Modern Magnetic Mirror Systems. Status and Perspectives.

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Abstract. Modern axially symmetric magnetic mirror traps are, at present, among the most simple magnetic systems for plasma confinement. Two of three such systems with different principles of plasma confinement (multi mirror and gas-dynamic) are discussed in the paper. In recent years studies of these systems provided substantial progress in suppression of longitudinal heat losses to the end walls via electron thermal conductivity, in stabilization of plasma MHD instabilities and in understanding of key physical phenomena determining plasma confinement and heating in these mirror systems. As a result of that dense ($n \approx 10^{21}$ m^{-3}) plasma in multi mirror trap (GOL-3) was heated up to $T_e \approx T_i \approx 2$ keV or even higher. The energy confinement time of order of 1 ms was achieved and the maximum value of $n \cdot \tau \approx 2 \cdot 10^{18} m^{-3} \cdot s$ was obtained. Up to now any limitations, preventing from subsequent growth of plasma parameters have not observed. As to the gas-dynamic trap it is used to generate plasma physics database for powerful (2 MW/m^2) 14 MeV neutron source (E_n = 14 MeV) for fusion materials testing. In the paper the results of the most important experiments and calculations are presented. At present, the upgrade of the GDT device is completed. New neutral beam injectors with total power of up to 10 MW and duration of heating pulse of 5 ms (steady state regime from physical point of view) were constructed. According to calculations, feasibility of “moderate” neutron source with neutron flux of 0.5 MW/m^2 can be then demonstrated with the new neutral beam injection system.

I. Introduction

At present, the Budker Institute runs two large scale axisymmetric mirror experiments of different type. The first one is a multi mirror linear system GOL-3 and the second is gas dynamic trap (GDT). Principle of multi mirror plasma confinement was proposed in early 70s [1]. It was successfully proven in experiments with a rare alkaline plasma in the period 1973-75 [2]. According to the initial idea [3] the multi mirror reactor should operate with a dense (order of $10^{24} m^{-3}$) plasma confined by strong (order of 10 T) magnetic field. It was suggested to heat the plasma by powerful relativistic electron beam (REB). The main requirements of the theory of longitudinal multi mirror plasma confinement [1] can be met for a dense plasma if the reactor is several hundred meters long. Such a high density plasma even if the magnetic field is ~10T has a pressure which is significantly higher than the magnetic field pressure, i.e. $\beta >> 1$. Then it was proposed to provide radial equilibrium of such a plasma by well conducting material wall, which withstands radial plasma pressure whereas radial heat conductance is being controlled by the magnetic field (so called “wall confinement” [4]).

Another problem of the multi mirror reactor is how to provide efficient plasma heating. It arises because the REB can effectively deposit its energy into plasma only via collective processes. The first experiments on study of REB – plasma interaction were begun in 1972 [5]. They indeed have demonstrated that plasma can be efficiently heated under certain conditions. In the first experiments the total beam energy amounted to only 50 J. In the present experiments at GOL-3 total energy of REB exceeds this level by almost four orders of magnitude. As a result of this increase, many new phenomena were recently discovered. In particular, for the first time an effect of strong, by three orders of magnitude, suppression of longitudinal electron heat conduction was observed [6]. Correspondingly, high electron temperature amounting to several keVs was reached [7].

Significant efforts were spent to come to present day status of multi mirror machine studies. As to plasma heating by REB is concerned, modern technology of high voltage generators for REB production was developed stepwise using intermediate generators of REB with water insulation and with the REB energy of 1, 4 and 20 kJ. The present day REB for the GOL-3 facility has total energy content exceeding 200 kJ, the energy of electrons of 1 MeV and maximum beam current of 50 kA. The pulse duration of the REB was most dramatically extended amounting at present up to $8\cdot10^{-6}$s.

