Vacuum Arc Thruster development and testing for micro- andnanosatellites

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Abstract:This paper will describe the development of Vacuum Arc thruster (VAT) for micro and nano satellites. Firstly, this VAT thruster is integrated on-board student microsatellite Horyu-4, which was developed in Kyushu Institute of Technology (KIT), Japan. Satellite will be launch in the fiscal year 2015 by H2A rocket. The main purpose of this thruster is attitude control, orbit keeping and satellite deorbiting. This paper will describe principle of VAT. First model of VATconsistsfrom aluminum- the anode, and Carbon Fiber Reinforced Plastic (CFRP)- the cathode. Specific impulse of this thruster is 1300 s, the impulse bit is 2μNs at 0.45J. Angular velocity produced by thruster per one discharge is 50μdeg/s. To increase VAT frequency and thrust it is purposed to use the new CFRP propellant, with bigger adhesive properties for water, which can decrease time duration between discharges. The propellant was developed in KIT. This work measured arc numbers of new propellant, calculated impulse bit for the new material and efficiency of thruster.

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 (called mass shot)
I_{bit}	: Impulse bit
f	: frequency
W	: energy
C	: capacitance
U	: apply voltage

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I. Introduction

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

Over 200 spacecraft operated around the world use 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 group.

A new type of electric -arc engine is a Vacuum arc thruster (VAT) developed at Kyushu Institute of Technology, which works on the principle of pulsed plasma accelerator with hard working body with pulsed discharge carried using energy stocked in the capacitor circuit and without discharge electrode.

The engine of this type has the following advantage - the ability to control precision at the lowest possible unit impulse thrust (virtually no residual impulse). Thanks to this feature loss energy consumption and the working fluid flow can be minimized. VAT is considered optimal for the executive organ systems, which require high accuracy relative position of the spacecraft (it does not create disturbing moments due to fluctuations in fuel tanks) and is an easy and cheap alternative systems with flywheels.VAT is the ideal for angular stabilization system (ASS).

VAT on the solid propellant has important advantages, such as the absence of valves in the supply system the working fluid, speed, a small quantity of a single pulse, a great resource on the number of inclusions, simple design, no igniter so no high voltage. All this makes it the only acceptable orientation system for MS.

II. Horyu-4 satellite project

Microsatellite Horyu-4 (Fig. 1) was designed in Kyushu Institute of Technology and will be launch in 2015 by H2A rocket. In project take part 43 students include international students from 16 countries. Name of this satellite is Arc Event Generator and Investigation Satellite (AEGIS), Horyu-4. HORYU-4 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.. Orbit altitude 575 km and inclination 31 deg. Main mission is discharge experiments onboard, secondary is high voltage solar arrays which will produce 350 volts, degradation by discharge and Langmuir probe. Extra missions: Vacuum Arc Thruster (VAT), Electron Emitting Film, Camera, Singer others.

Discharge experiments will be provide by On-board oscilloscope (OBO) and Arc Vision Camera (AVC). First one will be operate with HVSA`s current probe and measure VAT`s discharge current too. AVC will photography the solar arrays before and after the discharge spark, and will photography VAT`s discharges.

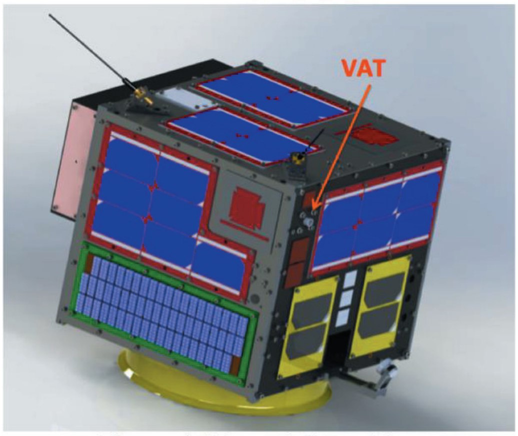


Figure 1. Horyu-IV satellite

Full success of main mission is obtain data on satellite attitude, satellite position, plasma density.

III. Vacuum Arc Thruster (VAT)

Vacuum Arc Thruster is an extra mission. The principle (Fig. 2) consists in generating a vacuum arc thanks to the load accumulated into the condenser directly from HVSA. Main discharge capacitance charging from the solar array system (300 V) and in necessary moment produce arc discharge.

In electric field propellant particles will be evaporate in triple junction point. Moving these particles to the anode, heat propellant and generate plasma. In same moment, become short-circuit in plasma between cathode and anode. As a result - arc discharge. This process very quick, around 5 microseconds. In time, very quick decrease capacitor voltage from 300 V and become current race from zero to 1200 A and back.

