Mechanism for ion acceleration in a collision of magnetosonic shock waves

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It has been shown experimentally that hydrogen and deuterium ions can be accelerated to high energies along a magnetic field in a collision of two quasiperpendicular magnetosonic shock waves. The energy spectrum of the accelerated ions was measured by a time-of-flight system. The maximum energy of the accelerated ions is ~10 MeV. The acceleration distance is $\leqslant 8$ cm. Possible mechanisms for the acceleration of ions to high energies along a magnetic field are discussed. © *1995 American Institute of Physics.*

In Refs. 1 and 2 we showed theoretically and experimentally that ions can be accelerated by a "traveling" electric field generated by two colliding quasiperpendicular magnetosonic shock waves with field vectors directed along the magnetic field. In this case the synchronization condition is satisfied by varying the initial collision angle (θ_0) of the two magnetosonic shock waves in such a manner that the particle being accelerated is at rest in the reference frame of the collision region, while in the lab frame it is moving at a velocity $V_f/\sin\theta(Z)$ under the influence of an electric field $2E_0\sin\theta(Z)$ (V_f is the velocity of the front of the magnetosonic shock wave, E_0 is the electric field at the front of this wave, θ is the angle between the front and the axis $Z\|H_0$, and H_0 is the initial magnetic field). This idea was verified experimentally by experiments on an apparatus described in detail in Ref. 2 under the condition that the angle θ was held constant. Deuterons were accelerated to an energy $\leqslant 1$ MeV on that apparatus. However, the induced-activation method used to determine the energy in those experiments was incapable of studying the correlation between the parameters of the beam of accelerated ions and dynamic processes in the plasma in each acceleration cycle. It was thus not possible to study the efficiency of this new acceleration mechanism. By the "efficiency" of the acceleration mechanism we mean the product $\varepsilon_{\text{max}}N$, where ε_{max} is the maximum energy of the accelerated particles, and N is the number of particles in a pulse.

The experiments also showed that placing any detector (magnetic, electrostatic, etc.) in the wave-collision region causes a nearly complete blocking of the acceleration of ions along the magnetic field. In further experiments we accordingly used a time-of-flight method, with optical and scintillation detectors outside the collision region. Two photodetectors (with a spatial resolution ~1 mm) were placed in the discharge chamber to detect the emission from the plasma excited by the electric field of the shock front. These detectors could be moved along and across the magnetic field. At the beginning and end

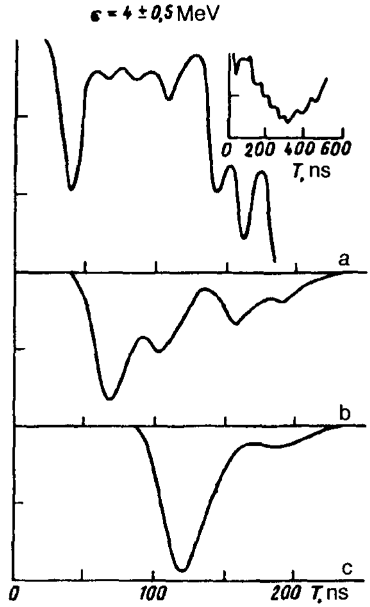

FIG. 1. Oscilloscope traces of pulses from the detectors. a—Optical pulse; b—transmitted scintillation pulse; c—final scintillation pulse.

of the ion guide (100 cm long, with a guiding magnetic field ~0.3 T), we placed polystyrene scintillators. The light from these scintillators was transferred by optical fibers to photomultipliers. The first scintillator (5 mm in diameter, 1.5 mm thick) overlapped part of the beam of accelerated ions. The second scintillator (15 mm in diameter, 1.5 mm thick) overlapped the rest of the beam. It was assumed that the energy of the accelerated ions varied only slightly over the beam cross section. An aluminum film, 8 μm thick, shielded the scintillators from light and also from slow ions and electrons (the threshold in terms of the energy of deuterons was 0.75 MeV).

Comparison of the time intervals between the signals from the scintillators and from the photodetectors clearly revealed a correlation between the ion acceleration process and the plasma glow in the wave-collision region (Fig. 1). By moving a photodetector along the magnetic field and by detecting the plasma glow in the collision region, we estimated the distance over which acceleration could occur: ~8 cm.

The energy of the accelerated ions was determined from the time of flight over two intervals: 170 cm, which is the distance between one photodetector and the scintillator detectors, and 100 cm, which is the distance between the scintillation detectors. Within the measurement errors (±1 MeV for an energy of 10 MeV), the energies found for these two intervals agree well with each other. The energy of the accelerated deuterons varied from pulse to pulse over the range 3–10 MeV. The number of accelerated particles at the final scintillation counter was determined from the following information: data from a calibration of the photomultipliers with the help of a light-emitting diode, in photoelectrons; the measured attenuation of the light in the optical fiber; and a calculation of the light yield from an individual particle in a plastic scintillator. The result is $2-10\times 10^3$ particles in a pulse. The low intensity of the light detected may be due in large part to a large possible beam emittance and a nonuniformity of the guiding magnetic field of the system for transporting the beam of accelerated particles. However, we have not yet studied this question.

