Mirror based fusion neutron source: R&D status and applications

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1. Introduction

The Budker Institute of Nuclear Physics in worldwide collaboration develops a project of a 14 MeV neutron source for fusion material studies and other applications [1,2]. The projected neutron source of plasma type is based on the gas dynamic trap (GDT), which is a special magnetic mirror system for plasma confinement [3]. Essential progress in plasma parameters was performed in recent experiments at the GDT facility in the Budker Institute, which is a hydrogen (deuterium) prototype of the source. Stable confinement of hot-ion plasmas with the relative pressure exceeding 0.5 was demonstrated. The electron temperature was increased up to 0.9 keV in the regime with additional ECRH of a moderate power [4]. These parameters are the record for axisymmetric open mirror traps. These achievements shift the projects of a GDT-based neutron source on a higher level of competitive ability and make possible today to construct a source with reasonable parameters, suitable for materials testing. The first part of this paper presents a brief review of basic experimental results obtained on the GDT device in recent years. The second part of the paper focuses on numerical simulations of the GDT neutron source and its possible applications including a fusion material test facility and a fusion-fission hybrid system.

2. Resent results of the GDT experiment

Fig.1 shows the layout of the GDT experimental device with quarter-section. This is a 7 m long axisymmetric mirror trap with high mirror ratio (B_0 = 0.3 T, B_m up to 15 T) for plasma confinement. Warm maxwellian plasma is confined in a gas dynamic regime, which is characterized by collisional particle losses into the end chambers of the device. An inclined

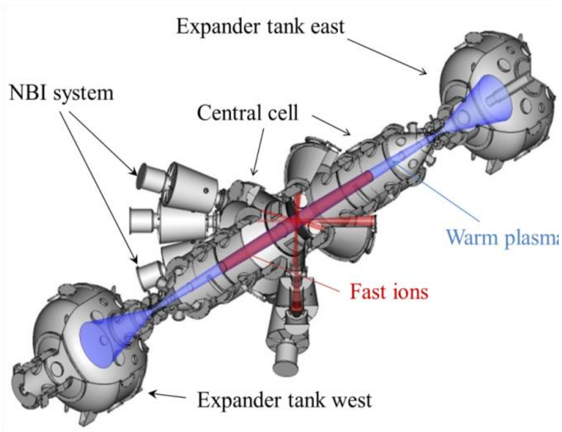

Fig. 1 *The layout of GDT experiment.*

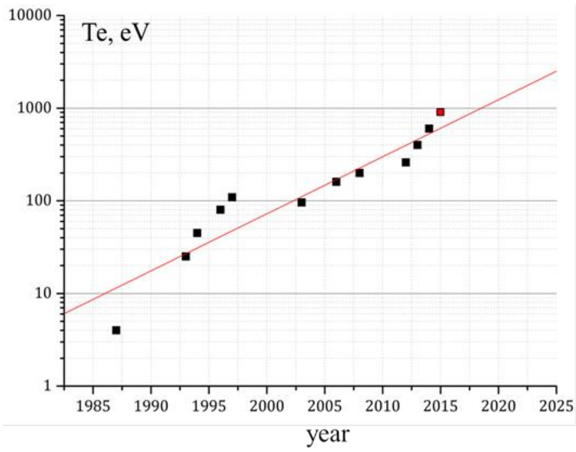

Fig. 2 *Electron temperature in GDT experiments vs. year of achievement.*

injection of eight deuterium atom beams (with energy 20-25 keV and total power 5 MW) produces fast ions oscillating back and forth between the hills of the magnetic field. The peaks of the fast ion density appearing near to their turning points represent the volumes of high plasma pressure and intense fusion neutron production.

Fig. 2 presents the rise of the electron temperature in GDT experiments over recent 40 years. The maximal electron temperature obtained in this year (red point) exceeds 0.9 keV that is correspond to electron temperature in first tokamaks. This result was achievable due to the additional ECR heating by the new ECRH system (two 54.5 GHz gyrotrons with 0.4 MW power each + beam lines) [5].

Obtained in the GDT experiment electron temperature substantially exceeds previously predicted [2] limit for T_e in a magnetic mirror trap with neutral beam injection: $T_e \sim 0.01 E_{inj}$, were E_{inj} is the energy of injected neutral atoms. Thus it is possible to abandon this prediction and use in GDT-NS modeling a self-consistent value of the electron temperature.

