A DT Neutron Source for Fusion Materials Development

T.C. Simonen 1), A.A. Ivanov 2), A.W. Molvik 3), D.D. Ryutov 3)

1.) University of California. Berkeley, California, USA
2) Budker Institute of Nuclear Physics, Novosibirsk, Russia
3) LLNL, Livermore, California, USA

e-mail contact of main author: simonen42@yahoo.com

Abstract. Fusion energy will require materials to withstand the harsh bombardment of energetic fusion neutrons. The 2 MW Deuterium-Tritium Dynamic-Trap Neutron Source (DTNS) described here would supply a 14 MeV neutron flux of 2 MW/m^2 over an area of a square meter for material and subcomponent evaluation and qualification. DTNS is based on experimental results from the Gas Dynamic Trap (GDT) in Novosibirsk Russia. Neutrons are produced by injecting energetic ions that are trapped between axisymmetric magnetic mirrors. The energetic ions are imbedded in warm plasma that provides both macro- and micro-stability. The recent GDT achievement of 60% beta now provides a basis for extrapolation to a DTNS design, of the same size and gyro radius as GDT, by increasing the neutral beam energy to 80 keV and the magnetic field to 1.2 Tesla. This paper describes the features of DTNS, physics scaling, methodology and engineering features.

1. Introduction

The development of fusion energy requires the development of materials and technology capable of withstanding the harsh fusion nuclear environment for many years. This paper explores the possibility of developing a facility to test and qualify materials and blanket sub-module units in a continuous high flux of fusion Deuterium-Tritium 14 MeV neutrons. The 2 MW Deuterium-Tritium Dynamic-Trap Neutron Source (DTNS) described would supply a neutron flux of 2 MW/m^2 over an area of 1 m^2 for material and subcomponent evaluation and qualification.

Neutron-material interactions on a small scale are being investigated in fission reactors and in accelerator driven neutron sources which do not generate a true 14 MeV fusion neutron spectrum. Thus there is a need for a larger scale 14 MeV DT fusion neutron source. Three general types have been proposed: a rotating target neutron source (RTNS) [1], a linear DTNS [2-4] and a tokamak based Fusion Nuclear Science Facility (FNSF) [5,6]. The characteristic features of these concepts are given in Table I. The key differences are the neutron flux, test area available, and tritium consumption per full power year (FPY). The neutron flux and test area of RTNS is extremely small. DTNS has higher neutron flux and larger test area, sufficient to test blanket sub-module units. DTNS has low tritium consumption, thus does not require tritium breeding. FNSF has large area enabling full blanket module development, but these blankets must produce the tritium needed.

Table I. Typical Characteristics of 14 MeV Neutron Source Concepts.

	RTNS	DTNS	FNSF
Neutron Power (MW)	0.00002	2	200
Neutron Flux (MW/m2)	0.2	2	2
Test Area (m^2)	0.0001	1	70
Tritium Consumption (kg/FPY)	~0	0.14	14

A key physics difference between the GDT [2-4] and toroidal concepts is that the magnets are a linear array of circular (axisymmetric) magnets in a magnetic mirror configuration, as illustrated in Fig. 1. Because of the linear axisymmetric configuration, there is no toroidal curvature inducing neoclassical banana radial transport and driving drift-wave instabilities. Furthermore, circular coils can be built with higher magnetic field, mirror ratio and smaller size than minimum-B magnets popular in the 1980's [7, 8]. Therefore the magnetic mirror ratio can be larger (~20) than minimum-B systems (~2). Energy losses are primarily axial. This paper considers a DTNS design with magnetic mirror ratio 17 and length 7 m.

