Future Perspectives and Status of Magnetic Mirror Studies in Novosibirsk*)

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In the paper, we present the Budker Institute long term plans for development of the plasma physics database for an advanced fuel fusion reactor based on the axisymmetric linear magnetic trap. An analysis of the existing database gained in the experiments at the open magnetic systems in the Budker Institute and worldwide is presented. To develop the required database a stepwise approach is applied, which suggests construction of the several experimental devices with progressively increased plasma parameters, which incorporate the different constituents of the approach.

Keywords: plasma, magnetic mirror, gas-dynamic plasma confinement, plasma stability, plasma neutron source

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1. Introduction

Open magnetic traps are currently considered as a possible alternative to create a plasma neutron source based on them for testing materials and other applications [1–3]. The main obstacle to the use of open traps in the future as a thermonuclear reactor is a relatively small value of the gain factor Q. Quite a lot of ideas on increasing Q have been discussed recently [4–7]. All of them require a thorough experimental study at sufficiently high plasma parameters.

Since its foundation in the 60s, at the initiative of the founder of the Institute academician G.I. Budker, an intensive development of open magnetic traps is being carried out. Modern generation of these systems in the Institute is presented by several devices including GDT, GOL-NB and others. The paper analyzes the database on the open traps developed at the Institute taking into account the data gained on open magnetic mirrors of previous generations [3]. The generated database, of course, coincide with that developed in the mirror-machines worldwide (see review [8]), especially in USA, Japan and Russia, but extends that considerably. Analysis of this data base enables one to conclude that the design of the plasma neutron source for material tests based on the gas-dynamic trap described in [9, 10] is sufficiently proven. Experiments with plasma in a continuous mode are required to achieve full confidence. In the current experiments at GDT with a pulse duration of 5 - 10 ms plasma is clearly far from steady state. So, at the GDT device, the electron temperature grows almost linearly, reaching at the end of the heating pulse with a duration of ~5 ms a value close to 1 keV [11]. In addition, in experiments with longer duration, it is necessary to maintain the balance of particles in the plasma. Usually used for this purpose, gas puffing from the periphery may be ineffective due to poor penetration of particles into the hot plasma, strong cooling of the plasma at the periphery and increase of the charge exchange ion losses. Application of the pellet injection also meets certain difficulties: it requires too small size of pellets and a large injection frequency, which are not achieved so far. These challenges are to be met by the next generation of open magnetic confinement systems, which are already under construction or are planned for the near future at the Budker Institute. These constructed or planned experiments are discussed in this paper. In case of successful implementation of the methods of reduction axial plasma losses proposed in [4–7] and solving problems of the maintenance of stationary conditions in the plasma, fusion reactor based on an axisymmetric magnetic trap, including advanced fuels with small neutron yield (D-D or D-He^3) or completely without neutron emission, like p-B^{11} becomes feasible.

2. Lessons Learned from Previous Generation of Magnetic Mirror Devices at BINP

AMBAL-M experiment

Historically, the first experiment with mirror-machine arranged in Budker Institute was the ambipolar trap AMBAL with quadrupole anchor cells and later on the axially symmetric AMBAL-M experiment [12]. The main goals of

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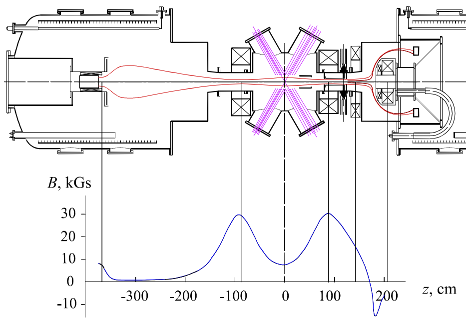

Fig. 1 End cell of AMBAL-M: ambipolar confinement and MHD stability of hot plasma in axisymmetric geometry.

