Development of Target Injection System by Using Electromagnetic Coils*)

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In this paper, we propose a fuel target injection method using electromagnetic coils for fusion power reactors. When a current pulse is applied to the coil, the iron sabot is attracted by electromagnetic force and enters the coil. As the current pulse attenuates, the magnetic force dissipates, and the iron sabot is propelled out of the coil due to inertia. The fuel target is separated from the iron sabot by a sabot separator consisting of ring-shaped permanent magnets. It is found that the velocity of the injected target increased to some extent by increasing the number of coil turns. It has been demonstrated that multi-stage acceleration using multiple coils is effective for increasing the velocity of the injected target.

Keywords: fusion power reactor, fast ignition, target injection, high-speed camera

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1. Introduction

Fast ignition scheme is an inertial fusion approach in which fuel is compressed by a laser and subsequently ignited using additional heating lasers [1–4]. By separating the compression and heating stages, the fast ignition scheme can achieve ignition with approximately 1/10 of the laser energy required by the central ignition scheme, which relies solely on compression lasers. To heat the core plasma without the influence of the high-density plasma, a hollow cone-shaped component is attached to a fuel shell.

KOYO-Fast is a conceptual design of the fast ignition laser fusion power plant [5]. It consists of four power reactors, each capable of producing 320 MW of electric power. The ignition process involves the use of a 1.1 MJ, 32-beam implosion laser and a 100 kJ, single-beam additional heating laser. The reaction occurs at a rate of 4 Hz within each reactor. Considering that there are two fuel injectors per reactor, one injector operates at a frequency of 2 Hz. The injected fuel is expected to travel at a speed of 300 m/s. To ensure precise laser irradiation, the target position accuracy at the laser irradiation point should be within the laser spot, which is approximately 300 micrometers in diameter. Additionally, the cone directing the additional heating laser must be precisely aligned. Therefore, a system capable of achieving high-speed and high-precision injections is required.

Research and development of a pellet injection system has been carried out at General Atomics since the 1990 s. In the 2000 s, they reported a gas gun system that utilizes helium and is capable of shooting up to 12 targets at a frequency of 6 Hz, reaching speeds of approximately 400 m/s [6]. In the 2010 s, they presented a system in which an aluminum tube with a 1 cm diameter was ejected at a speed exceeding 50 m/s using a magnetic field generated by coils [7]. However, these systems were developed for central ignition fuel targets without cones. For fast ignition fuel targets, a more controlled injection system is required.

In Japan, several reports on injection systems have been published. Sakae et al. developed a gas gun device and conducted experiments using cylindrical projectiles [8]. Mori et al. developed a 10 Hz repetitive injection system using free-fall for bead targets [9]. However, there have been no reports on the injection of targets with cones.

We have developed an injection system for fast ignition targets using high-pressured gas. In the previous paper, we reported on the behavior of injected fast ignition mimic targets with cones [10]. The velocity of the injected target increases with the injection gas pressure, reaching approximately 100 m/s. However, the target flight angle varies over a wide range shot by shot. One possible reason for the variation in target attitude is the gas flow in the observation chamber. Therefore, we attempted to accelerate the target not using gas, but rather through magnetic attraction. By eliminating the use of gas, we can prevent disturbance to the targets. The electromagnetic coils generate a controlled magnetic force, which can be more precisely controlled compared to the force exerted by gas. In this paper, we present the injection system using electromagnetic coils and the preliminary results of the injection experiments.

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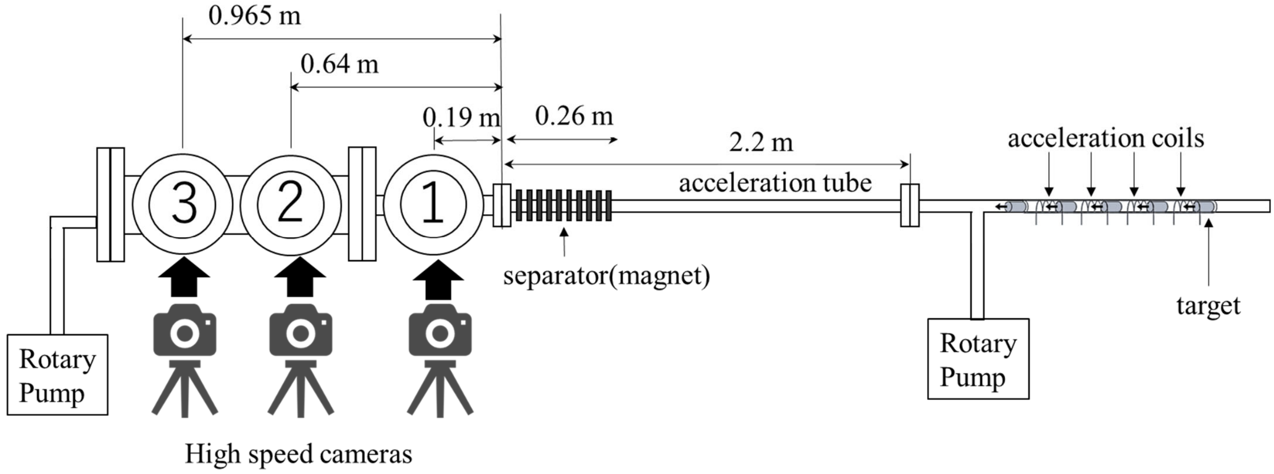

Fig. 1 Schematic diagram of our target injection system.

