Characterization of Silicon Photovoltaic Module Durability Guided by Luminescence and Thermal Imaging

Development of In-Situ Imaging with a Low-Cost Camera System

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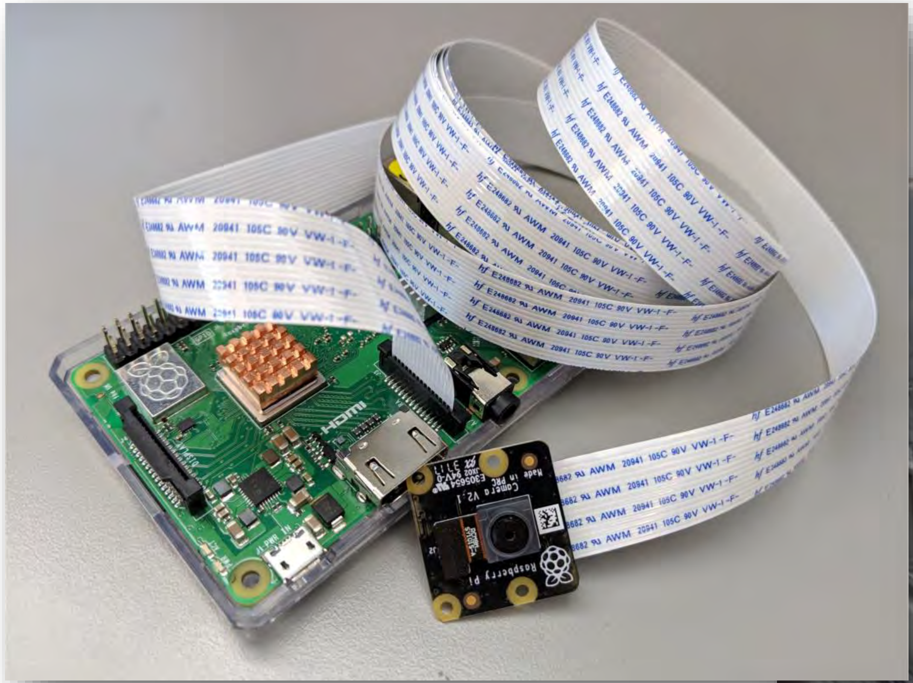
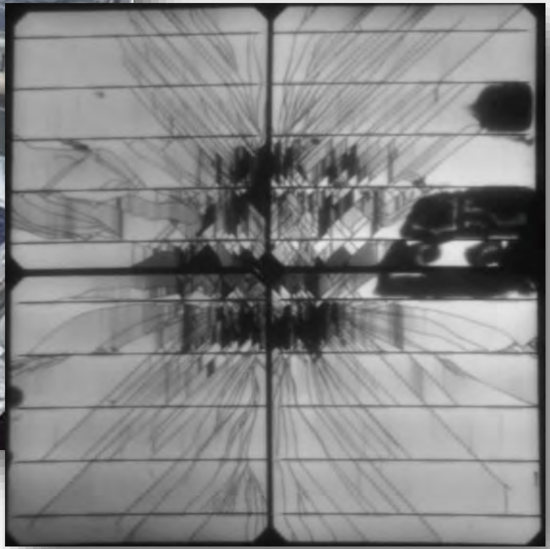




Outline

Development of low-cost in-situ electroluminescence imaging

- Hardware setup
- Software development
- Image acquisition considerations
- Image processing

Examples of in-situ imaging

- Temperature-dependent mini-module EL images
  - Cell Cracks
  - Interconnects
- Identifying LID/LeTID in Combined Accelerated Stress Testing (CAST)
  - Comparison of mimos with differing LID/LeTID susceptibility
  - ***early stages of analysis – full experiment still in progress***

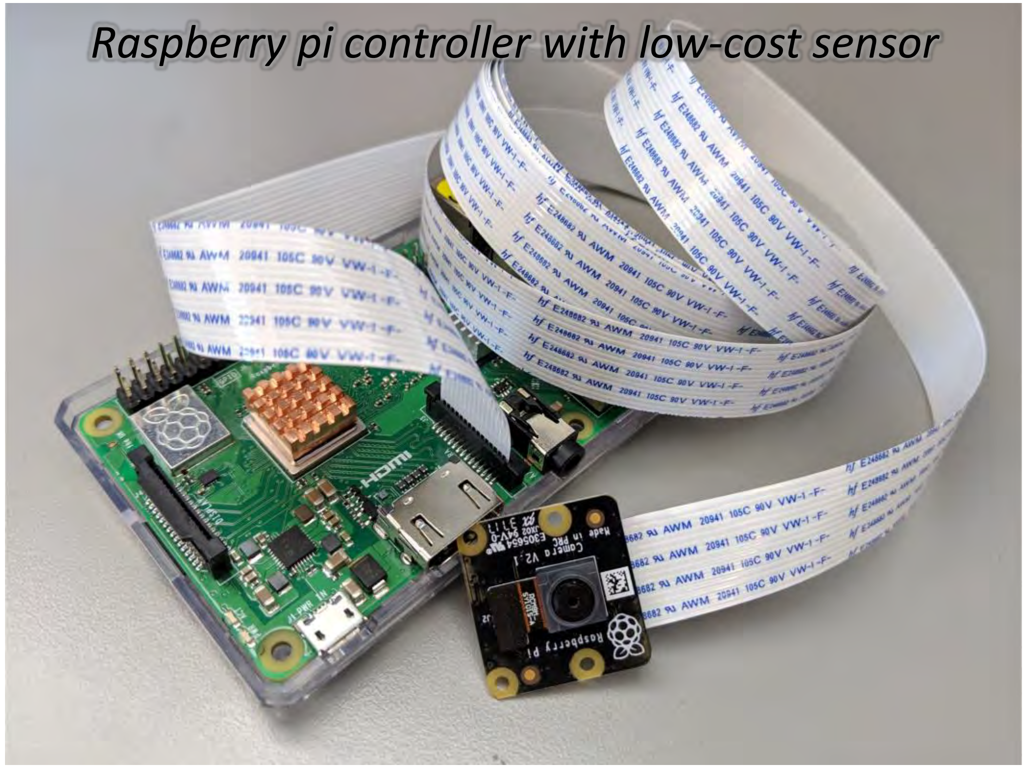
The Case for Low-Cost Scientific Imaging

Similar methods have been used for imaging air quality and cavities

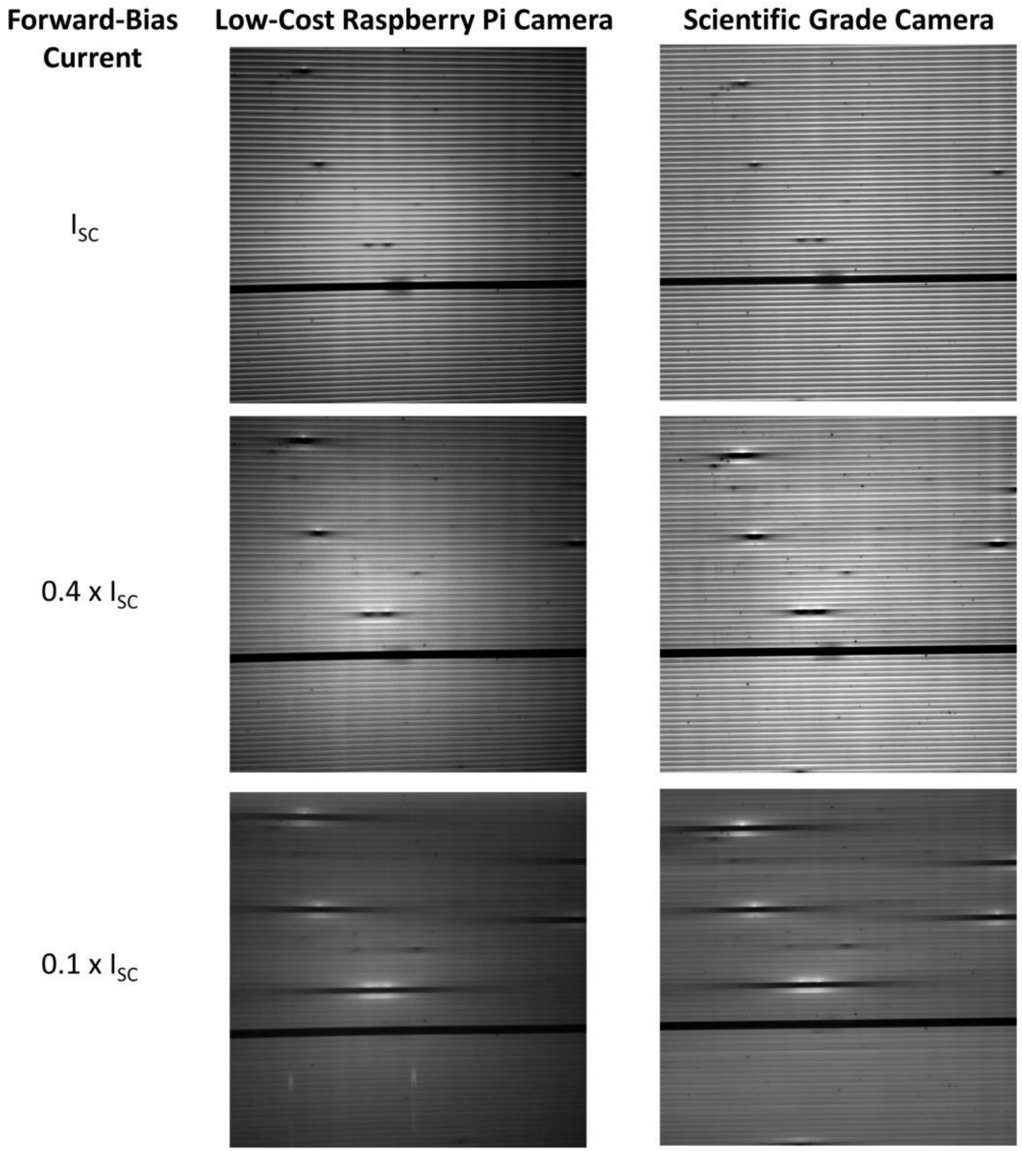
- *e.g. T.C. Wilkes et al - smoke stacks, volcanoes, etc*

Great interest in low-cost sensors in PV community

- *e.g. PVRW presentation by W. Hobbs, more affordable imaging solutions by Tau Science, in-situ imaging where sensor will get destroyed, etc.*



Measurements on a Commercial Thin-Film Module



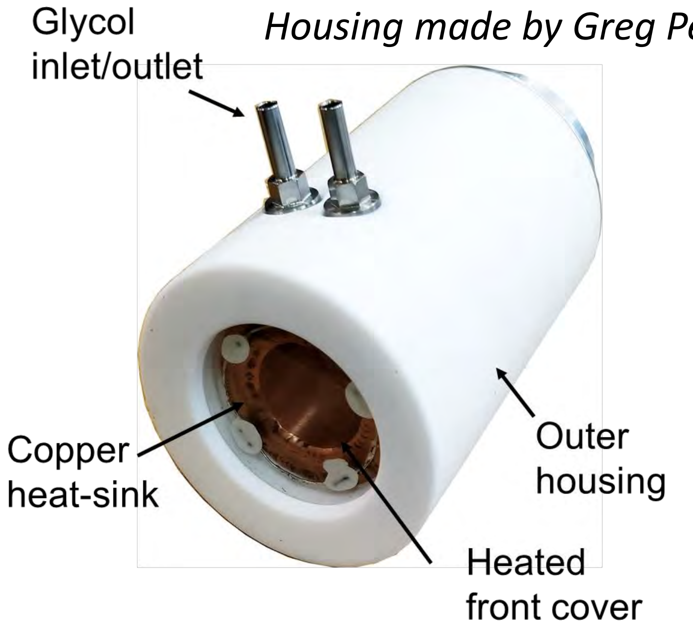
Sulas-Kern, D.B. and Johnston S. *Chapter 6: Luminescence and thermal imaging of thin-film photovoltaic materials, devices, and modules* in "Advanced Characterization of Thin Film Solar Cells" Editors: M. Al-Jassim and N. Haegel, p. 135, IET **2020**.

Hardware Development for In-Situ Electroluminescence During Accelerated Stress

Low-Cost Camera: Sony IMX219PQ 8.08Mpixel sensor with Arducam LS-61018-CS lens ($70)
Low-Cost Computing Unit: Raspberry Pi 3 Model B+ microcontroller ($30)

Hardware Constraints:

- **0.6 meter working distance above the sample plane** → need wide-angle lens
- **Harsh environment** → Custom camera housing with PTFE outer housing, copper heat-sink inner housing, glycol feed through for liquid cooling, desiccant and heated front cover for defogging, outdoor-rated HDMI feedthrough to extract data



Housing made by Greg Perrin

Owen-Bellini, M.; Sulas-Kern, D.B.; Spataru, S.; North, H.; Perrin, G.; Hacke, P. *46th Photovoltaics Specialists Conference (PVSC)* **2019**, 10.1109/PVSC40753.2019.9198956.
Owen-Bellini, M.; Sulas-Kern, D.B.; Perrin, G.; North, H.; Spataru, S.; Hacke, P. *IEEE J. Photovolt.* **2020**, 10, 1254-1261.

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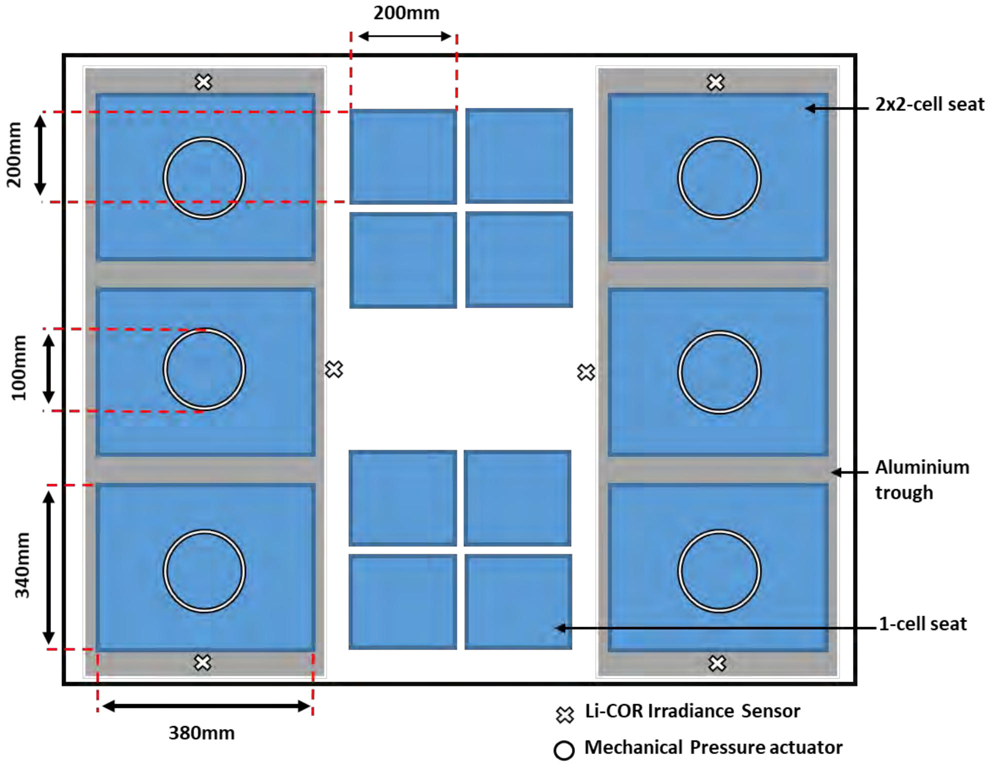

