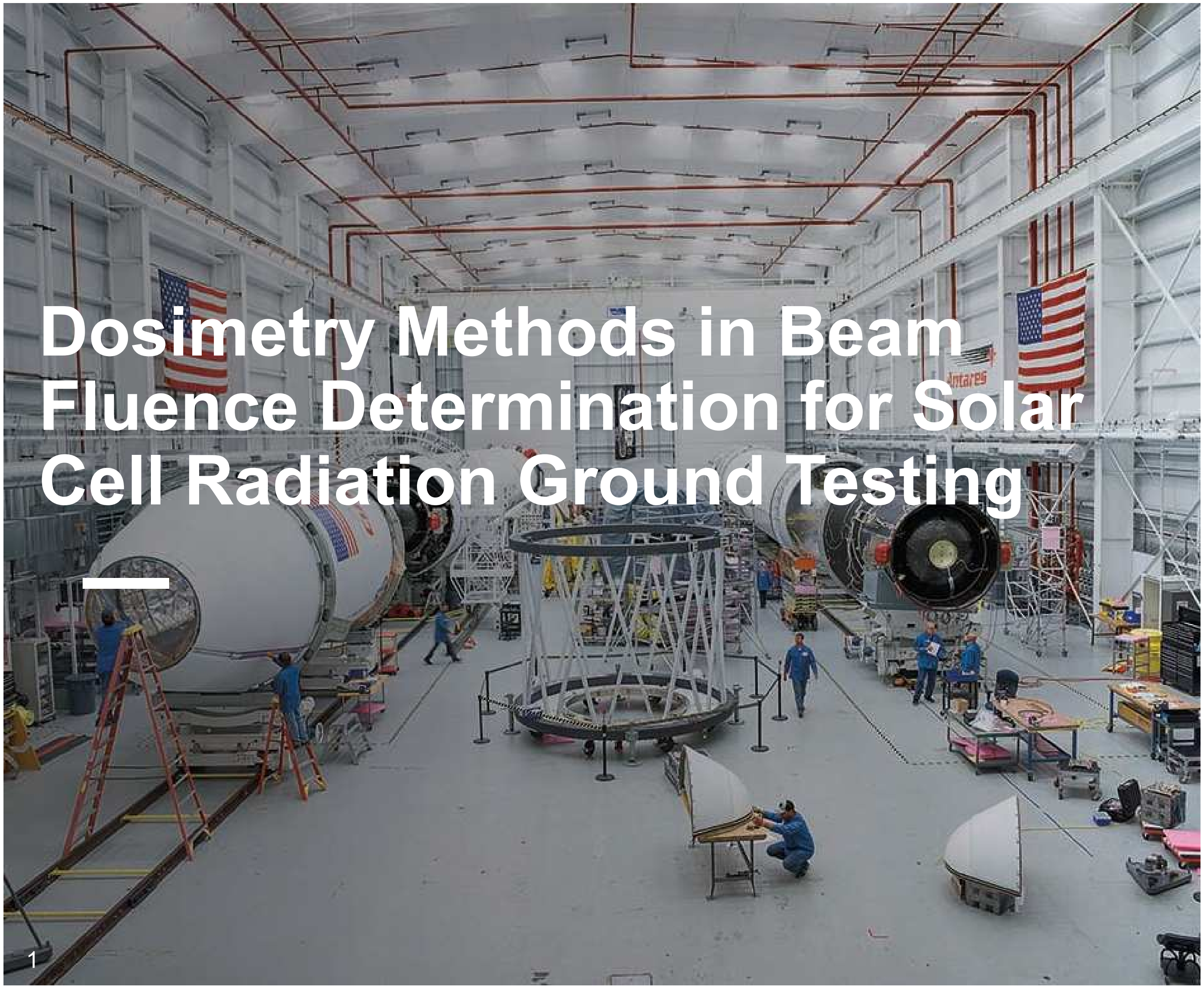


Dosimetry Methods in Beam Fluence Determination for Solar Cell Radiation Ground Testing

Scott Messenger
Senior Staff Space
Survivability Physicist
Steven Witczak
Jeff Warner

April 25, 2024

2024 Space Power Workshop

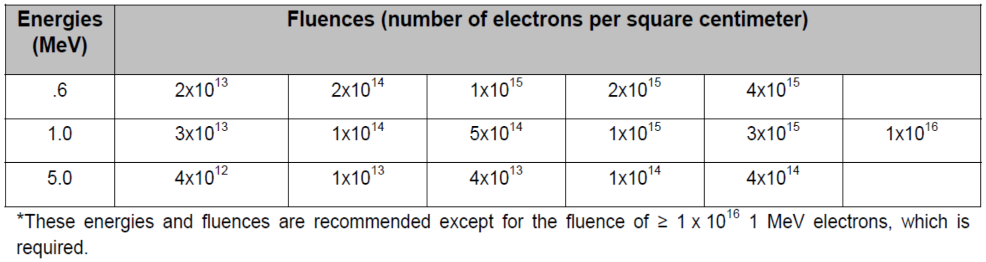
Outline

- ***Motivation/Purpose***
  - ***AIAA S-111A & ECSS-E-ST-20-08C standards***
  - Ground Test Data Anomalies
- Prior Experience in Electron Transport @ NeoBeam Facility (2010)
- Facility Descriptions
- Ionizing vs. Nonionizing Energy Deposition
  - Stopping power (dE/dx) vs NIEL
  - Effect of threshold energy on NIEL
- MCNP6 Transport Results
  - TID vs DDD deposition
  - Derived fluences for ground testing
- Summary
- Path Forward

AIAA S-111A (2014) US Space PV Standard

- Currently in revision
- Section 8 addresses electron & proton ground testing to develop the necessary parametric degradation curves for EQFLUX/SCREAM applications
- Provides Tables of suggested energies/fluences for cell degradation properties

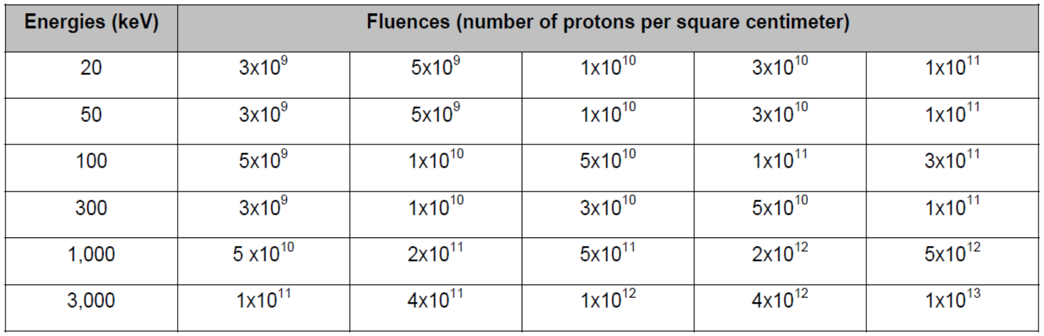
Table 2 — Electron energies and fluences*



Energies (MeV)	**Fluences (number of electrons per square centimeter)**					
.6	$2x10^{13}$	$2x10^{14}$	$1x10^{15}$	$2x10^{15}$	$4x10^{15}$	
1.0	$3x10^{13}$	$1x10^{14}$	$5x10^{14}$	$1x10^{15}$	$3x10^{15}$	$1x10^{16}$
5.0	$4x10^{12}$	$1x10^{13}$	$4x10^{13}$	$1x10^{14}$	$4x10^{14}$	

*These energies and fluences are recommended except for the fluence of ≥ 1×10^{16} 1 MeV electrons, which is required.

Table 3 — Suggested proton energies



Energies (keV)	**Fluences (number of protons per square centimeter)**				
20	$3x10^{9}$	$5x10^{9}$	$1x10^{10}$	$3x10^{10}$	$1x10^{11}$
50	$3x10^{9}$	$5x10^{9}$	$1x10^{10}$	$3x10^{10}$	$1x10^{11}$
100	$5x10^{9}$	$1x10^{10}$	$5x10^{10}$	$1x10^{11}$	$3x10^{11}$
300	$3x10^{9}$	$1x10^{10}$	$3x10^{10}$	$5x10^{10}$	$1x10^{11}$
1,000	$5 x10^{10}$	$2x10^{11}$	$5x10^{11}$	$2x10^{12}$	$5x10^{12}$
3,000	$1x10^{11}$	$4x10^{11}$	$1x10^{12}$	$4x10^{12}$	$1x10^{13}$

- Dosimetry stated to require calibrated Faraday cups (“shall” statement)

“The fluence **shall** be measured using a validated **Faraday cup** for dosimetry and if desired, supplemented by other methods. The dosimetry shall be accurate to at least ±10%.”

ECSS-E-ST-20-08C (2012) EU Space PV Standard

- Recently revised in 2023
- Refers to ISO 23038 “Space systems – Space solar sells – Electron and proton irradiation test methods” for guidance in performing the tests
- Sections 7.5.13 & 7.5.14 addresses electron & proton ground testing, respectively
- Provides guidelines for beam energies & fluxes dependent on given mission
  - Electrons: **Only 1 MeV required** w/ flux < 5×10^{11} $e^{-}/cm^{2}/s$
  - Protons: 2 energies required to confirm validity of 1 MeV electron data
- No explicit direction on beam dosimetry
  - Allows beam facility choice of method
  - ISO 23038 referral (contains some comments regarding Faraday cups – no “shalls”)

Outline

- ***Motivation/Purpose***
  - AIAA S-111A & ECSS-E-ST-20-08C standards
  - ***Ground Test Data Anomalies***
- Prior Experience in Electron Transport @ NeoBeam Facility (2010)
- Facility Descriptions
- Ionizing vs. Nonionizing Energy Deposition
  - Stopping power (dE/dx) vs NIEL
  - Effect of threshold energy on NIEL
- MCNP6 Transport Results
  - TID vs DDD deposition
  - Derived fluences for ground testing
- Summary
- Path Forward

SolAero by Rocket Lab Results (2023 SPW)

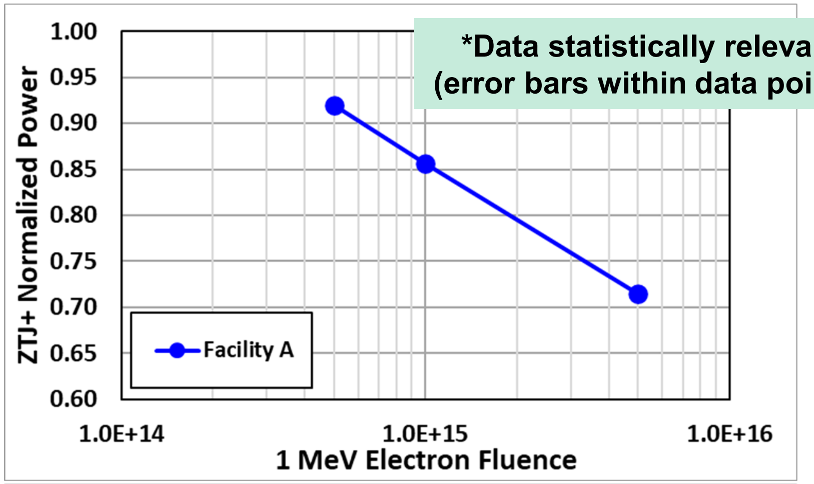
RADIATION TESTING AT
SOLAERO TECHNOLOGIES

