Numerical simulations of a fusion neutron source based on the last GDT experimental data

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1. Introduction

For a number of years the Budker Institute of Nuclear Physics, Novosibirsk, Russia in collaboration with the domestic and foreign organizations develop the project of 14 MeV neutron source, which can be used for fusion material studies and for other application [1,2]. The projected neutron source of plasma type is based on the plasma Gas Dynamic Trap (GDT), which is a special magnetic mirror system for plasma confinement [3]. Compared to others, that of a GDT-based neutron source has essential advantages. A research activity of the Budker Institute aims at completing the database of the GDT in the range of high plasma parameters, which are relevant for the neutron source, and at demonstrating its feasibility and suitability by prototype experiments.

The GDT-based neutron source (GDT-NS) could also be a candidate for fusion driving sub-critical systems (FDS) dedicated to nuclear waste transmutation [4] and fission fuel breeding [5].

2. Resent results of the GDT experiment

In the last year at the GDT facility in the Budker Institute, which is a hydrogen prototype of the source obtained several important results: the electron temperature was increased over 0.6 keV and the relative plasma pressure β was up to 0.6 in a quasi-stationary regime [6]. These parameters are the record for axisymmetric open mirror traps.

Fig.1 shows the layout of the GDT devise with quarter-section. Relative pressure values β (estimated from the local magnetic field perturbation data measured by MSE diagnostic) vs. fast ions total energy contents in different GDT experiments are presented on Fig.2.

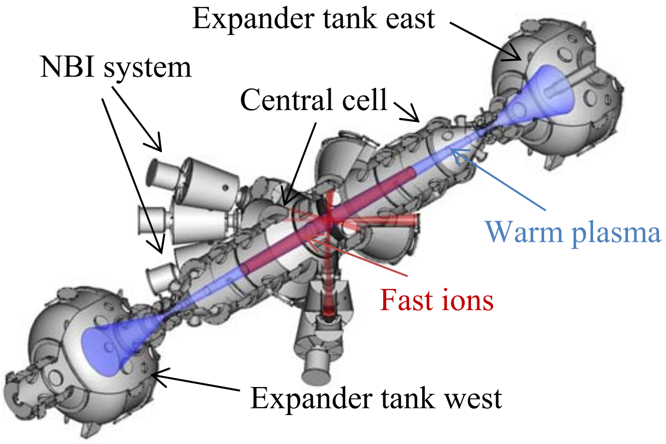


Fig. 1 *The layout of GDT experiment.*

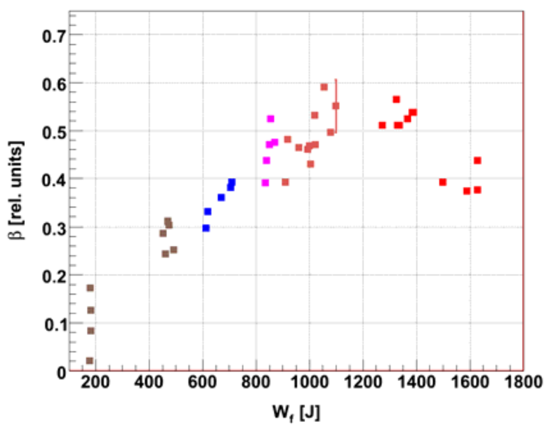


Fig. 2 *Relative pressure β (MSE data) vs. fast ions total energy content.*

As it is seem from the data, plasma β exceed 0.5 that corresponds to fast ion density up to $5x10^{19}$ m^{-3} with $<E_i>$=10 keV.

Fig. 3 presents the rise of the electron temperature in GDT experiments over last years. The maximal electron temperature obtained in this year exceed 0.6 keV that is correspond to electron temperature in few small tokamaks. This result was achievable due to the additional ECR heating. The ECRH system (two 54.5 GHz gyrotrons with 0,4 MW power each + beam lines) was installed at the GDT facility during upgrading [7].

