EXCITATION OF STRONG COLLISIONLESS SHOCK WAVES IN A PLASMA

R. Kh. Kurtmullaev, V. K. Malinovskii, Yu. E. Nesterikhin, A. G. Ponomarenko

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Some experimental results on the excitation of strong collisionless shock waves in a plasma are presented. In this case the thickness of a shock front, propagating at right angles to an external magnetic field, is determined by cooperative processes: excitation and decay of plasma oscillations resulting from distortion and subsequent "overturning" of the wave front [1].

The condition for formation of a shock front may be written thus:

$$T < \frac{r}{V_a} \approx r \frac{\sqrt{4\pi\rho}}{H + H^\circ}. \qquad (1)$$

Here r is a characteristic dimension of the system, V_a the Alfvén velocity, T the amplitude build-up time for the variable magnetic field H°.

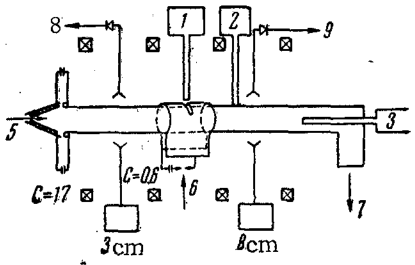

Fig. 1. Block diagram of experimental device: 1) monochromator; 2) trap; 3) scintillator and photomultiplier; 4) magnetic field coil; 5) source; 6) igniter; 7) to pump; 8, 9) to oscillograph.

The given method of exciting a shock wave is associated with collisionless heating of the plasma, during which most of the energy must be transmitted to the ions. When the amplitude of the magnetic field H° is insufficient to "overturn" the shock wave, the energy stored in it can be very effectively transmitted to the plasma, or rather its electrons, in a very short time ($t \sim 1/\omega_{0i}$), at the expense of a buildup in current instability, if the following condition is satisfied:

$$v_j \gtrsim v_0 \approx \left(\frac{2kT}{m_e}\right)^{1/2}. \qquad (2)$$

Here v_0 is the electron thermal velocity.

Conditions promoting current instability may be created not only by generating strong shock waves but also by exciting ordinary high-frequency waves of an amplitude such that criterion (2) is known to be satisfied (thus, for example, in [2], magnetoacoustic waves were excited). For heating the plasma with high-amplitude waves it is also possible to use "decay" instabilities, for example, the instability of Alfvén waves in relation to the simultaneous excitation of fast and slow magnetoacoustic waves [1]. With this method of heating, the energy of the variable magnetic field is transmitted directly to the ions (if $T_e \geq 4T_i$).

The experimental plasma was produced using a conical source working on the gas formed upon breakdown of a plexiglas insulator [3]. As shown in Fig. 1, the energy reserve of the source was determined by two capacitors $C_1 = 17$ μF charged to a voltage u = 10 kV. This energy amounted to approximately 1.5 kJ, half of which was transmitted to the plasma. The source discharge current I ~ 350 ka had a period of the order of 5 μsec and was practically damped out during the first half-period.

The plasmoid expelled from the source was transported along a glass tube 5.2 cm in diameter and 200 cm long, located in a longitudinal quasistationary magnetic field H created by discharging a bank of IM 150/5 capacitors (80 units) into two pairs of Helmholtz coils 1 m in diameter. The magnitude of H could be varied from 0 to 2 kOe with a uniformity of not less than 3% along the axis and a period of $5 \cdot 10^{-3}$ sec.

To excite shock waves in the plasmoid as it moved along the plasma guide, a copper loop was placed about one meter from the conical accelerator (length 30 cm, diameter 5.4 cm, and inductance $L^\circ \approx 10$ cm) across which a line with capacitance C = 0.6 μF and working voltage 50 kV was discharged with a controlled delay relative to the moment of triggering the source.

The period of the exciting system was 10^{-6} sec, and the ratio of the effective inductance to the total inductance $L^\circ/L_0 \approx 0.25$. The amplitude of the variable magnetic field at the axis of the turn was $7 \cdot 10^3$ Oe.

Figure 2 shows oscillograms in which the effect of triggering the exciting loop at different sections of the plasmoid is clearly seen (upper trace – signal from monochromator, H_β line; lower trace – photomultiplier signal).

