White Paper for *Frontiers of Plasma Science Panel*

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Indicate the primary area this white paper addresses by placing "P" in right column.
Indicate secondary area or areas by placing "S" in right column

	"P", "S"
• Plasma Atomic physics and the interface with chemistry and biology	
• Turbulence and transport	P
• Interactions of plasmas and waves	S
• Plasma self-organization	S
• Statistical mechanics of plasmas	

Indicate type of presentation desired at Town Hall Meeting.

	"X"
Oral	
Poster	X
Either Oral or Poster	
Will not attend	

Title:	Science and Application of Axisymmetric Linear Magnetic Confinement
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SUMMARY:

Scientific challenge: Understand confinement and stability of a high-temperature plasma in an axisymmetric magnetic mirror, particularly when operated in the gas-dynamic regime, and examine the basic plasma physics phenomena that appear in mirror geometry.

Approach: Expand collaborative work on existing mirror experiments, and initiate planning for a well-diagnosed medium-scale axisymmetric magnetic mirror experiment.

Impact: Improved predictive capability for plasma confinement and stability, expanded understanding of both laboratory and astrophysical mirror physics, and development of the mirror for fusion applications such as a high-flux neutron source.

- ***Describe the research frontier and importance of the scientific challenge.***

A new frontier in magnetic mirror research is opening, encouraged in particular by recent experiments on the GDT device at the Budker Institute that have demonstrated the production and confinement of stable high-*Te* plasmas.[1,2] The recorded *Te* of 660 ± 50 eV is a threefold increase over previous experiments at GDT and other comparable mirror experiments, and is sufficient for operation of the concept as a high-flux steady-state neutron source.[3] GDT is an axisymmetric magnetic mirror plasma confinement device, with high mirror ratio ($R = 35$) operating in the gas-dynamic regime (Fig. 1). Electrons are heated by a newly installed 0.7 MW electron cyclotron resonance heating (ECRH) system in addition to standard neutral beam heating. The neutral beam heating also produces a large population of well-confined fast ions that appear to slow down classically without anomalous loss.

The magnetic mirror configuration has a rich research history,[4] but poor electron thermal confinement, and resulting low *Te*, has long been considered the Achilles heel of the magnetic mirror. Previous experiments never demonstrated an electron temperature higher than 280 eV.[5] Classical estimates of the heat flux lost along the field lines in a simple mirror scale as a high power of *Te*, and suggest that a device the size of GDT would lose power at the GW level for a *Te* of 500 eV. However, GDT, with its high mirror ratio and sufficiently collisional plasma, operates in the gas-dynamic confinement regime. This regime is the plasma analogy to an ideal gas flow out of a container through a pinhole leak; isotropic collisional plasma flows out of a magnetic flux tube constricted by a high mirror ratio.[6] In the gas-dynamic regime electron energy is lost due to plasma streaming along the magnetic field lines at the ion-acoustic velocity. Plasma outflow expands by a factor >100 into large expansion tanks; this leads to good confinement of the electrons by the formation of an ambipolar potential. In this situation the heating power density required to support a stationary discharge at a given electron temperature scales as $Te^{3/2}$. This scaling has been demonstrated experimentally on GDT in discharges in which only neutral beam heating is applied, and in discharges with both neutral beam heating and ECRH.

The axisymmetric magnetic mirror possesses an appealing 2D simplicity, but is inherently MHD unstable, with a variety of modes degrading confinement. These modes are controlled on GDT by a technique called "vortex confinement."[7] Differential rotation of outer plasma layers induced by an externally applied radial electric field produces a vortex-like structure that results in stable confinement of hot plasma in the core region. The sheared flow provides no linear stabilization but instead introduces a new small scale for nonlinear dissipative saturation of flute modes.

