

Qualification, Production, and Program Status of SolAero's Inverted Metamorphic and Upright Ge Solar Cells

Space Power Workshop 2021

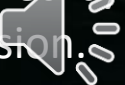
*Daniel Derkacs, Dan Aiken, Zac
Bittner, Marc Breen, Ben Cho, Brad
Clevenger, Andrew Espenlaub,
Navid Fatemi, Frank Fencl, John
Hart, Greg Johnston, Jeremy
Leshin, Clay McPheeters, Ahmad
Mansoori, Wondwosen Metaferia,
Nate Miller, Jeremy Moore, Pravin
Patel, Albert Perry, Peter Schmid,
Hans Schoon, Alex Stavrides*



This work was supported in part by AFRL:

Contracts FA9453-14-C-0370 (Space Vehicles Directorate)
and FA8650-13-C-5501 (ManTech Office)

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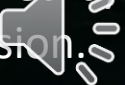
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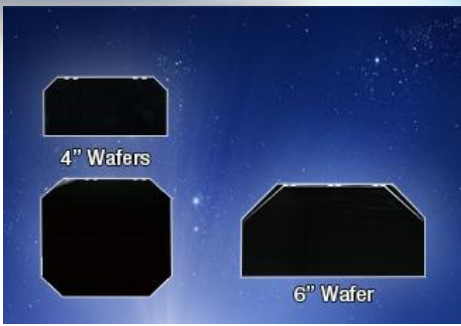
- 1. SolAero Overview**
- 2. Germanium-Based Solar Cells Technical Roadmap**
- 3. IMM Solar Cells Technical Roadmap**
- 4. Summary**



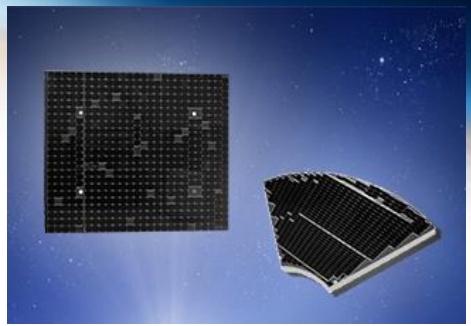
Integrated Product Manufacturing

SolAero Technologies

- Established in 1998
- World's only vertically integrated manufacturing facility for satellite solar power subsystems
- 150,000 ft² semiconductor and solar panel manufacturing facility
- >4 MW of power manufactured
- ~730 satellites on orbit and >500 scheduled for launch



High Efficiency Solar Cells



Satellite Solar Panels

SolAero Solar Products

- Solar cells & CIC assemblies
- Solar PVA modules & panels



Custom Composite Production



Custom Panel Production

SolAero Composite Products

- Solar array substrates
- Composite payload panels
- Optical benches

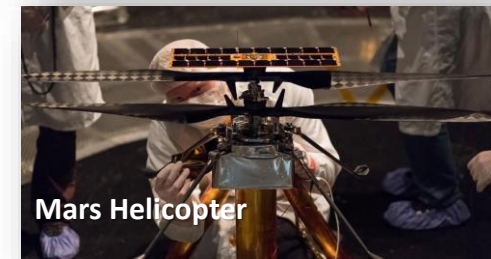


Volume Solar Panel Production



Volume Composite Production

- **US Government & Commercial GEO Telecom Satellites**
 - Broadband, TV/Radio, Phone, Aviation, Military Telecomm, Missile Tracking
- **US & Global Governments & Space Agencies**
 - Civil Space, Earth Observation, Interplanetary Exploration
 - Defense Intelligence, Surveillance & Communication
- **Non-GEO (NGSO) Satellites & Constellations**
 - USG & Commercial in LEO and MEO
 - Broadband, Missile Tracking, Earth Observation
 - Delivering >1,000 solar panels to OneWeb Satellites

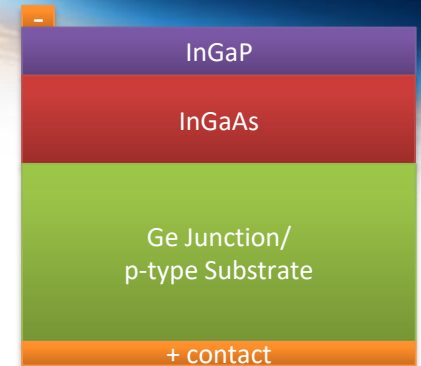


Solar Cell Technical Roadmap



Triple Junction Solar Cells on Germanium

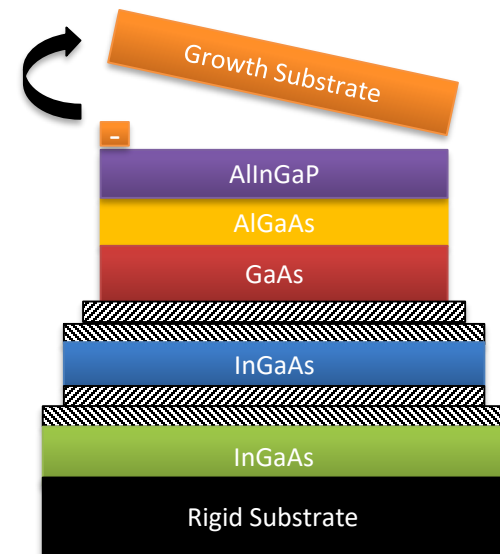
- ZTJ : 4th generation 3J (85% PRF, 1MeV 1E15 e-/cm²)
- ZTJ+ : 5th generation 3J with higher radiation hardness (87% PRF)
- ZTJ-Ω : 6th generation 3J for low rad, proton dominated environments



Example 3J

Quadruple Junction Solar Cells on Germanium

- Z4J : 1st generation 4J with high radiation hardness (90% PRF)
- Z4J+ : 2nd generation 4J with high radiation hardness (90% PRF)
 - Design is nearly locked and ready for delta qualification