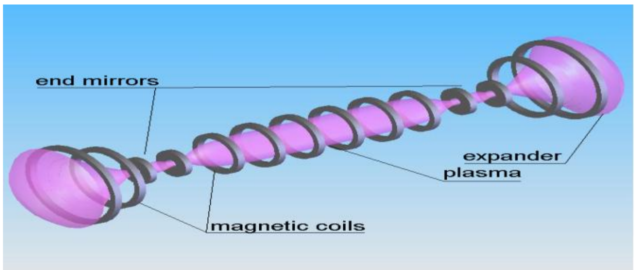

Figure 1 An illustration of an axisymmetric magnetic mirror configuration

An advantage of toroidal systems is that the neutron production efficiency (Q) increases with larger radius. This however leads to a large system. In contrast, the Q of a linear system increases with high mirror ratio, so is constrained by magnet technology. As a result, the Q of a mirror neutron source tends to be lower than a toroidal system. While higher Q is desirable, there are several attractive features of mirror systems. The smaller size and lower fusion power means that tritium burn-up is less so tritium breeding within the fusion neutron source is not required. The relative simplicity of a linear system also insures lower construction and operating cost as well as faster and easier construction and maintenance. Engineering constraints [9] are also eased due to the lack of plasma currents in a mirror system so that high pressure beta limits are reached with steady exhaust power spread over a large area beyond the magnet system, rather than abrupt disruptions and giant edge modes which produce intense mechanical forces and localized heat loads within the vacuum vessel.

2. Highlights of GDT Experimental Achievements

The achievement of 60% beta plasma in GDT at the Budker Institute of Nuclear Physics in Novosibirsk Russia sparked interest in this confinement configuration as a potential neutron source for testing and validation of fusion system materials and fusion blanket sub-module units. In contrast to previous magnetic mirror concepts the GDT configuration employs simple circular magnet coils (see Fig. 1) which enables higher magnetic fields, higher mirror ratio and smaller size than complex minimum-B magnet configurations employed in the 1980's. In this paper we extend GDT to a DTNS design with the same physical size and gyro radius to minimize physics extrapolation uncertainties. DTNS would operate with higher energy and power neutral beams and higher magnetic field than GDT.

Recent GDT experimental results have been published [3,10] and not repeated here. GDT (illustrated in Fig. 2) employs up to 5 MW of 20 keV neutral beam power injected at 45 degrees into a 0.3 T solenoid with a mirror ratio up to 30. The plasma approaches steady state in the 5 ms experiment duration. The DD neutron flux peaks at the turning points by a factor of 5 relative to the mid-plane flux. The plasma beta is determined from a motional Stark effect diagnostic. Relative to the vacuum field the local plasma beta reaches 60%. Relative to the local beta-depressed magnetic field the beta is near 100%. In accordance with MHD theory the plasma beta appears to be limited by ballooning modes which do not trigger undesirable intense pulses of plasma energy, but rather a continuous saturated energy flow. The electron temperature reaches 250 eV consistent with classical modeling. This modeling predicts the 750 eV required to achieve 2 MW/m2 in DTNS. At the present 250 eV level of the current GDT device, the neutron flux with 80 keV neutral beam injection would be about 0.5 MW/m^2, similar to that projected for ITER

