Collisionless electrostatic shock generation using high-energy laser systems

Y. Sakawa\textsuperscript{a}, T. Morita\textsuperscript{b}, Y. Kuramitsu\textsuperscript{c} and H. Takabe\textsuperscript{d}

\textsuperscript{a}Institute of Laser Engineering, Osaka University, Suita, Osaka, Japan; \textsuperscript{b}Faculty of Engineering Sciences, Kyushu University, Kasuga, Japan; \textsuperscript{c}Department of Physics, National Central University, Taoyuan, Taiwan; \textsuperscript{d}Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany

\textbf{ABSTRACT}

Collisionless shock is ubiquitous in space and astrophysical plasmas, and is believed to be a source of cosmic rays. In this review article, historical achievements of three different types of collisionless shocks, i.e. magnetohydrodynamic, electromagnetic, and electrostatic (ES) shocks, in theory/simulation, observation in space and astrophysical plasmas, and laboratory experiments are shown. An overview is given on recent progress of collisionless ES shock experiments using high-energy laser systems for two schemes. One is an interaction between laser-produced high-density ablating plasma and a low-density ambient plasma, and the other is an interaction between laser-ablated counter-streaming plasmas using double-plane target. For the former scheme, detailed measurements of structures of collisionless ES shock and ion-acoustic soliton, and the transition from double-layer to collisionless ES shock are conducted by proton radiography. For the latter scheme, optical diagnostics are used to observe global structures of plasmas and shocks; collective laser Thomson scattering method is applied to clarify local plasma parameters, such as electron and ion temperatures, flow velocity, and electron density; and proton radiography is employed to measure a shock electric field. The measured large density-jump, steepening of self-emission profile, plasma parameters in the up- and down-stream regions of a shock, and the narrow width of the shock electric field compared with the ion-ion Coulomb mean-free-path reveal the evidence for the formation of collisionless ES shock.

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\textbf{CONTACT}
Y. Sakawa sakawa-y@ie.osaka-u.ac.jp

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1. Introduction

Collisionless shock is a shock wave generated in a collisionless plasma, in which Coulomb collisions are negligible. Whereas the shock-front thickness of collisional shock is of the order of Coulomb mean-free-path (MFP), that of collisionless shock is much smaller than the MFP, and wave–particle interactions and collective effects of electric and magnetic fields play essential roles in the shock formation. Collisionless shock is ubiquitous in space and astrophysical plasmas, such as Earth’s bow shock and supernova remnant (SNR) shocks.

Courant and Friedrich predicted the possibility of collisionless shocks in a plasma for the first time in 1948 [1]. In 1950, De Hoffmann and Teller gave the first theoretical investigation of magnetized shocks [2]. First observation of collisionless shock (Earth’s bow shock) was done by spacecraft in 1963–1964 [3,4]. In 1965, Kurtmullaev et al. and Paul et al. conducted the first generation of collisionless shock in laboratory experiments [5,6]. First simulation of collisionless shock was performed for electrostatic shock in 1970 [7] and for magnetized perpendicular shock, which propagates perpendicular to an external magnetic field, in 1971 [8].

Since then, collisionless shock has been studied more than half century as one of the most important topics in plasma, space, and astrophysics. This is because collisionless shock is believed to be the source of cosmic rays and rich in plasma physics, e.g. excitation of waves and instabilities, wave–particle interaction, plasma turbulence, multi-scale physics, nonlinear physics, and so on. In collisional shock, kinetic energy of supersonic particles in the upstream region is dissipated by collisions between particles, i.e. the upstream particles are decelerated to subsonic, heated or kinetic energy is converted to thermal energy in the downstream region of shock wave. In collisionless shock, in addition to heating, due to the interaction between incoming charged particles and electromagnetic field in plasma, acceleration of charged particles and generation of non-thermal component occur. Several acceleration mechanisms at collisionless shock in the Universe have been predicted, e.g. diffusive shock acceleration [9,10], ion [11] and electron [12] shock surfing acceleration, and shock drift acceleration [13,14].
In general, we can distinguish collisionless shock in three categories. The first is the one under an external magnetic field, i.e. magnetized or magneto-hydrodynamic shock, and we call it MHD shock. The second and third are the ones in the absence of an external magnetic field; electromagnetic turbulence sustaining shock (EM shock), and electrostatic shock (ES shock). (a) MHD shock is ubiquitous in the space and astrophysical plasmas. (b) EM shock is predicted to be mediated by self-generated turbulent electromagnetic field such as in gamma-ray bursts (GRBs) afterglows [15]. The Weibel instability is a leading candidate for the generation mechanism of turbulent electromagnetic field and shocks [16]. (c) ES shock is rare in the Universe. It may occur even with an external magnetic field under special conditions, such as in the auroral zones [17–20], but here we focus only on the cases without external magnetic filed. In the following, we will briefly review achievements in these three types of collisionless shock.

