On-board Plasma Plume Diagnostics for ETS-9 All-electric Satellite

IEPC-2019-449

Presented at the 36th International Electric Propulsion Conference
University of Vienna, Austria
September 15-20, 2019

Kiyoshi Kinefuchi[1], Kiyokazu Koga[2], Hiroaki Kusawake[3], Yuta Tsuchiya[4],
Kenichi Kubota[5], Shinatora Cho[6], Tadahiko Sano[7] and Tsutomu Fukatsu[8]
Japan Aerospace Exploration Agency, Tsukuba, Ibaraki, 305-8505, Japan

Yasuo Terakado[9]
Meisei Electric Co., Ltd., Isesaki, Gunma, 372-8585, Japan

Shinji Hatta[10]
MUSCAT Space Engineering, Munakata, Fukuoka, 811-4145, Japan

and

Naoji Yamamoto[11]
Kyushu University, Kasuga, Fukuoka, 816-8580, Japan

Abstract: All-electric satellites apply high-power electric thrusters for orbit rising and station keeping. These thrusters expose the satellite to high-density plasma environment, which causes interactions between the plasma and the spacecraft, e.g., charge exchange ion backflow and bombardment to the satellite. To obtain the magnitude of the interaction in JAXA's all-electric satellite called the Engineering Test Satellite 9, three kinds of plasma sensors, a Langmuir probe, a quartz crystal microbalance and a retarding potential analyzer, have been developed. The sensors were designed based on the results of a plasma plume simulation with hybrid particle-in-cell approach in consideration of severe radiation environment affecting all-electric satellites. The paper reviews the sensor development including relevant tests and the plume simulation.

[1] Associate Senior Research Engineer, ETS-9 Project, Space Technology Directorate I.
[2] Associate Senior Research Engineer, Research Unit I, Research and Development Directorate.
[3] Senior Research Engineer, Research Unit I, Research and Development Directorate.
[4] Research Engineer, Research Unit I, Research and Development Directorate.
[5] Research Engineer, Aeronautical Technology Directorate.
[6] Research Engineer, Research Unit II, Research and Development Directorate.
[7] Function Manager, ETS-9 Project, Space Technology Directorate I.
[8] Project Manager, ETS-9 Project, Space Technology Directorate I
[9] Division Manager, Space and Defense Division.
[10] President.
[11] Professor, Department of Advanced Energy Science and Engineering.

I. Introduction

The Japan Aerospace Exploration Agency (JAXA) has been developing an all-electric geostationary satellite named the Engineering Test Satellite 9 (ETS-9, Fig. 1). A domestically manufactured 6-kW class Hall effect thruster (Fig. 2) will be installed in ETS-9. To evaluate the high-power plasma plume effect of the Hall thruster, this satellite will be equipped with three kinds of on-board plasma sensors: LP (Langmuir Probe), QCM (Quartz Crystal Microbalance) and RPA (Retarding Potential Analyzer).

These plasma sensors provide crucial information for the Hall thruster operation in orbit. In a Hall thruster, low energy ions produced thorough the charge exchange (CEX) collision process readily flow back to the satellite due to the potential difference. The ion bombardment to the satellite causes ion sputtering that is a critical issue to solar cells and thermal blankets. The RPA measures the energy distribution of the ion backflow and the QCM provides the sputtering rate caused by the ion bombardment. The satellite charging plays an important role in the sputtering mechanism; therefore, potential difference between the satellite and space plasma potential should be detected. The LP can measure the potential difference as well as plasma density and electron temperature. The plasma interaction characteristics to be obtained by ETS-9 will be used to optimize the design of successive satellites.

In this paper, the design and development of the plasma sensors for ETS-9 will be briefly reviewed. First, the plasma plume simulation result used for the sensor design is shown. Then the design procedure of each sensor is discussed. The development status of the sensors including relevant test results is also provided.

Fig. 1 Engineering Test Satellite 9 (ETS-9) in electric orbit rising.

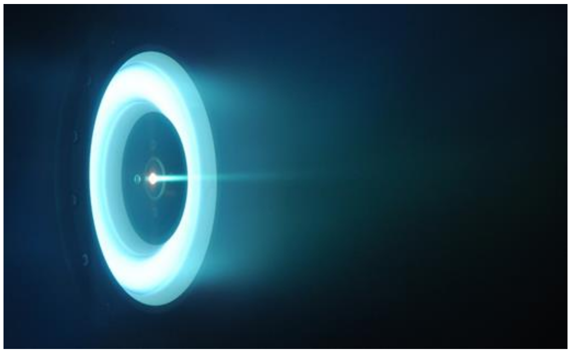

Fig. 2 6-kW Hall thruster for ETS-9 in operation.

