*Enabling renewable energy breakthroughs through better data.*

# Low-Current Diagnostic Metric for Photovoltaic Module Damage

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*Presented at 52nd IEEE PVSC, June 13, 2024 (Seattle, WA, USA)*

134 Manufacturers

850 Unique Datasheets

3438 Unique Make/Model Combinations

2303 (67%) Dated | 1135 (33%) Undated

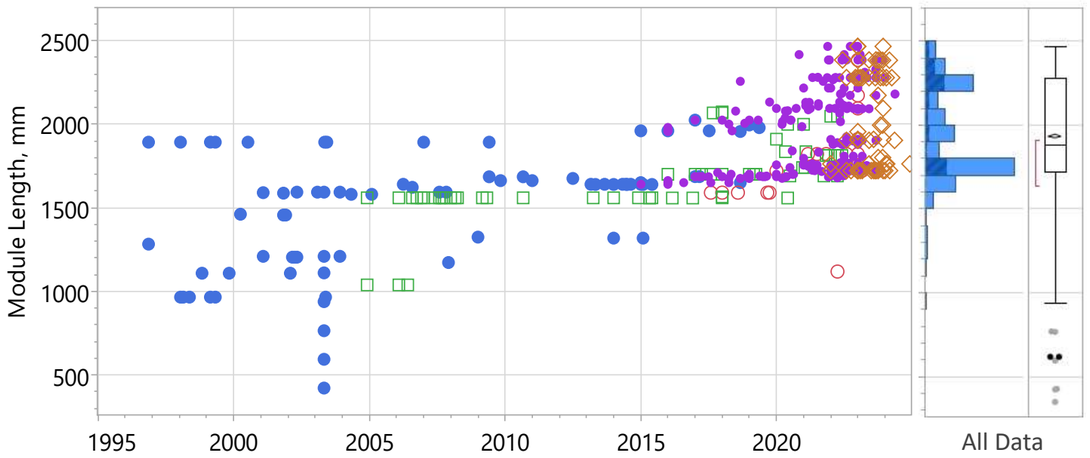
**POSTER**

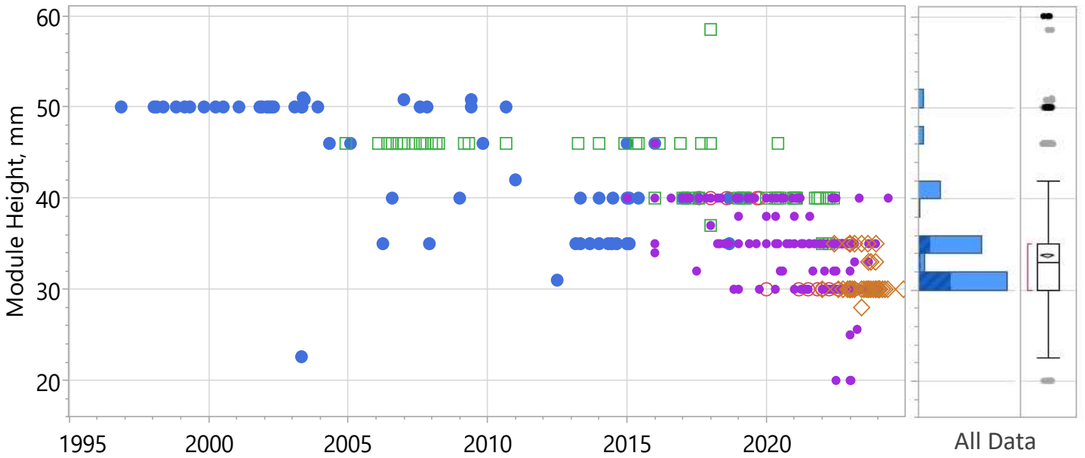
**J21**

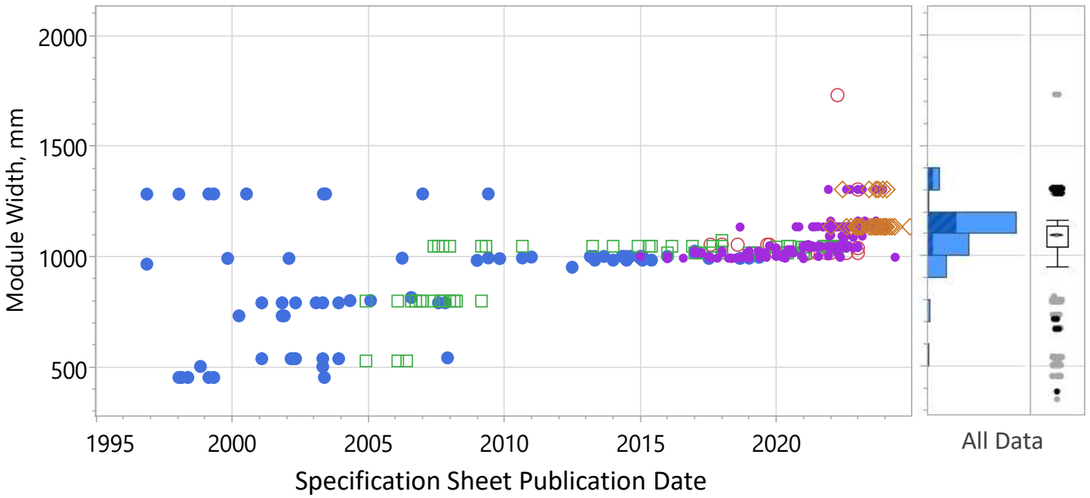
**AREA 7: PV MODULES, MANUFACTURING, SYSTEMS AND APPLICATIONS**

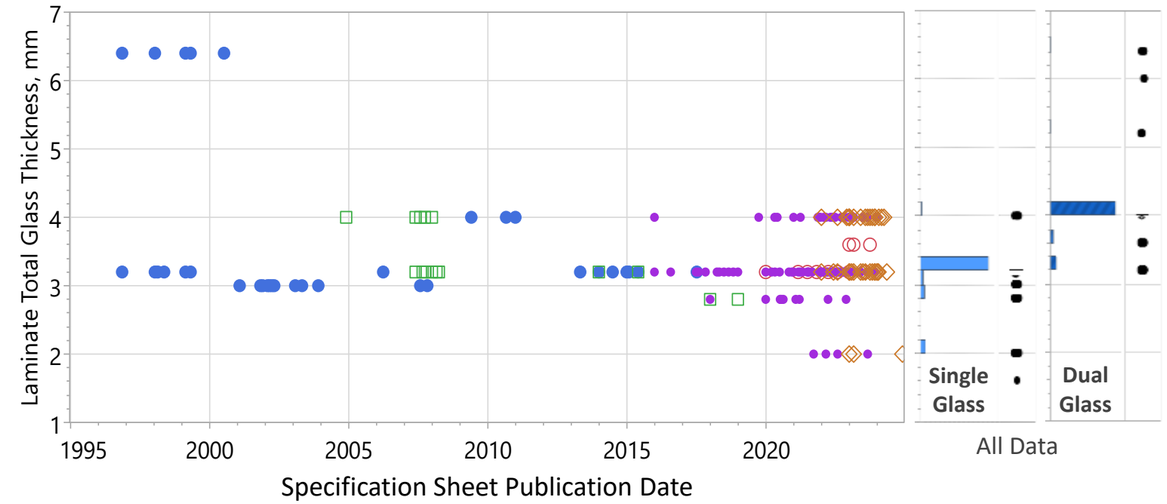
Aluminum back side field (BSF)
Heterojunction
Interdigitated Back Contact (IBC)
PERC
Topcon

