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# Time-Resolved Cavity Ring-Down Spectroscopy for Erosion Sensor of Hall Thruster

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**Abstract:** *The life limiter of Hall thruster is ion bombardment on the acceleration channel. To estimate the lifetime of the thruster, sputtered atoms should be measured. However, the conventional method, the endurance long term test requires a huge amount of time and money. Therefore, erosion sensor using cavity ring-down spectroscopy has been developed. In this study, titanium atoms were measured as erosion material by our built sensor. Then, the large noise caused by the discharge current oscillation was observed so that time-resolved system was introduced and improved the measurement accuracy.*

**Keywords:** Space Propulsion, Hall thruster, Erosion measurement, Spectroscopy

## 1. INTRODUCTION

In past a few decades, electric propulsion achieved more than 5,000 hours and succeeded in various space missions. Additional to it, space missions exceeding 10,000 hours has been also increased and several studies about extending life has been conducted[1]. To extend the lifetime, it is necessary to optimize thruster's shape and magnetic field configuration.

The primary lifetime limiter is wall erosion due to ion sputtering[2]. To evaluate the lifetime of the thruster, the measurement of sputter erosion is necessary. However, the conventional measuring method, the durability test spends tremendous cost both in the manpower and the time[3]. Moreover, measuring parameters is enormous and the erosion is infinitesimal so that the conventional method is impractical. Therefore, fast time response and high sensitive sputter erosion measurement system is required. Considering these requests, in this study, sputter measurement system using cavity ring-down spectroscopy (CRDS)[4] for electric propulsion has been developed.[5-7]

## 2. CRDS

Cavity ring-down Spectroscopy (CRDS) is a highly sensitive spectroscopic method to which laser absorption spectroscopy (LAS) is applied. Figure 1 shows the principle of CRDS. CRDS has an optical cavity consisting of two high reflectivity mirrors and it confines a laser beam. When the absorption species which has same excitation wavelength with the laser exist in the cavity, the species eats the incident laser and the transmitted laser is attenuated. Then, the transmitted light is called ring-down signal and, the ring-down time is defined when the ring-down signal become 1/e times. From the ring-down time, the density of the measuring atoms can be calculated.

In the CRDS, the laser beam reflects in the cavity many times so that optical path can be longer and measuring sensitivity can be enhanced compared to LAS.

The ring-down signal, $S(t, \gamma)$ is given as

$$S(t, \gamma) = S_0 \, exp \left[ -\frac{t}{\tau(\gamma)} \right] \qquad (1)$$

$\tau(\gamma)$ is defined as ring down time, which $S_0$ reaches $1/e$ times.

When measuring atoms don't exist in the optical cavity, the ring down signal is attenuated only by the mirrors, on the other hand, when the atoms exist, its absorb the laser light. Then, ring down time is given as

$$\tau(\gamma) = \frac{L}{c[(1 - R) + \int k(x, \gamma) \, dx]} \qquad (2)$$

When measuring atoms don't exit, $\tau_0$, ring down time is given as

$$\tau_0 = \frac{L}{c(1 - R)} \qquad (3)$$

because the term of absorption can be ignored.

When absorption degree, $ABS(\gamma)$ is defined as integral of absorption coefficient, from equations (2) and (3) it can be expressed as

$$ABS(\gamma) \equiv \int k(x, \gamma) \, dx = \frac{L}{c} \left[ \frac{1}{\tau(\gamma)} - \frac{1}{\tau_0} \right] \qquad (4)$$

Accordingly, absorption degree can be obtained from measurement of ring down time. From equation (4), absorption spectrum of measuring atoms can be obtained when the laser frequency is swept. Line density of lower level on the optical path of the laser beam can be calculated as

$$\int N_i \, dx = 8\pi \frac{g_i}{g_k} \frac{\gamma_{ki}^2}{A_{ki} c^2} \left( \int Abs(d\gamma) \right) \qquad (5)$$

An estimation of the minimum detectable absorbance can be obtained from the noise of ring down time in the CRDS. The minimum detectable absorbance, $ABS_{min}$ is calculated as

$$ABS_{min} = \frac{\Delta \tau_0}{\tau_0} (1 - R) \qquad (6)$$

where $\Delta \tau_0$ is standard deviation for $\tau_0$.

