MAI TAI

Mitigating Arc Inception via Transformational Array Instrumentation

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NAC Technology, Innovation, and Engineering Meeting

September 5, 2024

Outline

- Overview of MAI TAI
- Introduction to Spacecraft Charging and Arcing
- Active Mitigation concept
- Active mitigation enables new tech
- ECI Experiences & Lessons Learned

Goal: enable **resilient**, **high voltage**, **high power density** solar arrays

MAI TAI

- FY24 Early Career Initiative (ECI) Award
- Funded by NASA’s Space Technology Mission Directorate (STMD)
- 2-year, $2.5 million effort
- **Research and Development**

TRL 4 → TRL 6

Team

Early Career

- **Meghan Bush** – Principal Investigator
- **Jeremiah Sims** – Co-Investigator
- **Dr. Kristina Vailonis** – Thin Films
- **Brooke Weborg** – Data Analysis, Machine Learning
- **Darcy DeAngelis** – Safety and Mission Assurance
- **Natalie Weckesser** – Operations Research Analyst
- **Alexis Arroyo** – Electrical Engineering Support
- **Hana Winchester** – Data Science Summer Intern

Senior Staff & Mentors

- **Dr. Boris Vayner** – Spacecraft Charging Expert
- **Dr. Timothy J. Peshek** – Space Photovoltaics
- **Dr. Kristen John** – Lunar Dust Impacts

NASA GRC Team

M. Bush

J. Sims

K. Vailonis

B. Weborg

D. DeAngelis

N. Weckesser

A. Arroyo

B. Vayner

T. J. Peshek

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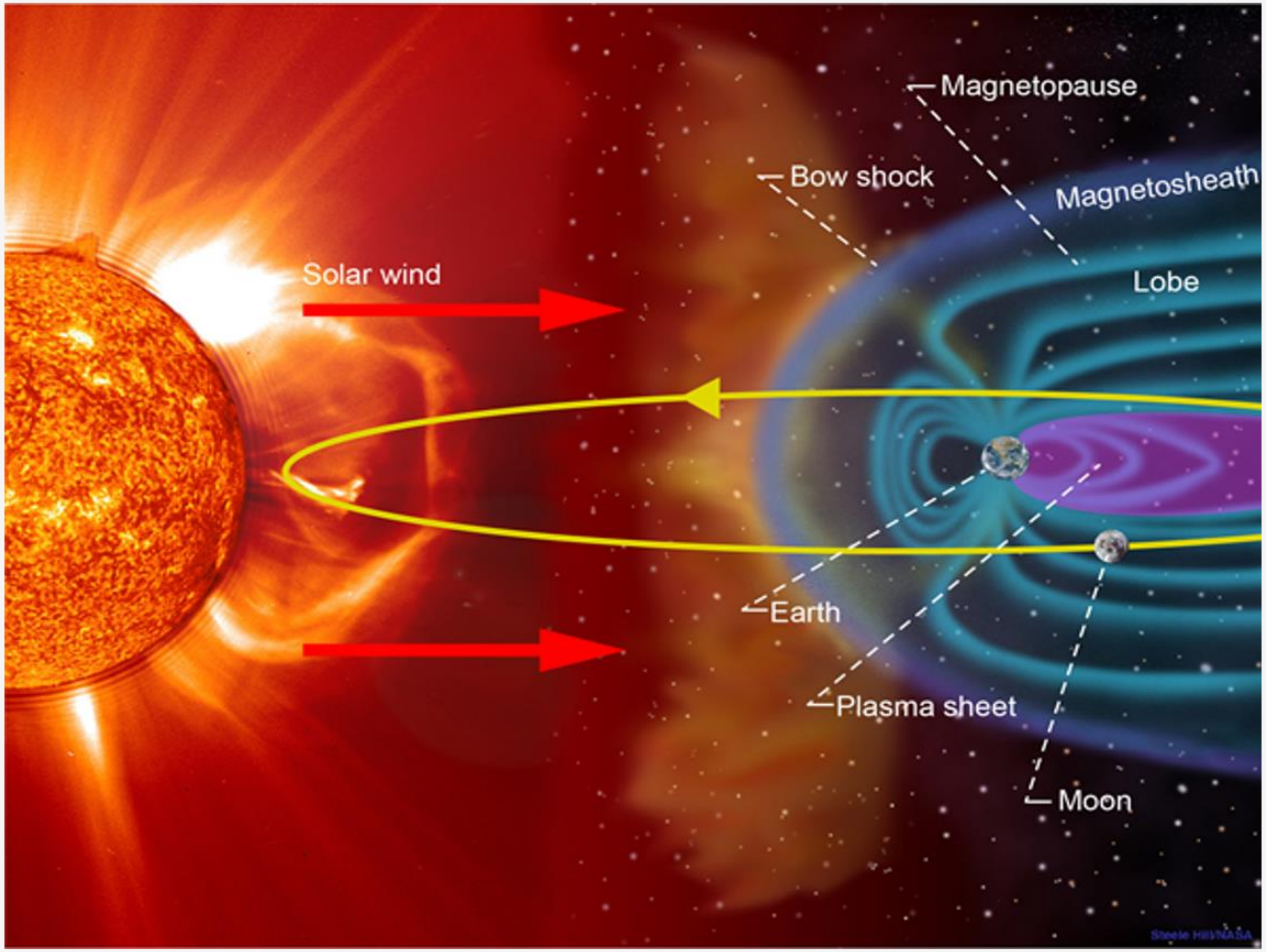
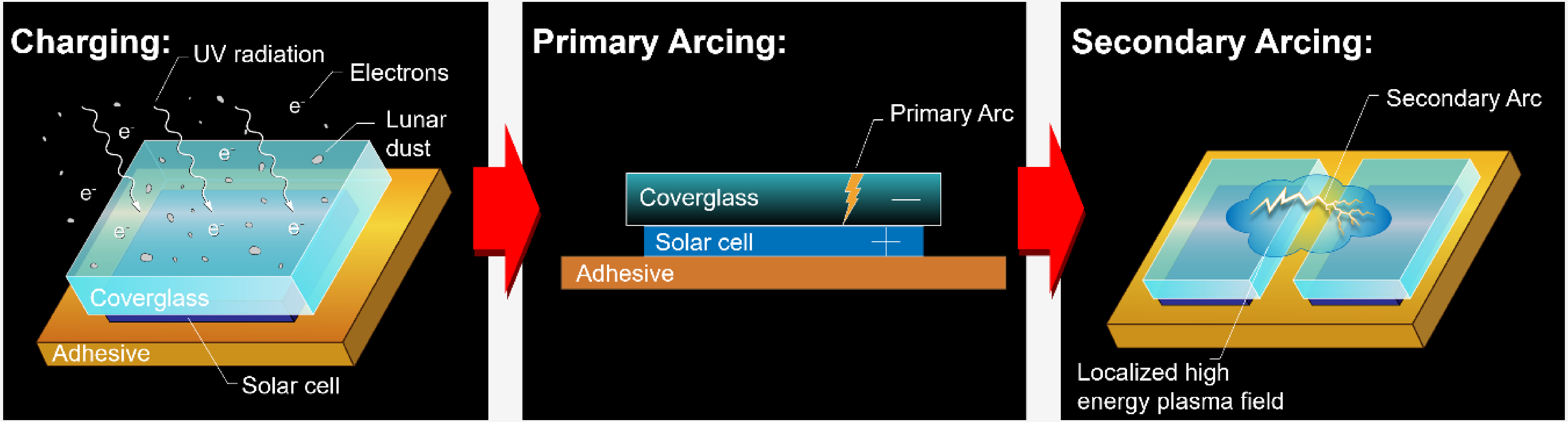
Spacecraft Charging