Dual | Single



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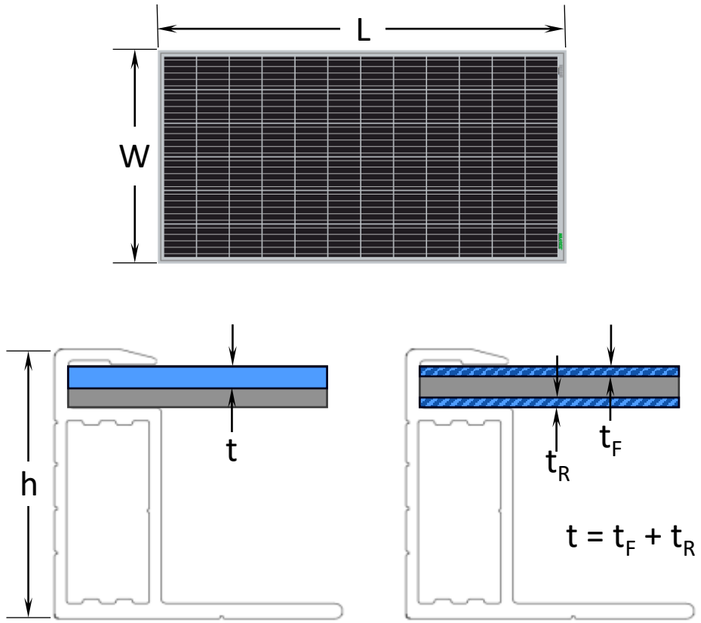
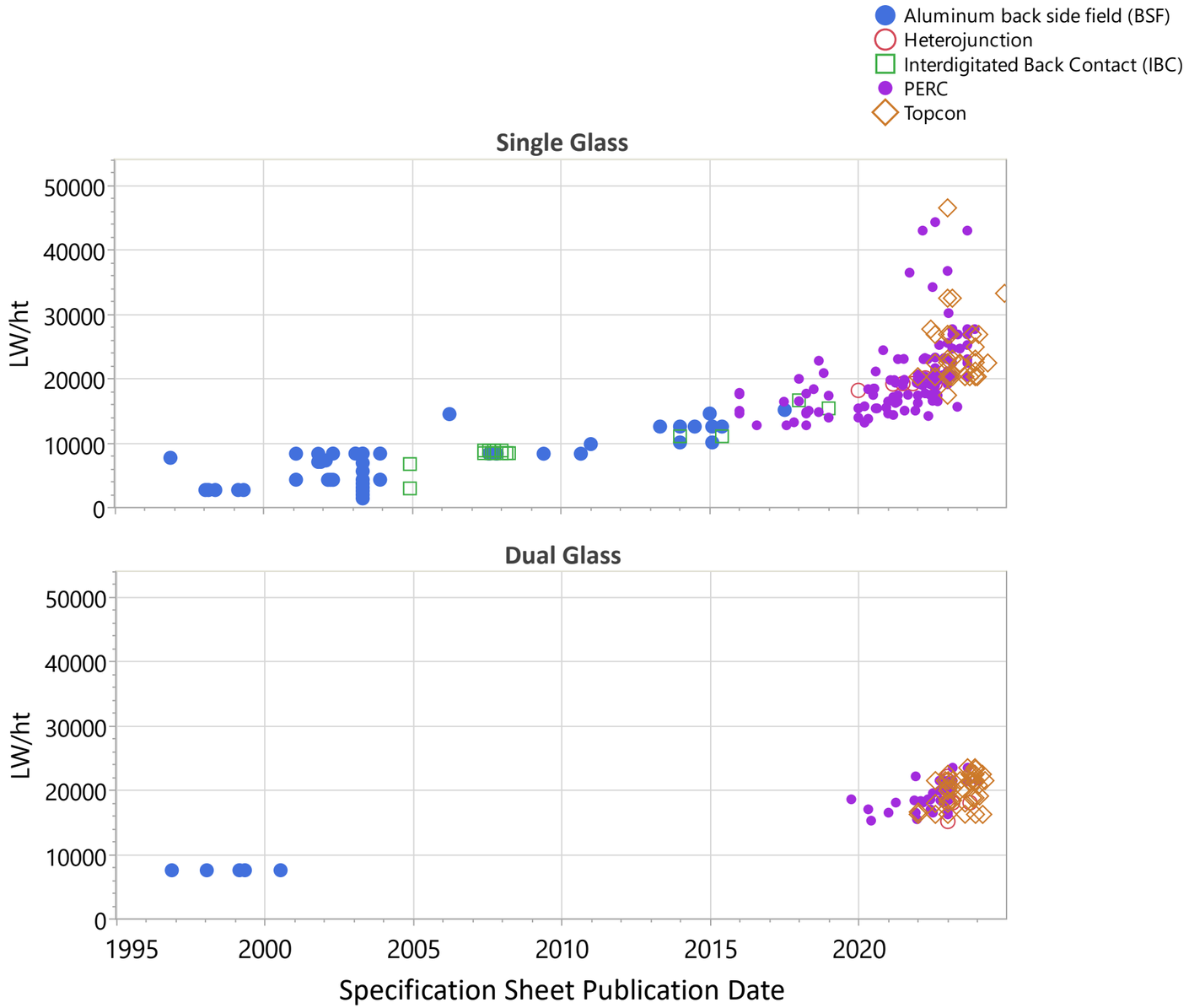



$$\frac{L \cdot W}{h \cdot t}$$



# Non-visible damage is difficult to detect in the field

Shipping, Handling, and Installation

Non-Catastrophic Extreme Weather

Thermal Fluctuations

**Electroluminescence Imaging**

Night
Specialized equipment
Expensive
Day
Noisy
Blind under busbars

**Infrared Imaging**

Hot spots
Specialized equipment
Ohmic losses
Visibility to severe cracks
Blind to minor cracks

**Ultraviolet Fluorescence**

Specialized equipment
Time-delayed response
Visibility to cracks under busbars
Pattern influences effectiveness

**Photoluminescence Imaging**

Labor intensive
Specialized equipment

**Indoor I-V Curve Tracing**

Specialized equipment
High power requirement
Laboratory
Module size limitations

**Field I-V Curve Tracing**

Day only
Time-intensive
Disruptive to generation
Susceptible to external influences

# Priorities for improved diagnostic metric

Single Point Measurement

High Damage Sensitivity

Low Power Requirement

Few Implementation Barriers

Wide Applicability



*Presented at 52nd IEEE PVSC, June 13, 2024 (Seattle, WA, USA)*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theconversation.com/solar-panels-on-half-the-worlds-roofs-could-meet-its-entire-electricity-demand-new-research-169302


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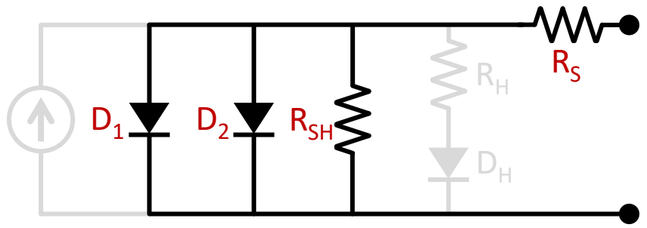
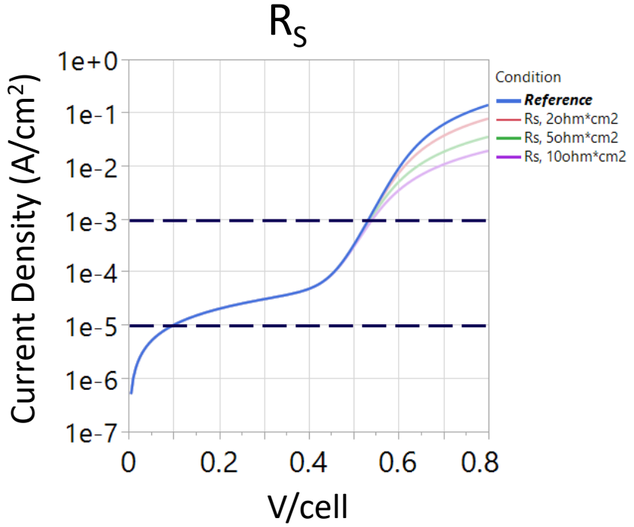
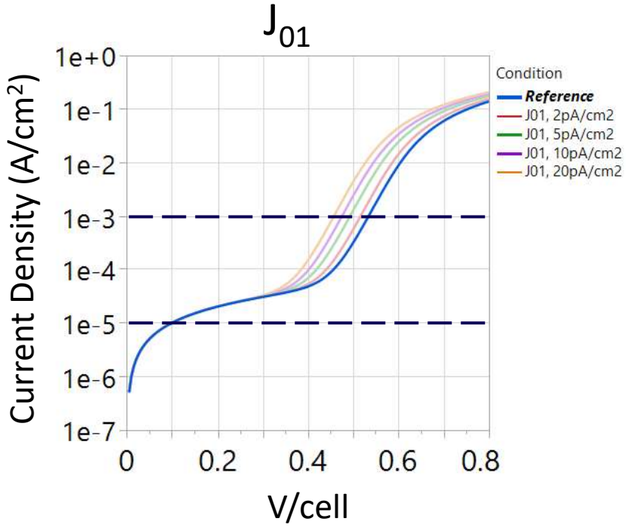
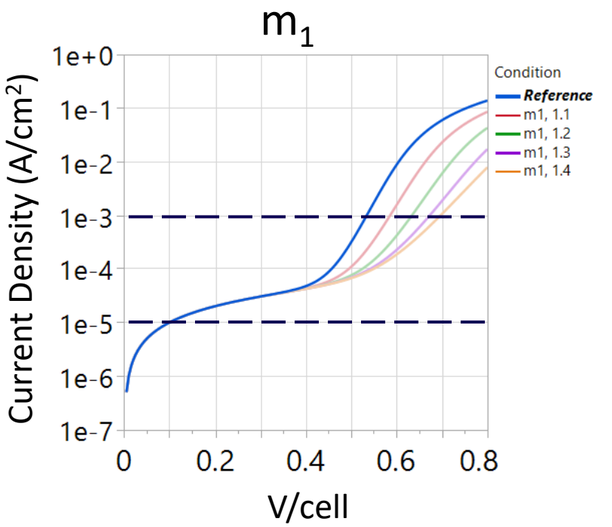
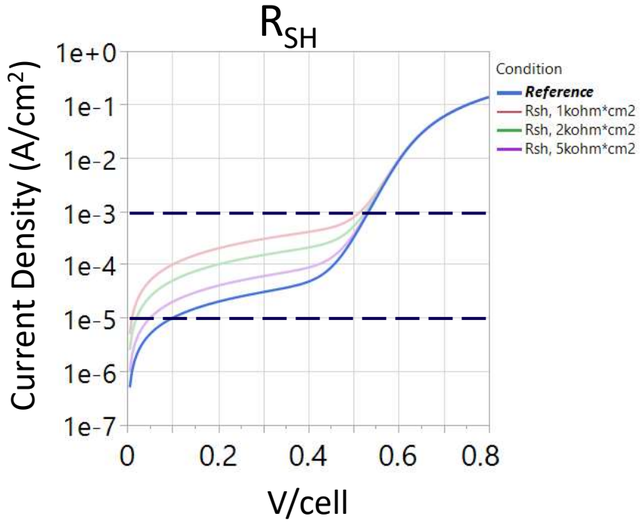


