Parametric Numerical Analysis of Plasma Behaviors in a Magnetic Nozzle for a Laser Fusion Rocket

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Abstract : We developed the numerical simulation method to analyze a plasma behavior in a magnetic thrust chamber for a laser fusion rocket. Here, we used a laser ablation plasma instead of a fusion plasma because there are many challenges to satisfy the Lawson criterion in inertial confinement fusion. We have used the two-dimensional radiation hydrodynamics code to simulate a laser ablation process and the three-dimensional hybrid code to simulate an interaction between an external magnetic field and an unsteady plasma flow. To validate the accuracy of our numerical simulation code, we compared the ion flux on the numerical simulation with the experimental results. As a result, we succeeded in reproducing the ion flow that has similar speed compared from the experimental result. In addition, we propose the inside irradiation to simulate a condition of a proposed flight model of a laser fusion rocket. As a result, the velocity distributions of a plasma became slower than the outside irradiation method.

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I. Introduction

On a future space exploration missions, we will cruise a longer distance than ever before. Then, the mission time should be long if we use existing technologies. A long mission time in the space will cause many problems, for instance, damages for a spacecraft and crews, increase the required resources such as air, water, food, and the operation costs. It is absolutely essential to develop a spacecraft that can cruise at high speed. One of the key component to realize it is a propulsion system.
Laser Fusion Rocker (LFR) is one of the candidates for interplanetary manned flight in the future because it can generate both large thrust and high specific impulse simultaneously. The concept design of the LFR was proposed by Lawrence Livermore National Laboratory.[1] It is estimated that we can make a round trip to mars in half a year. In LFR system, fusion plasma is controlled by an external magnetic field. The magnetic field controls the direction of plasma flow and converts its charged particle energy to thrust energy. This magnetic nozzle system is called "magnetic thrust chamber". The mechanism of magnetic thrust chamber is shown in figures 1(a)-1(c). At first, plasma produced by inertial confinement fusion expands in an external magnetic field produced by an electromagnetic coil. Then, the plasma compresses the magnetic field until the magnetic pressure balances with the plasma pressure. At the same time, a magnetic cavity appears in a plasma due to a diamagnetic current that is produced by Larmor motion. As a result, the plasma is accelerated by a Lorentz force between the diamagnetic current and the external magnetic field. Then, the coil is accelerated to opposite direction by a reaction force.

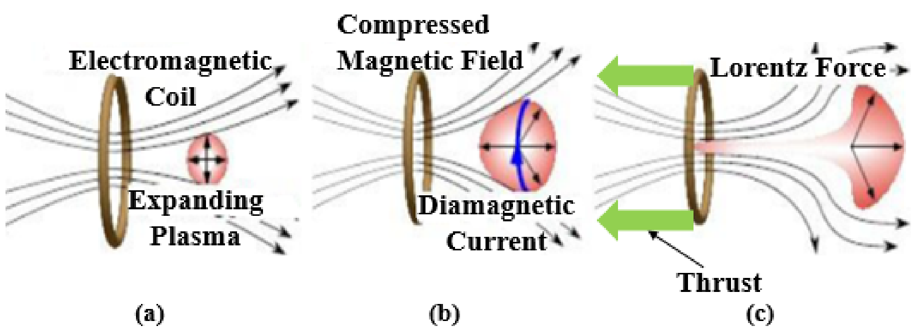

Figure 1. The mechanism of a magnetic thrust chamber

We have plan to demonstrate a laser fusion rocket using a fusion plasma, but, there are many challenges to satisfy the Lawson criterion in an inertial confinement fusion. Thus, we have been trying to demonstrate the magnetic thrust chamber system using a laser ablation plasma. In the previous experimental researches with Gekko-XII (GXII) laser (maximum output energy of 1 kJ/beam) and Extreme Ultra Violet (EUV) database laser facilities (∼10 J) at the Institute of Laser Engineering, Osaka University, we have examined the behaviors of plasmas with the observation of self-emission,[2–4] interferometry, and Thomson scattering, and magnetic fields with B-dot probes. In addition, thrust generation has been confirmed with magnetic thrust chamber experimentally using pendulum thrust stand.[5,6] Recently, the experiment on the thrust vector control was conducted.[7] In the previous numerical researches,[8] we have simulated plasma generation process by a laser irradiation using one-dimensional (1D) and two-dimensional (2D) radiation hydrodynamics (RHD) codes,[9,10] and interaction between plasmas and magnetic fields using three-dimensional (3D) hybrid code.[11]

II. Methods

Our numerical simulation consists of four codes. Fig. 2 shows the flowchart.