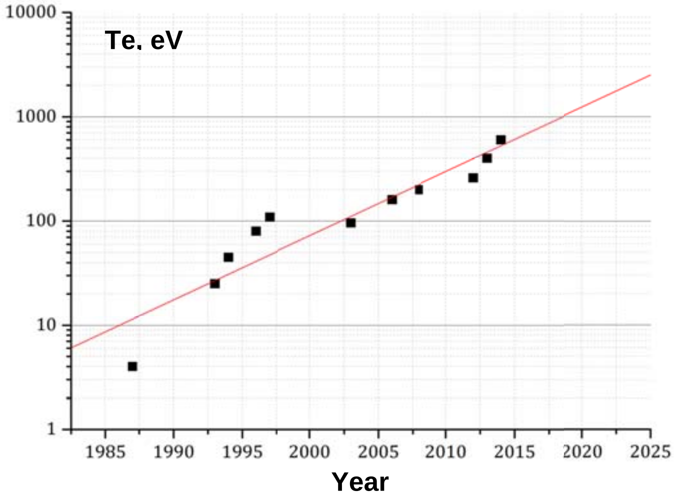


Fig. 3 *Electron temperature in GDT experiments vs. year of achievement.*

These 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 such neutron source based on the achieved experimental data.

3. Instruments & tools

During the last years several transport codes have been developed and applied for computational studies of GDT-NS in parallel to the experimental research.

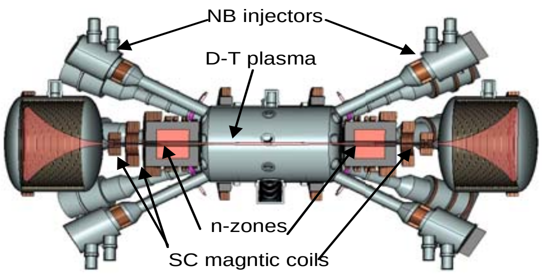
The plasma physics calculations of the neutron source's parameters have been performed by the Integrated Transport Code System (ITCS) [8]. ITCS is developed since 1990's in collaboration with Research Centre Dresden-Rossendorf, Germany for GDT simulations and includes different modules for plasma, particles transport and neutron production modelling. The main 3D Monte-Carlo module for fast ion transport MCFIT+ has been substantially upgraded for adequate modeling of the various versions of the GDT based neutron source (GDT-NS). The new physical phenomena (as a vortex confinement, ambipolar plugging, high β etc.) were included into account in this code development. 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 neutron source optimization research were made by the new one-dimensional plasma code DOL that is developing in Budker Institute for fast calculation of main plasma parameters evaluation in the mirror trap.

Neutron processes in the fuel blanket were simulated by NMC/NMC+ Monte-Carlo code which has being developed as a very flexible general purpose tool for the tasks of particle transport calculation in both static (NMC) and dynamic (NMC+) systems were parameters vary in a short period of time [9,10].

4. The GDT based neutron source simulation

The powerful 14 MeV neutron source was simulated on the base of the gas dynamic trap achieved results (Te~0.6 keV, β ~0.5). The GDT-NS is a plasma device that confines a deuterium-tritium plasma is an axially symmetric mirror machine of the GDT type, 10 m long and with a mirror ratio of 15. The source parameters and layout are presented on Fig. 4. The idea of the source is extremely simple. If high energy deuterium and tritium neutral beams are injected at an angle to the axis of the trap into "warm" plasma, then a population of fast sloshing ions is produced. Their density is strongly inhomogeneous along the axis with strong peaks close to the turning points. Nuclear reactions will mainly occur as result of fast-fast D-T collisions. As simulations show, in the vicinities of the turning points a 14 MeV neutron flux density of 2 MW/m^2 or even more can be achieved on the area of ~1 m^2.



Magnetic field:	B_0	1 T
	B_m	15 T
Warm (target) plasma:		
temperature	T_e	0.75 keV
density	n_e	2-5 x 10^{20} m^{-3}
Neutral beam injection:		D^0+T^0
energy,	$E_{D/T}$	65 keV
power,	P_{inj}	36 MW
Fast ion mean energy:		30 keV
Fusion power (in neutrons):		1.25 MW

Fig. 4. *Schematic layout and main parameters of the GDT-based neutron source*

5. Optimization of GDT neutron source for a driver in FDS

The first analysis of possibility to use the GDT based neutron source as a driver in the sub-critical system for MA burning was made in [4]. It has shown necessity to optimize the GDT-NS parameters. Some optimizations of the GDT-NS as a driver for subcritical MS burner were presented in the papers [9, 11]. In this section we will present a preliminary result of simulation for the new optimized neutron source based on axisymmetric mirrors and mirror based fusion-fission hybrid system for MA burning.

