**Article:**

Kuramitsu, Y., Matsukiyo, S., Isayama, S. et al. (28 more authors) (2016) Spherical shock in the presence of an external magnetic field. Journal of Physics: Conference Series. 012056. ISSN 1742-6596

https://doi.org/10.1088/1742-6596/688/1/012056

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2016 J. Phys.: Conf. Ser. 688 012056

8th International Conference on Inertial Fusion Sciences and Applications (IFSA 2013) IOP Publishing
Journal of Physics: Conference Series **688** (2016) 012056 doi:10.1088/1742-6596/688/1/012056

# Spherical shock in the presence of an external magnetic field

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**Abstract.** We investigate spherical collisionless shocks in the presence of an external magnetic field. Spherical collisionless shocks are common resultant of interactions between a expanding plasma and a surrounding plasma, such as the solar wind, stellar winds, and supernova remnants. Anisotropies often observed in shock propagations and their emissions, and it is widely believed a magnetic field plays a major role. Since the local observations of magnetic fields in astrophysical plasmas are not accessible, laboratory experiments provide unique capability to investigate such phenomena. We model the spherical shocks in the universe by irradiating a solid spherical target surrounded by a plasma in the presence of a magnetic field. We present preliminary results obtained by shadowgraphy.

## 1. Introduction

Collisionless shocks are universal phenomena in space and astrophysical plasmas, where supersonic or super Alfvénic plasma flows encounter sounding media, such as shocks in supernova remnants. A remarkable feature of collisionless shocks is the nonthermal acceleration of energetic particles or cosmic rays. It is widely believed that the cosmic rays are accelerated in the shock environments, where one of the most important factors is the field orientation against the shock normal. However, one of the most uncertain values in the astrophysical observations is the magnetic field. For instance, the relation between the field orientation and the acceleration

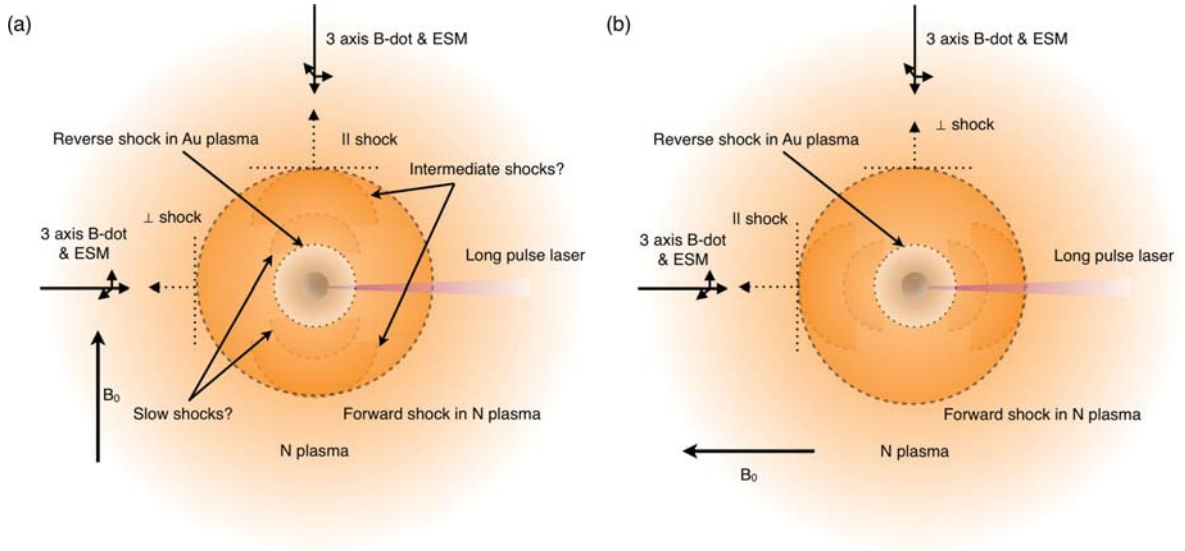


**Figure 1.** Schematics of the experimental conditions. In order to avoid the anisotropy caused by the laser, two magnetic field geometry will be applied.

efficiency of the cosmic rays is a long-standing and fundamental unsolved problem. So far, numerical simulations had been only ways to investigate such the problem [1, 2, 3].

