Neutralization of Beam-Emitting Spacecraft by Plasma Injection

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An impulsive plasma injection has been used to study charge neutralization of the Space Shuttle orbiter while it was emitting an electron beam into space. This investigation was performed by Space Experiments with Particle Accelerators on Spacelab-1. A plasma consisting of 10^{19} argon ion-electron pairs was injected into space for 1 ms while an electron beam was also being emitted into space. The electron beam energy and current were as high as 5 keV and 300 mA. While the orbiter potential was positive before the plasma injection and began to decrease during the plasma injection, it was near zero for 6 to 20 ms after the plasma injection. The recovery time to the initial level of charging varied from 10 to 100 ms. In a laboratory test in a large space chamber using the same flight hardware the neutralization time was 8 – 17 ms and the recovery time was 11 – 20 ms. The long duration of the neutralization effect in space can be explained by a model of diffusion of the cold plasma which is produced near the orbiter by charge exchange between the neutral argon atoms and the energetic argon ions during plasma injection.

I. Introduction

ELECTRON beam experiments in space have been carried out extensively since Hess's first experiment[1] in 1969. These experiments promise to increase our knowledge and understanding of the physics of the interactions of beams and plasmas (including those of the ionosphere and magnetosphere). Even prior to Hess's first experiment, one of the major questions was how to inject an electron beam even though the vehicle must charge. Based on theoretical studies by Beard and Johnson,[2] Parker and Murphy,[3] and Linson,[4] beam emission beyond several tens of milliamps from a sounding rocket with a characteristic size of meters should cause charging well above 1 kV. However, after more than 25 electron beam experiments have been carried out in space, the effect of vehicle charging due to electron beam emission (up to 0.8 A) has been found to be not serious as long as the experiment is performed in the lower ionosphere. This is apparently the case because a beam plasma discharge or return current discharge can be ignited easily in this region and the necessary neutralizing current is supplied to the vehicle.[5]

The ignition of a beam plasma discharge is strongly influenced by the environment. If an electron beam is emitted in a region like the distant magnetosphere, ignition of the beam plasma discharge cannot be expected, because the density of both the plasma and the neutral gas is extremely low compared with the lower ionosphere. Electron beam experiments are useful for applications such as remote-sensing of electric and magnetic fields in the geomagnetic cavity and tail. For such experiments, it is very important to know how to effectively neutralize the charged vehicle artificially.

Three methods have been proposed to reduce positive potential of a spacecraft emitting an electron beam: charge collection by using a large conducting area connected to the spacecraft, simultaneous plasma injection, and, simultaneous neutral gas injection. Large collector screens were tested during Hess's experiment[1] and during Echo I.[6] The screens gave the expected results, but using a large current collector is not feasible in the distant magnetosphere. The injection of a plasma or a neutral gas has been considered,[5] and has the added advantage of neutralizing the charge of the beam as well, suppressing beam divergence. These methods have been tested in the series of Echo experiments,[6,7] but direct evidence for effective vehicle neutralization has not been obtained in the experiments.[8]

Space Experiments with Particle Accelerators (SEPAC) was carried out by the Space Shuttle Mission Spacelab-1.[9] Spacelab-1 was launched in November 1983 into orbit at an altitude of 245 km with an inclination of 57 deg. The study of orbiter charging and neutralization was a major goal of the experiment. Charging of the orbiter due to electron beam emission alone was strongly dependent upon the attitude of the orbiter with respect to the velocity vector.[10] One of the SEPAC objectives was to perform an active experiment by simultaneously injecting a high-power electron beam and a high-density plasma into ionosphere. During the 10-day mission, electron beam experiments were conducted four times with beam energy and currents up to 5 keV and 300 mA. During two of the four experiments, the plasma injector was simultaneously operated to neutralize the charged orbiter. This paper presents the results of those neutralization experiments and describes a model which appears consistent with the experimental results.

