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Well-defined atomic hydrogen target driven by electromagnetic shock wave for stopping power measurement

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Abstract

The precise estimation of stopping power is crucial to predict the beam energy loss in the target for heavy-ion fusion and heavy-ion-driven high-energy density physics experiments. The electromagnetic shock wave has been proposed to generate a well-defined atomic hydrogen target for the stopping power measurement with dissociation effects. We measured the angular distribution profile of the discharge plasma and the plasma velocity in the electromagnetic shock tube by high-speed framing cameras. To improve the uniformity of the discharge plasma and the velocity, an external magnetic field was applied in the electromagnetic shock tube. The plasma velocity was up to approximately 40 km/s for an initial hydrogen gas pressure of 100 Pa and the velocity decreased with the initial pressure and the propagation length. The framing cameras showed that angular distributions of the discharge plasmas were not uniform and the initial angular distributions were important for the development of plasma profiles. The interaction of the plasma with the external magnetic field was estimated using the ratio of the plasma dynamic pressure to the magnetic pressure. The estimations offer more magnetic fields to improve the discharge uniformity due to the interaction.

Keywords: Electromagnetic shock tube; Heavy-ion fusion; Stopping power

1. INTRODUCTION

Stopping power in matter is an interesting research for heavy-ion fusion, heavy-ion-driven high-energy density physics experiment, and fast ignition in inertial confinement fusion (Tabak *et al.*, 1994; Zwicknagel, 1998, 2009; Ogawa *et al.*, 2000; Roth *et al.*, 2001). Reliability of stopping power in matter under normal temperature and pressure is relatively well established (Paul, 2006; Ziegler *et al.*, 2008); however, the interaction of the charged particles with high-density and/or hot temperature matter is not yet fully understood. In particular, the interaction in the low beam energy region is interesting because Grisham (2004) proposed the moderate energy ions could be utilized as a driver for high-energy density physics experiment using a sub-range target. The interaction between the projectile and the electron of the target is strong when the projectile velocity is close to that of electron. In this energy region, the beam energy deposition profiles are sensitive to the electronic-state in the target. Although the change of the electronic-state due to dissociations is fundamental for the ion-driven high-energy density physics experiments, there are poor experimental data. A calculation (Hasegawa *et al.*, 2009) showed that the dissociation effect gives rise to a 20% increase of the peak stopping cross-section. Therefore, we focus on the measurement of the stopping power with the dissociation effect. It is expected that the dissociation effect can be observed most significantly for hydrogen, which has only valence electrons. The carbon ions with ~400 keV/u are planned as projectiles for the stopping power measurement.

The electromagnetic shock wave was proposed as a method to obtain atomic hydrogen targets. It is the principle of the electromagnetic shock tube that the electromagnetic force between the discharge current flowing in the plasma and the self-magnetic field induced by the current accelerates the discharge current sheet toward the top end of the tube and the shock wave is formed in front of the accelerated fluid region. When we have a proper shock wave velocity, the shocked region can become dissociated matter. The past experiments using an electromagnetic shock tube with face-type electrodes (Hasegawa *et al.*, 2009) showed that the duration of the shocked region was not enough for reliable stopping power measurements and the duration of the atomic

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hydrogen needs an order of micro-second as long as the beam pulse width supplied from our Tandem accelerator facility is several hundred nano-seconds.

The coaxial electromagnetic shock tube is proper to establish a well-defined target because Kondo *et al.* (2006) generated a steady one-dimensional shock wave using the coaxial shock tube. To obtain much longer duration, we developed a coaxial electromagnetic shock tube with a long electrode section (Kondo *et al.*, 2014) where the electromagnetic interaction could be involved actively. In the coaxial tube, the shock wave was detected by a laser refraction method and the discharge plasma, which works as a piston to produce the shock wave, was observed by fast framing cameras and photodiodes. The maximum duration of the shocked region between the shock wave and the discharge plasma reached to about 8 µs, which was enough for stopping power measurement. However, much higher shock velocity, approximately 28 km/s, was required to dissociate the hydrogen gas completely (Kondo & Oguri, 2015).

Photographs taken by the fast framing camera showed that the current sheet was unstable, which could result in the insufficient acceleration by the electromagnetic interaction. The uniformity of the discharge plasma is a key issue to establish the sufficient shock velocity for the atomic hydrogen target because the discharge plasma works as a pusher for the hydrogen gas. Alfvén *et al.* (1960) reported that an external magnetic field contributes uniformity of the discharge. Here, we present the experimental results, including effects of the external magnetic field.

