AXIALLY SYMMETRIC MAGNETIC MIRROR TRAPS. RECENT PROGRESS IN PLASMA CONFINEMENT AND HEATING

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New results of studies of plasma heating and confinement in the axisymmetric mirror traps are presented. It is shown that due to excitation of the instability at the bounce frequency (bounce instability) the effects of multi-mirror confinement can observed even at the densities by two-three-orders of magnitude lower than those predicted by the Budker, Mirnov and Ryutov theory (GOL-3 facility). This effect makes the multi-mirror reactor more realistic. A small size mirror cell was incorporated with the gas dynamic trap (GDT). Due to the transverse injection of two neutral beams (E_{NB}=20 keV) ion hot plasma was obtained in the compact mirror cell. As a result of that the plasma flux to the end wall decreased by 5 times. Besides, the threshold of the Alfven ion cyclotron instability (AIC) was determined in the same experiment with accumulation of fast ions in the compact cell. It follows from this experiment that in the GDT based neutron source the AIC instability will not excite in spite of anisotropic plasma.

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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 $L >> \lambda_{ii} >> \ell$ (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. 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 of 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). As to the power consumption, in the most pessimistic case, it is not more than 60 MW [10]. 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. 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 ($n_e \approx 10^{23}\ldots10^{24}\ m^{-3}$) 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 [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 of hundreds 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.

GOL-3. THE 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, maximum magnetic field was 5.5 T. There were two end mirrors with the field up to 11T. In the second case, 55 mirror cells 22 cm long each one, 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 = 3 kA, 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 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 $8 \cdot 10^{-6}$ s. To inject the REB in plasma the initial beam with cross section of 140×4 cm is transformed in the round beam with the diameter of 5 cm.

GOL-3. EXPERIMENTS ON 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. After switching off the REB injection corresponded well to the formula: $T_e = T_{e\ max}/(1+\alpha t)^{2/5}$, here $\alpha = f \cdot (n_e, Z_{eff})$ Thus, during the time of 10…20 µs plasma electrons cooled several times and achieved the value of $T_e \approx 100…150$ eV. Although the cooling process (after termination of REB injection) 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 another device, GOL-M, at the same REB current and plasma densities as mentioned above ($n_{beam}/n_e \sim 3 \cdot 10^{-4}…10^{-3}$), 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 [14] and an excitation of ion sound turbulence [15]. According to [16], in the case of REB-plasma interaction, the coefficient of electron thermal conductivity instead of $\chi_{\|} \sim v^2_{Te}/\nu_{ei}$ should be equal to $\chi_{\|} \sim v^2_{Te}/\Gamma$, here Γ is the growth rate of the beam instability, $\Gamma \sim \gamma^{-1} \cdot \theta^{-2} \cdot \omega_{pe} \cdot n_b/n_e$. 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 [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.

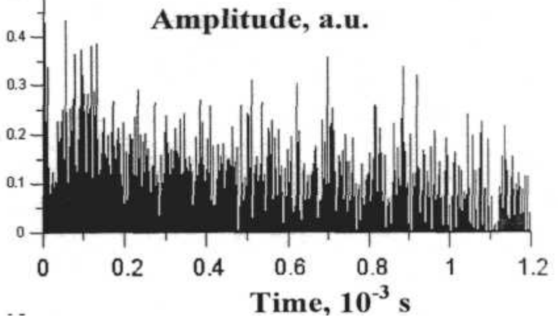

Fig. 1. Time behavior of neutron radiation

Absolutely another picture of plasma heating has observed in the multi-mirror geometry of magnetic field. The typical duration diamagnetic signal instead of 10-20 µs 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 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 meters 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 appears 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 [17].

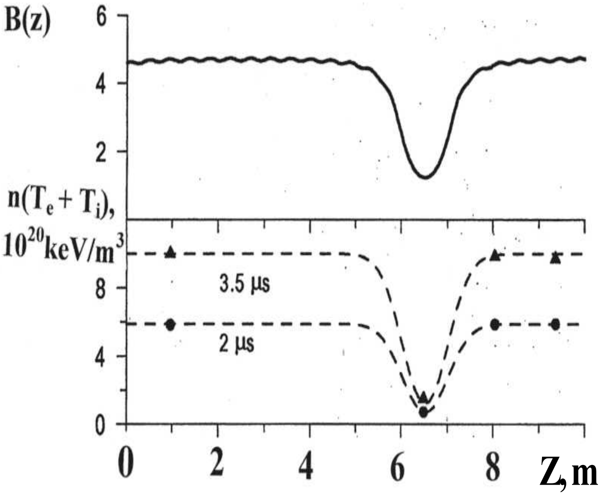

Fig.2. Upper trace: magnetic field strength along the axis of the system. Below: plasma diamagnetism (it is proportional to T_e) along the axis after 2 and 3.5 µs from the start of REB injection

For $n_e \sim (3…5) \cdot 10^{20}\,m^{-3}$ this time is estimated as 20…30 µs.