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II. SEPAC Instrumentation and Experiment

The active SEPAC instruments include an electron beam accelerator (EBA), magneto-plasma-dynamic arcjet (MPD-AJ) and a neutral gas plume injector(NGP). Diagnostic instrumentation includes a monitor TV camera (MTV) and the diagnostic package (DGP). The configuration of these instruments on the Spacelab-1 pallet is shown in Fig. 1. The MPD-AJ injects an argon plasma of 10^{19} ion-electron pairs straight upward with respect to the Spacelab pallet during 1 msec every 15 s. The MPD-AJ plasma accelerator operates by releasing 5×10^{19} atoms of neutral argon gas near the electrodes. Discharge occurs 1.2 ms later, and plasma is injected into space. The electron beam accelerator and plasma injector were located and injection times planned so that the electron beam traveled through the plasma cloud. The diagnostic package consists of a Langmuir probe, floating probes, and electron energy analyzer, a photometer, a vacuum gauge, and plasma wave receivers.

During the Spacelab-1 mission, the two sequences of the neutralization experiment (SEPAC Functional Objectives FO-7-1 and 7-2) were performed consecutively in darkness. FO-7-1 was executed over Midway Islands (longitude: 172.3 to 184.9 deg, latitude: 34.3 to 18.4 deg) from 335d/07h:06m to 07:11 GMT. FO-7-2 was executed over the South Pacific Ocean (longitude: 211.6 to 226.1 deg, latitude: −24.9 to −40.2 deg) from 335/07:24 to 07:29 GMT. The firing sequences of the electron beam accelerator and plasma injector are shown in Fig. 2. The electron beam was operated from 3 kV, 100 mA to 5 kV, 300 mA. The beam was operated for 5 s and the plasma plume was injected at 0.5 s after the start of each electron beam emission.

The configuration of the orbiter with respect to the velocity vector and the magnetic field for these experiments is shown in Fig. 3. Both the beam and the plasma plume were injected toward $-z$ direction. The configuration with respect to the velocity vector is nearly the same for the two experiments. The angle between the magnetic field and the z-axis of the orbiter changed from 34 to 52 deg during FO-7-1, and it changed from 73 to 47 deg during FO-7-2.

III. Experimental Results

Three cylindrical floating probes 25 cm apart from each other were mounted on a pole over the top of the diagnostic package. The top probe was located at 0.7 m out of the shuttle cavity. The surface area of the gold-plated electrodes and the impedances to ground were 50.3 cm^2 and 10 MΩ, respectively.

The potential of the floating probes is measured with respect to orbiter ground and thus was negative during the electron beam operation because the orbiter was charged positively with respect to the plasma. A typical potential variation measured by the top probe is shown in Fig. 4 for the beam of 4.9 kV, 168 mA in FO-7-2. Here, two characteristic times can be defined in the potential of the floating probe. The time period while the potential is zero after the plasma injection is called the neutralization time, t_n. The time required for the potential to return the original level (before the plasma is injected) is called the recovery time, t_r. The measured potential of the floating probe does not measure the orbiter potential exactly, due to its location

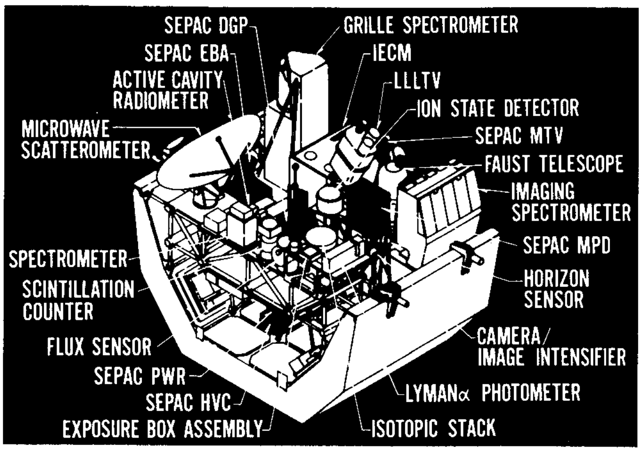

Fig. 1 Configuration of the Spacelab-1 pallet instruments. SEPAC instruments are shaded.

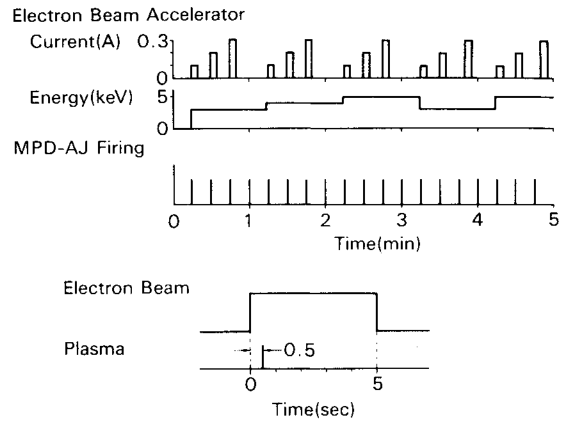

Fig. 2 Firing sequence of the electron beam and plasma in FO-7 with the detailed timing of the EBA and MPD-AJ.

