Spatial distribution and extraction of ionic components of a rotating plasma in developed resonant ion-cyclotron instability

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Experimental observation of spatial and energy separation of different ionic components of a rotating plasma under stationary conditions is reported in the presence of ion cyclotron instability.

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Resonant ion cyclotron instability in a rotating plasma occurs when $2\omega^i_{\rm rot}\approx\omega_{\rm Bi}$, where $\omega_{\rm Bi}=e_iB_0/m_iC$ is the cyclotron frequency of ions with mass m_i and charge e_i, $\omega^i_{\rm rot}\sim cE_r/rB_0$ is the frequency of the revolution of these ions in a radial electric field E_r crossed with a longitudinal magnetic field B_0, and r is the distance from the discharge axis.[1,2] The development of this instability is accompanied by spatial concentration and heating of the ions, for which resonance takes place in a narrow region where the oscillations are localized, with subsequent ejection of the ions along the magnetic field.

The observed effect differs from the previously considered methods of separating ions of different sorts.[3–6] The separation of ions of different isotopes in a plasma in crossed fields[3] is due to centrifugal force and is not connected with cyclotron resonance. The use of ion cyclotron resonance to extract from a plasma ions of different sorts[4–6] is based on the effect of the increase of the transverse energy of the ions by the external alternating electron field in the stable plasma.

The experiments were performed with a reflection-discharge plasma under stationary conditions at $n_e=10^8$–10^9 cm^{-3}, $T_e\sim 10$–50 eV, $B_0\leqslant 1.5$ kOe, $E_r\leqslant 300$ V/cm (for a description of the setup see[2]). By choosing the resonant values of B_0 and E_r at a given mass of the working gas (N_2, O_2, Ar, He and their mixtures) it is possible to excite cyclotron oscillations, and the ions of the working gas, as well as the ions having a mass that is a multiple of the mass of the working-gas ions, will be accelerated and leave the discharge. We measured the distribution of ions with masses 14(N^+), 16(O^+), 18(H_2O^+), 44(CO_2^+), 40(Ar) and others, along the radius of the plasma column, by optical and mass-spectrometric methods. A typical radial distribution of the ion masses is shown in Fig. 1. It is seen from this figure that both the intensities of the optical radiation of the molecular and atomic nitrogen ions ($\lambda=3914$ Å for N_2^+ and $\lambda=5679$ Å for N^+), and the ion fluxes along B_0, gathered by the mass spectrometer directly from different sections of the discharge, are distinctly separated in space. The distributions of the ion fluxes and the intensities of their optical radiation along the radius are analogous to the radial distribution of the amplitude of the ion cyclotron

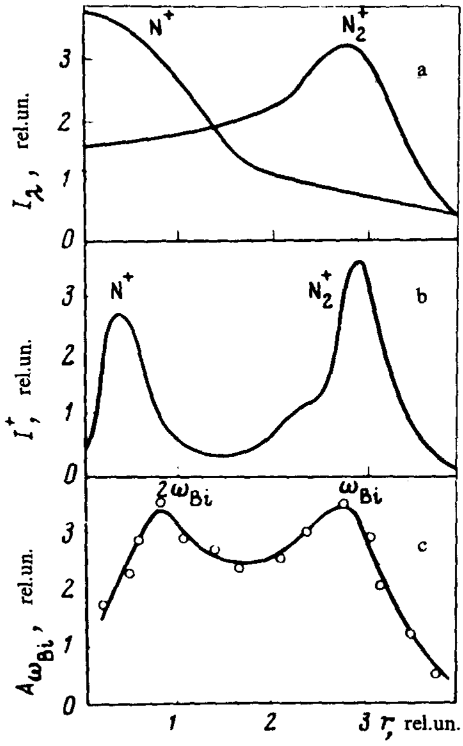

FIG. 1. Radial distribution: a) of the intensity of the optical rotation of molecular and atomic nitrogen ions, b) of the fluxes of the ions leaving the plasma along B_0, c) of the amplitudes of the ion cyclotron oscillations.

oscillations (see Fig. 1). The dependences of the fluxes of ions of different masses and energies on the discharge parameters (E_r, B_0, n_e, P) are also analogous to the dependence of the amplitude of the cyclotron oscillations on these parameters.[2]

