Multi-Year Study of Crack-Induced Degradation in Fielded Photovoltaic Modules

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Duramat Fall Workshop.

Denver, CO

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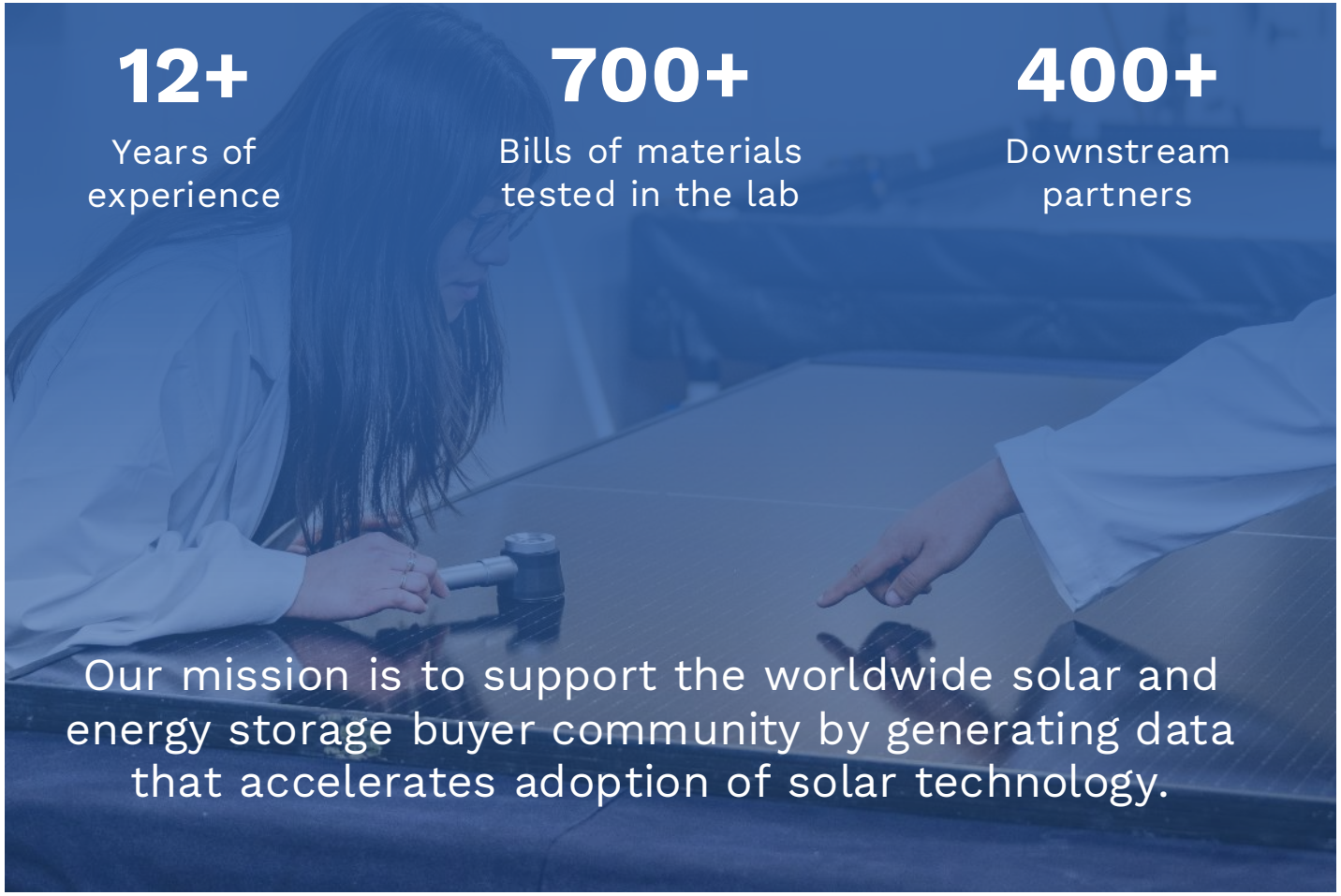
Kiwa PVEL is the Independent Lab of the Downstream Solar Market



Services at a glance:

- Extended reliability and performance testing for PV modules
- Batch testing of PV modules
- Outdoor testing of PV modules, inverters and energy storage
- Data services for PV buyers and investors

See more details at kiwa.com/pvel

Outline

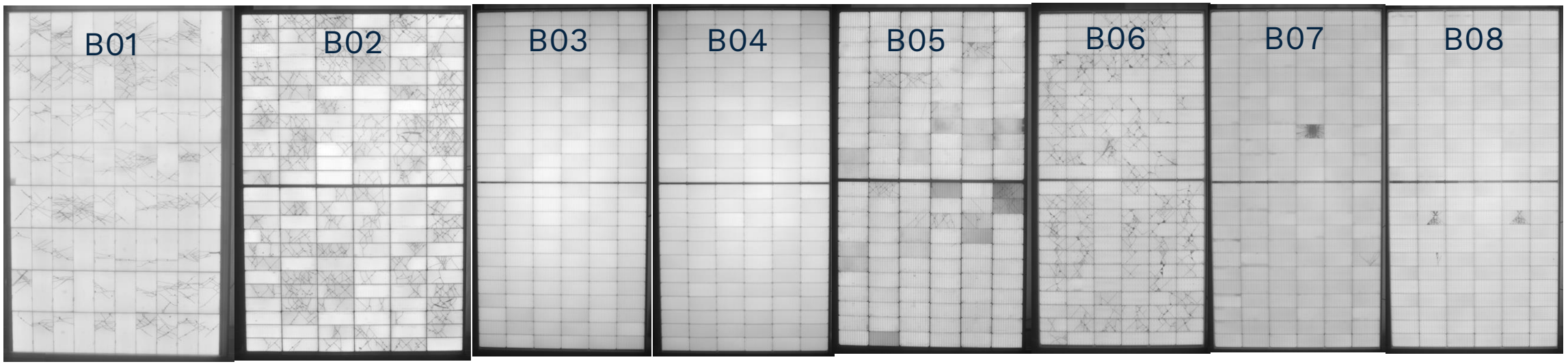
- About the study
- Background + Methods
  - Year on year
  - Dark IV analysis
- Results
  - Cell cracks + outdoor performance.
  - Cell cracks + degradation
  - By BOM

Duramat study

Outdoor aging study

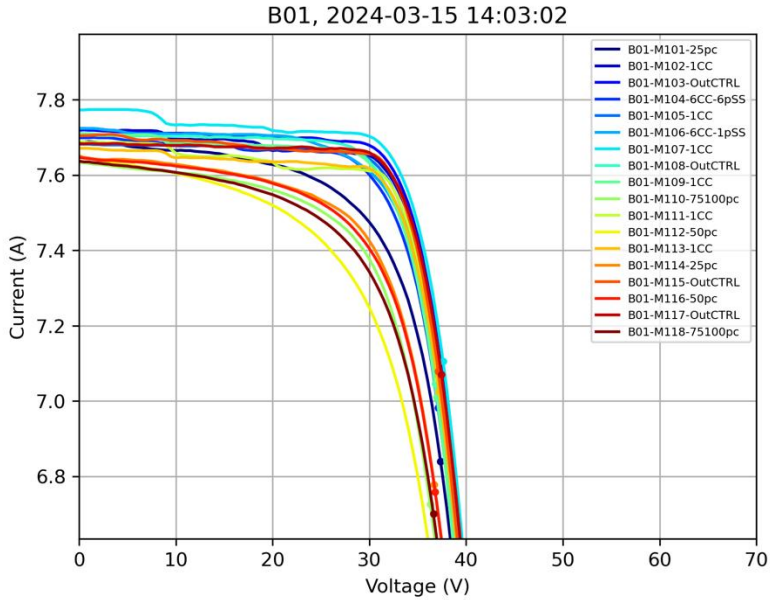
- 104 modern modules (8 unique BOMs) deployed outdoors.
- Samples received a variety of cracking stress, from 0% to 100% cracked cells.

BOM	Cell Technology	Back glass (BG) Back sheet (BS)	Number of Busbars	Number of Cells	Nameplate Pmp W	Number of Samples
B01	n-HJT	BS	20	80	410	19
B02	n-TOPCon	BS	6	144	415	22
B03	n-TOPCon	BG	6	144	565	15
B04	n-TOPCon	BG	16	144	570	15
B05	p-PERC	BS	12	132	400	17
B06	n-TOPCon	BS	6	144	445	8
B07	n-TOPCon	BS	6	144	535	8
B08	p-PERC	BS	6	144	545	8



About the Dataset

- IV curves (2 second length)
  - Every 30 minutes
  - Minimal capacitive effects.
  - **At night too**
- Irradiance
- Back of module temperature
- Wind speed
- Spectrum
- Visual cameras (minutely)
- Lab Flash indoors pre-deployment
- EL (twice a year)
- UVF (twice a year)
- Data is all aligned nicely in a csv file.



Methods / Background

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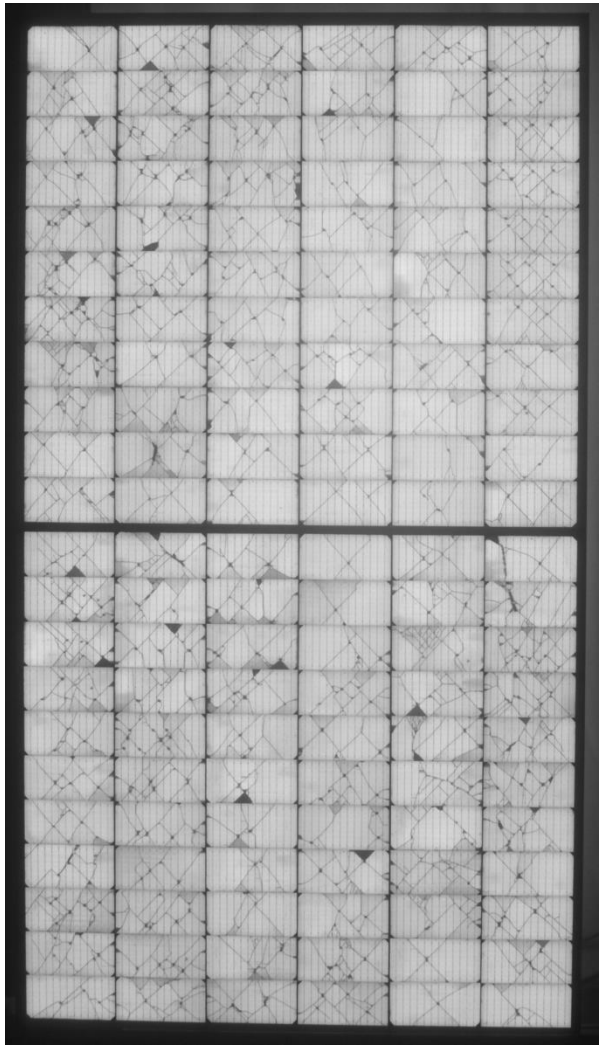
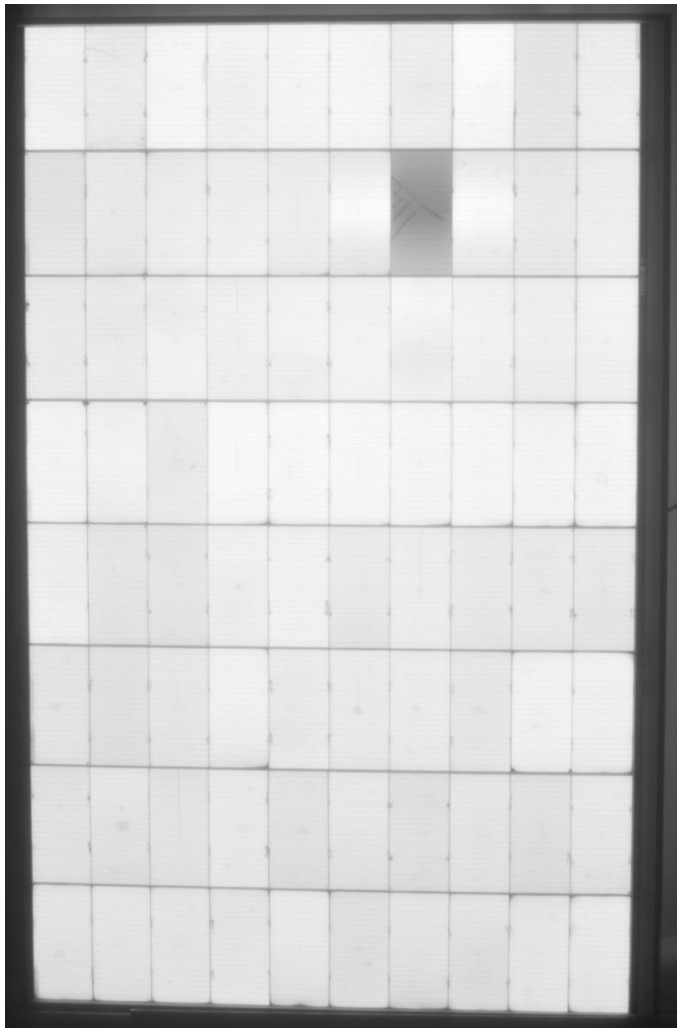
What could happen over time.

