CONFINEMENT OF HOT ION PLASMA WITH β=0.6 IN THE GAS DYNAMIC TRAP

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A so called vortex confinement of plasma in axially symmetric mirror device was studied. This recently developed approach enables to significantly reduce transverse particle and heat losses typically caused by MHD instabilities which can be excited in this case. Vortex confinement regime was established by application of different potentials to the radial plasma limiters and end-plates. As a result, the sheared plasma flow at periphery appears which wraps the plasma core. Experiments were carried out on the gas dynamic trap device, where hot ions with a mean energy of $E_h \approx 9$ *keV and the maximum density of energetic ions* $n_h \approx 5\cdot 10^{19} m^{-3}$ *were produced by oblique injection of deuterium or hydrogen neutral beams into a collisional warm plasma with the electron temperature up to 250 eV and density* $n_w \approx 2\cdot 10^{19} m^{-3}$. *Local plasma* β *approaching 0.6 was measured. The measured transverse heat losses were considerably smaller than the axial ones. The measured axial losses were found to be in a good agreement with the results of numerical simulations. Recent experimental results support the concept of the neutron source based on the gas dynamic trap.*

I. INTRODUCTION

The development of fusion energy sources requires materials which can withstand energetic neutrons and plasma during decades. The Gas Dynamic Trap (GDT) in Novosibirsk [1] was intended to be used for development of a fusion neutron source to test and validate appropriate materials [2]. Recent results with β=0.6 [3] provides a firm basis for extrapolating to a fusion relevant neutron source. Relative to previous magnetic mirror neutron sources[4,5], the GDT concept uses simpler axisymmetric magnets and consumes less tritium providing about 2MW/m^2 neutron flux. Besides testing materials, the GDT based neutron source can be used in a fusion driven system for burning minor actinides of nuclear waste [6].

The main part of the Gas Dynamic Trap device is an axially symmetric magnetic mirror with high mirror ratio for confinement of plasma, which consists of two ion components with different energies (Fig.1). First of them is warm ions with isotropic in velocity space Maxwellian distribution function, with temperature about 200 eV, density $n_w \approx 2\cdot 10^{19} m^{-3}$. These ions are confined in the gas-dynamic regime[1]. The second component is hot ions, which are produced as a result of oblique injection of hydrogen or deuterium beams into plasma. Energies of injected atoms are in the range of 22-25 keV. The hot ions are confined in the adiabatic regime performing bounce oscillations between the mirror points near the mirror ends. Energy confinement time of hot ions is determined by the electron drag and turns out to be much less than its angular scattering time. Thus the hot ions have anisotropic in the velocity space distribution function, relatively small angular spread, and their density and pressure are peaked in the mirror points. The mean energy of the hot ions is $E_h \approx 9$ keV, and their density near the mirror points reaches $n_h \approx 5\cdot 10^{19} m^{-3}$. The temperature of electrons reaches $T_e \approx$ 250 eV.

In 2009 the GDT device was substantially upgraded: power of atomic injection system was increased, magnetic field was increased, and diagnostics were updated. The GDT parameters after upgrade are listed in Table I.

The experimental program at the GDT device is focused at obtaining the fundamental knowledge of physics of plasma confinement in the open magnetic traps and on the other hand at gaining a database for development of a high-flux neutron source.

