A neutron source based on gas dynamic trap for fusion-fission hybrid systems

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1. Introduction

To become an economic and save energy supplying technology nuclear fusion research has to solve several material problems. The most critical of them are caused by intense irradiation of high energetic neutrons. To develop appropriate materials, which can withstand the high neutron load, suitable neutron sources are necessary as irradiation facilities for testing material samples. Since the start of nuclear fusion programme various proposals for such a facility were made.

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]. Such DT-plasma source surrounded by sub-critical fission blanket provides some advantages as compared to accelerator-driven systems. Firstly, presence of 14 MeV neutrons in the generated spectrum allows to increase the efficiency of neutron production by (n,2n) reactions, which is a threshold behaviour, in the core region of the blanket. Moreover, the 14 MeV neutrons provide also greater incineration/transmutation capabilities of the system, since this permits even lower k_{eff}-regimes. Finally, the spatial distribution of the neutrons in a source opens new design possibilities for fusion-fission system.

2. Instruments & tools

The plasma physics calculations of the neutron source's parameters have been performed by the Integrated Transport Code System (ITCS) [6]. 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 was adopted for GDT neutron source condition. New physical phenomena such as a vortex confinement, improved axial confinement, ambipolar plugging, high β etc. were included in these simulations. 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 several resent developed plasma codes. A zero-dimensional code GENESIS (GENeral Evaluation SYStem) was developed in 2011 for brief simulations main plasma parameters in GDT and GDT-NS [7]. "Zero-dimensionality" suggests distribution function dynamics being considered with respect to system parameters averaged over fast particles movement area. Also the code is

Fig.1 Neutron emission rate along the machine axis.

equipped with additional module for linear neutron emission power calculation. Since the past year a new one-dimensional plasma code DOL is developing in Budker Institute for fast calculation of main plasma parameters evaluation in the mirror based neutron source. Verification of the developed plasma codes was provided by comparisons between GENESYS, DOL and ITCS/MCFIT calculation results together with the experimental data obtained in D–D GDT experiment [8] is presented on the figure 1. As it can be understood from the given graph, code results demonstrate satisfactory convergence with the experimental data.
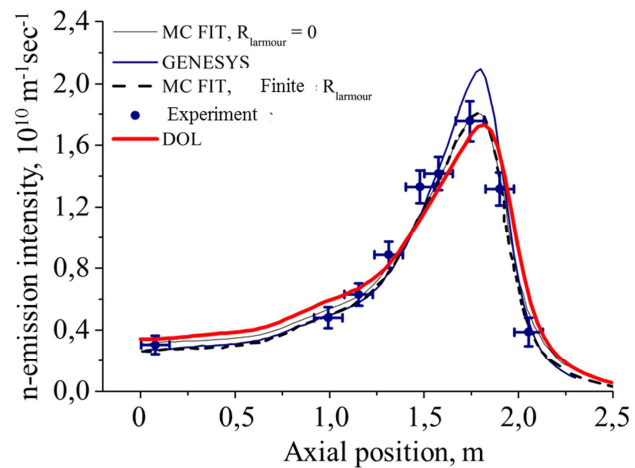
Neutron processes in the fuel blanket were simulated by NMC – a Monte-Carlo code being developed as a very flexible general purpose tool for the tasks of particle transport calculation in both static and dynamic systems were parameters vary in a short period of time [7,9]. The main idea of the developed code is extensive use of object-oriented paradigm for almost unlimited flexibility and expandability followed by only slight performance decrease. The code structure (see Fig.2) is built so as to make the majority of modelling workflow elements interchangeable. Hence it is possible to solve a wide range of tasks while employing the algorithms being most efficient for the given problem. Code calculation results were verified on a number of benchmark models described in [10]. The verification results for criticality coefficients of the fast spectrum benchmarks are presented in Fig. 3.
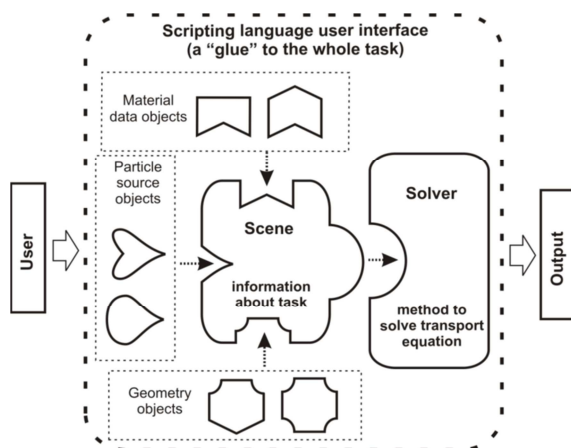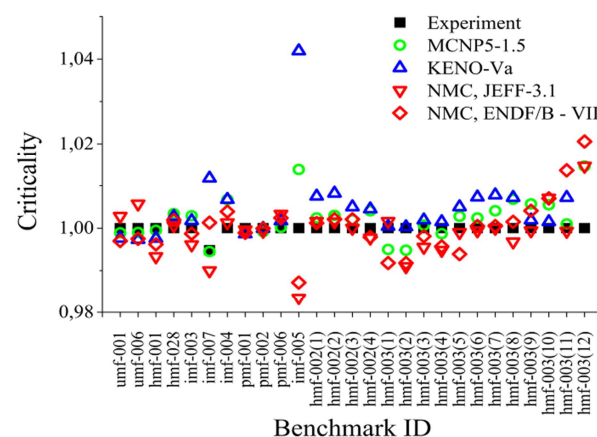

Fig.2 NMC code structure

Fig.3 Verification of NMC code

2. The GDT based neutron source

The powerful 14 MeV neutron source on the base of the gas dynamic trap plasma device that confines a deuterium-tritium plasma has been primarily developed as irradiation test facility for fusion material studies and for other application [1,2]. A research project of the Budker Institute aims at completing the database of the GDT in the high plasma parameter range, which is essential for the neutron source project. The basic version of the source dedicated for fusion material studies 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.

