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Experiment with Ambipolar Plug on GDT device

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Development of the neutron source for first wall material treatment is a high-priority task of the fusion technology studies closely connected with the ITER project and following burning plasma experiments. One of suggested approaches is a project of 14 MeV volumetric neutron source based on the gas dynamic trap (GDT) version with multi-component plasma [1]. A projected GDT-based neutron source acting as a driver in the subcritical burner of nuclear waste [2] is also considered as a perspective approach. One of the key problems in the physics of open magnetic traps is the problem of longitudinal confinement. An effective way to solve this problem can be by creation of a so called ambipolar potential in the additional mirror section [3]. This work is devoted to study of plasma confinement in the additional mirror section of GDT facility.

The Gas Dynamic Trap (Fig. 1) is an axially symmetric mirror with a long central solenoid and high mirror ratio for confinement of two plasma components. One of them is dense collisional background plasma (“target plasma”). This component is produced in the beginning of experiment with the help of arc-discharge source of plasma and is confined in the gas-dynamic regime. After the trap is filled by background plasma the heating beams are switched on. Hydrogen or deuterium beams are injected in the center of GDT. They are ionized in the target plasma and form the second plasma component – population of fast ions. These ions are confined in the adiabatic regime and slowing down due to collisions with electrons. The target plasma is then heated up to a maximum of about 180 eV. Duration of the beam injection is 5 ms. During this time appears the population of fast ions with mean energy of about 10 keV and density in the mirror points of 4 x 10^{13} cm^{-3}.

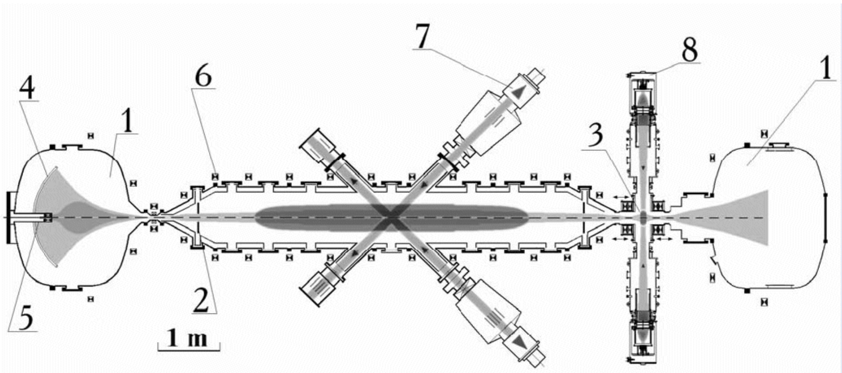

Fig. 1. GDT experimental layout: 1 – expander end tanks, 2 – biased limiter, 3 – compact mirror, 4 – plasma dump, 5 – plasma gun, 6 – magnetic coil of central solenoid, 7 and 8 – neutral beam injectors

To construct a compact mirror one additional vacuum chamber and a coil have been attached to one of the GDT mirror throats (Fig.1). Magnetic field in the center of the compact mirror is $B_0 = 27$ kGs, the mirror ratio is 2, the distance between centers of magnetic mirror coils is 43 cm, the inner diameter of vacuum chamber is 70 cm. The additional mirror section is filled with background plasma (with the density of $\sim 10^{13}$ cm^{-3}) streaming from the central cell of GDT. To create the population of fast ions two focused neutral beams with energy of 21-23 keV and with total power of 0.9 MW are injected into the compact mirror cell perpendicularly to the direction of magnetic field. The pulse duration is 4 ms. The formed fast ion plasmoid has average energy of about 13 keV and density up to 4.5 x10^{13} cm^{-3}. This is more than an order of magnitude greater than the density of the target plasma. Detailed investigation of compact mirror experiment in the case of low beam power (0.2-0.3 MW) was performed previously, [4]. It was found that the fast ion confinement was governed by coulomb collisions and charge-exchange processes on neutral beams. Two new effects are observed now that the neutral beams power is increased. The first one is the microinstability due to strong plasma anisotropy in the velocity space. The second effect is the ambipolar suppression of the particle flux to the expander.

