Thermonuclear Prospects of Modern Mirror Systems

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Abstract. At present, two modern axisymmetric magnetic mirror systems for plasma confinement are studied in the Budker Institute: multi-mirror trap (GOL-3) and gas dynamic trap (GDT). In the case of multi-mirror system GOL-3, a dense plasma ($n_e \approx 10^{21} m^{-3}$) with temperatures $T_e \sim Ti \approx 2$ keV was obtained. The most important results described in the paper are as follows. It was shown that electron thermal conductance along the magnetic system (12 m) can be suppressed by more than three orders of magnitude. As a result of that, plasma electrons heated by relativistic electron beam (REB) have achieved the temperature $T_e > 2$keV. In the case of multi-mirror geometry a mechanism of fast ion heating was discovered. At last, one should mention that untill now no limitations preventing further growth of plasma parameters in this system have been observed. Estimations of parameters of multi-mirror thermonuclear reactor are given in this paper.
Termonuclear prospects of the GDT are not so clear, but the GDT principle of confinement of collisional „warm“ plasma together with the use of oblique injection of fast D, T atoms allows to create an efficient 14 MeV neutron source (NS) for structural materials testing for thermonuclear reactors. The main idea of the GDT NS is as follows. A flux of fast atoms of D and T is injected into a warm plasma under an angle to the axis and captured in it. As a result, a population of sloshing ions of high energy is created. The maximum density of sloshing ions and correspondingly of neutron flux are formed in the vicinities of turning points. Thus, only small part of total area of vacuum chamber (of 1 m^2) will be irradiated by significant neutron flux density (of order of 2 MW/m^2). Due to that the tritium consumption should be small enough (~ 0.15 kg/yr).
The most important physical results are described in the paper. In particular, demonstration of MHD stabilization of plasma in axisymmetric geometry of magnetic field at $\beta \approx 60$ %, suppression of longitudinal plasma flux by ambipolar effect produced by additional compact mirror trap (CMT) filled with anisotropic plasma with $\langle E_i \rangle \gg T_e$, a study of Alfven ion-cyclotron (AIC) instability in the CMT with strongly anisotropic ions ($W_\perp/W_\| \approx 35$) The status of works on the program of GDT-U is presented

1.Introduction.