Data provided by SolAero by Rocket lab

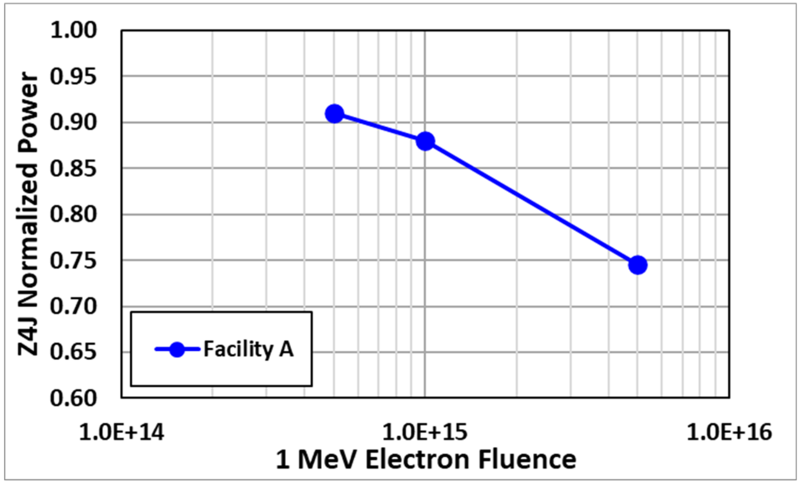
High energy electron exposures

Facility A

***Dosimetry: Faraday cup w/ adjusted energies**



*Data statistically relevant (error bars within data points)



SolAero by Rocket Lab Results (2023 SPW)

RADIATION TESTING AT
SOLAERO TECHNOLOGIES

Data provided by SolAero by Rocket lab

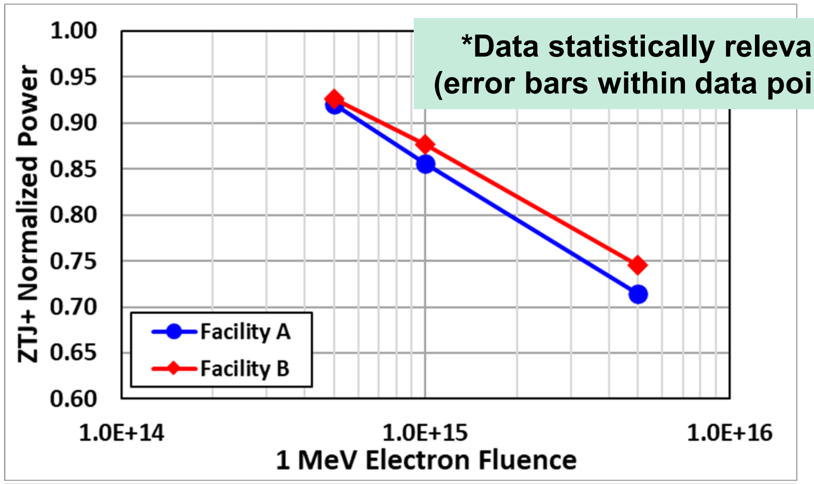
High energy electron exposures

Facility A

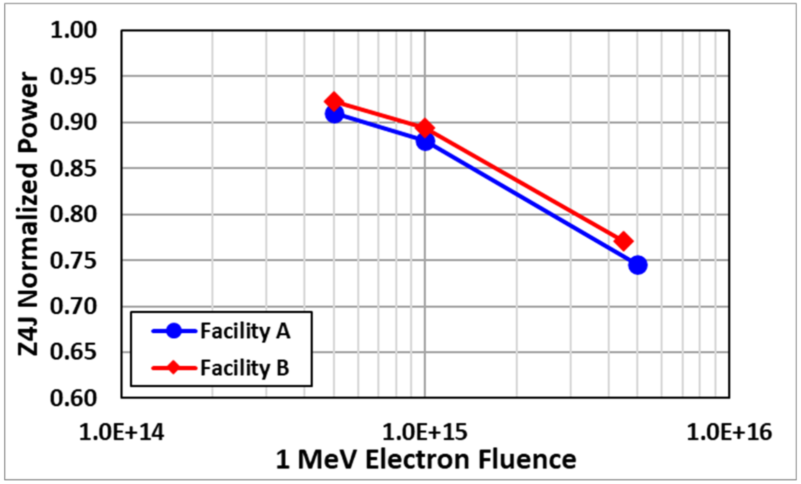
***Dosimetry: Faraday cup w/ adjusted energies**

Facility B

***Dosimetry: Radiochromic films**



*Data statistically relevant
(error bars within data points)



SolAero by Rocket Lab Results (2023 SPW)

RADIATION TESTING AT
SOLAERO TECHNOLOGIES

Data provided by SolAero by Rocket lab

High energy electron exposures

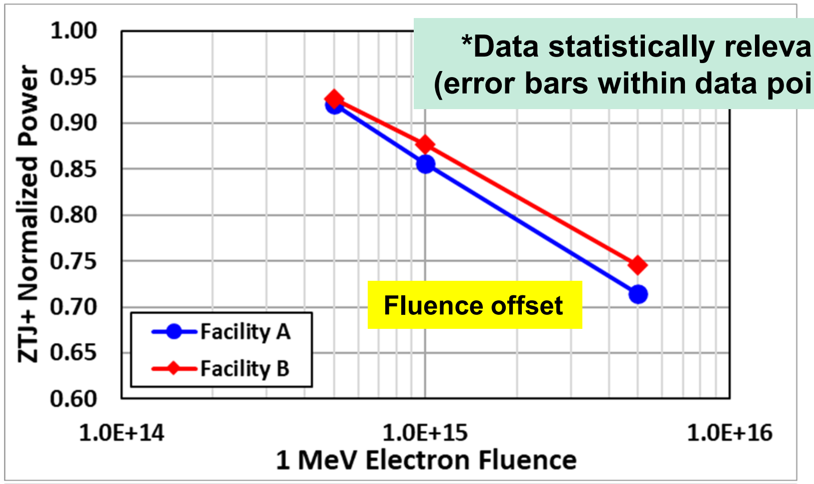
Facility A

***Dosimetry: Faraday cup w/ adjusted energies**

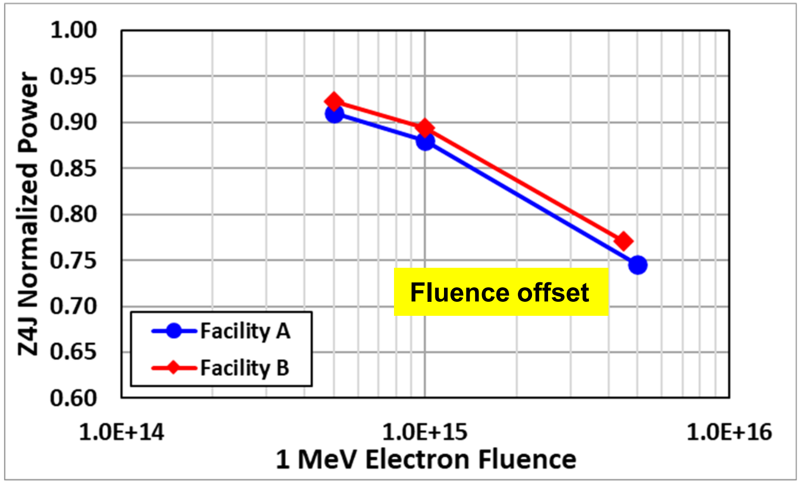
Facility B

***Dosimetry: Radiochromic films**

Noted *linear dependence in fluence* exists



*Data statistically relevant
(error bars within data points)



SolAero by Rocket Lab Results (2023 SPW)

RADIATION TESTING AT
SOLAERO TECHNOLOGIES

Data provided by SolAero by Rocket lab

High energy electron exposures

Facility A

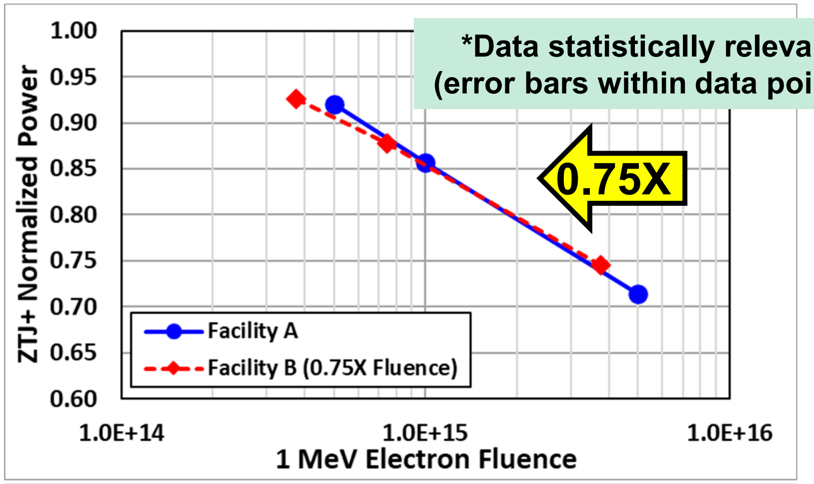
- *Dosimetry: Faraday cup w/ adjusted energies

Facility B

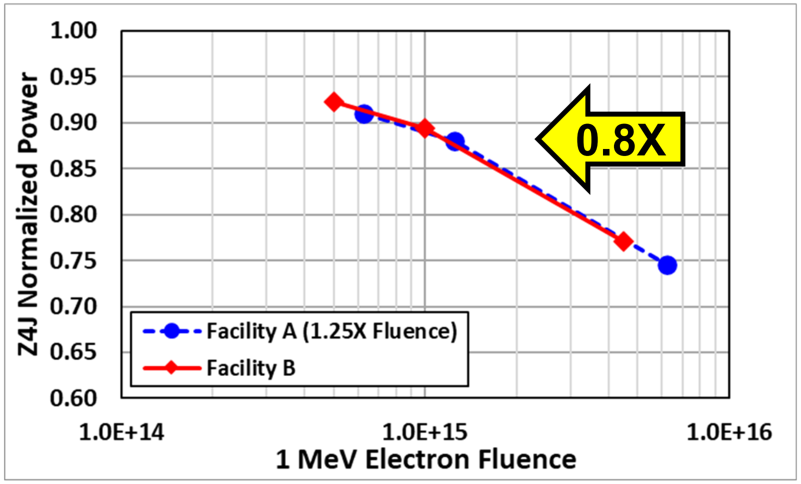
- *Dosimetry: Radiochromic films
- *Scaled fluence to meet Facility A results

Noted *linear dependence in fluence* exists (20 to 25% difference)

***Similar differences exist for the other PV parameters**



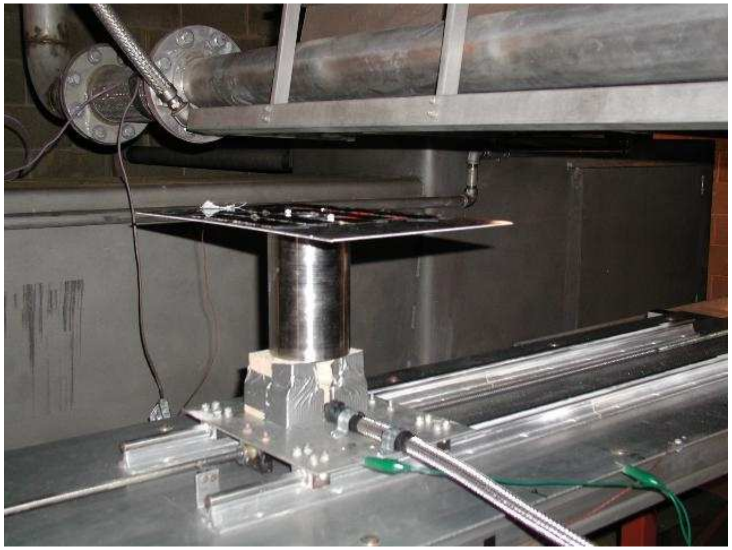
*Data statistically relevant (error bars within data points)