To define the type of the microinstability in the compact mirror a system of high-frequency electrostatic and magnetic probes is used. The observed oscillations have a well-defined threshold. In Fig. 2 the diamagnetism of fast ions and the amplitude of high-frequency magnetic field oscillations are plotted versus time. Oscillations occurs when a threshold quantity of diamagnetism of plasmoid is reached. This corresponds to cumulative density of fast ions $n > 3 \times 10^{13}$ cm^{-3} with average energy 12-13 keV. In these experiments the plasma parameters are as follows: the ratio of ion pressure to magnetic field pressure is β=0.02, the anisotropy, i.e., the ratio of the perpendicular kinetic energy $\langle E_{\perp} \rangle$ to the parallel kinetic energy $\langle E_{\|} \rangle$ averaged over the velocity distribution of ions, is A=35, the ratio of ion gyroradius to plasmoid radius is $a_i/R_p \approx 0.23$. In Fig.3 the

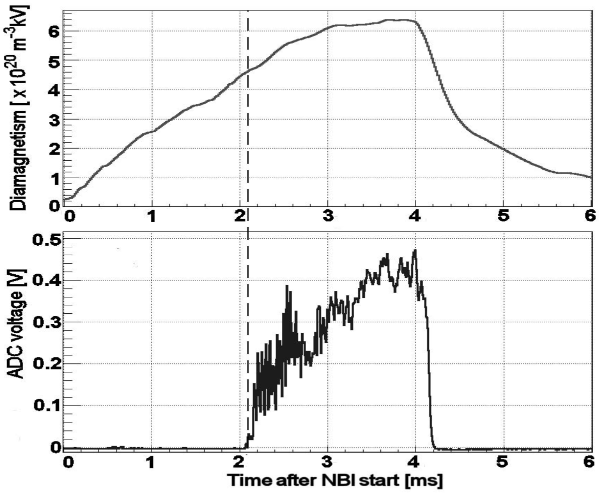

Fig. 2. The diamagnetism of hot ions and the amplitude of high-frequency magnetic field oscillations versus time

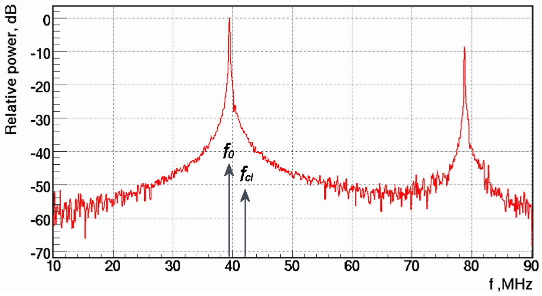

Fig. 3. The cross amplitude spectrum

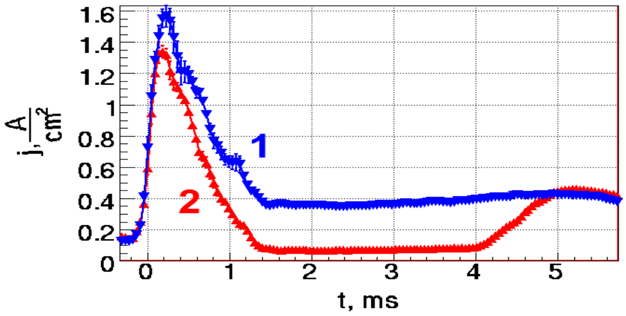

Fig. 5. Time evolutions of ion flux density in the expander cell 1 – without and 2 – with neutral beam injection into the compact mirror

cross amplitude spectrum of two signals from the azimuthal probes in the center of compact mirror is drawn. A coherent oscillation appears as a narrow maximum at the frequency mode $f_0 = 39.65\pm0.15$ MHz. The second maximum corresponds to the second harmonic of the mode. The actual magnetic field (taking into account plasma diamagnetism) at the midplane of compact mirror in these experiments is 27.6±0.3 kGs. Corresponding ion-cyclotron frequency is $f_{ci} = 42\pm0.5$ MHz. Thus there is a shift of observed oscillation frequency which is expected for the AIC mode $f_0 < f_{ci}\,(1 - \langle E_{||}\rangle/\langle E_{\perp}\rangle)$. In Fig. 4 the azimuthal mode analysis is shown. The phase shifts are recorded at f_0 versus angles between azimuthal probes. Solid line corresponds to the mode number m=-1, while the dashed line to m=-2. In most experiments the observed azimuthal mode was m=-1, occasionally the second mode appears. Oscillations with higher mode numbers is not detected. A negative m indicates propagation in the electron diamagnetic direction. In summary, registration of small azimuthal mode numbers, of oscillation frequency below the local ion-cyclotron frequency, and of the rotation of the magnetic field of the wave in the direction of ion gyration is a weighty argument that the fluctuations observed in the compact mirror of GDT are due to the Alfven ion cyclotron instability. It is important to note that the plasma confinement is not noticeably degraded due to this microinstability.

