MAGNETOACOUSTIC OSCILLATIONS AND INSTABILITY OF AN INDUCTION PINCH

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The results of an experimental investigation of an induction pinch are presented. It is shown that the radial oscillations that arise in rapid compression of the plasma are of magnetoacoustic nature. Pinch instabilities are also noted at high shock-wave intensities.

FREE magnetoacoustic oscillations in a dense plasma have been investigated by means of an experimental arrangement similar to that usually used for induction compression and heating of a plasma.[1-3]

A schematic diagram of the experiment is shown in Fig. 1. The magnetic field is excited by a uniform turn with an inductance of 30 cm;* preionization is obtained by means of an rf generator with a nominal power of 200 kw, which is connected through a $^3/_4\lambda$ coaxial cable to a coil arranged coaxially with the turn that produces the main magnetic field. This scheme makes it possible to avoid trapping of the rf magnetic field in the plasma since the frequency of the main field is 59 kc/sec while the frequency of the generator is 50 Mc/sec. The magnetic field strength in the main coil is 25,000 oe while the amplitude of the rf field is 50 — 70 oe.

The discharge is produced in a quartz vacuum chamber. When a glass chamber was used it deteriorated gradually under the effect of the discharge. The vacuum chamber is evacuated to an initial pressure of 10^{-7} mm Hg while heated to 450 — 500° C.

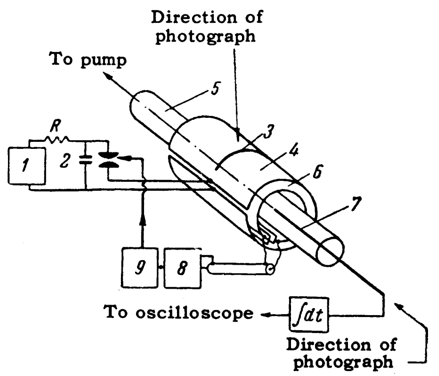

FIG. 1. Schematic diagram of the apparatus; 1) 50-kv charging supply, 2) capacitor bank (C = 50 μf, U_{max} = 50 kv), 3) slit in turn, for photography, 4) main magnetic field coil, 5) quartz vacuum chamber, 6) coil for rf ionization generator, 7) magnetic probe, 8) ionization rf generator (f = 50 Mc/sec, P = 200 kw), 9) trigger unit.

*1 cm = 10^{-9} henry.

Most of the experiments were carried out in air in the pressure range $10^{-1} - 10^{-2}$ mm Hg; some experiments were also performed with hydrogen, argon, xenon, and helium in the pressure range $10^{-1} - 10^{-3}$ mm Hg.

The investigation of discharge behavior was carried out by means of a high-speed camera (SFR-2M) and a magnetic probe, which was located at the axis of the vacuum chamber. The discharge was photographed laterally through vertical slits in the main coil and in the radio-frequency coil and was also photographed axially from the end of the system. Framing operation and the streak mode were both used.

In Fig. 2 we show lateral photographs of discharges in hydrogen, air, and argon. In the pictures in Figs. 2b and 2c it is evident that the emission intensity of the discharge is small in the first half-cycle as compared with the subsequent half-cycles.

Figure 2b was obtained with rather strong preionization; no preionization was used in Figs. 2a and 2c. Similar pictures were obtained through the end face.

In Fig. 3 we show photographs obtained by frame photography of a preionized discharge in air. Radial oscillations of the plasma tube are noticeable in each half-cycle of the magnetic field; the strength of these oscillations increases markedly from the first half-cycle to subsequent half-cycles. This feature is illustrated in Figs. 3a and 3b and in Fig. 4, which are end photographs of discharges in air with strong preionization. In the end photograph obtained with frame operation (Fig. 3) it is evident that the emission from the gas is distributed in the form of a circular layer in the first half-cycle; it can be assumed that the