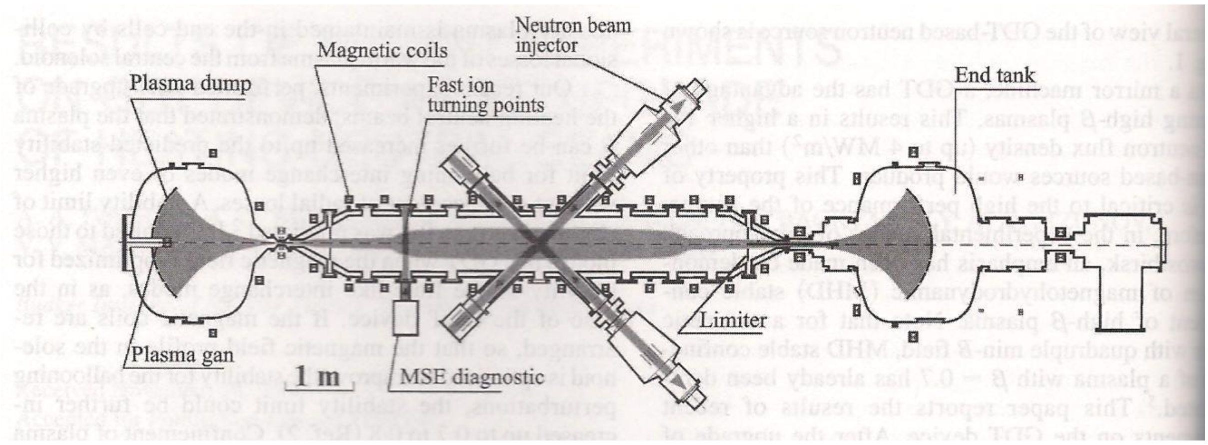

Fig. 2. GDT layout illustrating skew neutral beam injection and large end expanders

3. Physics Issues

Critical physics issues associated with extrapolating to DTNS include MHD stability of the axisymmetric system, micro-stability of the neutral beam driven system, and electron temperature of the open system.

3.1.MHD Stability

It was discovered in the 1960's that an axisymmetric mirror, (a simple mirror) is MHD unstable. This shifted research emphasis to minimum-B mirrors with everywhere good magnetic curvature. More recently several methods to achieve axisymmetric MHD stability have been proposed and demonstrated as summarized in Ref [12] and references there in. These methods are listed below. Most remarkable is the achievement of 60% beta , with classical confinement in the GDT device [10] and 30% beta in the University of Wisconsin Phaedrus device using ponderomotive rf stabilization [13]. Other noteworthy experiments include the Kyoto HIEI, UCLA SURMAC and Korea Hanbit. In this paper we extend the GDT technique of applied radial electric shear to higher magnetic field and plasma temperature in the DTNS device which has the same physical and gyro-radius size as GDT. Finite-Larmor-Radius (FLR) and plasma exhaust may play a role in GDT and would be effective in DTNS.

MHD Stabilization Methods of Axisymmetric Mirrors include the following:

- Expansion plasma pressure: End loss in good curvature region
- Cusp anchor: Good curvature in end cusps
- Divertor anchor: Good curvature of axisymmetric divertor
- Vortex stabilization: Sheared azimuthal plasma flow short-circuits of MHD modes
- Nonparaxial mirror: Sharp magnetic curvature
- Line tying: Currents to end walls short out electric fields of MHD modes
- Wall stabilization : Like in tokamak with feedback to control slow growing modes
- Ponderomotive: Radio-frequency power produces ponderomotive stabilizing force
- Dynamic Stabilization: ECH pulses at rate exceeding MHD growth rate
- Plasma rotation: Rapid plasma rotation provides centrifugal force
- Kinetic stabilization: Injected ions in good curvature exhaust region
- End-wall funnel :Electron compressibility forces plasma to remain centered
- Surface Stabilization: Localized cusp magnetic fields at plasma surface
- Finite Larmor Radius Stabilization

3.2. Micro-stability

Micro-instabilities of energetic ions injected by neutral beams can plague mirror systems. The GDT concept mitigates deleterious micro-instabilities by a number of methods:.

- The high mirror ratio of GDT reduces the size of the ion loss-cone
- At low electron temperature (~1% of beam energy) the loss-cone is minimized
- The presence of a ~50% warm plasma component fills the residual loss cone
- Skew neutral beam injection mitigates Alfven Ion Cyclotron (AIC) instabilities
- Ions reflect at steep magnetic gradient inhibiting global modes

Fluctuations in GDT are weak. The hot ion confinement is consistent with classical electron drag also indicating the lack of virulent instabilities. Figure 3 is the Monte-Carlo calculated monotonic energy distribution, with only a small loss cone, is expected to be stable [14].