II. Plume Simulation

The plasma sensors were designed based on a plume simulation of the domestic Hall thruster. A simulation tool called MUSCAT was applied to the simulation. MUSCAT was originally developed for spacecraft charging analysis[1] and upgraded for the analysis of interaction between exhaust plume of electric thrusters and spacecraft. For the plasma plume modeling, MUSCAT employs a hybrid PIC (Particle-In-Cell) approach. A detailed electron model development is under progress, but here simply assuming Boltzmann equilibrium and quasi-neutrality $n_e = n_i$, one can obtain

$$n_e = n_{ref} exp\left(\frac{e(\phi - \phi_{ref})}{kT_e}\right)$$

$$\phi - \phi_{ref} = \frac{kT_e}{e} ln\left(\frac{n_i}{n_{ref}}\right)$$

Here the electron temperature is assumed to be 8 eV. The code is considered to be six particles: Xe, Xe^{+}, Xe^{2+}, CEX Xe, CEX Xe^{+}, and CEX Xe^{2+}. The computational domain is described in Fig. 3. The satellite body and a solar paddle were considered. The thruster was located on z-axis.

The simulation results of Xe^{+} number density and Xe^{+} CEX number density are shown in Fig. 4. In this simulation, the potential difference between the satellite and the plume was assumed to be 30V. The primary ions travel straight while the CEX ions diffuse radially. Three plasma sensors were designed based on the simulation as described in the next section.

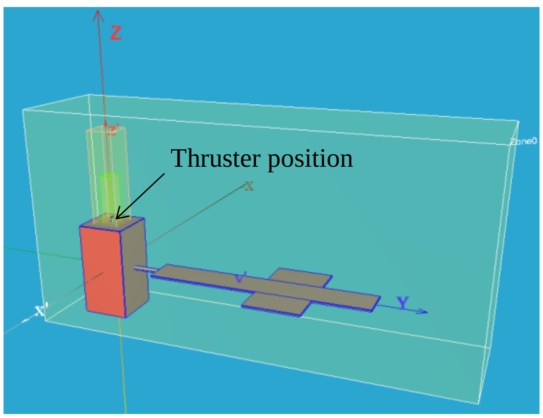

Fig. 3 Computational domain of plasma plume simulation.

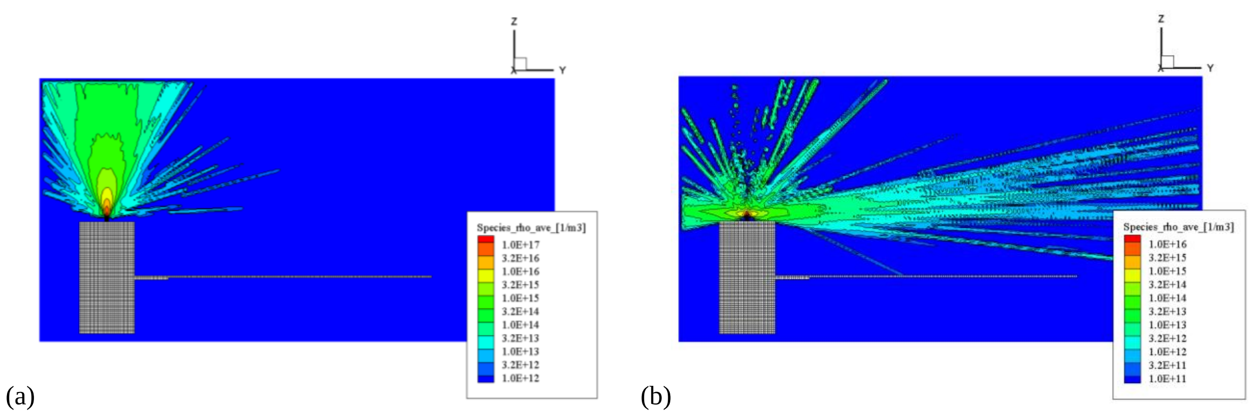

Fig. 4 Plasma plume simulation example. (a) Xe^{+} number density and (b) Xe^{+} CEX number density.

