# Experimental demonstration of thrust vectoring magnetic nozzle with multi-axis thrust measurement system

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**We have developed a non-mechanical thrust vectoring system that consists of independently controlled four coils for plasma propulsion. To evaluate the controlling performance, we have conducted demonstration experiments using a laser ablation plasmas. Multi-axis thrust measurement system using piezoelectric elements was developed and used to measure the two-dimensional thrust vector. We found some issues about the multi-axis thrust measurement system through the experiments. The major issues were the asymmetric vibration due to the low accuracy of assembling, and the difficulty to pick up a thrust signal from the output signal due to the large vibration from the coils. In this conference, we will share the current status of the thrust vectoring system and multi-axis thrust measurement system, and the improvement plan.**

## Nomenclature

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| $PZ$ | = piezoelectronic element |
| $C_{piezo}$ | = capacitance of piezoelectric element |
| $R_{piezo}$ | = impedance of piezoelectric element |

## I. Introduction

THRUST axis must be on the center position of the mass of a spacecraft through a mission to make the attitude stable. Despite this requirement, the center of mass often moves during a mission due to some reasons, such as propellant consumption, mechanical separation of a small probe, and expansion of antenna, solar panel, and science equipment. On the previous space crafts, mechanical gimbal was widely used to adjust the thrust axis. There is a lubrication problem on every mechanical system. It is a more difficult problem in space due to low ambient pressure, radiation, atomic oxygen environment, and so on[1]. Frictional

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wear may restrict a long-term exploration mission in the future, such as exploration for trans-Neptunian objects or Oort cloud.

As a non-mechanical thrust vectoring method, multi-coil magnetic nozzle system has been proposed[2,3]. The magnetic nozzle consists of several coils, and independently controlled electric current drives each coil. The electric current controls the magnetic field structure. In this system, the controlled magnetic field guides a plasma plume resulting in a vectored thrust. Although the thrust vectoring system has been investigated[2,3,4], thrust vector measurement has never been performed experimentally.

A multi-axis thrust measurement system is required to evaluate the experimental performance of the thrust vectoring system. A pendulum-type thrust stand is widely used to measure thrust, and the 2D dual pendulum thrust stand has been developed[5]. The pendulum thrust stand requires an active control system using an actuator. We attempted to develop a passive measurement system using a piezoelectric device.

## II. Experimental system

### A. Multi coil system

We developed a multi-coil system that consists of four square coils as shown in Fig. 1. The four square coils around the cone show the multi-coil system and the white arrows on the coil surface show the direction of driving current. Every coil generated a magnetic field facing the inner area. This system generated up to 300 mT on the initial target position (25 mm from the coil surface that is facing the target) for several hundred microseconds. The capacitor bank system[6] drove the coils. The cone shows a drive laser. The laser ablates a target and generates a plasma. The initial plasma expands toward the upstream of the laser. The plasma interacts with the magnetic field and changes its direction, and, the plasma goes to the downstream to generate thrust. In this process, the thrust axis should be the same as the center axis of the coil when all coils generate the same intensity of the magnetic field.

Figure 2 shows the experimental setup. This figure is the overhead view from the downstream. The drive laser was injected from the backside of the multi-coil system and passed through the inner area of the system, and ablated the target that was placed on 25 mm aware from the coil surface. B-dot probe was placed on 5 mm downstream from the target, and 4 mm downward from the laser axis. We assumed that there was no effect from the probe to the thrust measurement because it was on the downstream region.

