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Influence of Reflected Ions on the Magnetic Structure of a Collisionless Shock Front*

P. E. Phillips and A. E. Robson
Center for Plasma Physics and Thermonuclear Research, The University of Texas at Austin, Austin, Texas 78712
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A special probe has been used to detect ions reflected from a collisionless shock wave propagating perpendicular to the field in a magnetized, low-β plasma. Reflected ions are observed only above a critical Alfvén number $M_A \approx 2.7$, and their orbits coincide with the familiar "foot" on the magnetic structure of supercritical shocks. We discuss the origin of the reflected ions.

It is well known that the magnetic profile of a shock wave propagating perpendicular to the field in a magnetized low-β plasma undergoes a distinct change of shape when the Alfvén number M_A (shock velocity/Alfvén speed) is increased above a critical value M_A^* of about 3.[1-3] For $M_A<M_A^*$ the magnetic field makes a simple monotonic jump of width $\sim(7-10)c/\omega_{pe}$, while for $M_A>M_A^*$ a double structure develops in the shape of a "foot" or "pedestal" extending out in front of the main jump. The height of the foot relative to the total jump increases with M_A, but the length remains approximately constant at $\sim 2c/\omega_{pi}$.

A critical Alfvén number also occurs in the hydromagnetic theory of shock waves in plasma. For $M_A< 2.7$ continuous steady-state solutions of the fluid equations can be found connecting upstream and downstream states with resistivity as the only dissipative mechanism. For $M_A> 2.7$ discontinuities arise unless additional dissipative mechanisms are invoked.[4,5] It is reasonable, therefore, to associate the observed change of structure at $M_A\sim 3$ with the onset of a nonresistive dissipative mechanism in the shock.

The reflection of a small fraction of ions from the shock front can provide such a mechanism[6-8] and would also cause a perturbation of the magnetic structure ahead of the shock.[9,10] Indirect evidence of counterstreaming ion flow when $M_A>3$ has been obtained from energy analysis of charge-exchanged neutral atoms received at the wall of a shock tube.[2] The Doppler shift of ion lines has also been used to detect ions reflected from the magnetic piston in a θ pinch.[11] In this Letter we describe a direct measurement of ions reflected from a supercritical shock front, and show that their orbits coincide with the foot region of the magnetic profile.

The experiments were performed in a 45-cm-diam tube in which a hydrogen plasma of density 5×10^{14} cm^{-3} and initial temperature ~1 eV is produced by an oscillatory axial discharge. The plasma is magnetized with a uniform axial field of up to 1000 G. Shock waves with $M_A\sim 2$ to 5 are produced by applying a rapidly rising magnetic field to the outside of the plasma by means of a short θ-pinch coil wrapped around the midplane of the tube. The apparatus, which has been described elsewhere,[12] was originally designed for the study of oblique shocks, but on the midplane where the shock is traveling perpendicular to the ambient field, shock structures characteristic of perpendicular propagation are observed.

Simultaneous measurements were made at 8 cm radius with three different types of probe. A single-loop magnetic probe gave the magnetic

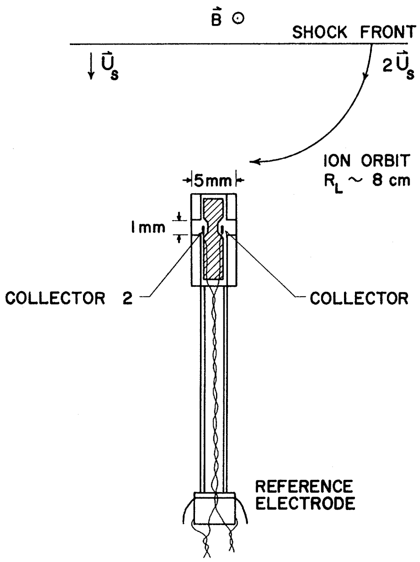

FIG. 1. Details of the ion probe. The stainless-steel collector electrodes are mounted on an insulating support and surrounded by a glass sheath. The reference electrode is 8 cm below the collector.