(a) MHD shock: In space plasmas, electric turbulence, reflected ions, and particle acceleration associated with collisionless Earth’s [21–26] and Saturn’s [27] (MHD) bow shocks have been observed by satellites. From the observation of SNRs, structures of collisionless MHD shock and particle acceleration at the shock front have been studied [28–33]. Numerical simulation has revealed a lot of interesting physics on collisionless MHD shock, such as supercritical shock structure [34] and reflection/acceleration of ions at shock [35–38].

Experimental investigation of collisionless MHD shock has been conducted with high-energy laser systems [39–44]. Recently, Niemann et al. have reported the first observation [45,46] of collisionless MHD perpendicular shock, which was predicted by hybrid-simulation [47], using the Large Plasma Device [48] and a high-energy laser system [49]. No clear particle acceleration has been investigated experimentally for the MHD shock yet.

(b) EM shock: In 1999, Medvedev and Loeb predicted that the Weibel instability is driven unstable in unmagnetized counter-streaming plasmas, and self-generated turbulent electromagnetic field mediates collisionless EM shock [16]. Many researchers have conducted relativistic particle-in-cell (PIC) simulations to investigate EM shock formation, generation of long-lived strong magnetic field and energetic particles in GRBs [50–54]. Formation of Weibel-instability mediated EM shock using ultra-high-intensity lasers has been predicted using PIC simulations [55,56].

Kato and Takabe have performed two-dimensional non-relativistic PIC simulation for the first time, and shown generation of collisionless ion Weibel-instability mediated EM shock in counter-streaming plasmas without an external magnetic field [57]. Possibility of an experiment with high-energy laser has been discussed, and found that high-density (electron density $\sim 10^{20} \text{cm}^{-3}$) and high-flow velocity ($\sim 1000 \text{km/s}$) plasmas are required to produce collisionless Weibel shock [58,59]. In order to achieve these plasma parameters, a high-energy laser system with an energy of $> \text{hundreds of kJ}$ or the world largest laser, the National Ignition Facility (NIF) laser (LLNL, U.S.A), is required [58,59].
We have conducted the Weibel-instability mediated collisionless EM shock experiments with Omega and Omega EP laser systems (Rochester U., U.S.A), and measured plasma parameters such as electron and ion temperatures, electron density, and flow velocity of counter-streaming plasmas [60–62] with collective Thomson scattering (CTS) [63], and filamentary structure produced by the Weibel instability [62,64,65] with proton radiography [66,67]. Now the NIF experiment is going on.

(c) ES shock: In 1970s, experimental [68–70] and numerical/computational [7] studies on collisionless ES shock using double-plasma device were conducted. In 2000s, experiments on ion acceleration in the radial direction to the incident high-intensity laser beam by a radial collisionless ES shock in an underdense plasma have been reported [71–73]. Nilson et al. have reported the experimental generation of high Mach-number ES shock in an underdense plasma with a high-intensity laser beam [74], with an experimental condition similar to that in [72].

Numerical simulation has revealed ion acceleration at a relativistic ES shock generated in an overdense plasma due to reflection of ions in the upstream region by the shock front [75–83], and mono-energetic proton acceleration by ES shock has been shown experimentally [84–86]. These mono-energetic protons have a potential to be used in several applications including medical treatment [87]. Parameter regimes of the generation of EM and ES shocks and transition between the two shocks have been discussed [56,88].

Basic physics of collisionless ES shock generation has been studied numerically [89–93] and experimentally using high-energy laser systems [94–99]. In the experiments using high-energy laser systems, there are two schemes for the generation of collisionless ES shock. One is an interaction between laser-produced high-density ablating plasma and a low-density ambient plasma [94,95], and the other is an interaction between laser-ablated counter-streaming plasmas using double-plane target [96–101].

Using the former scheme, Romagnani et al. have conducted detailed measurements of structures of collisionless ES shock and ion-acoustic soliton by proton radiography [94]. Ahmed et al. have demonstrated the transition from double-layer to collisionless ES shock [95].

