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Space Technology and Applications International Forum 2006

A Study of Spacecraft Charging Due to Exposure to Interplanetary Protons

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15 February 2006

Hilton Albuquerque Hotel
Albuquerque, New Mexico

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Agenda

Spacecraft Charging by Protons

- Introduction and Objectives
- Review of Published Articles
- Theoretical Requirements
- Interplanetary Proton Environment
- Experiments and Results
- Summary

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Spacecraft Charging by Protons

Primary Objective

Long life spacecraft may be exposed to one or more major solar storms during the mission lifespan. This research task was undertaken to determine the risk to long duration interplanetary spacecraft from spacecraft charging due to exposure to solar energetic protons.

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Why Study Proton Spacecraft Charging?

- Majority of Spacecraft Charging research utilizes electron charging
  - Most spacecraft operate in Earth Orbit
  - Electrons dominate most common Earth orbits
    - Low Earth Orbit (LEO)
    - Polar Earth Orbit (PEO)
    - Geosynchronous Earth Orbit (GEO)
      - May change under the influence of a Coronal Mass Ejection (CME) or a solar flare
  - For the same energies, electrons are more mobile and penetrate further into matter

- Interplanetary spacecraft spend little time in Earth orbit
  - Susceptible to direct exposure to solar event protons from Coronal Mass Ejections and solar flares
  - Dominant charge species becomes energetic protons during solar proton events

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Why Study Proton Spacecraft Charging?

- Little research available regarding proton charging
  - Very few examples of dielectric charging with protons
  - No direct comparisons between proton and electron charged materials
  - Not enough research in the literature to determine risk
- General assumption is that protons pose no risks
- No proof of this assumption and little if any discussion

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Spacecraft Charging by Protons

Questions to be Considered

- Do protons charge dielectrics to the point of breakdown?
- Assuming they do, what are the conditions necessary for this process to occur?
- When and Where in space are these conditions met?
- What mitigations are needed to reduce the risk to the spacecraft?

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Review of Published Articles

- Almost all articles regarding proton charging of dielectrics were written by Russian authors over the last two decades
  - Akishin
  - Khorasanov
  - Gromov
  - Boev
- General result is that energetic protons can charge dielectric samples to the point of dielectric breakdown

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Review of Published Articles

A. I. Akishin

- Exposed glass blocks to proton beams
  - 100 MeV protons
  - Penetrated 3 cm into glass
- Dielectric discharge trees observed
  - Lichtenberg figures created
  - 10^{13} protons/cm^2 fluence
  - One discharge split glass
  - Photographs of discharges published in research papers
- Plasmoid ejected at discharge
- Electromagnetic radiation released at the time of discharge
  - 1-10 MHz
  - High intensity light pulse

Top: Block of glass split by discharge. Note the second Lichtenberg figure in the bulk of the glass.

Left: Close up of another Lichtenberg figure from proton irradiated glass.

Both from 100 MeV proton with a fluence of 10^{13} cm^{-2}.

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Review of Published Articles

G. L. Khorasanov

- Exposed PMMA and an Epoxy Resin (EDT-10) to protons
  - 70 cm diameter, 50 cm thick samples
  - Energy 10-70 MeV
  - Current density of 60nA/cm^2
- Reported dielectric breakdowns in both materials
  - Lichtenberg figures created
  - Came 10-50 seconds after start of exposure
  - Fluence from $3x10^{12}$ to $5x10^{12}$ protons/cm^2
  - Accompanied by burst of bright light and electromagnetic radiation
- Reported that most discharges occurred with energies >30 MeV
- Samples irradiated in air

Review of Published Articles

V. V. Gromov

- Modeling solar wind protons
  - 0.23 MeV protons, 60 nA/cm^2
  - 0.8 MeV protons, 1 nA/cm^2
- Irradiated thin sheets of dielectrics
  - 52 μm PETP (Mylar)
  - 75 μm PTFE (Teflon)
- Mapped charge distribution in the bulk of the dielectrics
  - Depth depended on energy
  - Higher energy traveled further
  - Regions of negative charge near regions of positive charge
- No discharges noted

