AXISYMMETRIC OPEN MAGNETIC SYSTEMS FOR PLASMA CONFINEMENT

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At present, three modern types of different mirror machines for plasma confinement and heating exist in Novosibirsk (Gas Dynamic Trap, -GDT, Multi-mirror, - GOL-3, Tandem Mirror, -AMBAL-M). All these systems are attractive from the engineering point of view because of very simple axisymmetric geometry of magnetic configurations. In this paper, the status of different confinement systems is presented. The experiments most crucial for the mirror concept are described such as a demonstration of different principles of suppression of electron heat conductivity (GDT, GOL-3), finding of MHD stable regimes of plasma confinement in axisymmetric geometric of magnetic field (GDT, AMBAL-M), an effective heating of dense plasma by relativistic electron beam (GOL-3), observation of radial diffusion of quiescent plasma with practically classical diffusion coefficient (AMBAL-M), etc. The main plasma parameters achieved in mentioned above systems are presented.

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I. INTRODUCTION

At present, there are two main types of magnetic configurations for plasma confinement: closed (like tokamak, stellarator, etc) and open (like mirrors). Advantages of the open systems are as follows.

1.Most of such systems can operate in steady state regime. At the same time, effects of disruptions are not appeared in them.

2.Plasma pressure can be comparable with magnetic field pressure. As to multi-mirror system, the β value, in this case, can be even significantly higher than unity (so called “wall confinement”).

3.There are no divertor problems in the mirror case.

4.Open systems are convenient for direct energy conversion of charged particles. This circumstance can turn out to be especially important in a future for “low-neutron” schemes of fusion reactions.

Physical and technological feasibility of controlled fusion will be finally demonstrated in the frame of ITER project. However, the program of studies on controlled fusion will not complete on that. In the nearest future fusion reactors with D-T fuel seem the most appropriate from technical point of view. Thus, before the next step of fusion program (DEMO) after ITER all the structural materials should be tested on resistance to irradiation by high power flux of 14 MeV neutrons. It follows from this that problem of construction of high power neutron source should be solved as soon as possible. One of the systems discussed below, namely, gas dynamic trap has a good perspective as a volumetric neutron source with rather low tritium and power consumption in comparison with other candidates. At the same time, the area and volume of the testing zone in this source are enough for tests.

At present, studies of plasma confinement and heating in the open systems are carried out in Japan, Korea and Russia. The complete set of modern mirror type systems exists in Novosibirsk. Among them there are multi-mirror system (GOL-3), gas dynamic trap (GDT), and ambipolar (tandem) mirror machine (AMBAL-M). The most important results and the status of Novosibirsk studies in the field of magnetic mirrors are described in the paper.

II. GAS DYNAMIC TRAP (GDT)

A gas dynamic trap (GDT) for plasma confinement was first proposed in the Budker Institute [1] as a possible approach to development of a fusion reactor. It is essentially one of the simplest systems for magnetic plasma confinement. As a matter of fact, GDT is an axially symmetric magnetic mirror of the Budker-Post type, but with a high mirror ratio (R>10) and with a mirror to mirror length L exceeding a mean free path λ for the ion scattering into loss cone. Thus, due to frequent collisions the plasma confined in the trap is very close to isotropic Maxwellian state, and, therefore, many instabilities, which are potentially dangerous for the classical magnetic mirrors with a collisionless plasma, can not excite anymore. Moreover, in contrast to the conventional mirrors, longitudinal plasma losses are not sensitive to the ion angular scattering rate that might be enhanced by micro instabilities. This attractive feature of the GDT plasma confinement can be understood by consideration of a simple model. Namely, the plasma losses through the GDT end mirrors qualitatively are similar to those of a collisional gas in the bottle with a small hole through which it leaks out. The smaller cross section of the hole, the longer time is needed for gas to escape. The total number of particles in the trap is equal to LSn_0 (here n_0 is a plasma density and S is the plasma cross section at the central part of the trap) and the number of particles leaving the trap through end mirrors per second can be estimated as $\mathbf{n_0V_{Ti}S_m}$ (here $\mathbf{V_{Ti}}$ is ion thermal velocity and $\mathbf{S_m}$ is the plasma cross section in the mirrors. Then the confinement time can be determined as $\boldsymbol{\tau} \approx \mathbf{LSn_0/S_mn_0V_{Ti}} = \mathbf{R{\cdot}L/V_{Ti}}$ and it appears to be proportional to the mirror ratio **R** and length **L** of the trap. According to this relationship, plasma lifetime can be made long enough and appropriate to the fusion applications if the device is long enough and mirror ratio is high. Numerous advantages of the GDT approach follow from this very simple and reliable physics of longitudinal plasma confinement and from axial symmetry of the system. The experiments on study of the effects of gas dynamic plasma confinement are carried out on GDT device. The vacuum chamber of the GDT consists of a cylindrical central cell 7 m long and 1 m in diameter and two expander tanks attached at both ends.

