EXCITATION OF STRONG COLLISIONLESS SHOCK WAVES IN A DEUTERIUM PLASMA

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In [1] it was shown that shock waves with a front width much less then the ion mean free path can be excited in a rarefield plasma in a quasi-stationary magnetic field.

It follows from theory [2] that at least two conditions must be satisfied in order to effectively heat the ions: 1) $t < R/V$ (where t is the characteristic buildup time for the magnetic field, V_a is the Alfven velocity, and R is the transverse dimension of the chamber); 2) $H > 2-3H_0$ (H is the alternating magnetic field generating the wave, and H_0 is the quasi-stationary field).

This article gives preliminary results of experiments on heating a hydrogen plasma by strong collisionless shock waves.

The plasma was created in a glass vacuum chamber 16 cm in diameter and about 2.5 m long and confined to the system axis by magnetic mirrors (the period of the quasi-stationary field of the magnetic trap was 5 μsec, $H_0 = 0.5-2$ k$_0$e, and the mirror ratio $\alpha \sim 1.4$). The plasma was first ionized by a conical ϑ-pinch and deuterium admitted in pulses (0.1 cm^3 at $p = 500-700$ mm Hg) regulated outside the mirror configuration [3]. After a few tens of microseconds the plasma passed through the mirror and uniformly filled the volume of the magnetic trap; in the middle of this trap there was a cylindrical loop 30 cm long, which generated shock waves. A special accumulator with capacitance 0.6 mmf discharged across this loop at voltage of 60–100 kV. The alternating magnetic field on the loop axis reached 4–6 k$_0$e after ~0.3 μsec.

We studied the plasma parameters using familiar diagnostic methods: microwave probing ($\lambda = 0.4$, 0.8, and 3 cm), X-ray and neutron radiation pick-ups, and charged particle energy analyzers. High-speed photographic methods using image translators (IT) and magnetic probes [1] placed different distances from the radius made is possible to study the formation processes, the motion of the "magnetic piston," and its associated shock wave.

Since the light intensity of the deuterium plasma in the first quarter-period of discharge proved insufficient for reliable optical registeration of the initial stages of the process at the necessary range of concentrations ($n = 5 \cdot 10^{12} - 3 \cdot 10^{13}$ cm), helium was used as the working gas (a comparison of pictures taken in succession showed that the behavior of the plasma remained almost constant).

Figure 1 gives photographs of the plasma luminosity obtained through the end of the vacuum chamber by the IT. Frames 1 and 2 clearly show the evolution of the current sheet formed ("magnetic piston") exciting the shock wave whose appearance was registered by the magnetic probes.

The moments of exposure are shown on the current oscillogram (Fig. 2b) (exposure time $t \approx 15 \cdot 10^{-9}$ sec); Figs. 2a and 2c give the neutron radiation, while Fig. 2d indicates time marks of 2 μsec. The signals corresponding to the shock wave and current sheet for the oscillogram in Fig. 3a are of different polarity, since the fields H and H_0 were oppositely directed.

