OPEN ENDED AXIALLY SYMMETRIC SYSTEMS. RESULTS AND PERSPECTIVES

A.V. Burdakov, A.A. Ivanov, E.P. Kruglyakov

Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia

Significant progress of the simplest axisymmetric magnetic systems for plasma confinement and heating is described. Two of such systems are presented in this paper: multi mirror (GOL-3) and gas dynamic (GDT) traps. In the GOL-3 case the temperatures $T_e \approx T \approx 2$ keV were obtained in a dense (of order of $10^{21}m^{-3}$) plasma and the maximum value of $n\tau_E \approx 2 \cdot 10^{18} m^{-3}s$ was achieved. Any physical limitations which could prevent from further grow of plasma parameters did not find out. The most important results obtained in the experiments on GDT are described. A new step (GDT-U) has been prepared and the first preliminary experiments with quasi-stationary plasma heating have started. According to calculations, the parameters of the GDT-U should demonstrate the feasibility of "moderate" (0.5 MW/m^2) 14 MeV neutron source for structural materials tests of fusion reactor.

PACS: 52.55.Jd

INTRODUCTION

At present, the Budker Institute runs two large scale axisymmetric mirror experiments of different type. The first one is a multi mirror system (GOL-3) and the second is gas dynamic trap (GDT). Principle of multi-mirror plasma confinement was proposed by Budker, Mirnov and Ryutov [1] in early 70s. The first successful experiments to prove the idea were done with a rare alkaline plasma in the period 1973-75 [2]. According to the initial idea [3] the multi-mirror reactor should operate with a dense (order of $10^{24}m^{-3}$) plasma confined by strong (order of 10T) magnetic field. The plasma should be heated by powerful relativistic electron beam (REB). The main requirements of the theory of multi mirror plasma confinement [1] can be met for the dense plasma if the reactor has several hundred meters in length. The magnetic field even being as strong as 10T is too small to provide transverse plasma confinement. In order to overcome this difficulty it was proposed to use material wall to withstand plasma pressure whereas radial energy losses are being controlled by the magnetic field (so called "wall confinement") [4]. Another problem of the multi mirror reactor is how to provide efficient plasma heating. The first experiments on study of REB – plasma interaction were begun in 1972 [5]. They indeed have demonstrated that plasma can be efficiently heated under certain conditions. In the first experiments the total beam energy amounted to only 50 J. In the present experiments at the GOL-3 device total energy of REB exceeds this level by almost four orders of magnitude. As a result of this increase, many new phenomena were recently discovered on GOL-3. In particular, for the first time an effect of strong (by three orders of magnitude) suppression of longitudinal electron heat conduction was observed [6]. Correspondingly, high electron temperature amounting to several keVs was reached [7]. In the case of multi-mirror configuration fast ion heating up to 2 keV was also observed [8]. Besides, it turned out that the heating and confinement of ions are significantly more effective than that one could expect using the estimates based on binary Coulomb collisions theory. Indeed, it is shown that there exists a mechanism of enhanced scattering of axially moving ions which leads to their trapping into the mirror cells and to corresponding increase of their longitudinal confinement time [9]. This suggests significantly wider range of parameters for the reactor compare to the initial theory.

At present, the GOL-3 has extremely high energy density in plasma flux exhaust which typically is in the range of 1…50 MJ/m^2. This provides rather unique opportunity for testing of structural materials for ITER and DEMO under effect of energetic plasma flow with hot electrons.

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

One of the most important factors determined the lifetime of fast ions in the GDT and the efficiency of neutron production is the electron temperature. At present, in the GDT experiments T_e is limited to ~100 eV. This value is too low for the neutron source. In the nearest future it is planned to extend the NB duration from 1 up to 5 ms. According to calculations, it will result in increase of T_e up to 200 eV. Additionally, installation of new injectors is planned with increased injection power. They should be mounted on the GDT in the end of this year. It follows from the calculations that the electron temperature of 300 eV will be then obtained. As soon as it happens this will demonstrate feasibility of the neutron source with "moderate" neutron flux (~0.5MW/m^2). To demonstrate practicability of full scale NS the device named "Hydrogen prototype" is planned to be constructed later on.

GOL-3 EXPERIMENTS

Many efforts were put forth to come to present day status of multi mirror machine studies. As to plasma heating by REB is concerned, modern technology of high voltage generators for REB production was developed stepwise using intermediate generators of REB with water insulation and with the REB energy of 1, 4 and 20 kJ. The present day REB for the GOL-3 facility has the energy of the beam electrons of 1 MeV and maximum beam current of 50 kA. The duration of the REB pulse was most dramatically changed amounting at present up to $8 \cdot 10^{-6}$ s.

