N87-20073

LABORATORY PLASMA INTERACTIONS EXPERIMENTS - RESULTS AND IMPLICATIONS TO FUTURE SPACE SYSTEMS

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I. INTRODUCTION

Space system plasma interactions have long been recognized as limiting factors in the reliability of space systems. Plasma interactions (PI) not only produce effects that may adversely affect the operation of space systems, (e.g., the occurrence of electrostatic discharges), but may also induce significant modifications in the ambient environment. The PI enhanced environment may in turn modify the interaction processes, compounding the adverse effects.

The reliable prediction of the space system PI processes would require the use of an extremely large and complex computer code. Fortunately, an alternate approach, which combines test/analytical techniques, has proven to be a viable process. In this approach, the important interaction mechanisms are identified by laboratory simulation tests, and the experimental data are then used to analytically predict the effect of PI on space systems. This approach was used on the Galileo electrostatic discharge (ESD) program[1]. Laboratory simulation tests have distinct advantages over that of in situ flight tests. They:

(1) are relatively inexpensive,
(2) offer virtually unlimited operation time, and
(3) provide diagnostic instruments that are generally more complete.

Therefore, laboratory simulation experiments provide more quantitative and detailed data on the PI phenomenon. Inevitably, laboratory simulation results need to be validated by flight experiments. The design of flight experiments will be more precise if a comprehensive data base of laboratory test results is readily available. Therefore, in the PI arena, the role of laboratory simulation testing is crucial.

This paper presents results from several selected laboratory PI experiments. The important physical processes identified by these results and the implications to future space systems are discussed. These experiments are:

(1) ESD - high voltage solar array interaction
(2) ESD - dielectric charging
(3) Spacecraft charging and multibody interaction
(4) Electron beam injection

II. RESULTS FROM SELECTED PLASMA INTERACTION EXPERIMENTS

A. ESD Generated by High-Voltage Solar Array Plasma Interactions

The deployment of high-voltage solar arrays is necessary to satisfy the power requirements of spacecraft of the next century[2]. However, there is a concern that ESD events caused by the interaction of exposed high-voltage surfaces with the plasma environment may interfere with future missions. At the Jet Propulsion Laboratory, experiments were performed to investigate the environmental conditions under which solar arrays will discharge and to characterize the electromagnetic interference (EMI) generated by typical ESD events. Figure 1 shows the experimental setup for this investigation.

Two types of solar cells were used to fabricate the solar arrays used for this investigation, 2 cm by 2 cm "PIX" cells and 5.9 cm by 5.9 cm "VOLT" solar cells.[3] For the same surface area, the PIX array had a much larger area of exposed conductors than the VOLT array. Since discharges usually take place at the exposed conductors, the difference in the exposed surface area accounts for the main difference in the observed discharge phenomenon.

In this series of experiments, the high voltage array was simulated by applying a high negative voltage bias to the metallic interconnects of the arrays. Figure 2 shows the dependence of the discharge rate on the plasma density. This set of data was obtained when the biased high voltage was at a potential of -626 V with respect to the facility ground. At a low plasma density ($<10^4/cm^3$), a discharge may not occur, whereas at a high plasma density ($>10^6/cm^3$), the discharge rate may be as high as 10/sec. Therefore, the operation of high-voltage solar arrays will be less susceptible to discharge at high altitudes (where the density is lower).

As expected, the radio frequency (rf) radiation generated during a discharge event scales with the applied voltage.[3] Figure 3 shows the rf spectrum caused by the discharge of a PIX array when biased at a potential of 1000 V. The same diagram also shows the existing allowable wideband emission specifications on the shuttle.[4]

The rf radiation generated by the discharge of a simulated high voltage array was higher than the allowable specifications. The operation of the shuttle or future space systems may not be affected by this level of rf radiation, but the science measurements and the detection of electromagnetic waves in particular would definitely experience the interference caused by the inadvertent ESD events. Discussions have been held that indicate space station science experiments would require EMI specifications more stringent than those for the shuttle[5]. In view of the data displayed in Figures 2 and 3, it is obvious that high-voltage array ESD needs to be controlled. The recommended methods are:

(1) Operate the high voltage array at a low potential (below the threshold potential) so that ESD cannnot occur.

(2) Cover exposed conductors with an insulator.

B. ESD Generated by Dielectric Material Charging

Many experiments have been performed at various institutions on dielectric charging and discharging.[6,7,8] These experiments have usually focused on:

(1) Enhanced environments,
(2) EMI generation.

Measurements[6] have indicated that during an ESD event, the ambient environment was significantly modified (Figure 4), with resulting increases in:

(1) local plasma density,
(2) EMI level,
(3) optical emission, and
(4) neutral gas pressure.

In a typical discharge, the plasma generated at the discharge region may have a density as high as $10^{11}/cm^3$. Since the typical plasma density in the ionosphere is $10^6/cm^3$ or less, even after taking into account diffusion of the discharge generated plasma, the ambient density 1 meter away from the discharge region may be an order of magnitude higher than the ambient plasma. The discharge rate and the threshold voltage of a high-voltage solar array depend strongly on the ambient plasma density. If an ESD event occurs in the vicinity of a high-voltage solar array, it may cause unexpected arcing of the high-voltage array. Discussions were held that noted an accurate prediction of the natural space environment was needed to enhance the reliability of future space systems.[9] This paper shows that a precise estimate of the ESD-enhanced plasma environment is an absolute necessity to insure the survivability of future space systems.