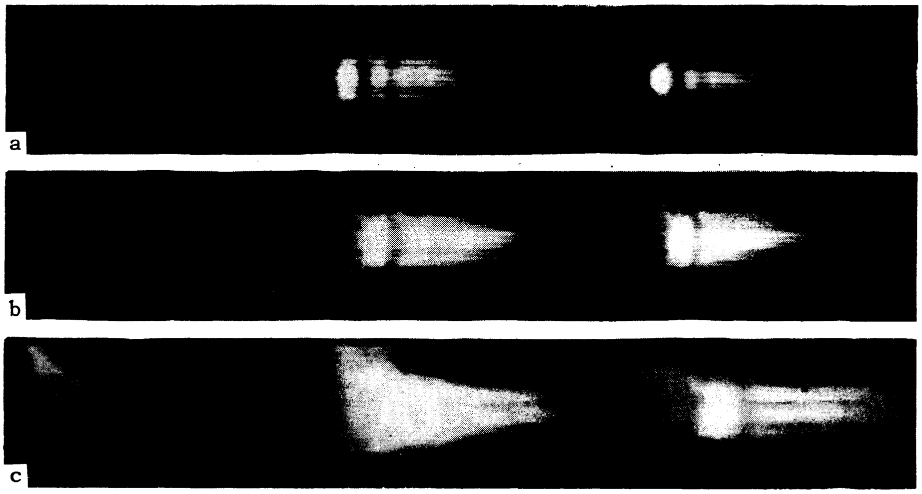

FIG. 2. Lateral photographs of the discharge obtained with a streak camera (peak field H_{max} = 25,000 oe, half-cycle 8 μsec); a) hydrogen, p = 1.3 × 10^{-1} mm Hg; b) air, p = 8 × 10^{-2} mm Hg, c) argon, p = 7.8 × 10^{-2} mm Hg.

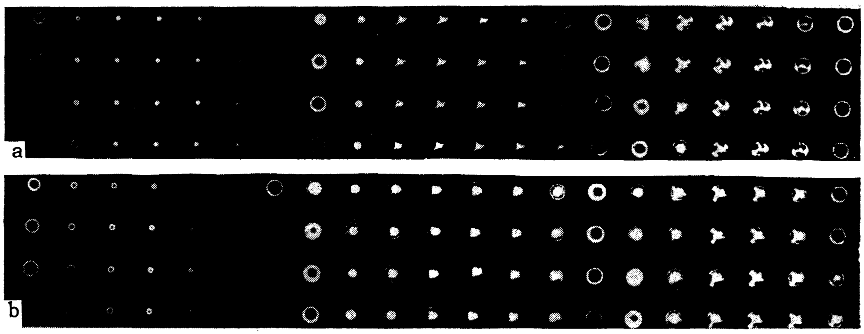

FIG. 3. Axial photographs of discharges in air taken with a framing camera (H_{max} = 25,000 oe, with preionization): a) p = 4 × 10^{-2} mm Hg, b) p = 8 × 10^{-2} mm Hg. The time interval between frames is 0.3 μsec.

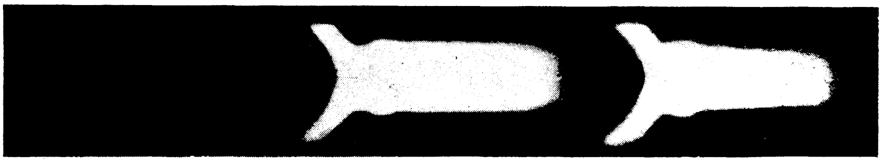

FIG. 4. Axial photographs of discharges in air taken with a streak camera (preionization. p = 8 × 10^{-2} mm Hg.)

radial oscillations are oscillations of the cold plasma located inside this circular layer. The fields outside the circular tube and outside the plasma are in the same direction.

A similar treatment of the effect is given in a paper by Niblett,[2] in which the oscillation period is described by the following formula:

$$\tau = 2\pi \sqrt{NM_i}/H,$$

where N is the total number of ions over the cross section of the pinch and M_i is the ion mass.

Great interest attaches to the behavior of the plasma during the second, third, and subsequent half-cycles of the magnetic field, because in these cases the density distribution (as is evident from the frame photographs) is approximately uniform.

Magnetic-probe measurements show that in the second half-cycle (preionization) or in the third half-cycle (no preionization, Fig. 5) the magnetic field trapped in the plasma is in the opposite direction to the field outside the plasma. As a result, mixing of these fields at the periphery of the plasma column leads to the formation of a circular plasma layer in which there is no magnetic field. Field growth inside the plasma is inhibited in this stage.

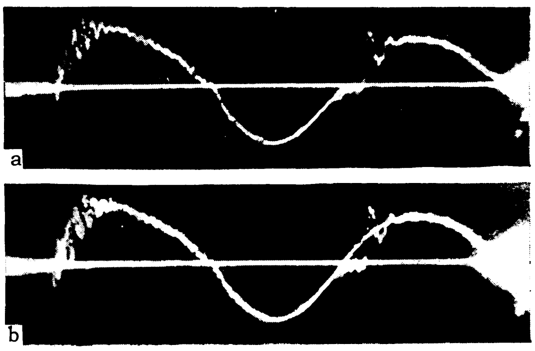

FIG. 5. Oscillogram of the magnetic field at the axis of the discharge chamber (H_{max} = 25 koe, T/2 = 8.5 μsec, p = 8 × 10^{-2} mm Hg): a) with plasma, b) combined oscillograms of the magnetic field outside the plasma and in the center of the plasma column. No preionization.

