Charge Dissipation in Germanium-Coated Kapton Films at Cryogenic Temperatures

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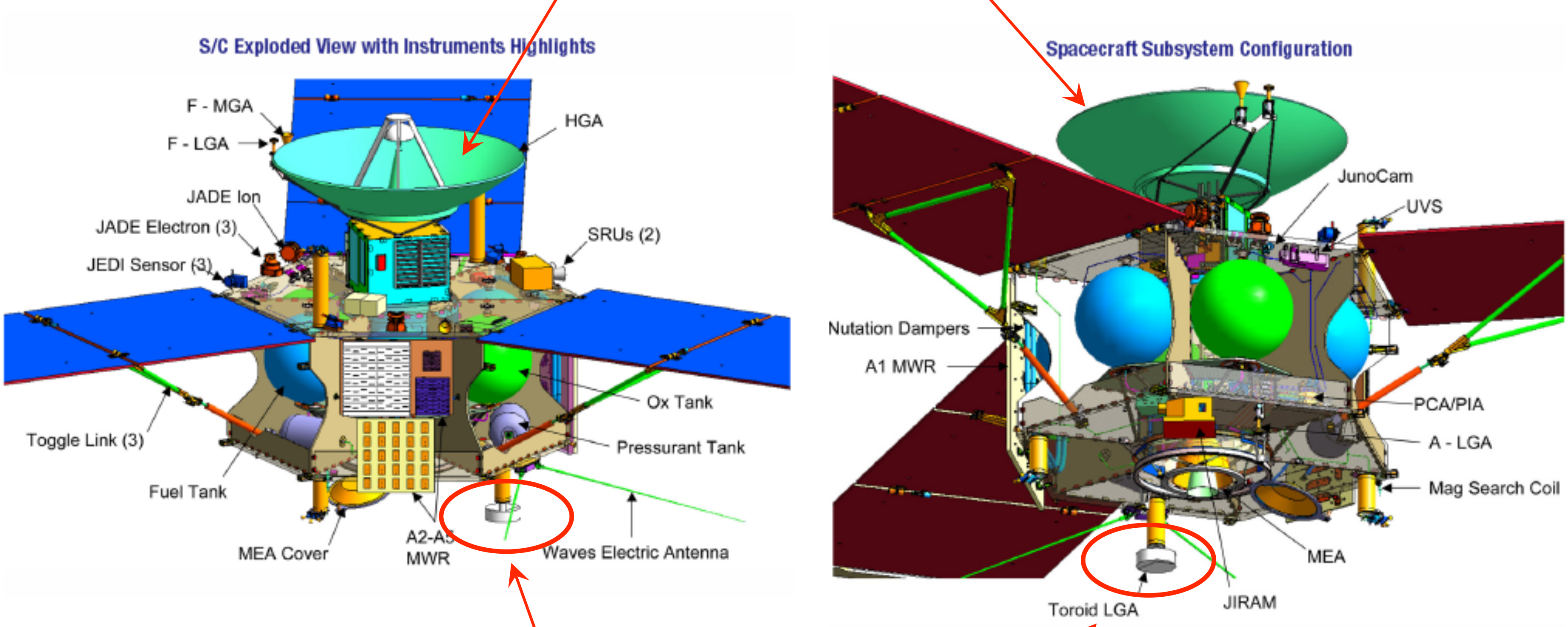
Outline

- Background: NASA JUNO mission
  - Design drivers
  - Solution options
- Experimental results at flight-like temperatures
- Discussions
- Proposed solution for future missions
- Conclusions

Background:
JUNO Spacecraft Configuration

High-Gain Antenna (HGA)



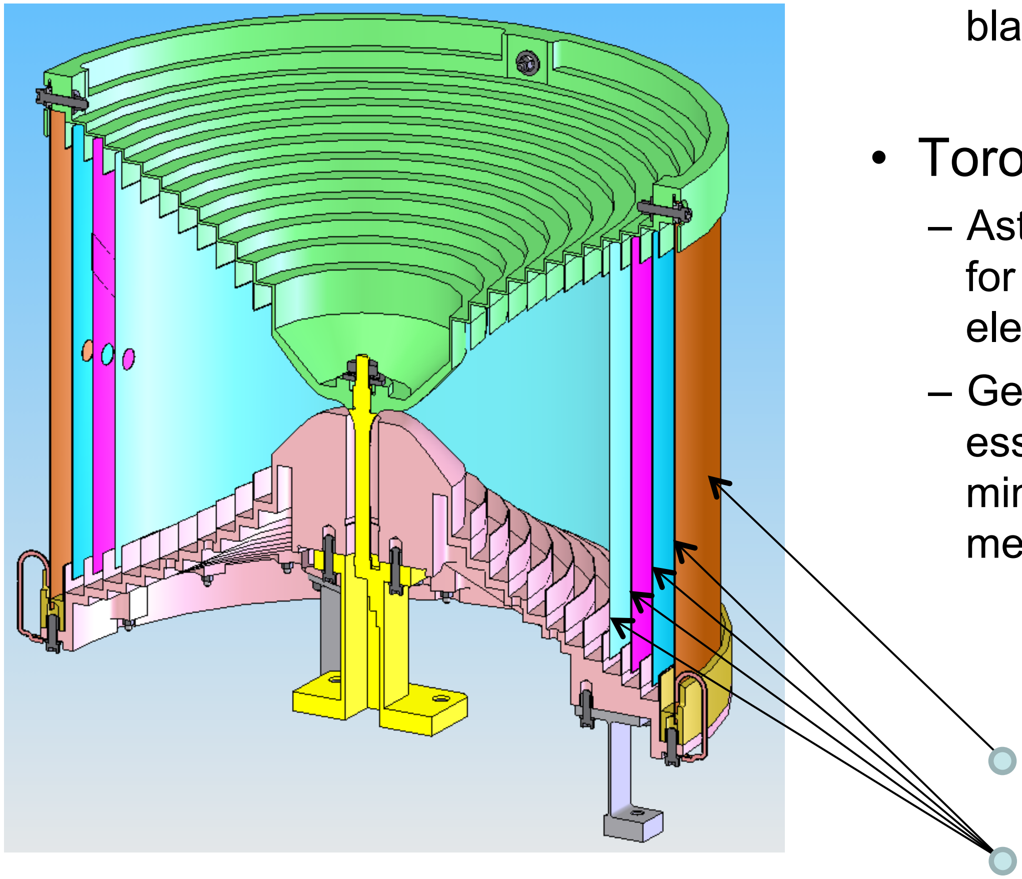
Toroidal Low-Gain Antenna (TLGA)