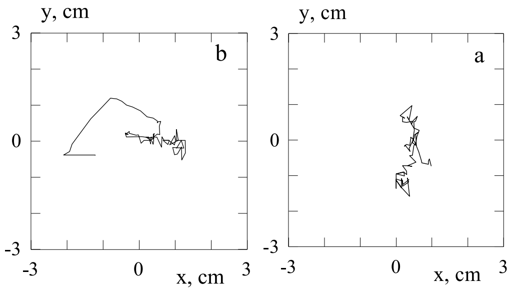

Fig. 2 Radial excursion of plasma center of mass without half-cusp (left) and without it (right).

the AMBAL-M experiment were the study of the ambipolar plasma confinement and achieving the MHD stability of hot plasma in axisymmetric geometry using the half-cusp anchor cells. The end cell of the AMBAL-M experiment with the attached half-cusp MHD anchor is shown schematically in Fig. 1. The ring shape plasma gun [13] was used to provide initial plasma build-up. It was observed that during the gun operation, the plasma column is macroscopically stable but experiences radial excursion of large amplitude. This was attributed to line-tying to the dense plasma inside the gun and differential plasma rotation induced by non-homogeneous radial electric field between the gun electrodes. Contribution of the plasma filled the half-cusp to plasma stability manifested yourself by considerable decrease of the amplitude of the radial excursions when the half-cusp was engaged as shown in Fig. 2.

In the same experiments, it was observed that in geometry shown in Fig. 1 during the gun operation there is quite effective mechanism of ion heating in the plasma jet expanding along the magnetic field lines. It was found out that the effect depended upon the magnitude of radial electric field in the gun and development of small scale fluctuations in plasma. The experiments shown that these fluctuations are excited because of the Kelvin-Helmholtz instability in plasma. Simultaneously the ion heating due to development of the instability caused quite unexpectable effect of the electron heating inside the mirror trap (see Fig. 3). The measurements of axial profile of the electron temperature exhibits its strong variation with significant jump at the entrance magnetic mirror. Subsequent measurements and numerical modeling shown that at the entrance magnetic mirror the ions gain large transverse velocity because of the Kelvin-Helmholtz instability development in small magnetic field region between the plasma gun muzzle and the entrance mirror. As a result, the ion velocity distribution becomes to be strongly anisotropic and significant part of ions arrived at the entrance magnetic mirror are reflected back, so that the ion density here decreases. This gives rise to development of a local drop of ambipolar potential and appearance of the thermal barrier for electrons. Then inside the magnetic mirror the electrons are heated by energy transfer from hot ions to ~50 eV.

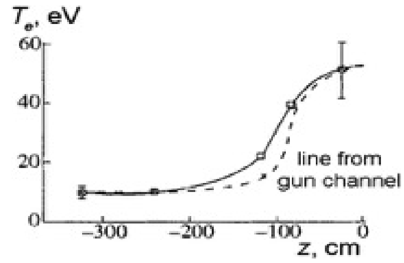

Fig. 3 Axial profile of electron temperature in AMBAL-M experiment (solid line – along field line from the plasma gun channel, dashed – along axis).

GOL-3 experiment

In experiments at the GOL-3 device it was demonstrated that axial injection of high power electron beam with energy 1 MeV and current of 20 kA during 1 ms into linear device with a multi-mirror magnetic field leads to efficient heating of both electron (Te upto 4 keV) and ion (Ti = 2 keV) plasma components [14]. Relaxation of the electron beam goes through excitation of Langmuir plasma waves to large amplitudes. The excited waves become nonlinear and strongly increase the scattering rate of electrons. As a result, in the experiments it was observed that during the electron beam injection, the electron heat conduction is strongly suppressed by small-scale turbulence induced by electron beam [14]. According to theoretical predictions (see [14] and the references therein), the multi-mirror trap can only effectively slow down the plasma axial spreading if the ion mean free path is comparable to a mirror-to-mirror distance. However, it is appeared, in contrast with theoretical predictions, to be effective for considerably smaller plasma density due to excitation of instability of plasma flow in non-homogeneous magnetic field. That means that the multi-mirror sections can be effectively applied as the end plugs for the systems like gas-dynamic trap with not too dense plasmas.

