Mirror Based Fusion Neutron Source: Current Status and Prospective

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Abstract. The paper presents a recent progress in experimental studies and status of numerical simulations of the mirror based fusion neutron source developed by the Budker Institute of Nuclear Physics (Novosibirsk, Russia) and its possible applications including a fusion material test facility and a fusion-fission hybrid system. Current research activity is supported by the Russian Science Foundation (project N 14-50-00080).

INTRODUCTION

The Budker Institute of Nuclear Physics (BINP) 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 (see Fig.1), which is a hydrogen (deuterium) prototype of the source [4]. 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 two-component plasma confinement. Warm maxwellian plasma is confined in a gas dynamic regime, which is characterized by collisional particle losses through small magnetic "bottlenecks" into the end chambers of the device. An inclined injection of eight deuterium atom beams (with energy 20-25 keV and total power 5 MW) produces fast sloshing 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 local volumes of high plasma pressure and intense fusion neutron production, which is important for GDT-based neutron source project.

Stable confinement of hot-ion plasmas with the relative pressure β exceeding 0.5 was demonstrated. In these experiments the density of fast deuterons with the mean energy of 10 keV reached $5\text{x}10^{19}$ m^{-3}. The result was obtained by using a new efficient method of transverse plasma confinement, so called "vortex confinement" [5]. 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 maximal electron temperature was increased up to 1 keV that corresponds to electron temperature in first tokamaks. The result was achieved due to the additional electron cyclotron resonance heating (ECRH) by two 54.5 GHz gyrotrons with 0.4 MW power each [6]. It should be noted that the experimentally obtained electron temperature in GDT 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 the mirror-based neutron source modeling a self-consistent value of the electron temperature.

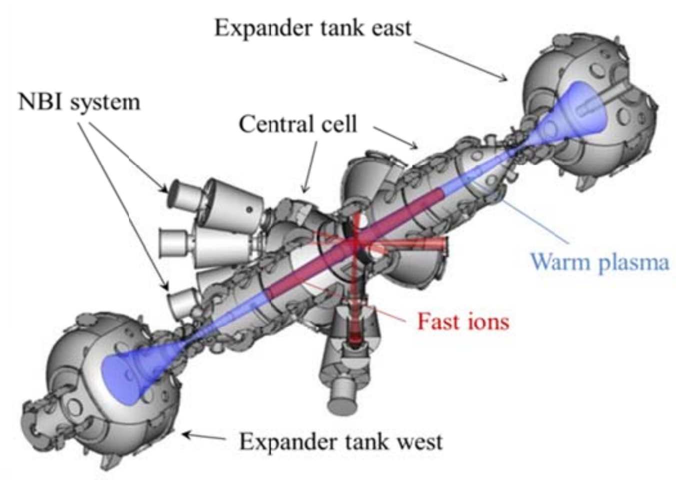

FIGURE 1. The layout of GDT experiment.

The GDT experimental achievements and recent progress of the Budker Institute in development of neutral beams for fusion studies [7] shift the projects of a GDT-based neutron source (GDT-NS) on a higher level of competitive ability and make possible today to construct a source with reasonable parameters, suitable for materials testing.

Another mirror–trap concept proposed by the Budker Institute as a neutron source is a gas-dynamic multiple-mirror trap (GDMT) [8] combines the features of existing GOL-3 [9] and GDT devices, namely the GDT-like central cell with sloshing ions produced by intense neutral beam injection, and the multiple-mirror end sections to suppress axial plasma losses. Such a combination became feasible due to recent findings in both GOL-3 and GDT experiments [10, 11].

The next sections of this paper present a status of numerical simulations of linear plasma neutron sources based on the achieved experimental data.