Background:
Design Drivers

- RF performance
  - Insignificant RF attenuation (no data rate or communication impact)
    - ➢ *Minimum mobile charge*
- IESD performance
  - Adequate charge dissipation, minimization of IESD risk
    - ➢ *Moderate amount of mobile charge*
- Thermal performance
  - Low emissivity needed to retain heat
    - ➢ ***Solution: Thin surface coating of amorphous Ge ($\varepsilon \approx 0.02$)***

Background:
JUNO Antennas

- High Gain Antenna (HGA):
  - Ge coated Kapton 100CB thermal SLI blanket cover
- Toroidal Low Gain antenna (TLGA):
  - Astroquartz (woven silica glass fibers) used for support structures and polarizing elements
  - Ge coating (transparent to RF energy) not essential to TLGA, but implemented to minimize effects on science instruments measuring electron and ion environments



DuPont Kapton Options:

Carbon-Loaded "Black Kapton"

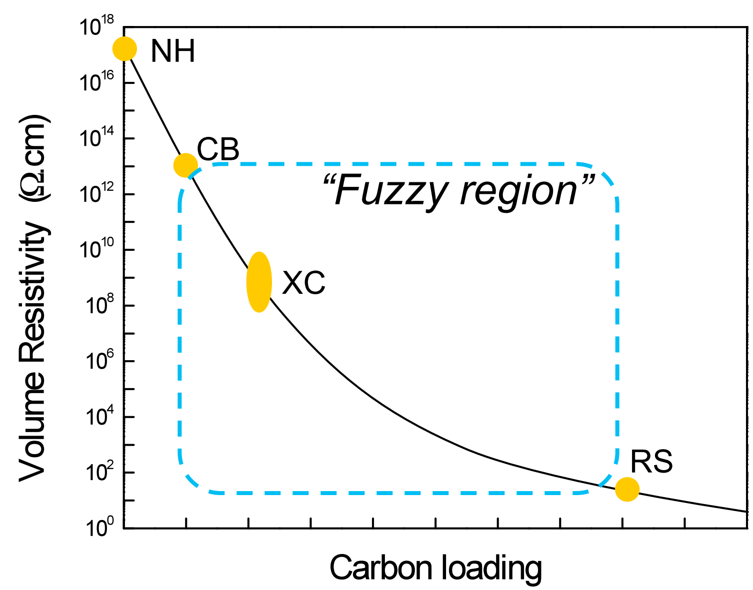
DuPont Kapton:

- A large variety of polyimide products tailored to specific applications
- Limited range of carbon-loaded "Black Kapton"

Type	Application	Volume resistivity Ohm.cm	Surface resistivity Ohm/sq
NH	General purpose	1.5 x 1E17	
KJ	Thermoplastic	1.0 x 1E17	
CR	Corona resistant	2.3 x 1E16	
MT	Alumina-filled; thermal	1.0 x 1E14	
MTB	Black MT version	1.0 x 1E12	
CB	Black NH versioin	1.0 x 1E13	
XC	Black, highly C-loaded	1E8 - 1E10	1.0 x 1E7
RS	Black, highly C-loaded	~10	100

General trends:

- Carbon loading reduces resistivity
- Low C fraction: resistivity control depends on carbon dispersion
- Very high C fraction: resistivity control depends on carbon percolation
- In the "fuzzy region", resistivity control is poor



