Investigating the Recovery Mechanism of Bifacial PV Modules Affected by Polarization-type Potential-Induced Degradation (PID-p) in the Field

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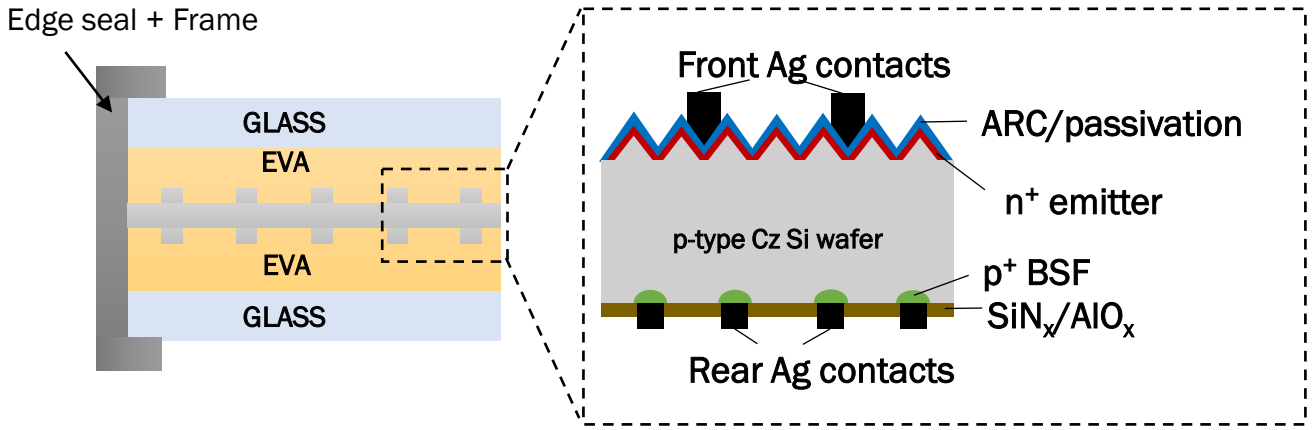
Outline

1. Motivation
2. Background: Bifacial module technology
3. Background: Polarization-type Potential-Induced Degradation (PID-p)
4. Evidence of PID-p occuring in the field
5. Recovery experiments
6. Conclusion

1. Motivation

- Confirm whether PID-p is occuring in the field
- Create predictive models for PID-p
- Understand PID-p recovery
- How we can distinguish PID-p over other degradation mechanisms

2. Bifacial module technology



- Commercial Glass/Glass bifacial Passivated Emitter and Rear Cell modules or PERC (from 1 manufacturer)
- Encapsulant : Ethylene Vinyl Acetate (EVA) – a flexible, transparent, rubber-like plastic
- Rear passivation layers **:** SiN_x/AlO_x

- **PID-p susceptibility confirmed** in chamber (Al foil, dark, 25°C, 54% RH, 168 H) [2], no other PID type detected
  - On the rear side at negative bias
  - On the front side at positive bias

Modules advertised PID free !

[2] Mahmood et al : Susceptibility to polarization type potential induced degradation in commercial bifacial p-PERC PV modules. Progress in Photovoltaics (2023) doi.org/10.1002/pip.3724

UCF

3. Polarization-type Potential-Induced Degradation [1]

Potential difference cells/frame

⬇

Charges accumulation in passivation stack

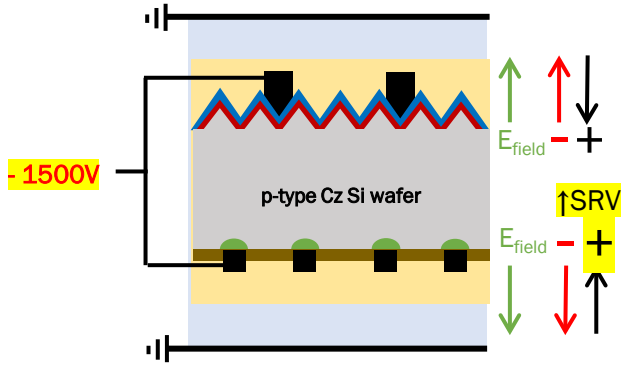
⬇

Increase surface recombination velocity (SRV)