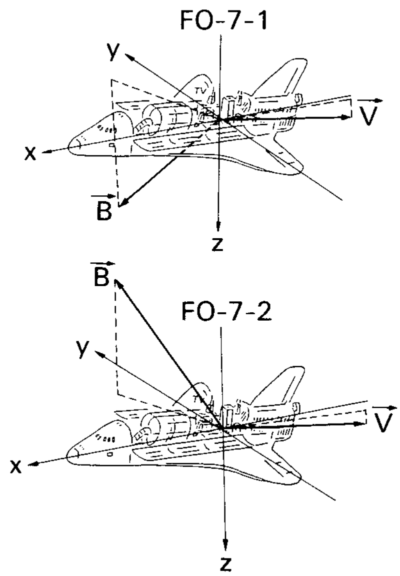

Fig. 3 Configuration of the orbiter with respect to the velocity vector and magnetic field.

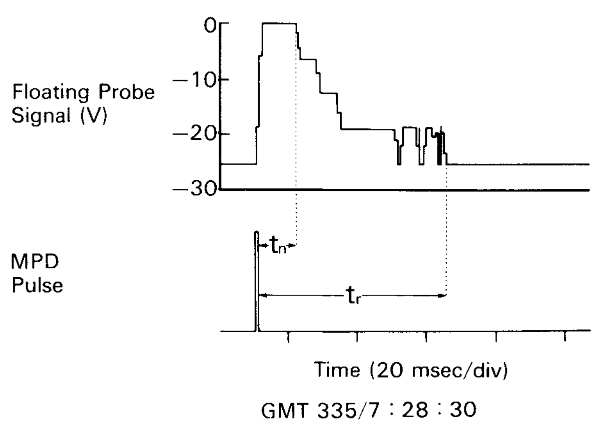

Fig. 4 Typical example of charge neutralization by MPD plasma injection.

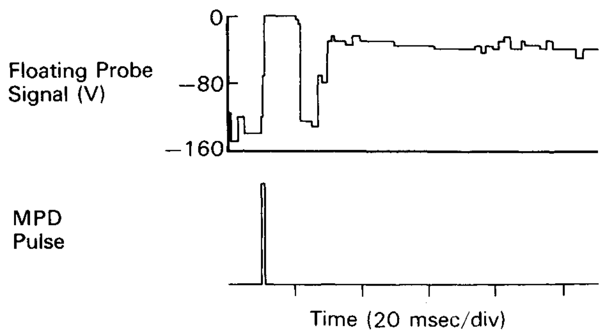

Fig. 5 Example of charge neutralization by MPD plasma injection in a ground laboratory experiment.

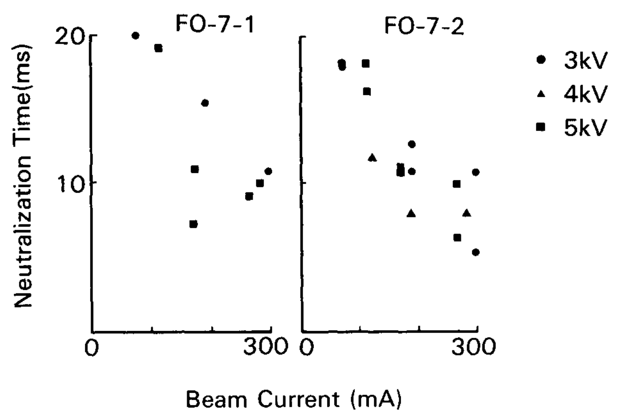

Fig. 6 Dependence of neutralization time on beam current.