After this stage there is a sharp discontinuity in magnetic field at the axis of the plasma column (up to values exceeding the field outside the plasma by 1.5 — 2 times). Oscillations of the magnetic field are observed (with decreasing amplitude) inside the plasma both in the growth suppression stage and immediately after the break; the field oscillates about a variable value close to that of the field outside the plasma. To an accuracy of 20 — 30% the period of these oscillations coincides with that obtained by photography.

The initial compression can be attributed to the formation of a relatively weak shock wave. The velocity of the shock wave $v = 2.3 \times 10^6$ cm/sec and the width of the front is approximately 0.7 cm for a discharge in air ($p = 8 \times 10^{-2}$ mm Hg). The discontinuity in magnetic field at the axis can be explained by the collision of strong shock waves coming together from two sides of the circular plasma layer in which there is no magnetic field.

The radial oscillations of the visible boundary of the plasma column and the oscillations in the intensity of magnetic field would appear to indicate that we are observing magnetoacoustic oscillations of a plasma cylinder. It is somewhat difficult to give an exact description of the boundary conditions for the present experiment since the plasma is surrounded by a copper shield with a longitudinal break.

Foregoing a detailed analysis, we consider two limiting cases. If it is assumed that the shield does not prevent free radiation of the electromagnetic waves at infinity the boundary condition is that of a cylinder executing axially symmetric oscillations in an infinite space.[4] In the absence of surface currents this boundary condition gives

$$J_0(kR)\, H_1^{(2)}(k_0R) = J_1(kR)\, H_0^{(2)}(k_0R) / n_\perp,$$

where J is the Bessel function, k and k_0 are the wave numbers in the plasma and in vacuum, and $n_\perp$ is the plasma refractive index transverse to the magnetic field. In the present case $n_\perp \gg 1$ so that the boundary condition reduces approximately to $J_0(kR) \approx 0$, whence $\mu \equiv kR = 2.4, 5.5, \ldots$.

The opposite limiting case corresponds to the assumption that the plasma oscillates as though it were completely surrounded by a copper shield.[5] In this case the lowest natural frequency corresponds to the asymmetric oscillation characterized by $m = 1$; in this case the boundary condition is of the form $J_1(kR) = 0$, whence $\mu = 1.84, 5.3, \ldots$. This condition applies for the magnetoacoustic region, i.e., the frequency should be appreciably lower than the ion cyclotron frequency, as is observed in the present case. For comparison with the experiment we can use the results obtained by Frank-Kamenetskii[5,6] and write the natural frequencies of the magnetoacoustic oscillations in the form

$$f = \frac{\mu_{nm} H_0}{2\pi R \sqrt{4\pi\rho^*}}, \qquad \rho^* = Mn_i \Big/ \left(1 - \frac{n_0}{n_0 + n_i}\,\frac{\tilde{\nu}^2}{\tilde{\nu}^2 + \omega^2}\right),$$

where ρ^* is the effective density, μ_{nm} is the n-th root of the m-th Bessel function, M is the ion mass, n_i is the ion density, and n_0 is the neutral particle density

$$\tilde{\nu}^2 = \nu_{ni}(n_0 + n_i)/n_i = \nu_{in}(n_0 + n_i)/n_0.$$

Inasmuch as the condition $\tilde{\nu}^2 \gg \omega^2$ applies in the present case, the neutral particles are effectively carried along and $\rho^* = M(n_0 + n_i)$. Thus,

$$f = \mu_{nm} H_0 / 2\pi R \sqrt{4\pi M (n_0 + n_i)}.$$

Substitution in this expression of the experimental values for three different gases allows us to form the table below.

The following conclusions can be drawn from this work:

1) The dependence of the natural oscillation frequencies on gas mass is in good agreement with theory;

2) The agreement between the absolute values of the computed and observed frequencies is somewhat worse because we have not taken account of a number of factors such as plasma temperature, nonlinearities, multiply charged heavy-gas ions, etc.

The largest contribution is probably due to the nonlinearity of the oscillations, since the magnetic-probe oscillograms show that the amplitude of the radial oscillations is generally not small (cf. Fig. 5). Poorer agreement is found for argon, where only the first oscillation can be seen clearly, that is to say, the oscillation is almost a weak shock wave.