INSTRUMENTS AND TOOLS FOR SIMULATIONS

During the past few years the *Linear Neutron Source Code Package* (LNSCP) has been created and applied for numerical studies of GDT-NS and other mirror-based neutron source projects in parallel to the experimental research. This package is a development of the *Integrated Transport Code System* (ITCS) [12] and includes different numerical codes for plasma, gas and particle transport, neutron production, magnetic field etc. The main of them are the one-dimensional plasma code DOL [13] and updated 3D Monte-Carlo fast ion transport code MCFIT+ [14]

The DOL code has been developed to perform fast calculations of plasma parameters in possible GDT upgrades and modifications including fusion neutron source as well as NS optimization research [15]. The code is intended to calculate the dynamics of plasma processes in mirror traps with two-component plasma. In this code, the distribution function of fast ions is calculated by solving the bounce-averaged kinetic equation with allowance for variations in the fast-particle distribution function along the trap axis for the case of the time scale order $\tau_{ci} \ll \tau_{||} \ll \tau_d \sim \tau_s \sim \tau_{ex}$. Here, τ_{ci} is the time of cyclotron gyration; $\tau_{||}$ is the bounce-oscillation period; and τ_d, τ_s, and τ_{ex} are the characteristic times of deceleration, scattering, and charge exchange of fast particles, respectively. Longitudinal losses of warm plasma are modelled using a superposition of confinement mechanisms in the limiting cases. In particular, the possibility of plasma confinement in the gas-dynamic or weakly collisional case is taken into account and the effect of the ambipolar potential created by the population of fast particles is also allowed. In addition, the DOL code allows one to simulate the interaction of plasma with the neutral gas created as a result of hot atom injection.

The detailed description of the DOL code and nonstationary model of an axisymmetric mirror trap with non-equilibrium plasma (which is its bases) is presented in [13].

The three-dimensional Monte Carlo fast ion transport code MCFIT+ is a new updated version of the MCFIT code which was developed since the late of 90’s in collaboration with German partners from the Helmholtz-Zentrum Dresden-Rossendorf (HZDR) [16] for simulation of fast ion transport in GDT experiments.

The code based on the theory of binary Coulomb collisions and the equations of classical magnetohydrodynamics. In the main scheme of the MCFIT code, which is standard for the Monte Carlo method, statistically independent histories of fast particles are generated and their contributions are summed up into well-defined estimation values for each parameter of interest. After simulating N particle histories, the final result for each parameter is calculated as an average with the statistical error determined by R.M.S. deviations. It is evident that the method converges as $N^{-1/2}$. Thus the Monte Carlo code MCFIT simulates the linear transport of neutral beam produced energetic ions in given magnetic field, target plasma and neutral gas.

Last years, the MCFIT code has been substantially upgraded (to MCFIT+) for adequate simulation of various versions of the GDT-NS. The GDT-related physical phenomena were taken into account during the code modification:

- The main MCFIT module MOVER was corrected for simulation of particle transport in non-paraxial magnetic field.
- The high-β value causes a deformation of the vacuum magnetic field and, consequently, of the fast ion distribution too. To consider this non-linear effect the time and spatial distribution of azimuthal fast ion currents, calculated by MCFIT+, are used to compute the correction of the magnetic field according to the Biot-Savart law (*BiSav* code). Then, this β-corrected, time dependent magnetic field is used by MCFIT+ in an iteration procedure.
- An interaction of test particles not only with warm target plasma and gas, but also with fast ions was taking into account by an iteration procedure. Such process as beam particles ionization by fast ion impact, fast-to-fast ion scattering and charge exchange also as fusion reactions are simulating now by MCFIT+. For this feature, the calculation results of previous iterations (fast ion density distribution, energy and angle distribution function) are used as input data for the next iteration.
- A strong fast ion density in GDT and its modification produces a high electrostatic potential that reduces the warm ion density of the target plasma. An approximate relationship between the densities of warm and fast ions and electrons may be inferred applying Boltzmann's law for the electron and for the target plasma ion densities. MCFIT+ calculated warm ion and electron densities of target plasma in the 3D space by using unperturbed warm plasma density and fast ion distribution from input data in an iteration procedure.
- The MCFIT+ code was supplemented with a special block for analyzing the energies of fast particles falling into the loss cone and reaching the mirror section. As a result, the absolute values of the fast ion flux were obtained for given energy intervals at the edge of each (western and eastern) mirror [17].

The iteration process by using the MCFIT+ code and supporting programs (BiSav, PlasmaX and NeuFIT codes) is shown schematically on Fig.2.