RF vs. IESD Performance,

or Kapton CB vs. Kapton XC

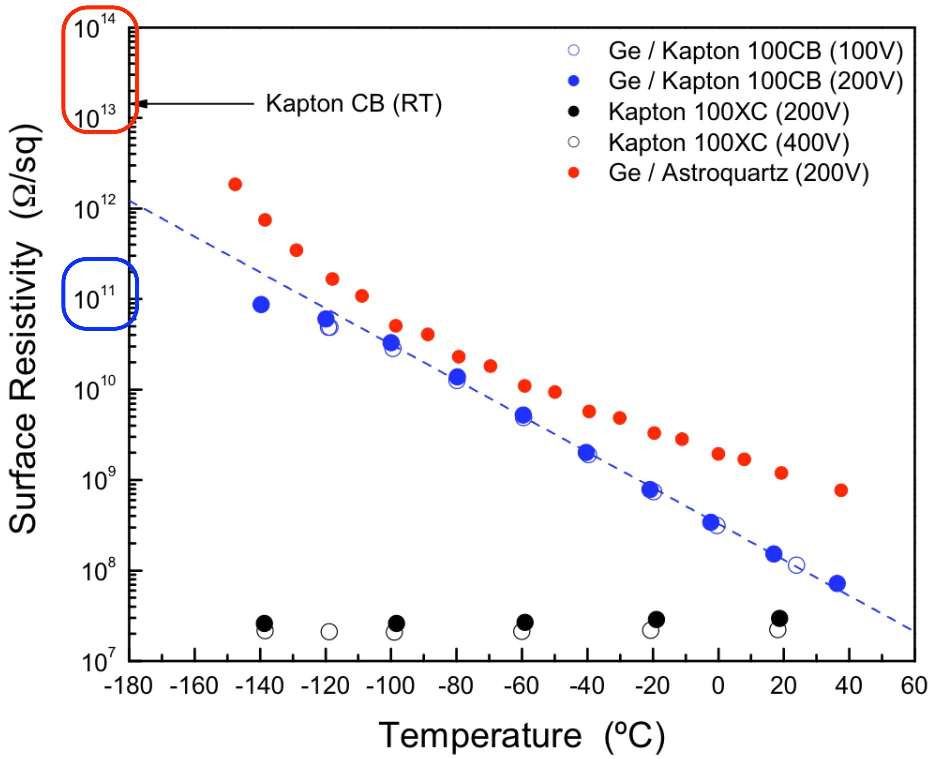
National Aeronautics and Space Administration
Goddard Space Flight Center

Telecom Link Margins to Track

	Case	SC Antenna	SC Pointing	Coding	Earth Antenna	Data Rate	CB: Margin over 2 sigma w/o Ranging	CB: Margin over 2 sigma w/ Ranging	XC: Margin over 2 sigma w/o Ranging	XC: Margin over 2 sigma w/ Ranging	Note:
	High Rate						100CB Kapton		100XC Kapton		
1	Science Data Downlink	HGA	Earth	Turbo-Long Frame	Any 34m	18 kbps	1.52	1.22	1.22	0.92	-0.3dB represents approximately 7% reduction in data rate/return
2	Ka Science	HGA	Earth	N/A	DSS 25	N/A	2.53	N/A	1.53	N/A	
2a	X Science	HGA	Earth	N/A	DSS 25	12 kbps	1.83	N/A	1.53	N/A	-0.3dB represents approximately 7% reduction in data rate/return
	Main Engine Maneuvers										
3	DSM	Toroidal	DSM attitude	N/A	DSS 63	tones-3s	3.96	N/A	3.96	N/A	
4	JOI	Toroidal	JOI attitude	N/A	DSS 14	tones-3s	1.91	N/A	1.91	N/A	
5	PRM	Toroidal	JOI attitude	N/A	DSS 14	tones-3s	1.12	N/A	1.12	N/A	
	Nominal Cruise										
6	Pre-DSM Cruise	Forward LGA	Earth	Turbo-Long Frame	Any 34m	100 bps	13.68	13.38	13.68	13.38	
7	Post DSM, Pre EFB Cruise	Aft LGA	Sun	Turbo-Long Frame	Any 34m	100 bps	1.14	0.84	1.14	0.84	
8	Cruise-Max Range	HGA	Earth	Turbo-Long Frame	Any 34m	100 bps	19.97	19.67	19.67	19.37	-0.3dB represents approximately 7% reduction in data rate/return
9	Post-PRM	MGA	Earth	RS-Short Frame	Any 34m	10 bps	1.28	0.98	1.28	0.98	
10	Post-PRM	HGA	0.5 deg off Earthpoint	RS-Short Frame	Any 34m	10 bps	22.85	22.55	22.55	22.25	-0.3dB represents approximately 7% reduction in data rate/return
11	Post-PRM	HGA	1.0 deg off Earthpoint	RS-Short Frame	Any 34m	10 bps	1.91	1.61	1.61	1.31	-0.3dB represents approximately 7% reduction in data rate/return
	Safe Mode										
12	Worst Case	MGA	Sun-pointed	RS-Short Frame	70m	10 bps	7.13	N/A	7.13	N/A	

The IESD "better" Kapton hurts 0.3dB at X (7% of data return) and 1dB at Ka

Problem Encounter:
Resistivity vs. Temperature



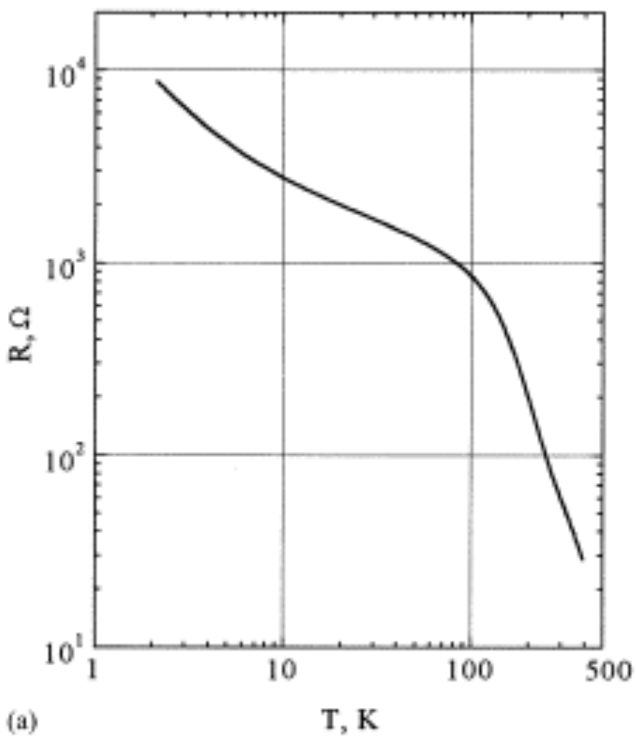
- The Ge surface resistivity increases by several orders of magnitude from RT to the expected operation temperatures
- The Ge coats of AQ and Kapton have different electric behavior

