Axisymmetric magnetic mirror applications – neutron source to fusion power plant

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### Outline

<table>
<thead>
<tr>
<th>Neutron source</th>
<th>Fusion-fission hybrid</th>
<th>Pure fusion</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Neutron source diagram" /></td>
<td><img src="image2.png" alt="Fusion-fission hybrid diagram" /></td>
<td><img src="image3.png" alt="Pure fusion diagram" /></td>
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</tbody>
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#### Risk:
- Minor extension of tested physics
- Q ~ 0.07
- Q ≤ 0.7 low risk – test line-tied stability
- Test MHD & micro-stability

#### Fusion power
- Q > 0.7
- 0.2 < Q ≤ 10
- Q > 10

#### Drive power
- Q > 4 (tandem) competes with fission breeders
- Simpler fusion power. Perhaps thick-liquid walls

#### Motivation
- Materials/component R&D for MFE, IFE DEMO
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Gas Dynamic Trap (GDT) at Novosibirsk – stable, axisymmetric magnetic mirror

Long-pulse to steady-state 5 MW GDT could test plasma-materials interactions (PMI) to 400 MW/m², to simulate diverter heat loads. – R. Goldston

Warm plasma:

\[10^{19}-10^{20} \text{ m}^{-3}, \ T_e \sim 200 \text{ eV}\]

Fast ions \((H^+, D^+):\)

\[\sim 5 \times 10^{19} \text{ m}^{-3}, \langle E \rangle \approx 10 \text{ keV}\]

\[\beta \leq 60\%\]
## Performance of various neutron sources

<table>
<thead>
<tr>
<th></th>
<th>RTNS 1982-87 D-T</th>
<th>IFMIF D+Li</th>
<th>DTNS (FNSF) D-T</th>
<th>FNSF (FDF/CTF) D-T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron Power (MW)</td>
<td>20 W</td>
<td>0.1</td>
<td>2</td>
<td>100-300 30-160</td>
</tr>
<tr>
<td>Flux (MW/m²)</td>
<td>0.2</td>
<td>2/5</td>
<td>2</td>
<td>2 - 3 1 - 3</td>
</tr>
<tr>
<td>Availability goal</td>
<td>≥0.7</td>
<td>≥0.7</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Area (m²)</td>
<td>.0001</td>
<td>0.01</td>
<td>1</td>
<td>70 /15</td>
</tr>
<tr>
<td>Depth (cm)</td>
<td>5/1</td>
<td>5/1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tritium (kg/FPY) [Full-Power Year]</td>
<td>~0</td>
<td>0</td>
<td>0.1</td>
<td>~2 to 20 without breeding</td>
</tr>
</tbody>
</table>

RTNS – Rotating Target Neutron Source  
FNSF – Fusion Nuclear Science Facility (FDF & CTF are small D-T burning tokamaks for component development)
Neutron spectrum of DTNS – similar to ITER

- No spectrum conversion for displacements per atom (dpa), He/dpa, and H/dpa, or activation
- Activation data – no false positives from neutrons above 14 MeV

Dynamic-Trap Neutron Source (DTNS)

Optimized for materials test + significant subcomponent tests

Axisymmetric linear facility is maintainable, flexible, reconfigurable


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Development needed for FNSFs

**Steady-state neutral beams: DTNS – 30 MW at ~80 keV**
- Neutral beams reliable on tokamaks: TFTR (120 keV, 1 s \(\rightarrow 1000\) s)\(^1\) & DIII-D (80 keV, 5 s)\(^2\). Power 20-24 MW, availability 90-95%.
- **Lifetimes uncertain.** Ion source filament lifetime >2 weeks; sputter lifetime of accelerator electrodes similar order. Need ~1yr.
- Leverage NBI development from China, Korea, India?

**Steady-state cryopumps**
- All FNSF need cryopumps regenerated during full-power operation

**Remote handling**


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Direct conversion of NBI residual ion beam – option

Efficiency ~65% achieved, ~75% if mostly full-energy ions [1]

- Efficiency of ~70% possible
- Nearly eliminates decrease in efficiency at high-beam-energy
- Direct conversion (DC) can be added, or deleted; depends on R&D success.
- Save $5-10 M/yr at $0.10/kW hr


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Dynamic-Trap Neutron Source DTNS – low risk

• DTNS is extrapolation of successful GDT – low scientific risk
  – Neutral-beam energy x4 [to DIII-D level]
  – Neutral-beam current x1.5
  – $B_{\text{min}} \times 6$
  – Same plasma length, radius, and $B_{\text{peak}}$
  – $T_e \sim 0.8 \text{ keV}$ from scaling law

• DTNS not part of test – low technology risk
  – Power densities low on DTNS
  – Tritium-breeding blankets not required for fueling (burns ~0.1 kg/yr)
  – Samples outside vacuum wall, change wall during maintenance
  – Insert samples thru airlock: expose to α’s, PMI, neutrons >2 MW/m²?

• DTNS differs from tokamak FNSF:
  – Superconducting magnets – lower operating power/costs
  – Maintainable without individual magnets separating into 2 pieces
Mirror fusion-fission hybrid: burn waste or compete with fission breeder [Moir 1.4.3]

Detailed report is available – Moir, Martovetsky, Ryutov, Molvik, Simonen
Can axisymmetric mirrors provide pure fusion with Q>10?

- Need to demonstrate MHD and micro-stability with low end-loss, several mechanisms to test – at low cost on GDT.
- Power/particle balance computations: Q=10 solution (below)*, Q>10?
- Q=10 sufficient with direct conversion of end loss and neutral-beams?
- Helium-ash accumulation?

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Axisymmetric tandem mirrors – potential for attractive pure-fusion power

Strengths

- **All mirrors eliminate**
  - a. Disruptions (no significant plasma current)
  - b. High power density to diverter strike points (large area for end loss).

- **Axisymmetric mirrors**
  - a. Eliminate neoclassical and resonant radial transport
  - b. Allow high-B tandem mirror end cells, don’t need thermal barriers
  - c. Easy to maintain or modify
  - d. Low costs for stability tests, on GDT
  - e. Technologies within ITER range

- **Thick liquid walls of 0.5-1m thick molten-salt flibe eliminate most materials issues (dpa, He/dpa, H/dpa)**

Conclusions – Axisymmetric mirrors have attractive applications

• Long-pulse GDT could test PMI to 400 MW/m$^2$ to simulate extreme diverter heat loads

• DTNS can test materials & subcomponents for a tokamak FNSF and a fusion DEMO

• Mirror fusion-fission hybrid: burn waste (single-cell) or compete with fission breeder (tandem mirror)

• Axisymmetric tandem mirrors have potential for attractive pure-fusion power
Selected References


