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Vacuum Arc Thruster Development and Testing for Micro and Nano Satellites

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This paper will describe the development of the Vacuum Arc thruster (VAT) for micro and nano satellites with the main purposes of: attitude control, maintaining orbit-satellite deorbiting. Firstly, this VAT thruster is integrated on-board student microsatellite Horyu-IV, which was developed at the Kyushu Institute of Technology (KIT), Japan. The satellite will be launched in the fiscal year 2015 by H2A rocket. This paper describes the principles of VAT as a direct drive from High Voltage Solar Array (HVSA). Expected performance of this vacuum arc thruster with passive ignition (space plasma condition) was measured. We propose a method for improving the thruster efficiency. Results show that the impulse bit was of the μNs order, and the thrust–56 nN– and efficiency– 2.5%–were calculated. Moreover, it was found that the impulse bit changes with the applied voltage. A new CFRP material was developed and used as a cathode for the purpose of improving efficiency. Discharge characteristics of current and the arc rate are presented. Measurements of impulse bit were also done for the VAT in configuration with two different propellants (commercial and new CFRP) and with a permanent magnet of 300 mT.

Key words: Thruster, Satellite, Discharge, Propellant

Nomenclature

L	: string length
x	: displacement
g	: gravitational acceleration
m	: weight of thrust target
v	: average velocity of vapor
Δm	: vapor mass per one shot
I_{bit}	: Impulse bit
f	: frequency
W	: energy
C	: capacitance
U	: apply voltage
v_E	: average velocity
I_{bit}	: impulse bit

Subscripts

PPT	: Pulsed Plasma Thruster
VAT	: Vacuum Arc Thruster
HVSA	: High Voltage Solar Array
CFRP	: Carbon Fiber Reinforced Plastic
AEGIS	: Arc Event Generator and Investigation Satellite
OBO	: On-board oscilloscope
AVC	: Arc Vision Camera
QMS	: Quadruple Mass Spectrometer
LEO	: Low Earth Orbit

1. Introduction

Firstly, electric propulsion was used on-board Russian interplanetary station, satellite “Zond-2”. Pulsed plasma thrusters (PPT) were used for satellite orientation. They opened a way to space via electric propulsion. From 90th significantly expanded the range of problems that can be solved by thrusters, because of the miniaturization of space technology and development of small spacecraft.

Over 200 spacecraft have operated around the world using electric propulsion for station keeping, orbit raising, or primary propulsion. Electric propulsion is now a mature and widely used technology on spacecraft. Electric thrusters typically use much less propellant than chemical rockets because they have a higher exhaust speed (operate at a higher specific impulse) than chemical rockets. Due to limited electric power the thrust is much weaker compared to chemical rockets, but electric propulsion can provide a small thrust for a long time. Electric propulsion can achieve high speeds over long periods and thus can work better than chemical rockets for some deep space missions.

One of the most useful and effective thrusters for small satellites with power consumption less than 100 W is propulsions from ablation thrusters.

A new type of electric arc engine, Vacuum arc thruster (VAT), was developed at the Kyushu Institute of Technology. It works on the principle of pulsed plasma thruster accelerator with pulsed discharges that carried by using energy stocked in the capacitor, with solid propellant- cathode, and with passive ignition (no igniter).

The vacuum arc thruster design is very simple and lightweight. Vacuum arc thrusters use a solid metal rod as a propellant that does not require additional equipment, such as piping, valves, and fuel tanks, as does a liquid or gas type propellant. The electrodes in a vacuum arc thruster act as the propellant themselves, and the number of parts required for the propulsion is therefore greatly reduced.

Upon thrust of the vacuum arc, metal vapor and plasma are ejected. When a vacuum arc is generated between the electrodes, vapor is exhausted from the cathode. Therefore, the performance of the vacuum arc thruster depends on the cathode material.[1)]

The novelty of this research is using Carbon Fiber Reinforced Plastic (CFRP) as propellant material. CFRP is a material often used as back face material for solar paddles. Past studies show that CFRP generates discharge easily and the discharge threshold voltage is less than 100 V in plasma inverted gradient. The vacuum arc thruster of this research uses this discharge for ignition of the vacuum arc.[2)]

Moreover the vacuum arc thruster presented in this article proposes to use solar cells as the direct drive, so that a booster circuit is not necessary. The direct drive carried out by high voltage solar array which can supply a stable 350 V and it was demonstrated in orbit by a micro-satellite "HORYU-II" developed at Kyushu Institute of Technology (Kyutech) in 2012.[3)] This paper describes the performance measurement results of the vacuum arc thruster using CFRP propellant.

