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Dawn Ion Propulsion System: Initial Checkout After Launch

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The first 80 days after launch of the Dawn mission were dedicated to the checkout of the spacecraft with a major emphasis on the ion propulsion system. All three ion thrusters, all three thruster-gimbal assemblies, both power processor units, both digital interface and control units, and the entire xenon feed system were completely checked out, and every component was found to be in good health. Direct thrust measurements agreed well with preflight expected values for all three thrusters over the entire throttle range. Measurements of the thruster-produced roll–torque verified that each thruster produced less than the maximum allowed value of 60 μNm at full power. Thruster electrical operating parameters and power processor unit efficiencies also agreed well with preflight expected values based on acceptance test data. Two of the three ion thrusters were fully checked out within 30 days after launch. Checkout of all three thrusters was completed 64 days after launch. Deterministic thrusting with the ion propulsion system began on 17 December 2007.

Nomenclature

e = electronic charge, 1.6×10^{-19} C
F_T = thrust loss factor due to ion beam divergence
J_A = accelerator grid current, A
J_B = beam current, A
J_B^+ = single-ion-beam current, A
J_B^{++} = double-ion-beam current, A
J_S = current measured by the beam power supply, A
m_i = ion mass, kg
T = thrust, N
V_B = voltage measured by the beam supply, V
V_N = net accelerating voltage, V
V_{NC} = neutralizer common voltage, V
α = thrust loss due to double ions

I. Introduction

THE Dawn spacecraft was launched on 27 September 2007 in the early morning shortly after dawn on an eight-year mission to explore the main-belt asteroid Vesta and the dwarf planet Ceres. The first 80 days after launch were dedicated to a thorough checkout of the spacecraft. A principal focus of this checkout activity was the ion propulsion system (IPS). Proper functioning of the IPS is critical to the success of the mission. The IPS is required to provide all of the postlaunch ΔV (aside from the Mars gravity assist), including the heliocentric transfer to Vesta, orbit capture at Vesta, transfer between science orbits at Vesta, escape from Vesta, heliocentric transfer to Ceres, orbit capture at Ceres, and transfer between science orbits at Ceres. To accomplish this, the ion propulsion system must provide a total ΔV of approximately 10.6 km/s to the spacecraft, which had an initial wet mass of 1218 kg including 425 kg of xenon and 46 kg of hydrazine. Additional details of the mission and spacecraft are given elsewhere [1–4].

A simplified block diagram of the Dawn IPS is given in Fig. 1. The ion propulsion system includes three 30-cm-diam xenon ion thrusters of the type flown on the Deep Space 1 (DS1) mission [5–8], two power processing units (PPUs), and two digital control and interface units (DCIUs). The IPS includes a lightweight, composite xenon tank developed specifically for Dawn that can store up to 425 kg of xenon. In addition to the xenon tank, the xenon feed system consists of two plenum tanks, a xenon control assembly (XCA), a high-pressure subassembly, nine service valves, the interconnecting tubing, and nine flexible propellant lines that go across the gimbal interfaces. Finally, the IPS includes three two-axis thruster-gimbal assemblies (TGAs). Each TGA provides two-axis thrust-vector control with a capability of approximately ± 8 deg in one axis and ± 12 deg in the other. Only one ion thruster is operated at a time on the Dawn spacecraft.

The xenon feed system, described in [9], controls the pressure in each plenum tank to control the xenon flow rate to each thruster. The pressure is controlled using a bang–bang regulation system that cycles high-pressure solenoid valves in response to the difference between the measured plenum pressure and the required pressure.

The Dawn ion propulsion system is designed to be single fault tolerant. To accomplish the mission, at least two ion thrusters, two TGAs, one PPU, and one DCIU must be fully functional after launch. During the 80-day checkout period, the functionality of all of the IPS hardware was tested and the results are summarized herein. A list of the key IPS-related checkout activities is given in Table 1. Operation of the IPS during normal cruise, which began on 17 December 2007, is described by Garner et al. [10].

II. IPS Preparation Activities

After launch, several activities were performed to prepare the ion propulsion system for operation. These activities began at launch plus 4 days with the bake out of the propellant lines downstream of the flow control devices in the XCA followed by cathode conditioning, pressurization of the plenum tanks, initialization of each TGA, cathode ignition, and operation of each thruster in diode mode for 2 h. The checkout plan identified FT3 as the first thruster to be tested. This thruster can be operated by either PPU, is referred to as the "shared" thruster, and is physically located in the center position as indicated in Fig. 2. Thruster FT2 is on the sun side of the spacecraft, positioned below the high-gain antenna, and FT1 is on the shade side of the spacecraft.

The plan called for FT3 to be operated from PPU-1 during the initial checkout (ICO) phase. Each PPU has relays that switch its outputs between each of two thrusters. The relays in PPU-2 can be in any state when the shared thruster FT3 is operated by PPU-1, but it is

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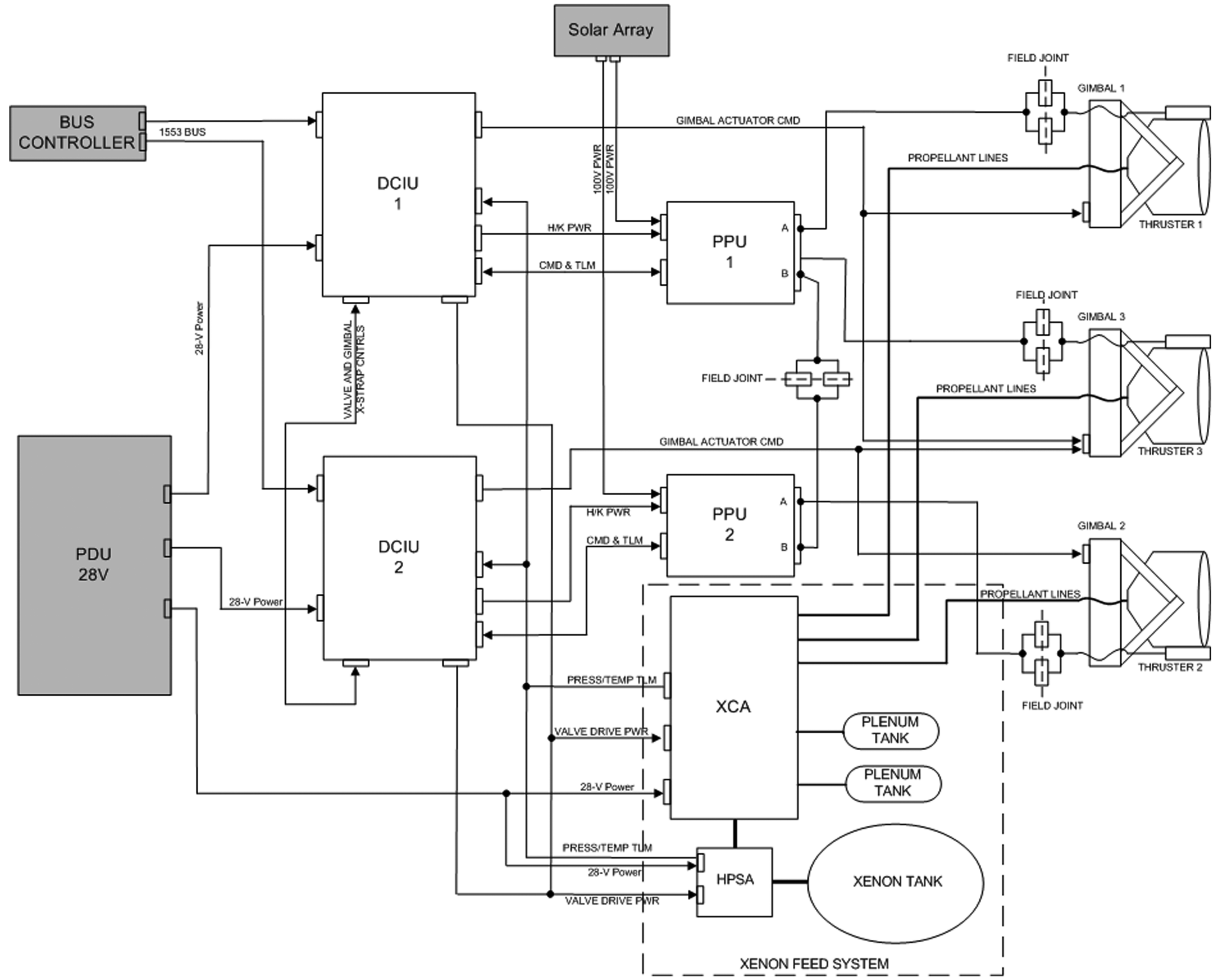

Fig. 1 Simplified IPS block diagram.

preferred that they be set such that their outputs are switched to FT2. To reinforce the desired state of the relays in PPU-2 after launch, the first activity for the IPS was to turn on DCIU-2 and PPU-2 and command the relays to FT2. This activity also provided early insight to the state of health of DCIU-2, PPU-2, and the xenon feed system (XFS). All the telemetry from DCIU-2 indicated that both it and PPU-2 were functioning normally, that DCIU-2 was correctly reading all the analog signals from the XFS, and that the xenon tank and plenum tank pressures were as expected (i.e., still at the values set before launch).

The next activity was the propellant line bake out, which was successfully completed without incident. Cathode conditioning was performed on each thruster before the initial cathode ignition. Cathode conditioning is used to bake absorbed water from the cathode emitters. The procedure followed the same cathode conditioning process used on DS1 [8] and in each of the key long-duration thruster life tests [11,12]. PPU-1 was used for the cathode conditioning of both FT1 and FT3, whereas PPU-2 was used for FT2. The cathode heater currents and voltages for all six cathodes (two in each thruster) were as expected based on prelaunch data.