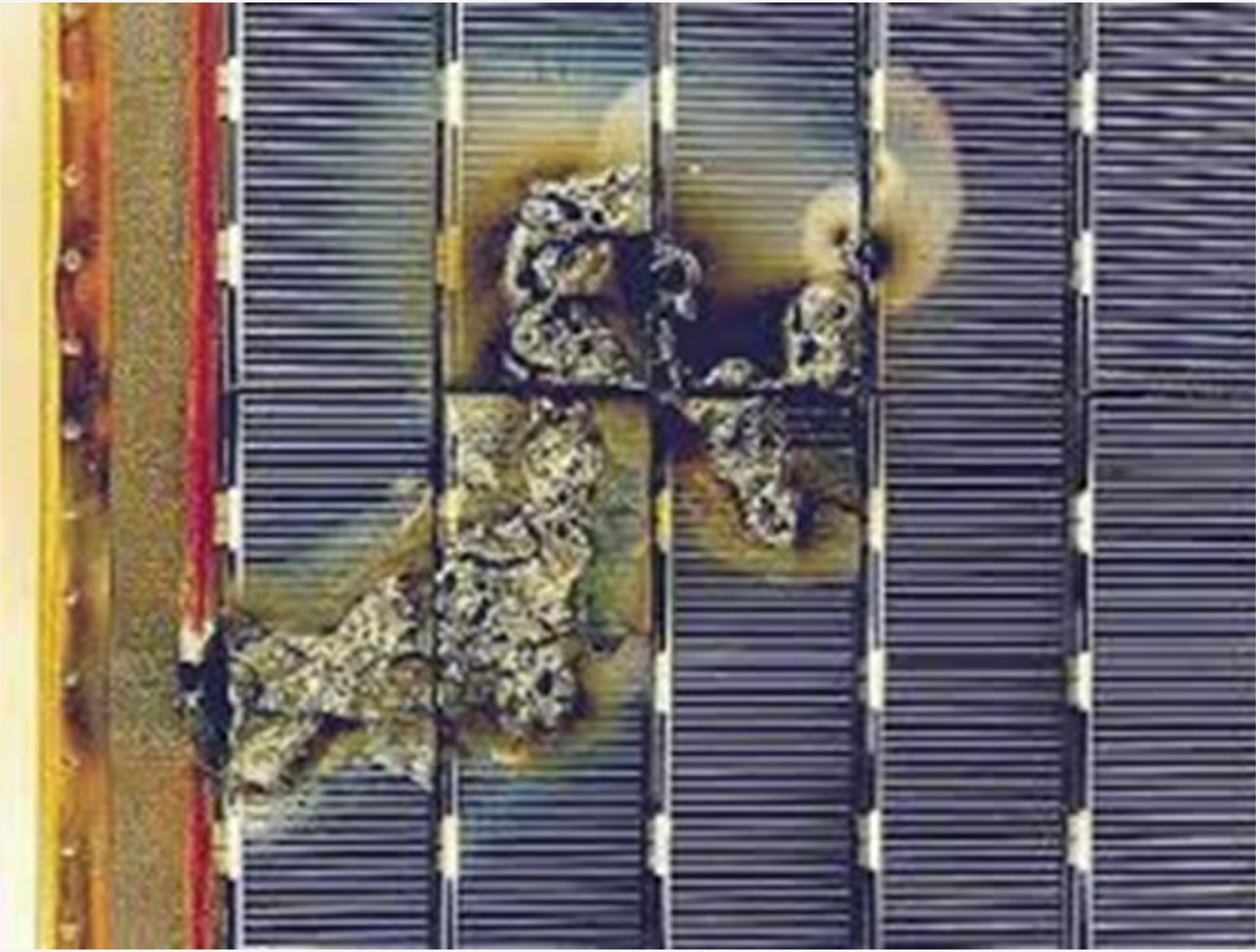


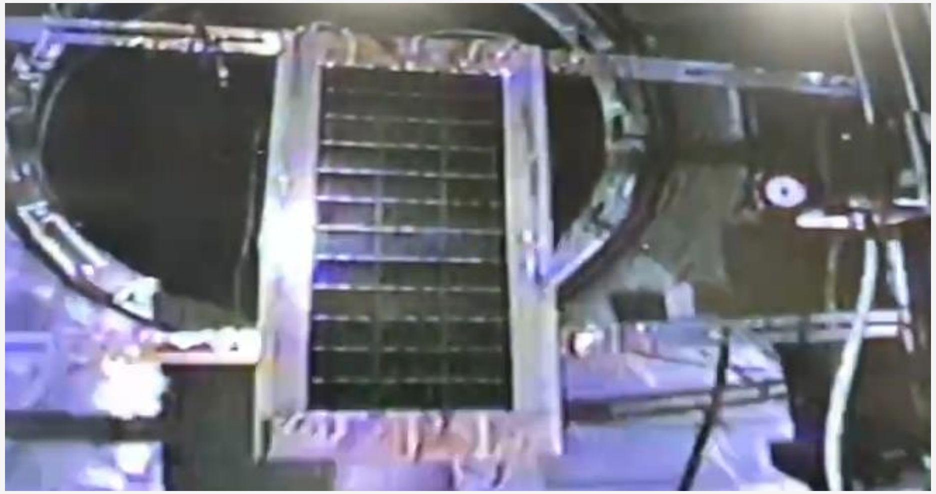
- Charging regimes on the lunar surface vary wildly throughout the lunar cycle
- Passive mitigation techniques **design for worst-case scenario**

