7th Asia-Pacific Conference on Plasma Physics, 12-17 Nov, 2023 at Port Messe Nagoya

PIC Simulations of Perpendicular and Parallel Piston-Driven Shock Dynamics in a Magnetized Plasma

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In astrophysical systems, magnetized collisionless shocks are frequently observed [1]. In laboratory experiments, these shocks can be replicated on a smaller scale by using laser-driven piston plasmas in the presence of a magnetized background plasma [2,3]. An essential factor in these experiments is the angle (θ_B) between the direction of shock propagation and the background magnetic field. This study is meant to help with experiments and will provide valuable information to design and understand those experiments better.

To investigate shock formation and evolution, we conducted quasi-1D collisionless piston-driven shock simulations, varying the shock angle from $\theta_B = 90°$ to $\theta_B = 30°$. The results demonstrate that, regardless of the angle considered, the spatial and temporal scales of shock formation are similar when measured using the perpendicular component of the magnetic field.

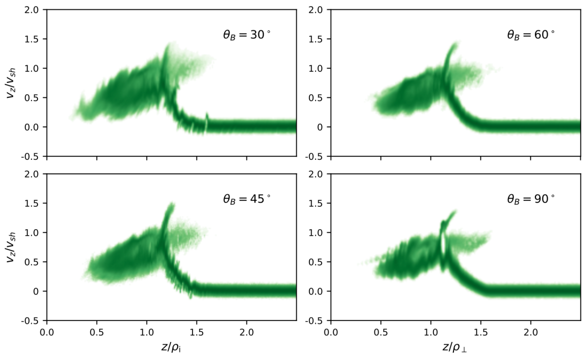

Figure 1 Phase space plots of the velocity v_z of the ambient ions along z for four shock angle θ_B at $t = \tau_\perp$. The velocity is normalized by the shock speed v_{sh}, z is normalized by the perpendicular gyroradius $\rho_\perp$, and time is normalized by the perpendicular gyroperiod $\tau_\perp$. Darker green indicates stronger concentrations of the ions. At the same normalized time, the phase space distribution from all simulations are similar.

Despite having different shock angles, Figure 1 reveals that the velocity distribution in all simulations appears similar when observed at the same distance and time, quantified in terms of $\rho_\perp = m_i v_p/(q_i B_\perp)$ and $\tau_\perp = m_i/(q_i B_\perp)$. Here, m_i denotes the ion mass, v_p represents the piston speed, q_i is the ion charge, and $B_\perp$ corresponds to the magnetic field perpendicular to the shock propagation direction.

The piston plasma accumulates magnetic flux per unit length, which is proportional to the average rigidity of the piston ions, expressed as $\frac{m_i v_p}{q_i} = \rho_\perp B_\perp$. This magnetic flux is crucial for the shock formation process. It serves as a minimal requirement for bending and redirecting an excessive number of incoming upstream particles within the shock layer.

The observed constancy of the perpendicular magnetic field can be easily explained. The time and distance required for shock formation are inversely proportional to $\sin\theta_B$. Consequently, at lower θ_B values, shock formation takes longer and covers a greater distance in absolute units. However, since $B_\perp$ (perpendicular magnetic field component) remains dominant over $B_\parallel$ (parallel magnetic field component), shock formation still evolves similarly when expressed in normalized units.

At a later stage when shocks become stationary, we examine the extent of perpendicular heating and parallel heating. For all considered values of θ_B , the perpendicular heating exhibits similarity. In the case of $\theta_B = 90°$, the parallel heating is negligible because the parallel temperature is extremely small compared to the perpendicular temperatures. This may imply that the absence of variation along the magnetic field suppresses the parallel heating. Conversely, for all other θ_B values, there is variation along the magnetic field in the downstream region, making parallel heating effective. Furthermore, this parallel heating is more pronounced for smaller θ_B values.

The PIC simulations were conducted on the Summit supercomputer at the Oak Ridge Leadership Computing Facility at the Oak Ridge National Laboratory. We acknowledge support by the National Science and Technology Development Agency (NSTDA) and National Research Council of Thailand (NRCT): High-Potential Research Team Grant Program (N42A650868), by grant RGNS 63-045 from the Office of the Permanent Secretary, Ministry of Higher Education, Science, Research and Innovation, and from the NSRF via the Program Management Unit for Human Resources ¥& Institutional Development, Research and Innovation (B37G660015).

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