Compatibility of advanced divertor solutions with high core performance (Snowflake & Super-X)

(A personal view)

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CCFE is the fusion research arm of the United Kingdom Atomic Energy Authority
Scope

Theme:
- do advanced divertors help or hinder high performance cores?
- how can we be sure enough to propose for DEMO?
- how do we handle the uncertainty?

Topics
- Innovative divertors: why and what?
- Status (brief)
- What divertor aspects affect core performance?
- What core aspects affect divertor?
- Key interface issues
- Some comments on next steps
Power & particle flow – issues and integration

Main chamber PFCs

MW/m², erosion, melting, fatigue

Core Plasma

P_{rad}

P_{aux}

P_{\alpha}

Suitable pedestal

SOL width, seeding for radiative losses, turbulent transport, control, transients, start-up, ramp-down

SOL + Divertor plasma

Divertor target PFCs

MW/m², erosion, melting, fatigue

Divertor chamber PFCs

Neutron MW/m²

P_{\text{electric}}, \Delta P_{\text{electric}}

T breeding

L-H access, ELMs, separatrix conditions (e.g. f_{e,i}(v)) etc

Burn control

Stability control

P_{\text{SOL}} control?

Impurities

Fuel

Impurities

Fuel

SOL + Divertor plasma

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Stability control

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T breeding

L-H access, ELMs, separatrix conditions (e.g. f_{e,i}(v)) etc
Advanced divertors – why?

• Power exhaust for DEMO extremely demanding
  – Numbers (power, erosion etc) and control
  – Radiation degradation of PFCs, operating point (DBTT)
• Not yet sure that conventional approach will have appropriate margin, or how/when we will be sure.
• If need higher performance core (higher exhaust power) and ability to handle excursions, may need more margin

⇒ Seek alternates with more margin & flexibility for exhaust plasma and PFCs, for back-up, and/or better plasma

• Attractive features, new insights into exhaust physics, but many issues of physics benefit & technical feasibility, which will need to be solved
Advanced divertors – what?

- Change magnetic geometry to
  - increase flux expansion
  - add volume for radiation
  - Increase connection length: cooling, let cross-field transport act
  - partly shield targets
- Started with snowflake and super-X, but variants
  - optimum may not be like today’s options
- Most need extra volume

Pioneers include: Ryutov (snowflake); Kotschenreuther, Valanju, Mahajan (super-x).
Snowflake geometry

- Variants (SF+, SF-) depending on location and proximity of the two x-points
- Currently open geometry
  - solution for pumping and neutral/impurity compression to be developed.

Holger Reimerdes, EPS 2013, PPCF 2013

Snowflake on TCV. NSTX, DIII-D PFCs just below null-point
Advanced divertors – engineering

- **Challenges:**
  - Precise PFC alignment for max benefit from flux expansion (esp snowflake)
  - Large coil currents if coils outside TF (snowflake)
  - Technology & maintenance if coils inside TF (e.g. double-decker)

- **Internal coils may be much easier in FNSF/CTF if TF coils demountable**

- **Double decker:** are the forces manageable?
  - Yes, first estimate, using “aircraft wing” type skin & spar, steel structure (~10MA max in-vessel current for $I_p=16MA$)

See also N Asakura poster P13
Status of research

• Experiment – encouraging but limited data:
  – Sustained snowflake H-modes on DIII-D, NSTX, TCV, reduced power flux to target, mitigated ELM impact
  – Same PFCs for SF & conventional – i.e. realistic alignment
  – Limited parameter ranges so far
  – No super-X or other long leg data yet

• Theory and modelling – early stages
  – SOLPS-like modelling of snowflake and super-X
  – Theory studies of change in turbulence in snowflake
  – Preparing turbulence calculations in super-X
DIII-D: peak heat flux reduced 2.5X by SF

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

Base plasma:
- Graphite PFCs + lithium coatings
- $I_p=0.9$ MA, $P_{\text{NBI}}=4$ MW, $P_{\text{SOL}} \sim 3$ MW
- $q_{\text{peak}} \leq 8$ MW/m$^2$, $q_{\parallel} \leq 100$ MW/m$^2$