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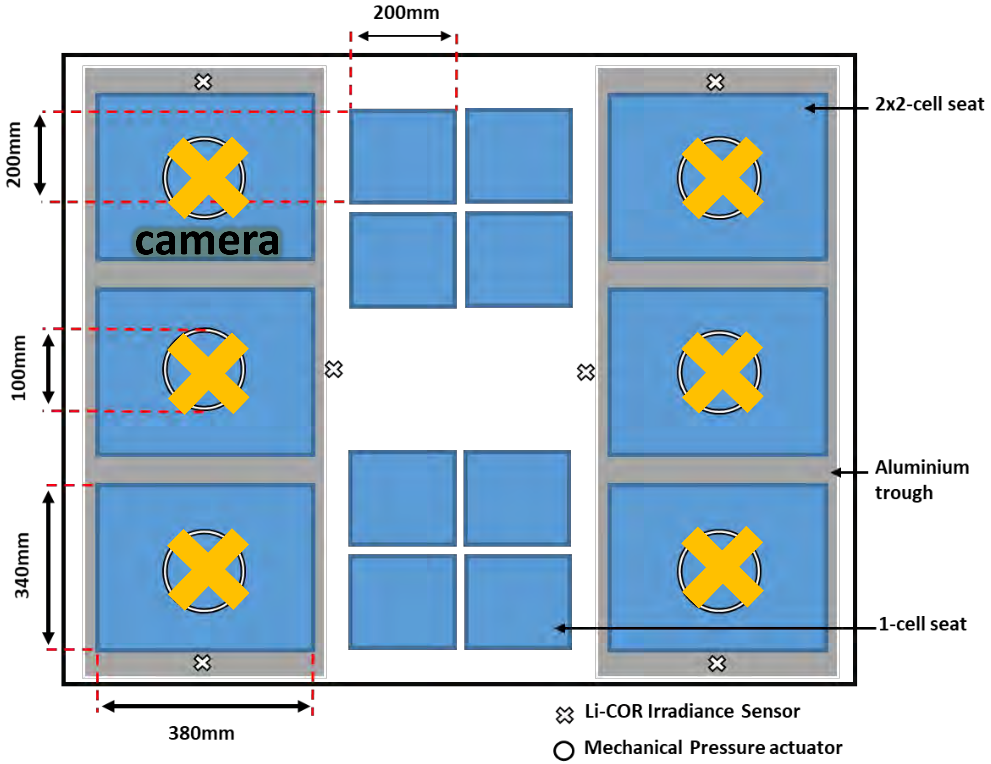

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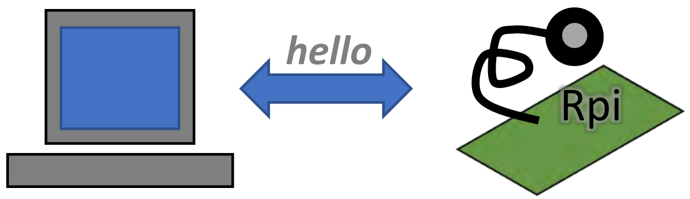
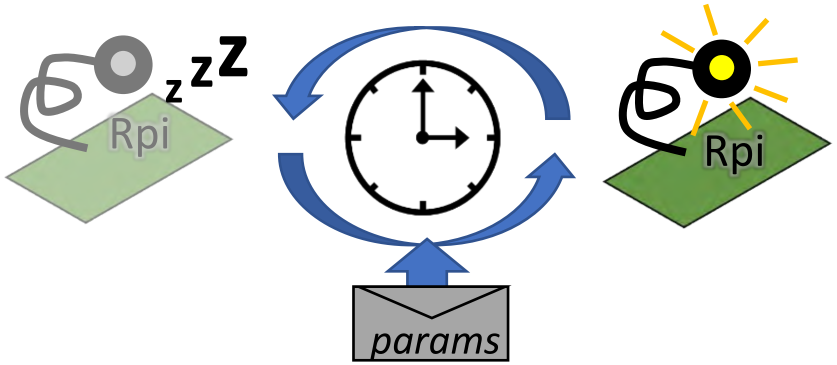
Software Development: Synchronizing Image Acquisition with Stress Testing

SSH Protocol
- Set pathway to communicate between lab computer and raspberry pi controllers



Cron Job
- Set a recurring task on the Raspberry Pi Unix system
- e.g. Every 1 minute, check for parameter file from Labview.



Bash Script
- Perform system operations
- e.g. execute python scripts; restart Raspberry Pi if camera froze; lock system to prevent multiple scripts running

Python Script *using PiCamera*
- Create log file
- Set GPIO output pin high (***CAST stalls***)
- Read parameter file (chamber position, sample-ID, experiment-ID, time stamp, number of averages, temperature, voltage, current, ISO, exposure time)
- ***Capture images***
    - Open camera
    - Set exposure, framerate, ISO, analog/digital gain, turn off auto settings
    - Capture X number of raw jpg images in a row
    - Close camera
- Set GPIO output pin low (***CAST continues***)
- Write parameter file (including camera parameters)
- Convert raw jpg image to text array
- De-bayer image and sum RGB planes
- Delete raw files
- Stack all image arrays and calculate median
- Correct barrel and tangential distortion
- Save images
- Check bytes stored and delete oldest files if needed
- Close all files and connections

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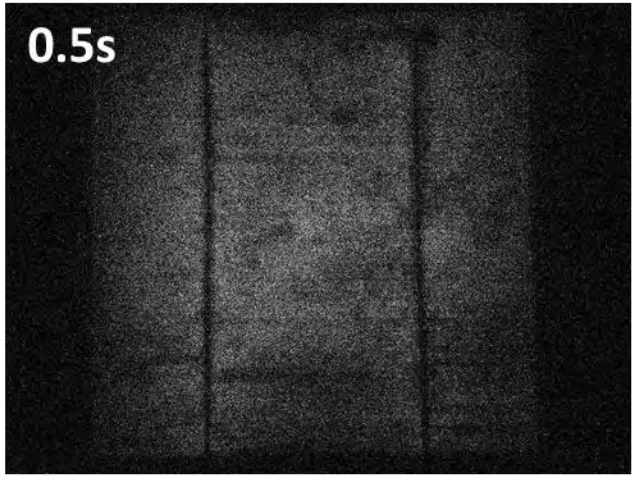
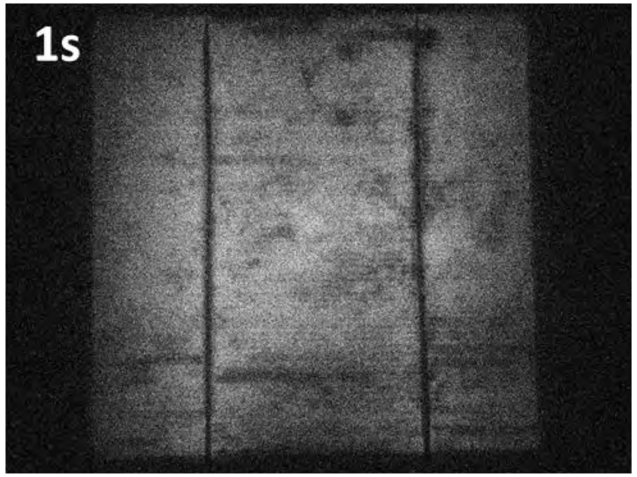
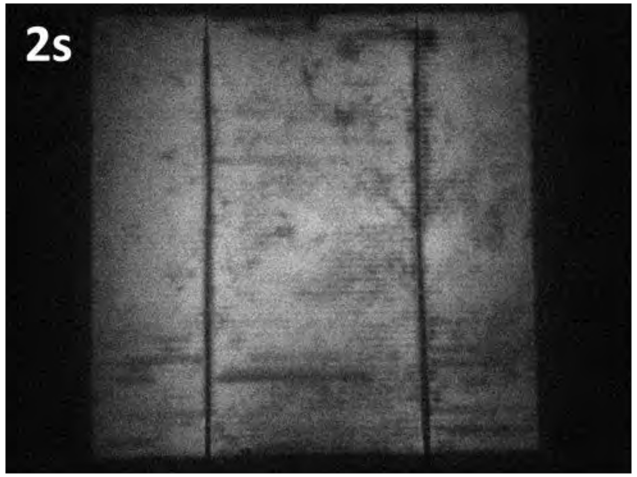
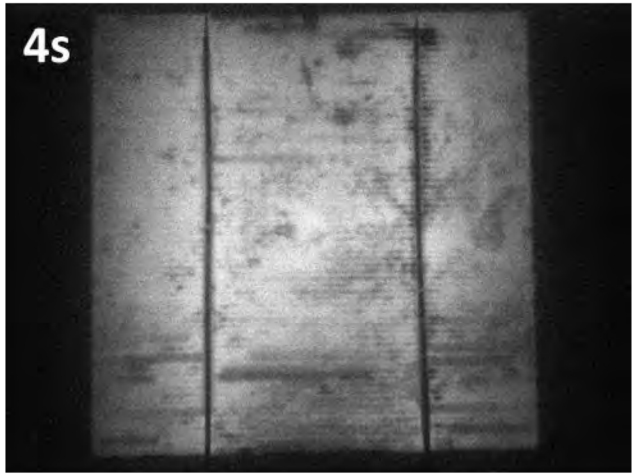
Checking Camera for Linear Response: *Solar cell at 8A with varying integration times*

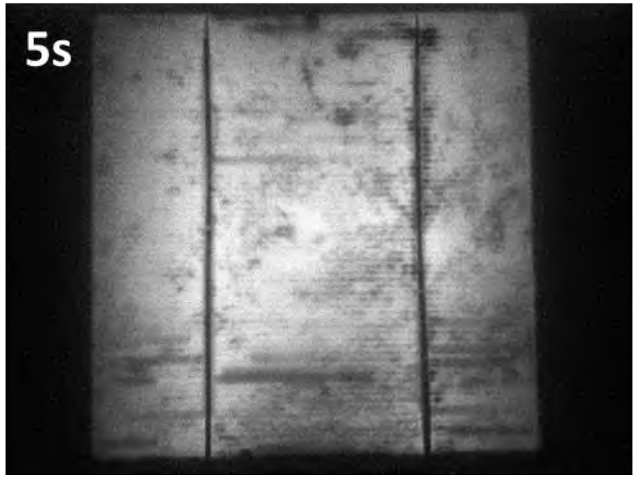
Linear response is important for on-the-go adjustments to avoid camera saturation while maintaining consistent injection parameters.

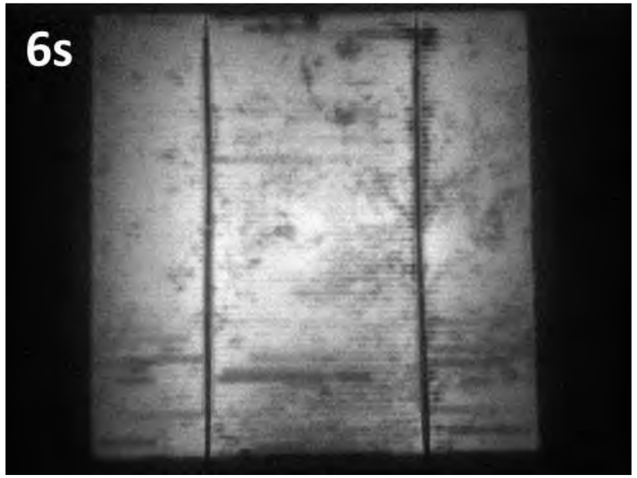


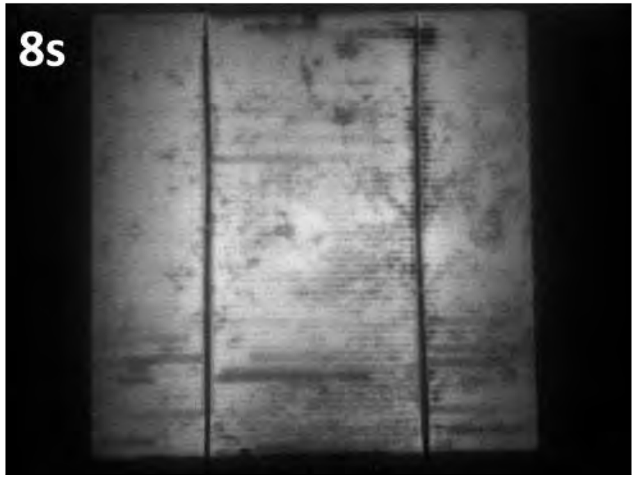












Obstacles:

- Default timeout initially caused system crash with integration time longer than 8s.
- Hardware limit to 10s integration time.

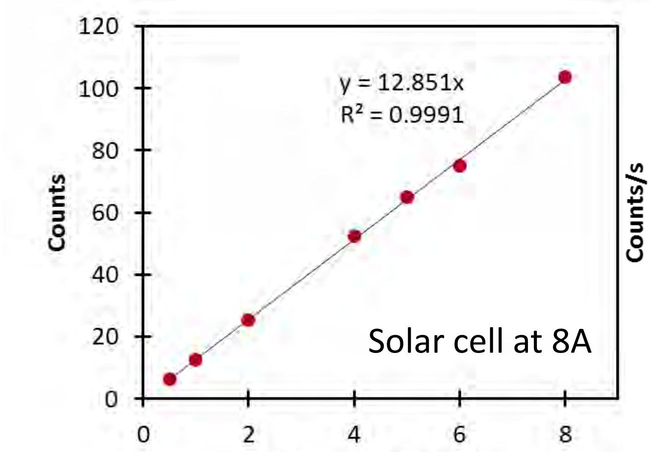
Checking Low-Cost Camera for Linear Response: *Comparison to Scientific-Grade Camera*

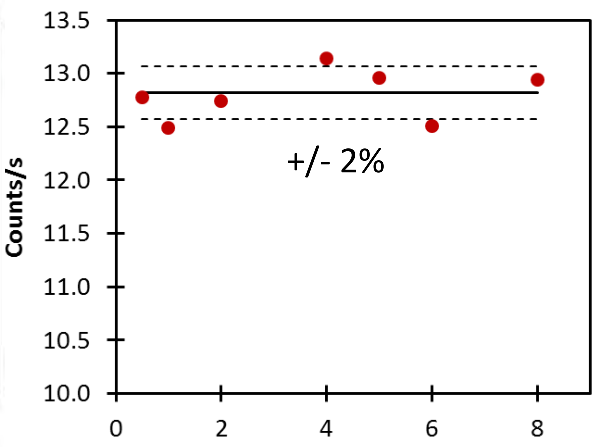
Low-cost camera:

- hardware-limited to 10s integration time
- ~100x lower sensitivity than scientific-grade camera
- Achieves linear response of counts vs time

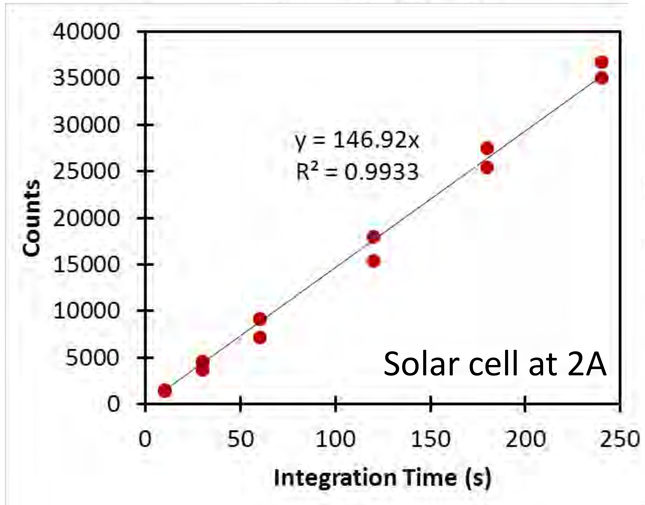
Side note: The source of intensity variation (+/- 8% stdev) in scientific camera is solar cell heating up over time, so the luminescence was changing. The low-cost camera was not sensitive enough to notice the solar cell heating because it was only collecting 10 – 100 counts above baseline.