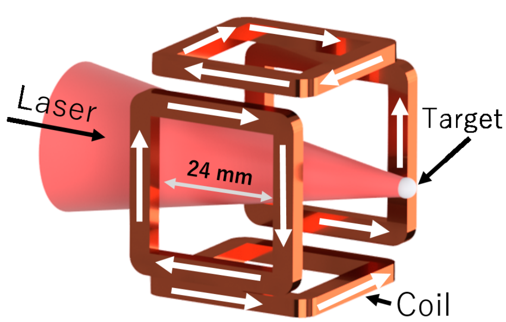


**Figure 1. Multi-coil system using four square coils**

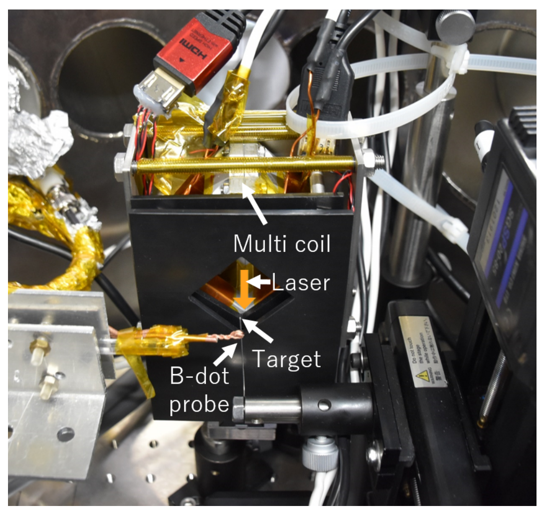


**Figure 2. Experimental setup**

### B. Multi-axis measurement system

We have developed the multi-axis thrust measurement system using piezoelectric elements (PA4JEW, Thorlabs, inc.). Figure 3 shows the side view of the system. In this system, the multi-coil and piezoelectric elements were fixed by the clamping of the stainless plate and the plastic plate. The parts that were placed between the coil and the target was made by plastic to avoid the magnetic field shielding by an eddy current. The clamping force was managed through the tightening torque of the screws. The clamping force was 144 N: the recommended load value on the spec sheet. We placed this system along the laser axis and perpendicular to it. The thrust vector was measured by eight piezoelectric devices. Two devices were placed on each side of each axis. Here, it was able to measure the two-dimensional thrust vector on the horizontal plane. In front of the measurement system, the plastic plate was placed to avoid the thrust generation by direct collisions of plasma.

Figure 4 shows the measurement circuit. This piezoelectric element has the capacitance of 70 nF and the impedance of 300 m$\Omega$ at Resonant Frequency, 450 kHz. The output signal was transferred through the shielded cable and terminated by a carbon-resister of 50 $\Omega$. When a compression force is applied to piezoelectric elements, it generates the electric charge of 29nC/N.

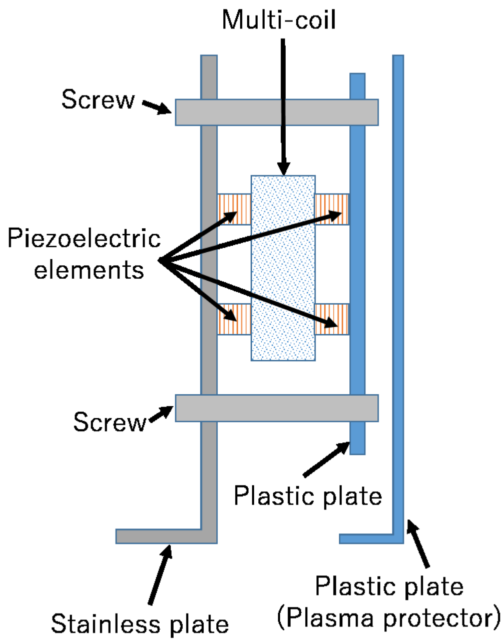


**Figure 3. Side view of the thrust measurement system**

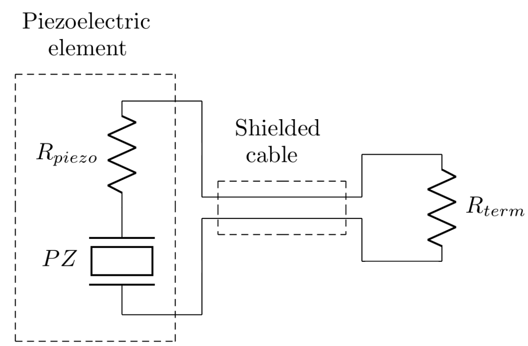


**Figure 4. Measurement circuit of the output signal from a piezoelectric element**

## III. Experimental result

The demonstration experiment with laser ablation plasma was conducted. The ablation target was a ⌀0.5 mm rod made by 5052 aluminum alloy. The ablation laser was 1064 nm Nd: YAG laser. The laser energy and pulse widths were 1 J and 400 ps, respectively. In the following result, the directions of compression force are defined as shown in Fig. 5. Every result shows the total value of the output signal from the piezoelectric devices that were placed in each direction, except the right direction. On the right direction, the result shows the twice value of the output signal. The one of the piezoelectric device placed in the right direction was disconnected due to a failure of the setup.