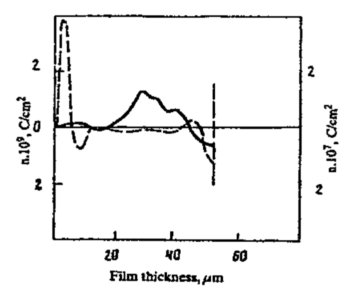

Fig. 2 Distribution of electric charge in the thickness of the irradiated PETP film: irradiation time 3 s, E_p=0.8 MeV, total injected charge ~$1.3 \cdot 10^{-9}$ X; solid line (left ordinate aces); broken curve - irradiation time 9 s, E_p=0.23 MeV, total injected charge ~$4.0 \cdot 10^{-7}$ C (right ordinate aces); the vertical line corresponds to the film thickness.

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Review of Published Articles

S. G. Boev and V. A. Paderin

- Mathematical model for proton charge deposition

- Electric fields in the dielectric
  - Changes with time
  - Dependent on Radiation Induced Conductivity (RIC) and range of deposition
  - Incident energy dependent
    - Higher energy = Higher RIC

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Theoretical Requirements

- Theoretical calculation of the required fluence
- Most dielectric break down under fields of >10^5 V/cm
- Relationship between field strength E and number of protons
  - Using Gauss's Law

$$\oint_S \varepsilon \vec{E} \bullet d\vec{S} = Q_{enclosed}$$

  - Use parallel plate capacitor model for simplicity
    - Range dispersion is small for a uniform energy
    - Energies in space are not uniform, but adequate for first order calculation
  - Gaussian pillbox model for an infinite charge sheet gives

$$E = \frac{Q_{enclosed}}{2\varepsilon S}$$

  - Two opposing charge sheets (parallel plane capacitor) gives interior field of

$$E_{parallel} = \frac{Q_{enclosed}}{\varepsilon S}$$

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Theoretical Requirements

- Charge density from Electric field
  - Defining charge density as quantity of charge per area

$$\rho_{surface} = \frac{Q_{enclosed}}{S} = \varepsilon E_{parallel}$$

  - Charge density is dependant on material properties and the electric field
  - Parameters for worst case calculation
    - $E=10^5$ V/cm
    - $\epsilon_r=1$
    - $\epsilon_0=8.854\times10^{-14}$ F cm^{-1} = 8.854×10^{14} C V^{-1} cm^{-1}
  - Charge density worst case

$$\rho_{surface} = 8.854\times10^{-9}\,\frac{C}{cm^2}$$

$$\rho_{surface} = 5.5\times10^{10}\,\frac{protons}{cm^2}$$

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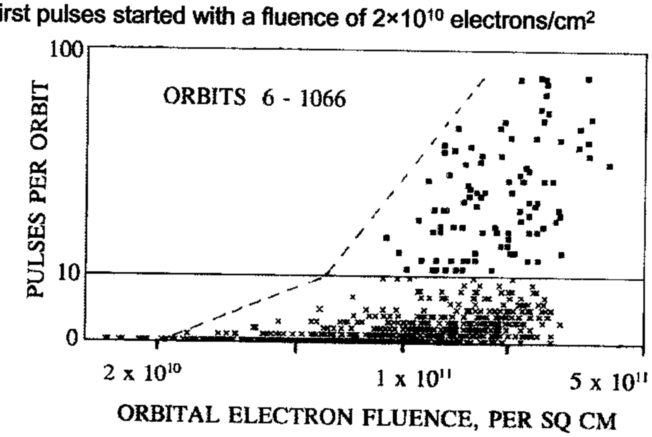
Theoretical Requirements

