PERSPECTIVES OF DEVELOPMENT OF MAGNETIC MIRROR TRAPS IN NOVOSIBIRSK

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The paper reviews the characteristic features of a volumetric neutron source based on the gas dynamic trap and the results of current experiments at GDT device on modeling of the operational regimes of the neutron source. Some limiting factors in the current experiments and possible next steps towards more comprehensive modeling in future experimental device are discussed. Also discussed are the recent findings in the GOL-3 experiment and their consequences for the next step experimental device.

I. INTRODUCTION

In recent years, significant progressed has been achieved in studies of a gas-dynamic trap [1,2], which can be potentially used as a volumetric neutron source for fusion material development and other applications [3,4]. The gas-dynamic trap, as being an axially symmetric magnetic mirror, offers many potential advantages for the application: the high beta value, topological simplicity, the absence of axial plasma current and disruption-like events, intrinsically steady-state operation, natural He-ash removal out of the ends and low heat loads on plasma-absorbing surfaces in the end-tanks. The practical use of the gas dynamic trap as high flux neutron source does require not too high electron temperatures that would be about 1keV or even less. Even though such temperatures were not demonstrated so far, they seem to be within a reasonable extrapolation from the values achieved already experimentally [5]. It has also been gradually realized that the relatively low electron temperature in some mirror machines of the past was probably related not to intrinsic problems of the mirror configuration in general, but rather to specific modes of operation of the corresponding devices. So, achievement of the required electron temperatures seems rather feasible.

In the next section the characteristic features of the GDT-based neutron source are briefly reviewed.

II. GAS DYNAMIC TRAP AS A NEUTRON SOURCE

The gas dynamic trap (GDT) [1,2] has been proposed as a possible approach to an open ended fusion reactor. It would produce power in a long, axially symmetric, high-β, magnetic solenoid. The axial losses from the solenoid are reduced by a strong increase in the magnetic field at the end mirrors under the condition that a mirror to mirror length exceeds the ion mean-free path of scattering into a loss cone. In contrast to the conventional mirrors operated with a collisionless plasma, in the GDT, the rate at which ions are lost out of the ends is of the order of an ion-acoustic speed V_{Ti}. The resulting plasma lifetime can then be roughly estimated as $\tau \approx R \times L / V_{Ti}$, where L is the machine length, and R is the mirror ratio.

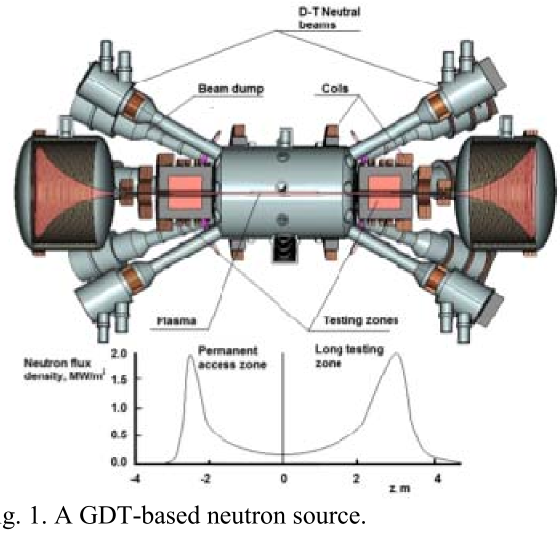

Fig. 1. A GDT-based neutron source.

By increasing the length of the system and mirror ratio it is possible to obtain the plasma life time required for a reactor [1,2]. A more near-term application of the

GDT concept is a 14 MeV neutron source for fusion

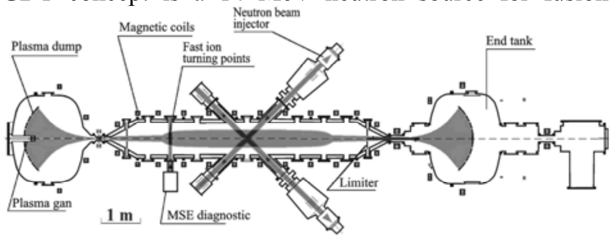

Fig. 2. Layout of the GDT device.