These research accomplishments on GDT strongly encourage further development of the axisymmetric magnetic mirror for both fusion application and basic plasma physics research. The experimental demonstration of stable high-*Te* plasmas raises a number of questions with broad relevance to fusion science:

- What is the relationship of vortex confinement to other plasma self-organization phenomena such as H-mode in tokamaks? What are the limits of the technique and can it be extended?
- Are there alternative stabilization techniques (for example, non-paraxial surface stabilizers)?
- How does the physics of confining a high-temperature plasma in an axisymmetric magnetic mirror (no neoclassical transport) challenge our understanding of turbulence and transport?
- What are the limits to fast ion confinement in this magnetic configuration, given that no damaging fast-ion loss modes have yet been observed? Are there pressure-driven modes?

In addition to the above, an effort in magnetic mirror research that included a well-diagnosed experiment would provide the opportunity to examine basic plasma physics questions such as these:

- What particle heating and/or energization mechanisms may be active in astrophysical examples of magnetic mirror configurations? What wave-particle interactions are important?

- Can instabilities driven by anisotropic particle distributions lead to the formation of high-energy ion tails similar to those observed in astrophysical settings?
- What are the characteristics of turbulence driven by anisotropic particle distributions? How do those characteristics change as the level of anisotropy is varied?
- What is the physics of electron cyclotron heating in a mirror geometry? What are the nonlinear limitations on such heating? What is the role of the finite distance between the electron turning points?

- ***Describe the approach to advancing the frontier and indicate if new research tools or capabilities are required.***

Since there are no magnetic mirror facilities in operation in the U.S., initial research would need to be done collaboratively. Currently, the most active mirror research program is at the Budker Institute in Novosibirsk, Russia. In addition to the GDT facility described above, the Budker Institute also hosts the GOL-3 device, a multi-mirror configuration heated by a high-energy electron beam (Fig. 2).[8] The plasma density in this device is high such that the collision free path length is much less than the system length. In this situation particle transport is diffusive in character, and the confinement time scales as the square of the mirror ratio and the number of mirror cells.

Collaboration is the path to near-term participation in mirror research, but planning should begin for a new medium-scale axisymmetric magnetic mirror experiment in the U. S. The size of this device could be similar to GDT, but should have higher magnetic field, longer pulse, and more stored thermal energy. This experimental capability would afford substantial flexibility, for example, the ability to range from the gas-dynamic regime to confinement of an anisotropic particle distribution. The relative simplicity of an axisymmetric mirror means that this facility could be built either at a university or a national lab. In addition to being a device with which to answer physics questions such as those posed above, the plasma parameters would be within a factor of two of a practical fusion neutron source.

- ***Describe the impact of this research on plasma science and related disciplines and any potential for societal benefit***.

There is the potential for both scientific impact and societal benefit from a new research effort on plasma confinement in axisymmetric magnetic mirror devices. As a linear configuration, the magnetic mirror differs profoundly from toroidal configurations such as the tokamak and stellarator. Yet fundamentally plasma confinement is still provided by charged particles gyrating around magnetic field lines. Thus the mirror challenges our understanding of plasma confinement by a magnetic field, but still provides connection points to the more widely studied toroidal configurations. Our fusion science should encompass the mirror if our goal is to develop robust predictive capability.

Physics mechanisms active in astrophysical contexts are often difficult to replicate in the laboratory. A well-diagnosed magnetic mirror would provide an additional tool to access plasma conditions in which phenomena of space and astrophysical relevance could be studied.

The most likely near-term societal benefit from continued magnetic mirror development is application of the gas-dynamic configuration as high-flux steady-state neutron source.[9] Experiment has demonstrated that fast ions injected into this configuration slow down classically via Coulomb collisions with electrons, and do not exhibit anomalous loss. Design studies indicate that a practical neutron source would operate at an electron temperature of about 700 eV, similar to the *Te* recently demonstrated. Since the fast ions spend the majority of their time in the turning points near the mirror throats, two areas of maximum neutron flux are naturally produced. This feature, along with the cylindrical symmetry of the configuration, simplifies neutron sourcing and shielding. Immediate application of such a fusion neutron source would be materials testing and development. Other possible applications include neutron imaging, subcritical fission reactors, and nuclear waste processing.

