Acceleration of plasma ions through the collision of two magnetoacoustic collisionless shock waves

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Results are communicated from experimental studies of the process of deuterium ion acceleration parallel to a magnetic field as a result of the collision of two quasiperpendicular magnetoacoustic shock fronts at a fixed angle. The deuteron energy, measured by the activation method using the $^{14}N(d,n)^{15}O$ reaction, was found to be 1.2 ± 0.5 MeV. The ion trapping mechanism in the acceleration mode parallel to the magnetic field is discussed. Theoretical estimates of the rate of acceleration due to the change in the angle of the colliding fronts of the two magnetoacoustic shock waves as a function of space and time are presented.

1. INTRODUCTION

It has been shown experimentally[1-3] that ions can be accelerated both perpendicular to the front (ion reflection from the potential discontinuity) and parallel to it (the resonant method) by a collisionless magnetoacoustic shock wave. In both cases the motion of the accelerated particles is transverse to the magnetic field, which is one limitation on the energy of the accelerated particles for laboratory devices, since, e.g., for deuterons even at an energy of 1 MeV the product of the magnetic field strength H and the Larmor radius ρ is equal to $H\rho \simeq 2 \cdot 10^5$ G $\cdot$ cm.

Theoretical studies[4] reveal that magnetoacoustic collisionless shock waves have a strong electric field at the front which, under the right conditions, could be used to accelerate ions to high energies over a short distance.

In the present work we study theoretically and experimentally several questions in connection with the acceleration of particles parallel to the magnetic field when two quasiperpendicular magnetoacoustic collisionless shock waves collide.

2. THEORETICAL JUSTIFICATION

The essence of the method proposed in Ref. 5 is clear from consideration of the following model problem:

Two waves with planar fronts and with an electric field E in the front parallel to the direction of propagation move with velocity V_f toward one another at an angle θ with respect to the external magnetic field $\mathbf{H}_0$ directed parallel to the z axis (Fig. 1). The collision region (quasiwave) of the front moves in the z direction with velocity $V_f/\sin\theta$, and the field strength is equal to $2E\sin\theta$. In order to maintain synchronization the angle between the colliding waves must change as a function of space and time so that the quasiwave propagates in the z direction with increasing velocity. The velocity with which synchronized particles move in this field is equal to

$$V_s(z) = \frac{V_f}{\sin\theta(z)}. \tag{1}$$

By solving the nonrelativistic equation of motion (we are concerned with ion acceleration) and using Eq. (1), we can ultimately derive the dependence of the velocity of the synchronized ion on the position z:

$$\left(\frac{V_s}{V_f}\right)^3 = \frac{6qE}{mV_f^2}z + \left(\frac{V_0}{V_f}\right)^3. \tag{2}$$

Here $V_0 = V_f/\sin\theta_0$ is the initial ion velocity; θ_0 is the initial angle between the colliding waves; and q and m are the charges and mass of the accelerator ions. Assuming that the field E is strong, from (2) we can derive an expression for the increase $\Delta\varepsilon$ in the energy:

$$\Delta\varepsilon \simeq \tfrac{1}{2}(6\sqrt{m}V_f qEz)^{2/3}. \tag{3}$$

Using the expression for the electric field derived in Ref. 4 for the case of quasiperpendicular propagation of a magnetoacoustic collisionless shock wave we have

$$E \simeq \frac{m_i}{q_i}V_A^2[2(M_A - 1)]^{3/2}\frac{\omega_p}{c}, \tag{4}$$

where q_i and m_i are the charge and mass of the plasma ions, V_A is the Alfvén speed, ω_p is the electron plasma frequency, M_A is the magnetic Mach number ($V_f = M_A V_A$), and c is the velocity of light. It is convenient to express the result in terms of the prescribed initial ion energy

$$\varepsilon_0 = \frac{m(M_A V_A)^2}{2\sin^2\theta_0}, \tag{5}$$

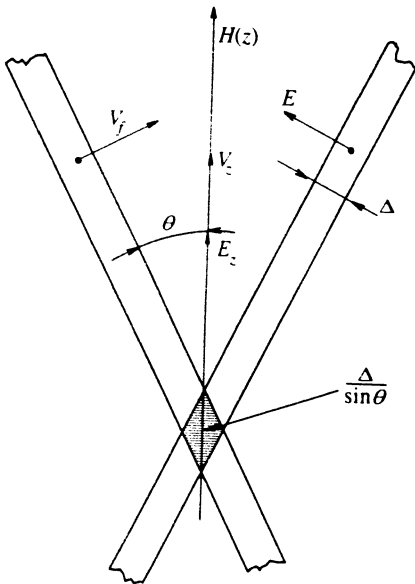the initial value θ_0 of the angle, and the magnetic field strength. Then we have

