LOW-FREQUENCY OSCILLATIONS OF PLASMA IN THE GAS DYNAMIC TRAP

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Vortex confinement is a new and effective method of convective losses suppression in gas-dynamic trap. Low frequency oscillations of radial magnetic field were observed during study of plasma MHD activity. Experimental data confirm the main statements of the vortex confinement theory. We also observed displacement of fast ions turning point. It can be explained by high beta equilibrium effects.

I. INTRODUCTION

The gas-dynamic trap (GDT) is a long magnetic mirror cell with a high mirror ratio. The facility is intended for confinement of collisional plasma with an isotropic Maxwellian velocity distribution (Ref. 1). Confinement of such plasma in the GDT is similar to that of a gas in a vessel with a small hole. The particle lifetime in the GDT is about $\tau_{||} = L\times R/V_i$, where L is the trap length, R is the mirror ratio, and V_i is the ion thermal velocity. The prospects of creating an efficient GDT-based thermonuclear reactor are still unclear, because for the existing technology of generation of a super strong magnetic field in the mirrors such a reactor should be longer than 1 km. Nevertheless it seems rather promising to create a GDT-based high-power source of thermonuclear D-T neutrons (Ref. 2). This source can be used to solve problems of fusion material research (Ref. 3) and control subcritical fission reactors including devices intended for afterburning of radioactive nuclear reactor wastes (Ref. 4). In contrast to the GDT-based reactor the collisional plasma in the GDT-based neutron source is expected to be relatively cold ($T_e \approx T_i < 1\ keV$) and inappropriate for efficient thermonuclear reactions. It is planned that neutrons in such plasma will be produced by creating populations of deuterium and tritium ions having thermonuclear energies and anisotropic velocity distributions. Such ions can be produced by oblique injection of atomic beams. The density and temperature of the collisional plasma, as well as the atomic beam energy, should be such that the characteristic deceleration times of deuterium and tritium nuclei are much shorter than the characteristic time of their angular scattering. In this case hot ions will preserve a relatively small angular spread and form zones with an increased density in the vicinity of the reflection regions where the neutron fluxes will be peaked and where material research modules or active elements of subcritical fission reactors can be installed. The function of the collisional (target) plasma is also to trap the atomic beams, provide MHD stabilization, and suppress microinstabilities.

GDT facility is intended for simulation of plasma physics processes that should take place in the neutron source (Ref. 5). The main loss channel that determines the balance of particles and energy in the GDT is the gas-dynamic plasma outflow through the mirrors (Ref. 6).

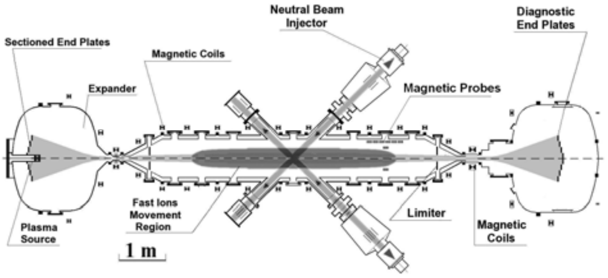

Fig. 1. GDT device layout

The main part of the GDT facility is an axisymmetric mirror system with a length of 7 m and mirror ratio of $R = 35$, designed for the confinement of a two-component plasma (Fig. 1). One component is collisional target plasma with an isotropic Maxwellian velocity distribution. This component has electron and ion temperatures of up to 200 eV and a density of $\sim 3\cdot 10^{13}$ cm^{-3} and is confined in a gas-dynamic mode, because the ion path length with respect to scattering into the loss cone is less than the trap length. The other component – fast ions with an average energy of ~10 keV and a density of up to $5\cdot 10^{13}$ cm^{-3} – is produced by intense neutral beam injection (NBI). This component is confined in a collisionless adiabatic mode. The energy of injected neutral particles is 22–25 keV, the total NBI power being up to 4.8 MW. The relative plasma pressure in the mirror system reaches a value of $\beta = 8\pi n\langle\varepsilon_\perp\rangle/B^2 = 0.55$ (Ref. 7), where n and $\langle\varepsilon_\perp\rangle$ are the density and average transverse energy of fast ions, respectively, and B is the magnetic induction, which, in this series of experiments, was 0.3 T in the central plane of the trap.

It is well known that the magnetic field configuration in an axisymmetric mirror system is unfavorable for MHD-stable plasma confinement. In standard GDT experiments MHD stability is achieved by means of additional plasma sections having favorable magnetic field geometry and attached to the magnetic mirrors. The density of the outflowing plasma in the expanders (the regions behind the GDT mirrors) is high enough, so that they could be used as MHD stabilizers (Ref. 8). Special coils enclosing the end tanks create a magnetic field directed oppositely to the main field. Thus magnetic field configuration is favorable for MHD stability in the expander. Besides the expanders, an additional cell having a cusp magnetic configuration and connected to one of the GDT ends is also used as an MHD stabilizer (Ref. 9).