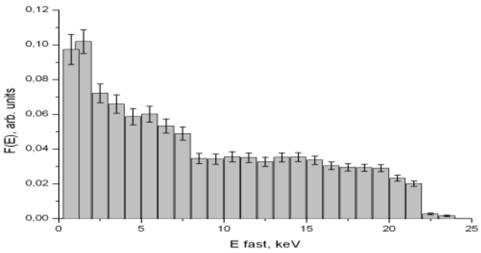

Figure 3. A Monte Carlo calculation of the GDT ion energy distribution function.

.

3.3. Electron Temperature

A widespread concern about open magnetic systems is axial electron energy transport with the consequence of low electron temperature which saps energy from the hot ions that produce the fusion neutrons. Since the 1980's improved understanding of electron energy transport has been developed [15]. The key requirement for inhibiting axial electron energy transport is to expand the magnetic field before field lines impinge on the end wall. This expansion (from the mirror to end wall) must exceed the square root of the ratio of the ion-to-electron mass ratio to insure that secondary electrons from the end wall can't penetrate into the hot plasma. In GDT this ratio is typically ~100. In addition the density of neutrals in the end region must be maintained sufficiently low in order to limit their ionization which introduces cold electrons. GDT data indicates that the electron temperature follows classical scaling and is unequivocally above that predicted by end thermal conduction [16].

4. Extrapolation ot GDT Results to DTNS

There are a wide range of parameters available for the design of a DTNS. Here we select a design of the same size and gyro radius as GDT in order to minimize uncertainties in extrapolating physics performance. Figure 4 illustrates a schematic of a potential DTNS configuration [10] with 17 T field magnetic mirror coils at the ends of a 1.0 T solenoid.

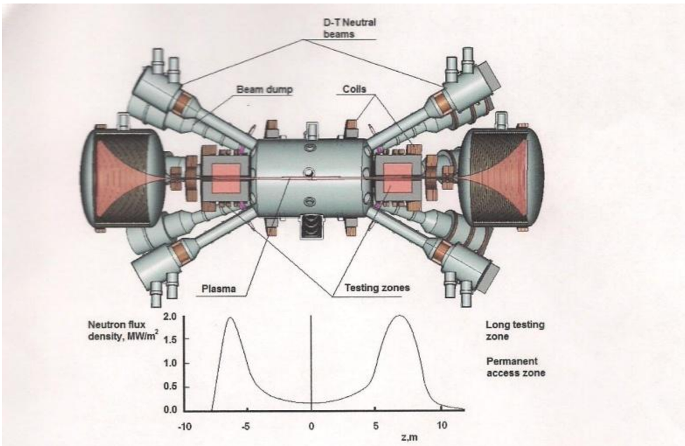

Fig. 4. Overview of a DTNS with the axial magnetic field profile.

Neutral beams (40 MW at 80 keV) inject skew to the magnetic field axis. The injected ions bounce between the mirror reflection locations. As the ions reflect they accumulate at the turning points producing zones of intense neutron production (2 MW/m^2), where material samples and blanket subcomponents can be located for evaluation [3,4].

This design produces 2 MW of neutron power extrapolated from GDT experimental results with classical collisional confinement. A summary of parameters is indicated in Table II. (TNS is a Tandem Mirror Neutron Source discussed later)

Table II. Extrapolation to DTNS with the same size and ion gyro-radius as GDT.

(All concepts have 7 m mirror-to-mirror length, 15 cm plasma radius, 3 cm mean ion-gyro-radius, mirror ratio of 17, and 60% beta.)