- What are possible impacts of cell cracks on module performance?

- Impact 1: **disconnected area grows.**



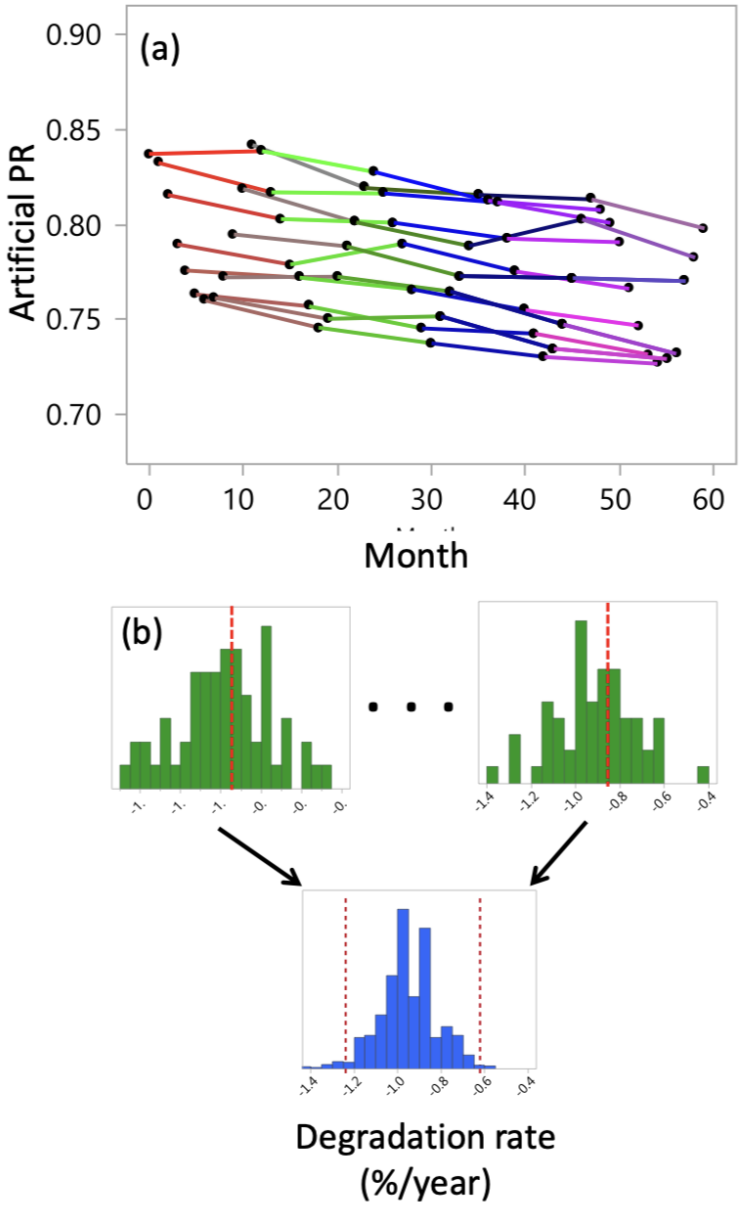
- Impact 2: **Increased recombination** (shunting) due to unpassivated edges



[1] T. J. Silverman, N. Bosco, M. Owen-Bellini, C. Libby and M. G. Deceglie, "**Millions of Small Pressure Cycles Drive Damage in Cracked Solar Cells**," in IEEE Journal of Photovoltaics, vol. 12, no. 4, pp. 1090-1093, July 2022, doi: 10.1109/JPHOTOV.2022.3177139.

Year-on-year analysis

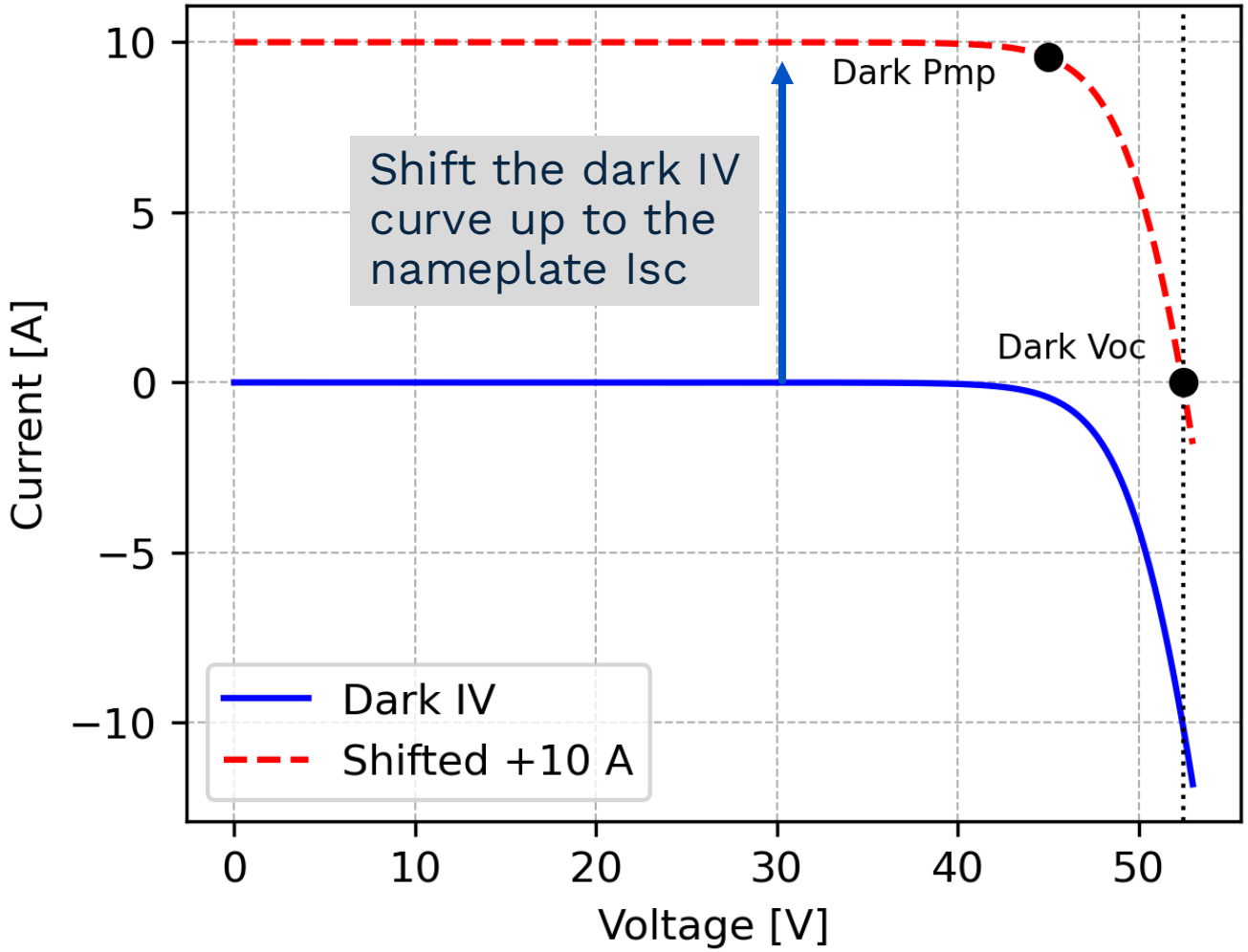
- YOY analysis used in Rdtools.
- Concept:
  - Don’t try to fit a line, instead, subtract this year’s data minus last years.
  - Make a histogram and take the mean/median/std.
- Typically just applied to power/energy. We will use it for all iv params (Voc, Isc, FF, etc.)



[1] D. C. Jordan, M. G. Deceglie and S. R. Kurtz, "PV degradation methodology comparison — A basis for a standard," 2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC), Portland, OR, USA, 2016, pp. 0273-0278,

