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An Ion Machined Accelerator Grid for a 20-cm ECR Ion Thruster

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A flat carbon-carbon composite accelerator grid for a 20-cm ECR xenon ion thruster with aperture diameters adaptive to local beam current densities was designed and fabricated. The apertures were designed and drilled so small that their upstream edges are slightly impinged by ion beams. A 2000-hour thruster operation was carried out in order to obtain optimum aperture geometry distributions for maximum propellant utilization efficiencies for two thruster configurations: a standard configuration with SmCo magnets for 500 mA beam generation and an enhanced configuration with NdFeB magnets for 530 mA beam generation. Evolution of 3087 apertures enlargement by the ion machining was inspected using an A3-size flatbed scanner with a back light. Grid open area fractions for the two thruster configurations calculated from the aperture sizes at the downstream edge were 12.9% and 14.5%, respectively. Redesign and fabrication of new grids with thus obtained optimum aperture geometries and much reduced transparencies will remarkably improve propellant utilization efficiencies of the original thruster with a 25% transparent accelerator grid.

Keywords: electron cyclotron resonance, ion thruster, xenon, carbon-carbon composite, ion optics, flatbed scanner

1. Introduction

In order to advance the technology of electron cyclotron resonance (ECR) microwave discharge ion thrusters known as the “μ(mu)” family, we have been developing a 20-cm diameter thruster μ20 after successful development and flight experiences of an asteroid explorer “Hayabusa” employing four 10-cm diameter thrusters μ10 [1]. In contrast to the μ10 whose ion beam current was saturated to 150 mA at higher microwave powers than 30 W, the μ20 is expected to generate 500 mA ion beam current with 100 W microwave power and 1100 – 1300 V acceleration voltage, yielding beam ion production cost (discharge power per unit beam current) of 200 W/A and thrust of 27 mN (millinewton) thanks to enlargement of the discharge chamber and moderate plasma density below cutoff. The μ20 will be applied to deep space missions with larger delta-v and more massive spacecraft than Hayabusa.

The magnetic field and magnet arrangement for μ20 are illustrated in Fig.1. Magnetic field and propellant injection method of the ion source has been optimized to minimize the beam ion production cost. The performance is highly dependent on the propellant injection method that affects electron-heating process. More than ten configurations including end-wall and side-wall injections had been experimentally investigated [2]. The best injector layout shown in Fig.1 provides 10 – 20% more efficient ion beam production than the worst injector layout. This discharge chamber showed sufficiently small microwave reflection without use of any stub tuners [3]. However, the beam current profiles were far from uniform and propellant utilization efficiency (a beam current fraction to the xenon flow rate equivalent current) was as conservative as 66.7% due to low ionization fraction and relatively high neutral atom density. To improve the propellant utilization, open area fraction of the accelerator grid (the negatively biased second electrode) should be as small as possible.

In this paper we study the optimum accelerator grid geometry with a very small open area fraction that maximizes the propellant utilization. Firstly, an extremely small hole accelerator grid (SHAG) made of carbon/carbon composite is designed and fabricated roughly based on a measured beam current density profile. The apertures are designed so that their upstream edges are slightly impinged

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by ion beams. The grid is ion machined in an approximately 2000-h long duration tests to obtain more precise aperture size distribution which is self-determined by the beam current density profile. Long duration tests are conducted at different beam current levels. Ion machined aperture distributions and open area fractions after these two tests are inspected using a flatbed scanner. These results will help us to design flight model of grids.

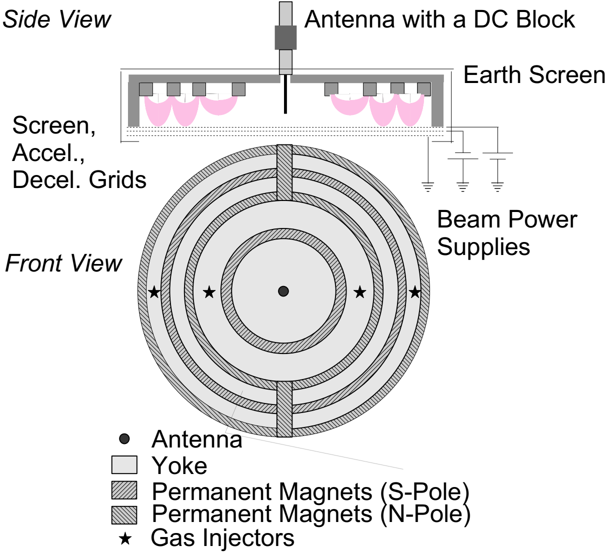


Fig.1 Cross sectional side and front views of the 20-cm diameter ion thruster μ20.

