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NOVOSIBIRSK MIRROR TRAPS. STATUS AND PROSPECTS

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Among the systems for magnetic plasma confinement there are open-ended traps, which strongly differ from the systems with closed magnetic configurations. All three types of modern mirror systems have been proposed in Novosibirsk. Two open-ended axisymmetric systems (multi-mirror and gas dynamic traps) are presently in operation here [1]. Proposed multi-mirror (M-M) plasma confinement realizes when $L >> \lambda_{ii} >> \ell$. Here L is the total length of the device, ℓ – single mirror cell size and λ_{ii} – ion mean free path. This condition is satisfied and the diffusion estimate, $\tau \sim L^2/ \lambda_{ii} \cdot V_{Ti}$ for the M-M confinement time is applicable if the plasma density is of the order of 10^{24} m^{-3} or higher. Recently, it was shown that that due to collective effects this estimate is applicable even for significantly lower plasma density in the range of 10^{21}-$10^{22} m^{-3}$. This makes the thermonuclear reactor on the basis of M-M system much more realistic. At present, the experiments on plasma heating and M-M confinements are carried out on the GOL-3 device.

The second plasma confinement system, 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) and length *L* exceeding the mean free path of scattering into the loss cone (see [2]). Under these conditions plasma confined in the trap is almost isotropic. The plasma lifetime could be then estimated as $\tau \sim RL/V_{Ti}$. Given this estimate, even for $R \approx 100$ the GDT-based fusion reactor appears to be as long as several kilometers. At the moment prospects of such reactor are not clear. Nevertheless, the GDT approach seems quite adequate for creation rather simple and powerful 14 MeV neutron source (NS) for fusion materials tests and other applications. The NS length could be rather moderate ~10–15 m. In the GDT-based NS, deuterium and tritium neutral beams are injected into a "warm" target plasma under a small angle to the axis. Injection of the beams gives rise to population of energetic ions oscillating back and forth between the turning points near end mirrors. Density of the energetic ions and, correspondingly, neutron flux density have strong peaks near the turning points. Therefore this system with 60 MW power consumption, even having small efficiency of neutron production is capable of producing high neutron flux of 2 MW/m^2 in testing zones ~ 1 m^2 in area [3]. Correspondingly, tritium consumption of the neutron source is small enough, ~ 0.15 kg/yr.

GOL-3 main parameters and results. The GOL-3 device is 12 m long and consists of 55 mirror cells connected in series. Maximum field in mirrors is 4.8 T, minimum field is 3.2 T. Diameter of vacuum chamber placed inside magnetic coils is 10 cm and preliminary plasma diameter is 8 cm. Typical plasma density in the experiments is $10^{21}cm^{-3}$. Plasma in the GOL-3 is heated by injection of 1 MeV, $8 \cdot 10^{-6}$s duration relativistic electron beam (REB) at the end. Current density of the beam in plasma is 1-1.5 kA/cm^2.

It was shown that due to collective processes of excitation of strong Langmuir turbulence the energy deposited into plasma by REB amounted to 40 %. This resulted in heating of plasma electrons up to the temperature $T_e \approx$ 2-4 keV, which was maintained during the beam injection and decreased rapidly when it stopped. This behavior of the T_e means that during the REB injection axial electron heat conduction is suppressed by more than three orders of magnitude. The effect has been proven by additional experiment. The phenomenon is explained by enhanced scattering of electrons on high amplitude Langmuir waves excited by the beam. The effect retained when the REB duration was extended from $8 \bullet 10^{-6}$s to $12 \cdot 10^{-6}$s.

The fast electron heating has been observed in both cases of the multi-mirror or homogeneous magnetic field. In contrast to this, the fast ion heating effect has never observed in homogeneous magnetic field and was observed in the multi-mirror geometry. The experimental data indicated that the time of ion heating was significantly less than the ion – ion collision time.

Theoretical consideration supported by measurement of plasma velocities indicated that the fast ion heating occurred due to steep pressure gradients which developed in multi-mirror magnetic field during injection of REB. As it is seen from formula for the growth rate of the beam instability, $\Gamma_b \sim \omega_{pe} \bullet N_b/N_e$, the strongest heating of plasma electrons will take place in the mirror planes.

Correspondingly, the highest plasma pressure should observe there. Thus, the non-homogenous plasma heating initiated the counter plasma flows in the cells and their subsequent relaxation with energy transfer to plasma ions. It was also observed that the axial plasma flow in corrugated magnetic field interacted with particles trapped in local mirror cells. This interaction resulted in the excitation of an instability and enhanced ion scattering with effective scattering length close to the length of the individual cell. The instability manifested itself in density oscillation in the cells with a period $T \approx \ell/V_{Ti}$ and corresponding regular oscillations of D-D neutron flux. These bounce oscillations facilitate the efficient exchange between the transit and trapped ions. Note that the conditions when the ion mean free path is close to the length of individual mirror cell corresponds to the longest plasma lifetime. Due to excitation of the instability in the individual cells the optimal conditions are realized at significantly smaller density compared to predictions of theory considering binary ion-ion collisions.