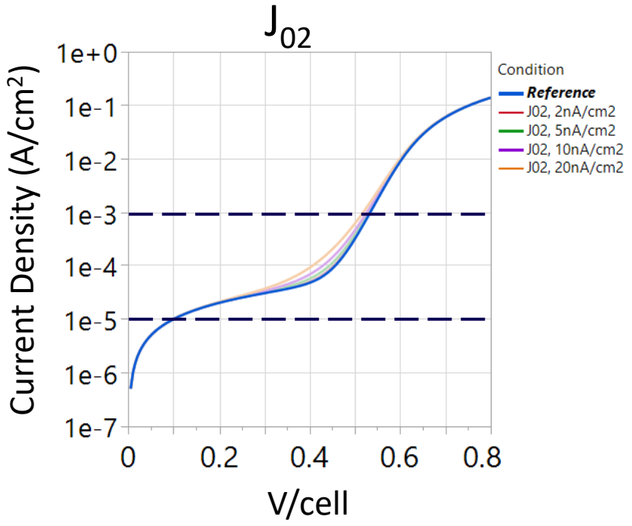

Current Density Thresholds
Upper: 1mA/cm$^2$
Lower: 0.01mA/cm$^2$

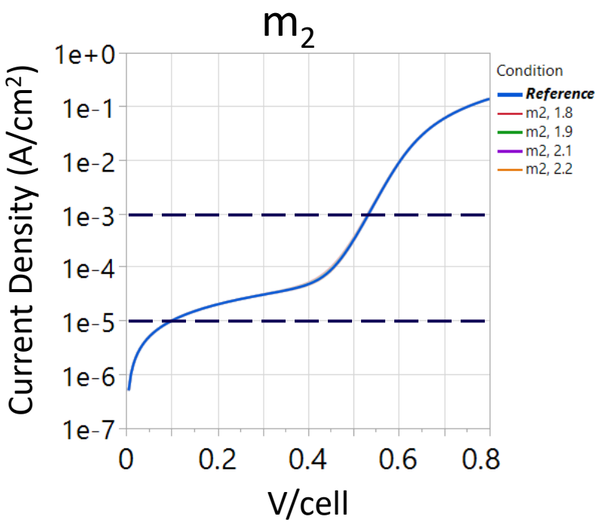


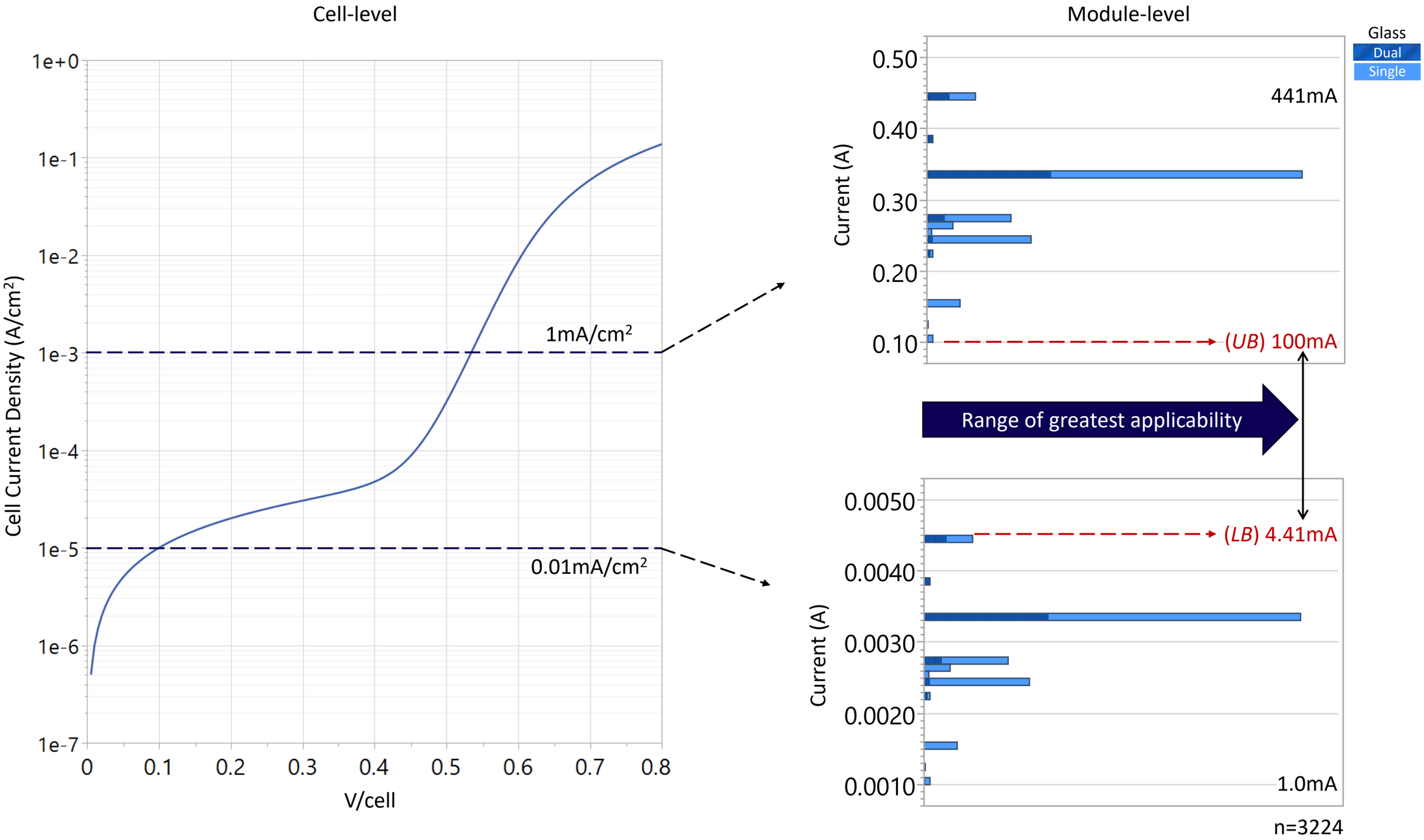




Cell-level
Module-level
Glass
Dual
Single
1e+0
1e-1
1e-2
1e-3
1e-4
1e-5
1e-6
1e-7
Cell Current Density (A/cm²)
1mA/cm²
0.01mA/cm²
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
V/cell
0.50
0.40
0.30
0.20
0.10
Current (A)
441mA
(UB) 100mA
Range of greatest applicability
0.0050
0.0040
0.0030
0.0020
0.0010
Current (A)
(LB) 4.41mA
1.0mA
n=3224

