STUDY OF MICROINSTABILITIES IN ANISOTROPIC PLASMOID OF THERMONUCLEAR IONS

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The following work presents the results of investigation of microinstabilities in the anisotropic synthesized hot ion plasmoid (SHIP). Plasmoid is located in a small mirror section that is installed at one side of the GDT facility, which is an axially symmetric magnetic mirror device of gas dynamic trap type. To define the type and the parameters of the developing microinstability a set of high-frequency electrostatic and magnetic probes was used. The microinstability observed in the additional section of GDT is the Alfven ion cyclotron instability (AIC), because of small azimuthal wave numbers, magnetic field vector rotating in the direction of ion gyration and oscillation frequency below the actual ion cyclotron frequency. AIC instability threshold was registered at the following plasma parameters: fast ion density $n > 3 \times 10^{13}$ cm^{-3}*, ratio of ion pressure to magnetic field pressure* $\beta \approx 0.02$*, anisotropy* $A = 40$*,* $a_i/R_p \approx 0.23$*, where* a_i *is the ion gyroradius and* R_p *is the plasmoid radius.*

I. INTRODUCTION

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 creation of a so called ambipolar potential in the additional mirror section [1]. Ambipolar potential is created by hot ions with anisotropic velocity distribution function. These ions appear in the result of neutral beam injection perpendicular to magnetic field. In the previous conducted experiments scientists encountered the developing of different microinstabilities due to the strong plasma anisotropy [2-5]. These microinstabilities led to the fast scattering of particles in a loss-cone and therefore lessened the ambipolar effect. Thus studying of microinstabilities is an important goal of plasma physics and controlled thermonuclear synthesis.

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 [6,7]. A projected GDT-based neutron source acting as a driver in the subcritical burner of nuclear waste [8] is also considered as a perspective approach.

To provide both the physics database and technologies necessary for this project, in 1986 experiments on the model of a Gas Dynamic Trap was started in the Budker Institute of Nuclear Physics.

In 2004-2009 Gas Dynamic Trap experiments were conducted with hot ion anisotropic plasmoid which was created and confined in additional compact mirror [9]. High hot ion density in relation to background plasma density and strong anisotropy (mean perpendicular-to-longitudinal energy) can cause the developing of two most dangerous microinstabilities: Alfven ion-cyclotron instability (AIC) and drift cyclotron loss-cone instability (DCLC).

This work is devoted to study of microinstability developing in anisotropic plasmoid of thermonuclear ions confined in compact mirror of GDT facility. The aim of this work was to define microinstability type and its threshold experimentally.

II. COMPACT MIRROR AT GDT

The Gas Dynamic Trap device is an axially symmetric linear system with a long central solenoid and high mirror ratio for confinement of two plasma components. One of them is dense collisional background plasma with temperature about 2-3 eV ("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 filling the trap with background plasma heating beams are switched on. Hydrogen or deuterium beams are injected in the centre of GDT. They are ionized in the target plasma and form the second plasma component – population of hot ions. These ions are confined in the