2. Horyu-IV Satellite Project

Microsatellite Horyu-IV (Fig. 1) was designed at the Kyushu Institute of Technology and will be launched in 2016 by H2A rocket. Forty-three students have taken part in the project, including students from 16 countries. The name of this satellite is Arc Event Generator and Investigation Satellite (AEGIS), Horyu-IV. HORYU-IV is a cubic-shaped nano-satellite with dimensions of 490mm × 490mm × 495mm, including antennas and mirror holder, with an approximate mass of 10kg. The size of the satellite main external structure is 331mm × 285mm × 331mm, without antennas and mirror holder. The planned orbit altitude is 575 km with an inclination of 31 deg. The main mission is to conduct discharge experiments on-board. The secondary mission is to test high voltage solar arrays which will produce 350 volts, to operate VAT and Langmuir probe. Extra missions: Vacuum Arc Thruster (VAT),[4] Electron Emitting Film, Camera, Singer, and others.

Discharge experiments will be monitored by On-board oscilloscope (OBO) and Arc Vision Camera (AVC). The first will be operated with HVSA's current probe and measure VAT`s discharge current too. AVC will photograph the solar arrays before and after the discharge spark, and will photograph VAT`s discharges.

Full success of this mission is to obtain data on satellite attitude, satellite position, and plasma density.

The VAT mounts on the -Z panel of Horyu-IV (Fig. 1).[5]

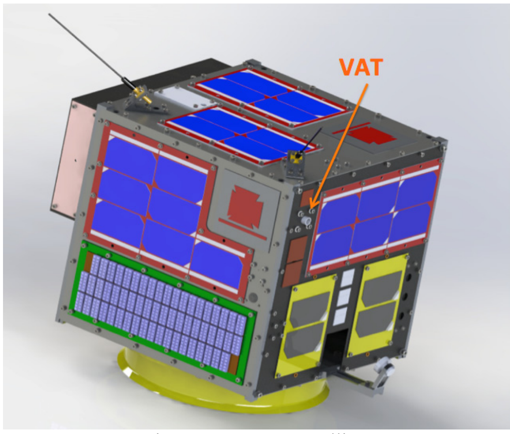

Fig. 1. Horyu-IV satellite.

3. Vacuum Arc Thruster (VAT)

The Vacuum Arc Thruster is an extra mission. The main components for this VAT are: electron supply source (electron collector), capacitor, voltage source, and protective resistor. The voltage source must supply a voltage higher than the electric discharge threshold value. The principle (Fig. 2) consists in generating a vacuum arc thanks to the load accumulated in the condenser. The main discharge condenser charges from the High Voltage Solar Array system (~350 V) and at the necessary moment produces arc discharge.

The following is a step-by-step description of the operation of this thruster. The insulator and/or a dielectric are charged by the ions of a plasma environment or space plasma. It is carried out by high density plasma in LEO, where a maximum of 10^{12} m Ex. 10^{-3} electron densities exists. Electric field concentration generates at the boundary of the cathode and insulator. To neutralize the potential difference between the cathode and insulator, accelerated electrons emit from the cathode, and move to the insulator. However, secondary electrons are emitted by the collision of accelerated electrons. Therefore as the charging of the insulator becomes larger, the electric field concentration becomes stronger, and the electrons continue to accelerate. Sufficiently accelerated electrons collide with the ambient molecules and ionize the molecules. The ionized electrons collide with the next molecules. Molecules are ionized successively. Finally, the cathode and anode are electrically connected, and vacuum arc discharge occurs. The vacuum arc between the anode and cathode is formed by the charges stored in the capacitor (10μF), and upon vacuum arc generation, metal vapor is ejected from the discharging point of the cathode. The reaction of this ejected metal vapor results in the generation of thrust that compels the satellite to move. The discharge process is very quick, around five microseconds.[6]

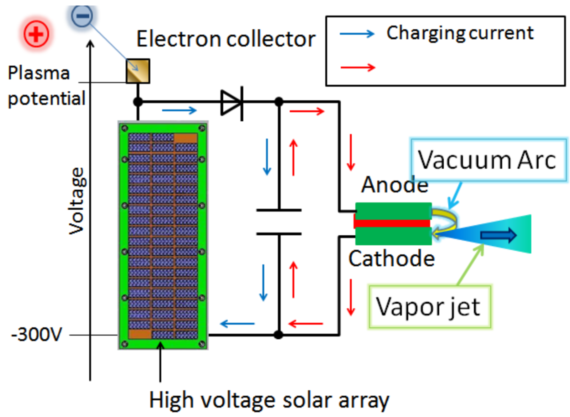

Fig. 2. Principle of VAT system.