GDT experiment

In the GDT experiment, stabilization by pressureweighted curvature in axisymmetric geometry was thoroughly studied [15]. The stability limits found generally are in agreement with the theory [16]. Kinetic effects in MHD stability (finite Larmor radius effect) was studied through the measurements of the width of unstable mode spectra as a function of the plasma parameters. A transition from regime in which the rigid displacement mode dominates to the regime with excitation of the several MHD modes were observed in accordance with relevant theory.

Stabilization of axially symmetric plasma by cusp end cell was also studied. The results are discussed in [17]. Generally, in the experiments, the plasma parameters were limited because of accumulation of fast ion in the central cell and subsequent loss of MHD stability. This was attributed to reduction, during the experiments the energy transfer rate between the fast ions and bulk electrons, which are determined the plasma parameters in the cusp anchor cell. This led to a lag in the growth of the plasma pressure in the anchor cell from that of the fast ion pressure in the central cell. Therefore, the plasma subsequently experiences the transition beyond the MHD stability limits. Basically, it is a result of a pulse character of the experiments and transient regimes of plasma accumulation in anchor cell of the device. In the experiments with accumulation of the fast ions, the $\boldsymbol{\beta}$ value in their turning points near the end magnetic mirrors reaches ~ 0.6 close to theoretical stability limit against ballooning [18]. The cross-field transport suppression by induced plasma rotation was observed. The profile of azimuthal plasma rotation in GDT was control by using the segmented electrodes installed at the end wall and limiters in the central cell. It induces the sheared plasma rotation that led to saturation of the amplitudes of the unstable MHD modes and suppression of the radial plasma transport [19]. At the same time, in the experiments at GDT device, it was observed that this effect is accompanied by a radial pinch of the fast ions, so that their slowing down in plasma and motion in the crossed electric and magnetic fields lead to moving of their Larmor centers to magnetic axis [19]. The effect of sheared plasma rotation enabled to confine the plasma in the central part of GDT device even when the geometry of magnetic field lines in the end tanks was not favorable for MHD stability.

Another important finding in the GDT experiments is the suppression of axial electron heat flux by magnetic field flaring beyond the mirrors towards the end wall [3]. In the GDT experiments, it was found out that there is no considerable deterioration of fast ion confinement that would be connected with excitation of kinetic instabilities, namely DCLC or ion Alfven anisotropic modes. As a result, confinement of the fast ions appeared to be close to classic one and anomalies in ion angular scattering or slowing down were not observed [20]. Probably the most important achievement in the GDT experiment in the last years is the effective electron heating with ECRH. The ECRH application in the experiments in parallel with neutral beam heating enabled to reach in the open confinement device

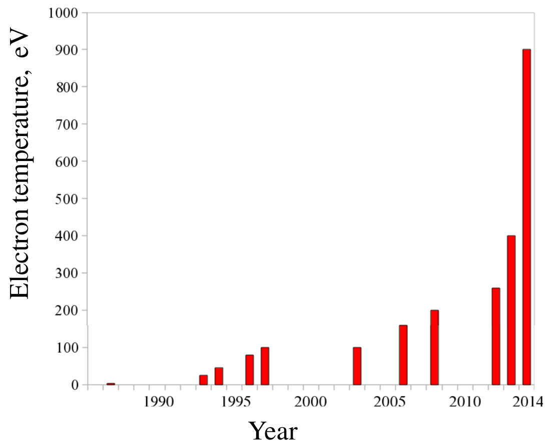

Fig. 4 Increase of electron temperature in GDT over the years.

a record electron temperature approaching 1 keV [11] (see Fig. 4). These experiments were done in collaboration with the Institute of Applied Physics RAN, Nignii Novgorod. This allows us to consider the prospects of using open traps to create powerful neutron sources with Q = 0.1 on their basis and, in the case of proving the possibility of further increase in the electronic temperature, for pure fusion reactors.

