Collisionless shock wave in a supersonic plasma stream with $\beta \simeq 1$

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Experiments have been carried out on the formation of a collisionless shock wave as a supersonic plasma stream with $\beta \approx 1$ is stopped in a nonuniform magnetic field.

Questions of the dynamics of high-energy, supersonic plasma streams in nonuniform magnetic fields are of major interest in several applications.

Most of the corresponding theoretical and experimental research has been carried out for collisional plasma, with $L \gg \lambda_{ii}$ (L is the length of the plasma, and λ_{ii} is the ion mean free path), and with $\beta \ll 1$ ($\beta = 8\pi P/H_e^2$, where P is the plasma pressure, and H_e is the external magnetic field).[1]

The recent development of high-power plasma accelerators[2] sets the stage for producing high-energy plasma streams with $\beta \simeq 1$, which are generally collisionless.

In this letter we report an experimental study of the dynamics of a supersonic collisionless plasma stream with $\beta \simeq 1$ in a magnetic field which increases along the path of the stream.

The experiments were carried out in the MK-200 apparatus (Fig. 1), which is an electrodynamic plasma accelerator with pulsed gas injection.[3] The accelerator is supplied by a capacitor bank with $C_0 = 1150\ \mu\text{F}$ at a working voltage $U_0 = 20$ kV. The vacuum chamber of the accelerator is connected to a thin-walled metal liner 30 cm in diameter, in which a system of multiturn solenoids produces a quasisteady magnetic field of special profile (Fig. 2a).

The diagnostic complex includes diamagnetic probes for measuring the plasma pressure, a system of magnetic probes for measuring the internal magnetic field in the stream, x-ray diagnostic apparatus (which works by the filter method) with temporal and spatial resolution for measuring the electron temperature, neutron detectors with temporal and spatial resolution, and a Mach-Zehnder interferometer with a laser light source ($\lambda = 6945$ Å) for measuring the plasma density.

The characteristics of the stream of deuterium plasma from the accelerator were measured in a region of uniform field in the cross section of probe II. The plasma density was found to be $n \approx 1.8 \times 10^{15}\ \text{cm}^{-3}$, the ion temperature $T_i \approx 0.85$ keV, and the electron temperature $T_e \approx 100\ \text{eV} \ll T_i$; we also found $\beta \simeq 1$. The plasma radius, the velocity, and the Mach number at the front of the stream were $R_p \approx 6$ cm, $v_0 \approx 5 \times 10^7$ cm/s, and $M_0 \approx 1.8$; these values decreased monotonically along the length of the stream. The characteristic time for ion-ion collisions under these conditions is $\tau_{ii} \simeq 60\ \mu\text{s}$, considerably longer than the transit time $L/v_0 \simeq 10\ \mu\text{s}$ (L is the length of the plasma duct). In other words, the stream is collisionless.

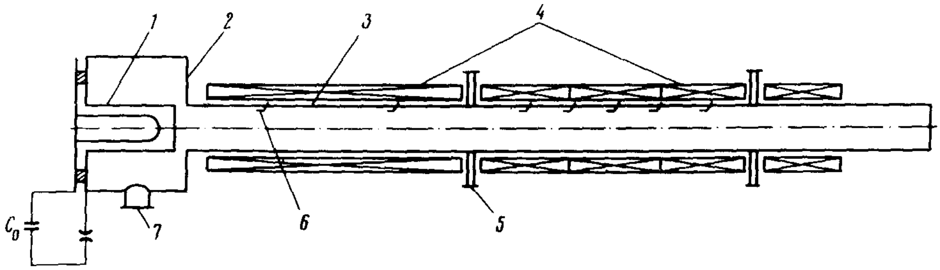

FIG. 1. The experimental apparatus. 1—MK-200 accelerator; 2—vacuum chamber; 3—liner; 4—solenoids; 5—diagnostic windows; 6—diamagnetic probes; 7—vacuum pump.

Figure 2b shows the shape of the plasma stream in the plasma duct as reconstructed from the signals from a sequence of seven diamagnetic probes, at various times. We see that the front of the stream is moving at $v_0 \approx 5 \times 10^7$ cm/s and undergoes a monotonic radial contraction as it moves in the increasing magnetic field. The contraction of the stream results in a heating of both the ions and the electrons, but the condition $T_e \ll T_i$ prevails throughout the process. At the field maximum (at the cross section of probe VII) the plasma properties reach $T_i \approx 1.5$ keV, $T_e \approx 350$ eV, $R_p \approx 3.5$ cm, and $n \approx 7 \times 10^{15}$ cm^{-3}.

