STATUS OF MODERN MIRROR STUDIES IN NOVOSIBIRSK

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Mirrors have a number of advantages in comparison with the closed magnetic systems like tokamak, stellarator, etc. In principle, mirrors are very attractive from the engineering point of view, if the plasma confined in axisymmetric magnetic systems would be MHD stable. At present, the MHD stabile confinement has already been demonstrated for all axisymmetric traps designed in Novosibirsk for the value of β value as high as 0.4. Some important results were obtained recently in the GOL-3and GDT experiments. In the paper, the status of two mirror traps in Novosibirsk is presented and description of the main experiments is given.

PACS: 52.55.Jd

1. INTRODUCTION

At present, the plasma parameters of systems with closed magnetic configurations like tokamak and stelarator are the highest among plasma confinement systems. However, there exists a class of open magnetic configurations (mirrors) which can be very attractive (anyway in future) as perspective fusion systems. At the moment there are three types of modern mirror machines. Advantages of open-ended systems are as follows:

1. Each of the mirror systems can be very simple from the engineering point of view if they are made fully axisymmetric.
2. Open-ended systems are very convenient for direct energy conversion of charged particles. This circumstance can turn out to be especially important in future for "low-neutron" schemes of fusion reactors.
3. All the systems use magnetic field very effectively. Plasma pressure can be comparable with magnetic field pressure. In one of the systems the β value can be even significantly higher than unity (so called multi mirror system with transverse "wall confinement").
4. Two of three systems can operate in steady state regime. At the same time, effects of disruptions do not appear in them.
5. There are no divertor problems in the mirror case.
6. The most attractive 14 MeV neutron source for structural materials tests can be constructed on the basis of mirror machine.

Physical and technological feasibility of controlled fusion will be finally demonstrated in the frame of ITER project. However, the program of studies on controlled fusion will not complete on that. In the nearest future fusion reactors with D-T fuel seem the most appropriate from technical point of view. Thus, before the next step of fusion program (DEMO) after ITER all the structural materials should be tested on resistance to irradiation by high power flux of 14 MeV neutrons. It follows from this that problem of construction of high power neutron source should be solved as soon as possible. One of the systems discussed below, namely, 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 of this source are enough for materials tests.

In more distant future, the schemes with a use of low-neutron nuclear reactions will be realized. In this case, open systems will be the most appropriate.

At present, studies of plasma confinement and heating in the open systems are carried out in Japan, Korea and Russia. The complete set of modern mirror type systems exists in the Budker Institute of Nuclear Physics, 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. MULTI MIRROR SYSTEM GOL-3

From physical point of view the simplest confinement system could be presented as a pipe with a dense ($\lambda_i << L$) plasma in the longitudinal magnetic field. (Here L is the pipe length, λ_i is the ion mean free path). The time of life of such system can be estimated as $\tau_0 \cong L/V_{Ti}$, where V_{Ti} is the ion thermal velocity. The size of this confinement system is large enough, however, if a corrugated magnetic field with the size of corrugation (or single mirror cell size) I is used under condition, when $l << \lambda_i << L$ (the case of dense plasma), then the longitudinal expansion of plasma in such a system will have diffusional character, i.e. $\tau \cong L^2/\lambda_i V_{Ti}$ [1]. More strictly, the lifetime is evaluated by the formula: $\tau \cong R^2 \cdot L^2/\lambda_i V_{Ti} = \tau_0 R^2 L/\lambda_i$ (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 of the order of 100 meters. The theory validity [1] was confirmed by special experiments on rare alkaline plasma behavior in the multi-mirror magnetic field [2]. At present, such experiments are continued with a dense hydrogen plasma on GOL-3 device (see below).

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" [3]. In this case, plasma is placed into a well conducting pipe with relatively «weak» (~10 T) magnetic field. As calculations have shown, after fast plasma heating the redistribution of the magnetic field and plasma density over the pipe cross section occurs.

The field strength and plasma density at the axis are not substantially varied. However, near the wall they become several tens times higher (because of two effects: magnetic flux conservation, and the β value much higher than unity). As a result, the cooling time of plasma of about 10 cm in diameter because of strong suppression of the transverse heat conduction turns to be satisfactory from the viewpoint of the Lawson criterion at rather moderate initial magnetic field (~10 T) [3, 4].