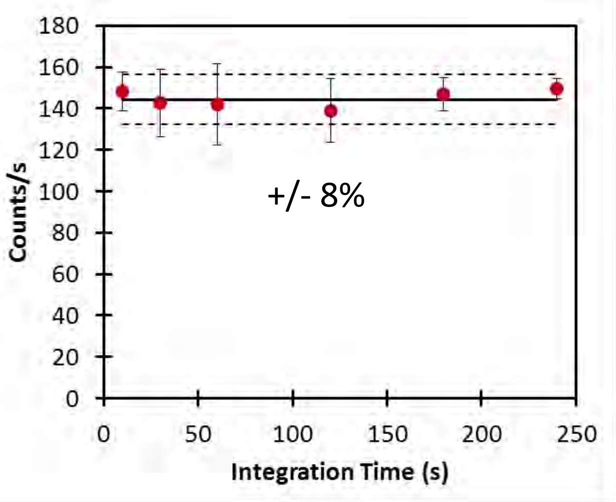
Low-Cost Camera

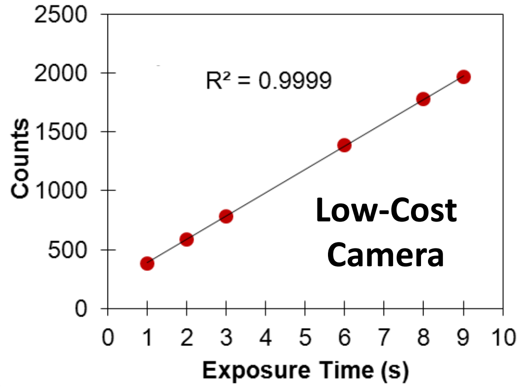


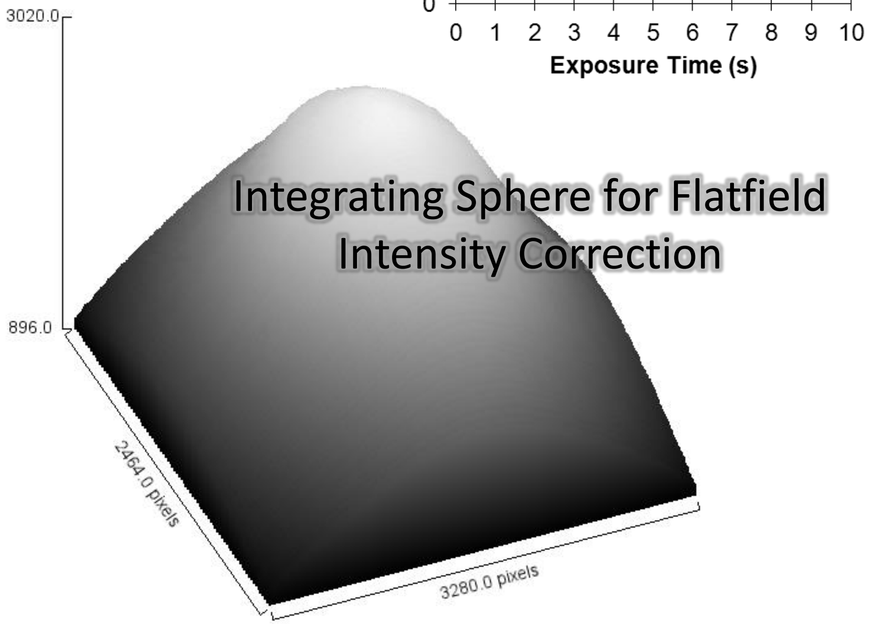


Scientific-Grade Camera





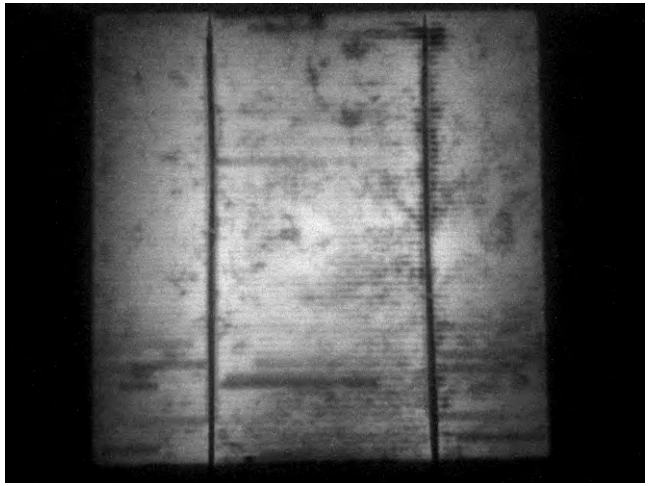




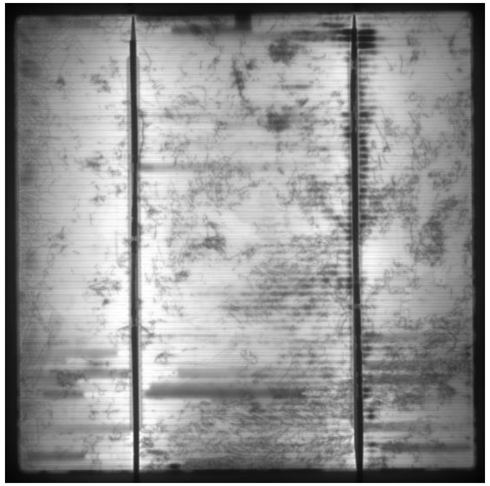
Checking Low-Cost Camera for Linear Response: *Comparison to Scientific-Grade Camera*

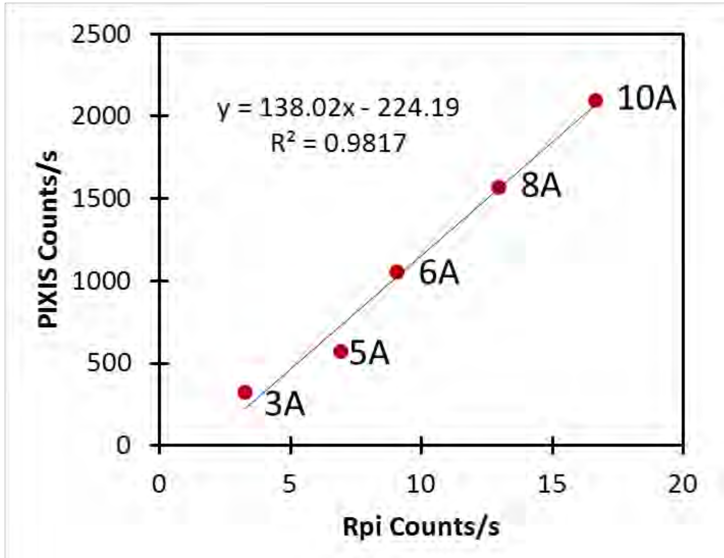
Low-cost camera collects only few counts/s resulting in a shallow image depth, but the response is linear and consistent with scientific camera.

Raspberry Pi, 8A (8s)

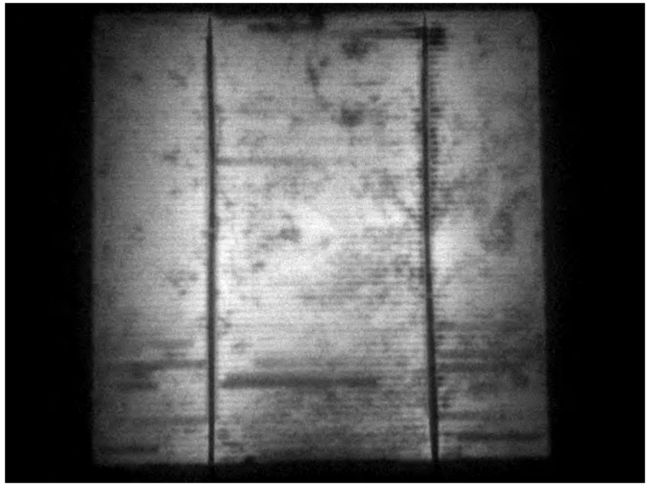


PIXIS, 8A (20s)

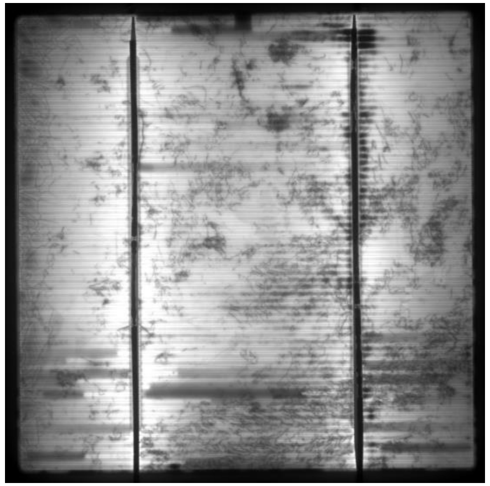




Raspberry Pi, 10A (8s)



PIXIS, 10A (10s)



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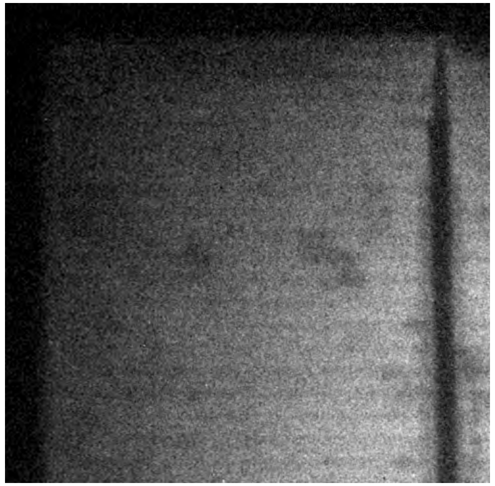

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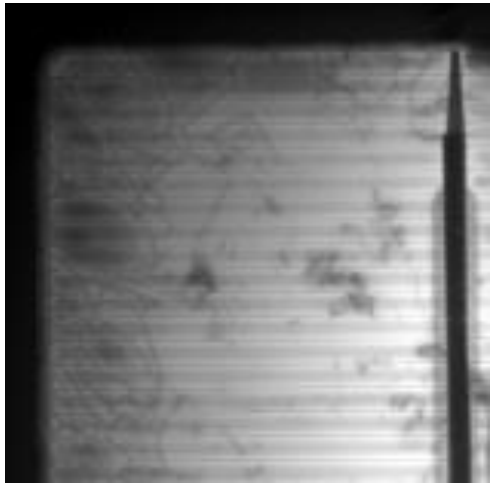
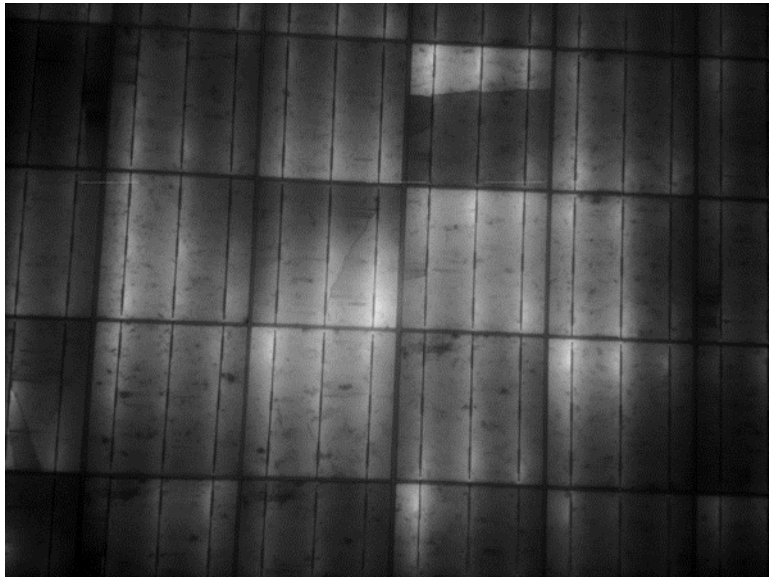


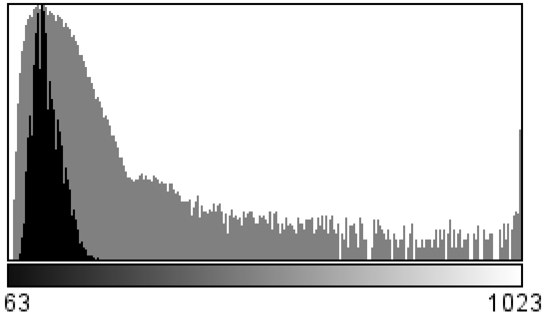
Necessary Image Correction Procedures Depend on Lens Selection

Lens Comparison: *6018CS collects the most light (highest pixel counts) and has an appropriate field of view at 80cm from module*

Original Lens

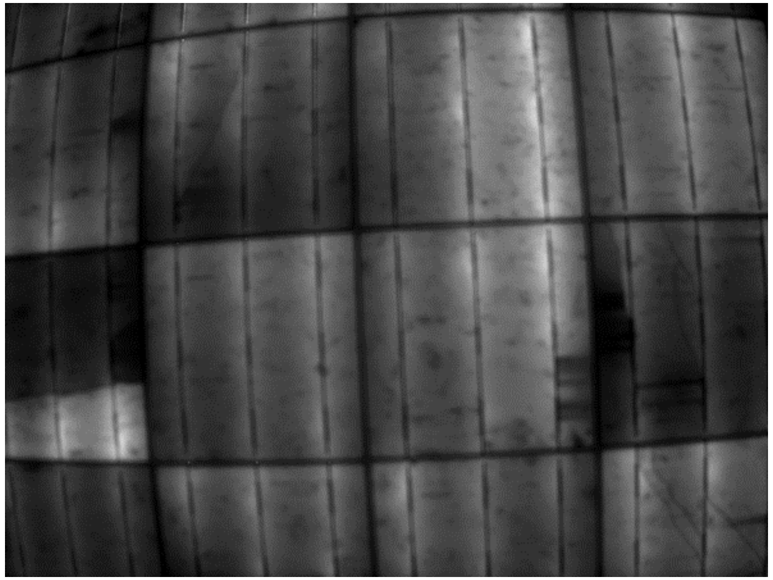
Infinite focal length
Small aperture
1/4" optical format

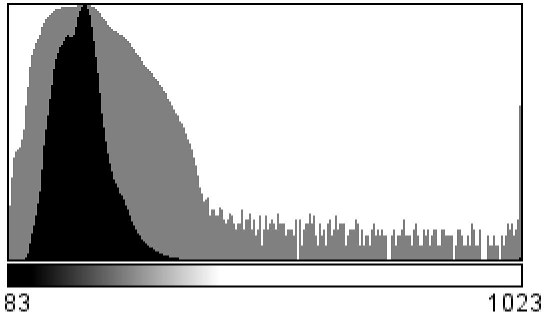




LS-2717CS Lens

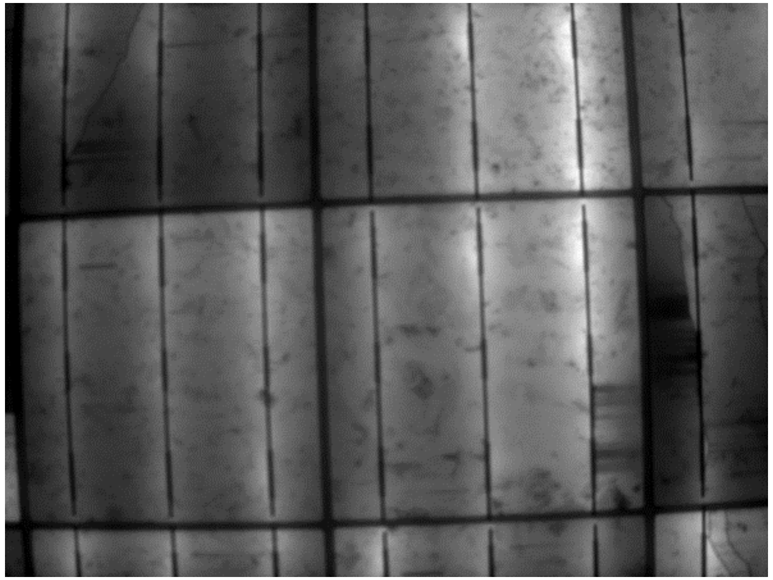
4.0 mm focal length
f/1.4 aperture
1/3" optical format