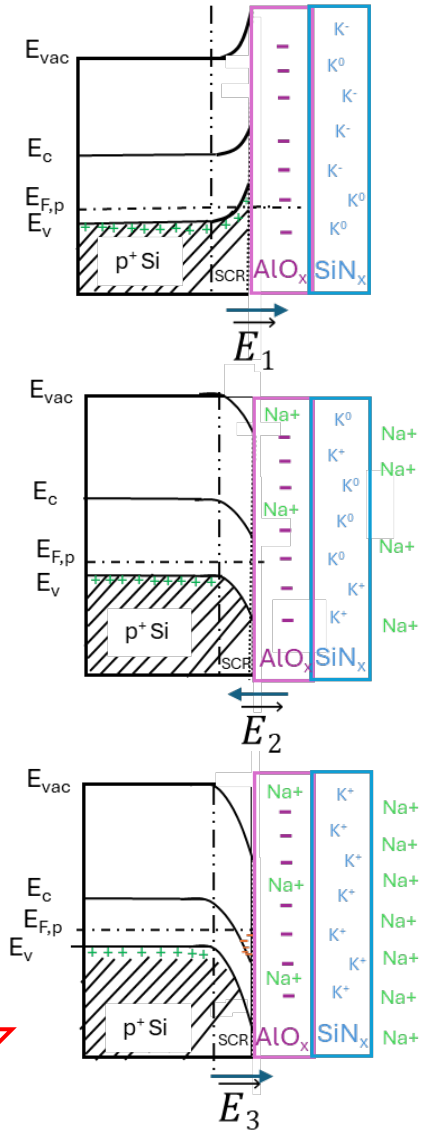
⬇

↓EL intensity, ↓ P_{max} (driven by I_{sc})

Negative bias impacts rear side
(accumulation of positive charges)



PID-p degradation (at negative bias)



State A : Accumulation (upward band bending)

Majority carriers (holes) accumulation in the SCR creates an Intrinsic electric field $\overrightarrow{E_1}$ repelling minority carriers (electrons) from the Si Surface. Fixed negative charges in the AlO_x also repel electrons.

State B : Depletion (downward band bending)

Depletion of majority carriers (holes) in the SCR. Electric field $\overrightarrow{E_2}$ attracts the minority carriers (electrons) to the Si Surface.
SRV increase

State C : Inversion (downward band bending with E_c crossing $E_{f,p}$)

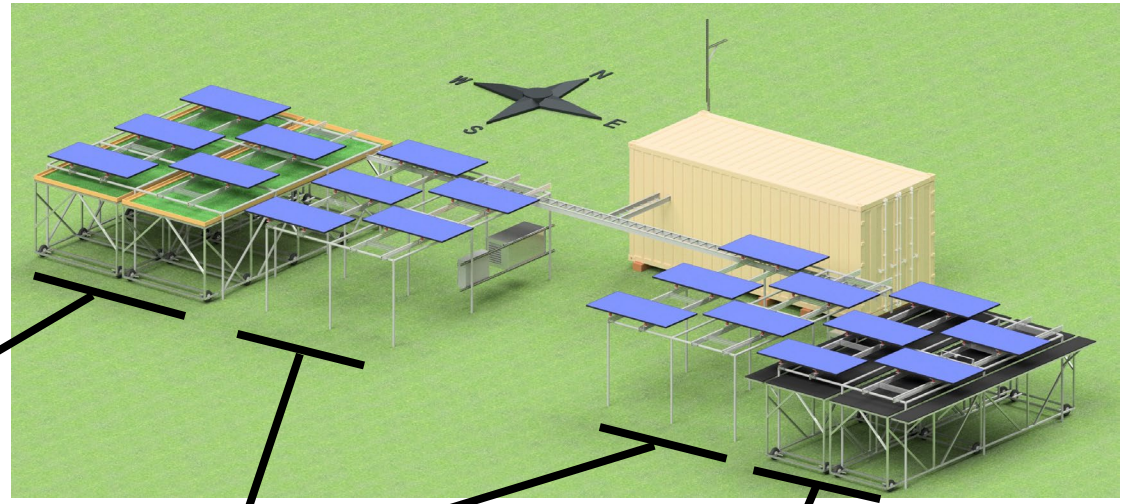
In the SCR, minority carrier electrons accumulate at the Si interface, restauring an Electric field $\overrightarrow{E_3}$ repelling the minority carriers (electrons) to the Si Surface.
SRV decrease