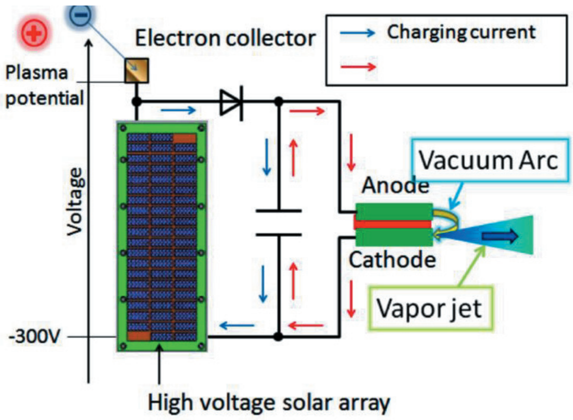


Figure 2. Principle of VAT system

VAT design is very simple (Fig. 3). Outer part is a circular aluminum anode. Outer anode diameter is 13 mm, thruster length is 21 mm. Into anode is an tube insulator (tube with outer diameter 7 mm and inner diameter 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 energized by HVSA in 300 V.

As a propellant was choose Carbon Fiber Reinforced Plastic (CFRP). Was measured average velocity of evaporated particles from VAT by Quadruple Mass Spectrometer (QMS) for three different propellants, which before was choose potential propellants. It was Tungsten, Aluminum and CFRP (Fig. 4).

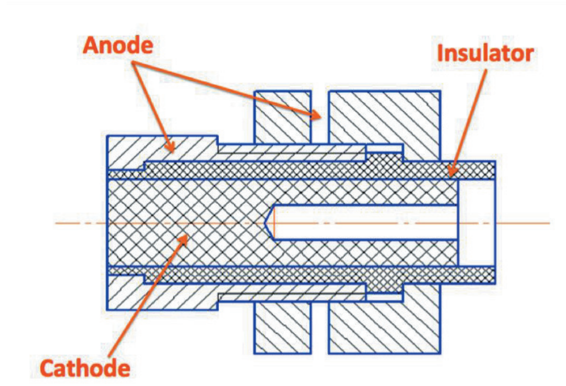
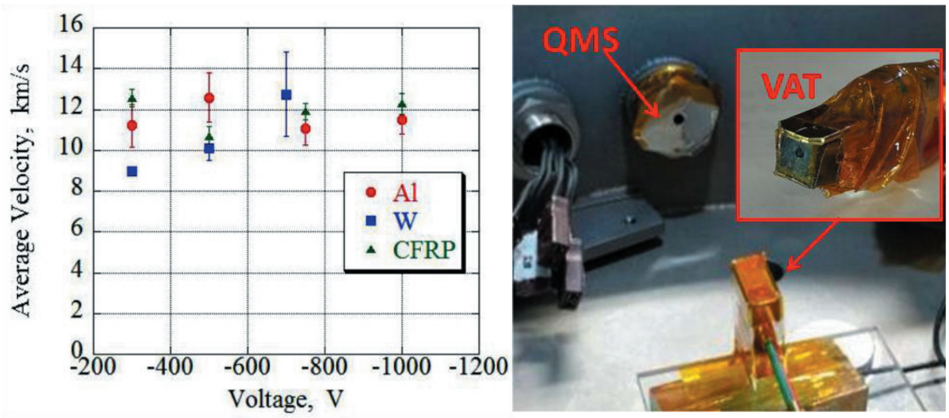


Figure 3. Vacuum Arc Thruster geometry

Measurements provided in general vacuum chamber with vacuum in 1E-3 Pa. QMS was install inside chamber and measure velocity in the special hole of Aluminum plate in the section of spectrometer (QMS) tube. A considerable number of triple junction points was registered for the material CFRP, which was followed by working body for VAT



a. **b.**

Fig. 4. a) Average velocity dates for different propellants;
b) Scheme of experiments to measure average velocity

Working voltage on-board Horyu-4 microsatellite is 300 V. So, to indicate discharge parameters (Fig. 5)make experiments in LEO chamber with electron cyclotron plasma source to provide conditions similar to space. Pressure in chamber was 10-3 Pa, electron temperature 1.7 eV, electron density 2.5E11 m-3, gas Xenon. Was detected that each discharge has a length in 5 microsec.