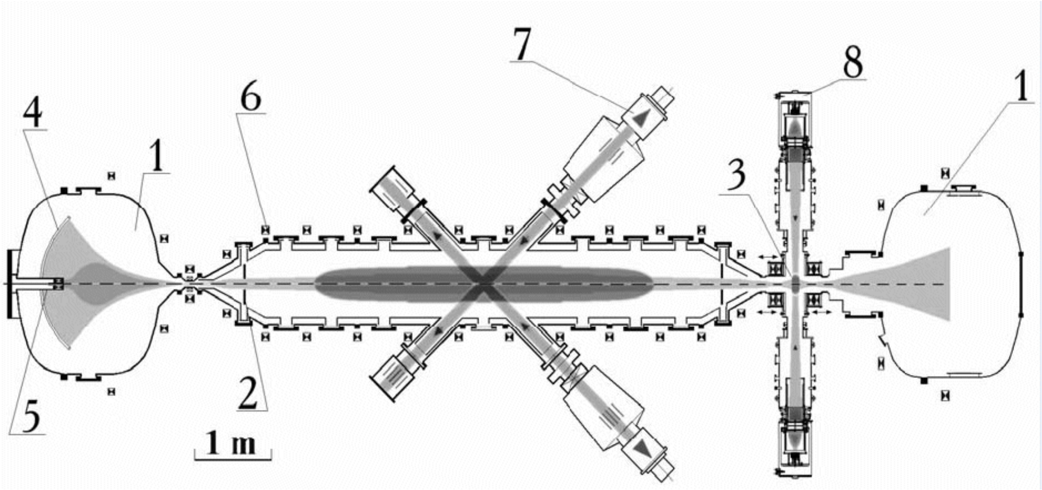

Fig.1. GDT experimental layout: 1 – expander end tanks, 2 –biased limiter, 3 – SHIP, 4 – plasma dump, 5 – plasma gun, 6 - magnetic coil of central solenoid, 7 – neutral beam injector, 8 – neutral beam injector for SHIP.

adiabatic regime and gradually are being dragged by target plasma. Target plasma is heated then up to 150 eV. Duration of beam injection is 5 ms. During this time a population of hot ions with mean energy about 10 keV and density in the mirror points 4 x 10^{13} cm^{-3} appears.

In the 2004 first experiments with synthesized hot ion plasmoid (SHIP) have begun [9]. To construct a compact mirrors one additional vacuum chamber and a coil have been attached to one of the GDT ends (Fig.1). Magnetic field in the central section of compact mirror equals to $B_0 = 24$ kGs, mirror ratio – 2, distance between the centres of magnetic mirror coils - ~ 43 cm, inner diameter of vacuum chamber ~ 70 cm. The additional mirror section is filled with background plasma (density n = 10^{13} cm^{-3}, temperature T = 70 eV) streaming from the central cell of GDT. To create the population of hot ions with strong anisotropy two focused neutral beams with energy of 21-23 keV and with total power of 1 MW are injected perpendicularly to the direction of magnetic field. Hot ion plasmoid had average energy about 13 keV and density ~ 5 x10^{13} cm^{-3} – more than an order greater than density of target plasma ions. Experimentally was shown an effect of ambipolar suppression of the particle flux to the expander. The flux density of ions from the central cell is decreased by five times during the injection of beams in the compact mirror. When some plasma parameters became critical the appearance of plasma potential oscillations was registered. Their frequency was close to the ion-cyclotron frequency which correspond to the magnetic field in the equatorial plane of compact mirror. This fact could be an evidence of microinstability development because of strong plasma anisotropy in compact mirror.

III. EXPERIMENTAL IDENTIFICATION OF THE MICROINSTABILITY TYPE. RESULTS OF MEASUREMENTS

To define the type of the developing microinstability in compact mirror of GDT a system of high-frequency electrostatic and magnetic probes was used.

Observed oscillations had well-defined threshold. In the Fig.2 the diamagnetism of hot deuterons (a), the amplitude of high-frequency magnetic field oscillations (b) and the plasma anisotropy (c) estimated as a ratio of the perpendicular kinetic energy $<E_\perp>$ to the parallel kinetic energy $<E_{||}>$ averaged over the velocity distribution of ions are plotted versus time. As it can be seen, oscillations occurred when a threshold quantity of diamagnetism of plasmoid was reached. At this moment the density of hot deuterons with average energy 12 - 13 keV is $n > 3 \times 10^{13}$ cm^{-3}, while in the case of hydrogenous beam injection the threshold density was two times less. Observed threshold density corresponds to ratio of deuteron pressure to magnetic field pressure β = 0.02 for parameters of the experiment. The plasma anisotropy was A=40, the deuteron gyroradius to plasmoid radius ratio was $a_i/R_p \approx 0.23$. The instability threshold is much higher than the traditional scaling $\beta_\perp A^2 > 8$ [5,10] and corresponds to the scaling of $\beta A{\sim}1$[11].