# Waaree WSM-390

72-cell
Monofacial
Mono-PERC

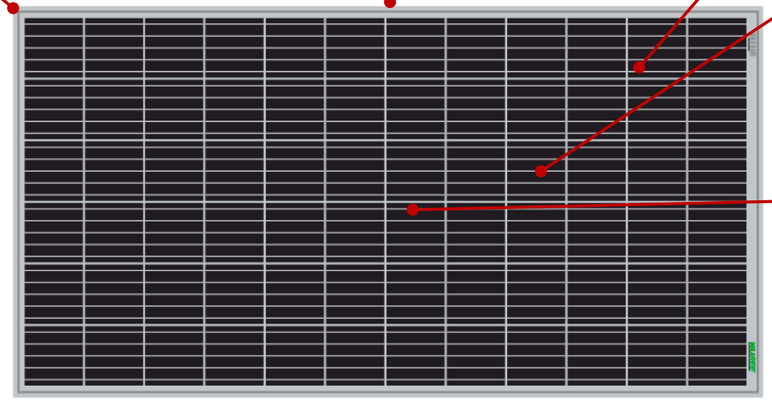
Corner Impact

Edge Impact

Rear Object Impact

Front Standing

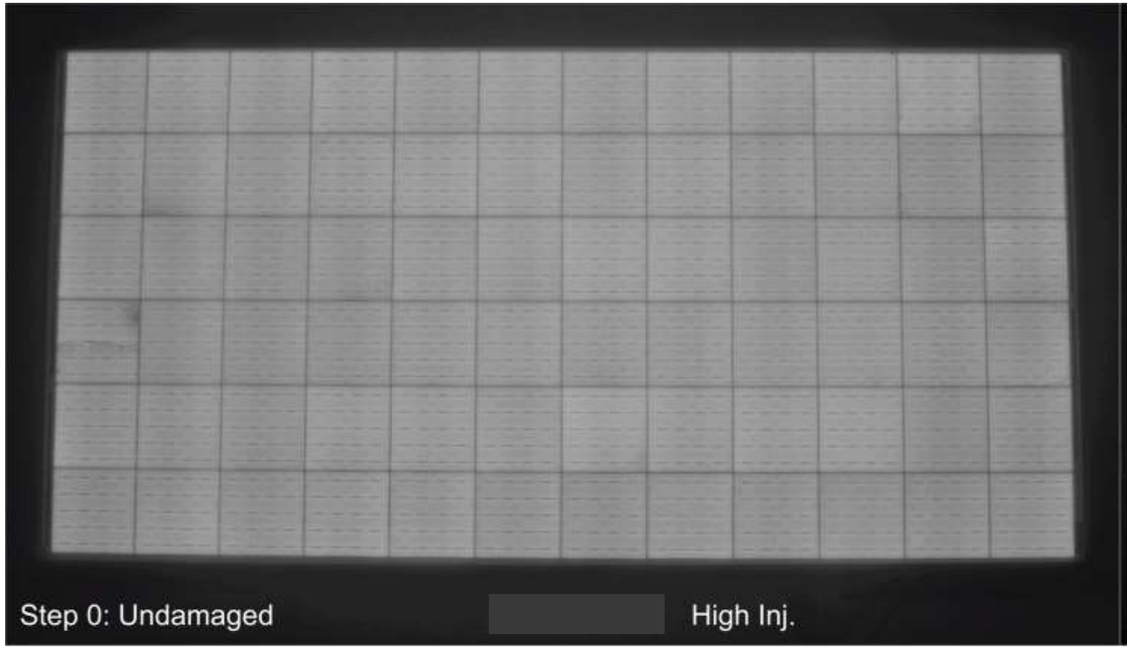
UCF/FSEC PV Module Characterization Facility

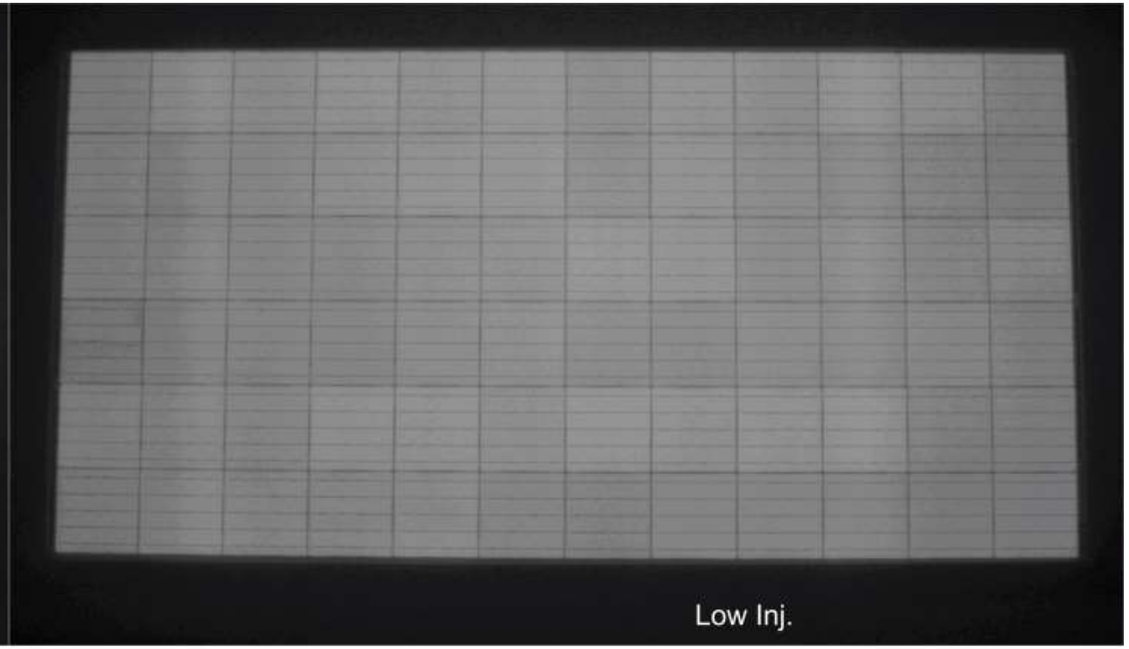


Front Walking

| Models | Pmax (W) | | Vmp (V) | | Imp (A) | | Isc (A) | | Voc (V) | | Module Eff. (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | STC | NOCT | STC | NOCT | STC | NOCT | STC | NOCT | STC | NOCT | |
| WSM-390 | 390 | 288.2 | 40.10 | 37.47 | 9.73 | 7.69 | 10.03 | 8.11 | 48.85 | 44.99 | 19.58 |

| | |
|---|---|
| Temperature coefficient of Current (Isc), α (%/°C) | 0.05 |
| Temperature coefficient of Voltage (Voc), β (%/°C) | -0.27 |
| Temperature coefficient of Power (Pm), γ (%/°C) | -0.37 |
| NOCT (°C) | 46 ± 2 |
| Operating temperature range (°C) | -40 to 85 |




**Waaree WSM-390**
Monofacial
Mono PERC
72-cell
$I_{sc}$ = 10.03A
$A_{MOD}$ = 17690.805cm$^2$
$J_{sc}$ = 40.821 mA/cm$^2$