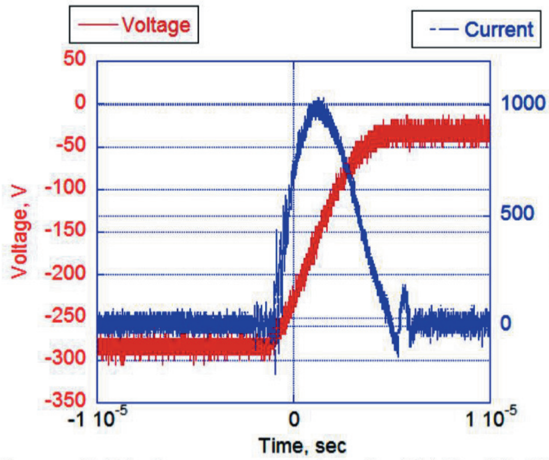


Figure 5. Discharge parameters for VAT with CFRP

A. Impulse bit measurements

For CFRP propellant was measures impulse bit (Fig. 6). Experiments for impulse bit measurements provided by special target with mass 20 microgram produced from polyimide. Target locates very close to the surface of propellant and in the moment of discharge we can see target inclination. By the geometry of inclination calculate velocity of evaporated particles from CFRP and Impulse bit.

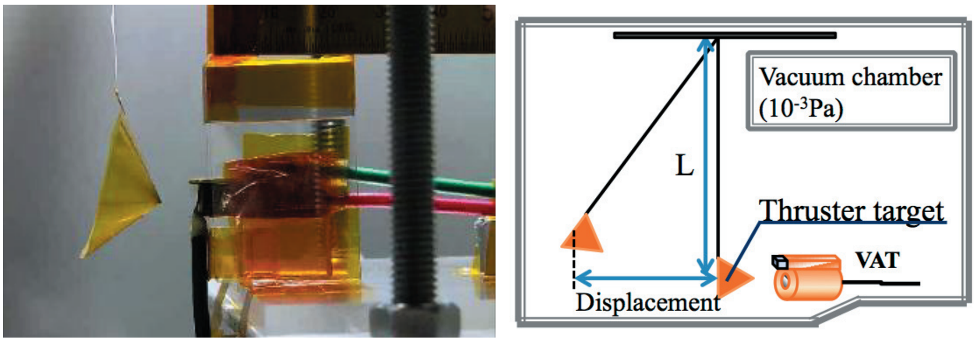


Figure 6. Impulse bit measurement system

To calculate Impulse bit was used next Eq. 1:

$$F \cdot \Delta t = m\sqrt{2g(L - \sqrt{L^2 - x^2})} \tag{1}$$

Where is F-thrust of VAT;Δt – discharge time, m- target mass, L- distance from target to filaments fixing place, x- displacement.
Changing parameter was applied voltage, which changed from 150 volts to 350 volts. Results presented on Fig. 7.

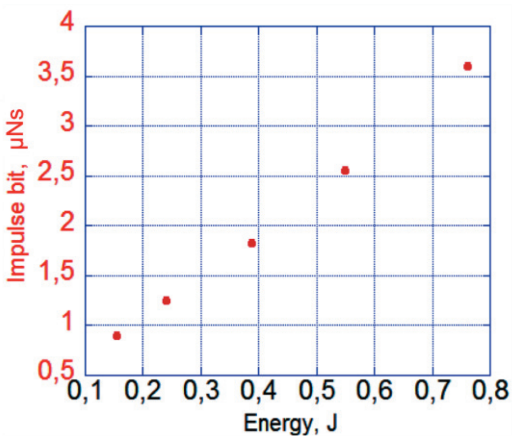


Figure 7. Impulse bit dates for VAT with CFRP

Knowing discharge period and impulse bit was calculated thrust for VAT which will be operate on-board Horyu-4 with 300 V apply and CFRP propellant with frequency 0.83 mHz:

$$\mathrm{F} = \mathrm{I_{bit}} \cdot \mathrm{f} = 2 \cdot 10^{-6}\mathrm{Ns} \cdot 0.83\mathrm{mHz} = 1.66\ [\ \mathrm{nN}] \tag{2}$$

and efficiency of this thruster:

$$\delta = \frac{\mathrm{I_{bit}} \cdot \mathrm{v_E}}{2 \cdot \mathrm{W}} \cdot 100\% = \frac{2 \cdot 10^{-6}\mathrm{Ns} \cdot \mathrm{v_E}}{\mathrm{C} \cdot \mathrm{U}^2} \cdot 100\% = 2.66\ \% \tag{3}$$