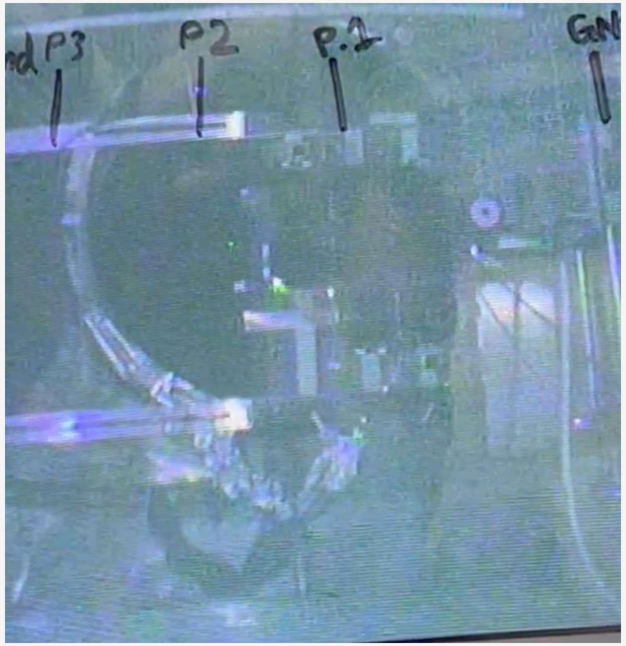
Spacecraft Charging



Secondary Arcing



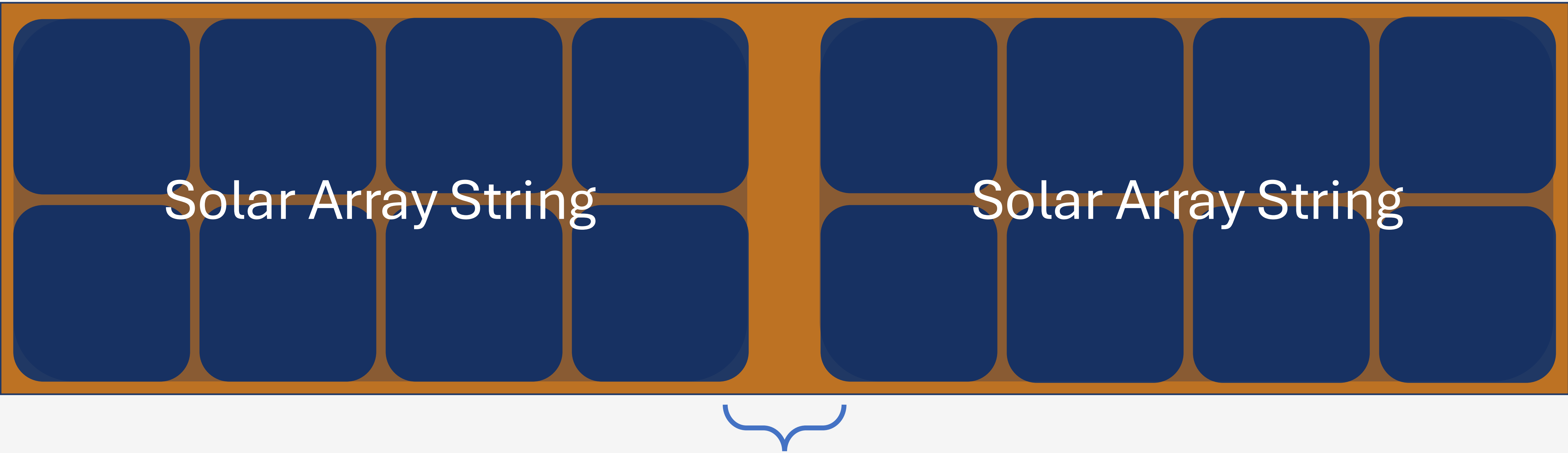




slow motion

real time

Current State of Practice

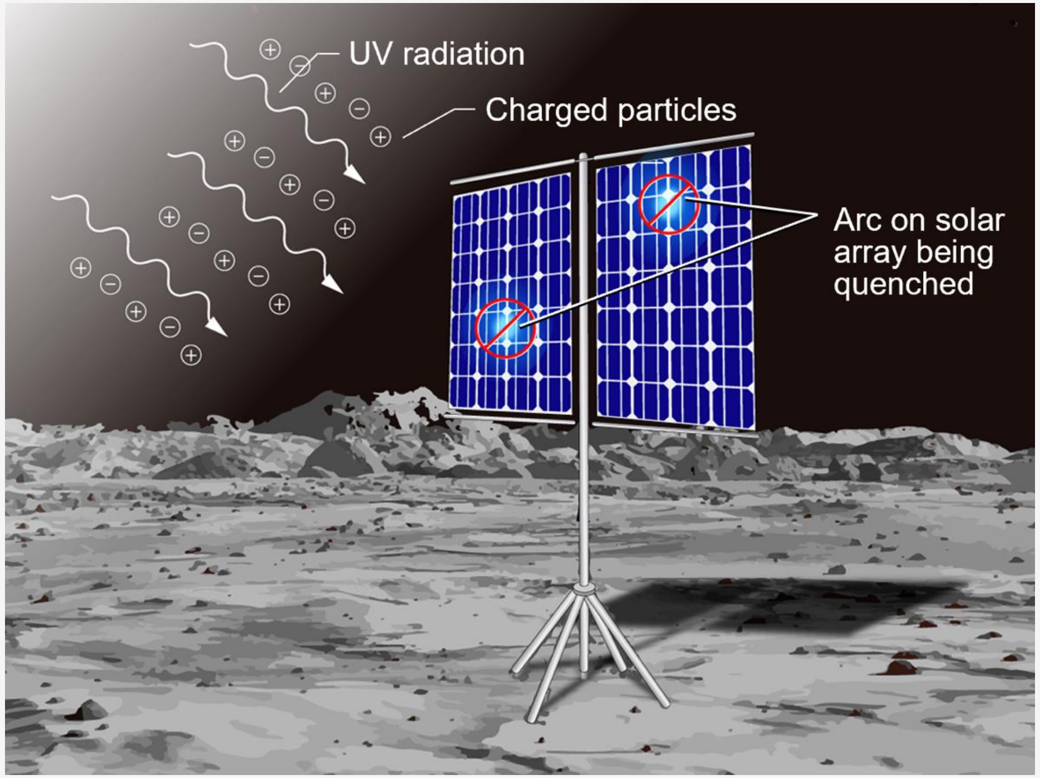


Distance between strings: **above a cell-dependent threshold**

Cell-to-cell voltage: **< 40V**

Does not account for *next-generation solar cells* (larger/higher voltage, thin film) and *lunar environment*

Capabilities under Development



Passive:

- Aimed at thin film solar cells (susceptible to primary arcing)
- Develop and test architecture to prevent primary arcs

Active:

- Improve upon secondary arcing protections
- Novel high-speed circuitry that detects and quenches secondary arcs

Adaptive:

- Protect solar arrays in variable charging environments while maximizing power
- Develop dataset and ML/AI algorithm for controlling circuitry in lunar environmental extremes

Benefits

- **High Voltage Operations**: bypassing current best practices allows for higher bus voltages, **lowering conductor mass** and **increasing power output**
- **Enable next-generation solar cells**: prepare novel solar cells to **survive the harsh lunar surface charging environment**
- **Boost reliability and resiliency of solar arrays**: lower risk of arcing damage **increases array lifetimes**