- Confirmation of calculation
- CRRES electron fluence versus pulses
  - First pulses started with a fluence of 2×10^{10} electrons/cm^2



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Interplanetary Proton Environment

- JPL Proton Fluence Model - 1991
  - J. Feynman, et. al*
  - Updated with little change in 2002**
  - Solar Proton Event fluences 1963-1998
  - Mostly from Coronal Mass Ejections (CME)
  - Plotted recorded CMEs by energy, total fluence, and relative probability of occurrence
- Historical look at CME characteristics at 1 A.U.
  - It is not known if measured worst case is actual worst case
  - Time period covers multiple solar cycles
  - Fluences would change with distance from Sun

* Feynman, J., Sitale, G., and Wang, J., "Interplanetary Proton Fluence Model: JPL 1991," *Journal of Geophysical Research*, **98(A8)**, 3,281-13,294 (1993).

** Feynman, J., Ruzmaikin, A., and Berdichevsky, V., "The JPL proton fluence model: an update," *Journal of Atmospheric and Solar-Terrestrial Physics*, **64**, 1679-1686 (2002).

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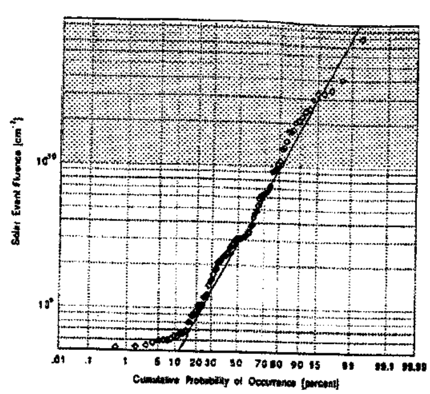
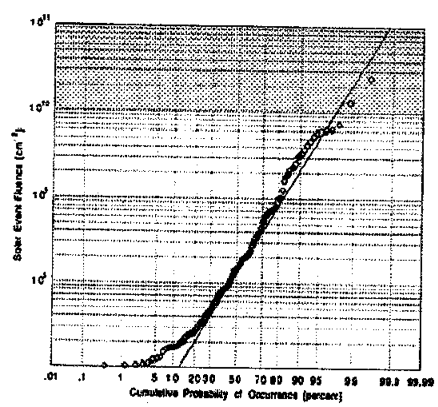
Interplanetary Proton Environment

JPL Proton Fluence Model – 1991



a. >1 MeV protons



b. >4 MeV protons

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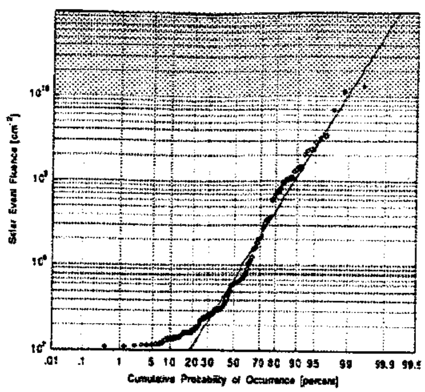
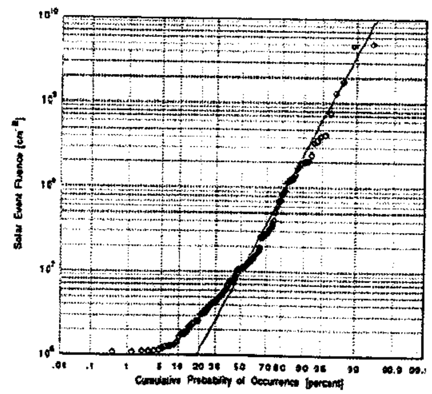
Interplanetary Proton Environment

JPL Proton Fluence Model – 1991



c. >10 MeV protons



d. >30 MeV protons

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Interplanetary Proton Environment

TABLE *a*. Fluence Values for the 10 Largest Events in the Range Where Energy >1 MeV

Year	First Day	Last Day	>1 MeV Fluence
1989	272	314	7.92E+10
1989	225	251	4.05E+10
1978	113	130	3.43E+10
1981	126	147	3.24E+10
1989	66	80	3.23E+10
1981	281	295	2.92E+10
1991	68	102	2.50E+10
1978	44	51	2.40E+10
1982	325	357	2.20E+10
1989	331	340	2.07E+10

Read 7.92E+10 as 7.92×10^{10}. Values are in 10^{10} cm^{-2}. These data cover day 270 of 1972 through day 126 of 1991.

