

## LABORATORY SIMULATION OF MAGNETOSPHERIC PLASMA SHOCKS

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**Abstract.** An experimental simulation of planetary magnetospheres is being developed to investigate the formation of collisionless shocks and their effects. Two experimental situations are considered. In both, the solar wind is simulated by laser ablation plasmas. In one case, the “solar wind” flows across the magnetic field of a high-current discharge. In the other, a transverse magnetic field is embedded in the plasma flow, which interacts with a conductive obstacle. The ablation plasma is created using the “Tomcat” laser, currently emitting 5 J in a 6 ns pulse at 1  $\mu\text{m}$  wavelength and irradiance above  $10^{13}$  W/cm<sup>2</sup>. The “Zebra” z-pinch generator, with load current up to 1 MA and voltage up to 3.5 MV produces the magnetic fields. Hydrodynamic modeling is used to estimate the plasma parameters achievable at the front of the plasma flow and to optimize the experiment design. Particle-in-cell simulations reveal details of the interaction of the “solar wind” with an external magnetic field, including flow collimation and heating effects at the stopping point. Hybrid simulations show the formation of a bow shock at the interaction of a magnetized plasma flow with a conductor. The plasma density and the embedded field have characteristic spatial modulations in the shock region, with abrupt jumps and fine structure on the skin depth scale.

**Keywords:** collisionless bow shock, magnetosphere, laboratory simulation

### 1. Introduction

Laboratory simulations have been considered for decades a source of information complementary to observational data and computer simulations for understanding physical phenomena related to collisionless shocks in extraterrestrial plasmas (Baranov, 1969; Podgorny and Sagdeev, 1969; Drake, 2004; Horton and Chiu, 2004; and references therein). In this paper we present the development of an experiment planned to simulate the interaction of the solar wind with a planetary magnetosphere, namely to investigate the formation of collisionless bow shocks and magnetospheres from magnetic obstacles.

The surrogate solar wind is generated by laser ablation and it interacts with a magnetic field powered by a z-pinch generator. This approach, based on higher energy density “solar wind” and stronger magnetic fields leads to interaction regions



smaller and time scales shorter than in previous experiments and is advantageous from the point of view of diagnostics. For example, the  $z$ -pinch can generate magnetic fields up to megagauss values and this makes possible the measurement of the magnetic field distribution in the dense plasma using non-perturbative diagnostics such as Faraday rotation and Zeeman splitting.

## 2. Experiment Design

To evolve into relevant physical states, the experimental system must have similar characteristics to the natural system it attempts to model. A few of these constraints are detailed here. To form a shock, the plasma flow velocity ( $u$ ) has to exceed both the sound velocity ( $M > 1$ ) and the Alfvén velocity ( $M_A > 1$ ). Also, collisions have to be prevented from perturbing the formation of the shock, which means that the mean free path for ion-ion collisions ( $\lambda_{ii}$ ) has to be much larger than the space scale of the shock which is given by the ion Larmor radius ( $r_{Li}$ ). Practical matters have to be considered as well. For example, the magnetic field strength must be adequate to stop the plasma flow in the original direction (to form a “magnetopause”) before reaching the magnetic field source. Additional constraints are imposed by the sensitivity of diagnostics.

All these requirements are satisfied by an expanding Hydrogen plasma with flow velocity  $u = 4 \times 10^7$  cm/s, density  $n_e = n_i = 10^{17}$  cm $^{-3}$ , temperature  $T_e = T_i = 400$  eV, and magnetic field strength  $B = 30$  kG. In this case  $M = 1.4$ ,  $M_A = 2.1$ ,  $\lambda_{ii} = 4.8$  cm,  $r_{Li} = 0.14$  cm,  $c/\omega_{pi} = 0.07$  cm,  $\beta = 1.8$ ,  $\omega_{ci} = 3 \times 10^8$  rad/s. To obtain further insight in the details of the experiment, necessary for the experimental design, particle-in-cell (PIC) and hybrid simulations were performed with these parameters.

A 1D ( $x$ ) PIC simulation of the collisionless interaction of a plasma flow across a magnetic field in the direction of a positive gradient of the field strength showed that the ions are stopped and reflected, and that they transfer half of their directed kinetic energy to the electrons (Sentoku, 2004). A 2D PIC simulation in the plane ( $x, z$ ) perpendicular to the magnetic field lines was performed with scaled parameters (Sentoku, 2004). When flowing in the magnetic field, the plasma does not expand in the  $z$  direction and the flow continues beyond the stopping point predicted by pressure balance. This simulation confirmed that the ions are stopped when half their directed kinetic energy is imparted to electrons, resulting in significant electron heating and the population of a non-Maxwellian high-energy tail. Due to the geometry adopted, these predictions do not take into account the plasma flow along the magnetic field lines ( $y$ ).