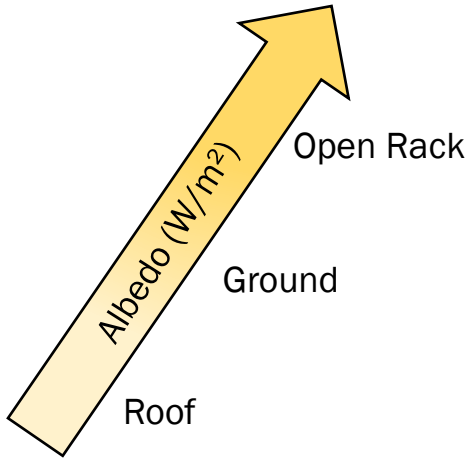
[1] Molto, C. et al : Review of potential-induced degradation in bifacial photovoltaic modules, Energy Technology, (2023) doi.org/10.1002/ente.202200943

4. PID-p in the field : Outdoor High-Voltage (HV) testbed

- Location : Cocoa (Florida)
- Voltage range : -3500 V to +1500 V
- Sensors : MET station, wetness, thermocouples, Irradiance (POA & albedo), UV (POA & albedo)
- Modules IV traced and LC monitored
- 3 mounting configurations :

Schematic representation of the HV testbed and pictures of the mounting racks