Figures (Maximum 1 page)

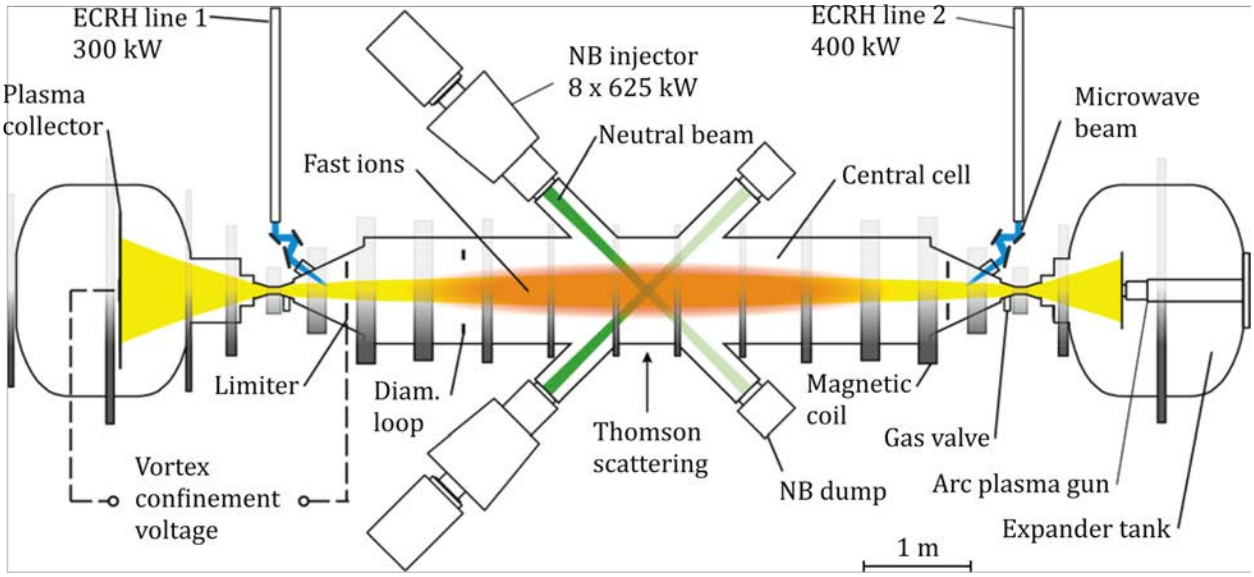

Fig. 1. Schematic outline of the GDT device.