FIG. 1. Schematic of the interaction of the magnetoacoustic shock waves in the experiment on ion acceleration ($V_z = V_f/\sin\theta$).

$$\Delta\varepsilon = (M_A - 1)\left(\frac{m_i}{m}\right)^{1/3}\left(12\,\frac{\sin^2\theta_0}{M_A}\frac{q}{q_i}\frac{\omega_{ec}z}{c}\,\sqrt{m_e c^2 \varepsilon_0}\right)^{2/3},$$ (6)

where $\omega_{ec} = eH_0/m_e c$ is the electron cyclotron frequency and m_e is the electron mass. Some results of calculations for a hydrogen plasma are shown in Table I.

It is of interest to consider the particle acceleration process when the synchronization condition is not satisfied, e.g., for the case of a constant collision angle of the two magnetoacoustic collisionless shock waves, which is easy to verify experimentally.

Consider the problem of the one-dimensional problem of a charged particle in an electric field having the shape of a square wave of given width L and amplitude E_0 propagating uniformly in space with velocity U without changing shape. The field E_0 is directed parallel to the motion. The initial particle velocity is V_0.

By solving the equation of motion we can show that the maximum velocity of particles accelerated by this step wave is equal to

$$V_{max} = U\left(I + \sqrt{\frac{2qE_0L}{mU^2}}\right),$$ (7)

and is achieved when the initial velocity is

$$V_0 \geqslant U\left(I - \sqrt{\frac{2qE_0L}{mU^2}}\right).$$ (8)

It is clear that this problem models the situation when magnetoacoustic collisionless shock waves collide with one another (Fig. 1). Then we have

$$U = \frac{M_A V_A}{\sin\theta}, \quad L = \frac{\Delta}{\sin\theta}, \quad E_0 = 2E\sin\theta,$$ (9)

$$\Delta \approx \frac{c}{\omega_p\sqrt{2(M_A - 1)}}.$$

Here Δ is the width of the shock front in the quasiperpendicular approximation.[4] [In this approximation E is given by Eq. (4).] Substituting (9) in (7) and (8) we find for the maximum energy of the accelerated particles

$$\varepsilon_{max} = \frac{m}{2}\left(\frac{M_A V_A}{\sin\theta}\right)^2\left[I + \frac{2\sqrt{2(M_A - 1)}}{M_A}\sin\theta\right]^2,$$ (10)

and for the initial velocity

$$V_0 = \frac{M_A V_A}{\sin\theta}\left[I - \frac{2\sqrt{2(M_A - 1)}}{M_A}\sin\theta\right].$$ (11)

Then the maximum acceleration distance is

$$Z_{max} \approx \frac{c}{\omega_p}\frac{M_A}{(M_A - 1)\sin^2\theta}.$$ (12)

3. DESIGN OF THE EXPERIMENT AND EXPERIMENTAL RESULTS

The experiment was performed in a device for accelerating a high-current discharge in crossed E and H fields.[6]

Two pairs of electrodes of length 30 cm, width 4 cm, separated by ≈ 2 cm were located in a ceramic chamber with interior diameter of 18 cm and length $L = 150$ cm. The electrodes were at an angle with respect to the axis of symmetry of the axial magnetic field of a mirror configuration (mirror ratio ~ 1.4).

After preliminary vacuumization the chamber was filled with gas, the magnetic field was switched on, and a discharge ($I_{max} \approx 5$ kA, length ≈ 3 ms) was induced between the electrode pairs. Drifting in both directions from the discharge gaps, the plasma filled the chamber. At a certain time (in the course of a millisecond pulse) a high-power current pulse ($I_p > 20$ kA, length 1.5 μs) was transmitted through the discharge gaps. Two plasma streams produced in the powerful discharge in crossed E and H fields, moving toward one another across the magnetic field

TABLE I.