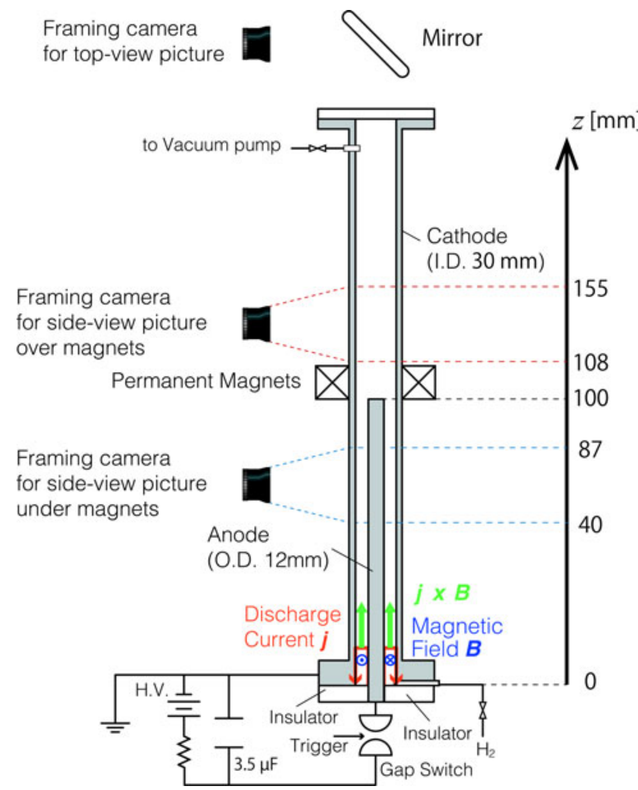

Fig. 1. This picture shows electromagnetic shock tube, equivalent circuit, and framing camera positions for discharge plasma self-emission profile. z is a distance from the bottom of the electrodes.

2. EXPERIMENTAL SETUP

Figure 1 shows the electromagnetic shock tube. Hydrogen gas with initial pressure p_0 from 100 to 1000 Pa was filled in the shock tube. The sufficient shock velocity in the initial pressure is a requirement to obtain the target for the stopping power measurement (Kondo *et al.*, 2014). The central electrode with a 100 mm length and with a 12 mm outer diameter was connected to a gap switch and capacitors with a total capacitance of 3.5 µF. The inner diameter of the outer electrode was 30 mm. To observe the shock velocity in the bottom of the electrodes, the outer electrode with a slit window was placed in this experiment. A charging voltage of 17 kV was applied. The high-voltage probe (Tektronix, Inc., P6015A) and the current monitor (PEARSON, Inc., 5664) were placed. The maximum discharge current was 25 kA. The spark discharge was controlled by the trigger signal, which was given to the gap switch.

The permanent magnets, which were ring-shaped quadrupole magnets, consisted of four neodymium magnet segments with 90°. The inner and outer diameters of the quadrupole magnets were 52 and 70 mm, respectively. The magnet was located at the top of central electrode ($100 \leq z \leq 105$) as shown in Figure 1. The magnetic flux density at the center of outside surface was about 0.5 T and an average radial magnetic field in the middle of the electrodes corresponds to about 0.015 T.

The fast framing camera with charge-coupled cameras (Hamamatsu, Inc., C6558) and high-speed gated image intensifier units (Hamamatsu, Inc., C2925-01) could take two pictures for the single discharge. The framing camera had three positions. A position under the magnet position ($40 \leq z \leq 87$ as shown in Fig. 1) was to obtain pictures of the discharge plasma before the external magnetic field interaction. The second position over the magnet position ($108 \leq z \leq 155$ as shown in Fig. 1) could give us the discharge plasma behavior after the magnetic field interaction. It was the last position that the framing camera with a mirror was located over the top of the shock tube to obtain the angular distribution of the plasma self-emission.

3. RESULTS AND DISCUSSION

We had three times discharges for each experimental condition to confirm the reproducibility. The framing camera showed the discharge plasma propagation as shown in Figure 2. Each exposure time was 10 ns. We could not distinguish between the shock wave and the piston discharge plasma because the duration between two regions was not enough long considering the previous results (Kondo & Oguri, 2015). Here it is assumed that the emission region is the discharge plasma.

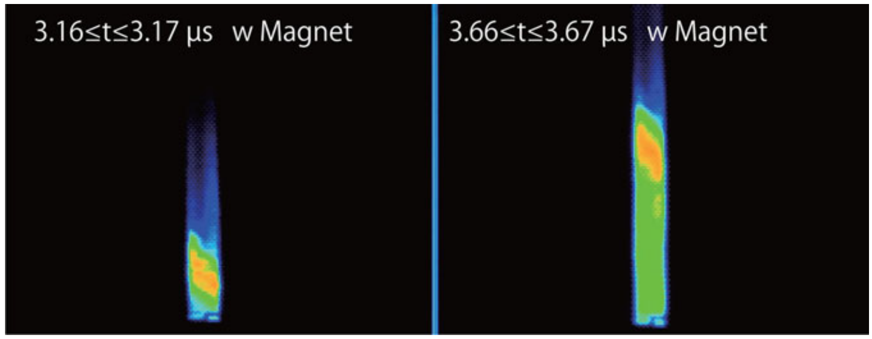

Fig. 2. A discharge plasma propagation with the magnet for a 400 Pa initial pressure. This view area was over the permanent magnet position. The spark discharge started at $t = 0$.