Example IMM

Inverted Metamorphic Solar Cells - IMM

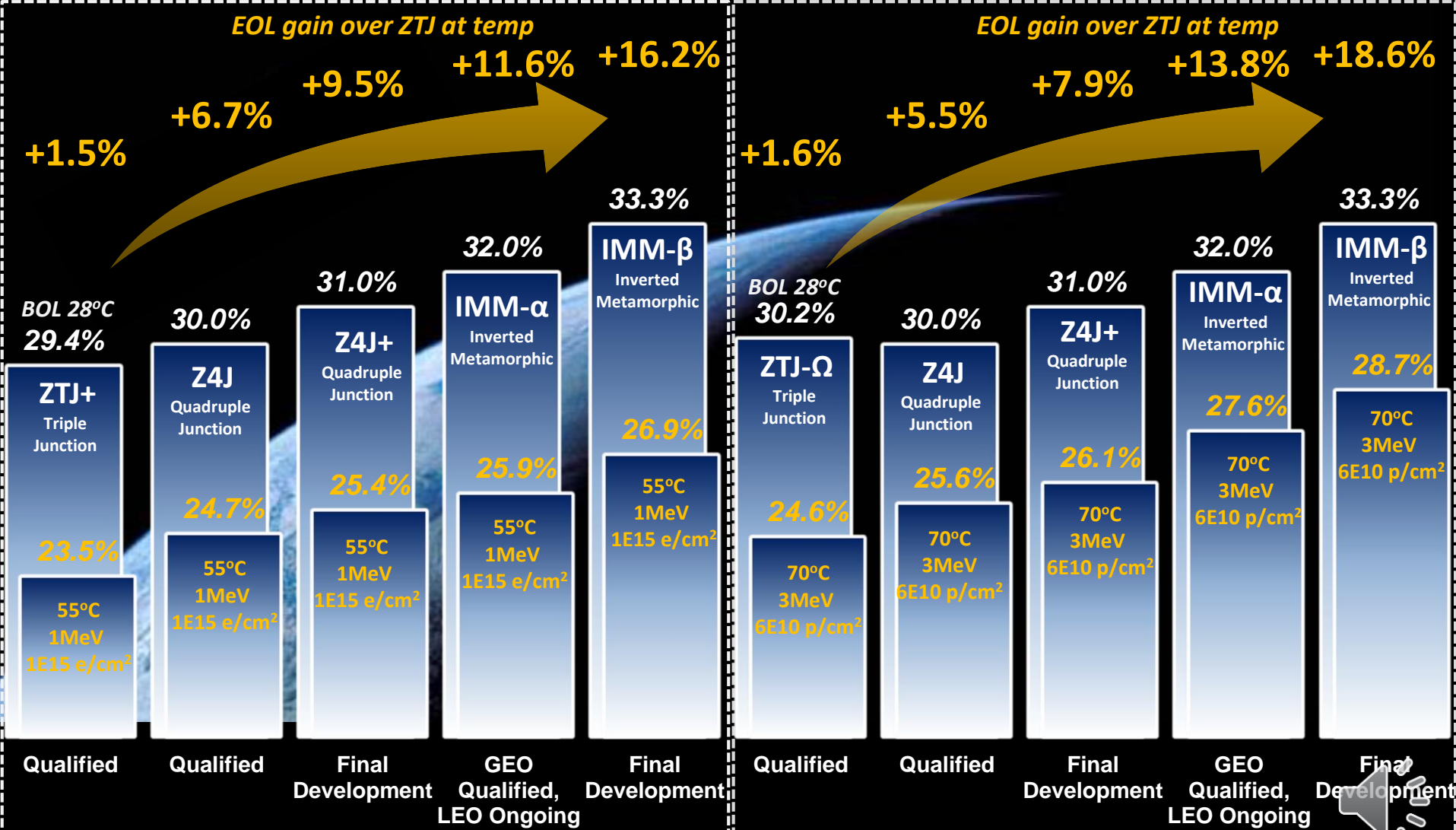
- IMM cells are 42% lighter than 140-μm thick Ge-based cells
- IMM-α : 1st generation 5J IMM (87% PRF)
- IMM-β : 2nd generation 5J IMM (87% PRF)
 - Design is nearly locked and ready for delta qualification

Cell Technology Roadmap – 1353W/m²

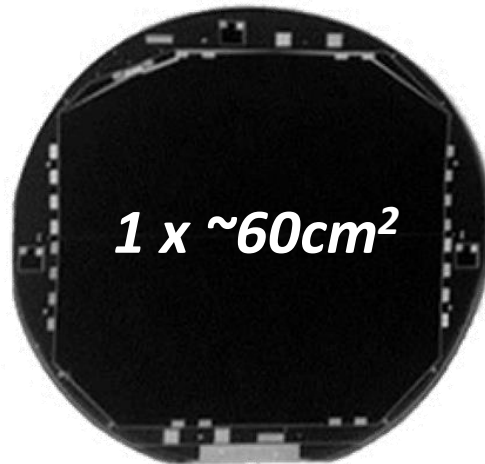
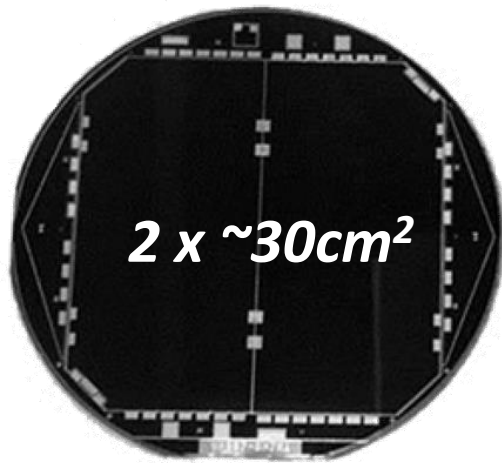
- IMM and Z4J products provide a pathway to higher performance under real operating conditions