The VAT design is very simple (Fig. 3). The outer part is a circular aluminum anode. Outer anode diameter is 13 mm, and thruster length is 21 mm. Inside the anode is a tube insulator (tube with outer diameter of 7 mm and inner diameter of 5 mm), and the internal electrode is a cathode-CFRP (diameter is 5 mm). The anode is grounded on the wall of the satellite and the cathode is energized by HVSA of 300 V.

The thruster head is mounted to the main discharge capacitor circuit board (Fig. 4), with a capacitance of 10 μF. This board together with the VAT head mounts to the -Z panel of Horyu-IV satellite by four screws. Between thruster board and satellite wall are metal washers. To avoid arc discharge on the inner structure (inside the satellite), the VAT's surface and connection places was isolated by RTV glue.

3.1. Work propellant

Carbon Fiber Reinforced Plastic (CFRP) was chosen as a propellant. The average velocity of evaporated particles from VAT was measured by Quadruple Mass Spectrometer (QMS) for three different propellants (Fig. 5), which before were chosen as potential propellants. They were Tungsten, Aluminum and CFRP.[7]

A Quadrupole Mass Spectrometer (QMS) was used to detect the metal vapor ejected by CFRP (Carbon Fiber Reinforced Plastic), Tungsten, and Aluminum. A QMS (model number: RGA200) made by SRS was used in this experiment. QMS mainly consists of an ionizer, quadrupole rods, a faraday cup (to detect ion), and a Secondary Electron Multiplier (SEM). During arcing, propellant vapor is ionized and flies through the quadrupole rods, which generates an electric field. Every ion, except for the ones with a specific mass-to-charge ratio (for CFRP it is 12), collides with the quadrupole rods. The ions are detected by the Faraday cup. The output from the Faraday cup is then amplified by the SEM, whose signal is measured. However, the signal intensity does not relate to the gas mass, and the vertical axis unit therefore uses arbitrary units (a.u.) to show the relative relationship.

The time-of-flight between the thruster and the QMS was measured. The exhaust velocity v_e was calculated using Eq. (1).

$$V_e = \frac{d}{t} \quad (1)$$

where d [m] is the distance between the thruster and the QMS, and t [s] is the time-of-flight.

In this experiment, the m/z ratio was set to 12 to detect carbon. The QMS pressure was 10^{-4} Pa. The chamber pressure was 10^{-3} Pa. The capacitance was 10 μ F, and the supply voltage was 300V.

Measurements were carried out in a general vacuum chamber with vacuum in 10^{-3} Pa. Tube of QMS which has an aluminum plate with a hole in a one side was connected to the chamber (Fig. 6). Accelerated Carbon molecules from the VAT cathode came to the hole in the Aluminum plate and were registered by QMS. A considerable number of triple junction points were registered for the material CFRP, which was subsequently selected as a working body for VAT.

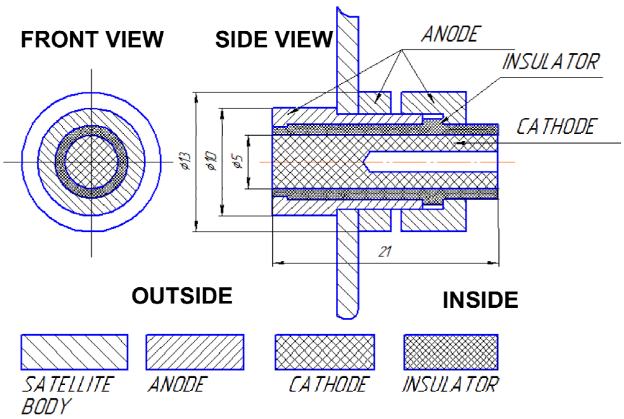

Fig.3. Vacuum arc thruster design.

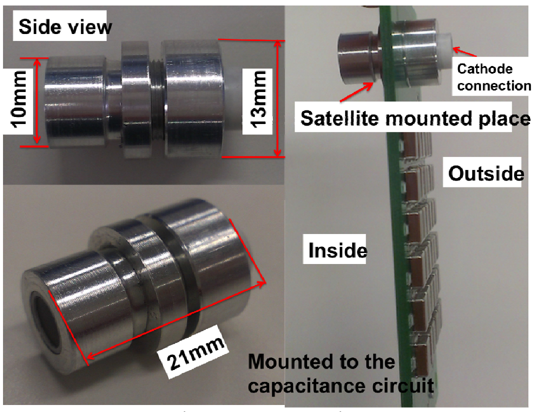

Fig. 4. VAT mounting.