Physics of plasma – beam interaction was studied in great details at GOL-M device (linear device with short pulse REB) using registration of collective scattering of CO_2 laser radiation. It was experimentally shown for the first time that Langmuir turbulence is being excited as a result of the REB-plasma interaction [19]. Later on [20] an excitation of ion-acoustic turbulence was observed with a level exceeding by five orders of magnitude the thermal one. The excitation of the ion-acoustic turbulence in non-isothermal ($T_e/T_i >>1$) plasma by REB can be explained by a collapse of large amlitude Langmuir waves. On the final stage of the collapse, short wave ion-acoustic waves are excited. The phenomenon of the collapse in the case of strong Langmuir turbulence excited by REB has been observed experimentally in the GOL-M device [21].

In the case of multi-mirror configuration fast ion heating up to 2 keV was also observed in GOL-3 facility [8]. Besides, it turned out that the heating and confinement of ions are significantly more effective than that one could expect using the estimates based on binary Coulomb collisions theory. Indeed, it was shown that there exists a mechanism of enhanced scattering of axially moving ions which leads to their trapping into the mirror cells and to corresponding increase of their longitudinal confinement time [9]. This suggests significantly more wide range of operational parameters for the reactor compare to the initial theory. This enables to consider the problem of multi mirror reactor with greater optimism.

It is worthwhile to note here that, at present, GOL-3 facility has extremely high energy density in plasma exhaust, which typically is in the range of 1-50 MJ/m^2. This provides rather unique opportunity for testing of structural materials for ITER and DEMO under effect of energetic plasma flow with hot electrons and ions.

The second system, the GDT [10], is essentially the Budker-Post type mirror trap but with high mirror ratio ($R>>1$) and high enough plasma density, so that effective ion mean free path of scattering into loss cone ~ $\lambda_{ii} \ln R/R$ is smaller than the length of the device - L. From physical viewpoint the reactor based on the GDT concept seems to be very reliable because in the collisional plasma micro instabilities do not excite. However, as it follows from the results of [11], such a reactor appears to be rather long, order of ten kilometers, and its minimal power is therefore drastically high (order of 40 GW). However, there exists an intermediate important problem which can be solved with the aid of the GDT. At present, a powerful 14 MeV neutron source (NS) is urgently required for materials testing for future fusion reactor. In [12] an idea of the GDT based neutron source was proposed. For moderate plasma parameters the most crucial problems of plasma confinement in the GDT based neutron source have been already studied. In particular, strong suppression of electron heat conductance to the end walls by axial drop of the magnetic field has been demonstrated [13]. The MHD-stable plasma confinement in axisymmetric magnetic configuration of GDT was also successfully demonstrated in the experiments [14-16]. In the recent years, a lot of studies both theoretical and experimental have been done to support the development of the GDT based neutron source. Detailed description of that activity can be found, for example, in [17]. Note that besides the GDT NS many other schemes of neutron sources were proposed in recent years. Comparison of other proposed NSs with the GDT NS was presented in [18]. The analysis shows that the GDT NS has a number of advantages in comparison with other candidates to the role of the neutron source for testing structural materials for future fusion reactor. In particular, among other candidates, the GDT NS has the lowest power and tritium consumption (60 MW and 150 g/yr correspondingly). At the same time, this source satisfies the requirements of material scientists concerning to both neutron flux density (2 MW/m^2 or 10^{14}neutrons/$cm^2\cdot s$) and the testing zone area (of the order of 1 m^2).

One of the most important factors, which determines the lifetime of fast ions in the GDT and therefore the efficiency of the neutron production, is the electron temperature. At present, in the GDT experiments T_e is limited to ~100 eV. This value could be considered as being too low for the neutron source. At present, the new power supplies have been constructed to extend the duration of neutral beam injection from 1 up to 5 ms. It should result in increase of T_e up to 200 eV. Additionally, installation of new injectors is planned which will increase the injection power from 4 to 10 MW. These injectors are planned to be mounted on the GDT by the end of 2006. It follows from the calculations that the electron temperature of 300 eV could be then obtained. As soon as it happens this will demonstrate feasibility of the neutron source with "moderate" neutron flux (~$0.5 MW/m^2$). To demonstrate practicability of full scale NS the device named "Hydrogen prototype" is planned to be constructed later on.