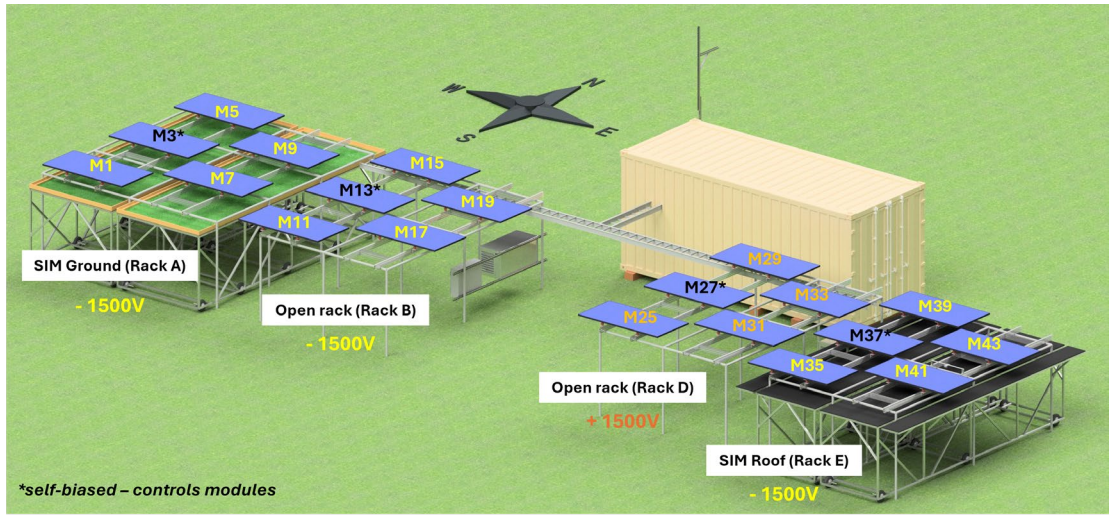
Ground (*1)
Modules 30cm above ground

Open Rack (*2)
Modules 2m above ground

Roof (*1)
Modules close to roofing membrane

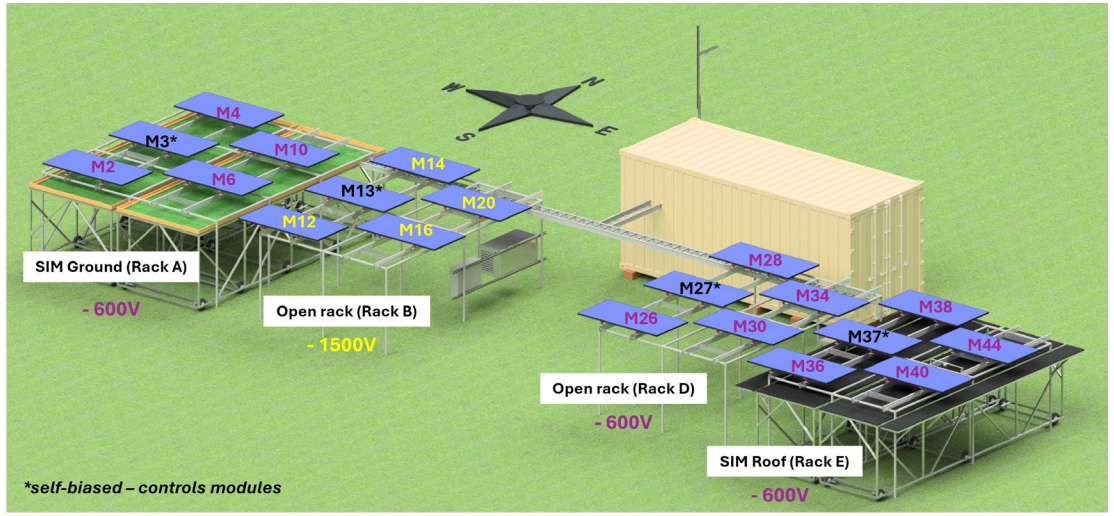
4. PID-p in the field : Experimental plan

ROUND 1 PID OUTDOOR TESTING
(1 year - 20 new modules)



- Assess impact mounting configuration (Rack A, B, E)
- Test PID-p susceptibility at positive bias (Rack D)

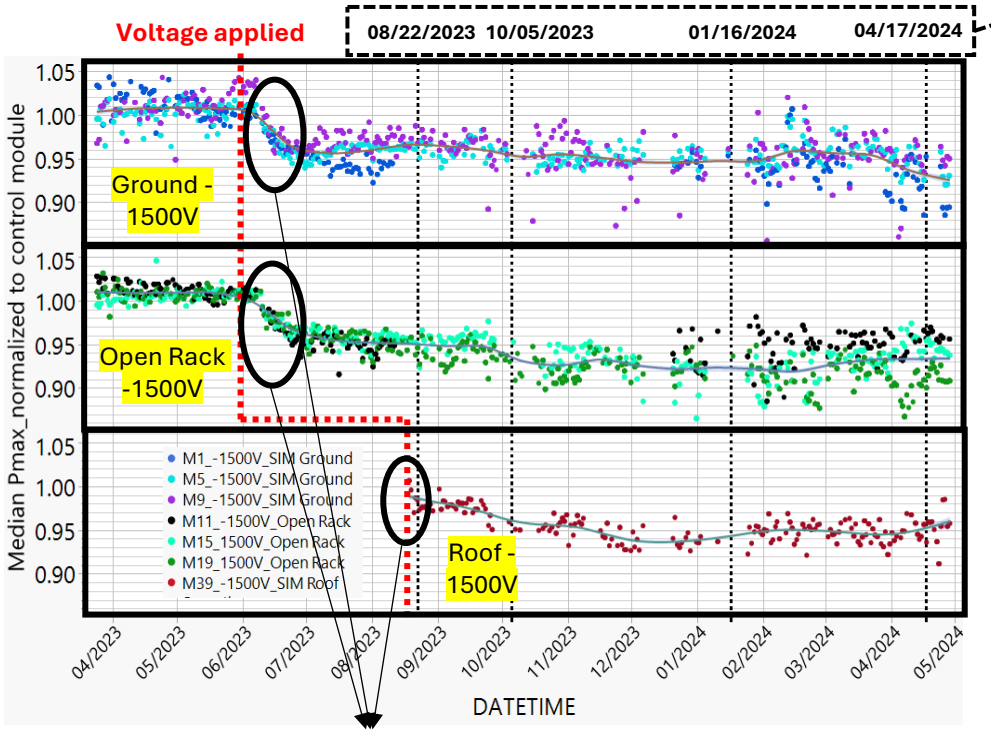
ROUND 2 PID OUTDOOR TESTING
(3 weeks- 20 new modules)