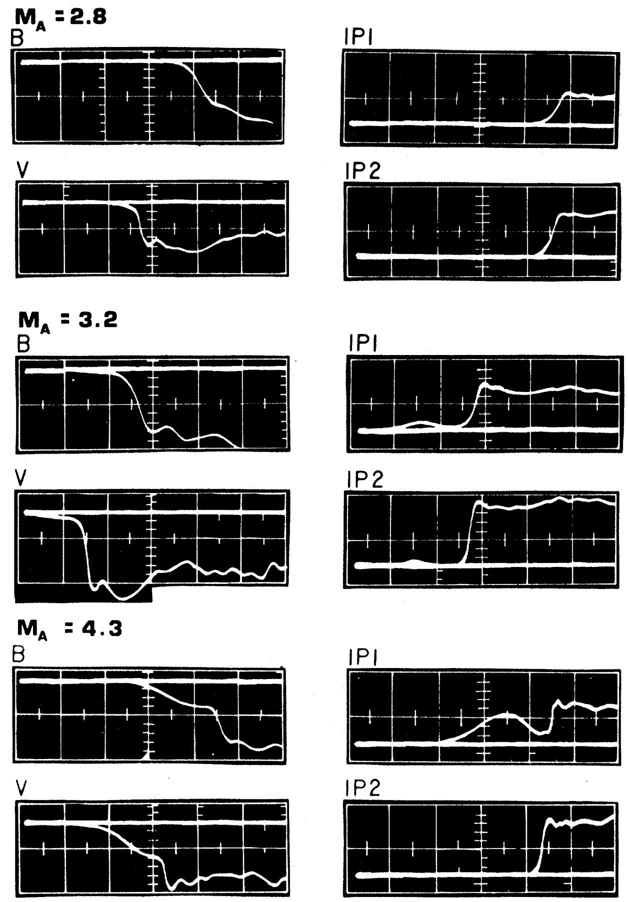

FIG. 2. Oscilloscope traces from the multiple probe assembly for three different Alfvén numbers. Each case shows synchronized traces from the magnetic probe (B), the electric probe (V), and each electrode of the ion probe. Note that the B and V traces are shown inverted; the field and potential both increase in going from front to back of the shock. The displacement of the V and B traces is used to measure the shock velocity. Time scale, 50 nsec/cm.

structure, an electric probe gave the electric potential structure, and a special probe was constructed to detect ions reflected from the shock front. This probe is shown in Fig. 1. The probe was aligned so that reflected ions could only enter the hole over collector 1, but because of their large orbits could not enter the hole over collector 2. The two collectors were biased 100 V negative with respect to the unshocked plasma potential, and so collected the ion saturation current from the plasma, greatly attenuated by the holes in the outer glass sheath. All three probes were within a centimeter of the midplane: The electric probe was offset 1 cm in the radial direction ($r = 9$ cm) and was used in conjunction with the magnetic probe to measure the shock velocity at each shot. The electric probe consisted of a 0.5-mm-diam platinum sphere supported on a 0.5-mm-o.d. glass-sheathed wire. The probe was unbiased and connected to a circuit of 185 Ω impedance, which measured its potential relative to a reference electrode in the unshocked plasma. As in previous experiments[1,12] this probe is assumed to measure the plasma potential.

Keeping the shock velocity approximately constant at 2×10^7 cm/sec, M_A was varied by varying the initial field. Signals from the probes as M_A was increased are shown in Fig. 2. A signal was received on both collectors of the ion probe when the shock front passed over it; for $M_A < 2.7$, the two signals were identical and are attributed to the increase in the ion saturation current as the density and temperature increase through the shock. For $M_A > 2.7$, the characteristic foot structure appeared on the magnetic and electric probe traces, and an additional positive current was recorded in this region by collector 1. This current was in the opposite direction to $\nabla\times\vec{B}$, and we attribute it to ions reflected from the shock. With the initial and driving magnetic fields reversed, the positive current appeared only on collector 2.