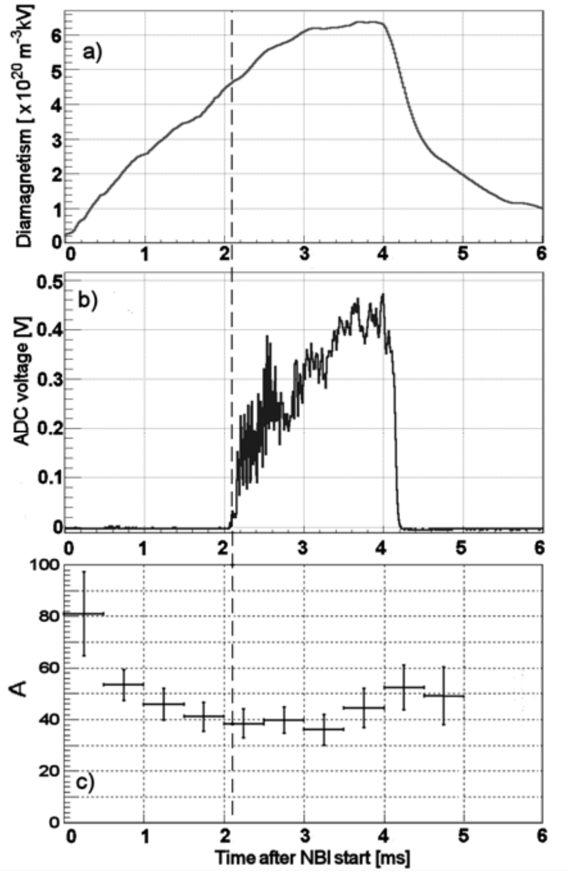

Fig.2: The diamagnetism of hot deuterons (a), amplitude of high-frequency magnetic field oscillations (b) and plasma anisotropy *A* (bottom, c) versus time.

To define the phase and the frequency of the oscillations digital time-series data from the probes were Fourier analyzed and cross power spectral densities were determined. In Fig.3 the cross amplitude spectrum of two signals from the azimuthal probes in the centre of compact mirror is drawn. A coherent oscillation appears as a narrow maximum at the frequency mode f_0 = 39.65±0.15 MHz. The second maximum corresponds to the second frequency mode. The actual magnetic field (taking into account plasma diamagnetism) at the midplane of compact mirror in these experiments was 27.6±0.3 kGs. Corresponding ion-cyclotron frequency is f_{ci} = 42±0.5 MHz. Thus there is a shift of observed oscillation frequency which is expected for the AIC mode $f_0 < f_{ci}\,(1 - \langle E_{||}\rangle/\langle E_{\perp}\rangle)$.

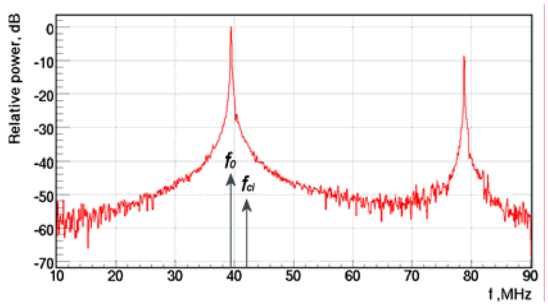

Fig. 3. The cross amplitude spectrum.

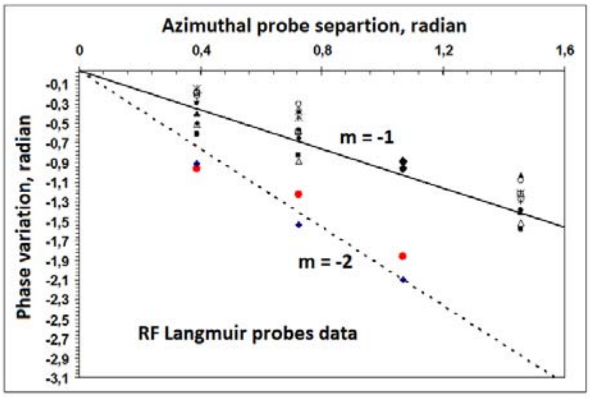

Fig.4. Azimuthal mode analysis.