The device has an axisymmetric magnetic field configuration. The main parameters of the device are presented in the Table 1.

Table 1. Parameters of the GDT device.

Parameter Value

Mirror to mirror distance7 mMagnetic field: at midplaneUp to 0.3 TTarget plasma: density3-20×10^{19}m^{-3}Radius at the midplane8-15 cmElectron temperatureUp to 130 eVNeutral beams: energy15–17 keVpulse duration1.1 msInjection powerMax 4.1 MWInjection angle45ºDensity of fast ions10^{19}m^{-3}Mean energy of fast ions8 –10 keVMaximal plasma ß40%

2.5-15 T

In mirrors

Neutral beam injection is used for plasma heating, Besides, due to oblique injection (at 45° to the axis of the device) a population of fast sloshing ions is formed. In the case of injection of tritium and deuterium beams this population can produce (mostly in the vicinity of turning points) high power neutron flux.

The experiments on the GDT device have already enabled to obtain several principal results.

MHD stabilization in Axisymmetric Geometry

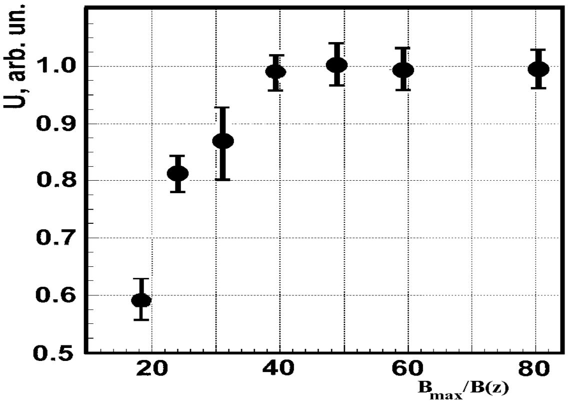

Fig.1. Plasma potential in the central cell depending on ratio of magnetic field in mirror to the field at the point where the movable segment of end wall is placed

It was successfully demonstrated that the MHD plasma stability can be achieved in axially symmetric magnetic field. Flute modes were stabilized by using external anchor cells in which the field line curvature is favorable for stability. The stability is achieved if the contribution of the anchor cells to pressure-weighted curvature overcomes negative contribution of the central cell. Remote anchor cells of two different types were experimentally tested. The first one is an expander end cell in which the plasma from the mirror throat expands along gradually decreasing magnetic field to the end walls. The magnetic field inside the expander end cells is formed by a combination the above mentioned decreasing magnetic field of the central cell and the field of additional large radius expander coils mounted at the end tanks. A current in these coils is opposite to that of the central cell coils providing the required concave form of the field lines. An additional coil set installed in one of the end tank enables to form here a cusp end cell. Effects of stabilization by the cusp end cell were also studied. These experiments have shown that the problem of MHD stabilization of the plasma in the axisymmetric magnetic configuration can be successfully solved [3]. Theoretical studies of ballooning modes stability in GDT predicts that the central cell β must be less than 0.7-0.8 for stability [4]. In order to obtain such a high β limit, magnetic field profile in the central cell has to be properly optimized. For the GDT device, magnetic field in the central cell differs from this optimized field and, therefore, the β limit amounts to 0.36 in this case. Recently, on-axis β exceeding 0.4 was obtained and measured in GDT near turning point of the fast ions by Motional Stark Effect diagnostics [5].

