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Space Experiment on Plasma Interaction Caused by High-Voltage Photovoltaic Power Generation

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A High Voltage Solar Array Experiment has been developed for space demonstration and will be operated onboard the Space Flyer Unit. The flight experiment should demonstrate the generation of high-voltage photovoltaic power with a maximum bus voltage of 260 V. In addition, the plasma interactions caused by the high voltage will be investigated during the flight of the satellite in low Earth orbit. Laboratory experiments and numerical simulations predict about 1 mA of ion collection and a maximum arc rate of several arcs per ten seconds during the Experiment.

Nomenclature

e = electric charge
k = Boltzmann constant
L = characteristic length of solar array
M = ion mass
N_e = electron density
N_i = ion density
N_0 = plasma density at background
P = parameter for a scaling law
T_e = electron temperature
U = orbital velocity
V = electrical potential
V_a = absolute value of bias voltage
v = ion velocity
ε = permeability of vacuum
ϕ = electrical potential normalized by ion kinetic energy, $MU^2/2e$

Introduction

HIGH-POWER solar arrays must be driven by high bus voltage and require efficient solar cells mounted on very large panels. The high-voltage photovoltaic power generation reduces not only power losses in the transmission cables but also their weight. However, this power generation requires the development of a new technology for power regulation besides the conventional shunt methods. The control of the high voltage and the environmental interactions proves to be a new technological challenge. At high bias voltages, the spacecraft will interact with the ionospheric plasma.[1] Conventional solar arrays are operated at voltages of 28 or 50 V. Although for the Space Station Freedom high-voltage solar arrays biased at 160 V are planned,[2] such high-voltage power generation has not been tested in the low-Earth-orbit (LEO) environment until now. For the first time the High Voltage Solar Array (HVSA) Experiment[3] will demonstrate high-voltage photovoltaic power generation in LEO. The HVSA Experiment is one of fourteen space experiments on the Space Flyer Unit (SFU),[4] a Japanese reusable free-flying platform, which will be launched by the Japanese H-II rocket in March 1995. For approximately 8 months the SFU will be positioned on an orbit of approximate 500-km altitude and 28-deg inclination, before being retrieved by the Space Shuttle and brought back to Kennedy Space Center. In this paper the design and components of the HVSA Experiment and the laboratory research activities on plasma interactions are presented. The HVSA Experiment will be finished by the time this paper is published.

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Background

If the power efficiency of solar cells is not drastically improved, higher power generation requires a larger solar array area and longer transmission power cables. The consequence is an increase of the power-cable weight and power loss. High bus voltages reduce these problems, but new technologies must be developed to control the high voltage and the plasma interaction.

Control of High Voltage

Controlling the bus voltage of the solar array has two aspects: voltage variation and power regulation. With a high-voltage capability, the voltage on the array can be increased in phases as the array outgasses. The series–parallel connecting circuit in Fig. 1 can be used to change the bus voltage of a high-voltage solar array. The voltage–current curve of the solar array depends on the series–parallel connection of the solar cell modules, which can be changed by switches. When all switches are opened, all solar cell modules are connected in parallel. Closing all three switches results in a full series connection, generating the maximum voltage. An additional configuration of the array connection is possible, with only the center switch open. In this case, a parallel connection of two solar arrays connected in series is obtained. Thus, the series–parallel circuit of the solar array permits selection of the output voltage with constant electrical power.

The series–parallel configuration also can be applied to the power regulation of the solar array. Depending on the configuration of the high-power solar array, several types of power regulation can be used, such as full shunt and partial shunt methods. In the digital sequential shunt method[5] (Fig. 2a), the solar array is divided into several modules, each of which either generates its voltage or is short-circuited in digital manner by a shunt dissipator. The short-circuited module never supplies its power to the bus line, on account of the blocking diode. On–off switching of the modules can regulate the average electrical power of the solar array. Finally, the condenser bank smooths voltage ripples on the bus line. Figure 2b represents the new regulation method, used for the HVSA Experiment: digital sequential open-voltage regulation.[6] The solar array is divided into several modules, which are connected in a series–parallel circuit. When a module is switched to the full parallel connection, it does not supply any electrical power to the bus power line, because it is blocked by back-biased diodes. The power generation by the solar array can be controlled by means of digital sequential switching of the series–parallel connections. Blocked modules are off line. The digital sequential open-voltage regulation method is distinguished from other conventional ones in having modules on or off line.

