Initial Flight Test Results of the LIPS-200 Electric Propulsion System on SJ-9A Satellite

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Abstract: LIPS-200 ion electric propulsion system has been developed by Lanzhou institute of physics (LIP) since 1990s and its first flight test was conducted on SJ-9A satellite launched on October 10, 2012. After the checkout and activation in orbit were finished, the first firing operation has been implemented successfully on November 7, 2012. The first-phase test plan was completed until December 9, 2012, and the second-phase test plan was implemented continuously. In this paper, the initial test results of the LIPS-200 on SJ-9A satellite in the first phase are presented in details.

I. Introduction

The application of the electric propulsion with higher specific impulse on spacecraft can increase payload or decrease launching cost. Countries like USA[1], Russia[2], Europe[3] and Japan[4] have already applied electric propulsion in space missions with notable technical and economic benefits. China has set north-south station keeping（NSSK）mission of satellites in geostationary Earth orbit（GEO） as the foremost target of electric propulsion application[5], and then China will expand its application into deep space exploration, orbit transferring from LEO to GEO, and etc[6].

Before an electric propulsion is applied on spacecraft formally, it has undergone development phases of ground test and flight test. In order to qualify of the ion electric propulsion system(IEPS) in space for China's GEO satellite NSSK mission, an IEPS flight test plan on SJ-9A satellite has been carried out, which has performed the first orbit flight of China's electric propulsion system. Lanzhou Institute of Physics (LIP) has developed the LIPS-200 IEPS for the SJ-9A satellite flight test. After the SJ-9A satellite was launched in 2012, the LIPS-200 IEPS has already finished its first-phase test plan, and the second-phase test is being conducted. The initial test results in the first phase are presented in details.

II. IEPS On SJ-9A Satellite

The flight test IEPS on SJ-9A satellite is a single-string system founded on LIPS-200 ion thruster (IT). Its constitutes is shown in Fig. 1, including IT, power processing unit (PPU), electric-propulsion control unit (ECU), xenon tank (XT), pressure regulation unit and flow control unit (PRU&FCU), line connection unit (LCU). Among them, LCU's function are not only the cable connecting box between PPU and IT, and but also the electric-check interface.

The LIPS-200 IEPS has already performed much of its test proof on the ground, but the compatibility between IEPS and the host satellite is hard to be tested on ground, and the difference of the IEPS performance under space condition and ground condition need to be identified because of the boundary influence or dimension limits in ground vacuum chamber. Therefore, the following flight test purposes are included in the SJ-9A satellite IEPS:

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（1）To validate the IEPS's adaptability to the space environment;

（2）To scale the IEPS's performance in orbit;

（3）To validate stability and repeatability of the IEPS firing in orbit;

（4）To validate the compatibility between the IEPS and the Satellite's other systems.

In order to get characteristics and affection of the IEPS plasma plume, a diagnostic unit was developed and flighted as well, including Langmuir probe, retarding potential analyzer, quartz crystal microbalance. The more introduction to diagnostic unit is not covered here.

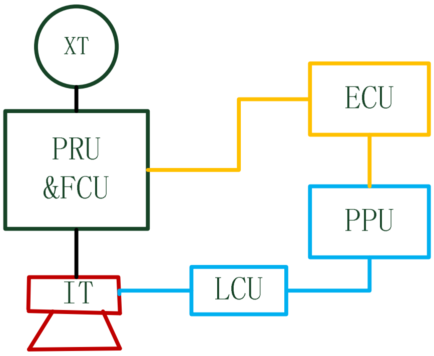

Fig. 1 Constitute of the flight test IEPS on SJ-9A satellite

The telemetry parameters of the IEPS on SJ-9A satellite include: pressure P_T and temperature T_T of XT, output pressure P_W of PRU, temperature T_C of cathode FCU, temperature T_A of anode FCU, temperature T_N of Neutralizer FCU, input voltage V_0 and current I_0 of PPU, beam voltage V_B and current I_B, acceleration voltage V_a and current I_a, anode voltage V_A and current I_A, cathode heater voltage V_{CH} and current I_{CH}, Neutralizer heater voltage V_{NH} and current I_{NH}, cathode keeper voltage V_{CK} and current I_{CK}, Neutralizer keeper voltage V_{NK} and current I_{NK}.

