Axisymmetric Magnetic Mirrors for Plasma Confinement. Recent Development and Perspectives

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Abstract: Mirrors are the only one class of fusion systems which completely differs topologically from the systems with closed magnetic configurations. 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, and 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 the present 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 geometry of magnetic field (GDT, AMBAL-M), an effective heating of a dense plasma by relativistic electron beam (GOL-3), observation of radial diffusion of quiescent plasma with practically classical diffusion coefficient (AMBAL-M), etc. It should be mentioned that on the basis of the GDT it is possible to make a very important intermediate step. Using "warm" plasma and oblique injection of fast atoms of D and T one can create a powerful 14 MeV neutron source with a moderate irradiation area (about 1 square meter) and, accordingly, with low tritium consumption. The main plasma parameters achieved are presented and the future perspectives of different mirror machines are outlined.

1. Introduction

At present, there are two main types of magnetic configurations for plasma confinement: closed (like tokamak, stellarator, etc) and open (like mirrors). Although plasma parameters in the closed configurations look much more impressive, advantages of the open systems could be useful in future for the fusion program. It should be mentioned the most important features of open systems:

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.

The feasibility of controlled fusion will be finally demonstrated in the frame of the ITER project. However, next after ITER step of fusion program (DEMO) cannot be done without high power 14 MeV neutron source for tests of materials. One of the systems discussed below (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 materials tests.

At present, the most 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 the magnetic mirrors will be described in the paper

2. Gas dynamic trap (GDT)

A gas dynamic trap (GDT) was proposed as a possible approach to a creation of fusion reactor [1]. The GDT is one of the simplest systems for magnetic plasma confinement. In 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, generally can not excite. Moreover, in contrast to the conventional mirrors, longitudinal plasma losses are not sensitive to the ion angular scattering rate that might be enhanced by microinstabilities. It is rather simple to obtain an estimation of the confinement time in the GDT: $\tau \approx \mathbf{R \cdot L / V_{T_i}}$. The fusion reactor on the basis of GDT, according to this relationship, should have a length of the order of ten kilometers or even more. It should be mentioned that as a 14 MeV neutron source the GDT has good perspectives. That's why the experiments on study of the effects of gas dynamic plasma confinement and heating are carried out on GDT device very intensively. The device has an axisymmetric magnetic field configuration. The main parameters of the device are presented in Table 1.

TABLE 1: PARAMETRS OF THE GDT DEVICE.

Parameter	Value
Mirror to mirror distance	7 m
Magnetic field: at midplane In mirrors	Up to 0.3 T Up to 15 T
Target plasma: density	$3\text{-}20 \times 10^{19}$ m^{-3}
Radius at the midplane	8-15 cm
Electron temperature	Up to 130 eV
Neutral beams: energy	15–17 keV
pulse duration	1.1 ms
Injection power	Max 4.1 MW
Injection angle	45^{o}

Neutral beam injection is used for plasma heating. 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 provided several principal results. In particular, it was 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 was favorable for stability. If the favorable curvature of the magnetic field lines in the region of plasma expansion beyond the end mirrors was high enough, the MHD stability was achieved. More rigid stabilization in the sense of the MHD stability was demonstrated by installing a cusp in one of the expander tanks. These experiments have shown that the problem of MHD stabilization of the plasma in the axisymmetric magnetic configuration can be successfully solved [3]. As a result, on-axis β exceeding 0.4 was recently obtained in GDT device near turning point of the fast ions [4].

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 magnetic field lines from the mirror to the end wall the theory [5] predicts strong reduction of the longitudinal electron heat losses. A nature of this

phenomenon is explained by an increase in ambipolar potential at the central cell when plasma density in the diverging stream decreases significantly between mirror and end wall. Really, in the case of large expansion of the magnetic field lines when the expansion ratio $B_m/B(z)$ exceeds $40 \div 50$ ($\sim\sqrt{M/m}$), the end wall position does not influence upon the electron temperature in the central cell [6].
If to estimate perspectives of GDT as a fusion reactor, note that from the physical point of view such a reactor would be one of the simplest because of its axial symmetry and more predictable behavior of collisional plasma confined. However, it turned out that GDT-based reactor had rather large length (about 10 km) and required tremendous power (of order of 10 GW) for plasma heating. Nevertheless, there exists very important intermediate step for this concept. On the basis of the GDT with an oblique injection of neutral beams (D and T) one can obtain a high power 14 MeV neutron source with the parameters sufficient to test the materials for future fusion reactor: the testing zone area of 1 m^2 and 14MeV neutron flux density of 2 MW/m^2 , or 10^{18} neutrons/m^2 s (for more detail see the paper FT/P1-24 of this Conference).