LS-6018CS Lens

6.0 mm focal length
f/1.4 aperture
1/2.7" optical format



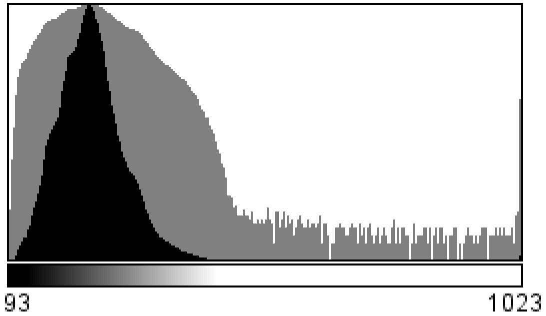


Image Processing on Rpi Unit Prior to Saving:

Distortion Corrections and Image Stacking

Mean

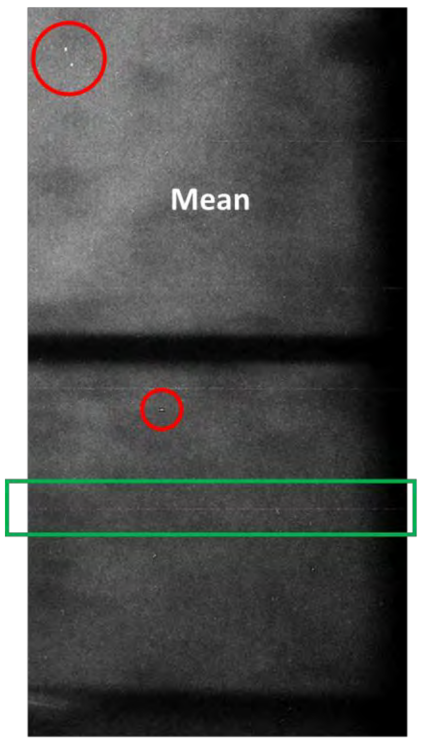
Calculate mean across a given x,y pixel for n images.
** propagates artefacts that exist in single image**

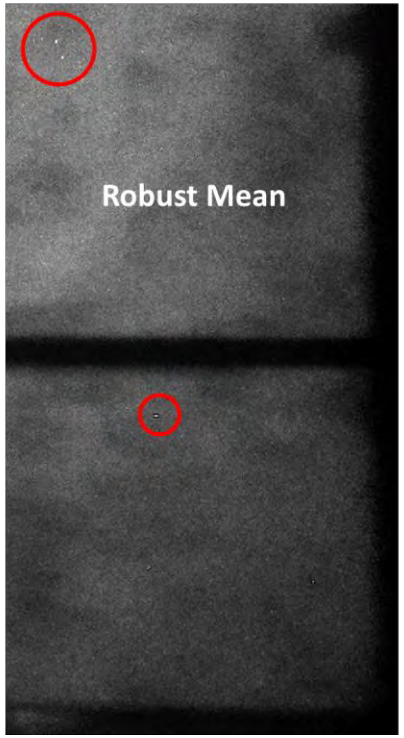
Robust Mean

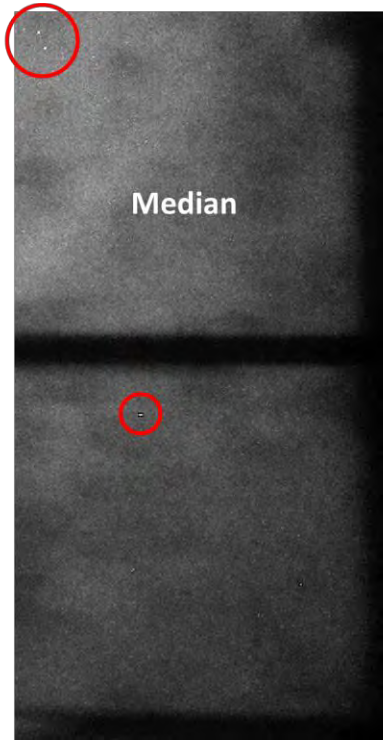
In each of n images, check if each pixel x,y has acceptable standard deviation. If not, do not use pixel in average.

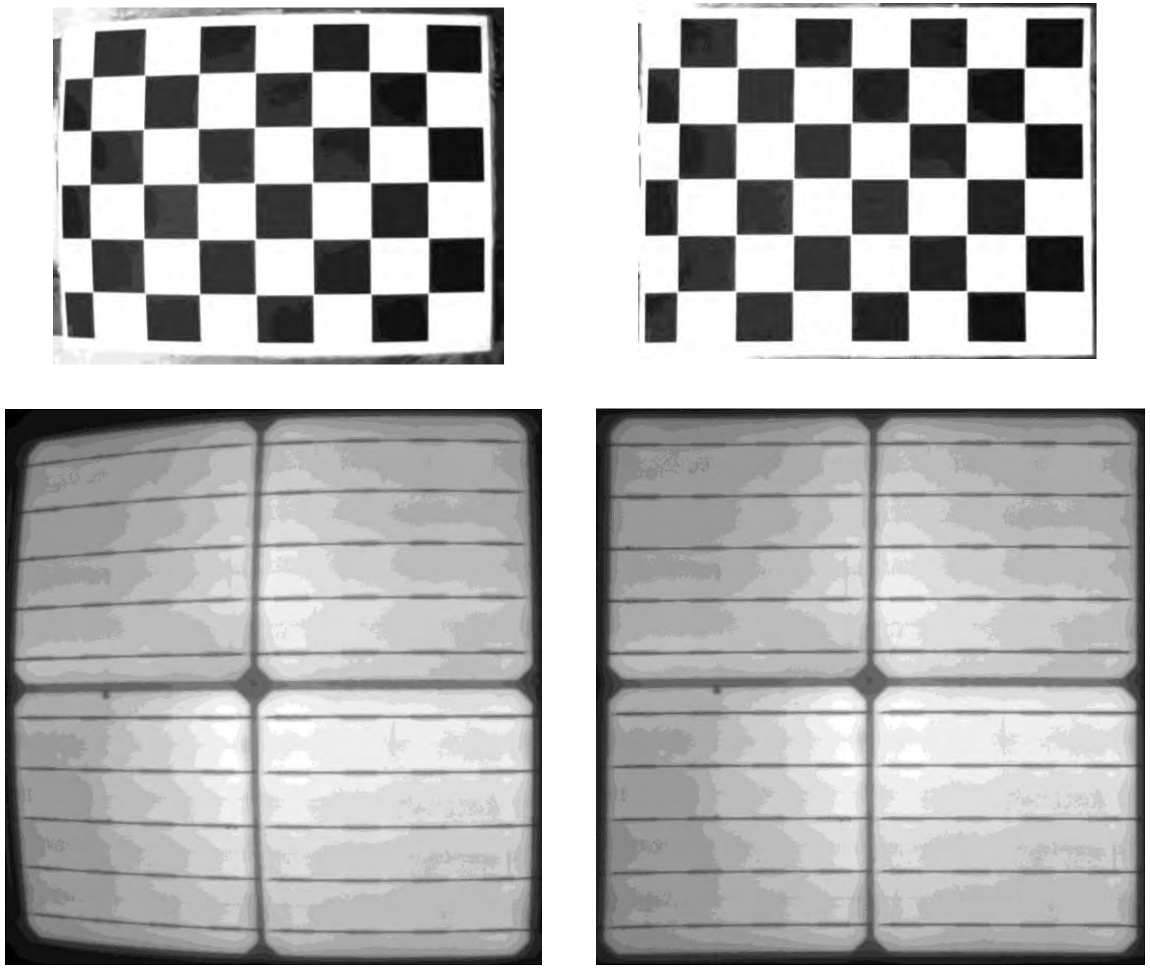
Median

Calculate median for x,y pixels. Since this is the center value, it is more robust to outliers of one-time occurrence (such as cosmic rays).









$$Xcorrected = x(1+k_1r^2+k_2r^4+k_3r^6)$$
$$Ycorrected = y(1+k_1r^2+k_2r^4+k_3r^6)$$

Barrel Distortion

$$Xcorrected = x + [2p_1xy + p_2(r^2 + 2x^2)]$$
$$Ycorrected = y + [p_1(r^2 + 2y^2) + 2p_2xy]$$

Tangential Distortion

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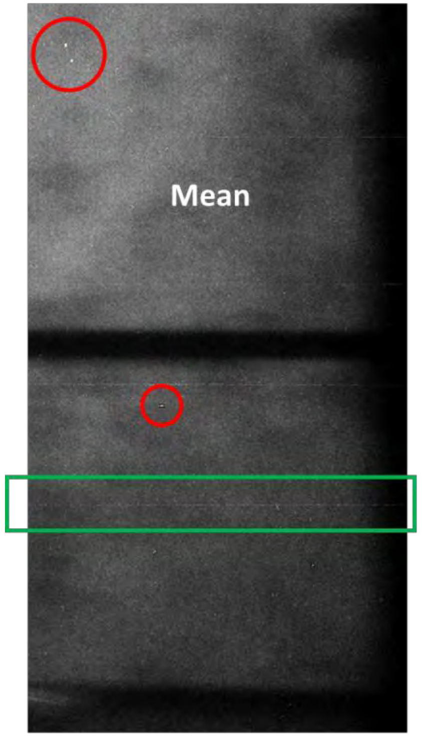
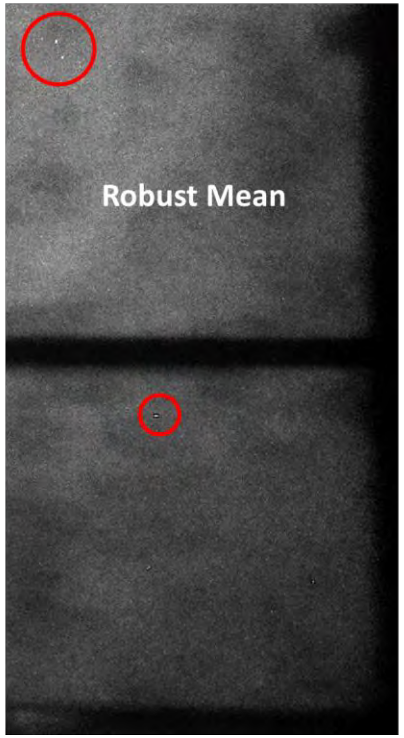
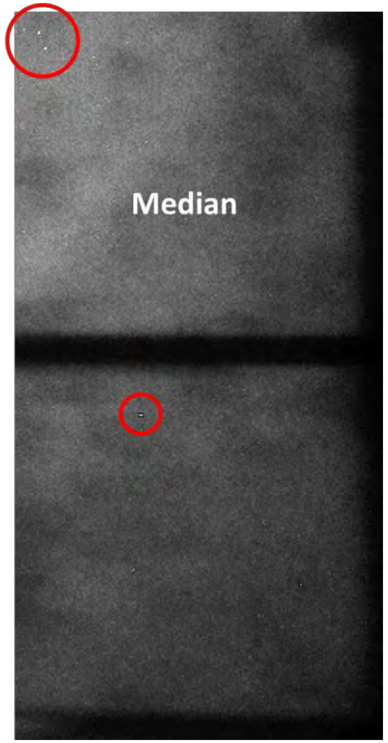
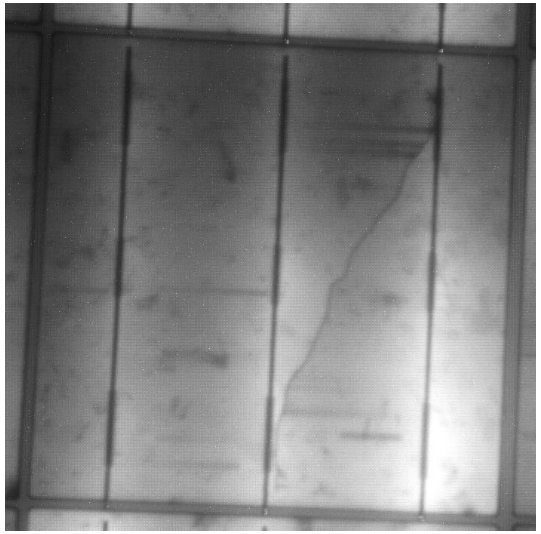


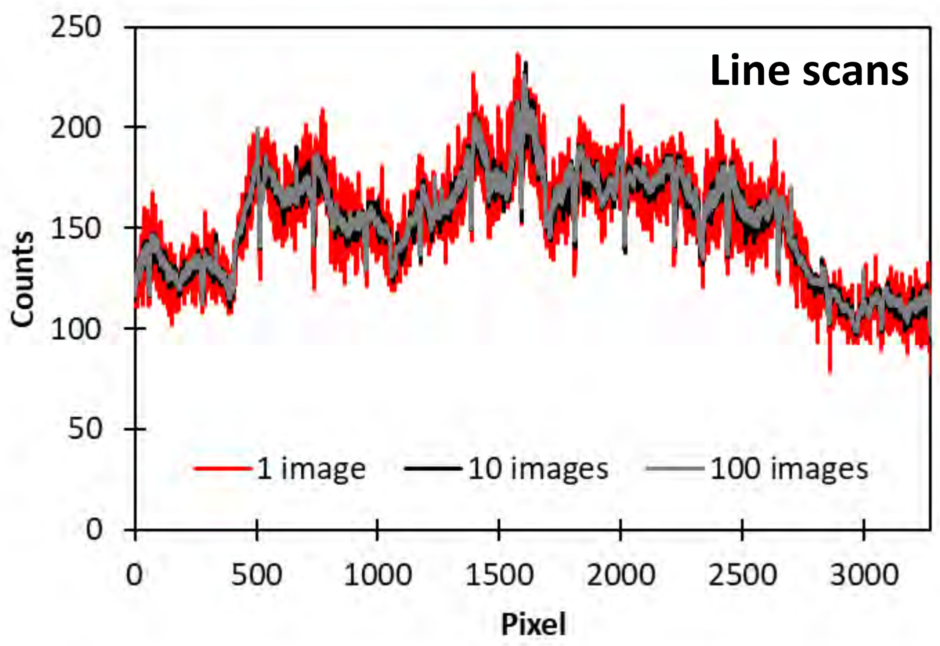


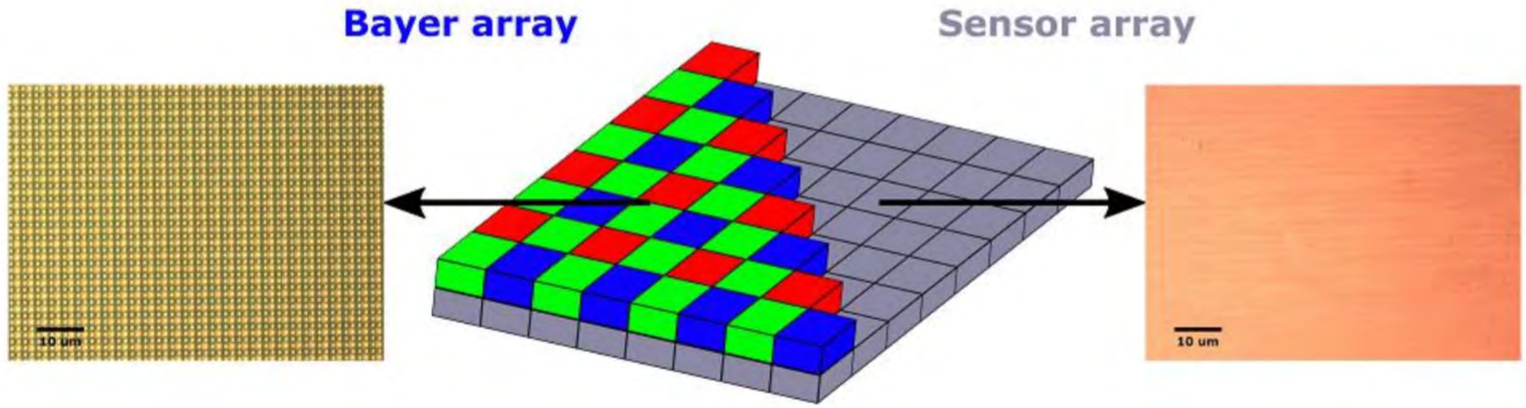


1 image

100 images

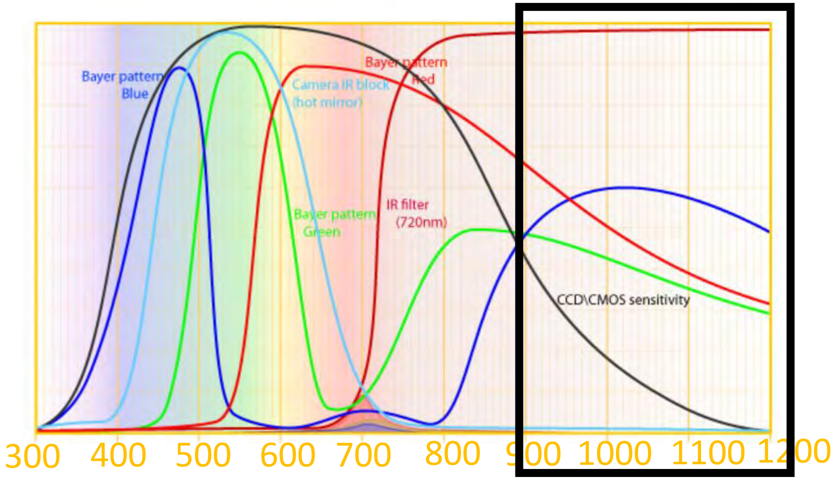






Wilkes, T.C. et. al. *Sensors* **2016**, 16, 1649.