Suppression of the Longitudinal Electron Heat Conduction

One of the most critical issues related to plasma confinement in mirrors is the danger of too high electron heat losses due to direct plasma contact to the end wall. However, for sufficiently high expansion of the field lines from the mirror to the end wall the theory [6] predicts strong reduction of the longitudinal electron heat losses. A nature of this phenomenon links to an increase in ambipolar potential at the central cell when plasma density in the flowing out flux decreases significantly between mirror and end wall. This potential force reflects back most of the central cell electrons. The ambipolar potential of the central cell was experimentally measured as a function of a distance from a movable segment of the end wall to the mirror [7]. As it is seen in Fig.1, in the case of large expansion of the magnetic field lines the movable wall does not influence on plasma potential in the central cell. Correspondingly, the electron temperature remains constant. However, when the expansion ratio decreases ($B_m/B(z) < 40 \div 50 \sim \sqrt{M/m}$), the potential drops down and the electron temperature in the center cell falls down thus indicating an increase in longitudinal losses. It should be pointed out that in the case of plasma which is heated by relativistic electron beam (GOL-3) there appeared absolutely another way to suppress the electron heat flux (see below).

If to estimate perspectives GDT as a fusion reactor, one should say that from physical point of view such a reactor will be one of the simplest, because only axisymmetric coils are used and collisional plasma behavior is more predictable. However, from technical viewpoint there are several objections. In [Ref.8] the parameters of the GDT reactor are presented. To decrease the length of reactor the use of mirror coils with $B_m = 45$ T are supposed. But even in this case, the length of reactor is estimated to be 3-6 km and the injection power as 12.3 – 7.5 GW. With a decrease in magnetic field strength of mirror coils the reactor length and injection power should be increased. Thus, at present, there is no realistic decision of the problem of GDT based reactor. Nevertheless, there exists very important intermediate step for this concept.

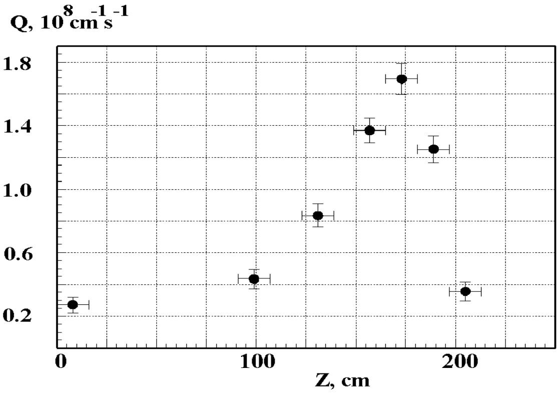

Fig.2. Neutron flux distribution along the axis of GDT device. Point z = 0 corresponds to the middle plane.

GDT based Neutron Source

Besides fusion reactor, there is another near term application of the GDT concept. This suggests construction of a 14 MeV neutron source on the basis of GDT with a multi-component plasma. The parameters of such a source (primary neutron flux density is 2 MW/m^2, test zone size is 1m^2) are chosen to meet the requirements of fusion materials testing.

In recent years, several neutron source projects have been proposed. Among those the GDT based source seems to be one of the most attractive because of very moderate consumption of power (60 MW) and tritium (150 g per year). The main idea of the neutron source involves an oblique injection of deuterium and tritium neutral beams with an energy of order of 100 keV into a ''warm'' collisional target plasma confined in GDT. Injection of the neutral beams gives rise to energetic anisotropic ion population with a density profile being strongly inhomogeneous along the system axis. The maximum of the fast ion density will be located in the vicinities of turning points and the minimum – at the middle plane of the trap. This results in generation of strongly inhomogeneous neutron flux with maxima located at the same place as those of the fast ion density. Since the neutrons are mostly produced in the fast triton and deuteron collisions, the neutron specific yield is proportional to fast ion density squared. Therefore, the neutron flux peaks near the turning points are even stronger than those of the density. The effect of neutron flux peaking was demonstrated in the experiments on the GDT device with injection of deuterium neutral beams with energy of 15-17 keV and 4 MW total power incident at the central cell plasma (see Fig.2). The measured profile was found to be in reasonable agreement with that predicted by numerical simulations [2].