Initialization activities for the XFS and TGAs were performed before cathode ignition for thruster operation in diode mode. The XFS initialization pressurized the plenum tanks from their launch pressures to the pressures required for thruster startup. Before launch the pressures in the plenum tanks were set to the approximate values required for main cathode and neutralizer ignition, resulting in a pressure difference between the two tanks. This pressure difference was used as a diagnostic for detecting leakage through the latch valve (LV3) that connects the two plenum tanks. After launch IPS telemetry confirmed that there was no change in the pressure of either plenum tank, indicating that none of the normally closed latch valves, including LV3, leaked or changed state during launch. Initialization of the TGAs began with the confirmation that each thruster-gimbal assembly had not moved from its launch position during launch. Each TGA was then driven to its neutral position in preparation for thruster operation. All three TGAs were found to be in good health and performed as expected.

The final preparation activity before operation with beam extraction was to bake out each thruster by operating it in diode mode for two hours. In diode mode, the xenon feed system provides main, cathode, and neutralizer flow rates corresponding to full power operation and the PPU ignites and operates the neutralizer cathode to neutralizer keeper discharge at 2.4 A and the main cathode to anode discharge at 13.0 A, but high voltages are not applied to the thruster by the beam or accelerator power supplies. Before launch the cathodes were purged with dry nitrogen almost continuously from the time they were first assembled. At certain times during the spacecraft assembly and test process, however, it was not possible to purge the cathodes. The total time off purge at the time of launch for the cathodes in each of the Dawn ion thrusters is given in Table 2. This slightly exceeded the specified maximum allowable time off purge of 1200 h (which was conservatively based on environmental exposure tests performed in support of the International Space Station plasma contactor development). Because the absorption of water by the cathode emitters is known to be a self-limiting process, this was considered to be low risk. Ignition of the cathodes is essential

Table 1 Summary of key IPS checkout activities

Event	Event date, DOY 2007	Mission time, days after launch	Power level	Xenon used, g	Event duration, h	Cumulative Xe used, kg
Launch	270	0	N/A	0.0	N/A	0.00
Propellant line bake out	274	4	N/A	0.0	24.0	0.00
FT3 cathode conditioning	274	4	N/A	0.0	5.0	0.00
FT3 TGA initialization	274	4	N/A	0.0	0.7	0.00
FT3 first diode-mode bake out	278	8	0	22.1	2.0	0.02
FT3 main plenum blowdown	278	8	Blowdown	44.8	7.0	0.07
FT3 ICO ML27–111	280	10	27–111	165.8	25.2	0.23
FT3 normal 1 diode mode	281	11	0	11.1	1.0	0.24
FT3 normal 1	281	11	111	43.9	4.0	0.29
FT3 normal 2 diode mode	282	12	0	11.1	1.0	0.30
FT3 normal 2	282	12	111	39.0	3.5	0.34
FT3 normal 2 gyroless diode	282	12	0	11.1	1.0	0.35
FT3 normal 2 gyroless	282	12	111	22.1	2.0	0.37
FT1 cathode conditioning	283	13	N/A	0.0	5.0	0.37
FT1 TGA initialization	283	13	N/A	0.0	0.7	0.37
FT1 diode mode	283	13	0	23.0	2.0	0.39
FT1 blowdown	283	13	Blowdown	46.3	7.0	0.44
FT1 ICO ML27	284	14	27	44.6	7.7	0.48
FT1 ICO redo ML27–111	296	26	27–111	178.8	26.8	0.66
FT1 normal 1 diode mode	298	28	0	10.7	0.9	0.67
FT1 normal 1 pointing calibration	298	28	111	44.2	4.0	0.72
FT1 normal 2 diode mode	298	28	0	10.6	0.9	0.73
FT1 normal 2 pointing calibration	298	28	111	44.2	4.0	0.77
FT3 gyrofull desat diode mode	303	33	0	12.2	1.1	0.79
FT3 gyrofull desat ML111	303	33	111	32.9	3.0	0.82
FT3 gyroless desat diode mode	303	33	0	12.9	1.2	0.83
FT3 gyroless desat ML 111	303	33	111	32.9	3.0	0.86
FT2 cathode conditioning	305	35	N/A	0.0	5.0	0.86
FT2 TGA initilization	305	35	N/A	0.0	0.7	0.86
FT2 diode-mode bake out	305	35	0	4.8	0.4	0.87
FT3 LDST diode-mode bake out	309	39	0	11.1	1.0	0.88
FT3 LDST ML111	310	40	111	1816.9	165.9	2.70
FT3 normal 1 diode mode	317	47	0	11.0	1.0	2.71
FT3 Normal 1	317	47	111	43.8	4.0	2.75
FT2 ML27–69	318	48	111	139.9	16.3	2.89
FT2 diode-mode RWA	319	49	0	2.6	13.7	2.89
FT2 ML111 RWA	319	49	111	32.7	3.0	2.93
FT2 diode-mode Jets	320	50	0	10.5	1.0	2.94
FT2 ML111 jets	320	50	111	33.0	3.0	2.97
FT3 FSW 7.0 validation diode mode	334	64	0	10.9	1.0	2.98
FT3 FSW 7.0 validation Ml111	334	64	111	43.7	4.0	3.02

to the operation of the ion thrusters, and its successful demonstration after launch represented a major milestone in the checkout activities.

FT3 was the first thruster to be started. The neutralizer cathode was successfully started 21 s after the completion of the 6 min preheat time. The discharge cathode started immediately upon application of the start voltage. The thruster was then operated in diode mode for approximately 2 h. The second thruster to be started was FT1. The neutralizer and discharge cathodes for FT1 both started immediately after the 6 min preheat. This thruster was also then operated in diode mode for 2 h. FT2 was the final thruster to be started. Again, both the neutralizer and discharge cathodes for FT2 started immediately after the 6 min preheat. This thruster is located on the $+X$, sun side of the spacecraft. Thermal concerns limited the diode-mode bake out duration to only 20 min for FT2. This was necessary to make sure that no fault-protection temperature limits for the thruster were exceeded during this bake out for the given sun angle. The shortened diode-mode operation of FT2 was successfully completed. The shorter bake out for FT2 was not considered to be an issue because the thruster was more than adequately baked out by virtue of being heated by the sun for weeks before its first operation.

III. Thruster Checkout

A key objective of the overall spacecraft checkout activity was to determine the health and performance of each of the three ion thrusters in the IPS. The Dawn ion thrusters are designed to operate over the range of PPU input powers from 532 to 2483 W (at beginning of life). This power range is divided into 111 different throttle levels referred to as mission levels (MLs), ranging from ML1 for the lowest power in thrust mode to ML111 for full power, as shown in Table 3, with ML0 reserved for diode-mode operation. The planned checkout of the ion thrusters called for operating at five different mission levels (ML27, 48, 69, 90, and 111) ranging in PPU input powers from 952 to 2483 W. Electrical parameters, thrust, and the roll torque produced by each thruster were measured at each of these five throttle levels.

During the entire checkout activity, a total of 3 kg of xenon was processed by the IPS: 0.40 kg by FT1, 0.22 kg by FT2, and 2.38 kg by FT3. This xenon was processed in approximately 285 h of IPS operation.

A. FT3 Performance Characterization

The center thruster, FT3, was started for operation with beam extraction for the first time on day of year (DOY) 2007-280, 10 days after launch. After the 6 min cathode preheat, both cathodes lit immediately upon application of the start voltages and the thruster was successfully started at ML27. FT3 was then operated at ML27 for the next 11 h. The first 7 of these 11 h were used to bleed the plenum tanks in the xenon feed system down to the correct flow rates for ML27 operation. The last 4 h at ML27 were used to obtain good thrust measurements. After 11 h at ML27 the thruster was throttled to ML48, at which it was operated for 4 h, followed by 4 h at ML69 and 4 h at ML90. Finally the thruster was throttled to ML111, at which it was planned to be operated for 4 h. However, operation at this throttle level had to be cut short due to thermal concerns elsewhere on the

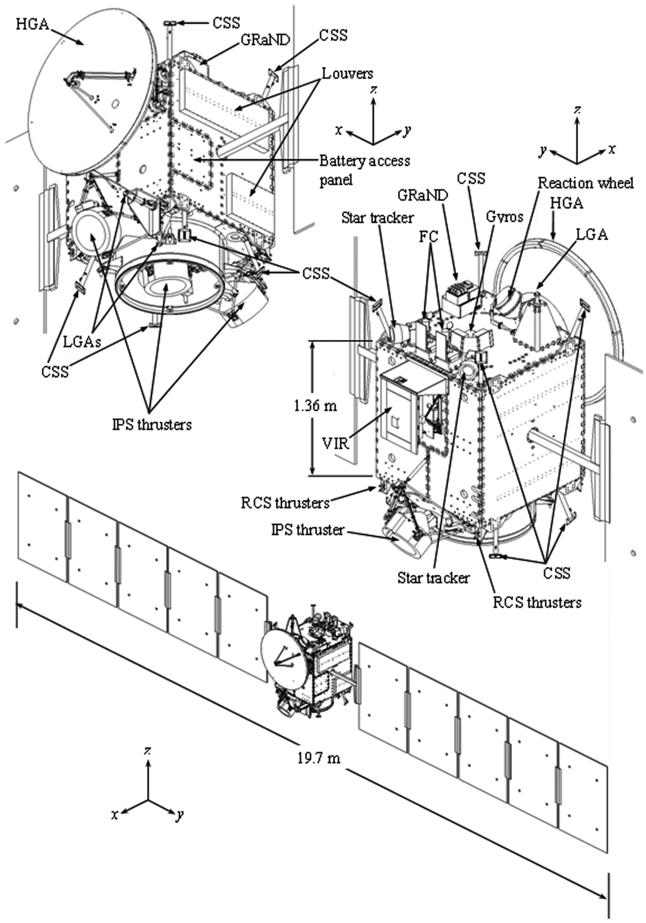

Fig. 2 Dawn spacecraft configuration.

spacecraft unrelated to the IPS. The actual time at ML111 was approximately 1 h. In this performance characterization test series, FT3 was operated continuously for 25 h. Steady-state thruster and PPU temperatures were achieved at each throttle level except for the shortened test at ML111.

