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AXISYMMETRIC MAGNETIC MIRROR APPLICATIONS – DIVERTER TEST STAND TO FUSION POWER PLANT

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Axisymmetric mirrors can be MHD-stabilized by end losses. Neutral-beam-sustained operation to β~0.6, and T_e~0.2 keV, with 5 ms 5 MW neutral beams on the Gas Dynamic Trap (GDT) has been demonstrated at the Budker Institute in Novosibirsk, Russia. Applications of this concept can reduce risks in the fusion program. A GDT-scale facility could test plasma-material interactions (PMI) at up to 400 MW/m^2 and 5 s pulse duration for diverter development. Extrapolation of the GDT to a Dynamic Trap Neutron Source, DTNS, provides a DT-fusion neutron flux of 2 MW/m^2 over 1 m^2, at a power-plant efficiency of Q ~ 0.07. (A DTNS enables development and testing of materials and sub-component structures, for fusion power plants, MFE or IFE. A DTNS functions regardless of whether the tested components work. These developments would reduce risks for a tokamak Fusion Nuclear Science Facility (FNSF)). Further extrapolation to 0.2 ≤ Q ≤ 10 single-cell or tandem mirror yields several fusion-fission hybrid applications. Further extension to a pure-fusion axisymmetric-tandem-mirror power plant, requires Q>10. Tandem mirrors demand the use of different stabilization techniques that are not dependent on out-flowing plasma, a number of which have been proposed, and could be experimentally tested on the GDT.

I. INTRODUCTION

ITER is to demonstrate the scientific and technical feasibility of magnetically-confined fusion energy.[1] To construct a DEMO fusion power plant, we require data from additional facilities.[2,3] The International Fusion Materials Irradiation Facility (IFMIF) is proposed to provide a high flux of ~14 MeV neutrons to irradiate small samples to qualify materials for DEMO.[4] It is compared with other fusion neutron sources in Table 1.

A Dynamic Trap Neutron Source (DTNS)[5] complements the IFMIF, and reduces risks, by removing the small uncertainties from neutron-spectrum conversion of dpa (displacements per atom) for materials damage; and He/dpa and H/dpa ratios. Dosimetry is simpler since the spectrum and flux don't depend on angle from a deuteron-beam axis but are invariant with azimuthal angle, vary slowly with axial position, and predictably with radius. A DTNS provides 100x more area for irradiating samples and developing low-activation materials for fusion. A similar availability, ≥70%, is required.

A Fusion Nuclear Science Facility (FNSF)[2,3,6,7] is needed to develop components for a DEMO facility. A DTNS[5,8] performs some functions of an FNSF while eliminating the risks of disruptions, and of high-power-density diverters. It can develop subcomponents for an FNSF, with reduced neutron damage to neutral beams, see Section II.B. Operating costs are reduced because all magnets can be superconducting. The DTNS is compared with FNSF requirements in Section II.B.1.

The major developments required are steady-state neutral beams, cryopumps with regeneration during full-power operation, and remote handling which are required for most FNSF as well as for DEMO, and are discussed in Section II.B.2.

We also suggest developing direct conversion of the residual ion beam, already demonstrated on a 2 A, 100 keV neutral beam,[9,10,11] in order to reduce the electrical power costs of operation, as discussed in Section II.B.3.

In this paper, we will discuss current Gas Dynamic Trap (GDT) operation[12,13] and direct extrapolations of the GDT. We will briefly discuss a diverter test stand, and discuss a neutron source application in greater detail; both applications are near term. A diverter test stand can use present GDT parameters, extending the pulse from 5 ms to 1-5 s.[14] A DTNS has the same plasma length, radius, and peak magnetic field as the GDT; the minimum magnetic field and neutral beam energy are increased by factors of 6 and 4 respectively, and the scaling predicts a

TABLE 1: Neutron source comparison

	IFMIF D+Li	DTNS D-T	FNSF (FDF/CTF)
Neutron power (MW)	0.1	2	100-300 30-160
Flux (MW/m^2)	≤8.5	2+	2-3 1-3
Availability	≥0.7	≥0.7	0.3
Area (m^2)	0.01	1	70 15
Tritium (kg/FPY)	0	0.1	~2-20 without breeding

factor of 4 increase in T_e.[5,15] Finally, we will briefly discuss further applications: a fusion-fission hybrid with Q~0.7 that is a small extrapolation from the GDT, and a pure fusion power plant that requires Q > 10 and is based on an axisymmetric tandem mirror.

