OBSERVATION OF SHOCK WAVES IN A COLLISIONLESS PLASMA

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The properties of a strong electromagnetic wave propagated across a magnetic field are studied in a rarefied plasma at densities ranging from $\sim 10^{11}$ to 10^{14} cm^{-3}. It is observed that the steepness of the compression wave front increases by a factor of at least 2.5, and that a shock wave is formed. The shock front has an observed minimal time width of 2×10^{-8} sec. It is found that the propagation of a rarefaction wave through the collisionless plasma is not accompanied by shock wave formation. In this case the wave front flattens out.

It has been shown in the experiments of Babykin, Zavoiskiĭ et al [1] on turbulent heating of a plasma that the plasma electrons can be heated to high temperatures by means of large amplitude electromagnetic waves. The propagation of a strong electromagnetic wave through a plasma in the presence of turbulent heating was observed in [2], where it was shown that the maximum electron temperature is already attained during the first quarter cycle of shock-circuit operation. A mechanism involving current instability in the wave is proposed in [1] to account for such rapid heating of the electrons.

Results of previous investigations [1,2] give reason to hope that collisionless shock waves can be propagated through a plasma in a direction strictly transverse to the magnetic field. The energy dissipation in these waves is due to the instability of the current at the shock front. The possible existence of such shock waves was first indicated by R. Z. Sagdeev [2].

The aim of the present work was to ascertain the nature of the propagation of strong electromagnetic waves in a rarefied plasma, to explore whether shock waves can exist in such a plasma, and to investigate the energy dissipation mechanism which leads to heating of the electrons. It should be remembered, however, another electron heating mechanism is possible for a plasma in which the concentration of neutral particles is large. This mechanism is connected with the ionization of the atoms in the wave front. In each ionization event the newly formed electron is accelerated by the electric field of the wave and starts to move along a cycloid with a drift velocity equal to the velocity of the electrons in the wave. For this mechanism to be effective the number of electrons freshly produced in the wave front by ionization must be comparable to the number of charged particles originally there. In other words, the concentration of neutral atoms must be greater than $1/\tau < \sigma_{\text{ion}} v >$, where τ is the time width of the wave front.

The experiments were carried out under conditions similar to those used for turbulent heating. The experimental set-up described in [2] was used with the diameter of the discharge chamber enlarged to 6 cm and the high-frequency oscillatory circuit comprising an artificial line. The line produced in the discharge chamber a pulsed magnetic field, with a trapezoidal time profile of amplitude $\tilde{H}$, length T, and rise time τ_0. Two such lines with different line parameters were used in the experiments. The first line had $\tilde{H} = 600$ Oe, $T = 2.5 \times 10^{-7}$ sec and $\tau_0 = (3-4) \times 10^{-8}$ sec; the second line had $\tilde{H} = 900$ Oe $T = 4 \times 10^{-7}$ sec and $\tau_0 = (6-7) \times 10^{-8}$ sec.

The process of wave propagation in the plasma was observed by taking high speed streak photographs of the diameter of the plasma cylinder through a narrow slit mounted on the end of the discharge tube [2]. Monochromatic light from individual helium lines was used for this purpose. In order to detect the steepening of the wave front and to measure its width a high frequency magnetic probe was employed. It was 2 mm in diameter and was introduced into the plasma through one end of the discharge chamber at a distance of 1 cm from the system axis. The probe recorded the time rate of change of the magnetic flux through the cross-section of a miniature coil. The width and slope of the wave front were determined from the half-width and amplitude of the probe pulses, observed on an oscilloscope.

The charged-particle concentration ahead of the wave front was determined by means of a microwave interferometer and streak photographs of the plasma emission spectra. The electron temperature on both sides of the wave front was determined for the intensities of the time-resolved helium spectral lines.[2]

The following facts have been established as a result of the experiments. In a plasma with $\sim 10^{11} < n_e < 10^{14}\ cm^{-3}$, a compression shock wave is observed traveling from the walls of the discharge chamber towards the axis at approximately the Alfvén velocity. It has a sharply defined front, in which an intense dissipative process occurs, and the electron temperature jumps from ~ 0.1 eV ahead of the front to several eV behind the front. The time-width of the front deduced from streak photographs of the diameter of the plasma cylinder, did not exceed $(3-4) \times 10^{-8}$ sec at an initial pressure $p_0 = 6 \times 10^{-3}$ mm Hg, plasma density $n_e \approx 3 \times 10^{13}\ cm^{-3}$, constant magnetic field $H_0 = 300$ Oe, $\tilde{H} = 600$ Oe, and $\tau_0 = (3-4) \times 10^{-8}$ sec. The measurement accuracy was limited mainly by the instrumental time-width of the streak camera, which depends on the streak velocity employed.

The steepening of the shock front was observed and measured by means of the magnetic probe. In a plasma with $n_e \approx 4 \times 10^{12}\ cm^{-3}$, $H_0 = 300$ Oe, $\tau_0 = (6-7) \times 10^{-8}$ sec, $\tilde{H} = 900$ Oe, and $p_0 = 6 \times 10^{-3}$ mm Hg, the time-width of the front was $\sim 2 \times 10^{-8}$ sec, which is barely double the theoretically predicted value $c\sqrt{mM}/eH$ [3].