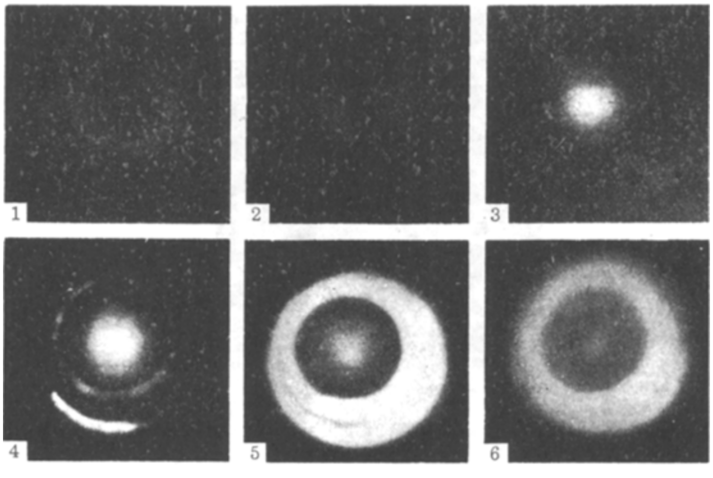

Fig. 1

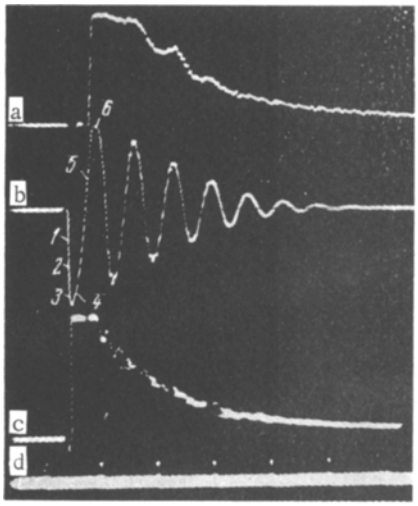

Fig. 2

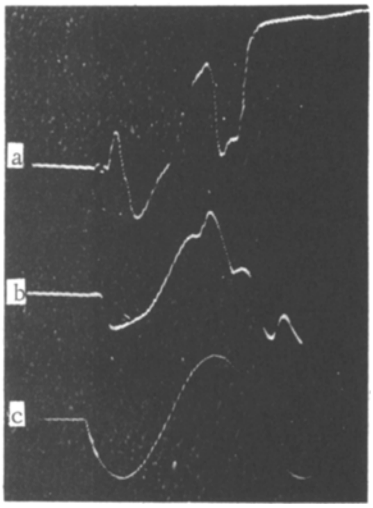

Fig. 3

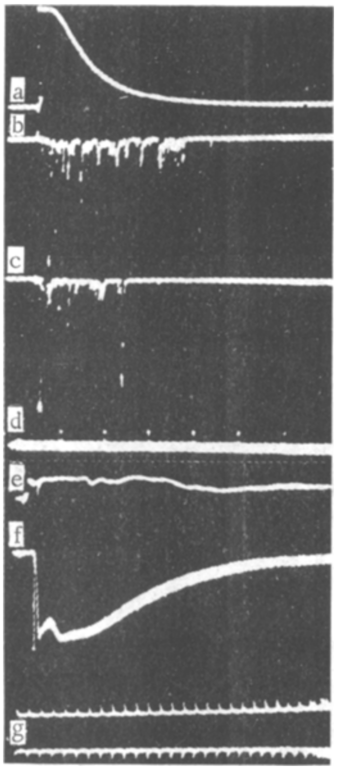

Fig. 4

Under the experimental conditions the velocity of the shock wave determined from the delay of the magnetic signals varied from 10^7–10^8 cm/sec for a front width of 1–3 cm. It became clear after processing the oscillograms and high-speed photographs that during the first quarter-period the shock wave accumulates on the chamber axis and the current sheet effectively compresses the heated plasma. The configuration of the magnetic field in the shock loop permits the plasma to flow partly along the magnetic lines of force; this apparently explains the nature of the luminosity registered in Fig. 1(frame 4).

At the beginning of the second half-period breakdown began at the chamber wall (in experiments with deuterium at a density $n \leq 10^{13}$ cm^{-3} breakdown shifted to the beginning of the third half-period) and the growing magnetic field continued to compress the plasma in the center of the chamber. When the current was a maximum, the plasma had a diameter of 2 to 3 cm (Fig. 1a, frame 6). The compression process was accompanied by neutron radiation; here, the electrostatic analyzer mounted behind the magnetic mirror stabilized the ions and electrons with a longitudinal energy of up to 15 keV (see Figs. 4a, b, and c). In experiments with a shock loop consisting of two cone frustrums making an angle of ~5° with the axis, a neutron signal appeared during the first quarter-period (Fig. 2c). Figure 3 gives an oscillogram of signals from the magnetic probes in the plasma under the loop at distances: a) 0.25R, and b) 0.7R from the chamber axis; c) current oscillogram in the shock loop T = 1.8 μsec.

The duration of neutron radiation varied in the range 15–100 μsec, the total number neutrons after discharge being 10^6–10^7. The space distribution of the neutron radiation was studied using nuclear emulsions. This made it possible to determine the longitudinal dimension of the radiation source, which turned out to be 20 cm. There were no discrepancies found in the space distribution to indicate that accelerating mechanisms were present. Photoelectric techniques (foils, crystals, photomultipliers) were used to measure the transverse electron energy. Most of the γ-quanta registered lay in the 7–10 keV energy range. Figure 4 shows the neutron radiation correlated with the readings of the charged-particle analyzer: a—n°; b—ions, 1 keV; c—ions, 10 keV; d—time marks, 10 μsec; e—"cut-off" of microwaves at λ = = 3 cm; f—X-ray radiation caused by electron drift across the magnetic field; g—time makes 50 μsec.

The experimental results confirm that ions may be intensely heated when strong collisionless shock waves are excited and the plasma is subsequently compressed by a current sheet. Optical and magnetic measurements during the first half-periods did not reveal noticeable instabilities, which, in our opinion, is extremely important in explaining the neutron formation mechanism. The ion temperature, computed assuming a thermonuclear formation mechanism for neutrons, was ~10 keV for $n \leqslant 10^{13}$ cm^{-3} which is in agreement with data obtained by the charged particle energy analyzer and magnetic probes.

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