High Injection: $I_{sc}$
Low Injection: 0.1 $I_{sc}$

EL: Kepco / Agilent
Voltage control
Nikon D5100/950nm

DIV: Kepco / Agilent
Voltage control

LIV: Sinton FMT-350

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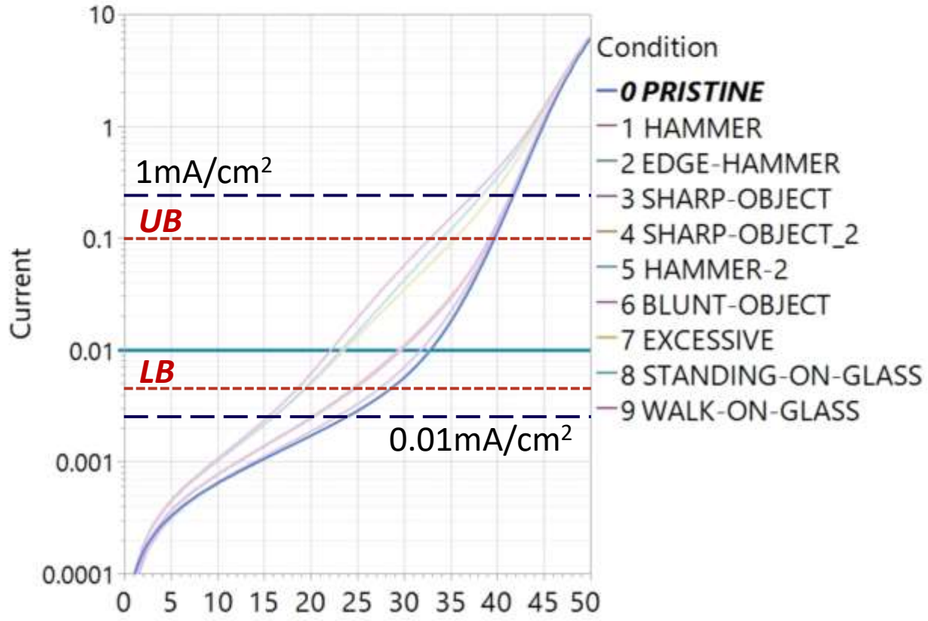
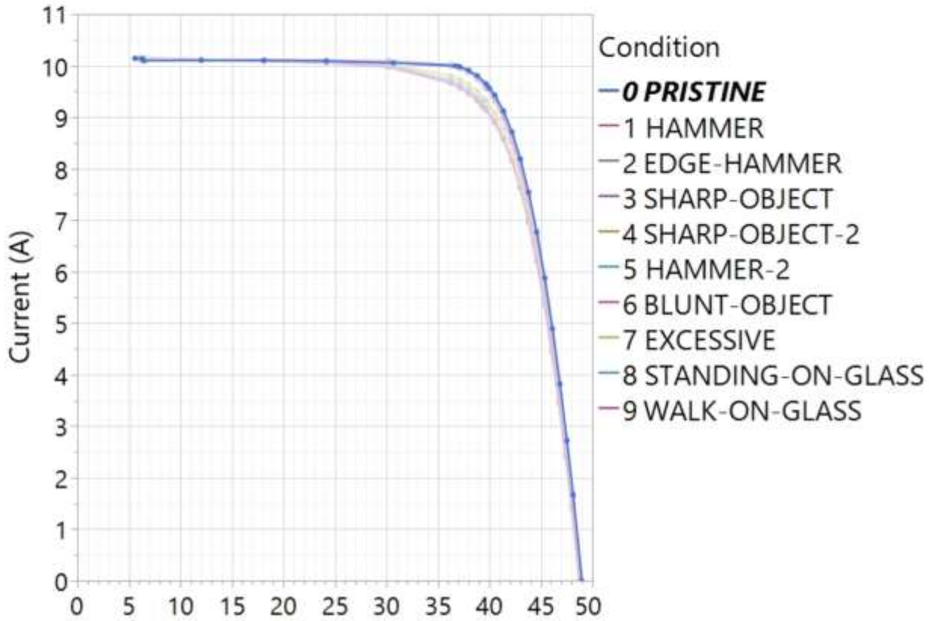
Current Density Equivalencies:

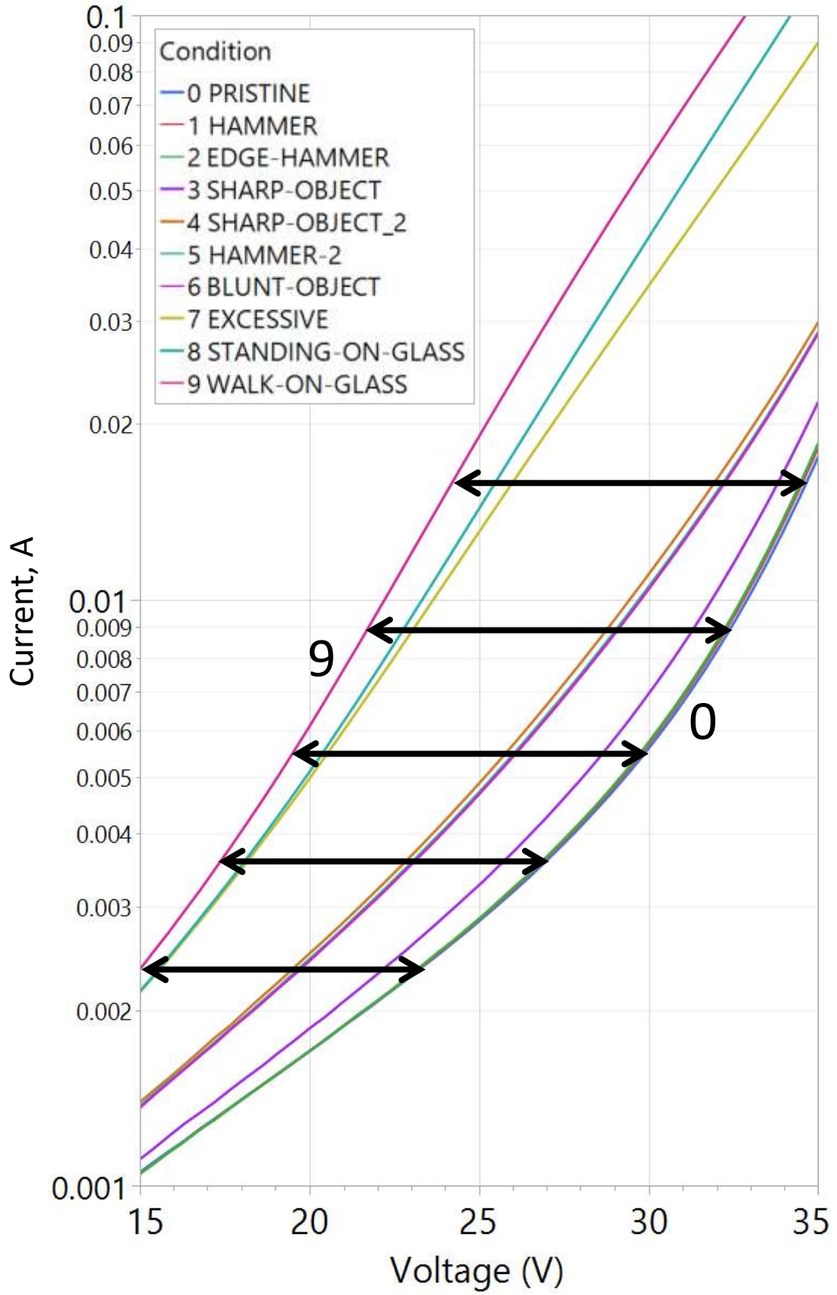
1mA/cm$^2$:
$I_1 = I_{sc}(1 / J_{sc})$
= 245.7mA

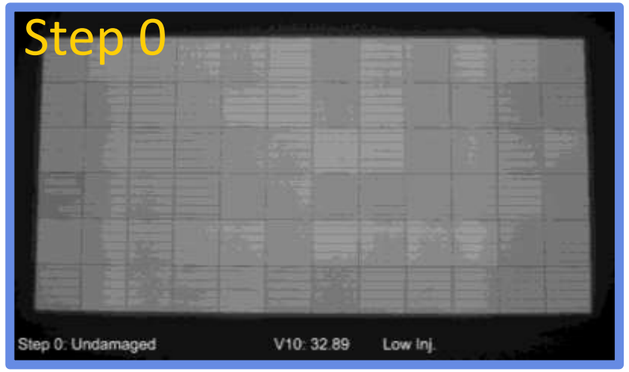
0.01mA/cm$^2$:
$I_{0.01} = I_{sc}(0.01 / J_{sc})$
= 2.457mA