Results of charging/discharging experiments of common dielectric materials have indicated that the magnitude of ESD-generated EMI will increase with the area of the test sample. That is, the EMI effect could be very severe for large space systems. During a discharge, charges stored on the surface of the dielectric material were released. The collapse of the corresponding image charge induces a current in the structure of the spacecraft. This current became the source of the conducted emission. Figure 5 shows the experimental data on the scaling of this discharge current as a function of the surface area.[6] In this figure, the test level generated by a MIL-STD 1541 sparker[10] (the existing ESD susceptibility test standard for space systems) is indicated by the shaded area. The data show that an improved test technique/fixture is needed for testing large space structures.

C. Charging and Multibody Interaction

For an equipotential spacecraft, charging by itself will not cause the occurrence of ESD events. Only when a potential difference exists between different parts of the spacecraft can ESD occur, as in the case of dielectric charging, or when a potential difference exists between two different spacecraft. In this section, the latter case will be considered. The occurrence of ESD due to the contact of two or more spacecraft at different potentials is also known as multibody interaction. This phenomenon may occur when a free flyer, such as an astronaut and his/her extravehicular activity (EVA) equipment, is subjected to charging by auroral electrons in the wake of a large spacecraft (Figure 6a). Under this condition, the potential of the large spacecraft will be at or near the space potential, whereas the potential of the free flyer will be at a high negative potential with respect to space. When the free flyer comes into contact with the large spacecraft, ESD may occur if the potential difference is sufficiently large. An experiment was performed to investigate this phenomenon. Figure 6 shows the experimental setup. In this experiment, a piece of spacesuit material was irradiated by an electron beam of energy of 15 keV. The resulting surface potential was observed to be 10 kV. When a grounded probe approached this surface, an ESD event occurred before any physical contact was made.[11] Figure 7 shows the transient current pulse detected with a 50 ohm load resistor. The peak voltage was observed to be 50 V. If this signal appeared on the input of a sensitive circuit, significant damage to the IC could occur.

In this experiment the spacesuit material and the probe simulated the free flyer and the large space structure, respectively. The electron beam provided the current source for the charging of the capacitor formed by the free flyer and the large spacecraft. This current helped maintain the potential of the free flyer during its approach to the large spacecraft. Similar conditions may occur if the EVA equipment is accidentally irradiated by particle beams.

In the next century, frequent EVA is expeceted for the servicing space system. The control of the adverse effects generated by multibody interaction is a must to insure the survivability of these space systems. Several techniques may be employed, two of which are:

(1) Impose restrictions onthe docking of freeflyers during the occurrence of an aurora and during beam injection experiments.

(2) Use a plasma neutralizer to reduce the differential charging before docking a free flyer.

D. Injection of Electron Beams into the Ionosphere

Beam injection in space is expected to be more common in the next decade.[12] Several applications will require beam injection. They include active beam injection experiments, communications, and charge neutralization. Although electron beam injection experiments have taken place during the last twenty years, the basic mechanisms of beam plasma/space vehicle interaction are not well understood. Laboratory experiments have been performed to simulate beam injection into the ionosphere. In these experiments, an electron beam was injected into a vacuum region which has a finite neutral pressure, usually in the range of 10^{-5} torr.[13,14] The flow of the beam current depended critically on the ionization of the residual neutral gas pressure. The results of a beam injection experiment performed in a double plasma device indicated that the space charge of the electron current initially created a negative virtual cathode potential well which limited the flow of electrons.[14] This self-consistent potential profile also decelerated the injected electrons, and the resulting electron distribution resembled a half Maxwellian distribution. As the beam current was increased, a double layer (DL) structure was formed (Figures 8 and 9). The formation of this double layer allowed the injected electrons to reappear as beam electrons in the high potential regions. These beam electrons ionized the neutral gas producing a low energy background plasma. The resulting electron distribution was a bump-on-tail distribution function. As the injected beam current density was further increased, the amount of ionization increased to such an extent that the negative virtual cathode type potential well collapsed, and the flow of injected electrons was no longer inhibited by space charge effects. This caused a further increase in the ionization rate, resulting in the ignition of the beam plasma discharge (BPD) phenomenon.

The effects described above were similar to the injection of an electron beam from a spacecraft (Figure 8). In the flight experiment of Winckler et al.[15], at a low current density, the potential of the spacecraft was raised to a high positive potential. This was due to the fact that there was insufficient ambient plasma to provide for the return current. Consequently, the spacecraft potential was raised to a higher voltage to provide a larger collection area for the return current. The Winckler experiment indicated that at a high beam current density, the ambient plasma density increased by more than an order of magnitude. This was attributed to the ignition of BPD. Since the ambient density was high, there was sufficient return current and the spacecraft potential was observed to be approximately near the space potential. Another phenomenon of beam injection in space was the large amplitude fluctuations in the plasma density in the vicinity of the spacecraft. This phenomenon resembles that of the moving double layer (sheath) phenomenon observed in the laboratory.[16]

In a beam injection experiment, electrostatic and electromagnetic turbulence are generated by beam plasma interactions.[14] Depending on the plasma and beam parameters, turbulence at electron plasma, ion acoustics, ion cyclotron, and whistler modes may be generated. The power levels of these beam-generated turbulences depend on the power of the electron beam. Multimegawatt beam injection experiments have been proposed for spacecraft of the next decade. The electromagnetic compatibility (EMC) aspects of these beam injection systems need to be considered in detail for future space systems.