Removing Filters from Sensor Array



Removing bayer filter improves IR transmission and eliminates debayering image processing step. Eliminating debayering improves image resolution.

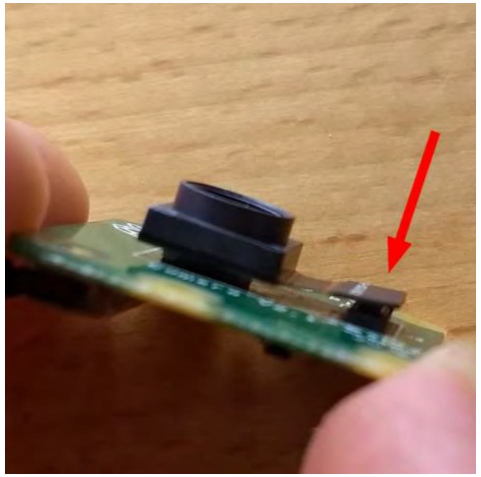
Possible methods to remove filter:

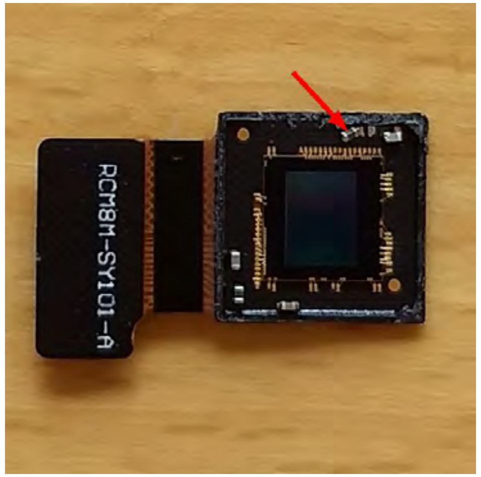
Mechanical Filter Removal

- Scrape with wooden stick
- Scrape with tweezers or blade

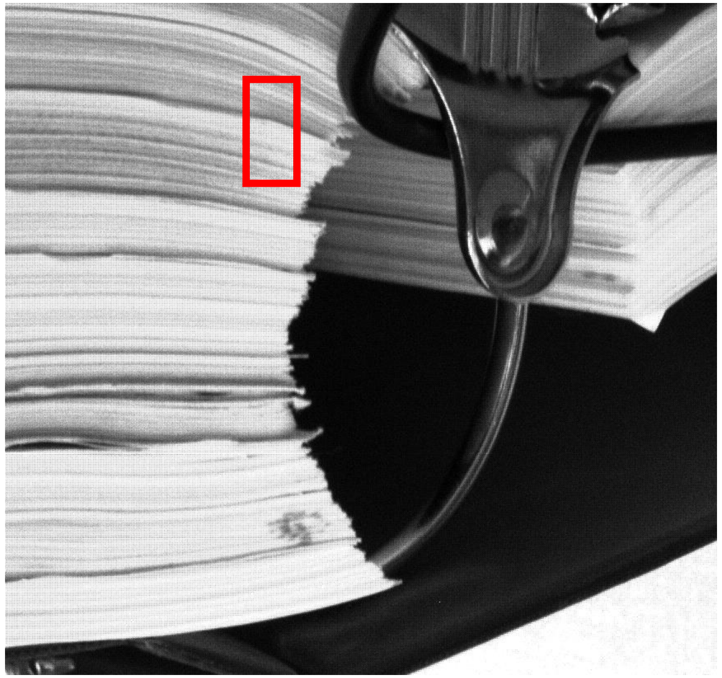
Chemical Filter Removal

1. Immerse in photoresist remover such as Dupont Posistrip® EKC830 (70-100 C, 10-30 min)
2. Rinse + repeat photoresist soak
3. Wash sensor
    - n-butyl acetate, acetone, IPA

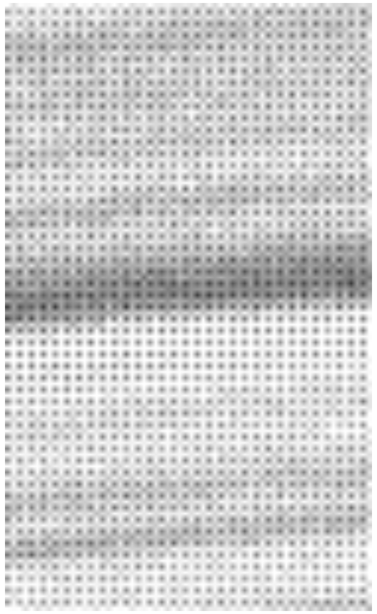


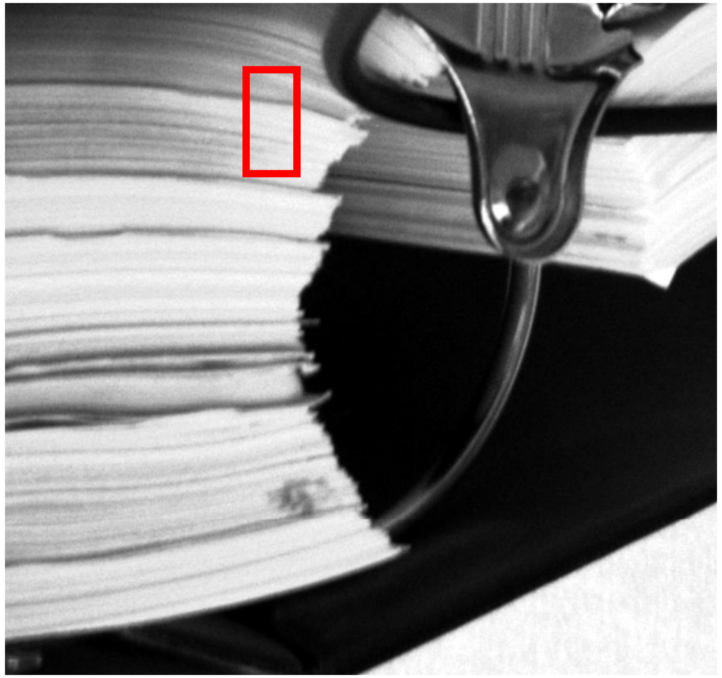


http://eladorbach.blogspot.com/2016/05/debayering-raspberry-pi-camera.html

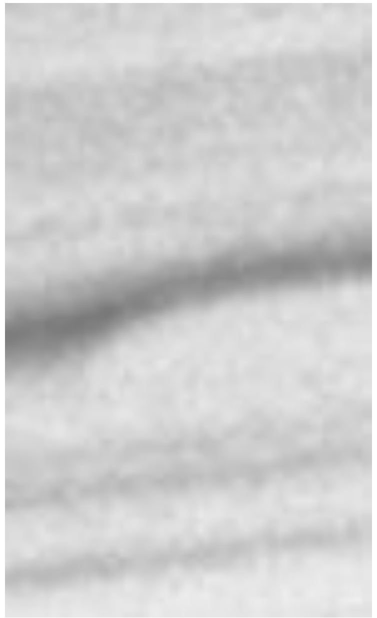


Sum all RGB Pixels





Demosaic + Sum

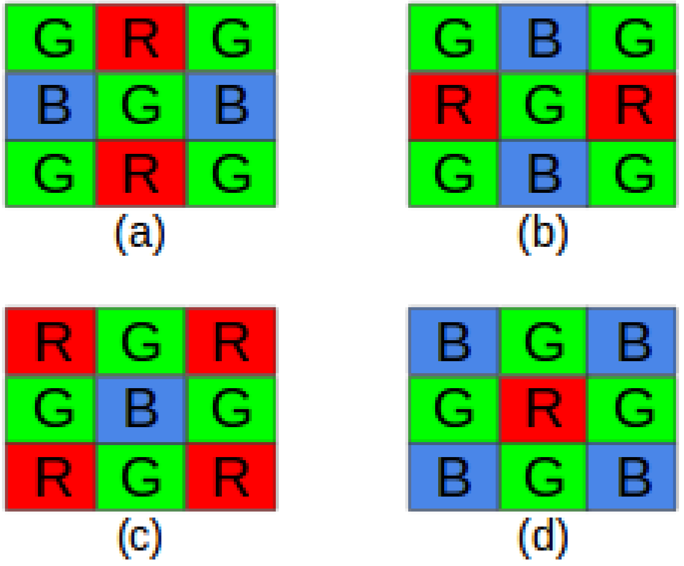


Demosaicing vs. Sum of Pixels

- Twice as many green pixels compared to red or blue pixels creates a checker-board pattern for the raw image
- Demosaicing interpolates a “color” value for each pixel depending on the intensities of neighboring pixels
- Demosaicing decreases the image resolution but improves “color accuracy” per pixel.
- Do we need demosaicing for an IR image?
  - Answer: yes, because IR transmission through varies for RGB pixels

Example of How Demosaicing Works:

Resolution decreases, multiple pixels averaged together for each color



Finding Red and Blue Values

Pixel with **Green** filter (case a or b)

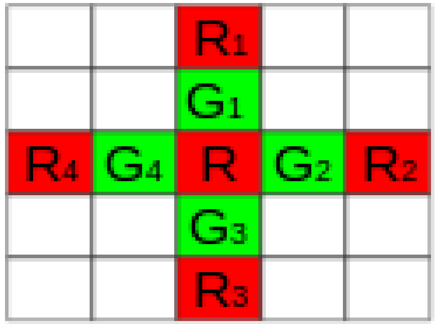
- Red value is (R1+R2) / 2
- Blue value is (B1+B2) / 2

Pixel with **Blue or Red** filter (case c/d)

- Already have blue (or red) value
- Red value is (R1+R2+R3+R4) /4 for blue pix
- Blue value is (B1+B2+B3+B4) /4 for red pix

For our application, it is not worth the effort to remove the Bayer filter.

Therefore, we perform image demosaicing prior to saving the images.



Finding Green Values

- Method varies depending on relative axial intensities
- G =
  - (G1+G3)/2 if |R1-R3|<|R2-R4|
  - (G2+G4)/2 if |R1-R3|>|R2-R4|
  - (G1+G2+G3+G4)/4 if |R1-R3|=|R2-R4|

https://github.com/codeplaysoftware/visioncpp/wiki/Example:-Bayer-Filter-Demosaic

Outline

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  - Cell Cracks
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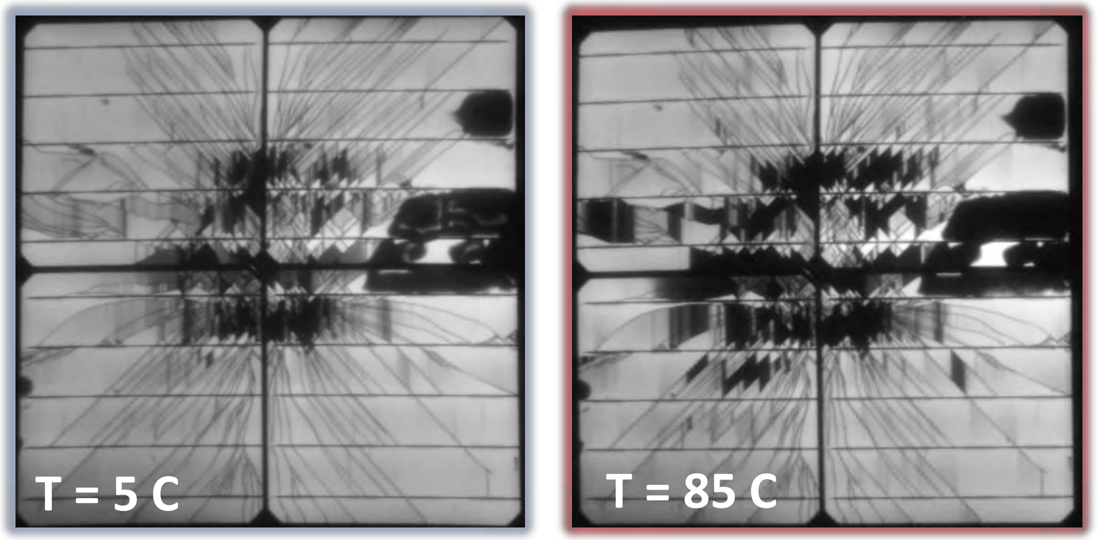
  - Comparison of mimos with differing LID/LeTID susceptibility
  - ***early stages of analysis – full experiment still in progress***

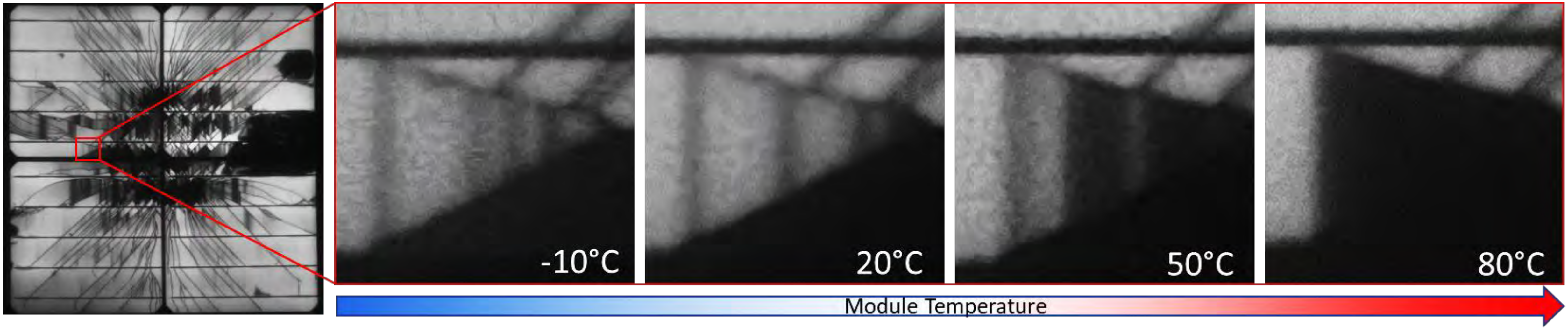
Temperature-Dependent Crack Connectivity Characterized with In-Situ Imaging



Sample: Glass/glass mini module with cracked cells and cracked glass surfaces due to high mechanical loading >5400 Pa

Result: High temperature increases fraction of disconnected cell regions due to thermal expansion that can displace cell fragments.

Lesson: Modules tend to operate above standard temperature (25C), so damage may be underestimated during standard characterization.