The maximum electron temperature that was achieved so far in the experiments at the GDT device amounts to 130 eV. Taking into account that the neutron flux strongly increases with the electron temperature, it is now planned to upgrade the device in order to increase T_e up to 250-300 eV. As calculations show, this can be achieved if the magnetic field at the central cell of the GDT will be increased from 0.22 up to 0.35 T and the neutron beam power from 4 up to 10 MW with extension of the pulse duration from 1 to 4 - 5 ms. It is also assumed that the injection energy will be increased from 15 - 17 up to 25 keV. In the case if this temperature increase will be experimentally demonstrated, the construction of the GDT based neutron source providing neutron flux density of 350-450 kW/m^2 becomes feasible [9]. The full scale neutron source will provide 2 MW/m^2.

III. MULTI-MIRROR SYSTEM GOL-3

From physical point of view the simplest confinement system could be presented as a pipe with a dense ($\lambda_i << L$) plasma in the longitudinal magnetic field. (Here **L** is the pipe length, λ_i is the ion mean free path). The time of life of such the system can be estimated as $\tau_0 \cong L / V_{Ti}$, where V_{Ti} is the ion thermal velocity. The size of the confinement system is large enough, however, if a corrugated magnetic field with the size of corrugation **l** (or what would be the same, single mirror size, **l**) is used under condition when $l << \lambda_i << L$, then the longitudinal expansion of plasma in such a system will have diffusional character, i.e. $\tau \approx L^2 / \lambda_i V_{Ti}$. More strictly (see [Ref.10]), the lifetime is evaluated as $\tau \cong R^2 L^2 / \lambda_i V_{Ti} = \tau_0 R^2 L / \lambda_i$ (here **R** is the mirror ratio). It follows from the formula, that for a dense (more than 10^{23} m^{-3}) plasma the length of such fusion reactor could be less than 100 meters. The theory validity [10] was confirmed by special experiments on alkaline plasma behavior in the multi-mirror magnetic field [11]. Besides longitudinal confinement, there is a problem of transverse confinement. As calculations have shown, in the case of a dense high temperature plasma, its transverse confinement will require magnetic field of a few megagauss. This difficulty can be overcome if to combine the longitudinal multi-mirror confinement with the transverse «wall» confinement [12]. In this case, plasma is placed into a well conducting pipe with relatively «weak» (~10 T) magnetic field. As calculations have shown, after fast plasma heating the redistribution of the magnetic field and plasma density over the pipe cross section is occurred (see Fig. 3).

The field strength and plasma density at the axis are not substantially varied. But near the wall they are several tens times higher (because of two effects: magnetic flux conservation, and the β value much higher than unity). As a result, the cooling time of plasma of about 10 cm in diameter because of strong suppression of the transverse heat conduction turns to be satisfactory from the viewpoint of the Lawson criterion at rather moderate magnetic fields (~10 T) [12]. For experimental checking of these calculations it is required to put into a plasma a few hundred kilojoules in a short time. At present, the most powerful facility GOL-3 for studying the phenomena of interaction of relativistic electron beam (REB) with a dense plasma and also for plasma confinement is under operation in Novosibirsk. The parameters of GOL-3 are close to those required. Therefore, the “wall” confinement experiment looks now quite realistic.

GOL-3 facility can be operated in two modifications of magnetic field: homogeneous (long solenoid and two end - mirror coils) for a study of plasma heating by REB, and multi-mirror modification for the experiments on hot plasma confinement. Layout of the installation is shown in Fig.4. Preliminary plasma in GOL-3 is produced in a stainless steel chamber with 10 cm inner diameter. Plasma has 8 cm diameter and 12 m in length. Plasma density is varied within 10^{20} – 10^{23}m^{-3} range. Its heating is provided by powerful REB with energy content of 200 kJ and with the following parameters: $E_b \approx$ 1MeV, $I_b \approx$ 30kA, $I_b \approx$ 8·10^{-6} s. The diameter of the beam in the plasma is 6 cm. To make an experiment on “wall” confinement in multi-mirror magnetic field one should solve several problems.

