PROGRESS IN STUDIES OF MAGNETIC MIRRORS AND THEIR PROSPECTS.

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Abstract. *The most important results obtained in the experiments with modern magnetic mirrors of the Budker Institute are presented in the paper. These results relate to multiple mirror installation GOL-3 and gas dynamic trap (GDT). In comparison with conventional mirror machines the modern mirrors are characterized by significantly improved longitudinal confinement of plasma. Besides, they can be operated in axial symmetric geometry. Anyway, it has been already shown that transverse losses can be significantly suppressed in the axisymmetric case.*

The results which have been obtained in studies of modern mirrors permit us to consider important practical applications of these confinement systems. In particular, a unique 14 MeV neutron source (NS) for testing fusion materials can be built on the basis of the gas dynamic trap (GDT NS). Among the most important results one should mention a suppression of transverse losses with the aid of the so call "vortex confinement", decrease of longitudinal losses by creation of ambipolar potential outside the main trap, an increase in plasma β up to the level of $\beta \approx 60\%$, determination of the excitation threshold of the AIC instability responsible for the lifetime of fast ions in the trap, etc.

As to GOL-3, a lot of important physical results were obtained recently. In particular, the efficiency of relativistic electron beam (REB)-plasma interaction was achieved of 50%, strong (up to several thousand times) suppression of longitudinal electron conductivity was obtained, the electron temperature $T_e \approx$ 2-4 keV and ion temperature $T_i \approx$ 2 keV were observed, improved longitudinal plasma confinement in comparison with the original theory predictions was discovered and explained.

1 Introduction.

The Budker – Post magnetic mirrors distinguished by the very simple physics and simplicity (see **Figure 1**) have played a great role in the beginning of fusion studies and gave a lot of important results. However, after the works of A.A.Galeev [1] as well as R.Post and M.N.Rosenbluth [2] clouds appeared over classical mirrors. D.V.Sivukhin [3] has shown very bad prospects of this concept of plasma confinement even without taking into account the loss cone. In the seventies, in spite of the outstanding results of 2XIIB mirrors disappeared gradually from fusion laboratories.

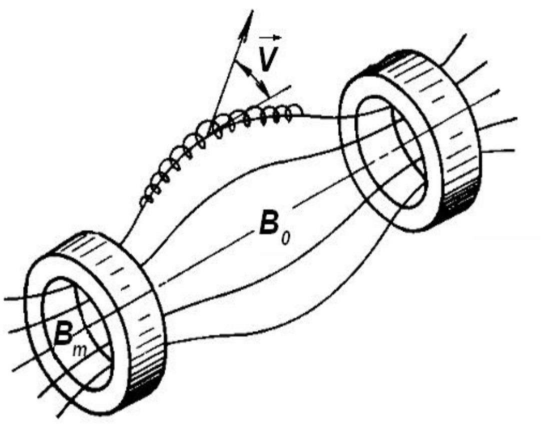

Figure 1 A scheme of magnetic mirror

The first serious revision of the mirror concept has occurred in 1971 – 1972 [4, 5]. The simplest fusion reactor can be presented as a long pipe with a dense (λ_{ii}<<L) plasma placed in longitudinal magnetic field, here λ_{ii}

is the ion mean free path, L is the total size of the system. The longitudinal confinement time for such reactor is estimated as: $\tau_o \sim L/v_{Ti}$, where v_{Ti} is the ion thermal velocity. The length of such system is high enough,

however, if instead of homogeneous magnetic field a corrugated one is used, then the longitudinal expansion of plasma in such a system will have diffusion character, that is $\tau \approx L^2/\lambda_i v_{Ti}$ This estimation is correct when $l \ll \lambda_i \ll L$ (here l is the period of corrugation or single mirror cell size). More exactly (see Ref.[4]) the lifetime is evaluated by the formula: $\tau \approx R^2 L^2/\lambda_i v_{Ti} = \tau_0 \cdot R^2 \cdot L/\lambda_i$ (here R is the mirror ratio, $R=B_{max}/B_{min}$) Thus, the increase of confinement time in comparison with τ_0 is determined by factor $R^2 \cdot L/\lambda_i \gg 1$. It follows from this estimation that the length of multi-mirror reactor can be limited by 100-300 meters (depending on plasma density). In the case when plasma pressure is significantly larger than magnetic one, so called "wall confinement" [6] can be used with transverse cooling time high enough from the viewpoint of the Lawson criterion. To try to observe experimentally wall confinement effects one should deposit into a plasma about 1 MJ of energy. In this sense to study effects of longitudinal confinement is more simple problem.