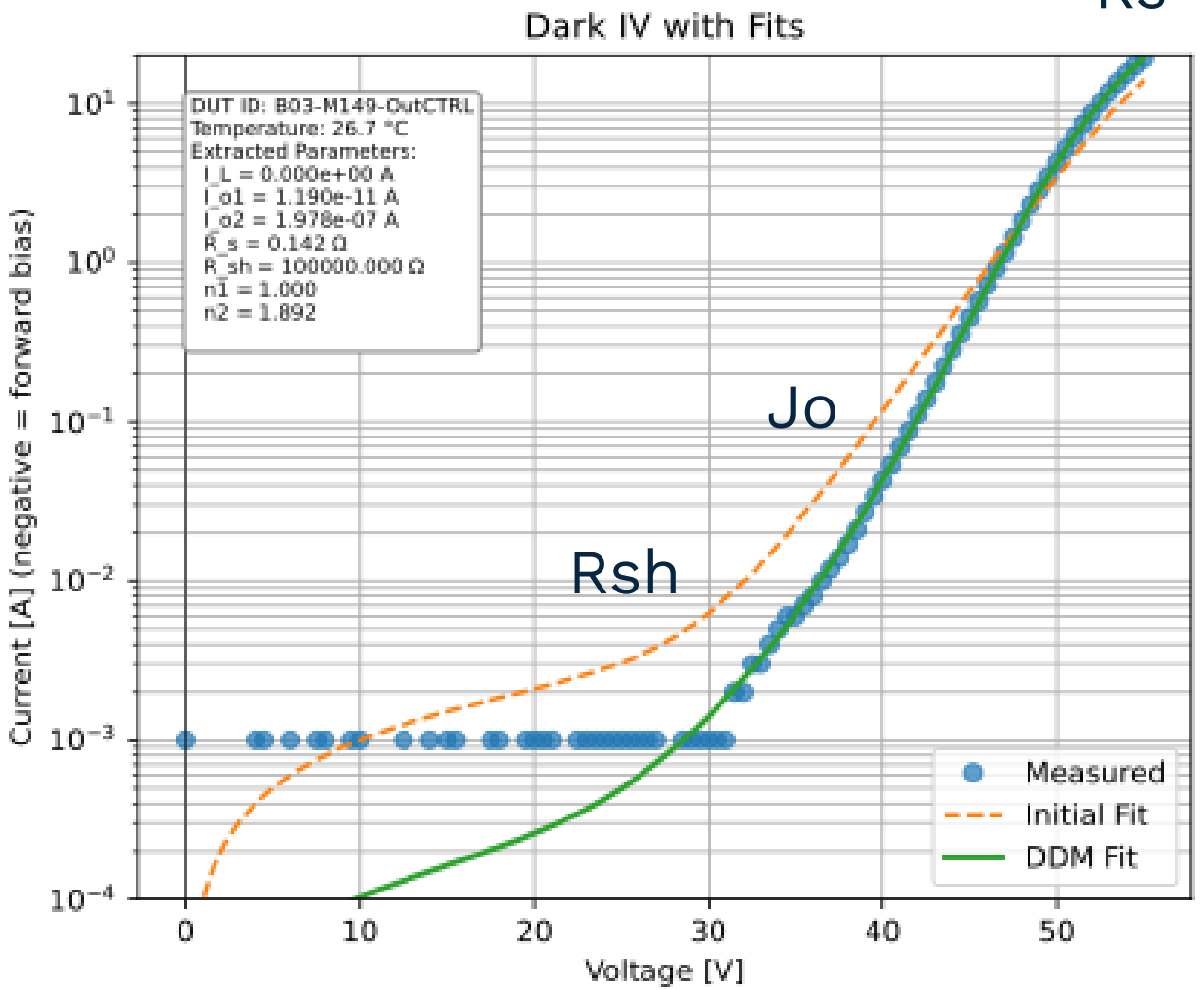
Dark IV Analysis

- **Dark IV**: IV curve taken at night.
- Define Dark Voc/Pmp as the Voc/Pmp of the shifted IV curve
- Why dark analysis?
  - Temperature is more controlled at night.
  - Ignore effects of soiling.
  - Many types of degradation are observed cleanly in the dark.



Dark IV Analysis

- Possible to do a double diode model fit.
- But fits are tricky, let's stick with the simple parameters.



Results

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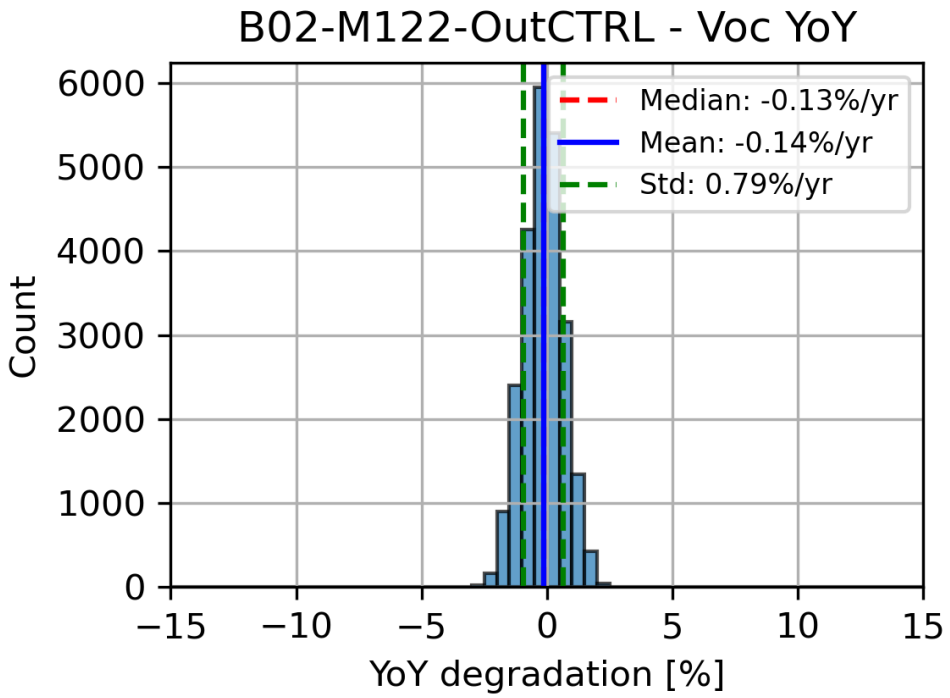
Dark Voc analysis

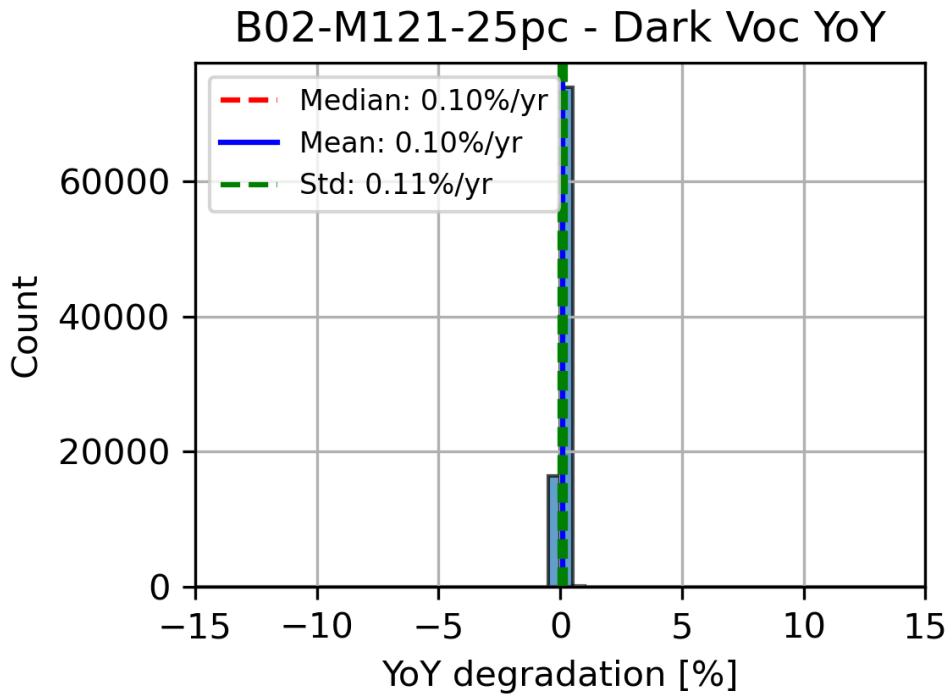
- Interesting to compare dark Voc degradation to light Voc: **less noise using Dark analysis.**
- In dark, irradiance and temperature have less uncertainty.