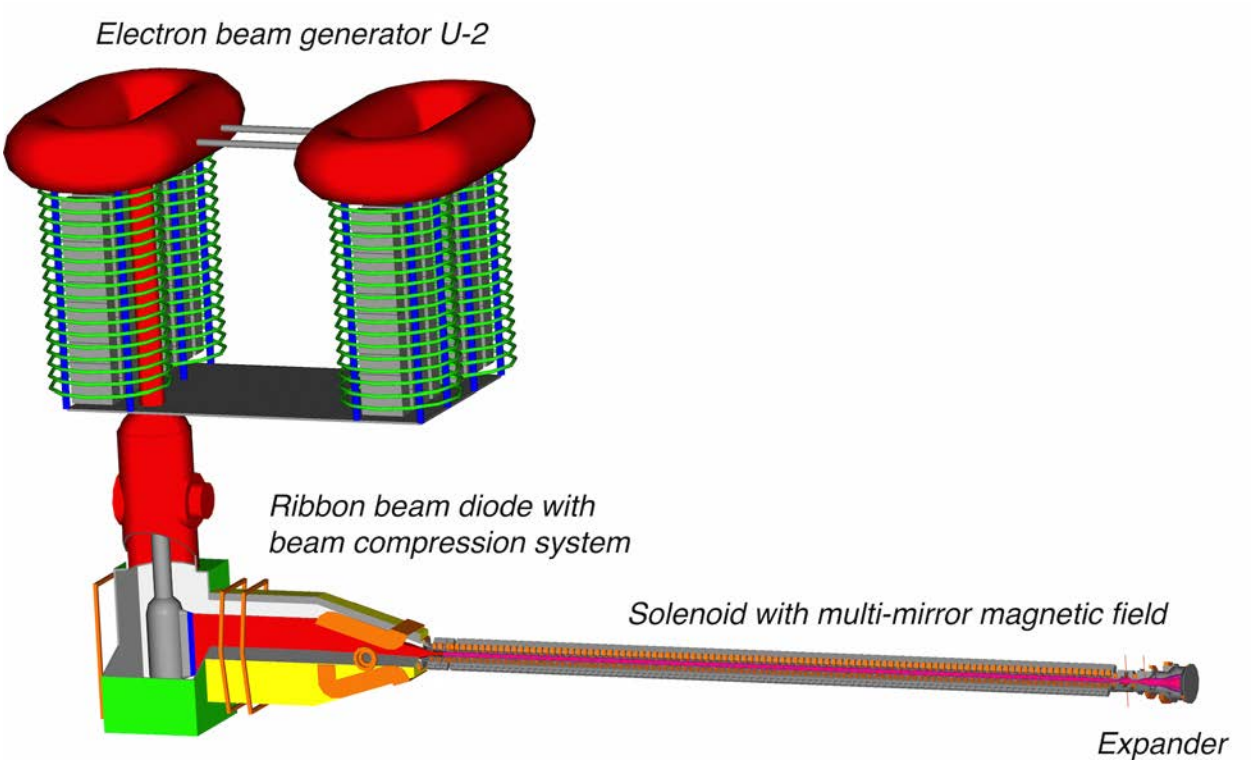

Fig. 2. Layout of the GOL-3 device.

References (maximum 1 page)

[1] P. A. Bagryansky, A. G. Shalashov, E. D. Gospodchikov, A. A. Lizunov, V. V. Maximov, V. V. Prikhodko, E. I. Soldatkina, A. L. Solomakhin, and D. V. Yakovlev, "Threefold Increase of the Bulk Electron Temperature of Plasma Discharges in a Magnetic Mirror Device," Phys. Rev. Lett. **114**, 205001 (2015); http://dx.doi.org/10.1103/PhysRevLett.114.205001

[2] P. A. Bagryansky, Yu. V. Kovalenko, V. Ya. Savkin, A. L. Solomakhin, and D. V. Yakovlev, "First results of an auxiliary electron cyclotron resonance heating experiment in the GDT magnetic mirror," Nucl. Fusion **54**, 082001 (2014); http://dx.doi.org/10.1088/0029-5515/54/8/082001

[3] A. A. Ivanov and V. V. Prikhodko, "Gas-dynamic trap: an overview of the concept and experimental results," Plasma Phys. Controlled Fusion **55**, 063001 (2013); http://dx.doi.org/10.1088/0741-3335/55/6/063001

[4] R. F. Post, "The magnetic mirror approach to fusion," Nucl. Fusion **27**, 1579 (1987); http://dx.doi.org/10.1088/0029-5515/27/10/001

[5] T. C. Simonen and R. Horton, "The highest energy confinement measured on TMX-U," Nucl. Fusion **29**, 1373 (1989); http://dx.doi.org/10.1088/0029-5515/29/8/012

[6] V. V. Mirnov and D. D. Ryutov, "Linear gasdynamic system for plasma confinement," Sov. Tech. Phys. Lett. **5**, 279 (1979).

[7] A. D. Beklemishev, P. A. Bagryansky, M. S. Chaschin, and E. I. Soldatkina, "Vortex Confinement of Plasmas in Symmetric Mirror Traps," Fusion Sci. Technol. **57**(4), 351 (2010).

[8] A. V. Burdakov, A. A. Ivanov, E. P. Kruglyakov, and A. D. Beklemishev, "Axially Symmetric Magnetic Mirrors: History of Development and Future Prospects," Fusion Sci. Technol. **63**(1T), 1 (2013); http://dx.doi.org/10.13182/FST13-1T28

[9] P. A. Bagryansky, A. A. Ivanov, E. P. Kruglyakov, A. M. Kudryavtsev, Yu. A. Tsidulko, A. V. Andriyash, A. L. Lukin, and Yu. N. Zouev, "Gas dynamic trap as high power 14 MeV neutron source," Fusion Eng. Des. **70**, 13 (2004); http://dx.doi.org/10.1016/j.fusengdes.2003.08.002