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

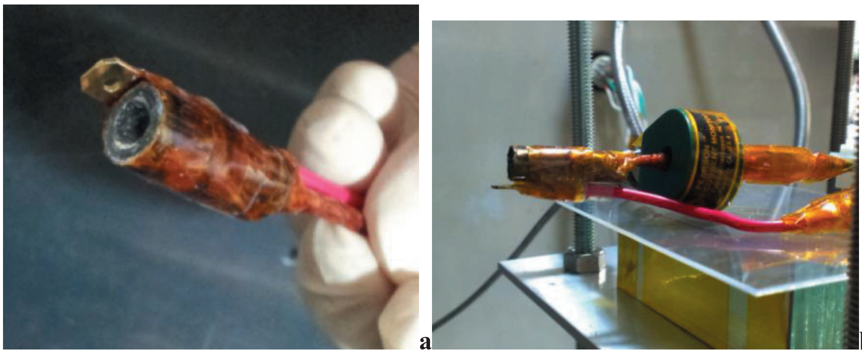
IV. Methods of efficiency improving

To increase impulse bit, and as a result- thrust, purposed to use new type of CFRP material. This improvement can give frequency increasing. In LEO chamber we have to waiting for discharge around 20 min, so frequency is about 0.83 mHz. Water molecules can accelerate discharge. So, to CFRP was added water. Was bought CFRP list and as an absorber of water used silica powder, and glue, to connect everything together (Fig. 8).

a b c

Figure 8. a) CFRP sheet; b) silica powder; c) cathode from new CFRP

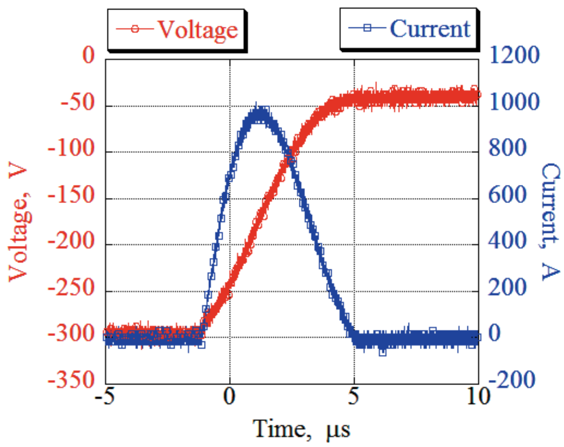
For simple VAT model was cut line of CFRP sheet with size 10 mm x 13 mm. Mixed silica powder with water and glue (Araldite). This mixture was applied to the part of CFRP sheet and twisted into the shape of a cylinder around cupper rod, through which electricity is fed to cathode. As the anode was use Aluminum plate and insulator- polyimide (Figure 9).



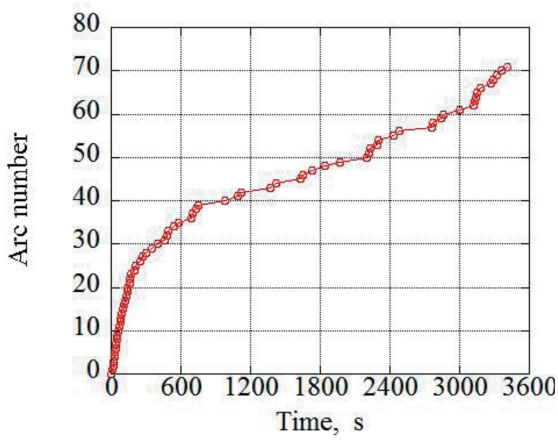
a b

Figure9. a) Simple model of VAT with new CFRP;b)Scheme of experiment for new type of VAT.

For new propellant was provided discharge current measurements and measurement of arc numbers or frequency. In the same condition with previous experiments in LEO chamber discharge time per one discharge is about 5 microsec, but frequency 0.02 Hz (3816 discharges in 72 minutes) (Fig. 10).



a.



b.

Fig. 10. a) Discharge dates for VAT with new CFRP propellant
b) Arc numbers measurement

To compare results with previous, was measured and calculated Impulse bit for new propellant (Figure 11).