In this study, titanium atoms were detected as erosion material by the CRDS system. The detailed parameter for excitation from ground state is shown in Table 1 and Fig. 2.
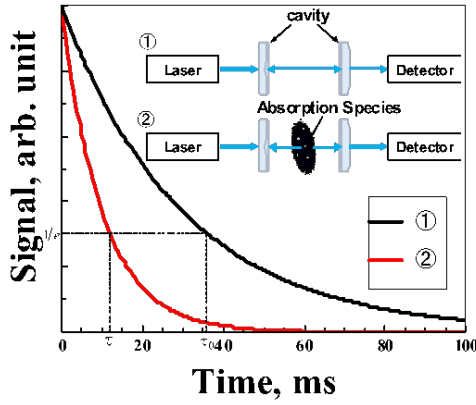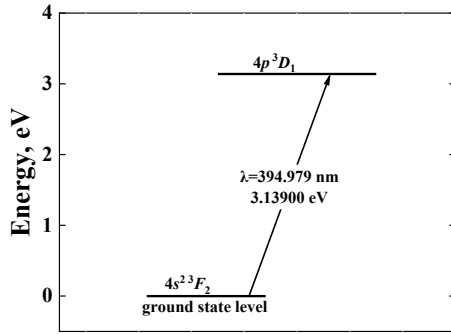
Fig. 1. Principle of CRDS



Fig. 2. Grotrian diagram from ground state of Ti[8]

Table 1. Transition parameter from ground state of Ti[8]

| Transition | $\lambda$[nm] | $A_{ki}$ | $g_i$ | $g_k$ |
|---|---|---|---|---|
| $4s^2\ ^3F_2 \to 4p\ ^3D_1$ | 394.979 | $5.60 \times 10^7$ | 5 | 3 |

## 3. EXPERIMENTAL
### 3.1 CRDS SYSTEM

Figure 3 shows a schematic diagram of our built CRDS system. A Littrow external cavity diode laser (DL100 pro, TOPTICA) was used as a laser light source. To detect the titanium atoms, the wavelength was swept from 394.976 nm to 394.984 nm. The modulated laser was divided into probe light, reference light and etalon light by beam splitters. The probe light was modulated to the 1st order diffracted light by acousto-optic modulator (AOM), the light was reduced by ND filter to restrain absorption saturation, and the light passed through the cavity. Finally, the signal was amplified by photomultiplier tube (PMT) and detected. The reference light was used for optogalvanic spectroscopy. The light was chopped by optical chopper and passed through the HCL. The passed signal wad amplified by lock-in amplifier to improve S/N ratio. The etalon light was detected after passed through the etalon (FSR=1.5 GHz).

### 3.2 TIME-RESOLVED CRDS

Hall thruster has a discharge current oscillation. It causes the fluctuation of ring-down signal and makes the measurement noise large. When the operating parameters such as the magnetic field configuration were slightly changed to assess the life time of Hall thruster, it is not available to recognize the small difference of the effect. Therefore, the-time resolved CRDS system which can be resolved by the phase of the discharge current oscillation was developed.

Time-resolved CRDS is to analyze the data with the phase of the discharge current frequency. Then, Volterra Engine[9] which can constantly lock the discharge current frequency was used. Figure 6 shows the time variation of the discharge voltage and discharge current. Then, ON/OFF switching frequency was 20 GHz and the duty ratio was 20%.

### 3.3. VACUUM FACILITY

The measurement was conducted in vacuum chamber at Kyushu University as shown in Fig. 7. The vacuum chamber was a cryogenically pumped, cylindrical, stainless steel vacuum chamber that is 1.0 m in diameter and 1.2 m in length. It has a rotary pump, two turbo molecular pumps and a cryogenic pump maintaining the pressure below $7.0 \times 10^{-4}$ Pa without thruster operation and $8.8 \times 10^{-3}$ Pa (for xenon) during thruster operation.

### 3.4. HALL THRUSTER

In this study, a 200 W class magnetic layer type Hall thruster developed at Kyushu University was used for ion source. The overview of the thruster is shown in Fig 8. The outer diameter is 56 mm and the inner diameter is 40 mm. The anode is located 25 mm upper from the thruster exit. The acceleration channel is made of boron nitride. The thruster has 4 solenoidal coils at each corners and a solenoidal coil at the center of the thruster to create and control radial magnetic field in the acceleration channel. The magnetic flux density and configuration can be changed by controlling the ratio of the inner coil current to the outer coil current.