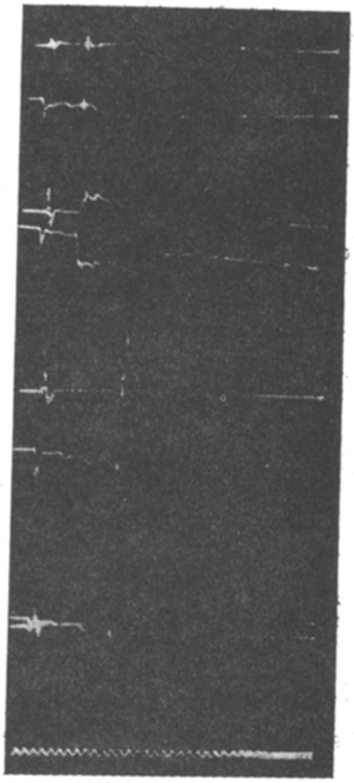

Fig. 2. Excitation of a shock wave in dense part of plasmoid. Upper trace – H_β line; lower trace – photomultiplier, u = 8 kV, calibration curve 200 kc. The frames correspond to the values: 1) u = 0, H = 0; 2) u = 40 kV, H = = 0.9 kOe, t_d = 19 μsec; 3) u = 40 kV, H = 0, t_d = 45 μsec; 4) u = 40 kV, H = 0.9 kOe, t_d = = 45 μsec.

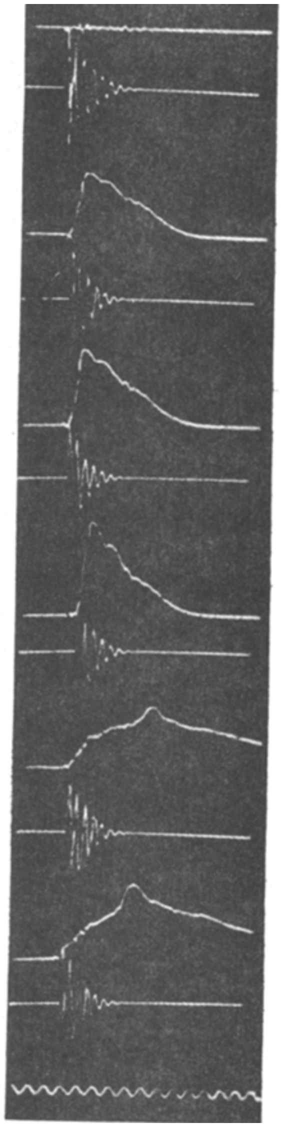

Fig. 3. Current in loop and brightness of H_α line, u = 46 kV, calibration curve 500 kc. The frames correspond to the values: 1) u = 0, H = 0; 2) u = 8 kV, H = 0, t_d = 45 μsec; 3) u = 8 kV, H = 0.9 kOe, t_d = 45 μsec; 4) u = 9 kV, H = 1.8 kOe, t_d = 45 μsec; 5) u = 8 kV, H = 0, t_d = 19 μsec; 6) u = 8 kV, H = 0.9 kOe, t_d = 19 μsec.

The charged particle concentrations in the plasmoid corresponding to the moments of the first and second shocks (oscillograms 2 and 3 in Fig. 2), measured by a double Langmuir probe, attained the respective values $n_1 \approx 5 \cdot 10^{14}$ cm^{-3} and $n_2 \approx 5 \cdot 10^{16}$ cm^{-3} (source voltage u = 8 kV). The probe was calibrated by irradiation of the plasma at wavelengths of 3 cm, 8 mm, and 4 mm.

The energy absorbed by the plasma as a result of shock wave generation, measured from the damping ratio, proved to be equal to 120 J, or roughly 70% of the energy stored in the loop (Fig. 3, upper trace – monochromator signal, H_α line; lower trace – loop current). Elementary calculations show that in this case for $n_2 \approx 5 \cdot 10^{16}$ cm^{-3} the maximum temperature to which the plasma can be heated is not more than 50-100 eV per particle. Calorimetric and diamagnetic measurements, similarly conducted [4], agree satisfactorily with these calculations.