2. Experimental setup and methodology

2.1 Experimental apparatus

Fig.1 illustrates permanent magnet arrangement in the discharge chamber. Microwaves at the frequency range of 4.25 – 4.4 GHz generated by a traveling wave tube amplifier are launched through a quarter wavelength antenna located at the center of the discharge chamber by way of coaxial cables and a DC block. In the nominal configuration for 500-mA beam generation, all the magnets were SmCo types. In a thrust enhanced configuration for 530-mA beam generation,.all the magnets were replaced with NdFeB types except for innermost magnets. The NdFeB magnets have 20% higher surface magnetic flux densities than the original SmCo magnets, and maximum operating temperature limit of 190 ºC which is well above the actual operating temperature of 135 ºC inside the ion thruster. The innermost magnet rows are spaced almost twice as far as the other three rows. This design helps microwave propagate to the outer ECR regions without being disturbed by the dense plasma production around the inner ECR regions. The two radial magnetic bridges between the second and the fourth rows counted from the center, shown in Fig.1, support the transport of high-energy electrons between the inner and outer discharge regions by $\boldsymbol{E}\times\boldsymbol{B}$ drift or grad B ($\boldsymbol{B}\times\nabla\boldsymbol{B}$) drift. The propellant was injected downstream in parallel to the thruster center axis. The total flow rate of xenon was controlled with a single controller, and the propellant feeders were evenly divided before being connected to the ports. The vacuum pressures in the test chamber were 6.0×10^{-5} Pa without load and 1.0×10^{-3} Pa with 10 sccm (standard cubic centimeters per minute) xenon flow. Typical discharge pressure during beam extraction is 0.01 Pa, approximately. For simplicity, no neutralizer was used. Currents and voltages were gathered and monitored every 2 seconds using an Agilent Technologies 34970A data acquisition control unit. The limit check capability of this unit enabled day and night continuous operation without human supervision.

2.2 A small hole accelerator grid and a flatbed scanner for grid inspection

Ion optics of the ion thruster μ20 is a triple grid system. They are flat shaped and made of carbon/carbon composite material for longer life thanks to its low sputtering yields to xenon ions. Grid thicknesses are 0.75 mm for the screen grid and 1.0 mm for both the accelerator grid and the decelerator grid. Grid separations are 0.55 – 0.6 mm between the screen and accelerator and 0.45 mm between the accelerator and decelerator. Beam voltage, accelerator voltage, and decelerator voltage are 1300 – 1350, -150, and 0 V, respectively.

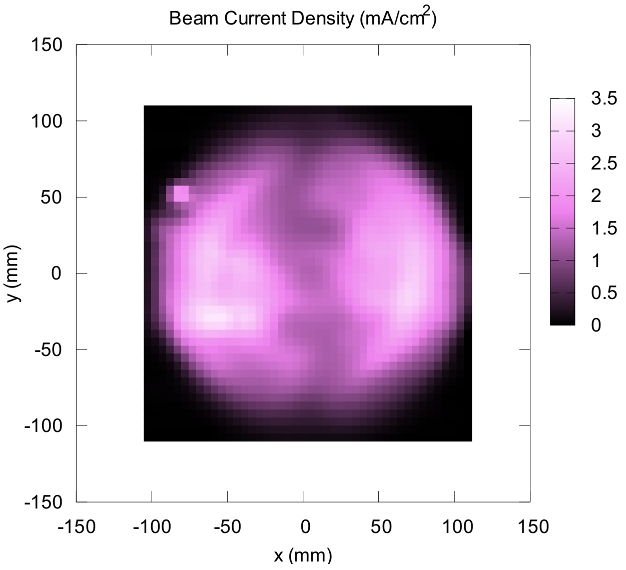


Fig.2 A beam current density profile at the nominal operating condition using an original accelerator grid (10 sccm, 100 W, 500 mA). A high density spot at x=80, y=50 is a data anomaly due to high voltage breakdown.

A SHAG was designed considering the beam current density distribution (Fig.2) measured with an array of Langmuir probes using an original accelerator grid with

1.8-mm diameter apertures [3]. A two dimensional ion optics code OPT [4] was used to roughly estimate the beam waist size at upstream edge of apertures. The aperture size distribution from 0.9 to 1.3 mm is shown in the upper left of Fig.6. Physical open area fraction of the new grid was reduced to 9% from the original value of 25%. The aperture diameters were so small that excessive accelerator grid impingement currents were expected. In fact, at first, the accelerator current was as large as 10% of the screen current, but it rapidly decreased 2% within initial 33 hours of operation.

