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MAGNETO-ACOUSTIC RESONANCE IN A TOROIDAL SYSTEM

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Magneto-acoustic resonance is observed in a toroidal system with a longitudinal current when a small amplitude excitation is superimposed. The resonance frequency is close to the calculated value; however, the increase of the magnetic sound amplitude along the column axis was not very significant. The effect may be employed for high-frequency heating of a plasma in toroidal systems with a strong magnetic field.

INTRODUCTION

In the work of our laboratory on the excitation of magneto-acoustic resonance,[1-5] the experiments were carried out in a homogeneous magnetic field. With this geometry it is impossible to maintain a plasma for a long time, and so the study of plasma heating and dissipative mechanisms under these conditions is difficult. In the present work a toroidal chamber with a longitudinal current is used as a magnetic trap. The possibility of exciting magneto-acoustic resonance in such a system has up until now not been considered.

From the point of view of stating the problem, the simplest is the excitation of the resonance uniformly along the axis of a torus. If the toroidality (the ratio of the minor radius of the torus to its major radius) is small, then for an approximate treatment we can use the model of an infinitely long cylinder with uniform excitation. In this case one can speak of purely transverse (with respect to the longitudinal magnetic field) propagation of oscillations in the plasma pinch.

Since a plasma with current is most stable in systems with a strong magnetic field ("Tokamak," "Stellarator"[6,7]), an experimental device was built with a large ratio of the longitudinal magnetic field to the current's own field. An experimental arrangement of the stellarator type with homogeneous excitation in the traps is technically more complicated and creates difficulties in the interpretation of results; hence in our experiments an apparatus with a current filament was used.

A longitudinal current together with a metallic screen guarantees equilibrium of the plasma column.[8] The study of magnetic sound is thereby complicated, since the magnetic field now has a helical character due to an additional component produced by the longitudinal current. The intensity of this component of the field, which we shall call H_φ, according to the criterion of stability of Kruskal-Shafranov,[9] should satisfy the inequality

$$H_\varphi R / H_z a < 1 / q,$$

where H_z is the intensity of the longitudinal magnetic field, a/R is the "toroidality" (the ratio of the minor radius of the plasma filament to its major radius), and q is a positive integer greater than one.

We shall henceforth assume that the toroidality is small. In this case the toroidal system differs from a right cylinder, first, in that there are no end effects and, secondly, in the helical character of the field. If the pressure of the plasma p is so small that $H_\varphi^2/8\pi \gg p$, then the equilibrium of the plasma in this approximation requires fulfillment of the condition

$$H_\varphi^2(r) + H_z^2(r) = \text{const}, \qquad r \leqslant a.$$

Assuming a uniform current distribution over the cross section of the plasma column, the field H_Z should satisfy the simple condition

$$H_z^2(r) = H_{z0}^2 + H_\varphi^2(a)(1 - r^2 / a^2),$$

where H_{z0} is the intensity of the magnetic field outside of the plasma column. Accordingly, the magnitude of the longitudinal field in the center of the column should be

$$H_z^2(0) = H_{z0}^2 + H_\varphi^2(a).$$

Using these expressions, it is easy to obtain the correction factor to apply to the resonant frequency of the magneto-acoustic oscillations in a uniform magnetic field. If we limit ourselves to frequencies that are small in comparison with

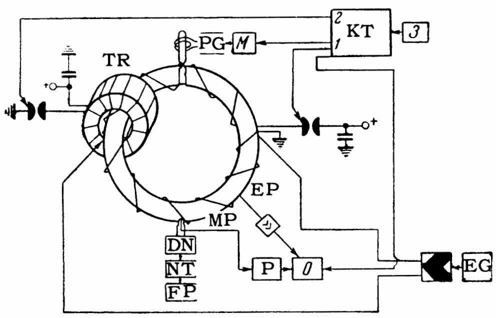

FIG. 1. Schematic diagram of the apparatus: TR, toroidal transformer; PG, M, pre-ionization generator and modulator; DN, NT, FP, pumping system; MP, magnetic probe; KT, Z, synchronization unit; EP, double electric probe; EG, excitation generator; P, O, preamplifier and oscilloscope.

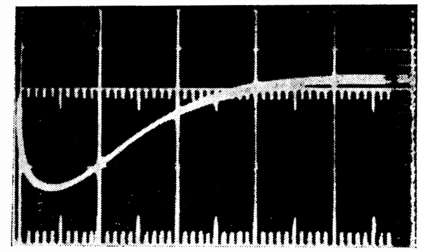

FIG. 2. Shape of the magnetic field pulse (time scale–100 μsec per large division).

both the "hybrid" and the plasma frequencies and assume that the plasma frequency is significantly higher than the electron cyclotron frequency, the desired expression is

$$\omega' = \omega (H_{z0}^2 + H_{\varphi 0}^2)^{1/2} / H_{z0},$$

where ω' and ω are the frequencies of the radial oscillations of the plasma column in a helical and a uniform magnetic field, respectively; $H_{\varphi 0} = H_\varphi(a)$.