III. SUMMARY

The experimental results discussed in this paper show the significance of the effects caused by spacecraft plasma interactions, in particular the generation of EMI. As the experimental results show, the magnitude of the adverse effects induced by PI will be more significant for spacecraft of the next century. Therefore, research is needed to control possible adverse effects. Several techniques to control the selected PI effects were discussed. Tests, in the form of flight experiments, are needed to validate these proposed ideas.

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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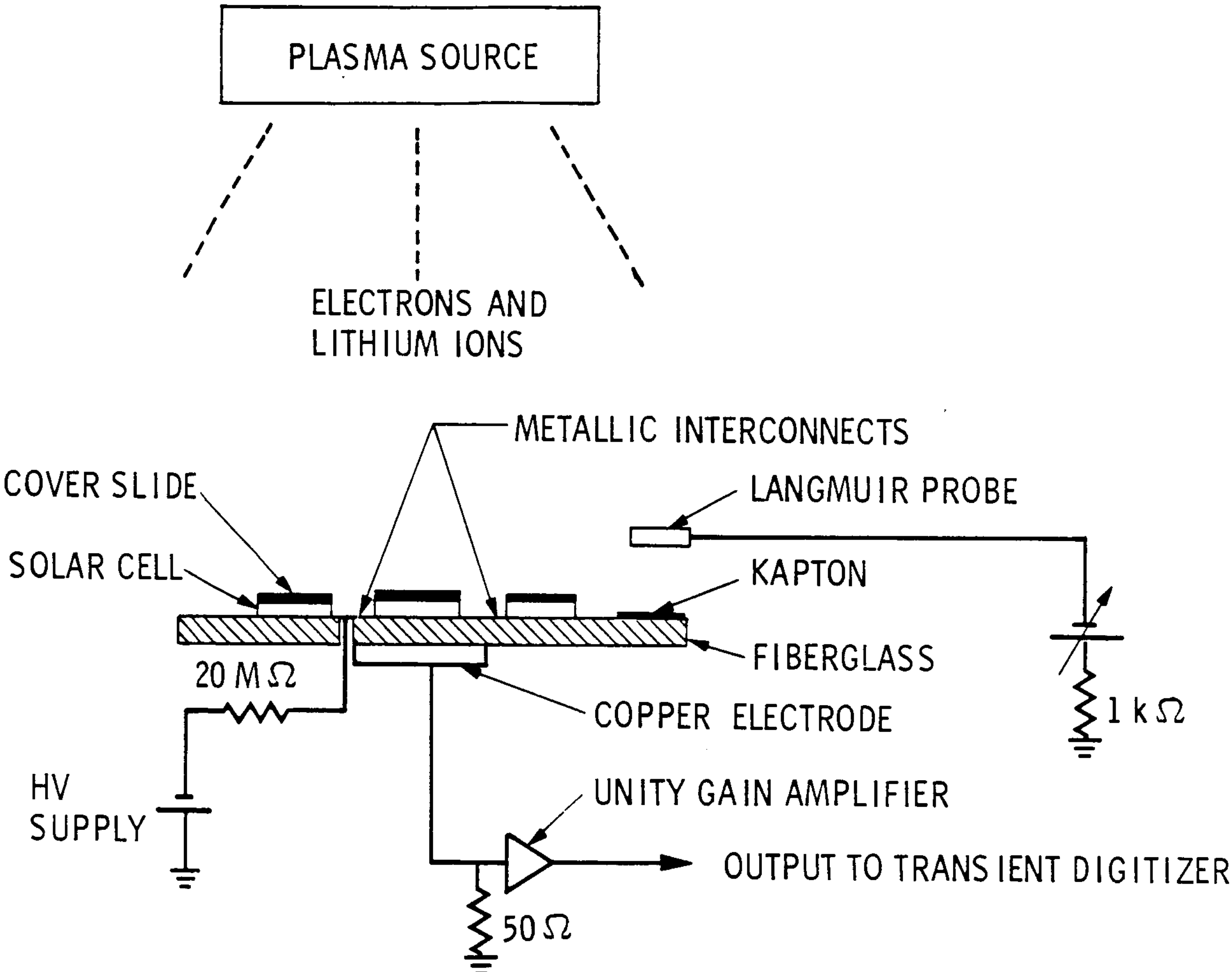

Figure 1. Schematic of the experimental setup for the investigation of high-voltage solar array plasma interaction.