- Assess impact environmental conditions (Rack B (Open, -1500V) Round 1 vs Round 2)
- Assess impact of voltage magnitude (Rack B vs Rack D)
- Confirm impact of mounting configuration (Rack A, D and E)

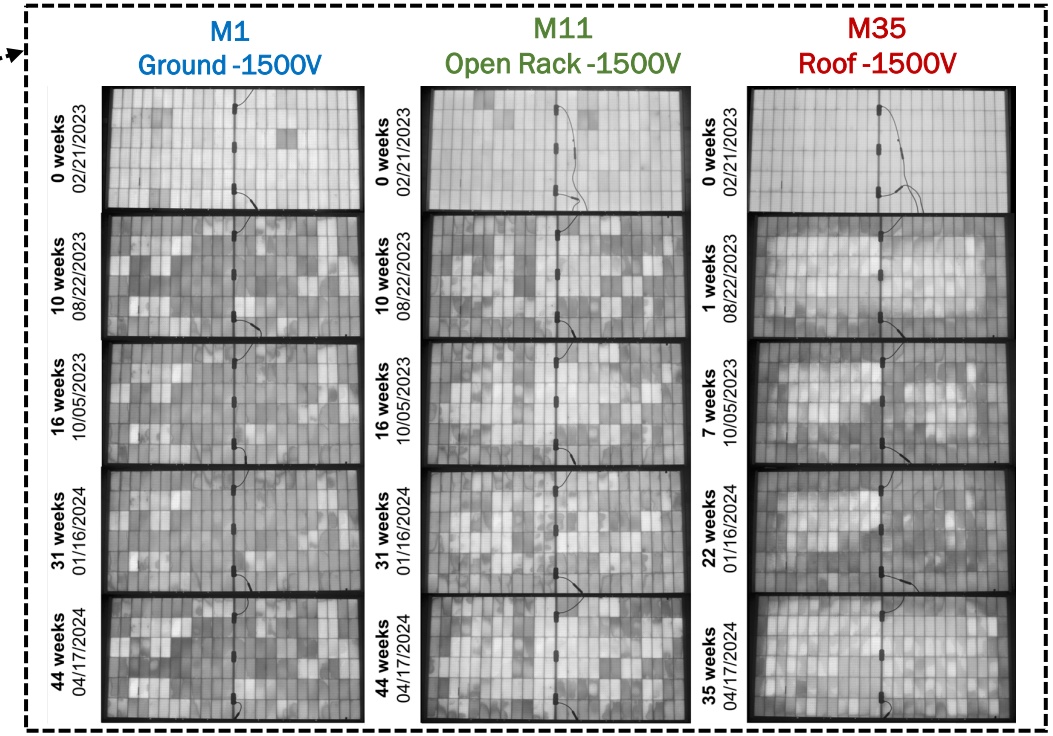
4. PID-p in the field : Results Round 1

P_{max} outdoor data (normalized to control)