Plasma Interactions

The space system collects electrons and ions from the surrounding plasma. Since the mobility of the electrons is higher than that of the ions, the solar array will become negatively biased to achieve a zero-net-current condition. Thus, the potential difference between a

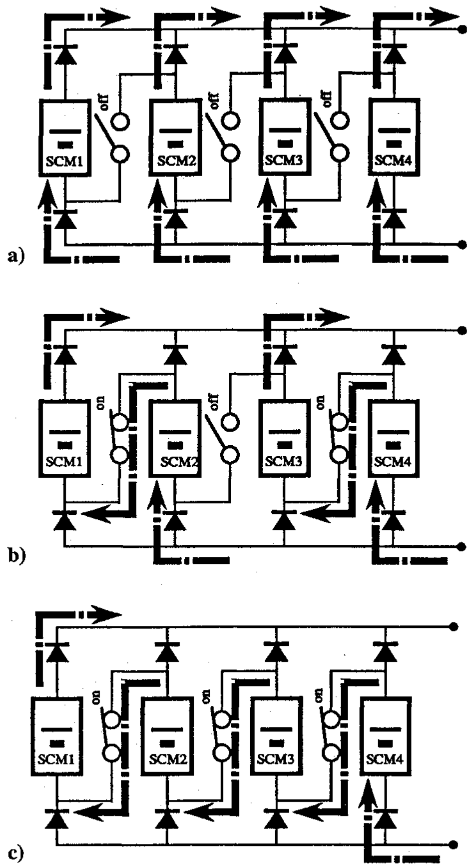


Fig. 1 Series–parallel connecting circuit of the solar array: a) parallel connection, b) two series by two parallel connection, and c) series connection.

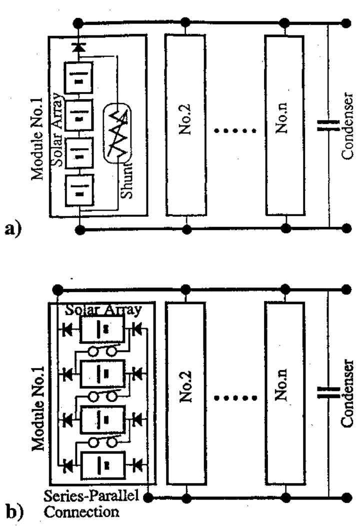


Fig. 2 Power regulation method for space solar array: a) digital sequential shunt regulation and b) digital sequential open-voltage regulation.

space system equipped with a high-voltage solar array, and a docking spacecraft may cause malfunctions. The plasma current also results in power leakage from the high-voltage solar array, and the momentum exchange between the plasma and the spacecraft produces a drag force. Finally, ion impact may erode material through sputtering, and arcing on the solar cells may not only induce electromagnetic interference but also damage the solar cells.

High Voltage Solar Array (HVSA) Experiment

The flight objectives of the HVSA Experiment were defined to be the demonstration of high-voltage photovoltaic power generation in the LEO environment, the verification of the technique of series–parallel circuits for a high-voltage solar array, and the investigation of the ionospheric plasma interactions with the high-voltage solar array.

This experiment will be onboard the SFU,[4] which has eight standardized payload unit boxes, six of which are available for space experiments. The performance of the SFU is summarized in Table 1. The HVSA flight hardware consists of several components: the versatile power control unit (VPCU), the solar cell modules (SCM), and the electron collector (EC). The VPCU is located in one of the payload unit boxes. The SCMs and EC are mounted on the Two-Dimensional Deployable Array[7] (another experiment), a triangular membrane structure with a pair of masts extensible to more than 3.5 m (Fig. 3). Figure 4 shows the ground test to deploy the Two-Dimensional Deployable Array on which four SCMs and the EC are mounted along one of the masts. An SCM consists of 135 silicon solar cells, 2 by 4 cm, connected in series. Four SCMs will be able to generate 80-W maximum power and 260-V maximum bus voltage. Figure 5 indicates the electrical circuit of the HVSA Experiment. The VPCU will change the electrical connection of four SCMs using five series relay (SR) switches on the basis of the series–parallel configuration and dissipate the generated electrical power in the internal load.

