Issues for stellarator divertors

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What are the requirements of a plasma facing component system?

1. Power removal
2. Particle handling
3. Core compatibility
4. Acceptable material lifetime
5. Maintainability
Why divertors?

1. Power removal
   - Modify downstream via parallel transport
   - Volumetric power loss
   - Detachment

2. Particle handling
   - Closure increases n0 pressure, facilitate pumping

3. Core compatibility
   - Separate impurity source from main plasma
   - H-mode access

4. Acceptable material lifetime
   - Reduce $T$, $\Gamma$ to mitigate sputtering, erosion

5. Maintainability

6. Downside: Geometry largely fixed by above, uses a lot of volume $\Rightarrow$ $$
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Stellarator divertor systems

- Helical divertor: LHD
  - Continuous divertor between helical coils

- Island divertor: W7-AS/X
  - Control edge resonance and intersect islands with PFCs.

- Intercept ordering of flux bundles for non-resonant boundary: NCSX, HSX
  - Patterns determined by "l" of configuration. Not sensitive to edge transform

- Compared to tokamaks
  - Components are toroidally and poloidally discrete
  - Boundary between closed and open field lines in tokamak is not stochastic
Advantages of 3D divertors

• Stellarators have ‘natural divertors’
• Long connection length
• Possibly take advantage of multiple nulls
  – May have significant poloidal asymmetry if transport is ballooning
• Flexibility in configuration space to optimize divertor along with magnetics
  – Including pulling flux to locations between coils with significant expansion, alphas to specialized targets
• Possible to operate without ELMs?
• High density operation $\rightarrow$ better divertor conditions
• Possible that power channel width scaling is better in 3D systems? Or optimize to increase heat flux width
• Momentum loss makes detachment easier?
  – Detachment more stable than tokamak? Can get $T_e$ low enough?
Issues for 3D divertors

- Island divertor may require active control
  - Sensitivity to bootstrap current?
  - Find window in shear? Low shear: risk of core islands, high shear: small edge islands

- Neoclassical impurity accumulation

- Access to high recycling regime
  - Required for He pumping?

- Alpha losses, fast ion orbits reaching ‘behind’ components

- Stochasticity in transition from closed to open field lines
  - Switch from ion orbit loss to electron streaming, can’t maintain strong E gradient for H-mode?
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\[
\Gamma_a = -D_{11}^a n_a \left( \frac{n_a'}{n_a} - q_a E_r \right) + \left[ \frac{D_{21}^a}{D_{11}^a} - \frac{3}{2} \right] \frac{T_a'}{T_a}
\]

\[
\Gamma_I = -D_{11}^I n_I \left\{ \frac{n_I'}{n_I} + \left[ \frac{D_{21}^I}{D_{11}^I} - \frac{3}{2} \right] \frac{T_I'}{T_I} - \frac{q_I}{q_i} \left( \frac{n_i'}{n_i} + \left[ \frac{D_{21}^I}{D_{11}^I} - \frac{3}{2} \right] \frac{T_i'}{T_i} \right) \right\}
\]

Impurity accumulation
Screening if negative

ITER size, n=1e20 m⁻³, E_r=0

- ~TJ-II
- ~HSX
- NSTX
- RMP
- Tok. Err
- ITER
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Issues for 3D divertors

- Erosion
  - Unmitigated tons of material are eroded per year in reactor
  - Can achieve $T$, $n$ needed?
  - $T_e < 5 \text{ eV}$, $n_e > 10^{21} \text{ m}^{-3} \ast$
  - More of an issue because of toroidally and poloidally localized deposition?

- Geometry and flux patterns are complex
  - Tokamaks detach where heat flux is highest

- Stable detachment requires distance between x-point and wall
  - But increases sensitivity to B error

- Modeling gaps even larger than tokamaks

*Stangeby and Leonard, NF ’11
Research needs and opportunities

• Testing of divertor concepts
  – Basic concepts can be explored at existing facilities
  – Facility to specifically test advanced, reactor relevant divertor (W, pumping, etc).
    Innovative material concepts.

• Model validation and advancement
  – Access to high recycling regime, divertor flux widths, detachment
  – Prediction of heat flux width
  – Try to access high $n_e$, low $T_e$ through modeling for reactor parameters to show erosion problem solvable

• Identify target functions for divertors and include in optimization
  – Development of robust divertor solutions with good properties
  – Tools: field line following, spiral/Hamiltonian method, EMC3-EIRENE
  – Possible to develop continuous divertor, localized to outboard side?

• Many research questions will be addressed on W7-X
  – Integrated core-edge solutions
  – Divertor flux width
  – ELMs and H-mode
  – Island divertors
Research needs and opportunities

• Analytic theory
  – Identification of divertor concepts, optimization criteria
  – Prediction of heat flux widths

• Code development and computation
  – Fast, efficient boundary models without significant grid work
  – Investigate access to high n, low T regime; high recycling
  – Investigate stability of detachment
  – Implementation of edge, divertor, target functions in optimization

• International facilities
  – Integrated core-edge solutions, divertor flux width, ELMs and H-mode, operation with island divertors

• Domestic program
  – Testing of divertor, material concepts

• Technology
  – Criteria and constraints for divertor design (max fluxes, erosion, constraints on geometry from maintainability, curvature limits, etc)
Backup slides
Modeling gaps

• Matching detachment: downstream conditions, transition
• Matching flows in SOL
• First principles prediction of cross-field transport
• Neglect blobs, main chamber fuelling
DIV3D

Peak flux: ~16MW/m²

EMC3

Peak flux: ~12MW/m²

Core Islands
- Grigull

**Divertor plasma regimes: downstream parameters**

Peak densities and temperatures from probe array

**Region A:**
- Downstream peak $T_{ed}$ stays above 20 eV
  --- > attached spot
- Inconsistent with low $T_{es}$
  --- > inhomogeneous $T_{es}$?

**Region D:**
- Rollover up to detachment of $n_{ed}$, $\Gamma_{pd}$
  (confirmed by 2D $H_a$ data)
- $T_{ed} > 2$ eV at detachment (from $H_a/H_e$)
The route to detachment (1)

Mean free paths for particle collisions are long: \( \Lambda_{\text{coll}} \propto T_u^2 / n_u \), \( T_u \sim T_e \sim T_i \), \( \Lambda_{ee} \sim \Lambda_{et} \sim \Lambda_{ii} \)

SOL collisionality: \( \nu^* = L / \Lambda_{\text{coll}} \) low

Power flow to surface largely controlled by target sheath: \( q_{\text{fs},t} = \gamma n_t c_{st} T_t + n_t c_{st} \varepsilon_{\text{pot}} \)

\( \gamma = \) sheath heat transmission coefficient
\( \varepsilon_{\text{pot}} = \) potential energy per incident ion

\( \nu^* \) rises as \( n_u \) rises, finite electron heat conductivity:

\( q_{\text{cond}} = -K_{\parallel} dT / ds_{\parallel} \), \( K_{\parallel} = K_0 T_0^{5/2} \) (note: \( \kappa_{0,e} \gg \kappa_{0,i} \))

allows parallel T gradients to develop \( \Rightarrow T_t \) decreases, but pressure balance maintained \( (\nabla p_{\parallel} \sim 0) \) so that \( n_t \) rises strongly \( (T_t \propto n_u^2) \)

\( \lambda_{\text{ion}} (\propto 1/n_t) \) decreases so that target recycling increases strongly \( \Rightarrow \) flux amplification

As \( T_t \downarrow \), radiation loss increases \( \Rightarrow T_t \downarrow \) further