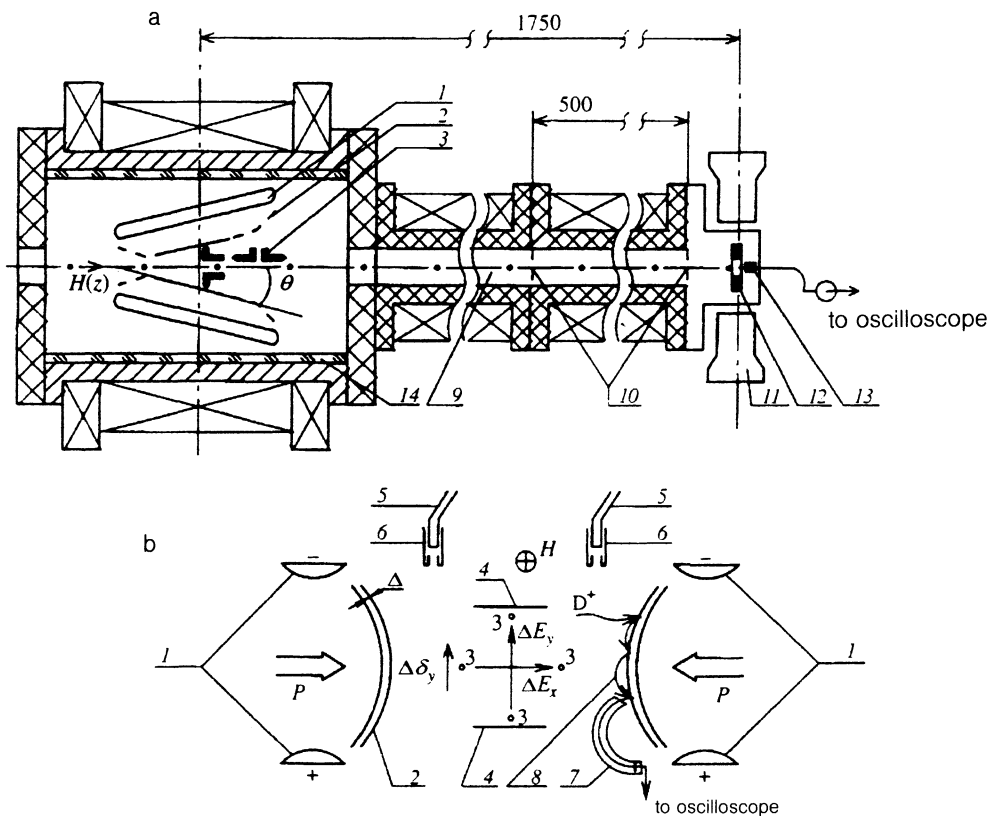| M_A	1.2	1.5	2	1.2	1.5	2	1.2	1.5	2
H_0 , kG	10	10	10	100	100	100	100	100	100
ε_0 , eV	10^6	10^6	10^6	10^5	10^5	10^5	10^6	10^6	10^6
$\Delta\varepsilon$, MeV	84.5	182	300	84.5	182	300	392	845	1400

FIG. 2. Design of the apparatus (a) and disposition of the diagnostic devices (a,b) in the working chamber: *1*—electrodes; *2*—wave front; *3*—probes; *4*—electrodes for producing the controllable current; *5*—light guides; *6*—collimators; *7*—magnetic spectrometer; *8*—trajectory of a particle accelerated perpendicular to the magnetic field; *9*—ion guide; *10*—drift probes; *11*—spectrometric locks using NaI; *12*—BN target; *13*—collector; *14*—ceramic chambers; *P* is the plasma stream.

$(H_0 \approx 10^4$ G) created magnetoacoustic disturbances[7,8] in the background plasma with an extended (parallel to H_0) front ($\leqslant 10$ cm). The two magnetoacoustic shock waves collided at an angle of $\theta \leqslant 12°$. Using various drift probes we measured the plasma parameters (Fig. 2).

The shape and velocity of the magnetoacoustic disturbances were measured with the magnetic probes with an open loop (diameter ≈ 3 mm). The discontinuity in the potential at the front was measured with double floating probes oriented both parallel to and perpendicular to the magnetic field and located at various points on the chamber axis, which enabled us to measure the velocity with which the quasiwave (the collision region) moved along the magnetic field. Probes placed at various radii of the chamber permitted the shock wave velocity perpendicular to the magnetic field to be determined. The use of optical channels made from fiber optics enabled us to observe the emission of the disturbed plasma with a spatial resolution of less than 1 mm.