II. AXISYMMETRIC MIRROR PERFORMANCE

The Dynamic Trap Neutron Source (DTNS) is an axisymmetric mirror concept based on the Gas Dynamic Trap (GDT) facility at the Budker Institute of Nuclear Physics (BINP) in Novosibirsk, Russia. The GDT uses neutral beam injection of hydrogen or deuterium to fuel hot-ion plasma that is imbedded in warm plasma fueled by gas injection.[12] The name, 'gas-dynamic trap' is based on the analogy to a container of gas with pinholes at the ends; the gas lifetime is inversely proportional to the area of the pinholes. Similarly, the GDT uses 'mirrors', high magnetic fields at either end, to squeeze the plasma flux tube to a small area. The warm plasma lifetime is determined by the thermal flow of isotropic warm plasma through this small area.

Operation of the GDT has demonstrated electron temperatures (T_e) exceeding 0.2 keV, and is consistent with theoretical predictions that anomalous electron heat losses are eliminated by expanding the magnetic field by more than the square root of the ion to electron mass ratio (i.e. ≥70 for DT).[15] This prevents secondary electrons from the end walls from reaching the hot plasma. The plasma beta (ratio of plasma pressure to magnetic field pressure) has reached 60%, more than sufficient for neutron source applications.[12,13]

Axisymmetric magnetic mirrors use only circular magnet coils. In the 1950's, plasmas in such facilities were discovered to be MHD unstable (the plasma would rapidly escape radially); but in recent years, a number of techniques have been invented to stabilize an axisymmetric geometry.[16] The GDT provides 'good curvature' outside the mirrors, the pressure of the escaping warm plasma there is sufficient to stabilize a hot ion plasma within the mirror cell. The neutral beams (NB) are injected at the midplane of the mirror cell, at an angle of 45 deg. Trapped hot ions from NB injection reflect at the ends, where the magnetic field is twice the midplane field, and are referred to as 'sloshing ions.'

Sloshing ions have been demonstrated to produce microstable plasmas.[17] Micro-instabilities are high-frequency (≥ion cyclotron frequency) oscillations caused by anisotropic or non-Maxwellian distributions of ions, or sometimes electrons, in a mirror. The instabilities decrease hot-ion lifetimes by scattering ions, those scattered to have most of their energy parallel to the magnetic field escape through the magnetic mirrors and are lost.

Micro-stability has been observed in the GDT, where the magnitude and spatial distribution of deuterium-deuterium produced neutrons agrees with calculated hot-ion distributions, limited by electron drag with the measured T_e, and classical ion-ion scattering; no increase in ion scattering due to micro-instabilities is observed.[12]

All magnetic mirrors have the advantages of inherently steady-state operation, diverter geometry with the possibility of large plasma-strike areas, and no significant plasma currents to drive disruptions.

Axisymmetry brings the additional advantages of (1) no neoclassical or resonant radial transport, which toroidal devices and non-axisymmetric mirrors are subject to. (2) Higher magnetic fields are achievable with circular coils, this enables a tandem mirror to achieve good plasma confinement without requiring thermal barriers; because high-field end cells can be smaller, so can be sustained with less neutral beam power than can larger, lower field cells. However, for a neutron source, a single cell with high mirror fields provides adequate performance, although tandem-mirrors could achieve similar performance with reduced neutral beam power and cost of operation.[18] (3) Construction and maintenance are simplified. Tritium-breeding, or other, blankets can be cylindrical.