The measured performance data for FT3 over the 25 h characterization test are given in Fig. 3. The five different throttle levels are indicated in Fig. 3a. The vertical lines in this figure indicate high-voltage recycle events (not all recycle events show up in these figures). There were 20 high-voltage recycles in the first hour after the application of high voltage, six in the second hour, and one in the third hour. Over the full 25 h test, there were a total of 85 high-voltage recycles. In the 65 h of acceptance testing on the ground before launch, there were a total of only 43 high-voltage recycles with this thruster. The higher initial recycle rate after launch is indicative of particulate contamination of the thruster during the spacecraft assembly, test, and launch operations (ATLO). The recycle rate decreased with thruster operating time as the high-voltage arcing eliminated the particulate contamination. The long-duration system test described later, in which FT3 was operated continuously at ML111 for 165.7 h, had an average high-voltage recycle rate of 1.5 recycles/day. During normal thrusting cruise at ML111, this rate dropped to ∼1 recycle every 3 days [10].

The thruster electrical performance from the in-flight characterization test is compared with that from the thruster acceptance test performed at the test facility of the thruster vendor (L3

Table 2 Off purge times

Thruster	Time off purge, h
FT1	1231
FT2	1120
FT3	1087

Communications Electron Technologies, Inc.) in Table 4. In this table, "actual" refers to the in-flight data, and "expected" refers to the ground-base thruster acceptance test data. These data indicate that the thruster operation in-flight is very similar to that observed on the ground. Also given in the table is the PPU efficiency at each throttle level. It is clear that the PPU is also performing as expected in-flight. Measured thrust levels are given in a subsequent section.

B. FT1 Performance Characterization

The cathodes in the outboard thruster, FT1, located on the $-X$ side of the spacecraft were ignited for the first time 13 days after launch for the diode-mode bake out. The thruster was started with beam extraction for the first time 26 days after launch on DOY 2007-296. After the 6 min cathode preheat, both cathodes lit immediately upon application of the start voltages and the thruster was successfully started at ML27. Performance characterization for FT1 followed the same procedure used for FT3, starting with 11 h of operation at ML27, stepping up in power through ML28, 69, and 90, and ending at ML111, with 4 h spent at each throttle level. In this performance characterization test series, FT1 was operated continuously for 28 h, and steady-state thruster and PPU temperatures were achieved at each throttle level.

The key electrical parameters for FT1 over the 28 h performance characterization test are given in Fig. 4. The five different throttle levels are indicated in Fig. 4a, and the vertical lines indicate high-voltage recycle events. The short vertical lines result from small pressure spikes caused by the operation of the xenon bang–bang pressure regulation system. There was only one high-voltage recycle in the first 11 h after the application of high voltage and only 11 over the full 28 h test. The lower initial recycle rate for FT1 compared with FT3 is a reflection that this thruster accumulated less particulate contamination during ATLO.

The thruster electrical performance from the in-flight characterization test is compared with that from the ground thruster acceptance test in Table 5. These data indicate that the operation of FT1 and PPU-1 in-flight is very similar to that observed on the ground.

The IPS is designed so that the entire Dawn mission can be accomplished with just two ion thrusters. With the completion of the checkout of FT1 on 25 October 2007, two ion thrusters (FT1 and 3) were fully checked out within 30 days after launch.

C. FT2 Performance Characterization

The outboard thruster on the $+X$ side of the spacecraft, FT2, was started for the first time with beam extraction on DOY 2007-318, 52 days after launch. After the 6 min cathode preheat, both cathodes lit immediately upon application of the start voltages and the thruster was successfully started at ML27. Performance characterization for FT2 followed the same procedure used for FT3 and 1 starting with 11 h of operation at ML27 and stepping up in power to ML28 and then ML69, but with only 3 h at each of these throttle levels. Operation at higher power levels was not attempted with FT2 at this time. The sun angle on the spacecraft at the time of this test resulted in higher-than-expected temperatures for the FT2 gimbal pads. Although these higher temperatures were not a threat to the health of the thruster, they were sufficiently high that operation at ML90 or ML111 may have resulted in exceeding the fault-protection temperature limits assigned for the gimbal pads. Rather than change the fault-protection limits for FT2, it was decided to simply eliminate operation at ML90 and delay operation at ML111 until a more favorable sun angle could be used. This was done the next day (on DOY 2007-319). In the performance characterization test series, FT2 was operated continuously for 19 h, including 12 h at ML27 and 3.5 h each at ML48 and ML69. The following day (on DOY 2007-319), FT2 was operated for 3 h at ML111 and for another 3 h at ML111 on the following day.

The key electrical parameters for FT2 over the 18 h performance characterization test are given in Fig. 5. There was only one high-voltage recycle in the first 14 h after the application of high voltage and 21 over the 18 h test.

The thruster electrical performance from the in-flight characterization test is compared with that from the ground thruster acceptance

Table 3 Dawn IPS throttle table

Level, ML	PPU input power, kW	Thruster input power, kW	Thrust, mN	Total flow	ISP	Truster efficiency
111	2510	2303	91.4	3.03	2990	0.582
110	2492	2286	91.0	3.03	2976	0.581
109	2474	2269	90.5	3.03	2962	0.580
108	2457	2252	90.1	3.03	2948	0.579
107	2439	2235	89.7	3.03	2935	0.577
106	2421	2218	89.3	3.03	2921	0.576
105	2403	2201	88.8	3.03	2907	0.575
104	2380	2183	86.7	2.84	3022	0.589
103	2362	2165	86.3	2.84	3006	0.587
102	2343	2147	85.8	2.84	2991	0.586
101	2324	2130	85.4	2.84	2976	0.585
100	2305	2112	85.0	2.84	2960	0.584
99	2286	2095	84.5	2.84	2945	0.583
98	2267	2077	84.1	2.84	2929	0.581
97	2255	2068	82.1	2.66	3047	0.593
96	2237	2051	81.6	2.66	3029	0.591
95	2219	2035	81.2	2.66	3014	0.590
94	2201	2018	80.8	2.66	2998	0.589
93	2183	2001	80.4	2.66	2982	0.587
92	2165	1985	80.0	2.66	2967	0.586
91	2147	1968	79.5	2.66	2951	0.585
90	2131	1955	77.0	2.52	3011	0.581
89	2114	1939	76.6	2.52	2996	0.580
88	2097	1923	76.2	2.52	2981	0.579
87	2080	1907	75.8	2.52	2965	0.578
86	2063	1892	75.4	2.52	2950	0.577
85	2045	1876	75.0	2.52	2934	0.575
84	2028	1860	74.6	2.52	2919	0.574
83	2006	1842	72.3	2.36	3017	0.581
82	1988	1824	71.8	2.36	2999	0.579
81	1969	1807	71.4	2.36	2981	0.578
80	1950	1789	71.0	2.36	2963	0.576
79	1931	1772	70.5	2.36	2945	0.575
78	1912	1754	70.1	2.36	2926	0.573
77	1893	1737	69.6	2.36	2908	0.572
76	1869	1717	67.1	2.20	2997	0.575
75	1849	1698	66.6	2.20	2976	0.573
74	1829	1679	66.2	2.20	2956	0.571
73	1809	1660	65.7	2.20	2935	0.569
72	1788	1642	65.2	2.20	2914	0.568
71	1768	1623	64.8	2.20	2892	0.566
70	1748	1604	64.3	2.20	2871	0.564
69	1734	1593	62.0	2.06	2947	0.562
68	1716	1576	61.5	2.06	2927	0.560
67	1697	1558	61.1	2.06	2907	0.559
66	1679	1541	60.7	2.06	2886	0.557
65	1660	1524	60.2	2.06	2865	0.555
64	1641	1507	59.8	2.06	2845	0.554
63	1623	1489	59.3	2.06	2824	0.552
62	1602	1471	56.8	1.90	2913	0.552
61	1585	1455	56.4	1.90	2893	0.550
60	1568	1440	56.0	1.90	2873	0.548
59	1552	1424	55.6	1.90	2852	0.547
58	1535	1408	55.2	1.90	2832	0.545
57	1518	1392	54.8	1.90	2811	0.543
56	1501	1376	54.4	1.90	2791	0.541
55	1473	1351	51.6	1.75	2859	0.535
54	1458	1337	51.3	1.75	2839	0.534
53	1442	1322	50.9	1.75	2819	0.532
52	1427	1307	50.5	1.75	2799	0.531
51	1411	1293	50.2	1.75	2779	0.529
50	1396	1278	49.8	1.75	2759	0.527
49	1380	1264	49.4	1.75	2739	0.525
48	1361	1246	47.0	1.60	2841	0.526
47	1344	1230	46.6	1.60	2815	0.523
46	1327	1214	46.2	1.60	2794	0.522
45	1310	1198	45.8	1.60	2770	0.520
44	1293	1182	45.4	1.60	2746	0.517
43	1276	1166	45.0	1.60	2722	0.515
42	1259	1150	44.6	1.60	2697	0.513
41	1235	1127	42.0	1.45	2783	0.508
40	1219	1112	41.6	1.45	2756	0.506
39	1203	1097	41.3	1.45	2734	0.504
38	1187	1082	40.9	1.45	2709	0.502
37	1172	1067	40.5	1.45	2684	0.500
36	1156	1052	40.1	1.45	2659	0.497
35	1140	1037	39.7	1.45	2634	0.495
34	1106	1005	36.7	1.30	2696	0.483
33	1089	989	36.3	1.30	2668	0.481
32	1072	973	36.0	1.30	2639	0.478
31	1056	957	35.6	1.30	2610	0.475
30	1039	941	35.2	1.30	2580	0.473
29	1022	925	34.7	1.30	2551	0.470
28	1006	909	34.3	1.30	2520	0.467
27	973	878	31.6	1.16	2584	0.455
26	949	855	31.0	1.16	2537	0.451
25	924	832	30.4	1.16	2490	0.447
24	900	809	29.8	1.16	2441	0.442
23	876	786	29.2	1.16	2392	0.437
22	852	762	28.6	1.16	2342	0.431
21	827	739	28.0	1.16	2290	0.425
20	807	720	26.3	1.09	2288	0.410
19	794	708	26.0	1.09	2259	0.407
18	781	695	25.7	1.09	2230	0.403
17	768	683	25.3	1.09	2200	0.400
16	755	670	25.0	1.09	2170	0.396
15	741	658	24.6	1.09	2139	0.392
14	728	646	24.3	1.09	2108	0.388
13	706	625	23.9	1.09	2077	0.389
12	693	612	23.5	1.09	2045	0.385
11	679	600	23.2	1.09	2012	0.381
10	666	587	22.8	1.09	1979	0.376
9	653	575	22.4	1.09	1945	0.371
8	640	562	22.0	1.09	1911	0.366
7	627	550	21.6	1.09	1876	0.361
6	584	510	20.9	1.10	1794	0.361
5	573	501	20.6	1.10	1767	0.357
4	563	491	20.3	1.10	1739	0.352
3	553	481	20.0	1.10	1711	0.348
2	543	472	19.6	1.10	1682	0.343
1	532	462	19.3	1.10	1653	0.338
0	390	350	N/S	3.03	N/A	N/A