Among the systems for plasma confinement there are some traps with open-ended magnetic field lines, which strongly differ from the systems with closed magnetic configurations. All three types of modern mirror systems proposed in the Budker Institute [1-3] are working in several countries of the world.. A system with ambipolar principle of longitudinal confinement (tandem mirrors) is studied in Japan [4] and Korea[5]. Two open systems for plasma confinement (multi-mirror and gas dynamic traps) are working in Russia, Novosibirsk [6]. The first system, based on multi-mirror principle of plasma confinement, was proposed in Ref. [1]. If a plasma density is so high that $L \gg \lambda_{ii} \gg \ell$ (here L is the total length of the magnetic system, ℓ – single mirror cell size and λ_{ii} – ion mean free path), then the longitudinal confinement time can be described by the diffusion law: $\tau \sim L^2/ \lambda_{ii} \cdot V_{Ti}$, here V_{Ti} is an ion thermal velocity. As it follows from [Ref. 1], more correct formula should include factor R^2 , here $R = B_{max}/B_{min}$ is the mirror ratio. Thus, finally $\tau \approx R^2 \cdot L^2/ \lambda_{ii} \cdot V_{Ti}$ The accuracy of this proposal was checked in the experiments with rare cold alkaline plasma [7].
The second system, the so called Gas Dynamic Trap (GDT), is a version of classical Budker – Post mirror trap but with a very high mirror ratio, R (of a few tens), with a relatively large length L exceeding mean free path λ_{ii} lnR/R, with respect to scattering into the loss cone (see [3]). This target plasma is almost isotropic. One should add that this plasma looks like classical. Because of frequent collisions the micro instabilities are not excited in it. A very simple consideration allows to estimate the lifetime of plasma in the trap. If the plasma 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: $\tau \sim LSn/S_m nV_{Ti}$, here S is the cross section of plasma in the mid plane, and $S_m = S/R$ – the cross section of the "hole". Thus, $\tau \sim RL/V_{Ti}$.
According to this ratio, even for R≈100 the length of this simplest fusion reactor on the basis of the GDT should be more than 1 km [8]. Thus, at present, the thermonuclear prospects of the gas dynamic trap are not clear, but this scheme can be used for solving problems very important for fusion program. The gas dynamic principle of a plasma confinement together with the use of oblique injection of fast D,T atoms into the target plasma allows to create an efficient 14 MeV powerful neutron source (NS) for fusion material tests [9]. In this case, the length of the source could be rather moderate (~10m). As calculations show, the full scale GDT NS could produce of about 2 MW of 14 MeV neutrons ($\sim 10^{18} m^{-2} s^{-1}$) at the area of 1 m^2.
The main idea of the GDT NS is as follows. A flux of fast atoms of D and T is injected into a warm plasma under an angle to the axis and captured there. As a result, a population of sloshing ions of high energy is created. The maximum density of sloshing ions and correspondingly of neutron flux are formed in the vicinities of turning points. Thus, only a small part total area of the vacuum chamber total area (of 1 m^2) will be irradiated by a significant neutron flux density (of order of 2 MW/m^2). Due to that, the tritium consumption should be small enough (~ 0.15 kg/yr). It should be mentioned that the neutrons produced are originated mostly from collisions of fast D, T ions. Thus, it is not necessary to heat target plasma up to very high temperatures. Due to the fact that only a small part of plasma volume produces neutrons, the tritium consumption of the GDT NS is low enough (~ 150g/yr). As to the power consumption, in the most pessimistic case, it is not more than 60 MW [10]. The status and the prospects of the GDT and GDT NS are described in the paper.
Both systems studied now in the Budker Institute are rather simple since they have fully axially symmetric geometry. Initial idea of multi-mirror reactor was based on the concept of longitudinal confinement of a very dense plasma ($n_e \approx 10^{23} - 10^{24} m^{-3}$) in the corrugated magnetic field. Since for such densities $n(T_e + T_i) >> B^2/8\pi$ at any reasonable magnetic fields, it was supposed that the transverse confinement should be carried out by well conducting metallic wall (the so called "wall confinement" [11]). A principle of such confinement is based on the conservation of magnetic flux inside the tube after pulsed heating of plasma. After heating, the flux redistributes itself, forming near the wall a thin layer of strong magnetic field (of 300 T). The calculations presented in [Ref.11], have shown that transverse plasma cooling occurs slower than it requires the Lawson criterion. Thus, one can discuss the possibility of such reactor in spite of large technical difficulties. Fortunately, recent results of experiments on multi-mirror trap GOL-3 have shown that the longitudinal multi-mirror confinement is possible even at densities hundred times lower than that discussed by the authors of this method.
In the paper, the phenomena are described which allow to obtain rather dense plasma ($n_e \approx 10^{21} m^{-3}$) with high enough temperatures ($T_e \approx T_i \approx 2$ keV) and to confine it.

2. GOL-3 Facility. Main Parameters.

The main experiments on plasma heating and confinement were done in two modifications of magnetic system: homogeneous and multi-mirror. In the first case, the total length of solenoid was 7 m. Maximum magnetic field was 5.5 T. There were two end mirrors with the field up to 11T. In the second case the length of the system was 12m. 55 equal mirror cells were placed along the axis. The maximum magnetic field in each cell was $B_{max} = 4.8$ T, minimum one was
3.2 T. A vacuum chamber consisted of a stainless steel tube with inner diameter of 10 cm. Plasma diameter was 8 cm. The preliminary plasma (hydrogen or deuterium) with typical density of $10^{21} m^{-3}$ was produced by oscillating direct discharge (U = 30 kV, I = 3kA,

