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A Study of Spacecraft Charging Due to Exposure to Interplanetary Protons

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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
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.

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
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

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?
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

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/cm² 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
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 60 nA/cm²
- Reported dielectric breakdowns in both materials
  - Lichtenberg figures created
  - Came 10-50 seconds after start of exposure
  - Fluence from 3x10¹² to 5x10¹² protons/cm²
  - Accompanied by burst of bright light and electromagnetic radiation
- Reported that most discharges occurred with energies >30 MeV
- Samples irradiated in air

V. V. Gromov

- Modeling solar wind protons
  - 0.23 MeV protons, 60 nA/cm²
  - 0.8 MeV protons, 1 nA/cm²
- 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. 3 Distribution of electric charge in the thickness of the irradiated PETP film: irradiations time 2 s, E₀=0.23 MeV, total injected charge 2.0x10⁻⁹ C (solid line, left ordinate axis), dose curve: irradiations time 9 s, E₀=0.23 MeV, total injected charge 4.0x10⁻⁹ C (right ordinate axis); the vertical line corresponds to the film thickness.


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

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
    \[ \oint_S E \cdot d\vec{S} = Q_{enclosed} \]
  - 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
    \[ E_{parallel} = \frac{Q_{enclosed}}{\varepsilon S} \]
Theoretical Requirements

- Charge density from Electric field
  - Defining charge density as quantity of charge per area
    \[ \rho_{\text{surface}} = \frac{Q_{\text{enclosed}}}{S} = \varepsilon E_{\text{parallel}} \]
  - Charge density is dependant on material properties and the electric field
  - Parameters for worst case calculation
    - \( E = 10^5 \) V/cm
    - \( \varepsilon_r = 1 \)
    - \( \varepsilon_\infty = 8.854 \times 10^{-14} \) F cm\(^{-1}\) \( = 8.854 \times 10^{-14} \) C V\(^{-1}\) cm\(^{-1}\)
  - Charge density worst case
    \[ \rho_{\text{surface}} = 8.854 \times 10^{-9} \frac{C}{cm^2} \]
    \[ \rho_{\text{surface}} = 5.5 \times 10^{10} \frac{\text{protons}}{cm^2} \]

Theoretical Requirements

- Confirmation of calculation
- CRRES electron fluence versus pulses
  - First pulses started with a fluence of \( 2 \times 10^{10} \) electrons/cm\(^2\)
Interplanetary Proton Environment

- JPL Proton Fluence Model - 1991
  - J. Feynman, et. al*
  - Updated with little change in 2002**
  - 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

Interplanetary Proton Environment

JPL Proton Fluence Model – 1991

TABLE 1. Proton Values for the 10 Largest Events in the Range Where Energy > 30 MeV

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Interplanetary Proton Environment

TABLE 3. Proton Values for the 10 Largest Events in the Range Where Energy > 30 MeV

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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

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 > 10^9 V/cm
    - Fluence of ~5x10^10 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
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 $5 \times 10^{10}$ 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 $\sim 10$ MeV to model possible space conditions
    - Obtain pulse shape characteristics to compare with electron induced pulses
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

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
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

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/cm² current density
    - Chosen to slowly bring up fluence
  - Planned ending fluence of 10¹² protons/cm²
    - Exceeding theoretical fluence
- Test Facility
  - Crocker Nuclear Laboratory Cyclotron, University of California, Davis
Dielectric Discharge Testing

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

Test information
- Test dates: 10-11 March, 2005
- 10 MeV protons
- 0.1 to 1.0 nA/cm² current density
  - Increased as test proceeded to speed process
- Fluences of up to $10^{13}$ protons/cm²
- Dielectric discharges were observed, but not on all samples
  - No Teflon sample discharged
  - Maximum discharges with Polymide 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
Dielectric Discharge Testing

Polyimide PCB Dielectric Discharges

![Graph showing dielectric discharge testing results with time (nanoseconds) on the x-axis and current (amps) on the y-axis. The graph includes data for 60keV electrons, 10MeV protons, electron pulse, and proton pulse.]
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 \( \sim 3 \times 10^{12} \) protons/cm\(^2\)
    - Larger pulses didn't happen until after \( \sim 10^{13} \) 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?

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
Acknowledgements

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