Figure 6 shows the signal from the piezoelectric devices with the laser, and without a target and a magnetic field. In this case, the laser was absorbed by a beam dump that was placed on the edge of the chamber. The spike signals on the laser timing, 0 ms, are noise from the laser. There is a signal early in time at t 0.4 ms. The source of this signal is unclear, but there is a possibility of switching noise.

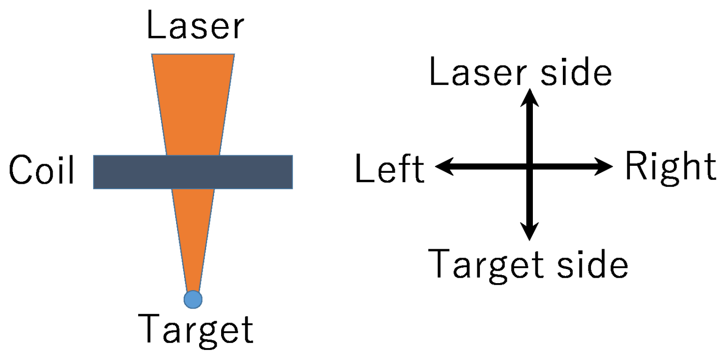


**Figure 5. Difinition of the direction**

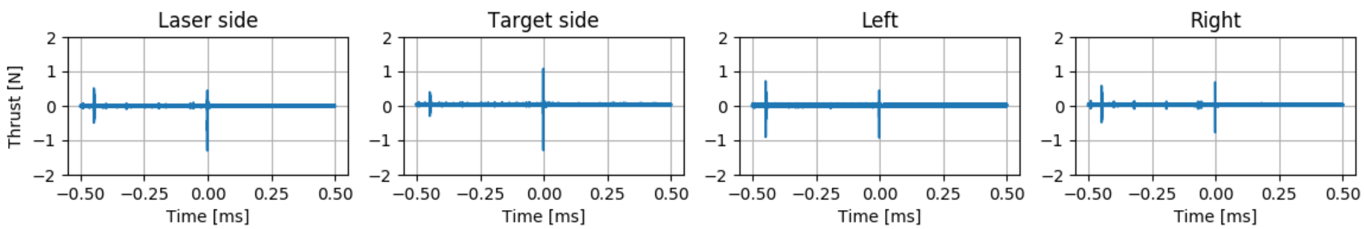


**Figure 6. The signals from the piezoelectric devices with the laser, and without a target and a magnetic field**

Figure 7 shows the signals from the piezoelectric devices with the laser and the target, and without a magnetic field. The timing of the spike signals is similar to that without a target. However, the signal amplitude on the laser timing, t 0 ms, is larger than it. The difference between these two cases is the existence of the plasma and the distance between the piezoelectric devices and laser-solid interaction point. Previous research suggests the laser-produced plasma reached 150 mm from the target in 500 ns [7]. It means the plasma had at least 300 km/s. The laser parameter was different, but the intensity was similar between this experiment and the previous one. When a plasma has the velocity of 300 km/s, it reaches the piezoelectric devices in 80 ns. The signals are the complex signal of the radiation noise from the laser-solid interaction, and an electric field by the plasma.

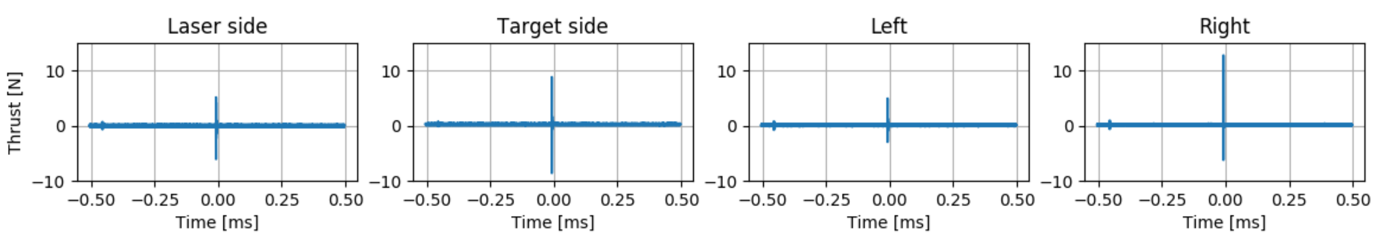


**Figure 7. The signals from the piezoelectric devices with the laser and the target, and without a magnetic field**

Figure 8 shows the comparison between the signals from piezoelectric devices in two cases. The case A shows the signals with the magnetic field, and without a laser and a target, and the case B shows the signals with the laser, the target, and the magnetic field. In these cases, every coil was driven by 500 V. Both waveforms are quite similar except the noise. It means the force by the coil vibration was dominant compared to the thrust. On the case B, the signals have 1 V positive bias except for the laser side and noise through the measurement. The trend appeared before the injection of laser and turning on the magnetic field. The source and the propagation path of this bias and noise are unclear.