T = 120 μs). The geometry of experiments makes it possible to use relativistic electron beam (REB) as the most powerful source of energy for plasma heating. Such investigations began many years ago in Novosibirsk [12]. At that time, the energy stored in the REB was of 50 J. At present, typical energy of the REB in described experiments is 120 kJ. The main parameters of the beam passing along the plasma in the GOL-3 are as follows. The energy of electrons is 1 MeV, maximum REB current is up to 30 kA, typical current density of the REB in the plasma is 1-1.5 kA/cm^2, and the beam duration is $8\cdot10^{-6}$s. To inject the REB in plasma the initial beam with cross section of 140X4 cm^2 is transformed in the round beam with the diameter of 5 cm.

3. GOL-3. Experiments on a study of turbulent processes in plasma.

The results of plasma heating in two magnetic configurations were found to be absolutely different. In the homogeneous magnetic field with two end mirrors plasma electrons at density of 10^{21}cm^{-3} heated up to more than 2 keV during the beam injection. Just after switching off the beam the fast cooling of plasma electrons was observed because of longitudinal electron thermal conductance. The time behavior of T_e after switching off the REB injection corresponded well to the formula: $T_e = T_{e\ max}/(1+\alpha t)^{2/5}$, here $\alpha = f(n_e, Z_{eff})$. Thus, during the time of 10 - 20μs plasma electrons cooled several times and achieved the value of $T_e \approx$.100-150 eV. Although the cooling process describes well by classical longitudinal electron thermal conductance, simple estimations show that it is impossible to heat plasma by REB till high temperature (of 2 keV), observed in the experiment. In order to explain the experimentally observed maximum value of electron temperature one should suppose that the electron thermal conductance is three orders of magnitude lower than that of classical one [13]. 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 REB current and plasma densities as mentioned above ($n_{beam}/n_e \sim 3\cdot10^{-4} - 10^{-3}$), the strong Langmuir turbulence was excited in plasma during the REB injection. That led to beginnings of relatively slow density fluctuations because of appearance of collapsing cavities [14] and an excitation of ion sound turbulence [15]. According to the Ref.[16], in the case of REB-plasma interaction, the coefficient of electron thermal conductivity instead of $\chi_\parallel \sim v^2_{Te}/\nu_{ei}$ should be equal to $\chi_\parallel \sim v^2_{Te}/\Gamma$, here Γ is the growth rate of the beam instability, $\Gamma \sim \gamma^{-1}\bullet\theta^{-2}\bullet\omega_{pe}\bullet n_b/n_e$. In this formula θ is the angular spread of the beam, γ is the relativistic factor, and ω_{pe} is the electron plasma frequency. The estimations presented in Ref [16], have shown that if the level of turbulence is W/nT ~ 15%, the value of the electron thermal conductivity should be of 10^3 times lower than that of the classical one. Indeed, approximately this level of turbulence observed in the GOL-M experiments. So, the problem of thermal insulation of plasma and heating of electrons in open systems with REB is solved, anyway during injection time.

Absolutely another picture of plasma heating has observed in the multi-mirror geometry of magnetic field. The typical duration diamagnetic signal instead of 10 - 20μs now is 10^{-3}s.

Approximately the same duration has radiation of neutrons in the case of deuterium plasma [17] (see Fig.1) Thus, it means that the mechanism of very fast ion heating exists. This effect is explained by a few phenomena. The effectiveness of REB-plasma interaction depends on the ratio of n_b/n_e. It means that the