GEO: 1MeV 1E15 e-/cm², 55°C

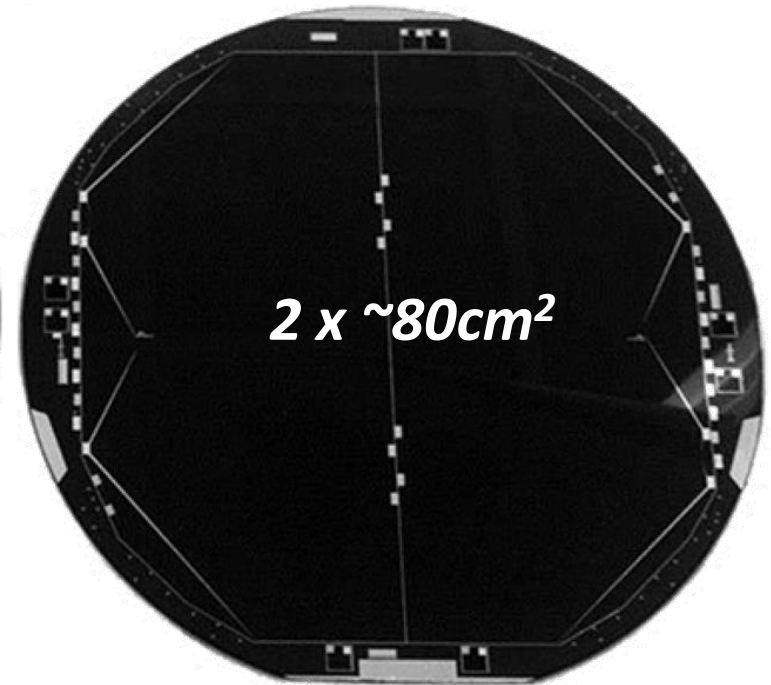
LEO: 3MeV 6E10 p+/cm², 70°C



- *Ge and IMM products available on 4" and 6" wafers*
- *Standard and custom cell sizes available*



4" Wafers



6" Wafer

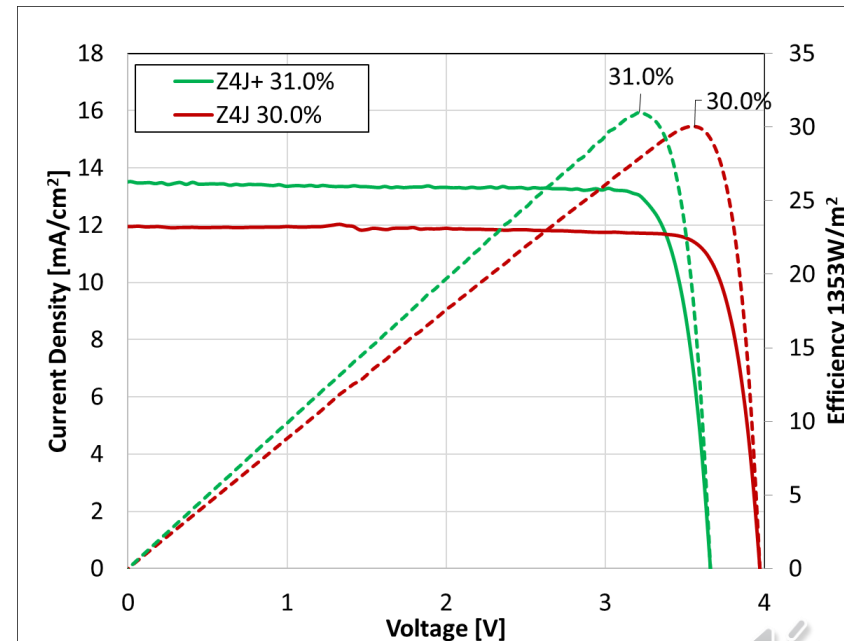
Germanium-Based Solar Cell Roadmap



- **Z4J : 30% radiation-hardened 4J cell**
 - Superior electron & proton radiation hardness
 - 90% PRF after exposure to 1-MeV 1E15 e-/cm²
 - Fully qualified to AIAA-S111-2014 Standard

Z4J Electrical Performance		
	1353 W/m ²	1361.1 W/m ²
η , 28°C	30.0%	29.8%
V _{oc} volts	3.95	
J _{sc} mA/cm ²	12.0	
V _{mp} volts	3.54	
J _{mp} mA/cm ²	11.45	

- **Z4J+ : 31% radiation-hardened 4J cell**
 - 90% PRF after 1-MeV 1E15 e-/cm²
 - Equivalent to 32% efficiency with 87% PRF
 - Structure is expected to be locked by Q3
 - Delta qualification planned late 2021



Next Generation Ge-Based Solar Cells

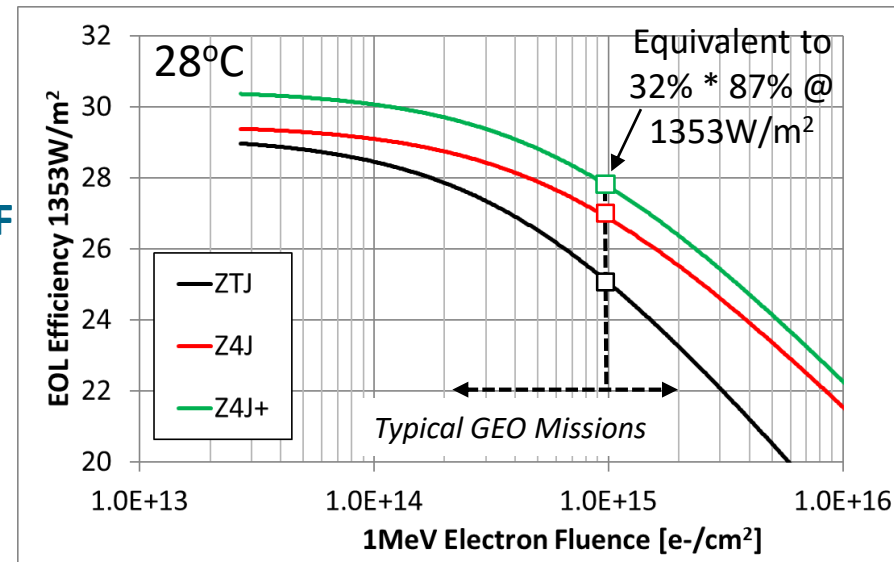
- **Z4J : 30% radiation-hardened 4J cell**
 - Superior electron & proton radiation hardness
 - 90% PRF after exposure to 1-MeV 1E15 e-/cm²
 - Fully qualified to AIAA-S111-2014 Standard

+7.2% EOL P_{mp} over ZTJ at 1E15

- **Z4J+ : 31% radiation-hardened 4J cell**
 - 90% RF after 1-MeV 1E15 e-/cm²
 - Equivalent to 32% efficiency with 87% PRF
 - Structure is expected to be locked by Q3
 - Delta qualification planned late 2021