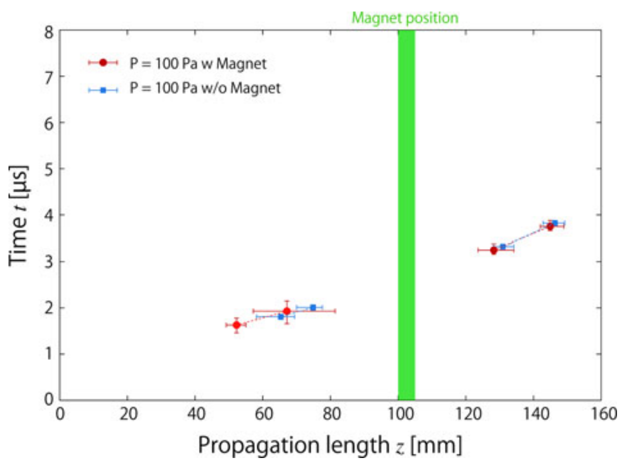

Fig. 3. T–z relationship for a 100 Pa initial pressure. The magnet position ($100 \leq z \leq 105$) is shown. The spark discharge started at $t = 0$.

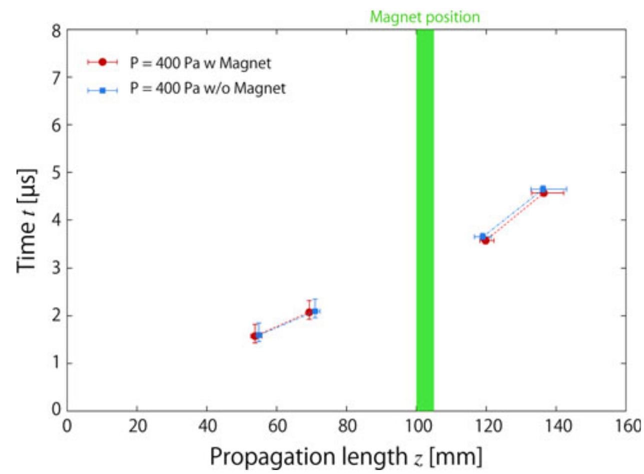

Fig. 4. T–z relationship for a 400 Pa initial pressure.

When the initial pressure was 100 Pa, propagation time t versus propagation length z with and without magnets for two areas (under and over the magnet positions) is shown in Figure 3. The dot means the average value and the error bars show the minimum and maximum values for the three discharges.

When the initial pressures are 400 and 1000 Pa, t–z relationships are shown in Figures 4 and 5, respectively.

We show the top-view pictures for a 100 Pa initial pressure in Figure 6. The two top or bottom pictures were obtained at the same shots. The two left profiles in Figure 6 show the central electrode clearly because the plasmas did not pass through the electrode at the moment. On the other hand, the two right profiles show that the discharge plasma spreads over a wide region and the plasma passed through the central electrode section with the magnet. Although we expected that the magnetic field interaction improved the discharge plasma uniformity that made no significant difference of the plasma profiles. These pictures showed that the profiles of the sequential discharge plasma were similar to the initial profiles.

The average velocities of the discharge plasmas are shown in Table 1. The results showed that the velocity decreased

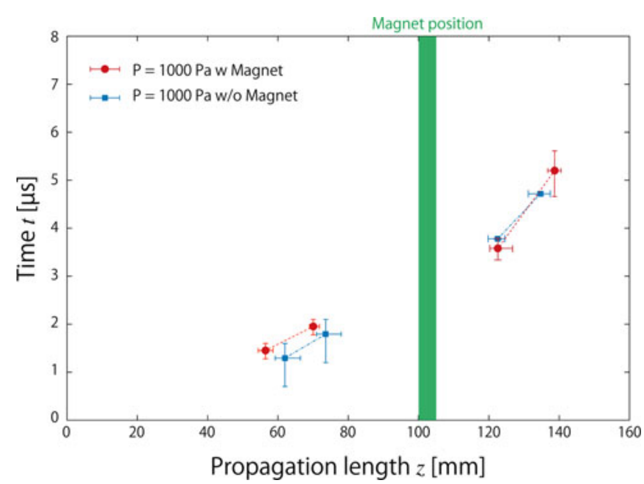

Fig. 5. t–z relationship for a 1000 Pa initial pressure.