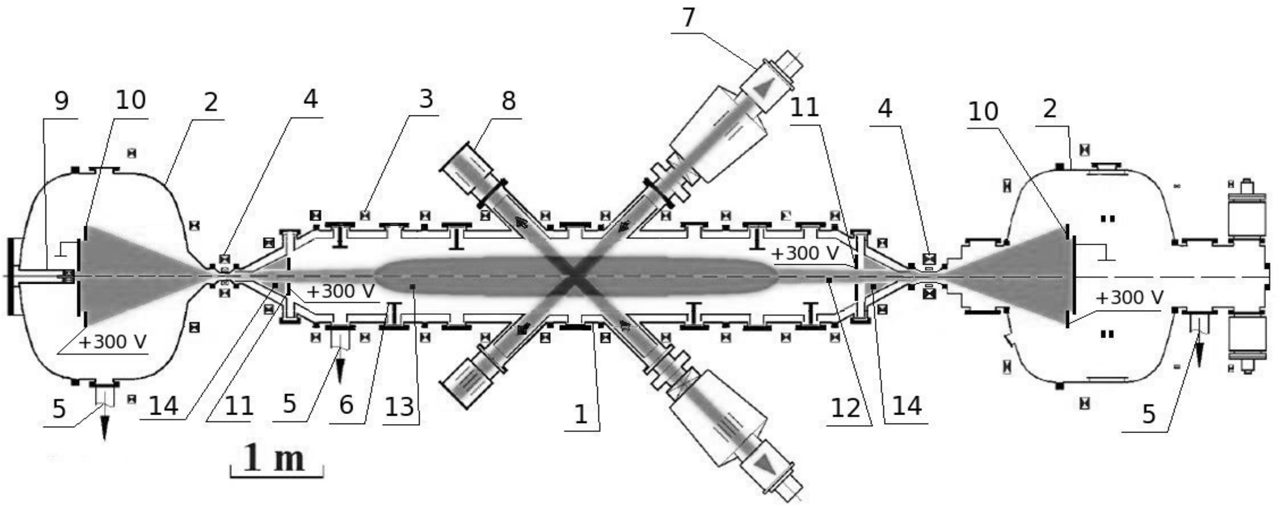

Fig. 1 Schematic of the GDT device: 1 – central vacuum vessel; 2 – end tanks; central solenoid coils; 4 – mirror coils; 5 – vacuum pumping ports; 6 – titanium evaporators; 7 – neutral beam injectors; 8 – neutral beam dumps; 9 – initial plasma source; 10 – sectioned end-plates (central parts are grounded, internal rings are biased with approximately +300 V; 11 - biasing limiters; 12 – warm plasma column; 13 – hot ion column; 14 – boxes for cold gas fueling.

In the general case the magnetic field of an axially symmetric magnetic trap is not providing the MHD stable plasma confinement [7]. In this work we present the results of experiments where the "vortex confinement method" was used for the suppression of perpendicular losses due to development of unstable MHD modes in the axially symmetric mirror device without additional stabilizing magnetic cells. This involves the differential plasma rotation at periphery. Interaction between shear flows and plasma motions due to instabilities in axially symmetric mirrors can lead to an improved radial confinement [8], observed also in the GDT experiments and confirmed by simulations [9]. Shear flows, driven by using the biased end-plates and limiters, in combination with finite-Larmor-radius effects are shown to be efficient to radially confine high-β plasma even with magnetic hill on axis. Interpretation of the observed effects as the "vortex confinement", i.e., confinement of the plasma core in the dead-flow zone of the driven vortex, agrees rather well with simulations. Theoretical scaling laws predict such confinement scheme to be also applicable at higher plasma temperature and density.

Local plasma β approaching 0.6 was measured in the steady-state regime of plasma confinement. At the same time the longitudinal losses of particles and energy are in a good correspondence with gas-dynamic model of collisional plasma streaming through the mirrors and the role of perpendicular losses is insignificant. Recent experimental results support the concept of the neutron source based on the gas dynamic trap.

TABLE I. Parameters of the GDT device

Mirror-to-mirror distance	7 m
Magnetic field at the mid-plane	up to 0.35 T
Mirror ratio	33
Total neutral beam power	up to 5 MW
Trapped beam power	1.8 MW
Time of neutral beams operation	5 ms
Injection angle	45°
Warm ion density at the mid-plane	$2\cdot10^{19}\mathrm{m}^{-3}$
Fast ion density at turning points	up to $5\cdot10^{19}\mathrm{m}^{-3}$
Electron temperature	up to 250 eV
Plasma radius at mid-plane	0.14 m

II. EXPERIMENT

Typical experimental scenario at the GDT device was the following:

- At first the magnetic field was created.
- Then the preliminary plasma having temperature of 10 eV filled the trap with the help of plasma source behind the mirror at one of the GDT sides. Exit aperture of the source was in the plane where magnetic field was 100 times less than that in the mirrors. Duration of the plasma source operation was 4 ms.
- After the plasma generator shutoff the injection of neutral beams started. The injection system consisted of 8 injector modules. The duration of neutral beam injection was 5 ms.
- At the same time started the injection of gaseous hydrogen or deuterium azimuth evenly into the peripheral

plasma with the help of two pulsed valves located near the magnetic mirrors where plasma had relatively small diameter. The duration of gas injection was usually a little bit longer than 5 ms. The central vacuum vessel and the end tanks are pumped out by 1.5 m^3/s turbomolecular pumps each. In order to improve wall conditions in the central cell of vacuum chamber Ti-evaporators have been installed which are capable of deposition a sufficiently thin metallic film on the inner surface of the chamber in shot time just before plasma shot [10].