It should be noted that the effectiveness of uniform excitation likewise can depend on the magnitude of the ratio $H_{Z0}/(H_{Z0}^2 + H_{\varphi 0}^2)^{1/2}$, since the exciting field should be directed along the lines of force of the helical field, and not along the direction of H_Z, as occurs in the case of a uniform magnetic field.

DESCRIPTION OF THE APPARATUS

The experimental arrangement (Fig. 1) consisted of an evacuated glass chamber, the large diameter of which (2R) was 50 cm and the small diameter (2a), 5 cm. The chamber was pumped out to the limiting vacuum, 10^{-6} Torr, with a BA-0.1 diffusion system. A metallic screen was put on over the outside of the chamber; its minor diameter was 6 cm, and the thickness of the copper was 0.5 cm. The screen had a longitudinal slit along the entire surface and one meridional slit. The winding of the longitudinal magnetic field was laid on the external surface of the screen. The magnetic field was produced in pulses by means of a discharge of a condenser battery. The shape of the magnetic field pulse is shown in Fig. 2. The pulse length was about 250 μsec, and the maximum value of the intensity of the field was about 4 kOe.

The longitudinal current in the plasma was produced by discharging a capacitor in the primary circuit of a toroidal transformer, the secondary circuit of which was the plasma loop. The maximum electric field intensity in the secondary circuit attained 1 V/cm. The longitudinal current did not exceed 10^3 A in most of the experiments; this satisfies the Kruskal-Shafranov criterion rather well.

Excitation of the magneto-acoustic resonance was effected by a low-power generator, the output of which was conducted via a system of current-distributing resistors to the longitudinal slit in the toroidal screen. The intensity of the high-frequency (hf) field H_Z was so low that the parameters of the plasma practically did not change when it was applied, i.e., in this sense the conditions of the experiment were linear. The total resistance of the circuit was chosen equal to the wave resistance of the generator transmission line. The inductive impedance of the toroidal screen for currents creating the longitudinal hf field in the chamber, equal to $\omega L \approx 2\pi a^2 \omega / R$, was much less than the active impedance. This permitted experimenting in a certain range of frequencies without retuning the excitation system. In our case the resonance was investigated near the frequencies f equal to 10 and 30 Mcs. It should be mentioned that this same toroidal screen was used as the return conductor for the winding of the longitudinal magnetic field; in this way it was possible to diminish greatly the effect of transverse leakage fields on the discharge.

The electrical and magnetic probes for measurement of the plasma parameters were introduced into the discharge chamber through special pipes. One of these was used to establish the hf pre-ionization, since current spark-over of a gas in chambers of small cross section is difficult. For hf pre-ionization a pulse generator operating at 8 Mcs with a pulse power of the order of 10 kW was employed. The working gas in all the experiments was hydrogen in the range of pressures from 10^{-3} to 5×10^{-3} Torr.

EXPERIMENT

The hf pre-ionization pulse was applied with a certain lead in time relative to the moment of switching on the magnetic field, or simultaneously

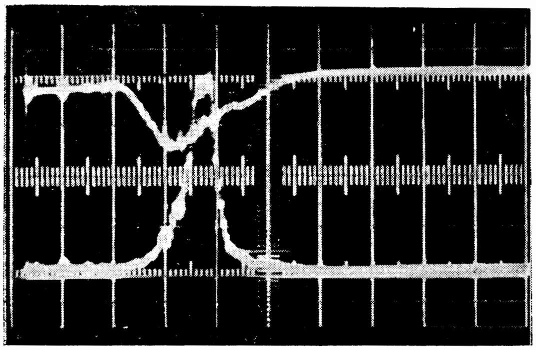

FIG. 3. Oscillogram of the current (upper curve) and concentration in the discharge chamber (lower curve); $u_{max} = 9 \times 10^{12}$ cm^{-3}, $H_0 = 1400$ Oe (time scale—25 μsec per large division).

with it; then after a lag of several tens of microseconds, the longitudinal current came on, and this was recorded by means of a Rogowski loop on the outside of the conducting screen.

Figure 3 shows the current pulse in the chamber, obtained with the Rogowski loop and the pulse of the concentration build-up, measured by a double electrical probe introduced into the plasma. The hf excitation of the magnetic sound was applied steadily throughout the whole experiment.