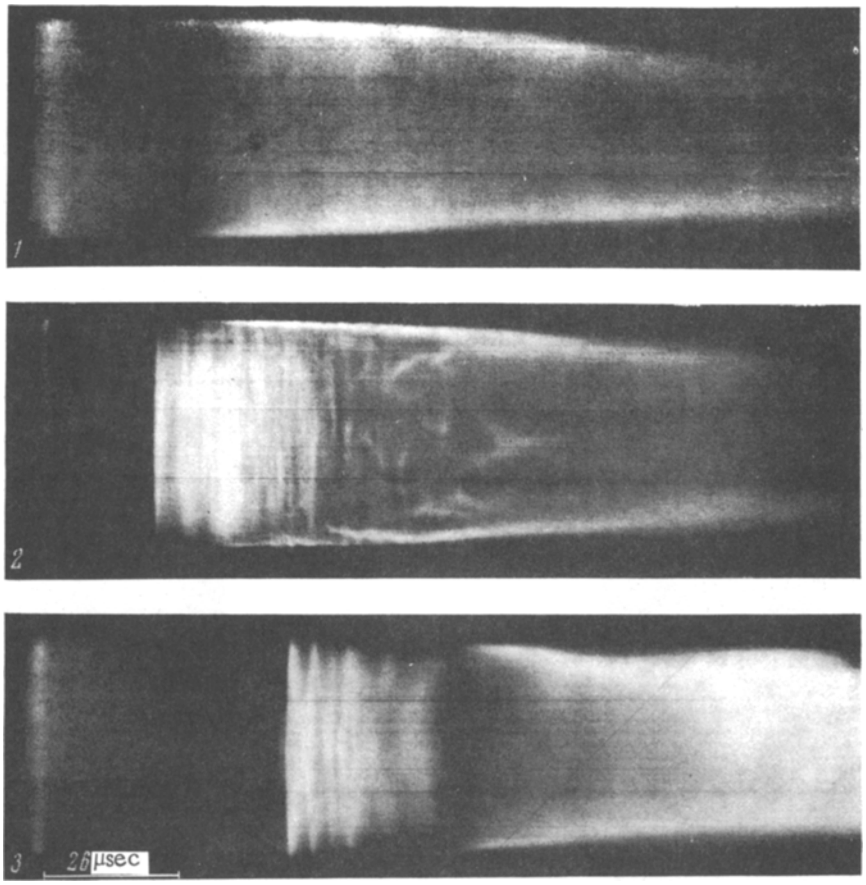

Fig. 4. High-speed photographs of a plasmoid after line discharge across exciting loop. Source voltage $u = 8$ kV, $H = 0.9$ kOe, frame 1) line voltage $U = 0$; frame 2) line voltage $U = 50$ kV, shock generation time $t_d = 20 \cdot 10^{-6}$ sec; frame 3) line voltage $U = 50$ kV, shock generation time $t_d = 46 \cdot 10^{-6}$ sec.

Figure 4 shows a series of high-speed photographs obtained through a slit located in a plane perpendicular to the motion of the plasmoid directly beyond the loop. It is easy to see that when the line is discharged, periodic oscillations, apparently magnetoacoustic, are set up in the plasma.

In order to increase the contribution of energy per particle, experiments were carried out on exciting shock waves in that part of the plasmoid where the charged particle concentration did not exceed $n = 10^{14}$ cm^{-3}. For this purpose, the source voltage was reduced to 4 kV.

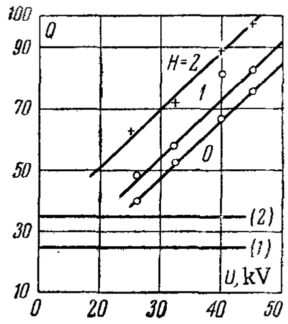

Fig. 5. Calorimetric measurements of the energy Q (joules) absorbed by the plasma at $t_d = 15 \cdot 10^{-6}$ sec, $u = 4$ kV for $H = 0, 1, 2$ kOe. Initial values of the energy of the plasmoid (1) for $H = 0$ and (2) for $H = 2$ kOe. Line voltage $U = 0$.