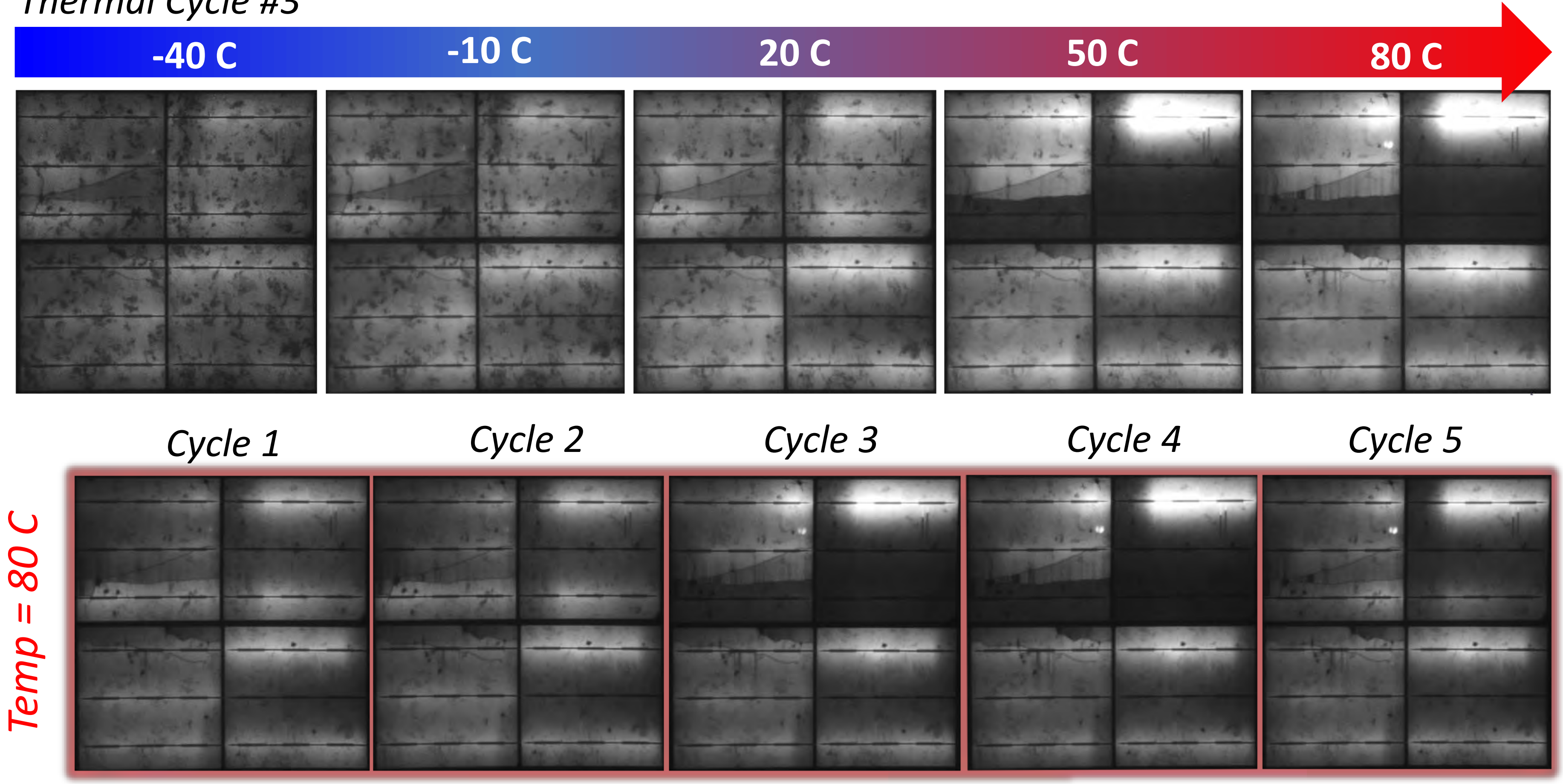
Owen-Bellini, M.; Sulas-Kern, D.B.; Spataru, S.; North, H.; Perrin, G.; Hacke, P. *46th Photovoltaics Specialists Conference (PVSC)* **2019**, 10.1109/PVSC40753.2019.9198956.

Owen-Bellini, M.; Sulas-Kern, D.B.; Perrin, G.; North, H.; Spataru, S.; Hacke, P. *IEEE J. Photovolt.* **2020**, 10, 1254-1261.

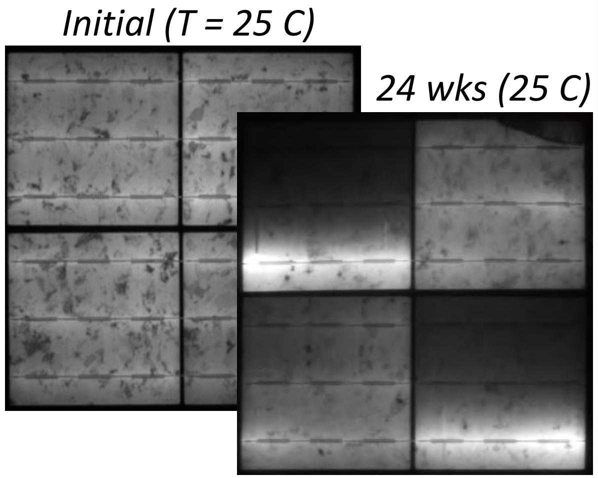
Interconnect Failures Characterized with In-Situ Imaging and IV

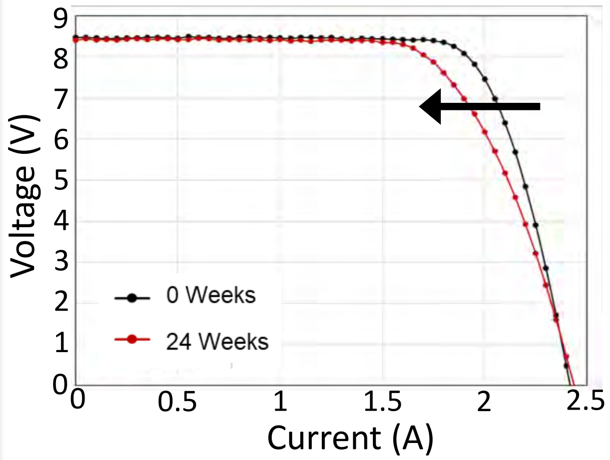
Sample: Multi-crystalline Al-BSF glass/backsheet mimo; 25 weeks of CAST Tropical cycle.
Result: Series Resistance from ribbon debonding in CAST; Connection is temp-dependent.

Thermal Cycle #3



In-Situ IV Shows Series Resistance





Time (wks)	V_{oc} (V)	I_{sc} (A)	P_{max} (W)	FF (%)
0	2.53	8.5	15.92	74.1
24	2.52	8.44	12.93	60.8

Owen-Bellini, M.; Sulas-Kern, D.B.; Spataru, S.; North, H.; Perrin, G.; Hacke, P. *46th Photovoltaics Specialists Conference (PVSC)* **2019**, 10.1109/PVSC40753.2019.9198956.
Owen-Bellini, M.; Sulas-Kern, D.B.; Perrin, G.; North, H.; Spataru, S.; Hacke, P. *IEEE J. Photovolt.* **2020**, 10, 1254-1261.

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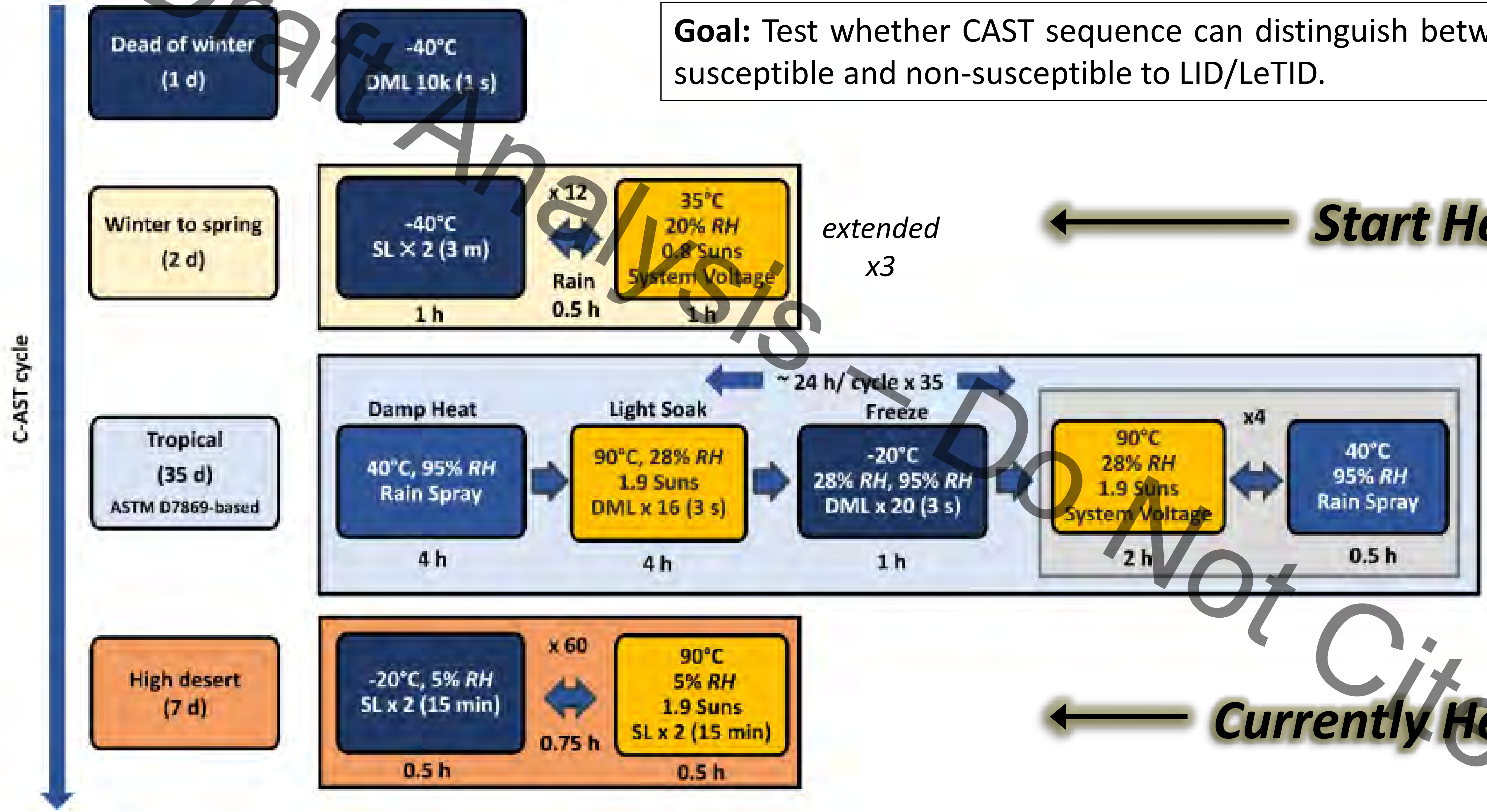
Identifying LID/LeTID in Combined Accelerated Stress Testing (CAST)

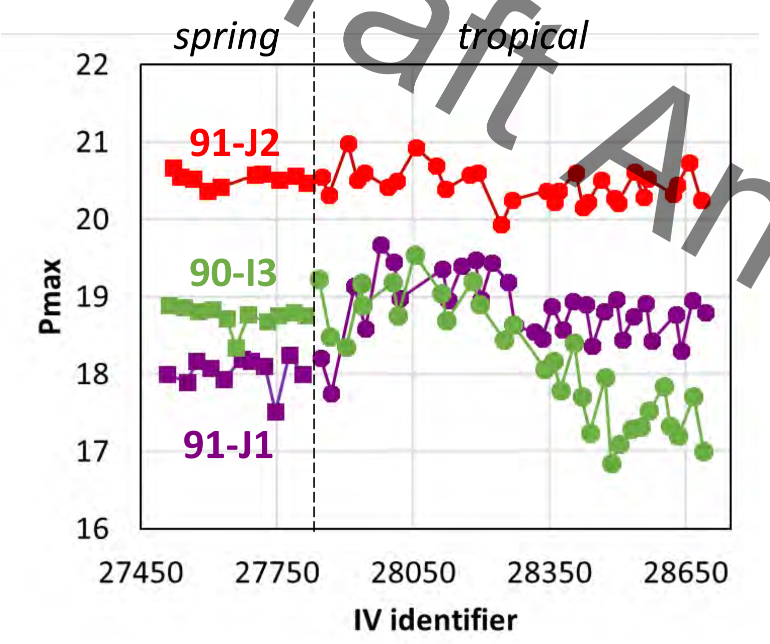
Goal: Test whether CAST sequence can distinguish between cells susceptible and non-susceptible to LID/LeTID.

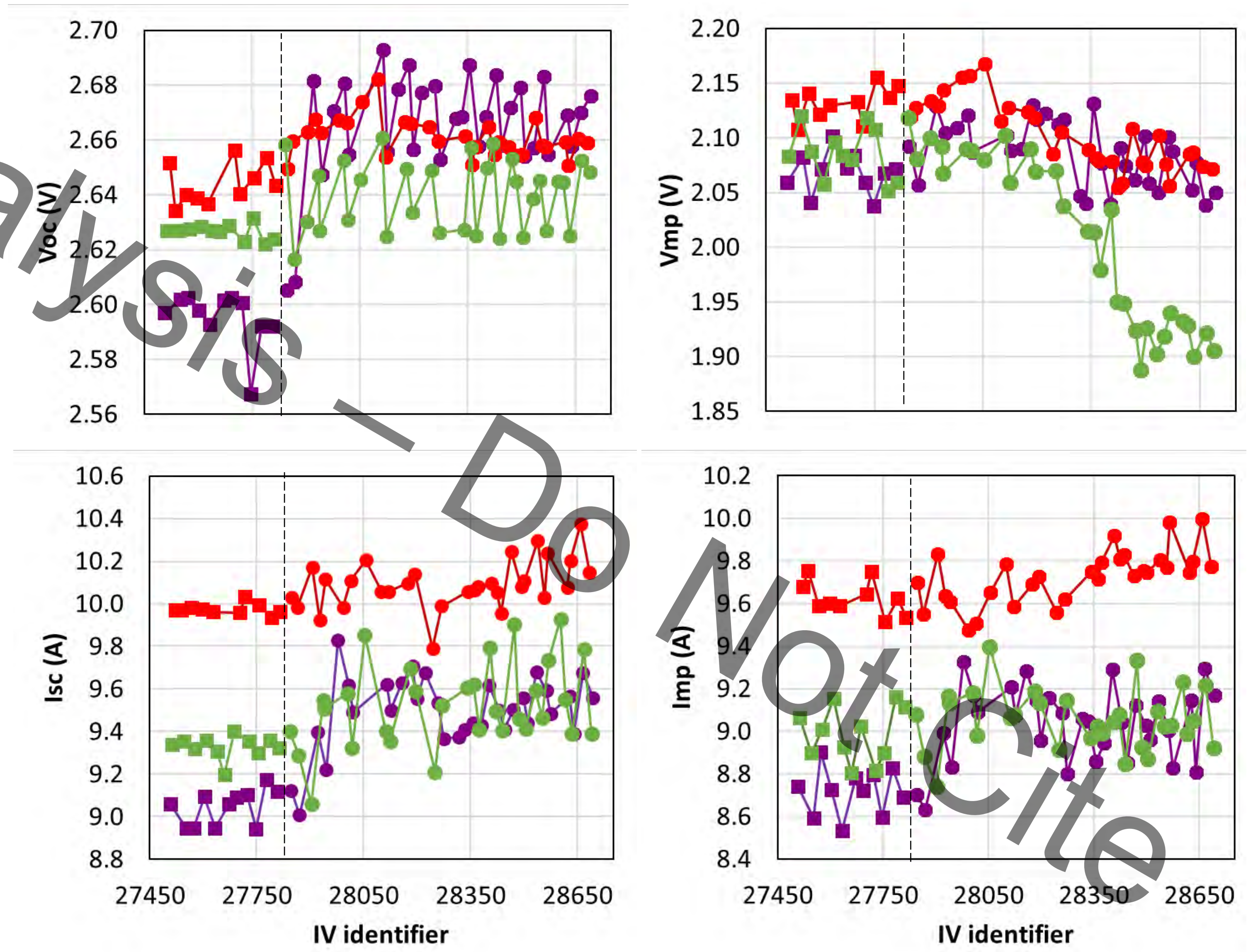


Start Here

Currently Here

Identifying LID/LeTID in Combined Accelerated Stress Testing (CAST)