In control experiments with xenon at high pres-

Gas	p, 10^{-2} mm Hg	$10^{-17}A(n_0+n_i)$	$10^{-4}H_0$, oe	Frequency f, Mc/sec			f_{calc}/f_{exptl}	
				exptl.		calc.		
				$\mu=1.84$	$\mu=2.4$		$\mu=1.84$	$\mu=2.4$
H_2	13.4	1	1	2.1	2.7	1.6	1.3	1.6
N_2	8.0	8	1.7	1.3	1.6	1	1.3	1.6
Ar	7.8	11	2	1.3	1.6	0.8	1.6	2.0

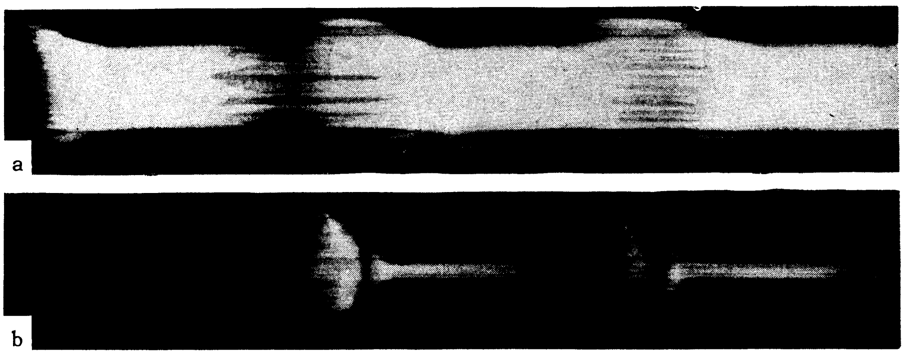

FIG. 6. Lateral photographs of discharges in xenon taken with a streak camera: a) $p = 1.5 \times 10^{-1}$ mm Hg. b) $p = 1.5 \times 10^{-2}$ mm Hg. No preionization.

sures (Fig. 6a) it is impossible to observe a strong plasma compression since the quantity $M(n_i + n_0)$ becomes appreciable and the characteristic times become comparable with the period of the main magnetic field. In addition, the stronger dissipation in these gases leads to weaker trapping of the magnetic field.

The experiments on the heavy gases at low pressures are of interest in themselves. Thus, the oscillogram (Fig. 6b) shows the effect of compression and formation of a shock wave at $p = 1.5 \times 10^{-2}$ mm Hg. Under these conditions the frequency of collisions may be comparable with the natural frequency of the plasma column and this should lead to incomplete entrainment of the neutral particles and strong attenuation due to charge exchange. These effects would explain the inability to excite oscillations under these conditions.

The experimental data given above also give qualitative information concerning the stability of the plasma under conditions of rapid radial compression.

As first noted by Kvartskhava,[7] end-view pictures disclose a clearly defined discharge instability which manifests itself in irregular expulsion of plasma "tongues" in approximately the radial direction. This result is completely verified in the present work. This form of instability is characteristic of a discharge in a long cylinder in which the radial distribution of magnetic field is approximately uniform.*

Analyzing the end-view frame photographs we note that the instabilities arise in the second, third, and subsequent half-cycles of magnetic field. The first half-cycle, which is characterized by slow compression and low temperature is, on the other hand, completely stable.

*A special case of an induction compression of plasma has been considered by Osovets and his co-workers;[8-10] in this case the discharge was produced in a chamber with small ratio of length to diameter, in which a specially chosen stable magnetic field configuration was produced.

Since the instability appears in photographs taken along the axis of the discharge (cf. Fig. 3) but is not seen in the lateral photographs, it may be assumed that the expelled plasma tongues extend along the lines of force of the magnetic field. The formation of plasma tongues starts at the time of maximum plasma compression. It may be assumed that this effect is associated with accelerated plasma motions, so that we are observing some kind of inertia instability.

CONCLUSIONS

Rapid transverse compression of a plasma leads to the excitation of free time-damped magnetoacoustic oscillations of the plasma column. Effects associated with the expulsion of plasma tongues are observed at maximum compression of the circular plasma layer; these tongues extend along the field lines and are evidently due to some form of inertia instability.

The excitation of oscillations can be regarded as the result of rapid compression, by shock waves, of a circular layer of plasma in which there is no field; this layer is formed as a result of mixing of the fields inside and outside the plasma, which are in opposite directions.

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64