test in Table 6. These data indicate that the thruster, FT2, and PPU-2 operation in-flight are very similar to that observed on the ground.

IV. Thrust-Vector Control

Thrust-vector control of the spacecraft with FT3 was initiated within 3 min after the thruster was first started at ML27. This was done to minimize the buildup of momentum in the reaction wheel assemblies (RWAs). In thrust-vector control mode, the ion thruster provides pitch and yaw control of the spacecraft, with the RWAs providing roll control. The attitude control system was designed to minimize the duty cycle of the TGA actuators. Each actuator (provided Starsys, Inc., Louisville, Colorado) consists of a two-phase, 45 deg stepper motor driving a two-stage planetary gearbox that drives a standard harmonic drive system with a 100:1 gear reduction. A duty cycle of 100% corresponds to a step rate of 50 steps/s. The actuator duty cycle during thrust-vector control was expected to be less than 1%. The actual duty cycle over the 25 h characterization test of FT3 was 1.2%. Subsequent tests at ML111 indicated an actuator duty cycle of approximately 0.5%. The TGA actuators were life tested for 18 times the required life assuming a 1% duty cycle over the mission in which the thruster operating time is divided evenly among the three thrusters.

Thrust-vector control of the spacecraft with FT1 was also initiated within 3 min after the thruster was started at ML27. There were no issues performing thrust-vector control with the outboard thruster FT1, even though it is not aligned along the principal axes of the

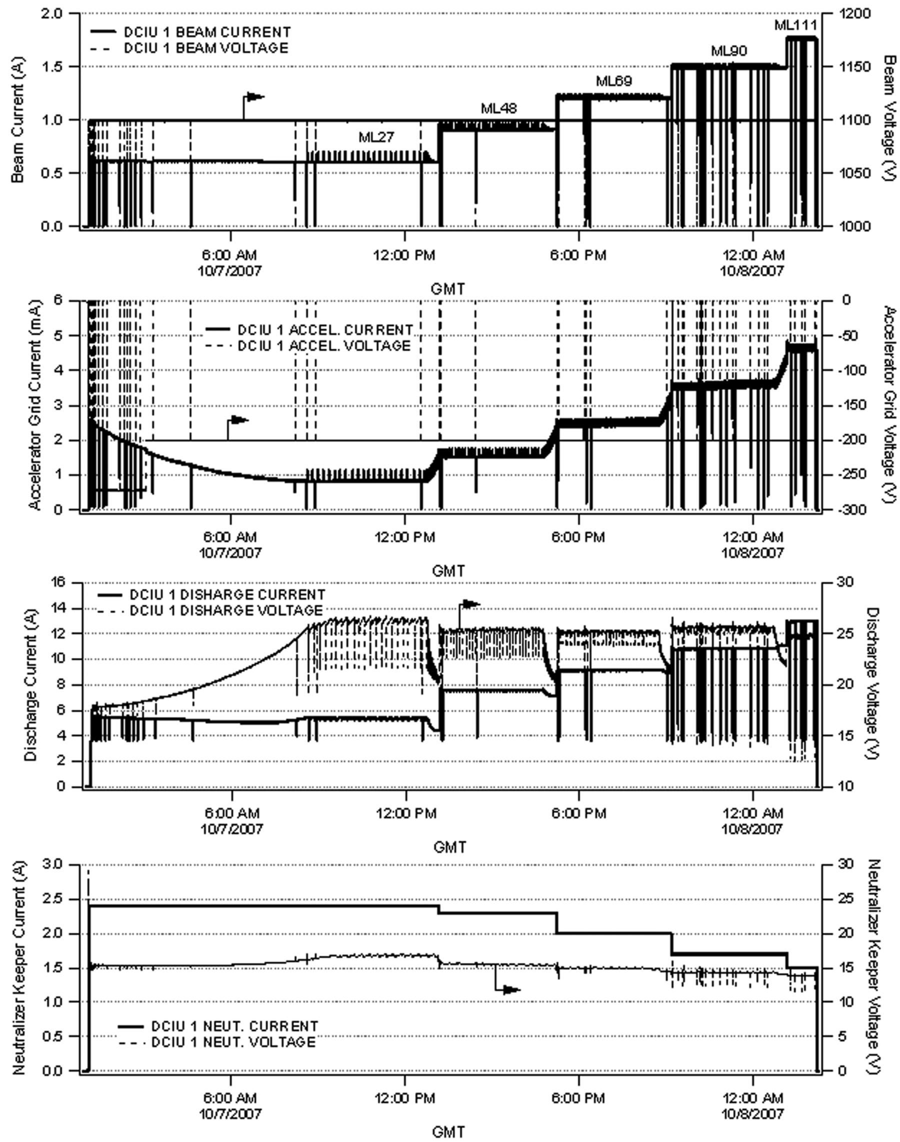

Fig. 3 Electrical parameters from the 25-h-long FT3 characterization test.

spacecraft. The TGA actuator duty cycle over the 28 h characterization test of FT1 was 0.9%.

Finally, thrust-vector control of the spacecraft with FT2 was initiated within 3 min after it was first started at ML27. The TGA actuator duty cycle over the 18 h characterization test of FT2 was 2.1%. This value is higher than for FT1 or 3 because the characterization test of FT2 was limited to the lower power and thrust levels, which result in higher actuator duty cycles. Subsequent operation of FT2 at ML111 resulted in an actuator duty cycle of less than 1%.

V. Comparison of Measured and Predicted Thrust

A. Measured Thrust

The thrust was measured for each thruster, using the technique described in [13], at each of the five throttle levels: ML27, 48, 69, 90, and 111 (with the exception of FT2, for which the thrust was not measured at ML90). At each throttle level the thruster was operated long enough to reach a steady-state temperature (with the only exception being FT3 at ML111). However, the thrust measurements showed essentially no difference in thrust before reaching the thermal equilibrium.

The measured thrusts (called actual) are compared with the preflight expected values for each thruster in Table 7. These data indicate excellent agreement with the preflight predictions and very little thruster-to-thruster differences.

The preflight expected values for the thrust were calculated using the standard ion thruster equation for thrust:

$$T = \alpha F_T J_B \sqrt{\frac{2 m_i V_N}{e}} \tag{1}$$

where α is the thrust loss due to double ions, F_T is the thrust loss to due beam divergence, J_B is the beam current, m_i is the mass of a xenon ion, V_N is the net accelerating voltage, and e is the electron charge. The beam current is the current measured by the beam supply, J_S, minus the current measured by the accelerator grid power supply, J_A, that is, $J_B = J_S - J_A$. The preflight expected values for J_A are given in Tables 4–6. The net accelerating voltage is the measured beam supply voltage, V_B, minus the neutralizer coupling voltage V_{NC}, that is, $V_N = V_B - V_{NC}$. The neutralizer coupling voltage is not measured on the Dawn spacecraft and was assumed to be 14 V ± 5 V in the thrust calculations.

1. *Double-Ion Thrust Loss*

The double-ion thrust loss factor is calculated from the ratio of double-to-single ion beam currents:

$$\alpha = \frac{1 + (\sqrt{2}/2)(J_B^{++}/J_B^{+})}{1 + (J_B^{++}/J_B^{+})} \tag{2}$$

Table 4 FT3 initial checkout results

Mission level		Beam		Accel.		Discharge			Neutralizer		PPU			Required	
		J_B, A	V_B, V	J_A, mA	V_A, mA	J_D, A	V_D, V	Discharge loss, eV/ion	J_{NK}, A	V_{NK}, A	Input power, W	Efficiency	Dissipated power, W	Main plenum, psia	Cath plenum, psia
27	Expected	0.610	1100	0.83	−200	5.44	26.7	239	2.4	15.6	952	0.907	89	18.69	23.50
	Actual	0.606	1100	0.83	−200	5.38	26.3	233	2.4	16.8	935	0.908	86	18.80	23.50
48	Expected	0.910	1100	1.57	−200	7.39	25.4	207	2.3	14.7	1340	0.920	104	30.95	23.50
	Actual	0.907	1100	1.54	−200	7.38	25.4	207	2.3	15.4	1329	0.919	108	31.30	23.50
69	Expected	1.200	1100	2.79	−200	8.87	25.0	185	2.0	14.5	1713	0.923	132	44.44	23.50
	Actual	1.197	1100	2.44	−200	8.89	25.2	187	2.0	14.8	1694	0.927	123	44.70	23.50
90	Expected	1.490	1100	4.12	−200	10.55	25.1	178	1.7	14.1	2105	0.923	162	56.21	27.30
	Actual	1.487	1100	3.54	−200	10.69	25.6	184	1.7	14.3	2073	0.933	138	56.40	27.30
111	Expected	1.760	1100	5.63	−200	12.99	24.4	180	1.5	13.9	2483	0.924	189	67.35	35.04
	Actual	1.756	1100	4.59	−200	13.09	25.0	186	1.5	13.9	2435	0.937	154	67.30	35.00