Dark IV not typically used for time series

LIGHT



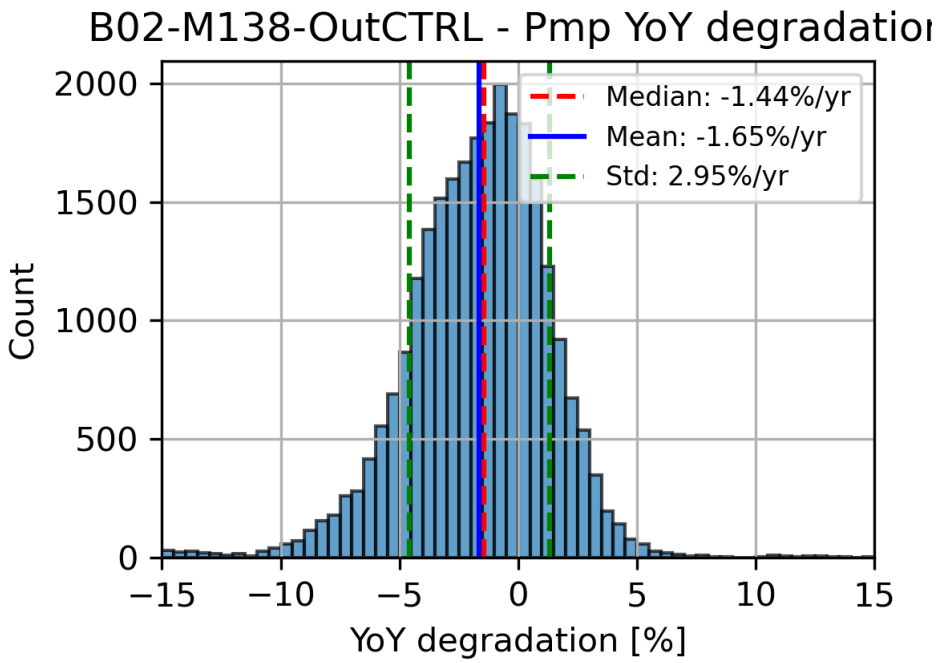
DARK



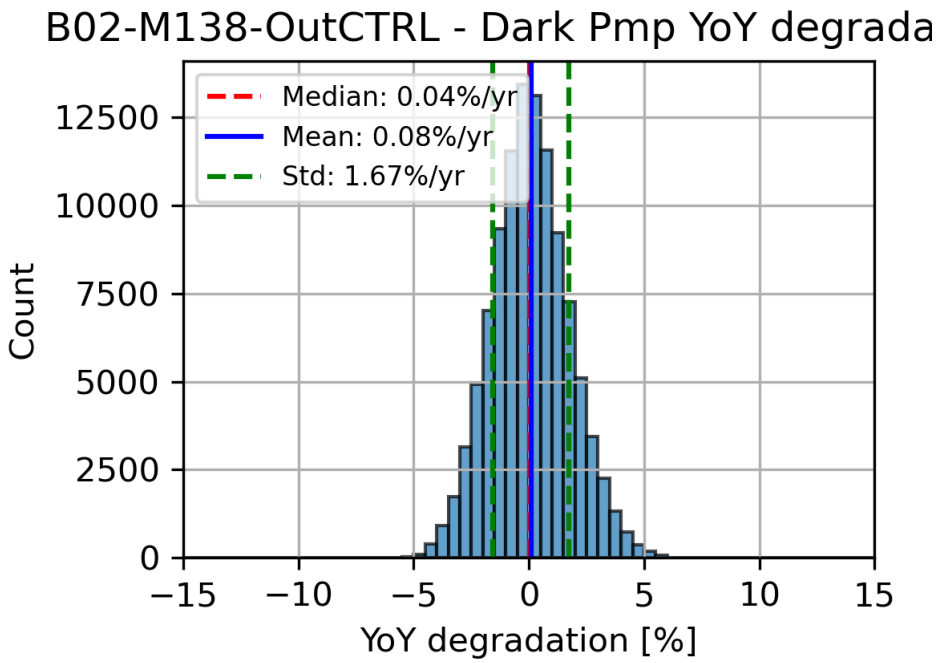
Dark Pmp analysis

- Dark Pmp is also more stable than light Pmp

LIGHT



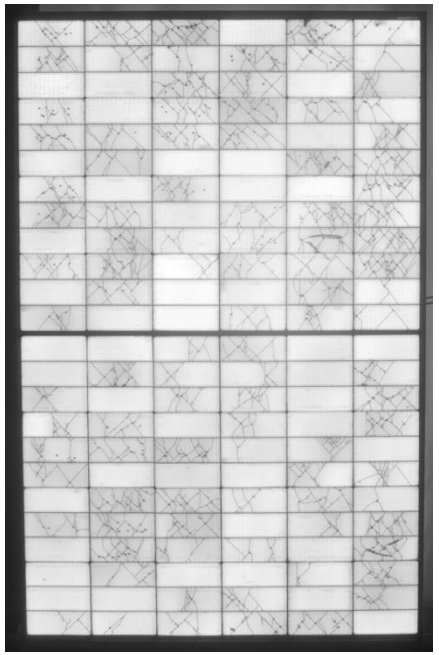
DARK

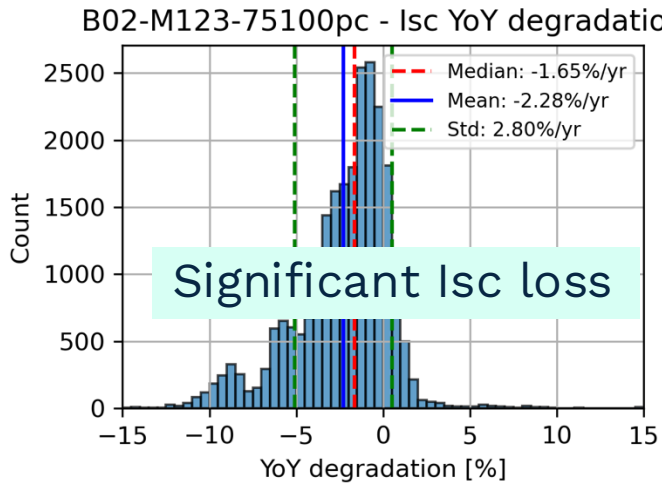


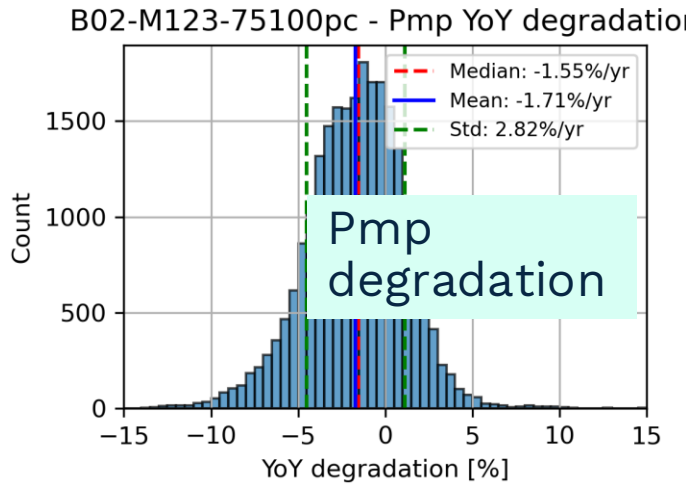
Example: Highly cracked module

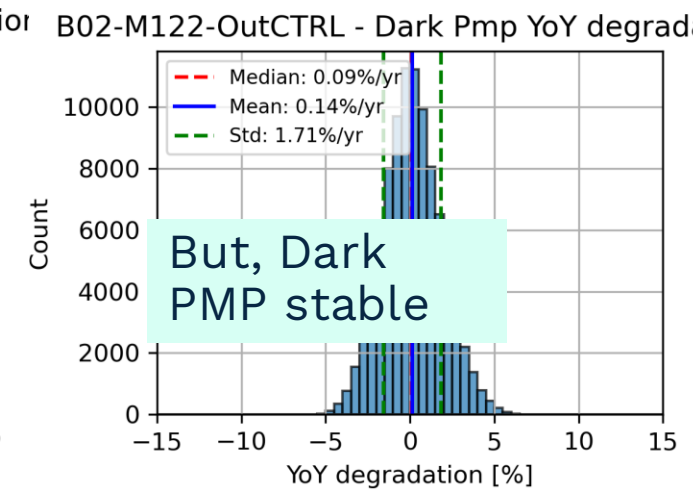
No dark pmp loss,
no dark Voc loss.

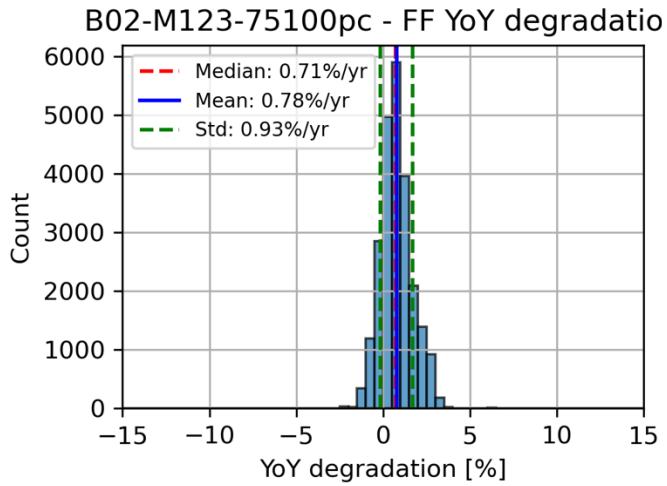
Looks like
just soiling.

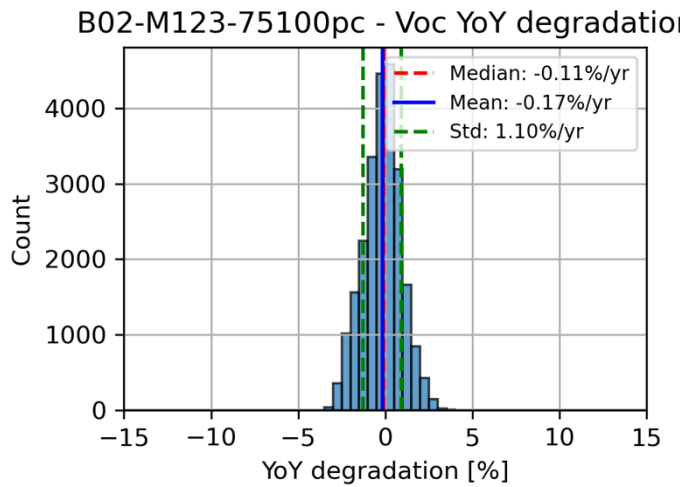


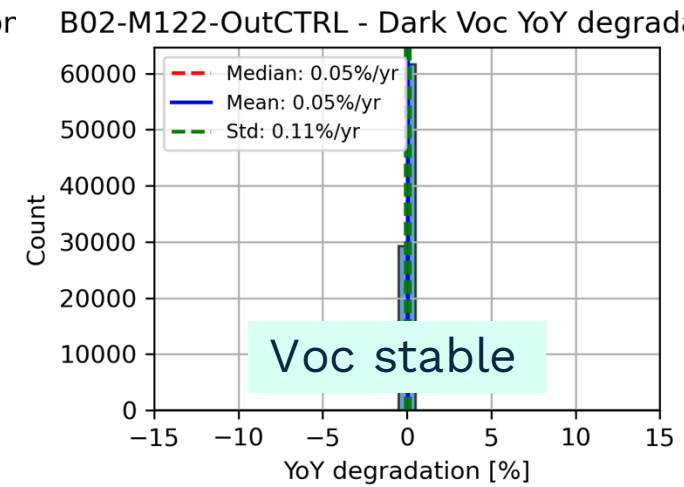








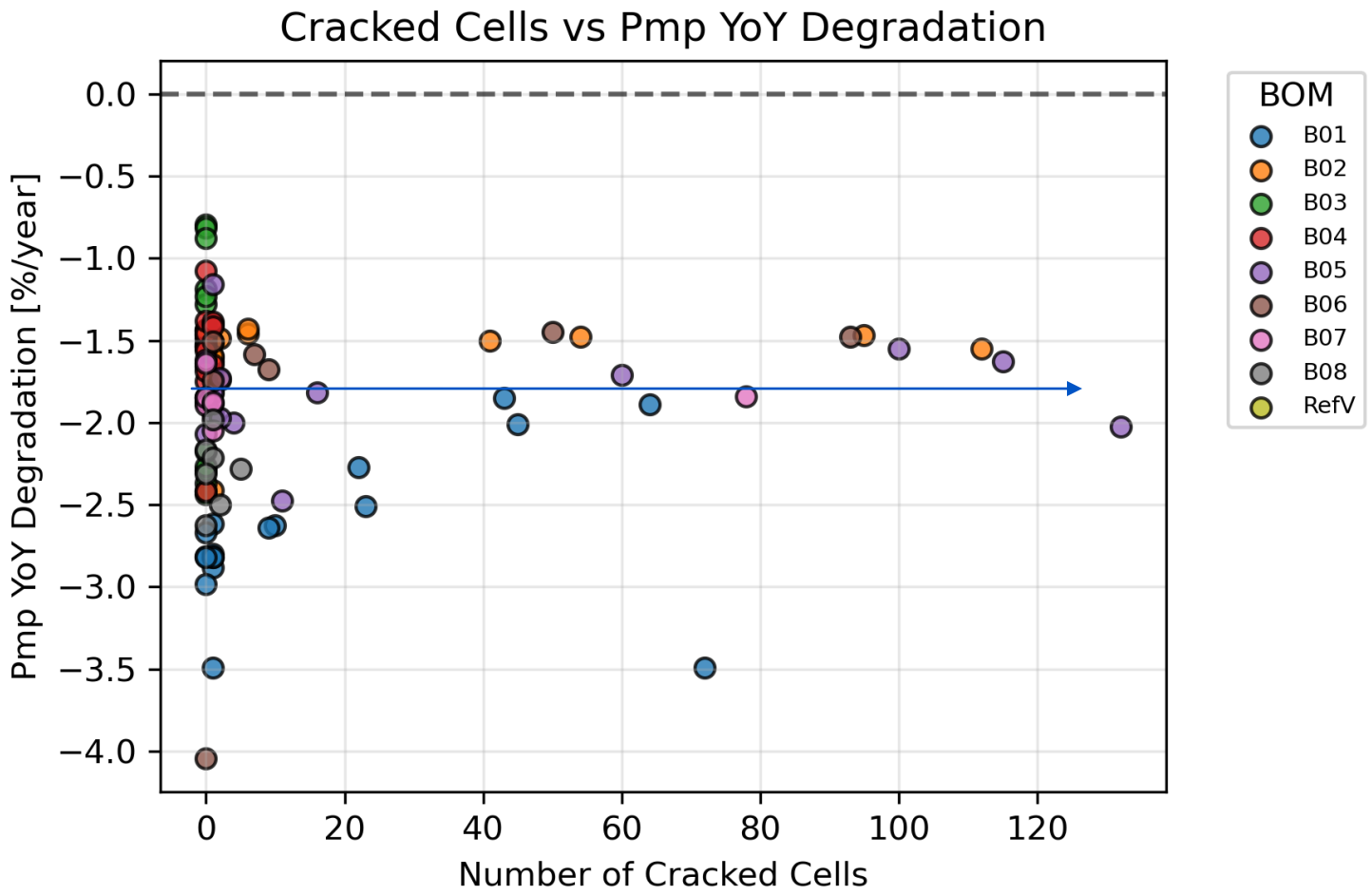




Possible Degradation Mode 1: Pressure cycles open up cracks

If cracks are opening, it is small enough that it cannot be seen in Pmp degradation.

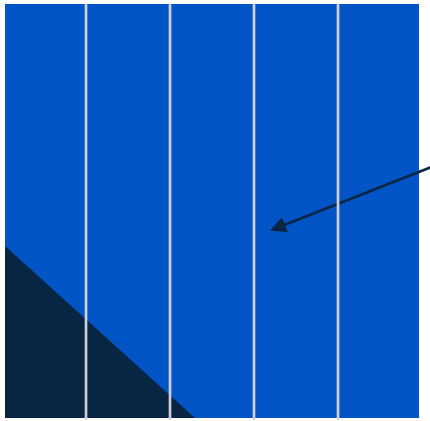
No evidence of extra Pmp loss for higher cracked numbers of cracked cells.