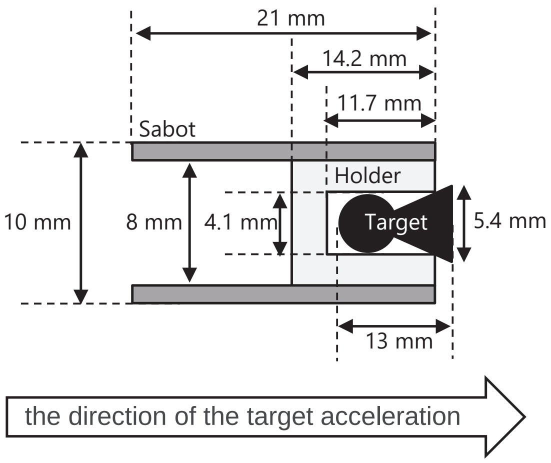

Fig. 2 Schematic diagram of target assembly.

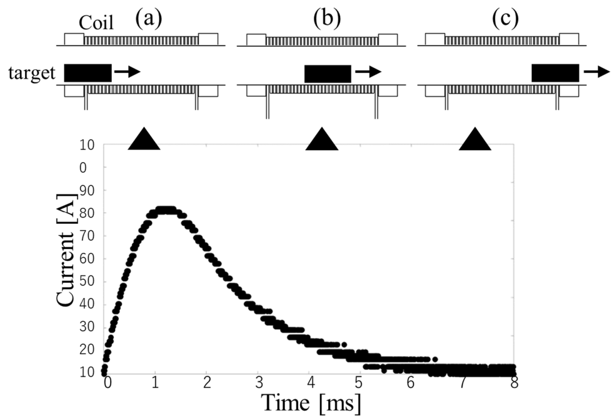

Fig. 3 Principle of injection using electromagnetic coils.

2. Experimental Setup

Figure 1 shows the schematic diagram of our target injection system utilizing electromagnetic coils. The system consists of two rotary pumps, multiple acceleration coils, an acceleration tube, a sabot separator, and an observation chamber with three windows. The inner diameter of the acceleration tube is 10 mm. Figure 2 shows an illustration of the target assembly. The size of the targets is identical to that of the KOYO-Fast target. As shown in Fig. 2, a target is inserted into a holder and then secured within an iron sabot. Both targets and holders are fabricated from DURACON ® due to its low friction properties. The target weights 0.17 g, while the sabot with the holder weights 4.20 g. The assembled target is positioned at the entrance of the acceleration tube and propelled forward by the magnetic force generated by the acceleration coils. Ring-shaped permanent magnets are employed as the sabot separator. As the assembled target passes through the sabot separator, eddy currents are induced on the surface of the sabot. The interaction between the magnetic field and the eddy currents generates a Lorentz force that decelerates the sabot [10, 11]. Additionally, the iron sabots are attracted to the permanent magnets, resulting in the ejection of the target from the target holder due to inertia. We used high-speed cameras, SA-Z and NOVA (manufactured by Photron Ltd.) and HX-1 (manufactured by nac Image Technology Inc.) to observe the injected targets. Further details regarding the image analysis can be found in the previous paper [10].

3. Experimental Results

The principle of injection using electromagnetic coils is simple. As shown in Fig. 3, when a current pulse is applied to the coil, it functions as an electromagnet. The iron sabot is attracted to the electromagnet and enters the coil (Fig. 3 (a)). When the iron sabot reaches the center of the coil, the current pulse attenuates (Fig. 3 (b)). Consequently, the magnetic force dissipates, causing the iron sabot to be propelled out of the coil due to inertia (Fig. 3 (c)). Capacitors (100 μF, 4 pieces) are employed as a current source.

We fabricated coils with a length of 50 mm by wind-

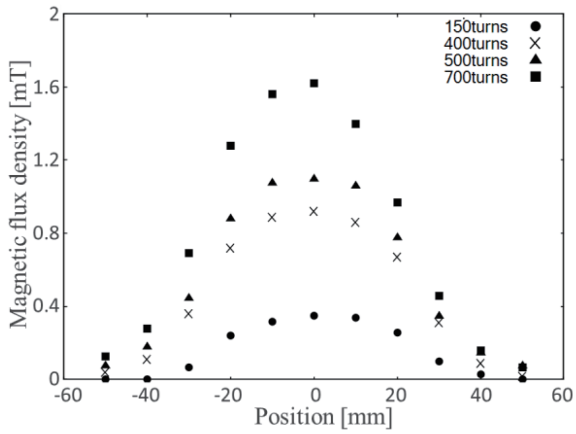

Fig. 4 Magnetic flux density distribution of coils.