Kato and Takabe have shown PIC simulation for collisionless shock in counter-streaming plasmas, and found that ES shock is produced in the early stages before the final Weibel-instability mediated EM shock is formed [90]. Sorasio et al. have shown a possibility of high Mach-number collisionless ES shock formation in counter-streaming plasmas in which temperatures and densities are largely different [89]. Motivated by these predictions [89,90], some authors have studied the latter scheme; the generation of collisionless ES shock in counter-streaming plasmas using double-plane target and one-directional high-energy laser systems [96–101]. Morita et al. have measured a large density-jump [96], and Kuramitsu et al. have shown the temporal evolution of the emission profiles
Plasma parameters, such as electron $T_e$ and ion $T_i$ temperatures, flow velocity $v_d$, the average charge number $Z$, and electron density $n_e$, in the up- and down-stream regions of a shock have been measured by Collective TS (CTS) [98], and shock electric field has been investigated by proton radiography [99].

In the next section, we review collisionless ES shock experiments using high-energy laser systems; both in an interaction between laser-produced ablating plasma and an ambient low-density plasma (Section 2.1), and laser-produced counter-streaming plasmas (Section 2.2).

2. Collisionless ES shock experiments using high-energy laser systems

2.1. Collisionless ES shock in an interaction between laser-produced ablating plasma and an ambient low-density plasma

2.1.1. Collisionless ES shock and ion-acoustic soliton: LULI 100TW laser experiment [94]

The first experiment was performed at the LULI 100TW laser facility at LULI, France. A main laser pulse (1064 nm, 470 ps, intensity $I \sim 10^{15}$ W/cm$^2$) was focused onto a metal foil (25 µm thick Tungsten or aluminum foil), and a high-density ablation plasma ($\sim 10^{18}$ cm$^{-3}$) interacted with a low-density ambient plasma ($\sim 10^{15}$ cm$^{-3}$) produced via photoionization (mainly driven by the thermal radiation from the target) of the residual gas ($\sim 10^{-3}$ mbar) in the target chamber. The electric field distribution and the shocks’ structures have been reconstructed by proton imaging technique [66,102]. A second laser beam (1064 nm, 300 fs, $I \sim 10^{18}$ W/cm$^2$) was focused onto a thin Tungsten target to generate a proton beam.

Figure 1(a) shows a proton imaging data at the peak of the drive laser pulse. The arrow indicates the laser beam direction. In Figure 1(b) and (c), modulations associated with a train of solitons are visible in the region II. Figure 1(d)–(g) and 1(h)–(k) show an ion acoustic soliton (IAS) and a collisionless ES shock (CS),

![Figure 1](image-url)

Figure 1. (a) Typical proton imaging data with protons of 7 MeV energy. (b)–(c) Detail and RCF optical density lineout corresponding to the region II showing modulations associated with a train of solitons. (d)–(k) Details of the region III and correspondent lineouts of the probe proton density $\delta n_p/n_{pu}$, reconstructed electric field $E$, and reconstructed normalized ion velocity $u/c_{ia}$ in the case of (d)–(g) an ion acoustic soliton and (h)–(k) a collisionless shock [94].
respectively, observed in the region III (the CS detail Figure 1(h) corresponds to a different shot not shown here). The proton density modulation $\delta n_p/n_{pu}$ ($\delta n_p = n_p - n_{pu}$, $n_p$ and $n_{pu}$ are the perturbed and unperturbed proton densities, respectively), electric field $E$ ($E \propto - \int n_p/n_{pu} dX$, $X$ is the spatial coordinate in the reference frame moving with the shock), and the ion velocity distribution $u/c_{ia}$ ($u/c_{ia} \propto - \int E dX$, $c_{ia}$ is the ion acoustic velocity) in IAS (CS) are shown in Figure 1(e), (f), and (g) [(i), (j), and (k)], respectively. The measured structures for IAS and CS agreed with those calculated from the Korteweg-de Vries (KdV) and the Korteweg-de Vries-Burgers (KdV-B) equations [103], respectively. Furthermore, the modulated pattern of the shock front associated with a reflected ion bunch in the region IV are also seen in Figure 1(a). When a collisionless shock is observed, ion reflection could be the dissipation mechanism responsible for the transition from a soliton structure to a collisionless shock.

To summarize, the shocks’ structures and related electric field distributions were reconstructed and interpreted within the framework of the nonlinear wave description based on the KdV-B equation.

2.1.2. Transition from current free double-layer to supervritical collisionless ES shock VULCAN laser experiment [95]

The second experiment was conducted at the VULCAN laser facility at the Rutherford Appleton Laboratory, UK. A main laser pulse (1064 nm, 1 ns, 120 J, $I \sim 10^{15}$ W/cm$^2$) was focused onto a gold foil, and an ablation plasma interacted with an ambient plasma ($\sim 10^{16}$ cm$^{-3}$) produced via photoionization of the ambient nitrogen gas ($10^{-1}$ mbar). The temporal and spatial evolution of electric field distribution has been measured by proton radiography [66,102].