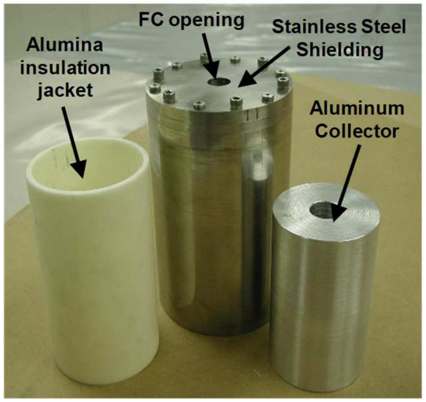


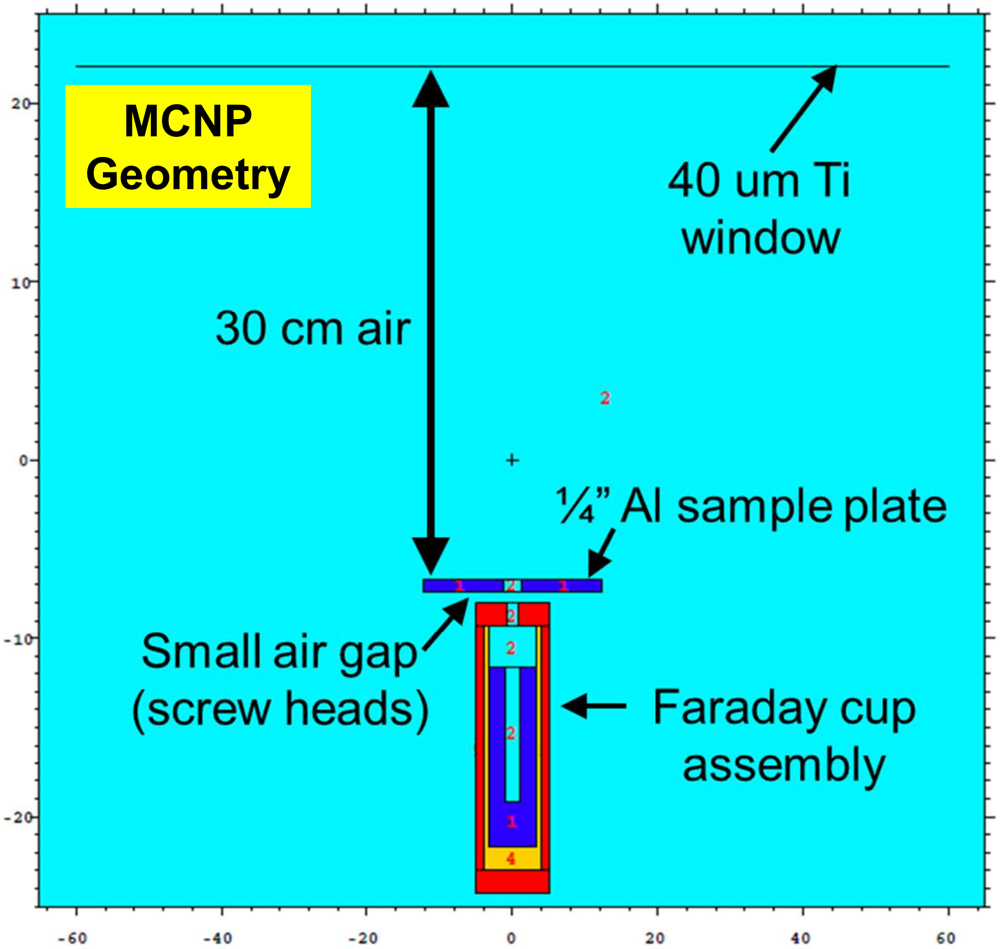
Outline

- Motivation/Purpose
  - AIAA S-111A & ECSS-E-ST-20-08C standards
  - Ground Test Data Anomalies
- ***Experience in Electron Transport @ NeoBeam Facility (2010)***
- Facility Descriptions
- Ionizing vs. Nonionizing Energy Deposition
  - Stopping power (dE/dx) vs NIEL
  - Effect of threshold energy on NIEL
- MCNP6 Transport Results
  - TID vs DDD deposition
  - Derived fluences for ground testing
- Summary
- Path Forward

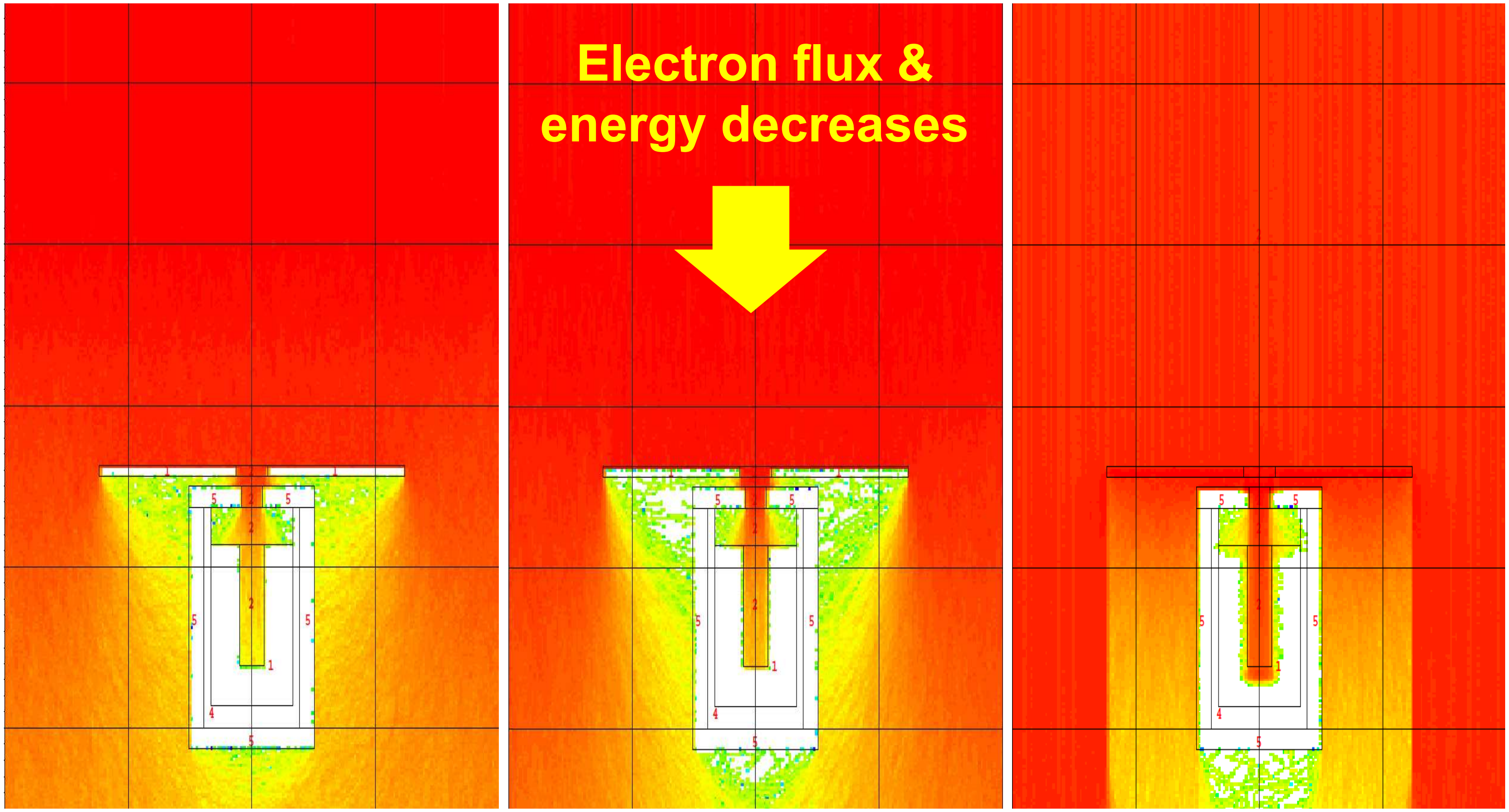
NeoBeam Experience (IEEE Trans. Nucl. Sci. 57, 3400 (2010)







NeoBeam Experience (IEEE Trans. Nucl. Sci. 57, 3400 (2010)



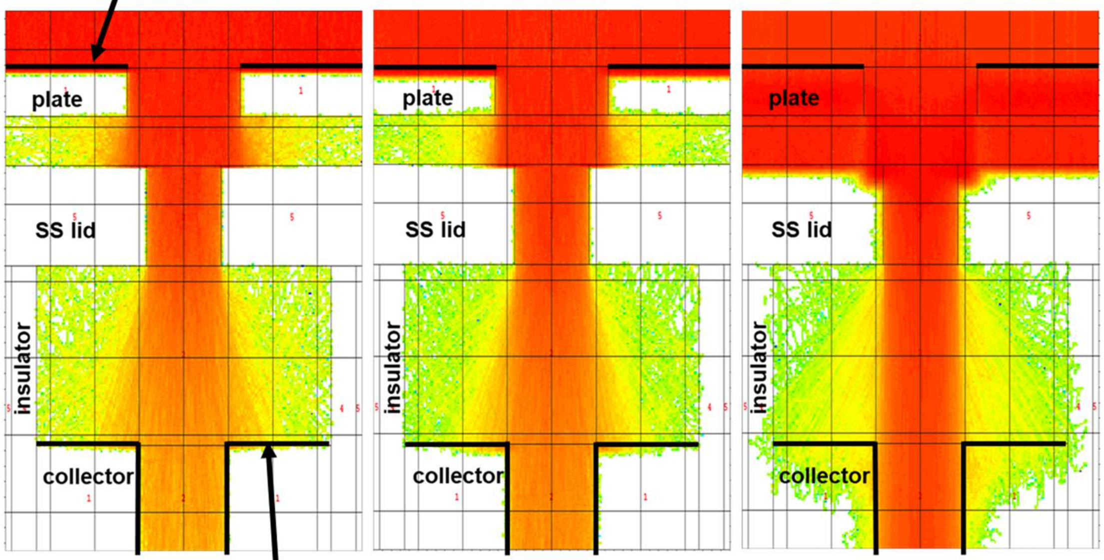
Electron flux & energy decreases

600 keV **1 MeV** **5 MeV**

NeoBeam Experience (IEEE Trans. Nucl. Sci. 57, 3400 (2010))

- MCNP simulations found 2 competing mechanisms
  - Flux at sample location w.r.t. Faraday cup charge collection **(increased DDD)**

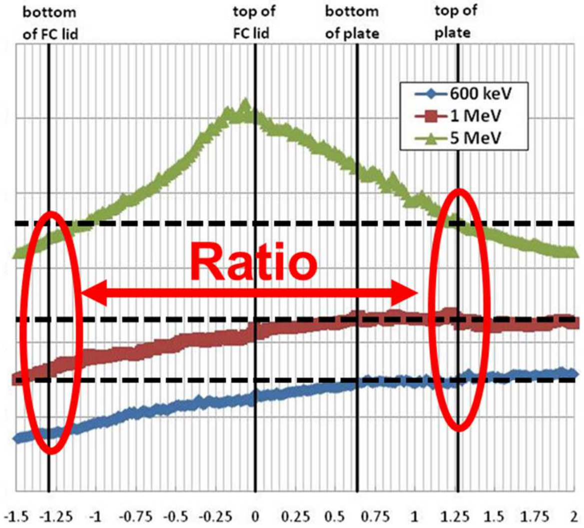
Flux at sample



600 keV **1 MeV** **5 MeV**

Flux collected by FC

IEEE Trans. Nucl. Sci 57, 3400 (2010)