Table 1 System performance of SFU

Weight	4000 kg for launch configuration 1000 kg for mission payloads
Dimensions	4.46-m diam × 3.07-m length Modified octagonal modularized structure
Power	Solar array paddle 2.7 kW Total 1.4 kW A pair of flexible solar array paddles 9.7 × 2.4 m
Navigation guidance and control Autonomous navigation system with GPS and IMU Guidance with onboard computer S/W Three-axis stabilized attitude control Control accuracy: position ±100 m velocity ±0.1 m/s pointing ±1 deg	
Communication and data management S band Telemetry data rate 16 kbps Data recorder 80 Mbit Command bit rate 1 kbps	
Reaction control and orbit change Monopropellant hydrazine thruster 3 N ×12; 23 N ×12	
Main structure	Al alloy truss
Bus unit	2 units Machined Al alloy panels
Payload unit	6 units Machined Al alloy panels, honeycomb sandwich panels Exhaust heat 160–360 W for each unit box Thermal louver, heat pipe, and passive thermal control

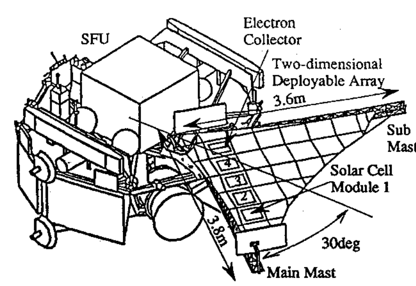


Fig. 3 Configuration of Two-Dimensional Deployable Array with solar cell modules and electron collector on SFU.

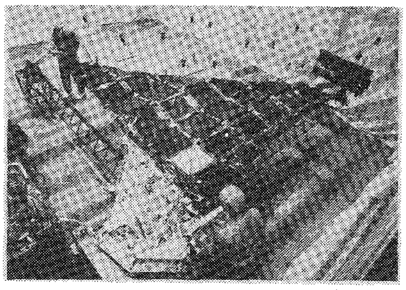


Fig. 4 Deployment test of Two-Dimensional Deployable Array at a qualification test.

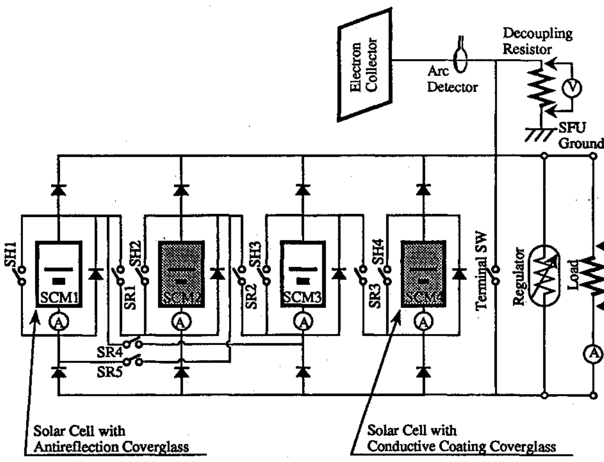


Fig. 5 Electrical circuit of HVSA Experiment.

During the flight experiment, the voltage–current characteristics of the solar array, the plasma leakage current on each SCM, the occurrence of arcing, and the potential difference between the solar array circuit and the SFU ground will be measured. Figure 6 shows the voltage–current characteristics of the solar array measured during the qualification test. The shunt regulator (Fig. 5) stabilizes the output voltage so as to bypass extra current, as seen in the dashed line of Fig. 6. The solar-array circuit of the HVSA Experiment is connected electrically to the ionosphere through the EC, because it is isolated from the SFU by a 100-kΩ resistor. External forces affecting the solar array and enhanced by the high voltage will be detected by the attitude control system of the SFU.

The cover glasses of two solar cell modules are coated with a conventional antireflection coating, and the other two are coated with an indium–tin oxide conductive coating. Conductive-coated cover glasses are generally applied to spacecraft to prevent differential charging at high altitude. The HVSA Experiment will examine the effect of conductive-coated cover glasses on plasma interactions. By closing only the relay switches SR1 to SR3, the solar cell module 1 with antireflection-coated coveralls will have the most negative potential. On the other hand, electrical closing of the relays SR3 to SR5 makes the SCM2 with the conductive-coated coveralls the most negatively biased. Table 2 summarizes the characteristics of the HVSA Experiment. The other experiments on the SFU, the Space Plasma Diagnostic Package and the Space Environment Monitor, have a plasma probe and an impedance probe, etc.[8] The plasma probe will determine the floating potential of the SFU relative to the ionosphere. The impedance probe will monitor the plasma density.