Background: Signature of cell disconnections

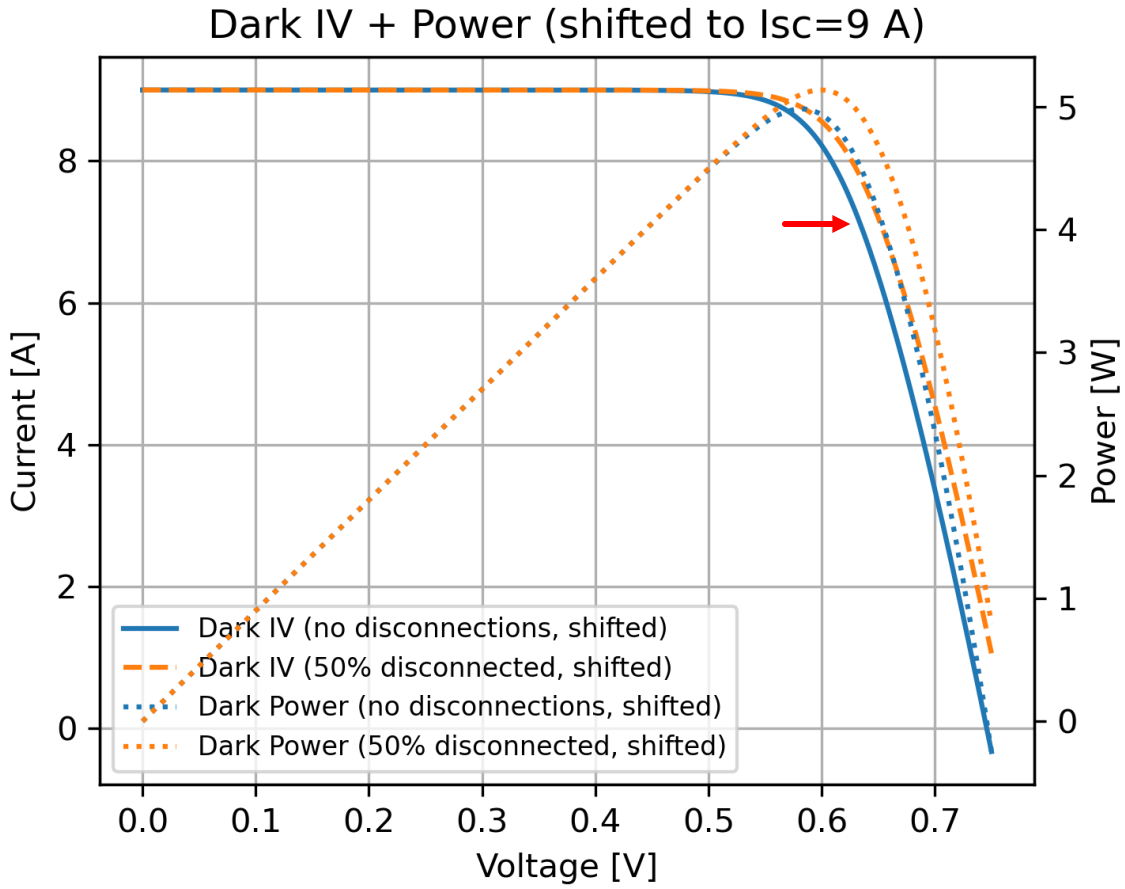
$$I = I_L - I_0 \left[\exp\left(\frac{V + IR_s}{nV_T} \right) - 1 \right] - \frac{V + IR_s}{R_{sh}}$$

Io goes down, need more V to get to the same I



SDM: Io scales with connected area.

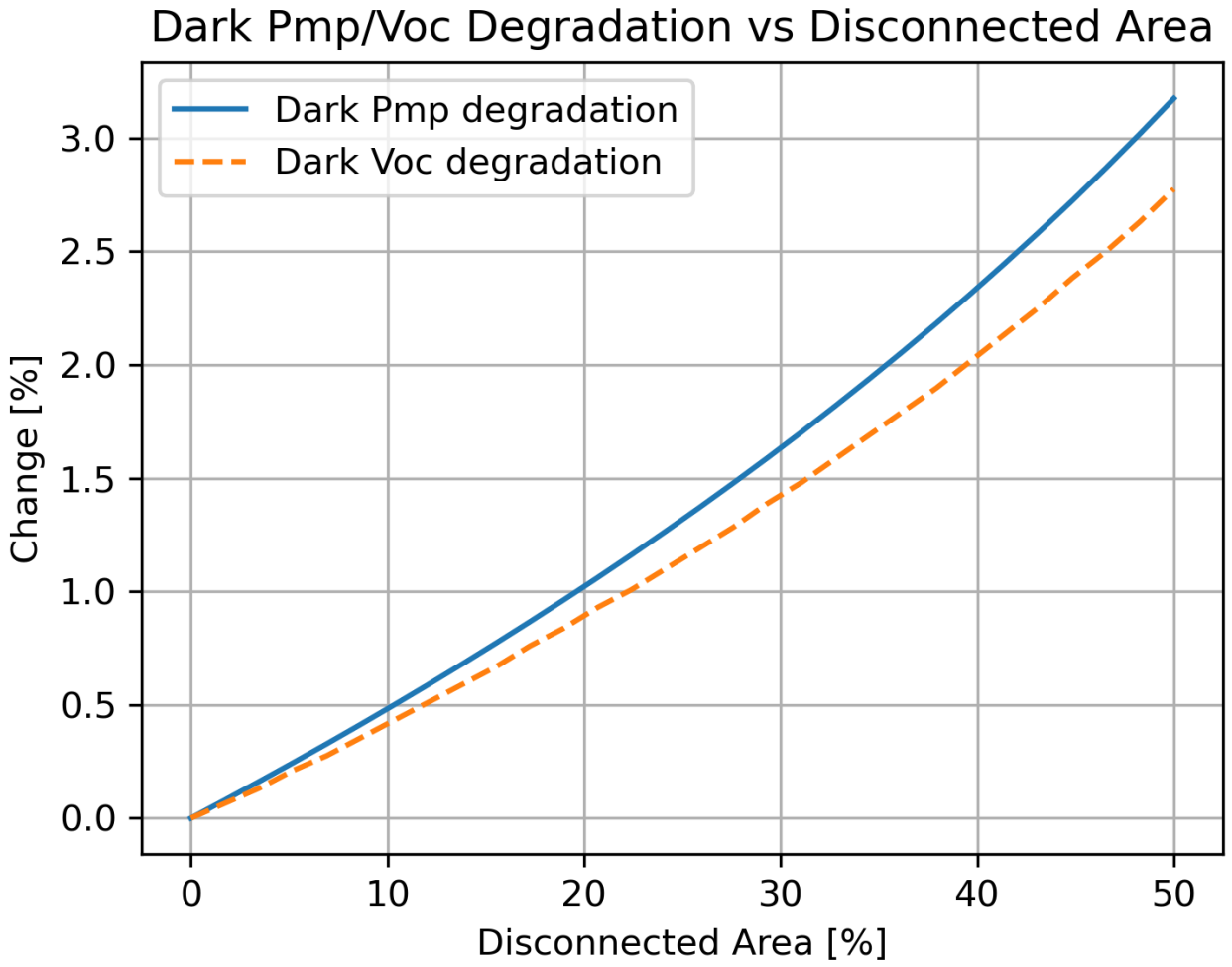
- At first the cell fragments are all held together by the wires.
- As the module ages, the wires break.
- Expect the **recombination parameter Io to decrease** by a factor proportional to the fraction of the cell disconnected from the electrical circuit.
- Thus: dark Voc and dark Pmp expected to **increase**.



Background: Impact of disconnections on dark iv params

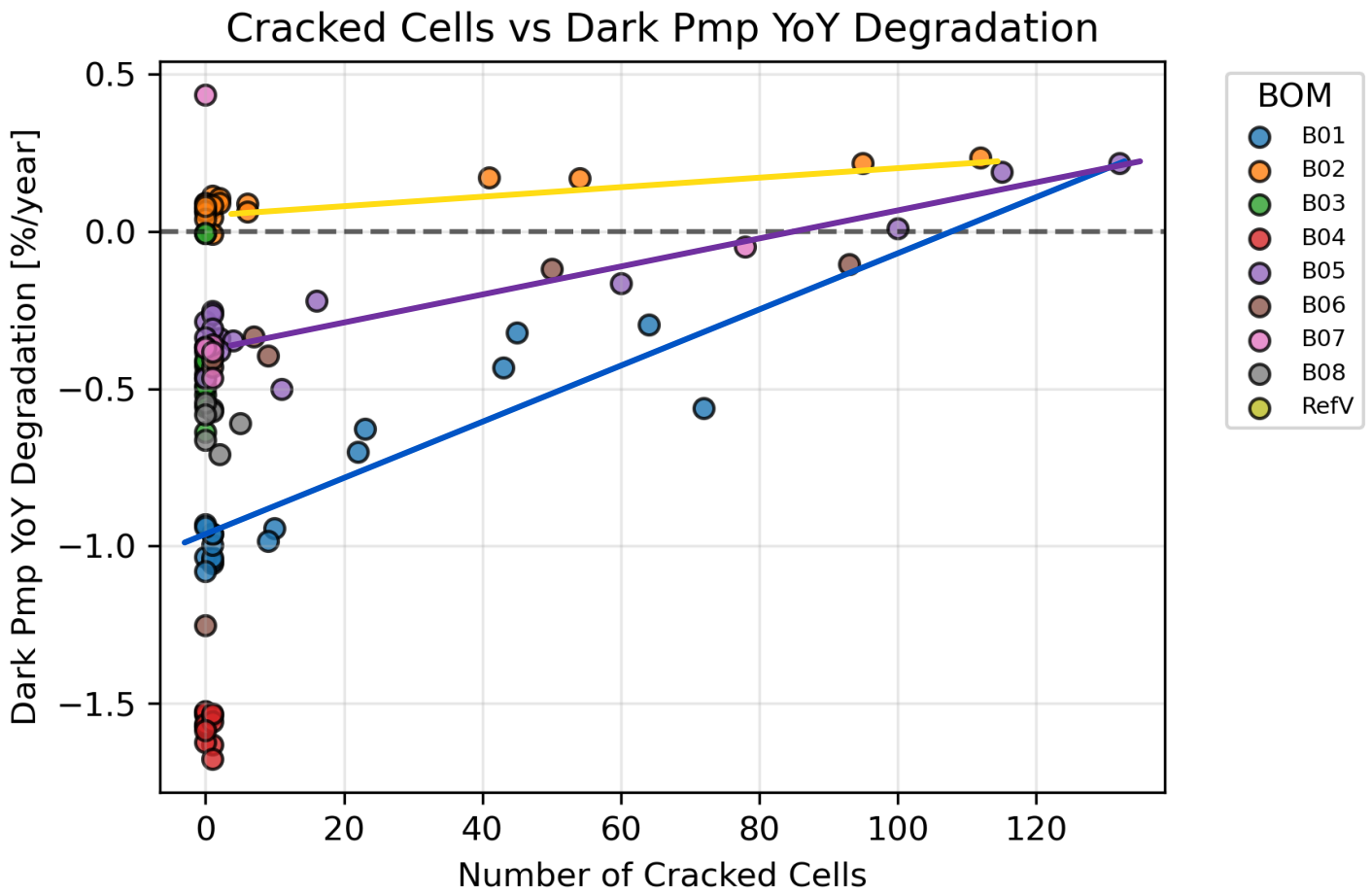
- Roughly, expect that a +1.0% change in Dark Pmp could be explained by a 20% increase in disconnected area.
- (Note this is for a single cell, things can more complicated with variation within a module.)