materials development [3,4] (see FIG.1). For this purpose, the energetic D and T ions with anisotropic angular distribution are confined in GDT providing a high neutron flux density in localized regions. The energetic ions are provided by the angled injection of about 100 keV, D/T neutral beams at the center of the solenoid. Then, a rather moderate electron temperature of 0.5 ÷ 1 keV is then sufficient to generate a neutron flux as high as 2 MW/m^2 even with rather moderate power consumption. For the given temperature of a warm plasma and the beam energy, the fast ion angular distribution remains rather narrow, and centered on the initial value of the pitch angle during their slowing down to considerably lower energies. The fast ion density is then strongly non-homogeneous along the solenoid with sharp peaks near the turning points where the ion axial velocity is small. The neutron flux density is also strongly peaked in the same regions that house the testing zones. As a mirror machine, a gas dynamic trap has the advantage of confining high-β plasmas. This results in a higher 14 MeV neutron flux density (up to 4 MW/m^2) than would be produced by other plasma based sources. It is worthwhile to note that the GDT concept does not assume significant role of electrostatic plugging of the end losses, as in tandem mirrors [6,7], and does not incorporate complex thermal barrier physics [8]. The GDT plasma contains a large fraction of collisional warm plasma to provide both magnetohydrodynamic and microstability to the plasma. Initial approach [1,2] suggested plasma stabilization against flute modes by using external cells, where magnetic field has favorable curvature and non-negligible plasma pressure is sustained by axial losses from central solenoid. Other stabilization mechanisms would be applicable for the gas dynamic trap [9,10]. One of those, namely, radial plasma confinement with an azumuthal plasma flow in the periphery (vortex confinement, see [11]) driven by biased end plates and radial limiters has been observed experimentally [12]. Presence of large gyro-radius ions also introduces finite-Larmor-radius stabilization effects. Sets of the basic parameters for different versions of the GDT-NS are given in TABLE 1. Summarizing, the characteristic features of the GDT-NS are

- axial symmetry (no complex min-B magnets, high plasma beta, no neoclassical transport);
- MHD stability, as initially proposed, is provided by external cells, where magnetic field has favorable curvature and non-negligible plasma pressure is sustained by axial losses from central solenoid;
- peaks of neutron production is provided by skew injection of D-T neutral beams under requirements that fast ion relaxation is determined by classical angular scattering and slowing down;
- operation at maximal plasma beta limited by MHD ballooning/interchange modes (β ~60%);
- the electron heat flux to the end walls is suppressed by sufficient decrease of magnetic field in expanders [ ];
- electron temperature is sufficiently high (~1% of beam energy) to accumulate fast ions, and at the same time is low enough to avoid formation of large hole in the velocity space and development of microinstabilities
- warn isotropic plasma serves as a target for neutral beams and provides MHD and microstability.

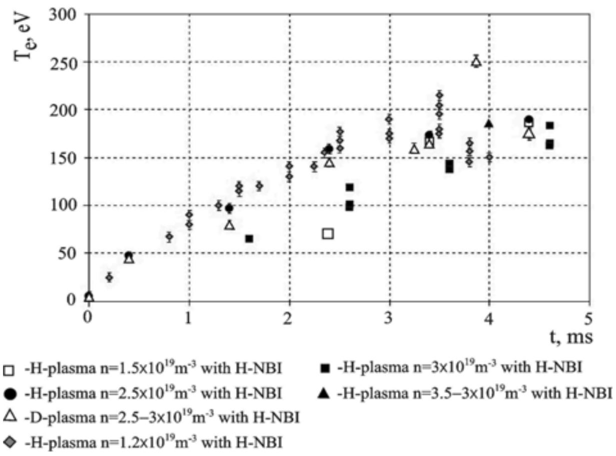

Fig. 3. Electron temperature in GDT *vs* time.

Accordingly, the physical issues to be studied for the GDT-NS include demonstration of adequately high electron temperature, steady state operation, determination of ballooning instability threshold, plasma equilibrium at high β, effect of ambipolar fields on confinement, plasma rotation/vortex barrier scaling against magnetic field, plasma density, etc. Efficiency of different MHD stabilizers, including those emerged in the past and in the recent years, like non-paraxial mirror [10], plasma dump shaping, tail-waving [13] etc. Application of auxiliary heating (ICRH, ECRH, axial injection of electron beams) should be studied as well.

