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Numerical analysis of hydrodynamic instability in magnetized laser ablation flow

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ABSTRACT

We have conducted radiation magneto-hydrodynamics (RMHD) simulations of Richtmyer–Meshkov instability (RMI) in a magnetized counter flow produced by intense lasers. A jet-like plasma from a planar plastic target is formed and maintained in several-tens of nanoseconds by expanding plasma from rear side of two separated laser spots, and parallelly located another target is ablated by the radiation from the plasma, reproducing past experimental works. A planar shock driven by the radiation interacts with the jet as a nonuniform density structure, resulting in the RMI. The magnetic field is amplified up to ~40 times greater than the background value at the interface at which the instability occurs. However, a certain extent of the amplification results from the compression effect induced by the counter flow, and the obtained amplification level is difficult to be measured in the experiments. An experiment for observing a clear amplification must be designed through the RMHD simulations so that the RMI takes place in the low-density area between two targets.

1. Introduction

Massive stars end their lifetimes by an enormous explosion called supernova, which is a phenomenon emitting a large amount of energy that may be an origin of high-energy photons observed at ground. Supernova remnants (SNRs) are formed by interstellar matters gathered due to shock waves, and brighten up with a wide wavelength range from radio to gamma ray. In particular, the shock wave propagating in an inhomogeneous interstellar medium in the SNRs provides the acceleration field of high-energy particles, and the accelerated particles are the important sources of radiation. Therefore, investigating the mechanism of the particle acceleration due to the shock waves in the SNRs is significant for understanding the origin of cosmic rays.

Recently, synchrotron X-ray emissions were observed in a shell of the SNR RX J1713.7-3946 decaying with a one-year timescale [1]. For justifying electron cooling of synchrotron emissions in such a short timescale, strong magnetic fields is needed in a few hundred times greater level than the background one of 10^{-10} T.

On the other hand, as recently pointed by several authors, the background magnetic field may be amplified by accompanied turbulence [2]. Since there are density inhomogeneities of an interstellar medium in front of a supernova-driven shock wave, some eddies are formed by the Richtmyer–Meshkov instability (RMI) [3,4] and develops the perturbation on the surface of the density discontinuity. Since the vortex sheets are formed in the density-discontinuity surface due to the RMI, the rotating electric current is induced by the shear flow and amplifies the magnetic field [5,6]. In theoretical and numerical study, magnetic fields are amplified up to two orders of magnitude from those of the background by the RMI [6,7]. Since there might be some microfield in the SNRs, it will be amplified to the considerable level that creates high-energy particles through the well-developed turbulence, while the magnetic field also has some suppression effects on the RMI in the magnetized flow [8–10].

Several laboratory-astrophysics experiments relevant to the SNR environment were performed by high-power lasers that produces an interacting field among shock waves, magnetic fields, and density inhomogeneities [11,12]. Although the hydrodynamic instability has been observed in such laser experiments [13,14], no clear indication of the field amplification has been found yet with an external magnetic field. Numerical analysis is helpful to examine

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an evolution of the magnetic field in the laser-produced plasma flows and to design the optimal experiments. So, we have developed a two-dimensional radiation hydrodynamics (RHD) code including the magnetic induction equation, and simulated for the experiments of a counter flow from double plastic targets irradiated by high-power lasers.

2. Numerical modeling

The magnetic Reynolds number $R_m = UL/\eta$ is defined with the characteristic velocity U, the scale length L, and the plasma diffusivity η. In a laser-produced ablation plasma considered now, $R_m > 100$ for $U > 10^7$ cm/s, $L \sim 10^{-1}$ cm, $n_e \sim 10^{18}$ cm^{-3} and $T_e > 100$ eV, since the diffusivity can be estimated by $\eta = c^2 m_e \nu_{ei\|}/4\pi n_e e^2$, where c is the speed of light, m_e the electron mass, $\nu_{ei\|}$ the electron–ion collision frequency as a function of the electron temperature T_e, n_e the electron number density, and e the electron charge [12]. In this condition, the magnetic diffusion may not play a main role on flow morphology; therefore, ideal magnetohydrodynamics (MHD) is assumed by neglecting it for the flows appearing in this paper.

We have developed a two-dimensional RHD code [15,16], whose basic equations are two-dimensional Euler equations and realistic EOS including source terms;

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho \boldsymbol{u}) = 0, \tag{1}$$

$$\frac{\partial \rho \boldsymbol{u}}{\partial t} + \nabla\cdot(\rho \boldsymbol{u}\boldsymbol{u} + P) = \boldsymbol{S}_B, \tag{2}$$

$$\frac{\partial e}{\partial t} + \nabla\cdot[(e+P)\boldsymbol{u}] = S + \boldsymbol{u}\cdot\boldsymbol{S}_B, \tag{3}$$

$$\frac{\partial \varepsilon_i}{\partial t} + \nabla\cdot(\varepsilon_i \boldsymbol{u}) + P_i \nabla\cdot\boldsymbol{u} = S_i, \tag{4}$$

$$\frac{\partial \varepsilon_e}{\partial t} + \nabla\cdot(\varepsilon_e \boldsymbol{u}) + P_e \nabla\cdot\boldsymbol{u} = S_e, \tag{5}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla\times(\boldsymbol{u}\times\boldsymbol{B}), \tag{6}$$

where ρ, $\boldsymbol{u}$, e, ε, and $\boldsymbol{B}$ are the density, flow velocity, total specific energy, internal energy, and magnetic field, respectively. The total energy, pressure, and energy source consist of ion and electron contributions; $e = \varepsilon_i + \varepsilon_e + \rho|\boldsymbol{u}|^2/2$, $P = P_i + P_e$, and $S = S_i + S_e$, where the subscript i and e represent ion and electron, respectively.