Counterintuitively, expect Dark Pmp and Dark Voc to increase as cell fragments become electrically disconnected.



Dark Pmp degradation rates match expected behavior for slight disconnection.

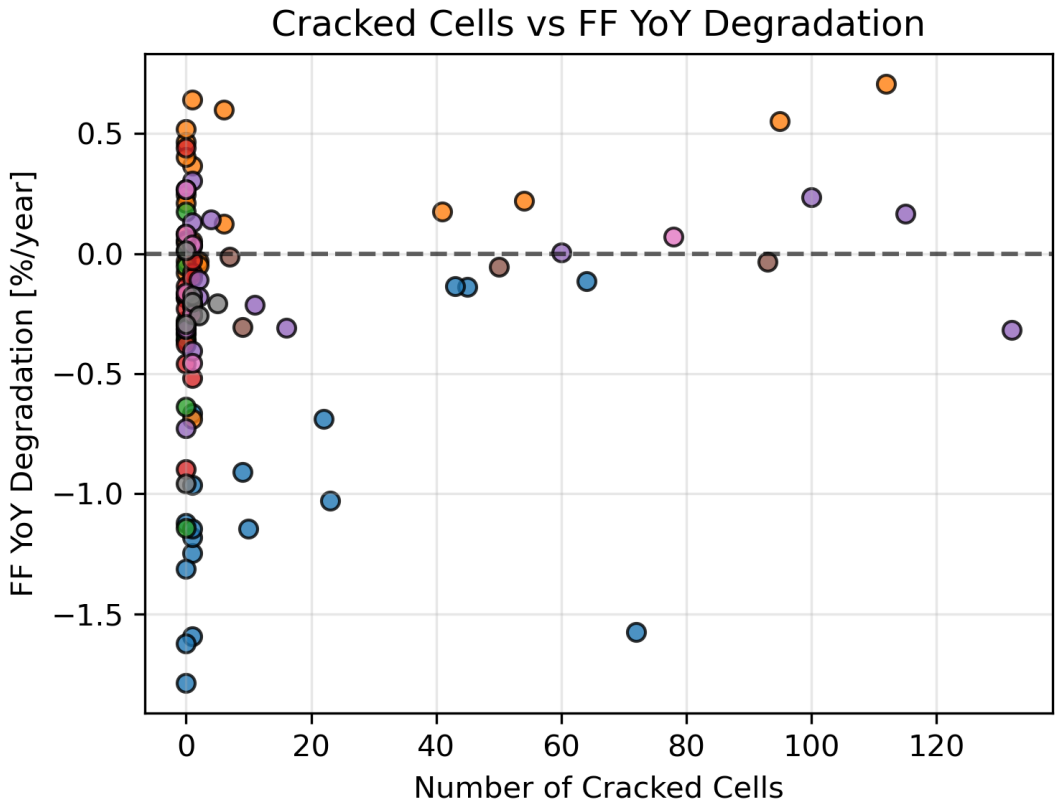
- Dark Pmp incrases more for modules with more cracked cells, **matches expectation for slight amounts of increased disconnection.**
- Implication: the worst cracked modules are developing an additional ~10% extra disconnections over time.
- But note, this was too small to be observed in Light Pmp

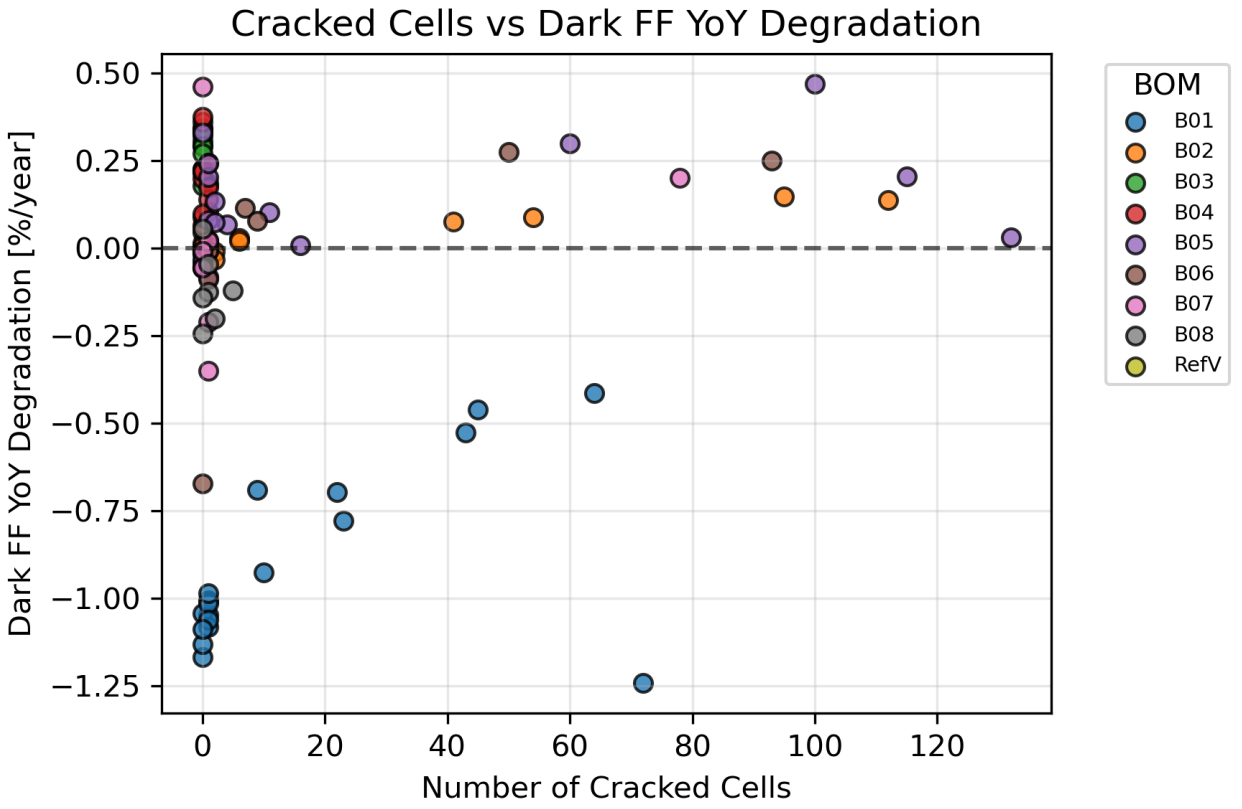


Possible Degradation Mode 2: Increased Shunting

- Increased shunting would cause FF and Dark FF degradation.
- But, FF does not degrade more for higher numbers of cracked cells.

No evidence of shunting increasing over time for highly cracked modules.





Initial power degradation (INDOOR Characterization)