- *Lack of data at actual operation temperatures creates significant uncertainties in extrapolating material behavior to –180 ºC*

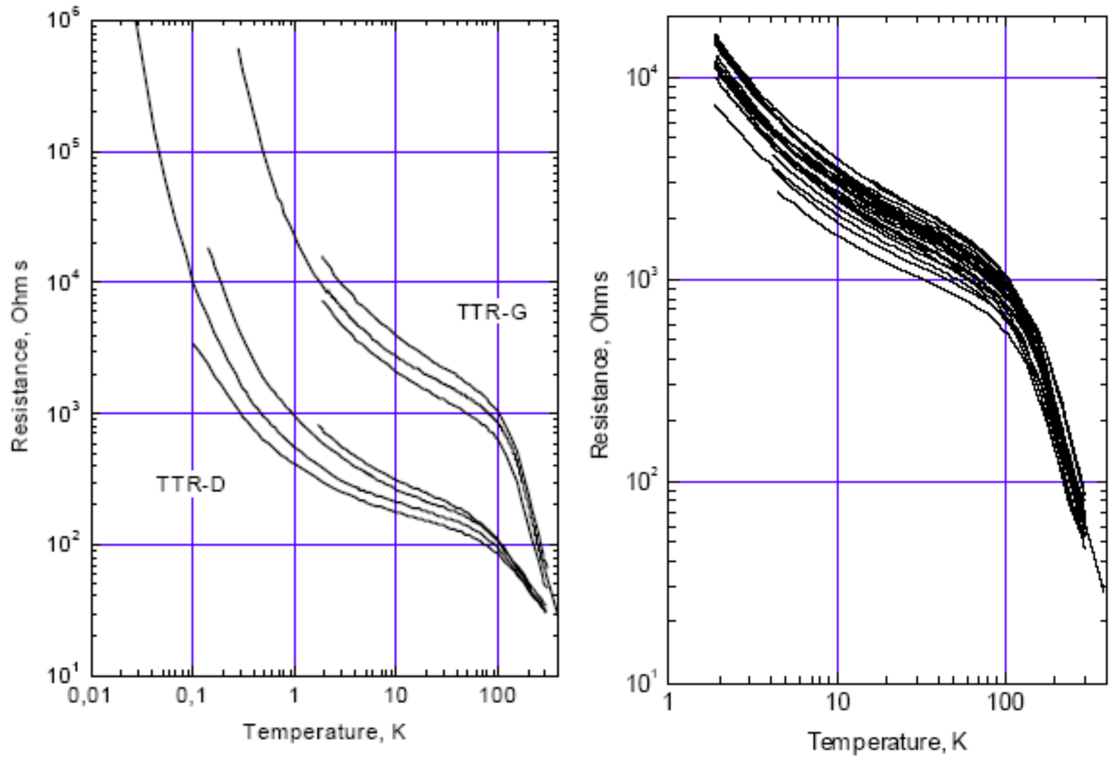
Current data suggest that at –180 C:
- ➢ 10^{11} Ohm/sq for Ge/Kapton CB
- ➢ 10^{13}-10^{14} Ohm/sq for Ge/Astroquartz

Ge Resistivity at Low-T

Literature on Ge Film Thermometers



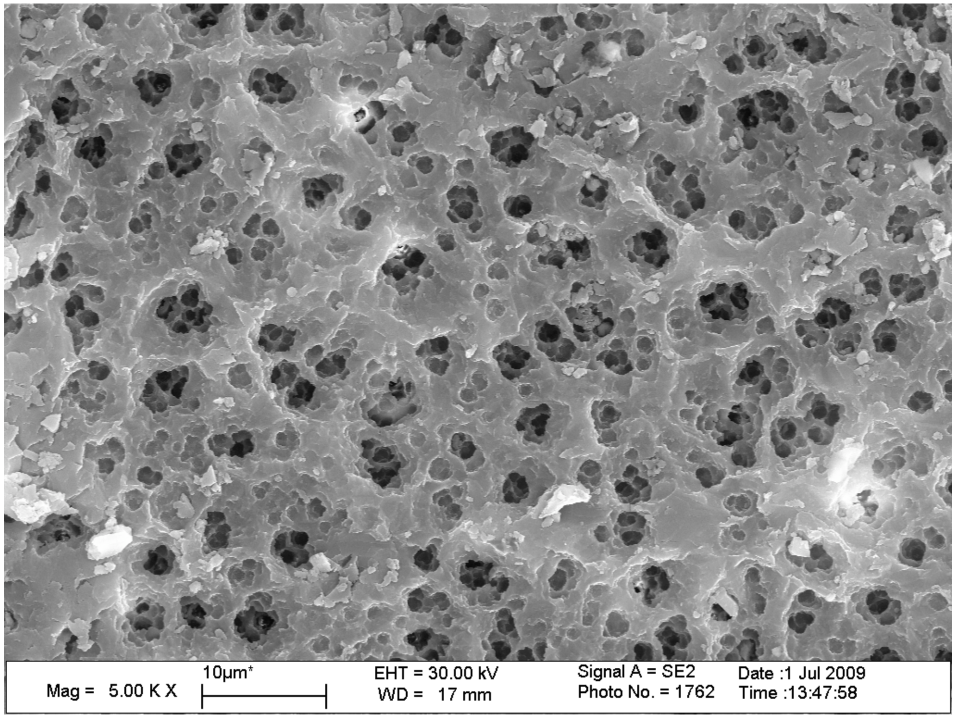
Resistance of a Ge film thermometer
N.S. Boltovets *et al.*, *Sensors and Actuators A* **92** (2001) 191