The local plasma density was determined by a technique based on the measurement of the Hall potential by floating probes perpendicular to the plasma stream $\Delta\delta_y$ of the current being monitored.[9] Using the one-fluid approximation we can derive from the generalized Ohm's law a relation for the electron density:

$$N_0 = \frac{\Delta\delta_y B_z}{\Delta E_x e} \tag{13}$$

and the frequency of two-particle collisions

$$v_{ei} = \frac{\Delta E_y e B_z}{\Delta E_x m_e}, \tag{14}$$

where ΔE_x and ΔE_y are the change in the x and y components of the electric field in the plasma when the current $\Delta\delta_y$ flows perpendicular to the plasma stream; B_z is the magnitude of the magnetic field; and e and m_e are the charge and mass of the electron.

Thus, by measuring the quantities E_x, E_y, and B_z when the current $\Delta\delta_y$ being monitored was flowing and in its absence ($\Delta\delta_y = 0$), we can use relations (13) and (14) to find the plasma parameters. The energy per unit volume fed into the plasma when the probe current flows should be less than that previously contained in the plasma. The spatial resolution associated with the density measurement was ≈ 1 cm.

In an ion guide located coaxially with the working chamber and having a guiding magnetic field, movable mesh probes were used to measure the velocity with which charged particles flow out (plasma structures). At the end of the ion guide (of length 100 cm) a target made from boron nitride (BN) was placed. By measuring the induced activity of this target [the reaction $^{14}N(d,n)^{15}O$] with a $\gamma-\gamma$ coincidence spectrometer [made from two NaI(Tl) scintillation crystals] we were able to determine the energy and total flux of the accelerated deuterons. Part of the target was screened by a copper collector, which was used to monitor the current properties of the accelerated ions (Fig. 2a).

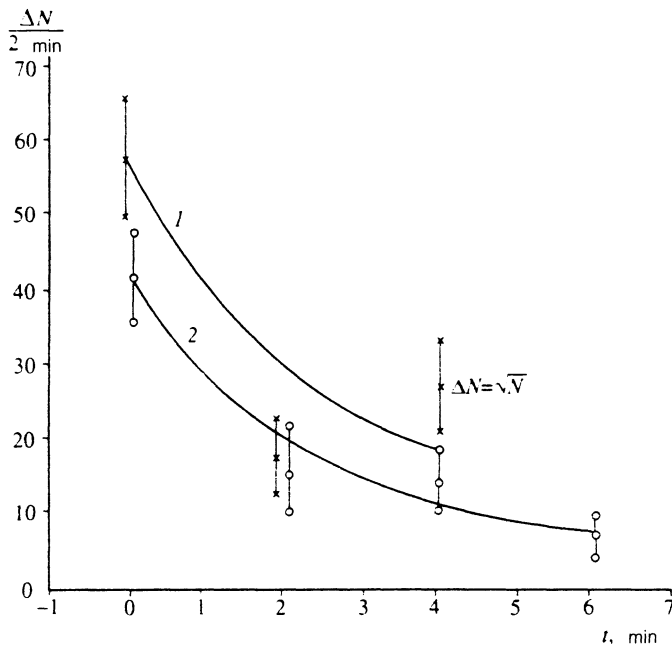When a single quasiperpendicular magnetoacoustic

FIG. 3. Curves of the decay of the activity induced in the BN target by the accelerated deuterons. *1*—Decay curve for the induced activity from a single acceleration cycle; *2*—decay curve for the induced activity summed over 18 acceleration cycles.

shock wave was excited in a deuterium plasma ($N_0 \approx 3 \cdot 10^{14}$ cm^{-3}, $T_0 \approx 2$ eV, Alfvén Mach number $M_A \sim 1.2$, initial field strength $H_0 \approx 10^4$ G) the E_z field components measured by floating probes oriented parallel to the magnetic field, was close to zero. The velocity of the wave front was equal to $\sim 10^8$ cm/s. In the drift tube at a distance of ≈ 50 cm we observed bunches of fast particles having velocity greater than V_f, after which a flux of slow particles was detected with a continuous spectrum. The wave potential φ (measured with probes oriented perpendicular to H_0) and the discontinuity in the magnetic field had the typical structure of the pre-front of the shock.