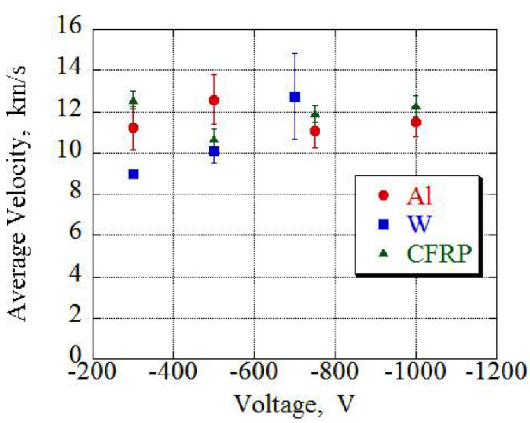

Fig 5. Average velocity dates for different propellants.

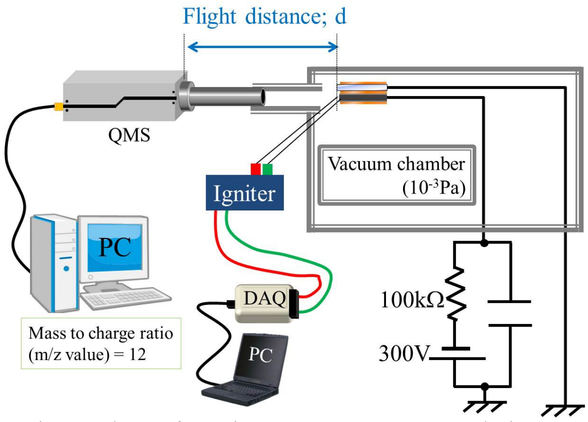

Fig. 6. Scheme of experiments to measure average velocity.

3.2. VAT`s discharge characteristic

Vacuum arcs were generated by passive ignition. We cannot control the frequency of VAT discharges with passive ignition because an igniter system for thruster ignition is not used, and it is necessary to wait for discharges. Test setup and conditions are shown in Fig. 7. In this experiment, the capacitor value is 10 μ F. Power is supplied to the cathode of 300 V and the electric circuit of thruster was installed outside the vacuum chamber. Inside the chamber, the plasma density was 10^{12} m^{-3} with an electron temperature of 1.7eV and a backpressure of 10^{-3} Pa. An Electron Cyclotron Resonance (ECR) plasma source was used for simulation of LEO grade plasma and measurements were performed by using a Langmuir probe. Propellant of VAT is CFRP cathode and its cross section was a circle with a diameter of 5 mm.

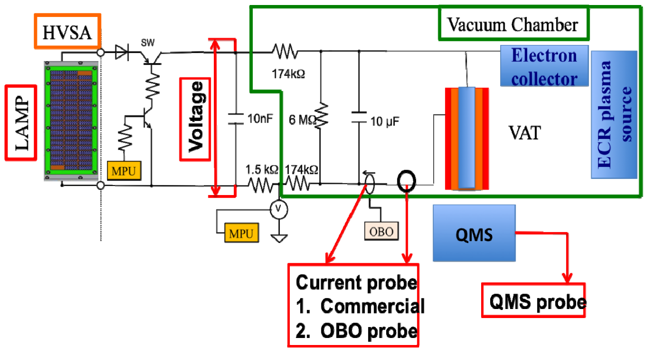

Fig. 7. VAT setup condition.

Testing was done in frame of integration testing for Horyu-IV engineering model. As a power supply source was used real model of HVSA, OBO (on-board oscilloscope) to detect discharge current. Several probes provided measurements. The first probe controlled the level of applied voltage from HVSA (in testing was detected voltage 327 V). The second probe measured discharge current. The discharge current waveform is presented in Fig. 8. It was detected that each discharge has a length of 5 µs. Maximum arc current is 650- 700 A. In 5 μ s we have a main capacitor full discharging and the next charging until the new VAT`s discharge will occur. Higher current levels are accommodated by more emission sites. These emission sites are initiated at locations where there are local microprojection or dielectric inclusions which cause local enhancement of the applied electric field. The ion bombardment and Joule heating keep the temperatures required for cathode material vaporization and electron emission.