The dynamics of the rest of the stream is different. Here the radius increases

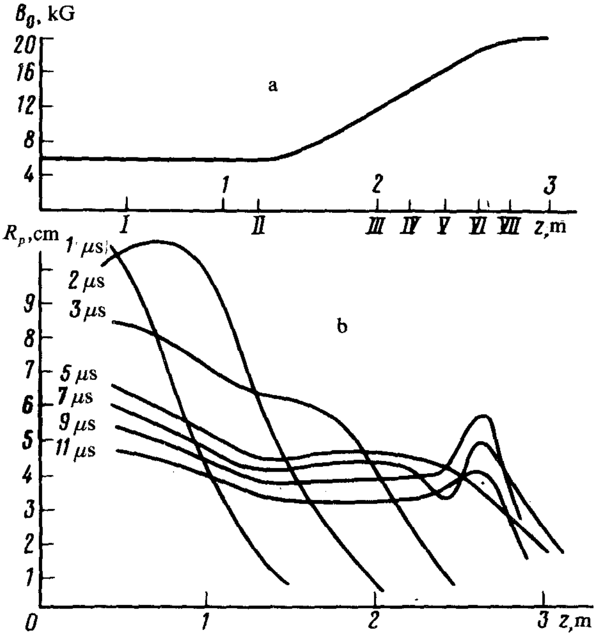

FIG. 2. a: Distribution of the vacuum magnetic field $B_0(z)$ in the liner. I–VII—Cross sections with diamagnetic probes. b: Shape of the plasma stream, $B_0(z)$, at various times. Here $t = 0$ is the moment at which the stream enters the plasma duct.

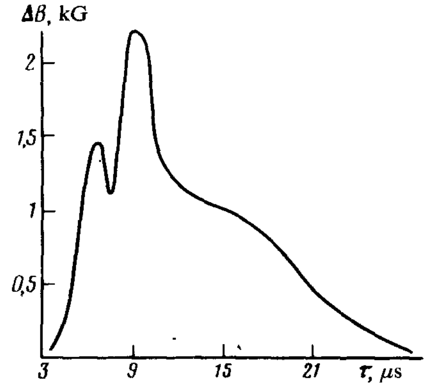

FIG. 3. Oscilloscope trace of the output signal from probe VI.

sharply as the stream moves through the region of increasing field ($t = 7\ \mu s$ in Fig. 2b), as is demonstrated most clearly by probe VI (Fig. 3). The first peak on the oscilloscope trace corresponds to the front of the stream and is detected by all the probes. The second peak appears only when the tail of the stream moves in the region of increasing fields; it is totally absent from the signals from the first and second probes. Although the increase in the radius of the stream does not lead to any significant increase in the plasma pressure ($\Delta P/P \ll 1$, since $R_p \ll R_1$, where R_1 is the liner radius), the thermal energy density per unit length of the stream, $\epsilon = \frac{3}{2}\pi R_p^2 P$, increases by a factor of more than two in this region. This fact is evidence of an effective dissipation of the kinetic energy of the stream, i.e., of the formation of a collisionless shock wave. According to the measurements, the shock forms in a cross section where the Mach number is $M \simeq 1$, as it would in an ordinary hydrodynamic flow,[4] but at $\beta \simeq 1$ the flow behind the wavefront is more complicated. The heating of the plasma disrupts the balance between the magnetic pressure and the gas pressure and causes a significant expansion of the stream, so that the flow behind the front is two-dimensional. The width found experimentally for the relaxation zone (at $t = 7\ \mu s$ in Fig. 2b) is $\delta \simeq 10$ cm. This value cannot, however, be unambiguously associated with the width of the shock front, which should be nonplanar in this situation.[5]

The formation of a collisionless shock wave under these experimental conditions, with $T_e \ll T_i$, can be attributed to the onset of the firehose instability. This instability is driven by an anisotropy of the plasma pressure which arises during the compression of a collisionless plasma stream, as was first pointed out in Ref. 6. Under the condition[7] $l/r_{\omega_i} M_0 \gg 1$ (r_{ω_i} is the ion Larmor radius, and l is the characteristic dimension of the field gradient), the stream becomes hydrodynamic, so that a shock wave forms at[8] $M \simeq 1$. Under these experimental conditions we have $r_{\omega_i} \approx 1.0$ cm, and the inequality above holds. According to Ref. 7, the width of the shock front should be $\delta \sim 10 r_{\omega_i} \simeq 10$ cm in this case, and this conclusion is consistent with the experimental data.

Evidence for well-developed turbulence comes from the anomalous value of the magnetic-field diffusion coefficient behind the shock front: $D = 1.6 \times 10^7\ \mathrm{cm^2/s} > D_B$, where D_B is the Bohm coefficient.

The corresponding effective mean free path of the ions in this region is $\lambda_{ii} \sim D / v_T \approx 0.5$ cm $\approx r_{\omega_i}$,

Although the formation of a collisionless shock wave in a supersonic plasma stream as the stream is compressed in an exit cone places an upper limit on the degree of compression that can be achieved by this method; it allows this mechanism to be used for effective plasma heating.

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