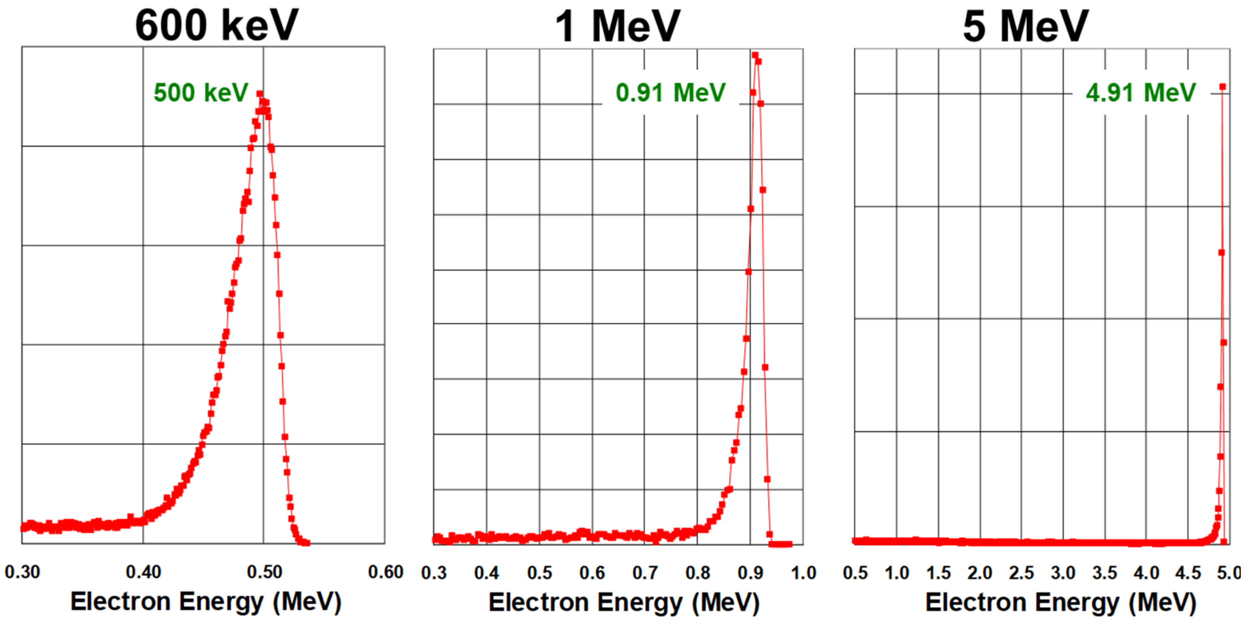


Fluence Factor: sample/FC

5 MeV: 1.075 (7.5%)
1 MeV: 1.482 (50%)
600 keV: 1.899 (90%)

NeoBeam Experience (IEEE Trans. Nucl. Sci. 57, 3400 (2010)

- MCNP simulations found 2 competing mechanisms
  - Energy deposited into DD due to electron beam degradation **(deceased DDD)**



DDD deposition Factors: Energy dependence & DDD deposition

5 MeV: 0.858 (3.57 MeV equivalent)
1 MeV: 0.838 (0.83 MeV equivalent)
600 keV: 0.528 (0.413 MeV equivalent)

NeoBeam Experience (IEEE Trans. Nucl. Sci. 57, 3400 (2010)

- MCNP simulations found 2 competing mechanisms
  - Flux at sample location w.r.t. Faraday cup charge collection **(increased DDD)**
  - Energy deposited into DD due to electron beam degradation **(deceased DDD)**

Beam Energy	Flux	Energy	Total
600 keV	1.899	0.528	1.003
1 MeV	1.482	0.838	1.242
5 MeV	1.075	0.858	0.922

Net 25% extra effect due to beam conditions/dosimetry techniques

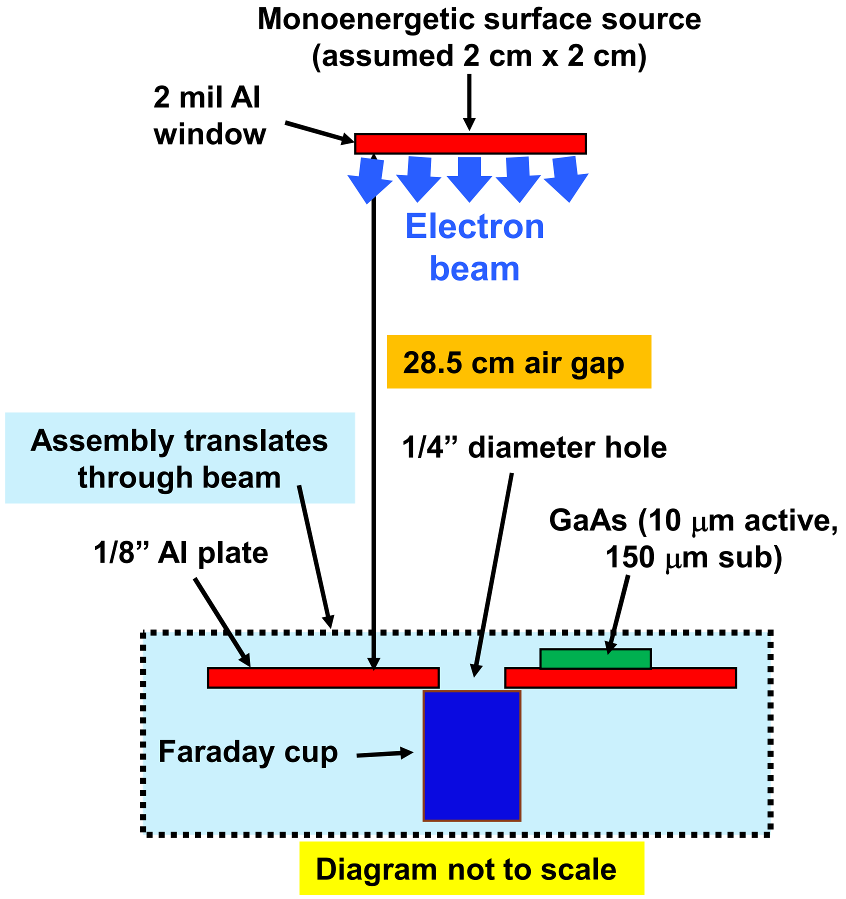
IMPACT (2010)

***Increased awareness of beam geometry noted – need both Flux & DDD deposition**
***MC simulations successfully used to explain discrepancies in experimental data and analyze other beam/source geometries**

Outline

- Motivation/Purpose
  - AIAA S-111A & ECSS-E-ST-20-08C standards
  - Ground Test Data Anomalies
- Prior Experience in Electron Transport @ NeoBeam Facility (2010)
- ***Facility Descriptions***
- Ionizing vs. Nonionizing Energy Deposition
  - Stopping power (dE/dx) vs NIEL
  - Effect of threshold energy on NIEL
- MCNP6 Transport Results
  - TID vs DDD deposition
  - Derived fluences for ground testing
- Summary
- Path Forward

Electron Radiation Facility A - Geometry



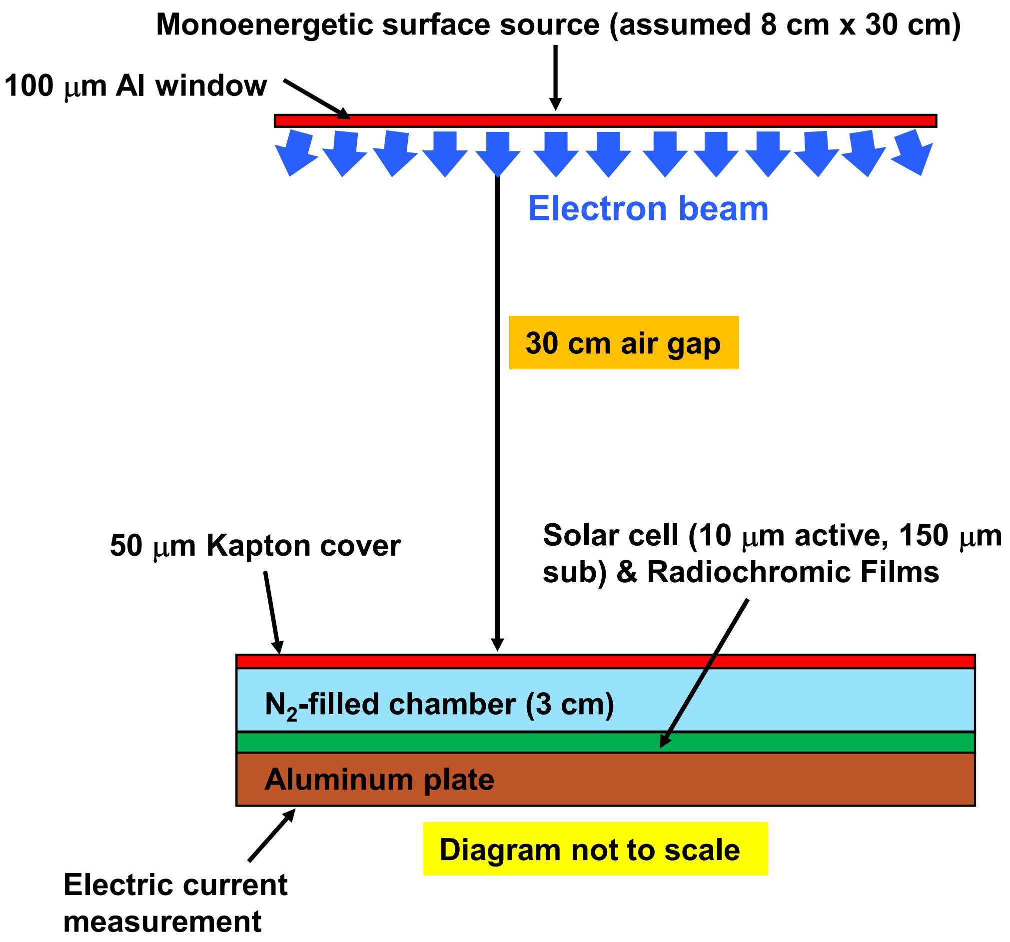
Dosimetry (Facility A)

1. Calibrated Faraday Cup (counts # charge particles/Coulombs)
   a. Energy/fluence "corrected" for electron transport effects using Monte Carlo simulation code ITS (Integrated Tiger Series) – ETRAN
   b. Faraday cup used to collect/integrate charge to drive beam current
2. Secondary dosimetry obtained using NIST-calibrated calorimeter
3. Energy calibrations using solid state detectors over a range of terminal energies