Among many devices designed and constructed in the scope of the program of REB – plasma interaction study one should mention GOL-M device. Unique diagnostics based on registration of collective scattering of CO_2 laser radiation were worked out there. Using these it was experimentally shown for the first time that Langmuir turbulence is being excited as a result of the REB-plasma interaction [19]. Later on [20] an excitation of ion-acoustic turbulence was observed with a level of oscillations exceeding by five orders of magnitude the thermal one. The excitation of the ion-acoustic turbulence in non-isothermal (T_e/T_i >>1) plasma by REB can be explained by a collapse of Langmuir waves in the case of strong Langmuir turbulence. On the final stage of the collapse, due to plasma density and pressure drop inside and outside a cavity the short wave ion-acoustic waves are excited. The phenomenon of the collapse in the case of strong Langmuir turbulence has been observed experimentally on the GOL-M device [21].

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

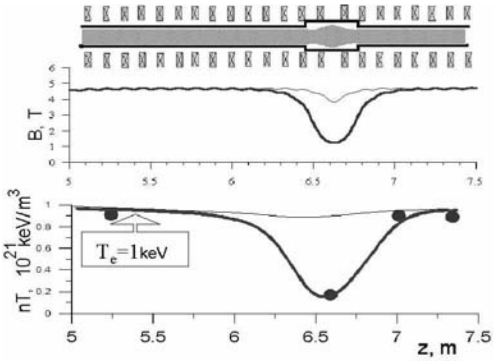

Fig.1. Direct observation of anomalously low longitudinal electron heat conductance during the process of collective relaxation of REB in plasma

In minimum magnetic field the REB current density is also minimal providing smaller energy release in this region. Correspondingly, the electron temperature was measured to be constant outside the local magnetic "well" and high (T_e ~ 1 keV). At the same time, it was significantly less in the bottom of the well (T_e~150 eV). It should be noted that this very steep temperature gradient is sustained during REB injection and disappears immediately after switching off the beam.

More reach physics appears with the transition to multi mirror geometry of the magnetic field. These experiments were done with longer solenoid (12 meters). The beam duration was $8 \cdot 10^{-6}$ s (instead of $3 \cdot 10^{-6}$ s in the first experiments), there were 55 mirror cells with B_{max}= 5T and B_{min} = 3.5 T. Typical plasma density was varied in the range of (0.5…2) · 10^{21} m^{-3}. After transition from homogeneous magnetic field to multi mirror configuration significant progress in the GOL-3 parameters was observed as it is seen in Fig.2. Energy confinement time was increased by two orders of magnitude. Recently the energy confinement time exceeded 10^{-3} s at the density level of order of 10^{21} m^{-3}.

It has been already mentioned that after switching off the REB current the effect of suppression of electron thermal conductance disappeared immediately. As a consequence of that the electron temperature of plasma fell down rather quickly. Thus, the diamagnetic signal observed on the upper trace of Fig. 2 can be explained by high ion temperature. This result is rather unexpected. In the process of REB-plasma interaction only plasma electrons can be directly heated. The ions stay cold because the temperature equilibration time is much longer than the energy confinement time. Nevertheless, three independent methods of measurements of the ion temperature which were applied (besides diamagnetism) have shown that plasma ions were heated rather fast (within tens of microseconds) and the level of the ion temperature could be estimated as 2 keV at plasma density $n_e \cong 10^{21} m^{-3}$ [23].

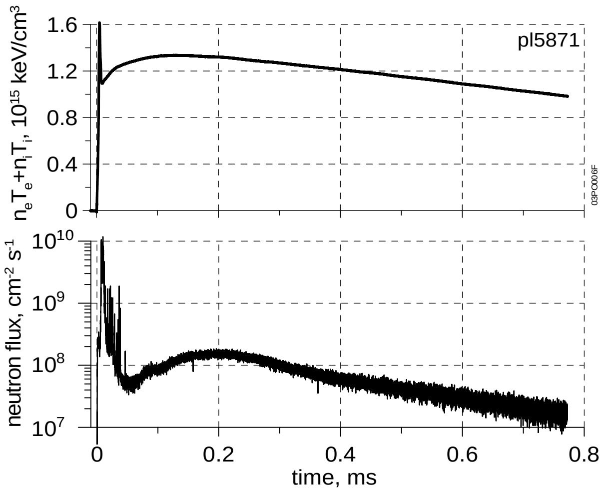

Fig.2. Multi mirror system GOL - 3. Comparison of temporal variation of plasma pressure and neutron flux. deuterium density is $1.5{\cdot}10^{21}$ m^{-3}, z = 2.08 m from the injection point

