A Study of Spacecraft Charging due to Exposure to Interplanetary Protons

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Abstract. The interplanetary space environment is composed mostly of low energy (E < 100 keV) plasma from the solar wind and high energy (E> 1 MeV) protons from solar energetic particle events. Satellites orbiting Earth are shielded to some degree from these events by the Earth's magnetic field but spacecraft traveling between planets and space nuclear systems on the lunar or Martian surface are exposed to these solar protons directly. A major concern for spacecraft is bulk dielectric charging, a form of spacecraft charging that can lead to dielectric discharges, a form of internal electrostatic discharge (IESD) that can damage sensitive electronics. The majority of research regarding IESD has been concerned with the electrons in the space environment around the Earth and at Jupiter; little research has been done on the charging of spacecraft in interplanetary space due to solar event protons. This paper provides a review of the literature regarding IESD due to protons and presents the results of recent laboratory experiments. Topics for further research are also suggested.

Keywords: Spacecraft Charging, proton, dielectric discharge, IESD.
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INTRODUCTION

Spacecraft charging remains a current topic of research and a concern for designers of both Earth orbiting and interplanetary vehicles (Garrett, 2002). In Earth orbit, the majority of spacecraft charging results from the collection of energetic electrons on the surface or in the bulk of dielectrics leading to internal electrostatic discharges (IESD) which can damage sensitive electronics used on spacecraft. Many papers have been written on the both types of spacecraft charging in the environments found in Low Earth Orbit (LEO), Polar Earth Orbit (PEO), and Geosynchronous Earth Orbit (GEO) examining the correlation between the radiation environment and failures in satellites due to discharges from the charged dielectrics (Purvis, 1984; Whittelsey, 1999; Frederickson, 1992; Czepiela, 2000; Lai, 1998), but few have covered the topic of charging of spacecraft dielectrics by protons as found in interplanetary space.

The paucity of papers covering this issue is not surprising since most spacecraft flown are Earth satellites, for which the dominating charging environments are the Van Allen trapped particles, not the interplanetary proton environment. The magnetic field around the Earth shield orbiting craft from the full effect of solar protons. The Earth's environment is one where trapped energetic electrons dominate the effects observed on spacecraft in the outer radiation belts while trapped protons dominate in the inner belts. Little correlation between proton flux in Earth's inner belts and spacecraft charging has been found. Satellites designed to correlate spacecraft charging with the space environment, such as the Combined Release and Radiation Effects Satellite (CRRES), did not specifically find discharges linked to proton exposure (Frederickson, 1992).

For spacecraft flown on missions away from the Earth the issue of charging due to protons is more of a concern. The space environment on the Moon, between planets, and at Mars is dominated by the low energy plasma of the solar wind (Haymes, 1971), a small flux of high energy particles from the Galactic Cosmic Rays, and occasional bursts of high energy protons from solar proton events such as associated with Coronal Mass Ejections (CME) or solar flares (Feynman, 1996). While work has been performed studying the effects high energy protons have on the operation of particular devices, little is known about the charging of spacecraft due to protons in these environments.

This paper provides a review of the literature available on the topic of dielectric charging and breakdown generation by proton beams and reviews the worst case prediction of charge required to induce dielectric breakdown. Results from laboratory experiments inducing discharges in dielectrics are presented.

DIELECTRIC CHARGING BY PROTONS

A review of the literature for dielectric charging produced work by only a few authors with the majority of work performed in Russia over the last decade and a half. The work of four key researchers was found to have relevance to the topic of proton charged dielectrics and is detailed below.

Some of the most important results relating proton exposed delectrics with reported discharges were reported by Akishin, et al. in BK-108 and STK-120 optical glass exposed to 100 MeV protons with proton fluences of 10^{13} cm^{-2} (Akishin, 1991a, 1996). Resulting discharges produced both plasmoids ejected from the discharge channel and electromagnetic radiation in the range of 1 to 10 MHz. In both glasses the discharge channel was approximately 100 μm in diameter and about 3 cm in length. Models for the electric fields in the proton exposed materials were presented based on the mobility of electrons created by ionization in the material as energetic protons pass through before coming to rest. Using this argument an equation relating the energy and density of protons required to create a discharge was developed (Akishin, 1991b).