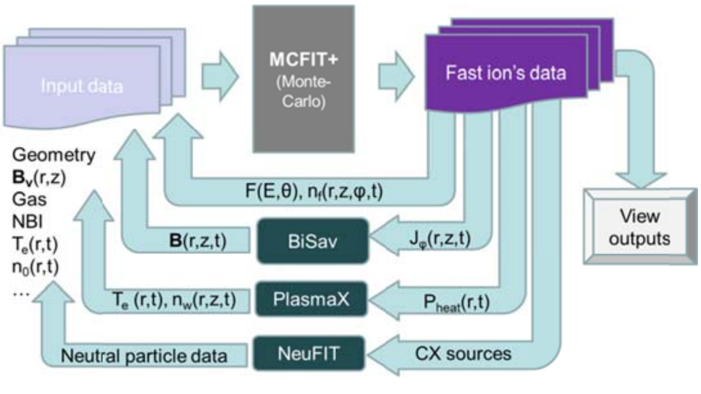

FIGURE 2. MCFIT+ iteration process structure.

The updated MCFIT+ transport code allows now to calculate a large variety of fast ion parameters. The result of the calculations are presenting in a form of a discrete distribution on a phase space mesh defined by the user via a sequence of time intervals. The main parameters are as follows: fast ion density distribution (separate for H,D and T if required), the global and local energy balance data, the spatial distribution of nuclear fusion reactions (DD and DT), the neutron flux to specified spatial regions ("detectors"), and the distribution functions of fast ions over energy and pitch angle. At present, the MCFIT+ code most completely describes the transport of fast ions in axisymmetric mirror traps and mirror based fusion devices.

RESULTS OF THE NEUTRON SOURCE SIMULATIONS

Table 1 presents a summary of simulation results for several GDT variations. The first column (a) shows the GDT experimental parameters were also simulated by the numerical codes described above. Results of this simulation are in a good agreement with experimental data, which is the best proof of our numerical tools. The second column (b) presents parameters of the GDT-U project—a possible next step of the GDT experiment. Detailed description of this numerical research will be presented by E. Kolesnikov in [18].

TABLE 1. Main results of GDT and GDT-base neutron source simulations:

	(a)	**(b)**	**(c)**	**(d)**
Parameters	**GDT exp.**	**GDT-2 (next)**	**GDT-NS**	**GDMT-NS**
Magnetic field, B_0/B_m (T)	0.34/12	0.5/15	1/15	1/9
Effective mirror ratio, k	35	30	15	75
Mirror-to-mirror distance, L (m)	7	7	10	10
NB injected/heat power, (MW)	5/3	9.6/7.2	40/30	40/30
NBI energy, E_{inj} (keV)	25	20	65	65
Pulse duration, (s)	0.005	0.03	continuous	continuous
Warm ion density, n_w (10^{20} m^{-3})	0.3	0.5	0.2	0.3
Fast ion density, n_f (10^{20} m^{-3})	0.5	0.7	2.5	3.5
Mean ion energy, T_i (keV)	10	10	35	30
Electron temperature, T_e (keV)	0.25/0.9 *	0.4/1*	0.7	1.5
Relative plasma pressure, β	0.6	0.5	0.5	0.5
Plasma radius, a (cm)	14	10	8	8
DT fusion neutron power, P_n (MW)	–	–	1.5	3
DT fusion energy gain factor, Q_{fus}	–	–	0.05	0.1

* with an addition ECRH

The numbers of DT fusion neutron source projects were simulated on the base of the achieved GDT experimental results. 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 (c) of Table 1. The GDMT based neutron source has improved axial confinement with the effective mirror ratio k up to 75 and high T_e. The simulated GDMT-NS parameters are presented in column (d). They allow to propose the GDMT-NS as a basic for different applications including fusion material test facilities and moderate fusion driven (hybrid) systems (FDS). Optimization of GDT- and GDMT-based neutron sources for hybrid system is presented by D. Yurov in [19].

A fusion neutron source based on DD-fusion reaction (tritium-free fuel) attracts a lot of interest recently. The multiple-mirror open magnetic system for plasma confinement is a most suitable configuration for realization of such neutron source. We have calculated parameters of the DD-fusion neutron source with moderate neutron flux of about 10^{12} $s^{-1}cm^{-2}$ in a 3 m long and Ø46 cm section that can be surrounded by fission core. The results of the simulations and possible applications of moderate DD-fusion neutron source are described in [20].

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