GDT performance extrapolates to T_e = 0.8 keV in the DTNS,[5,18] which results in a fusion gain of Q = 0.07 and a fusion power of 2 MW. These values of Q and power are lower than a tokamak FNSF,[6] but have the strong advantage that tritium (T) consumption is only 0.1 kg/FPY (Full Power Year).[8] With such low T consumption, it can be purchased, and T-breeding is not required to fuel the DTNS. T-breeding blankets can therefore be developed on the DTNS, without the requirement that they immediately succeed in breeding.

II.A. PMI Facility

A GDT-scale facility can be a test stand for plasma-material interactions (PMI) and plasma-facing components (PFC), with power densities of up to 400 MW/m^2, relevant for reducing diverter risks.[14] In particular, there is interest in developing liquid lithium diverters to handle high power densities. With neutral beams injecting ~5 MW into magnetic fields of ~0.2 T in a GDT-like facility, one end can use magnetic field curvature or biased limiters to produce MHD stability, while the other end continues the peak magnetic field of 1-2 T out to the materials samples. The lack of expansion of the magnetic field at this end limits T_e to ~50-100 eV, rather than the ~200 eV achieved on the GDT with 5 MW of injected NBI.

We assume that half of the power goes to the stabilizer end, the other half to the PMI end. For a midplane radius of 0.1 m, and a peak magnetic field of 6× the midplane field we find the area there is 0.0314 m^2/5 = 0.0063 m^2, resulting in a power density of 400 MW/m^2.

A version of this with 1 s pulse durations could be built with 20 keV, 1 MW neutral beam systems[19] made by the Budker Institute for Tri-Alpha Energy, Inc.[20]

II.B. Dynamic Trap Neutron Source

For simplicity, we are proposing single-cell mirrors for applications as a neutron source for fusion materials and sub-component development (and for some fusion-fission hybrid applications). However, if experiments were to demonstrate an axisymmetric tandem mirror that was both MHD and micro stable, then enhancing the confinement by factors of several would significantly reduce the neutral beam power, hence the operating costs of a neutron source.[18] Such experiments could be done on the GDT, or a similar-scale facility, at relatively low cost.

The DTNS is shown in Fig. 1. Its requirements, performance, and issues are discussed elsewhere in greater detail.[5,8] The two ends could be used for different testing purposes: for example one end could test materials complementing the IFMIF, the other subcomponents complementing other FNSFs.[6] Subcomponent dimensions can be as large as 0.3-1 m along the axis and azimuth.

II.B.1. DTNS compared with FNSF requirements

The Fusion Program study report "Research Needs for Magnetic Fusion Energy Sciences" discusses what we must do in addition to ITER in order to build a DEMO to achieve commercialized fusion energy.[3] A DTNS can contribute to all five research themes:

1. It will have burning plasma that can be used for other purposes such as diagnostic development.

2. DTNS will create a predictable, steady-state plasma with a significant fusion power of 2 MW, although with Q ~0.07 it will not be high performance. With a design goal of ≥70% availability, it will greatly aid R&D for a DEMO. A DTNS could provide data on fusion system operation, fuel management, safety, reliability, availability, and maintainability needed to develop fusion energy. Over a several year period, it will provide a high neutron fluence of 5-20 MW-yr/m^2.

3. It can contribute to taming the plasma-materials interface with both neutrons and alphas that can bombard samples. As discussed in Section II.A, it can also produce high power densities to simulate the highest diverter heat loads, but at the expense of lowering T_e and decreasing the fusion power and neutron production.

4. It can contribute to harnessing fusion power: through developing materials and subcomponents including T-breeding blankets and heat recovery. It can demonstrate the feasibility of tritium self-sufficiency without requiring it.