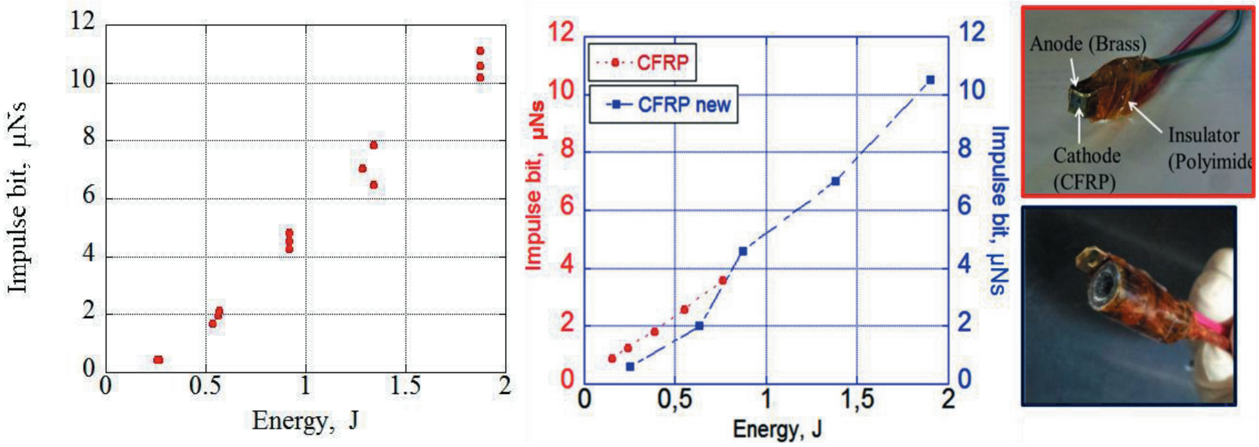


Figure 11. Impulse bit dates for VAT with new CFRP (compare to simple CFRP)

More better electrical conductivity than Aluminum has Cupper, so to compare results was provided the same experiments in the same conditions for thruster consists of CFRP new (with water, silica powder and glue) and aluminum anode (plate) or cylindrical cupper anode. As we can see from the results (Fig. 12), dates of impulse bit are the same within the error.

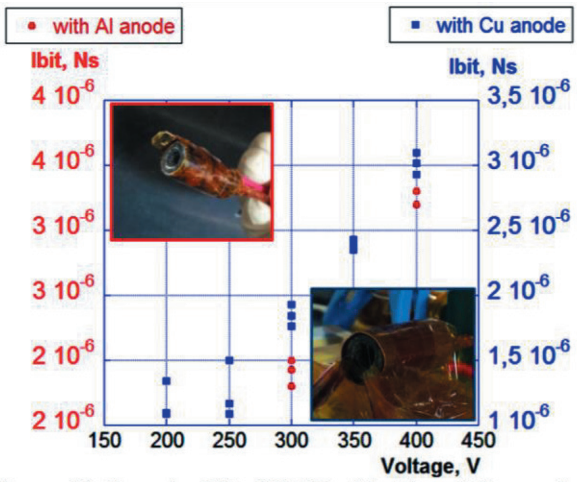


Figure 12. Impulse bit of VAT with Al and Cu anode.

As was described in [7], applying a permanent magnet to the thruster system can improve thrust. We apply to the system magnet with magnetic field 0.3 T. To locate magnet system in two different position to the thruster (thruster on the middle of permanent magnet, thruster on the cross section of magnet), was measured impulse bit. For experiment was used CFRP new and cupper anode and polyimide insulator. Results presented compare to thruster without permanent magnet in the assembly with Cupper anode (Figure 13).

Results for system with magnet in the cross section of thruster and when thruster locate in the middle of magnet are the same within the error. But against to system without magnet we can see improvement in 30%.

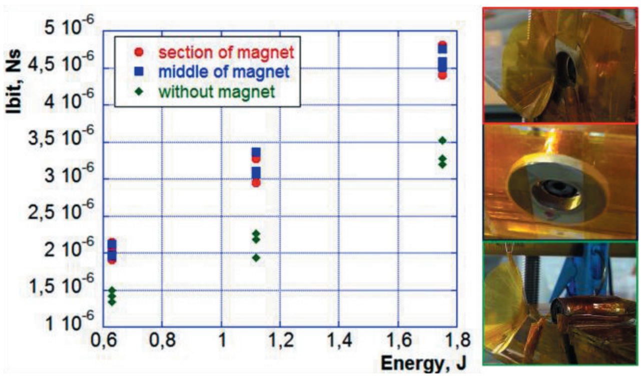


Figure 13. Impulse bit for VAT with Cu anode and Permanent magnet.

V. Conclusion

Horyu-4 satellite project and Vacuum Arc Thruster was presentedas a propulsion system on-board. Carbon Fiber Reinforced Plastic (CFRP) was chosen as a work propellant for VAT by dates analysis. Was measured discharge parameters, impulse bit and calculated thrust and efficiency. Purposed ways for thruster exist dates improving. Describe new type of CFRP material developed in Kyushu Institute of Technology. For new propellant was measured discharge current and impulse bit in the same condition with previous VAT model and results presented in comparison. Was tried the thruster system with Aluminum and Cupper anode, and was applied magnet system,which improved impulse bit in 30 %.

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