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 fulfill. 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 [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 $\lambda_{ieff} \sim \ell$.

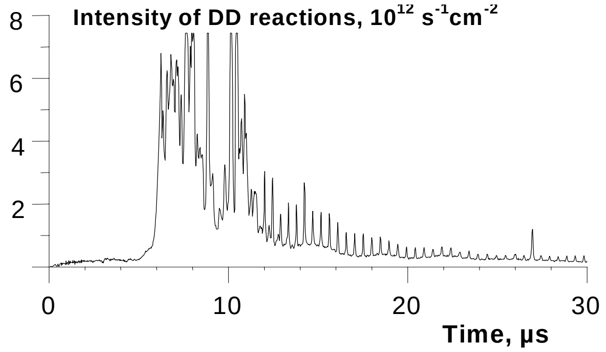

Fig.3. Generation of D-D neutrons as a result of collisions of opposite streams of deuterons

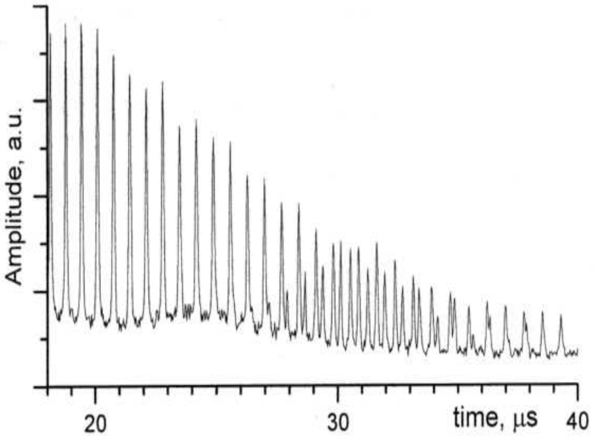

Fig.4. Regular structure of neutron radiation with $T \sim l/V_{Ti}$ as a consequence of bounce instability

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].

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 $B_o = 0.2\ldots0.22$ 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 experiments on demonstration of plasma MHD stability in the axisymmetric magnetic field by increase in a curvature of the field lines [22] and by the use of additional external cusp cell incorporated with the GDT [23] were made. 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 [24]. 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 [22].

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 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. At present, the total power of the NB injectors is equal to 3.5 MW at the duration of 5 ms. The work on the increase in the power is in progress. 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 a great deal new results were obtained.

GDT. EXPERIMENTS WITH ADDITIONAL COMPACT MIRROR CELL

A compact external mirror cell of 30 cm long with $B_{max} = 5.2$ T and $B_{min} = 2.4$ T 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 ($A = W_{\perp}/W_{\|} \approx 35$) 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 flux to the end wall in the steady state conditions decreased by 5 times.

One of vagueness in the parameters of the GDT NS connects with the necessity to create two-component anisotropic plasma where micro instabilities can excite. 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 $A = W_\perp / W_\parallel \approx 35$.

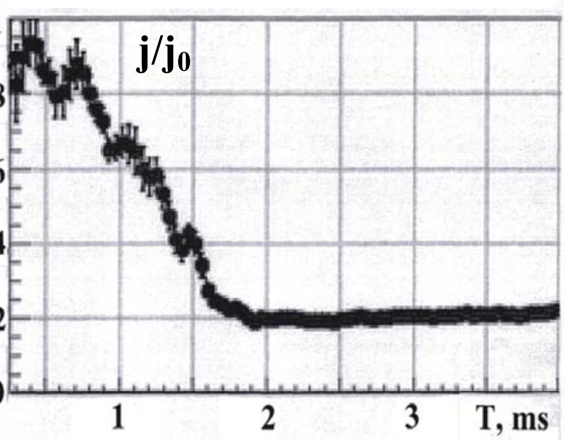

Fig.5. Ambipolar plugging of the flux flowing out the GDT. The injection of fast atoms into compact mirror cell begins at T = 0

This instability was identified as the Alfven ion cyclotron (AIC) instability. The restrictions put on the plasma parameters from the viewpoint of exitation of micro instabilities are soft enough. It means that this phenomenon will not appear in the case of the full GDT NS.

Recently an efficient method of the MHD stabilization by application of different potentials to the end plates and limiter was used and studied. It was shown that the sheared rotation can effectively stabilize the MHD modes of high β plasma (up to β = 0.6) in the GDT and can reduce the radial transport. These results are in good agreement with the theory [25].