	GDT	DTNS	TNS
Mirror-to-mirror Length, m	7	7	7
Central Magnetic Field, B_o, Tesla	0.3	1.0	1.0
Mirror Magnetic Field, B_m, Tesla	5	17	20
End Wall Magnetic Field, B_w, Tesla	0.01	0.03	0.03
Neutral beam energy, E_b, keV	20	80	80
Neutral beam power, P_b, MW	5	40	20
Electron Temperature, T_e, keV	0.25	0.75	2.0
Neutron Flux, MW/m^2	0.5*	2.0	2.0

*If operated with tritium 80 keV neutral beam injectors

For the 0.25 keV electron temperature achieved in GDT, a neutron flux of 0.5 MW/m^2 could be achieved, near that projected for ITER. To achieve 2 MW/m^2 in DTNS requires 40 MW of 80 keV neutral beam injection. . For neutral beam energies between 60 and 110 keV the DTNS neutron power flux can be estimated approximately as [3]

$$\text{Neutron Flux (MW/m}^2) = 2.5\ \text{Te(keV)}.$$

5. A Tandem-mirror Neutron Source (TNS)

A limiting aspect of the DTNS concept is the outflow of collisional warm plasma used to provide micro-stability to the neutral beam injected energetic ions that produce the neutrons. This plasma outflow is the major power drain holding down the electron temperature. Since the electrons cool the energetic ions, the electron temperature determines the neutral beam power needed to produce a given neutron flux.

The tandem mirror electrostatic end-plug concept can reduce the outflow of warm plasma by creating positive potential peaks to confine warm ions.. However sustaining the high end-plug plasma density requires neutral beam power. We use here, as a basis of our considerations, the GDT-SHIP concept and experimental data from the LLNL TMX experiment [16]. We use the magnetic field axial profile illustrated in Fig. 6. The central field B_o is 1.0 T, the peak mirror field B_m is 20T and the plug minimum field B_p is 7 T.

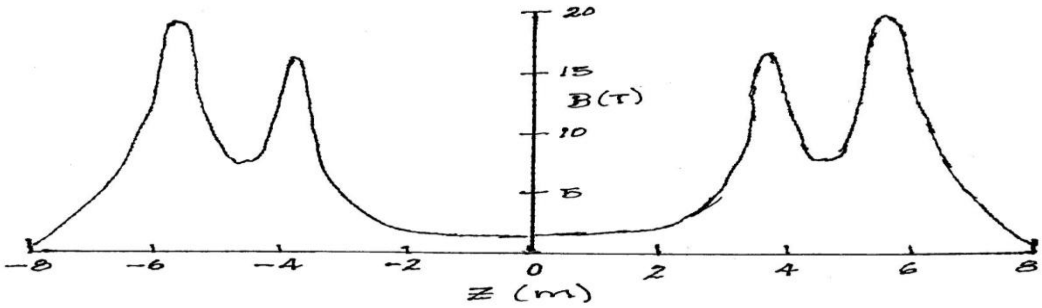

Figure 5 . An example of a TNS axial magnetic profile.

Here again we consider a TNS central cell design that is the same physical size and gyro-radius as the GDT experiment with performance similar to that routinely achieved in TMX. Just as in DTNS, TNS would utilize 80 keV neutral beams and a central magnetic field of 1.0 to match the GDT ion gyro-radius. To maintain a mirror ratio similar to GDT, the peak field is B_m = 20 T. The plug minimum field is chosen to be B_m = 7 T so the plug can sustain a high-density plasma with a modest plasma beta to minimize Alfven Ion Cyclotron (AIC) fluctuations. The imbalance illustrated in Fig. 5 mirror peaks helps provide end cell microstability. Finally, a mirror ratio of 3 (rather than 2) reduces the plasma potential ($5T_e/(R-1)$) that expels low energy ions which stabilize micro-instabilities.

Based on TMX data [16], the ratio of plug to central density is taken as $n_p/n_c = 4$, a routinely achieved value. Higher values are possible but tend to limit the penetration of the warm plasma to the plug region needed to suppress DCLC fluctuations. A 4-fold reduction in plasma outflow enables the electron temperature to rise to 2 keV. To sustain the neutron production at a level of 2 MW/m^2 requires a neutral beam power of 20 MW (10 MW in the center cell and 5 MW in each end-cell). This reduces the total heating power by a fact of 2 (relative to DTNS) which more than compensates for the cost of a second high field mirror coil at each end. This TNS concept is being developed in the SHIP [17] configuration of the GDT facility. Besides the physics issues describe above, one needs to evaluate the possibility of trapped particle modes and the accumulation of alpha exhaust.