In GDT experiments the relative plasma pressure β exceed 0.5 that corresponds to fast ion density up to $5x10^{19}$ m^{-3} with $<E_i>$=10 keV. All these results were obtained by using a new efficient method of transverse plasma confinement, so called “vortex confinement” [6]. Shear flows, driven via biased end plates and limiters, in combination with finite-Larmor-radius effects are shown to be efficient in confining high-beta plasmas even with a magnetic hill on axis.

The GDT experimental achievements make possible today to construct a source with reasonable parameters, suitable for materials testing. The next sections of this paper are devoted to the numerical simulation of several neutron sources based on the achieved experimental data.

3. Results of the GDT neutron source simulations

During past few years several transport codes have been developed and applied for computational studies of GDT-NS in parallel to the experimental research. The plasma physics calculations of the neutron source’s parameters have been performed by the Integrated Transport Code System (ITCS) [7]. ITCS includes different modules for plasma, particles transport and neutron production modelling. The main 3D Monte-Carlo module for fast ion transport MCFIT+ has been substantially upgraded for adequate simulation of the various versions of the mirror based neutron source. The experimental and theoretical foundations of these phenomena were obtained in the GDT-U experimental facility in the Budker Institute. Brief simulations of GDT plasma parameters and optimization researches were made by the one-dimensional plasma code DOL that is developing in Budker Institute for fast calculation of main plasma parameters evaluation in the mirror trap [8].

Table 1 presents a summary of simulation results for several mirror based neutron source projects. The first column shows achieved GDT experimental results for comparison with parameters of the projected devices. The GDT experiment regime was also simulated by the numerical codes described above and results of this simulation are in a good agreement with experimental data that is the best proof of our numerical tools.

TABLE 1. Main results of neutron source simulations:

Parameters	GDT exp.	GDT-U (next)	GDT-NS	GDMT NS	Mirror NS
Magnetic field, B_0 / B_m [T]	0.34/12	0.5/15	1/15	1/9	2/15
Effective mirror ratio, k	35	30	15	10…100	7.5
NB injected/heat power, [MW]	5/3	9.6/7.2	40/30	40/30	100/90
NBI energy, E_{inj} [keV]	25	20	65	65	80
Pulse duration, [s]	0.005	0.03	continuous	continuous	continuous
Warm ion density, n_w [10^{20} m^{-3}]	0.3	0.5	0.2	0.3	0.08
Fast ion density, n_f [10^{20} m^{-3}]	0.5	0.7	2.5	3.5	1
Mean ion energy, T_i [keV]	10	10	35	30	60
Electron temperature, T_e [keV]	0.25 / 0.9*	0.4 / 1*	0.7	1.5	6
Relative plasma pressure, β	0.6	0.5	0.5	0.5	0.5
Fusion energy gain factor, Q_{fus}	-	-	0.05	0.1	0.5
Fusion neutron power, P_n [MW]	-	-	1.5	3	45

* with additional ECRH

The second column presents parameters of the GDT-U project – next step of the GDT experiments. A strong modernization of the GDT magnetic system for 0.5 T in midplane and up to 15 T in mirrors is planned. Also a new NBI system includes four modules with 2.4 MW 20 keV D-beam each with 30 ms pulse duration and corresponded power supply will be realized in near future. The main goals of the update are the demonstration of increasing mirror plasma parameters closed to moderate GDT neutron source project and achieving steady-state confinement. Fig.3 shows a time dependence of the ion (T_i) and electron (T_e) temperatures in GDT-U during NBI heating only. As it's seem the 30 ms power beam injection is enough for a physical steady-state regime. An additional ECRH can increases the electron temperature over 1 keV for parameters in Table 1.