Discharges from proton irradiated Polymethylmetacrylate (PMMA) and Epoxy Resin disks (7 cm in diameter, 5 cm thick) were reported by Khorasanov with proton energies ranging from 10 to 70 MeV and fluences from 10^{12} to 10^{13} cm^{-2} (Khorasanov, 1994). Lichtenberg figures were reported in the PMMA samples accompanied by both a flash of light and an electromagnetic pulse. Similar results were reported for the Epoxy Resin samples, though the fluence required prior to a breakdown in the materials was less than that required for the PMMA due to the higher insulating properties of Epoxy Resin. In both cases, when the energy of the proton beam was decreased below 30 MeV, the probability of a discharge in the dielectric materials decreased.

Gromov exposed sheets of Mylar (polyethylene terephthalate, PETP) and Teflon (PTFE) to 0.23 and 0.8 MeV protons to examine the surface charging and volume distribution of charge at energies typical of the solar wind (Gromov, 1992). Exposure times ranged from 3 to 9 seconds with a beam current density of 10^{-9} A/cm^2 for the 0.8 MeV protons and 6×10^{-8} A/cm^2 for the 0.23 MeV protons giving a maximum fluence of approximately 5×10^{10} cm^{-2}. Measured surface charge was found to increase with time in a non-linear fashion due to radiation and drift leakage.

Boev et al. mathematically modeled the build up of energetic protons in the volume of a plane-parallel dielectric with grounded electrodes on both front and rear surfaces (Boev, 1987, 1991). Electric fields in a dielectric exposed to protons were shown to be dependent on the change in the Radiation Induced Conductivity (RIC) of the material as it is exposed. Experimental results confirmed that the total charge in an exposed dielectric depends on both the energy of the protons incident on the dielectric and the RIC due to incident protons.

CHARGE DENSITY CALCULATION

For most materials the field strength needed for the dielectric material to change from a solid state to plasma is on the order of 10^5 V/cm. Using Gauss's Law in SI units, (1), and the parallel capacitor model as a simple worst case situation we obtain an equation for the electric field within a dielectric, (2).

$$\oint \varepsilon \vec{E} \bullet d\vec{s} = q \tag{1}$$

$$E = \frac{q}{2\varepsilon S} \tag{2}$$

Here $\vec{E}$ is the electric field created by the sheet of deposited protons and $d\vec{s}$ is the differential surface element of this sheet of charge. The relative permittivity of the dielectric times the permittivity of free space is given by the equation $\epsilon = \epsilon_o \epsilon_r$ and q is the charge enclosed within the surface of integration. For the parallel plate capacitor model where there are two sheets of opposing charges the electric field from both sheets of charge combine via vector addition and can expressed as (3).

$$E = \frac{q}{\varepsilon S} \tag{3}$$

$$\rho_s = \frac{q}{S} = \varepsilon E \tag{4}$$

The surface charge density, ρ_s, required to produce an electric field of sufficient strength to cause dielectric breakdown is thus given in (4) and is equal to approximately $5\epsilon_r \times 10^{10}$ cm^{-2}. For a worst case evaluation, let ϵ_r=1 so that $\epsilon = \epsilon_o$ and the required density of protons is $\rho_s = 5\times10^{10}$ cm^{-2}.

While the above calculation provides a minimum case fluence before a dielectric breakdown may occur, the above model assumes a single layer of charge at a set distance from a grounded electrode. This situation can be created in a laboratory environment using monoenergetic beams, but is unrealistic in interplanetary space since the sun emits protons with a full spectrum of energies from 1 keV to hundreds of MeV. Protons with varying energies will produce a multitude of layers of charge in spacecraft dielectrics with different charge densities depending on fluence of protons per energy on that particular dielectric surface.