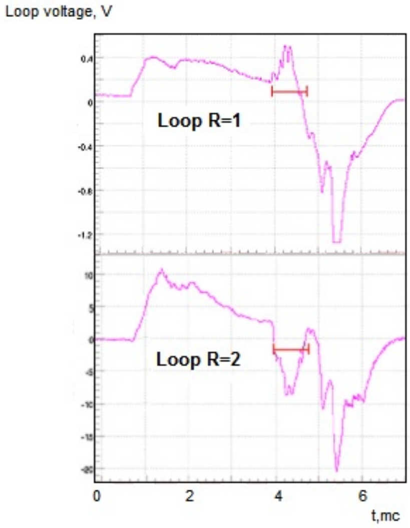

Fig. 4. Signals from diamagnetic loops.

There are also the technical issues, the most important of which are development of continuous neutral beams with 65keV energy and 40-50MW power with small divergence and focusing (prototypes exist already), handling of plasma exhaust (~10^{22} particles s^{-1}), neutron shielding of sensitive elements, high frequency pellet injector ~1kHz, plasma sustainment, optimization of SC mirror magnets for high magnetic fields.

The physical issues at adequately high electron temperature of 300-400eV and density ~$10^{20}m^3$ should be addressed in the experiments on the next-step device called Hydrogen-prototype of the neutron source [14]. At moderate plasma parameters the supporting experiments are carried out at the GDT device, whose layout is shown in FIG. 2. Vacuum chamber of the device consists of a cylindrical central cell 7 m long and 1 m in diameter and two expander tanks attached to the central cell at both ends. A set of coils produces an axisymmetric magnetic field with a mirror ratio variable from 12.5 to 75.0 when the central magnetic field was set to 0.28T. Recently, magnetic field in solenoid was increased to 0.33T for mirror ratio set to about 30. Initial plasma with density $3\div6\times10^{19}m^{-3}$ and radius 6÷7 cm at the mid-plane is produced by a plasma gun located in the end tank.

In the recent experiments [5], the plasma was heated and fast ions were produced by injection of a 5ms pulse of 20-25keV, 3.5- 4.5MW neutral beams at the center of the device at 45^0 to the axis. The external min-B cells, which provided MHD stability of the plasma in the solenoid, were not engaged. Instead, the radial plasma transport was controlled by biasing the segments of end wall and radial plasma limiter in the solenoid. This produced a vortex (sheared E × B flow) at periphery.

TABLE I.

Parameter	2 component version	3 component version	Fully SC version
Tritium beam energy, keV	240	94	65
Deuterium beam energy, keV	-	80	65
Tritium beam power, MW	20	6.5	
Deuterium beam power, MW	-	8.5	
Electron temperature, keV	0.6	1.1	0.65
Plasma density, m^{-3}	2 $x10^{20}$	2 $x10^{20}$	2 $x10^{20}$
Plasma radius, m	0.06	0.08	0.06
Mirror ratio	20	15	10
Central field, T	1.25	1.8	1.3
Injection angle, deg.	20	40	30
Max. neutron flux , MW/m^2	3.9	1.8	1.8
Power consumption, MW	50	60	47

Then, the inherently unstable flute modes nonlinearly saturated due to the line-tying mechanism and generation of transverse currents in the vortex region [11]. Therefore plasma resides in the vortex interior without considerable radial losses. The electron temperature (see Fig.3) exceeded 200eV during a shot consistent with classical modeling.

The higher electron temperatures, approaching 250eV were obtained in the regimes when the density was not sustained by gas puff from periphery [5]. Density of the fast ions with mean energy 10-12keV reached ≈ $5\times10^{19}m^{-3}$ in the turning point regions and substantially exceeded that of the target plasma ($1.5\div3\times10^{19}m^{-3}$ at the mid-plane). This resulted in development of peaks of the ambipolar potential and considerable reduction of plasma axial losses in the region near plasma axis. The local plasma beta in the turning point region was determined from a motional Stark effect diagnostic. Relative to the vacuum field the local plasma beta reaches about 0.6.