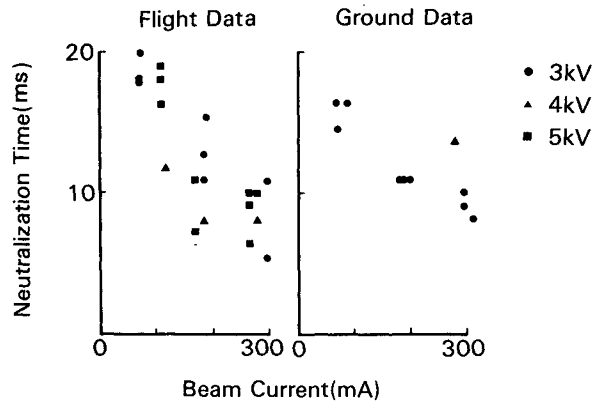

Fig. 7 Comparison of flight and ground neutralization times.

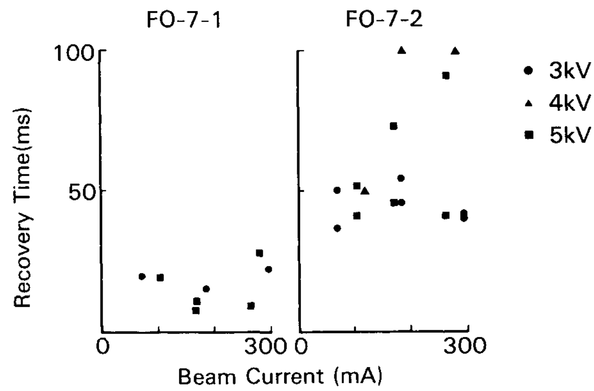

Fig. 8 Dependence of recovery time on beam current.

and low input impedance, but it gives some basic information on the orbiter potential. The orbiter potential before the plasma injection has been estimated to be around +10 V during electron emission for FO−7−1 and to be above +10 V but much less than +1 kV during electron emission for FO−7−2, judging from the data from the Langmuir probe and electron energy analyzer.[10] For the times on SL-1 when the plasma plume was injected during the electron beam operation, the potential of the floating probes became zero for 6−20 ms. The potential returned to the initial level (before the plasma injection) during the next 1−90 ms. The measurements of floating probe show that the positive potential of the orbiter during electron emission was reduced by the plasma injection. When the potential measured by the floating probe is zero, the orbiter potential is thought to be quite close to the ambient space potential.

The ambient plasma density could not be measured during the two experiments because the Langmuir probe was thought to be located inside the plasma sheath at that time. The plasma density measured by the probe exceeded $5\times10^6 cm^{-3}$ when the plasma was injected.

The effect of the plasma injection on the floating probe measurement was quite different from that observed in the ground laboratory test as shown for comparison in Fig. 5. In this case the beam energy and current were 2.9 keV and 200 mA. The ground test was conducted in a space chamber 8 m in diameter and 10 m height, in which the flight hardware was mounted on a simulated pallet and electrically disconnected from the chamber wall. There was no plasma source besides the SEPAC instrumentation. The potential difference between the simulated pallet and the chamber wall was measured and recorded directly with a laboratory voltmeter. In that ground test, the floating probe signal was zero for about 10 ms after the plasma injection as in the space experiment. While the floating probe measured zero potential, the potential difference between the simulated pallet and the chamber wall was also zero. The floating probe signal then returned to its initial level in a few milliseconds. The floating probe signal then approached zero (within about 20 V) due to the effect of the neutral gas which flowed out from the MPD head and was partially ionized by the electron beam providing a return current of electrons. In space, the transition of the probe signal from zero back to the initial level was much slower and there was no effect of the neutral gas evident. Figure 6 shows the dependence of the neutralization time on the beam parameters for the two flight experiments. There appears to be no significant difference in neutralization time between the two FOs. The neutralization time generally decreases as the beam current increases but it does not seem to depend on the beam voltage. The neutralization time measured in the ground test is shown in Fig. 7 for comparison. In the figure, the data from FO−7−1 and FO−7−2 are plotted on the same panel and labeled flight data. The neutralization time is almost the same between the flight and ground data. The dependence of the recovery time on the beam parameters is shown for the flight data in Fig. 8. The recovery time in FO−7−2 is generally longer than that in FO−7−1.

IV. Discussion

The experimental results can be summarized as follows:

1) The neutralization time decreases as the beam current increases and is approximately the same as that observed in the space chamber test. This suggests that the neutralization time is determined by a local plasma effect whose scale is comparable to or less than the scale of the space chamber (~10 m).

