DEVELOPMENT OF A HIGH-FLUX FUSION NEUTRON SOURCE USING RECENT ADVANCES IN TECHNOLOGY

On a path to fusion energy

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Abstract

Simple mirror magnetic traps such as the Gas Dynamic Trap configuration have the potential to be a cost effective DT neutron sources for fusion materials and subcomponent testing. The principle is to use a warm plasma in a simple mirror with a non-thermal fast ion tail that is confined long enough for useful neutron production. Before a full scale DT test facility can be built, several physics issues should be addressed to retire risk and design issues. Here we consider the impact of recent development in high field magnets on the simple mirror path to fusion and explore how high field magnets may allow for compact and low capital cost neutron sources. Along the GDT line (long skinny mirrors) the new generation of high field magnets provides higher fields and mirror ratios than previously available. We have performed neutron yield ca using the CQL3D Fokker-Plank code to model neutral beam and high harmonic fast wave heating in a proof-of-principle GDT using new high temperature superconductors. Thinking beyond the paraxial GDT, the new high field magnets may also allow for more innovative non-paraxial geometries such as Ryutov’s short-fat mirror. We present preliminary equilibrium calculations and perform a stability analysis for m=1 and ballooning modes in this geometry. Modelling of the fast ions suggests that sloshing ions may both provide greater MHD stability by turning in good curvature regions but also potentially self-plug the trap through high fast ion densities at the turning points.

1. INTRODUCTION

Neutron sources are extremely valuable but costly to build. There are many commercial applications for neutrons, including neutron radiography, neutron diffraction for residual stress analysis, semiconductor doping, medical isotope production, and fission actinide transmutation. There are also academic research applications including fusion and fission reactor materials testing, neutron activation analysis, biological imaging, and protein structure determination. Today, these markets are served by nuclear fission reactors and spallation neutron sources. Both of these technologies require massive facilities that are extremely expensive to build and maintain. Fission reactors also face severe regulatory challenges in the US, causing shutdowns of some of the few remaining facilities that provide neutron irradiations services.

Magnetic confinement of high-energy ions fusing with a confined plasma-target could yield the reaction rates needed for a high-flux fusion neutron source for materials testing with good efficiency. DT Neutron sources producing 14 MeV neutrons have evolved from rotating target systems in which a deuterium beam strikes a tritiated and cooled target plate into DT gas-target sources now being developed for medical isotope production[1] which could also be used for materials testing, but only at fluences marginally large enough for future DEMO applications. A higher fluence alternative would be the accelerator-based neutron sources such as in which a 40 MeV deuterium beam strikes a lithium target, generating a neutron spectrum that would mimic the DT 14 MeV neutron spectrum. These are embodied by the DONES and IFMIF projects. A third alternative is the GDT trap proposed by Ryutov, et al that would utilize high energy neutral beams that are ionized and trapped in a warm background plasma. The ions would be trapped for a slowing down time in a magnetic field and collocated with a confined target plasma, allowing a much greater probability for fusion reactions. Its long been known that such a non-thermal systems can perform with high efficiency Q~1 if non-thermal ions are sufficiently confined.

The GDT approach also offers a path towards other nuclear testing beyond a simple study of materials damage---and may be a short cut to component testing such as that needed for blankets. It has very distinct advantages compared to tokamak-based nuclear science facilities such as FNSF. The tokamak physics is not yet ready for steady-state operation and the tritium requirements are overwhelming, requiring breeding from day one. On the other hand, recent experiments using the simple magnetic mirror geometry of the Gas Dynamic Trap (GDT) have demonstrated plasma confinement and stability close to the physical limits allowed by charged particle interactions,[3,4] the GDT has easy-to-build circular and planar magnet coils with inherent capability for steady-state operation, and materials/component test facilities have been designed with low tritium demands and fusion neutron fluences/fluxes that are adequate for materials and subcomponent testing [1,2]. Neutronics calculations show large test volumes capable of generating the 20 dpa/yr from a proper DT neutron spectrum that is needed for testing nuclear materials. It also appears possible to jump start research on tritium breeding blankets and begin addressing critical subcomponent testing.

