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PLASMA HEATING BY MAGNETO-ACOUSTIC WAVES

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PLASMA HEATING BY MAGNETO-ACOUSTIC WAVES

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SUMMARY

This paper discusses the possibilities of using the magneto-acoustic resonance for heating the ion component of a plasma. The experimental apparatus is described in detail. Explored also is the possibility of plasma heating by oblique magneto acoustic waves of great amplitude. The scheme of this experiment is also described.

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Heating of Ions at Magneto-acoustic Resonance. The forced radial oscillations of a uniform plasma cylinder in a permanent magnetic field have a resonance character, provided the natural frequency of the plasma cylinder coincides with the frequency of the external longitudinal variable field. This phenomenon, called magneto-acoustic resonance, was theoretically foreseen in [1], and then revealed and experimentally investigated in [2].

The resonance amplitude increase of a variable magnetic field in a plasma as compared with the amplitude of the field in vacuum (effect of spatial amplification of a variable field), is described in the works [3, 4].

The possibilities are considered in the present work of utilizing the magneto-acoustic resonance for the heating of plasma ion component [5]. The principle of the experimental installation's scheme is represented in Fig.1.

(*) NAGREV PLAZMY MAGNITNO-ZVUKOVYMI VOLNAMI

A cylindrical vacuum chamber, made of glass, is placed coaxially with a selenoid inducing a permanent magnet's field of 2 koe intensity. The plasma oscillations were excited by a high-frequency energizer circuit. The amplitude of the high-frequency field in vacuum constituted 75 oe, whereupon the power transmitted to the plasma in a pulse of 3 μ sec duration attained 300 kw. The oscillation frequency was 20 Mc/sec. The experiments were conducted at an initial hydrogen pressure in the chamber of $5 \cdot 10^{-4} - 1 \cdot 10^{-3}$ mm Hg. After a few tens of μ sec upon the switching of the HF-generator on, gas breakdown took place. The diameter of the formed plasma column was equal to the diameter of the chamber under the HF-circuit (6 cm).

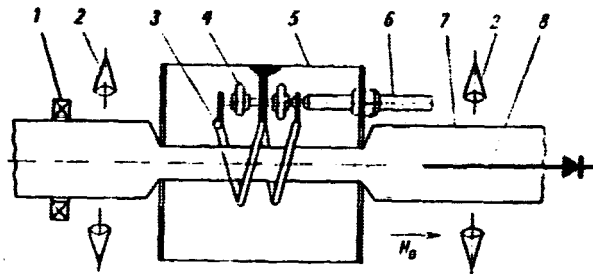


Fig.1. Block-diagram of the experimental installation

- 1.- Diamagnetic pick-up; 2.- interferometer antennas;
- 3 - 6.- HF-circuit's elements; 7.- glass vacuum chamber;
- 8.- magnetic sonde

The variation of plasma concentration was registered by the interferometer operating at 8 mm wavelength. The interferometer antennas and the magnetic sonde were disposed at 3 cm from the edge of the circuit. The oscillograms of phase incidence and HF-field strength are plotted in Fig.2. The amplitude dependence of $\tilde{H}_z$ -component on time have at that point a maximum for concentration $n = 1.5 \cdot 10^{13} \text{ cm}^{-3}$. The frequency of radial magneto-acoustic oscillations, computed for this value of concentration, coincides with a precision to 20% with the resonance frequency at the center of the circuit. Note that in these conditions the effect of spatial amplification is small (in vacuum the strength of the HF-field constituted $1.2 \tilde{H}_z$ in the plasma). However, the coincidence of frequencies, as well as the spatial distribution of HF-fields in the plasma

allow us to draw the conclusion on the excitation of magneto-acoustic resonance on the basic oscillation mode.