The first experiments on multi mirror system with alkaline plasma have confirmed the predictions of the theory and shown a significant increase in the plasma lifetime of the multi mirror trap [7, 8].

As estimations show the multi mirror reactor can be built in a plasma density range within $n_e = 10^{23}$-$10^{24} m^{-3}$. Correspondingly, the transverse magnetic confinement requires too high values of magnetic fields (of 300 T). Thus, one should use transverse "wall .confinement" scheme with $\beta \gg 1$ [6]. Fortunately, due to the bounce instability observed in the GOL-3 experiments [9] it turn out that the effective ion mean free path λ_{eff} is of order of l even in a "rare" plasma ($n_e \sim 3 \cdot 10^{21} m^{-3}$). That means that multi mirror fusion reactor with magnetic confinement ($\beta < 1$) at reasonable magnetic fields (of the order of 10 T) is possible.

In 1976 – 1977 ambipolar trap (or tandem mirror) was proposed in Novosibirsk and in Livermore [10, 11]. Unfortunately the experiments in Novosibirsk stayed unaccomplished and we shall not discuss further this subject.

Among modern mirrors the last system, - so called Gas Dynamic Trap (GDT) was proposed in 1979 by V.V.Mirnov and D.D.Ryutov [12]. It is a Budker – Post mirror trap with a very high mirror ratio (R~10 – 100). If the plasma in the trap is dense enough ($\lambda_{ii}/R < L$), the confinement time can be estimated as a time of gas escape from a vessel through a small hole: $\tau \sim Ln/S_m n V_{Ti}$, here L is the length of the trap, S_m is the cross section of the "hole", $S_m = S/R$, S – the cross section in the mid plane, and V_{Ti} is the ion thermal velocity. Thus, $\tau \sim RL/V_{Ti}$. The advantage of this concept consists in the absence of micro instabilities in the dense collisional plasma. Unfortunately, the confinement time in such a system is low enough. The fusion reactor on this principle should be of several km long [13]. Fortunately, this scheme can be used to solve very important for fusion program problem. The gas dynamic principle of plasma confinement allows one to create an efficient 14 MeV powerful neutron source (NS) for fusion material testing. In this case, the length of the source could be rather moderate (of the order of 10m). As calculations show, the full scale GDT NS could produce about 2 MW of 14 MeV neutrons ($\sim 10^{18} m^{-2} s^{-1}$) at the area of 1 m^2. The tritium consumption of the GDT NS is low enough (~ 150g/yr). It should be mentioned that the GDT NS is the only one plasma based NS where neutrons can be obtain with the use of oblique injection of energetic D, T atoms into a "warm" plasma. According to calculations optimal energy of injected atoms should be of 65 keV. One of advantages of the GDT NS consists in strongly inhomogeneous distribution of sloshing ions density along the system. Maximum sloshing ions density localizes in the vicinities of turning points. Correspondingly, the most part of the installation can operate without replacement of any elements during many years. As to testing zones area (0.5 m^2 from each side) they should replaced from time to time.

Below the most important recent results obtained on GOL-3 and GDT are presented.