During the measurement, Hall thruster was operated at mass flow rate of 0.68 mg/s.

As an electron source, hollow cathode (Ion Tech, HC252) was used. Operating gas was xenon. When the cathode was ignited, keeper voltage was 14 V and mass flow rate was 0.27 mg/s. While operation, keeper current was set at XX A.

### 3.6. SETUP

The experiment was conducted by using the experiment setup as shown in Fig. 4. The laser passed 30 mm front and the titanium target was set 60 mm front from the thruster exit. When the thruster operates, ions are accelerated and sputtered the target. Then, titanium atoms were produced and measured by the laser. Thruster and the CRDS system was mounted in the carbon box for the protection from the heat and distributed titanium atoms.
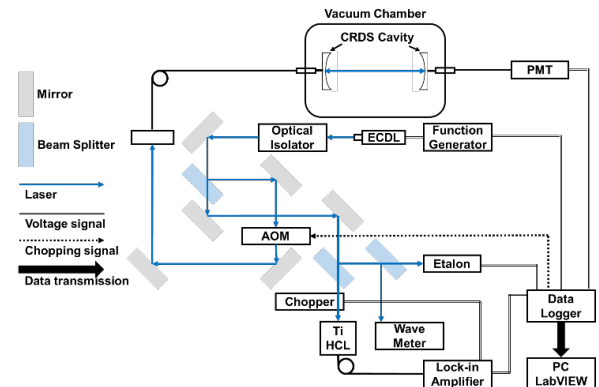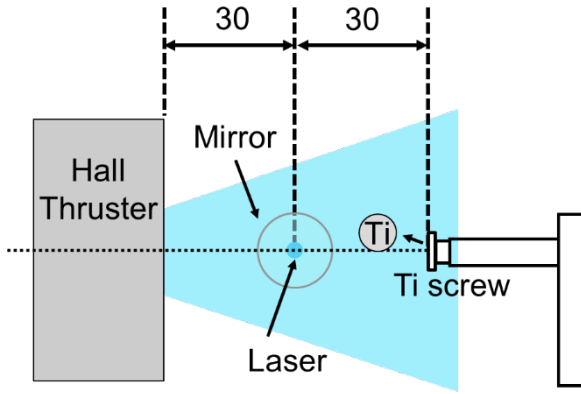


Fig. 3. Schematic diagram of CRDS system

Fig. 4. Experimental setup

## 4. RESULTS AND DISCUSSION

Figure 5 shows time variation of mirror reflectivity. It is clear that the mirror reflectivity was gradually decreasing during the measurement. The data was alternately obtained under vacuum and thruster operation 10 times each. Then, about 100 ring-down signals under each conditions were obtained at a time.

The mirror reflectivity under vacuum was higher than that under thruster operation because the mirrors were contaminated by the titanium atoms which was produced from the target. While the mirror reflectivity was decreasing under thruster operation, the mirror reflectivity was slightly increasing under vacuum. This would be because the titanium atoms on the mirrors were evacuated.

Figure 6 shows absorbance when the time-resolved CRDS was not used. Figure 7 shows absorbance when the time-resolved CRDS was used. When the time-resolved CRDS was used, it is clear that the dispersion was reduced.

Figure 8 shows absorbance distribution calculated by 300 ring-down signals. Figure 9 shows absorbance distribution calculated by 10,000 ring-down signals with time-resolved CRDS. The two has peak at absolute frequency of around -4 GHz, however, compared to fig. 8, the dispersion seems to be small. Therefore, the time-resolved effect could be observed.
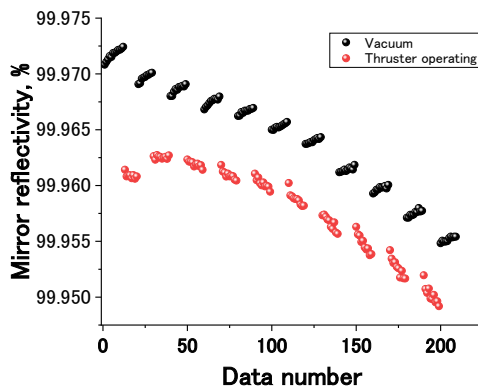