The set of plasma parameters reached so far in the GDT experiment is $n\tau E_i > 5.0 \times 10^{17}$ keVm^{-3}s, plasma density $>10^{20}$ m^{-3} in the region of turning point of fast ions, at the same here $\beta \leq 60\%$ (at B = 0.6 T).

3. New Generation of Magnetic Mirror Devices at BINP

Summarizing what said above, the initial goals of the GDT project have been achieved and the expected plasma parameters were even exceeded, especially as to the electron temperature and plasma beta.

At the same, even if the gas dynamic trap has demonstrated in transient regime achievability of the plasma parameters adequate to high flux neutron source or fission-fusion hybrid it suffers from too high axial plasma loss rate. Then, what further should be done to realize the parameters of the mirror-based fusion reactor? The quality of confinement can be improved by several measures as:

- Application of the multi-mirror end plugs
- Confinement of very high-β plasma or field reversal
- Application of end plugs with rotating plasma in multi-mirror solenoid with rotational transform
- Application of the traveling mirrors
- Application of ambipolar effects

All these effects should are planned to be studied in the next generation of plasma devices in the Budker Institute. The strategy of the development suggests construction of several experimental devices. The central role is devoted to construction of Gas-Dynamic Multi-mirror Trap (GDMT),

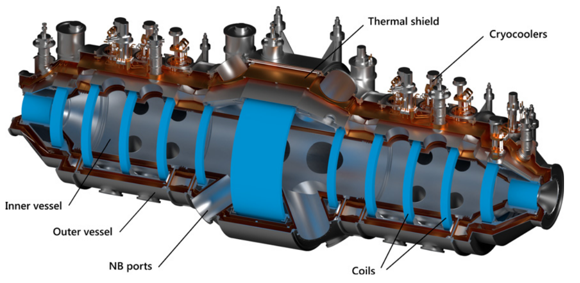

Fig. 5 Cutaway view of the GDMT central cell arranged as “diamagnetic” trap.

which will have to demonstrate the technologies, which are essential for mirror-based neutron sources or, in future, for mirror-based fusion reactors.

The specific role plays also the plasma sustainment technique, which suggests application of plasma feeding, heat removal in steady state from the system, stationary pumping system, steady state high energy neutral beams and ECRH, superconducting coils. The issues related to development of these systems can only be addressed in the experiments with stationary high temperature plasmas.

The main features of the GDMT project [6] are

1. Equivalent Q~1 (previously Q = 0.1) with modest scale up from the current experiments
2. Steady-state plasma
3. Heating and sustainment with neutral beams (60 - 80 keV, 10 - 50 MW, 1 - 5 s and DC operation), ECRH (2 - 5 MW) and electron beams
4. End loss reduction with: extremely high mirror field, multi-mirrors, plasma rotation in the mirrors with rotational transform, “diamagnetic” confinement – regime of confinement with β

The major problem in the GDMT construction is insufficient database to select the main method of MHD stabilization in this device in steady state regime of confinement.

The device will be constructed using a number of modules, which provide high enough flexibility in experiments. The central part of the trap is suited for injection of the skew neutral beams. Using the additional modules of magnetic system, one can produce the arrangement of a diamagnetic trap shown in Fig. 5 or the neutron source prototype. In this configuration the GDMT device parameters are the following:

1. Confinement zone length -4 m
2. Magnetic field uniformity -3% at r = 30 cm
3. Low AC-loss NbTi cable 0.3 T - 3 T within 5 s
4. Magnetic mirror field upto 18 T
5. Magnetic field energy upto 65 MJ
6. Individually powered coils
7. Steady state operation with magnetic field up to 2 T and pulsed operation at 3 T

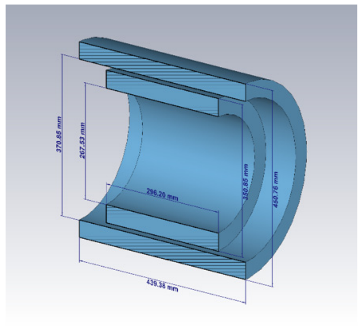

Fig. 6 Cut-away view of NbTi/NbSn coil of GDMT device.