2. Multi Mirror Trap.

The key elements of multi mirror system GOL-3 are:
1.Relativistic Electron Beam (REB) for plasma heating (E_b~ 1 MeV, I_b ~ 30 kA, $\tau_b \sim 8\cdot10^{-6}$ s).
2. Long (12 m) solenoid capable to operate with homogeneous magnetic field B_0 = 5 T with two end mirrors B_m= 11 T) and in the multi mirror geometry (B_{max}= 4.8 T, B_{min} = 3.2 T; single cell longitudinal size, l = 22 cm).
3.Hydrogen (deuterium) plasma is produced in a density range $n_e = 10^{20}$ -10^{22}m^{-3}.
At present, rather impressive results on plasma confinement and heating have been obtained on multi-mirror facility GOL-3. It follows from these results that due to some collective phenomena the longitudinal confinement can be even better than that predicted by the theory. Correspondingly, there exists a possibility to achieve the plasma parameters required for fusion reactor of reasonable length and with relatively rare plasma. In this case, instead of "wall confinement" one can use magnetic one.
The first experiments on the GOL-3 have been done with plasma ($n_e \sim 10^{21}$m^{-3}) placed in the solenoid with homogeneous magnetic field of 5T. In the end mirrors 11 T magnetic field was used. The beam diameter in plasma was 6 cm. These experiments have demonstrated high efficiency of REB-plasma interaction. At present, the REB energy losses in the plasma achieved up to 50%. Because of strong longitudinal electron thermal conductivity the plasma electron temperature after heating could not exceed 100-150 eV for applied heating power. However, in fact the electron temperature measured by Thomson scattering achieved the level of T_e >1keV. As calculations have shown [14] this level of temperature is only possible if the longitudinal thermal conductance of plasma is three orders of magnitude less than the Spitzer one.
Direct experimental demonstration of this effect was made on the GOL-3 [15]. For that, magnetic field in a part of solenoid with strong homogeneous magnetic field was decreased from 5 T down to 2 T. In these conditions the electron temperature at the bottom of magnetic well was several times less than that in the homogeneous magnetic field (as if in mirrors).
The experimental results on suppression of the longitudinal thermal conductance can be explained by an excitation of micro turbulence during REB - plasma interaction. As it was shown on the another device, GOL-M, at the same current density of REB and plasma densities, the strong Langmuir turbulence was excited in plasma during the REB injection. That led to beginning of relatively slow density fluctuations because of appearance of collapsing cavities [16] and an excitation of ion sound turbulence [17].
Thus, the strong Langmuir turbulence is responsible for heating of plasma electrons. The growth rate of the turbulence is proportional to $\omega_{pe}\cdot n_b/n_e$, here n_b is the density of the beam electrons. It is clear that an energy release in plasma in the vicinity of magnetic well should be strongly non uniform along the axis of the system. Minimum energy release will correspond to the bottom of the well where the ratio of n_b /n_e has the least value. Correspondingly, the electron temperature in this point should be also minimum. The maximum T_e should be in maxima of magnetic field, or, other words, in mirrors. Of course, if the longitudinal thermal conductivity is high, the temperature drop should disappear rapidly. However, in fact, the drop of temperatures exists during 5-6 microseconds since the beginning of REB injection and only later one can notice an increase the electron temperature in the center of the well.
The experiments on plasma heating and confinement in multi mirror magnetic field were made with plasma (typical density of 10^{21}m^{-3}) placed in 12 m long solenoid. Typical total energy content of the REB was 120-150 kJ. The current density of the REB was slightly higher than in previous experiments: the beam diameter in mirrors was 4 cm against 6 cm in the case of homogeneous magnetic field.

Since the mechanism of REB - plasma interaction in both cases (homogeneous and multi-mirror geometries) is the same, the time behavior of energy content after heating differs significantly. In **Fig.2** one can see temporal behavior of plasma diamagnetism in two cases. It is seen that in homogeneous magnetic configuration the plasma pressure (a) falls down rather rapidly because after switching off the REB current usual thermal conductivity along the magnetic field restores and the cooling of electrons occurs rather quickly. The curve (b) demonstrates significant increase of diamagnetism duration in the multi-mirror geometry. Such a behavior of second curve is explained by fast heating of ions up to 1- 2 keV practically during the REB injection. The fast transfer of energy of electrons to ions can not be explained by classical binary e-i collisions. The mechanism of fast exchange of energy can be explained as follows. We have already mentioned about inhomogeneous energy release depending on n_b/n_e. The maximum energy release will occur in the vicinities of maxima of magnetic field and minimum will be observed near midplanes of each mirror cell. Thus, many blobs with high electron pressure will appear and these blobs will expand along the system axis toward areas of minimal pressure. In other words, the mechanism of fast ion heating is explained as a collective acceleration of ions because of strong longitudinal electron pressure gradient. The duration of this process is rather short. As it follows from the experiments, ion heating occures during the time when the REB current exists. Besides diamagnetic measurements, three additional independent methods of measurements of the ion temperature were applied: observation of Doppler broadening of D_α line at the boundary of hot plasma, registration of charge exchange neutrals from hot plasma and measuring neutron flux of D-D reaction. All this methods are in reasonable agreement. All of them shows very short time of energy exchange between electrons and ions and give coincident value of maximum ion temperature, $T_i \approx 2$keV.

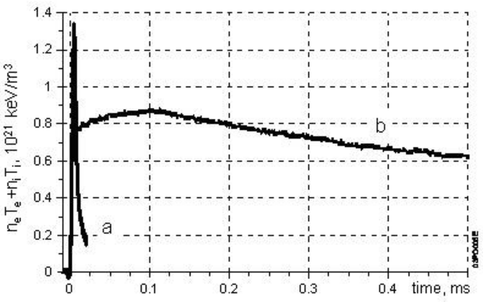

Fig.2 Temporal behavior of plasma pressure after REB injection
a)homogeneous b) multi mirror magnetic field