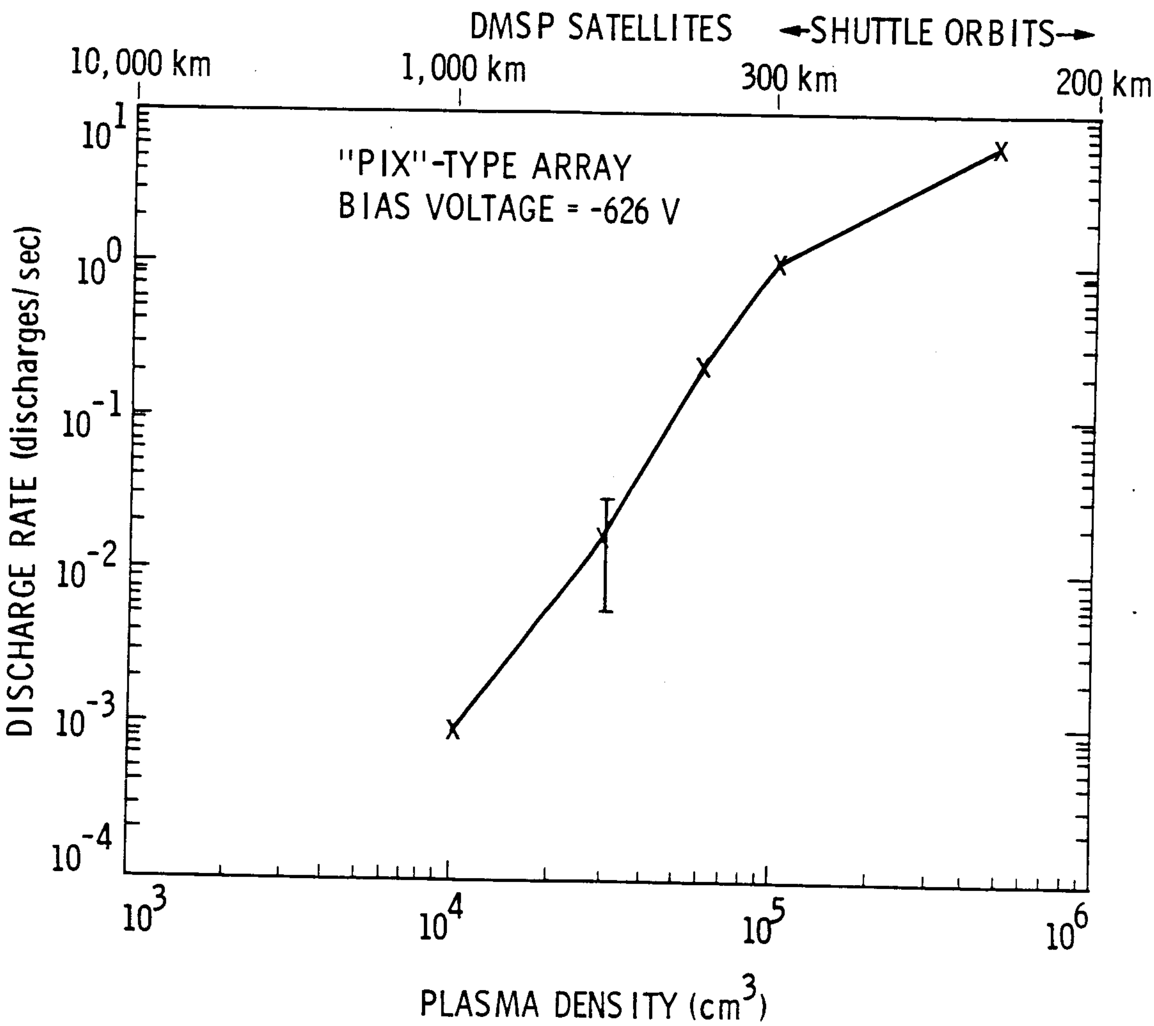

Figure 2. The observed discharge rate as a function of ambient plasma density.