The new version of the FDS system (see Fig. 5a) was designed for minor actinides incineration. Reactor core has been adopted from the gas-cooled European Facility for Industrial-scaled Transmutation (EFIT) reactor [12]. The main differences are the following: total heat power has been increased from 400 MWt to 800 Mwt; Li_2O-filled tritium

a)

b)

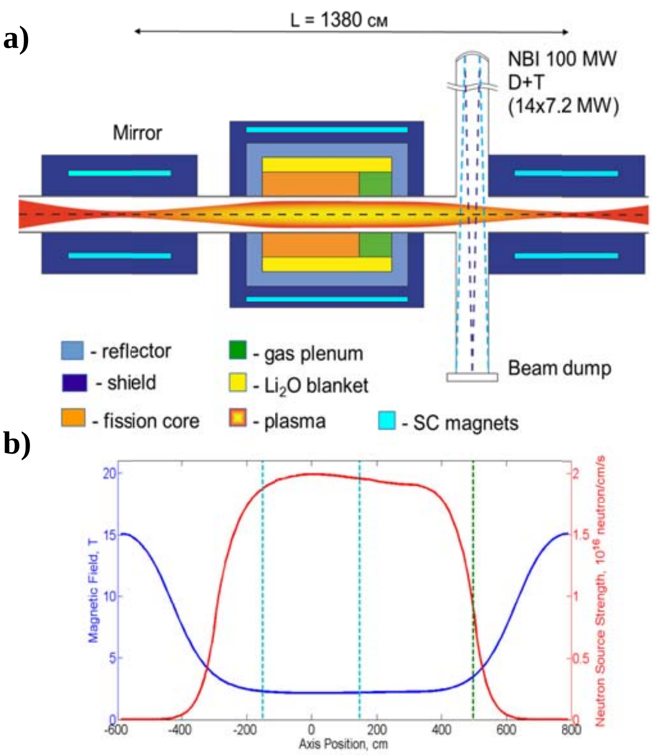


Fig. 5 a) *Schematic view of FDS with mirror NS.*
b) *Magnetic field strength (blue) and neutron emission yield (red) along the NS axis.*

breeding blanket has been added; the original fuel isotopic composition has been replaced with one described in benchmark model [13] (start-up MA and Pu isotopic composition has been considered). The system had three-batch shuffling scheme with total irradiation time of 6 years.

Fusion neutron source optimization has led us to the Budker-Post mirror model with 100 MW D+T neutral beam injection and $1.4x10^{19}$ neutrons/s total neutron source strength. Neutron emission profile of the neutron source is presented in the Fig. 5b. Small periphery injection of cold gas is required for the establishment of vortex confinement and DCLC instability suppression. It does not lead to significant deterioration of plasma parameters and decrease in fusion power right up to cold to fast ions ratio of 1%.

It has been determined during the numerical study, that such a source is completely adequate for a designed hybrid, if the fuel burnup does not exceed 100 GW_{th} days/t_{HM} and BOL criticality level is not less than 0.95. Tritium breeding ratio remains far beyond self-maintenance level during the all irradiation time.

6. Conclusions

- The wide set of computer codes was developed for modeling of the GDT neutron source and also nuclear power systems on its basis.
- Resent GDT experiments results show the possibility of realizing competitive neutron sources based on axisymmetric mirror cell.
- Numerical optimization of the GDT based neutron source for the driver in FDS MA burner was made. Proposed mirror based NS with Q_{fus} = 0.4 uses 100 MW of 80 keV NBIs and has 6 m long n-zone with up to $1.4x10^{19}$ n/s production.
- Two FDS MA burner systems with different k_{eff} were investigated. In result, each one can produce 800 GW_{th} of fission power and incinerates in 2 year (one cycle of 6 years campaign) about 509 kg MA with burning rate of 43 kg/TWh and very high burnup level.

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