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First observations of ion cyclotron emisison in the spherical tokamak Globus-M2

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Received March 18, 2024
Revised May 20, 2024
Accepted May 28, 2024

In the Globus-M2 tokamak, using magnetic probes, emission was detected in the ion-cyclotron frequency range (the frequency of the first harmonic is in the range from 4 to 12 MHz) in discharges with injection of a beam of high-energy atoms. The observed spectra are a set of equidistant harmonics at ion cyclotron resonance frequencies for hydrogen or deuterium ions; splitting of spectral lines is also observed. Under the assumption that the detected radiation is ion-cyclotron, its localization was established. Using a three-coordinate probe, the polarization of the radiation was determined.

Keywords: spherical tokamak, ion-cyclotron emission, Alfven cyclotron instability.

DOI: 10.61011/TPL.2024.09.59160.19923

The motion of ions along Larmor orbits induces bremsstrahlung (cyclotron) emission. However, unlike electron cyclotron emission, which is used widely for diagnostic purposes [1], cyclotron emission of individual ions cannot penetrate tokamak plasma. Observation of signals at ion cyclotron resonance frequencies ($f_{ci} = eB/2\pi m_i$, where B is the magnetic field induction and m_i is the ion mass) from plasma is made possible by the resonance of cyclotron rotation of ions with various plasma instabilities [2]. This ion cyclotron emission (ICE) has already been detected numerous times. It has been observed for the first time in experiments with a DT mixture: first at TFTR [3] and later at JET [4]. It was assumed that the resonance was established by thermonuclear alpha particles. These particles are produced in the center of plasma and, owing to the large size of their cyclotron orbits, may induce a nonequilibrium velocity distribution of ions at the periphery. Ion cyclotron emission may also be caused by fast ions produced during ion cyclotron heating or injection of a beam of high-energy atoms entering into resonance with plasma instabilities. In most cases, these instabilities are considered to be magnetoacoustic or Alfvén cyclotron ones [5,6]. Resonant particles interact in this model with a compression Alfvén wave, which, in contrast to a shear Alfvén wave, may propagate at ion cyclotron frequencies.

Globus-M2

[7] is a compact spherical tokamak with the following set of parameters: $R = 0.36$ m, $a = 0.24$ m, $A = 1.5$, $B_0 \leq 1$ T, and $I_p \leq 500$ kA, where R and a are the major and minor radii, respectively; A is the aspect ratio; B_0 is the toroidal field on the magnetic axis; and I_p is the plasma current. The Globus-M2 tokamak features an extensive diagnostic complex [8] and additional heating systems. Two injectors (NBI-1 and NBI-2 with power $P_{beam} \approx 1$ MW and energies $E_{\text{NBI-1}}$ up to 30 keV and $E_{\text{NBI-2}}$ up to 50 keV [9]) are installed at Globus-M2 for injection of hydrogen or deuterium atoms. The tokamak is fitted with Thomson scattering diagnostics, which provides an opportunity to measure the concentration and temperature profiles at 11 spatial points with a pulse repetition rate of 330 Hz [10]. Arrays of magnetic probes mounted along the toroidal and poloidal paths are used to record magnetohydrodynamic (MHD) disturbances. The toroidal array consists of eight fast magnetic coils that are arranged uniformly along the toroidal path of the tokamak chamber at an angle of 45° relative to each other and record the poloidal magnetic flux component. The probes are mounted inside the vacuum chamber and protected from heat flows by graphite tiles (with gaps between them that allow high-frequency electromagnetic radiation to reach these probes). The signal from probes is digitized at frequencies up to 250 MHz, which allows one to detect radiation in the ion cyclotron frequency range. The poloidal array is formed by 16 probes that record the poloidal magnetic flux component. The probes themselves have the form of coils with a thin wire with polyimide insulation wound on them. These coils are covered with boron nitride plates (α-BN). A three-coordinate probe consisting of three coils oriented normally to different magnetic flux components is used to determine the structure of MHD disturbances (relationship between the magnetic field components). The three-coordinate probe coils have the same design as those installed in the toroidal probe array.