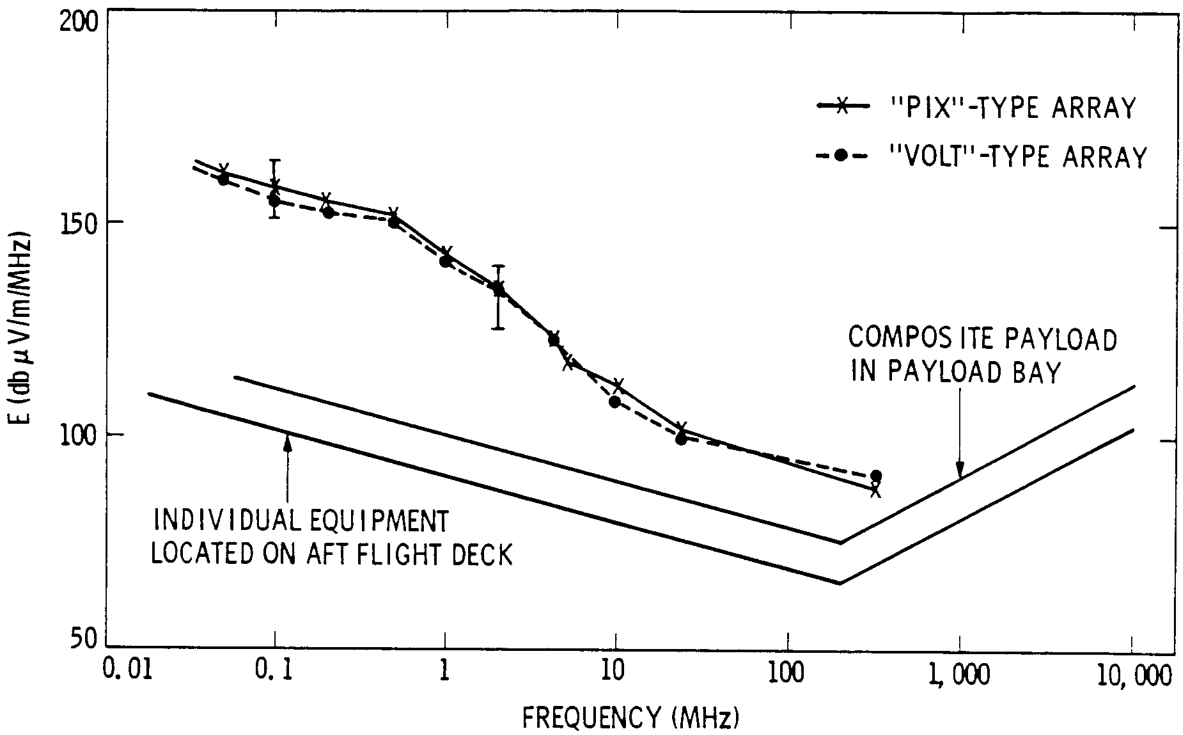

Figure 3. Rf Spectra generated by the discharge of solar arrays, the arrays were biased at 1000 volts.

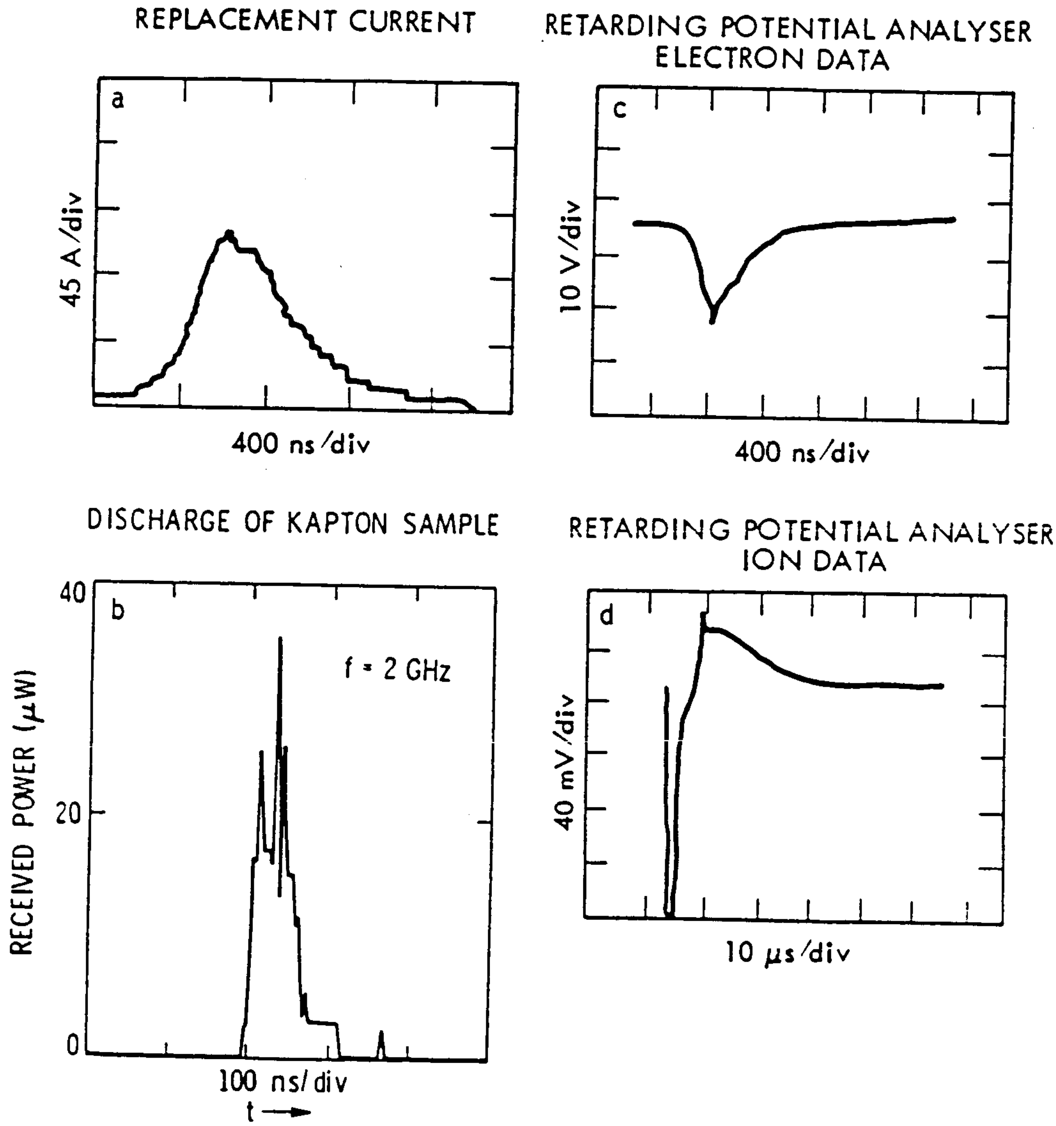

Figure 4. The enhanced environment created by a dielectric discharge. (a) discharge current, (b) rf radiation, (c) electrons, (d) ions