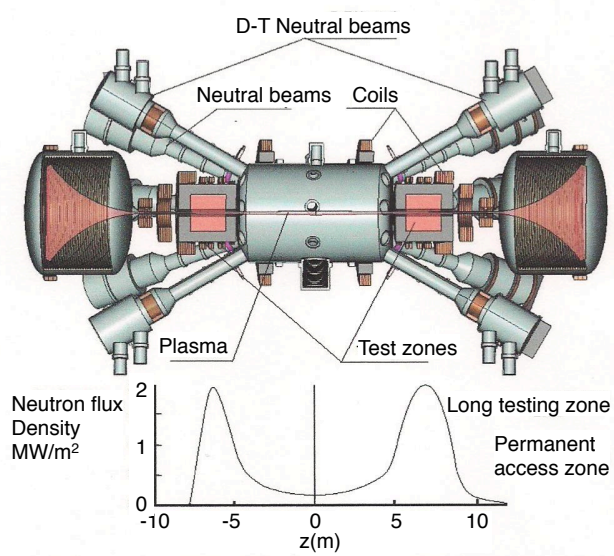

Fig. 1. DTNS showing major components, and neutron flux axial profile.

5. It can also contribute to optimizing the magnetic configuration, by providing a simpler alternative for driving fusion-fission hybrids, and perhaps pure fusion.

A DTNS has two major goals that align with the research thrusts discussed in Ref. 3:

Thrust 13: Establish the science and technology for fusion power extraction and tritium sustainability. This is one major thrust for a DTNS, which can test a number of variations for power extraction of high power process heat with production of electricity, and for tritium breeding, but can operate without requiring these to work.

Thrust 14: Develop the material science and technology needed to harness fusion power. This is the second major thrust for the DTNS, which offers many advantages. Like other FNSFs, it has an ITER-like neutron spectrum,[5] which makes it superior to IFMIF for developing low-activation materials. It also will be designed for an availability ≥70% (exceeding the 10-30% goal of an FNSF), which is required by the materials community for developing high-strength, high-temperature, radiation-resistant materials. Developing high availability aids in minimizing risk for DEMO.

A DTNS can also contribute to other research thrusts:

Thrust 1: Develop measurement techniques to understand and control burning plasmas. Many diagnostics could be tested on the DTNS. Others could have their resistance to neutrons and alphas tested.

Thrust 5: Expand the limits for controlling and sustaining fusion plasmas. The DTNS is designed to use positive-ion neutral beams because those work reliably today. It can use negative-ion neutral beams to reduce risks for ITER, or to support ITER commissioning.

Thrust 7: Exploit high-temperature superconductors and other magnet innovations to advance fusion research.

The DTNS uses all superconducting magnets, which are within the existing state-of-the-art.[21] Its axisymmetric geometry, high magnetic fields at the mirrors, lower magnetic fields through most of the mirror cell, and the moveable nature of magnets over the sample test volumes provide simple geometries, a range of performance, and ease of changing test magnets that qualify it as a magnet test stand for improving the state-of-the-art.

Thrust 10: Decode and advance the science and technology of plasma-surface interactions. Much of this can be studied with a GDT-scale facility. A DTNS-type facility can add neutron and alpha interactions.

Thrust 11: Improve power handling through engineering innovation. Direct conversion of residual ions from a neutral beam is one example.

The DTNS is designed to run steady state, with a goal of achieving availability exceeding 70%, which is judged necessary for materials development. Initial operation after commissioning is likely to achieve shorter periods, perhaps a few weeks at a time; limited by the weakest system, which could be neutral beam ion sources.

II.B.2. Technology Development for an FNSF

The major technology development issues for a DTNS are shared with tokamak FNSFs: steady-state neutral beams, cryopumps that can be recycled during full power operation, and remote handling. The Long-Pulse Source neutral beams,[22] developed for DIII-D and TFTR, are adequate for steady-state operation; but lifetimes of hot-filament cathodes are likely to be much less than a year (extrapolating from many short pulses with very few filament failures). Development is also needed to extend lifetimes, of accelerator electrodes to a year.

Other developments required include beam dumps; which can be, for example, hypervapotrons or swirl tubes, both of which have been used extensively in the fusion program, if a water-cooling system can be made compatible with tritium operation. Preferably, fusion will use a different coolant that doesn't so readily become tritiated, but then more extensive development is needed, for which the DTNS could be an excellent test stand.