TABLE *b*. Fluence Values for the 10 Largest Events in the Range Where Energy >4 MeV

Year	First Day	Last Day	>4 MeV Fluence
1989	292	313	24.80E+9
1989	225	249	13.00E+9
1978	112	129	7.31E+9
1978	266	271	6.39E+9
1991	82	90	6.21E+9
1981	281	294	5.87E+9
1989	272	282	5.69E+9
1978	44	49	5.33E+9
1989	331	338	4.69E+9
1981	126	147	4.23E+9

Read 24.8E+9 as 24.8×10^{9}. Values are in 10^{10} cm^{-2}. These data cover day 270 of 1972 through day 126 of 1991.

TABLE *c*. Fluence Values for the 10 Largest Events in the Range Where Energy >10 MeV

Year	First Day	Last Day	>10 MeV Fluence
1989	292	313	13.10E+9
1972	201	233	11.30E+9
1989	225	249	6.89E+9
1989	272	288	3.41E+9
1991	82	98	3.23E+9
1978	266	271	2.88E+9
1978	107	129	2.42E+9
1969	89	113	2.30E+9
1981	281	294	2.06E+9
1971	25	30	1.49E+9

Read 13.1E+9 as 13.1×10^{9}. Values are in 10^{10} cm^{-2}. These data cover day 331 of 1963 through day 126 of 1991.

TABLE *d*. Fluence Values for the 10 Largest Events in the Range Where Energy >30 MeV

Year	First Day	Last Day	>30 MeV Fluence
1972	173	232	50.20E+8
1989	292	311	47.30E+8
1989	225	244	18.10E+8
1989	272	282	12.90E+8
1991	82	89	7.59E+8
1978	266	269	4.31E+8
1981	281	291	4.15E+8
1984	116	122	3.60E+8
1971	24	29	3.41E+8
1978	118	123	2.47E+8

Read 50.2E+8 as 50.2×10^{8}. Values are in 10^{10} cm^{-2}. These data cover day 331 of 1963 through day 126 of 1991.

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Interplanetary Proton Environment

- Limited energy range for concern
  - Historical CME points to < 10 MeV protons
    - Uncommon for energies > 4 MeV
    - Relatively common for energies ~ 1 MeV
- Measured fluences near theoretical model
  - Fluences of concern only occur with largest CMEs
  - Energies < 10 MeV
  - More common as energy decreases
- Only largest Coronal Mass Ejections are of concern
  - Largest occurred in 1972 and 1989

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Research Summary

- Spacecraft Charging by protons
  - Most applicable for interplanetary spacecraft
  - Not extensively studied
    - Only a few Russian authors
    - Discharges from proton charged dielectrics found
    - High energy, high current
- Theoretical Calculations
  - Worst case calculation
    - Electric field of > 10^5 V/cm
    - Fluence of ~5×10^{10} protons/cm^2
  - Some confirmation from CRRES electron fluence data
- Solar Proton event models
  - Worst case fluences for energies of < 10 MeV
    - Only occurs with largest CME events
  - More common for energies of < 1 MeV

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Research Summary

Questions to be Considered

- Do protons charge dielectrics to the point of breakdown?
  - Russian researchers have done so
- Assuming they do, what are the conditions necessary for this process to occur?
  - Fluences of 5×10^{10} protons/cm^2 or greater
- When and Where in space are these conditions met?
  - Largest CME events
- What mitigations are needed to reduce the risk to the spacecraft?
  - How similar are proton events to electron events?