The plasma heating increase at magneto-acoustic wave heating was registered by the plasma diamagnetism. The value of gas-kinetic pressure, measured by the diamagnetic effect, constituted $\sim 2 \cdot 10^{15} \text{ ev} \cdot \text{cm}^{-3}$. Substituting the measured value of concentration, $n = 1.5 \cdot 10^{13} \text{ cm}^{-3}$, we obtain $T_i + T_e = 140 \text{ ev}$. This result may be explained by heating of ions to a temperature in excess of 100 ev.

The investigation of plasma decay after switching the HF-generator off at the moment of time corresponding to maximum nT has confirmed that the diamagnetic effect is nearly fully determined by the pressure of ions. We plotted in Fig.3 the oscillograms of the diamagnetic signal and of the interferometer of the decaying plasma. The diamagnetic signal drop constant is 10 μsec . During that time the concentration varies by no more than 10%, while the temperature of electrons decrease by $\underline{e}$ times, this being determined by the intensity attenuation of hydrogen spectral lines, takes place in a time less than 3 μsec .

Measurement of the distribution of HF-fields in a stationary regime and of their attenuation in the decaying plasma has shown that, by comparison with plasma pressure, the pressure of the field wave may be neglected. The measurement of the Doppler widening of lines O^+ and Si^{++} yields for the value of the temperature of these ions 20 to 30 ev.

The fact of ion heating cannot be explained within the frameworks of classical mechanisms of energy dissipation of magneto-acoustic waves. In principle an anomalous dissipation of fields may take place as a consequence of excitation of HF-potential waves in the plasma. To verify this assumption an experiment was set up with the view of determining the average magnitude of the electric field in the plasma. Analysis of hydrogen spectral line widening has shown that the average value of the electric field constitutes 200 – 400 volts/cm. Within the precision of measurements this value coincides with the magnitude of the radial electric field of a magneto-acoustic wave, and this is why it does not provide the possibility of determining the energy density of noises. However, the anomalous character of magneto-acoustic wave damping is also indicated by the value of the effective collision frequency of ions, which is $\nu_{i \text{ eff}} \approx 2 \cdot 10^7 \text{ sec}^{-1}$, responsible for the total loss of momentum of radial-mass

motion. The quantity $v_{i \text{ eff}}$, obtained by several independent methods, exceeds by a factor of 3 the frequency of Coulomb collisions.

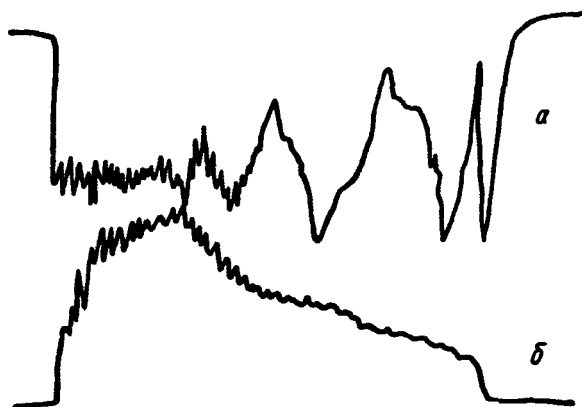


Fig.2. Interferogram obtained for the wavelength $\lambda = 8$ mm (a), and oscillogram of HF-frequency field intensity in the plasma (b)

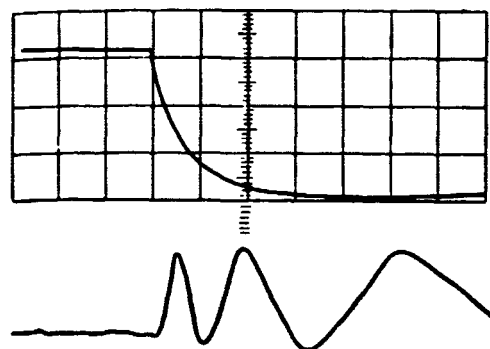


Fig.3. Characteristics of decaying plasma (scanning duration 10 $\mu\text{sec/cm}$: the diamagnetic signal is above, and the interferogram is below

The data, brought out in this work, are evidence that the magneto-acoustic resonance may be used for a direct transmission of energy to the plasma ion component. The magneto-acoustic resonance method allows us to heat the plasma in traps of various configurations, having regions in which the magnetic field is close to uniform.