+10.8% EOL P_{mp} over ZTJ at 1E15

Z4J Electrical Performance		
	1353 W/m ²	1361.1 W/m ²
η , 28°C	30.0%	29.8%
V_{oc} volts		3.95
J_{sc} mA/cm ²		12.0
V_{mp} volts		3.54
J_{mp} mA/cm ²		11.45



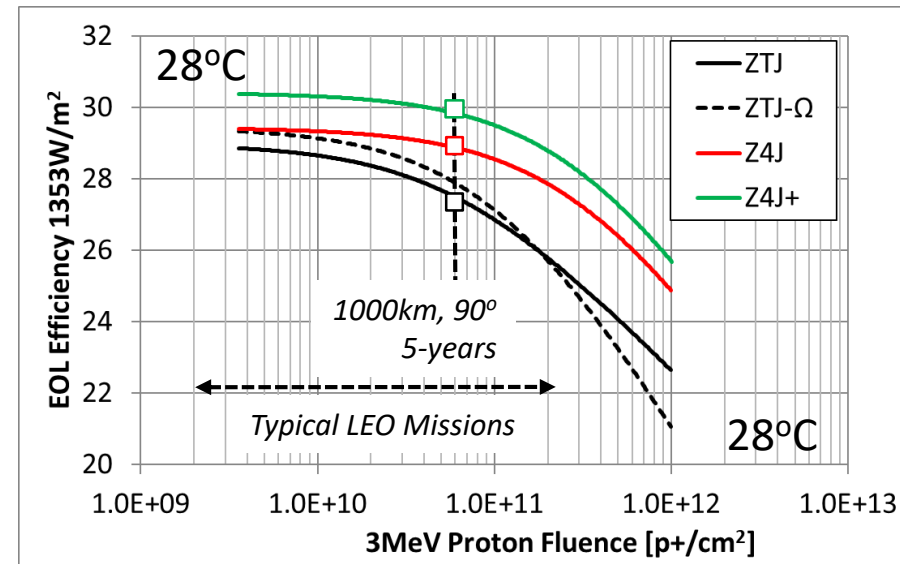
- **Z4J : 30% radiation-hardened 4J cell**
 - Superior electron & proton radiation hardness
 - 96% RF after exposure to 3-MeV 6E10 p+/cm²
 - Fully qualified to AIAA-S111-2014 Standard

+5.0% EOL P_{mp} over ZTJ for Polar LEO

- **Z4J+ : 31% radiation-hardened 4J cell**
 - 96% RF after 3-MeV 6E10 p+/cm²
 - Equivalent to 32% efficiency with 87% RF
 - Structure is expected to be locked by Q3
 - Delta qualification planned Q3 2021

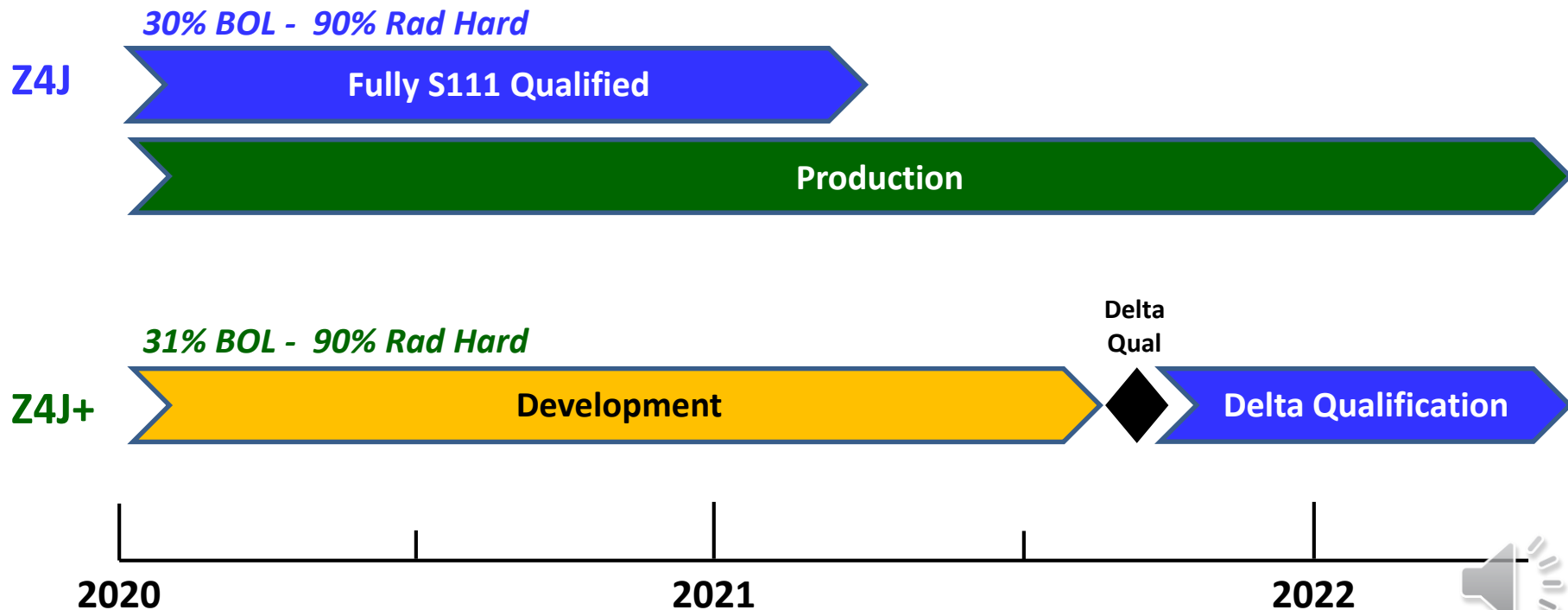
+8.5% EOL P_{mp} over ZTJ for Polar LEO

Z4J Electrical Performance		
	1353 W/m ²	1361.1 W/m ²
η , 28°C	30.0%	29.8%
V_{oc} volts	3.95	
J_{sc} mA/cm ²	12.0	
V_{mp} volts	3.54	
J_{mp} mA/cm ²	11.45	



