Helical Mirror Concept Exploration: Design and Status

A. V. Sudnikov, et al.
Budker INP SB RAS
Outline

1. Bases: multimirror confinement
2. Bases: vortex confinement
3. Motivation
4. Helical mirror conception
5. Required plasma parameters
6. Experimental device layout
7. Critical experiment features
Multimirror confinement

Chain of the mirrors \((R \sim 1.5–2)\)

\[ \lambda \sim l \] due to high density or high turbulence.

Transiting particles can be trapped due to collisions.

Trapped particles scatter in random direction

Plasma flow become diffusive. \(\tau \sim (\text{Number of cells}) \times \tau_{E0}\)

\[ \tau \sim R^2 \frac{L}{\lambda_i} \frac{L}{V_{Ti}} \]

A. V. Burdakov, Multiple Mirror Trap: Milestones and Future, \textit{Thursday Aug. 11, 09:00}

In experiment:


Early concept: moving mirrors

Vortex confinement

The confinement time for Co-NB is almost twice better than that for on-axis NB.

Momentum injection controls the axial fluxes via the potential well.


<table>
<thead>
<tr>
<th></th>
<th>On-axis NB</th>
<th>Co-NB</th>
<th>Counter-NB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron temperature, eV</td>
<td>220</td>
<td>260</td>
<td>150</td>
</tr>
<tr>
<td>Energy content kJ</td>
<td>1.8</td>
<td>1.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Beta</td>
<td>0.6</td>
<td>0.6</td>
<td>No data</td>
</tr>
</tbody>
</table>

Velocity profiles indicate change of sign of rotation with momentum injection

Plasma flow lines become closed $E\times B$ may be used to create rotation

A. V. Sudnikov, et al. 11th International Conference on Open Magnetic Systems for Plasma Confinement. 2016.08.09
Combination of a central GDT-like vortex-confined mirror with multiple-mirror axial plugs.

To the left: guide field in the concept-exploration device GOL-NB (in construction)

Smaller-scale GDMT-like experiment.

V. V. Postupaev, Status of GOL-NB Project, 
*Tuesday Aug. 9, 12:30*
Motivation

What if multiple mirrors move only in plasma's frame of reference?

Plasma rotates due to $E \times B$ as in vortex confinement.

Guide magnetic field is helical, corrugated along each field line.

High corruption velocity is achieved easily:

$$V_z = \frac{hcE_r}{2\pi rB_z}$$

Plasma is actively pumped inside the trap

Classical mirror: $\tau_E \sim L$

Multimirror $\tau_E \sim L^2$

Helical mirror $\tau_E \sim \exp(L)$

A. D. Beklemishe, Transport in Trap Sections with Helical Corrugation, Wednesday, Aug. 10, Poster #32.
Direction of the force depends on the directions of the electric and the magnetic fields and its helicity.

1. Helical confinement demonstration (*needed for future GDMT-like trap*)

*Counter-flow force*

Task 1: Demonstration of plasma flow suppression

Task 2: Optimal confinement regimes
2. Plasma flow acceleration (needed for plasma thruster)

*Co-flow force*

Task 1: Demonstration of the acceleration

Task 2: Plasma detachment

Both motivations require plasma stream in helical magnetic field


Required plasma parameters

\[ h \sim \lambda : \]
\[ n_i \sim \frac{T_i^2}{4\pi \Lambda e^4 Z^4 \hbar} \]
\[ \sim n_i \left[ 10^{13} \text{cm}^{-3} \right] \sim \frac{2}{\Lambda} \frac{T_i [eV]^2}{h [cm]} \]

Magnetized plasma:

\[ \rho_B \propto r, \rho_B \propto \frac{\lambda}{2\pi} \sim \frac{h}{2\pi}, r \sim \frac{h}{2\pi} \]

\[ B_z = \frac{2\sqrt{2\pi c \sqrt{T_i}}}{e\sqrt{m_i}} = 2\pi \cdot 10^{-2} \sqrt{\frac{T_i [eV]}{h [cm]}} \]

Superthermal velocity:

\[ E_r > B_z \frac{2\pi r V}{c} \sim \frac{2}{e m_i} \frac{T_i [eV]}{r [cm]} \]

Stationary:

\[ \tau \sim \frac{N \times h}{V_i} \sim \frac{\sqrt{m_i}}{4\sqrt{2\pi \Lambda e^4 Z^4}} \frac{T_e^3}{n_i} \sim \frac{2 \cdot 10^{-6}}{\Lambda} \frac{T_e [eV]^3}{n_i \left[ 10^{13} \text{cm}^{-3} \right]} \]

List of parameters:

\[ n_i \sim 10^{19} \text{m}^{-3} \]
\[ T_i \sim 10 - 100 \text{eV} \]
\[ B_{\text{max}} = 0.1 - 0.3 \text{T} \]
\[ E_r \sim 100 V/cm \]
\[ \tau \sim 0.1 \text{s} \]
\[ r \sim 5 \text{cm} \]
\[ h \sim 18 \text{cm} \]
\[ N = 12 \]
\[ R_{\text{mean}} \sim 1.5 - 2 \]
SMOLA concept exploration device

Plasma is trapped between high-field region of the plasma gun and the helical section.
SMOLA device: important parts

Plasma gun. Similar to G. Shulzhenko, Studies of plasma production in a linear device with plane LaB$_6$ cathode and hollow anode, Wednesday, Aug. 10, Poster #75.

Guide magnetic field. Straight component.

Correction coils. Magnetic axis before (red) and after (blue) correction.
Critical experiment features

Main effects:
- longitudinal transport depending on corrugation velocity;
- radial drift of ions in the electric field direction

A. D. Beklemishev, Transport in Trap Sections with Helical Corrugation, **Wednesday, Aug. 10, Poster #32**

Plasma density modifications:
- exponential density decay along the trap until \( h \sim \lambda \);
- pinching of ions to central region with low \( R \).

The critical experiment excludes all effects except the helical confinement:
- identical regimes of the plasma gun;
- identical end-plates biasing;
- identical magnitude of the magnetic field;
- quasi-steady state;
- magnetic fields of the opposite directions;
  -> different signs of the longitudinal force.
  -> plasma should be trapped at one magnetic field direction
      and pumped out at another
Conclusion

SMOLA: only one helical plug;
— the plasma is trapped between it and the high-field zone of the gun;
— constant plasma flow from the gun;
— models one end of the infinitely long central section of GDMT-like trap.

Helical mirrors could expand the existing set of the axial losses suppression methods in linear traps.

Even at moderate efficiency with an enhancement factor of $5–10$, they will significantly improve the prospects of the open traps making them more suitable for fusion applications.

A. A. Ivanov, The BINP Road Map for Development of Fusion Reactor Based on a Linear Machine, Thursday Aug. 11, 10:20
Thank you for your attention!

Helical mirrors

Force

Rotation

Expander

Confinement zone

Expander