PLASMA HEATING BY OBLIQUE MAGNETO-ACOUSTIC WAVES OF GREAT AMPLITUDE.

Plasma heating by oblique magneto-acoustic waves of great amplitude, generated by an impact turn, has been investigated. Studied earlier were the magneto-acoustic waves of small amplitude, excited in the plasma with the aid of a stationary generator [6]. The question of plasma heating by analogous waves was examined in the works [7, 8]. The structure of oblique nonlinear waves was also described earlier [10]. In the present work particular attention is given the plasma heating by such a wave.

The block-diagram of the experiment is represented in Figure 4. The hydrogen plasma was prepared in a magnetic field of 250 – 1000 oe intensity by means of pulse generators, whose frequency was of 21 Mc/sec. The nominal power of each generator constituted 100 kw with original hydrogen pressure of $4 \cdot 10^{-4}$ to 10^{-3} mm Hg. The concentration of electrons varied within the limits $2 \cdot 10^{12}$ to $2 \cdot 10^{13} \text{ cm}^{-3}$. The degree of ionization could have attained 50 to 70 percent.

and the temperature of electrons ~ 10 ev. A block-diagram of the excitation of a magneto-acoustic wave by a narrow turn (diameter 8 cm, width 3 cm) in a plasma column placed in a quasi-static magnetic field is shown in Fig.5. The variation of the HF-field of the impact circuit in time has the form of a damping sinusoid with characteristic frequency of ~ 11 Mhz. The HF-field on chamber axis under the loop reached a magnitude of about 1800 oe.

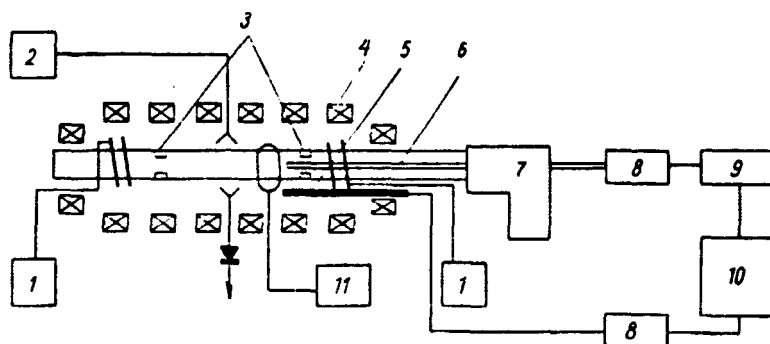


Fig.4. Block-diagram of the experimental installation:

- 1) pre-ionizing generators; 2) SHF-interferometer; 3) diaphragms; 4) magnetic field coils; 5) synchronization sonde; 7) pump; 8) - 9) amplifiers; 10) oscillograph; 11) impact circuit

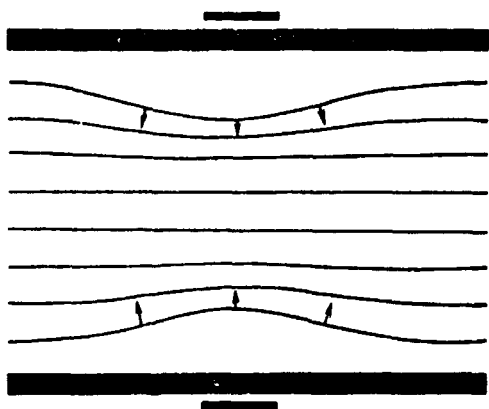


Fig.5. Sketch of nonlinear magneto-acoustic wave excitation

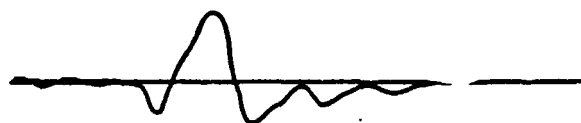


Fig.6. Signal from the magnetic sonde

$r = 1.5$ cm; $z = 4$ cm; total time of scanning: 1 μ sec

Fig.6 shows the oscillogram of the signal from the magnetic sonde obtained for $n = 2 \cdot 10^{13}$ cm^{-3} and $H_0 = 300$ oe