The GDT physics results are game changing: The Russian GDT device at Novosibirsk has (1) demonstrated plasma stability for axisymmetric mirrors using both end expanders and vortex stabilization, (2) high fast ion beta to maximize neutron production in a given magnetic field, and (3) sufficient electron thermal confinement that is deemed critical for minimizing ion energy loss due to collisions with electrons. Notably, a record high electron temperature of 1 keV has been set—is this the equivalent of the T-3 tokamak results in 60s?

At this stage, the neutron production in the Russian GDT is limited by its low magnetic field, short-pulse neutral hydrogen beam injectors, and the low energy beams (~20 keV). The major steps needed to complete the development of GDT are to increase the magnetic field, increase the energy of the fast ions, demonstrate a steady-state energetic ion source, and demonstrate steady-state operation of a GDT plasma. A future nuclear device would also require optimization of the plasma-facing materials, sample-volume exposure geometry, and techniques for handling/reprocessing tritium.

There are also technological developments from the past decade that makes the GDT (and mirrors in general) worth revisiting. The first is that practical high-temperature REBCO tape superconductors, when operated at very low temperature, are capable of producing steady-state magnetic field much stronger than the previous generation of NiSn superconductors (Iter technology). Very importantly, these superconductors are already being used to build magnets with fields as strong as ~40 Tesla at the National High Magnetic Field Lab and can likely create even stronger fields. The GDT's simple planar coil geometry (as opposed to more complicated toroidal confinement devices such as tokamaks) facilitates early application of the REBCO technology for plasma confinement; the existing magnets would be suitable already for application to the GDT due to the small bore (0.1 m) requirements of the mirror coils. Previous generations of mirrors were very limited in field strength, both by the maximum field allowed by the particular superconductor.

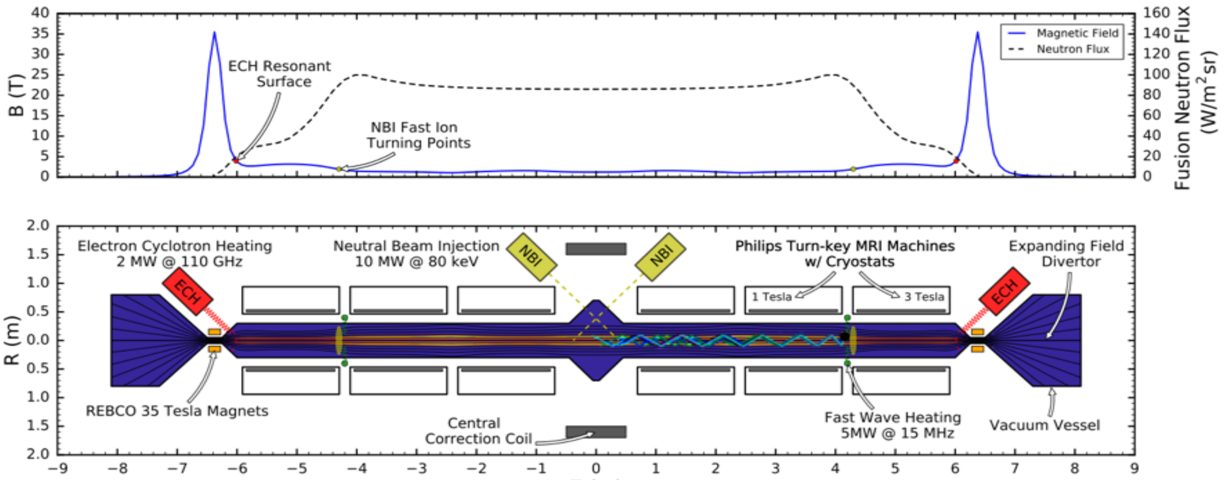

Figure 1: conceptual design of a GDT like device using REBCO magnets for mirror coils and low cost off-the-shelf MRI magnets for the central cell.