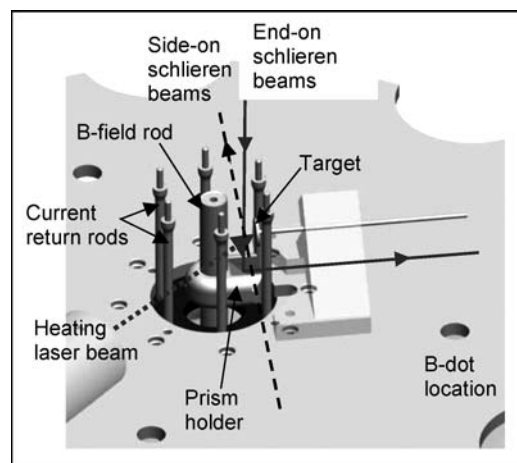
A 2D hybrid simulation (Sotnikov, 2005) performed in the ( $x, y$ ) plane determined by the plasma velocity and the magnetic field, predicted the formation of a collisionless bow shock at the interaction of a magnetized plasma flow with a conductive obstacle, in a regime relevant to the formation of cometary bow shocks.

The collisionless shock forms after several times the inverse of the ion cyclotron frequency ( $\omega_{ci}$ ).

### 3. Experiment Set-Up

In the present experiment the solar wind is simulated by an expanding laser ablation plasma and the magnetosphere by the azimuthal magnetic field produced by a  $z$ -pinch generator. This gives to some extent independent control on the parameters of the simulated “solar wind” and “magnetosphere”.

The plasma flow is created by the “Tomcat” laser with pulse energy up to 5 J at  $1\ \mu\text{m}$  wavelength and 6 ns pulse width. Focused to a spot diameter less than  $100\ \mu\text{m}$ , the laser irradiance on target is higher than  $10^{13}\ \text{W}/\text{cm}^2$ . The laser beam is incident at  $45^\circ$  on a thick plastic target. The “Zebra”  $z$ -pinch generates up to 1 MA load current with rise-time of about 100 ns. Depending on the load geometry, it can produce magnetic fields up to megagauss values. In the present experiment “Zebra” is used in the long pulse regime with maximum current 0.6 MA and rise time 200 ns. At the target position the typical magnetic field is 7 T and has a positive gradient along the normal to the target surface. The main components of the experimental set-up are shown in Figure 1. The vacuum magnetic field is measured with differential B-dot probes in the location indicated and in the top plate. The laser is typically synchronized with the  $z$ -pinch such that the ablation plasma is produced and evolves during a constant magnetic field period at the current peak. The experiment is optimized for high repetition rate by using a rotatable



*Figure 1.* The main components of the experimental set-up are the target heated by a laser pulse (dotted arrow) and the current-carrying load with a center rod and current-return rods (the top of the structure is hidden for clarity). The laser beam paths used for schlieren imaging are also shown.

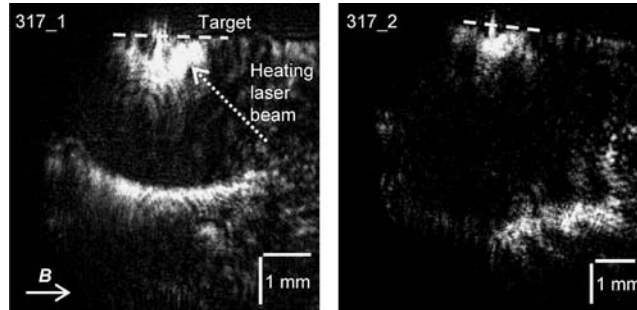


Figure 2. Top-view two-frame schlieren images. The position of the target, the direction of the heating laser beam, and the orientation of the magnetic field are shown.

target and an oversized field generating rod. In the current experiment, the vacuum is maintained lower than  $10^{-5}$  Torr to avoid any influence of the background gas.

Two-frame schlieren imaging is used to probe the plasma density gradients. A laser with 0.2 ns pulse width and 532 nm wavelength is used. The laser beam is split in two beams that follow the same path with 8 ns delay. The field of view is approximately 6 mm and is centered 2 mm in front of the target. The dark field image is created with a knife edge. The overall space resolution is better than  $10\ \mu\text{m}$ .

An example of schlieren images obtained with the current set-up (end-on) is shown in Figure 2. In the plane containing the normal to the target and the magnetic field vector ( $x, y$ ), the two frames show a plasma front with steep density gradient. This structure propagates perpendicular to the magnetic field and expands along the magnetic field lines at about the same rate. The front decelerates as it propagates towards stronger field regions. The formation of the steep gradient structure at the front of the plasma flow and its deceleration are similar to the predictions of the PIC simulations.

Upgrades are planned for all components of the experiment. The laser energy and the magnetic field strength will be increased, and a 2D dipole configuration will be implemented. To investigate the effects predicted by simulations, several diagnostics will be added including time-gated interferometry to measure the actual density distribution and time-gated space-resolved spectroscopy to detect the temperature increase expected at the stopping point.

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