The double-to-single ion beam current ratio was measured in two different ways on two physically different but functionally equivalent thrusters. During the extended life test (ELT) of the DS1 flight spare thruster, the double-to-single ion beam current ratio was measured periodically throughout the test [12]. The $E \times B$ probe used to make these measurements provided double-to-single ion current ratios that correspond to the average values across a "slice" of the ion beam spanning the full discharge chamber diameter. These measurements were made at selected throttle levels over the full throttle range of the thruster. The second set of double-to-single ion current measurements were made on the thruster designated EMT4 fabricated by NASA Glenn Research Center during the NSTAR project [5]. This thruster is functionally equivalent to the DS1 flight spare thruster fabricated by Hughes Electron Dynamics Devices (now L3 Communications Electron Technologies, Inc.). The measurements on EMT4 used an $E \times B$ probe that viewed a 1-cm-diam spot on the physical centerline of the thruster. These measurements were made at the same throttle levels over the thruster's full throttle range, as in the ELT. The results of these measurements are given in Table 8. The uncertainties given in this table are the 1-σ variations observed during the ELT.

The double-ion thrust loss factor in Eq. (2) requires the ratio of the total double-to-single ion currents emitted by the thruster. Neither of the aforementioned measurements provide this information. Therefore, these data were used to estimate the total ratio of double-to-single ion current in the beam. This was done by assuming that the ratio of double-to-single ion current measured on the thruster centerline was constant out to some critical radius, r_c, and zero from that radius to the edge of the grid. Using measurements of the total ion beam current density as a function of radial position across the grid, the value of r_c was selected so that the calculated double-to-single ion current ratio across the thruster diameter was equal to the measured slice value for each throttle level. This process separates the double-ion current density from the single-ion current density as a function of grid radius. The total double-to-single ion current ratio is then simply determined by integrating these two current density profiles over the grid area and taking the ratio. The end result of this process is given in Table 8 and Fig. 6. Centerline measurements of the double-to-single ion current ratios were made on each of the Dawn ion thrusters during thruster acceptance testing, and these results were consistent with the centerline data in Table 8.

2. *Beam-Divergence Thrust Loss*

The ion beam divergence was measured multiple times over the full throttle range during each thruster acceptance test. The thrust loss values based on the beam-divergence data from the Dawn FT1 acceptance test are given in Fig. 7. A sufficient number of measurements were made at each throttle level to calculate the 1-σ variations, which are also shown in this figure.

The double-ion and beam-divergence thrust losses from Figs. 6 and 7 were used in Eq. (1) to calculate the expected thrust values in Table 7.

B. Measured Roll Torque

It was observed on DS1 that the NSTAR ion thruster produces a roll torque about the thrust axis. For DS1, this torque was estimated to be about 10 μNm when the thruster was operated at the low-power end of the throttle range (ML10–20). On Dawn, measurements of the roll torques produced during thruster operation were obtained from the momentum buildup in the RWAs while in thrust-vector control mode. The results of these measurements are given in Fig. 8 for all three thrusters. These data indicate that FT2 is the best thruster, that is, has the lowest roll–torque magnitude and produces a torque in the opposite direction from the other two thrusters. This is interesting because FT2 has a magnetic field polarity that is reversed relative to the other two thrusters. It also has the most peaked beam profile, whereas FT3, which produces the largest roll torque, has the flattest beam profile. The direction of the roll torque produced by FT2 corresponds to the right-hand rule with your thumb pointing in the direction of the ion beam propagation.

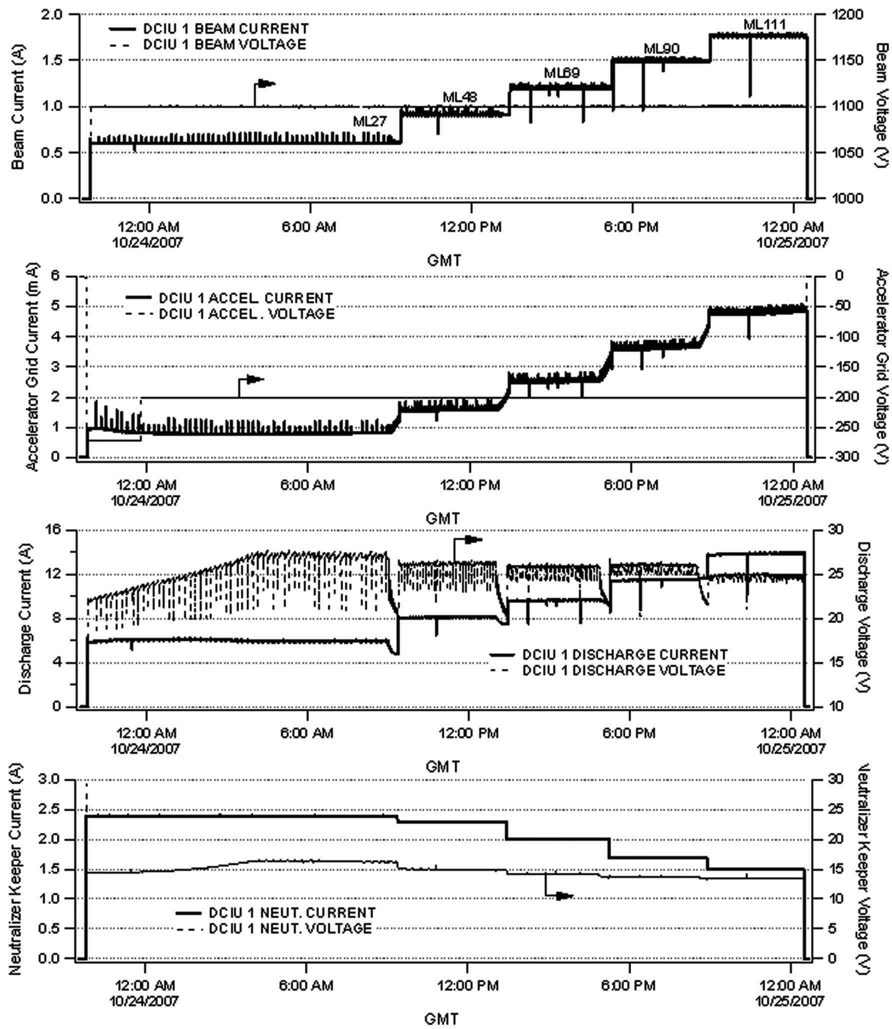

Fig. 4 Electrical parameters from the 28-h-long FT1 characterization test.

Three mechanisms for the production of this roll torque were evaluated during the Dawn IPS development: magnetic field effects, neutralizer misalignment, and grid clocking errors. The magnetic-field-induced roll torque considers the bending of the accelerated ion trajectories by the magnetic field from the discharge chamber that "leaks" through the grids. This mechanism produces roll torques that are in the observed directions for all three thrusters and produces the correct relative magnitudes for the thrusters. However, the absolute magnitudes are about a factor of 10 less than those observed. Angular misalignment of the neutralizer is completely inadequate to produce the observed roll torques for any reasonable misalignments. Grid clocking errors, in which the accelerator grid has a systematic rotation about the grid centerline relative to the screen grid, can in principle produce the observed roll torques for relatively small errors. For example, a systematic clocking error that produces a screen grid to accelerator grid aperture misalignment of 25 μm (0.001 in.) at the outermost radii of holes is sufficient to produce a roll torque of 60 μNm at ML111 for the ion beam profile typical of the NSTAR thruster. However, calculations of the roll torque for each thruster based on careful measurements of the grid clocking errors made during thruster assembly do not agree with the data in Fig. 8. These calculations do not correctly predict the magnitudes or even in some cases the directions of the measured roll torques.

VI. Long-Duration System Test

A long-duration system test (LDST) was performed that was designed to mimic the procedure that was going to be followed during the first 4 years of normal thrusting-cruise operations for the heliocentric transfer to Vesta. During thrusting cruise, the plan is to operate the IPS at full power for approximately a week, then shut down, rotate the spacecraft to point the high-gain antenna at Earth, and downlink the data from that week of thrusting. After completion of the data transmission, the thruster is restarted in diode mode to preheat it while the spacecraft is rotated back to the thrust attitude. Once in the thrust attitude, the thruster is restarted at full power for another week of thrusting.