The observed rate at which the electron temperature increases depends most probably on the collisionless mechanism of energy dissipation. Indeed, simple estimates of the number of ionizing collisions show that under the experimental conditions employed ($p_0 = 6 \times 10^{-3}$ mm Hg and $\langle \sigma_{ion} v \rangle_{max} = 2.5 \times 10^{-8}\ cm^3/sec$) the contribution of the foregoing ionization mechanism to electron heating can apparently be neglected.

The results discussed so far pertain to a compression wave, i.e. to the case where H_0 and $\tilde{H}$ are parallel. Experiment shows that the propagation of a rarefaction wave through a collisionless plasma is not accompanied by the formation of a shock wave. In this case the wave front is flattened to approximately the same degree as the steepening observed in compression-wave fronts.

To illustrate the results, Fig. 1a shows the process of formation and propagation of a shock wave through a helium plasma of density $(2-4) \times 10^{13}\ cm^{-3}$ and was obtained by taking streak photographs of the diameter of the plasma cylinder in 4686 Å He II light. The photograph was taken at $H_0 = 300$ Oe, $\tau_0 = (3-4) \times 10^{-8}$ sec, $\tilde{H} = 600$ Oe and $p_0 = 6 \times 10^{-3}$ mm Hg. The diameter of the discharge tube is reproduced to scale at the left of the photograph, and the profile of the pulsed magnetic field in vacuum is shown in the lower part.

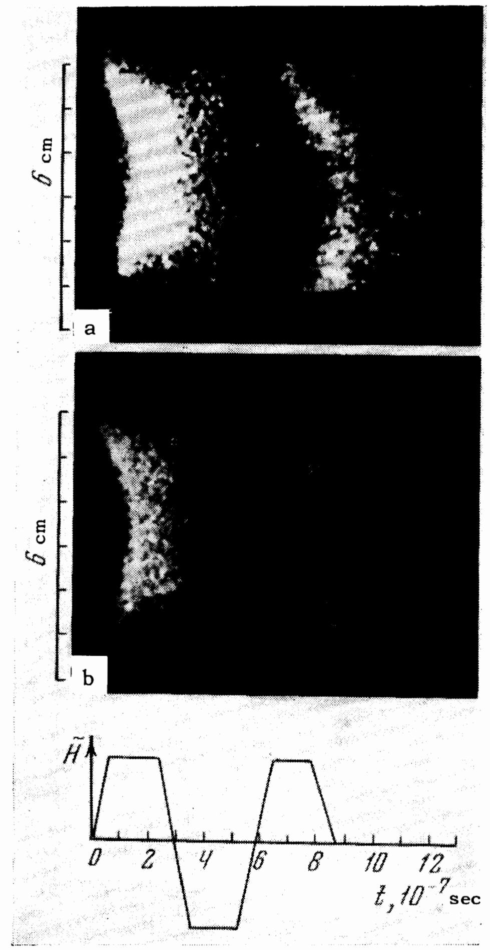

FIG. 1

Photograph 1a was obtained with normal printing exposure. Owing to the small photographic latitude of the printing paper used, the print does not show all the wave-front details present in the negative. A second print of the same negative, with a longer exposure, is shown in Fig. 1b. A rim of increased brightness along the wave front is clearly visible in it. It was this rim which was used for the estimate of the width of the front given above.

Figures 1a and 1b show also, a second compression shock wave, but no rarefaction shock wave corresponding to the negative pulse of the magnetic field.

Oscillograms of the magnetic probe signals are presented in Fig. 2, for $H_0 = 300$ Oe, $\tau_0 = (6-7) \times 10^{-8}$ sec, and $\tilde{H} = 900$ Oe. An oscillogram of the signal obtained with the discharge chamber evacuated is shown in Fig. 2a and corresponds to the derivative of the initial pulsed magnetic field in vacuum. The first (positive) pulse on it corre-

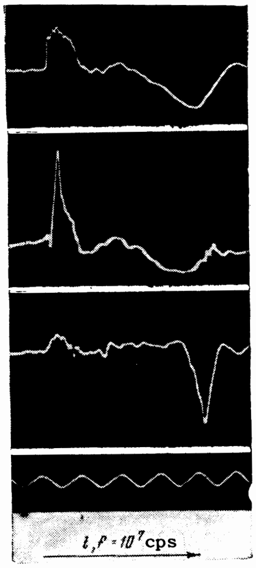

FIG. 2

sponds to the growth phase of the magnetic-field pulse, the second corresponds to the decay of the positive pulse and the rise of the subsequent negative pulse of magnetic field. It is therefore roughly double the width of the first.

The oscillograms in Figs. 2b and 2c were obtained with $n_e \sim 0.5 \times 10^{12}$ cm^{-3}. If H_0 was in the same direction as the first pulse from the artificial line, then a compression wave was first propagated through the plasma, followed by an expansion wave at the instant when the magnetic field pulse decreased. In Fig. 2b, which corresponds to this case, one can see that the slope of the compression wave front increases by at least a factor of 2.5, whereas the rarefaction wave front becomes flatter.

The oscillogram in Fig. 2c was obtained under the same conditions as in Fig. 2b, except that the direction of the constant magnetic field was reversed. In this case the first wave is the rarefaction wave and the second the compression wave.

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