Neutron damage to neutral beam sources in the DTNS will be down a factor of 10, since the neutron flux peaks at the ends of the DTNS,[5] where the materials and sub-component samples are located, but is a factor of ten lower in the center, where the neutral beams inject at 30-45 deg. from the axis. The availability goal for materials testing is >70%, which is greater than the 10-30% envisioned for FNSFs, increasing the neutron flux by factors of 2-7. These factors make the DTNS a good facility for developing steady-state neutral beams for a fusion environment: if beams are damaged by neutrons, they will provide materials and subcomponent data to 10 times higher fluence in this facility than in a tokamak FNSF. DTNS operation would allow neutral beams to be developed to higher reliability and longer lifetime for subsequent tokamak-based FNSFs.

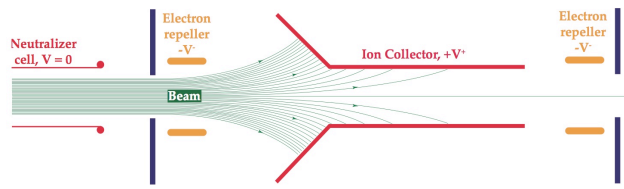

Fig. 2. A schematic ion-beam direct converter. In practice the ion collector has a Venetian-blind geometry to allow faster pumping of gas from recombination of collected ions.

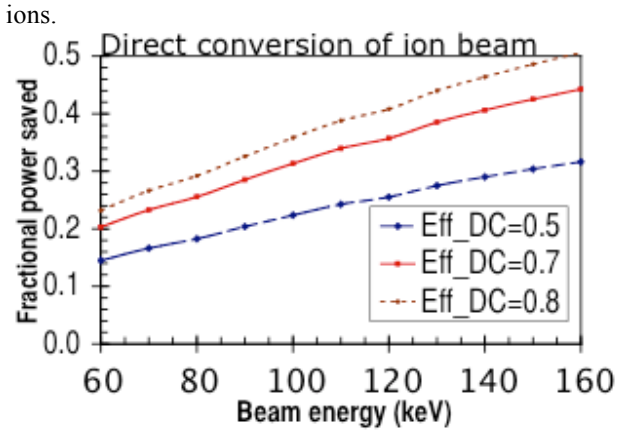

Fig. 3. The fractional power savings versus deuterium neutral beam energy for three possible efficiencies of direct conversion of the residual ion beam.

II.B.3. Direct conversion of ion energy

A fraction of a neutral beam remains as an ion beam, which is currently disposed of on a beam dump. An alternative is to recover the ion energy, as is shown in Fig. 2, and which has been demonstrated with a 2 A 100 keV neutral beam.[9] It was found that as much as f_{DC} = 70% of the energy in the ion component of the beam could be recovered, 80% or more is possible if the neutral beam consists of nearly 100% full energy atoms from neutralization of accelerated atomic ions. (Present day neutral beams have ~0.8 full-energy atoms, with the remainder at half and third energy from accelerated molecular ions that breakup in the neutralizer.) The direct-converter design here can be implemented as an upgrade or deleted from an operating facility. Of course, if a direct converter is removed, then a bending magnet and ion dump must be provided.

The ion beam component can be large: for 80 keV deuteron beams, f_+~0.4 of the beam is not neutralized, at 120 keV, this increases to f_+~0.6 of the beam. In terms of the neutralizer efficiency, f_0, $f_0 + f_+ = 1$. The fractional power savings Δf_+ are given by $\Delta f_+ = f_+ f_{DC}$, and are plotted in Fig. 3 versus deuterium neutral beam energy, for f_{DC} = 0.5, 0.7, and 0.8. For a facility injecting 30 MW

of neutral beam into a plasma, the cost savings total $5-10 M/FPY, using a cost-of-electricity of $0.1/kW hr; this translates to power costs of ~$1M/(MW-FPY). At this rate, one would recoup development costs quickly.

Direct conversion of end-loss ions has also been done;[10] but at the low energies of these ions in a DTNS, large charge-exchange cross sections convert a high fraction of these ions to neutrals; so that the recovery efficiency is low.[11]

II.C. FUSION-FISSION HYBRID

Moir has evaluated the fusion performance, Q, required for each of several fusion-fission hybrid applications, as he discussed at this conference.[21] The lowest requirement is to burn minor actinides, for which we need Q≥0.2; to burn transuranics, we need Q≥1; to produce fuel in a fast-fission blanket, we need Q≥2; and for fission-suppressed fuel production, we need Q≥4.

