$ MW
  - 3$^{rd}$ harmonic $P_{X3} < 1.5$ MW

On TCV, expected advantages of the SFD cover a large fraction of the SOL for SF-

- For SF+, the connection length is larger than for SND only in the immediate vicinity of the separatrix
Experimental studies of the snowflake divertor in TCV

Outline

• Effect of SF+ configuration on highly radiating regimes

• Evidences for enhanced cross field transport in the SF divertor
  - Convection driven cross-field transport in the null-point region
  - ExB drifts stronger than in SND
  - Increased radial gradients in SF-

• Outlook
  - X and Super-X divertor
  - TCV upgrade & upgrade+
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Investigate radiative power losses in the SF+ divertor

- SF+ → small changes expected w.r.t SND on TCV
- Increasing the density, SND radiates slightly more
  - SND has larger volume in outer SOL and close to target → colder region favouring C radiation
- Increasing Neon content, SF+ radiates more
  - SFD has a larger volume of inner SOL and close to X-point → hotter region favouring Ne radiation
- In both cases, full detachment not observed
- Maximum achieved density limited by MHD → Auxiliary heating required
- Use codes to interpret observations
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1. Comparison of experiments with modelling indicates an enhanced cross-field transport

- Use heat and particle flux at **secondary strike points** to diagnose cross-field transport
- Adjust cross-field diffusivities in **EMC3-Eirene model** to match fluxes at **primary SP**
- Modelled power flux at **secondary SP** based on constant cross-field diffusivity is too small

1. Cross field transport is even more enhanced during ELMs

What are the mechanisms at the origin of larger power distribution during ELMs?

- Transient change in the Snowflake topology (SF+ → SF-) induced by ELM currents?


- Enhanced cross-field transport by stronger drifts?

- Other mechanism?

2. Increased poloidal gradients in the SFD may increase cross-field transport due to ExB drift.

- Lower field line pitch in the SF divertor $\Rightarrow$ larger poloidal gradients $\Rightarrow$ larger $E_\theta$ $\Rightarrow$ stronger ExB drift than for SND!!


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2. Increased poloidal gradients in the SFD may increase cross-field transport due to ExB drift

\[ B_{t} \]

- B-field reversal supports importance of drifts on target profiles

Requires self-consistent simulations including drifts

3. Increased radial gradients will enhanced cross field transport

- “Snowflake minus”: Secondary x-point splits one side of SOL

- Model divertor cross field transport by convoluting profiles with Gaussian
  - Potential tool to diagnose divertor transport
3. Increased radial gradients will enhanced cross field transport


- Radial position $\rho_{X^2}$ determines power repartition to "outer" (or "inner") targets: Optimise one side of the divertor.

![Diagram showing power distribution at "outer" divertor targets with $P_i/P_{in}$ as a function of $\rho_{X^2}$]

- Power at "outer" divertor targets:

  - $P_i/P_{in}$ vs $\rho_{X^2}$

  - $SF^+$
  - $SF^-$

  - Radial position $\rho_{X^2}$

  - $SP2$
  - $SP4$
3. On TCV, Langmuir probes measurements are showing the same trend.
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• Outlook
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Plan to revisit the X divertor and address aspects of the Super-X divertor

- Continue X divertor studies [R. Pitts, et al., J. Nucl. Mat. (2001)] with additional heating

- Increase of the target radius in the Super-X divertor promises increased stability of the radiation front
TCV upgrades will broaden scope of assessment of alternative configurations

**1 MW NBI ion heating (2016)**
- For wider H-mode operating regime and hotter core plasmas near radiation limit

**Multiple diagnostic upgrades (2015)**
- Reciprocating probe at top/middle/bottom port (UCSD) and Visible Fast Framing camera (CCFE)
  - Cross-field transport
- Divertor spectroscopy (U. of York) and Multi-spectral imaging (DIFFER)
  - Physics of plasma detachment
- Second fast IR camera
  - Target heat loads at all strike points

**Heating power (2017)**
- Two dual frequency X2/X3, 1MW gyrotrons
- 1MW NBI
  - Increasing $T_{e,sep}$ and $P_{sep}/R$

**Divertor modifications (2017-2020)**
- Variable closure, possibly pumped divertor
  - Divertor physics
Summary

• TCV is well suited to study alternative divertor configurations
  - To confirm alleged advantages
  - To further the understanding of divertor physics

• Studies of highly radiating regimes in alternative divertor configurations have started
  - Expected to benefit from various on-going and planned TCV upgrades

• Experiments support three cross-field transport mechanisms that are enhanced in the snowflake
  - Convection driven cross-field transport in the null-point region
  - ExB drifts stronger than in SND
  - Increased radial gradients in SF-