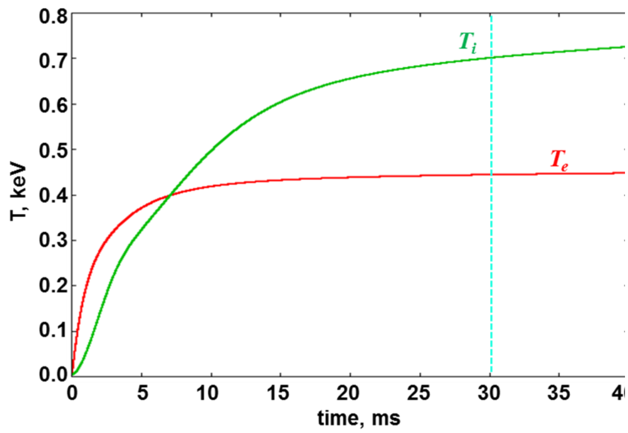

Fig.3. *Simulated temperature in GDT-U vs. time.*

The number of DT fusion neutron source projects were simulated on the base of the achieved GDT experimental results (T_e ~ 0.6 keV, β ~0.5). First of them is a model of GDT-NS proposed for fusion material research [2]. It is an axially symmetric mirror machine of the GDT type, 10 m long and with magnetic field B_0 = 1 T and mirror ratio of 15. The source parameters are presented in the column 3 of Table 1. The Gas-Dynamic Multiple-mirror Trap (GDMT) based on GDT and multiple-mirror trap GOL-3 results may be a near-term substitute [9]. GDMT based neutron source has improved axial confinement with the effective mirror ratio k up to 100 and high T_e. The simulated GDT-NS parameters (col.4 in the Table) allow to propose this neutron source as a basic for different applications including fusion material test facilities and moderate fusion driven (hybrid) systems (FDS).

The first analysis of possibility to use the GDT based neutron source as a driver in the sub-critical system (FDS) was made in [10]. It has shown necessity to optimize the GDT-NS parameters. Optimized mirror based NS with Q_{fus} = 0.5 uses 100 MW of 80 keV NBIs and has 6 m long n-zone with up to 1.4×10^{19} n/s production is presented in last column of Table 1. It assumes a kinetic regime of axial confinement, vortex transverse confinement and warm maxwellian plasma minority for the DCLC stabilization. This powerful NS is proposed for basic of future FDS (hybrids) for MA burning or for Th-reactor realizing (see Fig 4 and 5).

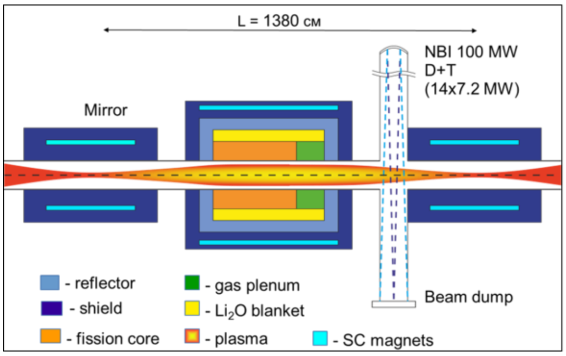

Fig.4. General layout of the mirror based FDS

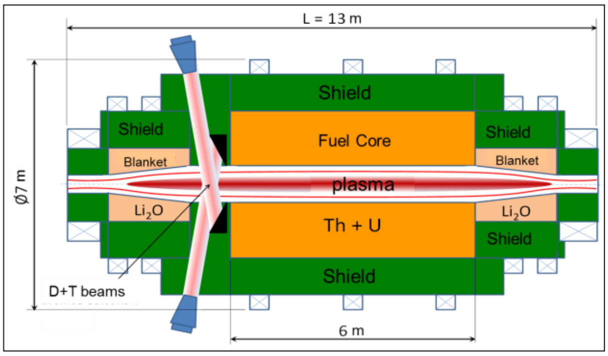

Fig.5 Mirror based hybrid reactor with Th+U fuel

4. Conclusions

Resent GDT experiments results show the possibility of realizing competitive neutron sources based on axisymmetric mirror cell.

The next step of GDT experiment was simulated. The results show the possibility of achieving steady state confinement with high plasma parameters.

Neutron sources based on GDT and multi-mirror GDMT were simulated. Proposed neutron sources with Q_{fus} up to 0.1 can be used as a basic for fusion material test facilities and moderate fusion driven systems (FDS).

Numerical optimization of the mirror based neutron source for the driver in FDS hybrid system was made. Proposed source with Q_{fus} = 0.5 can be used for effective MA burning or for Th-reactor realizing.

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