3. Multi-mirror system GOL-3

The simplest confinement system could be presented as a pipe with a dense ($\lambda_\mathbf{i} \ll \mathbf{L}$) plasma in the longitudinal magnetic field. (Here **L** is the pipe length, $\lambda_\mathbf{i}$ is the ion mean free path). The time of life can be estimated as $\tau_\mathbf{0} \cong \mathbf{L} / \mathbf{V}_{\mathbf{T_i}}$, where $\mathbf{V}_{\mathbf{T_i}}$ is the ion thermal velocity. The size of such a 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 $\mathbf{l} \ll \lambda_\mathbf{i} \ll \mathbf{L}$, then the longitudinal expansion of plasma in such a system will describe by diffusional low, i.e. $\tau \approx \mathbf{L}^2 / \lambda_\mathbf{i}\mathbf{V}_{\mathbf{T_i}}$. More strictly (see [Ref. 7]), the lifetime is evaluated as $\tau \cong \mathbf{R}^2\, \mathbf{L}^2 / \lambda_\mathbf{i}\mathbf{V}_{\mathbf{T_i}} = \tau_0\mathbf{R}^2\mathbf{L}/ \lambda_\mathbf{i}$ (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 was confirmed by special experiments on alkaline plasma behavior in the multi-mirror magnetic field [8]. 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 [9]. If plasma is placed into well conducting pipe (for conservation of a magnetic flux inside the tube) with relatively "weak" (of order of 10 T) magnetic field, then, as calculations have shown, the transverse cooling time of plasma of about 10 cm in diameter turns to be satisfactory from the viewpoint of the Lawson criterion. For experimental checking of these calculations it is required to put into a plasma a few hundred kilojoules in a short time.

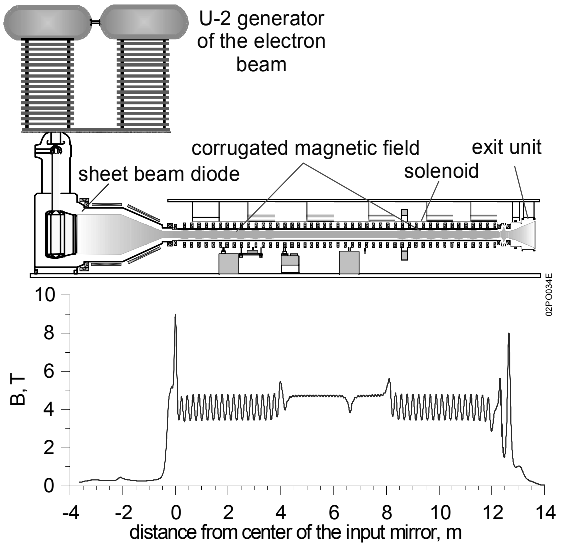

FIG. 1. GOL-3 layout and magnetic field distribution along the axis (the case of multi-mirror geometry).

At present, the most powerful facility GOL-3 [10] for studying the phenomena of interaction of relativistic electron beam (REB) with a dense plasma and for plasma confinement is under operation. The parameters of GOL-3 are close to those required. Therefore, the "wall" confinement experiment looks now quite realistic. At present, GOL-3 facility can operate in two configurations of magnetic field: homogeneous (long solenoid and two end - mirror coils) for a study of plasma heating by REB, and multi-mirror configuration for the experiments on hot plasma confinement. Layout of the facility is shown in Fig. 1. At present, rather high efficiency of the REB-plasma interaction was achieved. The beam losses up to 40% of its energy were observed in plasma at $n_e \approx 10^{21}$ m^{-3} [10]. In these experiments rather high electron temperature ($T_e \approx 2$ keV) was obtained. 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 [11].

As a first step in direction of "wall" confinement experiments a method of two-stage heating of a dense plasma has been developed [12]. In this case, preliminary "rare" ($n_e \approx 10^{21}$ m^{-3}) plasma is produced with an additional dense ($10^{22} \div 10^{23}$ 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. The main result of the recent GOL-3 experiments consists in the substantial increase in the energy confinement time in multi-mirror geometry. In this case, the confinement time more than ten times exceeds one in the case of plasma in the long solenoid with end mirrors (see the paper EX/P5-01 on this Conference).

4. Ambipolar trap AMBAL-M

The principle of ambipolar confinement of plasma was proposed in Novosibirsk [14] quite long ago, up to now. However 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 see (Fig. 2). Nevertheless, the important for tandem mirrors results have been already obtained:

1. MHD stable plasma ($T_e \approx 60$eV, $T_i \approx 200$ eV, $n_e \approx 2 \cdot 10^{19}$ m^{-3}) with length of 6 m and 0.4 m in diameter has been obtained;
2. During plasma build-up in the solenoid a strong radial diffusion has been observed with $D_\perp \approx 10^6$ cm^2/s. After the plasma source switching off, the radial diffusion has fallen down practically till the classical level ($D_\perp \approx 10^3$ cm^2/s);
3. 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 a result of injection of annular plasma stream through the input mirror, the Kelvin – Helmholtz instability is excited in the solenoid plasma. This phenomenon led to the stochastic ion heating. In addition, excitation of electrostatic oscillations in the plasma led to a significant inward radial flux that provided plasma density build-up on the axis;