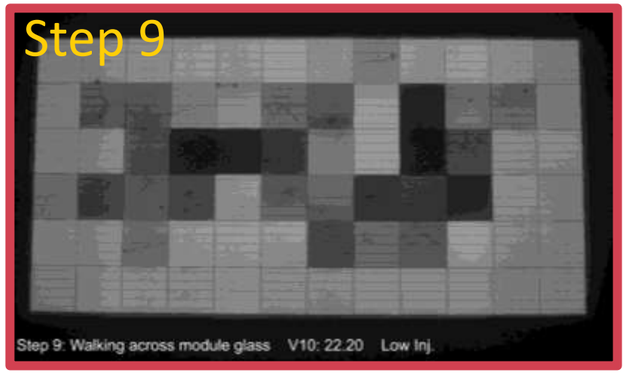
*UB* = 100mA
*LB* = 4.41mA



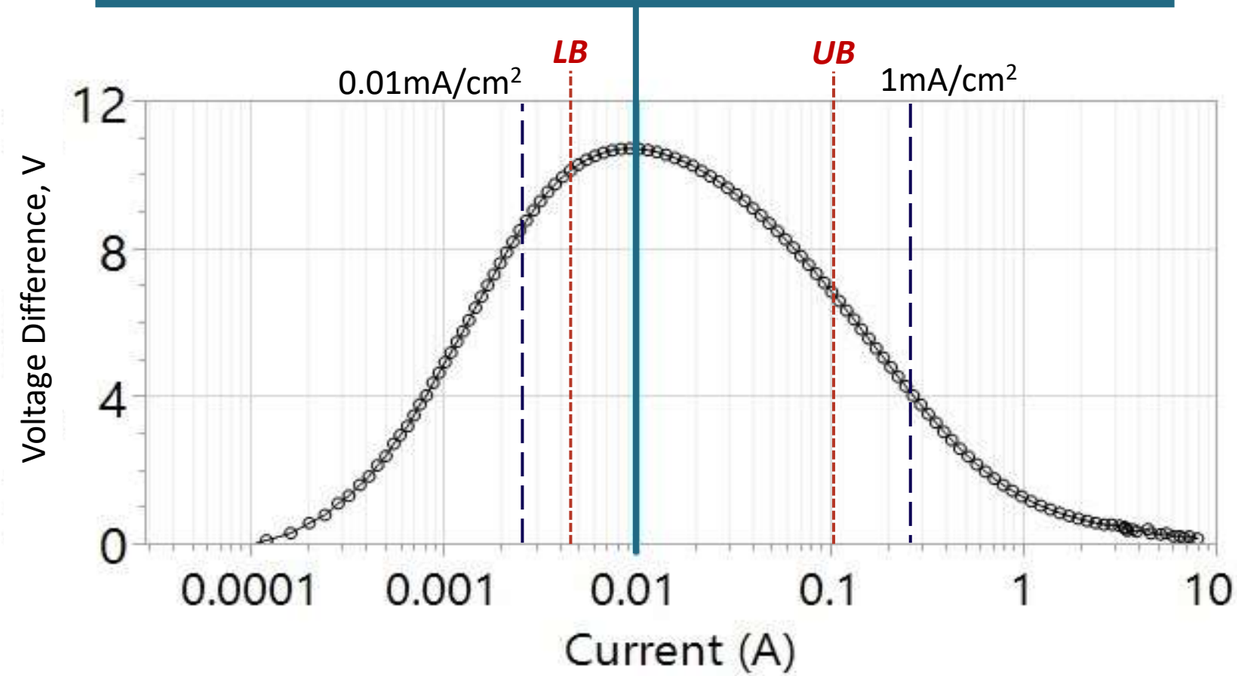






**V10**
The voltage required to inject 10mA through a module in the dark




*UB* = 100mA
*LB* = 4.41mA

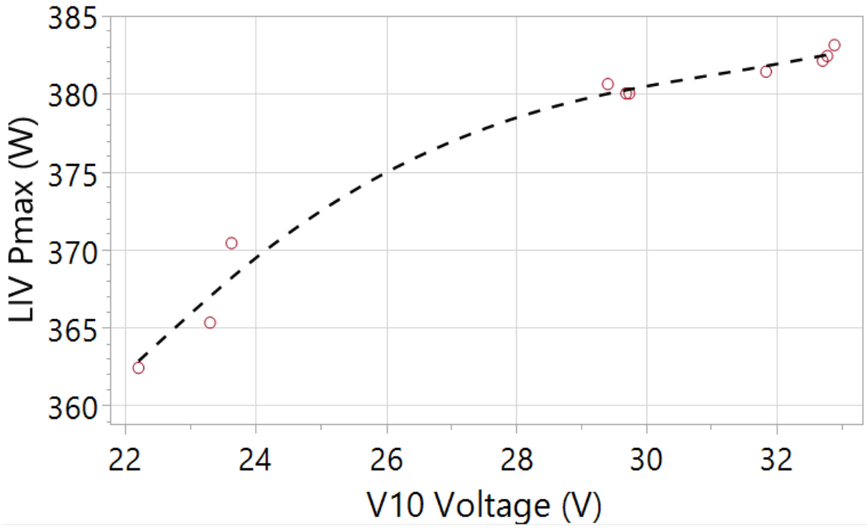


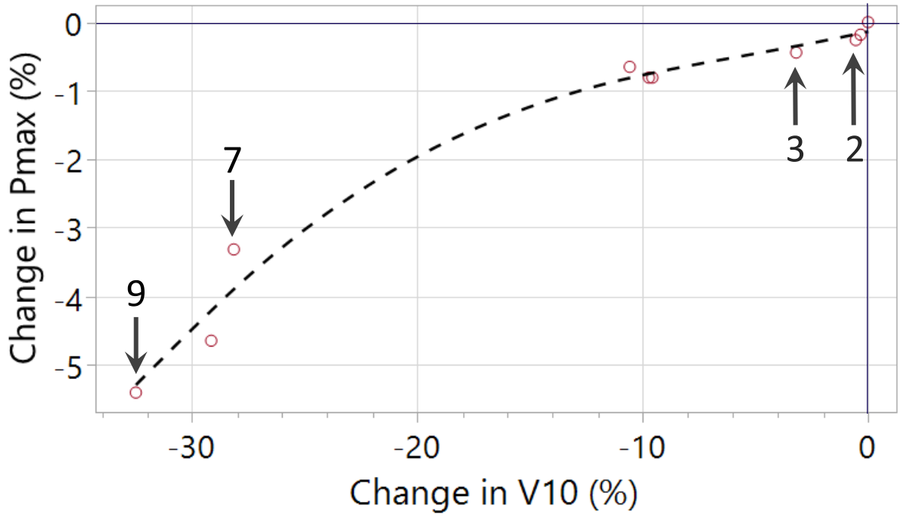
*Presented at 52nd IEEE PVSC, June 13, 2024 (Seattle, WA, USA)*

| Condition | EL Observation (delta) | LIV $P_{MAX}$ (W) | LIV $P_{MAX}$ (Ref %) | V10 (V) | V10 (Ref %) | V10 Measurement Power (W) |
|---|---|---|---|---|---|---|
| 0 Pristine | 1 cracked cell (reference) | 383.1 | – | 32.89 | 0.00 | 0.329 |
| 1 Hammer | No change | 382.4 | -0.18 | 32.78 | -0.33 | 0.328 |
| 2 Edge Hammer | No change | 382.1 | -0.26 | 32.71 | -0.54 | 0.327 |
| 3 Sharp Object | +7 small impact sites | 381.4 | -0.44 | 31.84 | -3.19 | 0.318 |
| 4 Sharp Object 2 | +16 small impact sites | 380.6 | -0.65 | 29.41 | -10.58 | 0.294 |
| 5 Hammer 2 | Crack growth from 3 sites | 380.0 | -0.81 | 29.69 | -9.73 | 0.297 |
| 6 Blunt Object | No change | 380.0 | -0.81 | 29.74 | -9.58 | 0.297 |
| 7 Excessive Impact | Crack growth from all sites | 370.4 | -3.32 | 23.63 | -28.15 | 0.236 |
| 8 Standing | Crack growth from all sites | 365.3 | -4.65 | 23.30 | -29.16 | 0.233 |
| 9 Walking | Crack growth from all sites | 362.4 | -5.40 | 22.20 | -32.50 | 0.222 |

LIV 3% uncertainty [1]

DMM 1% uncertainty [2]