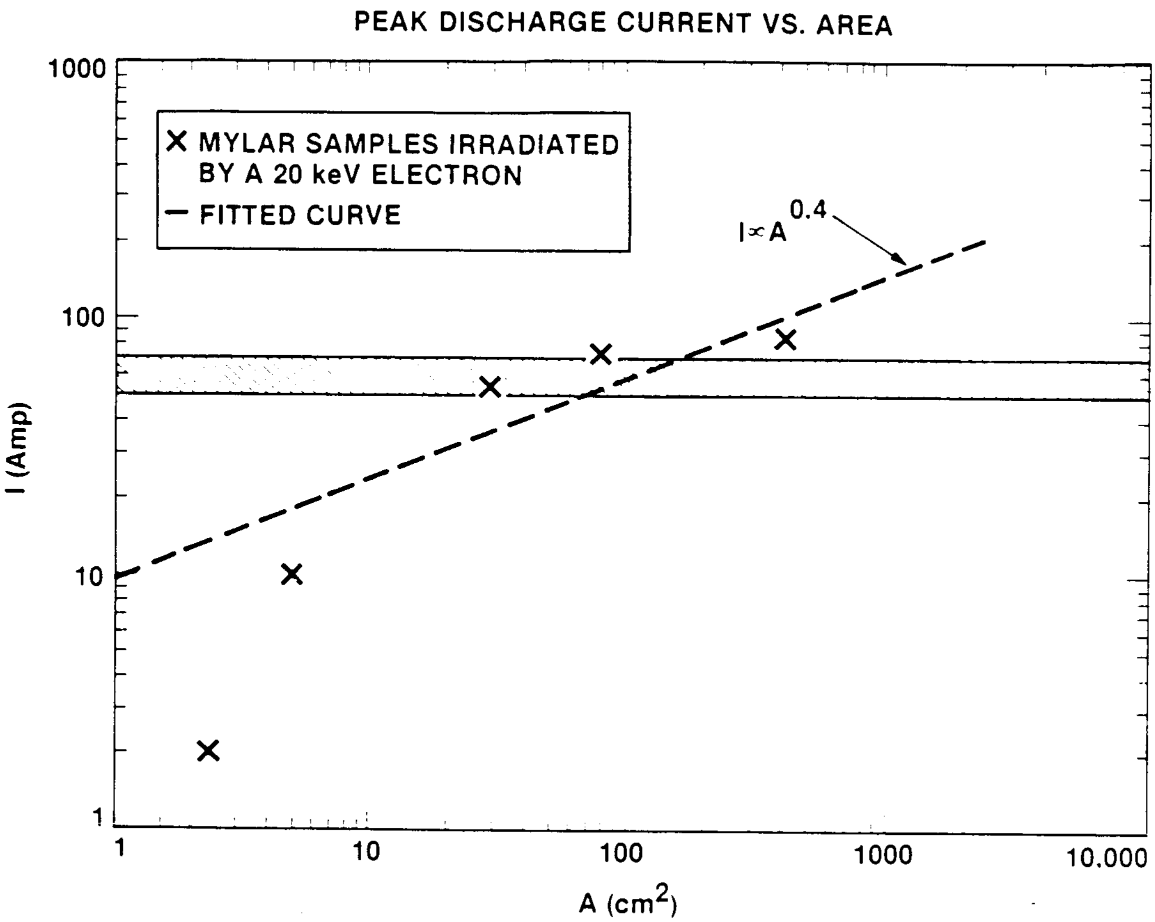

Figure 5. The observed peak discharge current as a function of the area of the Mylar samples