Measurements of the grid aperture diameters were attempted using a commercial A3-size flatbed scanner and a flat light source for tracing. This scanner has an optical resolution of 1200 dots-per-inch (0.0212 mm/pixel). Several tens of tracing papers were inserted between the backlight and the grid to obtain the best image contrast. Areas of each aperture were analyzed from a scanner image on one side of the entire grid, and area equivalent diameters and central positions of all 3087 apertures were obtained using an image processing program "ImageJ." This measurement technique is smart and suitable for flat grids, though they are rare in ion thrusters.

3. Results and discussion

3.1 Ion machining in long duration tests

During the long duration tests, the ion thruster was operated in a diode mode without a neutralizer. Even if the neutralizer is operated, electron backstreaming was not observed at all with a small negative voltage of -150 V applied to the accelerator grid, which is preferable for the development of longer life thrusters. The thruster operation was stopped many times for regeneration of cryogenic pumps, xenon tank replacement, cleaning of deposited carbons on the discharge chamber walls and grid inspections. Downstream surfaces of the screen grid and upstream surfaces of the accelerator grid sometimes had to be polished to maintain the withstanding voltage at the early stage of the long duration tests due to the severe carbon sputtering.

Table 1 and figures 3–5 summarize operating conditions and history of the tests. At the start of the ion machining process, the xenon flow rate was 8.0 sccm and the accelerator current was about 10% of the screen current. As the ion beamlets enlarged the accelerator grid, the xenon flow rate required to generate 500-mA beam gradually increased. The accelerator current continued to decrease to 1% of the screen current, but very slowly after 600 hours. After 1027 hours, the ion machining process at 500 mA in the screen current was voluntarily terminated. The xenon flow rate was throttled from 8.5 sccm to 3sccm during the ion machining process from 1027 hours to 1145 hours in the accumulated operating time, and the screen current reduced from the nominal 500 mA to the minimum 200 mA so that ions enlarge the downstream edges of the accelerator grid apertures. The accelerator current then increased from 4.5 mA to 7.0 mA. At the end of the ion machining process, aiming ion machining of the decelerator grid, the xenon flow rate and the screen current were changed to 5 sccm and 300 mA, respectively. This was because the decelerator current was the largest at this condition. The first set of ion machining processes was completed at 1153 hours. The original large hole accelerator grid requires 10.5 sccm of xenon flow for 500-mA beam generation. On the other hand, the ion machined SHAG requires only 8.5 sccm for the same beam current. The propellant utilization efficiency increased from 66.7% to 82.4%.

After the grid inspection at 1153 hours, grid gap was slightly increased so that the frequency of high voltage breakdowns drastically reduced. This change increased the required flow rate to about 10 sccm, but thruster operation became much more stable. After the 95 hours of maximum current operations at 515 mA using SmCo magnets, another discharge chamber with NdFeB magnets was dedicated to the long duration test. Ion machining of the accelerator grid was continued at higher beam currents. After 2107 hours of accumulated operational time, the grid was disassembled and analyzed again to obtain the aperture geometries corresponding to the averaged beam current of 530 mA with the NdFeB magnets.

Table 1. Summary of operating conditions

Accumulated operating time (hours)	Magnet type	Screen current (mA)	Flow rate (sccm)	Notes
0 – 33	SmCo	500	8	Severe direct impingement current
Grid inspection after 33 hours				
0 – 1027	SmCo	480 – 510 avg. 500	8 – 8.5	Nominal thrust
1027 – 1145	SmCo	200	3	Minimum thrust
1145 – 1153	SmCo	300	5	Medium thrust
Grid inspection after 1153 hours				
1153 – 1192	SmCo	300 – 540	5 – 10	Grid gap enlargement for mitigation of high voltage breakdowns
1192 – 1287	SmCo	510 – 515	10	Maximum thrust of SmCo
1287 – 1339	NdFeB & SmCo	480 – 550	9 – 10.5	Magnet change trials
1339 – 1796	NdFeB & SmCo	525 – 550 avg. 530	10.2	High thrust
1796 – 2107	NdFeB & SmCo	495-510	10.2	Nominal thrust
Grid inspection after 2107 hours				

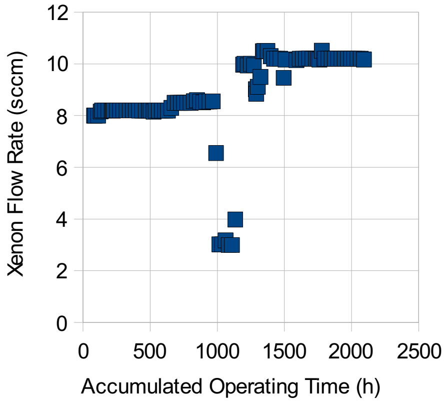


Fig.3 Daily average of xenon flow rate.