The high beta plasma in the GDT experiment does not exhibit gross instability for maximum plasma beta less than 0.6. When plasma beta approaches 0.6, the spontaneous redistribution of plasma pressure along the central solenoid and distortions of plasma shape in transverse cross section were observed in some shots. In these cases, plasma behavior is illustrated in Figs.4,5. Fig.4 shows signals from diamagnetic loops installed near

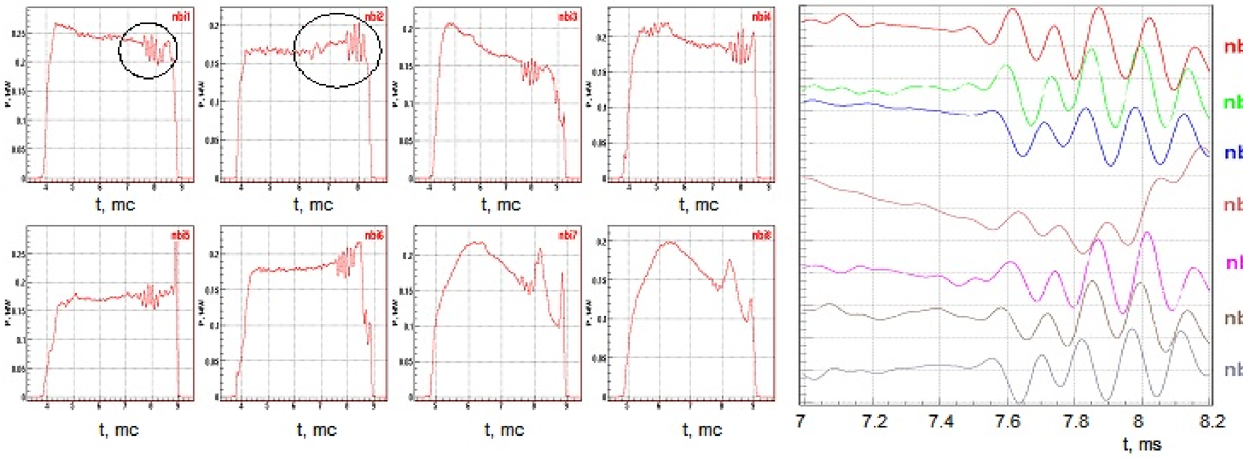

Fig. 5. Neutral beam attenuation signals.

the mid plane (at mirror ratio R=1) and the turning point of fast ions, where the mirror ratio was R=2. In this shot, when plasma beta was close to maximum attainable value of 0.6, at the end of the neutral beam pulse the signal from the loop installed near the fast ion turning point dropped considerably. At the same time, a signal from the loop installed near mid plane increased thus indicating redistribution of plasma pressure along the device. Signals from the neutral beam attenuation detectors in another high performance shot with beta close to 0.6 are shown in Fig. 5. It can be seen that at some moment all the signals started to oscillate with high amplitude indicating an elliptical distortion of plasma cross section and azimuthal rotation of the plasma column. Note that during these events no considerable plasma losses were measured both along the magnetic field and in the transverse direction. It is believed that they would happen above plasma beta of about 0.6, which in accordance this theory is a threshold for plasma ballooning. Additional measurements are still required to establish a correlation of these events with increase of plasma beta and other plasma parameters. Nevertheless, the observed phenomena anyhow indicate that the plasma in the GDT approaches a beta threshold and this might be a factor preventing from further increase of the plasma parameters towards the operational regime of the GDT-NS. Further progress can be then only possible with increase of the magnetic field. Another conclusion is that for the electron temperature and plasma density in high performance shots plasma in 5ms pulses did not reach a steady state. Further extension of the pulse duration (to at least 20ms for Te=200eV) is still required to reach steady state conditions in the experiments. These improvements have been planned already to accomplish in an Hydrogen Prototype of the GDT-NS.

FIG.6 shows artist view of the vacuum chamber and a set of the coils of this device. The main parameters of the facility is shown in TABLE II.

TABLE II. Parameters of the Hydrogen Prototype of the neutron source.