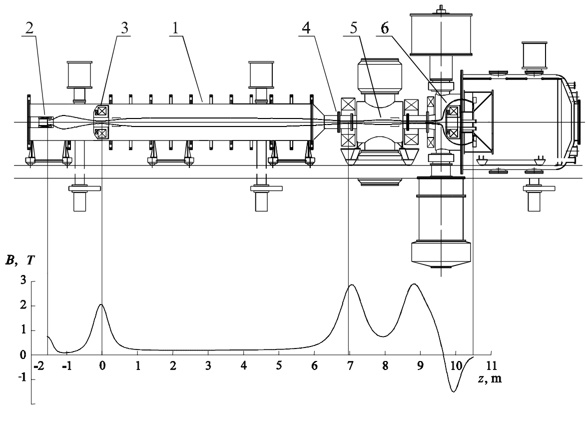

FIG. 2. The layout of AMBAL-M and magnetic field profile along the axis: 1 solenoid, 2 gas-discharge plasma source, 3,4 inp solenoid, 5 end mirror, 6 semicusp.

4. Recently, plasma density as high as $6{\cdot}10^{19}$ m^{-3} was obtained [15]. This result makes it possible to begin the experiments on ICRH with excitation of fast magneto-sound wave.

5. 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. In particular, value of plasma β more than 40% was obtained (GDT, AMBAL-M), the suppression of the electron heat conductivity was demonstrated (GDT, GOL-3), high efficiency of plasma heating by REB (40%) was achieved. Now the axisymmetric mirrors, most attractive from the engineering point of view, will be capable of providing higher plasma parameters. At present, however, the plasma parameters in mirrors are far from these in tokamaks. Therefore, for the nearest years, the main problem of mirror studies consists in an increase of the plasma parameters.

References

[1] V.V. MIRNOV, D.D. RYUTOV, “Gas dynamic linear trap for plasma confinement”, Pisma v JTP,.**5,** (1979), 678 (in Russian).

[2] A.V. ANIKEEV et al., “ Fast ion relaxation and confinement in the gas dynamic trap”, Nuclear Fusion, **v.40,** (2000), 753.

[3] A.V. ANIKEEV et al., “Energy balance and stability of GDT plasma under neutral beam heating”,Proc.22nd EPS Conf. On Controlled Fusion and Plasma Physics, **v.19C**, part IV, Bournemouth, (1995), p.193.

[4] A.A. IVANOV et al., “Local measurements of plasma beta in GDT using MSE diagnostic”, 4th Int.Conf on Open Magnetic Systems for Plasma Confinement (OS-2002), Jeju, Korea, July 1-4, (2002). To be published in Fusion Technology Transactions.

[5] I.K. KONKASHBAEV et al., “On the possibility of decreasing the electron thermal flux from open traps”, Sov. JETP, **74,** (1978), 956 (in Russian).

[6] A.V. ANIKEEV, et al., “Ion hot plasma with high energy content in GDT”, Fizika plazmy, **25, (**1999), 499 (in Russian, English translation see in Plasma physics report)

[7] G.I. BUDKER et al., “Influence of corrugation of magnetic field on expansion and cooling of a dense plasma”, Sov JETP Letters, **14**, (1971), 320 (in Russian).

[8] G.I. BUDKER et al., “Experiments on plasma confinement in multi-mirror magnetic trap”, Sov. JETP, **65**, (1973), 562 (in Russian).

[9] G.E. VEKSHTEIN et al., “Non-magnetic confinement of a dense plasma”, Journal of Applied Mechanics and Technical Physics, **6**, (1974), 3 (in Russian).

[10] A.V. ARZHANNIKOV et al., “Recent results on the GOL-3 facility”, Fusion Technology Trans., **35**, № 1T, (1999), 112.

[11] A.V.BURDAKOV et al., “ Experiments on the collective interaction of a microsecond relativistic electron beam with a plasma in the GOL-3 facility”, Sov. JETP, **82**, (1996), 1120.

[12] V.T.ASTRELIN et al., “Experiments on two-step heating of a dense plasma in the GOL-3 facility”, Sov. JETP, **86**, (1998), 489.

[13] V.S. KOIDAN et al., “Progress in plasma heating and confinement at the multimirror trap GOL-3”, paper EX/P5-01, this Conference.

[14] G.I. DIMOV et al., “Thermonuclear trap with double plugs” Fizika Plasmy, **2**, (1976), 597.

[15] T.D. AKHMETOV et al., “Experiments with dense plasma in the central solenoid of AMBAL-M”, 4th Intern. Conf. on Open Magnetic Systems for Plasma Confinement (OS-2002), Jeju, Korea, July 1-4, (2002)