A simple axisymmetric single-cell mirror was evaluated to yield Q~0.7, which is adequate for the first application. It looks like an expanded GDT, but would use line-tying to reduce MHD instability growth rates to where other techniques, such as feedback, could provide stability.[23] It is considered low risk, particularly since the stability could be tested in the GDT at low cost. Direct conversion of ion end-loss can increase the net electrical production efficiency, thereby increasing the effective Q, if charge-exchange of energetic end-loss ions can be kept low in the end expansion tanks. Direct conversion is also applicable to the residual ions in neutral beams as discussed in Section II.B.3. Direct conversion of end-losses is more effective for higher energy neutral beam injection, and higher electron temperature because charge exchange cross sections decrease rapidly for ion energies exceeding 40 keV per nucleon.[11]

Axisymmetric tandem mirrors could function in all of the hybrid areas above, if they can be stabilized. The risk of instability is greater for low-end-loss tandems; but the costs would be low to mitigate the risk by testing MHD and micro-stability on the GDT, to determine the adequacy of the proposed stabilization mechanisms.[15]

II.D. PURE FUSION

An axisymmetric tandem mirror, if demonstrated to be stable as discussed above, could make an attractive fusion power system. In addition to the strengths of axisymmetric mirrors, discussed at the beginning of Section II, it could avoid most of the fusion material issues and development by using thick-liquid walls of flibe surrounding the plasma.[24]

Liquid walls offer significant advantages:

1. A liquid is immune to the major damage mechanism in a solid, displacements per atom (dpa), because atoms/molecules move freely in liquids, whereas solid first walls need to survive for 100-200 dpa to provide several year lifetimes before replacement. Helium and hydrogen generation by neutrons lead to embrittlement and disintegration of solids, but these gases are free to leave liquids.
2. Activation is also less of an issue with flibe, whose constituents – fluorine, lithium, and beryllium – are all low-Z elements, which don't become highly activated.

Liquid walls also have some issues:

1. They have a high vapor pressure, in the 0.1 Pa range that can cool and erode the outside of a plasma. One solution, in a mirror, is to provide a low temperature (~10-30 eV) flowing plasma 'halo' that is thick enough to ionize and exhaust flibe vapor at the plasma edge before it reaches the hot core plasma.
2. Wall stabilization mechanisms do not work with molten salt wall because of its low electrical conductivity, plus low frequency instabilities could push a liquid wall out of position.

An initial computational study of power and particle balance for an axisymmetric tandem mirror was successful in finding solutions for Q≤10 (Ref. 25). An economical fusion power plant should have Q≥20. The studies to date did not include direct conversion of either neutral beam ion components or of ion end losses. Direct conversion of end losses, with an efficiency of only 0.5 would allow a Q of 10 to be as effective as a Q of 20 without direct conversion, and higher direct-conversion efficiencies have been achieved in experiments and modeling. Also, the effort to date is insufficient to provide confidence that Q = 10 is the upper limit for confinement, higher Q solutions may be found.[25,26]

III. CONCLUSIONS

We have discussed how a magnetic mirror can provide a low-risk plasma-materials test stand at present GDT performance levels. A neutron source, DTNS, based on a simple extrapolation of the successful GDT facility, can be used to develop materials and subcomponents for fusion energy power plants, but does not have the quandary of needing those subcomponents to work for the DTNS to function. DTNS capabilities include many of the requirements of both an IFMIF and a FNSF, and could significantly reduce risks for a subsequent tokamak FNSF and a DEMO. Higher-plasma-confinement applications involve more risk, but inexpensive experiments on the GDT could evaluate and mitigate the risk. These applications include a driver for a fusion-fission hybrid and a pure fusion axisymmetric tandem mirror. These eliminate some severe risks of present approaches if their MHD and micro-stability uncertainties are resolved.

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