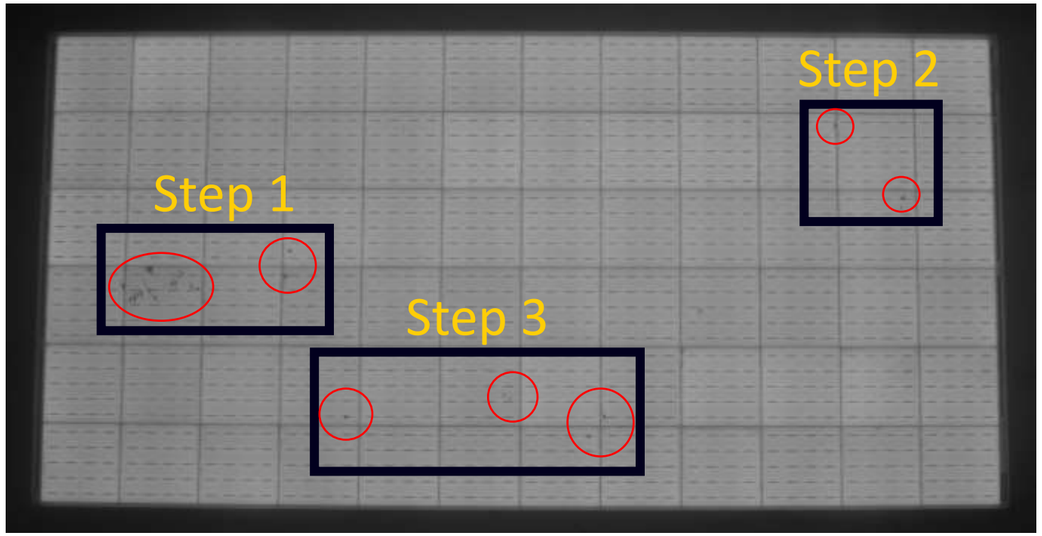


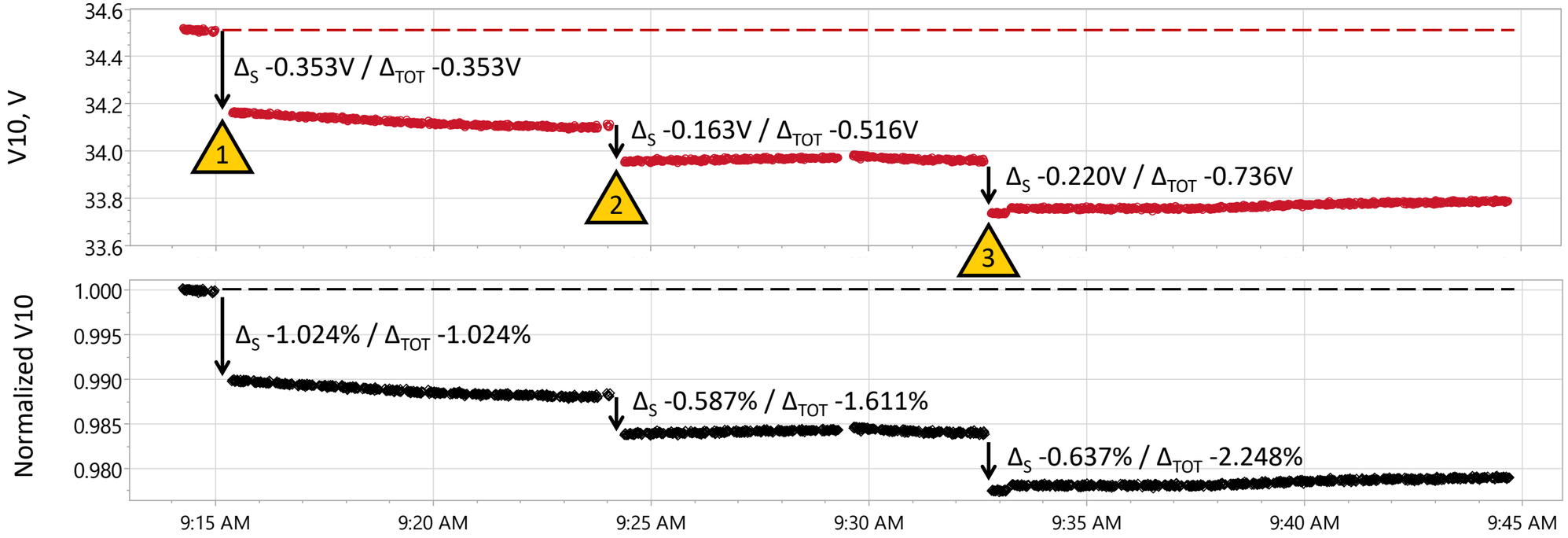




V10 shows greater sensitivity to damage than illuminated I-V

V10 measurement power is minimal


[1] M. Köntges, et al., "Review of failures of photovoltaic modules," Report IEA-PVPS T13-01, pp. 1–140, 2014.
[2] Keithley, "2700/2701/2750 Multimeter/Data Acquisition/Switch Systems Datasheet," 2018.