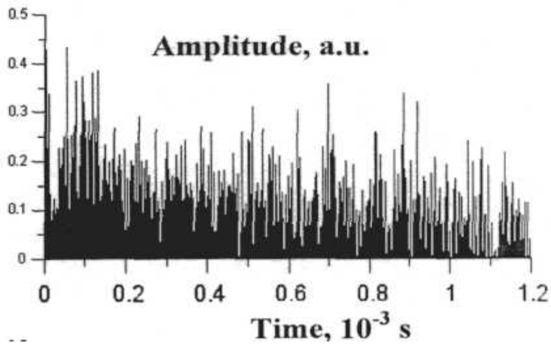

FIG. 1. Time behavior of neutron radiation

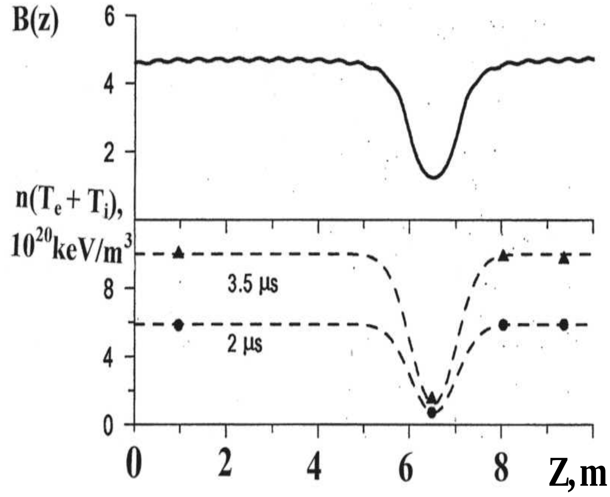

FIG.2. Upper trace: magnetic field strength along the axis of the system. Below: plasma diamagnetism (it is proportional to T_e) along the axis after 2 and 3.5 µs from the start of REB injection.

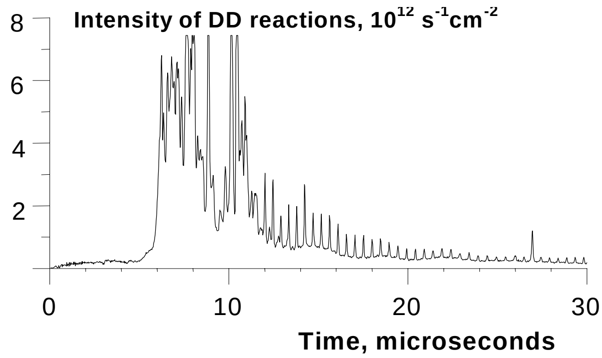

FIG.3. Generation of D-D neutrons as a result of collisions of opposite streams of deuterons

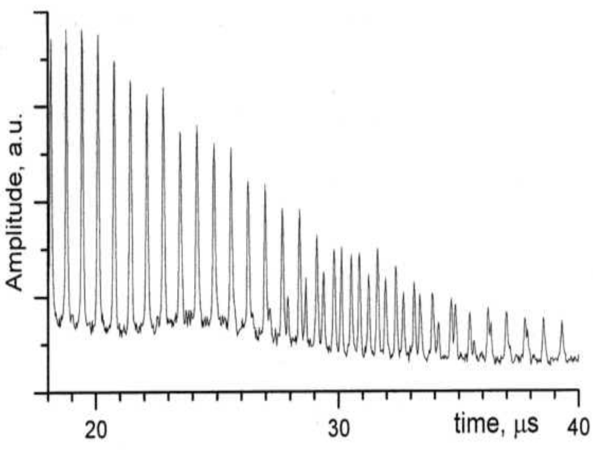

FIG.4. Regular structure of neutron radiation with $T \sim l/V_{Ti}$ as a consequence of bounce instability