GOL-3 Experiments. Plasma Heating in Homogeneous Magnetic Field

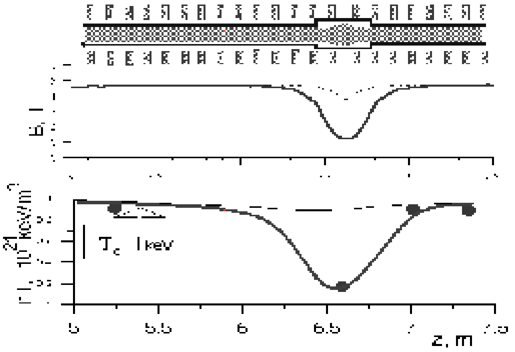

FIG.1.Direct observation of anomalously low longitudinal electron heat conductance during the process of collective relaxation of REB in plasma.

The first experiments have been done with homogeneous plasma (n_e~$10^{21}m^{-3}$) placed in 7 m long solenoid with 5T magnetic field. In the end mirrors magnetic field was 11 T. The beam diameter in plasma was 6 cm. These experiments have demonstrated high efficiency of REB-plasma interaction. In optimal conditions the electron beam energy loss in the plasma was up to 40 %. However, as it followed from estimation (see [6]), plasma heating strongly increases Spitzer longitudinal thermal conductance, so that the electron temperature cannot exceed 100-150 eV for the given heating power. In fact, the electron temperature achieved the level of T_e~2 keV. As calculations have shown this is only possible if the longitudinal electron thermal conductance is three orders of magnitude less than the Spitzer one [6]. As it follows from the results obtained on the GOL-M for the conditions similar to that on the GOL-3 (except the beam duration), it can be explained by enhanced scattering rate of plasma electrons due to presence of relatively slow density fluctuations related to ion-sound turbulence and collapsing cavities. Direct experimental demonstration of the suppression of longitudinal heat conductance was made in GOL-3 device [22]. For that, magnetic field in a section of solenoid was decreased (see in Fig.1).

The electron temperature was measured to be constant outside the local magnetic "well" and high (T_e ~ 1 keV). At the same time, it was significantly less in the bottom of the well (T_e~150 eV) because the REB current density is also minimal in this region providing here smaller specific energy release and electron heating. This very steep temperature gradient is sustained practically during all the time of REB injection and disappears quickly after switching off the beam.

More reach physics appears with the transition to multi mirror geometry of the magnetic field. These experiments were done with longer solenoid (12 meters) composed of 55 mirror cells with B_{max}= 5 T and B_{min} = 3.5 T. The beam duration was $8\cdot10^{-6}$s instead of $3\cdot10^{-6}$s in the first experiments, Initial plasma density was varied in the range $0.5\cdot10^{21} - 2\cdot10^{21}m^{-3}$.

GOL-3. Plasma Behavior in Multi Mirror Magnetic Field

After transition from homogeneous magnetic field to multi mirror configuration significant progress in the GOL-3 plasma parameters was observed as it is seen in Fig.2. Energy confinement time was increased by two orders of magnitude. Recently the energy confinement time exceeded 10^{-3}s at the density level of order of 10^{21}m^{-3}.

It has been already mentioned that after switching off the REB current, the effect of suppression of electron thermal conductance disappeared immediately. As a consequence of that the electron temperature fells down rather quickly. Thus, the diamagnetic signal observed on the upper trace of Fig. 2 can be only explained by high ion temperature. This result is rather unexpected. In the process of REB-plasma interaction only plasma electrons can be directly heated. The ions stay cold because the temperature equilibration time is much longer than the energy confinement time. Nevertheless, three independent methods of measurements of the ion temperature which were applied (besides diamagnetism) have shown that plasma ions were heated rather fast (within tens of microseconds) and the ion temperature could be estimated as 2 keV at plasma density $n_e \cong 10^{21}$m^{-3} [23]. The ion temperature was measured with the aid of Doppler broadening of D_α line at the plasma boundary, registration of charge exchange neutrals from hot plasma and by registration of D-D neutron flux, which is shown in lower part of *FIG.2*. All the methods have shown that ion temperature reached the level of 2 keV within tens of microseconds. As it is seen in *FIG.2*, plasma pressure and the neutron yield fall down very slowly with characteristic time ~ 10^{-3} s. Correspondingly, $n\tau$ product, at present, has reached ~ $2\cdot10^{18}$m^{-3}s.