Other technological developments include: 1. The ready availability of steady-state MW class gyrotrons at frequencies sufficient for high density electron heating. W7-X routinely operates with 140 GHz and the Iter gyrotrons are 170 GHz. The frequencies are sufficiently high to heat plasmas with densities in excess of 10^{20} m^{-3} and provide target plasmas suitable for neutral beam ionization. 2. Potentially negative neutral beams sources of deuterium neutral beams at energies of several 100 keV. 3. Lithium walls for reducing sputtering and secondary electron emission.

2. NEXT STEP GDT DEVICE BASED ON REBCO MAGNETS

We have carried out a preliminary theoretical design of a GDT-like device that exploits the technological and physics advances that make such a machine now possible. The device shown in Figure 1 proposes to use (1) off-the-shelf and low cost MRI magnets for the central cell, (2) state-of-the-art small and planar high field REBCO magnet for plugs, (3) state-of-the-art gyrotrons to allow high density operation, (4) sloshing to localize neutron yield away from sensitive high field magnets at edge, (5) radio-frequency heating at the fast-ion turning points to enhance neutron yield, (6) a liquid lithium expanding diverter for heat removal, electron thermal barrier and MHD stability---lithium seems essential for pumping neutrals, minimize sputtering by ion bombardment, and minimize secondary electron emission to allow the electron thermal barrier to form.

Equilibrium modelling of the magnetic geometry at finite pressure, we have designed a magnetic field coil set that can be built. To optimize the neutron production, we have used the CQL3D/GENRAY suite of codes. These codes model the plasma heating and the neutron production, modelling the evolution of the fast ion distribution function for both neutral beam injection and radiofrequency heating. Initial results were extremely promising. 5 MW of neutral beam injection power and 5 MW of rf heating at 15 MHz generated 10^{15} neutrons/sec in DD.

For the GDT device, we have preliminary calculations using that show high-harmonic fast wave power can partially replace neutral beam power, in creating a nonthermal, localized in axial length Z, distribution of hot ions and enhanced neutrons. Pitch-angle localization of fast ions due to cyclotron harmonic fast wave heating has been observed. For a GDT ion heating application, it appears that the HHFW must be used in conjunction with the neutral beams in order to obtain sufficient damping on ions. Compared to NB, the HHFW has an advantage for DD neutron in that it diffuses ions to very high energies, much beyond the neutral beams.

3. A SHORT FAT MIRROR NEUTRON SOURCE

The role of high field is important in the GDT in that in allows for higher mirror ratios than available with the previous generation of superconductors (for a central cell field of 1-2 T mirror ratios of >20 become available). For fast ion traps in which the slowing down of the fast ions occurs before the ions pitch angle scatter, this larger mirror ratio only benefits the confinement of the warm background plasma and so the higher mirror ratio leads to higher densities and electron temperature that improves the neutron yield, and only indirectly modifies the fast ions.

We speculate that the high field magnets may also facilitate new geometries that would simply be unworkable with the previous limits on field strength. One of these might be the so-called short-fat mirror proposed by Ryutov as a stabilizing end cell for the tandem mirror [6]. Ryutov's original calculation used to point-like dipole magnets to analyze the MHD stability of a non-paraxial geometry similar to that shown in Fig. 2 below. We have explored implementing this geometry in a single cell using a realistic coil set with current magnetic field limits for REBCO magnets. Note the high mirror ratios of this geometry (>100) require very high fields at the ends to achieve even most fields at the midplane. The device explored below is approximately 1 meter in size with 40 T end coils and a 0.4 T field at the midplane. Repeating his analysis for a full Grad-Shafranov solution with real coil geometry shows that the most unstable interchange mode (m=1) is stabilized by flux expansion. Stability is ultimately limited by ballooning stability in the periphery but but only at substantial betas.