with the initial pressure p_0 and the propagation length z and that the existence of the permanent magnet did not contribute an improvement of the plasma velocity. On the other hand, the experiments for 100 and 400 Pa initial pressures showed that the shock velocities in the bottom of the

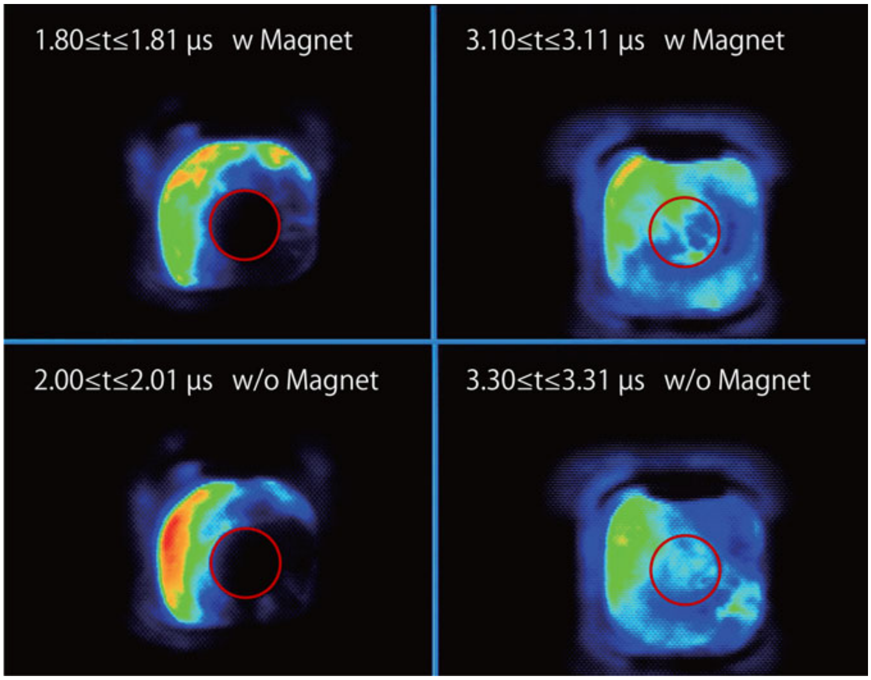

Fig. 6. The discharge plasmas were shown under and over the magnet positions for two left and right pictures, respectively. The center red circle represents the central electrode.

Table 1. *Average velocities of the discharge plasmas for initial pressures*

p_0 (Pa)	Area	v_{ave} (km/s) w Mag	v_{ave} (km/s) w/o Mag
100	Under mag. position	42	43
100	Over mag. position	31	29
400	Under mag. position	29	30
400	Over mag. position	16	16
1000	Under mag. position	25	21
1000	Over mag. position	10	13

w Mag, with magnets; w/o Mag, without magnets.

electrodes satisfied the requirement (~28 km/s) to obtain the atomic hydrogen target. The uniformity of the discharge plasma working as the piston is desired because we need to keep the shock velocity for the whole shock tube region.

A ratio of a dynamic pressure p_d to a magnetic pressure p_m is proposed to estimate an interaction of the discharge plasma with the magnetic field. It is assumed that the conductivity of the discharge plasma is high. We define the dynamic pressure p_d described by $(1/2)\rho v_{ave}^2$, where ρ is the initial mass density of the hydrogen gas and v_{ave} is the average velocity of the discharge plasma. The average between velocities under and over magnet positions as shown in Table 1 is applied to v_{ave}. Using permeability μ_0, the magnetic pressure p_m is given by $B^2/2\mu_0$. Here, B is the average radial magnetic field in the middle of the two electrodes of 0.015 T in the experiments. The ratio p_d/p_m is estimated to be ~1000 for an initial pressure of 400 Pa.

Alfvén *et al.* (1960) performed the experiment with better plasma uniformity due to the external magnetic field, showed that the velocity of the plasma was approximately 60 km/s and the typical magnetic field in the middle of the plasma gun was 0.06 T for the hydrogen pressure of 13 Pa. From these conditions, the ratio p_d/p_m is estimated to be 10, which shows that the active interaction of the plasma with the magnetic field is expected compared with our experimental condition.

4. SUMMARY

The experimental results showed that the shock velocity in the bottom region of the electrodes satisfied the requirement to dissociate the hydrogen gas completely. We successfully obtained the angular distribution profiles of the discharge plasmas and measured the plasma velocities before and after the magnetic interaction using the simple quadrupole magnets. The ratio of the plasma dynamic pressure to the magnetic pressure is useful to estimate the interaction of the plasma with the magnetic field and these show that more magnetic fields is required to improve the uniformity of the discharge plasma and the plasma velocity. The further investigation including a modification of the experimental setup for the improvement can realize the well-defined atomic hydrogen target for the stopping power measurement.

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