Figure 2(a) shows a typical proton radiograph at 170 ps after the arrival of the main pulse. Since the main target is placed at a finite distance from the proton source, protons with different energies reach the plasma at different times. By using a stack of several layers of radiochromic (RC) film, each layer of film

![Figure 2. (a) A proton radiograph of the interaction of the main laser pulse (red arrow) with a gold foil (left purple rectangle) at $t = 17$ ps. Notes: (b)–(d) Zooms of the proton radiographs of the region highlighted by the dashed white rectangle in (a) at (b) $t = 150$ ps (proton energy of 11.5 MeV), (c) 160 ps (10 MeV), and (d) 170 ps (9 MeV). (e), (g) Experimental electric field distribution and (f), (h) associated potential during the transition between the CFDL and the protoshock [95].](image-url)
acts as a filter for the following layers. Protons deposit energy mainly in the Bragg peak at the end of their range, and each RC film layer spectrally selects a narrow range of proton energies. Therefore, it is possible to measure the temporal evolution of the plasma structure, in a single laser shot [66,102]. Figure 2(b)–(d) represent the zooms of the same region as in Figure 2(a) at $t = 150$, 160, and 170 ps, respectively. Derived temporal evolution of electric field (potential) is shown in Figure 2(e)–(g) [(f)–(h)]. The electric field evolves from a bell-like shape to a symmetric bipolar structure, which is showing the precursory stages of the formation of a shock. The electrons diffuse out into the ambient plasma because of the larger thermal speed of electrons than that of ions, an ambipolar electrostatic potential or a current free double-layer (CFDL) [104] is set. The progressive pile-up of ambient ions by this potential introduces a local density maximum at the blast shell front. Initially the density distribution and, thus, the potential on both sides of this maximum are asymmetric; the density jump is larger towards the ambient plasma. The continuing ion pile-up forces the electric field pulse to evolve into a symmetric profile. As soon as the potential is strong enough to reflect the incoming ambient and blast shell ions, a forward and a reverse shock form. A potential jump of approximately 4 kV at $t = 150$ ps cannot decelerate the ambient nitrogen ions, which move at $2 \times 10^6$ m/s (Mach number $M \sim 10$ relative to the blast shell front). The potential at $t = 170$ ps has increased to 12 kV and the structure’s speed relative to the ambient plasma has decreased to $8 \times 10^5$ m/s ($M \sim 4$), which is sufficient to reflect ambient nitrogen ions in the reference frame of the expanding structure and form supercritical forward shock.

The measured evolution of the electrostatic potential associated with the shock revealed the transition from a CFDL into a symmetric shock structure, stabilized by ion reflection at the shock front.

### 2.2. Collisionless ES shock in counter-streaming plasmas using double-plane target

#### 2.2.1. Density-jump: Shenguang II laser experiment [96]

The first experiment was performed at Shenguang II laser facility (351 nm, 260 J/beam, 1 ns) in Shanghai, China. Figure 3(a) and (b) show the top view of the experimental setup and schematic view of the target design, respectively. We used double-plane target (plastic (CH), 2 mm $\times$ 2 mm $\times$ 100 $\mu$m, 4.5 mm separation). Four beams were focused on the inner surface of one of the CH foils (first CH) with the incident angle of $60^\circ$ from the target normal direction (focal spot diameter $D \sim 150 \mu$m, intensity $I \sim 6 \times 10^{15}$ W/cm$^2$). As diagnostics, Nomarski IF and SG were used with a probe laser (527 nm, 70 ps) and ICCD cameras. The plasma flow from the other CH foil (second CH) was produced by the radiation and/or plasma from the first CH, and counter-streaming plasma flows were created between the two foils.
Figure 3. (a) The top view of experimental setup. SG and IF represent the ICCD cameras for shadowgraphy (SG) and interferometry (IF), respectively, WP is the Wollaston prism and PL is the polarizer. (b) Schematic view of the target design. (c) The interferogram and (d) shadowgraph measured at \( t = 9 \) ns. \( x = 0 \) and 4.5 mm are the surface of the first and second CH foils, respectively. Four beams were focused on the first CH at \( x = 0 \) and \( y = 2.5 \) mm. (e) The density profile at \( y = 3.5 \) mm derived from (c). A large density-jump is observed at \( x \simeq 3.1 \) mm. (f) The average intensity profile from (d) for \( y = 3.0–4.0 \) mm [96].