Experimentation

- Issues to be addressed
  - Can we make typical spacecraft dielectrics discharge when exposed to energetic protons?
  - How similar are proton- and electron-exposed dielectric properties?
- Laboratory Experiment
  - Dielectric discharge
    - Attempt to create discharges from typical spacecraft dielectrics
    - Use protons ~10 MeV to model possible space conditions
    - Obtain pulse shape characteristics to compare with electron induced pulses

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Sample Selection

- Cable insulation dielectrics
  - Spacecraft can incorporate long cable runs
    - Power cables from power supply to instruments
- Potting compounds
  - Typically used in power supplies
  - Can be large pieces of dielectric
- Circuit board material
  - Used extensively throughout spacecraft
- Conformal Coating
  - Sealant on circuit boards

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Sample Selection

- Wire Insulation
  - PTFE (Polytetrafluoroethylene) – "Teflon"
  - FEP (Fluorinated Ethylene Propylene)
  - PFA (Perfluoroalkoxy)
  - ETFE (Ethylene Tetrafluoroethylene) – "Tefzel"
- Potting Compounds
  - Conathane EN11
  - Uralane
  - Silicone CV2510
- Conformal Coating
  - Solithane
- Printed Wiring Board (PWB)
  - Polyimide

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Sample Selection

- Sample size selected to fit existing test hardware
  - 5 x 5 cm samples
    - Fit in one charge storage carousel
    - Simplify long term test plans
  - Thickness
    - Ranged from 1.5mm – 3.6mm
    - Average ~ 2.5 mm
    - Greater than penetration depth of 10 MeV proton
      - Too thin and protons will go through rather than stop within the sample
- Copper electrode attached to rear side of all samples
  - Parallel plate capacitor model
  - Assisted in physically mounting sample

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Dielectric Discharge Testing

- Goal was to create dielectric breakdown "ESD" pulses
  - Same dielectric materials as charge storage tests
  - Proof of concept
    - Back up Russian reports
  - Using more realistic proton energies
- Test parameters
  - 10 MeV proton beam
  - 0.1 nA/cm^2 current density
    - Chosen to slowly bring up fluence
  - Planned ending fluence of 10^{12} protons/cm^2
    - Exceeding theoretical fluence
- Test Facility
  - Crocker Nuclear Laboratory Cyclotron, University of California, Davis

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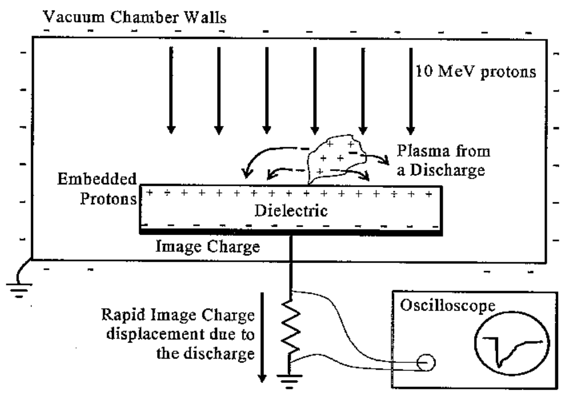
Dielectric Discharge Testing



- Theoretical a Dielectric Discharge due to implanted protons
- Same concepts have been applied to implanted electrons

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Dielectric Discharge Testing

- Test information
  - Test dates: 10-11 March, 2005
  - 10 MeV protons
  - 0.1 to 1.0 nA/cm^2 current density
    - Increased as test proceeded to speed process
  - Fluences of up to 10^{13} protons/cm^2
- Dielectric discharges were observed, but not on all samples
  - No Teflon sample discharged
  - Maximum discharges with Polyimide sample
    - Much smaller and fewer than expected
    - Expected shape and polarity
  - Tiny discharges from Uralane and Conathane samples
    - Discharges were extremely small and few in number
    - Opposite polarity from expectations