As discussed by Boev and Akishin another factor in determining the possibility of dielectric breakdowns involves both the intrinsic dark conductivity of the dielectric and radiation induced conductivity (RIC). The dark conductivity for electron exposed dielectric materials has been found in recent laboratory experiments to generally be in the range of 10^{-19} to 10^{-21} Ω^{-1}cm^{-1} (Frederickson, 2003a, 2003b; Green, 2005) but it is not experimentally known if these conductivity values hold true for protons which may conduct at different rates due to their larger mass and decreased mobility in typical dielectric materials. Likewise, the RIC caused by ionization of the dielectric as energetic particles pass through the material (Yang, 1992) is not known for proton exposed dielectrics. Presumably the energy and intensity of the incident protons will greatly affect the RIC component of the total conductivity with greater energies increasing the conductivity and reducing the ability of the dielectric to store charge. Determining the conductivity of a dielectric after exposure to energetic protons is a topic for further study.

SOLAR EVENT PROTON ENVIRONMENT

The most important source for interplanetary protons is the protons from solar energetic particle (SEP) events (Coronal Mass Ejectrions (CMEs) are the major source of these events). Due to the varying energies and fluxes of the SEP protons, dielectrics on spacecraft exposed to particles from these events will contain charged particles at varying depths inside the material leading varying charge densities throughout the bulk of the dielectric. In addition, the flow of protons is not constant but is highly time dependent.

The spectrum and fluences of particles in interplanetary space due to SEPs were modeled by Feynman using the fluence of interplanetary protons between 1963 and 1998 (Feynman 1993, 2002). The resulting JPL proton fluence model for solar event protons includes plots for the distribution of individual solar event fluences for protons in several energy ranges. From these distribution curves the probability of fluences of 10^{10} cm^{-2} from a single CME can be seen to decrease as the energy of the protons increases. Only the largest solar events have had proton fluences in the 10^{10} cm^{-2} range and these protons generally have had energies of less than 30 MeV. The model shows worst case fluences are common for protons with energies near 1 MeV, but as the energy of the particles increases, the fluences drop so that only the very largest solar events will produce enough protons with energies of 10 MeV or more to cause dielectric breakdown. The tables of the fluences for the top ten solar proton events in the time period covered in the JPL proton fluence model supports this conclusion.

EXPERIMENTAL RESULTS

With the above in mind, nine typical spacecraft dielectrics were selected and exposed to a beam of energetic protons to produce dielectric discharge pulses. Beam characteristics were limited to those that might be found in a large CME if encountered on the Moon, Mars, or in interplanetary space. All experiments were performed at the Crocker Nuclear Laboratory Cyclotron at the University of California, Davis on 10-11 March, 2005.

Sample dielectrics were chosen from those that could be expected to be exposed to the SEP protons: dielectrics from those used for wire insulation, potting compounds, and circuit board materials. In particular, four types of

Teflon: polytetrafluoroethylene (PTFE), fluorinated ethylene propylene (FEP), perfluoroalkoxy (PFA), and ethylene tetrafluoroethylene (ETFE), also known as Tefzel, were chosen as wire insulation materials. Potting compound materials chosen were Conathane EN-11, Uralane 5750A/B, Solithane 113, and silicon based CV2510. The circuit board material selected was Kapton polyimide with the typical green solder mask coating of Probimer 52 applied. Sample sizes were 5×5 cm with thicknesses ranging from 1.5 mm to 3.6 mm. A copper electrode was mounted to the rear of all samples for both sample mounting and discharge pulse measurement.

Each sample was exposed to the proton beam individually for times ranging from 20 minutes to two hours while being held at a vacuum of $\sim 5\times10^{-5}$ torr. During exposure, the rear electrode of the sample was monitored with an oscilloscope for the rapid movement of image charge away from the rear of the sample mirroring the movement of charge from the sample due to a dielectric discharge. Figure 1 shows a simplified version of the experimental setup including a plume of plasma spreading into the chamber from a dielectric discharge. With the movement of the ionized gas into the chamber, some negative charge within the plasma cloud will be attracted down to the positively charged surface leaving mostly positively charged ions and some of the implanted protons to spread out and toward the more negatively charged walls of the vacuum chamber. With the departure of positive charge, negative image charge will return to ground to rebalance electric fields in the sample electrode. Image charge flowing through the terminating resistor of the oscilloscope will produce a measurable voltage spike in direct relation to the image current spike and the discharge of current from the sample. For a proton charged samples, the spike seen on an oscilloscope will be negatively traveling since negative charge is moving from the sample to ground.