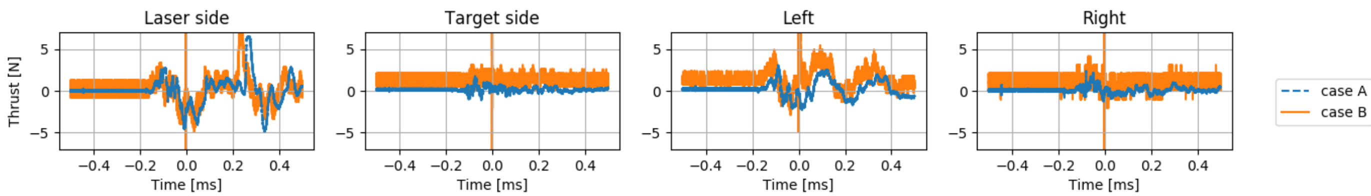


**Figure 8. case A: The signals from the piezoelectric devices with the magnetic field, and without a laser and a target , case B: The signals from the piezoelectric devices with the laser, the target, and the magnetic field**

## IV. Discussion and Summary

We have developed the thrust vectoring magnetic nozzle and multi-axis thrust measurement system. On the demonstration experiment, the piezoelectric elements detected some signals, but the thrust was not clear. Two major issues are investigated throughout the experiment.

The first issue is about the mechanical assembly. Theoretically, each output signal of the piezoelectric element that placed on the opposite side (Laser side–Target side, and Right–Left) should be an antiphase signal. However, there was no clear antiphase signal on the measured data. The cramping force by the tightening torque of the screw deformed the plastic plate because the rigidity of the plate was not enough. The applied force to each piezoelectric device was possibly not uniform by the deformation. The small clearance between the clamping plate and the coil winding wire should also be improved. The winding wire moves by the Lorentz force between the self magnetic field and the driving current. Then, the winding wire might touch the clamping plate and make a noise signal. These issues derive from the requirements that the coil module and the supporting parts must be mechanically independent except the surface of the piezoelectric device. We have to implement a fundamental review of a mechanical design of the multi-axis thrust measurement system to remove the unexpected deformation of the plate and the magnetic wire. In addition, we are also planning to measure the multi-axis thrust using an acceleration sensor instead of a piezoelectric element.

The second issue is that the vibration of the coil itself was dominant. We are planning to extend the magnetic field duration and make a laser shot after the vibration of the coil is converged. Figure 9 shows the signals from the piezoelectric devices with the magnetic field, and without a laser and a target in the long term. In this case, the vibration converges in 4 ms. When we use 10 ms duration of the magnetic field and make a laser shot on the after half of the duration, we will be able to divide the signal from the thrust from the coil vibration.

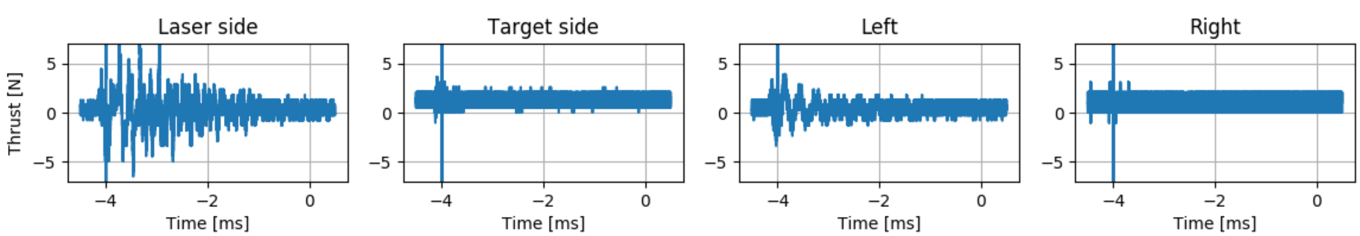


**Figure 9. The signals from the piezoelectric devices with the magnetic field, and without a laser and a target in the long term**

## Acknowledgments

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