STMD Shortfall 21596: *High Power Energy Generation on Moon and Mars Surfaces*

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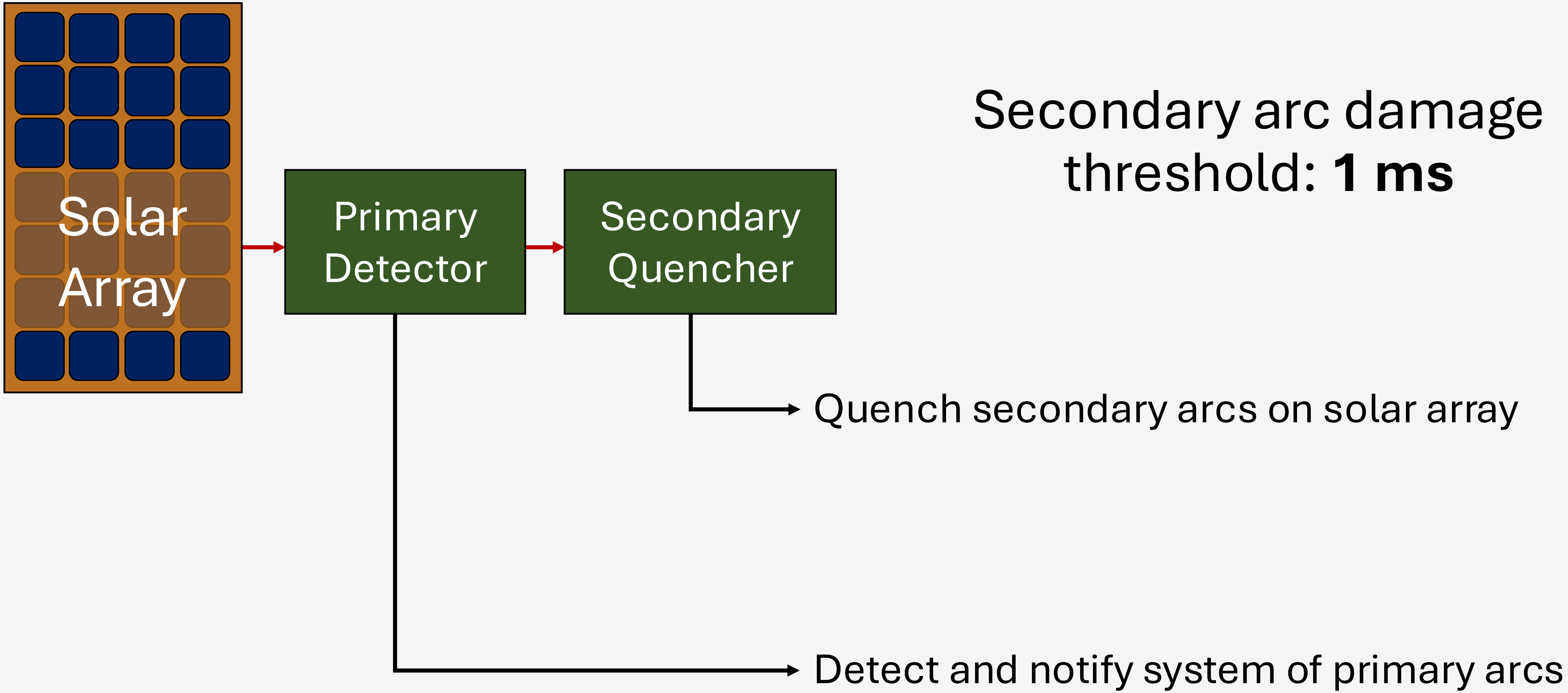
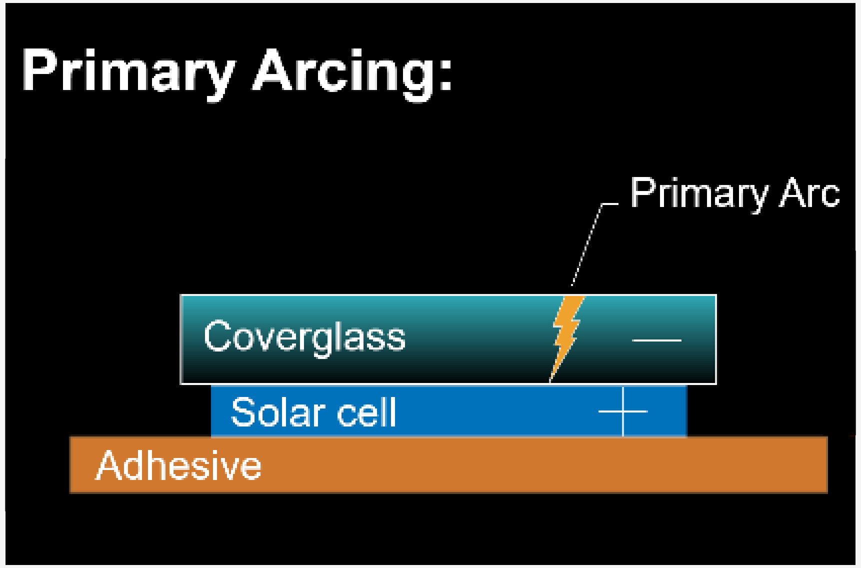
Active Arc Mitigation

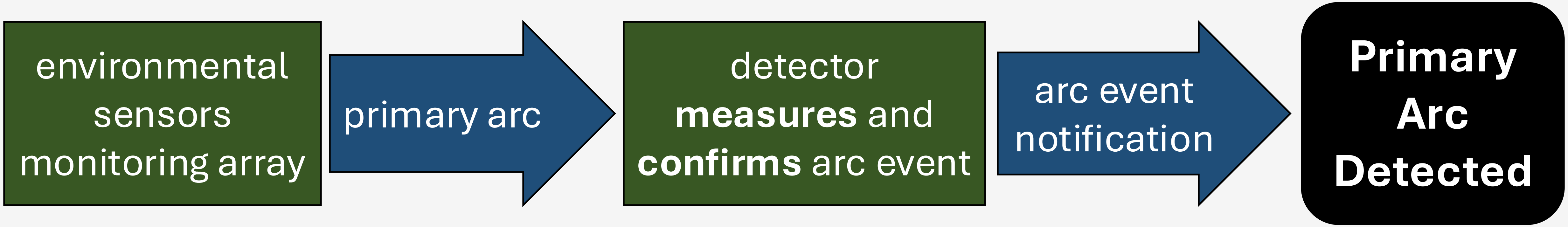
Secondary arc damage threshold: **1 ms**