The ion temperature was measured by measurement of Doppler broadening of D_α line at the boundary of hot plasma, by registration of charge exchange neutrals from hot plasma and by measurement of D-D neutron flux. All the methods have shown that high ion temperature reached the level of 2 keV within tens of microseconds. As it is seen in Fig.2 (bottom part), the neutron yield falls down very slowly and exists during the time scale of the order of 10^{-3} s. The maximum value of $n\tau$ product, at present, has achieved the level of ~ $2{\cdot}10^{18}$ m^{-3}s.

Possible mechanism of ion heating can be qualitatively explained as follows. During REB-plasma interaction in corrugated magnetic field the electron heating is strongly non uniform. The strongest heating of electrons should take place at the maxima of magnetic field where the REB current density is maximal. As a result, the electron pressure will be higher there and will be lower in the mid planes of each mirror cell (see Fig.1). These pressure drops are sustained by the REB.

As it has already mentioned, the longitudinal heat transfer is suppressed till the switching off the REB. After that the effective collision frequency of electrons falls down roughly by thousand times and the expansion of high pressure plasma clouds initially localized near mirrors and containing hot electrons together with cold ions will produce the counter fluxes of plasma with shock waves collisions and subsequent conversion of energy of directed movement into ion heating. Note that there is an additional effect which leads to shortening of effective ion mean free path and to increase of the longitudinal confinement time.

Regular oscillations of the neutron flux irradiated from single mirror cell can be observed practically during all the confinement time [24]. The period of these oscillations is of order of l/v_i , where l is a single cell size and v_i is ion thermal velocity. In principle, electrostatic plasma oscillations with phase velocities of the order of v_i experience strong dumping and can not exist for the case $T_e < T_i$. Nevertheless, they were observed experimentally and corresponded well to bounce frequency of ions. This contradiction can be explain by the fact that plasma in the multi mirror geometry is not homogeneous and the distribution function is non-equilibrium. In this case, bounce oscillations can exist in separate cells and play very useful role for improvement of longitudinal plasma confinement. Transit ions passing through a cell will scattered on the bounce oscillations and become trapped. Thus, an effective mean free path can be significantly reduce. For more details see [9].

In principle, axisymmetric multi mirror magnetic system is MHD unstable. However, as it was experimentally demonstrated in [22] there is a method of plasma stabilization in the sense of MHD.

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

GAS DYNAMIC TRAP (GDT)

Advantages of the GDT approach stem from very simple and reliable physics of longitudinal plasma confinement and from axial symmetry of the system. In contrast to the conventional mirrors, because of high mirror ratio and narrow loss cone, the collisional plasma confined in the trap is very close to isotropic Maxwellian state, and, therefore, many instabilities, which are potentially dangerous for the classical magnetic mirrors, can not excite in the regime of gas dynamic plasma confinement. Very simple consideration shows that the longitudinal confinement time in the device can be estimated as $\tau \approx R{\cdot}L/V_{T_i}$ and it appears to be proportional to the mirror ratio R and length L of the trap. The confinement time seems too small for fusion reactor, but, it is quite appropriate in the case of neutron source (NS) GDT based. The key element of the NS is the powerful oblique injection of neutral beams into “warm” plasma and formation there fast deuterons and tritons oscillating between turning points. The density of these anisotropic ions has strong maxima near the turning points. Correspondingly, the neutron flux maxima appear at the same places. According to our calculations, the GDT NS can produce the neutron flux density of 2 MW/m^2 (10^{14} neutrons/cm$^2{\cdot}$s) at the area of 1 m^2. At present, the main physical problems of the gas dynamic plasma confinement have already been solved, at least for moderate plasma parameters. In particular, it was shown that in spite of unfavorable curvature of magnetic field lines in the trap the plasma can be stabilized against excitation of MHD modes. It was shown experimentally that high enough favorable curvature of the field lines in the expander region beyond the mirrors stabilize the entire plasma [14]. The stability can be made significantly more rigid if additional cusp end cell is attached to the central solenoid of GDT [15]. At last, it should be mentioned that an influence of radial electric fields on transverse plasma losses was observed [16].