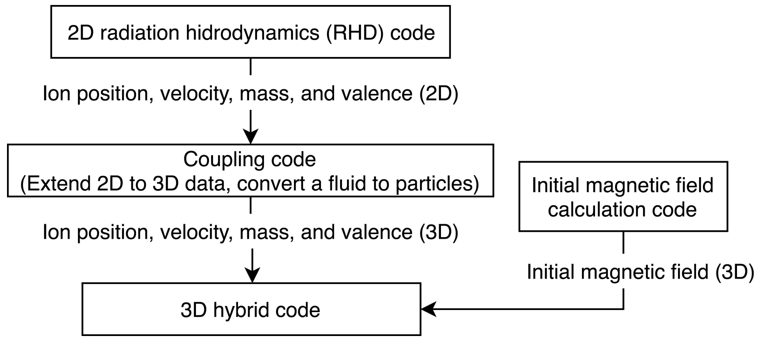

Figure 2. Flowchart of numerical simulation

Firstly, the laser ablation process is calculated by the 2D RHD code.[9,10] In this code, a plasma is treated as one-material and two-temperature fluid. A laser beam is considered as single and parallel beam with gaussian shape both in space and time. The calculation mesh type is Lagrangian at early in time (∼1 ns) and Eulerian after that. All of simulation space except the target is filled with low density gas. The composition of the background gas is assumed as same as target material. Secondly, the data from the radiation code are expanded to 3D data as axial symmetry. Here, the axis of symmetry is same as the laser axis. In addition, the ions are converted to the super-particles from the fluid based on the ion density distribution. The rotating angle around the axis of symmetry is decided randomly. Thirdly, the initial magnetic field from an electromagnetic coil is calculated by the magnetic field calculation code using Biot-Savart law. Finally, the 3D hybrid code[11] receives the expanded data and the 3D initial magnetic field data and calculates the interaction between a plasma and an external magnetic field. In this code, ions are treated as superparticles and electrons are treated as a cold and inertialess fluid. All of plasma temperatures, ion and electron temperatures, are assumed to be zero. The charge density of plasma is also assumed as quasi-neutral. The collisions between a plasma and solids (e.g. coil) are ignored. The number of the superparticles is 10^6. In the following simulations, every superparticle includes almost 10^{10} real ions. In this paper, we will talk about the plasmas from CH target but the RHD code can treat only one material. Thus, we used the averaged parameters of C and H ions.

A. Verification of the reproducibility of an experimental result in the numerical simulation

We have compared the result of numerical simulation with the previous experimental result. Fig.3 shows the experimental setup.

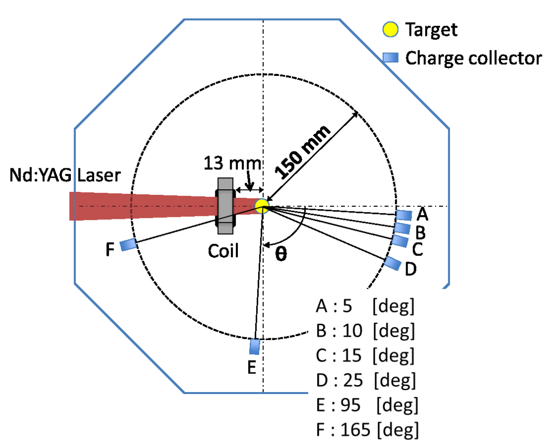

Figure 3. Experimental setup

The target, a polystyrene sphere of diameter 500 μm, is placed on the Target-Chamber-Center (TCC). The solenoid coil is placed 13 mm away from the target. The inner diameter, outer diameter, and length of the coil are 26 mm, 50 mm, and 10 mm, respectively. The Nd:YAG laser beam gets through the inside of the solenoid coil and it is focused on TCC. The laser energy, wave length, pulse width (FWHM), and spot diameter are 7.5 J, 1064 nm, 9.4 ns, and 500 μm, respectively. Charge collector is placed 150 mm away from the TCC. These charge collectors are maintained at negative potential with respect to the ground. Thus, they collect ions and measure the ion current.
To reproduce and analyze the detail of plasma behavior, we conducted numerical simulation. Figures 4 and 5 show the calculation model of the 2D RHD code and 3D hybrid code, respectively.