III. EPS Development in LIP

In accordance with the application for GEO satellite NSSK mission, LIP developed the LIPS-200 ion thruster laboratory model in 2003. LIPS-200 ion thruster engineering model was developed from 2004 to 2008, and propellant storage and supply subsystem, power processing unit and control unit were also made at the same time.

The project of LIPS-200 IEPS flight test on SJ-9A satellite was ratified at the end of 2008. The developments of performance model (PM), qualification model (QM) and flight model (FM) of the IEPS were gradually finished by LIP from 2009 to 2012.

In the development period of PM, a series tests were implemented. The function and performance both in element and in system were identified, the compatibility both in system and with the satellite was evaluated, and the validity of control procedure and telemetry were proved. In the development period of QM, the qualification test of every element was finished and their adaptability to environment was fully verified. That the performance index of the QM IEPS meet the design requirements were identified by system test. Fig. 2 is the main QM elements of IT, PPU, PRU&FCU and, LCU.

Fig. 2 photos of the main QM elements

In the development period of FM, each element finished its acceptance test, and the FM IEPS finished its system test. All tests showed that the FM IEPS have its good state and proper characteristics. Table 1 listed the main index of the FM IEPS, which meet the requirements.

The FM element was delivered in early 2012 and the IEPS began its AIT on SJ-9A satellite formally. In the whole satellite's AIT phase, the LIPS-200 FM IEPS experienced the electric property measurement, leakage check-up, dynamics test, thermal vacuum test, etc. The satellite was transported to Taiyuan Launch Field in August, 2012.

IV. Flight Test Course in the First Phase

The satellite was launched by LM-2C on October 14, 2012, and it reached the sun-synchronous orbit successfully one hour later. The flight test procedure in the first-phase of the IEPS is shown in Fig.3.

A. Initialization check-up

On the day when the satellite entered the orbit, the ECU was electrified for the first time through ground command. The IEPS was in operation mode but without xenon supplying to the IT. The IEPS telemetry data such as pressures, temperatures, voltage, and current were obtained and judged on ground. These data showed that the IEPS were in normal state, and telemetry data is the same with that at launch pad.

B. The pretreatment of the IEPS

To ensure the successful first firing of the IEPS in space, These pretreatments of gas line, hollow cathode (ie. cathode and neutralizer) , and discharge chamber need to be arranged at first. All the pretreatment was finished on November 5 and 6, 2012.

At first, the ECU was electrified through ground command when the satellite entered in visible region, and pressures and temperatures of the XT and PRU&FCU were measured in the stand-by mode. These data were compared with that in Initialization check-up, and it turned out that all were normal, as is shown in Table 2.

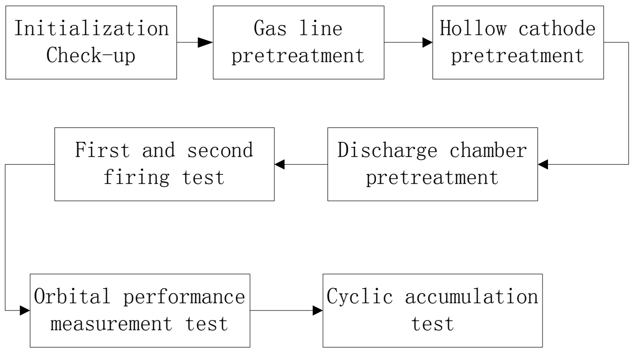

Fig.3 IEPS flight test procedure in the first-phase

Then gas line pretreatment was implemented. Output pressure control of the PRU was closed, and the xenon flow supply from the FCU to the IT was opened. The xenon gas was exhausted through the IT twice, 2 hours each time. The main purpose was to clean the impurity in the gas line and valves at downstream of the PRU&FCU. In the whole gas line pretreatment process, all the valves and the heaters worked well, the output pressure of the PRU changed from 0.2MPa to 0.05 MPa, and the temperature and pressure of the XT did not show any obvious change.