In the case of two colliding waves ($\theta \leqslant 12°$) the electric field of the quasiwave (collision region), whose potential satisfied $\varphi_z > 2E_0\Delta \sin \theta$ (where Δ is the thickness of the front) was detected parallel to the magnetic field. The potential was in the range $\varphi_0 < \varphi_z \leqslant 2\varphi_0$, so that the end collector measured the current pulse correlated with the appearance of the field E_z of fast deuterons having velocity larger than that associated with the excitation of a single wave. Using the $\gamma - \gamma$ spectrometer we measured the induced activity in the boron nitride target, i.e., we recorded the γ photons associated with annihilation of β^+ particles in the target material due to the reaction ^{14}N$(d,n)^{15}$O (^{15}O$\rightarrow\beta^+, \tau_{1/2} \approx 123$ s). The reaction was identified by measuring the decay curve. In individual acceleration cycles the yield of this reaction (Fig. 3, trace *1*) is considerably greater than the yield of the reaction summed, e.g., over 18 acceleration cycles (Fig. 3, trace *2*). In all cases the experiments were carried out under the same external conditions.

The efficiency with which the β^+ particles were detected by the $\gamma - \gamma$ coincidence spectrometer was measured using a ^{22}Na calibration source. The energy of the accelerated deuterons was determined by comparing the yield of the ^{14}N$(d,n)^{15}$O, reaction of the measured apparatus with the energy dependence of the relative yield of the same reaction obtained in a Van de Graaf tandem accelerator,[10] and was found to be 1.2 ± 0.5 MeV. The total number of deuterons passing through the target was equal to $\sim 5 \cdot 10^{10}$. The error in determining the energy was due to imprecise knowledge of some properties of the apparatus (e.g., the degree of neutralization of the deuteron beam).[11]

Calculations revealed that in order to achieve the energy found in the experiment when two magnetoacoustic shock waves collide at a fixed angle $\theta \approx 12°$ it is necessary that the initial energy (injection energy) of the particles moving in the direction of the acceleration vector (H_0) be equal to $\varepsilon_0 \geqslant 1.6$ mV_f^2 (for the conditions of our experiment where $V_f \sim 10^8$ cm/s holds it is necessary to have $\varepsilon_0 \approx 60$ keV). Then over an acceleration distance less than 5 cm the deuterium ions can be accelerated to $\varepsilon \geqslant 18$ mV_f^2 (~ 1 MeV), if the width of the region occupied by the accelerating electric field is $\approx \Delta/\sin \theta$, where $\Delta \approx c/\omega_p \sqrt{2(M_A - 1)}$ (Ref. 4). A particle source with the necessary initial energy ε_0 can be provided by either of the colliding waves, since in Ref. 3 it was shown experimentally that (in the direction perpendicular to H_0) particles can be accelerated in the front of the shock waves to energy $\leqslant 2$ mV_f^2. In fact, if the wave potential is given by

$$\varphi \approx \frac{1}{2\pi} \frac{H_0^2}{eN_0} (M_A - 1),$$

where N_0 is the background plasma density, then for $M_A \geqslant 1.2$, $N_0 \approx 10^{14}$ cm^{-3} and $H_0 \approx 10^4$ G, we have $\varphi > 10^4$ V. In this case in the resonant acceleration regime particles can be entrained which have a velocity $\sim 10^5$ cm/s in the coordinate system moving with the wave. The acceleration time is bounded, e.g., by the transverse dimensions of the chamber:
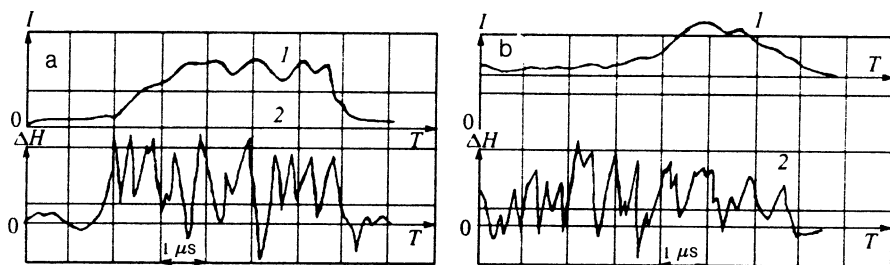
$$\tau_{ac} = d/2V_f \approx 5 \cdot 10^{-8} \text{ s.}$$

FIG. 4. Oscilloscope traces of the plasma emission (*1*) and the change in the magnetic field (*2*) in the region where the magnetoacoustic shock waves collide: a) in the absence of the preliminary turbulization of the plasma; b) with preliminary turbulization. Here $T=0$ corresponds to the time at which the process of exciting the magnetoacoustic shock wave begins.