Figure 3(c) and (d) show interferogram and SG, respectively, measured at \( t = 9 \) ns from the main laser. The \( x \) axis represents the distance from the surface of the first CH. In Figure 3(c), interference fringes suddenly shift, which indicates a large density-jump exists near the second CH. Figure 3(e) shows the density profile at \( y = 3.5 \) mm derived from Figure 3(c). This density-jump was fitted with \( \tanh \) function as shown in Figure 3(e). The downstream to upstream electron-density ratio \( n_1/n_0 \), the width \( W \) and the position \( x_s \) of the transition are evaluated as \( n_1/n_0 = 3.89 \pm 0.85, W = 48.6 \pm 34.5 \) \( \mu \)m, and \( x_s = 3.12 \pm 0.02 \) mm, respectively. The observed density discontinuity moved from \( x_s \simeq 3.55 \) to 3.12 mm in 4 ns, i.e. it propagates from right to left with \( v \simeq 130 \) km/s. Figure 3(f) shows the average (\( y = 3.0–4.0 \) mm) intensity profile of Figure 3(d). The intensity suddenly changes at the same position as the density-jumps (\( x \simeq 3.1 \) mm), which represents a large density-jump.

We performed a quasi-one-dimensional PIC simulation to investigate ES shock formation and propagation in counter-streaming plasma flows as shown in Figure 4 [90,96]. Initial conditions are as follows: ion to electron mass and temperature ratios are \( m_i/m_e = 1836 \) and \( T_e/T_i = 4 \), electron temperatures, densities, and flow velocities for the left- and right-plasmas are 50 and 750 eV, \( 2 \times 10^{18} \) and \( 6 \times 10^{18} \) cm\(^{-3} \), and 800 and 200 km/s, respectively. Two shocks are generated at \( \omega_{pet} \sim 800 \) and they propagate toward \( \pm x \) directions [Figure 4(a)–(c)]. At \( \omega_{pet} \sim 2000 \) [Figure 4(b)–(d)], it is clear that the incoming ions
Figure 4. Ion phase-space plots and corresponding density profiles at $\omega_{pe}t = 800$ [(a) and (c)] and 2000 [(b) and (d)], where $\omega_{pe}$ is the electron plasma frequency. The $x_1$ axis in (a), (b) and $x_2$ axis in (c), (d) are in units of the electron skin depth $\lambda_e = c\omega_{pe}^{-1}$. Ion to electron mass ratio $m_i/m_e$ is 1836, and electron to ion temperature ratio $T_e/T_i$ is 4 in both plasma flows. The initial electron temperature, density, and flow velocity are 50 eV, $2 \times 10^{18}$ cm$^{-3}$, and 800 km/s for the left-plasma, and 750 eV, $6 \times 10^{18}$ cm$^{-3}$, and 200 km/s for the right-plasma; the measured values are used for the electron densities and flow velocities [96].

are slowed down or reflected at two shock fronts, $x/\lambda_e = 26.5$ and 27.8 ($x = 81.3$ and 85.3 $\mu$m). The velocity of the left-side shock is about $v_s = 600$ km/s in the upstream rest frame, and a sound velocity in the upstream region is $C_s = 69$ km/s, therefore, the Mach-number of the left-side shock is $\sim 8.7$.

To summarize, a large density jump which represents ES collisionless shock generation in high-speed counter-streaming plasma flows was shown both in experiment and PIC simulation.

2.2.2. Temporal evolution of shock: Gekko XII laser experiment [97]

The second experiment was performed using Gekko XII (GXII) HIPER laser system (351 nm, $\sim 100$ J/beam, 500 ps, $D \sim 300$ $\mu$m, $I \sim 3 \times 10^{14}$ W/cm$^2$) at Institute of Laser Engineering, Osaka University. Figure 5(a) shows a schematic drawing of CH double-plane target (60 $\mu$m in thickness, separation of 4.5 mm). The target normal was aligned $30^\circ$ from the laser propagation axis. The diagnostics were transverse to the axis of the plasma, with two streak cameras and three ICCDs. The slits of the streak cameras were rotated by $30^\circ$ in order to measure the temporal evolution of the plasmas along the target normal direction.

Figure 5(b) shows a streaked self-emission pyrometry (SOP) image at a wavelength of 450 nm. In optically thin plasmas, the emission intensity strongly depends on the electron density. A sharp structure appears once the plasma from the left-plane reaches the plasma near to the right-plane. The fact that the plasma from the left-plane goes through the fast plasma from the right-plane is evidence of the collisionless interaction of the counter-streaming plasmas. The enhanced self-emission of the sharp structure results from an interaction between the fast plasma from the left-plane and the plasma near to the right-plane. The steepening of the structure indicates that a shock wave is excited. This shock propagated from the right to the left at the velocity of 40 km/s.
Figure 5. (a) Schematic of double-plane target. The target normal lies 30° from the laser axis. (b) SOP image. The laser timing corresponds to the top of the image. (c) Stack plot of line profiles of the SOP image in (b) from 7 to 27 ns. $x_2$ axis in (b) and (c) shows the spatial scale normalized to the ion inertial length. (d) Self-emission and (e) SG snapshots at $t = 25$ ns [97].