Recently laboratory simulations of space and astrophysical phenomena have been actively investigated with high-power and ultra intense lasers. Collsionless shocks have been successfully created in laboratory plasmas. Shock density and emission jumps and the time evolution were obtained with optical imaging [4, 5]. A turbulent shock electric field was observed with proton radiography [6, 7]. Together with the global imaging, local observation of the magnetic field has demonstrated the field origin in the universe [8]. Local quantities of plasmas such as the density, velocity and temperature for ions and electrons can be obtained by collective Thomson scattering measurements [9, 10] Moreover, it is also possible to measure the energy distribution functions of accelerated electrons with electron spectrometer [11, 12]. These are unique and great advantages of laboratory investigation of space and astrophysical phenomena, that is, the simultaneous observations of the global and local quantities and the energy distribution functions of particles. With these capabilities we investigate the shock propagations and the particle acceleration in the presence of a magnetic field, and their dependence on the field orientation. Furthermore, we will investigate the possibility to prove the existence of an intermediate shock, which is believed to exist in theoretical and numerical studies [13, 14, 15], however, no one has been experimentally observed it.

## 2. Experiment

The experiment is carried out with Gekko XII laser facility at Osaka University. Three beams of long pulse laser (energy of 100 - 120 J at $3\omega$, temporal and spatial Gaussian shape with 500 ps pulse duration and 300 $\mu$m spot, F/15 for each beam) irradiate a spherical solid target in order to create relatively isotropic plasma expansion. The experimental setup is shown schematically in Fig. 1. The target environment is gas filled with nitrogen (N), which is ionized with the radiations from the laser-solid interaction. In order to efficiently ionized the ambient gas a high-Z materials is used to enhance the radiations. We use a gold (Au) coated plastic balloon target. The ionized N ($3 \times 10^{17}$ cm-3) will be magnetized by an external magnetic field. The magnetic field is applied with two permanent magnet ($\sim 0.6$ T on surface with 20 mm diameter) to provide a relatively uniform and straight magnetic field $\sim$ 0.04 T for the region of interest. The shock formations and propagations in a magnetized plasma strongly depend on the orientation of the magnetic field with respect to the shock normal direction. We measure these difference with optical imaging, collective Thomson scattering (CTS), and magnetic induction probes (also know as B-dot probes). The electron density and distribution images are obtained with interferometer and shadowgraphy, respectively. Images of emissions from plasmas also obtained with spatial and temporal resolutions. The time evolution is obtained with self-emission streaked optical pyrometer (SOP) and streaked shadowgraphy. We measure the ion feature with CTS, providing us the local information of the plasma bulk velocity, the sound velocity and the electron density. The two channels of B-dots provide three vectors, local magnetic field in two different positions, corresponding to two different angles between the magnetic field and the shock normal.

We expect to observe the different shock conditions at the different angles, however, the direction of laser incidence also provides an effective anisotropy. In order to distinguish the effects of the magnetic field from the laser, we rotate the magnets to have two different magnetic field orientation keeping all the other experimental conditions. If the magnetic field is dominant over the laser incidence, anisotropy in shock propagations and the shock magnetic field are also rotate so as the magnetic field rotation. If the laser effect is dominant, even though the external magnetic field is rotated, we will observe nominally identical images and local magnetic field.

## 3. Results

Figure 2 shows images obtained from shadowgraphy with different conditions as (a) from 23 ns from main laser arrival and the nominal laser incidence has 30 degrees from the magnetic field, (b) the same as (a) except 28 ns from the main laser arrival and with different field of view, and (c) the same as (b) except the magnetic field is perpendicular to the laser incidence. The solid arrows and the solid circles in the images represent the directions of the magnetic field and the positions of the target (500 $\mu$m diameter) with the stalk before the shots. As marked by numbers two or three sharp lines can be recognized. These correspond to large density jump and hence possibly multiple shock waves. In Fig. 2 (a) three shock like structures degenerated as pointed by the dashed arrow. The degeneration of the shock like structures are seen in Fig. 2 (b) and 2 (c). The dashed lines in Figs. 2 (b) and 2 (c) show the tangential lines on the degeneration point and the normal lines to them. Since in Fig. 2 (c) the magnetic field is rotated 60 degrees from Fig. 2 (b), if the degeneration results from the shock propagation in the different field geometry, the dashed lines have to rotate 60 degrees. Our results show that there are some difference but not as large as expected. The degeneration is not purely determined by the magnetic field but the laser mostly affects the shock geometries. The number of shocks are in most cases two.