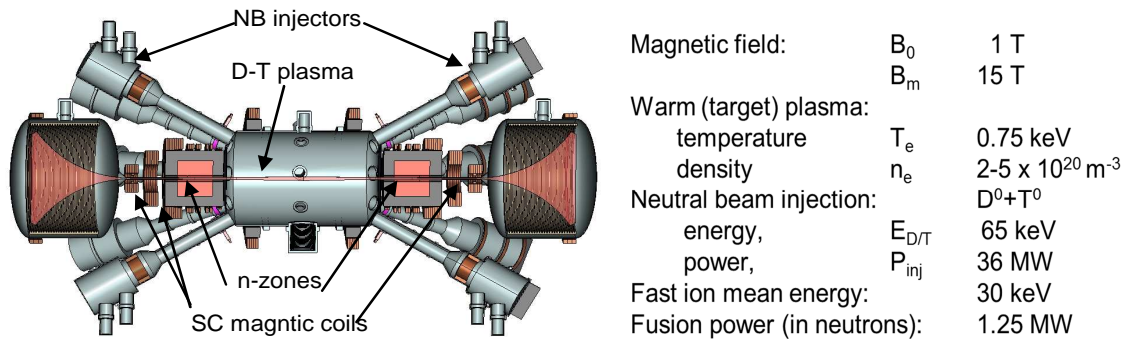| Magnetic field:	B_0	1 T
	B_m	15 T
Warm (target) plasma:		
temperature	T_e	0.75 keV
density	n_e	2-5 x 10^{20} m^{-3}
Neutral beam injection:		D^0+T^0
energy,	$E_{D/T}$	65 keV
power,	P_{inj}	36 MW
Fast ion mean energy:		30 keV
Fusion power (in neutrons):		1.25 MW

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

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

The idea how to apply the GDT-NS for FDS is to surround one or both neutron production zones (n-zones) by sub-critical fission reactor(-s). 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.

One option is the increase of the electron temperature T_e of the GDT-plasma. This value would reduce the energy loss rate of the high-energetic deuterons and tritons and, thereby, increase the fusion reaction rate considerably. In the "basic version" the electron temperature of the order of $10^{-2}E_{inj}$ was assumed (it is well established that under this condition the micro-turbulence is not excited in a mirror plasma). An artificial gas cooling of the electrons down to $T_e = 0.75$ keV has been introduced in the region of expander for increasing of MHD stability effect. But with the input parameters given at the previous section the self-consistent mathematical model of the GDT device [11] can yield the electron temperature up to 3.5 keV. This theoretical prediction is based on gas-dynamic collisionless model of the longitudinal plasma losses in GDT without electron heat conductivity and abnormal transverse losses. The last GDT experiment's results are in agreement with this model and confirm reality of our assumption [12].

By modifying the external magnetic field the ratio of the emission intensities of both neutron production volumes can be varied. Moreover, these zones can be longitudinally extended, and, even certain axial profiles of the neutron intensity could be adjusted. The

calculations show that for the basic GDT-NS the additional one meter of the "n-zone" produces 0.5 MW neutron power and "costs" 16 MW of electric power supply.

The most promising variant of a GDT NS for driven MA burner uses the both of described optimization: elongation of neutron emission zones by axial magnetic field modification and self-consistent electron temperature up to 2.5 keV. Also we take into account improved radial confinement by vortex method, reduction of the electron head losses from GDT and maximal plasma $\beta = 0.6$ according to last experimental results at GDT [12]. As a result, the improved version of proposed fusion neutron source is a 16 m long mirror device of the GDT type with a mirror ratio of 15. The energy of the injected particles is supposed to be 65 keV and the assumed total injection power is 75 MW and 120 MW total energy consumption. The source has a fusion power of 1.6 MW/m and a neutron production rate up to 2×10^{18} n/s in the simple cylindrical volume of 2 m length and 30 cm radius.

This neutron source can be used for application as a fusion driver in a nuclear waste burner and other fusion-fission hybrid systems.

4. Conclusions

− The wide set of computer codes was developed for modeling of the GDT neutron source and also nuclear power systems on its basis.

− Optimization of the GDT based neutron source for the purpose of decrease in energy "cost" of a neutron was executed.

− An increase of the electron temperature of the GDT-plasma up to the self-consistent value would result in an increase of the $Q_{el} \equiv P_{outel}/P_{supp}$ by a factor of about three.

− The GDT-NS offers the possibility for longitudinally stretching the neutron production volume. Thereby, the total strength and the energetic efficiency of the source can be substantially increased.

− A new improved model of the GDT-NS with high self-consistent $T_e \sim 2.5$ keV and longitudinal stretch was proposed and numerically simulated. This fusion neutron source with $Q_{fus} \equiv P_{fus} / P_{head} \sim 0.3$ has 2 m long n-zones with 1.5 MW/m neutron yield and up to 1.5×10^{18} n/s on each side. A system with two sub-critical MA burners driven by one such neutron source can produce total about 1.2 GW_{th} of fission power with an energy multiplication factor $Q_{el} = 4$ and incinerate in a year about 150 kg of MA that are produced by 5 LWR.

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