Experimental observation of axial ion loss during the Alfven ion-cyclotron instability in the GDT mirror

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Introduction

The gas dynamic trap (GDT) is an axisymmetric open system with a high mirror ratio for confinement of collision plasma and anisotropic hot ion population produced by an oblique deuterium neutral beam injection [1]. The hot ion component has the mean energy $E_h \approx 9$ keV and the maximum density $n_h \approx 3 \cdot 10^{13} cm^{-3}$. The collision warm plasma has the electron temperature up to $T_w \approx 250$ eV and density $n_w \approx 5 \cdot 10^{13} cm^{-3}$. The local relative plasma pressure β approaching 0.6 was measured [2]. These parameters allow to propose a project of the 2 MW / m^2 fusion neutron source based on the GDT with a simple geometry and relatively low construction and operation costs [3]. The high β coupled with the anisotropic distribution function of the hot ions potentially leads to the instability excitation and, consequently, plasma confinement degradation. The instability relevant to the plasma activity at frequencies of the order of the ion-cyclotron frequency was previously observed and investigated in the GDT experiment [4]. As a result, the instability was preliminarily identified as an Alfvén ion-cyclotron (AIC) instability, and as it has been obtained from the experiment the longitudinal velocity range of particles responsible for the AIC instability excitation is on the order of the initial longitudinal speed of injected ions. This range is consistent with the theory [5]. This paper presents an investigation of the hot ion losses in the GDT experiment during the AIC instability and comparison with the appropriate theoretical model.

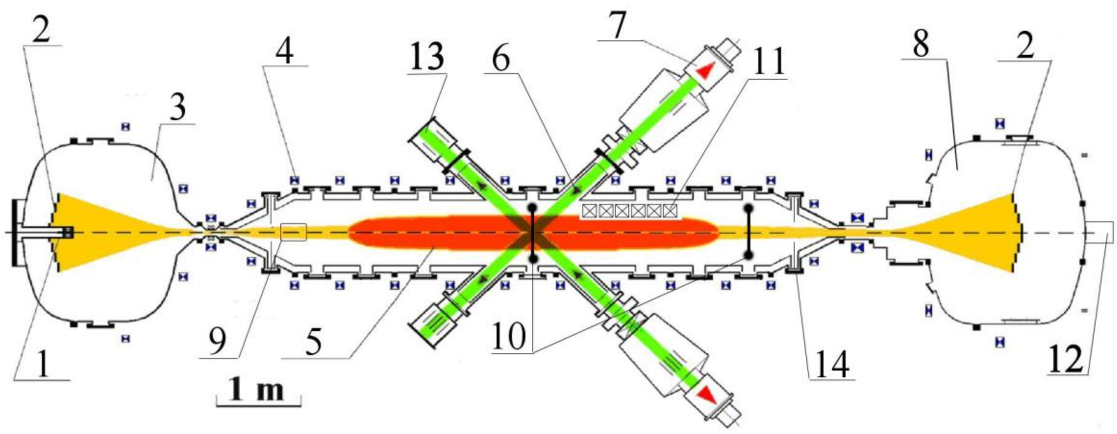

Fig. 1. Layout of the GDT experiment. 1 – plasma gun, 2 – plasma absorber, 3 – gun tank (eastern expander), 4 – coil of the magnetic system, 5 – fast ions motion region, 6 – deuterium beams, 7 – atomic injection system, 8 – western expander, 9 – gas box, 10 – diamagnetic loops, 11 – magnetic probes, 12 – energy analyzer, 13 – heating beams receivers tanks, 14 - limiter.

Experimental setup

A layout of the GDT experimental setup is presented on Fig.1. The longitudinal ion velocity is an important parameter responsible for AIC developing. Moreover it is required to measure magnetic field value, excited wave frequency and its longitudinal length in instability generation region. We have used the magnetic probes (11 on Fig. 1) for identifying wave parameters listed above.

The experimental investigation of longitudinal loss spectra were made by the modernized 5-channel energy analyzer [6] (see 12 on Fig.1), installed in at the end wall in the GDT expander cell. The magnetic analyzer was the main diagnostic for measurement of an axial fast ion loss value during AIC developing. Particles leaving the central cell continue driving along the force lines and enter through the vacuum valve to the chamber with the magnetic separator, which divides particles depending on its energy into different registration channels. As a result, the hot ion loss spectra in the range of 5 – 25 keV were obtained.

Numerical simulation

The energy distribution functions of hot ions leaving the trap through magnetic mirrors were numerically simulated by a Monte-Carlo transport code MCFIT [7]. In addition to this method a fast one-dimensional code DOL [8] was employed for hot ion spectra modeling. The experimentally measured energy distribution of ions leaving the GDT along magnetic lines is demonstrated on Fig. 2. Distributions obtained in numerical simulations using MCFIT and DOL codes are shown there for comparison with the experimental data.