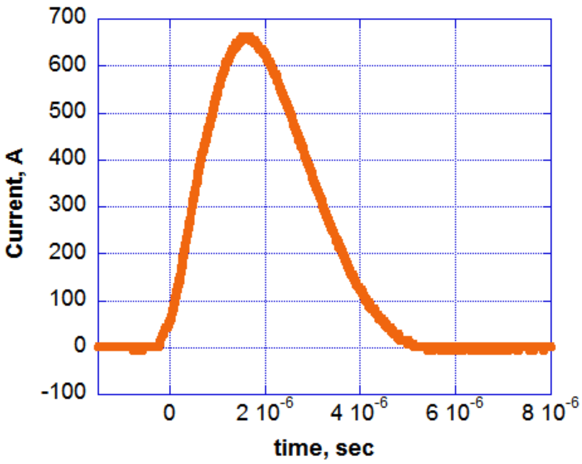

Fig. 8. Discharge parameters for VAT with CFRP.

If we loss a cathode material, it is cause cathode`s material craters, and because of this the power deposition by ion bombardment and ion heating decrease. It affects the frequency of discharges. The frequency was measured in LEO chamber, with a plasma source for passive ignition.[8)]

Testing to measure VAT discharge frequency was done in about 30 minutes. In that period 65 discharges were detected by an arc vision camera, installed outside the vacuum chamber. Each arc discharge detected triggered the camera, which made photos of discharges and counted them. Discharge frequency data is presented in Fig. 9 together with the discharge, photographed by the camera from outside the chamber.

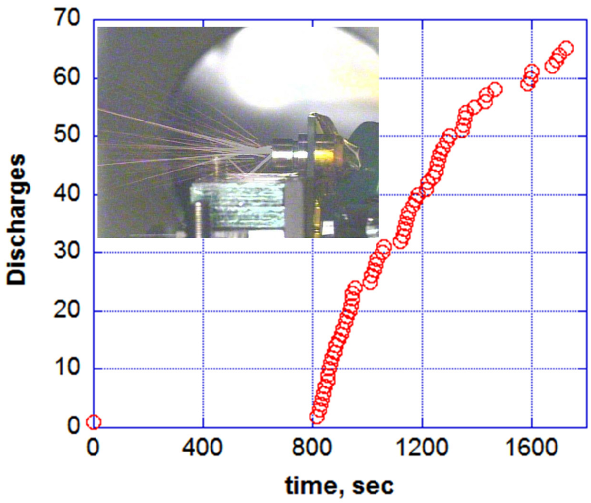

Fig. 9. Arc rate data of VAT.

The frequency of VAT, from Fig. 8, is 0.0376 Hz for a thruster configuration with a commercial CFRP cathode (propellant), Aluminum anode, capacitor 10 μF and applied voltage of 327 V.

3.3. Impulse bit measurements

The impulse bit for CFRP propellant was measured (Fig. 10). Experiments for impulse bit measurements were provided by a special target with a mass of 20 μgr produced from polyimide.[9)] The target was located very close to the surface of the propellant and at the moment of discharge we could see target inclination. By the geometry of the inclination the velocity of evaporated particles from CFRP and the impulse bit were calculated. Displacement of the thrust target was recorded by a digital camera (CASIO EX-F1).

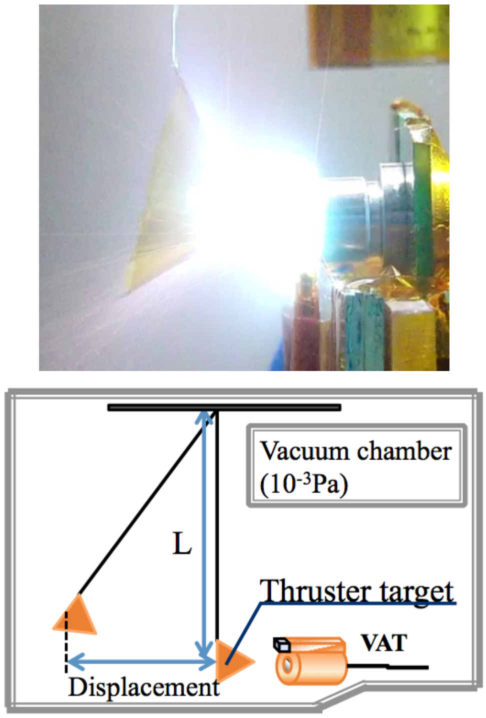

Fig. 10. Impulse bit measurement system.