The results of the investigation of excitation of magneto-acoustic resonance are presented in the series of oscillograms of Fig. 4. The upper curve in each figure describes the variation of the longitudinal current with time. The lower curve is the oscillogram of the signal from the magnetic probe, which recorded the level of the hf magnetic field in the center of the current filament. Figure 4a pertains to an experiment in which no magnetic sound excitation was applied. Correspondingly, the indications of the magnetic probe show no signal at this frequency (30 Mcs) in the plasma. Figure 4b shows the screening of the magnetic probe which occurs in the presence of the longitudinal current, but without a longitudinal magnetic field. The explanation of this phenomenon is that a component of the hf electric field is directed along the magnetic field of the current. Finally, Fig. 4c was obtained when both the current and the longitudinal magnetic field were present. On the oscillogram of the signal from the magnetic probe is clearly seen a resonance maximum, associated with a definite value of the longitudinal magnetic field and concentration.

The value of the concentration and the electronic temperature at the moment of resonance were determined with the double electric probe. This probe also served to give some information about the distribution of the concentration. The maximum concentration was approximately in the

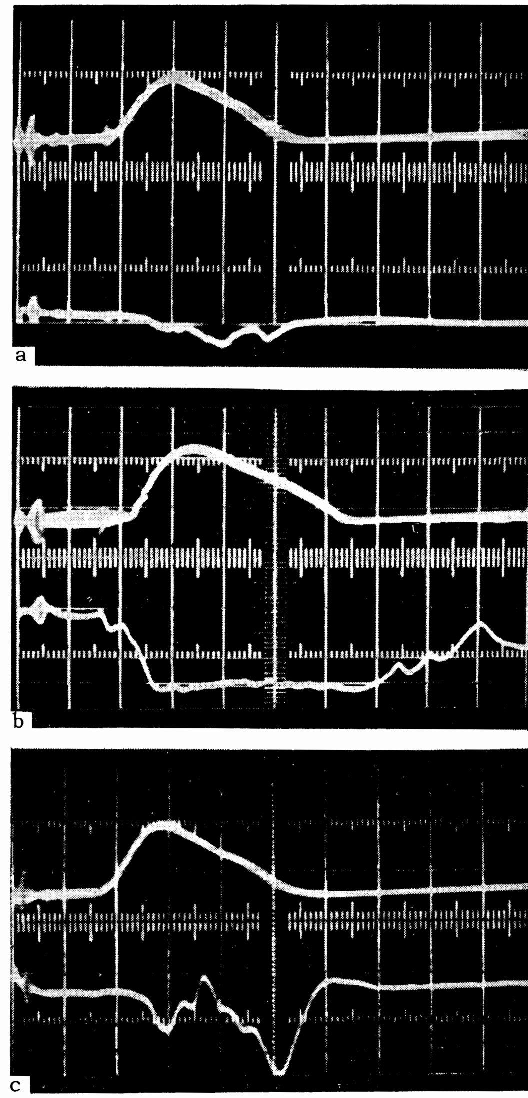

FIG. 4. Oscillograms of the current in the chamber and the signal from the magnetic probe: a—no excitation, magnetic field and current on; b—excitation applied, no magnetic field; c—magnetic field, hf excitation, and current all on.

center of the chamber and was equal to 9×10^{12} cm^{-3}. This magnitude yields an average value over the cross section of 6 to 7×10^{12} cm^{-3}. The electron temperature was 5 to 7 eV. From this it is seen that approximately $p \ll H_{\varphi}^2/8\pi$.

The value of the quasistatic magnetic field at the moment of resonance was about 1400 Oe. Substitution of these values in the expression

$$\omega = \mu (a\sqrt{4\pi\rho})^{-1} (H_{z0}^2 + H_{\varphi 0}^2)^{1/2},$$

where ρ is the density of the plasma and $\mu = ka$ is a number determined from the boundary conditions, gives satisfactory agreement between the experimental and calculated data.

The value of the number μ was chosen in accordance with measurements of the radial distribution of the magnetic field H_Z made with the magnetic probe. The distribution had a maximum in the center of the plasma column and diminished toward the boundary, i.e., qualitatively, it approached the dependence $H_Z(r) \sim J_0(kr)$, which goes to zero at $r = a$.[4] In correspondence with this, $\mu = 2.4$, which gives a calculated value of ω that is 25 to 30% lower that the excitation frequency.

CONCLUSION

These experiments show that it is possible to excite magneto-acoustic resonance in a plasma current of toroidal symmetry. This can serve as a basis for further experiments on high-frequency heating of plasmas in systems of the "Tokamak" type.

It should be noted that in the experiment described the coefficient of spatial amplification (the ratio of the amplitude of the hf field in the chamber without plasma to the amplitude of this field in a plasma) was only 1.5 to 2. On the basis of our experiments it is not yet possible to form any conclusion as to whether the low spatial amplification is due to increased dissipation of the hf energy in a plasma prepared by a current, or to the excitation system.

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