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 [9]. Vortex confinement occurs when the radial profile of electric potential in plasma has stepped structure, and potential jump is located in the peripheral radial area of plasma column. This potential profile was created with the help of special electrodes: radially segmented plasma absorbers located behind the mirrors near the planes where magnetic field is 100 times less than magnetic field in the mirrors, and also by means of radial limiters inside the trap close to the magnetic mirrors. The positive relative to the grounded internal sections of plasma absorbers voltage of 200-300 eV was applied to the radial limiters and external sections of plasma absorbers which are projected one onto another along the magnetic field lines. Such radial electric potential distribution generates the zone of plasma differential rotation in the peripheral radial area of plasma column. It turns out that combination of plasma differential rotation with its motion at the saturation stage of unstable MHD modes leads to 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]. Analytical and numerical models of vortex confinement occurring in the presence of electric potential drop in plasma close to the limiter radius were developed. The model takes into account the most essential effects: electric contact with limiters and end plasma absorbers, electron temperature gradient, finite ion Larmor radius effects, and thus is capable to describe the non-linear development of different large-scale instabilities. Particularly Kelvin-Helmholtz, flute-like and temperature-gradient instabilities are described.

Plasma vortex confinement described by the model is that hot central discharge part can be confined in the stagnant zone of vortex flow. If this flow is generated and supported by the external sources then the regime with small convective loss can be achieved. Though the plasma remains linearly unstable, convection is saturated at a low level, and the main thing is that the central convective cell does not reach the limiter. Non-linear convection saturation as well as the generation of the vortex flow are connected with the end current dissipation. This dissipation is especially effective for large-scale modes m=1, preferential selection of which occurs in plasma with hot ions due to finite ion Larmour radius effects. The main conclusion of the work [5] is that for gas dynamic trap the method of vortex confinement allows to minimize the power of energy perpendicular loss to the 10-15% of longitudinal loss power. And 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 projected neutron source based on the GDT device.

III. RESULTS

Several experimental series were carried out with different combination of hot ion and warm ion masses. The closest to the steady-state regime was the regime with hydrogen injection into the hydrogen plasma. The highest value of the diamagnetism was obtained in the regimes with deuterium injection into hydrogen or deuterium plasma. These facts are connected with the different value of energy confinement time of hot ions which is determined basically by the electron dragging and is proportional to the ion mass:

$$\tau_{ei} = \frac{3}{4\sqrt{2\pi}} \cdot \frac{m_i}{\sqrt{m_e}} \frac{T_e^{3/2}}{z^2 \cdot \Lambda \cdot e^4 \cdot n},$$

where m, z –mass and charge of hot ions, m_e, e, n, T_e – mass, charge, density and temperature of the electrons, Λ - Coulomb logarithm.

In the figure 2 local magnetic field perturbation, versus total energy of fast ion population is shown in the regime with deuterium injection into hydrogen plasma. Measurements were made at the centre of plasma column in the area of ion reflection with the help of beam-spectroscopic diagnostics based on the Motional Stark effect. Spatial resolution of the measurement of local magnetic field variation was 3 cm, time resolution – 1 ms. Mean value of local magnetic field variation to the vacuum magnetic field ratio in the series of measurements was $\Delta B/B_v$=0.32, maximal value obtained in one of the shots reached $\Delta B/B_v$=0.37.

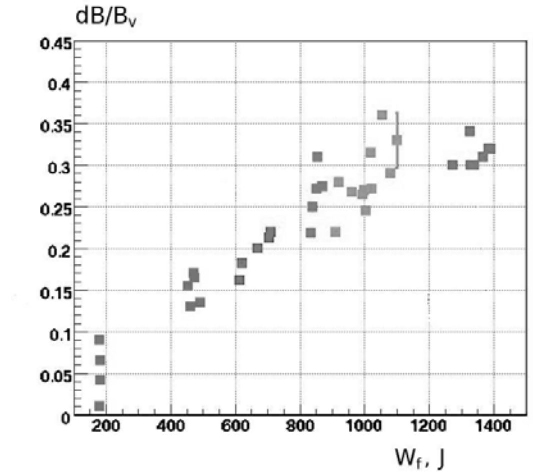

Fig. 2. Local magnetic field perturbation measured on the axes at the turning points region of hot ions versus total energy of fast ion population.

Value of the parameter β was calculated using the plasma equilibrium equation in the paraxial approximation:

$$\beta = 2 \cdot \frac{\Delta B}{B_V} - \left(\frac{\Delta B}{B_V} \right)^2 ,$$

where B_v – value of the vacuum magnetic field, $\Delta B = B_v - B$ – magnetic field variation due to the plasma diamagnetism, B – measured value of the magnetic field. Parameter β=0.54 corresponds to the $\Delta B/B_v$=0.32, β=0.6 corresponds to the maximum value $\Delta B/B_v$=0.37. Using values of β, B, and the mean energy of hot ions $<\varepsilon>$ maximum value of hot ion density can be estimated $n_h = \frac{\beta \cdot B_v^2}{8\pi \cdot <\varepsilon>}$. For the regime with β=0.6, $<\varepsilon> \approx$ 9 keV from the estimation it follows that $n_h \approx 5 \cdot 10^{19}$ m $^{-3}$.