Primary Arc Detector

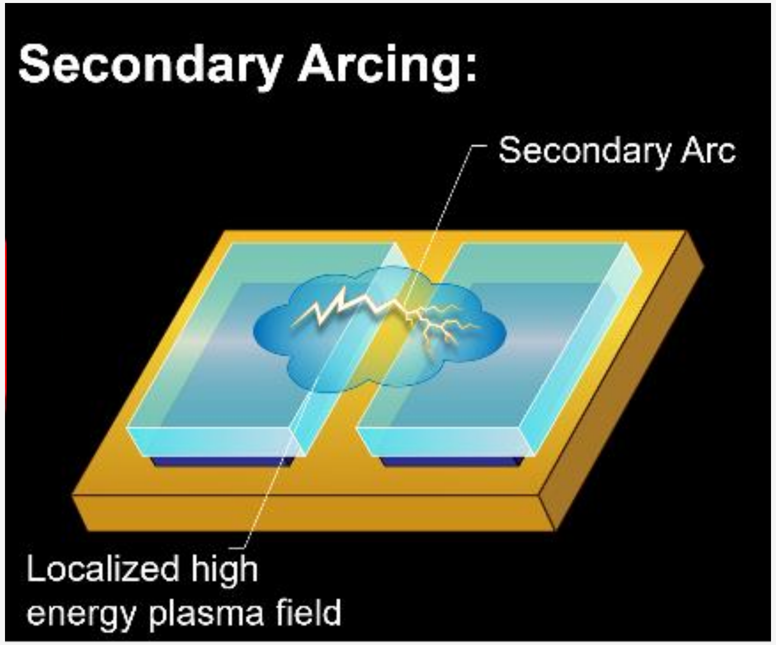
- Monitors the solar array current without interfering or impacting power
- Detects a primary arc event and notifies the system
- Key qualities: fast, accurate
- **Crucial for ML/AI integration and variable environment sensing**





Secondary Arc Quencher

- Reroutes and absorbs the current generated during a secondary arc
- Key qualities: fast, robust
- **Crucial for mitigating damage via secondary arcs**

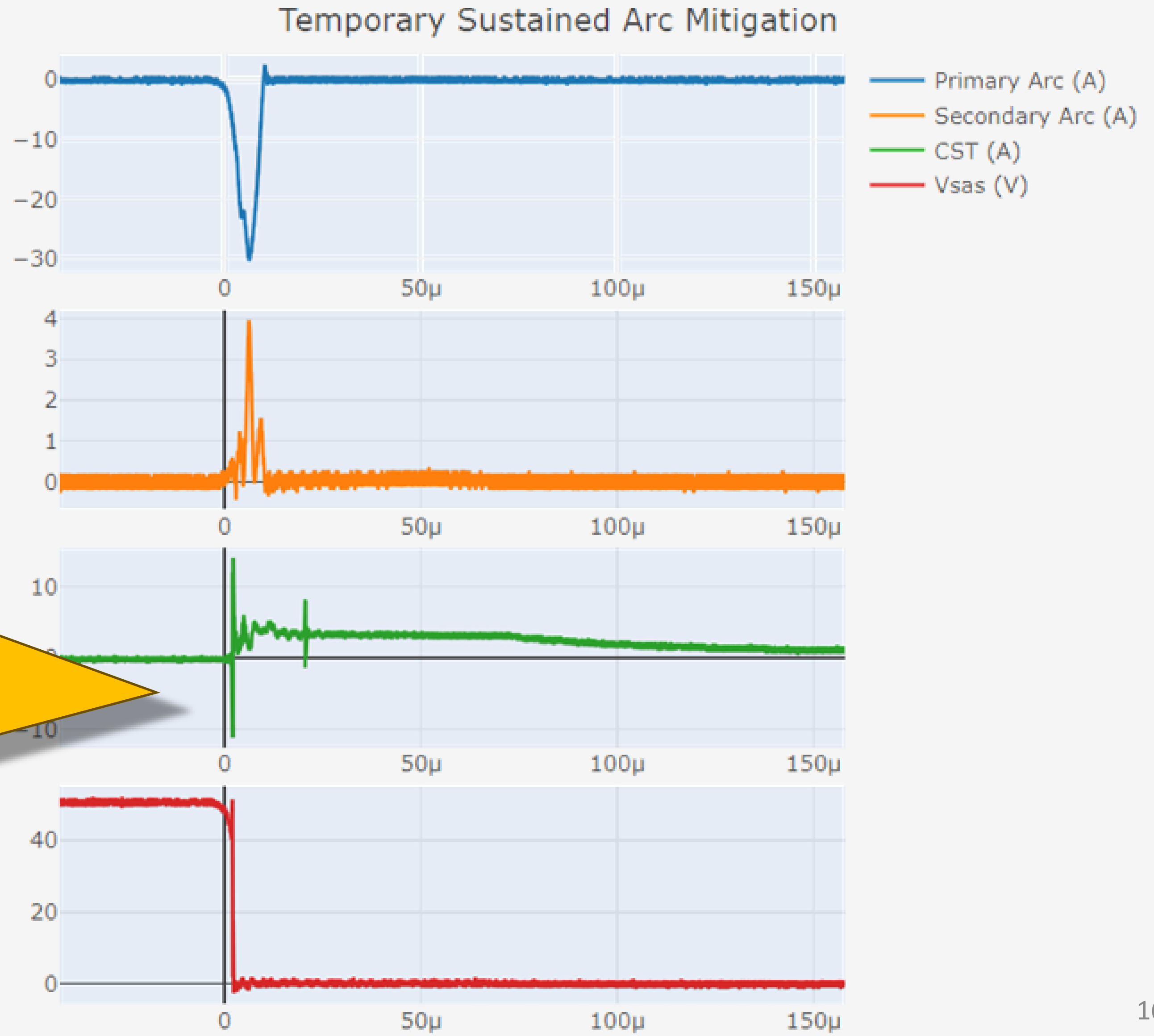


secondary arc current → quencher **redirects** and **dissipates** current → solar cells shorted → **Secondary Arc Quenched**

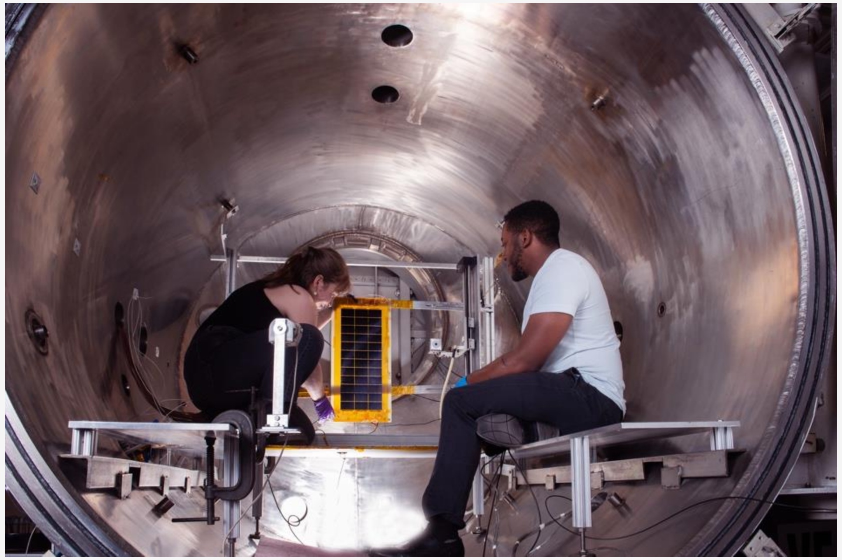
Secondary Arc Quencher

- Solar array voltage is shorted to 0 V
- Performance:
  - Average response time: **4.6 µs**
  - Typical quench time: **~17 µs**

AKA it works!