Another important problem for the GDT is longitudinal electron thermal conductivity. It was shown experimentally that if the magnetic field drops between mirror and end wall so that the ratio of B_m / B_w is larger than $(M/m)^{1/2}$ ~45 for hydrogen, axial electron conduction is suppressed and there is no influence of the end wall position on the electron temperature in the trap [13].

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

All these experiments carried out with the following parameters of the device. The mirror to mirror distance is 7 meters, plasma radius at the mid plain is 8…15 cm, magnetic field value in the mirrors is up to 15 T, and in the mid plane is 0.22 T. Plasma density is $3…20 \cdot 10^{19} m^{-3}$. The parameters of NB injectors are: the beam energy E_b = 15…17 keV, total injection power is up to P_b = 4 MW, the beam duration, τ_b = 1.1 ms, and the injection angle is 45^0. At these parameters the electron temperature of order 100 eV was obtained. This value is in a reasonable agreement with calculation results. Nevertheless, it is quite far from that required for demonstration of practicability of full scale GDT NS. At present, new injectors and new power supplies for them are under construction. The comparison of the present day GDT and the GDT upgrade parameters is given in the Table below.

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

Longer duration of neutral beam injection from physical view point corresponds to the regime of steady state operation. The experiments on the GDT-U are planned to start in autumn of 2006.

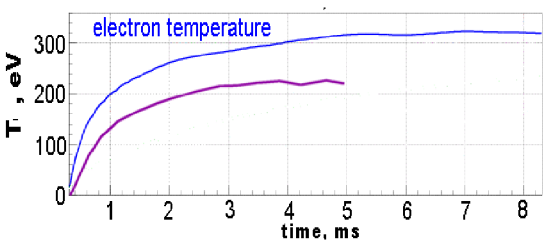

Fig.3. Electron temperature variation during time. Upper trace-10 MW, lower trace – 4 MW of injection power

It is seen in Fig.3 that, at present, the plasma of GDT does not reach steady state during the injection pulse. According to calculations, simple increase of the injection duration should double the electron temperature.

If the value of T_e=300 eV predicted by the code will be obtained, it will prove that "moderate" NS with neutron flux density of 0.5 MW/m^2 ($2.5 \cdot 10^{13}$neutrons/s·cm^2) is feasible. On the other hand, the distance between achieved (T_e = 300 eV) and required (T_e=750 eV) for full scale NS temperature will be small enough and degree of confidence to the simulation results becomes higher. At present, the activity connected with completion of construction of hydrogen prototype as a model of the full scale neutron source is re-started in Novosibirsk.

CONCLUSIONS

Taking into account recent successes of the GOL-3 on heating and confinement of a dense plasma, one can say that axisymmetric multi mirror system, attractive by its engineering simplicity, in principle, has perspectives as a fusion reactor with magnetic (but not "wall") confinement of plasma. High power relativistic electron beam looks as a realistic source of energy for this scheme.

Recent status of GOL-3 and under-discussion upgrade makes this facility very important for structural materials tests on resistance to high heat fluxes of electronic-hot plasma. Besides, a propagation of cloud of impurities formed as a result of disruption or ELM activity along and across magnetic field can be studied in this trap.

Very promising results can be obtained at the GDT in the nearest time. Till the end of 2006 it should be demonstrated with high probability the practicability of "moderate" neutron source. In the case of success, the modeling of the full scale neutron source would start soon. To our opinion, even "moderate" NS with large (~1m^2) size of testing zone could be very useful for material scientists. At present, they have nothing similar to the NS under discussion. Correspondingly, even DEMO can not be built without testing of materials.

REFERENCES

1.G.I.Budker, V.V.Mirnov, D.D.Ryutov. Influence of corrugated magnetic field on expansion and cooling of plasma // *Sov. JETP Lett*, 1971, v.14, #5, p.320.

2.G.I.Budker, V.V.Danilov, E.P.Kruglyakov. Experiments on plasma confinement in multi mirror trap // *Sov JETP.* 1973, v.65, #2(8), p.562; V.V.Danilov, E.P.Kruglyakov. Dynamics of plasma in multi mirror magnetic system // *Sov. JETP,* 1975, v.68, #6, p.2109.

3.G.I.Budker, E.P.Kruglyakov, V.V.Mirnov, D.D.Ryutov. On the possibility of creation of thermonuclear reactor with a dense plasma, confined by corrugated magnetic field // *Izvestia AN SSSR, Energetika i Transport.* 1975, #6, p.35 (in Russian).

