Observation of deuteron acceleration in a collision of magnetosonic shock waves in a plasma

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(Submitted 28 April 1992)
Pis'ma Zh. Eksp. Teor. Fiz. **55**, No. 12, 689–691 (25 June 1992)

An acceleration of deuterons has been observed experimentally during the collision of two quasiperpendicular magnetosonic shock waves at a fixed angle. Possible mechanisms for an injection of ions into a regime of acceleration along the magnetic field are analyzed.

Problems concerning the generation of fast protons and heavy ions in space,[1] on the one hand, and the need to increase the rate at which particles can be accelerated in the laboratory, on the other, are driving a search for unconventional acceleration methods involving the excitation of waves of various types in plasmas.[2]

In a previous study[3] we worked from the properties of collisionless magnetosonic shock waves[4] to propose an idea for accelerating positively charged ions by a "traveling" electric field. This traveling field would be generated by two colliding collisionless shock waves and would be directed along the magnetic field (Fig. 1). When the collision angle θ is chosen correctly, the particle being accelerated would be at rest in the coordinate system moving with the wave collision region, while in the laboratory system it would be moving at a velocity $V \simeq V_F/\sin\theta$ under the influence of the field $E_Z = 2E_0 \sin\theta (Z \| H_0)$. In this scheme there are no restrictions on the value of the product ρH (ρ is the Larmor radius of the ion being accelerated, and H is the magnetic field), in contrast with other mechanisms for accelerating ions at the front of a collisionless magnetosonic shock wave, in which the particle is moving perpendicular to H.

The present experiments were carried out in a ceramic chamber (18 cm in diameter with a length $L = 150$ cm). Two high-velocity streams of deuterium plasma were produced in a high-power discharge ($P \leqslant 200$ MW) in crossed fields $\vec{E} \times \vec{H}$. These streams were directed opposite each other and in directions tranverse with respect to the magnetic field ($H_0 \sim 2 \times 10^4$ G). They excited magnetosonic perturbations[5,6] with a long front ($\leqslant 10$ cm; the front was parallel to H_0) in the background plasma. Two pairs of plane electrodes were positioned at an angle ~6° with respect to the magnetic field lines. The angle at which the two collisionless magnetosonic shock waves collided was found to be $\theta \simeq 12°$ in a calculation which incorporated the magnetic field configuration.

During a perturbation by a single quasiperpendicular collisionless magnetosonic shock wave in a deuterium plasma (with $n_0 \simeq 10^{14}$ cm^{-3}, $T_0 \simeq 2$ eV, an Alfvén Mach number $M_A \simeq 1.2$, and an initial field $H_0 \simeq 10^4$ G), the field component E_Z was close to zero. This component was measured by floating probes oriented along the magnetic

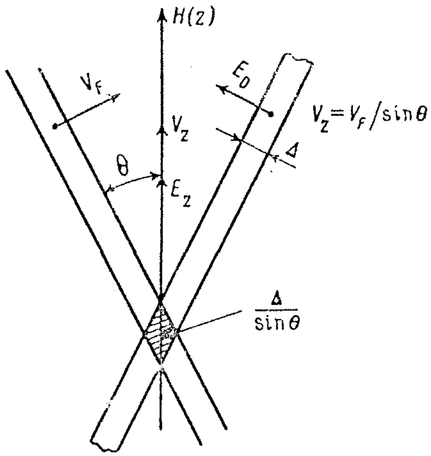

FIG. 1. Schematic diagram of the experiment.

field. In a drift tube (which was coaxial with the discharge chamber and which had a guiding magnetic field), bunches of fast particles with a velocity $> V_F$ were observed over a baseline ~50 cm. After these bunches we detected a flux of slow particles with a continuous spectrum (Fig. 2a). The wave potential φ (measured by probes oriented perpendicular to H_0) and the jump in the magnetic field had a characteristic structure with a precursor front.