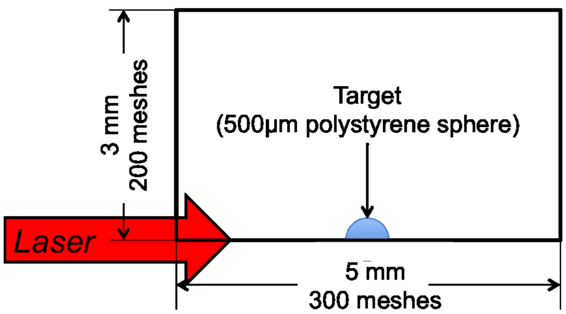

Figure 4. RHD code calculation model

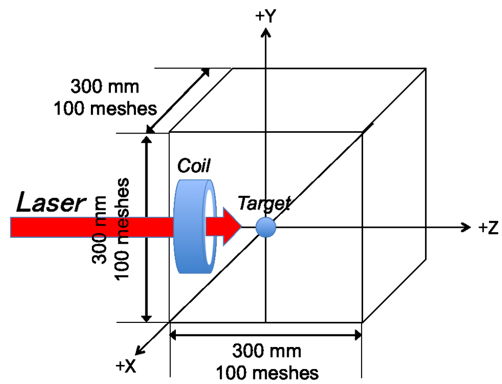

Figure 5. 3D hybrid code calculation model

In this simulation, we focused on the fast and low density plasma at the outer edge of the expanding plasma. When a spherical target is irradiated, a high speed and low density plasma will be generated on the surface of the target. Then, the center of the target has high density and low speed. If we convert the fluid to particles based on the density distributions, almost superparticles are placed on the center, low speed, region. In this case, we cannot simulate the high speed plasmas. To solve this problem, we removed the slow plasmas. The threshold value was set as the 5 % of the highest ions.

B. Inside irradiation : new experimental concept

In the proposed flight model of a laser fusion rocket, a target pellet consists of a fusion pellet and a propellant shell.[12] The fusion pellet is surrounded by the propellant shell. When the fusion pellet generates an energy by an inertial fusion, the inside surface of the propellant shell is heated by the fusion plasma. Then, the propellant will be ionized. To conduct an experiment based on this situation, we have to irradiate the inside of the shell target.
Figure 6 shows the schematic of an outside irradiation that is conducted on the previous researches. Outside irradiation was adopted in our previous experiments. In contrast, inside irradiation is shown in Fig.7. On an actual experiment, it is impossible to put a laser source inside a shell target. The experimental set up should be as shown in Fig.8. The single or multi laser beam is focused on the hole of a shell target. After that, the laser beam diverges is reflected back and forth in the cavity and irradiates the inside surface of the target. In addition, this inside irradiation method is good for a numerical simulation. When we use direct irradiation method, a fast plasma($\sim$350 km/s) will be generated on the surface of the target. Thus, we must calculate large space to simulate the whole of laser irradiation process. On the other hand, the mesh size must be small to calculate the laser irradiation process correctly. To satisfy both of these two conditions, the calculation cost should be quite high.

Here, we compared the results of the methods shown in Fig.6 and Fig.7 using 2D RHD code.

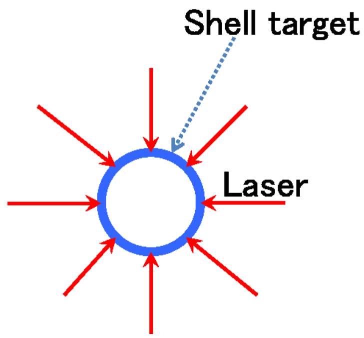

Figure 6. Outside irradiation

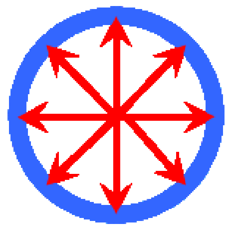

Figure 7. Inside irradiation

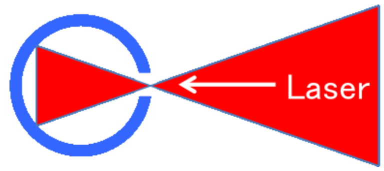

Figure 8. Inside irradiation (Experimental)