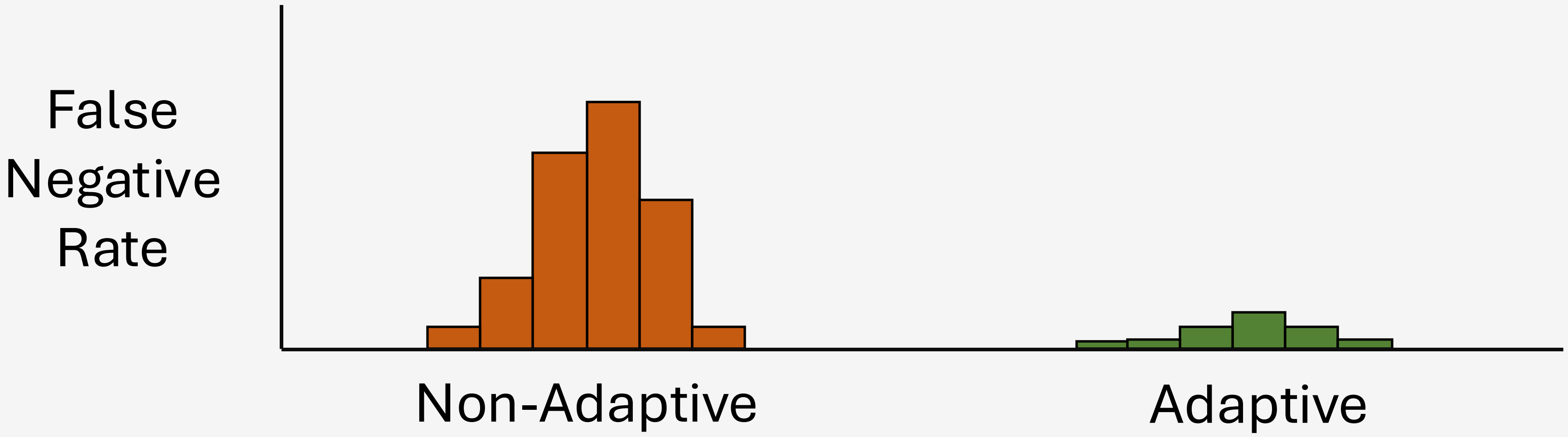


Testing in the PIF



Adaptive Mitigation

- Rely on the **primary arc detection circuitry**; use arc rate to determine the environmental hazard level
- Exploring incorporating different environmental sensor to help inform design
- Acquire large dataset via ground testing in the PIF to train ML models
- **Target: solar array operations as a function of local charging environment to maximize power output throughout the lunar cycle**



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Next Generation Solar Cells

- Significantly less mass, higher power density than SOA solar cells
- Cheaper fabrication costs
- Compatible with ISRU efforts

- **Must estimate time scale for damage**
  - Cannot withstand heat of primary arcing events
  - Understand damage mechanisms to inform protective architecture designs