Parameter	Value	Comments
Mirror to mirror length, m	10	
Magnetic field at midplane, T	1(0.7)	0.5s flattop
Mirror ratio	8-20	
Injection angle, deg.	30	
Injection energy, keV	30	0.02-0.1s energy loss time
Injection current, eq. A	600	
Plasma density, m^{-3}	2 1020	
Electron temperature, eV	~300	

III POSSIBLE OPTIONS FOR THE HP-NS DEVICE.

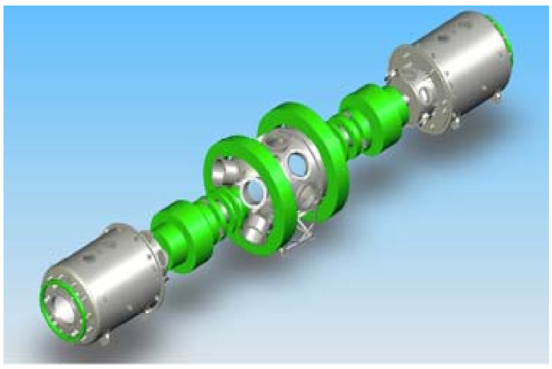

Fig. 6. View of the Hydrogen Prototype of the GDT-NS.

The design of the HP-NS device has been completed [14] and vacuum system and the most of the coils have been fabricated. However, there are several limiting factors for the experiments in the HP-NS in its present arrangment. First, the mirror coils cannot be energized for longer than ~0.1s and mirror field is limited to ~15T. Limitation on the mirror field means that the axial plasma losses cannot be further reduced by increasing the mirror ratio. If the electron temperature would exceed 250eV plasma does not reach a steady state again and further extension of pulse duration is required. Then another problem comes how to sustain the warm plasma density during a long pulse. Note, that different feeding rate may be required at different plasma radii. Several methods to sustain this plasma were assessed. These are high frequency (~1kHz) pellet injection, which required a new development, injection of micro particles or droplets, low energy neutral beams, etc. The 40 keV neutral beams to sustain the fast ions for pulse duration of up to 1s have been already developed [15].

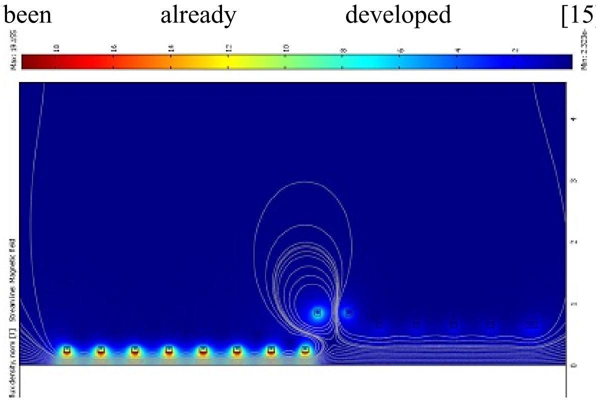

Fig. 7. Version of SC magnetic system with multiple end mirrors (V.Postupaev, 2010).

Limitation on mirror magnetic field, i.e. the mirror ratio can be, in principle, avoided by application of multiple-mirror plugs. Multiple mirror confinement has been studied both theoretically and experimentally obtaining good agreement [16,17]. Efficiency of axial confinement however depends upon the plasma density and temperature. Namely, an axial plasma expansion is slowed down considerably if for the given temperature and density the ion mean free path is much shorter than the device length L, but comparable with the mirror scale length - l. Then ions will undergo a random walk rather than direct transit out of the machine. This diffusive loss process will results in much slow axial expansion of a plasma compared to the case of homogenous magnetic field. However, if the mean free path is determined by classical scattering, optimal conditions for plasma confinement for the required ion temperatures correspond to irrelevantly high plasma density. At the same time, recent findings in the experiments on multiple mirror device GOL-3 in Novosibirsk demonstrated that under some conditions the regime of the longest axial plasma confinement in multiple magnetic field can be realized for considerably smaller plasma densities compared to the theoretical predictions accounting for the binary collisions. This related to an enhanced ion scattering caused by plasma turbulence excited during plasma expansion along the multiple magnetic field [17].