To calculate Impulse bit the following equation was used:

$$F\cdot\Delta t = m\sqrt{2g(L-\sqrt{L^2-x^2})} \tag{2}$$

where F is the thrust of VAT;Δt is thedischarge time, m is target mass, L is the distance from target to the filaments' fixing place, and x is displacement.

Impulse bit was measured for different levels of voltage applied to the cathode, from 300 V up to 800 V. Results are presented in Fig. 11. For each point the test was done three times.

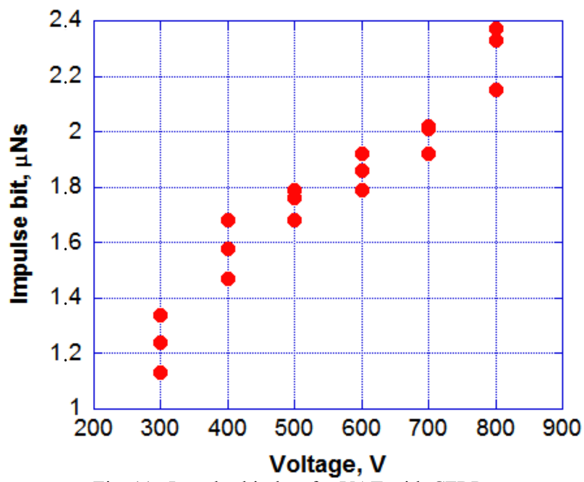

Fig. 11. Impulse bit data for VAT with CFRP.

The thrust for discharge period and impulse bit which were known were calculated for VAT in Eq. (3), which will operate on-board Horyu-IV with 300 V direct drive from the HVSA and CFRP propellant (commercial) with a frequency of 37.6mHz:

$$F = I_{bit}\cdot f = 1.5\cdot 10^{-6}\mathrm{Ns}\cdot 37.6\ \mathrm{mHz} = 56\ [\mathrm{nN}] \tag{3}$$

and efficiency of this thruster (Eq. (4)):

$$\delta = \frac{I_{bit} \cdot v_E}{2 \cdot W} \cdot 100\% = \frac{1.5 \cdot 10^{-6} Ns \cdot v_E}{C \cdot U^2} \cdot 100\% = 2.5\ \% \tag{4}$$

where C-discharge is the capacitance in main electric circuit, 10 μF, U-apply voltage, 300 V, v_E-average velocity, 12 km/sec.

4. Methods of Efficiency Improvement

To increase impulse bit, and as a result, thrust was used a new type of CFRP material. This improvement can increase frequency. Water molecules can accelerate a discharge, and increase frequency.[10] So, CFRP was added to water, and a CFRP list was bought as an absorber of water which uses silica powder, and glue, to connect everything together (Fig. 12); glue was "Araldite" type.

A simple VAT model was cut in line of a CFRP sheet with a size of 10 mm x 13 mm (Fig. 12 (a)). Silica powder (Fig. 12 (b)) was mixed with water and glue (Araldite). This mixture was applied to apart of the CFRP sheet and was twisted into the shape of a cylinder around the copper rod (Fig. 12 (c)) through which electricity is fed to the cathode. As the anode, an aluminum plate and insulator- polyimide was used (Fig. 12 (d)).

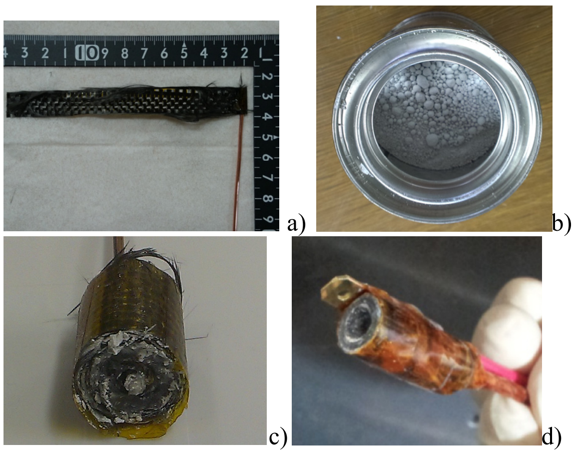

Fig. 12. a) CFRP sheet; b) silica powder; c) cathode from new CFRP; d) VAT with new CFRP propellant.

New propellants provided discharge for current measurements and measurement of arc numbers or frequency. This was similar to the conditions of the previous experiments in the LEO chamber. To test the new VAT configuration, a new CFRP propellant, polyamide insulator and Al anode were used. The current waveform was detected by an oscilloscope, and the current probe was installed on the cathode line inside the vacuum chamber. The main discharge capacitor is 14μF here. Was applied a voltage of 300 V. The thruster scheme used for testing is shown in Fig. 13.