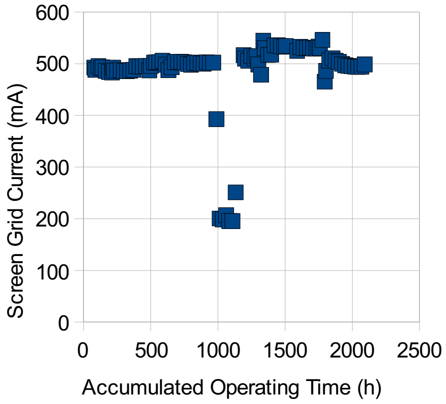


Fig.4 Daily average of screen grid current.

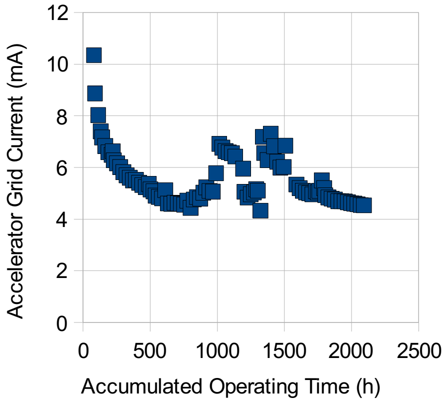
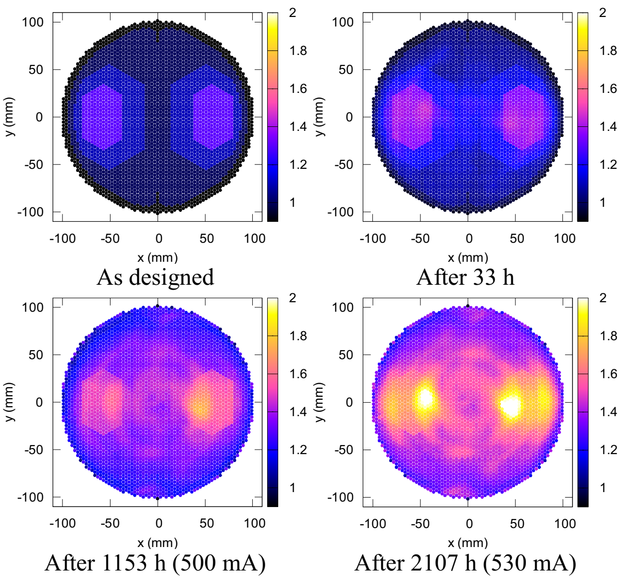


Fig.5 Daily average of accelerator grid current.

3.2 Ion machined aperture size distributions

Figures 6, 8 and 9 show distributions of area equivalent diameters of grid apertures. The aperture diameter of the screen grid as designed is all the same size, 3.05 mm in diameter. The measured diameters never changed as the cumulative operating hours increase. Thus the maps are not shown here. As shown in Fig.6, almost all the upstream edges of accelerator apertures were quickly enlarged by about 0.1 mm in diameter within initial 33 hours of operation. This corresponds to the rapid decrease of accelerator drain current from 50 mA to 10 mA. At this moment, the downstream edges were not eroded and the size distribution was exactly the same as designed. So the map is not shown here. After 1153 hours of operation, the both sides of accelerator grid was ion machined optimally for the beam current range of 200 – 500 mA. Fig.7 shows good linear trend between ion machined upstream aperture diameters and local beam current densities shown in Fig.2. Microscope observation showed us that the upstream edges were chamfered and the some regions of downstream edges were not circular any more and were asterisk shaped. The downstream side deformation was evident at low current density regions. Readers may notice that the aperture size distributions at 1153 hours are not symmetric. This was caused by asymmetry of the propellant feeders and corrected in the latter 1000 hours of operation. The distributions after 2107 hours are the optimum geometry for the beam current range of 200 – 530 mA. Aperture enlargement was remarkable on top of gas ports. At the central region, crossover limited beamlets eroded both sides of the accelerator and decelerator grids. The decelerator apertures were severely eroded in hexagonal shape after the 2107 hours of operations. The chamfer erosion progress of accelerator upstream surface is quick (several hundred hours), but the asterisk or hexagonal erosion speed is very slow (several thousand hours). This difference is caused by the current density difference between perviance-limited and crossover-limited beamlets.