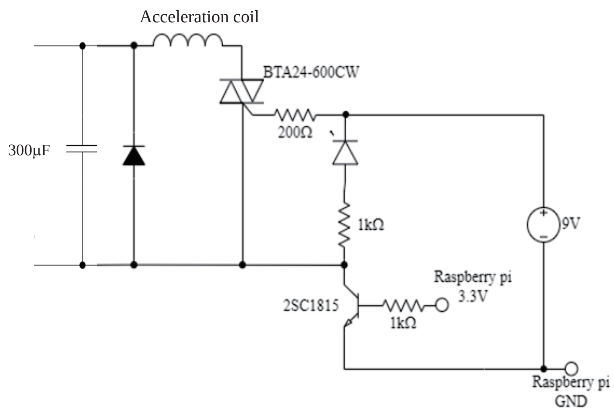

Fig. 5 Circuit diagram of the injection system.

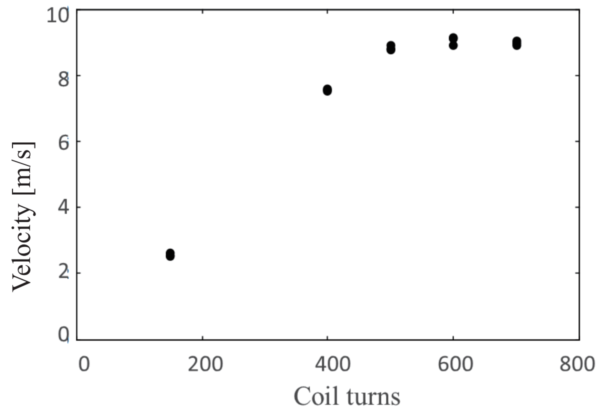

Fig. 6 Dependence of target velocity on number of coil turns.

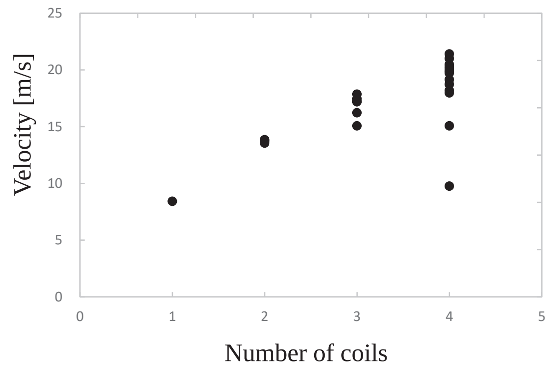

Fig. 7 Dependence of target velocity on number of coils.

ing a 0.8 mm diameter wire around an acrylic pipe with an outer diameter of 19 mm. Figure 4 shows the distribution of magnetic flux density measured using a gauss meter. The applied current was 0.1 A. It is seen that as the number of coil turns increases, the magnetic flux density also increases. Figure 5 shows the circuit diagram of the injection system. A Raspberry Pi signal (3.3 V voltage pulse) is inputted to the base of the triac, causing the transistor to turn on. This enables a 9 V voltage to be applied to the LED and a 1 kΩ resistor. Subsequently, the triac is triggered and allows current to flow from the capacitor to the acceleration coil. To prevent the flow of current back from the acceleration coil, a diode is connected in parallel with the capacitor. First, we conducted injections using a single coil. The measured velocity of the injected target is shown in Fig. 6. It is found that as the number of coil turns increases, the velocity of the injected target also increases. However, the velocity increase is not linear and plateaus once the number of coil turns exceeds 500. In the case of an injected speed of 8 m/s, it takes 3.1 ms to travel from the entrance of the coil to the center. As shown in Fig. 3, the current pulse is still active at 3.1 ms. Consequently, it is considered that the electromagnetic force pulls the target back towards the magnetic coil, resulting in a suppression of the velocity.

To further enhance the acceleration of the target, we implemented a multi-stage acceleration approach. As shown in Fig. 1, a series of coils is arranged in a linear configuration, and a current pulse is applied to each coil as the target reaches the entrance of the respective coil. The timing for applying these current pulses was determined based on the measured speed of the target and controlled using a Raspberry Pi. The outcome of this approach is shown in Fig. 7. It is clearly seen that multi-stage acceleration increases the velocity of the injected target. However, as the number of acceleration coils increases, the error bar in the velocity also becomes larger. This can be attributed to slight misalignments of the target position at each stage, which accumulate and ultimately lead to a substantial velocity error bar.

The achieved velocity of the injected target is lower compared to the desired value for a fusion reactor, however, it is important to note that this study represents a proof-of-principle preliminary experiment. By amplifying the current pulse and precisely timing its application to the coils, it is anticipated that the velocity of the injected target can be significantly enhanced.

4. Summary

We developed a target injection system utilizing electromagnetic coils. In accordance with electromagnetic principles, the magnetic field strength increases with the number of coil turns. As a result, the velocity of the injected target exhibits a certain degree of increase when the number of coil turns is increased. Employing multi-stage acceleration with multiple coils proves to be effective in augmenting the velocity of the injected target. However, achieving more efficient acceleration necessitates a more precise control of the current pulse. The findings regarding the target flight angle will be presented in a future publication.

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