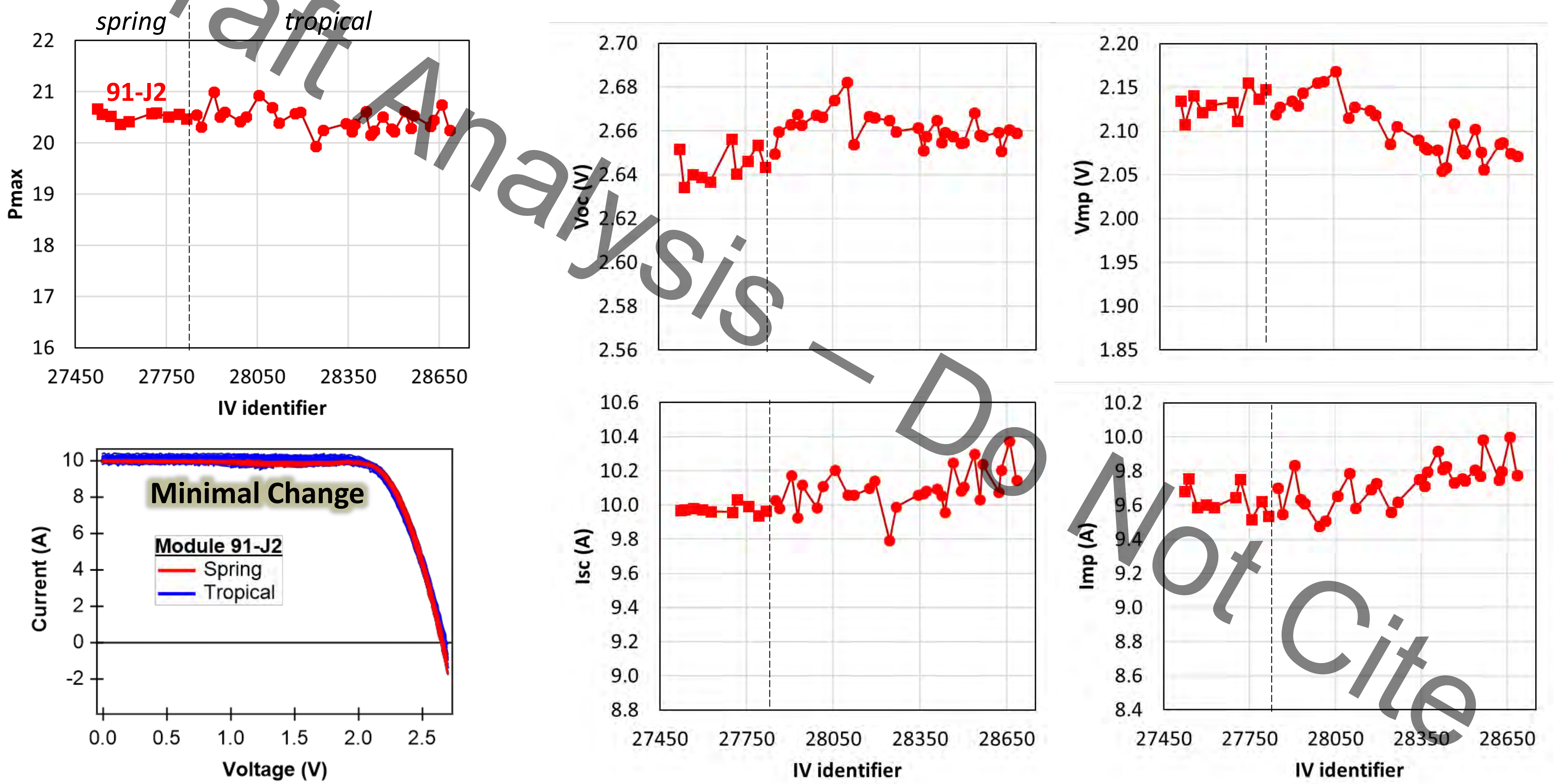


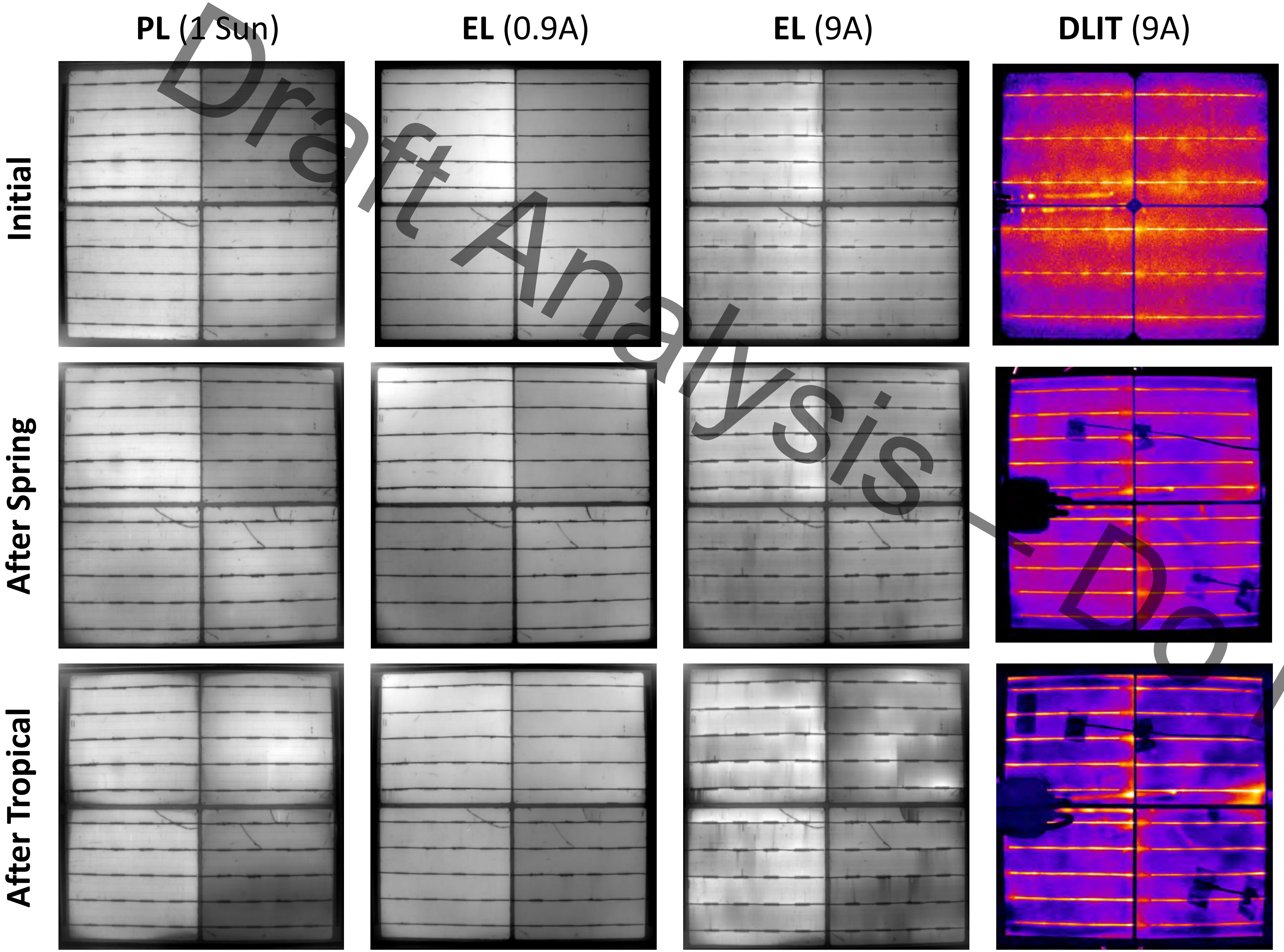


Sample Set: Three 4-cell PERC mini modules in G/BS package with EVA

- 90-I3: Likely susceptible to LeTID
- 91-J2: Stabilized for LID, likely not not susceptible to LeTID
- 92-J1: As-fired no stabilization

91-J2 Shows Minimal Degradation Through Spring and Tropical CAST Cycles





91-J2: *Imaging Shows Early Signs of Degradation*

"Checkerboard" pattern evolves

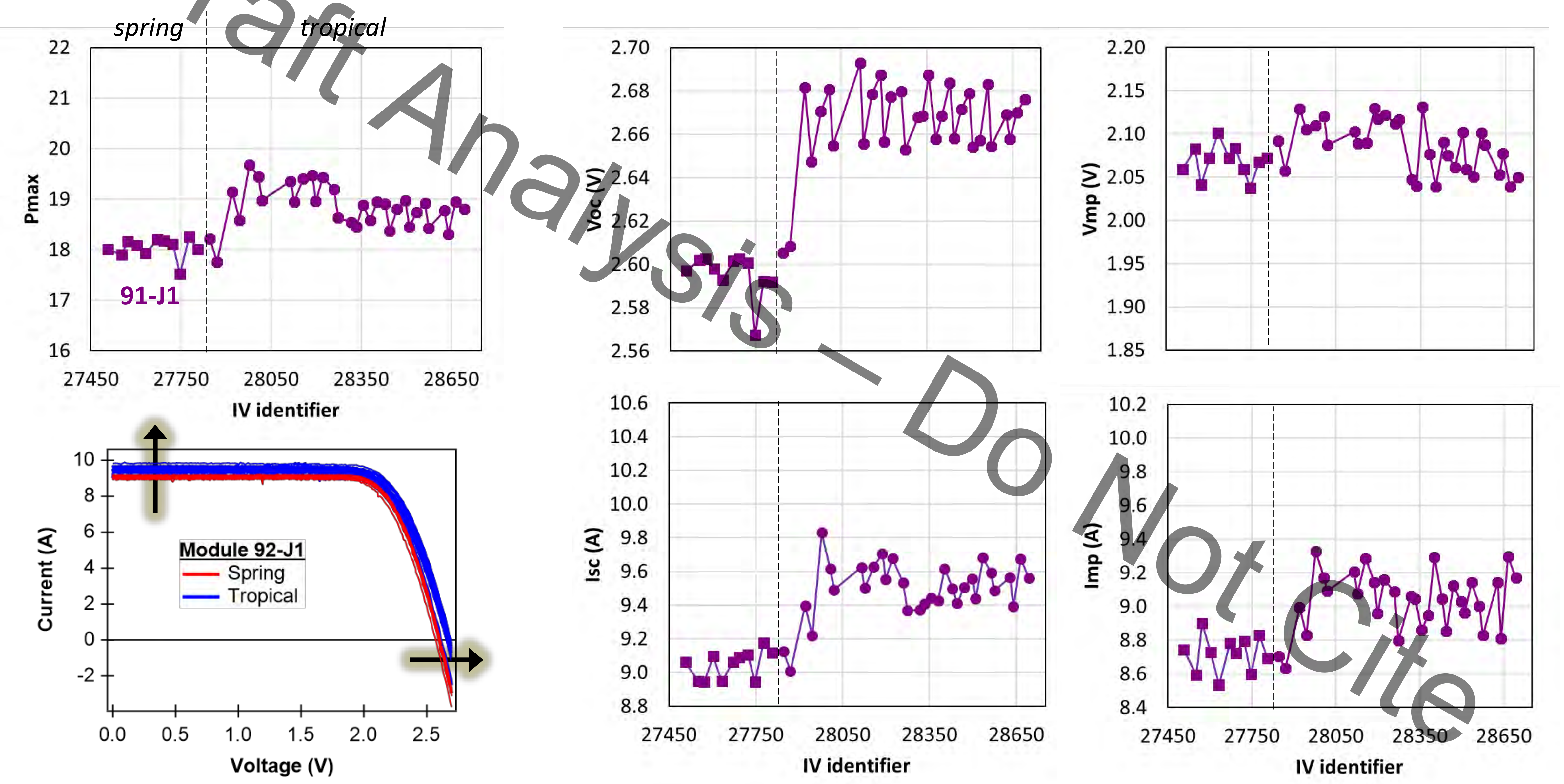
- LID/LeTID at different rates for different cells?

Contact issues / interconnects/ finger breakage after tropical cycle

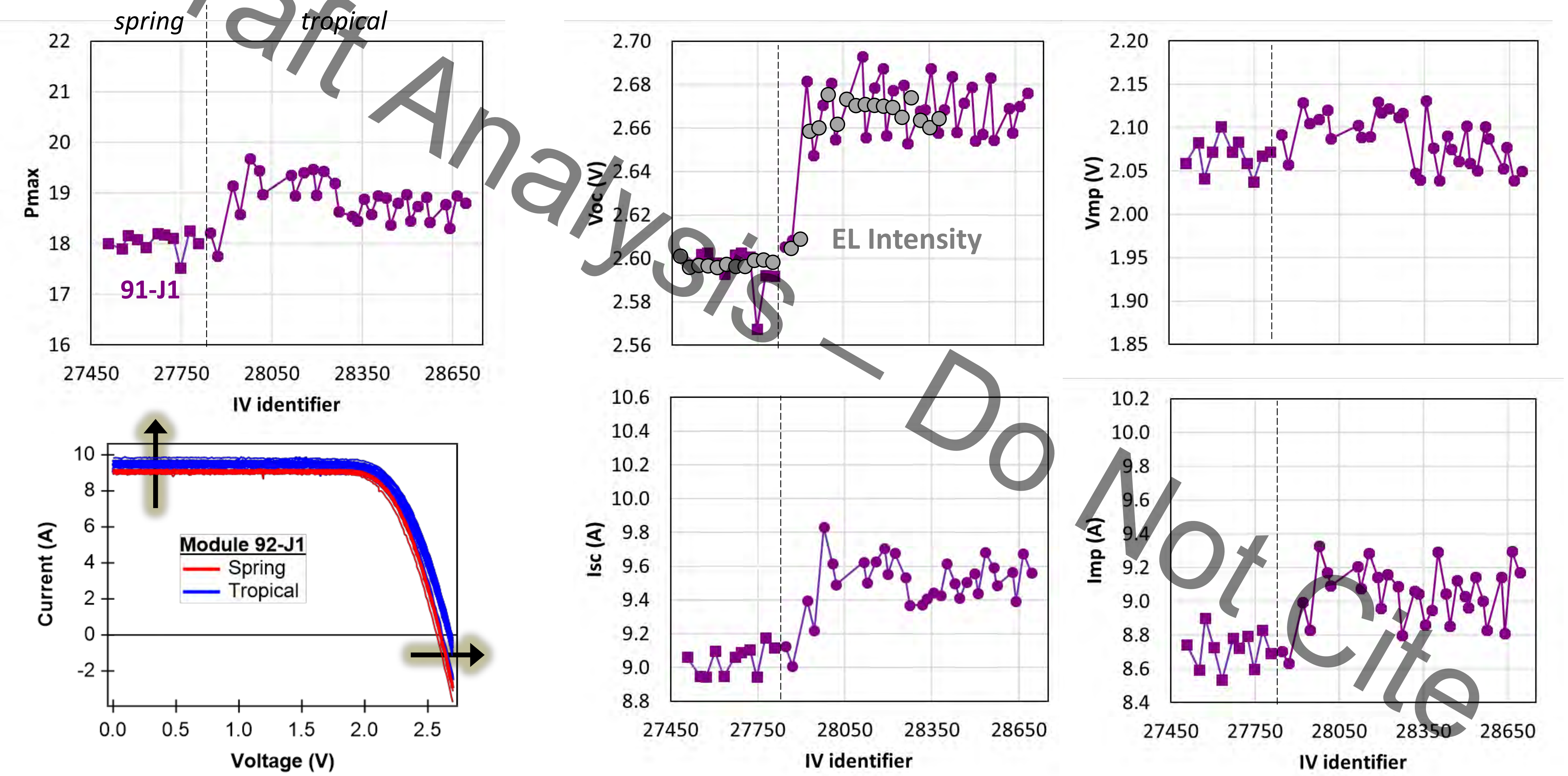
- Early stages have small effect on IV curves
- Responsible for small decrease in Vmp
- Could mask ability to see LID/LeTID effects in CAST?