In the frame of reference in which the shock is at rest, a reflected ion performs a cycloidal orbit in the upstream magnetic field $\vec{B}$ and the Lo-

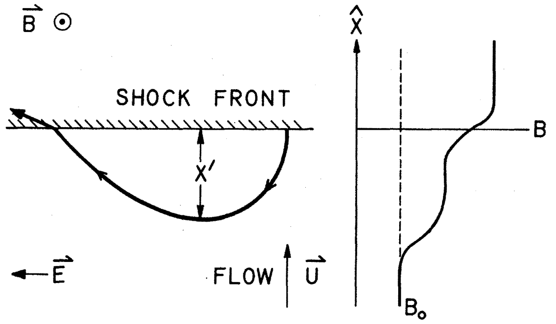

FIG. 3. Trajectory of a reflected ion compared with the structure of the magnetic field through the shock.

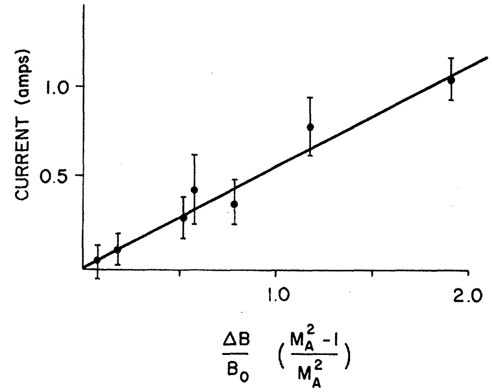

FIG. 4. Current to the ion probe as a function of the ratio of the magnetic field jump in the foot, ΔB, to the initial field B_0. The points from left to right correspond to $M_A = 3.0$, 3.3, 3.6, 3.8, 4.4, and 5.7, respectively.

rentz electric field $\vec{E} = -\vec{u}\times\vec{B}$, where $\vec{u}$ is the shock (flow) velocity (Fig. 3). The orbit is described by

$$x = u(\omega t - 2\sin\omega t)/\omega, \quad z = 2u(\cos\omega t - 1)/\omega,$$

$$\omega = eB_0/Mc,$$

where u is in the x direction, B is in the y direction, and M is the ion mass. The distance of the turning point from the shock is

$$x' = -0.68u/\omega = -0.68M_A c/\omega_{pi}.$$

If the upstream magnetic field B_0 has been increased in the foot to a value $B_f = (1+b)B_0$, the above expression must be reduced by the factor $1+b$. In the range $M_A \sim 3$ to 5, b is found from experiment to go from 0.1 to 1.0, hence the distance of the turning point is approximately constant at $\sim 2c/\omega_{pi}$, which corresponds to the observed length of the foot.

At first sight it might appear that the current of reflected ions, being diamagnetic, should decrease the field within their orbits. Woods[10] has developed a rather elaborate theory in which through the action of instabilities the current of reflected ions is neutralized by electrons, and the foot is created by a counter current of slow plasma ions. Our observation of an unneutralized reflected ion current does not support this theory. A simpler model due to Wong[9] attributes the increased field in the foot to an increased density of adiabatic electrons in the flow, which in turn arises from the need to preserve charge neutrality in the presence of the reflected ions. A complete treatment requires both the diamagnetic current of the ions and the effect of the density perturbation on the flow electrons to be taken into account; this will be given in a subsequent paper, but for the present we will simply quote the result, obtained in the approximation of small f and b, that

$$b = fGM_A^2/(M_A^2 - 1),$$

where f is the fraction of ions reflected, and G is a factor of about 6.

In Fig. 4, we show the reflected ion current recorded by the probe as a function of $b(M_A^2 - 1)/M_A^2$. The functional relationship above appears to hold up to $b \sim 2$, but difficulties in calibration of the probe prevented us from verifying the coefficient G.