III. Sensor Development

A. Langmuir Probe (LP)

A Langmuir probe (LP) can provide fundamental plasma properties such as plasma density, electron temperature and plasma potential. The LP developed for ETS-9 is based on the one installed on the Japanese Experiment Module at the ISS (International Space Station) as shown in Fig. 5 to measure space plasma environment[2]. The same design will be adopted for ETS-9, but the position of the plasma collector (the "ball" in Fig. 5) with respect to the satellite body must be adjusted because the depth of plasma sheath produced by the Hall thruster is different from that by space plasma. The depth of plasma sheath d can be estimated by the following expression.

$$d = 1.3\frac{\eta^{\frac{3}{4}}}{\lambda_e} \tag{1}$$

where,

$$\eta = \frac{qV}{k_B T_e} \tag{2}$$

and the Debye length λ_e is given as follows,

$$\lambda_e = \sqrt{\frac{\varepsilon k_B T_e}{n_e q^2}} \tag{2}$$

where V is potential difference between the satellite body and surrounding plasma. The electrical charging of the satellite should be considered for the position of the plasma collector. The position was determined using the plasma plume simulation shown in the previous section in consideration of the satellite charging.

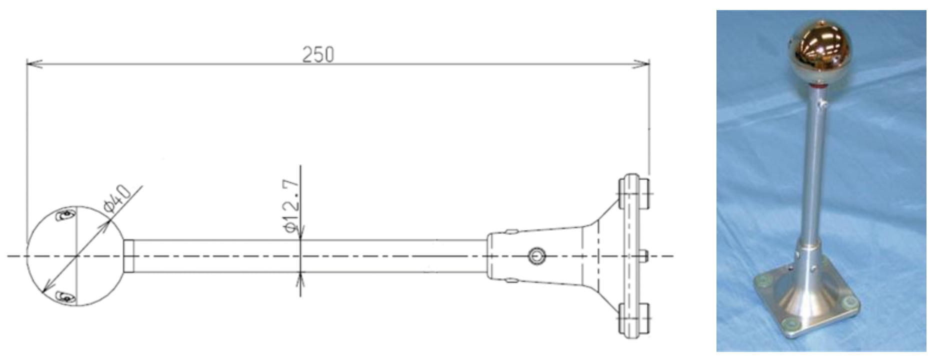

Fig. 5 LP installed on Japanese Module of ISS.

B. Quartz Crystal Microbalance (QCM)

The Quartz Crystal Microbalance (QCM) was designed based on the one used on Hayabusa2 asteroid explorer to evaluate plume effect of the microwave ion thrusters[3]. The QCM has two quartz crystals with electrodes made of gold: one is used just for measurement, and the other is for temperature compensation. One of the electrodes is exposed to outside through an aperture (see Fig. 6). Mass change of the electrode due to sputtering by energetic ions can be measured through the frequency change of one of the quartz crystals.

The radiation environment of ETS-9 is more severe than that of Hayabusa2 in terms of TID (Total Ionization Doze). For example, the radiation is expected to be 100 krad (Si) for 5 mm Al shielding of an all-electric satellite[4]. Therefore, the radiation tolerance of the QCM for ETS-9 needed to be improved. First, TID tolerance was evaluated in a gamma ray irradiation test campaign for the oscillation circuits and quartz crystals as shown in Fig. 7. The oscillation circuits worked properly up to 400 krad, but after that, the current to drive the quartz crystals exceeded the limitation. As for the radiation tolerance of the quartz crystals, no abnormal changes have yet been observed even over 700 Mrad. The quartz test is still under progress.

Based on the gamma ray test, the casing was redesigned. The QCM PM is shown in the right picture of Fig. 6; it has a titanium cover around the aperture and a thicker main casing made of aluminum. It also underwent some modifications to protect IC chips inside the casing.

The main life limitation issue of the QCM on this purpose might be the disappearance of the electrode due to the ion sputtering[5]. In Hayabusa2, the quartz crystal located very near the microwave ion thruster was unable to oscillate after 1700 hours consecutive operation of the thruster probably due to the disappearance of the electrode. As for ETS-9, the plasma density produced by the 6-kW Hall thruster is higher than that of the microwave ion thruster, hence the layout of the QCM on ETS-9 is determined in consideration of the electrode sputtering based on the plume simulation.