■ Ge-Based Four-Junction Solar Cells

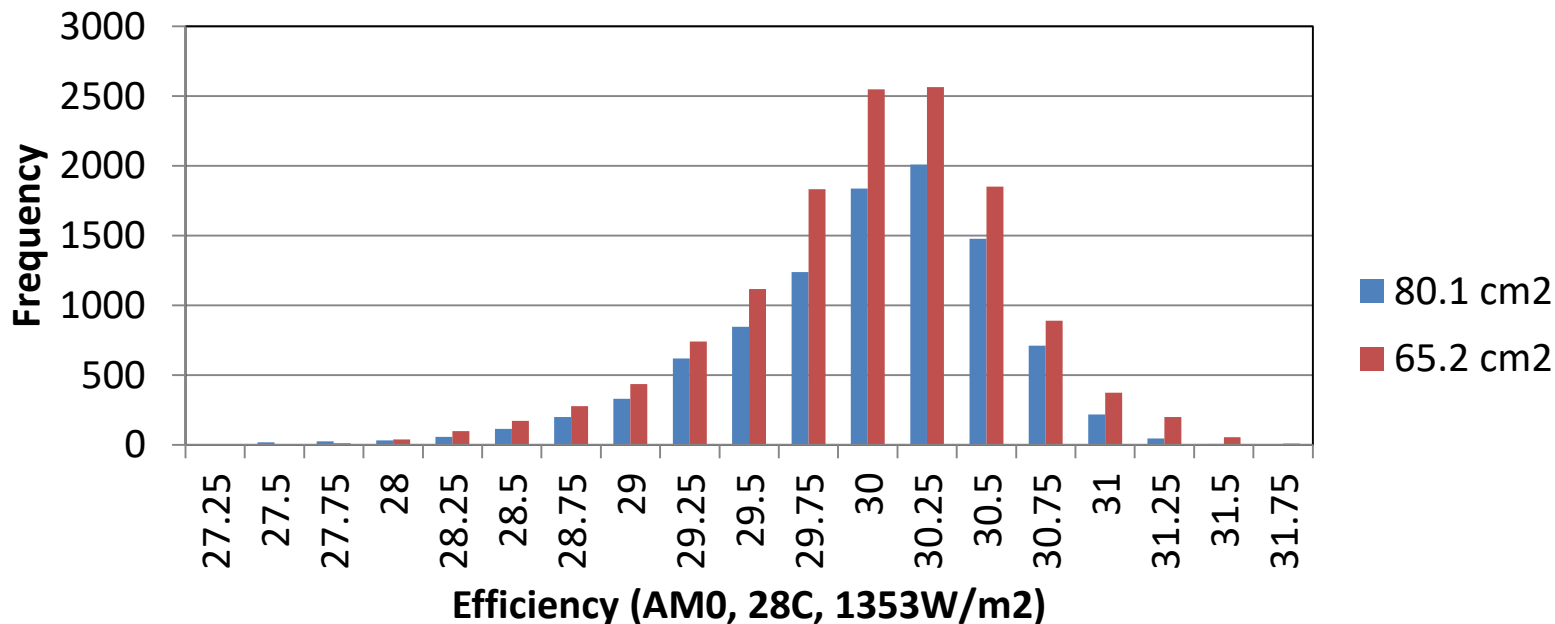
- Z4J & Z4J+
- Mechanical drop-in replacement for ZTJ
- Fully qualified for AIAA-S111-2014 Standard
- Z4J+ Delta qualification to S111 planned for late 2021



Example Z4J Builds

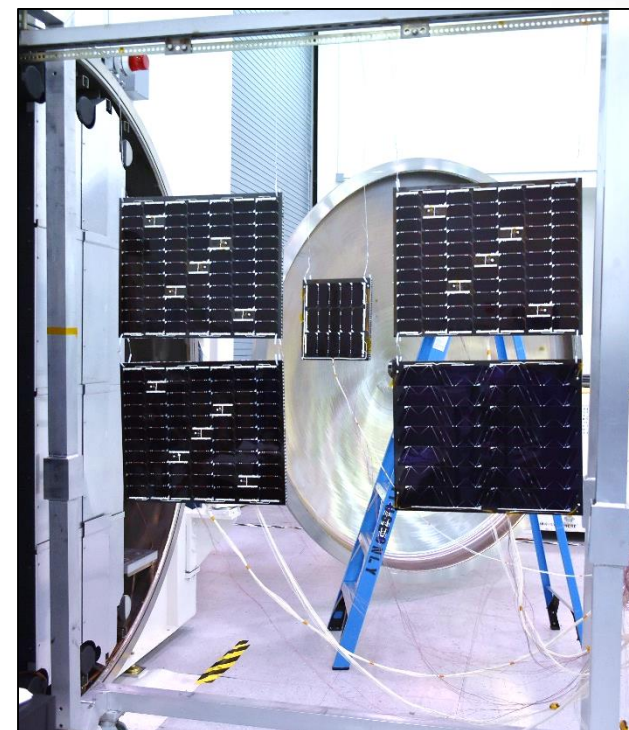
- **4" 1-pers**
 - 10,013 cells - 65.2-cm²
 - 30% median efficiency
- **6" 2-pers**
 - 9,795 cells - 80.2-cm²
 - 30% median efficiency

Z4J Electrical Performance		
	1353 W/m ²	1361.1 W/m ²
η , 28°C	30.0%	29.8%
V _{oc} volts	3.95	
J _{sc} mA/cm ²	12.0	
V _{mp} volts	3.54	
J _{mp} mA/cm ²	11.45	



- **Z4J solar cell qualification to AIAA-S111-2014 Standard**
 - **Three tasks under the AIAA-S112-2013 Standard are also under way**

AIAA-S111-2014 Task	Est. Completion Date
7.1 Weld or Solder Test	Completed
7.2 Integration Test (CET)	GEO: Completed LEO: Completed
7.3 Cell-Level Humidity Test	Completed
8.1 Electron Radiation Effects	Completed
8.2 Proton Radiation Effects	Completed
8.3 Bend Test	Completed
8.4 Breaking Load Determination	Completed
8.5 LIV Characterization at Temp	Completed
8.6 Quantum Efficiency	Completed
8.7 DIV Characterization	Completed
8.8 Capacitance	Completed
8.9 ESD Test	Completed
8.10 Accelerated Life Test	Completed
AIAA-S112-2013 Task	Est. Completion Date
S112 – AOI	Completed
S112 – Abs./Emission	Completed
S112 – ESD	freestanding CICs: Completed coupon: May 2021