Corrected Energies

0.78 MeV (0.7 MeV equiv.)
1.077 MeV (1 MeV equiv.)
2.05 MeV (2 MeV equiv.)

Electron Radiation Facility B - Geometry



Dosimetry

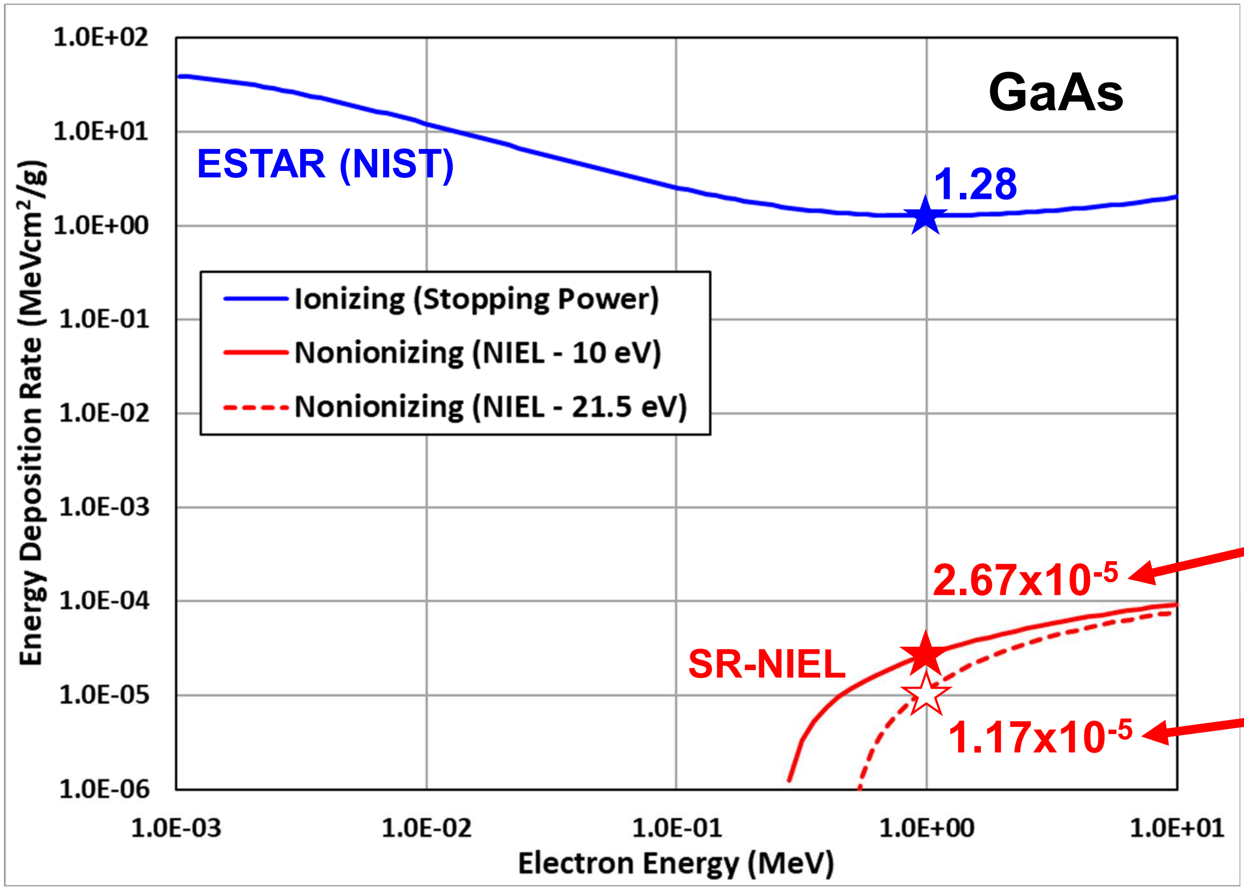
1. Calibrated radiochromic films (gets ionizing dose via optical absorption @ 510 nm)
    1. Far West Technologies (commercial)
    2. Electric current from aluminum plate used to determine beam current
2. FWT films had secondary calibrations using ^{60}Co gamma source
3. ^{60}Co gamma source calibrated using Fricke ionizing dosimeter
4. Energy calibration via neutron-induced Ag activation (using $^{9}Be(\gamma,n)^{8}Be$ to get neutrons)

Outline

- Motivation/Purpose
  - AIAA S-111A & ECSS-E-ST-20-08C standards
  - Ground Test Data Anomalies
- Prior Experience in Electron Transport @ NeoBeam Facility (2010)
- Facility Descriptions
- ***Ionizing vs. Nonionizing Energy Deposition***
  - ***Stopping power (dE/dx) vs NIEL***
  - ***Effect of threshold energy on NIEL***
- MCNP6 Transport Results
  - TID vs DDD deposition
  - Derived fluences for ground testing
- Summary
- Path Forward

NORTHROP GRUMMAN

Energy Loss Rates ($MeVcm^2/g$) – Ionizing vs Nonionizing

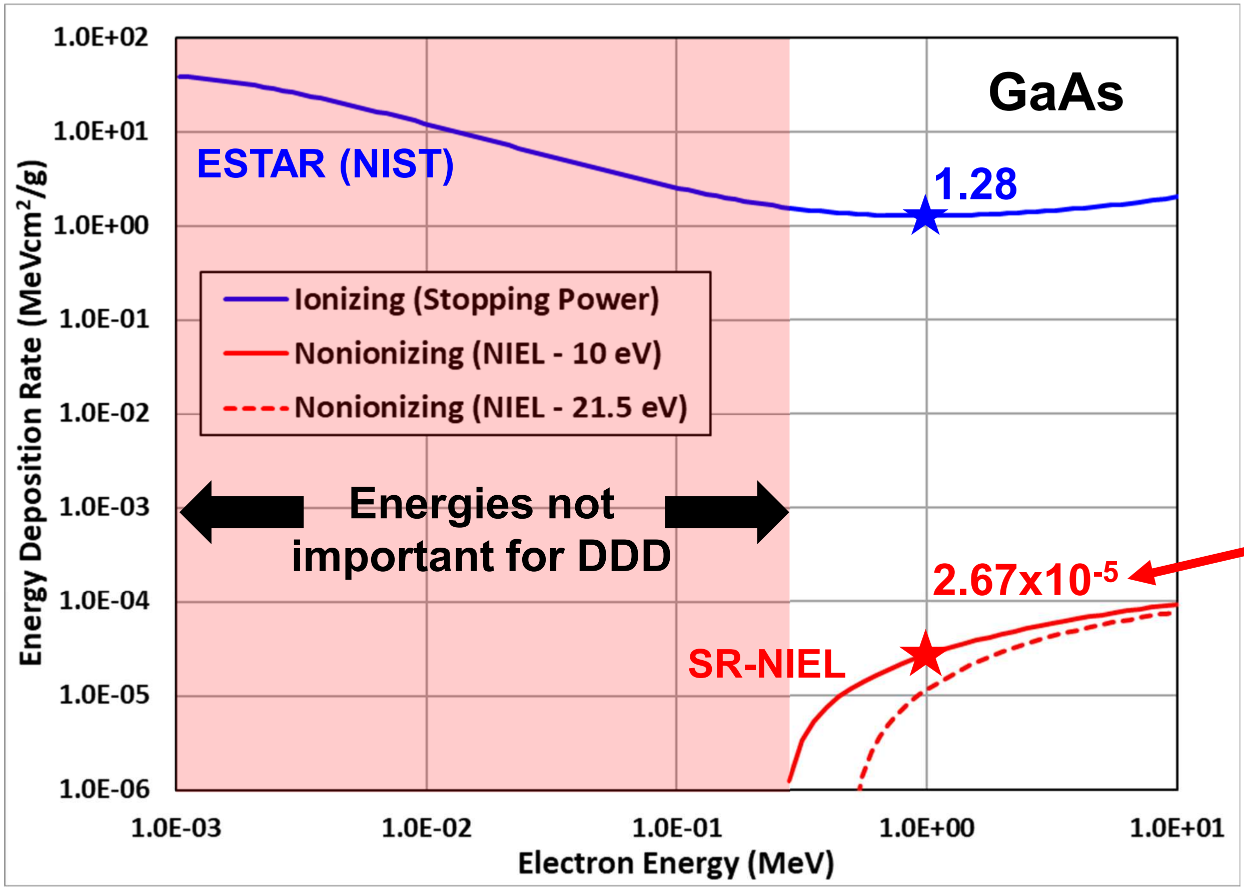


***Although most of the electron energy is lost due to ionization effects (stopping power, dE/dx), displacement damage is the primary solar cell (pn junction) damage mechanism (NIEL) and has a hard minimum energy to produce a displacement (T_d)**

Assumes 10 eV displacement threshold energy (T_d) –

Assumes 21.5 eV displacement threshold energy (T_d) –

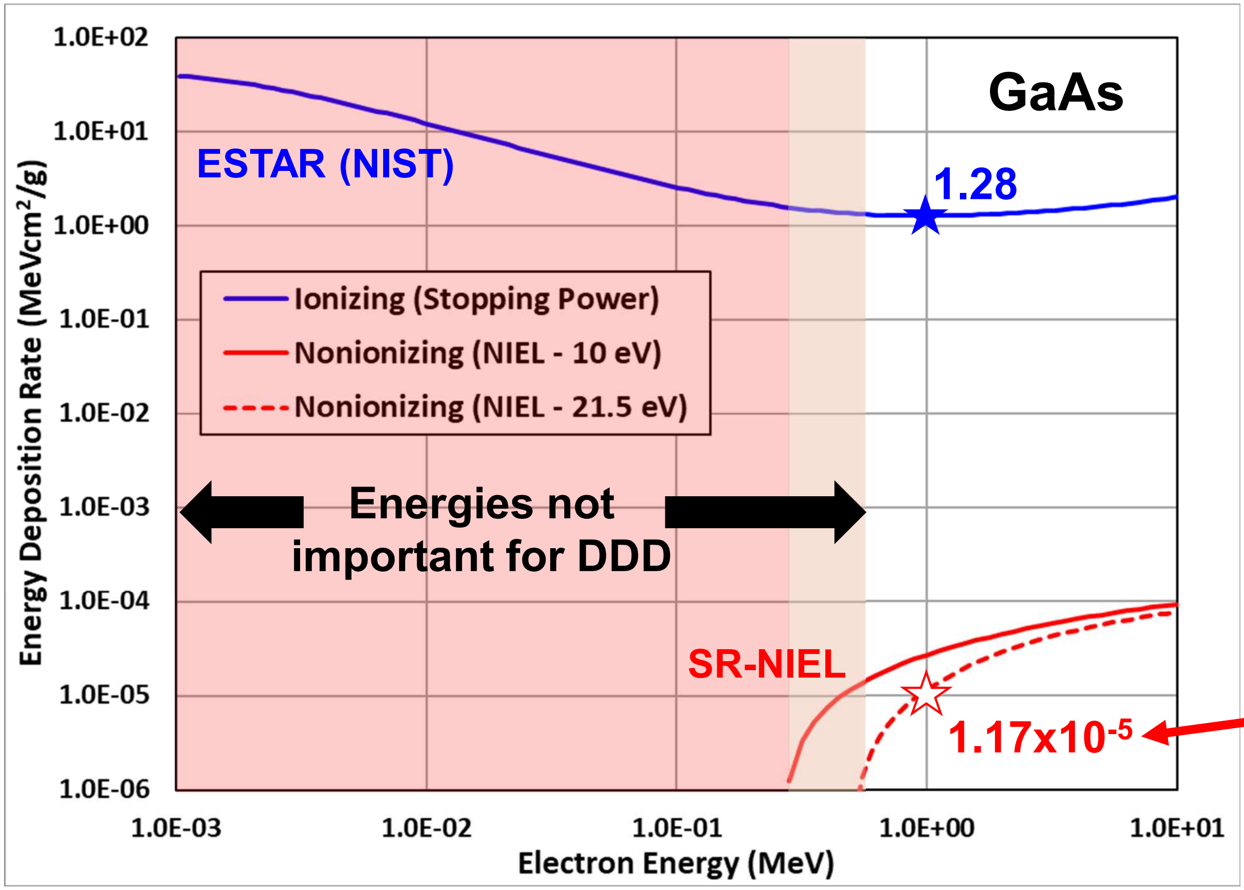
Energy Loss Rates (MeVcm^2/g) – Ionizing vs Nonionizing