Note: these images collected ex-situ outside of CAST chamber

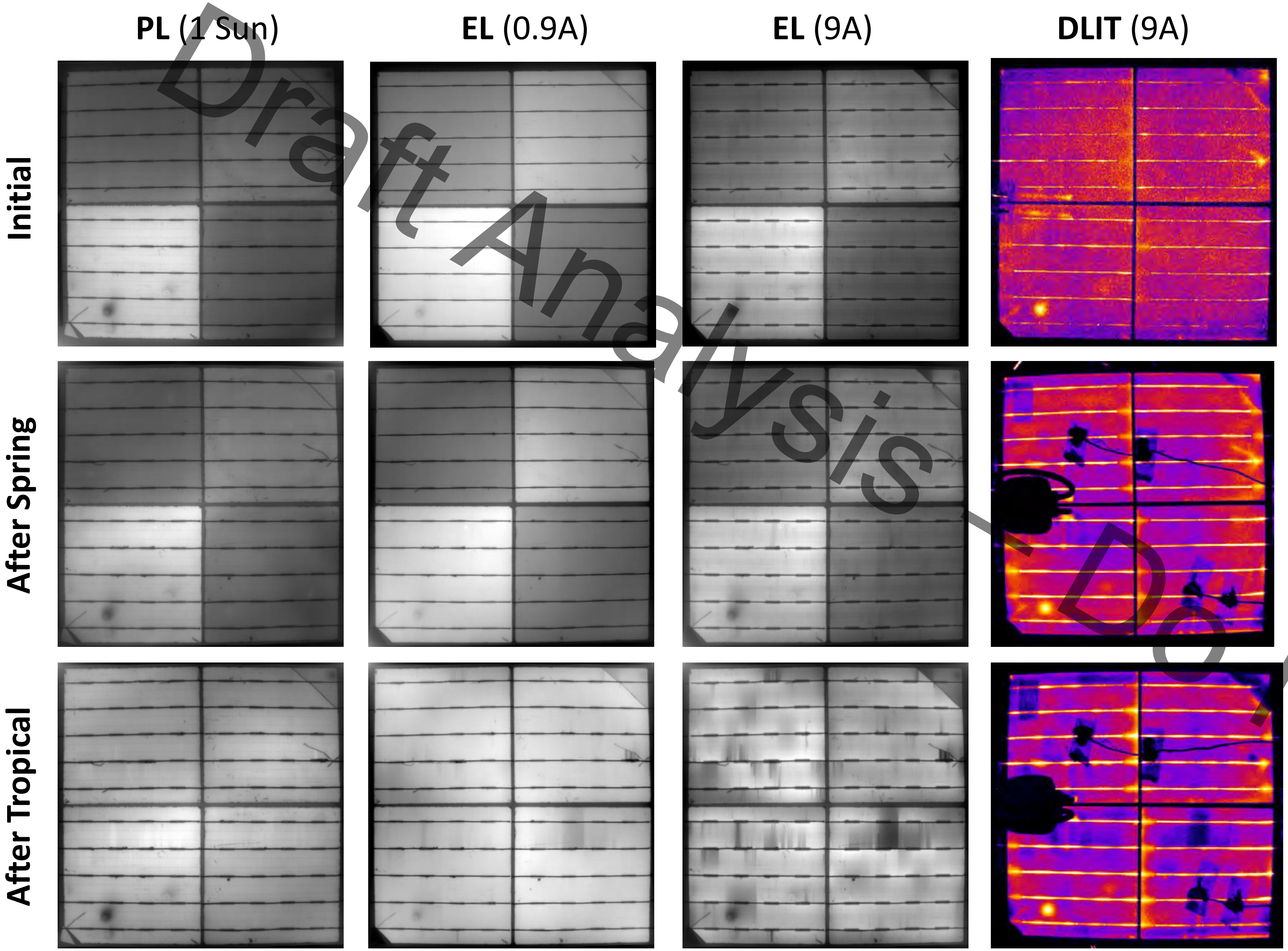
91-J1 Shows LID Recovery at Transition from Spring to Tropical CAST Cycle



Increase in In-Situ EL Intensity Tracks with Increase in Cell Voltage



92-J1: *Imaging Shows Early Signs of Degradation*



"Checkerboard" pattern evolves

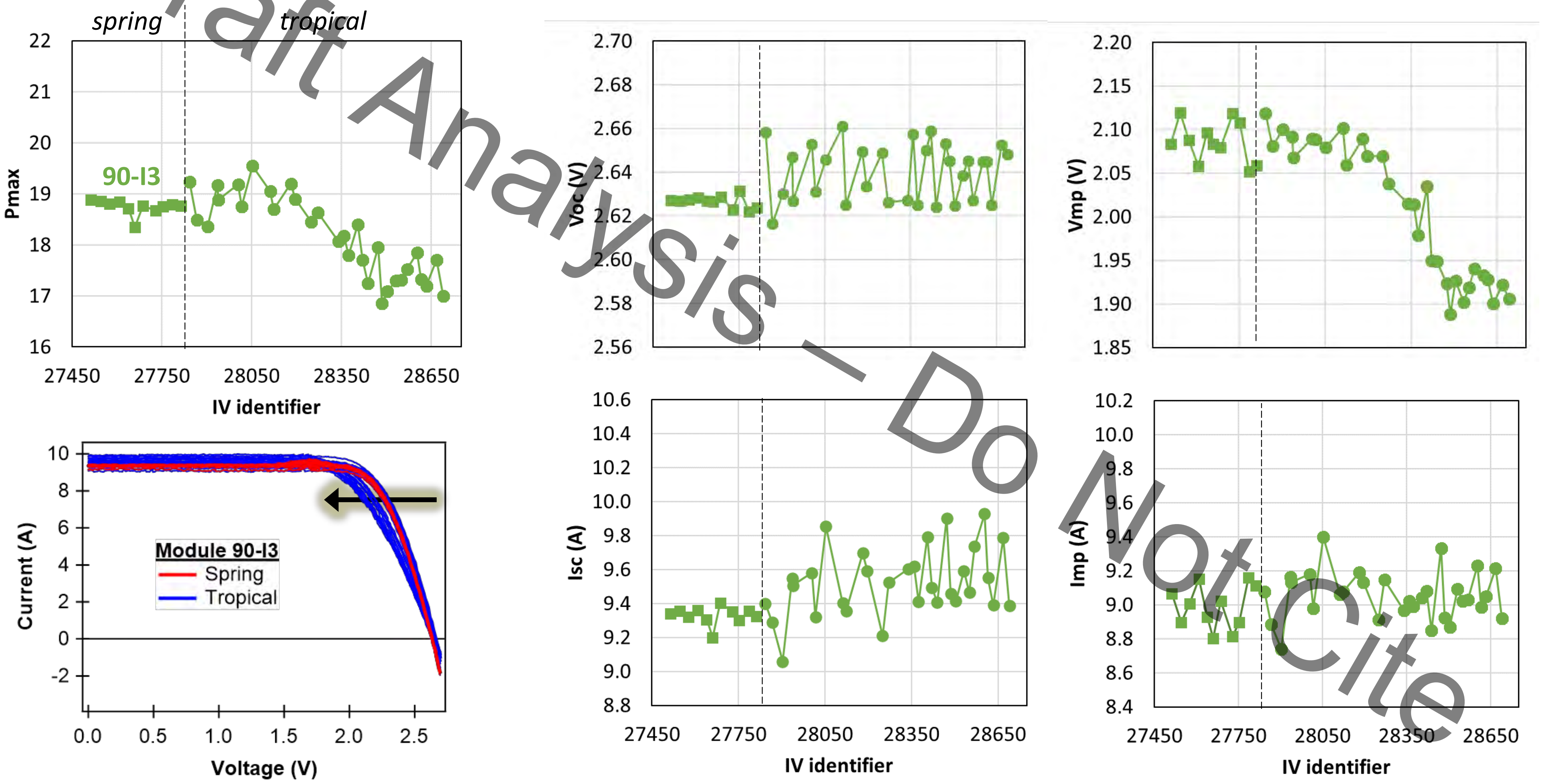
- More pronounced change compared to LID-stabilized cells

Contact issues / interconnects/ finger breakage after tropical cycle

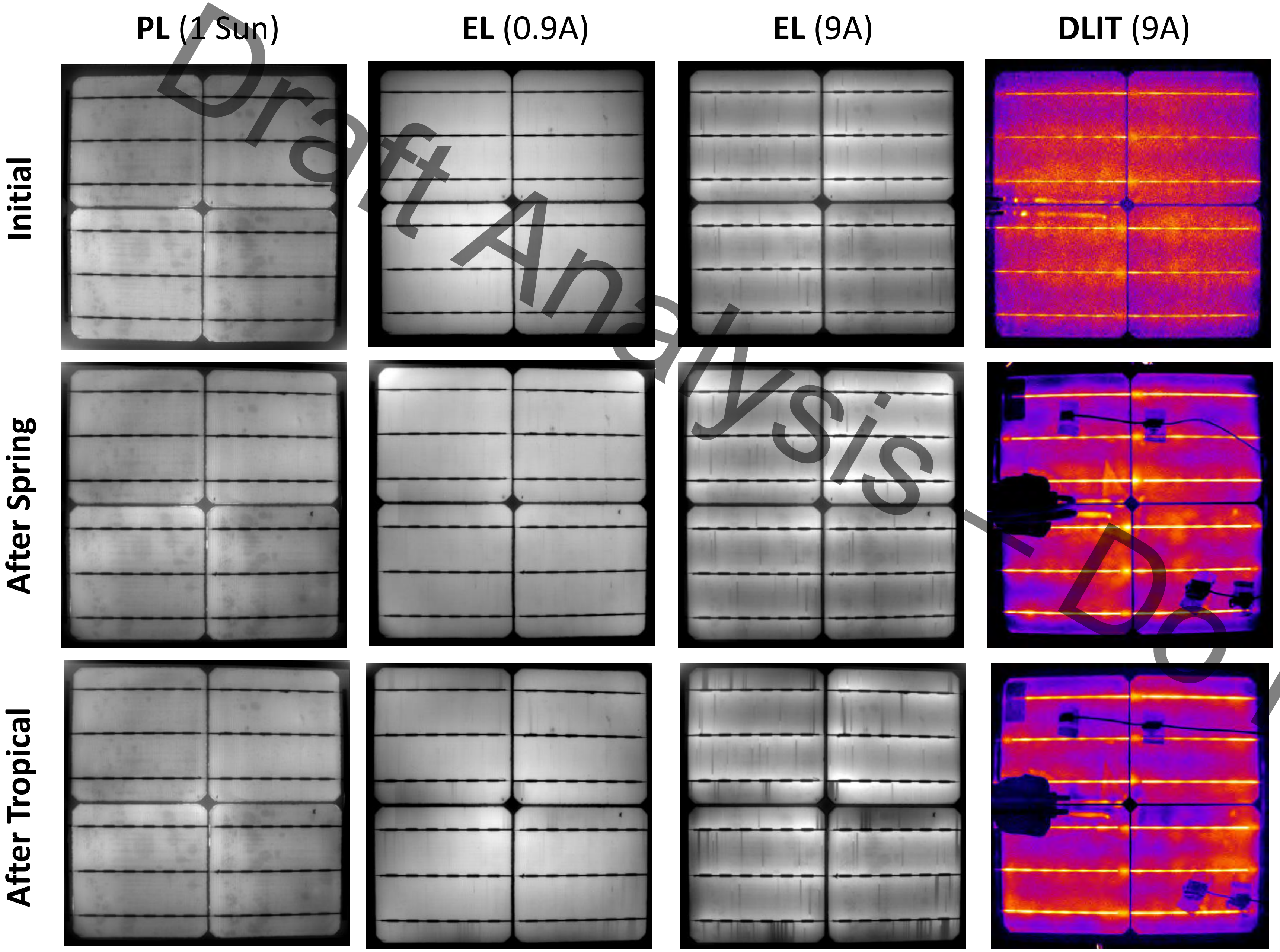
- Early stages have small effect on IV curves
- Responsible for small decrease in Vmp
- Could mask ability to see LID/LeTID effects in CAST?

Note: these images collected ex-situ outside of CAST chamber

90-I3 Shows Loss from Series Resistance During Tropical CAST Cycle



90-I3: *Imaging Shows Early Signs of Degradation*



No "Checkerboard" pattern

- Likely no LID observed in this case

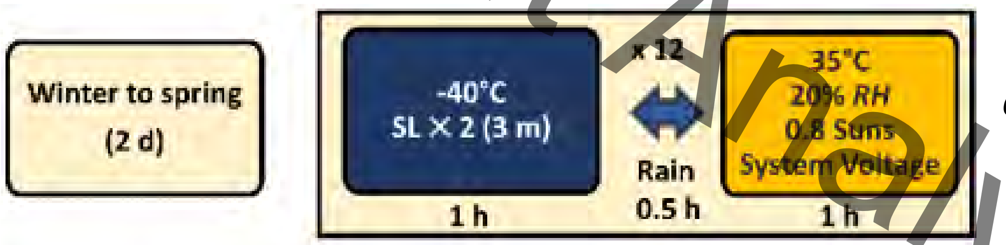
Contact issues / interconnects/ finger breakage after tropical cycle

- IV curves showed severe series resistance during tropical
- Responsible for decrease in Vmp
- Resistance effects don't appear in imaging to be more substantial than other mini modules

Note: these images collected ex-situ outside of CAST chamber

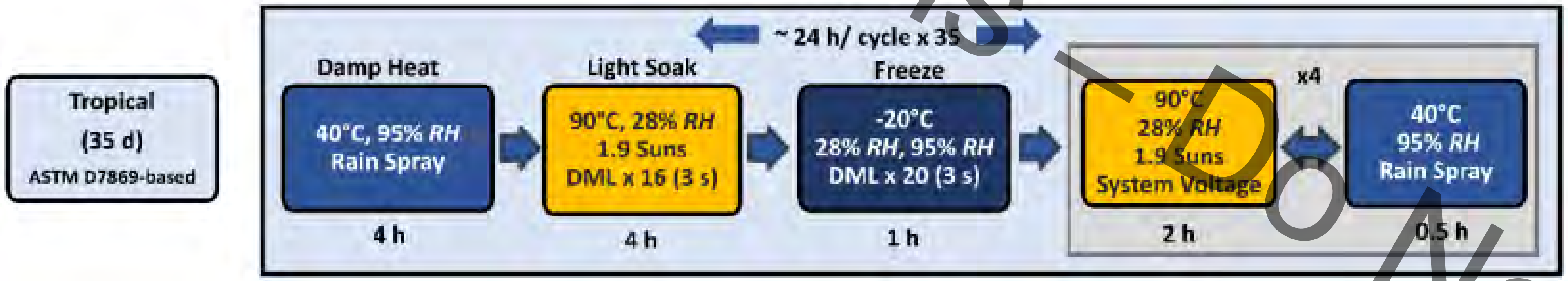
Identifying LID/LeTID in Combined Accelerated Stress Testing (CAST)

Goal: Test whether CAST sequence can distinguish between cells susceptible and non-susceptible to LID/LeTID.



extended x3

- ➢ Conditions did not appear to cause LID in cells known to be susceptible to LID.
- ➢ OR these cells were already in "state B" (degraded)



- ➢ When LID susceptible, LID recovery in 1 cycle.
- ➢ Rs effects after 6-10 cycles in all cases.

**** up next! ****

- ➢ Previous conditions did not show LeTID. Will "desert" conditions result in LeTID or other voltage decline?

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Characterization of Silicon Photovoltaic Module Durability Guided by Luminescence and Thermal Imaging

Development of In-Situ Imaging with a Low-Cost Camera System

Thank you for listening!

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