The efficiency of the acceleration mechanism also depends on the onset of the two-stream instability, which creates turbulence in the background plasma before the fronts of the magnetosonic waves interact. This turbulence increases the effective viscosity of the medium, which in turn ultimately leads to a spreading of the shock front.[4] Our study showed that the two-stream instability can be suppressed to a large extent by optimizing the relation between the density and temperature of the ions of the background plasma, by adjusting the power supplied to the discharge.

We furthermore do not rule out the possibility that the ions which are accelerated resonantly at the front of one magnetosonic shock wave[3] are captured in the acceleration process inefficiently, because the accelerating system is "not closed" azimuthally. It is possible that realization of ion acceleration along a magnetic field by means of a converging cylindrical magnetosonic shock wave of the "funnel" type, created by a magnetic-piston method, would raise the efficiency of the acceleration mechanism by many orders of magnitude.

The maximum rate of deuteron acceleration found experimentally is >100 MeV/m. This figure is clearly at odds with the results of the acceleration model which we discussed in Refs. 1 and 2. If deuterons are to be accelerated to the energies achieved experimentally according to this model, we would need a stronger electric field "traveling" along the Z axis.

In an earlier study using floating double probes,[2] we showed that in the case of a collision of two waves the potential (φ_Z) of the electric field traveling along the magnetic field is in the interval $\varphi_0<\varphi_Z\leqslant 2\varphi_0$, where φ_0 is the electric potential of an individual magnetosonic shock wave. This result is evidence that the maximum resultant field in the region in which the two magnetosonic shock wave interact may be $2E_0$, rather than $2E_0\sin\theta_0$. What might be responsible for such a situation? Calculations show that in the wave-collision region, as the magnetic fields associated with the wavefronts combine, the geometry of the magnetic field changes in such a way that the initial inclination of the magnetic field lines with respect to the Z axis increases. If we assume that the magnetic field is rigidly tied to the wavefront, then the angle at which the magnetosonic shock waves collide increases from θ_0 to α (Fig. 2a):

$$\tan\alpha\sim\tan\theta_0\left[2-\frac{1}{2(M_A-\frac{1}{2})^{1/2}}\right],$$

where M_A is the magnetic Mach number. Furthermore, the closed azimuthal current with a density $\leqslant 10^4$ A/cm^2, which may arise in an interaction of two polarized (in a transverse magnetic field) plasma streams, as the result of a flow of charge between regions differing in the sign of the charge (Fig. 2b), has a significant effect on the magnitude and spatial distribution of the magnetic and electric fields in the wave-collision region. The magnetic flux generated by currents of this magnitude is comparable to or greater than the

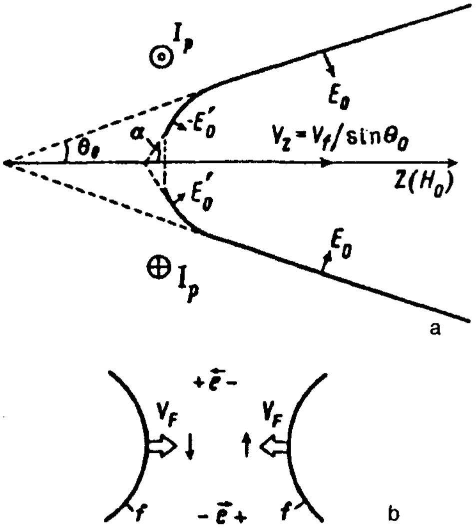

FIG. 2. a: Diagram illustrating the distortion of the electric fields in the region in which the shock waves collide. α—Resultant wave-collision angle; E_0'—resultant electric field of the wave; I_p—polarization current. b: Diagram illustrating the onset of an azimuthal polarization current in the region in which the magnetosonic shock waves collide. f—Front of a shock wave; arrows—electron drift direction.

magnetic flux of the unperturbed magnetic field. Estimates show that the azimuthal currents can increase the ratio $\tan\alpha/\tan\theta_0$ by another factor of 1.5 or 2. With $E_Z \simeq 2E_0$, $n_0 = 6\times 10^{13}$ cm^{-1}, $\theta_0 \simeq 15°$, $H_0 \approx 10^4$ Oe, and $M_A \simeq 1.5$, the accelerated deuterons can thus reach a maximum energy of several MeV.

However, we do not rule out the possibility that waves of other types [e.g., lower hybrid waves,[5] with a higher electric-field energy density (because of collapse)], may become involved in the acceleration process.

Determining the acceleration mechanism will require further experimental study of the spatial distribution of the electric field amplitude in the collision region. Such experiments might also be of assistance in identifying the types of waves involved in the ion acceleration.[6]

The purpose of this letter is to call the attention of theoreticians to this problem.

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