power transfer from the beam into plasma in the mid plain of each magnetic cell will be less than in the mirrors. Taking into account the effect of suppression of the thermal conductivity along the system one should conclude that the electron temperatures will be different in mentioned places. Special experiment was made with injection of the REB ($j_b \sim 1$ kA/cm^2) in preliminary plasma ($n_e \sim 10^{21}$m^{-3}) placed in homogeneous magnetic field 12 meter long with one mirror cell (or magnetic well). This experiment has demonstrated that during the REB injection the energy transfer from vicinities of the mirror to the mid plane of the cell is close to zero [18]. Indeed, as it is seen in Fig.2, there exists a significant overfall of plasma pressures (or T_e) between the points with maximum and minimum magnetic fields. It means that in the case of multi-mirror geometry one can observe appearance of plasma streams coming from the opposite directions. Thus, there appeared the mechanism of longitudinal accelerations of ions. As it is seen in Fig.3, after 5 µs from the start of beam injection very fast growth of D-D neutrons radiation is observed [18]. The experimental results concerning estimations of time of ion thermalization are presented in Ref.[17] For $n_e \sim 3\text{-}5 \cdot 10^{20}$ m^{-3} this time is estimated as 20–30 µs. These measurements were made with the aid of Doppler broadening of D_α line and by diamagnetism.

In contrast to electrons, hot ions exist rather long time of the order of 1 millisecond. It means that multi-mirror confinement “works” although the requirements of the theory of method do not fulfil. The solution of this phenomenon is seen in Fig.3. One can see there regular oscillations. More careful study of these oscillations (see Fig.4) shows that their period is estimated as $T \approx \ell/V_{Ti}$. The period of oscillations was corresponded to this formula with the changes of cell size and the ion temperature [19]. According to Ref [20], the behavior of neutron radiation is explained by excitation of the bounce instability. The bounce oscillations facilitate the efficient exchange between the flow of

transit ions and trapped particles. Due to that the effective ion mean free path decreases by two order of magnitude and achieved the value $\lambda_{i\,eff} \sim \ell$.
In the multi-mirror configuration the problem of MHD stability exists. However, taking into account the geometry of the REB current, the current for creation of the preliminary plasma and net current it is possible to obtain sheared structure of magnetic field where plasma is MHD stable. In detail this experiment and computer modeling is presented in [21].

4. Gas Dynamic Trap. Initial Parameters and First Experiments.

This trap is a classical mirror machine but with a very high mirror ratio (up to R = 75). The maximum magnetic field in the end mirrors is up to B_{max} = 15 T. In the mid plane magnetic field strength of 0.2 – 0.22 T was used in the most of experiments up to now.. At present, B_0 = 0.27 T. The distance between the mirrors is 7 m, and the diameter of the vacuum chamber is of 1 m. Preliminary plasma with diameter of 20 cm in the mid plane is prepared with a plasma gun. Additional gas puffing is used if necessary. Six neutral beam injectors (NB) under 45^0 to the axis direction are used. In the most of the experiments up to now, the total power of injectors was 4 MW, the energy of atoms (hydrogen or deuterium) was 15 – 17 keV, and the duration of injection was 1 ms. The typical target plasma density was $3{\cdot}10^{19}m^{-3}$ and fast ions density was of 10^{19} m^{-3}. The temperature of electrons is determined by the balance between energy transfer from fast ions and gas dynamic losses through the end mirrors and achieved 100 eV. In spite of a very frugal parameters, a great deal important experiments were made. In particular, the first experiments on demonstration of plasma MHD stability in the axisymmetric magnetic field by increase in a curvature of the field lines were made [24]. Another possibility to improve the MHD stability was checked with the use of additional external cusp cell incorporated with the GDT [22]. The effect of suppression of electron heat conduction to the end wall by the expansion of magnetic flux tubes in the expander was studied. It turned out that this effect was corresponded to theoretical predictions of Ref. [23]. The experiment on a study of distribution of D-D neutrons was carried out. It showed that in agreement with calculations, the generation of neutrons mostly localized near two turning points. The density of the neutron flux far off the turning points was by the order of magnitude less. The main results of this stage are presented in Ref. [24].

