Potential of Magnetic Mirrors

Development of
Fusion Energy Science:
Physics, Materials, Blankets

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What is New?

• Data from Russia
  – Axisymmetric Concept
• Material Science Mission
• First Principles Simulation and Validation
Axisymmetric Mirrors

- Circular Coils without Thermal Barriers
  - Simplified Engineering and Physics
    - No neoclassical radial transport
    - High mirror ratio and Natural Divertor
    - Ease of Construction and Maintenance
A Simple Mirror can be MHD Stable

- **Seven Tested Methods**
  1. Expander plasma Outflow (GDT)
  2. Plasma Rotation (MCX)
  3. Divertor (Tara)
  4. Pondermotive (Phadrus & Tara)
  5. End Wall Funnel Shape (Nizhni Novgorod)
  6. Line-Tying (UCBerkeley)
  7. Cusp End Plugs (GDT)

- **Four Untested Methods**
  1. Kinetic Stabilized Tandem Mirror (Post)
  2. Pulsed ECH Dynamic Stabilization (Post)
  3. Wall Stabilization & Feedback (Berk)
  4. Non-paraxial End Plugs (Ryutov)
2XII-B Beta=70% Ei = 10 keV

• Te=140 eV with Stream Stabilized DCLC Nonlinear Stability
• Reactor Study Q ~ 1
TMX-U Tandem Mirror

Sloshing Ions Improve Micro-stability
Te < 280 eV, \( \tau_{\text{e}} \sim 100x \) that of 2XIIIB
Reactor Q > 10 but complex Thermal Barrier
Thermal Barrier Confinement only at Low ne
GDT - Novosibirsk, Russia
60% Beta, Ei ~ 10 keV, Te < 230 eV
GDT DD Neutron Axial Profile Agrees with Theory
MSE Measurement of Beta

Delta B versus Plasma Energy

- 50% Normalized to Vacuum Magnetic Field
- 100% Normalize to Depressed Magnetic Field (FLR)
A 14 MeV Neutron Source to Qualify Materials & Subcomponents
Mirror Neutron Source Characteristics

• Compared to IFMIF-like Point Sources
  + 100x larger test volume
  + True 14 MeV Neutron Energy Spectrum
  + Potential for simultaneous neutron and plasma-wall interaction testing

Compared to Tokamak Volume Sources
  + burns 100x less tritium
  - 100x smaller test volume
Neutron Flux Increases With Te
(for various NBI energies)
Today’s Te ~ 0.2 keV would produce ~ 0.3 MW/m²
A Development Path

• GDT Collaboration (≈ 2 M$)
  – 20 keV – 5 ms NBI & 0.3/6.5 T Magnetic Field
  – Theory & Simulation
  – Diagnostics

• Next Step Collaboration (≈ 10 M$)
  – 40 keV – 1 sec. NBI & 1 T Magnetic Field

• Neutron Source Hydrogen Prototype Collaboration (≈ 40 M$)
  – 80 keV - ss NBI & 2 T Magnetic Field
## A Development Path

<table>
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<th>Parameter</th>
<th>GDT</th>
<th>Next Step</th>
<th>Neutron Source</th>
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Potential Scientific Value

Validate Predictive Simulation

• Eb/Te similar to ITER Alpha Particle Ratio
• Open Field-Line Divertor Physics
• Vortex ExB-shear Analogous to Tokamak Second –Stability B-shear and H-mode
• Nonlinear Velocity Space Flattening Analogous to Toroidal Radial Flattening
• Unity Beta, Vortex, Micro-Turbulence connections to Space and Astrophysics
Backup
Minimum-B Magnetic-well is MHD Stable
Simple Mirror is MHD Unstable
FIGURE 6. (a) Scheme of the vortex potential profile perturbed by the “rigid” $m = 1$ mode, which generates a quasi-uniform transverse “wind-field”, $f = f_0 \cdot r \cos \theta$. The flow-lines in the region $h > 0$ remain closed, if the perturbation amplitude is lower than the vortex amplitude, $2f_0 < 1$. (b) Potential profile in the perturbed flow-layer (slab). (c) Flow-lines in cylindrical geometry.
DCLC Simulation of Sloshing Ions

- $T_e$ Increases Loss-Cone Size
- Loss-Cone Drives Turbulence
- Turbulence Drives Plasma loss
- Plasma Loss Decreases $T_e$
- To Increase $T_e$ Increase Beam Energy to keep Similar Size Loss-Cone ($T_e \sim \frac{E_b}{\rho}$)