The next step is the hollow cathode pretreatment, both of the cathode and the neutralizer of the IT. The xenon gas was supplying to the IT as normal, the cathode and the neutralizer were heated for 1 hour in order to clean the impurity adsorption on inner surface of them. In the whole hollow cathode pretreatment process, the PRU&FCU operated well with telemetry data of temperatures and pressures as normal, the two heater power of the PPU functions well with telemetry data of voltages and currents as normal and stable.

At last, the discharge chamber pretreatment was done. The IT was started up as usual, but no beam was extracted out. The discharge chamber was fired twice for 0.5 hours each time. The main purpose is to clean the contamination deposited on the inner wall or on the grid. In the two processes, all telemetry data of the IEPS were proper and stable, and table 3 listed the telemetry data of the PPU. The neutralizer and the cathode were successfully started after being heated for 4.5minutes.

C. The First firing

After the whole pretreatment was finished, it was made sure that the IEPS gets ready for the first firing in orbit. When the satellite was entering visible region for the ground control station at 9:06 on November 7, 2012, the first firing command of the IEPS was implemented. The neutralizer, the cathode, the discharge chamber were started up automatically one by one, and the beam was extracted normally. After it was fired for 3 minutes, the IEPS was closed, so the first firing was performed perfectly. The second 3-minute firing of the IEPS was implemented successfully in visible region of another satellite circle.

In the two 3-minute firing test, these telemetry data of pressures, temperatures, voltages and currents are all in normal range. The neutralizer and the cathode was successfully started after it was heated for 270 seconds, the beam current were at about 0.77A for each time. All these telemetry data have presented in appendixes A, B and C, corresponding to test No.1 and No.2.

D. The orbital performance measurement

Four times of 10-minute firing were performed for performance scaling within 4 orbit circle on Nov.8, 2012. The main performance index of input power, thrust, and specific impulse were calculated using the telemetry data, corresponding to test No.3, No.4, No.5 and No.6 in appendixes A, B and C. This calculation index was compared to that on the ground system test. On the other hand, the thrust index was obtained by orbital altitude surveying method.

E. The cyclic accumulation test in the first-phase

The first-phase flight Test was carried out on Dec.10, 2012. Total of 22 firings were performed, including thrice 3-minute, eighteen times of 10-minute and once for break-down protection. Except the 21st for break-down protection, the other 21 times of tests were completed faultlessly. The IEPS worked well and stable, and all telemetry data have presented in appendixes A, B and C.

V. Flight Test Results and Discussion

A. The system scaling performance

In the four times of performance scaling tests, the average beam voltage is 1022 V and the average beam current is 0.78A, the thrust was calculated according to the following equation:

$$F = 1.651\times10^{-3}\alpha\beta I_{B}\sqrt{V_{B}}$$

In the equation, $\alpha = 0.98$, $\beta = 0.97$, the calculated average thrust is 39.1 mN. The 2955 s specific impulse was calculated within the flow rate of 1.35 mg/s, which was obtained by using telemetry temperature and pressure data of the FCU. The average power is 1199 W, which is got from telemetry input voltage and current. Otherwise the thrust is 36.2mN and the specific impulse is 2736 s which were calculated based on satellite orbit change.

A comparison between the scaling performance in orbit and the measured performance in the ground is shown on Table 4. It was shown that in-orbit performance based on telemetry data are much identical to ground data, but that based on orbit altitude change are smaller by 9%. The main cause for the latter case was believed from fitting error of the IT on the satellite. Because of the cleaner environment in orbit, start-up time of the IEPS become shorter than that on the ground.