To evaluate the role of the perpendicular loss in comparison with the longitudinal one and to make the scaling of electron temperature dependence on the power of plasma heating the series of measurements of different parameters were made at the regimes with different power of atomic beam injection. The system of atomic beam injection consists of 8 injector modules. Series of measurements were conducted at the regimes with hydrogen injection into hydrogen plasma using 2, 4, 6 and 8 injectors. Trapped power of the injected beams, plasma density and temperature and the power of charge-exchange loss 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 confinements at the GDT device
2. Stationary balance is determined by the equality of heating power of the atomic injection and the power of longitudinal loss in the case of gas dynamic plasma flow through the mirrors and absence of perpendicular loss.

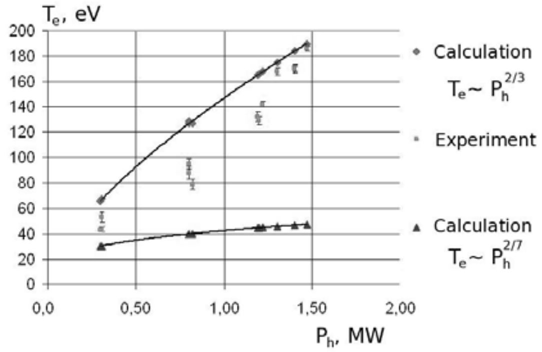

Fig. 3. The dependence of the electron temperature experimentally measured laser-scattering system (gray squares) and calculated temperature obtained from the equation (2) (dark squares) on the power of plasma heating. Results of calculations of electron temperature based on classical Spitzer's heat conductivity are plotted also for comparison (triangles).

According to conclusions of the work [1] which are in a good agreement with the results of experiment [2] the ion and electron flux densities at the middle cross-section of the mirror in the case of gas dynamic plasma flow are:

$$q_i = q_e = 1.53 \cdot n_w \cdot \left(\frac{T_e}{2\pi m_w} \right)^{1/2} ,$$

where m_w – the mass of warm ions, n_w – the density of warm ions in the trap. From the results of work [1,2] it also follows that every electron-ion pair exiting the trap should carry the mean energy of $8 \cdot T_e$ and the density of energy flux at the mirror cross-section is:

$$Q = 7.89 \cdot q_i \cdot T_e .$$

Equating the longitudinal loss power into 2 throats and plasma heating power it turns out:

$$P_{\|} = 2 \cdot Q \cdot S_m = \frac{2 \cdot Q \cdot \pi \cdot a^2}{R} = P_h , \qquad (1)$$

where $S_m = \pi \cdot a^2 / R$ – the area of middle cross-section of the mirror, a – plasma radius at the central section, R – mirror ratio, P_h – power of plasma heating by the atomic injection (it is equal to the trapped atomic beam power after deduction of charge-exchange loss of hot ions, it is considered that other possible loss channels of hot ions are negligible). Having substituted appropriate expression in the equation (1) and expressing T$_e$, we obtain in practical units:

$$T_e = 765 \cdot \left(\frac{P_h \cdot R}{n_w \cdot a^2} \right)^{2/3}, \qquad (2)$$

where P_h should be expressed in MW, n_w – in 10^{19} m^{-3}, a – in cm, T_e – in electron-Volts.

In the figure 3 the dependence of the electron temperature experimentally measured with the help of laser-scattering system and the calculated temperature obtained from the equation (2) on the different power of plasma heating are shown. One can see that for the temperatures T_e>150 eV results of estimation are in a good agreement with measured values. 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 on the figure 2:

1. transversal energy flux is negligible in comparison with the longitudinal one in the regime of vortex confinement. Scaling (2) based on the steady state balance between heat power and longitudinal heat loss in the gas dynamic regime of plasma flow through the mirror throats is in a reasonable agreement with experimental data.
2. Taking into account scaling (2) one can predict value of electron temperature more than 1 keV for heat power of ≈20 MW in the projecting neutron source based on the das dynamic trap. According results of computer simulations [6] this value of T_e is quite suitable for effective production of neutrons.

IV. CONCLUSIONS

On the basis of the experiments presented in this work the following conclusions can be made:

1. The longitudinal particle and energy loss are in the good agreement with the model of gas dynamic flow of the collisional plasma through the mirrors, and the perpendicular heating power loss does not exceed 15% of total plasma heat power.
2. Obtained results in the aggregate with some earlier results are the sufficient argument supporting feasibility of the project of the neutron source based on the gas dynamic trap.

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