BOM	Cell Technology	Back glass (BG) Back sheet (BS)	Number of Busbars	Number of Cells	Nameplate Pmp W
B01	n-HJT	BS	20	80	410
B02	n-TOPCon	BS	6	144	415
B03	n-TOPCon	BS	6	144	565
B04	n-TOPCon	BG	16	144	570
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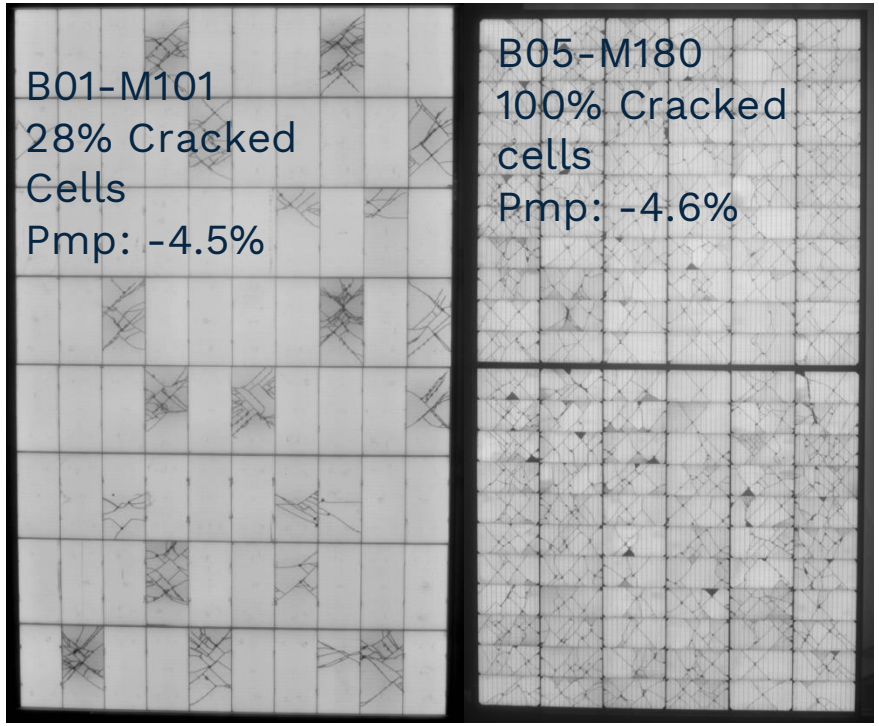
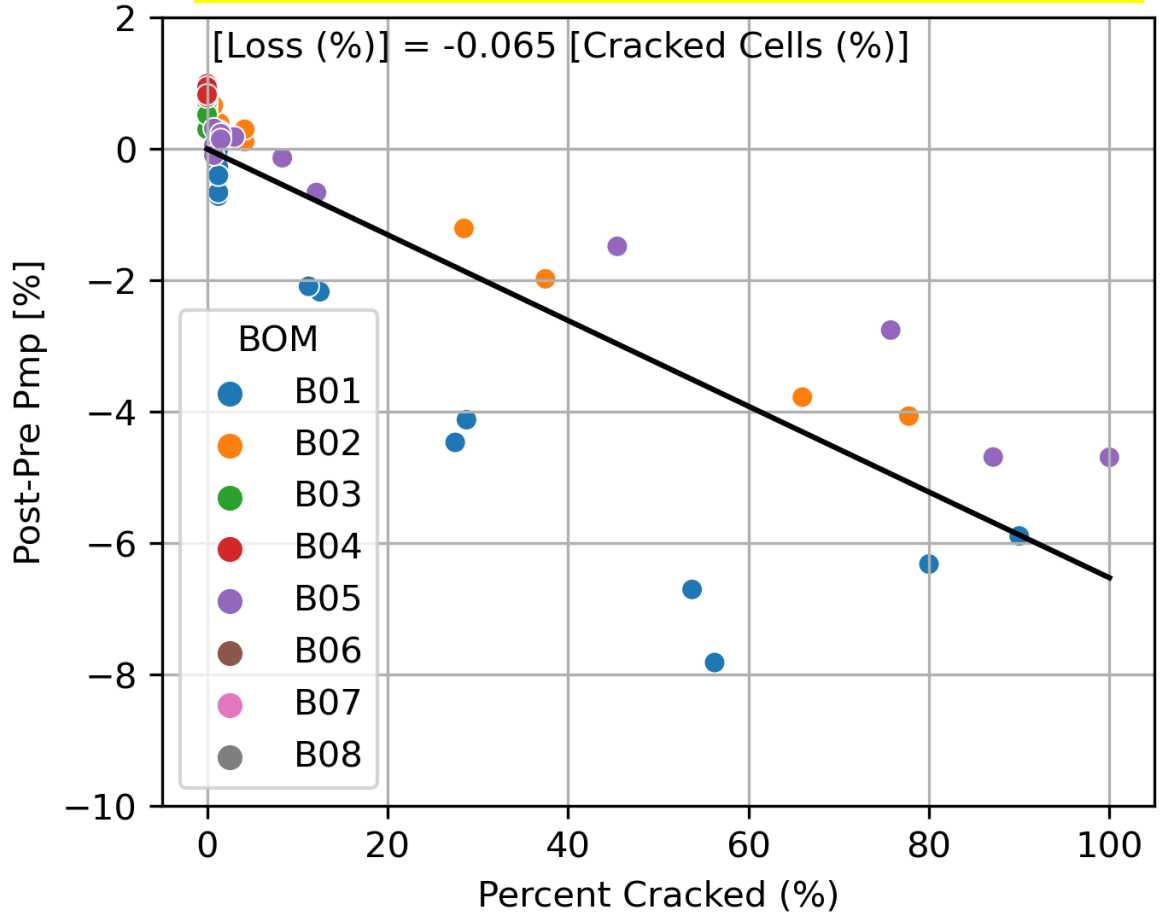
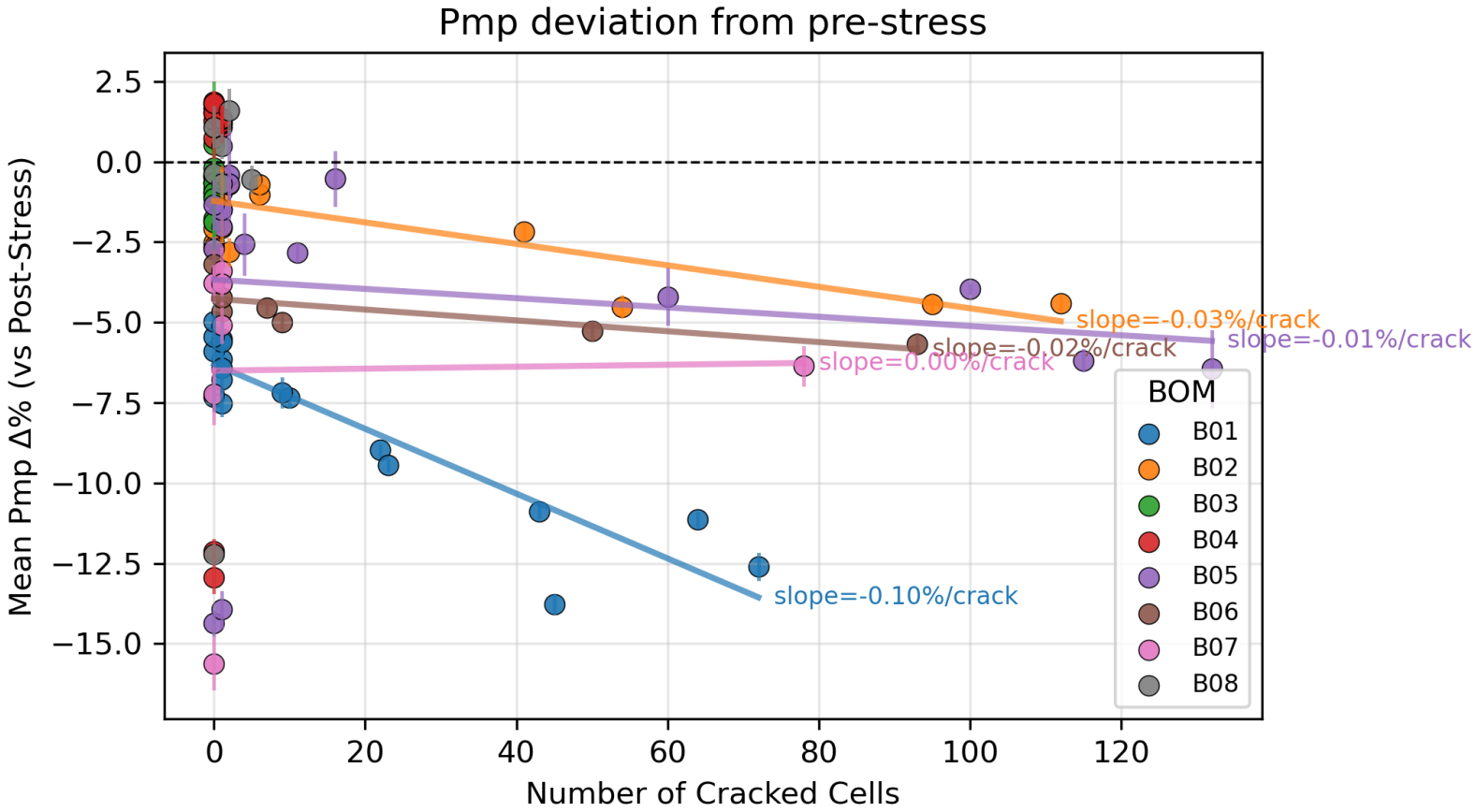


Power loss is initially suprisingly low, even for highly damaged modules



Pmp performance vs. number of cracked cells (OUTDOOR characterization)

- Analyzed one day of data in the middle of the dataset.
- B01 highly cracked modules have about 5% underperformance for highly cracked modules.
- Is 5% big or small?



Differences by BOM

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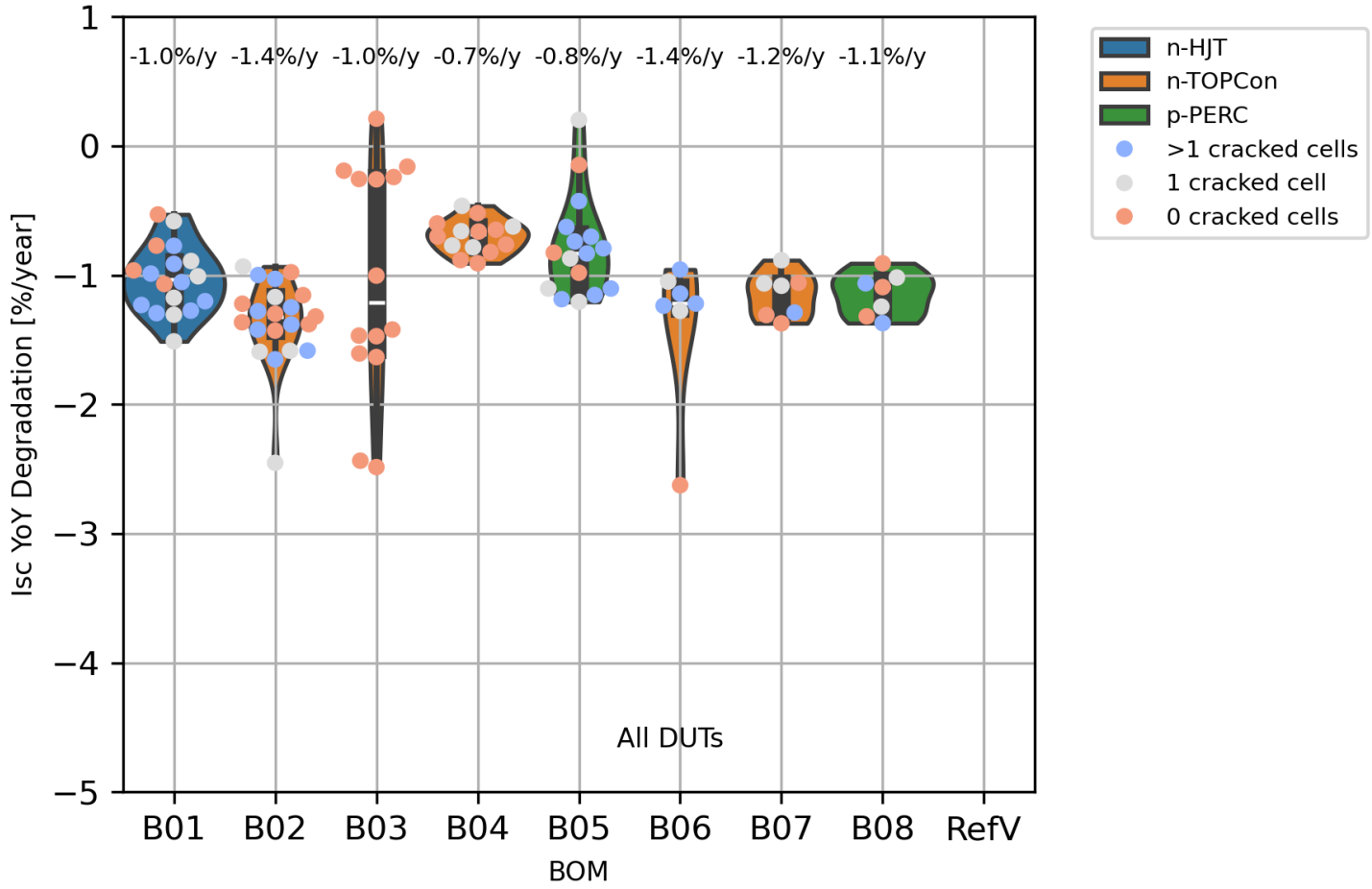
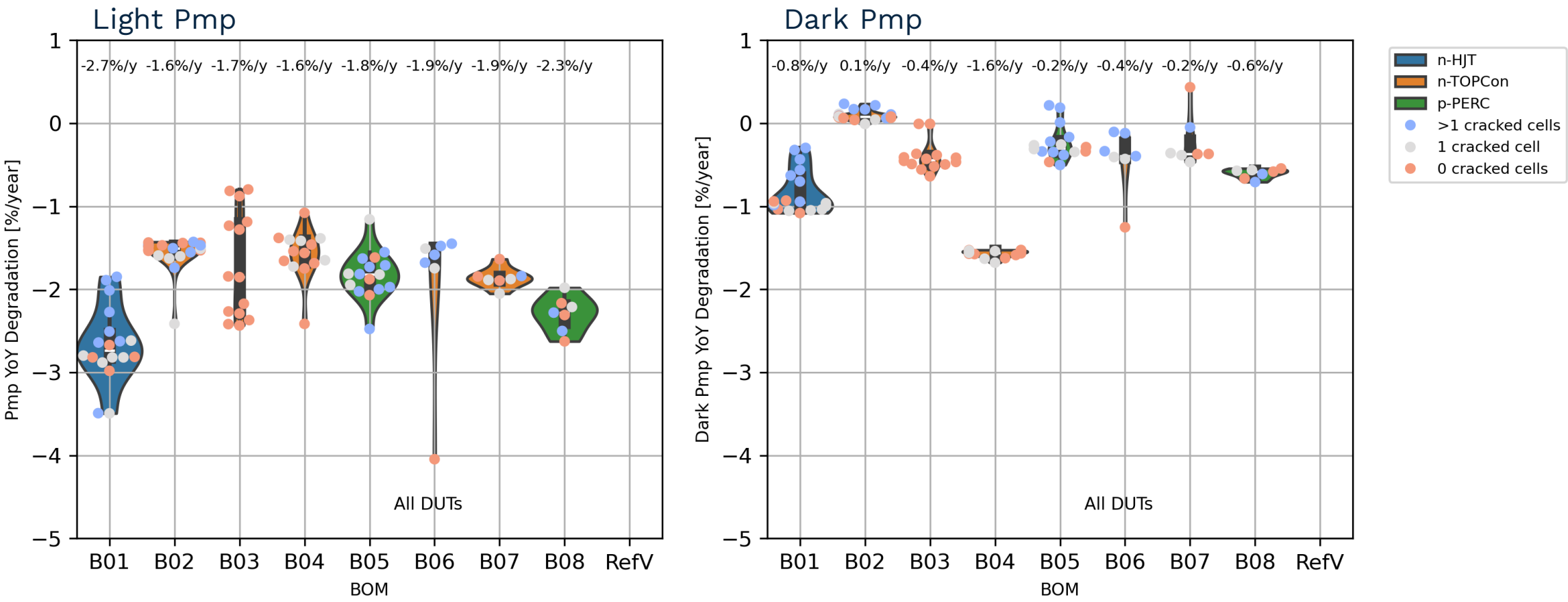
Modules show evidence of soiling

- **All modules show similar Isc YoY degradation.**
- Implies that soiling is significant, and at the level of about -1%/yr
- However, BOM differences exist.