Typical confinement time for plasma density of 10^{21}m^{-3} in the described experiments is of order of 10^{-3} s. From the viewpoint of the theory of multi-mirror confinement such value should observed for significantly higher plasma density. As a matter of fact it means that there exists a mechanism which makes ion mean free path, λ_{ii}, less than classical one. What a mechanism can decrease λ_{ii} ? The answer follows from [Ref. 18] where temporal behavior of D-D reaction neutron flux from a single cell was studied. Regular oscillation of neutron flux with the period equaled to $T \sim l/V_{Ti}$ [19] were identified as the bounce instability [9]. This instability excites when the hot plasma flow from the input up to output of the system appears. Oscillations of the neutron flux are explained by the density modulation of hot passing ions caused by the instability. Besides, this instability induces effective scattering of passing ions and thus, it decreases an effective ion mean free path and improve the longitudinal confinement.

It should be mentioned that plasma confined in any axisymmetric magnetic traps should be MHD unstable. However the problem of plasma stability can be solved. In particular, in the case of GOL-3 it was shown that magnetic shear turn out the important factor for good plasma confinement. Sheared structure of the magnetic field was formed by axial guiding magnetic field of the solenoid and by azimuthal magnetic field, which was generated by axial currents in the plasma(current of relativistic electron beam, return current to the beam and current of the preliminary linear discharge).. Safety factor for linear systems was $q= (H_z/H_\varphi) \cdot(2\pi r/L)$ (where H_z and H_φ are longitudinal and azimuthal components of the magnetic field, r and L are plasma radius and column length). Results of measurement of $\mu=1/q$ are given in **Fig.3** in

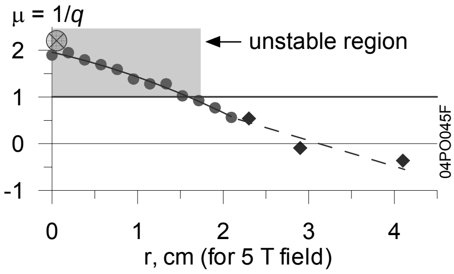

Fig.3 Rotary transformation factor at $T = 3.5\ 10^{-6}$ s after start of the REB injection. Black circles - X-ray footprint, cross – current density on the exit, diamonds – current measurements on the entrance of the system.

the stable operation regime of GOL-3. Features of this regime are appearance of sheared helical magnetic field and formation of magnetic surface with azimuthal field equal to zero inside the plasma column.

Recent findings in studies in the GOL-3 device offer a path to a multi-mirror reactor operating in steady state or in a pulse mode with $\beta \leq 1$ and moderate electron beam power. Below conceivable parameters of the pulsed reactor version are presented.

The length of the pulse reactor is 150 meters. The main plasma parameters are: Plasma diameter – 12 cm, the temperature – 12 keV, plasma density - $2 \cdot 10^{21} m^{-3}$, plasma $\beta = 0.9$. Magnetic fields B_{max} / B_{min} = 20T/10T are supposed. Energy deposited in plasma is of ~ 7 MJ, fusion energy per shot is of ~ 50 MJ. Energy confinement time is estimated as $\tau_E \sim 0.1$ s. The power of REB (of ~ 100 MW during 0.1 s) seems quite realistic.

The steady state version of reactor has a length of 350 meters. To achieve $Q \approx 5$ the REB power P = 159 MW should be used.

The versions of multi mirror reactor discussed above has obvious advantages in comparison with original version of “wall confinement”[6]. The new versions of reactor with rare plasma ($n_e \sim 10^{21} m^{-3}$) are capable to operate as in pulse so in steady state regimes.

3. Gas Dynamic Trap.

The works under the problem of GDT based neutron source began just after the appearance of the proposal (see Ref. [20]. The key idea of the GDT NS consists of the use of power oblique injection into “warm” plasma of small diameter (~20 cm). In result of capture of energetic neutral beams (D and T) a population of sloshing ions with the energy of 100 keV is formed in plasma. Maximum density of sloshing ions and the main yield of fusion neutrons appears at the vicinities of turning points see **Fig.4**).

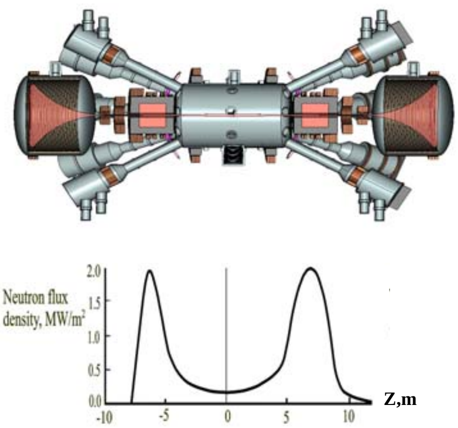

Fig. 4. Scheme of the GDT NS and longitudinal distribution of neutron flux.