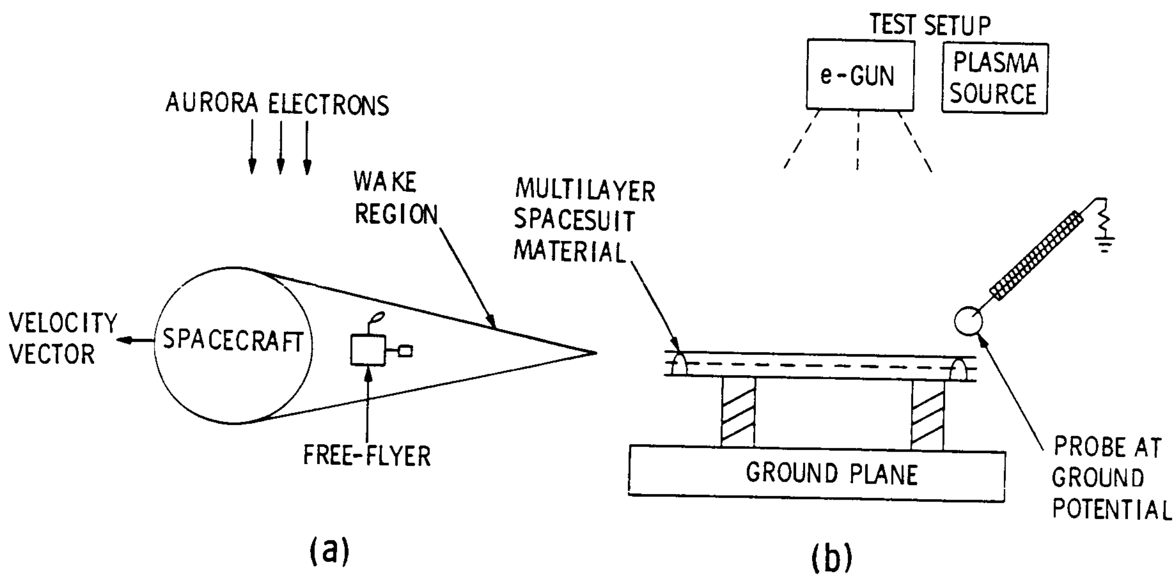

Figure 6(a) Charging of a free-flyer in the wake region of a large space structure
(b) Experimental setup for the investigation of multibody interactions

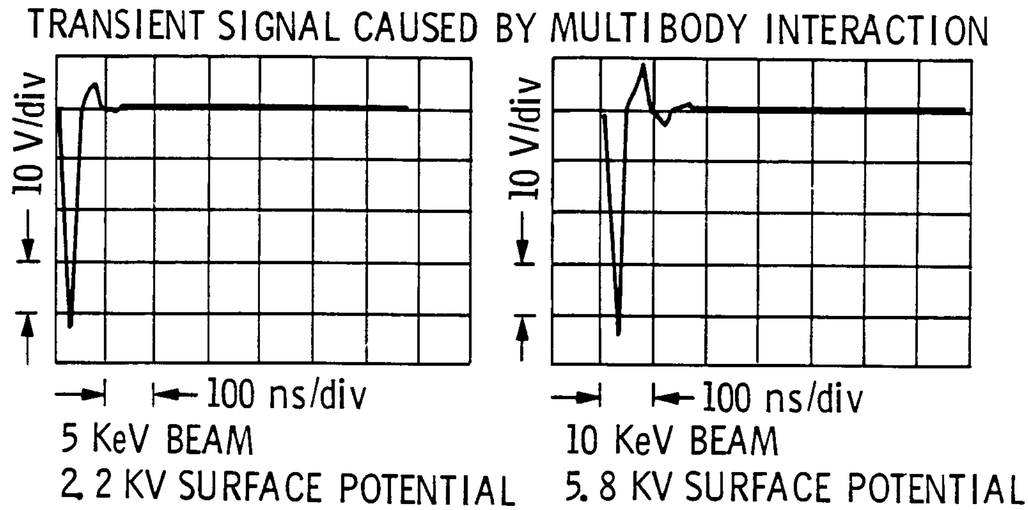

Figure 7. Transient signals generated by ESD events as a result of multibody interaction.