Efforts to optimize operation of the GDT with variation of plasma rotation led to discovery of a new way of efficient plasma confinement. Its nature is similar to confinement of material in the dead zone of a vortex flow. It is achieved by applying voltage to the limiters and the endplates of the device, thus creating shear-flow layer, which surrounds the core of the discharge. In this regime the gas-dynamic stabilization is shown to be unnecessary, as the confinement is excellent even with straight field lines in the expanders. While the axisymmetric equilibrium remains unstable, there appears a new dynamic state of confinement with approximate axial symmetry and low convective losses. The needed power consumption is a fraction of parallel ion losses (30 kW), while the theoretical scaling predicts the scheme to work even at fusion temperatures. The analytic theory (Ref. 10) describes the nonlinear dissipative saturation of the m=1 mode in the presence of the externally-driven vortex flow. Authors also give the two-dimensional drift-ordered MHD simulation of the vortex confinement in the GDT.

II. EXPERIMENTAL DATA

II.A. Oscillations in vortex confinement regime

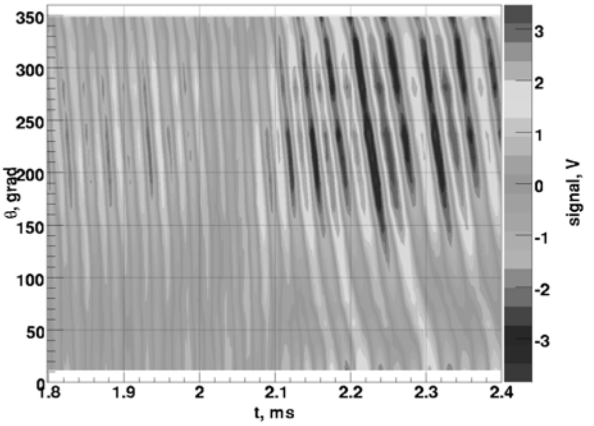

Fig. 2. Signal from the azimuthal set of probes. Time t=0 at the beginning of neutral beams injection, θ is the azimuthal coordinate.

Two sets of Mirnov probes were used to explore the oscillations character in regimes of vortex confinement. These probes measure the radial magnetic field produced by fast ions, therefore the probes were situated near the fast ions turning point (see Fig. 1) where radial field is maximal.

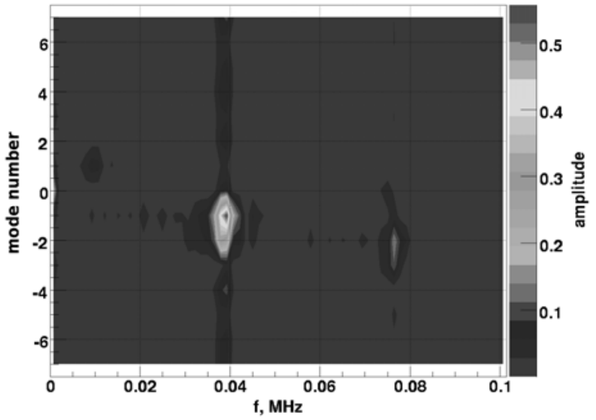

Fig. 3. Spectrum of signal from the azimuthal set of probes from 1 to 2 ms.

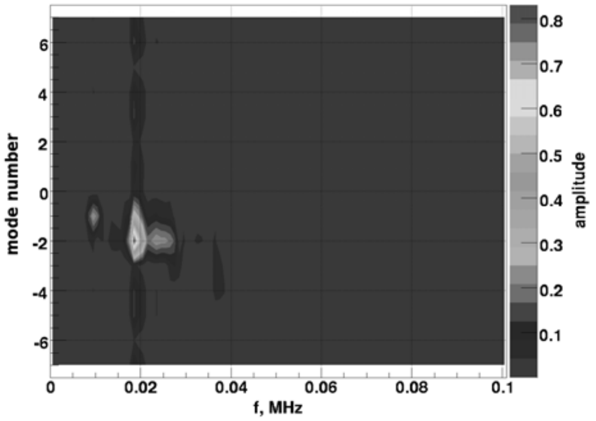

Fig. 4. Spectrum of signal from the azimuthal set of probes from 2 to 4 ms.

