Computational Study of Magnetic Field Amplification in Laser-Produced Shock Waves Relevant to Supernova Remnants

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Abstract. We have developed a two-dimensional magneto-radiation hydrodynamics code with an induction equation solver to analyze laboratory-astrophysics experiments relevant to a supernova remnant (SNR) environment. The computed magnetic field was amplified by a order of magnitude from the background level as expected for accelerating fields of cosmic rays in the SNR context. A part of the amplification of the magnetic field is caused by Richtmyer-Meshkov instability (RMI) that stretches a contact discontinuity. However, the maximum magnetic field is smaller than the theoretically predicted limit since the non-linear RMI cannot sufficiently grow and the field is amplified by the compression effect rather than the stretching in the present experimental condition.

1. Introduction

High energy cosmic rays are indispensable information to understand astrophysical phenomena and are emitted from various high-energy-density events in the universe. The supernova remnant (SNR) is a typical example of the acceleration field of such cosmic rays, in which strong shocks propagate in an inhomogeneous interstellar medium. 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 the synchrotron emissions in such a short timescale, strong magnetic fields are needed in a few-hundred-times greater level than the background one of 10^{-10} T. On the other hand, 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 Richtmyer-Meshkov instability (RMI), extend a density interface, and then strengthen the magnetic field. In theoretical and numerical study, magnetic fields are amplified up to two orders of magnitude from those of the background by the RMI [3, 4]. Several laboratory-astrophysics experiments relevant to the SNR environment were performed by high-power lasers [5, 6]. However, recent experiments taking into account shock waves, magnetic fields, and density inhomogeneities could not obtain no clear indication of the field amplification. Numerical analysis is helpful to examine an evolution of the magnetic field in the laser-produced plasma flows and to design the feasible experiments. So, we newly

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developed a two-dimensional magneto-radiation hydrodynamics (MRHD) code including the induction equation, and simulated for the experiments of a counter flow from double plastic targets irradiated by high-power lasers.

2. Numerical method

We use a two-dimensional RHD code, RAICHO [7], whose basic equations are two-dimensional Euler equations including energy source terms and realistic EOS. The source terms are estimated for electron/ion thermal conduction, X-ray radiation transfer, and laser absorption in a laser-produced plasma. The radiative transfer equation is simultaneously solved by the MGFLD with non-LTE (CRE) opacity. Numerical fluxes are estimated by the AUSM-DV approximate Riemann solver with second-order spatial accuracy adopted by the MUSCL approach. Two temperatures for electrons and ions are taken into account by solving additional energy equations for a thermally non-equilibrium medium. The laser absorption of inverse-bremsstrahlung is calculated by the two-dimensional ray-tracing.

The evolution of the magnetic field is estimated by the standard magneto-hydrodynamics (MHD) fashion, so the MOC-CT method [8] was installed to the original code. Numerical simulations were conducted for the experiments in which a planar plastic target was irradiated by high-power laser beams and another target was ablated by the X-ray radiation from the laser-heated target (Fig. 1). Ambient gas is nitrogen whose initial density is 4.6×10^{17} cm^{-3}. To numerically resolve these targets in a relatively wide computational region, we introduced unequally-spaced computational grids. In the experiments, several lasers were focused on a point with an offset from the target surface. With no offset, the lasers were focused on the target surface, so we modelled a single laser perpendicular to the surface in the corresponding simulation. On the other hand, since the lasers are split on the surface with any offsets, we input two lasers with a beam separation in the simulation, while the lasers are assumed to be parallel to each other. Note that the geometry of the numerical simulation is different from that of the experiment due to non-axisymmetric computation.