Figure 5(c) shows a stack of line profiles taken from the SOP image in Figure 5(b). As shown in Figure 5(c), from 7 to 9 ns the profiles grow continuously from left to right, and the plasma from the right plane simply expands thermally. At 13 ns, a structure is formed at $x \sim 3.4$ mm. As time evolves its profile steepens and it propagates to the left. The shock thickness was typically 100 µm.

Figure 5(d) and (e) show self-emission and SG [with an optical probe laser (532 nm, ~10 ns, ~300 mJ)] snapshots of the shock structures at $t = 25$ ns. The vertical and horizontal dashed lines are the target positions and the nominal positions of the regions of the plasmas imaged onto the streak camera slits, respectively. In Figure 5(d) a shock structure is clearly seen in front of the right plane at $x \sim 3$ mm. The curvature of the shock front indicates that actual shock thicknesses can be thinner than those seen in SOP line profiles. In Figure 5(e) a flat filament is seen at a similar position $x \sim 3$ mm, indicating the presence of a large density-jump.

These results strongly indicate collisionless ES shock formation in counterstreaming plasmas.

2.2.3. Shock and plasma parameters: Gekko XII laser experiment [98]
The third experiment was also carried out with Gekko XII HIPER laser system with CH double-plane target (3.8 mm × 3.8 mm × 200 µm in thickness, 4.6 mm in separation). Three beams were focused to the first foil with the incident angle of 45°. Figure 6(a) and (b) show side view and top view, respectively, and the axes $Z$ and $X$ are defined as in Figure 6(a). Thomson scattering (TS) probe laser (532 nm, ~350 mJ, ~10 ns) was focused on the center of the two foils. The scattered light was detected at 90° from the TS probe by using a triple-grating spectrometer (TGS). An ICCD with a minimum gate width of 2 ns was used for the TGS. The
Figure 6. The schematic view of the target. HIPER laser beams are focused on the inner surface of the first foil. TS probe is shown in (a) side view and (b) top view. (c) SOP image and (d) SG at 30 ns. The TS probe is focused at $x = 0$ and $z = 2.3$ mm, and its angle between the target normal direction is $60^\circ$. Therefore, if we assume the axial symmetry of the plasma, the trajectory of the TS probe is shown by the dashed line in (d). TS spectra at (e) P1 and (f) P2 shown in (d). The solid lines show the result of best fit. The dotted line is the theoretical function with the parameters obtained from the best fit (solid line). The probe laser wavelength $\lambda_c = 532$ nm is blocked with a notch filter as shown with a shaded area ($\lambda = \lambda_c \pm 0.06$ pm) [98].

Plasmas were diagnosed by optical diagnostics from the vertical direction with SG and SOP as shown in Figure 6(b).

Figure 6(c) shows SOP image. Counter-streaming plasmas are observed, resulting in shock formation as marked with white arrows. Shock S1 is a collisionless ES shock as discussed in Ref. [97]. Clear density-jumps are observed in SG at 30 ns [Figure 6(d)].

In order to derive plasma parameters, CTS ion-term measurement was performed. The TS spectra at $z = 2.4$ mm ($x = -0.2$ mm) (position P1) and 2.8 mm ($x = -0.9$ mm) (position P2) are shown in Figure 6(e) and (f), respectively. The separation between two ion-acoustic features is $2\lambda_{ac}$, and $\lambda_{ac}$ is determined by a frequency of ion-acoustic wave as $\omega \sim kC_s \sim k\sqrt{(ZT_e + 3T_i)/(m_i(1 + k^2\lambda_D^2))}$, where $\lambda_D$ is the Debye length. A smaller deviation ($\Delta\lambda$) from the laser wavelength and larger $\lambda_{ac}$ at P2 [Figure 6(e)] compared with those at P1 [Figure 6(f)] clearly shows that the flow from the first foil is decelerated and its temperature increases, i.e. a shock surface exists at $z \sim 2.5$ mm, and the positions P1 and P2 are the upstream and downstream of the shock, respectively. Derived plasma parameters for electrons and carbon ions at P1 and P2 were $T_e \approx 24$ eV, $T_i \approx 20$ eV, $C_s \approx 28$ km/s, $v_d \approx 89$ km/s, $Z \approx 2.9$, $n_e = 7.5 \times 10^{18}$ cm$^{-3}$, and $T_e \approx 103$ eV, $T_i \approx 71$ eV, $C_s \approx 62$ km/s, $v_d \approx 18$ km/s, $Z \approx 3.7$, respectively. At P1, since flow velocity is large and temperature is low, it is supersonic, whereas at P2, since flow velocity is small and temperature is high, it is subsonic, i.e. P1 and P2 correspond to upstream and downstream of a shock.
The temperature ratio between the downstream and upstream $T_1/T_0$ is expressed as a function of upstream Mach-number $M_0$ and the adiabatic constant $\gamma$ with the Rankine–Hugoniot relation: $T_1/T_0 = \left[2\gamma M_0^2 - (\gamma - 1)\right]/(\gamma + 1)^2 M_0^2$. Using the ion temperature ratio of $T_1/T_0 = 3.6$ and $\gamma = 5/3$, $M_0 = 3.0$ is obtained, which shows a good agreement with the measured $M_0 = 3.1$ for the slow shock velocity of $v_s \sim 0$.