III. Results and discussions

A. Verification of the reproducibility of an experimental result in the numerical simulation

In this simulation, the 2D RHD code and 3D hybrid code were connected at 33 ns. This time is almost $+2\sigma$ timing of the gaussian laser pulse because the peak timing of the laser intensity was 25 ns and the pulse width (FWHM) was 9.4 ns. On this timing, the plasma reaches the edge of the calculation area as shown in the left figures of Fig. 9. To connect the 2D RHD code and the 3D hybrid code, we converted the 2D RHD result data to 3D data as the initial data of the 3D hybrid code. Then, we removed the slow speed area as shown in Fig.9. The threshold value was set as 5 % of the fastest plasma. The total kinetic energy of the plasma was 13.14 J before removing and 13.08 J after removing. Thus, the removed area has only 0.5 % of the total kinetic energy of the plasma.

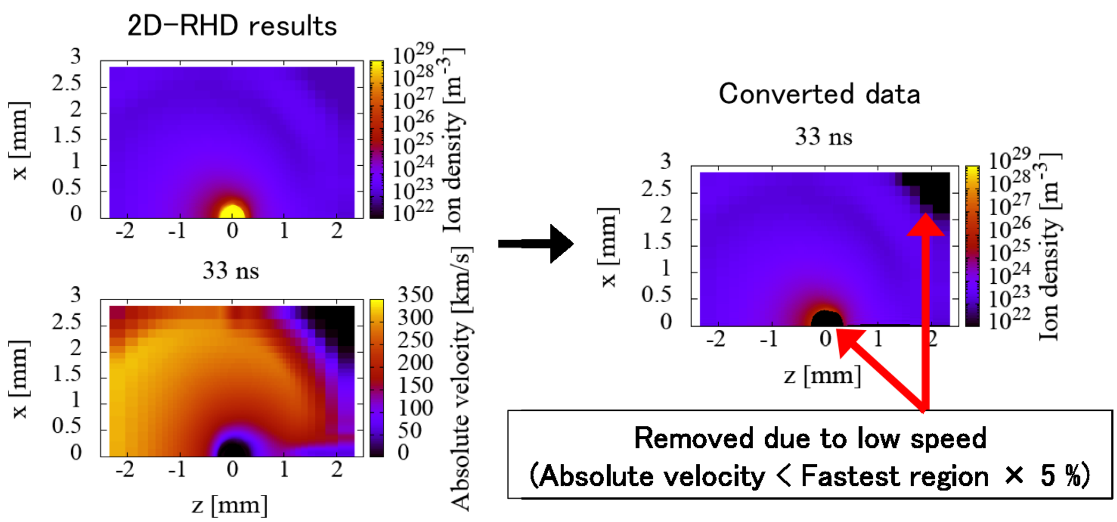

Figure 9. Results of 2D RHD code and the converted data using coupling code

Figures 10 (a)-(c) show the ion density distributions on 0.5, 1, and 3 μs. Here, the driving current of the solenoid coil is 90 kA·turn and the magnetic field strength at TCC is 1.1 T.