External Partners

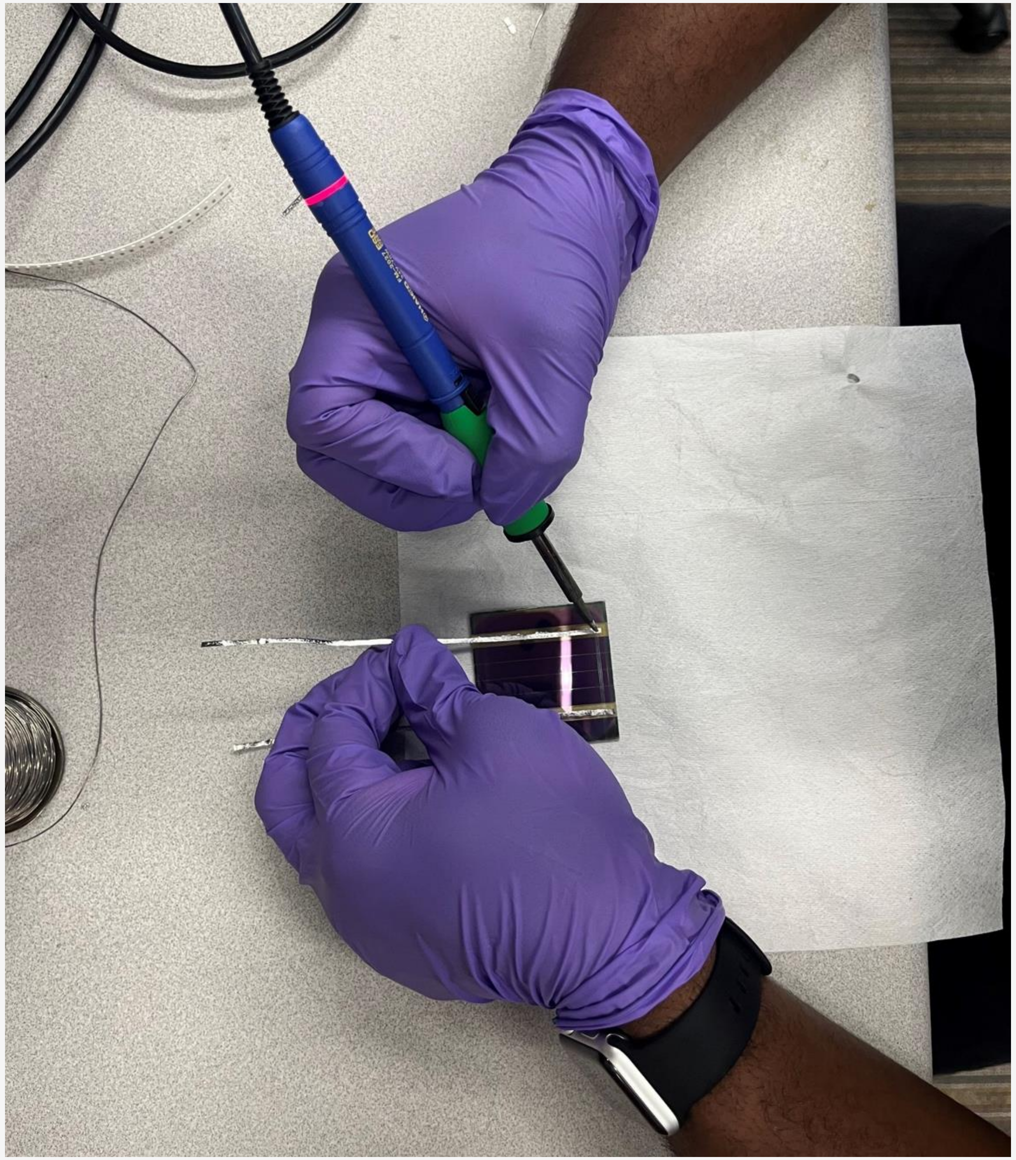
NATIONAL RENEWABLE ENERGY LABORATORY

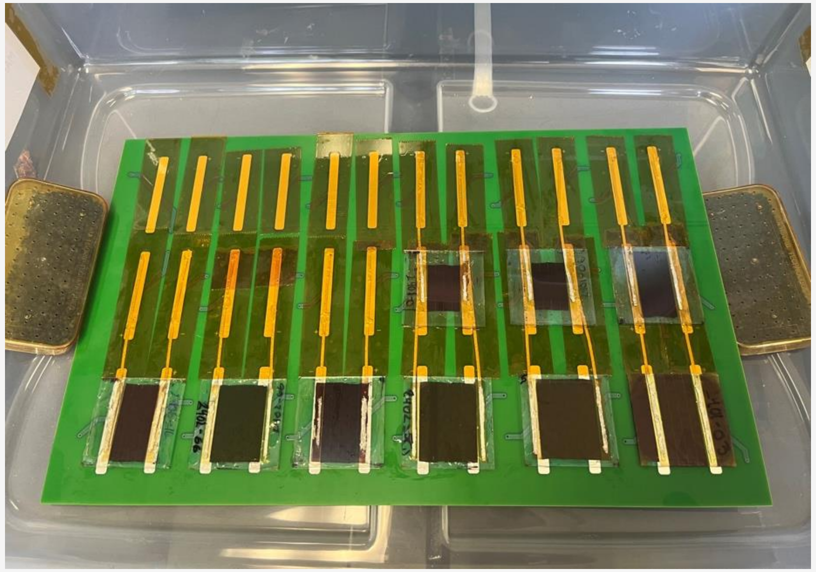
- Leaders in terrestrial solar cell R&D
- **Developing perovskites for space PV**
- **Advanced solar cell and materials characterization and testing**

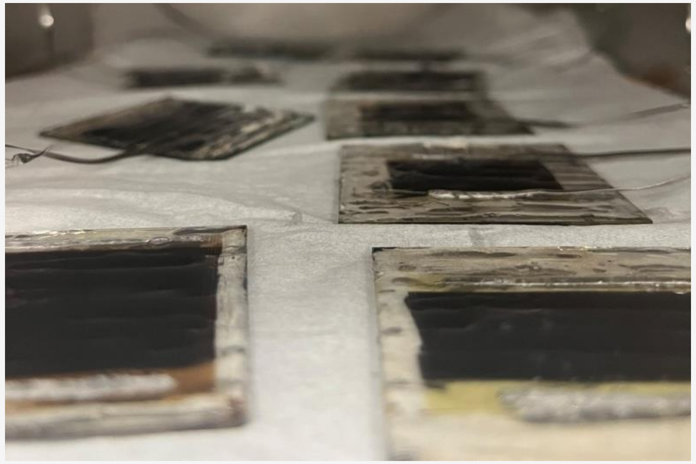
Arizona State University

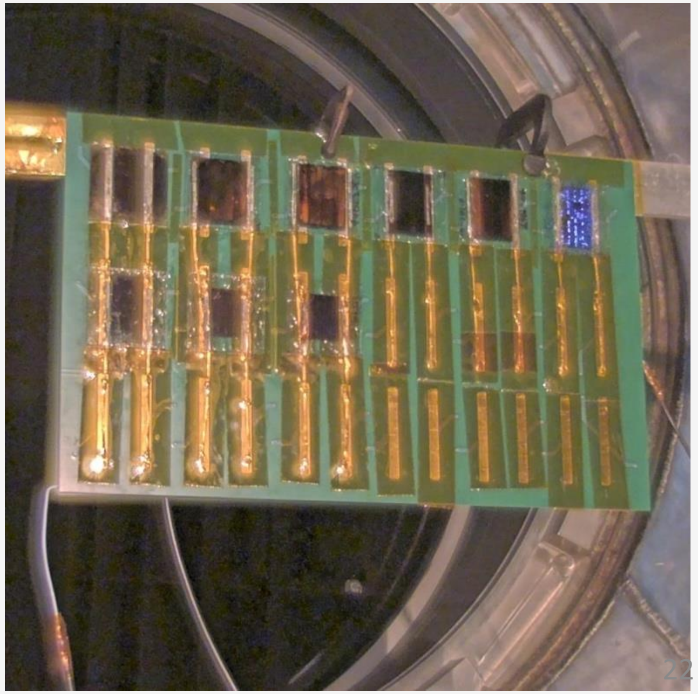
- State-of-the-art silicon solar cell fabrication and characterization facilities
- **Advanced defect characterization**

Progress – Perovskite Testing









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ECI Experiences, Lessons Learned

ECI Program: highly unique opportunity to provide early career researchers autonomy and support in pursuing next-level technology development

Programmatic:

- Tailoring flight-like Safety and Mission Assurance (SMA) documentation for an R&D effort, in pursuit of eventual flight demonstration
- Takes more time to initiate and run a contract than expected

Technical

- Improving test flow and data collection in the Plasma Interaction Facility
- Advanced circuitry development and testing

Forward Work

- Investigate arcing behavior in **charged dust environment**
- Further development and testing of **thin film solar cells**
- Further **validation** of the active arc mitigation circuitry
- **Machine learning algorithm** development and testing

Conclusion

MAI TAI aims to enable **resilient**, **high voltage**, **high power density** solar array installations on the lunar surface through novel arcing mitigation technology development.