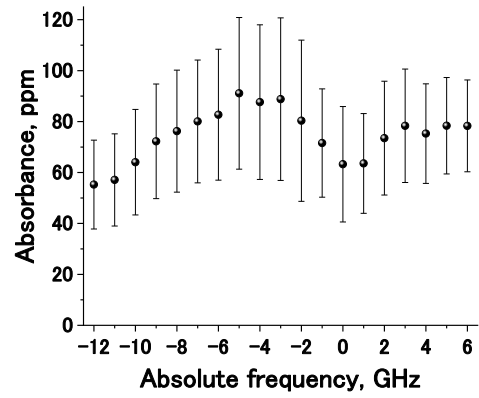Fig. 5. Time variation of mirror reflectivity



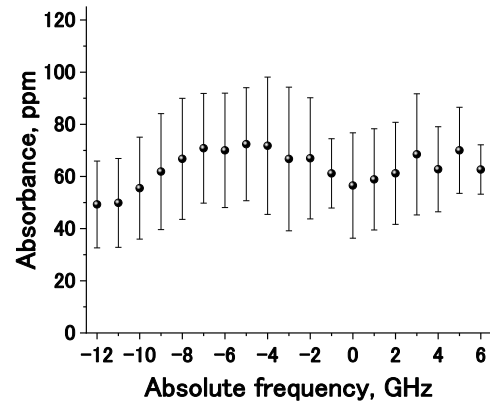Fig. 6. Absorption spectrum versus absolute frequency (all data)



Fig. 7. Absorption spectrum versus absolute frequency (time-resolved)
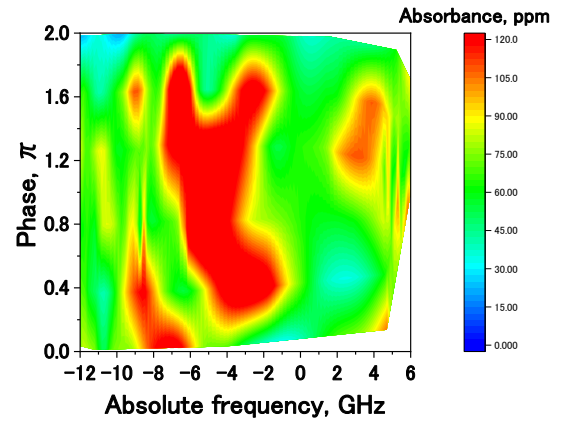


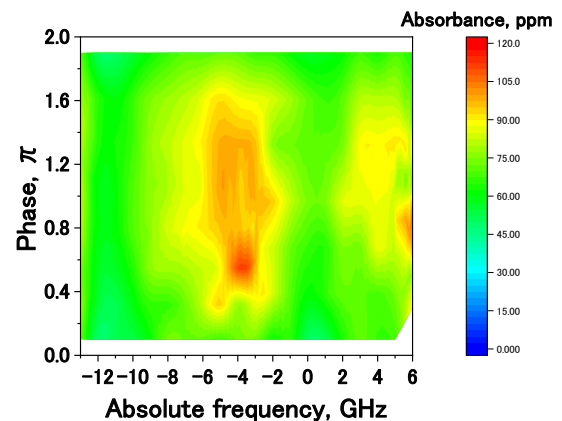Fig. 8. Absorbance distribution



Fig. 9. Absorbance distribution (time-resolved)

## 5. CONCLUSION

In this study, CRDS system was developed for the erosion assessment in Hall thruster. It was observed that the mirror reflectivity was gradually decreased during the Hall thruster operation because of the contamination of the sputtered particles on the mirror surface. On the other hand, the mirror reflectivity was improved when Hall thruster was not operating.

In addition, to improve the measurement accuracy, the time-resolved system was introduced. As a result, the dispersion could be reduced and our built time-resolved CRDS system was validated.

As a future work, this time-resolved CRDS system will be arranged to be able to detect aluminum atoms and measure the wall erosion of 200 KW class Hall thruster which was developed at Kyushu University.

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