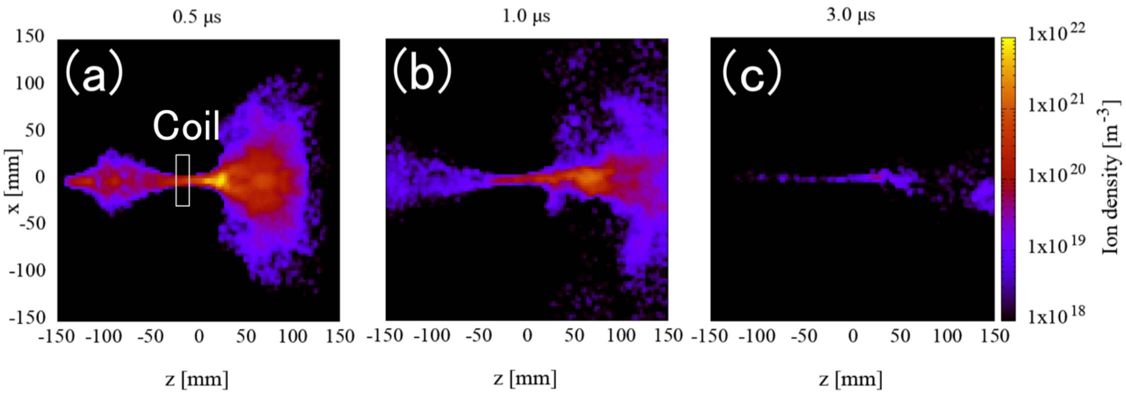

Figure 10. Ion density distributions calculated by 3D hybrid code

We compared the numerical result with the ion current waveforms that are measured by the charge collectors as shown in Figs.11 and 12.
On the 5 degrees, the timings of the first and second peak from the simulation are almost same as the experimental results. However, the amount of the ion current density at both peak are almost the same value unlike the experimental result. In addition, the ion current density is almost 40 times larger than the experimental result.
On the 15 degrees, the timings of the first peak from the simulation is almost same as the experimental results but the second peak does not appear. In addition, the ion current density is almost 70 times larger than the experimental result.

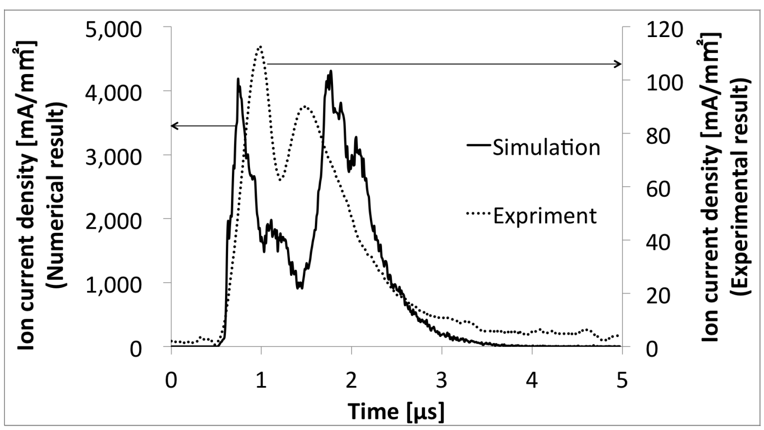

Figure 11. Ion current on the 5degree charge collector

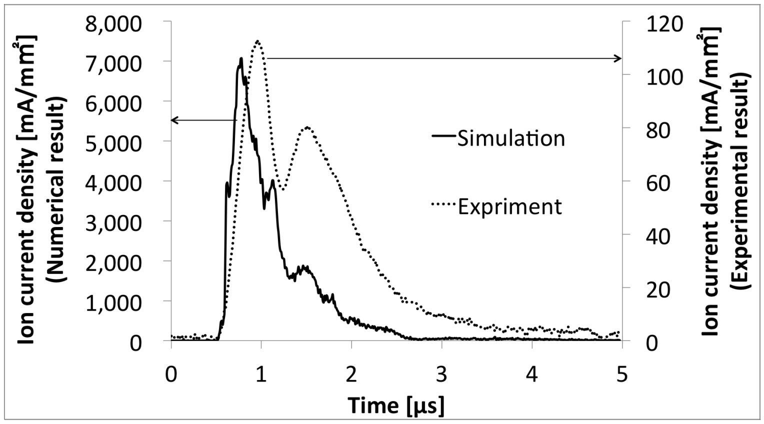

Figure 12. Ion current on the 15degree charge collector

Here, we checked the initial velocity profiles of these ions. The ions that has negative and positive velocities of z-direction as its initial velocity are categorized as "Reflected ions" and "Non-reflected ions". The reflected ions are interacted with the external magnetic field, certainly. Thus, if we can measure the reflected ions at the charge collector positions, the magnetic thrust chamber system works well.