The first set of probes is linear and consists of 13 magnetic coils with diameter of 4 cm in stainless steel shielding cases. These coils were placed along the plasma column at the radius 35 cm. The second set is azimuthal and contains 16 probes of the same construction. These probes placed around the plasma column at the radius 25 cm. Both sets placed near the turning point of fast ions, where plasma diameter is about 10 cm. Signals from the probes are proportional to time derivative of radial magnetic field.

By means of the diagnostics spectral characteristics of flute oscillations in regimes with vortex confinement were investigated. It was found that oscillations have the only one dominating mode at each moment; usually:

- from 1 to 2 ms of beam injection: mode m=1;
- from 2 to 4 ms of beam injection: mode m=2.

Figure 2 shows signal from the azimuthal set of probes when transition from m=1 to m=2 took place. When mode m=1 dominates (plasma column rotates as a cylindrical solid body, but column axis is shifted from the device axis) nearby maximum stripes pass one to another. In case when mode m=2 dominates (plasma column rotates as a solid body with elliptical cross section, column and device axes are matched) the slope angle of maximum stripes is changing and stripes pass next but one. Fig. 3 and Fig. 4 show spectra if this signal in different moments. It's clear from these figures that in period from 1 to 2 ms when mode m=1 dominates the oscillations frequency is about 40 kHz and from 2 to 4 ms oscillations of mode m=2 have frequency about 20 kHz.

Let us note that transition occurs quickly during one or two periods of oscillations. Frequency changes after the transition. This fact is in a good agreement with theory which predicts that mode number defines oscillations frequency. According to theory, measured frequency is

$$f = f_v - f_{amb} \cdot \mathrm{m}, \qquad (1)$$

where f_v is proportional to the voltage applied to the plasma edge and f_{amb} is ambipolar frequency defined by radial temperature profile. Using this formula and obtained data one can found $f_{amb} / f_v \approx 1/3$.

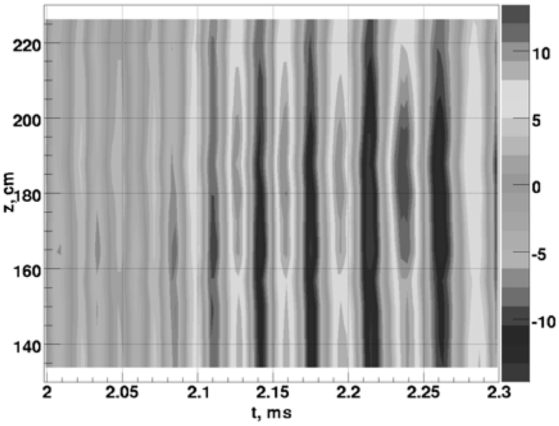

Fig. 5. Signal from the linear set of probes. Time t=0 at the beginning of neutral beams injection, z is the coordinate along mirror axis; z=190 cm corresponds to mirror ratio 2 calculated on vacuum magnetic field and z=140 cm to R=1.5.

Linear set of Mirnov probes and detectors of passed atomic beams were used to investigate longitudinal wavelengths. Signals from probes in linear set were cophased to each other (Fig. 5). It means that the axial wave length is longer than the characteristic size of the diagnostics (about 1 m).

Detectors of passed atomic beams allowed to calculate plasma linear density in central plane. These data can be used for finding correlations between signals from detectors (in central plane, R=1) and azimuthal Mirnov probes (in fast ions turning point, R=2). In phase where mode m=1 dominates there were no oscillations on beams detectors. It can be explained as follows. Let's assume that atomic beam diameter and plasma column shift δ are much less than column diameter a. In this case oscillations of linear density will be the second order of smallness δ/a. Therefore signal oscillations of the first mode are close to circuit noise. For the second mode linear density oscillations are proportional to the first order of δ/a (in this case 2δ is the difference between ellipse axes). The value of δ/a was found to be 5% and spectrum had one frequency about 40 kHz. This spectrum of linear density oscillations measured at the central plane (R=1) matches with spectrum of radial magnetic field at the turning point (R=2). Correlation analysis of these spectra shows that angular coordinates of plasma flute does not change with accuracy of 10 degrees from center to turning point. This fact proves the flute nature of the oscillations.

The magnitude of non-axisymmetric linear density oscillations mentioned above is sufficient to sustain radial resonant transport of fast ions in the steady-state phase of discharge. This transport mechanism can explain narrow radial profiles of fast ions observed in Ref. 11.