The discharge characteristics are presented in Fig. 14. The period of discharge time is the same as that for Horyu-IV VAT, about 5 μs. However, discharge current pick is two-times higher. For Horyu -IV VAT, discharge current is about 650 A, while the new CFRP propellant discharge current is 800 A.

Number of discharges was also counted (Fig. 15). Frequency is 0.019 Hz (testing time: 3816 sec, 72 discharges).

Copper has a better electrical conductivity than aluminum. So, to compare results, the same experiments were conducted under the same conditions for the thruster to consist in the new CFRP (with water, silica powder, and glue) and aluminum anode (plate) or cylindrical copper anode. As we can see from the results (Fig. 16), the impulse bits are the same within the error.

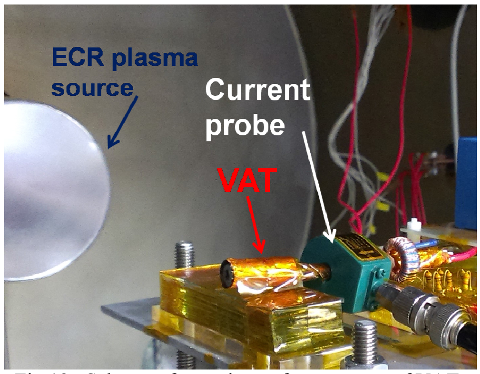

Fig.13. Scheme of experiment for new type of VAT.

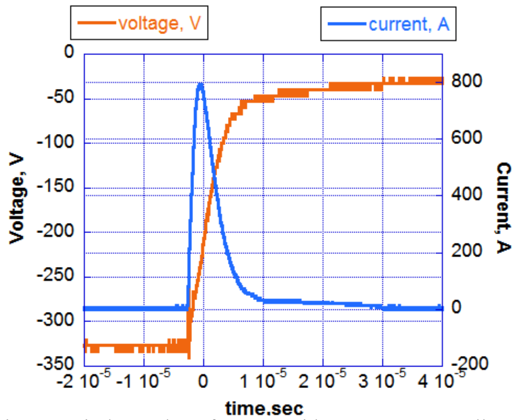

Fig. 14. Discharge dates for VAT with new CFRP propellant.

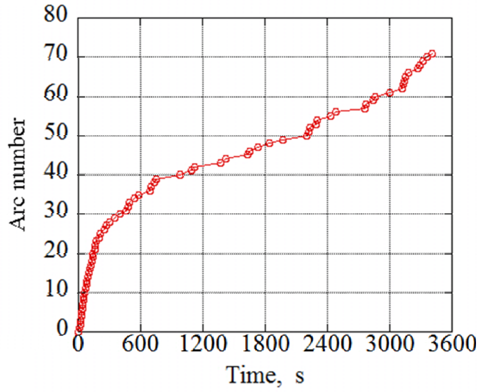

Fig. 15. Arc numbers measurement.

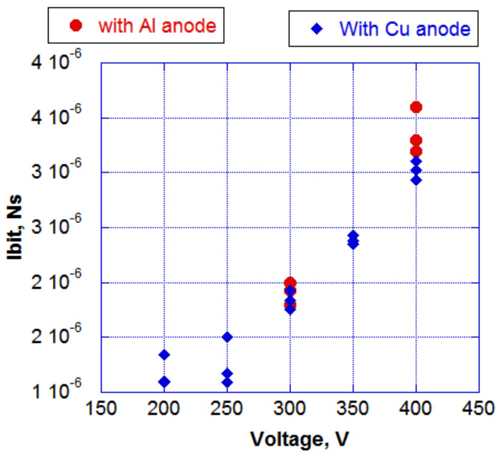

Fig. 16. Impulse bit of VAT with Al and Cu anode.

Applying a permanent magnet to the thruster system can improve thrust. We apply to the system magnet with a magnetic field of 0.3 T. To locate the magnet system in the two different position to the thruster (thruster on the middle of permanent magnet, thruster on the cross section of magnet) (Fig. 17), impulse bit was measured. New CFRP new and copper anode, and polyimide insulator were used for the experiment. The results presented compared to the thruster without permanent magnet in the assembly with the Copper anode (Fig. 18).