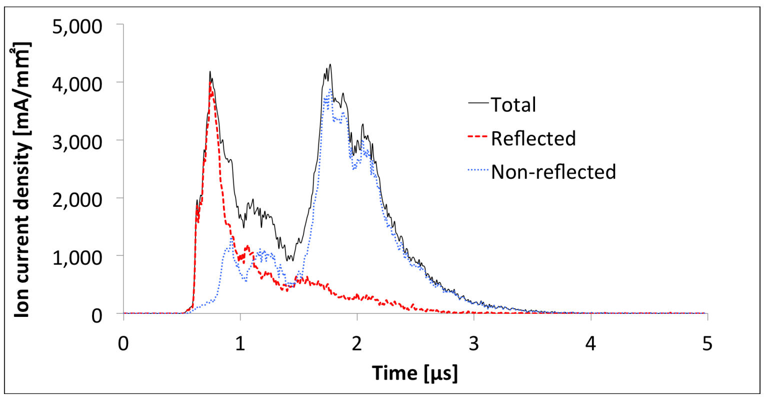

Figure 13. Initial velocity profiles of the ions that is measured on the 5degrees charge collector

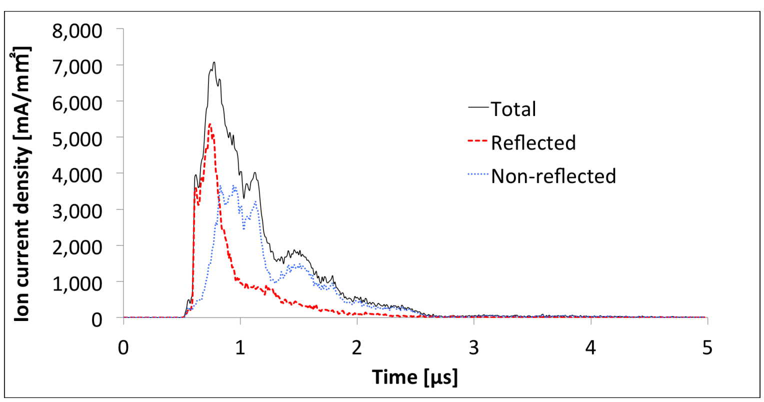

Figure 14. Initial velocity profiles of the ions that is measured on the 15degrees charge collector

As shown in these result, the reflected ions are observed at earlier timings than the non-reflected ions in spite of the fact that the flight pass of reflected ions should be longer than the non-reflected ions. This trend is caused by the one-side irradiation. On this condition, the coil side of the target is irradiated by the laser

beam. Thus, the high speed plasma is ejected toward the coil as shown in Fig.9. Then, the reflected ions has higher speed than the non-reflected ions.
The achievement point of this simulation compared to the previous researches is the reproducing the peak of the ion current at similar timing compared to the experimental result. However, there are large difference of the absolute value of the ion current.
The reason of the difference of the amount of ion current density is still unclear but there are some possible reasons. The possibilities are that the experimental data are underestimated and the numerical simulation data are over estimated. On the experiment, the charge collector was covered with the metal cap that has an aperture. Ideally, every charge collector faces its aperture to the TCC. If there are some misalignment, some amount of the ion flow hit to the metal cap. Then, the amount of the ion flow is decrease on the measurement position. On the numerical simulation, there are two possible reasons. First is the different of the ionization rates. On the ion current calculation in the numerical simulation, the ionization rate is assumed to be 3.5, totally ionized. If the ionization rate of the experimental condition is smaller than it, the results from numerical simulation are overestimated. Second is the collisions between the coil and ions. In the 3D hybrid code, the interactions between plasmas and coil are ignored. If an ion flight pass strikes the coil, the ion lose the energy. As a result, the ion current that is measured by the charge collector should be decreasing.

B. Inside irradiation : new experimental concept

We compared the plasma behaviors with outside and inside irradiation. The target is a polystyrene shell. The outer diameter and the thickness of it are 500 μm and 7 μm. The initial condition is shown in Fig.15. The mass density of the target and the background are 1050 kg/m^3 and 1 mg/m^3. The mesh is based on spherical coordinate system and the r-direction and θ-direction are divided into 500 and 30 meshes. The laser energy, wave length, and pulse width (FWHM) are 300 J, 1053 nm, and 1.3 ns, respectively. The peak of the intensity is at 5 ns in this simulation. This laser condition is decided based on the experimental plan with GXII at Osaka university. All of laser energy is injected uniformity over the target surface. Thus, every point on the target surface is irradiated with the same intensity.