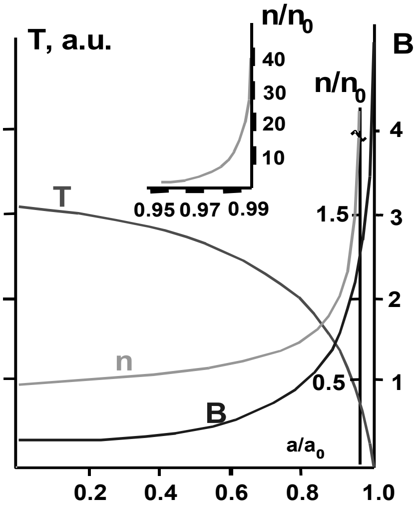

*Fig.3 Distribution of magnetic field strength **B**, plasma density **n**, and temperature **T** along the radius of well conducting pipe after pulsed plasma heating.*

1. Plasma heating with a high efficiency.
2. Suppression of electron heat conduction.
3. Production of hot high β plasma in strong magnetic field.

One can say that, at present, the two first problems mainly have been solved.

Plasma Heating by REB

Most of the experiments on study of collective REB-plasma interaction were made for the case where the plasma density was 1–2·10^{21} m^{-3}. As a result, rather high efficiency of the interaction was achieved. In plasma at $n_e \approx$ 10^{21} m^{-3} the beam losses up to 40% of its energy were observed [13]. In these experiments rather high electron temperature ($T_e \approx$ 2 keV) was obtained. It is important to note, that so high temperature cannot be reached in the case of classical electron heat conduction. Fortunately, because of excitation of microturbulence in plasma due to REB-plasma interaction an effective electron collision frequency grows by three orders of magnitude. This effect leads to significant suppression of longitudinal heat conduction [14].

As a first step in direction of “wall” confinement experiments a method of two-stage heating of a dense plasma has been developed [15]. In this case, preliminary “rare” ($n_e \approx$ 10^{21} m^{-3}) plasma is produced with an additional dense (10^{22} ÷ 10^{23} m^{-3}) local bunch. After heating a “rare” plasma, hot electrons transfer their energy to electrons and ions of the dense bunch via classical binary collisions. The experiments show that peak of pressure is then formed in the range of the bunch.

Experiments With Multi-Mirror Confinement

The first experiments on plasma confinement in multi-mirror geometry were performed in the following way. Ten mirror cells of 22 cm in length each were formed in the input and in the output of the facility. About 8 meters in the central part of the magnetic system were retained without changes. Mirror ratio in the cells of the corrugated parts is approximately equal to $B_{max}/B_{min} \approx 1.5$. The magnetic field distribution is given in Fig.4. (Recently the multi-mirror configuration was changed as it is seen in the figure).

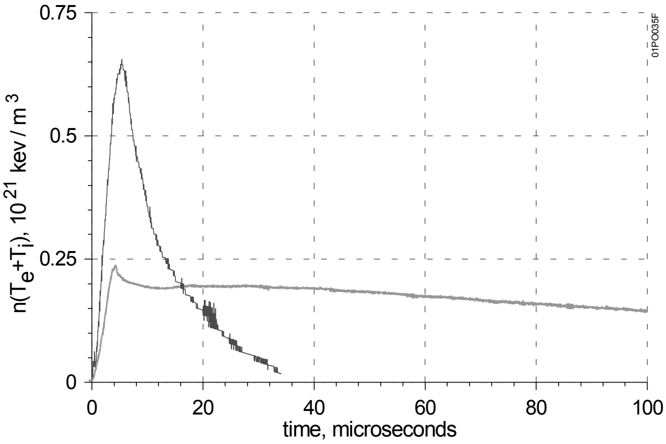

Fig.5 Temporal plasma pressure behavior after heating by REB for the cases of two magnetic configurations (homogeneous with two end mirrors and multi-mirror)

The main result of the recent GOL-3 experiments consists in the substantial increase in the energy confinement time. Fig.5. shows the plasma pressure in the midplane of the solenoid for two confinement systems. The signal of large amplitude and low duration presents the shot with plasma heating in 12 m long homogeneous magnetic field ($n_e = 2 \cdot 10^{21}$ m^{-3}). Another one is obtained for the multi-mirror geometry ($n_e = 10^{21}$ m^{-3}; energy content of the beam was lowered). New experiments in this direction are in progress. But even the obtained results allow to look forward with some optimism.