*Although most of the electron energy is lost due to ionization effects (stopping power, dE/dx), displacement damage is the primary solar cell (pn junction) damage mechanism (NIEL) and has a hard minimum energy to produce a displacement (T_d)

Assumes 10 eV displacement threshold energy (T_d) –

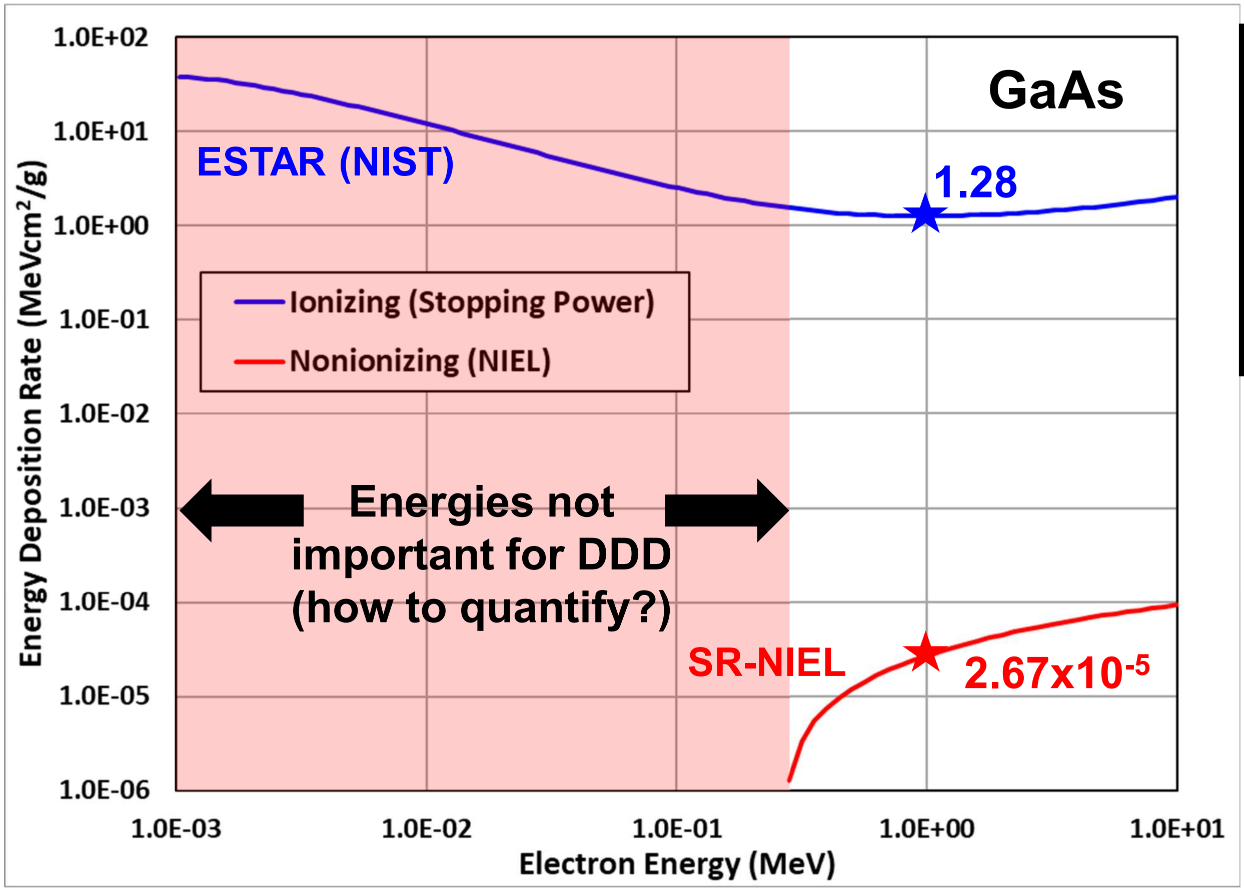
Energy Loss Rates (MeVcm^2/g) – Ionizing vs Nonionizing



***Although most of the electron energy is lost due to ionization effects (stopping power, dE/dx), displacement damage is the primary solar cell (pn junction) damage mechanism (NIEL) and has a hard minimum energy to produce a displacement (T_d)**

Assumes 21.5 eV displacement threshold energy (T_d) –

Energy Loss Rates ($MeVcm^2/g$) – Ionizing vs Nonionizing



***Ionizing Dose Calculation**

D_i (MeV/g) = dE/dx ($MeVcm^2/g$) * ϕ (e^-/cm^2)

***Displacement Damage Dose Calculation**

D_d (MeV/g) = NIEL ($MeVcm^2/g$) * ϕ (e^-/cm^2)

…..or, for energy spectra, ϕ is changed to differential energy spectra ($d\phi/dE$) and integrated over energy.

*We can convert derived TID & DDD values to equivalent fluences using "inverse" equations (*i.e.* divide by dE/dx or NIEL)

Outline

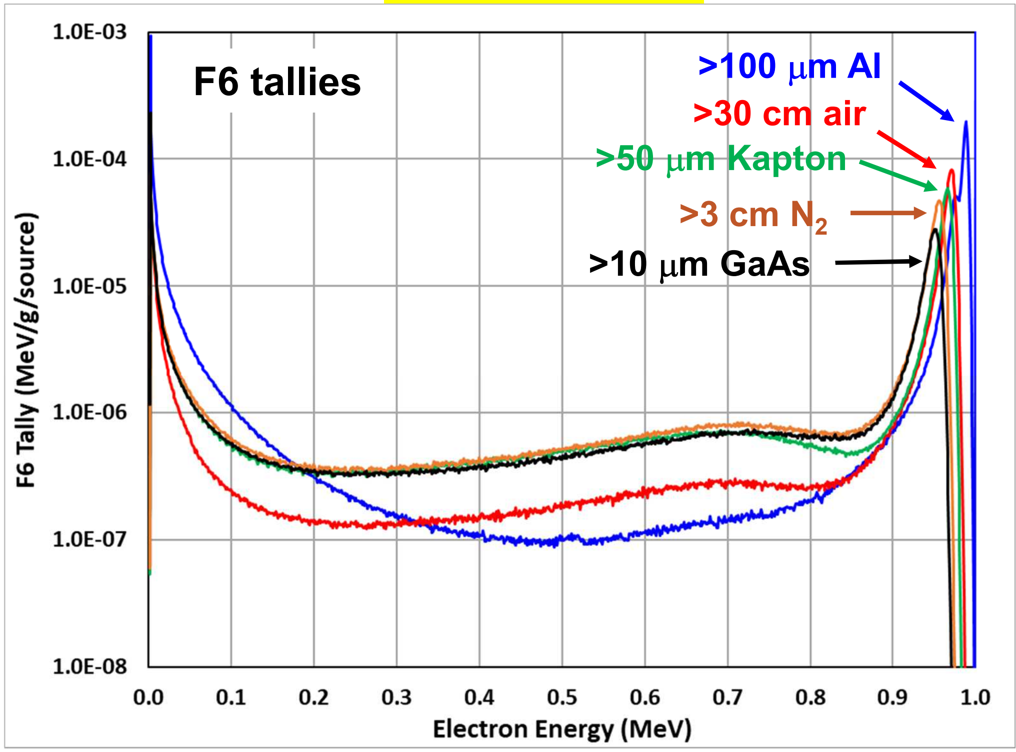
- Motivation/Purpose
  - AIAA S-111A & ECSS-E-ST-20-08C standards
  - Ground Test Data Anomalies
- Prior Experience in Electron Transport @ NeoBeam Facility (2010)
- Facility Descriptions
- Ionizing vs. Nonionizing Energy Deposition
  - Stopping power (dE/dx) vs NIEL
  - Effect of threshold energy on NIEL
- ***MCNP6 Transport Results***
  - ***TID vs DDD deposition***
  - ***Derived fluences for ground testing***
- Summary
- Path Forward

Electron Facility B (TID/DDD vs Distance from Window)

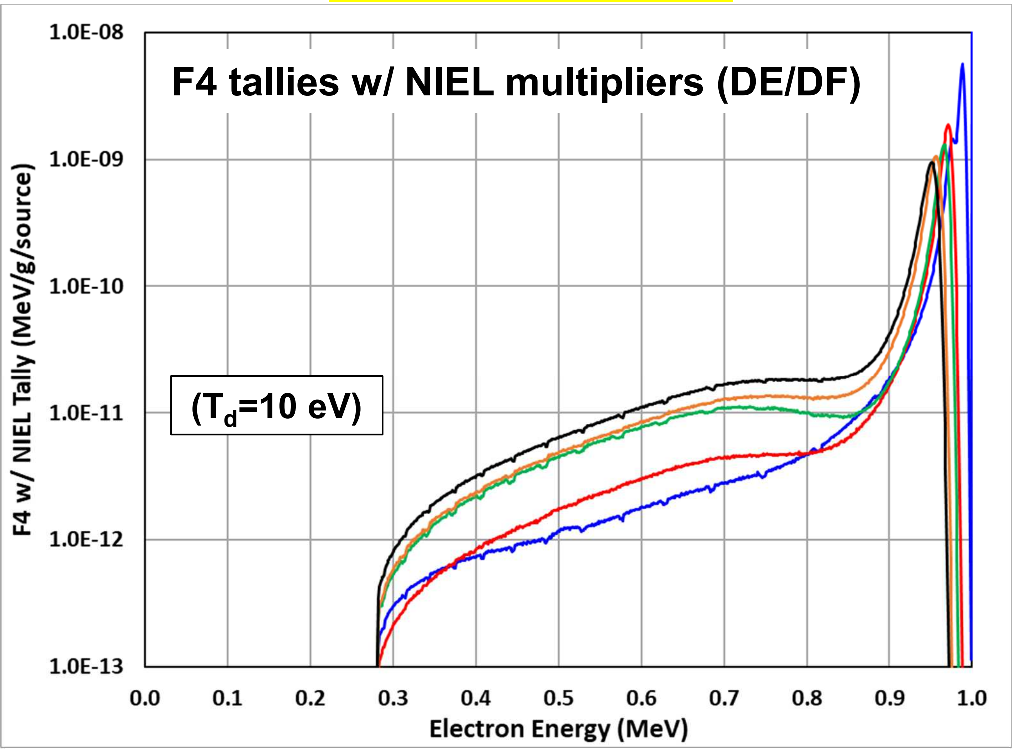
MCNP6.2

1 MeV Electrons

Ionizing Dose



Nonionizing Dose



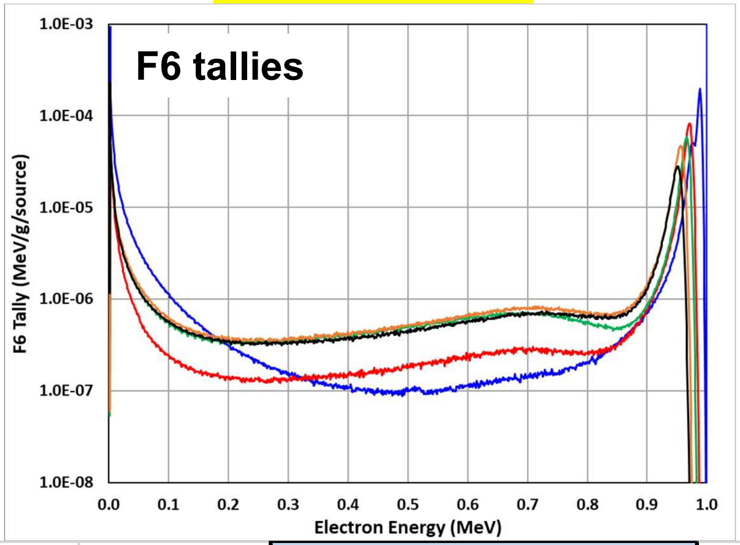
Notes: Peak energy decreases and develops spread as distance from source increases