**Z4J Qualification Coupons
(with 4-in. & 6-in. cells)**



IMM Solar Cell Roadmap



- **IMM- α : For all mission environments**

- **32% BOL efficiency**

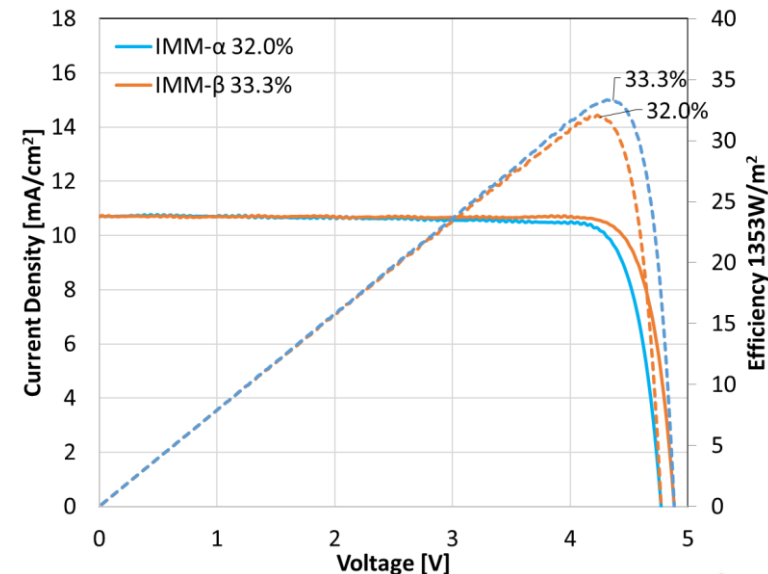
- Exceptional performance in GEO and LEO
 - 87% PRF after 1-MeV $1E15$ e-/cm²
 - S111 GEO thermal cycling completed, LEO cycling in progress
 - Several other GEO and LEO life-cycle coupons successfully completed cycling

IMM- α Electrical Performance		
	1353 W/m ²	1361.1 W/m ²
η , 28°C	32.0%	31.8%
V _{oc} volts	4.78	
J _{sc} mA/cm ²	10.66	
V _{mp} volts	4.28	
J _{mp} mA/cm ²	10.12	

- **IMM- β : For all mission environments**

- **33.3% BOL efficiency**

- 87% PRF after 1-MeV $1E15$ e-/cm²
 - α reduced by 3 points, ~3°C lower op
 - **Final optimizations near completion**
 - Delta qualification planned



- **IMM- α : For all mission environments**

- **32% BOL efficiency**

- Exceptional performance in GEO and LEO
 - 87% PRF after 1-MeV 1E15 e-/cm²
 - S111 GEO thermal cycling completed, LEO cycling in progress
 - Several other GEO and LEO life-cycle coupons successfully completed cycling

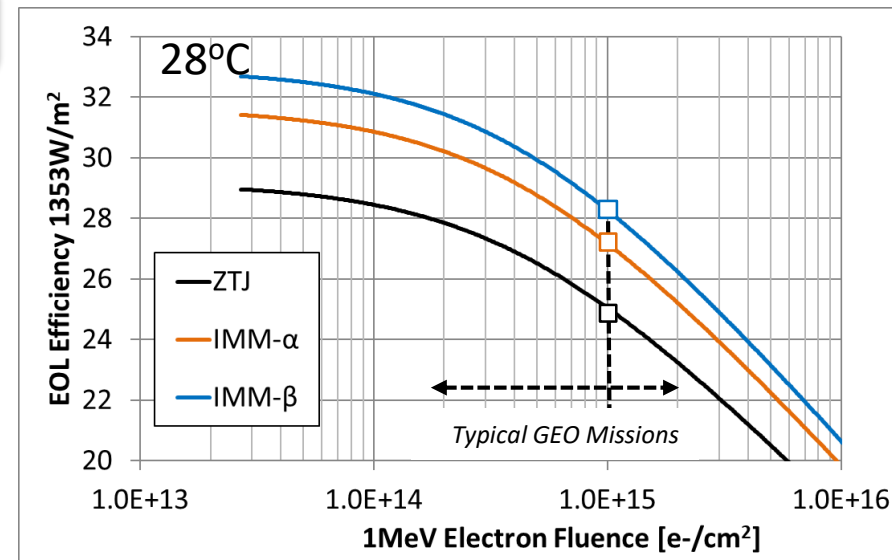
IMM- α Electrical Performance		
	1353 W/m ²	1361.1 W/m ²
η , 28°C	32.0%	31.8%
V _{oc} volts	4.78	
J _{sc} mA/cm ²	10.66	
V _{mp} volts	4.28	
J _{mp} mA/cm ²	10.12	

+11.7% EOL P_{mp} over ZTJ for typical GEO

- **IMM- β : For all mission environments**

- **33.3% BOL efficiency**

- 87% PRF after 1-MeV 1E15 e-/cm²
 - α reduced by 3 points, ~3°C lower op
 - **Final optimizations near completion**
 - Delta qualification planned



+16.2% EOL P_{mp} over ZTJ for typical GEO



- **IMM- α : For all mission environments**

- **32% BOL efficiency**

- Exceptional performance in GEO and LEO
 - 87% PRF after 1-MeV 1E15 e-/cm²
 - S111 GEO thermal cycling completed, LEO cycling in progress
 - Several other GEO and LEO life-cycle coupons successfully completed cycling

IMM- α Electrical Performance		
	1353 W/m ²	1361.1 W/m ²
η , 28°C	32.0%	31.8%
V _{oc} volts	4.78	
J _{sc} mA/cm ²	10.66	
V _{mp} volts	4.28	
J _{mp} mA/cm ²	10.12	