In this section, temporally and spatially resolved plasma parameters in the upstream and downstream regions of a shock were measured with CTS diagnostics, and agreed relatively well with the Rankine–Hugoniot relation.

2.2.4. Shock electric field measurement: Jupiter laser experiment [99]

The fourth experiment was performed with Jupiter laser facility (527 nm, $\sim 120$ J, 1.5 ns, $D \sim 500 \mu$m) at Lawrence Livermore National Laboratory, U.S.A. Double-plane Mylar (CHO) target (2 mm $\times$ 2 mm $\times$ 500 $\mu$m in thickness, 3 mm in separation) was used, and the inner surface of one of the disks (drive disk) was illuminated by a drive laser.

A laser pulse (160 J, 0.7 ps, wavelength of 1057 nm) was focused on an Au disk with a thickness of 25 $\mu$m to produce high-energy protons for radiography. The proton beam images electric and magnetic fields formed in the laser–produced plasmas on RC films located at an imaging plane. The RC films were stacked to detect protons in different energy ranges: 4.7, 7.0, 8.8, and 10.7 MeV with 10% energy width for each film. Figure 7(a)–(d) show the proton images at $t = 20$ ns for the proton energies of 4.7–10.7 MeV. A caustic structure, or a sudden change in proton intensity, which indicates a large electromagnetic field [64], is observed at $x \sim 15$ mm in each image. The line–out of the caustic for Figure 7(a)–(d) are shown in Figure 7(e)–(h).

The observed caustic structure corresponds to a shock front. Here, we assume that the protons are deflected by an electric field not by a magnetic field. The de-

![Figure 7](image-url)

Figure 7. The proton image taken at $t = 20$ ns for the proton energy of (a) 4.7, (b) 7.0, (c) 8.8, and (d) 10.7 MeV. The line–out at $x \sim 15$ mm for (e) 4.7, (f) 7.0, (g) 8.8, and (h) 10.7 MeV. (i) Caustic thickness as a function of proton energy. The measured thickness (solid squares) is evaluated as a full width at half maximum of each line–out shown in (e)–(h). Note: (i) The calculated thickness for $\delta = 1.5 \mu$m (solid line; the best fit result), $\delta = 8 \mu$m (dashed line), and $\delta = 0.01 \mu$m $\sim \lambda_D$ (dot-dashed line) [99].
Reflection angle $\alpha$ of the proton beam by a spherically symmetric flat–top potential is expressed as $\alpha(x_0) = (e\varphi_0x_0/2W\sqrt{\delta})F(\tilde{x}) = (e\varphi_0(\tilde{x}\delta + a)2W\sqrt{\delta})F(\tilde{x})$ [64], where $\tilde{x} = (x_0 - a)/\delta$, $\delta$ is the transition thickness, $a$ is the curvature radius of the potential structure, $W$ is the proton energy, $e\varphi_0$ is the potential energy, and $F(\tilde{x}) = (2/\pi)\int_{-\infty}^{\infty} d\eta/(\eta^2 + \tilde{x})^2 + 1$. In case of caustic formation on the imaging plane, $\partial x/\partial x_0 = 0$ is satisfied. Therefore, $1/\delta + (e\varphi_0/2W\delta\sqrt{\delta})[\delta F(\tilde{x}) + (\tilde{x}\delta + a)F(\tilde{x})] = 0$. Generally, this equation has two solutions ($\tilde{x}_1$ and $\tilde{x}_2$), however, the caustic positions $x(\tilde{x}_1)$ and $x(\tilde{x}_2)$ cannot be resolved in this experiment because of small separation between them. Therefore, these two caustics are observed as a single peak in the proton intensity, and the thickness of the electric field at the shock front ($\delta$) is comparable to $\delta \approx |x(\tilde{x}_2) - x(\tilde{x}_1)|$.