Build-up of fast ion density in the compact mirror is accompanied by the corresponding rise of electrostatic potential. This potential barrier reduces the plasma outflow. Fig. 5 demonstrates the difference between on-axis ion flux density measured in the expander cell with and without neutral beam injection into compact mirror cell. Particle losses through the compact mirror cell are about 5 times less in the presence of injection into the compact mirror. Fig. 6 shows the effect of the ambipolar plug as a ratio between ion fluxes in expander vs. the fast ion density in compact mirror. Outflow suppression is observed even at ambipolar potentials below

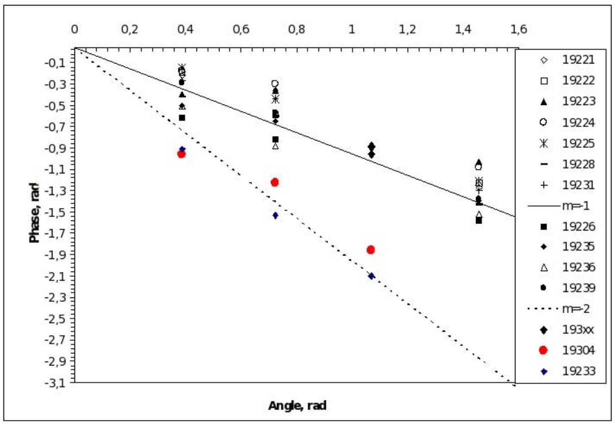

Fig. 4. Azimuthal mode analysis

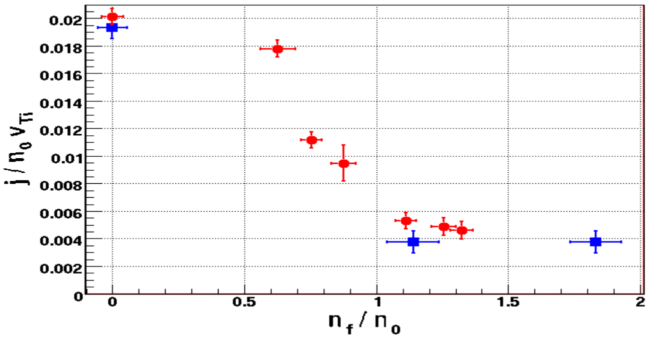

Fig. 6. Ion flux suppression vs fast ion density. Values are normalized on density n_0 and thermal velocity v_{Ti} of target plasma in the central cell.

the electron temperature: $e\varphi/T \approx \ln(n_f/n_0) < 1$. It is surprising, but can be explained as a result of the transition regime of the plasma flow in GDT. The length of GDT is comparable with the ion mean free path, L/λ=2-3, so that only ions with energies below temperature are effectively collisional, while ions in the tail of the distribution are collisionless. As a result, introduction of the ambipolar barrier of order T causes the flow regime to change from the gas-dynamic to the kinetic type, so that the losses can drastically decrease. However, there are additional particle losses caused by scattering of fast ions into the loss cone. Such ions have energies above ambipolar potentials, and their current cannot be suppressed.

Summary.

- Experiment with one ambipolar plug was carried out on GDT. Maximum fast ion density reached 4.5 x 10^{13} cm^{-3} with 0.9 MW neutral beams injected into the compact mirror cell.
- High frequency fluctuations were observed when the fast ion density in compact mirror exceeds the critical value. These fluctuations were identified as Alfven Ion Cyclotron instability, but do not lead to significant losses.
- Unexpectedly high efficiency of ambipolar plugging was observed. Particle losses were suppressed 5 times at ambipolar potential of the order of temperature. It is due to induced transition of target plasma confinement regime.

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