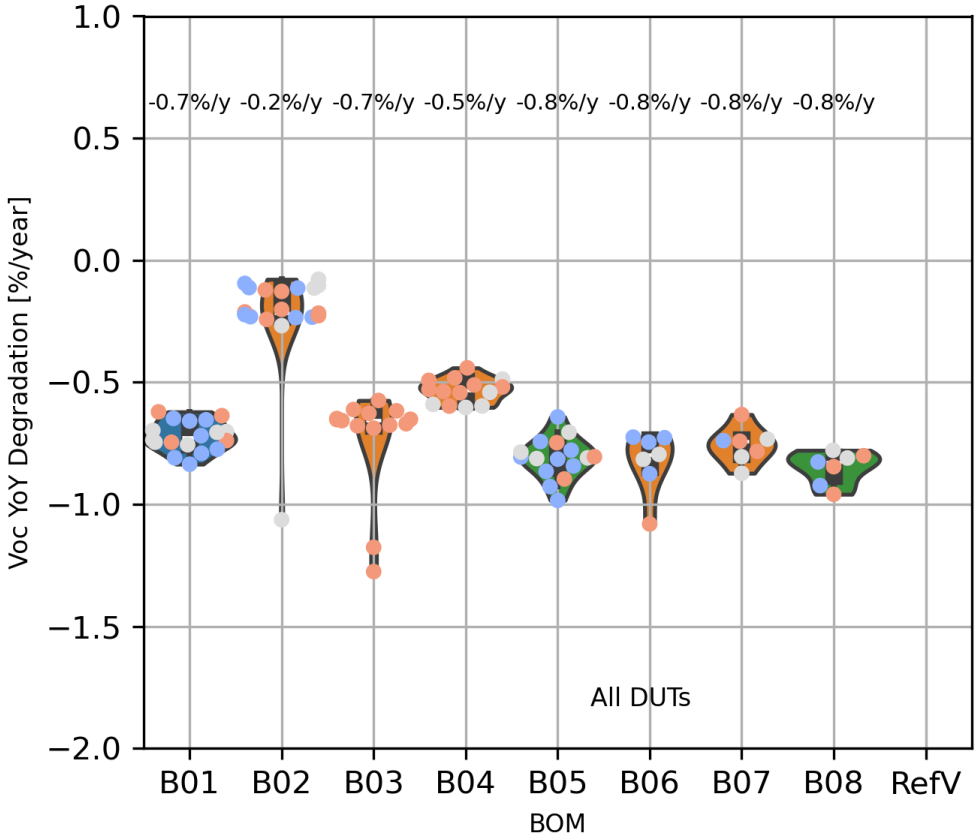
Pmp Degradation

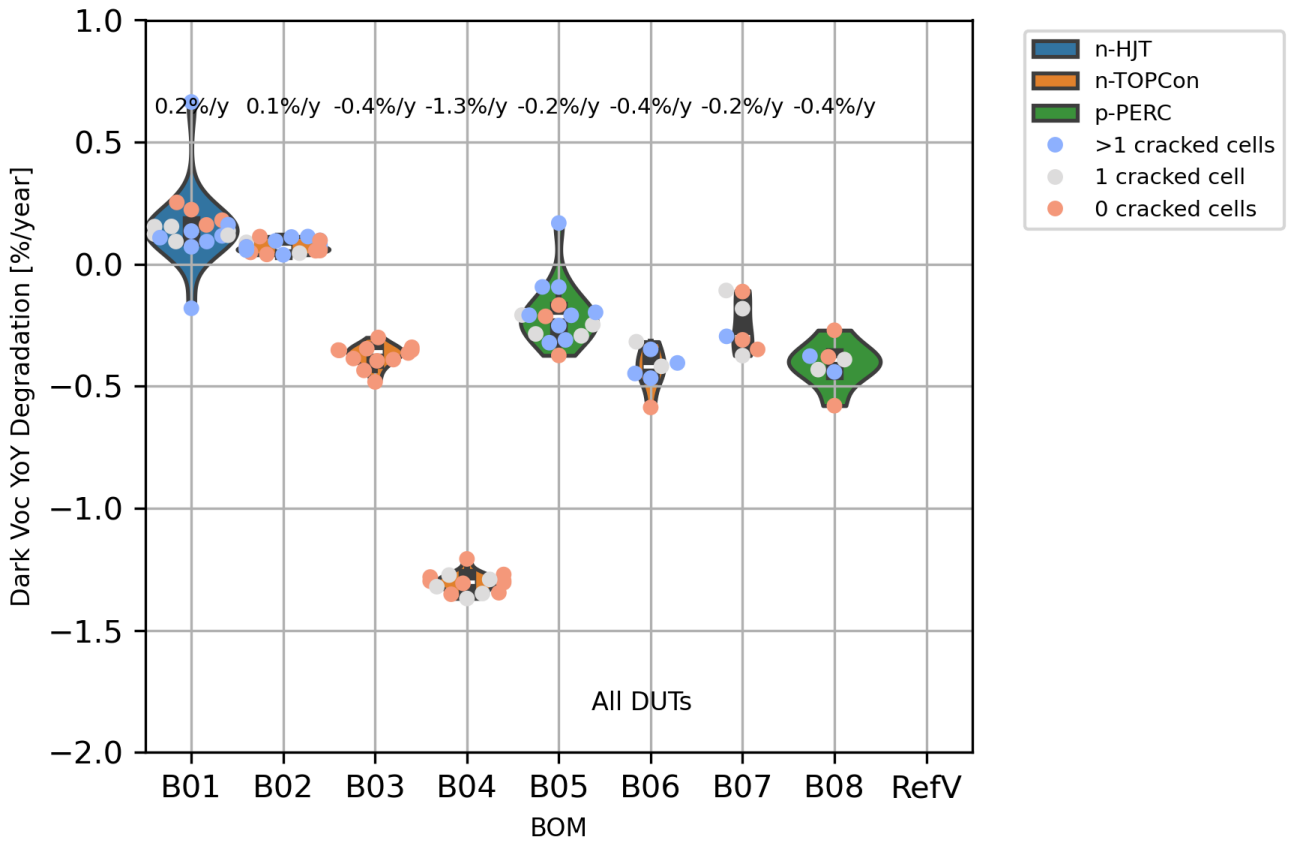
- Biggest signal occurs between BOMs.
- **These are high degradation rates, even when subtracting the ~-1%/yr soiling**



Voc Degradation

- Dark Voc degradation is typically less than light Voc degradation, except B04.
- Expect dark Voc loss shows a true degradation for most modules.

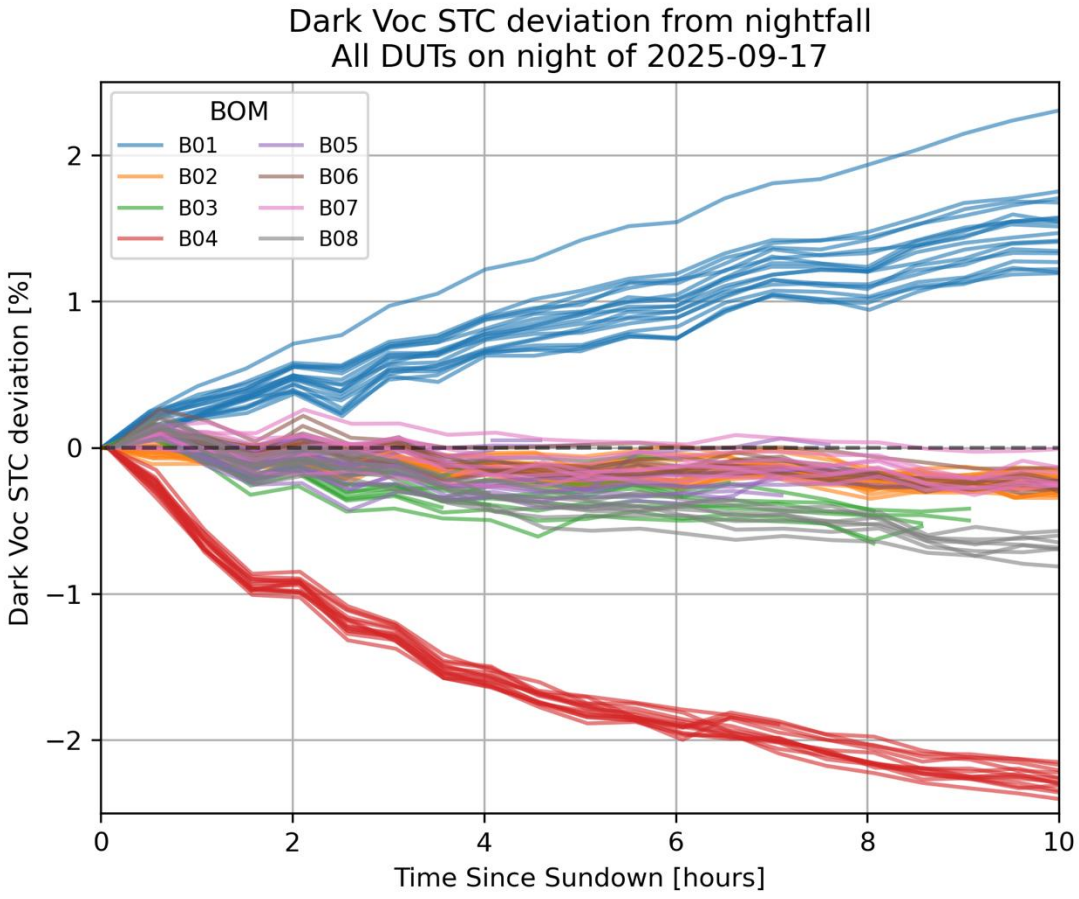




Night-time meta-stabilities.

Simmer down now...

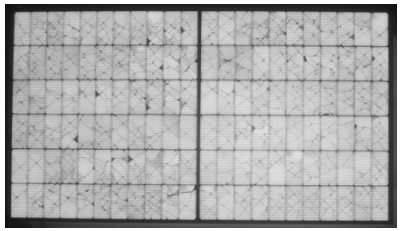
- B04: dark Voc drops at night
  - UVID?
- B01: HJT, dark Voc rises at night.
  - Why?



Party time.

Go to sleep...

Conclusions



- **Cell cracks**
  - Badly cracked modules underperform by ~5%
  - Cell cracks should not be a major performance concern.
  - No extra degradation observed over time due to cracks.
- **Outdoor exposure**
  - Dark IV analysis is useful for trending parameters over time.
  - Modules show significant Voc degradation of -0.2%/yr to -0.8%/yr.
  - Soiling is significant at -1.0%/yr
- **What's next?**
  - Decommission and perform final characterization.
  - Upload all data to datahub.

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