Experimental results in support of the neutron source based on an axisymmetric mirror trap

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Fusion energy deployment will require materials that withstand intense long-term bombardment by 14 MeV neutrons. Qualifying materials and components will require testing in such a neutron environment. The Gas Dynamic Trap (GDT) concept in Novosibirsk is proposed for a neutron and plasma source design to test and validate appropriate materials [1]. Recent results from GDT (at 60% beta [2]) provide a firm basis for extrapolating to a fusion-relevant neutron source. In comparison with previous magnetic-mirror neutron sources, the GDT operates with simpler axisymmetric magnets and at a higher efficiency. Another significant application of the GDT based neutron source is driving of hybrid fusion-fission reactors. Hybrid reactors can be used in the future for different applications including nuclear waste processing based on fusion driven burning of minor actinides [3,4].

The main part of the GDT facility (see Fig. 1) is an axially symmetric magnetic mirror with high mirror ratio. The confined plasma consists of two ion components: the background ions with a temperature of about 250 eV and density $2{\cdot}10^{19}$ m^{-3} confined in a gas-dynamic regime, and the hot ions, produced as a result of oblique injection of high-power (up to 5 MW) hydrogen or deuterium beams into the plasma. A distribution function of the hot component is essentially anisotropic in the velocity space; therefore density and pressure of the hot ions are peaked in the mirror (turning) points providing conditions for the fusion reactions. Presently mean energy of the hot ions is about 9 keV, and their density near the mirror points reaches $5{\cdot}10^{19}$ m^{-3}.

The following key physical problems should be solved to carry out the feasibility study of the GDT based neutron source.

1. It is necessary to insure the MHD stability of the plasma column. Another possible way is the development of an effective method to suppress the transverse particle and energy transport in the presence of the MHD instabilities. It should be mentioned, that magnetic configuration of the axisymmetric mirror trap is unfavorable for the MHD stability. It is very

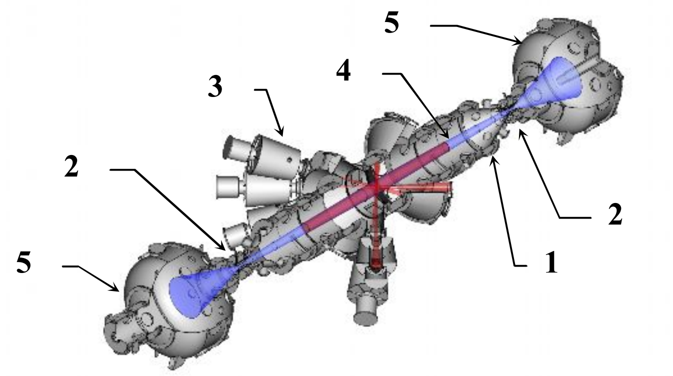

Fig. 1. The GDT layout: 1 – solenoidal magnetic coils; 2 – mirror coils; 3 – neutral beam injectors; 4 – plasma column; 5 – plasma absorbers.

important also to carry out plasma confinement in the regime with high beta (β≈1) and negligible level of transverse flow in comparison with longitudinal flux. In the opposite case mirror-based fusion systems are not competitive in comparison with similar systems based on tokamaks and stellarators.

2. It is necessary to prove in detail experimentally, that dependence of longitudinal plasma confinement time on heating power corresponds to theoretically predicted scaling for magnetic mirror systems and does not correspond to anomalous electron conductivity (e.g. Spitzer's one).

Results of the experiments oriented on the basic problems listed above are presented in this paper.

For the suppression of the perpendicular losses due to the development of MHD instabilities was implemented an earlier experimentally and theoretically well-grounded method of vortex confinement. Vortex confinement is put into effect if the radial profile of electric potential in plasma has a stepped structure, and potential jump is located in the peripheral radial area of plasma column. This potential profile was created by the means of special electrodes: radially segmented plasma absorbers located behind the mirrors and radial limiters close to the magnetic mirrors inside the central cell of the trap. The positive voltage relative to the grounded internal sections of plasma absorbers of 250-350 V was applied to the radial limiters and external sections of plasma absorbers. Those parts of the electrodes are projected one onto another along the magnetic field lines. Such radial electric potential distribution generates the

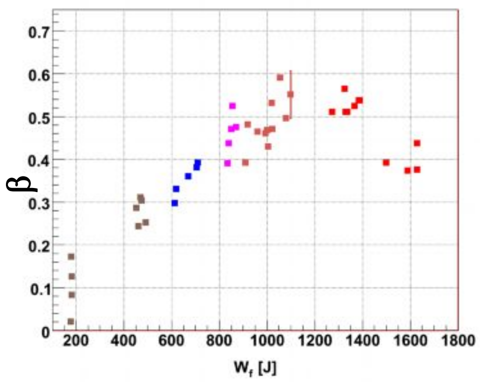

Fig. 2. Local β value measured on the axis at the turning points region of hot ions versus total energy of the fast ion population.