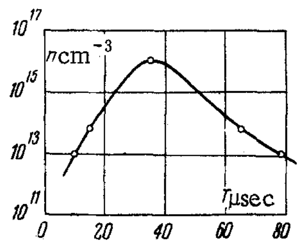

Fig. 6. Time distribution of particle density in the plasmoid under the loop, $u = 4$ kV, $H = 0.9$ kOe.

In this case, the condition for the formation and "overturning" of a shock wave was not properly satisfied, in spite of the considerable number of carbon ions in the plasma. However, calorimetric measurements (Fig. 5) showed that, as before, the plasma intensively absorbs energy stored in the loop.

Since in the regions of the plasmoids where shock waves were excited the concentration of charged particles fell by roughly a factor of 10^2, for the same energy absorption the plasma particles should have been heated up to ~ 10 kV.

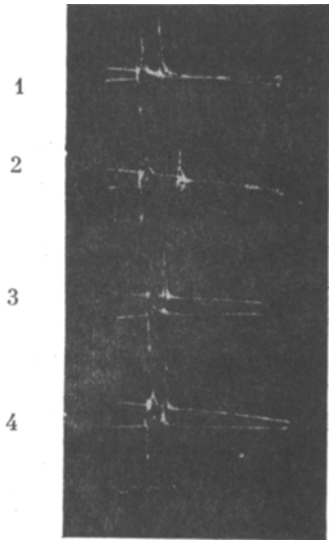

Fig. 7. X-radiation from plasma upon excitation of shock waves: u = 4 kV, U = 36 kV, H = 0.9 kOe, calibration curve 100 kc. Curves correspond to values: 1) t_d = 11 sec, one Al-foil, 15 microns; 2) t_d = 18 sec, one Al-foil, 15 microns; 3) t_d = 8 sec, one Al-foil, 15 microns; 4) t_d = = 8 sec, three Al-foils, 15 microns.

Figure 6 shows a plasmoid profile representing the time distribution of the particle density under the loop, the coordinate origin corresponding to the time of triggering conical source. Using these data, one can easily select the necessary delay time t_d that determines the moment of triggering the line.

Figure 7 gives results of X-ray measurements obtained by the standard photoelectric method (foil, crystal, photomultiplier, upper trace – X-radiation, lower trace – source current). It is clear from oscillograms 3 and 4 that three layers of aluminum foil 15 microns thick very effectively retard radiation from the plasma source itself and have only a very slight effect on the radiation from the plasmoid after triggering the line.

By means of several copper foils 40 microns thick, it was established that the X-radiation energy decreases in proportion to the increase in particle density (t_d) in the heating region.

Thus, with change in n from 10^{13} to 10^{14} cm^{-3}, the X-radiation energy fell from 80 to 25 kV (oscillograms 1 and 2 in Fig. 7), while with further increase in the charged particle concentration, $n \geq 10^{15}$ cm^{-3}, it completely disappeared.

To confirm the fact that the X-radiation appearing after excitation of a shock wave in a plasmoid is caused by heated plasma electrons incident on a scintillator covered with copper or aluminum foil, experiments were preformed with a trap located at right angles to a quasistationary magnetic field H. The collector of the trap was roughly 1 cm from the plasma boundary (Fig. 8). By varying H for different, but fixed values of t_d, we were able to ascertain the most probable energy of the heated electrons. Thus, Figs. 9 and 10 show the electron energy distribution curve for t_d = 15 sec and corresponding typical oscillograms of the trap current signals (upper trace – source current, lower trace – current at trap collector). Similar measurements of the transverse energy of the heated electrons agreed satisfactorily both with the above value for the X-radiation energy and with its dependence upon t_d.

Finally, we present an oscillogram (see Fig. 11) in which the sign of the trap current varies, evidently corresponding to an electron and an ion current flowing to the wall of the chamber.

Similar signals begin to appear with increase in the value of $t_d \geq$ 20 μsec ($n \geq 5 \cdot 10^{14}$ cm^{-3}), the contribution of the ion current becoming more and more predominant as the concentration of charged particles in this heating region increases.