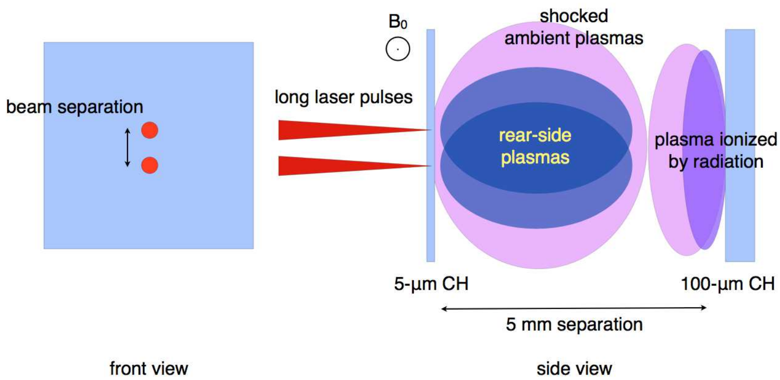

Figure 1. Simulation conditions.

3. Results

We have simulated the laser-produced plasma until 20 ns for the cases with 1-mm laser offset and without one, i.e. the corresponding beam separation. The laser intensities are 0.2×10^{14} W/cm^2/beam in the case with laser offset and 0.3×10^{14} W/cm^2/beam in the case without one. The spot radius is 100 μm and the pulse width is 1 ns in the both cases. One spot is separated from another by 500 μm in the case with offset. The experimentally-observed shadowgraphs at 20 ns after laser irradiation are shown in Fig. 2 (a) (with 1-mm offset) and in Fig. 3 (a) (without offset). Computed density and magnetic field are also shown in Fig. 2 (b)

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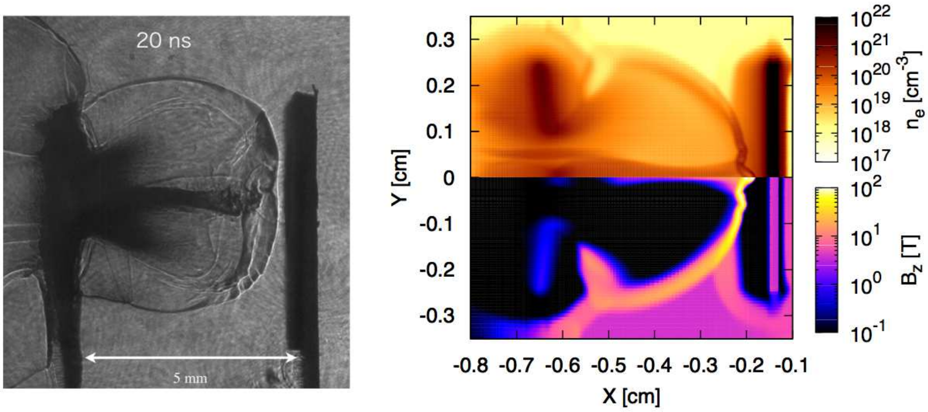
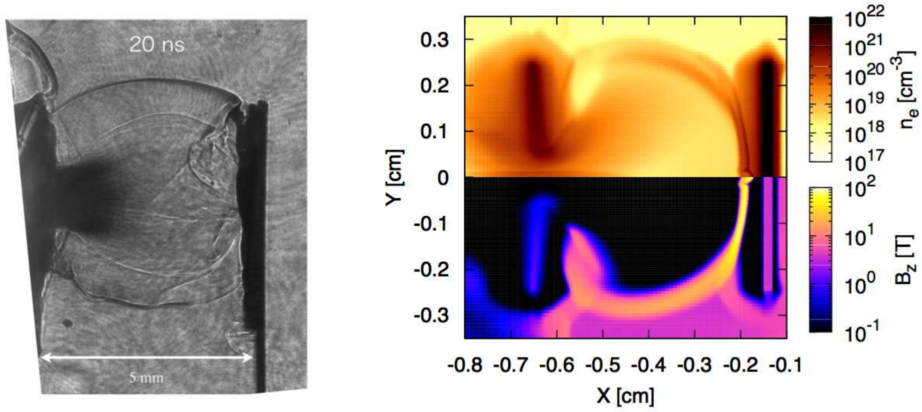


(a) experiment (b) simulation

Figure 2. (a) Shadowgraph of the experiment and (b) contours of computed number density of electrons (top) and magnetic field (bottom) in the case with offset at 20 ns.