Conceivable mechanism of ion heating is related with strongly non uniform electron heating in corrugated magnetic field. The strongest heating of electrons should take place at the maxima of magnetic field where the REB current density is maximal. As a result, the electron pressure will be higher there and will be lower in the mid-planes of each mirror cell since the growth rate of beam-plasma instability is proportional to n_b/n_p. As it has been already mentioned, the longitudinal heat transfer is suppressed till the switching off the REB. Expansion of high pressure plasma clouds initially localized near mirrors and containing hot electrons together with cold ions will produce the counter fluxes of plasma and subsequent conversion of their directed energy into ion thermal energy.

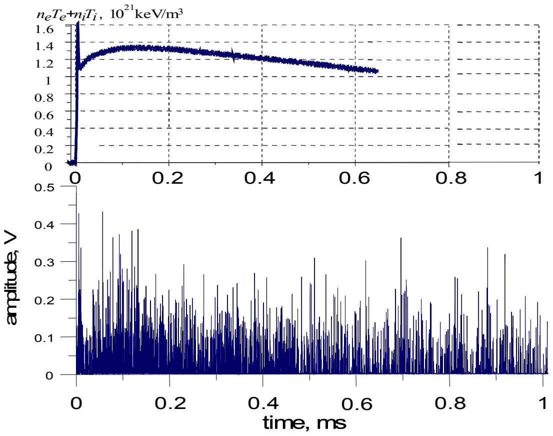

FIG.2. Multi mirror system GOL-3. Temporal variation of plasma pressure and neutron flux. Deuterium density is $1.5\cdot10^{21}m^{-3}$,z=2.08m from the injection point.

Note that there is an additional effect which leads to shortening of effective ion mean free path and to increase of the longitudinal confinement time. Regular oscillations of the neutron flux irradiated from single mirror cell [24] was observed practically during all the plasma decay. The period of these oscillations is close to l/v_i , where l is a single cell size and v_i is ion thermal velocity. In principle, electrostatic plasma oscillations with phase velocities close to v_i experience strong damping and can not exist for the case $T_e<T_i$. Nevertheless, they were observed experimentally and corresponded well to ion bounce frequency. This contradiction can be explained by the fact that plasma in the multi mirror geometry is not homogeneous and the distribution function is non-equilibrium. In this case, bounce oscillations can exist in separate cells causing transit ions scattering and trapping in local cells, so that axial plasma confinement improves. For more details see [9].

Note, that the plasma in the GOL-3 with axisymmetric magnetic field is MHD stable. It is provided using axial currents (the electron beam, return current and gas discharge current) flowing in plasma. If the sum of the beam current and the return current (net current) is not equal to zero, then the gas discharge current can have the same or counter direction. The stable plasma is sustained when the discharge current is directed opposite to the REB. Results of these experiments are summarized in [22].

GOL-3. Plasma -Wall Interaction Studies

The plasma parameters in GOL-3 makes it possible to model not only evaporation, ionization and destruction of wall materials in the case of ELMs in tokamaks, but also to study the impurity ions transport along magnetic field lines into hot plasma. The level of energy density in the plasma exhaust (1 - 50 MJ/m^2) also enables one to study plasma – wall interaction during major disruptions. It is important that the GOL-3 plasma has hot electrons and ions. At present, there is no other system with hot electrons and ions in plasma fluxes to simulate plasma - wall interaction in ITER and DEMO. For more detailed information see [25].