 Problems of Atomic Science and Technology. 2005. № 1. Series: Plasma Physics (10). P. 8-12

As a first step in direction of “wall confinement” experiments a method of two-stage heating of a dense plasma has been developed [5]. In this case, preliminary “rare” (n_e ¿ 10^{21} m^{-3}) plasma is produced with an additional dense (10^{22} ¿ 10^{23} m^{-3}) local bunch. After heating a “rare” plasma hot electrons transfer their energy to electrons and ions of the dense bunch with the aid of classical binary collisions. The experiments show that peak of pressure is really formed in the range of the bunch.

To validate theory of “wall confinement” it is required to put into a plasma a few hundred kilojoules in a short time. At present, the most powerful facility GOL-3 for studying the phenomena of interaction of relativistic electron beam (REB) with a dense plasma and also for plasma confinement is under operation in Novosibirsk. It operates in two configurations of magnetic field: homogeneous (long solenoid with homogeneous magnetic field and two end - mirror coils) for a study of plasma heating by REB, and multi-mirror geometry for the experiments on hot plasma confinement. Layout of the installation is shown in Fig.1.

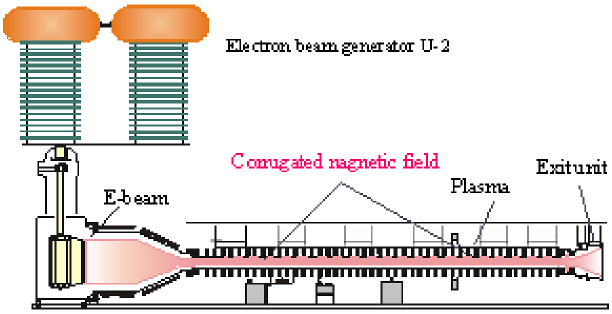

Fig.1. Layout of GOL-3

Preliminary plasma is produced in a stainless steel chamber with 10 cm inner diameter. Plasma has 8 cm in diameter and 12 m in length. Plasma density is varied within 10^{20} – $10^{23}m^{-3}$ range. Its heating is provided by powerful REB with energy content of 200 kJ and with the following parameters: E_b≈1MeV, I_b ≈ 30 -50 kA, τ_b ≈ 8· µs. The diameter of the beam in the plasma is 6 cm. To make an experiment on “wall confinement” in multi-mirror magnetic field the following problems should be solved:

1. Plasma heating with a high efficiency.
2. Suppression of longitudinal electron heat conduction.
3. Production of hot high β plasma in strong magnetic field.

At present, two first problems mainly have been solved. Most of the experiments on study of collective REB-plasma interaction were made for the case when the plasma density was 1–2·10^{21} m^{-3}. As a result, rather high efficiency of the interaction was achieved. In plasma at n_e ≈ 10^{21} m^{-3} the beam losses up to 40% of its energy were observed [6]. In these experiments rather high electron temperature (T_e ¿ 2 keV) was obtained. It is important to note, that so high temperature cannot be reached in the case of classical longitudinal 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 [7, 8]. The explanation of the effect was presented in [9]. Direct experimental demonstration of strong suppression of the longitudinal electron heat conduction was presented in [10]. For that special section of solenoid with decreased magnetic field strength was prepared (see Fig.2). The REB current density is minimum in the point with minimum magnetic field strength. Consequently, there observed rather weak heating in this point. At the same time, in the ranges with strong magnetic field (high current density and strong beam-plasma interaction) strong electron heating is observed (lower curve of Fig.2).

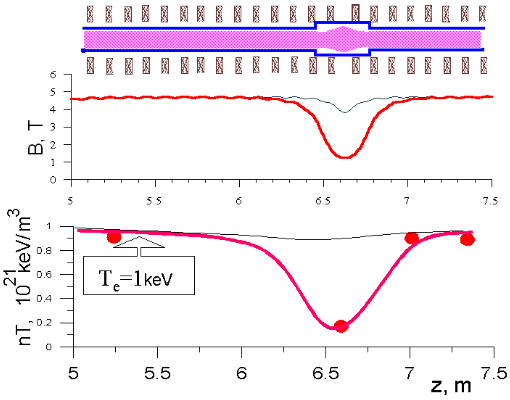

Fig.2. Direct observation of anomalously low longitudinal electron heat conductance during the process of collective relaxation of REB in plasma

It should be noted that the temperature drop of order 1 keV at the distance of half a meter sustains only when the REB is passing along the plasma. It disappears just after the electron beam switched off. Thus, this experiment really proves suppression of electron heat conduction. The experiments on longitudinal plasma confinement in multi-mirror geometry have been performed in several steps:

1.Ten mirror cells of 22 cm in length each formed at the input and at the output of the facility. About 8 meters in the middle part of the magnetic system were retained without corrugation. Mirror ratio in the cells of the corrugated parts was approximately equal to B_{max}/B_{min} ≈ 1.5 (the value of B_{max} was of 5 T).