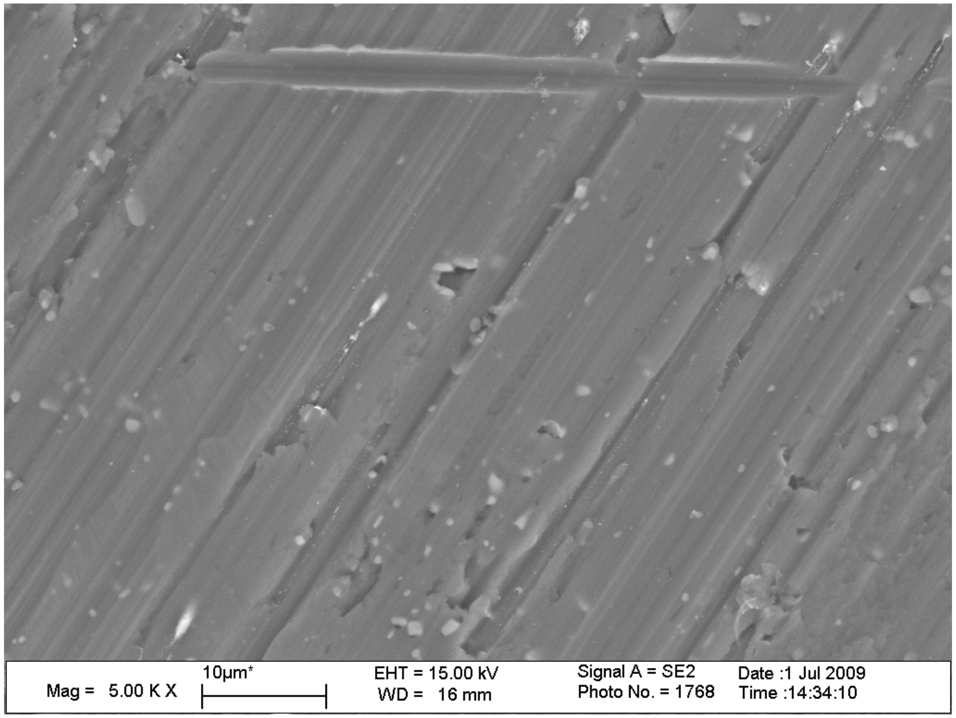
Resistance of different types of Ge film thermometers (left) and variability from the same wafer (right)
V.K. Dugaev *et al.*, *Sensors, 2002. Proceedings of IEEE* **2** (2002) 1275

Ge Film Morphology

Ge on Astroquartz

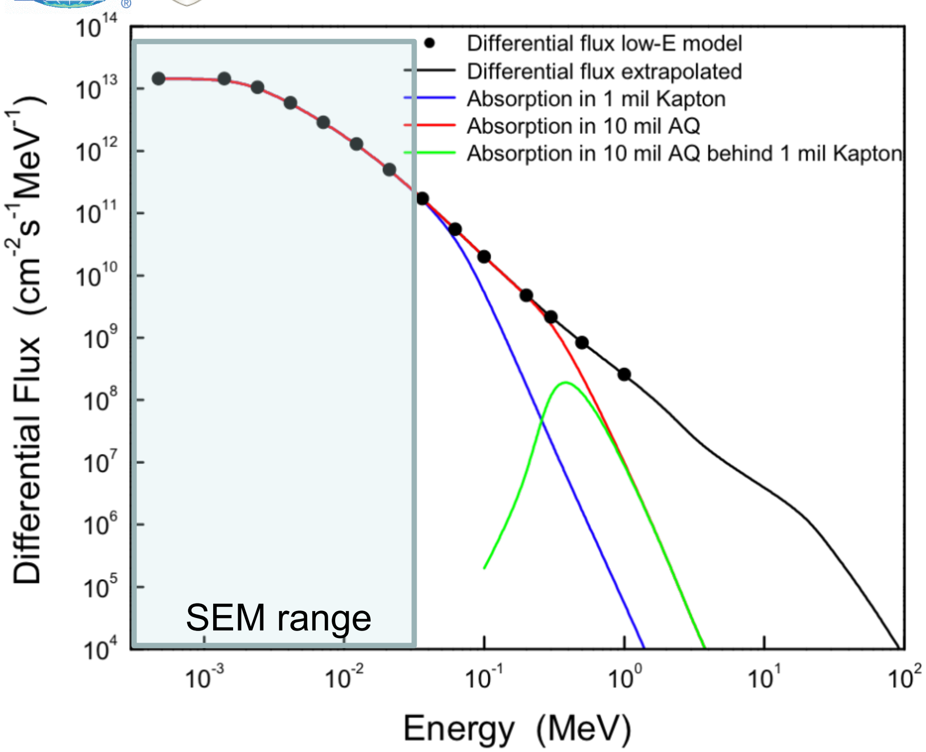


Ge on Kapton



SEM images of ~100 nm thick Ge layers on Astroquartz and Kapton show different film morphology, which may be responsible in the differences in the respective film resistivity at low temperatures.