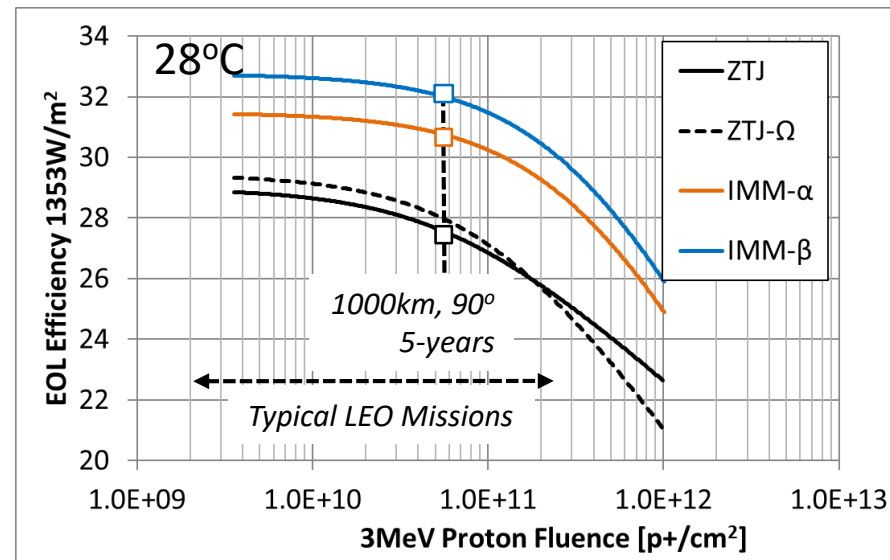
+8.5% EOL P_{mp} over ZTJ for typical Polar LEO

- **IMM- β : For all mission environments**

- **33.3% BOL efficiency**

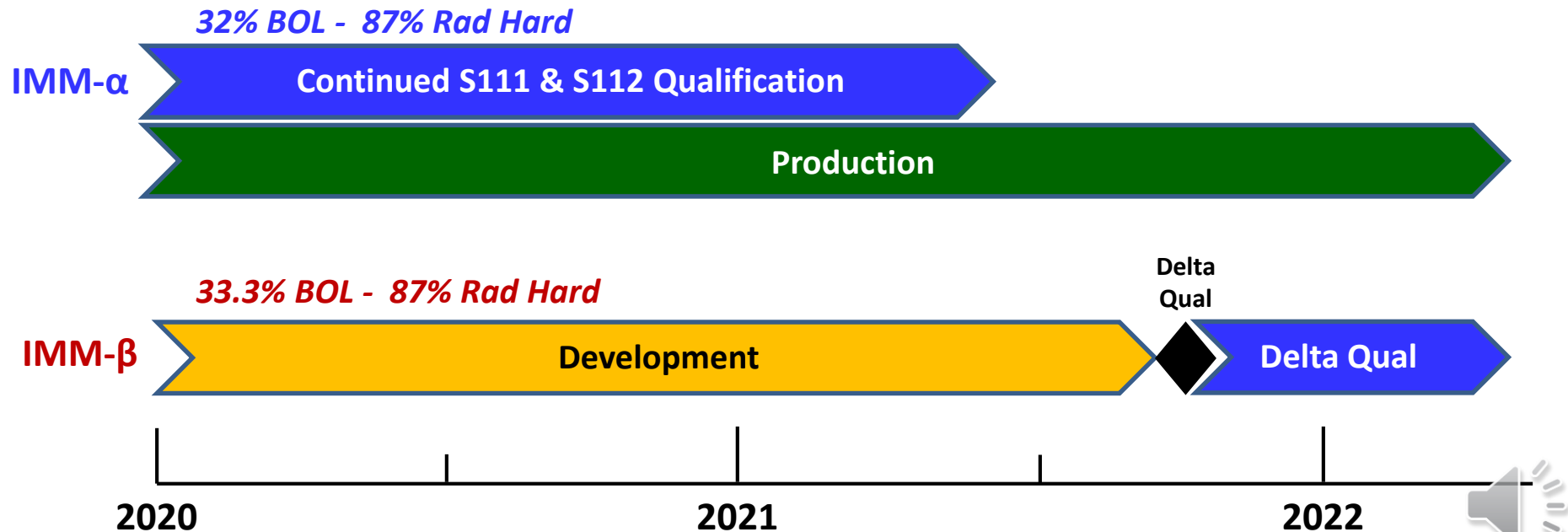
- 87% PRF after 1-MeV 1E15 e-/cm²
 - α reduced by 3 points, ~3°C lower op
 - **Final optimizations near completion**
 - Delta qualification planned

+12.9% EOL P_{mp} over ZTJ for typical Polar LEO



■ *Inverted Metamorphic Solar Cells*

- IMM- α & IMM- β
- The highest efficiency and the lowest mass space solar cell technology
- Full AIAA-S111-2014 qualification complete for GEO, LEO thermal cycling ongoing

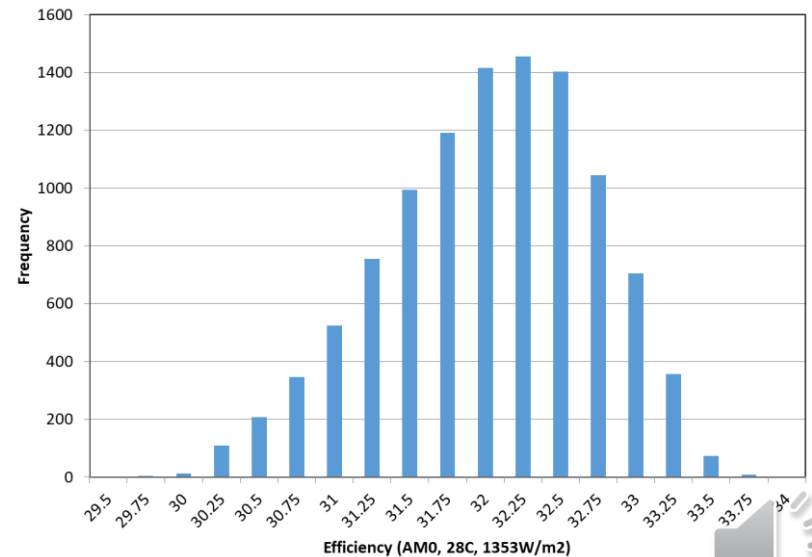


- **IMM- α Flight Program**
 - The flight panels for the initial 2 satellites delivered to customer for launch in September