2. Twenty mirror cells of 22 cm in the input and twenty ones in the output of 12 m magnetic system were formed.

3. Fully corrugated magnetic field along 12 m system was made with 22 cm single mirror size.

Significant progress in the GOL-3 parameters is seen in Fig.3. Energy confinement time substantially increased in the cases when magnetic system was reconstructed from homogeneous to partly multi-mirror and farther to fully multi mirror ones. Besides, it should be noted that at the same time the plasma pressure also significantly grew. Recently the energy confinement time exceeded 10^{-3}s at the density level of order of $10^{21}m^{-3}$.

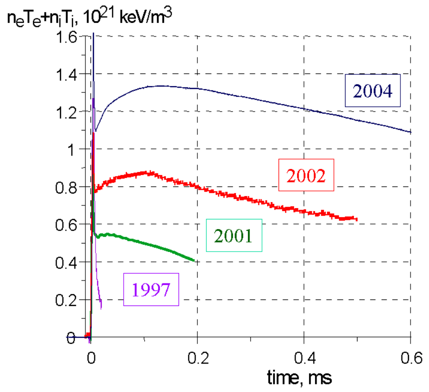

Fig.3. Plasma pressure behavior in the GOL-3 facility. 1997-uniform magnetic field with two end mirrors, $n_e=0.9\cdot10^{21}m^{-3}$(hydrogen); 2001-4 m corrugation from each side, $n_e=0.3\cdot10^{21}m^{-3}$(deuterium); 2002-fully corrugated magnetic field, $n_e=0.8\cdot10^{21}m^{-3}$(deuterium); 2004-improved heating with full corrugation, $n_e=1.5\cdot10^{21}m^{-3}$(deuterium)

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 of plasma falled down rather quickly. Thus, the energy content observed on the upper two traces are explained by the ion temperature. Three independent methods of measurement 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 of neutron flux of D-D reaction have shown that the ion temperature can be estimated of 2 keV at plasma density $n_e \cong 10^{21}m^{-3}$ [11]). As it is seen in Fig.4, the neutron yield falls down very slowly and exists during the time scale of order of 10^{-3}s. The value of nτ, at present, has achieved the level ~ $2\cdot10^{18}m^{-3}s$.

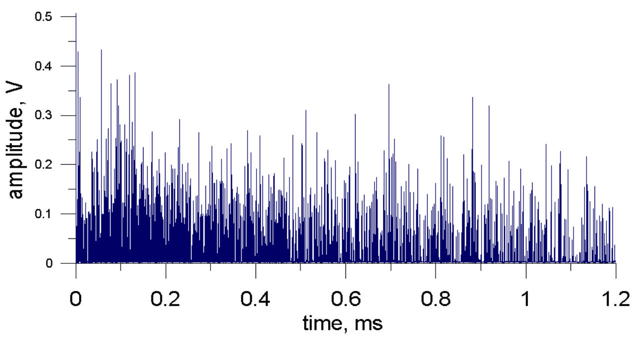

Fig.4. Neutron radiation of plasma in GOL-3 after plasma heating by REB (duration of REB is $8\cdot10^{-6}s$) recorded by digital PSD stilbene detector at Z=4.3m. Plasma density is $1.9\cdot10^{21}m^{-3}$

Possible mechanism of ion heating can be explain as follows. During REB-plasma interaction in corrugated magnetic field the electron heating is strongly no uniform. The strongest heating of electrons should take place at the maxima of magnetic field where the beam current density will be the largest one. As a result, the electron pressure will be higher there and the expansion of these hot clouds altogether with ions will produce the counter fluxes of plasma with subsequent conversion of energy of directed movement into ion heating.