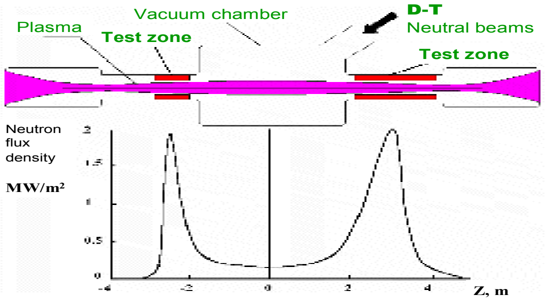

FIG.3. Layout of NS and neutron flux density distribution

Gas Dynamic Trap (GDT)

Advantages of the GDT approach stem from very simple and reliable physics of longitudinal plasma confinement and from axial symmetry of the system. In contrast to the conventional mirrors, because of high mirror ratio and narrow loss cone, the collisional 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, can not excite. The longitudinal confinement time in the device can be estimated as $\tau \approx R \cdot L / V_{T_i}$. It seems to be too small for fusion reactor, but, it is quite appropriate in the case of neutron source (NS) GDT based for reasonably high mirror ratio and L~20m. *FIG.3* illustrates the principle of operation of such neutron source. The key element of the NS is the powerful oblique injection of neutral beams (NB) into "warm" plasma and formation there fast deuterons and tritons oscillating between turning points. The density of these anisotropic ions is strongly peaked near the turning points. Correspondingly, the neutron flux maxima appear at the same places. According to our calculations, the GDT NS can produce the neutron flux density of 2 MW/m^2 (10^{14}neutrons/cm$^2 \cdot$s) at the area of 1 m^2. At present, the main physical problems of the gas dynamic plasma confinement have already been solved, at least for moderate plasma parameters. In particular, it was shown that in spite of unfavorable curvature of magnetic field lines in the trap the plasma can be stabilized against excitation of MHD modes. It was shown experimentally that high enough favorable curvature of the field lines in the expander region beyond the mirrors stabilizes the entire plasma [14]. The stability can be made significantly more robust if additional cusp end cell is attached to the central solenoid of GDT [15]. Plasma stability can be also improved by application of radial electric fields [16].

Another important problem for the GDT is longitudinal electron thermal conduction to the end walls. It was shown experimentally that if the magnetic field drops between mirror and end wall so that the ratio of B_m / B_w is larger than $(M/m)^{1/2} \sim 40$ for hydrogen, axial electron conduction is suppressed and there is no influence of the end wall position on the electron temperature in the trap [13].

Formation of the peaks of D-D neutron yield near the ion turning points have been demonstrated in the experiments with injection of deuterium beams into GDT, with complete agreement with simulation results [26].

Table I

	GDT 2003	GDT-U
Injection energy	15-17 keV	25keV
Power	4MW	9-10MW
Duration	1ms	5ms
Magnetic field at mid-plane	0.23T	0.3T
Electron temperature	~100eV	~300eV
Plasma density	$4 \cdot 10^{19}$ m^{-3}	$4 \cdot 10^{19}$ m^{-3}
Fast ion density	$2 \cdot 10^{19}$ m^{-3}	$5 \cdot 10^{19}$ m^{-3}
Average energy	8-10 keV	10-15 keV

All these experiments carried out with the following parameters of the device. The mirror to mirror distance is 7 meters, plasma radius at the mid plain is 8-15 cm, magnetic field value in the mirrors is up to 15 T, and in the mid plane is 0.22 T. Plasma density is 3 - $20 \cdot 10^{19}$m^{-3}. The NB energy is 15-17 keV, total injection power is up to P_b = 4 MW, the beam duration τ_b = 1.1 ms, and the injection angle is 45^0. At these parameters the electron temperature of order 100 eV was obtained. This value is in a reasonable agreement with calculation results. Nevertheless, it is quite far from that required for demonstration of practicability of full scale GDT NS. At present, new injectors and new power supply for them are practically ready. The comparison of the present day GDT and the GDT upgrade parameters is given in the Table I. Longer duration of neutral beam injection from physical view point corresponds to the regime of steady state operation. The experiments on the GDT-U are planned to start in the nearest time. Preliminary experiments will be carried out with existing injectors but with new power supplies providing $5 \cdot 10^{-3}$s pulse duration. By the end of the year new NB injectors will be mounted giving injection power up to 10 MW.