B. The break-down Protection event

In the 21st firing on December 6, 2012, the IEPS was shut down unexpectedly when the beam power turn on and its voltage raised to 879 V (the beam current 0.77 A), and the test was not finished as usual. The ECU sent a message of anode protection fault, this means that the anode current is lower than the protection threshold, which was set up to the ECU, and the ECU has detected this lower anode current and turned off the IEPS immediately. An elementary analysis was conducted, and the most suspectable cause was thought to be an electric break-down between grids. Some investigations will be made to prove this cause.

In the flight system, a discharge chamber firing were conducted with step-by-step commands on December 8, and it was finished unanimously and all the telemetry data are normal, and it showed the whole system were well but except beam power and acceleration power. Then the beam power and acceleration power were turned on solely without the xenon supplying, and the telemetry data showed these two power's output is normal, and the grids does not have electric short. So it proved that the flight system was in normal state.

Meanwhile, an experiment was conducted on the QM IEPS on ground to confirm that an electric break-down between grids might cause the anode current to be lower than the protection threshold. Simulation electric short between grids was imitated, and the anode current was watched with an oscillograph. It was found that the anode current reduced to nearly zero-output responding to the electric short as shown on Fig.4, and it confirmed that the analytical conclusion come into existence.

This experiment was repeated 60 times on the QM IEPS, not only the phenomenon repetition was identified, but also the fact that it does not have harmful effect on PPU was proved. After the break-down protection event and the system at normal were confirmed, one 3-minute firing (the 22nd) of the IEPS was conducted just like the first firing. The telemetry data showed that the process of stat-up and firing were all right without any abnormity. Meanwhile, it was confirmed that it would not affect the follow-up test.

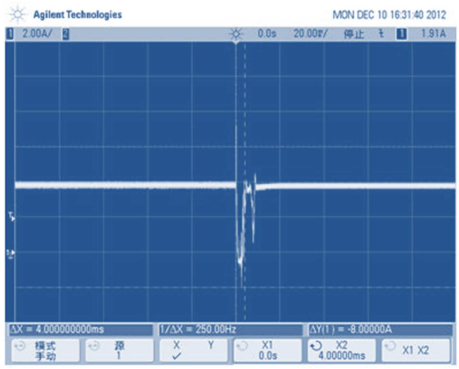

Fig.4 anode current at break-down simulation

C. Performance of the IT and PPU

The performance of the IT and PPU can be characterized by electric parameters. According to the telemetry data in Appendix C, the average beam voltage and current in each firing are shown in Fig.5. The beam voltages ranges from 1022 to 1032 V with the relative change in ±1%, and it meets the requirements. The beam current ranges from 0.72A to 0.81A, within the expected range.

Moreover, as are shown in Appendix C, the acceleration current is very stable (about 7 mA), and the acceleration voltage relative change is within ±2%, which meets the requirements.

Fig. 6 is the anode voltage and current curves drawn according to the telemetry data in Appendix C. The anode current change within the expected range of 4.37 to 4.45 A, exception of the abnormal in the 21st test. The anode voltage relative change is within ±3%, which is better than expected.