6. Summary

We have described a design concept for a 14 MeV fusion neutron source which is capable of testing and validating materials and blanket concepts at levels relevant to a DEMO following successful operation of ITER. These results could precede ITER DT operation at neutron fluxes exceeding those of ITER and on an accelerated time scale. While less capable than a toroidal neutron source, DTNS construction, operating and maintenance costs would be significantly less. The experimental data base is limited relative to toroidal concepts but the scaling from the GDT is based on first principles classical models and the engineering features are attractive. DTNS would be a step toward a possible axisymmetric mirror as a driver for a fusion-fission hybrid [14]. The knowledge gained in DTNS material testing, tritium handling and tritium retention minimization would be applicable to a wide range of fusion concepts.

7. Acknowledgements

The authors acknowledge helpful discussions with P. Bagryansky, A. Anikeev, V. Prikhodko, A. Beklemishev, K. Noack and the Mirror Study Group.

8.References

1. J. C. DAVIS ,et al., "RTNS-II Neutron Sources: Status Report," IEEE Transactions on Nuclear Science, **NS-26:3**, (1979) 3058.
2. V.V. MIRNOVand D. D. RYUTOV, "Linear Gas-DynamicSystem for Plasma Confinement," *Sov. Tech. Phys. Lett.*, **5**,(1979) 279.
3. P.A. BAGRYANSKY et al., "Gas Dynamic Trap as High Power 14 MeV Neutron Source", Fusion Eng. Des., **70**, (2004) 13.
4. U. FISCHER, A. MOESLANG, A.A. IVANOV, Fusion Engr. and Design, 48, (2000), 307.
5. A.M. GAROFALO, et al. "Mission and Overview of a Fusion Development Facility" IEEE Trans. Plasma Science **38** (2010) 461.
6. Y.K.M. PENG et al., "A Component Test Facility Based on the Spherical Tokamak". Plasma Phys. Control. Fusion **47** (2005) 3263.
7. P. KOMAREK AND G.L. KULCINSKI, "A comparison of th key features of tandem mirror technology test facilities" Nuclear Eng. and Design/Fusion **2** (1985) 193.
8. F.H. COENSGEN et. al, "High-Performance Beam-Plasma Neutron Sources for Fusion Materials Development", Nuclear Sci. and Tech.**106** (1990) 138.
9. A.W. MOLVIK et al., "A gas dynamic trap neutron source for fusion material and subcomponent testing" Fusion Science and Technology **57**, (2010) 369.
10. A.A. IVANOV et al., "Results of recent experiments on GDT device after upgrade of heating neutral beams", Fus. Sci. & Tech., **57** (2010) 320.
11. T.C. SIMONEN, "Development and applications of axisymmetric magnetic mirror concepts" Fus. Sci. & Tech., **57** (2010) 305.
12. .N. HERSHKOWITZ et al., "Mirror Devices," *Nucl. Fusion*,**30** (1990) 1761.
13. A. V. ANIKEEV and K. NOACK, private communication
14.. D.D. RYUTOV et. al, "Axisymmetric Mirror as a Driver for a Fusion-Fission Hybrid: Physics Issues" J. Fusion Energy DOI 10.1007/s10894-010-9328-5, 5 September 2010
15. P.A.. BAGRYANSKY, to be published.
16. T.C. SIMONEN, "Experimental Progress in Magnetic-Mirror Fusion Research" Proc. IEEE **69** (1981) 939.
17. P.A. BAGRYANSKY, et. al, "First Results from SHIP Experiment" Trans. of Fusion Science and Technology **47** (2005) 59.