After deploying the Two-Dimensional Deployable Array, the HVSA Experiment will generate high voltages up to 260 V. While in orbit, the deployed array faces the flux of the ionospheric plasma at various angles of attack, on which the magnitude of the plasma interactions will depend. Figure 7 indicates the flight configuration of the SFU with the deployed Two-Dimensional Array and the bus solar arrays. The SCMs will catch the ram flux of the plasma at daybreak and the wake at sunset. It is noted that the HVSA Experiment will generate high-voltage power in the period from ram to wake while in sunlight. At the end of the power generation cycle, the Two-Dimensional Deployable Array will be retracted. A typical experiment cycle of about 10 h consists of deployment, power generation, and array retraction. During the flight operation of the SFU about 10 HVSA Experiment cycles are planned. Beginning with a full parallel connection of the solar arrays, the generated voltage levels will be increased from cycle to cycle.

It is planned to retrieve the Two-Dimensional Deployable Array mounting the SCMs together with SFU. The arrays will be mechanically locked before retrieving. So, for the first time, a postflight examination of a high-voltage solar array exposed to the ionosphere is possible.

Table 2 Major characteristics of HVSA Experiment

Solar cell	2 × 4-cm Si cell Back-surface field and reflection 135 cells/solar cell module 4 solar cell modules
Cover glass	Antireflection coating Conductive coating
Electron collector	Gold-plated aluminum
Electrical output	260 V max, 1.2 A max, 80 W max
Function	Series–parallel connection of 4 solar cell modules Positive grounding to SFU Voltage stabilization Measurement of plasma leak current Detection of arcing

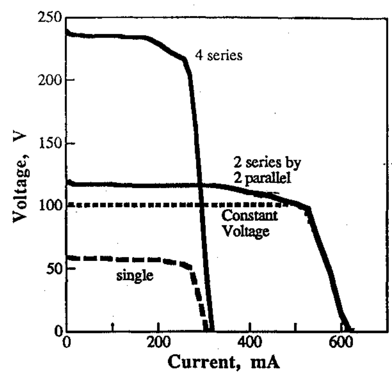


Fig. 6 Voltage–current characteristics of solar array measured by HVSA Experiment at a qualification test.

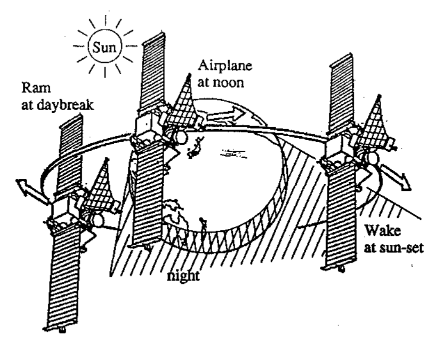


Fig. 7 Flight configuration of SFU for operation of HVSA Experiment.

Ground Research

The large difference in the mobility of ions and electrons causes almost all of the high-voltage solar array area to be negatively biased with respect to the ionospheric plasma and to collect ions rather than electrons. The size of the plasma current is mainly determined by the characteristics of ions. The absolute bias voltage and the ion kinetic energy corresponding to the orbital velocity are much larger than the thermal energy of the ion, creating a charge-limiting sheath around

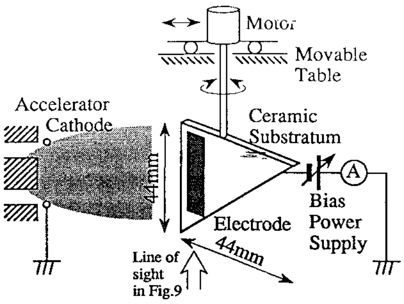


Fig. 8 Laboratory simulation on plasma interaction of HVSA Experiment.

the high-voltage solar array. In order to evaluate the magnitude of the plasma interaction due to the ion collection on the HVSA Experiment, numerical simulation and laboratory experiments on the foregoing model were conducted. The numerical simulation solves the Poisson [Eq. (1)] and the ion kinetic equation [Eq. (2)] in an iterative manner on the basis of the particle-in-cell method[9]:

$$\nabla^2 V = -\frac{e}{\varepsilon}(N_i - N_e) \tag{1}$$

$$M\frac{\mathrm{d}v}{\mathrm{d}t} = -e\nabla V \tag{2}$$

$$N_e = N_0 \exp(eV/kT_e) \tag{3}$$

The electron density is assumed to be determined by the Boltzmann distribution (3). A method to solve Eqs. (1–3) numerically is described in detail in Ref. 9. The calculation utilized a $120 \times 120 \times 50$ cell space and typically tracked 360,000 particles. It took about one hour for the FACOM VPP-500 parallel vector computer to solve each case.