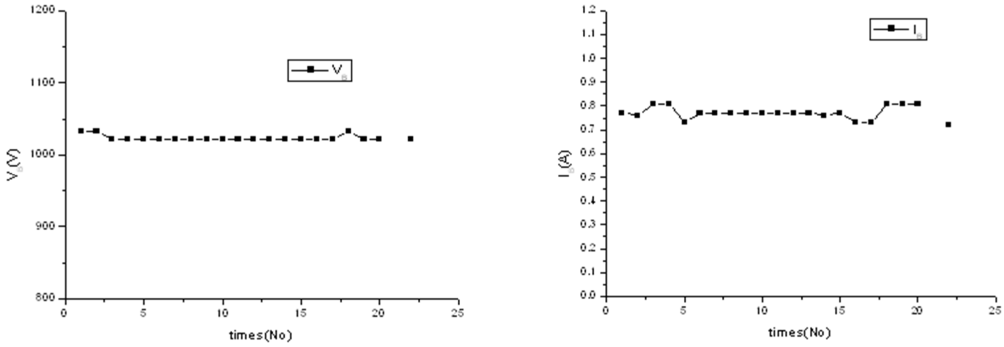

Fig.5 the average beam voltage(L) and current(R) in all tests

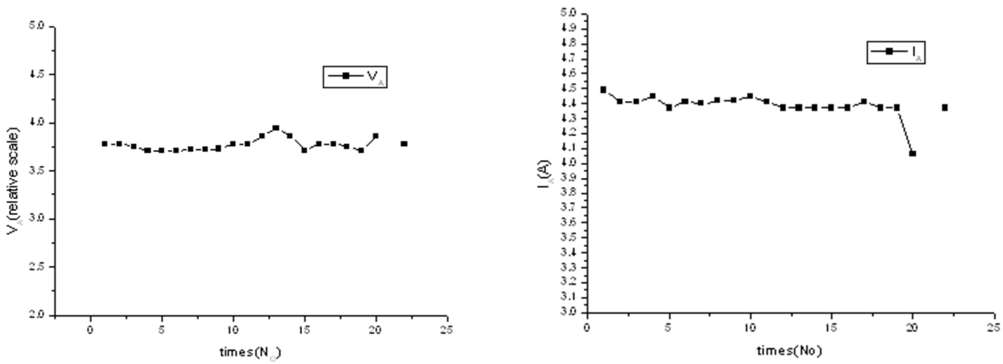

Fig.6 the average anode voltage(L) and current(R) in all tests

The heater voltages of cathode and neutralizer are very stable, and the heater current relative change is within ±3%. The cathode keeper current is stable and its relative change is less than ±1%, and the current relative change of neutralizer keeper is ±3%. The keeper voltage changes of the cathode and neutralizer is within ±2%.

D. Performance of XT and PRU&FCU

Performance parameters of XT and PRU&FCU is shown in Appendix A. Input pressures of the FCU range from 0.195MPa to 0.205MPa and keep excellent identical in each firing. Pressure changes of the XT range from 3.94MPa to 4.13MPa and they are related to its temperature changes from 16℃ to 22.4℃. Exception of the first test, temperature changes of the neutralizer FCU , the anode FCU and the cathode FCU do not exceed ±3℃, ralative to their rating temperatures of 100℃, 70℃and 100℃ respectively. Temperature changes of the anode FCU and the cathode FCU are shown in Fig.7. In the first firing, the temperature of the cathode FCU is much lower than rating temperature because the heating time is not long enough, and the time to begin heat has been adjusted so it is normal from the second firing.

E. the Compatibility with Satellites

In the total of 22 firings, the satellite's other subsystems worked well, in particularly power subsystem, communication subsystem, and AOCS subsystem. This shows that the IEPS is compatible with the host satellite, and the plasma plume has not affected the satellite's communication. The power bus voltage changes in all tests are shown in Fig.8, and the bus voltage raise dose not exceed 4V.

F. The system performance in first test phase

For each firing, the thrust can be calculated by equation as mentioned in V.A with telemetry data in appendix C, and it ranges from 36.1mN to 40.8mN as shown in Fig.8. The specific impulse ranges from 2776s to 3081s. The input power of the IEPS is obtained by a product of bus-line voltage and current, and it ranges from 1165W to 1225W as shown in the Fig.9 too.