3. GAS DYNAMIC TRAP (GDT)

A gas dynamic trap (GDT) for plasma confinement was first proposed in the Budker Institute [12] as a possible approach to development of a fusion reactor.

As a matter of 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 the ion mean-free path λ of scattering into a 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, can not excite in the gas dynamic regime of plasma confinement. Moreover, in contrast to the conventional mirrors, longitudinal plasma losses are not sensitive to the ion angular scattering rate that might be enhanced by micro instabilities. This attractive feature of the GDT plasma confinement can be understood by consideration of a simple model. Namely, the plasma losses through the GDT end mirrors qualitatively are similar to those of a collisional gas from the bottle with a pinhole leak. The smaller cross section of the hole, the longer time is needed for gas to escape. The confinement time in the device can be determined as $\tau \approx R\cdot L/V_{Ti}$ and it appears to be proportional to the mirror ratio R and length L of the trap. According to this relationship, plasma lifetime can be made long enough and appropriate to the fusion applications if the device is long enough and mirror ratio is high.

Advantages of the GDT approach stem from this very simple and reliable physics of longitudinal plasma confinement and from axial symmetry of the system. The experiments on study of the effects of gas dynamic plasma confinement are carried out on GDT device. The vacuum chamber of the GDT consists of a cylindrical central cell 7 m long and 1 m in diameter and two expander tanks attached at both ends. The device has an axisymmetric magnetic field configuration. The main parameters of the device are as follows. Mirror to mirror distance is 7 m, plasma radius at the midplane is within 8-15 cm, plasma density is $3\text{-}20\cdot10^{19}$ m^{-3}, electron temperature after neutral been injection is up to 130 eV, magnetic field value in the mirrors is up to 15 T, in the midplane is .22 T. The parameters of NB injectors are: the beam energy E_b = 15-17 keV, total injection power up to P_b = 4 MW, the beam duration τ_b = 1.1 ms, the injection angle is 45^0. The experiments on the GDT device have already enabled to obtain several principal results.

3.1 MHD STABILIZATION IN AXISYMMETRIC GEOMETRY

It was successfully demonstrated that the MHD plasma stability can be achieved in axially symmetric magnetic field. Flute modes were stabilized by pressure-weighted field curvature of the field lines when external anchor cells, in which the curvature was favorable for stability, were installed. The stability was achieved if the contribution of the anchor cells to pressure-weighted curvature overbalance negative contribution of the central cell. Remote anchor cells of two different types were experimentally tested. The first one was an expander end cell in which the plasma from the mirror throat expanded along gradually decreasing magnetic field to the end walls. The magnetic field inside the expander end cells was formed by a combination the stray field of the central cell coils and the field of additional large radius expander coils mounted at the end tanks. A current in these coils was opposite to that of the central cell coils providing the required concave form of the field lines. Additional coils installed in one of the end tank enabled to form here a cusp end cell. Effects of stabilization by the cusp end cell have been successfully demonstrated [13]. Theoretical studies of ballooning instability threshold in GDT predicts that the central cell β must be less than 0.7-0.8 for stability [14]. In order to obtain such a high β limit, magnetic field profile in the central cell has to be properly optimized. For the GDT device, magnetic field in the central cell differs from this optimized field and, therefore, the β limit amounts to 0.36 in this case. Recently, on-axis β exceeding 0.4 was obtained [15] in the GDT device.

3.2 SUPPRESSION OF THE LONGITUDINAL ELECTRON HEAT CONDUCTION

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 field lines from the mirror to the end wall the theory [13, 16] predicts strong reduction of the longitudinal electron heat losses. This relates to development of high enough ambipolar potential drop in expander when the density in the flowing out plasma decreases significantly between mirror and end wall. The ambipolar potential of the central cell was experimentally measured as a function of a distance from a movable segment of the end wall to the mirror [17]. As experiments have demonstrated, in the case of large expansion of the magnetic field lines the position of the movable end wall has no influence on plasma potential in the central cell. Correspondingly, the electron temperature also becomes not sensitive to the end wall position. However, when the expansion ratio decreases down to the level $B_m/B(z) < \sqrt{M/m}$, (here B(z) is the field strength at the movable end wall), the potential fell down and the electron temperature in the center cell decreased thus indicating an increase in longitudinal losses.