2) The recovery time increases weakly, if at all, as the beam current increases. However, recovery times in FO−7−1 and FO−7−2 differed significantly. Moreover, the recovery was much slower in the space experiments than in the space chamber. These two facts suggest that the existence and properties of the ionospheric plasma play an important role in recharging after neutralization.

A. Plasma Production by the Plasma Injection

The plasma injected from the plasma accelerator has an average velocity of 15 – 20 km/s with thermal speed of 5 km/s. Therefore, 10 ms after the injection, the center of the plume is located 150 – 200 m from the orbiter. Since the plasma is collisionless and traveling away from the orbiter, it cannot cause neutralization for more than about 10 ms. Even if the propagating plasma produces additional plasma through a wave-particle interaction such as critical velocity ionization, the secondary plasma cannot flow back to the orbiter along the magnetic field unless the magnetic field and the plasma velocity vector are parallel or antiparallel within 2 to 6 deg (see Fig. 3).

The required neutralization can be explained by production of a secondary plasma created by charge exchange between cold neutral A and the hot A ions, as described below. Of the 5×10^{19} neutral A atoms released by the MPD, approximately 1.5×10^{19} atoms escape the MPD before discharge. They expand hemispherically with an initial speed of 300 m/s out of the 25.4 mm diameter throat of the MPD. The line integrated areal density of the neutral A atoms is thus 1.6×10^{19} m^{-2}. The cross section for charge exchange for A and A^+ is 3×10^{-19} m^2 at the MPD energy.[11] Therefore, essentially all of the neutral A atoms in the interaction cone charge exchange, leaving the region as fast A neutral atoms. A cloud of secondary slow ions and electrons, which must stay with the ions, remain near the orbiter and can play an important role in neutralizing the orbiter.

B. Electron Current to the Orbiter from the Secondary Plasma

The electrons of the secondary plasma produced by charge exchange processes are attracted to the conducting surface of the orbiter to balance the positive charging of the orbiter. More electrons are absorbed than ions, to satisfy charge balance [beam current = e (electron flow – ion flow), where flow is in units of particles/s and e is the charge of an electron]. The excess ions in the secondary plasma accept ionospheric electrons, and as a result, the whole system of the orbiter and the plasma is neutralized. The electron current from the secondary plasma to the orbiter decreases with time. While the electron current to the conducting surface of the orbiter exceeds the beam current, the orbiter is completely neutralized. When the current from the plasma decreases below the beam current, the orbiter charges again.

C. A Quantitative Model of Neutralization

The plasma flux to the conducting surface of the orbiter will be calculated for a simplified configuration illustrated in Figure 9. The following assumptions will be made:

1) The plasma is produced at $t = 0$ in a cylinder with radius, r, and length, L, whose axis is parallel to the magnetic field. The conducting surface is a round plate with radius, a, located at the end of the plasma cylinder.

2) The secondary plasma flows along the magnetic field (parallel to the plasma cylinder) without any particle-particle interactions. The velocity distribution of the plasma diffusion is Maxwellian with root mean square velocity of v_p;

$$f(v_z) = \pi^{-0.5} n_0 v_p^{-1} \exp(-v_z^2/v_p^2) \tag{1}$$

The current density to the conducting surface is

$$j(t) = \int_0^{L/t} e v_z f(v_z)\ dv_z$$

$$= e n_0 v_p (1 - \exp(-(L/t)^2/v_p^2))/2\pi^{0.5} \tag{2}$$

When t is much larger than L/v_p, (2) is approximately

$$j(t) = e n_0 (L/t)^2 / 2\pi^{0.5} v_p \tag{3}$$

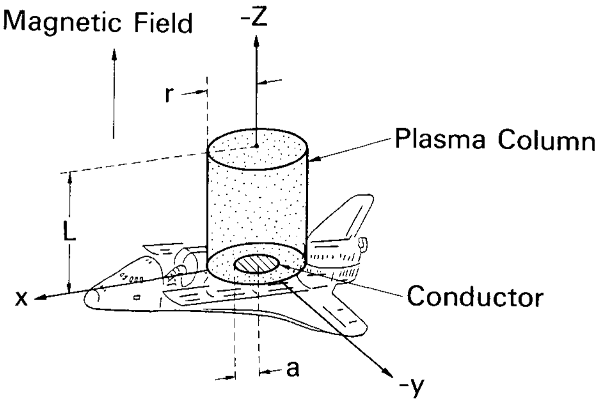

Fig. 9 Simplified configuration for the calculation of plasma flow.