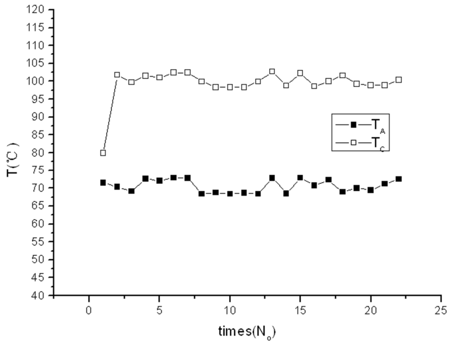

Fig.7 Temperature changes of anode FCU and cathode FCU

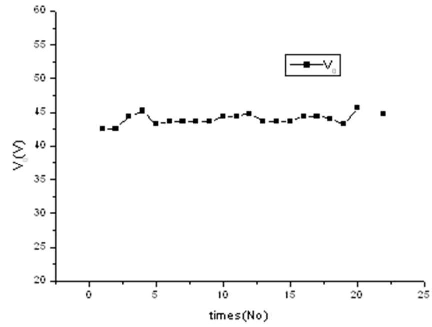

Fig.8 Power Bus Voltage Changes in All Tests

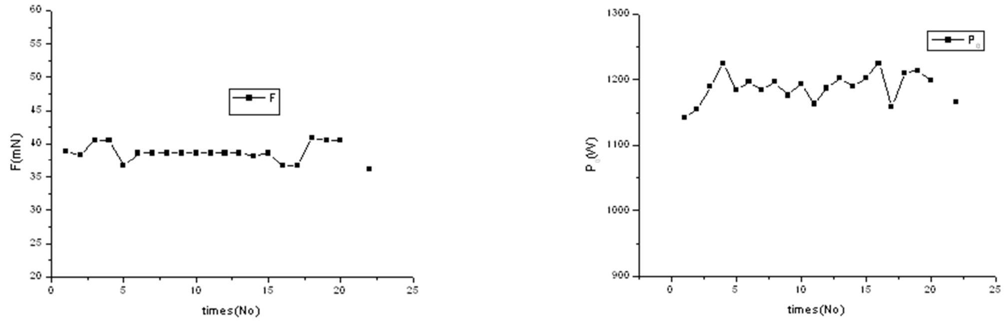

Fig.9 The Average Thrust(L) and Input Power(R) in All Tests

VI. Test of Second Phase and Extended Phase Plan

The second phase tests started from March 14, 2013. A simplified pretreatment procedure was implemented firstly because of about a half-year interval. One hour of cathode and neutralizer pretreatment and a half hour of discharge chamber pretreatment had been conducted respectively. The first formal 10-minute firing was conducted on March 15, 2013, and the telemetry data were normal.

The target of the second-phase tests is that the accumulated firing times should reach 200 and the accumulated time should be longer than 30 hours. By the end of July, 2013, the IEPS has fired more than 130 times, and the accumulated time is more than 20 hours. The second-phase test is still underway.

Because the propellant is more than what is needed for the first and second test, an extended test plan can be conducted after the second-phase tests have been finished. An optimal adjustment of the cathode flowrate and anode flowrate will be carried out in the extended test periods. All tests will be finished in 2013.

V II. Conclusion

The LIPS-200 Ion Electric Propulsion System developed by Lanzhou Institute of Physics has finished its first phase test on SJ-9A Satellite successfully. The telemetry data showed that the IEPS and each element worked well so far, and the IEPS is compatible well with other systems on the satellite. The performance in orbit are the input power of 1165W to1225W, the thrust of 36.1mN to 40.8mN, the specific impulse of 2726s to 3081s, and they all meet the expected index requirements.

The second-phase tests are being conducted right now and is coming to its end, an extended test is planned. All tests will be finished in 2013.