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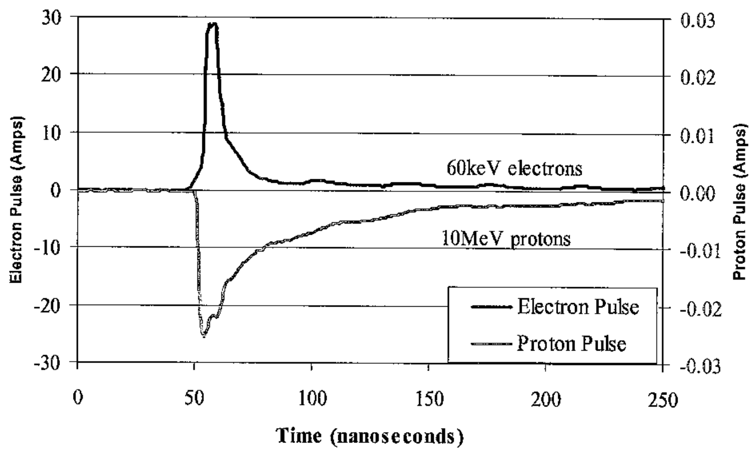
Dielectric Discharge Testing

Polyimide PCB Dielectric Discharges



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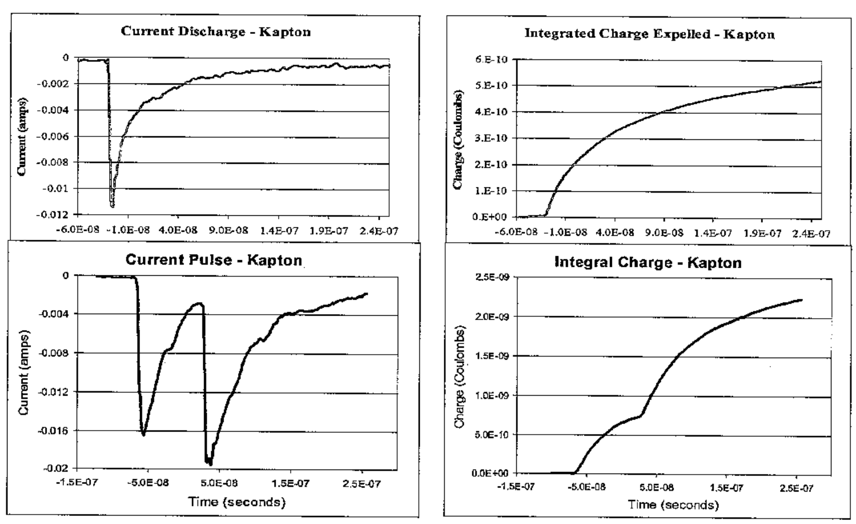
Dielectric Discharge Testing



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Dielectric Discharge Testing

- Pulses from proton irradiated dielectrics were obtained
  - Far smaller than expected
  - More fluence required than expected
    - Very small pulses for Kapton Polyimide starting at ~ 3×10^{12} protons/cm^2
    - Larger pulses didn't happen until after ~ 10^{13} protons/cm^2
  - Only the Kapton Polyimide pulsed as expected
  - All other samples either didn't pulse at all or only slightly

- More analysis is needed
  - Did the test set up influence unexpected results?

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Summary

- Literature search yielded few reports of proton related Spacecraft Charging Research
  - Almost exclusively Russian
  - Discharges reported, but not for space-like situations

- Theoretical worst case calculated
  - Worst case can be seen with worst case CME
  - Discharges may be possible
  - Conditions are rare

- Experimental testing
  - Dielectric discharge results only show small discharges with unpredicted characteristics

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Acknowledgements

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Special thanks due to Henry Garrett, Andrew Shapiro, Paul Willis, and Patrick Dillion for their contributions to this effort.