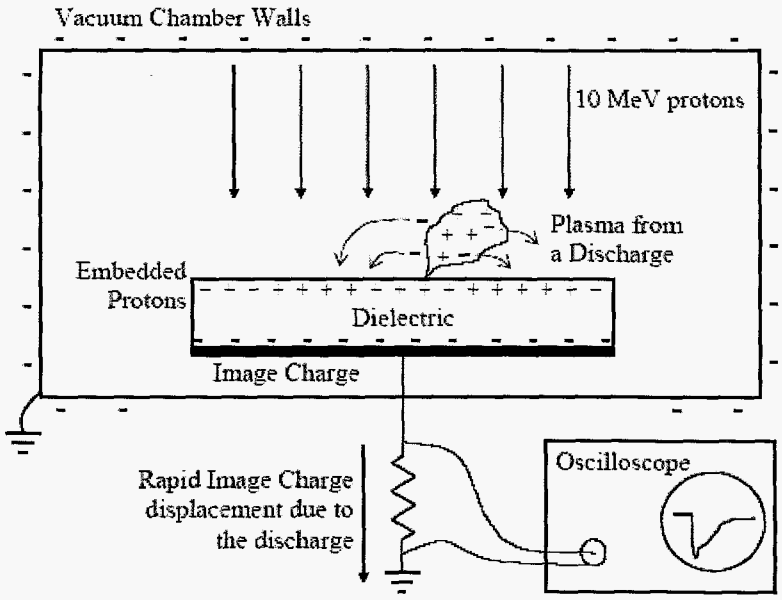

FIGURE 1. Experimental setup for the proton exposure dielectric discharge testing. An insulator with a rear electrode is placed in a vacuum chamber and exposed to high energy protons. The protons become imbedded in the sample material creating a field within the dielectric material. Opposing charges come up from ground to the rear electrode and the chamber walls to balance the generated electric field from the imbedded protons. When the local field strength exceeds the breakdown strength of the sample dielectric material, a discharge is created and ionized gas is emitted into the chamber as a plasma. Negative charges in the plasma will be attracted to the positively charged sample surface while the protons and positive ions will continue to move toward the more negatively biased grounded surfaces. Image charge will flow back to ground at the same rate as the plasma plume producing a spike through the terminating resistor of a 50-ohm oscilloscope equal to loss of charge from the sample during the discharge.

Discharges of this nature were seen during the 10 MeV proton exposures, but only for the Kapton Polyimide PCB sample. Figure 2 depicts one of these discharge pulses as the lower pulse shape. The upper pulse displayed in the figure is a pulse from the same material when exposed to 60 keV electrons. Note that while the shape of the pulses is almost identical, the magnitude of the electron induced pulse is two orders of magnitude greater than that from proton bombardment. Discharges were also observed from the Uralane and Conathane samples, but they were several orders of magnitude less than those from thee Kapton Polyimide samples and of the opposite polarity. In all cases, the fluence required to produce even these small discharges was on the order of $\sim 3\times10^{12}$ cm^{-2} or higher which

is much higher than theoretical worst case, and approaching the 10^{13} cm^{-2} reported by the Russian researchers. Most surprisingly, no sample from the Teflon family gave evidence of any dielectric discharges. At the outset of the test, it was thought that the Teflon materials would produce the most pulses since these dielectrics are considered very good insulators (Green, 2005) and previous testing with electron bombardment has produced frequent large dielectric discharges.