SEM-Based Charging Experiments



Worst JUNO orbit differential flux and electron absorption in Kapton, Astroquartz and Kapton-shielded Astroquartz

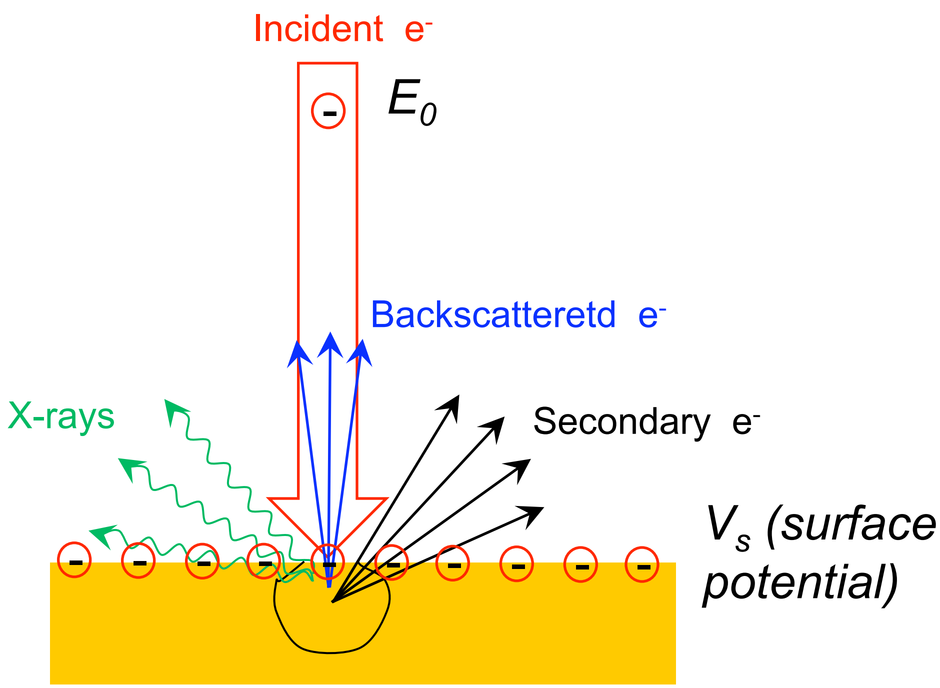
- The energy of SEM electrons (30 keV) is adequate for experimenting with thin film charging. Higher energy electrons contribution is ~%.
- SEM provides high electron density; must address radiation-induced conductivity
- Technique borrowed from zero-energy determination methods in electron microscopy.

JUNO example: Worst orbit absorption rate:

- Total: 8.4×10^{10} cm^{-2}s^{-1} = 13.4 nA/cm^2
- Kapton: 8.1×10^{10} cm^{-2}s^{-1} = 13.0 nA/cm^2
- AQ: 8.3×10^{10} cm^{-2}s^{-1} = 13.3 nA/cm^2
- AQ (shielded): 1.1×10^{8} cm^{-2}s^{-1} = 17.8 pA/cm^2