Detailed review of experimental data concerning the main properties of gas dynamic confinement is presented in [18]. Besides the above mentioned results one can find there the experimental data which demonstrate that the longitudinal lifetime is really proportional to mirror ratio R (anyway, up to R = 40). It is shown that the scattering of fast ions which appeared in the trap as a result of injection of fast atoms into plasma, is determined only by classical processes. In fact, it means that in spite of anisotropic distribution of fast ions in the trap, the micro instabilities are not driven. This result is very important from the viewpoint of future applications of the GDT concept.

Assessment of the perspectives of the GDT as a fusion reactor, indicates that from physical point of view such a reactor might be one of the simplest, because collisional plasma behavior is much more predictable. However, there are several critical points in the design of such a reactor. In [18] the parameters of the GDT reactor are presented. To decrease the length of reactor, installing of mirror coils with B_m = 45T are supposed. But even in this case, the length of reactor is estimated to be 3-6 km and the injection power is as high as 7.5 -12.3 GW. With reduction of magnetic field strength of mirror coils the reactor length and injection power should be correspondingly increased. Thus, at present, taking into account these technological constrains, a decision on construction of the GDT-based reactor would be unrealistic.

3.3 GDT-BASED NEUTRON SOURCE

Besides fusion reactor, there is another near term application of the GDT concept. This suggests construction of a 14 MeV neutron source on the basis of GDT with a multi-component plasma. The parameters of such a source (primary neutron flux density is 2 MW/m^2, test zone size is 1m^2) are chosen to meet the requirements of fusion materials testing. In recent years, several neutron source projects have been proposed (see, for instance, [19]). Among those the GDT-based source seems to be one of the most attractive because of very moderate consumption of power (60 MW) and tritium (150 g per year). The main idea of the neutron source on the basis of GDT involves an oblique injection of deuterium and tritium neutral beams with an energy of order of 100 keV into a ''warm'' collisional target plasma confined in the magnetic trap. Injection of the neutral beams gives rise to energetic anisotropic ion population with a density profile being strongly inhomogeneous along the system axis. The maximum of the fast ion density is then located in the vicinities of turning points and the minimum – at the middle plane of the trap. This results in generation of strongly inhomogeneous neutron flux with maxima located at the same place as those of the fast ion density. Since the neutrons are mostly produced in the fast triton and deuteron collisions, the neutron specific yield is proportional to fast ion density squared.

Therefore, the neutron flux peaks near the turning points are even stronger than those of the density. The effect of neutron flux peaking was demonstrated in the experiments on the GDT device with injection of deuterium neutral beams with energy of 15-17 keV and 4 MW total power incident on the central cell plasma (see Fig.5)[20].

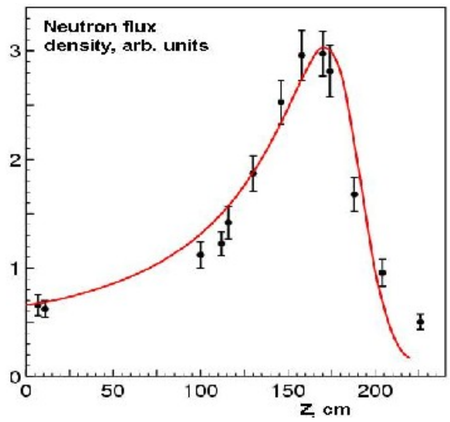

Fig.5 Axial profile of D-D neutron flux in GDT

The electron temperature that was achieved so far in the experiments at the GDT device amounts to 130 eV. Maximum electron temperature of the neutral beam heated plasma in the GDT device, as well as plasma β, is limited by the total available injection power and pulse duration. In basic design of the GDT-based neutron source which should consume 60 MW of electric power , neutron flux density of 2 MW/m^2 is to be provided within the testing zone (1 m^2). In this case T_e=750 eV should be provided. Note that reaching the electron temperature of the level of 300 eV can be considered as a very significant step towards realization of operational conditions in the GDT-based neutron source for materials testing [21]. The efficiency of the neutron production strongly depends on the electron temperature [22]. As numerical simulations have shown [23], a value of T_e=300 eV can be achieved if the magnetic field at the middle plane is increased from 0.22 up to 0.35 T and the neutral beam power is grown from 4 up to 10 MW with extension of the pulse duration from 1 up to 4-5 ms. It is also assumed that the injection energy will be increased from 15-17 keV up to 25 keV. In this case, if this temperature increase will be experimentally demonstrated, the construction of the GDT based neutron source providing neutron flux density of order of 500 kW/m^2 becomes feasible [22]. Simulated temporal behavior of plasma parameters in the GDT upgrade is shown in Fig.6. Note that in order to provide quasi-stationary level of T_e = 300 eV at W_{fast}=10 MW the NB duration of 4 -5 ms would be enough.