Electron Facility B (TID/DDD vs Distance from Window)

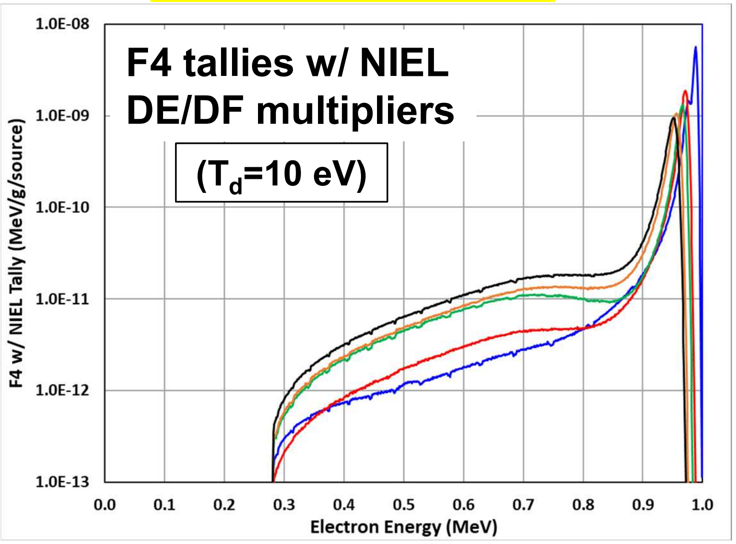
MCNP6.2

1 MeV Electrons

Ionizing Dose



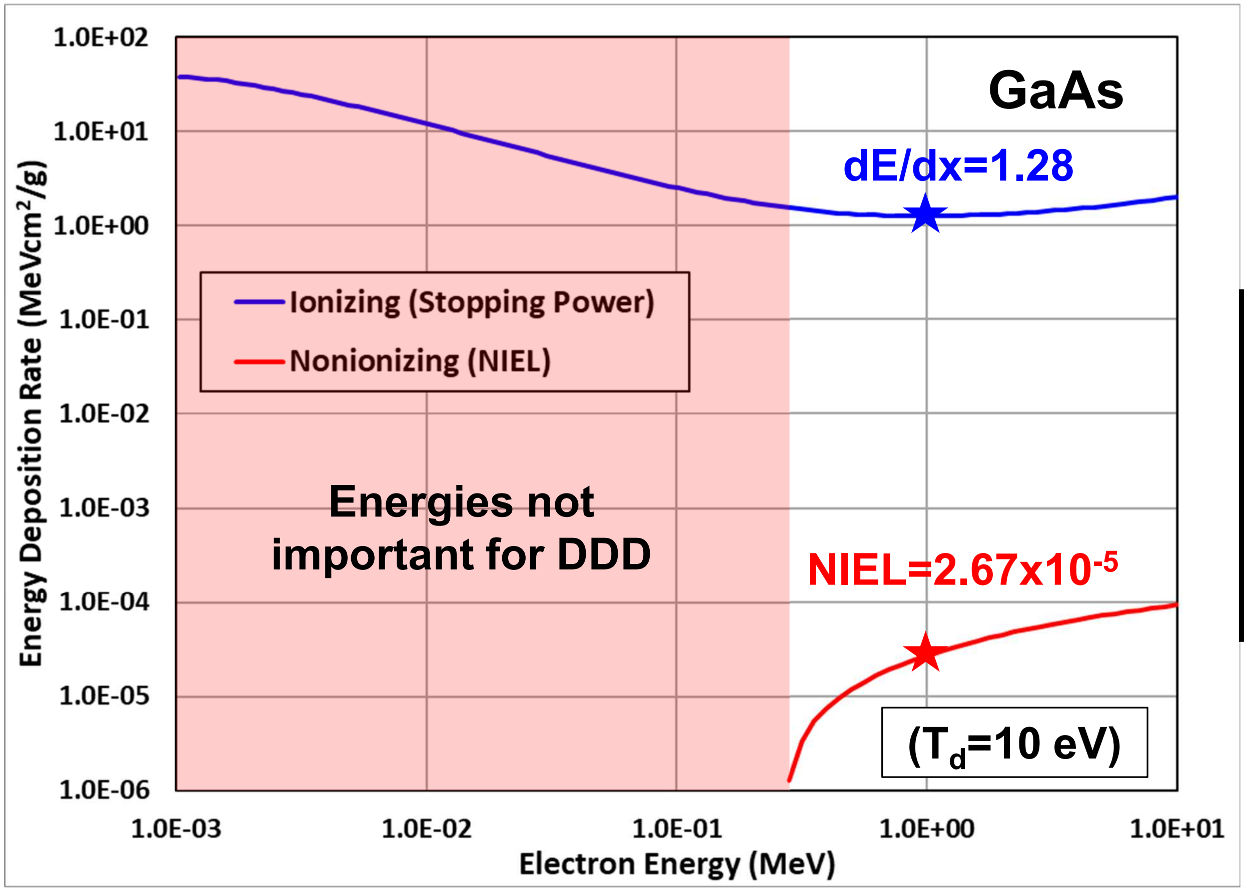
Nonionizing Dose



Integrated values over volume (F4/F6)

		T_d=10 eV	
	Layer	F4 w/ NIEL (DDD in MeV/g/source)	F6 (TID in MeV/g/source)
sum	>100 um Al	1.11E-07	6.08E-03
	>30 cm air	3.10E-08	1.95E-03
	>50 um Kapton	2.61E-08	1.97E-03
	>3 cm N2	2.59E-08	1.99E-03
	>10 um GaAs	2.67E-08	1.59E-03
	>150 um Ge	3.33E-08	2.43E-03

Energy Loss Rates (MeVcm²/g) – Ionizing vs Nonionizing



***We can convert derived TID & DDD values to equivalent fluences using "inverse" equations (*i.e.* divide by dE/dx or NIEL)**

***Ionizing Dose Calculation**

D_i (MeV/g) = dE/dx (MeVcm²/g) * ϕ (e^-/cm²)

***Displacement Damage Dose Calculation**

D_d (MeV/g) = NIEL (MeVcm²/g) * ϕ (e^-/cm²)

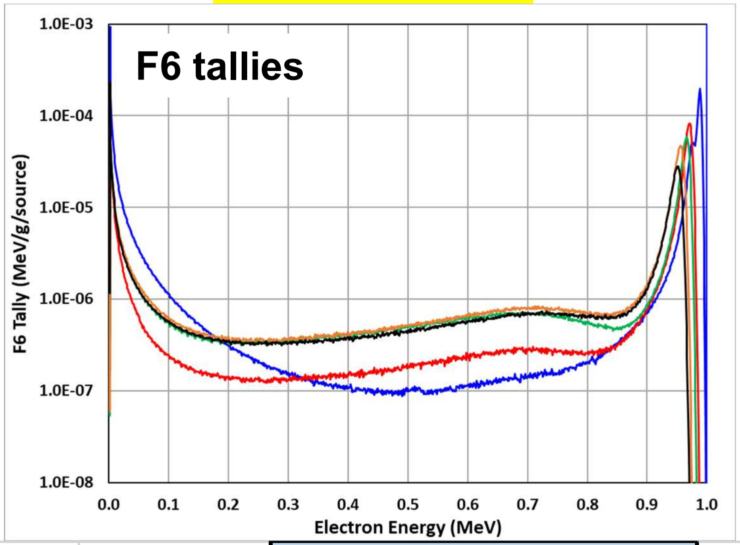
…..or, for energy spectra, ϕ is changed to differential energy spectra ($d\phi/dE$) and integrated over energy.

Electron Facility B (TID/DDD vs Distance from Window)

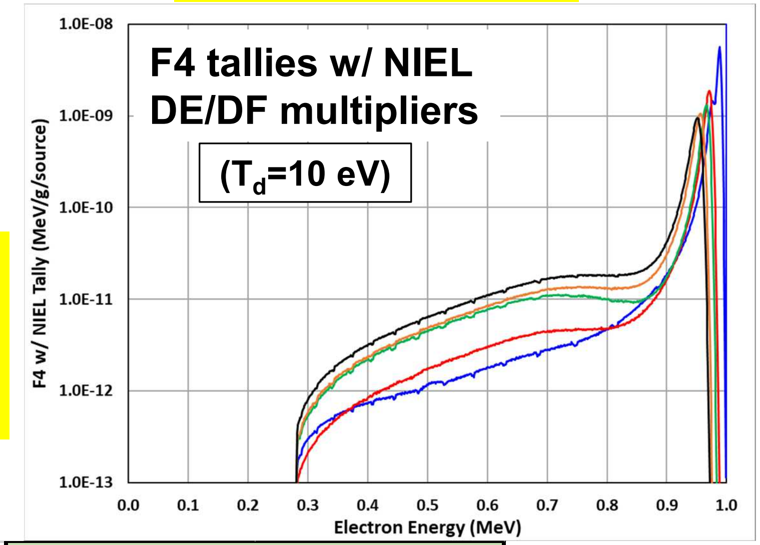
Ionizing Dose

1 MeV Electrons

Nonionizing Dose



Integrated values over volume (F4/F6)



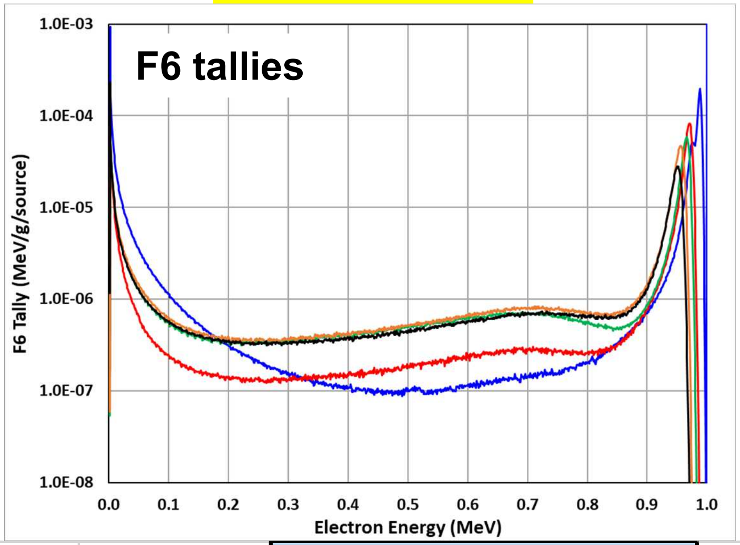
		T_d=10 eV		Derived 1 MeV Electron Flux	
	Layer	F4 w/ NIEL (DDD in MeV/g/source)	F6 (TID in MeV/g/source)	DDD	TID
sum	>100 um Al	1.11E-07	6.08E-03	4.18E-03	4.75E-03
	>30 cm air	3.10E-08	1.95E-03	1.16E-03	1.52E-03
	>50 um Kapton	2.61E-08	1.97E-03	9.78E-04	1.54E-03
	>3 cm N2	2.59E-08	1.99E-03	9.73E-04	1.56E-03
	>10 um GaAs	2.67E-08	1.59E-03	1.00E-03	1.24E-03
	>150 um Ge	3.33E-08	2.43E-03	1.25E-03	1.90E-03

Electron Facility B (TID/DDD vs Distance from Window)