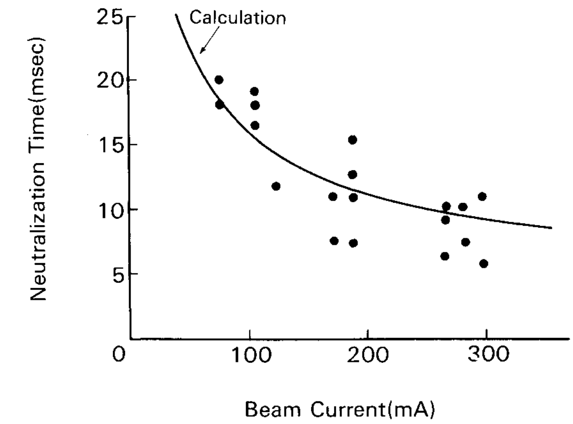

Fig. 10 Model neutralization time compared with flight data.

With the model assumption the neutralization time (t_n) and recovery time (t_r) are $j(t_n) = I_B/\pi a^2$ (I_B = beam current) and $j(t_r) = j_0$ (j_0: electron current density to the conducting surface from the ionospheric plasma), respectively. Using (3),

$$t_n = (\pi^{0.5} n_0 e / 2 v_p I_B)^{0.5} L a \propto I_B^{-0.5} \tag{4}$$

$$t_r = (n_0 e / 2\pi^{0.5} v_p j_0)^{0.5} L \propto j_0^{-0.5} \tag{5}$$

Thus the neutralization time decreases as the beam current increases. Assuming a conductive surface 3 m in radius, an initial plasma plume 5 m in radius and 10 m in length, velocity of plasma diffusion of 5000 m/s (near the velocity for ambipolar diffusion), t_n was calculated and is compared to the experimental results in Fig. 10. The calculated curve agrees quite well with the observation.

The recovery time does not depend on the beam current, but does depend on the electron current provided to the conducting surface of the orbiter from the ionospheric plasma. The recovery time increases as the electron current decreases. There is no direct information on the ambient plasma density and temperature during the two experiments. However, if we use typical ionospheric parameters ($T_e \sim 1000°$ K, $n_e \sim 10^5$/cc), the recovery time calculated from (5) is 30 ms. The electron current to the conducting surface depends on the plasma parameters (density and electron temperature) and the attitude of the orbiter with respect to the magnetic field. The angle between the magnetic field and the z – axis of the orbiter in FO – 7 – 2 is larger (47 – 73 deg) than that in FO – 7 – 1 (34 – 52 deg), as shown in Fig. 3. Since the conducting segments were mostly distributed inside the payload bay, the electron current to the conductors in FO – 7 – 1 would be larger than that in FO – 7 – 2, assuming the plasma parameters were almost the same during the two FOs. This effect may be one factor in the explanation of why the recovery time in FO – 7 – 2 is longer than that in FO – 7 – 1.

In the laboratory experiment, the neutralization occurs by the same process except that the secondary plasma is neutralized by the loss of excess ions at the simulated pallet and excess electrons at the wall. After the neutralization phase, the produced plasma is lost at a rate of the beam current. This situation is entirely different from that of the space experiment in which the produced plasma plume is neutralized by the ionospheric electrons. The recovery time in the laboratory test is expressed as:

$$t_r = t_n + R^2 h / a^2 v_p \tag{6}$$

here, R: chamber radius, h: chamber height.

For $R = 4$ m, $h = 10$ m, $a = 3$ m and $v_p = 5000$ m/s, the time scale of the second term is calculated as 3.5 ms. This time scale is consistent with the observation in the laboratory test.

V. Conclusion

Neutralization of the orbiter by plasma injection has been studied during the Spacelab-1 SEPAC experiments. Neutralization lasted several tens of milseconds after the plasma injection, although the duration of the plasma injection was only 1 ms. The main features of this neutralization have been explained by the existence of a cold secondary plasma near the orbiter which was produced by charge exchange processes between the released neutral gas atoms and injected high-speed plasma ions. This result suggests that the production of plasma that will remain near a vehicle will effectively neutralize it.

Acknowledgments

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