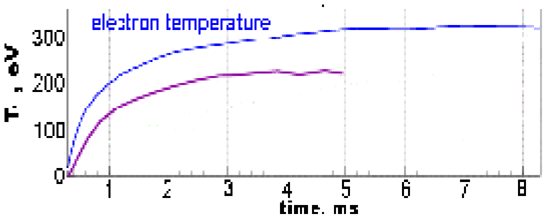

FIG.4. *Electron temperature variation during time. Upper trace - 10 MW, lower trace – 4 MW of injection power.*

It is seen in *FIG.4* that, at present, the plasma in GDT does not reach steady state during the injection pulse. According to calculations, simple increase of the injection duration (at injection power of 4 MW) should double the electron temperature. For 10MW injection, if the value of T_e = 300 eV predicted by code will be obtained, it will prove that “moderate” NS with neutron flux density of 0.5 MW/m^2 ($2.5 \cdot 10^{13}$neutrons/s$\cdot$cm^2) is feasible. On the other hand, the difference between achieved (T_e = 300 eV) and required (T_e=750 eV) for full scale NS temperature will be small enough and degree of confidence to the simulation results becomes higher. At present, the activity connected with completion of construction of “Hydrogen Prototype” as a model of the full scale neutron source is re-started in Novosibirsk.

In the GDT based neutron source fast ion density in the turning points is singificantly higher than background plasma density. This leads to formation in these regions the peaks of ambipolar potential, which in some cases considerably reduce warm plasma losses through the ends of the device. This effect was first studied in the GDT device. In order to obtain as high as possible local fast ion density peak, in the central cell of the device an additional, small size mirror cell was installed near the end magnetic mirror. The fast ions in the local cell were produced by injection of the two focused neutral beams with energy of 17keV and pulse duration of 0.9ms. Total injected power into the local mirror cell in the experiments was limited to 0.2MW. Target plasma streaming from the central cell into the local one has a density of 10^{13} cm^{-3} and electron temperature ≈70 eV. Peak density of accumulated fast ions was $1.2 \cdot 10^{19}$ m^{-3} in the regime with initial target plasma density of $0.8 \cdot 10^{19}$ m^{-3}. Warm plasma density was measured to be $0.4 \cdot 10^{19}$ m^{-3}, so that density of the fast ions in the small mirror cell exceeds that of warm ions by a factor of three. Under these conditions, according to expectations, considerable ambipolar potential develops in the local cell that results in ~ 50% reduction of plasma end losses through the mirror next to the local cell.

Conclusions

Recent successes achieved in the GOL-3 in heating and confinement of a dense plasma, demonstrate perspectives of axisymmetric multi mirror system, attractive by its engineering simplicity, as a fusion reactor with magnetic (but not "wall") plasma confinement. High power relativistic electron beam seems to be an appropriate energy source for the reactor.
Recent status of GOL-3 and under-discussion upgrade makes this facility very important for structural materials tests at high heat fluxes of electronic-hot plasma. Besides, propagation of cloud of impurities formed as a result of disruption or ELM activity along and across magnetic field can be studied in this trap, as well.
Very promising results could be obtained at the GDT-U device in the nearest future. Till the end of the year 2006, practicability of a "moderate" neutron source should be experimentally proven. In the case of success, the modeling of the full scale neutron source would start soon. To our opinion, even "moderate" NS with large (~1m^2) size of testing zone could be very useful for material scientists. At present, they have nothing similar to the NS under discussion. However, even after ITER campaign DEMO can not be constructed without testing of materials.

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