Upgrade of the GDT injection system assumes substitution of six existing ion sources by the new ones with increased current, extracting voltage and pulse duration. A prototype of the ion source has been developed, in which the beam focusing is provided by spherical shape of the grids, so that all beamlets are directed at the desired focal point. Adopted design has several advantages compared to the existed injectors, in which three plane electrodes are used, providing less divergent focused beam. The new injectors will be installed on the GDT device at the beginning of the next year.

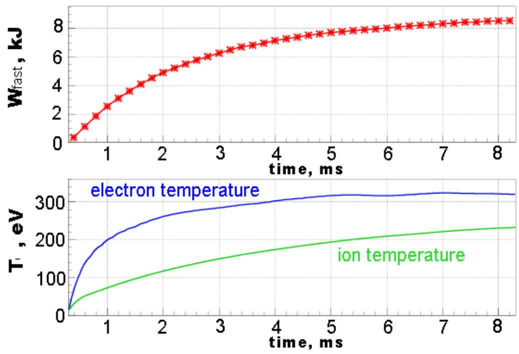

Fig.6. Temporal variation of fast ions energy content W_{fast}, electron and ion temperature in GDT-U

4. CONCLUSIONS

New physical phenomena of ion heating as a result of formation of electron pressure drop between regions with strong and weak magnetic field, which drives the plasma fluxes with opposite directions (GOL-3) at the center of local mirror cells, were observed experimentally. These phenomena simplify the ion heating problem in mirrors.

A number of crucial difficulties intrinsic to open systems such a large longitudinal electron heat conduction, problem of MHD stability in axisymmetric geometry has been solved in recent years. Now the axisymmetric mirrors, which additionally are the most attractive from engineering point of view, have very good perspectives. At present, the plasma parameters of mirrors are far from these in tokamaks. Therefore, for the nearest years, the main problem consists in an increase of the plasma parameters. But even with present day parameters mirrors are very attractive as high power 14 MeV neutron source for structural material tests for future fusion power plants.

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СОСТОЯНИЕ ИССЛЕДОВАНИЙ ОТКРЫТЫХ МАГНИТНЫХ СИСТЕМ В НОВОСИБИРСКЕ

Э.П. Кругляков, А.А. Иванов, В.С. Койдан

Открытые магнитные ловушки имеют ряд преимуществ по сравнению с замкнутыми магнитными системами, подобными токамаку, стелларатору и т.д. В принципе, открытые системы весьма

привлекательны с инженерной точки зрения, если плазма удерживается в осесимметричной магнитной конфигурации, оставаясь МГД устойчивой. В настоящее время МГД устойчивое удержание уже продемонстрировано для осесимметричных ловушек, исследуемых в Новосибирске, вплоть до величины β =0.4. Важные результаты получены недавно на установке ГОЛ-3 и в экспериментах с газодинамической ловушкой ГДЛ. В данной работе представлено состояние работ на двух магнитных ловушках в Новосибирске и приведены результаты основных экспериментов.

СТАН ДОСЛІДЖЕНЬ ВІДКРИТИХ МАГНІТНИХ СИСТЕМ У НОВОСИБІРСЬКУ

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Відкриті магнітні пастки мають ряд переваг у порівнянні з замкнутими магнітними системами, подібними токамаку, стелларатору і т.д. У принципі, відкриті системи досить привабливі з інженерної точки зору, якщо плазма утримується в осесиметричній магнітній конфігурації, залишаючись МГД стійкої. В даний час МГД стійке утримання вже продемонстроване для осесиметричних пасток, досліджуваних у Новосибірську, аж до величини β=0.4. Важливі результати отримані недавно на установці ГОЛ-3 і в експериментах з газодинамічною пасткою ГДЛ. У даній роботі представлений стан робіт на двох магнітних пастках у Новосибірську і приведені результати основних експериментів.