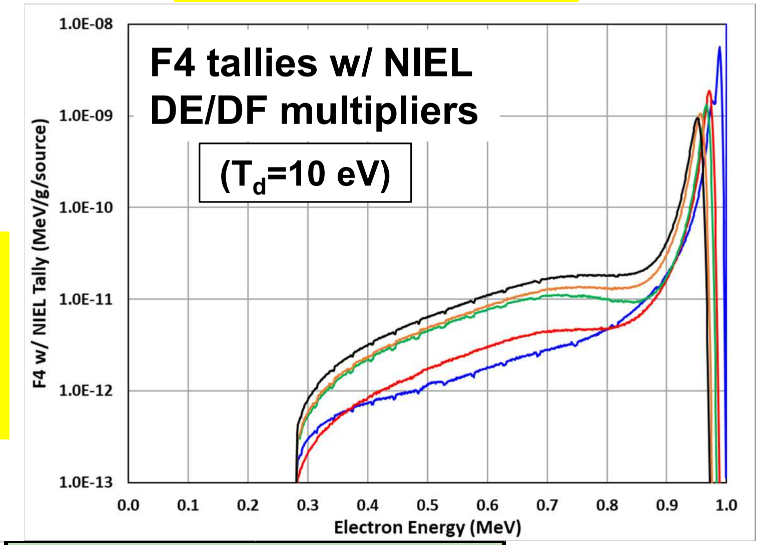
Ionizing Dose

1 MeV Electrons

Nonionizing Dose



Integrated values over volume (F4/F6)



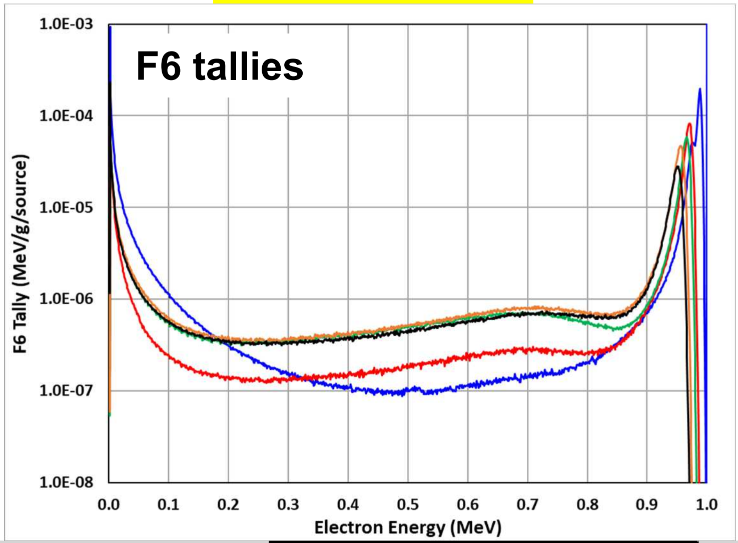
		T_d=10 eV		Derived 1 MeV Electron Flux	
	Layer	F4 w/ NIEL (DDD in MeV/g/source)	F6 (TID in MeV/g/source)	DDD	TID
sum	>100 um Al	1.11E-07	6.08E-03	4.18E-03	4.75E-03
	>30 cm air	3.10E-08	1.95E-03	1.16E-03	1.52E-03
	>50 um Kapton	2.61E-08	1.97E-03	9.78	E-03
	>3 cm N2	2.59E-08	1.99E-03	9.73E-04	1.56E-03
	>10 um GaAs	2.67E-08	1.59E-03	1.00E-03	1.24E-03
	>150 um Ge	3.33E-08	2.43E-03	1.25E-03	1.90E-03

$\phi_{DDD} < \phi_{TID}$

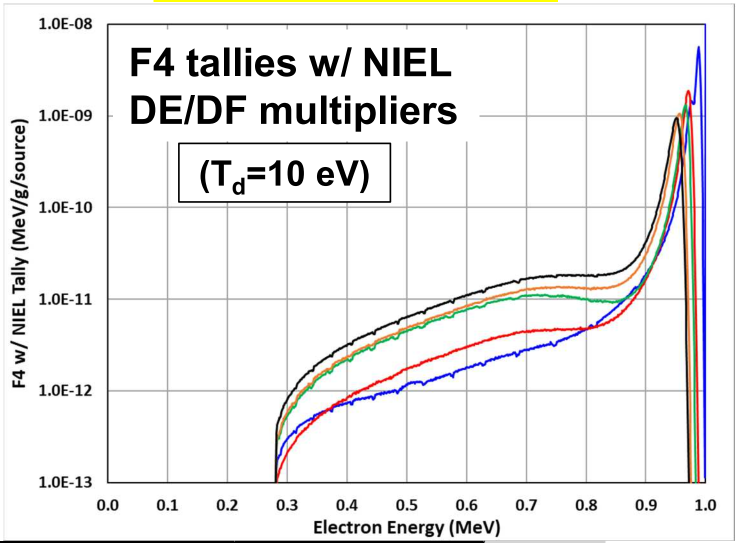
Electron Facility B (TID/DDD vs Distance from Window)

1 MeV Electrons

Ionizing Dose



Nonionizing Dose



		T_d=10 eV		Derived 1 MeV Electron Flux		
	Layer	F4 w/ NIEL (DDD in MeV/g/source)	F6 (TID in MeV/g/source)	DDD	TID	Ratio
sum	>100 um Al	1.11E-07	6.08E-03	4.18E-03	4.75E-03	1.14
	>30 cm air	3.10E-08	1.95E-03	1.16E-03	1.52E-03	1.31
	>50 um Kapton	2.61E-08	1.97E-03	9.78E-04	1.54E-03	1.57
	>3 cm N2	2.59E-08	1.99E-03	9.73E-04	1.56E-03	1.60
	>10 um GaAs	2.67E-08	1.59E-03	1.00E-03	1.24E-03	1.24
	>150 um Ge	3.33E-08	2.43E-03	1.25E-03	1.90E-03	1.52

24% higher flux w/ TID

1.24X

SolAero by Rocket Lab Results (2023 SPW)

RADIATION TESTING AT SOLAERO TECHNOLOGIES

Data provided by SolAero by Rocket lab

High energy electron exposures

Facility A

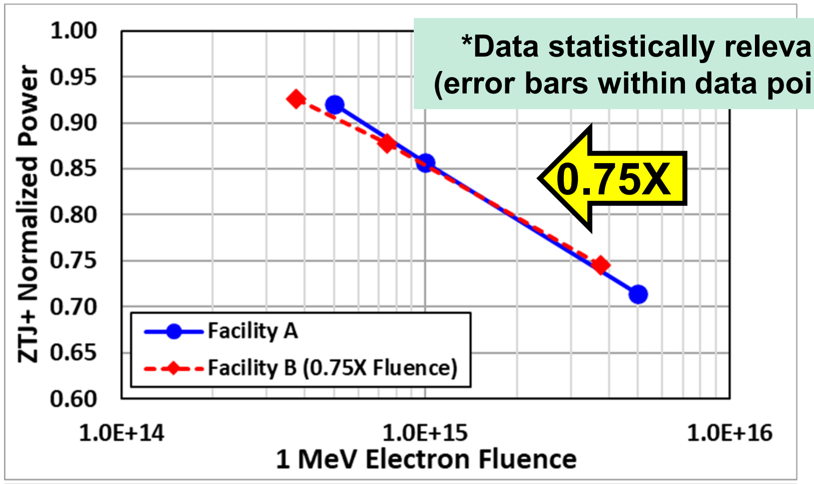
- *Dosimetry: Faraday cup w/ adjusted energies

Facility B

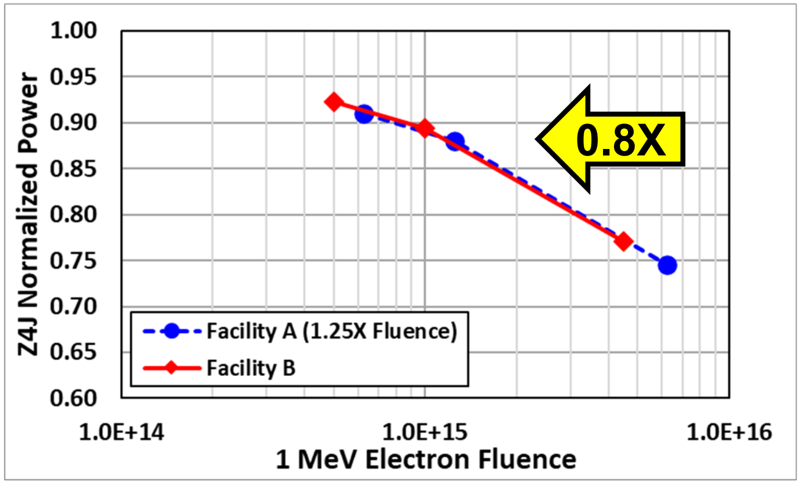
- *Dosimetry: Radiochromic films
- *Scaled fluence to meet Facility A results

1.25X higher flux means 25% lower fluence given to solar cells – OR 80% multiplier

*Similar differences exist for the other PV parameters



*Data statistically relevant (error bars within data points)



Outline

- Motivation/Purpose
  - AIAA S-111A & ECSS-E-ST-20-08C standards
  - Ground Test Data Anomalies
- Prior Experience in Electron Transport @ NeoBeam Facility (2010)
- Facility Descriptions
- Ionizing vs. Nonionizing Energy Deposition
  - Stopping power (dE/dx) vs NIEL
  - Effect of threshold energy on NIEL
- MCNP6 Transport Results
  - TID vs DDD deposition
  - Derived fluences for ground testing
- ***Summary***
- Path Forward

Summary

- MCNP6 has been used to determine the ionizing and non-ionizing dose profiles in an electron beam facility where electron transport through air occurs
- Results show that ***ionizing dose-derived beam fluxes are ~25% higher*** than its nonionizing counterpart
- Therefore, ***electron fluence (time-integrated flux) values are ~25% lower*** than expected
- These results are consistent with PV measurements from SolAero by Rocketlab on ZTJ+ & Z4J comparing 2 electron beam facilities
- Monte Carlo transport simulations can resolve noted discrepancies in experimental data and drive future ground testing protocols & standards
- To be introduced into latest AIAA S-111A revision (in process)
- Paper accepted as an oral presentation to the 2024 NSREC (Ottawa, CA)

Outline

- Motivation/Purpose
  - AIAA S-111A & ECSS-E-ST-20-08C standards
  - Ground Test Data Anomalies
- Prior Experience in Electron Transport @ NeoBeam (2010 NSREC publication)
- Facility Descriptions
- Ionizing vs. Nonionizing Energy Deposition
  - Stopping power (dE/dx) vs NIEL
  - Effect of threshold energy on NIEL
- MCNP6 Transport Results
  - TID vs DDD deposition
  - Derived fluences for ground testing
- Summary
- ***Path Forward***

NORTHROP GRUMMAN

Path Forward

- Need to re-evaluate dosimetry methods for solar cell radiation effects
  - Solar cell “control cells”
    - Are our current (pun intended) data reliable?
  - Faraday cups
    - Do they also suffer from counting non-relevant energies?
  - MC Simulations on electron/proton beam geometries
    - Air, vacuum, rastered, divergent
- Other nonionizing dosimetry methods
  - Gain degradation in 2N2222A bipolar transistors - ASTM E1855 (used for neutrons)
  - Light output degradation in GaAs LEDs (OSL sensor - IEEE TNS 58, 939 (2011))
  - Dark IV degradation in GaAs diodes (R2D3 - IEEE TNS 62, 2995 (2016) & IEEE TNS 66, 290 (2018))
  - Dark IV degradation in Si planar p-i-n diodes (many papers)
  - Si CCD degradation (?)
- Monte Carlo transport simulations can resolve noted discrepancies in experimental data and drive future ground testing protocols & standards

NORTHROP GRUMMAN