It is not feasible to simulate a full-scale solar array in the laboratory. We can correlate the ion collection of a miniature model in the laboratory with that on the HVSA Experiment in the ionosphere using a scaling law[10] based on a parameter P resembling perveance. Equations (1) and (2) derive the parameter P on the assumption of one-dimensional flow:

$$P = \frac{L^2 e N_0 U}{e V_a^{1.5}} \sqrt{\frac{M}{2e}} \tag{4}$$

A Hall-type accelerator generated an argon plasma stream with a plasma density of 10^9 to 10^{11} cm^{-3}, an electron temperature of 1.5 to 2.5 eV, and a velocity of 13 to 15 km/s in a vacuum chamber. The parameter P was evaluated at 70 when an electrode on a triangular ceramic plate of 44-mm side length was biased at -1 kV in the argon plasma stream of 10^{10}-cm^{-3} plasma density and 14-km/s ion velocity, as seen in Fig. 8. The ionosphere at 500-km-altitude orbit is characterized typically as having a plasma density of 5×10^5 cm^{-3}, an average ion mass number of 16.7, and an orbital velocity of 7.6 km/s. The HVSA Experiment operated at 260 V is estimated to have a P value of 70, where the characteristic length of the triangle array is assumed to be 3.8 m. The laboratory experiment can simulate a uniformly biased solar array with P from unity to infinity, although an exact solar array generally has a potential distribution on its surface. Full information on the experimental method is given in Ref. 10.

Figure 9 shows the charge-limiting sheath observed in the experimental simulation at ram-plasma flux. The line of sight for the observation is also illustrated in Fig. 8. This picture was processed from a video image in order to enhance light and shade. We can see the electrode and a screw head above the substratum and a bracket below it in Fig. 9. In the luminous plasma stream, the biased electrode was surrounded by a dark area, in which electrons expelled by the negative potential never excite the argon particles. The dark area is thought to correspond to the charge-limiting sheath. The numerical simulation indicates that the potential distribution around the conductor facing ram agrees with the experimental data, seen by the dark area in Fig. 9 and the contour at the normalized potential $\phi = 1$ in

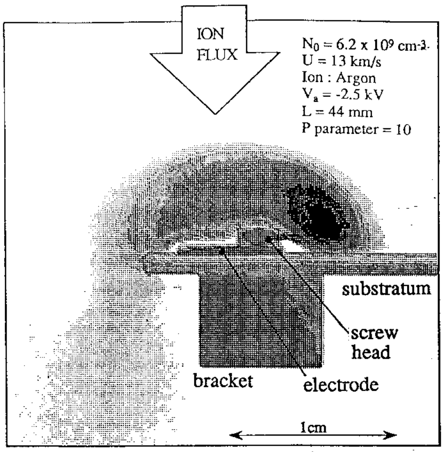


Fig. 9 Image of charge-limiting sheath formed on conductive plate of HVSA model in laboratory.

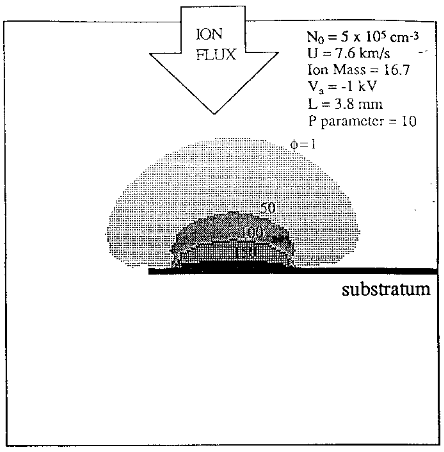


Fig. 10 Calculated equipotential contours around HVSA.

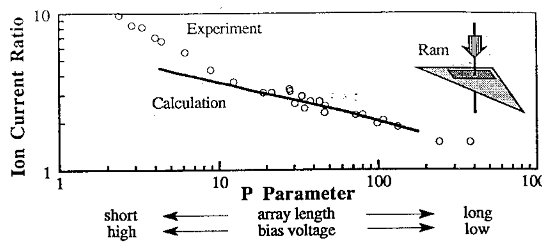
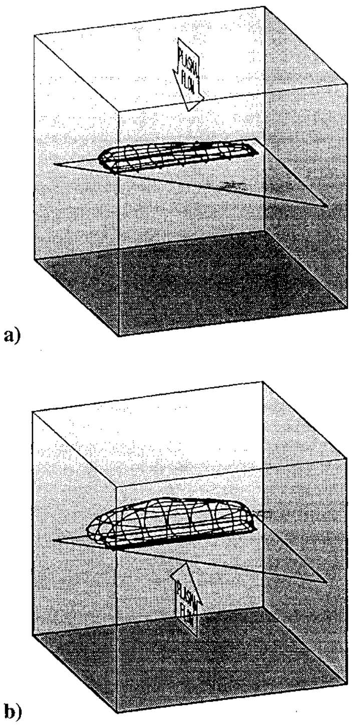