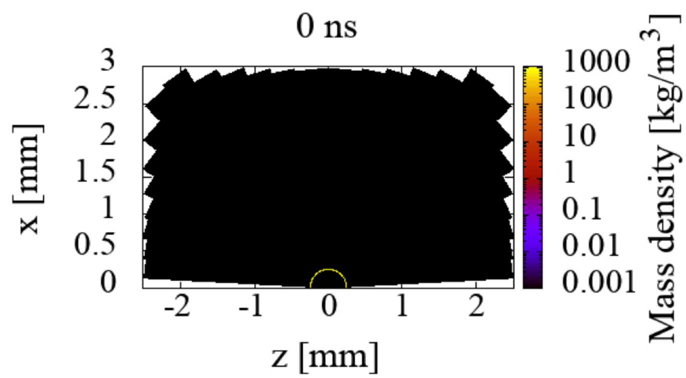

Figure 15. Initial condition of the 2D RHD code

Figures 16, and 17 show the absolute velocity and ion density distributions with outside irradiation, and inside irradiation. As shown in these figures, when we use inside irradiation method, the slower plasma is generated. Also, the boundary between the plasma and the background gas is very sharp.

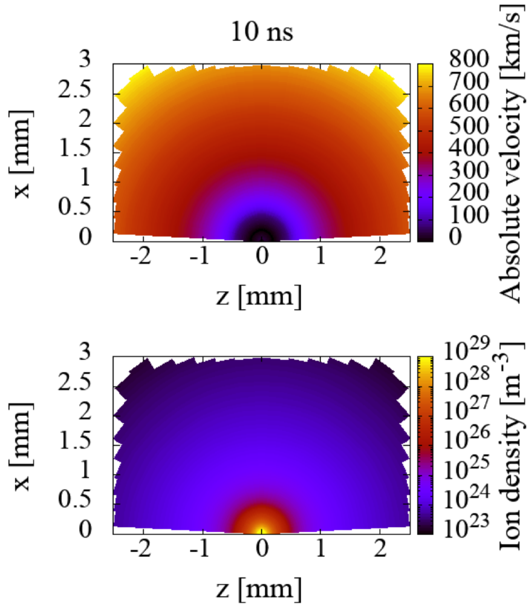

Figure 16. Outside irradiation

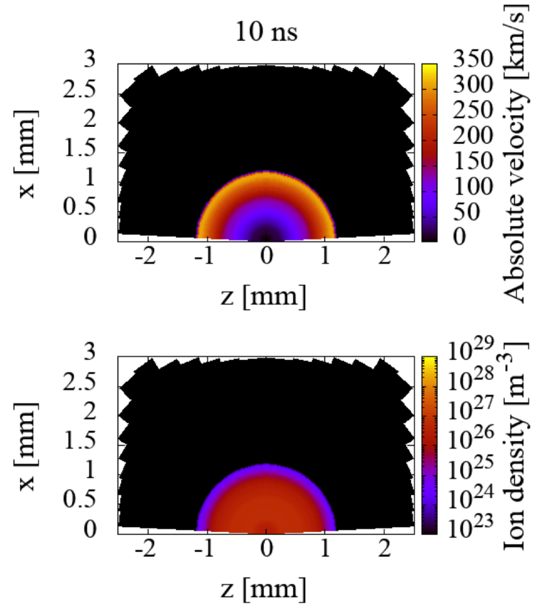

Figure 17. Inside irradiation

IV. Conclusion

We have succeeded in reproducing the plasma flow that has similar speed as compared with the experimental result. However, the differences of the absolute value of the ion current are still remaining. The difference of the ionization rate and the ignored collisions between the plasma and the coil are thought of as possible reasons. In addition, there are the possibility that the experimental data ware underestimated due to the misalignment of the setup of the charge collectors.

We conducted the numerical simulations of outside and inside irradiation method using 2D RHD code. When we use inside irradiation method, the slower plasma was observed numerically. This result is good for numerical simulation because when we use slower plasma, the calculation will be easier than the high speed plasma that is produced by the outside irradiation. To conduct an experiment using inside irradiation, we will make a detail plan about experimental condition such as target and laser conditions. Simultaneously, we will try to find the relationships between the target and laser parameters, and plasma parameters.

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