In the laboratory system over this time for $\omega_{ec}/\omega_p \geqslant 0.6$ a particle acquires a velocity $\geqslant 10^8$ cm/s at the front of the shock wave in an acceleration length $L \approx d/2\pi$. The dimensions of the pre-front, which are usually related to the pressure of the fast particles accelerated at the shock front,[12] will be determined by the magnitude of the Larmor radius of the accelerated particles. For $H_0 = 10^4$ G and an energy ~ 50 keV the Larmor radius is less than 3 cm.

When the accelerated charged particles undergo successive elastic scattering from irregularities of the magnetic field whose scale is comparable with the Larmor radius the particles can be trapped into the acceleration regime parallel to the magnetic field.

The experiments revealed that when a single magnetoacoustic wave propagates in the background plasma the time during which the perturbed plasma radiates is equal to the time during which magnetoacoustic disturbances exist in the region in question. For a single wave small modulations of both the radiation intensity and the amplitude of the magnetic field are typical over the whole propagation distance of the wave.

When two waves are excited, intense oscillations are observed in the region where they collide in both the magnetic field and in the plasma emission (Fig. 4a). Magnetic sensors at intervals of several centimeters along the magnetic field detected oscillations in the magnetic field 180° out of phase, which implies that the field frozen into the plasma is becoming turbulent. The scale of the turbulence parallel to the magnetic field was a few centimeters. The thickness of the turbulent plasma region in the direction transverse to the magnetic field was ~ 2 cm.

Preliminary measurements of the energy of the accelerated ions perpendicular to the magnetic field at the front of a single wave, using a magnetic spectrometer built into the interior of the working chamber, reveal that there are ions with momentum

$$m_i V_\perp \simeq \frac{eH\rho}{c} \cdot Z,$$

where m_i is the ion mass, $V_\perp$ is the ion velocity perpendicular to the magnetic field, and Z is the charge state.

In the case of deuterium this momentum corresponds to a velocity $\sim 10^8$ cm/s in a field $\sim 10^4$ G. The Larmor radius corresponding to this velocity is equal to ~ 1.5 cm. Thus, the presence of a magnetic field with turbulence scale on the order of a few centimeters and of ions (of the necessary energy) with Larmor radius of the same order strongly confirms the expectations expressed above regarding the mechanism for injection of ions of the necessary

energy into the acceleration regime parallel to the magnetic field when two magnetoacoustic shock waves collide.

Note that the development of turbulence when the oppositely directed plasma streams interact can occur prior to the collision of the shock waves, which leads to a marked change in the parameters of the shock waves propagating in the turbulent medium (Fig. 4b).

4. CONCLUSION

Thus, these results on investigations of the process of ion acceleration parallel to the magnetic field when magnetoacoustic shock waves collide at a fixed angle reveal that it is possible in principle to achieve this acceleration mechanism under laboratory conditions. In the future it is proposed to inject deuterium ions accelerated by this process with energy ~ 1 MeV into the acceleration regime, when the synchronization condition is satisfied. This would be a significant confirmation of the results of the calculations and the acceleration mechanism. In this case for $H_0 = 2 \cdot 10^4$ G, $\theta_0 \approx 30°$, $M = 1.5$, and $\varepsilon_0 = 1$ MeV it is proposed to accelerate deuterium ions over a distance ~ 20 cm to an energy $\varepsilon \geqslant 10$ MeV.

However, at this stage of the investigations in connection with the excitation of magnetoacoustic shock waves by plasma streams from discharge gaps, the acceleration process is random in nature, since experimentally there is a high probability for the conditions under which the two-stream instability can go to develop in the region of the intended collision prior to the time when the shock waves get there. Consequently, further studies are needed to clarify the threshold conditions for plasma to pass into the turbulent state when two oppositely directed beams interact.

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