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Table 1 The main requirements and achievements of the IEPS

SN	**element**	**requirement**	**achievment**
1	Thrust	（40±4）mN	39.9 mN
2	Specific impulse	（3000±300）s	3136 s
3	Maximum input power（42V-bus）	≤1350W	1209 W
4	IEPS dry mass	≤37kg	36.3 kg
5	Startup time	≤600s	242 s
6	Time for single firing	300～900 s	900 s
7	Total Number of Firing	≥200	400
8	Protection response for Neutralizer extinguish	≤3ms	2.0 ms
9	Beam divergence（90%）	<30^o	28.0^o
10	Thrust vector stability	≤0.5°	0.35°
11	Leakage	＜1×10^{-5}Pa·m^3/s	5.6×10^{-6}Pa·m^3/s
12	Reliability at end of life	0.98	0.985
13	Design lifetime	3 years	4 years
14	Xenon mass	1.5±0.5kg	1.60kg
15	Xenon purification	99.995%	99.995％

Table 2 Telemetry data of pressures and temperatures

SN	Element	Normal range	telemetry data	
			pretreatment	Initialization
1	P_T (MPa)	3～7	4.03	4.03
2	T_T (℃)	0～50	19.2	17.6
3	P_W (MPa)	0.20±0.01	0.198	0.201

Table 3 Telemetry data of the PPU in discharge chamber pretreatment

SN	Element	Normal range	telemetry data	
1	V_{CH}（V）	＞3.5	4.2	4.2
2	I_{CH}（V）	＞3.5	3.8	3.8
3	V_{NH}（V）	＞3.5	4.4	4.4
4	I_{NH}（V）	＞3.5	3.9	3.9
5	V_{NK}（V）	＞3.5	3.9	3.9
6	I_{NK}（V）	＞3.5	4.4	4.3
7	V_{CK}（V）	＞3.5	4.4	4.4
8	I_{CK}（V）	＞3.5	4.3	4.2
9	V_A（V）	＞3.5	3.9	3.9
10	I_A（V）	＞3.5	3.9	3.9

Table 4 Scaling Performance Comparison

Element	Data on ground	Data in orbit	Mark
Input power（W）	1250	1199#	#from telemetry data * from orbit change + from measure thrust
Thrust（mN）	39.7	39.1#	
	39.9+	36.2*	
Specific impulse（s）	2980	2955#	
	2985+	2736*	
Start-up time（min）	5～6	4～5	

Appendix A Telemetry data of XT,PRU and FCU in flight

Test No.	P_T	T_T	P_W	T_N	T_A	T_C
1	4.03	20.8	0.195～0.205	69.2	71.5	79.9
2	4.03	20.8	0.195～0.205	102.3	70.3	101.8
3	4.03	19.2	0.195～0.205	99.2	69.1	99.7
4	4.03	20.8	0.195～0.205	101.6	72.6	101.5
5	4.13	22.4	0.195～0.205	99.9	72.0	101.0
6	3.94	16.0	0.195～0.205	102.5	72.9	102.4
7	3.94	17.6	0.195～0.205	102.5	72.8	102.4
8	3.94	17.6	0.195～0.205	98.3	68.4	99.9
9	3.94	17.6	0.195～0.205	98.4	68.7	98.3
10	3.94	16.0	0.195～0.205	98.4	68.4	98.3
11	3.94	17.6	0.195～0.205	98.5	68.6	98.3
12	3.94	16.0	0.195～0.205	98.3	68.4	99.9
13	3.94	17.6	0.195～0.205	102.5	72.8	102.7
14	3.94	17.6	0.195～0.205	98.4	68.5	98.8
15	3.94	17.6	0.195～0.205	102.5	72.9	102.2
16	4.03	19.2	0.195～0.205	99.4	70.7	98.6
17	4.03	19.2	0.195～0.205	98.4	72.3	100.0
18	4.03	19.2	0.195～0.205	102.5	68.9	101.6
19	4.03	19.2	0.195～0.205	100.0	70.0	99.2
20	4.03	19.2	0.195～0.205	102.2	69.4	98.9
21	4.03	19.2	0.195～0.205	100.9	71.2	98.9
22	4.03	20.8	0.195～0.205	101.9	72.5	100.4