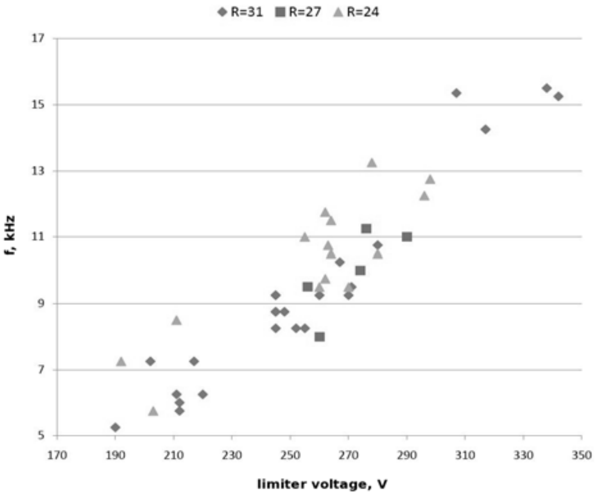

Fig. 6. Dependencies of oscillation frequency on limiter voltage at different mirror ratios.

To verify the theory of vortex confinement the series of experiments was carried out. Theory predicts linear dependence of oscillation frequency on voltage applied to the limiter. Fig. 6 demonstrates good accordance of experimental data to theoretical scaling.

II.B. Turning point displacement

An unusual peak on signal from diamagnetic loop placed near the turning point of fast ions was observed in some stable shots (Fig. 7). Before and after the peak signal from the linear set of Mirnov probes was found to be typical for vortex confinement regime: cophased oscillations with approximately constant amplitude along device axis (Fig. 8). At the moment of the peak the amplitude of oscillations increased and become highly dependent on longitudinal coordinate. Frequency of these oscillations corresponds to bounce frequency of fast ions with energy about 20 keV.

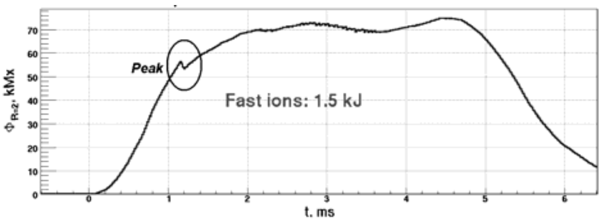

Fig. 7. Signal from diamagnetic loop.

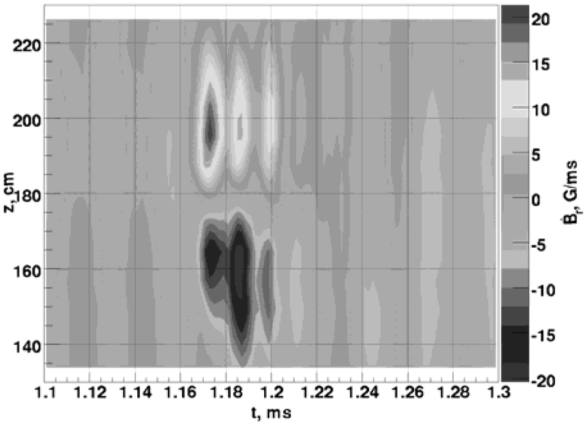

Fig. 8. Signal from the linear set of probes.

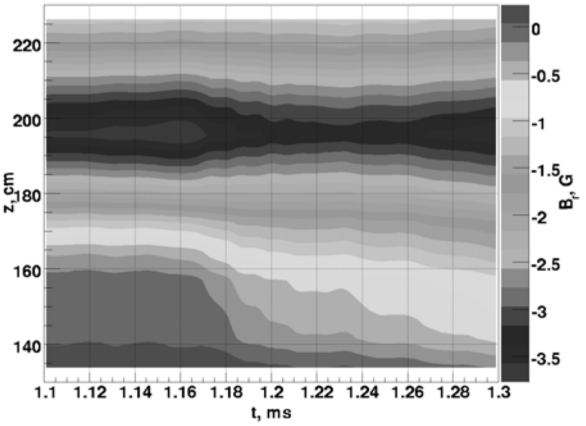

Fig. 9. Radial magnetic field under linear set of probes.

The value of radial magnetic field reconstructed by the signal of the linear set is shown on Fig. 9. Amplitude of the field was rapidly increasing in area between z=140 and z=160 cm (mirror ratio R=1.5-1.6 calculated on vacuum magnetic field) and decreasing near z=200 cm (R=2). It can be explained by displacement of part of fast ions turning point closer to the centre of device. It’s important to note that altering of magnetic field should be significant to realize the displacement of fast ions turning point. Possible mechanism of this effect is theoretically described in (Ref. 12).

III. RESULTS

Experimental data described above demonstrate agreement with the theory of vortex confinement. Oscillations observed have a flute character with only one dominating mode at each moment. Plasma rotates in the direction opposite to ambipolar rotation. Oscillations frequency has linear dependence on voltage applied to radial limiters.

Displacement of fast ions turning point was observed experimentally. It can be explained by high beta effects.

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