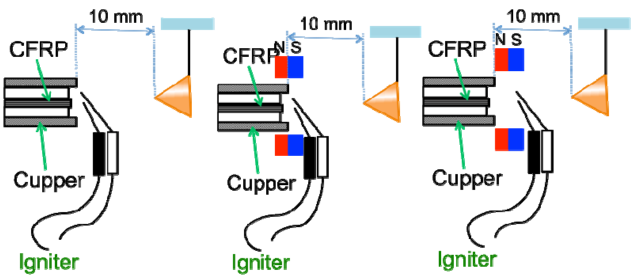

Fig. 17. Permanent magnet position to the VAT.

Results for the system with magnets in the cross section of the thruster and when thruster locates in the middle of magnet are the same within the error. However, in the system without magnets, we can see an improvement of 30%.

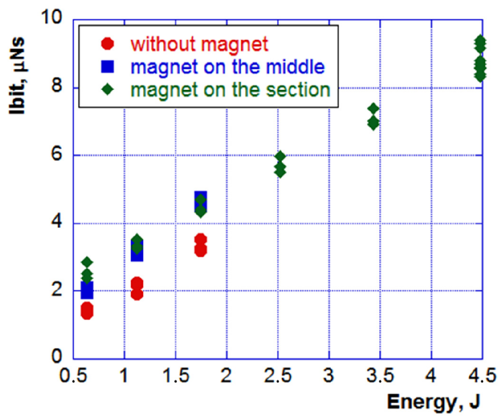

Fig. 18. Impulse bit for VAT with Cu anode and Permanent magnet.

To compare this result with the new propellant, an impulse bit measurement experiment was done for the original model of the VAT with commercial CFRP (Fig. 19), which will install on-board Horyu-IV microsatellites. The thruster system used the same condition in the general purpose chamber, such as the igniter (active ignition), vacuum 10^{-3}Pa, capacitor 10 µF; the electric circuit outside chamber was the same as the Horyu-IV system. Tests were done for the same VAT configuration: without a permanent magnet and with a permanent magnet. Figure 16 shows the situation of when a permanent magnet is installed.

As we can see from the Fig. 18, impulse bit increases if the level of applied voltage increases. Was confirmed, that permanent magnet, can improve the characteristics of I_{bit} in about 30 % in level of applied voltage of 800 V. It is can be attributed by the results of Joule heating and cathode material evaporation in this process.[11] Measured characteristics for Horuy-IV VAT, and for the new CFRP propellant, were combined in one table (Table 1). Because of some characteristics were not measured yet, the table is not full. In the future, we plan to finish this testing and do more experiments with new CFRP cathodes.

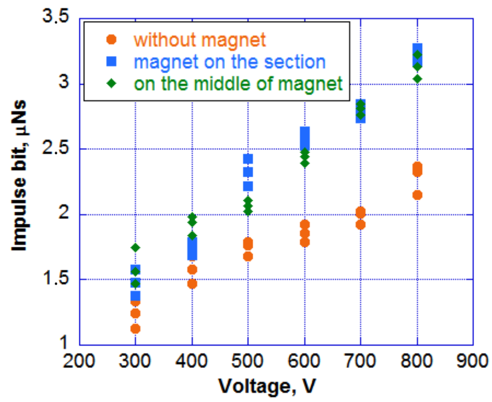

Fig. 19. Impulse bit for Horyu-IV VAT anode and Permanent magnet.

Table 1. Characteristics of different configuration of VAT.

U, Volt	VAT	CFRP new	VAT	CFRP new	VAT	CFRP new
	Frequency, Hz		Impulse bit,1E-6 Ns		Thrust, nN	
300	0.038	0.019	1.47	1.46	56	28
400		0.026	1.65	2.05		53
500		0.038	1.73	3.3		125
600		0.054	1.8			
700		0.161	2			
800		0.19	2.35			

5. Conclusions

The Horyu-IV satellite project and Vacuum Arc Thruster were presented as an on-board propulsion system. Carbon Fiber Reinforced Plastic (CFRP) was chosen as a work propellant for VAT by results analysis. Discharge parameters, impulse bit and calculated thrust and efficiency were measured. Ways were proposed to improve VAT's thrust. A new type of CFRP material which was developed at the Kyushu Institute of Technology was discussed. For the new propellant, discharge current and impulse bit were measured in the same condition as the previous VAT model, and results were presented for comparison. The thruster system with aluminum and copper anode was attempted, and a magnet system was applied, which improved impulse bit by 30%. Compared to the same testing for original thruster model for Horyu-IV, some results were on the same level, such as frequency at 300 V. The new propellant is smaller than the original thruster, but impulse bit is higher. These results need more testing in the future.

Acknowledgments

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