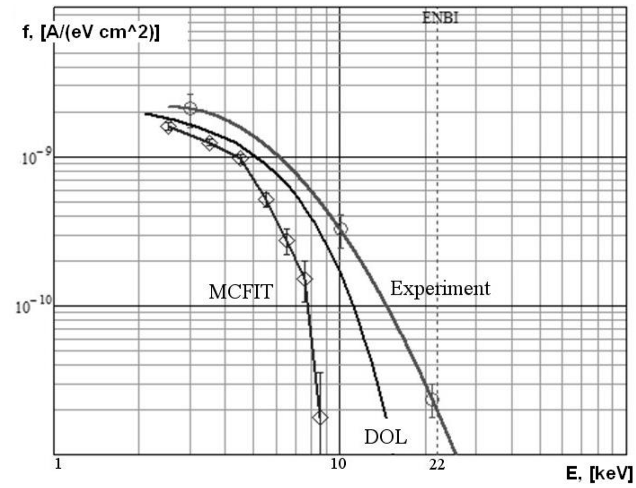

Fig.2. Experimentally measured ion energy distribution on the GDT end wall and results of simulations. The energy of injected atoms E_{NBI}=22 keV is pointed by a vertical line.

The tolerable agreement of the experimental spectrum with the simulation results points first, to the Coulomb character of hot ions interaction with warm target plasma and, second, to the validity of measurement method submitted. Insignificant distinction of absolute values in spectra shown on Fig. 2 is explained by the difference between input data in the models and real experiment parameters.

Results and discussion

The measured energy spectra of hot ions leaving the central cell facility during AIC developing are shown on Fig. 3.

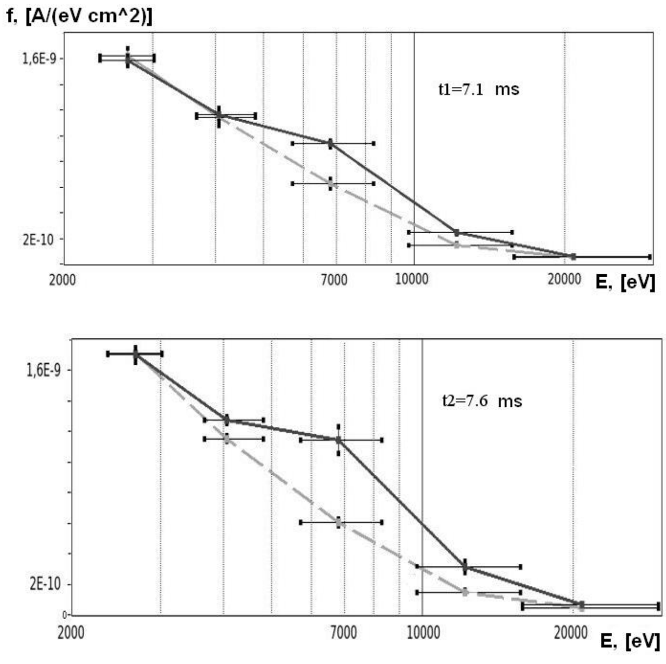

Fig. 3. Energy distributions of fast ions during AIC growth (solid line) and without it (dotted line) for different time points of the GDT experiment.

As it is seen on Fig.3 the ion flow increases during AIC growth in energy range 4 - 12 keV. These values are certainly less than energy of injected deuterium atoms E_{inj}= 22 keV. Obtained results confirm a hypothesis that the only minor group of hot ions is found to be in resonant conditions with the Alfven wave. This group has energies closed to ultimate value of E_{inj} and angle dispersion closed to injected atoms dispersion. The particles leave the resonance region during their relaxation without achieving the loss cone boundary. In that way the ions efficiently give their energy to electrons and heat it up.

The relative AIC power loss estimated as a $(P_{\|}^{AIC} - P_{\|}^{noAIC})/P_{tr}$, were P_{tr} is a power deposited to the plasmas by powerful atomic beams, gives us the values of 0.2% and 0.5% for different time points presented on Fig.3. This experimental fact shows that energy losses corresponded to the AIC are negligible.

Conclusion

The energy spectrum of hot ions leaving the trap through magnetic mirrors in the energy range of 2.5 keV – 22 keV was obtained for regime with AIC developing and without one. A fact that the ion loss flow has increased during the AIC growth in middle energy range indicates effective participation of hot ions in plasma heating, so that the drag time of hot ions less than the time of scattering to the loss cone.

The energy losses corresponded to the AIC are less than 1%. The result obtained confirms the theoretical prediction that only small group of hot ions actively interacts with the wave for the GDT experimental conditions. Those ions are located in the narrow region of phase space near the injection point. A small drag or scattering is sufficient for taking out from the resonance area.

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