4.G.E.Vekshtein, D.D.Ryutov, M.D.Spektor, P.Z.Chebotaev. Nonmagnetic confinement of dense plasma // *Prikladnaya Mekhanika i Tekhnicheskaya Fizika (Journ. of Appl. Mech. and Tekhn. Phys)*, 1974, #6, p.3.

5.A.V.Abrashitov, A.V.Burdakov, V.S.Koidan, et al. Plasma heating by relativistic electron beam // *Sov JETP Lett.* 1973, v.18, p.675.

6.V.T.Astrelin, A.V.Burdakov, V.V.Postupaev. Generation of ion-acoustic waves and suppression of heat transport during plasma heating by an electron seam. *Plasma Phys. Reports.* 1998, v.24, #5, p.414.

7.A.V.Burdakov, S.G.Voropaev, V.S.Koidan et al. Experiments on collective interaction of microsecond relativistic electron

beam with plasma on GOL-3 // *Rus. JETP*. 1996, v.109, #6, p.2078.
8.R.Yu.Akentjev, A.V.Arzhannikov, V.T.Astrelin et al. Experimental results on multiple mirror trap GOL-3 // *The 29th EPS Conf. on Plasma Phys. and Contr. Fusion, Montreux, 17-21 June 2002*. ECA, 2002, v.26B, P5-057.
9. A.D. Beklemishev. Bounce Instability in a Multi Mirror Trap // *Proceedings of the OS 2006 Conference, 17-21 July, 2006, Tsukuba, Japan*
10. V.V. Mirnov, D.D. Ryutov. Linear gas-dynamic trap for plasma confinement // *Sov. JETP Lett*, 1979, v.5, #11, p.678.
11. H.H. Hennies, E.P. Kruglyakov, D.D. Ryutov. The gas dynamic trap (GDT)-system as a promising engineering solution for a volumetric neutron sourse and an intermediate step to a fusion reactor // *The 9th Intern. Conf. on Emerging Nuclear Energy Systems (ICENES'98), Herzliya, Israel, June 28 – July 2, 1998*
12.I.A. Kotelnikov, V.V. Mirnov, V.P. Nagornyj, D.D. Ryutov. New results of gas-dynamic trap research // *Plasma Phys. and Controlled Fusion Res*., Vienna, IAEA, 1985, v.2, p.309.
13.A.V.Anikeev, P.A.Bagryansky, N.V.Stupishin. Longitudinal confinement of matter and energy in gas-dynamic trap // *Plasma Phys. Reports*. 1999, v.25, #10, p.842.
14. A.A. Ivanov, P.A. Bagryansky, A.V. Anikeev et al. Experimental study of curvature driven flute instability in the gas-dynamic trap// *Phys.of Plasmas*. 1994, 1, #5, part 2, p.1529.
15. A.V. Anikeev, P.A. Bagryansky, P.P. Deichuli et al. Observation of magnetohydrodynamic stability limit in a cusp anchored gas dynamic trap// *Phys.of Plasmas*, 1997, v.4, p.347.
16. P.A. Bagryansky, A.A. Lizunov, A.A. Zuev. Experiments with controllable application of radial electric fields in GDT central cell// *Trans. of Fusion Sci. and Techn*. 2003, v.47, #1T, p.152.
17. P.A. Bagryansky, A.A. Ivanov, E.P. Kruglyakov et al. Gas dynamic trap as high power 14 MeV neutron source // *Fusion Engineering and Design*. 2004, v.70, p.13.
18. E.P. Kruglyakov. Powerful neutron generators // *Journ. of Appl. Mechanics and Techn. Phys*. 1997, #4, p.566.
19. I.V. Kandaurov, E.P. Kruglyakov, M.V. Losev et al. CO_2 laser scattering on Langmuir electron plasma waves excited by REB // *Proc. ICPP, Nov. 22-28, 1989, New Delhi*. v.3, p.1121; L.N. Vycheslavov, I.V. Kandaurov, E.P. Kruglyakov. Direct observation of Langmuir turbulence in plasma by method of laser scattering // *Sov.JETP Lett*. 1989, v.50, #9, p.379.
20. V.S. Burmasov, I.V. Kandaurov, E.P. Kruglyakov et al. Observation of short-wavelength ion acoustic waves accompanying strong Langmuir turbulence in a magnetized plasma // *The 22nd EPS Conf. on Plasma Phys. and Contr. Fusion, 3-7 July, 1995, Bornemouth, UK*. v.19C, part 1, p.445.
21. V.S. Burmasov, I.V. Kandaurov, E.P. Kruglyakov et al. Manifestation of wave collapse in developed strong Langmuir turbulence in a magnetic field // *The 23rd EPS Conf. on Plasma Phys. and Controlled Fusion, 24-28 June, 1996, Kiev, Ukraine* v.20C, part 3, p.1253.
22. A.V. Burdakov, A.V. Arzhannikov, A.T. Astrelin et al. Fast heating of ions in GOL-3 multi mirror trap // *The 31st EPS Conf. on Contr. Fus.and Plasma Phys., 28 June-2 July, 2004, London.*
23.V.S. Koidan, A.V. Arzhannikov, V.T. Astrelin et al. Progress on the multi mirror trap GOL-3 // *Trans. of Fusion Science and Technology*. 2005, v.47, #1T, p.35.
24. A.V. Burdakov, A.V. Arzhannikov, V.T. Astrelin et al. Stable operation regimes in the multi mirror trap GOL-3 // *The 32nd EPS Conf. on Controlled Fusion and Plasma Physics, June 27-July 1, 2005, Tarragona, Portugal*. v.27A, P5-061.
25. A.V.Burdakov, A.V.Arzhannikov, V.T.Astrelin et al. Testing of carbon materials for fusion applications on linear plasma trap GOL-3 // *European Congress on Advanced Materials and Processes, Prague, 5-8 September, 2005*.
26. V.V. Maximov, A.V. Anikeev, P.A. Bagryansky et al. Spatial profiles of fusion product flux in the gas dynamic trap with deuterium neutral beam injection // *Nucl.Fus*. 2004, v.44, N4, p.542.