4.1. GDT Upgrade. Status and Prospects.

From the viewpoint of fast sloshing ions confinement the regime of operation of the GDT till recently was non stationary. The new improved injectors with total power of six units of 10 MW, with focusing of the beams and with pulse duration of 5 ms were designed and constructed. From the physical point of view, such a duration corresponds to the steady-state regime. Because of various reasons, at present, the total power of the NB injectors is equal to 3.5 MW at the duration of 5 ms. Unfortunately, too much time is required for grid assembly production and training. The work on the increase in the power is in progress. According to the calculations, at 10 MW of NB injection the electron temperature of 300 eV should be obtained together with required density of fast ions. We plan that after completion of the work with injectors the $T_e \approx 300$ eV will be achieved. It will signify that anyway the “moderate” NS with the neutron flux density of 0.5 MW at the area of 1 m^2 is a reality. But even with the achieved injection power of 3.5 MW a great deal new results important for the GDT NS can be obtained. In particular, recently more effective stabilization of MHD modes were achieved, effects of suppression of plasma flux flowing out from the GDT were observed, etc.. To study these phenomena, an additional compact external mirror cell was incorporated to the GDT.

4.2. GDT. Experiments with additional compact mirror cell.

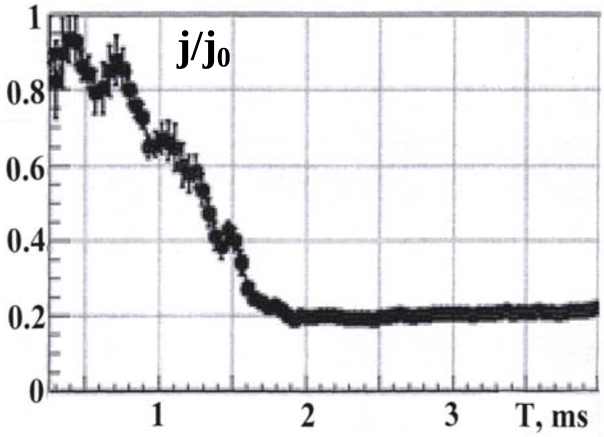

FIG.5 Ambipolar plugging of the flux flowing out the GDT. The injection of fast atoms into compact mirror cell begins at T = 0.

To obtain 2 MW of 14 MeV neutrons in the GDT NS, the electron temperature $T_e \approx 750$ eV is required. In this case, the power consumption should be of 60 MW. But it can be reduced if one can decrease the heat losses to the end walls. To try to suppress the longitudinal heat conductance the special experiment was carried out. A compact external mirror cell of 30 cm long with B_{max} = 5.2 T and B_{min} =2.4 was incorporated with the GDT. Two neutral beams from the injectors with the power of 1 MW (E=20 keV, t = 4 ms) were directed to the plasma flux flowing from the GDT ($n_{eo} \approx 10^{19} m^{-3}$). As a result of that, a strongly anisotropic plasma ($W_\perp/W_\parallel \approx 35$) with ratio n_h/n_c>>1 (here n_h is the density of hot and n_c is the density of cold ions) The maximum value of hot ions density achieved the value of $5{\cdot}10^{19} m^{-3}$. In this case, as it is seen in Fig.5, strong ambipolar plugging of the flowing flux is observed. Due to that the heat flux to the end wall in the steady state condition decreased by 5 times.