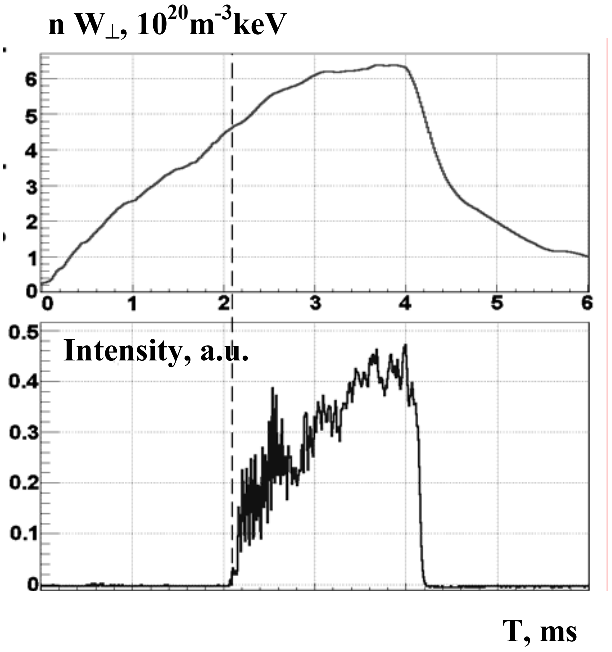

Fig.6. Plasma diamagnetism in the compact mirror cell during the NB injection (T=4 ms) and determination of threshold of the AIC instability (below)

CONCLUSIONS

A number of problems intrinsic to the open mirror systems have been solved 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 % (in the vicinities of turning points). 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. At present, 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 heating REB is elaborated to support the turbulence.

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. In the steady state version the reactor of 300 m long can produce 300 MW of fusion power with Q = 5.

A method of decreasing the longitudinal heat flux to the end walls was demonstrated in the GDT experiments. It was experimentally shown that the problem of decrease of lifetime of fast sloshing ions in the full scale neutron source on the basis of the GDT because of micro instabilities does not exist.

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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ОСЕСИММЕТРИЧНЫЕ ОТКРЫТЫЕ МАГНИТНЫЕ ЛОВУШКИ. НЕДАВНИЙ ПРОГРЕСС В УДЕРЖАНИИ И НАГРЕВЕ ПЛАЗМЫ

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Представлены последние результаты по удержанию плазмы в осесимметричных магнитных ловушках. Показано, что благодаря возбуждению неустойчивости на запертых частицах (bounce instability) многопробочное удержание плазмы может наблюдаться при плотностях на два – три порядка более низких по сравнению с предсказываемыми теорией Будкера, Мирнова и Рютова (ГОЛ-3). Этот эффект делает многопробочный термоядерный реактор более реалистичным. Небольшой пробкотрон был присоединен к газодинамической ловушке (ГДЛ). При поперечной инжекции нейтральных пучков (E = 20 кэВ, W = 1 МВт) в пробкотроне была получена ионно-горячая плазма. В результате поток плазмы, вытекающей из ГДЛ, был подавлен в 5 раз. Кроме того, удалось определить порог неустойчивости на быстрых анизотропных ионах и идентифицировать возбуждение альфвеновской ионно-циклотронной неустойчивости. Из полученных данных следует, что опасности возбуждения этой неустойчивости в нейтронном источнике на основе ГДЛ не существует.

ВІСЕСИМЕТРИЧНІ ВІДКРИТІ МАГНІТНІ ПАСТКИ. НЕДАВНІЙ ПРОГРЕС В УТРИМАННІ І НАГРІВАННІ ПЛАЗМИ

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Представлено останні результати по утриманню плазми в вісесиметричних магнітних пастках. Показано, що завдяки порушенню нестійкості на замкнених частках (bounce instability) багатопробпробкове утримання плазми може спостерігатися при щільностях на два – три порядки більш низьких, ніж завбачається теорією Будкера, Мирнова і Рютова (ГОЛ-3). Цей ефект робить багатопробковий термоядерний реактор більш реалістичним. Невеликий пробкотрон було приєднано до газодинамічної пастки (ГДП). При поперечній інжекції нейтральних пучків (E=20 кеВ, W = 1 МВт) у пробкотроні була отримана іонно-гаряча плазма. Внаслідок потік плазми, що витікає з ГДЛ, був подавлений у 5 разів. Крім того, вдалося визначити поріг нестійкості на швидких анізотропних іонах та ідентифікувати порушення альфвенівської іонно-циклотронної нестійкості. З отриманих даних витікає, що небезпеки порушення цієї нестійкості в нейтронному джерелі на основі ГДП не існує.