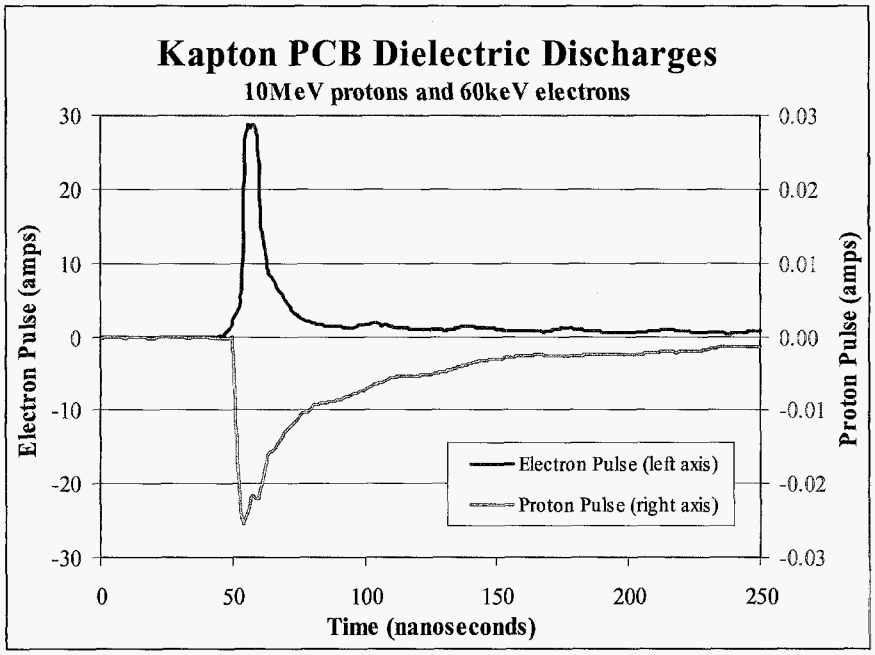

FIGURE 2. Electrical discharge signatures from Kapton Polyimde samples bombarded by protons and electrons. The upper trace (blue) resulted from bombardment by 60 keV electrons while the lower trace (red) from 10 MeV protons. Note that while the two traces have very similar shapes, the lower proton induced pulse is two orders of magnitude smaller than the upper electron induced pulse.

The scarcity of pulses during exposure to 10 MeV protons indicates that there are mechanisms at play such that the current simplistic models are not adequate to predict discharge behavior. While the inability to predict proton induced dielectric discharge is not surprising, the small size of the discharges that were obtained was unexpected. A scientific explanation for the lack of large or frequent pulses is not available, but initial observations point to the lower mobility of protons and the smaller number of free electrons available due to both the additional positive charge brought by the protons and the lack of electrons from the beam itself. If this round of testing is symptomatic of proton charged dielectric discharge, however, it is encouraging from an engineering perspective as the likelihood of a discharge from protons is less than that from electrons and any resultant discharges will be of little concern.

CONCLUSION

Spacecraft charging due to exposure to energetic solar particle event protons is a topic that is not well understood and has received little attention in the space community. Most spacecraft charging in Earth orbit is due to energetic electrons so the majority of studies have concentrated on electron charging of spacecraft surfaces and spacecraft dielectrics. While this concentration is adequate for Earth orbital missions, spacecraft that travel in interplanetary space for extended periods of time are more likely to be exposed to energetic protons emitted by the Sun during solar energetic particle events. These energetic particles, mostly protons, can charge dielectric surfaces on the spacecraft to high potentials to the point where dielectric discharges may occur. The fluence of particles that seem to be required for such discharges, however, has not yet been observed in even the largest of solar storms.

Dielectrics highly charged by exposure to energetic protons have been shown to discharge in laboratory experiments indicating that sufficient breakdown electric fields can be generated by the accumulation of positively charge

particles. These breakdowns, however, are orders of magnitude smaller than those found from much less energetic electron exposure. More testing needs to be performed to be certain that the result from this series of tests is typical or an anomaly for proton charged dielectrics. Such additional research should seek more understanding into the amount of fluence of protons required to produce a dielectric discharge, the shape and characteristics of proton induced discharge spikes, and the degree to which charge is stored in dielectrics after energetic proton exposure. These issues are of particular importance for spacecraft that intend to spend extended periods of time in interplanetary space. Examples of these future missions are Project Prometheus spacecraft and Mars or Lunar missions during times of high solar activity.

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