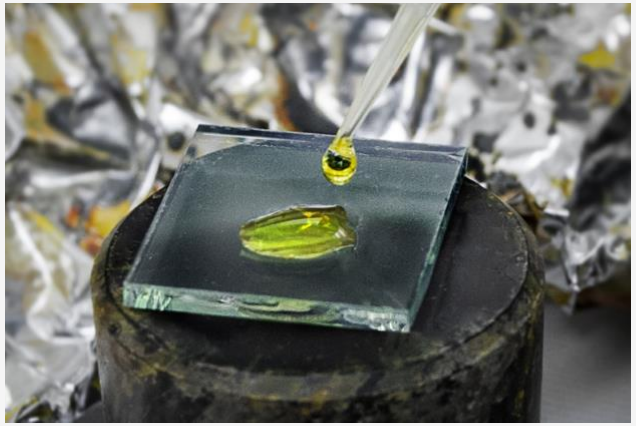
Backup Slides

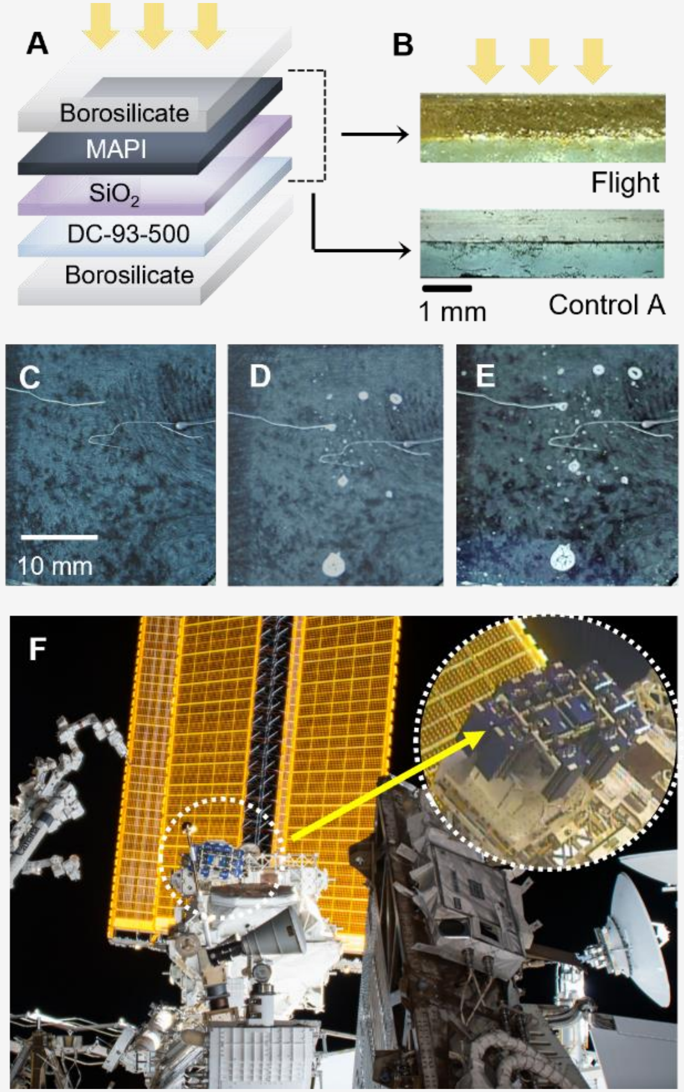
Safety and Mission Assurance

- The MAI TAI SMAP will guide all S&MA activities during development, build, and test of MAI TAI hardware and software (System Safety, Reliability, Quality Assurance, Risk Management)
- MAI TAI is a research project with an eventual goal to fly as a payload
  - Developed using NPR 7120.8 with input from NPR 7120.5
  - Allows for easier transition between program phases and reduces required future edits.
  - Few S&MA deliverables required for the research development phase, so SMAP has been tailored to create a framework for flight-required deliverables
- MAI TAI is pioneering an **agile-management structure** that will eliminate the need for major design reviews during the program.
  - S&MA milestones traditionally tied to design reviews (ex. Phase I Safety Review coincides with Preliminary Design Review).
  - Safety reviews instead align with **key technical milestones** at the PI’s discretion.
- The SMAP will be reviewed and concurred by the Safety and Engineering Review Board for implementation on August 26, 2024.

NREL

NREL
NATIONAL RENEWABLE ENERGY LABORATORY





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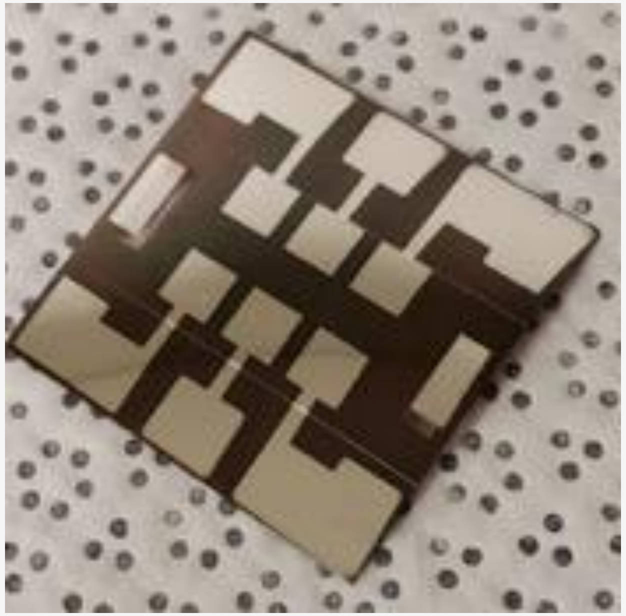
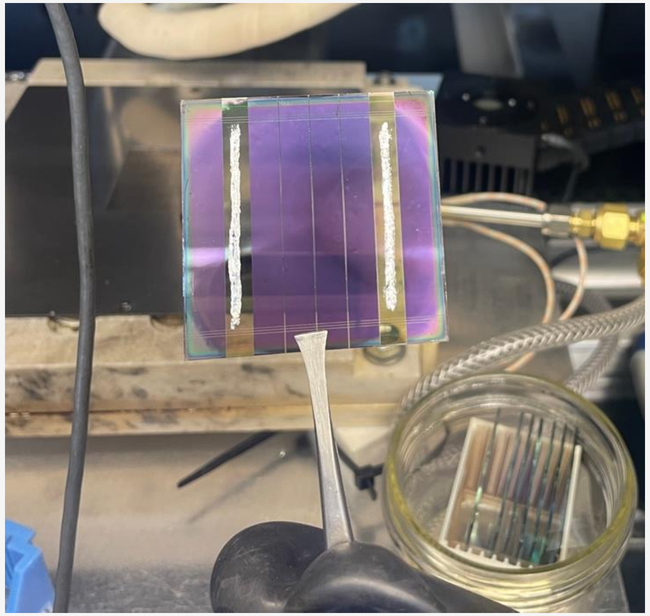
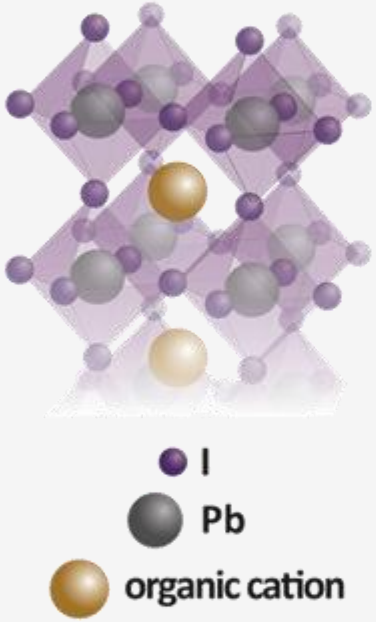




Perovskite crystal



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Passive Mitigation

Transparent Conductive Oxides (TCOs) dissipate built-up charge on the surface of solar cells *without* significant absorption of incoming light.

Characterization Plan: Analyze thin film coatings before and after exposure experiments to understand their performance in extreme environments.

PVD interior

Physical Vapor Deposition (PVD) System

Thin Film Characterization

Techniques:

- **Spectrophotometry:** *Optical properties (transmittance & reflectance)*
- **Fourier Transformed Infrared (FTIR)-Microscopy:** *allows for the visualization of the chemical composition of a sample*
- **Hall Effect Measurement:** *carrier mobility & conductivity*
- **X-ray Diffraction (XRD):** *bulk and thin film chemical analysis*
- **Scanning Electron Microscopy (SEM) w/ Energy Dispersive Spectroscopy (EDS):** *microscopy with elemental analysis*
- **X-ray Photoelectron Spectroscopy (XPS):** *material surface characterization- depth profile with elemental composition analysis*
- **Electron Beam Induced Current (EBIC) in SEM:** visualization of electrically active areas on a sample and *characterization of defect sites*