IV AMBIPOLAR TRAP AMBAL-M

In spite of the fact that the principle of ambipolar confinement of plasma was proposed in Novosibirsk [16] quite long ago, up to now, neither the construction of the ambipolar trap AMBAL with an average min **B,** nor the construction of the axisymmetric trap AMBAL-M have not been completed.

At present, fully axisymmetic system comprises end mirror with semicusp and part of a long central solenoid is under operation. The layout of installation and magnetic field configuration are shown in Fig.6.

Even on this installation the results important for tandem mirrors have been already obtained:

1. MHD stable hot plasma ($T_e \approx 60$ eV, $T_i \approx 200$ eV, $n_e \approx 2 \cdot 10^{19}$ m^{-3}) with length 6 m and with diameter 0.4 m was obtained;
2. A method of plasma production was proposed on the basis of a use of an annular gas-discharge plasma source. It was shown that as the result of injection of annular plasma stream through the input mirror at solenoid the Kelvin – Helmholtz instability is excited. This phenomenon led to the stochastic ion heating. Besides, excitation of electrostatic oscillations in the plasma led to a significant radial diffusion and plasma density build-up on the axis;
3. Measurements have shown that during filling the solenoid by plasma a strong radial diffusion was observed ($D_\perp \approx 10^6$ $cm^2/$**s). ** After switching of the plasma source the radial diffusion has fallen down practically till the classical level ($D_\perp \approx 10^3$ cm^2/s);
4. Recently the plasma density up to $6 \cdot 10^{19}$ m^{-3} was obtained [17]. This result makes it possible to begin the experiments on ICRH with the aid of fast magneto-sound wave.

V. CONCLUSIONS

A number of crucial difficulties intrinsic to open systems such as large longitudinal electron heat conduction, problem of MHD stability in axisymmetric geometry have been solved in recent years. Now the axisymmetric mirrors, most attractive from engineering point of view, will be able to provide a plasma with higher parameters. At present, however, the plasma parameters in mirrors are far from these in tokamaks. Therefore, for the nearest years, the main problem consists in an increase of the plasma parameters.

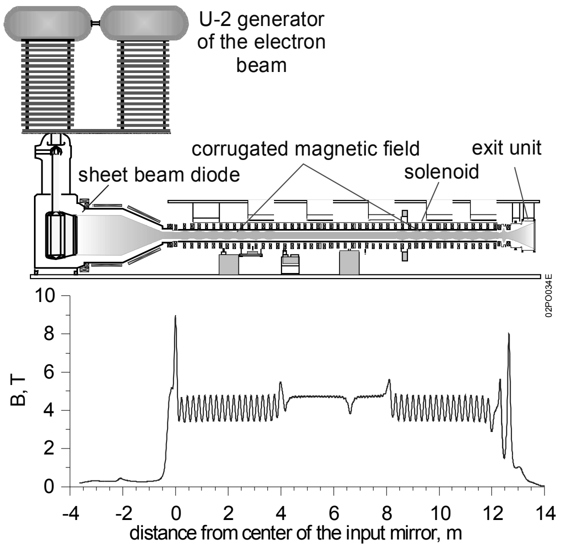

Fig.4. GOL-3 layout and magnetic field distribution along the axis (the case of multi-mirror geometry).

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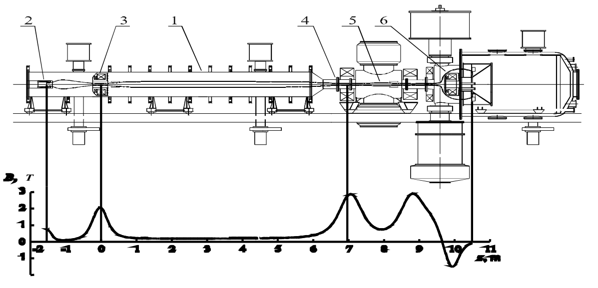

Fig.6 The layout of AMBAL-M and magnetic field profile along the axis. 1- solenoid, 2- gas discharged plasma source, 3,4- input and output mirrors of solenoid, 5- end mirror, 6- semicusp.