Thus, clear proof of the formation and "overturning" of a shock front was not obtained even in this experiment; nevertheless, the substantial absorption of energy by the plasma will undoubtedly stimulate the further development of such experiments.

In spite of the fact that upon excitation of shock waves in the region $t_d \geq$ 30 sec, for the parameters of the given device ($n = 10^{16}$ cm^{-3}, r = 2.6 cm, $H^\circ = 0\text{-}7 \cdot 10^3$ Oe) criterion (1) was known to be satisfactorily fulfilled, the low value of the energy per particle (commensurable with the directional energy of the plasmoid) still did not permit a conclusive experiment to prove the turbulent nature of the absorption of shock wave energy by plasma particles.

The experimental results on the considerable electron heating in the region $t_d <$ 15 μsec and the gradual disappearance of X-radiation with increase in the charged-particle concentration in the plasma heating region (the energy fraction per particle is reduced) do not contradict the theory (1).

When condition (1) is not properly satisfied, the energy of the high-frequency magnetic field H° is mainly expended on heating the electrons at the shock front.

The unsatisfactory reproducibility of the results at large $t_d >$ 20 μsec did not permit us to obtain sufficiently reliable quantitative measurements for determining the most probable velocity of the heated ions. At this time, we can only state the following: Assuming that the trap registers the incidence of heated hydrogen ions, ions with an energy

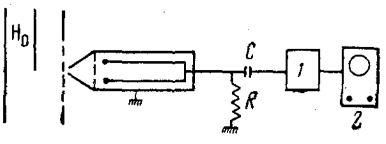

Fig. 8. Trap; R = 10^5 ohm, C = 10 μF; 1) cathod follower.

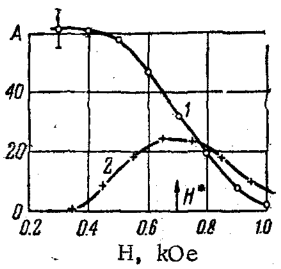

Fig. 9. Distribution of heated electrons obtained by means of a trap. A) Electron Current at collector in arbitrary units (curve 1); curve 2) derivative of the function A(H) used to find the most probable electron velocity from the relationship $v = 1.7 \cdot 10^7 H^* r$; r is the distance from collector to plasma boundary.

in the 1-3 keV range are observed at particle concentrations $n = 5 \cdot 10^{14}$ cm^{-3} in the plasmoid, while at $n \geq 10^{15}$ cm^{-3}, the energy is of the order of hundreds of volts.

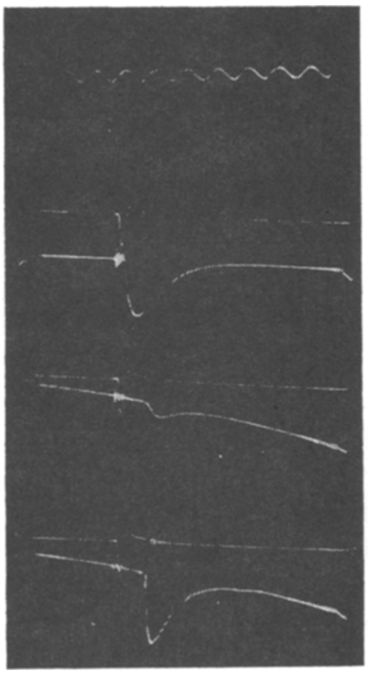

Fig. 10. Electron current at collector. u = 4 kV, $t_d = 15 \cdot 10^{-6}$ sec, calibration curve 145 kc. The oscillograms correspond to values; 1) H = 0, U = = 0; 2) H = 0.6 kOe, U = 0; 3) H = 0.6 kOe, U = 36 kV.

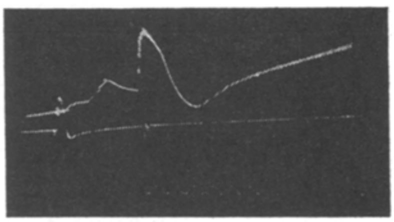

Fig. 11. Electron and ion current at trap. U = = 36 kV, u = 4 kV, H = 0.9 kOe, $t_d = 25 \cdot 10^{-6}$ sec, calibration curve 220 kc.

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