The LDST mimicked this process by operating FT3 for 167 h, then terminating thrust for 4 h, restarting FT3 in diode mode for 1 h, and then starting FT3 at ML111 and operating there for an additional 4 h. These last 4 h were to simulate the start of the following week's thrusting. The results from the LDST are given in Figs. 9 and 10. The thruster's electrical parameters in Fig. 9 indicate very stable thruster operation over this test. There was a slight increase in the accelerator grid current, which reached a steady-state value of approximately 6 mA. This is believed to be correlated to the slight decrease in the discharge voltage over this time. The neutralizer common voltage (measured as the voltage between neutralizer common and the spacecraft ground) was approximately 2 V over the course of this test. The unregulated 100 V bus input to the PPU during the LDST is given in Fig. 10. The step function change in array voltage at the left-hand side of this figure is the result of the thruster start and the corresponding power draw. The slow increase in bus voltage is the result of the increase in solar range over the week-long LDST. The solar array current shows a corresponding slow decrease as the PPU regulates the current drawn to maintain operation of the thruster at constant power. The step function increase in array voltage at the end of the test is the result of the thruster being shutdown. There were

Table 5 FT1 initial checkout results

Mission level		Beam		Accel.		Discharge			Neutralizer		PPU			Required	
		J_B, A	V_B, V	J_A, mA	V_A, mA	J_D, A	V_D, V	Discharge loss, eV/ion	J_{NK}, A	V_{NK}, A	Input power, W	Efficiency	Dissipated power, W	Main plenum, psia	Cath plenum, psia
27	Expected	0.610	1100	0.50	−200	6.00	27.6	271	2.4	16.5	984	0.907	89	18.19	23.47
	Actual	0.605	1100	0.81	−200	5.84	27.1	262	2.4	16.2	936	0.922	73	18.21	23.51
48	Expected	0.910	1100	2.67	−200	7.88	26.3	228	2.3	15.3	1340	0.920	104	29.86	23.47
	Actual	0.907	1100	1.59	−200	7.79	26.2	225	2.3	14.9	1320	0.936	84	29.87	23.51
69	Expected	1.200	1100	3.87	−200	9.37	25.8	201	2.0	14.7	1713	0.923	132	42.62	23.47
	Actual	1.197	1100	2.53	−200	8.99	25.9	195	2.0	14.2	1685	0.937	107	42.63	23.51
90	Expected	1.490	1100	5.10	−200	11.24	25.7	194	1.7	14.2	2105	0.923	162	53.70	27.27
	Actual	1.487	1100	3.63	−200	11.25	26.0	197	1.7	13.7	2075	0.941	123	53.69	27.30
111	Expected	1.760	1100	6.42	−200	13.94	24.6	195	1.5	13.9	2483	0.924	189	64.19	35.01
	Actual	1.756	1100	4.84	−200	14.00	24.9	199	1.5	13.5	2458	0.936	156	64.21	35.09

Table 6 FT2 initial checkout results

Mission level		Beam		Accel.		Discharge			Neutralizer		PPU			Required	
		J_B, A	V_B, V	J_A, mA	V_A, mA	J_D, A	V_D, V	Discharge loss, eV/ion	J_{NK}, A	V_{NK}, A	Input power, W	Efficiency	Dissipated power, W	Main plenum, psia	Cath plenum, psia
27	Expected	0.610	1100	1.57	−200	5.37	26.6	234	2.4	15.4	938	0.907	87	18.20	24.63
	Actual	0.606	1099	0.86	−200	5.54	26.2	240	2.4	16.5	948	0.898	97	18.41	24.85
48	Expected	0.910	1100	2.74	−200	7.34	25.3	204	2.3	14.5	1327	0.920	106	30.06	24.63
	Actual	0.907	1099	1.63	−200	7.65	25.0	211	2.3	15.1	1341	0.912	118	30.32	24.85
69	Expected	1.200	1100	3.97	−200	8.89	24.8	184	2.0	14.2	1701	0.923	131	43.15	24.63
	Actual	1.197	1099	2.63	−200	9.20	25.0	192	2.0	14.6	1711	0.921	136	43.49	24.85
90	Expected	1.490	1100	5.21	−200	10.70	24.9	179	1.7	13.9	2091	0.923	161	54.56	28.64
	Actual	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
111	Expected	1.760	1100	6.59	−200	13.22	23.9	180	1.5	13.7	2461	0.924	187	65.32	36.78
	Actual	1.756	1098	4.67	−200	13.46	24.2	185	1.5	12.0	2454	0.926	181	65.67	37.09

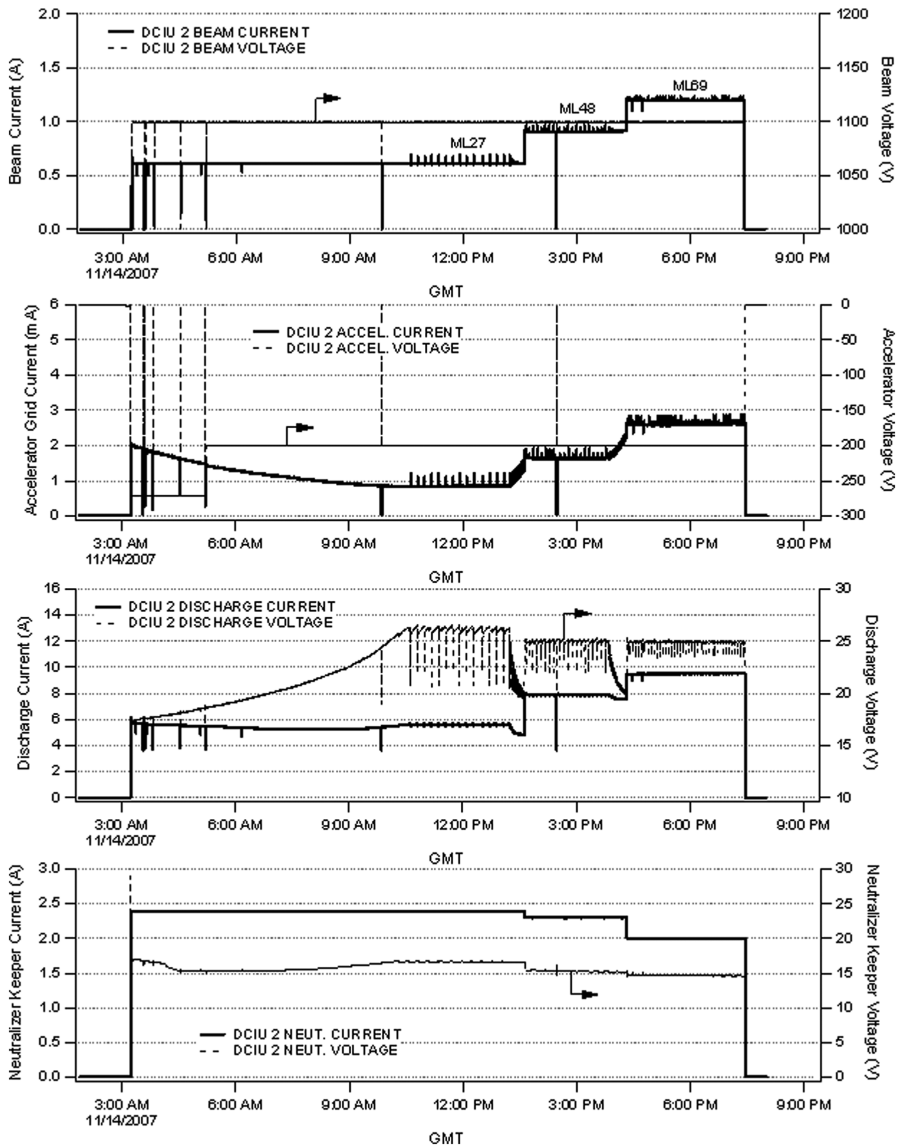

Fig. 5 Electrical parameters from the 18-h-long FT2 characterization test.

very few high-voltage recycles over the LDST. After a higher initial rate, the steady-state high-voltage recycle rate reached an average of approximately 1.5 recycles/day at ML111.

The TGA actuator steps were recorded over the course of the LDST. These data indicate an average duty cycle of 1.3%. Although this is higher than the 1% expected, it is not an issue for the actuator life. The duty cycle was greater than 1% because of planned desaturation events for the RWAs. The RWA desaturations are performed by the hydrazine thrusters in the reaction control system, which dumps the momentum built up due to the roll torque produced by the ion thruster. This produces a disturbance in the spacecraft attitude, which then produces an increase in the TGA step rate. In over 3500 h of subsequent operation with FT3 during normal thrusting cruise, the actuator duty cycle averaged less than 1%.

The internal PPU temperatures, gimbal actuator temperatures, and ion thruster temperatures during the LDST are given in Table 9. The PPU temperatures are measured at four locations inside the PPU: the base plate, the discharge power supply, the beam supply, and the

Table 7 In-flight measured thrust levels compared with preflight expected values

			FT1	FT2	FT3
Throttle level	Input power , W		Thrust, mN	Thrust, mN	Thrust, mN
ML27	940	Expected	31.4 ± 1.37	31.4 ± 1.37	31.4 ± 1.37
		Actual	31.69 ± 0.10	31.63 ± 0.09	31.59 ± 0.02
ML48	1320	Expected	47.1 ± 1.36	47.1 ± 1.37	47.1 ± 1.38
		Actual	47.13 ± 0.13	47.21 ± 0.13	47.04 ± 0.02
ML69	1685	Expected	62.1 ± 1.36	62.1 ± 1.37	62.1 ± 1.38
		Actual	62.06 ± 0.17	62.15 ± 0.18	62.02 ± 0.03
ML90	2075	Expected	76.7 ± 1.45	76.7 ± 1.46	76.7 ± 1.47
		Actual	76.95 ± 0.21	N/A	76.91 ± 0.04
ML111	2460	Expected	91.0 ± 1.65	91.0 ± 1.66	91.0 ± 1.67
		Actual	91.43 ± 0.23	91.72 ± 0.52	91.30 ± 0.07

Table 8 Double-to-single ion currents

	Centerline values	Slice values	Combined total	
Mission level	$J++/J+$	$J++/J+$	$J++/J+$	α
ML111	0.262	0.150 ± 0.018	0.091 ± 0.011	0.976
ML90	0.295	0.182 ± 0.011	0.103 ± 0.013	0.973
ML69	0.245	0.144 ± 0.008	0.077 ± 0.007	0.979
ML48	0.191	0.121 ± 0.011	0.068 ± 0.009	0.981
ML27	0.127	0.090 ± 0.017	0.058 ± 0.017	0.984
ML6	0.060	0.039 ± 0.005	0.022 ± 0.005	0.994

neutralizer supply. The base plate temperature is only about 27 C with the PPU operating at full power. The steady-state gimbal actuator temperatures are only 29 C. The temperatures at the ion thruster-gimbal mounting pads are between 120 and 126 C, and the temperatures on the thruster's front mask are only 88 C.