The source term in Eq. (2) comes from the magnetic force term, and the second term in the right hand side of Eq. (3) represents the work of it. By solving Eq. (6) for the magnetic field, we can estimate these source terms with the following form:

$$\boldsymbol{S}_B = \frac{1}{4\pi}(\nabla\times\boldsymbol{B})\times\boldsymbol{B}. \tag{7}$$

The remainder of the source terms is estimated for electron/ion thermal conduction, X-ray radiation transfer, and laser absorption in a laser-produced plasma;

$$S_i = -\nabla\cdot\boldsymbol{q}_i + Q_{ei}, \tag{8}$$

$$S_e = -\nabla\cdot\boldsymbol{q}_e - Q_{ei} + S_l + S_r, \tag{9}$$

where $\boldsymbol{q}$ is the thermal conduction flux, Q_{ei} the energy exchange rate for electron–ion collision, S_l the laser absorption rate, and S_r the heating rate for X-ray radiation transfer. The thermal conduction flux is given by the flux-limited diffusion approximation with the Spitzer–Härm conductivity [17]. The radiative transfer equation is also solved by the multi-group flux-limited diffusion with non-local thermodynamic equilibrium opacities. Numerical fluxes are estimated by the AUSM-DV approximate Riemann solver [18] with second-order spatial accuracy adopted by the MUSCL approach [19]. Two-temperatures for electrons and ions are taken into account by solving Eqs. (4) and (5) not only Eq. (3) for a thermally non-equilibrium medium. Although the laser absorption of inverse-bremsstrahlung can be calculated by the two-dimensional ray-tracing with the developed code, one-dimensional trajectory for each computational ray is assumed for simplicity in this paper.

The evolution of the magnetic field is estimated by the standard MHD fashion, so the method of characteristics coupled with constraint transport (MOC-CT) [20] was installed to the original code. In the MOC-CT method, Alfvén wave advection is estimated by differentiation of the simplified MHD equation along the characteristics using an appropriate formulation with staggered grid for keeping a constraint of $\nabla\cdot\boldsymbol{B} = 0$. Since the original RAICHO code is based on the finite volume method, the physical quantities are defined as cell-centered values. However, the MOC-CT should be operated with the staggered grid, that is, components of the vector quantities such as magnetic field and flow velocity are defined at cell-interfaces. Therefore, the flow velocity is redefined at the cell-interface before entering the MOC-CT procedure, while the magnetic field is always defined as the cell-interface quantity because it does not matter with the approximate Riemann flux directly in the framework just coupling the hydro-part and the magnetic field with a source term. Although this simple framework might produce some numerical errors of missing Alfvén waves or smearing the flow velocity through the interpolation between two grid systems, the test problem of the MHD shock tube proposed by Brio & Wu [21] shows that the developed code correctly works, representing the characteristic waves with the desired accuracy.

Numerical simulations were conducted for past experiments in which a planar plastic target (left side in Fig. 1) was irradiated by high-power laser beams and another target (right side in Fig. 1) was ablated by the radiation from the laser-heated target. Ambient gas is nitrogen atom whose initial density is 4.6×10^{17} cm^{-3}. We assumed that the nitrogen gas is quickly ionized and then magnetized because the radiation from the heated target goes through the ambient gas in temperature of ~5 eV in the first ~1.5 ns. The averaged ionization degree rises up to ~2, making the ion

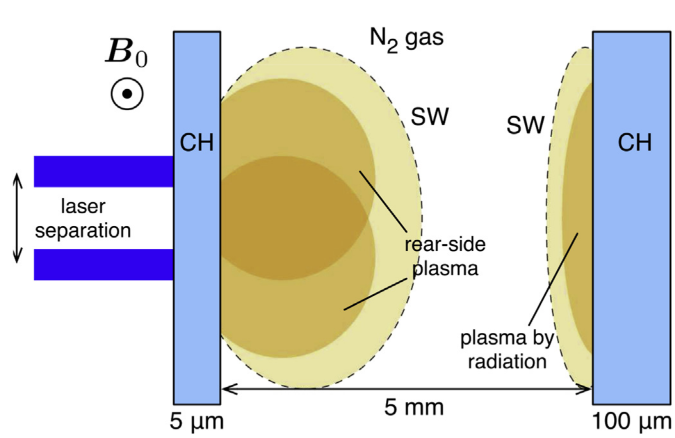

Fig. 1. Simulation condition of Richtmyer–Meshkov instability experiment in magnetized laser ablation plasma with double target configuration.