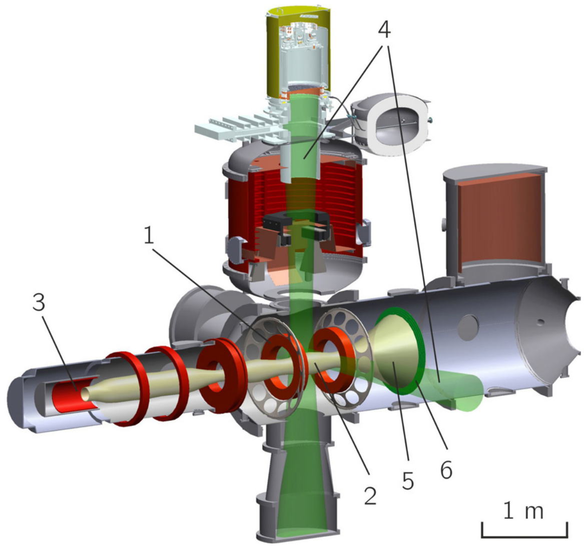

Fig. 7 CAT device. 1 - magnetic coils, 2 - plasma column, 3 - plasma gun, 4 - two neutral beams, 5 - expander, 6 - biased end plates.

By using the multi-mirror modules, the confinement properties of the trap can be varied. The magnetic mirror coil of GDMT are composed of the two coils as shown in Fig. 6, which is capable of producing the mirror field up to 18 T.

To support the GDMT construction, several experimental devices are now under construction in the Budker Institute and development of steady state high energy neutral beams is continued [21]. The GOL-NB device [22] will be used to study the multi-mirror end plugs and different stabilization mechanisms in this arrangement. A device with plasma rotation in helical multi-mirror magnetic field will be used to study the specific mechanism of end losses suppression proposed in [7]. Compact Asymmetrical Toroid (CAT) device (Fig. 7) is intended to study the magnetic field reversal with neutral beams, and plasma confinement at extreme β values.

Arrangement of the CAT experiment utilizes a simple mirror trap with mirror-to-mirror distance L = 60 cm, magnetic field of B_{min} = 2 kG, vacuum mirror ratio 2.0, warm plasma radius ~15 cm. The plasma is produced by injection of two neutral beams with energy of 15 keV and total equivalent neutral beam current of 240 A. The beams have the focusing length F = 250 cm, initial beam diameter 34 cm, convergence angle ±4 deg, angular divergence 0.6×1.7 deg. and impact parameter r ~ 10 cm.

Plasma build up scenario suggests generation of warm target plasma using plasma gun and accumulation of hot ions by charge-exchange and ionization of NBs in warm plasma up to field reversal. The geometry of the magnetic field at the entrance magnetic mirror through which the plasma from the gun enters the confinement region is similar to that in the previous experiment at AMBAL-M device when formation of the thermal barrier was demonstrated, as discussed in Sec. 2. From the other side, the magnetic field beyond the exit mirror is flared thus provided the electron heat flux suppression to the end wall. This suppresses the electron heat flux at both end of the mirror cell that is thought to provide a higher electron temperature. The database generated by these experimental devices will apply for the for GDMT design. Simultaneously we will learn

- How to stabilize the plasma at higher temperatures?
- How to further increase the electron temperature?
- How to sustain the plasma?

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