The main solenoid valve cycle rate measured during the LDST averaged 19.2 cycles/h. This is about 1.7 times the expected cycle rate of 11.1 cycles/h at ML111. Similarly, the cathode solenoid cycle rate was 5.6 cycles/h when the expected rate was 3.4 cycles/h. Subsequent analyses indicated that the expected values did not properly account for the temperature difference between the xenon tank and the solenoid valves. During thrusting, the xenon tank temperature was at least 3 C less than the solenoid valve temperature. During operation of the bang–bang pressure regulation system, the upstream solenoid valve is held open long enough for the pressure in the volume between solenoid valves to equilibrate with the tank pressure. However, because the solenoid valve temperature is greater than the tank temperature, the density of xenon in the volume between the solenoid valves is less than that in the tank. Therefore, calculations based on the tank temperature will underpredict the required solenoid valve cycle rate. Once the temperature difference was accounted for, good agreement with the measured solenoid valve cycle rates was obtained.

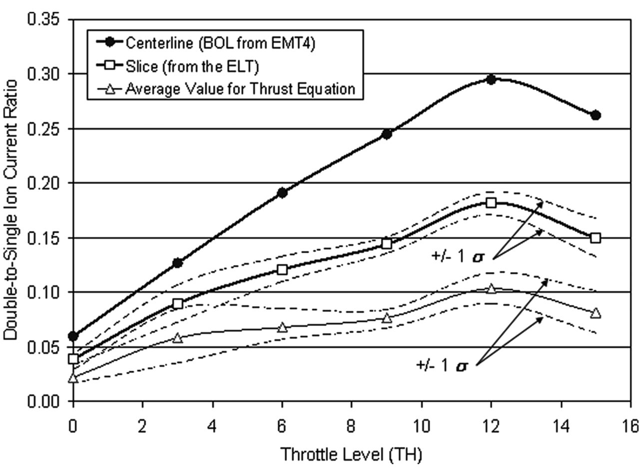

Fig. 6 Double-to-single ion currents vs mission level.

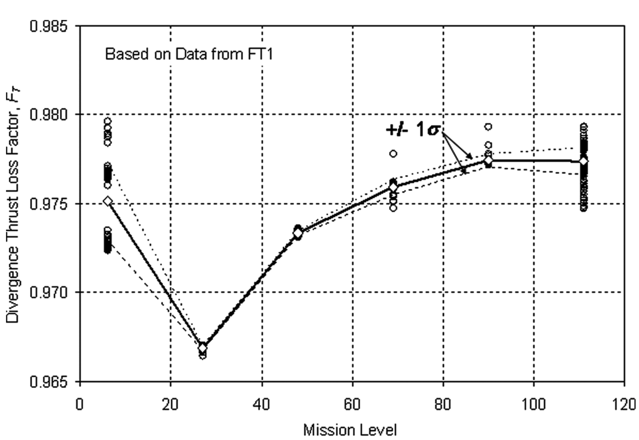

Fig. 7 Measured beam-divergence thrust loss factor from the acceptance test of FT1. The diamond data symbols indicate the average values at each mission level.

VII. Other Interesting Phenomena

The ion propulsion system performed almost exactly as expected during the initial checkout phase of the Dawn mission. Nevertheless, there were some interesting phenomena identified, as discussed next.

A. Accelerator Grid Voltage Change

The first interesting phenomenon is associated with the accelerator grid voltage. When each thruster is started, the accelerator grid voltage is maintained at −275 V for the first 2 h. This is done to assure that no electron backstreaming occurs during the thermal transient as the thruster heats up to its normal operating temperature. This thermal transient causes a temporary decrease in the grid-to-grid gap in the ion accelerator system [14]. After 2 h, the accelerator grid voltage is changed to its normal operating voltage of −200 V, resulting in a reduction in the thrust loss caused by beam divergence. At ML111 this produces a measured increase in the thrust of approximately 0.3 mN. The attitude control system (ACS) senses this change in thrust because it creates a disturbance to the spacecraft attitude. This slight change in thrust must be accounted for by the ACS, which is using the ion thruster for pitch and yaw control of the spacecraft. The ACS is constantly making small adjustments to the thrust-vector location. The step-function change in thrust means the thrust vector is no longer pointing in the correct direction, and the ACS responds with larger-than-normal movements of the thruster gimbal until the disturbance is damped out.

B. Thrust Measurement Sensitivity

The second interesting phenomenon is that when making thrust measurements the radiometric technique [13] is sufficiently sensitive that it can detect a single high-voltage recycle event. Incredibly, this

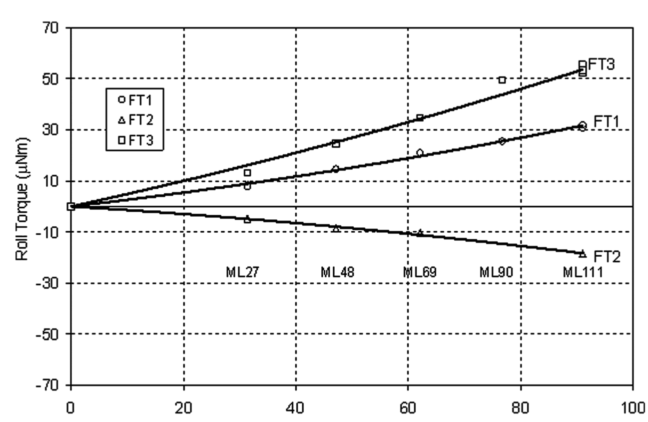

Fig. 8 Measured roll torques produced by the Dawn ion thrusters.

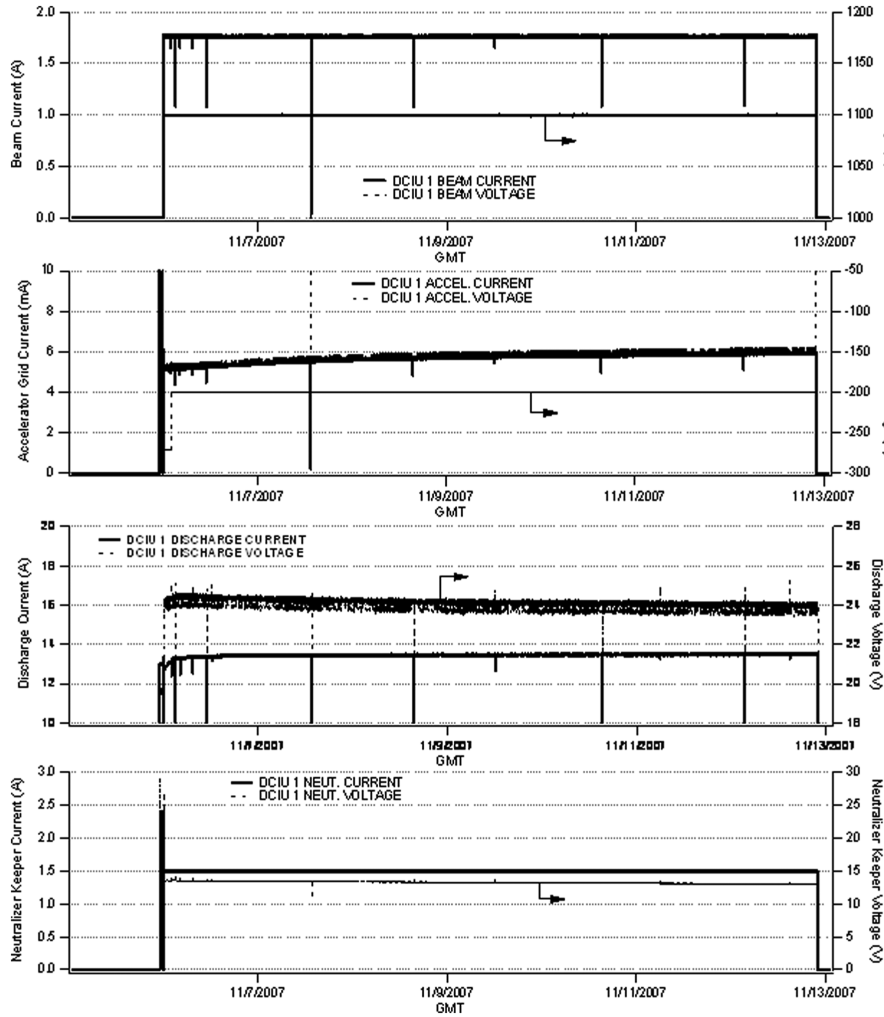

Fig. 9 Electrical parameters from FT3 during the long-duration system test (LDST).

technique can actually make good estimates of the duration of a recycle event (which typically lasts for about 1.5 s).

C. Xenon Tank Temperature

The third interesting phenomenon is associated with the temperature measurements on the xenon tank. There are four temperature sensors located at physically different positions on the exterior of the xenon tank. When the IPS is not thrusting, sensors 1 and 2 typically indicate temperatures that are approximately 1–2 C greater than sensors 3 and 4, but during thrusting this temperature difference disappears as indicated in Fig. 11. This occurs even if no xenon is being drawn from the tank, which was the situation at the start of each thruster characterization test in which each thruster was operated for several hours entirely from the xenon in the plenum tanks. When thrusting stops, the temperature difference is reestablished. This phenomenon is repeatable and occurs every time the IPS is operated. The saw-toothed pattern in the temperatures indicated by sensors 3

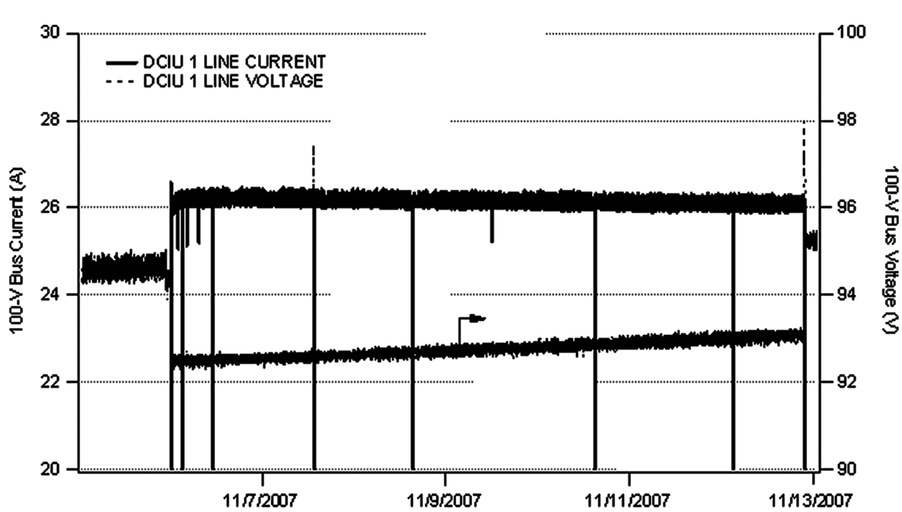

Fig. 10 The 100 V bus voltage over the LDST. The observed increase in the bus voltage is due to the increase in solar range during the week-long test.