With snowflake divertor
- H-mode confinement unchanged
- $W_{\text{MHD}} \sim 250$ kJ, $H_{98}(y,2) \sim 1$, $\beta_N \sim 5$
- Core impurity reduced up to 50 %
- Divertor heat flux significantly reduced
  - Between ELMs
  - During Type-I ELMs ($\Delta W/W \sim 5$-15 %)
- Radiative and CD$_4$ seeded divertor work well, MARFEs avoided. (Ne on DIII-D)

V Soukhanovskii, EPS 2013
TCV: ELM self-spreading

- ELM energy activates extra strikepoints – power spread more.
- Thought to be due to instabilities/convection driven by local pressure around X-point (also studied on NSTX, theory)

ELM power redistribution

\[ \sigma = 0: \text{perfect snowflake,} \]

\[ \sigma = \text{distance between X-points/a} \]

W. Vijvers, IAEA 2012, subm Nucl. Fusion 2013
Evidence for good core performance?

• Quite extensive snowflake experiments on DIII-D, NSTX and TCV, others to come (EAST, MAST…)

• Snowflake:
  – Sustained H-mode
  – Controlled configuration
  – High $\beta$ ($\beta_n \sim 5$ on NSTX)
  – Good confinement ($H_H \sim 1$)

• No super-X or double-decker data yet (MAST 2015/16 ff)

**Research at early stage, but promising**
## Where advanced divertor may affect core

<table>
<thead>
<tr>
<th>Factor</th>
<th>Possible impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-point position</td>
<td>Shape/triangularity (physics unclear, ignore here)</td>
</tr>
<tr>
<td>Upstream density (related to detachment threshold)</td>
<td>Pedestal foot, pedestal height and gradient/stability</td>
</tr>
<tr>
<td></td>
<td>Pedestal collisionality ($J_{bootstrap}$, transport &amp; stability)</td>
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<tr>
<td></td>
<td>Edge radiation level and control</td>
</tr>
<tr>
<td></td>
<td>Density limit</td>
</tr>
<tr>
<td>Upstream turbulence/blob source (if needed for SOL width)</td>
<td>Turbulent pedestal foot – may affect pedestal height</td>
</tr>
<tr>
<td>Main chamber neutral density (related to closure)</td>
<td>H-mode access, fuelling control</td>
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<tr>
<td></td>
<td>Pedestal structure (cf Li on NSTX?)</td>
</tr>
<tr>
<td></td>
<td>Density limit</td>
</tr>
<tr>
<td>Impurity density around X-point, esp if very high concentration for high $P_{rad, div}$</td>
<td>Core impurity level</td>
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<td></td>
<td>Edge radiation level and control</td>
</tr>
<tr>
<td>Upstream SOL flow</td>
<td>L-H threshold?</td>
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<td></td>
<td>Particle (fuel, He, impurity balance)</td>
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<tr>
<td>Others?</td>
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# Where core might affect divertor

<table>
<thead>
<tr>
<th>Factor</th>
<th>Possible issues/areas of impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triangularity</td>
<td>X-point position (origin of benefit unclear, ignore here)</td>
</tr>
<tr>
<td>Nature of pedestal needed (e.g. ELM-free, ELM type) L-H threshold</td>
<td>Upstream density&lt;br&gt;Main chamber neutral density&lt;br&gt;Upstream SOL flows?</td>
</tr>
<tr>
<td>Fuelling and fuel exhaust</td>
<td>Baffling and pumping arrangement and rate, impact on detachment conditions</td>
</tr>
<tr>
<td>Impurity concentration limits</td>
<td>Impurity concentration around X-point&lt;br&gt;Level of throttling of divertor</td>
</tr>
<tr>
<td>Edge radiation levels</td>
<td>Upstream density and temperature&lt;br&gt;Upstream impurity species and level&lt;br&gt;Impurity exhaust (for $P_{\text{rad}}$ control)</td>
</tr>
<tr>
<td>Ramp-up and ramp-down and slow transients, time-lags in control loop</td>
<td>Resilience of detached region to variations in power influx&lt;br&gt;Capability of primary targets (if slow &amp; fast transients hit same targets as DC power)</td>
</tr>
<tr>
<td>Others?</td>
<td>3-D effects</td>
</tr>
</tbody>
</table>
Main interaction areas to explore