IMM- α Solar Panel

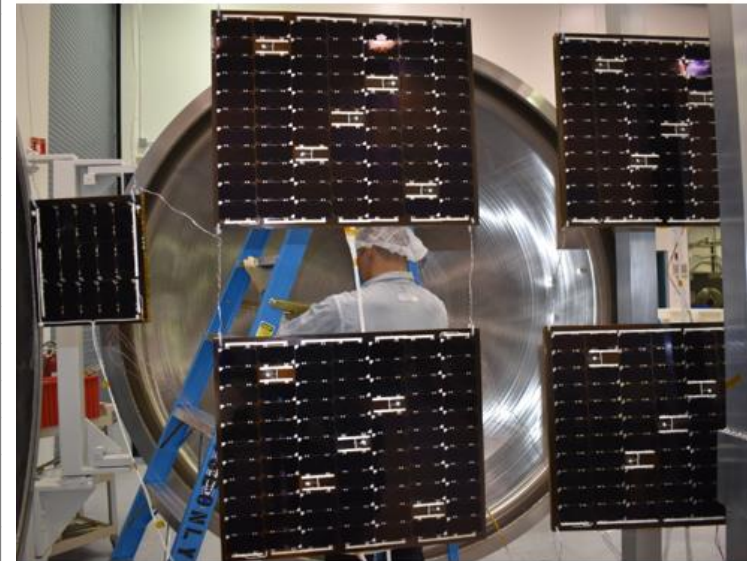
- **IMM- α BOL Efficiency Distribution**
 - 14.5kW IMM- α manufactured
 - 30.78 cm² cell area
 - 32.0% median efficiency
 - 33.8% highest efficiency



IMM- α S111 Qualification Status

- *Extensive confidence, characterization, qualification, & life-cycle coupon testing already performed with IMM- α cells*
 - Three tasks under the AIAA-S112-2013 Standard are also complete

AIAA-S111-2014 Task	Est. Completion Date
7.1 Weld or Solder Test	Completed
7.2 Integration Test (CET)	GEO: Completed LEO: Oct. 2021 Multiple confidence coupons >20K cycles completed
7.3 Cell-Level Humidity Test	Completed
8.1 Electron Radiation Effects	Completed
8.2 Proton Radiation Effects	Completed
8.3 Bend Test	Completed
8.4 Breaking Load Determination	Completed
8.5 LIV Characterization at Temp	Completed
8.6 Quantum Efficiency	Completed
8.7 DIV Characterization	Completed
8.8 Capacitance	Completed
8.9 Cell (Human Body Model) ESD Test	Completed
8.10 Accelerated Life Test	Completed
AIAA-S112-2013 Task	Est. Completion Date
S112 – AOI	Completed
S112 – Abs./Emission	Completed
S112 – ESD	Completed



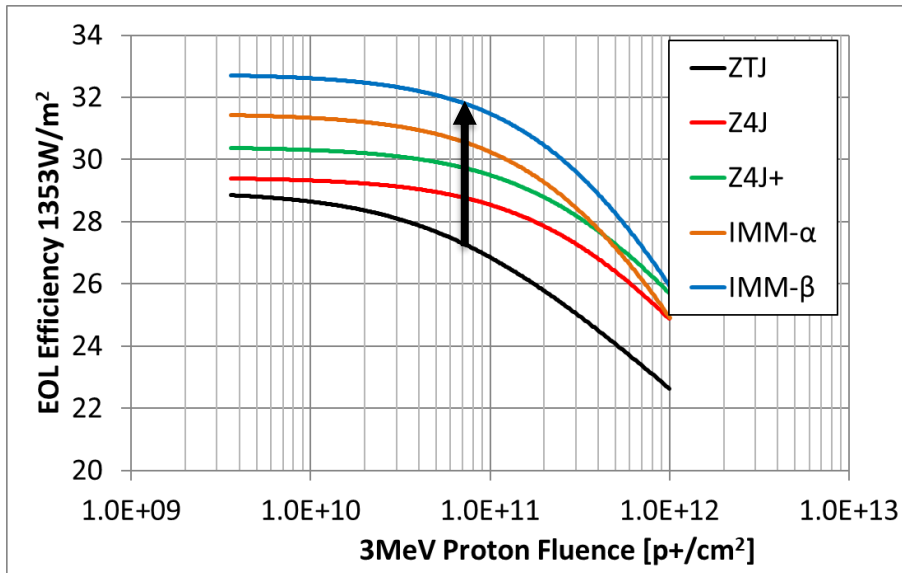
IMM- α Qualification Coupons



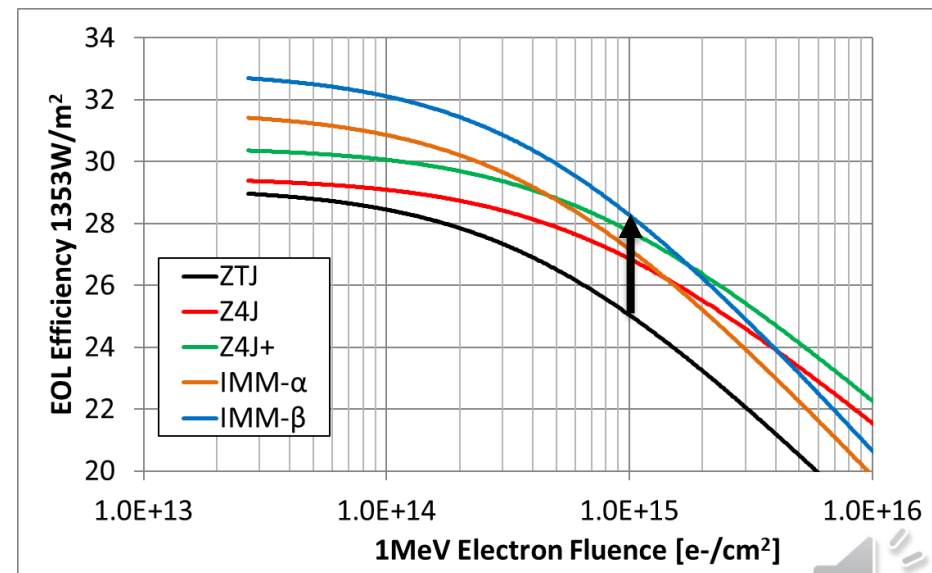
■ SolAero offers a suite of cell technologies that meet all customer's performance and cost requirements

- Z4J → +5% LEO and +7% GEO
- Z4J+ → +8% LEO and +10% GEO
- IMM-α → +14% LEO and +12% GEO
- IMM-β → +19% LEO and +16% GEO

Proton



Electron



SolAero gratefully acknowledges the support of our partners!

- *AFRL*
- *Aerospace*

Thank You