Suppression of the longitudinal electron heat conduction by the REB excited turbulence is required during all the time of plasma decay, which is now significantly longer than the REB duration. To overcome this problem an additional counter electron beam of larger duration is being developed. The beam energy is 150 keV, duration 10^{-4}s, current density in plasma 1kA/cm^2. At present, the achieved parameters of the additional beam are: E_b= 30 keV, j_b= 0.5 kA/cm^2, $\tau_b = 10^{-4}$s. The planned parameters of the beam should be obtained during this year.

The suppression of axial electron heat conduction is explained by a significant increase in electron collision frequency. It means that an increase in transverse plasma transport should be observed. Special experiment was made recently to study this possibility. For this experiment, the REB diameter in plasma was decreased down to 1cm by using a limiter. Inside this narrow beam the plasma parameters were the same as those in the experiments with broad beam, of 4-5 cm in diameter. This observation indicated that radial transport stayed to be considerably smaller than the axial plasma losses.

GDT layout and results. The GDT is an axisymmetric plasma confinement device about 11 m long. Mirror to mirror distance is 7 m, maximum mirror field is 15 T, magnetic field at the mid plane is 0.3 T. The plasma density in the experiments varied in the range $2 \div 5 \cdot 10^{19}$m^{-3}. Heating of plasma produced by oblique injection of six 15-17 keV neutral beams (NBs) at the center of the device. The total neutral beam power was about 4 MW. Recently, an upgrade of the injection system was done to increase the pulse duration from 10^{-3}s to $4.5 \cdot 10^{-3}$s and provide the beam focusing into a plasma. The main goal was to reach plasma steady state, at least from the physical viewpoint.

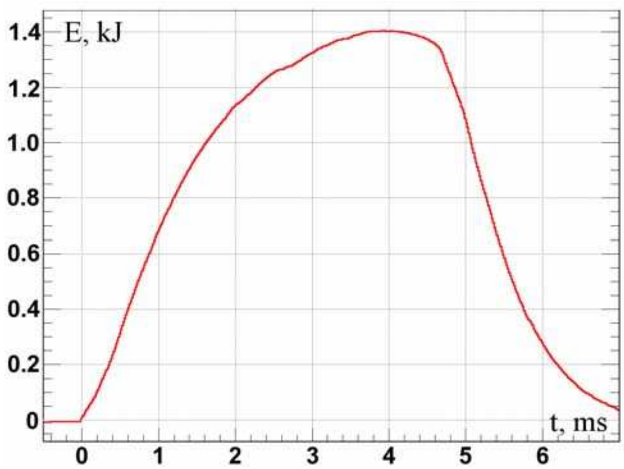

Figure 1. Time behavior of energy content of plasma in GDT during NB injection

Initial experiments with upgraded injection system were started. It was observed that a sheared plasma rotation induced by a biased limiter and end walls effectively stabilized the MHD for a plasma with β as high as 50 - 60 %. As it is seen in Fig.1, there are no any indications of MHD activity during high β shot.

In the experiments with compact mirror cell (ℓ=30 cm, B_{max}= 5.2 T, B_{min}= 2.4 T) incorporated into the main trap of the GDT, two important results were obtained. At first, the strong ambipolar plugging (up to 5 times) of the end losses was observed under condition when the strongly anisotropic ion hot plasma ($W_{\perp}/W_{\parallel} \approx 35$, density $5\cdot10^{19}m^{-3}$, ion energy 12 keV) was produced in the compact mirror cell by the perpendicular neutral beam injection. Excitation of the Alfven ion cyclotron (AIC) instability of anisotropic hot ion plasma ($N_i \approx 5\cdot10^{19}m^{-3}$) in the compact mirror cell was observed. The instability excitation threshold corresponded to the hot ions density in the compact cell of $N_h \approx 3\cdot10^{19}m^{-3}$ at A≈35. From this result it follows that for the parameters of full scale GDT NS the AIC instability will not appear and the energy losses will stay classical.

An electron temperature is a critical parameter for the GDT based neutron source that determines the energy losses of energetic ions. According to calculations, to obtain 2 MW of 14 MeV neutrons in the GDT NS, T_e should be as high as 750 eV [3]. Before the GDT upgrade, the T_e value was of about 100 eV. In the first experiments with upgraded injectors the temperature increased up to 150 eV at the steady state conditions that is equivalent to 0.2 MW of neutrons in the case of D-T plasma. Numerical simulations show that further increase in injected power up to 6MW, which is planned to be achieved with the upgraded injectors, would result in increase of the temperature up to 300 eV. This T_e corresponds to 0.5 MW/m^2 neutron flux in the GDT NS. Such a neutron power is of interest for fusion materials testing. At present, T_e achieved a level of 200 eV. Further increase in the injected NB power goes on.

References

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