- L-H access
- Edge pedestal structure (and density limit) – link to $P_{\text{fus}}$ directly
- Fuelling and pumping and high $n/n_G$
- Impurity control
- Edge/SOL turbulence (link to MW/m$^2$ in divertor)
- Transient control (slow and fast)

- Several of these are coupled
  - common to all exhaust solutions (advanced divertors help wider research)
  - depend on desired core scenario, divertor configuration
- Long term aim:
  - predictive capability to develop new exhaust approaches to required confidence level.
  - theory-based models validated on experiment
L-H transition

- Observations
  - $P_{\text{LH}}$: only modest changes from snowflake
  - Mixed data on effect of the leg length
- Questions/Issues
  - Vertical targets different?
  - Upstream SOL parameters affected by configuration
  - Edge magnetic shear increased by SF
- All may affect $P_{\text{LH}}$, but how, why?
- No validated theory model for effects of leg length, neutral density, SOL flows and gradients on H-mode access conditions

Appears generally compatible, but need more data, esp. long-leg. And some theory!

Longer leg $\rightarrow$ L-mode on MAST (close to L-H threshold)
Pedestal structure

- Pedestal not changed much by SF per se?
- NSTX: Li changes pedestal a lot, no ELMs (low neutrals?). SF restores ELMs
- But upstream density may change pedestal:
  - high → lower pedestal gradient
  - low \( n_u \) needs high \( T_u \), strong cooling (\( T_t/T_u \)) and not too large \( n_t \)
- Neutral density affects pedestal shape?
  - Closed divertor (super-X, double-decker): expect lower main chamber neutral density
- (Assume ELMs tackled anyway)

Appears generally compatible, but some questions
Fuelling, density limit and He exhaust

- High target density needed for detachment and He pumping
- May want low main chamber neutral density?
- Fuelling limited by gas handling of T plant
- Need main plasma close to Greenwald density (little data so far)
- Are these consistent?
- Does divertor change nature/value of density limit?
- Snowflake and long-leg: different requirements
  - How to pump snowflake? Is baffle required? Pumping of open snowflake being explored
  - Long-leg (super-X or double-decker): closed divertor and “easy” pumping; need tight control to avoid baffle contact

- **Research at early stage**
Impurity influx to core

- Snowflake: radiating region by X-point.
  - data is mixed whether a problem. Radiation localised (low-Z so far)
  - need to explore higher absolute $P_{\text{rad,div}}$ (higher impurity concentrations)

- Long-leg:
  - poloidal flux concentration at divertor throat may help entrainment of impurities & stabilisation of the detachment front

- Parameters such as mean free path not DEMO-like

- Research at early stage
Edge/SOL turbulence

• Much of the turbulence drive is upstream, but the divertor geometry affects the level.
• Whether additional cross-field transport is generated in the X-point or long leg region is not yet known.
• ELM pulse drives spreading in snowflake – relevant to inter-ELM?

• Research at early stage – enthusiastic activity
Transients, slow

• High performance scenarios often have complex time sequences (tailored current & power ramps etc)
  – Exhaust must work in start-up and ramp-down
  – Plasma control on DEMO likely to be worse than now
  – Response time > time to damage PFCs
• Advanced divertor must cope (e.g. remain detached)
  – If detached layer has to be close to target, is detachment marginal?
  – Experiment: snowflakes detach more easily. Expect same for long-leg configurations. Build on this.
  – Multiple impurity species may help
• (Assume ELMs tackled anyway)

• Research at early stage, scope for optimism
Summary of position

• **Snowflake**: promising early results
  – Experiments in H-mode, $H_H > 1, \beta_n \sim 5$ (NSTX).
  – Several uncertainties:
    • H-mode access (theory basis needed)
    • pedestal structure
    • fuelling and pumping, density limit
    • impurity control at high $P_{\text{rad}}$
    • slow and fast transients (same for conventional)
    • performance with acceptable PFC angle (detached helps?)
  – Advanced core regimes: little if any data

• **Super-X, long leg, “double decker”**:  
  – could lead to more margin/decoupling of divertor and main plasma than for conventional divertor?
Next steps?