The compactness and properties of the magnetic geometry have several intriguing properties as an ion trap for a neutron source. First the geometry is extremely simple, perhaps only surpassed by the levitated dipole in minimizing the number of magnets required. Relative to the dipole, it benefits from having magnets that can be supported and shielded. Moreover, the high technology REBCO magnets are very small and at the ends of the device—these magnets can be built now and have low stresses compared to large bore magnets required for toroidal magnets. Second, the very steep magnetic field gradients near the mirror coils provides for a very strong sloshing ion density enhancement in regions of good curvature; we speculate this may be the optimal geometry for improving MHD stability via the Rosenbluth-Hinton sloshing ion mechanism [5]. Similarly, the high density of fast ions (several times the warm ion density) should lead to a natural self-plugging of mirror: the ambipolar potential at the fast ion turning points will prevent warm ions from leaking out the ends. The compact geometry localizes the neutron production to a small volume. Preliminary results from the CQL3D modeling indicate that Equilibrium parameters or $n_e = 5\text{x}10^{19}$ m^{-3}, $T_i = 11$ keV D, $T_e = 1$keV and 10 MW of 75 keV tritium neutral beams injected into a deuterium plasma $7\text{x}10^{16}$ neutrons/sec are produced.

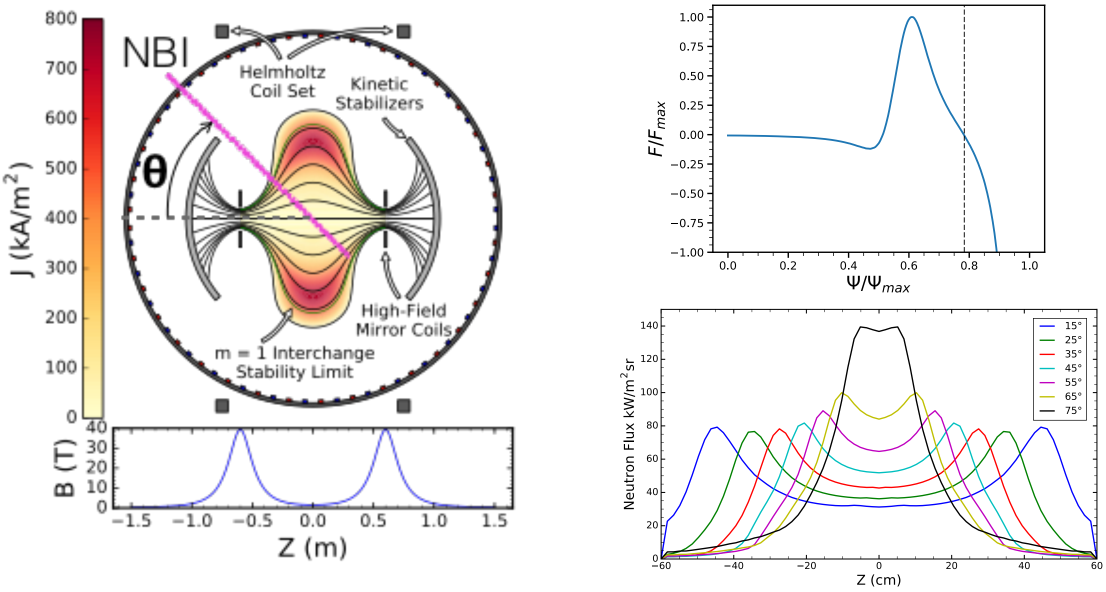

Figure 2. Left: MHD equilibrium with schematic of short-fat mirror. Upper right: Ryutov MHD analysis showing positive function F and MHD stability in periphery of plasma. Lower right: neutron yield profile vs injection angle.

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