Fig. 11 Collected ion current depending on parameter *P*. Symbols represent experimental data, curve numerical calculations.

Fig. 10. The collected ion current as a function of the parameter P is shown in Fig. 11 at the ram condition. The ion current is normalized by the ram ion current without bias voltage. For a wide range of P, the experimental data lie on a single curve and agree with the numerical result for parameters $P > 10$. The numerical code can predict the magnitude of the plasma interaction of the HVSA Experiment in LEO. Three-dimensional sheath contours are calculated as seen in Fig. 12, where the conductor is biased -260 V at its tip and 0 V at its root in the ionospheric plasma of plasma density 5×10^5 cm^{-3}, ion mass number 16.7, and ion velocity 7.6 km/s. The thickness of the sheath is proportional to the potential at the ram configuration. In the wake, the sheath is thicker than in ram and is controlled by the availability of plasma particles rather than by the potential. The total ion current of the HVSA Experiment is shown in Fig. 13 as a function of the position of SFU around the Earth, which is equivalent to the angle of attack of the plasma flow to the array. The maximum ion current was calculated and found to be 1.3 mA at the ram.

Arcing on solar cells is one of the most serious plasma interactions on high-voltage solar arrays. Arc-free operation of the high-voltage solar array is required for space systems. We conducted a laboratory



a)

b)

Fig. 12 Sheath configuration around HVSA Experiment in numerical simulation: a) ram, and b) wake.

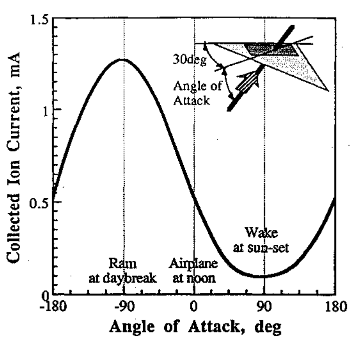


Fig. 13 Ion current depending on SFU circulation around the Earth in numerical simulation.

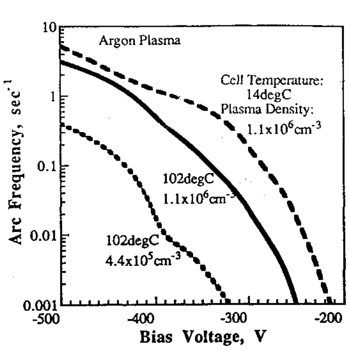


Fig. 14 Dependence of arcing frequency on bias voltage in laboratory simulation.

simulation of the arc using the real flight solar cells. A multipole back-diffusion plasma source generated an argon plasma of 10^5- to 10^6-cm^{-3} plasma density and 0.5- to 1.3-eV plasma temperature, which is equivalent to that in the ionosphere except for ion species. In this plasma, the solar cells were biased negatively to produce arc discharges. The arcing frequency for different plasma densities and cell temperatures is shown as a function of bias voltage in Fig. 14. The theoretical model predicts a maximum arc frequency of several arcs per ten seconds on the HVSA Experiment in the LEO environment.[11]

Conclusions

The HVSA Experiment integrated on the SFU will demonstrate photovoltaic power generation with a maximum 260-V bias voltage using series-connected silicon solar cells in LEO at 500-km altitude. The high voltage will cause ionospheric plasma interactions. The HVSA Experiment will measure the plasma leakage current, potential difference, arcing, and ion drag. If the HVSA Experiment is retrieved and returned successfully, it will provide significant information on the high-voltage solar array and the plasma interactions.

The plasma interactions of a high-voltage solar array were studied numerically and experimentally. The numerical simulations and the laboratory experiments agreed well with each other on the contour of the charge-limiting sheath and the dependence of the ion current upon a scaling parameter. The numerical simulations estimate the maximum leak current 1.3 mA and several arcs per ten seconds on the plasma interaction for the HVSA Experiment in the ionosphere.

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