• **Snowflake**: Expand plasma regimes & parameter range; investigate pumping; divertor characterisation
• **Super-X/long leg**: get on with them!
• Test/improve stability of radiation/detachment front
• Improve theory-based models of key mechanisms for extrapolation, especially of cross-field transport including detached region. Test and validate. Try to use models to integrate where no experiments
• Use differences in configurations as an exhaust research tool (e.g. to understand power spreading detachment threshold/control/stability) – for conventional exhaust as well
• May need some structured plans
• Work on the engineering and technology aspects
Prospects

• It may be possible/essential to develop DEMO core plasmas approximately (e.g. JT-60SA) and then “bolt on” a different divertor developed separately
  – think about divertor interface when developing core

• Assume cannot do a full-scale test before DEMO
  – there will always be a “gap” even in non-nuclear aspects
  – assess how much can be done with theory/models
  – what scale of integration test is worthwhile? (even none?)

• Significant optimisation likely to be needed on DEMO itself (true for any exhaust solution?)

• Steps smaller and simpler for first stage of a self-developing FNSF/CTF?
Advanced divertor path?

- Theory-based models of SOL and divertor, and link to core (often same as for conventional exhaust)
- Advanced divertors in medium-sized tokamaks
- Engineering & technology of advanced divertors
- JET, JT-60SA, ITER: core plasma optimisation
- Combining process (tbd!)
- Are major new facilities/upgrades needed? Scope and timing?
- FNSF (or CTF)
- DEMO
Conclusions

- Some very interesting possibilities for exhaust and potentially more freedom for the core optimisation
- Physics: not yet any showstoppers for combining advanced divertor with good core performance (from experiment, mainly)
- Technology: still open challenges – some advances
- R&D is at an early stage, several key issues to address in experiment, theory, engineering/technology
- Substantial uncertainty due to limited data, parameter ranges and understanding – main R&D areas known
- Need to identify process and level of demonstration and/or integration to allow decision for DEMO, or whether uncertainty means final integration best left to DEMO
- Field generates enthusiasm and new ideas, useful for exhaust as a whole.
Backup material
L-H transition

- Observations
  - $P_{LH}$ modest on NSTX - not an issue?
  - $P_{LH}$ not changed by SF on TCV
  - $P_{LH}$ raised by longer leg (JET, MAST, TCV), or lowered (C-Mod slot divertor)

- Questions/issues
  - Vertical targets different?
  - Upstream SOL parameters affected by configuration. E.g. flows? Now measurable, B2-SOLPS super-X model (Rozhansky)
  - Edge magnetic shear increased by SF

Longer leg $\rightarrow$ L-mode on MAST

Coherence imaging of SOL flows in MAST
Pedestal structure

- Pedestal ~unchanged for DIII-D, TCV SF vs conventional so far
- NSTX – Li changes pedestal a lot, ELM-less. ELMs return with SF
- But upstream density may change pedestal:
  - High → lower pedestal gradient for same $n_{\text{ped}}$
  - Pressure balance: $n_u T_u \sim 2 n_t T_t$ for $T_e = T_i$, $M_t = 1$, $M_u = 0$
  - low $n_u$ needs high $T_u$, strong cooling ($T_t/T_u$) and not too large $n_t$
- Neutral density affects pedestal shape?
  - Li on NSTX: much lower $dn/dr$ in pedestal (due to lower neutral density?)
  - Closed divertor (super-X, double-decker): expect lower main chamber neutral density
Tools for engineering feasibility study

- Equilibrium model used to generate concept
- Python used to model divertor region only, assuming simple core plasma
- This allows quick exploration of small modifications
- These can easily be fed to mechanical FEA in ANSYS