Let us now speculate on the origin of the reflected ions. Because of the finite ion temperature of the upstream plasma (taken to be equal to the measured electron temperature of 1.1 eV) a small fraction of the ions in the flow will be unable to surmount the potential across the shock. For example, from the measured potential jump at $M_A = 3.8$, we estimate that a fraction $f = 0.03$ of the ions would be reflected. From the height of the foot, on the other hand, we would estimate $f = 0.08$. More significant, however, is the behavior of the potential jump with increasing Alfvén number. The potential jump measured by the electric probes was compared with the potential required to slow down the ions to their downstream velocity, obtained from the conservation relations. For $M_A < 3$ the two agree, as is to be expected in a purely resistive shock. (Note that this correspondence also supports the assumption that the electric probe measures the plasma potential.) However, for $M_A > 3$ the potential is less than is required to slow the ions, while the current of reflected ions *increases*. This indicates that the ions are not being reflected by the macroscopic potential jump across the shock.

In the fluid model of shock structure a sonic subshock, decoupled from the magnetic field and limited only by viscosity, is found at the rear of the magnetic transition when $M_A > M_A^*$.[12] In a collisionless plasma the structure of the subshock will be determined by the dispersion due to charge separation, and it will become a trailing, oscillatory ion-sound wave train.[13] The wave train, being on the scale of the Debye length, cannot be resolved by our electric probe, but the ions will now be reflected from the first potential maximum, which will be greater than the mean potential recorded by the probe. The amplitude of the wave train increases with increasing M_A, resulting in an increasing fraction of reflected ions, as we observe. The reflection of ions in turn will decrease the wave amplitude, and a balance will be achieved in which the number of reflected ions is determined by the energy and momentum balance in the shock. Each reflected ion gains enough energy in the E_z field to surmount the potential barrier and enters the downstream flow with several times its upstream flow energy (Fig. 3). The reflection of ions thus provides a collisionless mechanism for converting flow energy into internal energy of the downstream plasma ions. Since the length of the foot corresponds to the unimpeded orbit of a reflected ion, we conclude that the ions experience little or no collective interaction in traversing the foot region.

Measurement of the downstream electron temperature in this[14] and other[15,16] experiments has shown that for $M_A > M_A^*$ a decreasing fraction of the available shock energy goes into the electrons, and so, by inference, an increasing fraction goes into the ions. Although neither the accuracy of the measurements nor the state of development of the theory permits critical comparison, it seems that this energy can be accounted for by the reflection of ions in numbers consistent with the observed foot on the magnetic profile.

Valuable discussions with H. V. Wong and A. B. Macmahon are gratefully acknowledged.

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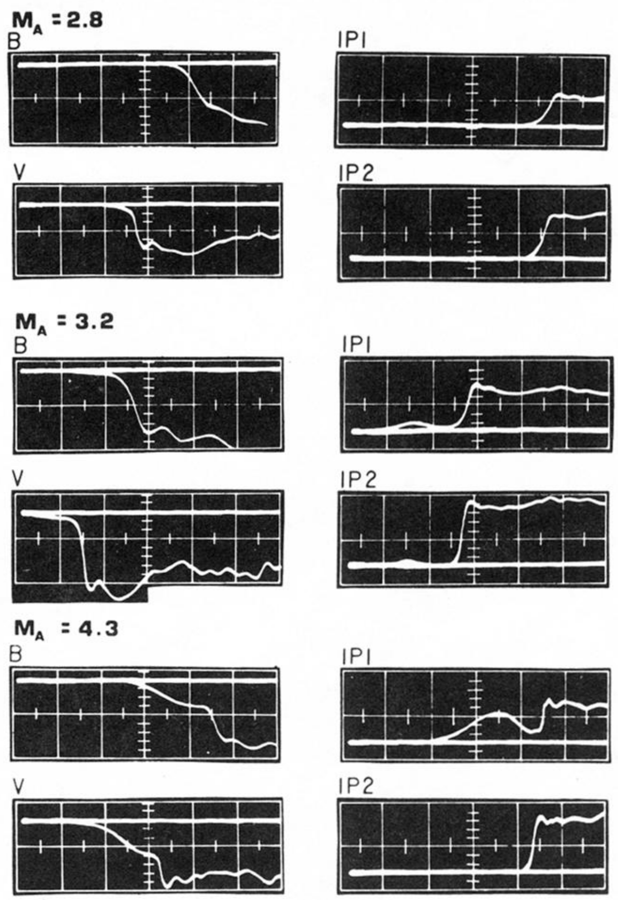

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