Fast magnetic probes at the Globus-M2 tokamak enabled first observations of oscillations at ion cyclotron resonance frequencies for deuterium (4–6 MHz) and at the ion cyclotron resonance frequency for hydrogen (8–12 MHz) in discharges with atomic beam injection. Multiple harmonics

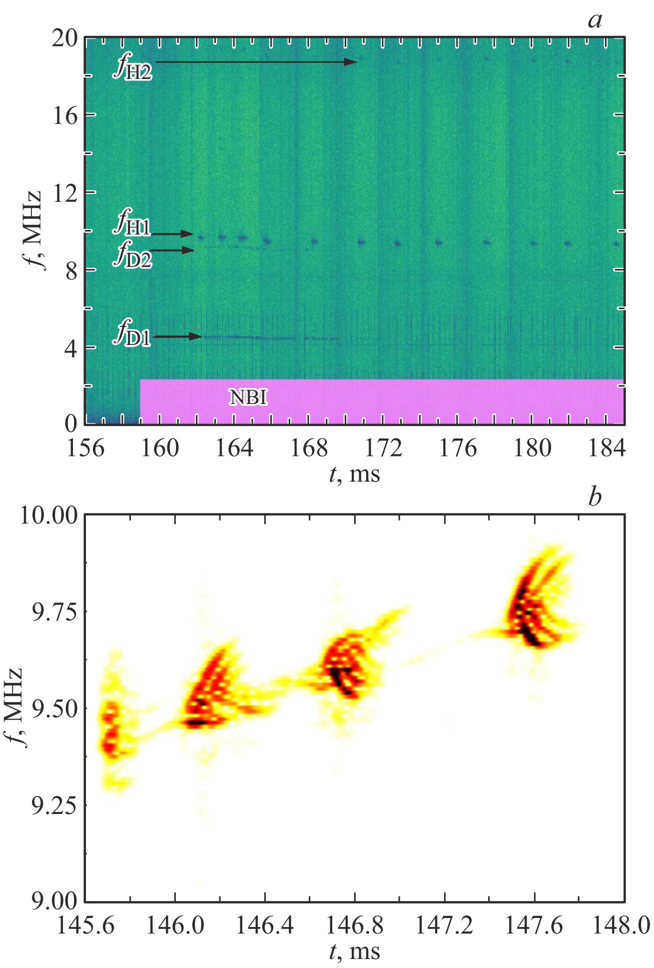

Figure 1. *a* — Spectral pattern of magnetic probe signal #42663 ($I_p = 235$ kA, $B = 0.75$ T, $P_{beam} = 0.67$ MW, and $E_{\text{NBI}} = 26$ keV); *b* — spectral pattern of magnetic probe signal #42358 ($I_p = 360$ kA, $B = 0.9$ T, $P_{beam} = 1.12$ MW, and $E_{\text{NBI}} = 45$ keV).

were also observed (Fig. 1, *a*). The detection of radiation in the ion cyclotron frequency range at the Globus-M2 tokamak was made possible by the modernization of magnetic probe diagnostics. As part of this technical upgrade, the number of toroidal magnetic probes was increased to eight, and the digitalization frequency was raised to 250 MHz. Since ion cyclotron emission may be used to determine the parameters of fast particles [11], ICE research is of interest for both reactor-type tokamaks and compact installations.

Ion cyclotron harmonics were observed in the process of injection of a deuterium or hydrogen beam into deuterium or hydrogen plasma at discharge parameters $300 < I_p < 400$ kA, $0.7 < B_0 < 0.9$ T and in a wide concentration range ($n_e = 10^{18} - 10^{20}\,\text{m}^{-3}$). The typical spectral pattern of a discharge with ICE is presented in Fig. 1, *a*. In discharge #42663 ($I_p = 235$ kA, $B = 0.75$ T), hydrogen was injected into deuterium plasma by the NBI-1 injector ($P_{beam} = 0.67$ MW, $E_{\text{NBI}} = 26$ keV) within a time interval of 160–185 ms. A long-lived mode starts to develop at the ion cyclotron resonance frequency 2 ms after the onset of injection. The first two harmonics of hydrogen and deuterium are also shown in Fig. 1, *a*.