Table 9 Selected component temperatures during the LDST

Component	Temperature, C
PPU 1	
Base plate	27.0
Discharge power supply	31.2
Beam power supply	40.7
Neutralizer power supply	36.7
Gimbal actuators for FT3	
1	28.9
2	28.9
Ion thruster (FT3)	
Gimbal pad 1	119.7
Gimbal pad 2	126.0
Front mask 1	87.9
Front mask 2	87.9

and 4 in Fig. 11 result from heater cycling. The period between temperature peaks is approximately 0.5 h.

Another interesting feature is also associated with the xenon tank temperature measurements. In Fig. 11 it was indicated that the temperature peaks about every 30 min due to heater cycling. However, during IPS thrusting not only do the temperature differences between the various temperature sensors decrease, but the period between temperature peaks starts to increase. During the LDST, the IPS was operated long enough for a new steady-state period between temperature peaks to be established. This new period was 11.2 h, more than 22 times longer than the period between peaks when the IPS was not thrusting. The xenon tank temperature data from the LDST are given in Fig. 12, which shows the 11.2 h period between temperature peaks. These peaks are not an issue for the flight system, but the cause for the change in the heater cycle period from 0.5 h when not thrusting to 11.2 h when thrusting is currently unknown.

D. Neutralizer Common Voltage

During an attempt to run thruster FT2 at ML111 for a characterization test on DOY 2008-099, an unexpected shutdown occurred during the diode-mode preheat of the thruster. Telemetry indicated a neutralizer common error was detected by the DCIU flight software (FSW) causing the DCIU to terminate diode-mode operation. A neutralizer common error occurs when the neutralizer common voltage, the voltage between spacecraft ground and the neutralizer cathode, exceeds a preset limit of +40 V.

As described by Goebel and Katz [15], large positive values of the neutralizer common voltage can be caused by an interaction of the plasma created by the thruster and the high-voltage solar array. During thruster operation either in diode mode or normal thrusting, this plasma interacts with the high-voltage solar arrays to drive the spacecraft ground potential negative of the ambient space plasma potential. The external plasma created by the thruster is denser in diode mode because of the lower ion velocities aggravating this effect. This denser plasma can result in the spacecraft ground potential being driven several tens of volts negative of the space plasma potential. The thruster's neutralizer, however, clamps neutralizer common to within ~15 V of the space plasma potential. In the Dawn PPUs, the impedance between neutralizer common and the spacecraft ground is 1.4 mΩ, which is sufficiently large that a voltage difference of greater than 40 V can be established between neutralizer common and the spacecraft ground if the solar array collects an electron current of only 29 μA.

Under these conditions, and as first observed by Brinza on DS1 [16], the current collected by the solar array and, therefore, the neutralizer common voltage is a function of the spacecraft attitude and which thruster is being used. It is also a function of the solar array output voltage. The solar array output voltage increases with solar range, and the maximum neutralizer common voltage measured during the diode-mode preheat follows this increase, as indicated in Fig. 13. In this figure, increasing calendar time corresponds to increasing solar range, causing both the solar array voltage and the maximum neutralizer common voltage to increase. Because this is a normal, and well-understood, behavior of the flight system, subsequent shutdowns due to neutralizer common errors were prevented by changing a parameter in the data tables stored in each DCIU. This change effectively prevents the flight software from checking for neutralizer common errors.

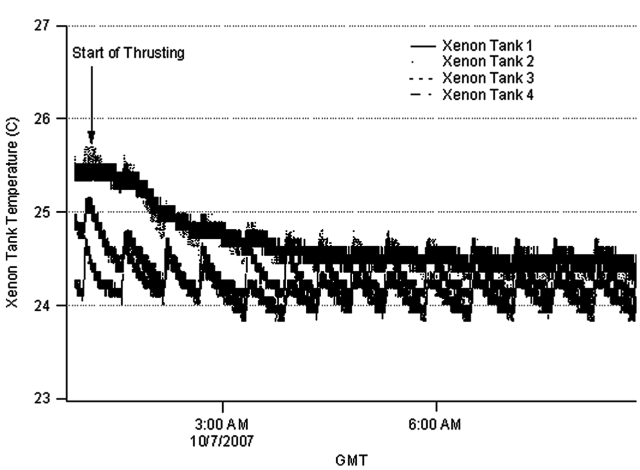

Fig. 11 Xenon tank temperature measurements during the first part of the FT3 characterization test at ML27. No xenon flow from the Xe tank occurred during the time frame shown in this figure (all the xenon flow to run the thruster came from the plenum tanks). The time between temperature peaks for sensor 4 is approximately 0.5 h.

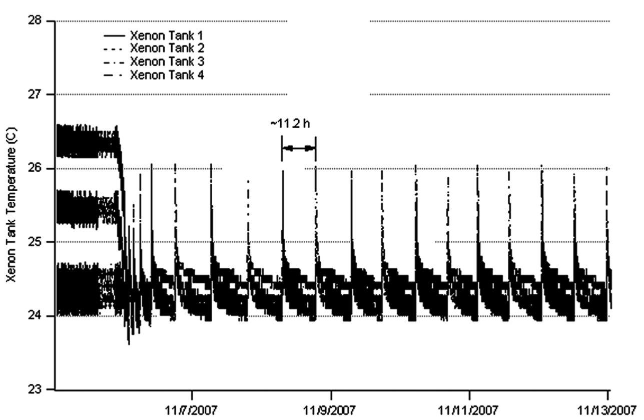

Fig. 12 Xenon tank temperature measurements during the LDST showing the 11.2 h period between temperature peaks.

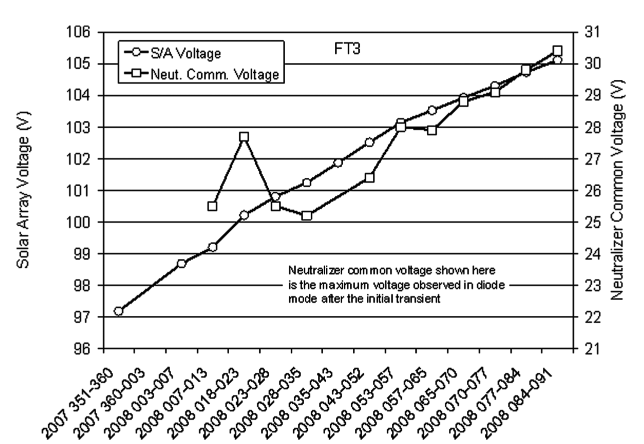

Fig. 13 Maximum observed neutralizer common voltage during diode-mode preheat increases with the solar array voltage.

VIII. Conclusions

Checkout of the ion propulsion system was a principal component of the initial checkout activity of the Dawn spacecraft. This activity took place over the first 80 days after launch on 27 September 2007. The full Dawn mission can be accomplished with just two of three ion thrusters in the IPS. Within 30 days after launch, checkout of two ion thrusters was complete. Checkout of all three thrusters was completed by 30 November 2007, 64 days after launch and after operating the IPS for 285 h and processing 3 kg of xenon.

Measurements of the thrust for each thruster at five throttle levels covering the input power range from 950 to 2480 W indicated that the measured thrusts agree well with the preflight expected values and that there is very little thruster-to-thruster difference. Electrical operating parameters for all three thrusters also agree well with the expected values based preflight acceptance testing performed more than 2 years earlier. These data confirmed that there are three healthy thrusters on the spacecraft. Operation of both PPUs in the IPS was demonstrated over the same power range (950–2480 W). PPU efficiency measurements agree well with preflight values over this throttle range. Internal temperature measurements indicate that the spacecraft's thermal control system does an outstanding job of rejecting the PPU's waste heat at full power as expected.

All three thruster-gimbal assemblies were still in their launch position after launch as expected and all three were fully functional. Operation of each thruster in thrust-vector control mode was successfully demonstrated. The gimbal actuator duty cycle during long-duration operation in thrust-vector control mode was found to be 1.3%. This was a little higher than the expected 1%, but is well within the life capability of the actuators, which were tested to 18 times the required life assuming a 1% duty cycle.

All components of the xenon feed system were in good health after launch and are functioning as expected. The pressures in the xenon tank and in the two plenum tanks indicated that none of the closed latch valves changed states or leaked during launch. In addition, subsequent operation of all thee ion thrusters indicated that none of the latch valves that were launched open changed state during launch. The xenon feed system operated exactly as expected throughout the checkout activities with the exception that the solenoid valve cycle rate was higher than predicted. Subsequent analyses that correctly accounted for the temperature difference between the xenon tank and the solenoid valves agreed well with the measured rates.

At the end of the Dawn spacecraft checkout period, the ion propulsion system had successfully completed all planned test activities and was ready for the start of deterministic thrusting, which began as planned on 17 December 2007.

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