(the sonde was placed on the side of the loop at about 1.5 cm from the axis of the chamber. One may notice the wave's oscillatory front (forward run-away of HF-harmonics), which is explained by the law of dispersion of magneto-acoustic oscillations at frequencies substantially exceeding the ion-cyclotron frequency.

In typical conditions of the experiment the pulsations had a dimension of 1 to 2 cm. The wave has three magnetic field components: $\tilde{H}_z$, $\tilde{H}_\phi$, $\tilde{H}_r$, which is evidence of its oblique propagation. In case of cylindrical symmetry the wave front's inclination angle is not constant. At the point $r = 1.5$ cm $z = 4$ cm, it is equal to 30° . The fields of the wave attenuate rapidly with the increase of distance from the central plane of the exciting loop. At $\tilde{H}_z = 1800$ oe, $\tilde{H}_\phi = 300$ oe, $n = 2 \cdot 10^{13}$ cm $^{-3}$, the amplitude at length of 7 cm from the loop drops by a factor of more than 3. As the amplitude of the excited wave increases, the attenuation length decreases. The main energy liberation takes place in immediate vicinity of the circuit, in a plasma volume of 15 cm length.

The investigation of the state of plasma behind the wave front was conducted with the aid of the diamagnetic pick-up encompassing the plasma, and of the interferometer, in the 8 mm wavelength. The oscillogram of plasma pressure (nT), obtained by the pick-up at the distance of 15 cm from the plane of the loop at breakdown geometry of the magnetic field, is plotted in Figure 7.



Fig.7. Signal (nT). One division corresponds to 1 μ second, and $nT = 8 \cdot 10^{14}$ ev $\cdot$ cm $^{-3}$

The signal corresponding to the main part of the wave, is suppressed by the filter. The pressure of the wave field in the plane of the diamagnetic pick-up is low by comparison with the plasma pressure. The maximum of nT is

$$nT = 8 \cdot 10^{14} \text{ ev} \cdot \text{cm}^{-3}$$

The switching-off of one of the plugs diminished the nT lifetime in the trap with 3.5 down to 1.2 μ sec; the magnitude of the signal dropped simultaneously. The dependence of the quantity nT on H_0 shows that the pressure of plasma does not increase noticeably with the rise of this quantity. As the initial concentration decreases, nT drops slowly.

The dependence of nT on the quantity $H^2/8\pi$ is linear. In our case the heating of the plasma cannot be explained by the collision mechanism and the Čerenkov absorption. Apparently, the effective dissipation of wave energy occurs on account of HF-oscillations' buildup of ionic sound and of plasma waves. Such an assumption is corroborated by SHF-noise emission near the

electronic plasma frequency and X-ray quanta, emerging at the head of the sonde placed at the same point as the magnetic sonde. The appearance of signals corresponds to wave front passage.

The effective energy absorption by the plasma, which bears in this work a collisionless character, is confirmed by decrement measurements of circuit attenuation, and also by additional ionization after the working off the impact circuit.

If we bring the energy in the plasma to a volume, where energy liberation takes place, we shall have $(nT)_{\max} = 6 \cdot 10^{15} \text{ ev} \cdot \text{cm}^{-3}$. The estimate of the temperature of electrons yields $\sim 300 \text{ ev}$. Indirect facts make it evident that the energy of the electron component exceeds substantially the energy of the ion component. However, no direct measurements of ion temperatures were conducted.

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