Near the low current limit of field-emission SEMs

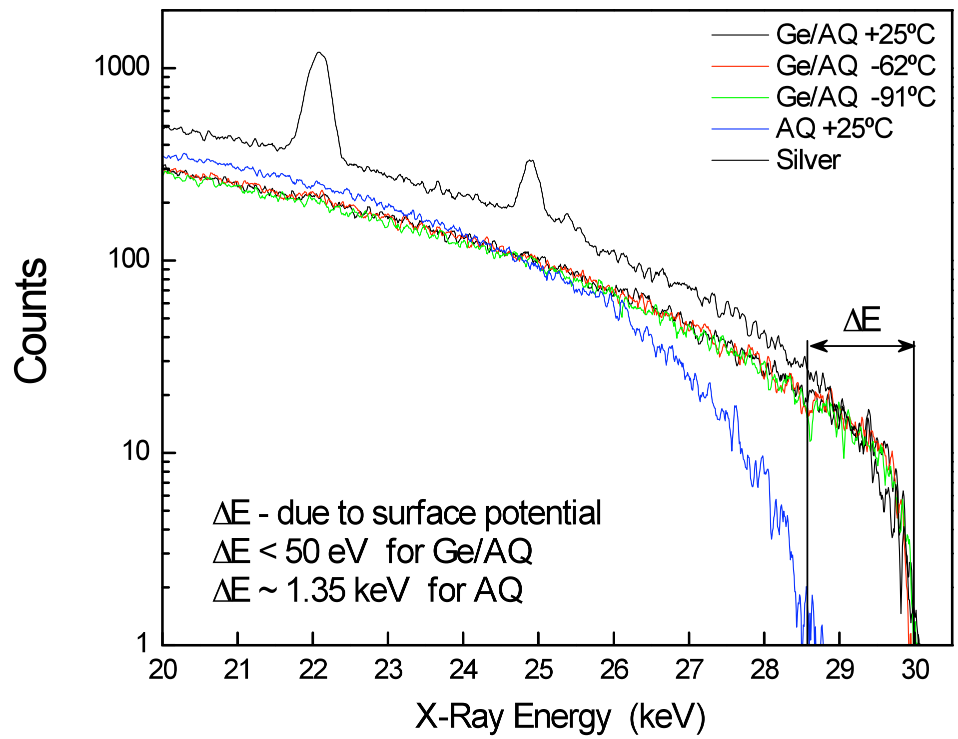
SEM-Based Charging Experiments

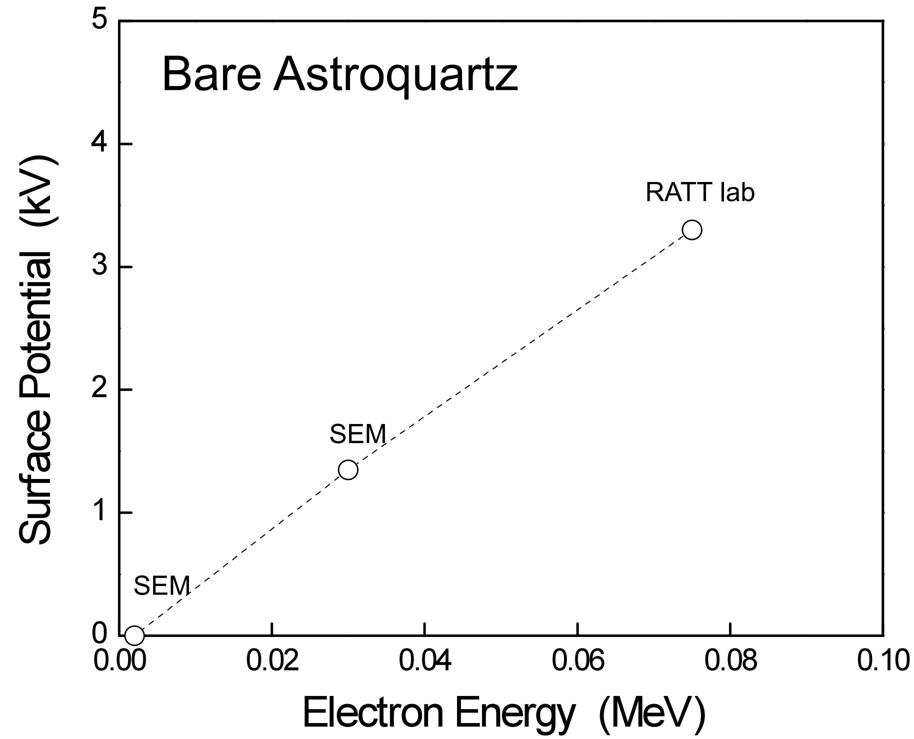


A schematic representation of the processes occurring when an electron beam impinges on a sample.

- SEM beam with incident energy E_0 charges the surface of an insulator to a potential V_s.
- Vs is determined by the current balance among incident, secondary and backscattered electrons
  - $V_s < 0$ for $E_0 <$ 50-70 eV
  - $V_s > 0$ for 50-70 eV $< E_0 <$ 1.5-2.5 keV
  - $V_s < 0$ for $E_0 >$ 1.5-2.5 keV
- Maximum energy in the x-ray spectrum:
  - $E_x = E_0 - eV_s$
- E_x, the end of the Bremsstrahlung x-ray spectrum, is a direct measure of surface potential, V_s.

SEM-Based Charging Experiments: *Applications to Astroquartz*





- Bare Astroquartz can charge up to several kilovolts in JUNO environment
- Ge/Astroquartz exhibits <50V surface potential at temperatures as low as -90 ºC
- Greater potentials may be expected at lower temperatures, but ~kV is unlikely

JUNO Solutions Approach

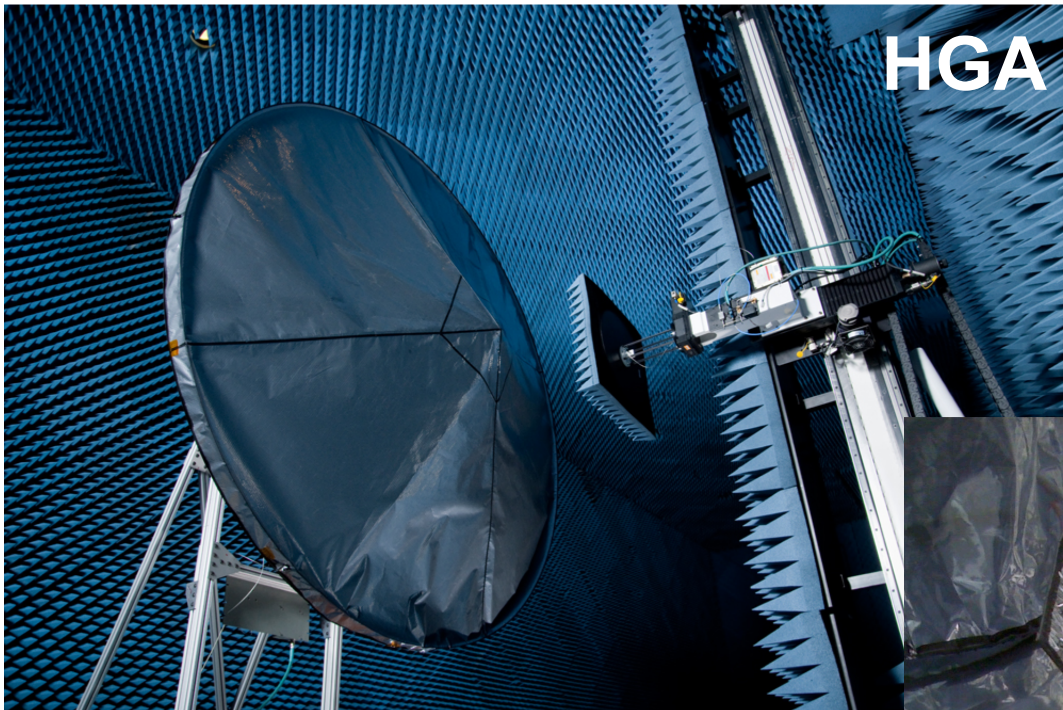
High Gain Antenna:

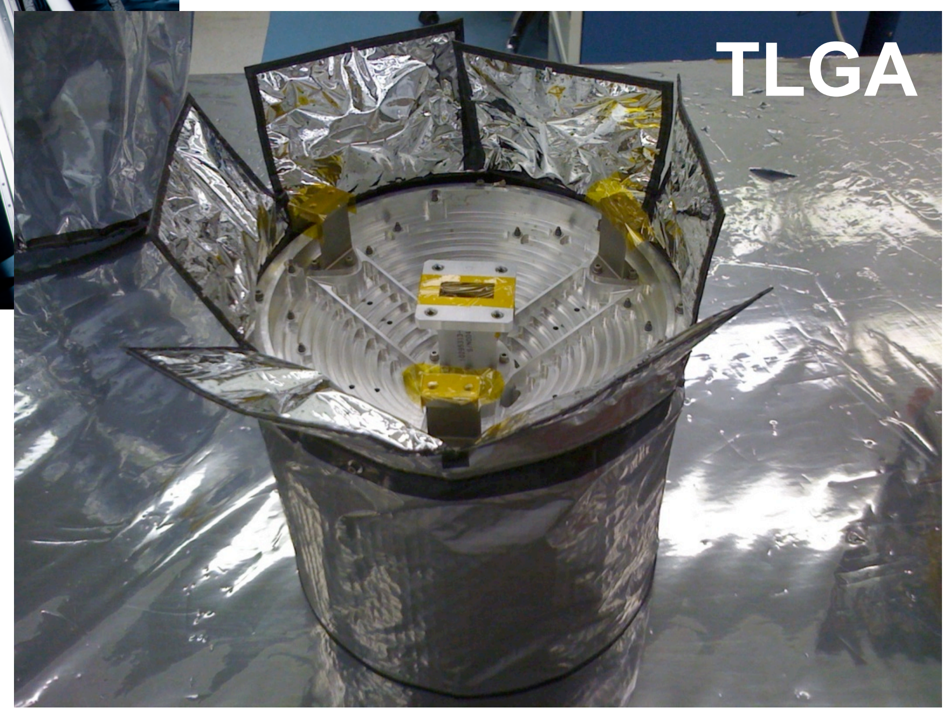
- The rear of the HGA is covered with Ge / Kapton 100XC
- The front of the HGA is covered with Ge / Kapton 100CB. Cannot use the XC Kapton due to its RF loss (0.3 dB at X-band and nearly 1 dB at Ka-band).
- Influence on science instruments is minimized. Several kV potential can build up near the center of the aperture and will diminish as you approach the outer edges of the dish.

Torodial Low Gain Antenna:

- The four inner cylinders remain Ge / Astroquartz
- Outer radome of Ge / Kapton 100CB added for better shielding (due to lower resistivity of the Ge layer on Kapton at mission operation temperatures)
- Frequent IESD events in bare Astroquartz have low amplitude and produce broad band RF pulses, which have insignificant effect.

JUNO Antennas –
Getting Ready





Proposed Alternatives:
Materials Engineering

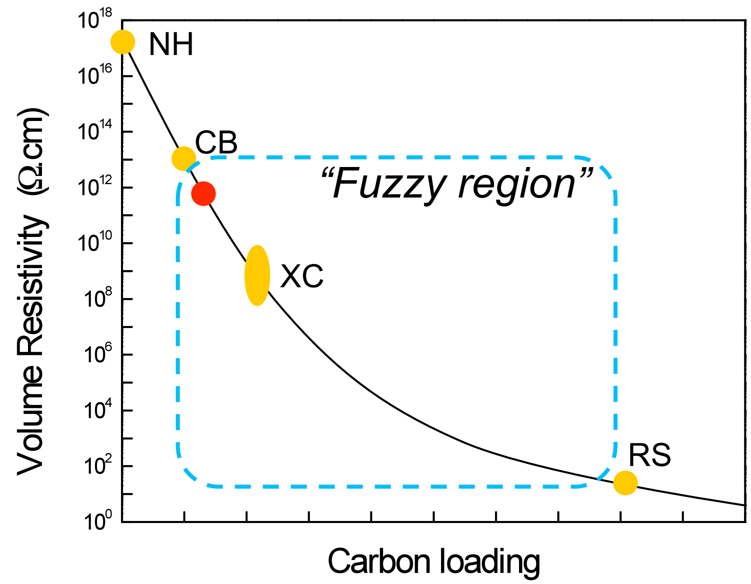
Develop new Kapton type film with resistivity between that of CB and XC:

- Carbon loading: XC has 2-3 times the C-loading of CB, which affects significantly the RF transmission
  - Target: <50% more carbon than CB

Note: Kapton is an anisotropic material; surface and bulk resistivities don't scale.

- Surface resistivity:
  - XC: ~10^7 Ohm/sq
  - CB: ~10^{13} Ohm/sq
  - Target: ~10^{10} Ohm/sq
- The new material will be in the "fuzzy region", where reproducibility and uniformity can vary greatly.

But does it matter?



Expected place of the proposed material with respect to CB and XC

Summary

- Ge-coated films / materials are often used on external spacecraft surfaces for thermal and IESD control
- Problems occur when RF supersedes IESD performance (antennas)
- Ge conductivity is suppressed at low (cryogenic) temperatures, which exaggerates IESD issues
- We have a reasonable IESD understanding and suitable mitigation measures for JUNO, but future missions can benefit from a new materials engineering approach.