Appendix B Telemetry data of cathode and neutralizer in flight

Test No.	V_{CH}	I_{CH}	V_{NH}	I_{NH}	V_{CK}	I_{CK}	V_{NK}	I_{NK}
1	4.25	3.82	4.41	3.90	4.37	4.41	3.82	4.21
2	4.25	3.90	4.41	3.94	4.37	4.41	3.82	4.18
3	4.25	3.90	4.41	3.94	4.39	4.41	3.82	4.18
4	4.25	3.94	4.41	3.98	4.41	4.41	3.82	4.14
5	4.25	4.02	4.41	4.02	4.37	4.41	3.82	4.14
6	4.25	3.88	4.42	3.94	4.33	4.42	3.81	4.25
7	4.25	3.88	4.42	3.95	4.36	4.41	3.80	4.14
8	4.25	3.90	4.42	3.95	4.37	4.42	3.81	4.21
9	4.25	3.89	4.42	3.95	4.38	4.42	3.81	4.29
10	4.25	3.94	4.41	3.98	4.41	4.45	3.94	4.14
11	4.25	3.98	4.41	4.02	4.41	4.45	3.82	4.21
12	4.25	3.98	4.41	4.02	4.45	4.41	3.90	4.29
13	4.25	3.98	4.41	4.02	4.45	4.41	3.94	4.29
14	4.25	3.98	4.41	3.98	4.41	4.41	3.86	4.29
15	4.25	3.98	4.41	4.02	4.37	4.41	3.78	4.14
16	4.25	3.98	4.41	3.98	4.41	4.41	3.82	4.18
17	4.25	3.98	4.41	3.98	4.41	4.41	3.86	4.25
18	4.25	3.98	4.41	4.02	4.37	4.41	3.82	4.41
19	4.25	3.98	4.41	4.02	4.33	4.41	3.78	4.18
20	4.25	3.98	4.41	3.98	4.41	4.41	3.90	4.33
21	4.25	3.94	4.41	3.98	-	-	-	-
22	4.25	3.78	4.41	3.86	4.41	4.37	3.86	4.25

Appendix C Telemetry data of anode and grid in flight

Test No.	V_A	I_A	V_B	I_B	V_a	I_a	V_0	I_0
1	3.78	4.49	1032	0.77	4.25	0.04	42.6	26.8
2	3.78	4.41	1032	0.76	4.25	0.04	42.6	27.1
3	3.75	4.41	1022	0.81	4.25	0.04	44.4	26.8
4	3.71	4.45	1022	0.81	4.25	0.04	45.2	27.1
5	3.71	4.37	1022	0.73	4.21	0.04	43.2	27.4
6	3.71	4.41	1022	0.77	4.23	0.04	43.7	27.4
7	3.72	4.40	1022	0.77	4.25	0.04	43.7	27.1
8	3.72	4.42	1022	0.77	4.23	0.04	43.7	27.4
9	3.73	4.42	1022	0.77	4.23	0.04	43.7	26.9
10	3.78	4.45	1022	0.77	4.25	0.04	44.4	26.9
11	3.78	4.41	1022	0.77	4.25	0.04	44.4	26.2
12	3.86	4.37	1022	0.77	4.25	0.04	44.8	26.5
13	3.94	4.37	1022	0.77	4.25	0.04	43.6	27.6
14	3.86	4.37	1022	0.76	4.25	0.04	43.6	27.3
15	3.71	4.37	1022	0.77	4.21	0.04	43.6	27.6
16	3.78	4.37	1022	0.73	4.25	0.04	44.4	27.6
17	3.78	4.41	1022	0.73	4.29	0.04	44.4	26.1
18	3.75	4.37	1032	0.81	4.25	0.04	44.0	27.5
19	3.71	4.37	1022	0.81	4.25	0.04	43.2	28.1
20	3.86	4.06	1022	0.81	4.41	0.04	45.6	26.3
21	-	-	-	-	-	–	-	-
22	3.78	4.37	1022	0.72	4.29	0.04	44.8	26.0