Burst-type mode development was observed in certain discharges. For example, rapid variation of the mode frequency (Fig. 1, *b*) associated with nonlinear interaction between resonant particles with a nonequilibrium distribution and waves in plasma (so-called „chirping" [12]) was observed in discharge #42358 ($I_p = 360$ kA, $B_0 = 0.9$ T, and $n_e = 5 \cdot 10^{19}\,\text{m}^{-3}$) in the process of injection of an atomic beam by the NBI-2 injector ($P_{beam} = 1.12$ MW, $E_{\text{NBI}} = 45$ keV, and the injection interval was 130–230 ms). This effect indicates that ICE is triggered by the interaction of a plasma wave with fast particles. Chirping has already been observed at the Globus-M tokamak for toroidal Alfvén eigenmodes (TAEs), oscillations in the sub-cyclotron range and in the helicon frequency range [13].

Signals from the three-coordinate probe were used to determine the wave structure. The ratio of toroidal, poloidal, and radial magnetic flux components detected in the course of ICE observations was obtained as a result of these measurements. Figure 2, *a* shows the ratio of disturbed toroidal and poloidal (tangent to the magnetic surface) components of the magnetic field within an individual ICE burst. The toroidal disturbance component is significantly greater than the poloidal one, and the resulting figure has the shape of a flattened ellipse elongated in the toroidal direction. This suggests that the magnetic field of a wave is largely co-directional with the external magnetic field. This ratio of magnetic field components is characteristic of compressional or magnetosonic waves (compressional Alfvén waves included).

If we consider this emission to be ion cyclotron in nature, its localization may be assumed. The frequency measured by the magnetic probe was compared with the ion cyclotron frequency calculated from the magnetic field distribution derived from the magnetic equilibrium reconstruction. It follows from the comparison of frequencies (Fig. 2, *b*) that oscillations are localized near the magnetic axis (for $f \sim 10$ MHz $R \sim 0.4$ m).

The data from poloidal array probes also revealed that all probes recorded the same frequency. An explanation for this may be devised under the assumption that particle trajectories are compact and localized near the equatorial plane, allowing the oscillation frequency to remain virtually unchanged in motion along the magnetic surface. This assumption is relevant in the case when a wave propagates along a certain magnetic surface and is excited due to resonance with fast particles. The latter is evidenced, among other things, by the observation of chirped bursts (Fig. 1, *b*). The authors of [14] noted that so-called „stagnant" trajectories are the likely trajectories of resonant particles.

The central localization of emission may be perceived as a sign that the chirping effect mentioned above arises as a result of a shift of the magnetic configuration toward a strong field. However, the characteristic time of burst