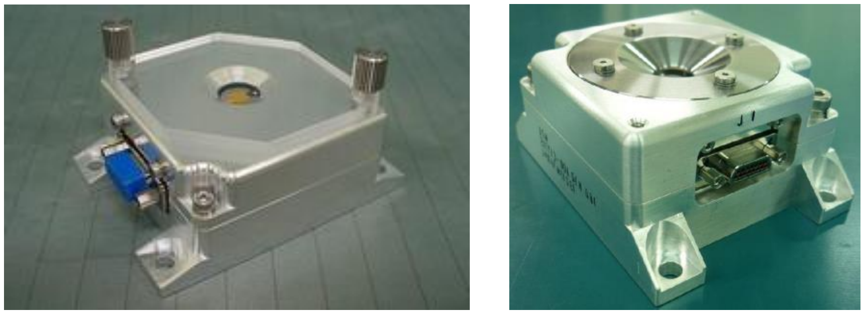

Fig. 6 Left: QCM installed on Hayabusa2 asteroid probe. Right: QCM for ETS-9.

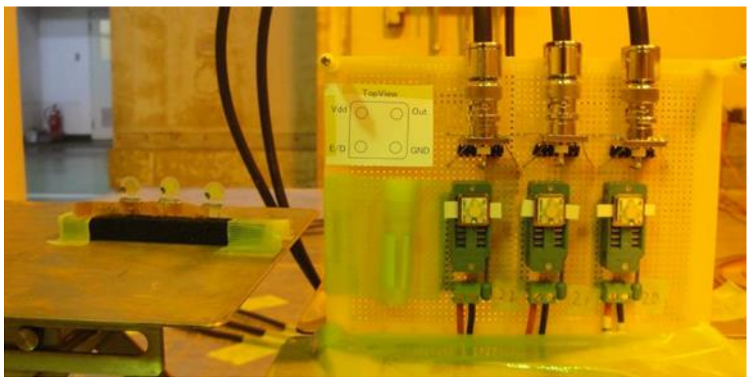

Fig. 7 Gamma ray irradiation test of quartz crystals and oscillation circuits.

C. Retarding Potential Analyzer (RPA)

A Retarding Potential Analyzer (RPA) gives ion energy distribution. Measuring the distribution is crucial because even a small number of ions at the high energy end of the Maxwellian distribution strongly affect the total sputtering.

The RPA for ETS-9 had to be developed from scratch as Japan has never developed an on-board RPA for satellites. The RPA consists of four grids and a collector. A voltage of 0 to 500 V is applied to the ion retarding grid to measure a wide range of ion energy including CEX ions and the accelerated main ion beam even in the case of satellite charging. The aperture has a diameter of 40 mm, as large as possible, and the ion current collector has an amplifier to measure low density plasma of roughly 1×10^{13} m^{-3} at least. The maximum ion density measured by the RPA is 1×10^{16} m^{-3} due to the Debye length on the grids.

A BBM test campaign of the RPA with the amplifier and a Hall thruster has been completed. The RPA sensor head is shown in Fig. 8. An example of the ion energy distribution is shown in Fig. 9. By comparing the current density of the plume measured by a Faraday cup with the collected ion current of the RPA, the current density can be obtained by the RPA as well. The setup of the calibration test for the current density is shown in Fig. 10. The calibration coefficient is roughly the same as expected through the permeability of each grid. An RPA EM will be fabricated and tested to check the whole sensor system including electronics in 2019. Then, an RPA PFM will be ready in 2020.

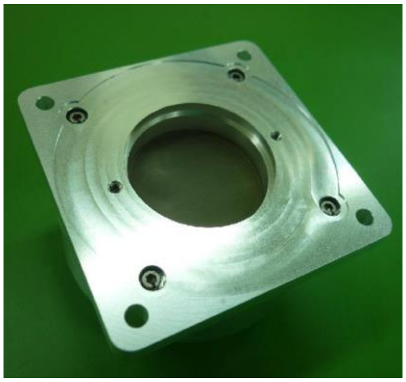

Fig. 8 RPA BBM.