In order to reduce sputtered material at the beginning of the operation, a flight model of SHAG should be redesigned by reference to the ion machined SHAG. If the upstream data are larger than the downstream data, the aperture will be chamfered from the upstream surface. The new SHAG is necessary to machine from only one side of the grid in order to be manufactured with high aperture position accuracy. Conveniently, the experimental results in this work suggest that the upstream side accelerator aperture edge diameters are always larger than the downstream edge diameters. Small hole accelerator grids optimal for 500-mA beam and 530-mA beam will have open area fractions of 12.9 % and 14.5%, respectively. These values were determined from the downstream side data shown in Fig.8.



As designed After 33 h

After 1153 h (500 mA) After 2107 h (530 mA)

Fig.6 Aperture diameter distributions of the upstream side of the accelerator grid.

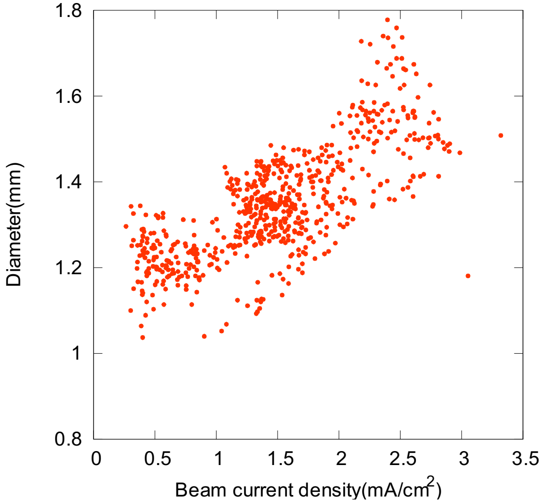
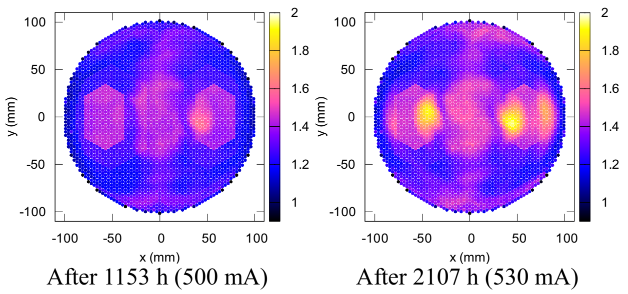
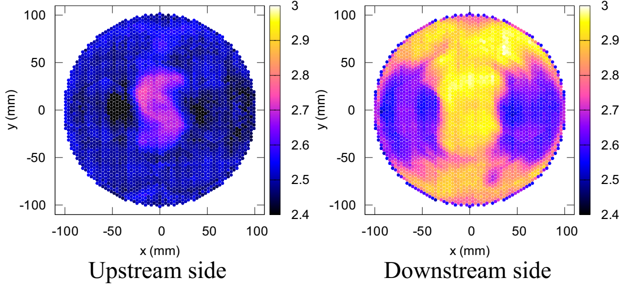


Fig.7 Relationship between ion machined upstream aperture diameters after 1153 hours of operation and local beam current densities.



After 1153 h (500 mA) After 2107 h (530 mA)

Fig.8 Aperture diameter distributions of the downstream side of the accelerator grid.



Upstream side Downstream side

Fig.9 Aperture diameter distributions of the decelerator grid after 2107 hours.

4. Conclusion

In order to increase the propellant utilization efficiency of the 20-cm ECR xenon ion thruster, optimum design of accelerator grid apertures were experimentally obtained. The roughly designed and fabricated SHAG whose initial open area fraction of 9% was ion machined in the 2107-hour long duration test. The 3087 aperture diameters were obtained using the flatbed scanner. The open area fraction for the nominal beam current of 500 mA generated by the discharge chamber with SmCo magnets was 12.9%. The open area fraction for the enhanced beam current of 530 mA produced by the new discharge chamber with NdFeB magnets and SmCo magnets was 14.5%. Both of them are much smaller than the 25% open area fraction of the accelerator grid in previous works, which improves the propellant utilization, for example, from 66.7% to 82.4%. The similar optimized grid can be redesigned and easily fabricated using mechanical drilling and chamfering.

5. References

[1] H. Kuninaka, K. Nishiyama; I. Funaki; T. Yamada; Y. Shimizu; J. Kawaguchi, Journal of Propulsion and Power **23**, (2007), 544.

[2] K. Nishiyama, T. Nakai, H. Kuninaka, 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit 9 – 12 July 2006, Sacramento, California, AIAA 2006-5176.

[3] K. Nishiyama, H. Kuninaka, Surface & Coatings Technology **202** (2008) pp. 5262 – 5265.

[4] Y. Arakawa and K. Ishihara, Proceedings of 22nd International Electric Propulsion Conference, Viareggio, Italy, IEPC-91-118, 1991.