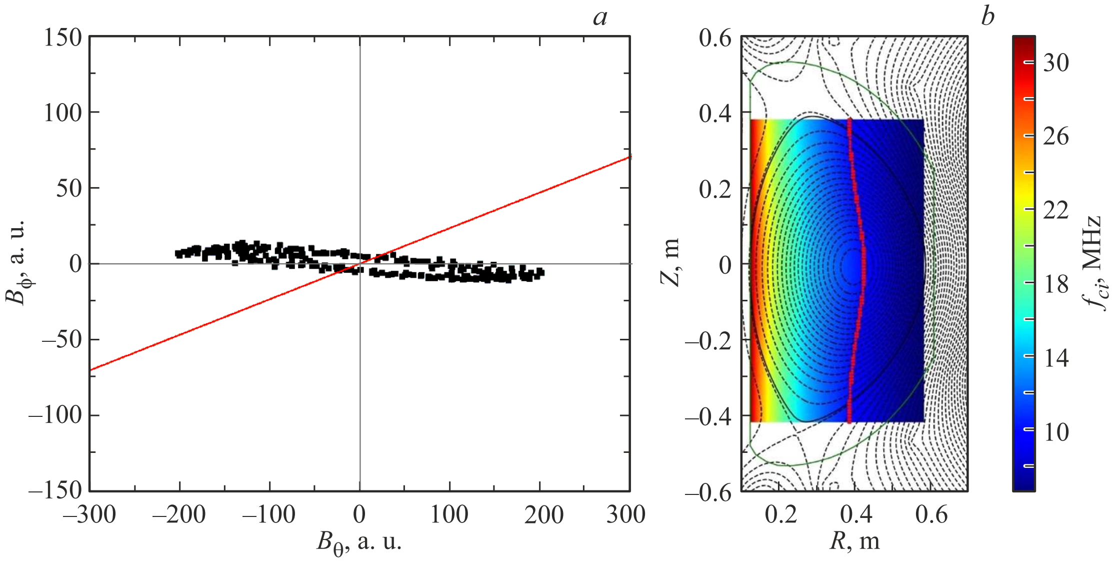

Figure 2. Discharge #42280, 173 ms. *a* — Ratio of the toroidal and poloidal components of the disturbed magnetic field. The red line indicates the slope of field lines in the region where the probe is mounted. *b* — Spatial distribution of the ion cyclotron frequency of the first harmonic of hydrogen. The solid red line denotes the frequency recorded by the magnetic probe. The magnetic configuration is represented by dotted curves. A color version of the figure is provided in the online version of the paper.

frequency variation is on the order of $400\,\mu$s, which is several times shorter than the characteristic time of magnetic configuration variation. This effect was discussed in literature and observed for other instabilities (ICE included [15]).

Localization makes it possible to determine the dependence of the ICE frequency on plasma parameters. Figure 3, *a* presents the dependence of the ICE frequency on the on-axis magnetic field magnitude. The obtained dependence is, as is to be expected for this emission, linear. To verify this conclusion, the Pearson correlation coefficient was calculated numerically using the following formula: $r_p = S_{xy}/S_xS_y$, where S_{xy} is the covariance of signals x and y and S_x, S_y are the standard deviations for signals x and y, respectively. The dependence in question has $r_p = 0.97$. The dependence of frequency on magnetic field was determined at fixed values of plasma current and electron concentration. The dependence of the ICE frequency on the local electron concentration measured using Thomson scattering diagnostics at the emission localization radius in constant magnetic field $B = 0.8$ T was also determined. Since ICE is driven by the resonance of suprathermal particles with plasma instabilities, the recorded frequency may differ from cyclotron frequency f_{ci} due to the dependence on plasma parameters found in the corresponding dispersion relation. For example, an inverse root dependence of frequency on the electron concentration is to be expected in the case of Alfvén cyclotron instability [6]: $f_A = kc_A$, $c_A = B/\sqrt{\mu_0\rho_i}$, where k is the wave number, c_A is the Alfvén velocity, μ_0 is the vacuum permeability, and ρ_i is the mass density of ions of the primary plasma component. Figure 3, *b* presents the dependence of frequency recorded by the probe on the local electron concentration. It can be seen that this frequency is independent of concentration. This, however, does not allow one to exclude Alfvén or fast magnetosonic waves from consideration, since it follows from the resonance condition between a wave and a particle (with the cyclotron rotation taken into account) that $\mathbf{v}\cdot\mathbf{k} + l\omega_{ci} - \omega = 0$ [6,16], where v is the particle velocity, k is the wave vector of a wave, and $l\omega_{ci}$ is the cyclotron harmonic with number l; i.e., if term $l\omega_{ci}$ is significantly larger than product $\mathbf{v}\cdot\mathbf{k}$, the dependence on Alfvén velocity may be insignificant compared to the large contribution of cyclotron rotation.