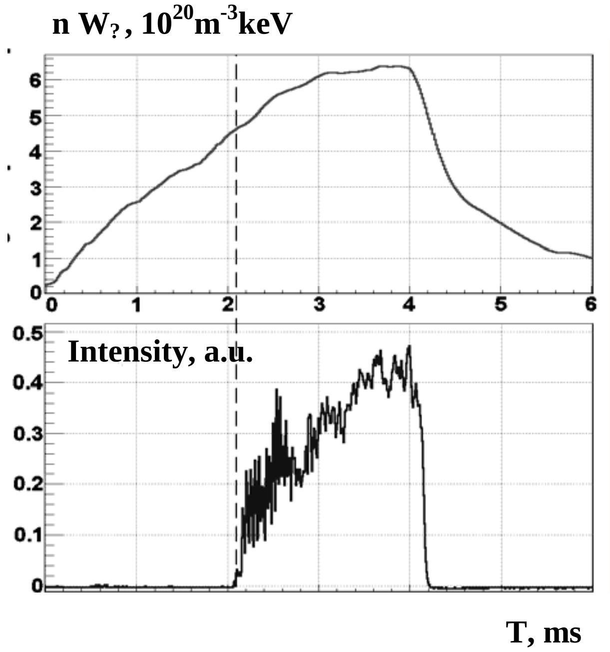

FIG.6. Plasma diamagnetism in the compact mirror cell during the NB injection (T=4 ms) and determination of threshold of the AIC instability (below).

One of vagueness in the parameters of the GDT NS connects with the necessity to create two component anisotropic plasma where micro instabilities can be excited. In this case, the increased losses of fast particles from the system should happen and the power consumption should increase.. Up to now, the losses in the GDT through the mirrors were classical. The micro instabilities were not observed. In the case of compact mirror cell with 90^o injection of fast atoms, a strong anisotropy was obtained and, in this case, the micro instability was observed (see Fig.6). The threshold of the instability corresponded to $n_h \approx 3{\cdot}10^{19} cm^{-3}$ at A = $W_\perp/W_\parallel \approx 35$. This instability was identified as the Alfven ion cyclotron (AIC) instability. The restrictions put on the plasma parameters from the viewpoint of stability are soft enough. That means that on the basis of the compact mirror cell, one can create the ambipolar cell for an improvement of longitudinal plasma confinement in the GDT NS.

Recently an efficient method of the MHD stabilization by application of different potentials to the end plates and limiter was applied and studied. It was shown that the sheared rotation can effectively stabilize the MHD.modes of high β plasma in the GDT and can reduce the radial transport. These results are in good agreement with the theory [20].

5. Conclusions.

A number of problems intrinsic to the open mirror systems have been cracked in recent years. Three methods of suppression of MHD activity were proposed for the GDT case. The experimentally measured value of beta in the MHD stable regime reached 60 %. Absolutely different method was applied in the GOL-3. In this case, the hot (T_i = 2 keV) dense ($n_e = 10^{21}m^{-3}$) plasma was confined during 1ms without MHD activity.
Among important positive findings, one should mention that multi-mirror confinement of a relatively rare (by two – three orders of magnitude lower than the Budker et al theory predicted [1]) plasma exists and has a theoretical explanation taking into account the useful role of the bounce instability. Up to now there are no any physical limitations to further increase in the plasma parameters in both types of open traps.
The method of suppression of longitudinal heat transfer during the time of the REB passing along the plasma has solved very serious problem of the multi-mirror reactor concept. One should point out that the same turbulence should increase the transverse heat transfer. In principle, that's truth, but up to now, the contribution of this effect to the energy balance is insignificant. The theory of transverse transfer for the discussed mechanism is in a rudimentary state.
In order to prevent the appearance of high heat conductance and fast cooling of the electrons after switching off the heating REB, a special electron beam of not so high power (160 keV, 1 kA/cm^2) but significantly longer than the REB is elaborated to support the turbulence.
A very promising method of decreasing longitudinal heat flux to the end walls was demonstrated in the GDT experiments. In principle, the method allows to decrease the power consumption in the GDT NS.
It is possible to estimate some parameters of the multi-mirror reactor. As an example, consider the plasma pipe 160 meters long with the effective cross section in a corrugated field of the order of 10 cm^2, and of 100 cm^2 in the homogeneous magnetic field (45 m long in the center). In this case, the energy, radiated by the D-T neutrons from the pipe during one pulse will be of 40 MJ with the Q value equal to 5.
The present day parameters of the GDT NS correspond to the neutron flux of D-T reaction of 0.2 MW/m^2. The nearest goal is the demonstration of feasibility of "moderate" NS (0.5 MW/m^2).

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