The GDT NS has a lot of advantages in comparison with other schemes of 14 MeV neutron source.

Because of small volume which produced main portion of neutrons this source requires a moderate power (of 60 MW).

The GDT NS has the simplest vacuum and magnetic systems because of axisymmetric geometry.

Plasma pressure can be comparable with magnetic one . It makes possible to obtain the highest density of neutron flux from a unit of volume in comparison with any other schemes of neutron sources. Thus, the main part of the neutron source chamber can function many years without replacement. NB injectors work in significantly more favorable conditions than those in tokamak case. The problem disruption does not exist. At last, there are no divertor problems.

Because of collisional character of “warm” plasma, its behavior is classical and microinstability are not exited. In this case, fast ions lose the energy mostly by drag on electrons and scatter to the loss cone due to Coulomb scattering.

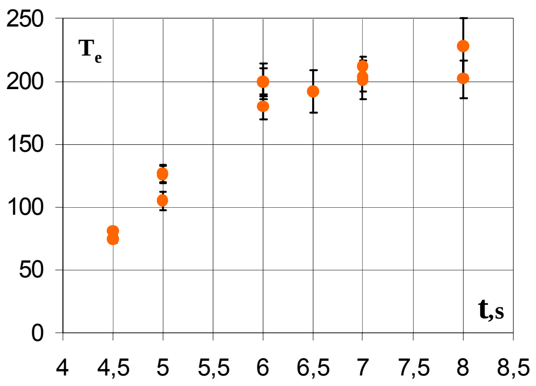

Fig.5 Temperature dependence on time at NB injection power P_{inj} = 6 MW

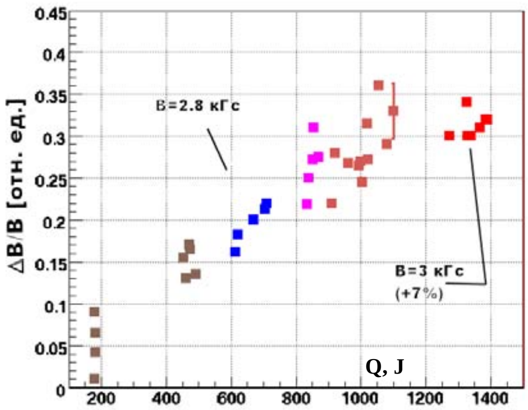

Fig.6 Measurement of magnetic field in plasma by the MSE diagnostics.

In all calculations the range of parameters is examined where micro instabilities are not excited. Such situation is realized when the electron energy does not exceed 1% of NB injection T. special experiments on excitation of micro instabilities have shown that the Alfven ion cyclotron instability is exited in the case of strongly anisotropic hot ions.

However, for the planned parameters of neutron source ($P_{NB\ inj}$ = 60 MW, P_n = 2 MW, E_{inj} = 65 keV, $n_e \sim 10^{20}m^{-3}$, and the energetic ions density, $n_h \sim 3{\cdot}10^{20}m^{-3}$, and) the freshold of this instability does not achieved.

One of the most important problem consist of obtaining required electron temperature T_e = 750 eV. At the moment the obtained temperature corresponds to the level of injection power (see **Fig.5**).

Among the most important results one should mention a suppression of transverse losses with the aid of the so call “vortex confinement”. At the moment the theory of this effect has been already made and the experiments have demonstrated reasonable agreement with the theory(see Refs [21]). The practical results of the application of “vortex confinement” consist of an increase in plasma β up to the level of β ≈ 60% (see Fig.6)

4. Summary

• The phenomena discovered at GOL-3 (efficient plasma heating by high-power electron beam, suppression of electron thermal conductance, bounce instability, etc.) makes multi-mirror reactor more realistic.

• Due to bounce instability effective ion mean free path decreases down to single mirror cell size. Thus, reactor will be able to operate with more rare (of order of $2{\cdot}10^{15}cm^{-3}$) plasma. It means that completely magnetic confinement can be used.

• Suppression of longitudinal thermal conduction by an electron beam can turn out useful for other open magnetic systems.

• At the moment, the data obtained in the GDT are sufficient to design the neutron source with power of several hundreds kW. At the same time, there are no physical limitations, inhibiting to creation of full scale neutron source.

• Progress in development of superconducting magnets can lead to significant simplification of the GDTns design.

• Besides, the GDT based fusion reactor can turn more realistic.

Acknowledgements

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