In addition, it turned out to be possible to fulfill the Alfvén resonance condition. In experiments at the Globus-M2 tokamak, the particle beam velocity was comparable to the Alfvén velocity (at $B = 0.85$ T, $n_e = 6\cdot10^{19}\,\mathrm{m}^{-3}$, and $E_{\mathrm{NBI}} = 46$ keV): $c_A = 1.6\cdot10^6$ m/s, while beam velocity $v_{beam} = 2\cdot10^6$ m/s.

Thus, it was found that ion cyclotron oscillations detected at the Globus-M2 tokamak have the following characteristics: they are localized at the center of a plasma filament and have a ratio of magnetic field components characteristic of compressional or magnetosonic waves. The emission frequency also depends linearly on the magnetic field magnitude and does not depend on the electron concentration. The probable source of emission is the resonance of a wave with fast particles.

Centrally localized ICE, which was observed during the injection of high-energy atoms, has been detected earlier in a number of experiments. Specifically, this emission has been detected at ASDEX-Upgrade [2], Tuman-3M [14], and DIII-D [17] in the conditions similar to those established at Globus-M2. These experimental setups did also reveal a lack of dependence of the ICE frequency on plasma density.

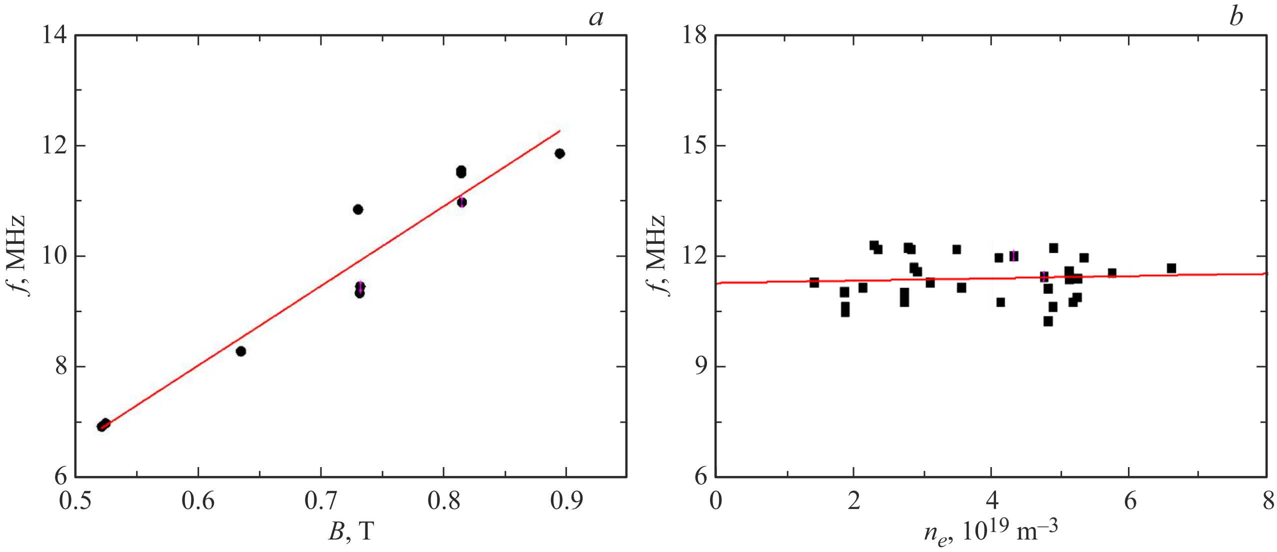

Figure 3. Dependence of the ICE frequency in the region of its supposed localization on the magnetic field magnitude (*a*) and the local electron concentration (*b*).

ICE with such parameters is classified as „central ICE" [2]; in spite of numerous observations, this type of emission is currently the least studied one.

Acknowledgments

Experiments were carried out at the unique scientific complex „Spherical Tokamak Globus-M," which is a part of the federal common research center „Material Science and Diagnostics in Advanced Technologies."

Funding

Heating (project 0034-2021-0001) and diagnostic (0034-2024-0028) systems of the tokamak were set up as part of the state assignment.

Conflict of interest

The authors declare that they have no conflict of interest.

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Translated by D.Safin