zone of plasma differential rotation in the peripheral radial area of plasma column. It turns out that combination of plasma differential rotation with plasma motion at the saturated stage of unstable MHD modes leads to the formation of a steady-state vortex structure of plasma flux lines. The analysis of the influence of the shear flow on the plasma confinement in the mirror system was carried out in the work [5]. The main conclusion based on the experimental results [2] and theoretical analysis [5] is that the method of vortex confinement for Gas Dynamic Trap allows to minimize the perpendicular energy losses power to the 10-15% of longitudinal one. Also, it is noteworthy that the additional energy consumption for the maintenance of the vortex confinement regime does not exceed several percents of total plasma heating power. These conclusions are also valid for the neutron source being projected which is based on the GDT device. The local β value versus the total energy of fast ion population in the vortex confinement regime is shown in Figure 2. The Measurements were made at the centre of plasma column in the area of ion reflection by the means of beam-spectroscopic diagnostics based on the Motional Stark effect. The maximum β value reaches β≈0.6.

The series of measurements in the regimes with different power of atomic beam injection were made in order to evaluate the role of the perpendicular losses in comparison with the longitudinal one and to make the scaling of electron temperature dependence on the plasma heating power. The system of atomic beam injection consists of 8 injector modules. Series of measurements were carried out in the regimes with hydrogen injection into hydrogen plasma using 2, 4, 6 or 8 injectors. Trapped power of the injected beams, plasma density and temperature and the power of charge-exchange losses of the hot ions were measured. The estimation of the electron temperature at the GDT device defined by the balance of heat fluxes in plasma was made taking into account the following considerations.

1. It is assumed that there is a steady-state regime relative to the all processes which define the plasma confinement at the GDT device
2. Stationary balance is

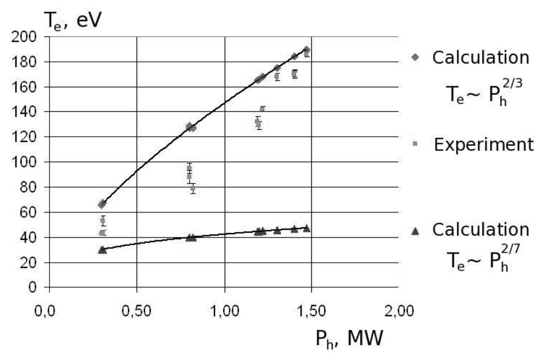

Fig. 3 The dependences of the electron temperature experimentally measured (gray squares) and computed temperature which was obtained from the scaling (1) (dark squares) on the plasma heating power. Results of calculations of electron temperature based on classical Spitzer's heat conductivity are plotted also for comparison (triangles).

determined by the equality of heating power of the atomic injection and the power of longitudinal losses in the case of gas dynamic plasma flow passing through the mirrors in the absence of perpendicular losses.

According to conclusions of the work [1], which are in a good agreement with the results of the experiment [1,6], the electron temperature satisfies the next scaling in the case of steady-state gas dynamic plasma flow passing through the mirrors and in the absence of perpendicular losses:

$$T_e \propto \left(P_h \cdot R\right)^{2/3}, \qquad (1)$$

where R – mirror ratio, P_h – power of plasma heating by the atomic injection (it equals to the trapped atomic beam power after deduction of the charge-exchange losses of hot ions; other possible loss channels of hot ions are assumed to be negligible).

The dependences of the electron temperature experimentally measured by the means of laser-scattering system and the computed temperature which was obtained from the scaling (1) on the plasma heating power are shown in Figure 3. One can see that estimation results are in a good agreement with measured values for the temperatures T_e>150 eV. Note that estimations were carried out in the frame of hypothesis about negligible level of transversal heat flux in comparison with longitudinal one. Results of calculations of electron temperature based on classical Spitzer's heat conductivity are plotted also for comparison.

Two circumstances are following from the data plotted in Figure 3.

1. Transversal energy flux is negligible in comparison with the longitudinal one in the regime of vortex confinement. Scaling (1) based on the steady-state balance between heat power and longitudinal heat losses in the gas dynamic regime of plasma flow passing through the mirror throats is in a reasonable agreement with experimental data.
2. Taking into account scaling (1), one can predict the value of electron temperature more than 1 keV for the heating power of ≈20 MW in the neutron source being projected which is based on the Gas Dynamic Trap. According to the results of computer simulations [3,4] this value of T_e is quite suitable for effective production of neutrons.

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[1] V.V. Mirnov and D.D. Ryutov, Sov. Tech. Phys. Lett., v. 5 (1979), 229.
[2] P.A.Bagryansky et al., Fusion Science and Technology, v. 59 (2011), No 1t, 31-35.
[3] K.Noack et al., Annals of Nuclear Energy, v. 35 (2008) 1216.
[4] D.V.Yurov et al., Fusion Engineering and Design, v. 87 (2012) 1684– 1692
[5] A.D. Beklemishev et al., Fusion Science and Technology, v. 57 (2010), 351- 360.
[6] P.A.Bagryansky et. al., Fusion Engineering and Design, v. 70 (2004), 13-33.