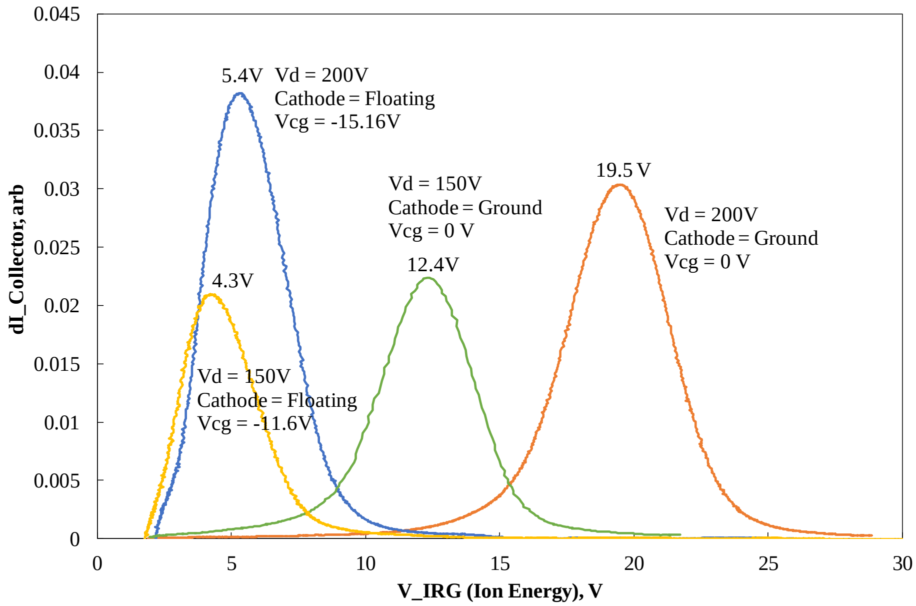

Fig. 9 Ion energy distribution behind a Hall thruster measured by RPA BBM.

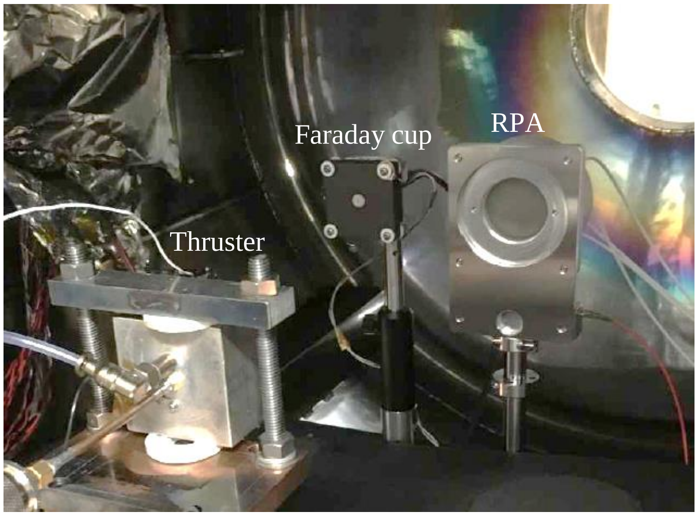

Fig. 10 Current density calibration test of RPA with Faraday cup.

IV. Conclusion

This paper reviewed the development status of three plasma sensors, LP, QCM and RPA, to measure a Hall thruster plume on JAXA's all-electric satellite ETS-9. The sensors were developed based on results of a plume simulation. The LP for ETS-9 is based on the one installed on ISS. The QCM designed based on the one used for Hayabusa2 asteroid probe has the improved radiation tolerance to withstand the severe radiation environment of all-electric satellites. As for the RPA development, the BBM test campaign with an ion current amplifier and a Hall thruster has been successfully completed. At the same time, calibration test was conducted to obtain the current density. All the three sensors will be ready in 2020 for the launch of ETS-9.

References

[1] J. Kim, K. Ikeda, S. Hatta, T. Muranaka, S. Hosoda, M. Cho, H. Ueda, K. Koga and T. Goka, "Final Development Status of Multi-Utility Spacecraft Charging Analysis Tool (MUSCAT)," AIAA Paper 2007-494, 2007.

[2] K. Koga and H. Matsumoto, "Measurement results of plasma monitor (PLAM) of Space Environment Data Acquisition equipment-Attached Payload (SEDA-AP) on International Space Station (ISS)" Proceedings of the 9th Spacecraft Environment Symposium, JAXA-SP-12-017, pp. 77-81, 2013.

[3] K. Nishiyama, S. Hosoda, R. Tsukizaki and H. Kuninaka, "In-flight Operation of the Hayabusa2 Ion Engine System on Its Way to Rendezvous with Asteroid 162173 Ryugu," IAC-18,C4,4,3,x45511, 2018.

[4] J. Matéo-Vélez, L. Artola, N. Bérend, J. David, B. Dirassen, G. Hubert, C. Inguimbert, D. Lazaro, Th. Nuns, D. Packan, Th. Paulmier and P. Sarrailh, "Estimating Space Environment Effects during All-Electric Telecom Satellite Missions," IEPC-2017-474, 2017.

[5] T. Muranaka, K. Ueno, R. Hattori, H. Nagai, M. Isaka, S. Hosoda and K. Nishiyama, "Measurements of Backflow Ions from Ion Thruster for Evaluation of Surface Erosion on HAYABUSA2," Proceedings of the 15th Spacecraft Charging Technology Conference, Paper No. 112, 2018.