In the case in which two waves collided, we detected a "traveling" electric field of a quasiwave (the collision region) along the magnetic field. The potential of this traveling field was $\varphi_Z > 2E_0\Delta \sin\theta$ (Δ is the front width). This potential was in the

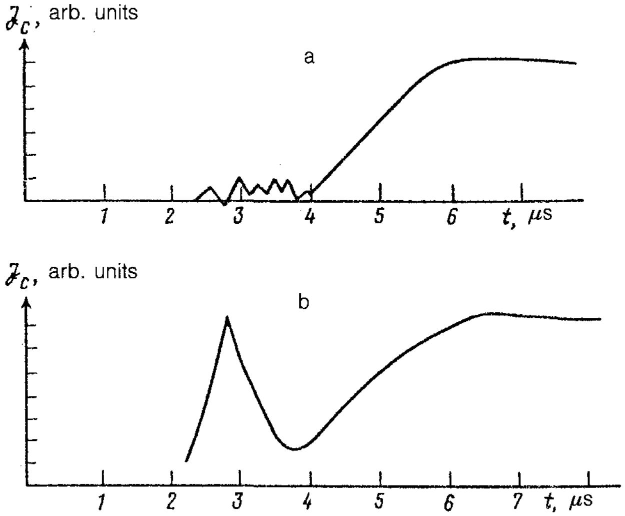

FIG. 2. Time evolution of the collector current.

range $\varphi_0 < \varphi_2 \leqslant 2\varphi_0$. The end collector detected a current pulse of fast deuterons (Fig. 2b) which was correlated with the appearance of the field E_2. The velocity of these deuterons was higher than that during excitation of a single wave.

Some further experiments were carried out to measure the energy of the accelerated deuterons by an induced-activity method. A boron nitride target—a disk 29 mm in diameter and 1 mm thick—was placed 1.5 m from the discharge chamber at the end of the drift tube. A metal collector at the center of this disk measured the current characteristics of the accelerated beam. Two NaI spectrometers, connected in a coincidence circuit, detected γ rays from the annihilation of β^+ particles in the target material from the reaction ${}^{14}\mathrm{N}(d,n){}^{15}\mathrm{O}$ (${}^{15}\mathrm{O} \to \beta^+$, $\tau_{1/2} = 123$ s). The reaction was identified from measurements of the ${}^{15}\mathrm{O}$ decay curve. The efficiency at which β^+ particles were detected by the γ-γ coincidence spectrometer was measured with the help of a calibrated ${}^{22}\mathrm{Na}$ source. The energy of the accelerated deuterons was determined by comparing the yield of the reaction ${}^{14}\mathrm{N}(d,n){}^{15}\mathrm{O}$, measured by an apparatus with an energy dependence, with the yield for the same reaction found on a tandem Van de Graaf accelerator.[7] This energy was found to be 12 ± 0.5 MeV. The total number of deuterons which passed through the target was $\sim 5 \times 10^{10}$. The error in the determination of the energy was a consequence of the inexact values of certain characteristics of the apparatus (e.g., the extent to which the deuteron beam was neutralized).

Calculations show that, in order to reach the energy found experimentally in the collision of two collisionless magnetosonic shock waves at a fixed angle $\theta \sim 12°$, the initial energy (the injection energy) of the particles moving along the direction of the acceleration vector ($\| H_0$) would have to be $\epsilon_0 \geqslant 1.6 m_d V_F^2$ (for our experimental conditions, with $V_F \sim 10^8$ cm/s, this energy would have to be $\epsilon_0 \simeq 60$ keV). Over an acceleration baseline < 10 cm, the deuterium ions can be accelerated to $\epsilon_{\max} \geqslant 18 m_d V_F^2$ (~ 1 MeV) if the width of the region occupied by the accelerating electric field is $\sim \Delta/\sin\theta$, where $\Delta \simeq C/\omega_{ep}\sqrt{2(M-1)}$, and ω_{ep} is the electron plasma frequency.[4] The source of the particles with the initial energy ϵ_0 required here might be each of the colliding waves, since Altyntsev *et al.*[8] have shown experimentally that it is possible to accelerate particles ($\perp H_0$) to an energy $\leqslant 2 m_i V_F^2$ at the front of a collisionless shock wave. During subsequent elastic scattering by irregularities of the magnetic field, with a length scale comparable to the Larmor radius of the accelerated particles, these particles might be captured into a regime of acceleration along the magnetic field. The presence of a so-called precursor front in the structure of a collisionless shock wave (this precursor front is usually associated with the pressure of fast particles accelerated at the front of the collisionless shock wave[9,10]) and the detection of fast particles which are moving along the magnetic field during excitation of one wave seem to support the idea that this mechanism for the injection of particles with the necessary initial energy is operating. We note in conclusion that estimates of the limiting capabilities of this acceleration mechanism involving the collision of two collisionless magnetosonic shock waves show that the acceleration rate might reach ~ 1 GeV/m.

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Translated by D. Parsons