In Fig.4 azimuthal mode analysis is shown. The phase shifts recorded at f_0 versus the angles between azimuthal probes for ten shots with experimental conditions held approximately constant are plotted. Solid line corresponds to the mode m= -1, dashed line – to the mode m = -2. In the most experiments observed azimuthal mode was m = -1, occasionally the second mode appeared. Oscillations with higher mode numbers were not detected. A negative m indicates propagation in the

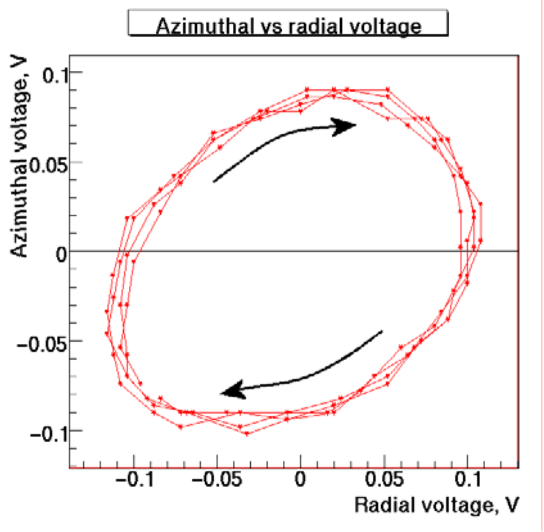

Fig.5. Azimuthal vs radial induced loop voltages. The field vector rotates in the direction of ion gyration.

direction of ion gyration.

In Fig.5 $V_\varphi(t)$ versus $V_r(t)$ - the loop-probe voltages induced by $\dot{B}_r(t)$ and $\dot{B}_\varphi(t)$ is plotted. The amplitude of azimuthal and radial component of magnetic field oscillations were about 100 mGs. The amplitude of axial magnetic field fluctuations is more than an order less. The probe was away from the centre on the radius of 15 cm. Rotation of the perpendicular B in clockwise direction in the picture corresponds to the rotation in the direction of ion gyration (a left polarized wave).

In summary, registration of small azimuthal mode numbers, oscillation frequency below the diamagnetically depressed ion-cyclotron frequency and rotation of the magnetic field of the wave in the direction of ion gyration is a weighty argument that fluctuations observed in the compact mirror of GDT are connected with the development of Alfven ion cyclotron instability.

Phase shift between the signals from the electrostatic probes on the same magnetic line (one in the centre of compact mirror and another in the expander) in different shots was random. This means that axial wave length is much less than the distance between the probes (70 cm) and the fluctuations are not flute-like and thus are not the results of developing of drift-cyclotron loss-cone instability. This is confirmed by the measurements from the array of probes with 1,5 cm separation on the same magnetic line in the expander. Correlation analysis shows that the axial wave length is not greater than 2 cm.

IV. CONCLUSION

The main results obtained during this work are the following:

- With the help of electric and magnetic high-frequency probes were investigated microfluctuations of plasma in the compact mirror of GDT device. These fluctuations were caused by strong anisotropy of ion distribution function in the velocity space. Amplitude of the fluctuations was approximately 100 mGs.
- Microinstability developing in the compact mirror is Alfven ion-cyclotron (AIC). This was proved by observing small azimuthal modes numbers m = 1–2, oscillation frequency below the diamagnetically depressed ion-cyclotron frequency and rotation of the magnetic field of the wave in the direction of ion gyration.
- The threshold of the AIC fluctuation was determined relative to the density of hot ions, ratio of ion pressure to magnetic filed pressure β, anisotropy A and the ion gyroradius to the plasmoid radius ratio a_i/R_p AIC microinstability developed when the density of hot ions n_f was greater than $3x10^{13}$ cm^{-3}, $\beta \approx 0.02$, anisotropy A = 40, for the ratio a_i/R_p of about 0.23.

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