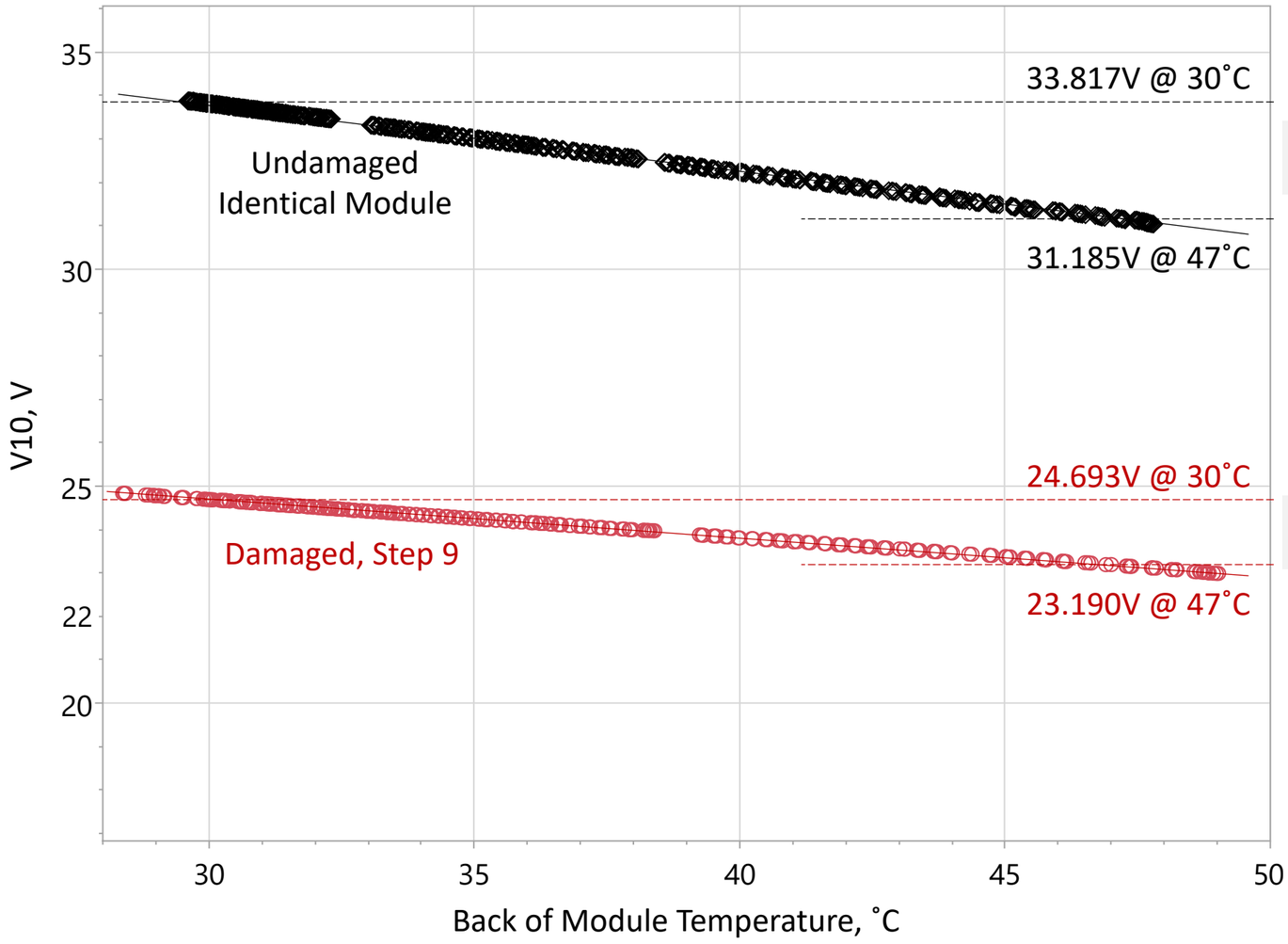



V10 response to damage introduction is instantaneous

V10 change is permanent

* Normalized V10 is to the median of the initial condition V10 voltages




m = -0.155 V/˚C
34.595V @ 25˚C

$\beta_{V10\_UNDAMAGED}$ = -0.510 %/°C

m = -0.088 V/˚C
25.135V @ 25˚C

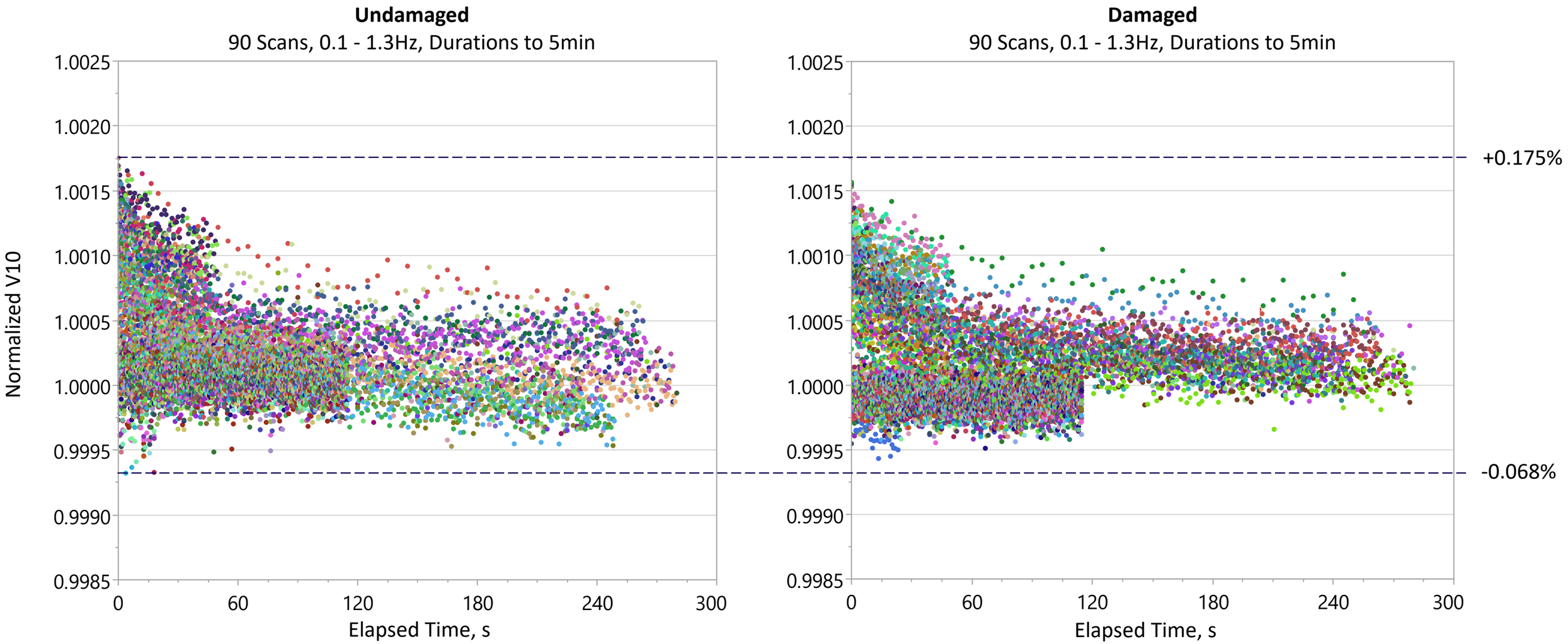
$\beta_{V10\_STEP9}$ = -0.389 %/°C

| Temperature (˚C) | ΔV10 (Undmg – Dmg) (V) |
|---|---|
| 25 | 9.460 |
| 30 | 9.124 |
| 47 | 7.995 |

V10 shows a linear response to temperature
Slope ($\beta_{V10}$) is a function of damage level?

ΔV10 decreases as temperature increases

$\beta_{V10} \neq \beta_{VOC}$




No apparent rate effect

Damage does not alter measurement stability

* Normalized V10 is to the median of each population; same module SN between states

# Priorities

Single Point Measurement

High Damage Sensitivity

Low Power Requirement

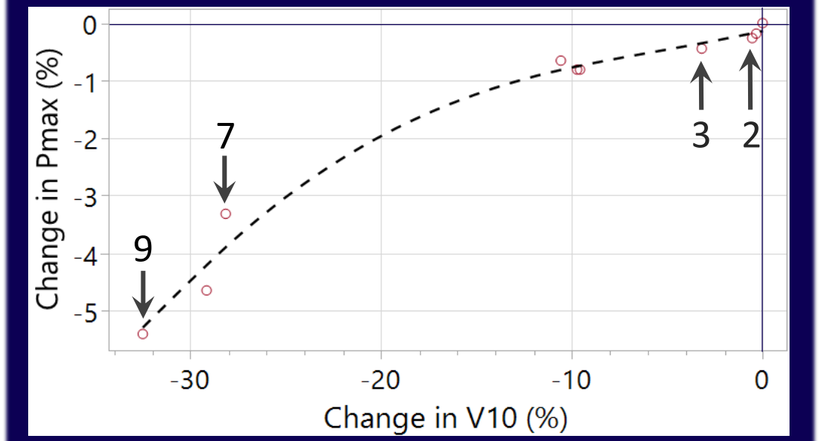
Few Implementation Barriers

Wide Applicability

## V10

The voltage required to inject 10mA through a module in the dark

### High Damage Sensitivity & Single Point Measurement

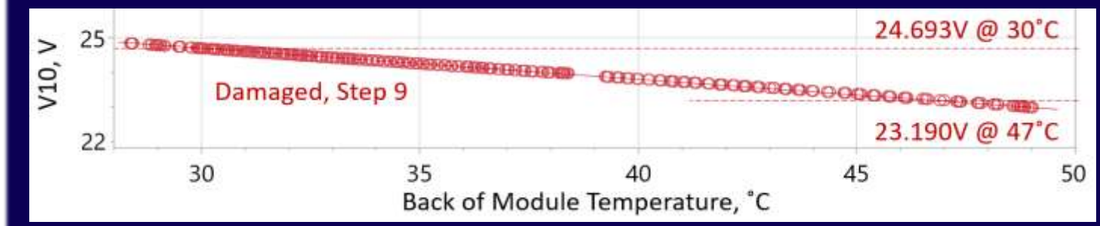



### Few Implementation Barriers

No specialized equipment / low power

Fast measurement

Stable measurement


### Low Power Requirement

| | |
|---|---|
| Module | < 1W |
| 1000V String | < 10W |
| 1500V String | < 15W |

Power ↓ as damage ↑

### Wide Applicability

Sensitive to damage which affects any device equivalent circuit parameter (excluding $R_S$)

Low power → Portable (shipping, install)

Field (string monitoring)

More work must be conducted . . . but V10 is promising.



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# Anticipated applications

**Transit**
- Evaluation of transportation sector components (trucking, warehouse handling)
- Single or multi-module (pallet) reusable, rechargeable monitor
- Coupled with position (GPS), shock (accelerometer), temperature monitoring
- Precise time, location, and extent of damage introduction → accountability

**Installation & Handling**
- Evaluation of handling procedures and compliance to procedures
- Junction box (blind monitoring) or plug-on device (spot check)

**Field Monitoring**
- String level – low power, night time measurement
- Non-catastrophic extreme weather (hail, snow, wind)
- Thermal cycling

**Manufacturing**
- Stringing and lamination operations
- Potential combination with EL metrology

Further development requires manufacturer and procurement partners

*Thank you for attending.*

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– Special Thanks –

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Further development requires manufacturer and procurement partners



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