## 4. Discussions and summary

The simplest interpretation of these structures are the forward and reverse shocks. When there are three structures, one might consider the contact discontinuity as one of them. However, it is not necessary to degenerate the shock waves if they are a pair of forward-reverse shock. One might think that the multiple shocks come from the multiple laser beams. The shock propagation velocities are about 500 km/s from the time of the images taken and the positions of the shock fronts. The spatial separation of the two or three shock fronts are $\sim$ 1 mm, corresponding to the time needed for the shock waves propagate is $\sim$ 2 ns. This is much larger than the main laser jitter, and thus, the multiple shocks do not correspond to the number of laser beams. In magnetohydrodynamics there can be 7 discontinuities when a magnetized plasma explodes in a magnetized plasma. In our experiment the Au plasma is unlikely magnetized due to its large mass and high velocity. Moreover, the Larmor radius of the N plasma is also very large, at least of the order or larger than the field of view of the shadowgraphy. The electrons of N plasma are well magnetized, and therefore, we have to consider the electron dynamics to understand

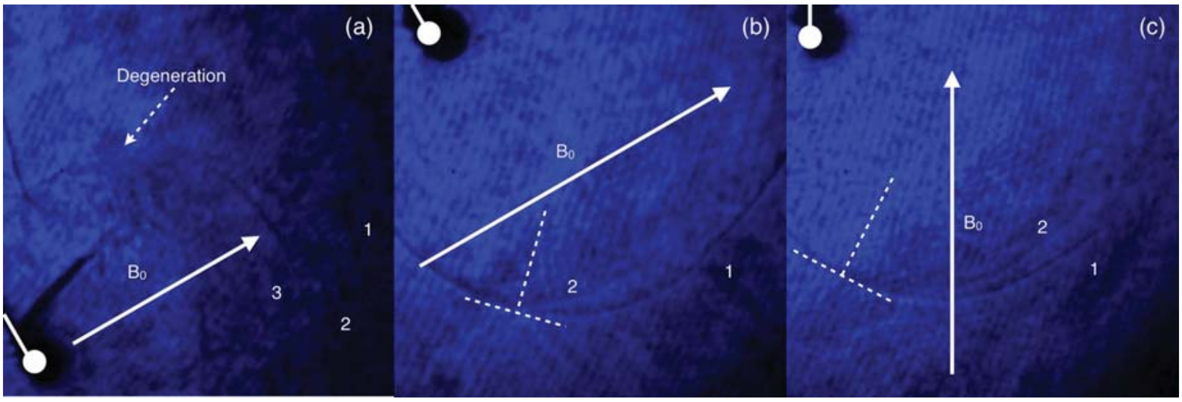


**Figure 2.** Images taken with shadowgraphy.

the observed structures. We need to characterize the N plasma with radiative hydrodynamic simulations. The radiation is stronger on the ablation side than the opposite side to the laser irradiation. Furthermore, the laser beams can directly ionize the N gas only on their paths. Anisotropies naturally arise from the laser configuration. In order to determine what kind of discontinuities they are and how the anisotropies arise, further analyses and experiments are required together with the aid of theoretical and numerical study.

We report the first experimental investigation on anisotropy of spherical shock in the presence of an external magnetic field. By irradiating a spherical solid target in an ambient media with laser, spherical shocks are excited in the presence of magnetic field. There are two or three shock like structures observed with optical diagnostics. These shock waves anisotropically expand and show degeneration on some directions. When magnetic field is rotated, the degeneration occurs in different place, but not as much as the change of magnetic field. This indicates that the laser configuration also affects the shock geometry. We have shown the first preliminary data of spherical shock wave, providing us rich and challenging phenomena to investigate. It should be noted that by changing the conditions of laser, target and magnetic field one can investigate variety phenomena, such as MHD shocks including the intermediate shock, micro-shocks governed by electron dynamics, and the shocks in SNRs.

## Acknowledgments
We would like to appreciate the technical supports from Institute of Laser Engineering.

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