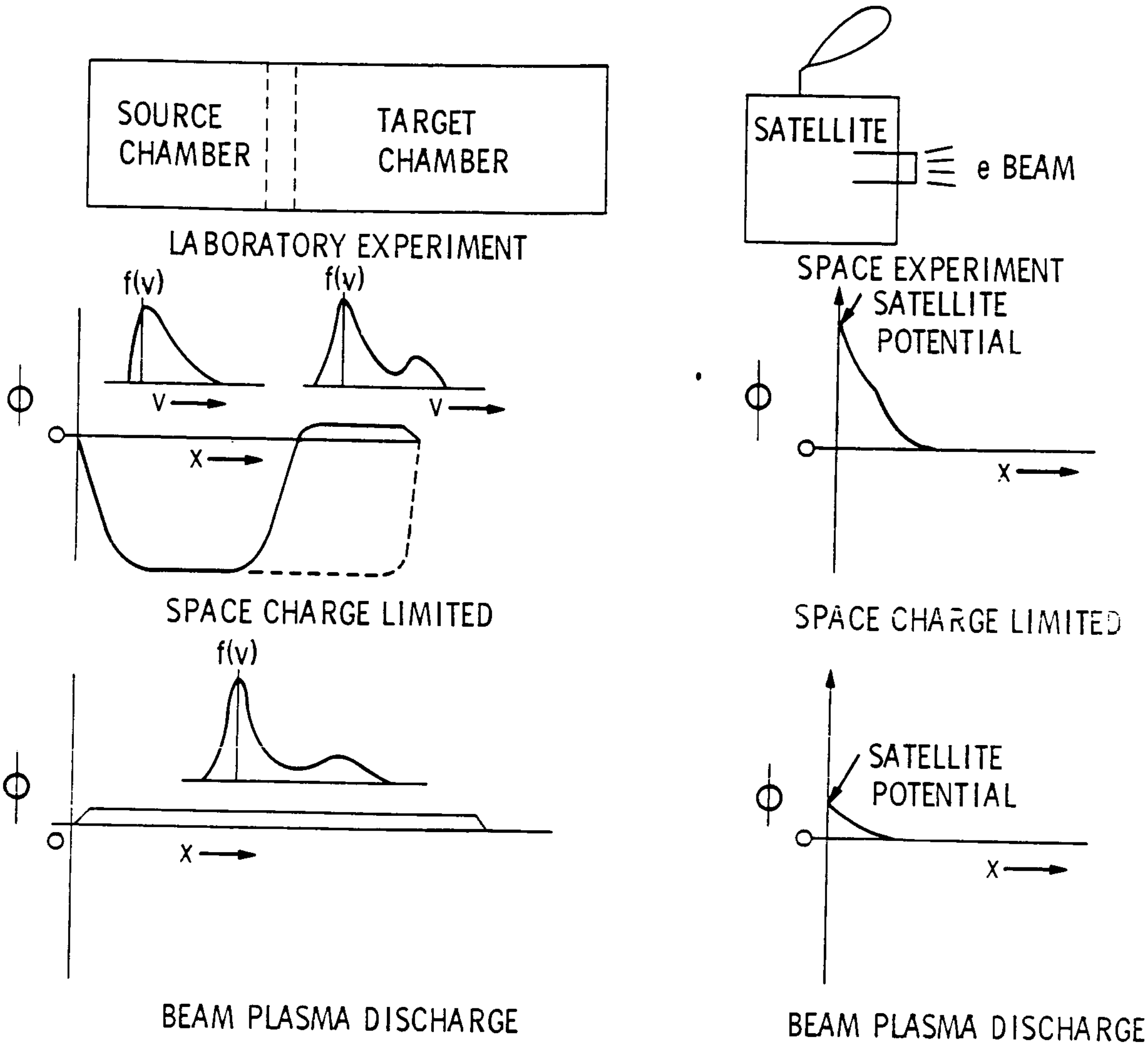

Figure 8. Comparison of Laboratory beam injection experiment with space-based beam injection experiments; the potential profile for each case is plotted. f(v) represents the distribution function of electrons.

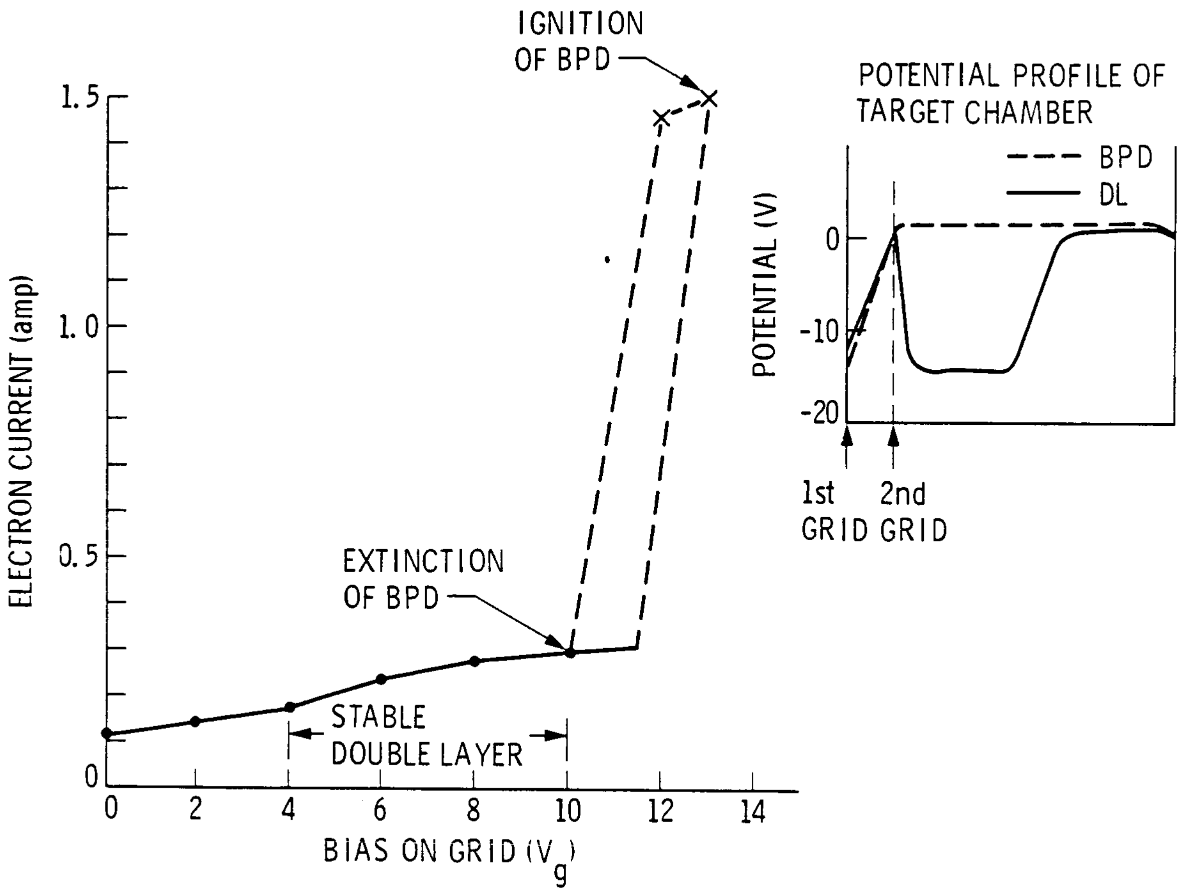

Figure 9. Different regimes of a beam injection experiment.