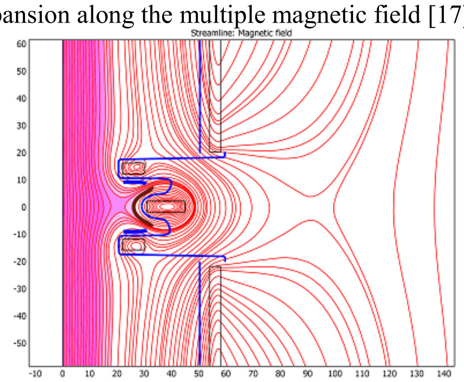

Fig. 8. Magnetic null divertor placed near the center of the central solenoid (A.Beklemishev, 2010), dimensions in cm.

An MHD stability in the GDT experiment has been studied with the external cells with favorable curvature of the field lines (expander and cusp end cells) showing the successful stabilization for the central cell plasma beta less than ~0.2 [18]. The reason for that is not yet well understood. Further studies with higher magnetic field and with local auxiliary plasma heating in the stabilizing cells are necessary to reveal the underlying physical mechanism of this limitation on plasma beta in the experiments. At the same time, several other methods could be applied including already proven vortex confinement, which, however, may not be compatible with stronger end loss plugging and a magnetic null divertor [19].

Preliminary consideration show that a superconducting magnet system would be an option for the HP-NS device enabling to reach plasma steady state with injection of 40keV, 1s neutral beams. Total power incident on plasma in access of 8-12MW, which can be provided by using 8-12 neutral beams [14], would be sufficient to heat the plasma electrons to 300-400eV.

Possible arrangement of the SC magnets forming a magnetic null divertor at plasma periphery between the central solenoid and multiple mirror end section is shown in FIG.7 (half of the system is shown for convenience). Similarly, the magnetic null divertor configuration can be arranged near the solenoid mid-plane, as shown in FIG.

Instead of the magnetic null divertor, the vortex confinement can be also used in the HP-NS device. FIG.8 shows confinement boundaries in terms of the effective mirror ratio and plasma radius for this case and HP-NS operational point well within the confinement region.

IV DISCUSSION

The GDT device has recently demonstrated its potential for future applications when stable confinement of high-β plasmas with electron temperatures approaching 250eV was achieved.

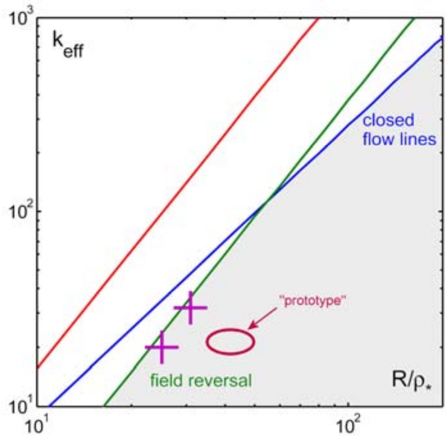

Fig. 9. Boundaries of plasma confinement with vortex (A.Beklemishev, 2010).

Critical physics issues associated with extrapolating of the present parameters of the GDT experiment to the high flux 14 MeV neutron source include MHD stability of the axisymmetric system, micro-stability of the neutral beam driven system, possibility of further increase of electron temperature, and sustainment of warm plasma density.

The current design of the Hydrogen Prototype of the Neutron Source provides only a limited capacity to study plasma steady state since duration of the current in the mirror coils is limited to less than 0.1s. Possible option for the next step experimental device which would be capable of addressing these issues with plasma in steady state is considered. It suggests injection of 40keV, 1s neutral beam injection and application of SC magnets.

In the previous design, injection of 30keV beams was assumed. Application of higher energy neutral beams would enable to also study dependence of electron temperature vs the beam energy. Application of different methods to provide the plasma MHD stability is considered including previously studied expander and cusp end cells with favorable curvature of the field lines. Magnetohydrodynamic stability of plasma can also be provided by juxtaposing at the ends of the central solenoid two sets of coils producing magnetic null divertors. Other possible mechanisms of MHD stabilization including sheared plasma flows generated at periphery by biased end plates are also considered. Auxiliary methods of plasma heating in future experiments are considered. These include injection of an electron beam though the end mirrors and ECR heating.

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