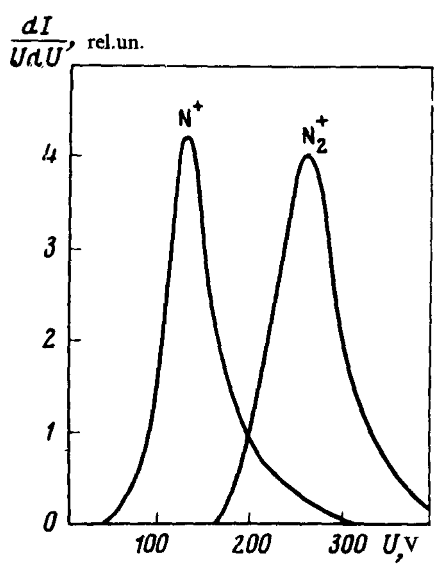

FIG. 2. Energy spectra of ions with different masses leaving the discharge along the magnetic field.

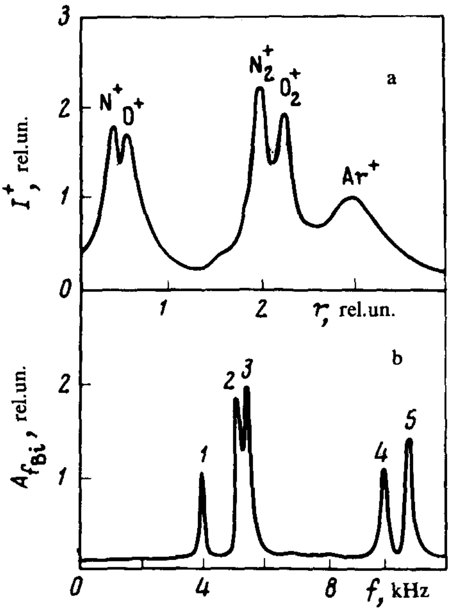

FIG. 3. a) Radial distribution of the fluxes of ions with different mass, leaving the plasma, along B_0; b) spectrum of ion cyclotron oscillations with frequencies corresponding to the ions Ar^+(1), O_2^+(2), N_2^+(3), O^+(4), N^+(5).

The energy spectra of ions with different masses, which leave the discharge along the magnetic field (see Fig. 2) lie in the interval 100–300 eV and are sufficiently monochromatic, so that ions of different masses can also be separated in energy.

Introduction into the discharge of gases whose atoms have a mass that is a multiple of the mass of the atoms of the working gas, or else have a mass close to the mass of the atoms of the working gas or its multiples, adds to the oscillation spectrum components having the cyclotron frequency of the introduced atoms, while the mass spectra of samples taken from the discharge reveal ions of the introduced gas with distinct radial localization (see Fig. 3).

It should be noted that ions of heavy atoms, with mass larger than the mass of the working-gas atom and for which resonance conditions are not satisfied are concentrated as a rule on the discharge axes, a fact that can be used to rid a plasma of undesirable impurities.

Under conditions when no cyclotron instability develops in a rotating plasma (for example, in a strong field E_r or a weak field B_0, when oscillations with frequency $\omega \gg \omega_{Bi}$ are excited), no ion separation by masses and energies is observed.

These experiments show that the observed effect of separation of different components are connected with the presence of ion cyclotron instability. However, the increased departure of the ions from the discharge region where these oscillations are localized can apparently not be connected with their acceleration by the electric field of the cyclotron oscillations, since the energy acquired by the resonant ions in this field is much less than observed in experiment.

It is possible that the observed phenomenon is connected with focusing of the resonant ions by the radial RF field of the natural ion-cyclotron oscillations, which cancel out the acceleration of these ions along the radius by the static field E_r. The resonant ions then acquire in the static longitudinal field E_z in the region of the potential drop between the anode and the cathode an energy $\Delta\epsilon \sim eV$, where V is the potential difference between the point where the ionization act took place and the cathode. In this case the region of the cyclotron oscillations plays, as it were, the role of a focusing device for the resonant particles. The RF field has a weak effect on the nonresonant particles. Becoming accelerated by the field E_r, they go off to the sidewalls of the discharge apparatus.

Thus, different ionic components become separated in space and in energy in a steady-state rotating plasma under conditions of developed ion cyclotron instability whose energy comes from a constant source.

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