(a) experiment (b) simulation

Figure 3. (a) Shadowgraph of the experiment and (b) contours of computed number density of electrons (top) and magnetic field (bottom) in the case without offset at 20 ns.

and Fig. 3 (b). Shock wave structures and contact discontinuities observed in the experiments are roughly reproduced in the simulations. Without offset, the laser-produced plasma simply expands from the rear side of the left target, and the growth of non-uniformity of the contact discontinuity is not so significant even after the interaction with the shock wave. On the other hand, with offset, a jet-like plasma is formed and collides with a counter flow generated by the radiation. The magnetic field becomes high at the area in which the laser-produced flow interferes with the radiation-produced one. The RMI seems to develop at the contact surface between the jet from the left target and the shock from the right target. The magnetic field profiles on the symmetry axis ($y = 0$) are shown in Fig. 4. The magnetic field is remarkably amplified near the contact surface. With offset, the magnetic field is globally large as compared with the case without offset because of the non-uniformity growing due to the jet propagation. The magnetic field is amplified to almost 40 times greater level than the initial condition of 3.5 T in our simulation. However, this value is one-order smaller than the theoretically predicted limit [4]. This may come from the fact that the magnetic field in this configuration is amplified by mainly the compression effect but the stretching of the contact surface because of the insufficient

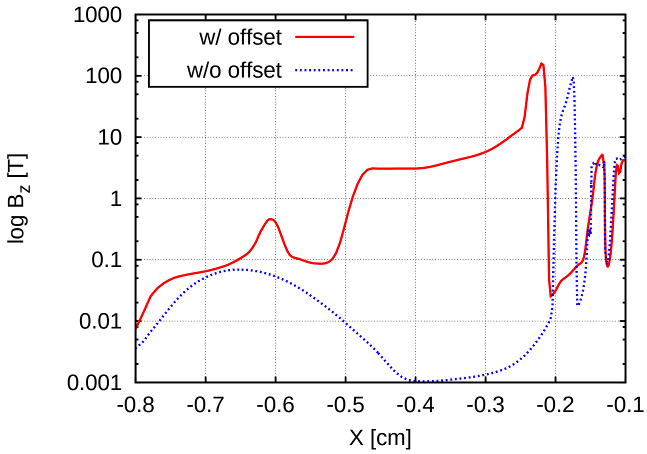


Figure 4. Magnetic field profiles in the symmetry axis at 20 ns.

evolution of the RMI. Here, the induction equation for the ideal MHD in a scalar form can be written as follows;

$$\frac{1}{2}\frac{\partial}{\partial t}|\boldsymbol{B}|^2 = -\boldsymbol{B}\cdot(\boldsymbol{v}\cdot\nabla)\,\boldsymbol{B} + \boldsymbol{B}\cdot(\boldsymbol{B}\cdot\nabla)\,\boldsymbol{v} - |\boldsymbol{B}|^2\nabla\cdot\boldsymbol{v}, \tag{1}$$

where the second and third terms of the right-hand side represent the stretching and the compression of the magnetic field, respectively [4]. The field amplification by the stretching term is expected in a highly nonlinear regime of the RMI. So, we should explore a suitable configuration of the experiment for observing the efficient field amplification using the developed code.

4. Conclusion

We have performed numerical analysis of the laser-plasma experiments relevant to the magnetic field amplification in the SNR. We developed two-dimensional MRHD code solving the induction equation by the MOC-CT method. The simulation results are in good agreement with the shadowgraphs of the experiments in terms of the jet-like plasma configuration and the shock wave propagation. Although the simulation results show that the magnetic field can be one-order amplified from the background level, the resultant amplification is lower than the theoretical limit yet. This is because that the growth of the non-linear RMI is not sufficient in the present condition. Thus, we should examine another condition resulting in more efficient field amplification and design a feasible experiment.

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