The measured thickness of the caustic for four proton energy is shown in Figure 7(i), and is fitted for various shock thickness $\delta$ and potential energy $e\varphi$. As a result, the best-fit result is obtained for $\delta = 1.5 \mu m (\sim c/\omega_{pe})$ and $e\varphi = 0.42$ keV. For $\delta = 8 \mu m$, the calculated shock thickness shows a large deviation from the measured ones. Note that the Carbon ion inertial length $c/\omega_{pi}$ is of the order of hundreds of $\mu m$ and is much larger than the shock thickness estimated here. On the other hand, since the difference in the calculated caustic thickness for $\delta = 1.5$ and $0.01 \mu m (\sim \lambda_D)$ is small, we cannot exclude a possibility to have a shock thickness smaller than $1.5 \mu m$, i.e. we can only conclude that $\delta \leq c/\omega_{pe}$. Therefore, the measured shock thickness is determined not by ion scale ($c/\omega_{pi}$), but electron scales ($c/\omega_{pe}$ or $\lambda_D$).

The ion–ion Coulomb MFP for counter-streaming plasmas is expressed as $\lambda_{ii} = 2\pi\varepsilon_0m_i^2\langle v_i \rangle^4/(n_iZ^4e^4\ln\Lambda)$ [105], where $\varepsilon_0$ is the vacuum dielectric constant, $\langle v_i \rangle$ is the average relative ion velocity, and $\ln\Lambda = \ln(\lambda_D4\pi\varepsilon_0m_i\langle v_i \rangle^2/(Z^2e^2))$. $\langle v_i \rangle$ can be estimated with time $t$ from laser timing and distance $L$ between two foils as $\langle v_i \rangle = L/t$. Using the measured $n_e = 5 \times 10^{18} \text{ cm}^{-3}$, $\langle v_i \rangle = 150 \text{ km/s}$ for $L = 3 \text{ mm}$ and $t = 20 \text{ ns}$, and assuming $Z \simeq 3$ for Carbon, we obtain $\lambda_{ii} \simeq 150 \mu m$ for carbon ions. Thicknesses of shocks without an external magnetic field, i.e. collisional, EM, and ES shocks are of the order of $\lambda_{ii}$, $c/\omega_{pi} \simeq 200 \mu m$, and $\lambda_D \simeq 0.01 \mu m$ for $T_e$ of few tens of eV, respectively [7,55,57,78,88,106]. On the other hand, the derived shock thickness $\delta$ was less than a few $\mu m$, $\delta < c/\omega_{pe}$ (which is $\sim 2 \mu m$), and much smaller than $\lambda_{ii}$ and $c/\omega_{pi}$, i.e. $\delta \ll \lambda_{ii}, c/\omega_{pi}$. Since we do not have good enough resolution in measurement, it is difficult to clarify whether $\delta$ is closer to $c/\omega_{pe}$ or $\lambda_D$. Therefore, the observed shock is neither collisional shock nor collisionless EM shock but collisionless ES shock. It is difficult to measure a shock thickness of less than a few $\mu m$ experimentally and it is an important future problem needed to be resolved.

To summarize, the thickness of the transition region associated with a shock was characterized by electron scales, suggesting the formation of collisionless ES shock.
3. Summary

In this article, we first reviewed historical achievements of three types of collisionless shocks, MHD, EM, and ES collisionless shocks, in theory/simulation, observation in space and astrophysical plasmas, and laboratory experiments.

In Section 2, we gave a recent progress of collisionless ES shock experiments using high-energy laser systems with two schemes; one is an interaction between laser-produced high-density ablating plasma and a low-density ambient plasma, and the other is an interaction between laser-ablated counter-streaming plasmas using double-plane target. For the former scheme, detailed measurements of structures of collisionless ES shock and ion-acoustic soliton, and the transition from double-layer to collisionless ES shock are conducted by proton radiograph. For the latter scheme, the measured large density-jump, steepening of self-emission profile, plasma parameters in the up- and down-stream regions of a shock, and the narrow width of the shock electric field compared with the ion-ion Coulomb MFP reveal the evidence for the formation of collisionless ES shock.

Successful generation of collisionless MHD [45,46] and ES shocks, and experimental approach to study collisionless EM shock [60–62,64,65] in laboratory indicate that laboratory experiment can be an alternative approach to study space and astrophysical plasma physics. Furthermore, recent achievement of mono-energetic proton acceleration by collisionless ES shock produced by ultra-high-intensity laser system [84–86] shows a possibility to apply the collisionless shock to several applications including medical treatment.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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