ОТКРЫТЫЕ АКСИАЛЬНО-СИММЕТРИЧНЫЕ СИСТЕМЫ. РЕЗУЛЬТАТЫ И ПЕРСПЕКТИВЫ

А.В. Бурдаков, А.А. Иванов, Э.П. Кругляков

Уделено внимание описанию значительного прогресса параметров простейших осесимметричных магнитных систем для удержания и нагрева плазмы. Две магнитных системы представлены в работе: многопробочная (ГОЛ-3) и газодинамическая (ГДЛ). В случае ГОЛ-3 температуры $T_e \approx T_i \approx 2$ kэВ получены в плотной (порядка 10^{21}м$^{-3}$) плазме, при этом была достигнута максимальная величина $n\tau_E \approx 2{\cdot}10^{18}$ м$^{-3}$с. Какие-либо физические ограничения, которые могли бы воспрепятствовать дальнейшему росту параметров, не были обнаружены. Представлены наиболее важные результаты, полученные в экспериментах на установке ГДЛ. Подготовлен новый шаг (ГДЛ-U), и начаты первые предварительные эксперименты с квазистационарным нагревом плазмы. Согласно расчетам, ГДЛ-U должна продемонстрировать осуществимость «умеренного» 14 МэВ источника нейтронов для испытаний конструкционных материалов термоядерного реактора.

ВІДКРИТІ АКСІАЛЬНО-СИМЕТРИЧНІ СИСТЕМИ. РЕЗУЛЬТАТИ І ПЕРСПЕКТИВИ

О.В. Бурдаков, О.О. Іванов, Е.П. Кругляков

Приділено увагу опису значного прогресу параметрів найпростіших вісесиметричних магнітних систем для утримання і нагрівання плазми. Дві магнітних системи представлені в роботі: багатопробкова (ГОЛ-3) і газодинамічна (ГДЛ). У випадку ГОЛ-3 температури $T_e \approx T_i \approx 2$ keВ отримані в густій (порядку 10^{21}м$^{-3}$) плазмі, при цьому була досягнута максимальна величина $n\tau_E \approx 2{\cdot}\,10^{18}$ м$^{-3}$с. Які-небудь фізичні обмеження, що могли б перешкодити подальшому росту параметрів, не були виявлені. Представлені найбільш важливі результати, отримані в експериментах на установці ГДЛ. Підготовлено новий крок (ГДЛ-U), і почaті перші попередні експерименти з квазістаціонарним нагріванням плазми. Відповідно до розрахунків, ГДЛ-U повинна продемонструвати можливість здійснення «помірного» 14 МеВ джерела нейтронів для іспитів конструкційних матеріалів термоядерного реактора.