	Degradation rate (%Pmax loss/day)	Licor Albedo dose (W/m²/day)
ROOF	-7.612×10^{-1}	26.5
GROUND	-3.252×10^{-1}	359.1
OPEN RACK	-2.497×10^{-1}	710.6

Indoor EL data (rear side at I_{sc})

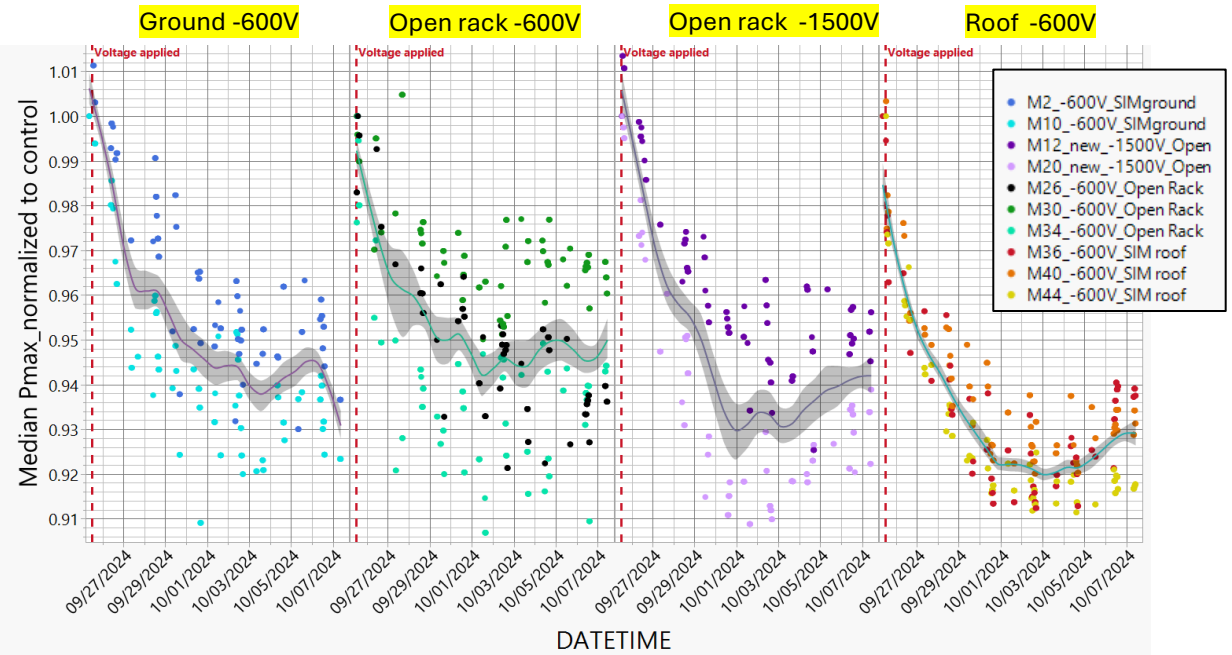


- PID-p evidenced at -1500V, no degradation at +1500V
- Fast P_{max} drop (1-2 weeks) up to 5-6% and stabilization
- EL checkerboard pattern : different cells PID-p susceptibility
- Albedo light slower the degradation [3]

[3] Hacke et al.: Polarization-type potential-induced degradation in bifacial PERC modules in the field. EPJ Photovoltaics (2025) doi.org/10.1051/epjpv/2025004

4. PID-p in the field : Results Round 2

P_{max} outdoor data (normalized to control)



ROUND 2	Degradation rate (%Pmax loss/day)	Licor Albedo dose (W/m²/day)	UV Albedo dose (W/m²/day)
ROOF -600V	-1.296	10.69	0.044
GROUND -600V	-1.270	158.17	0.046
OPEN RACK -600V	-1.019	307.92	0.407
OPEN RACK -1500V	-1.486	307.92	0.407

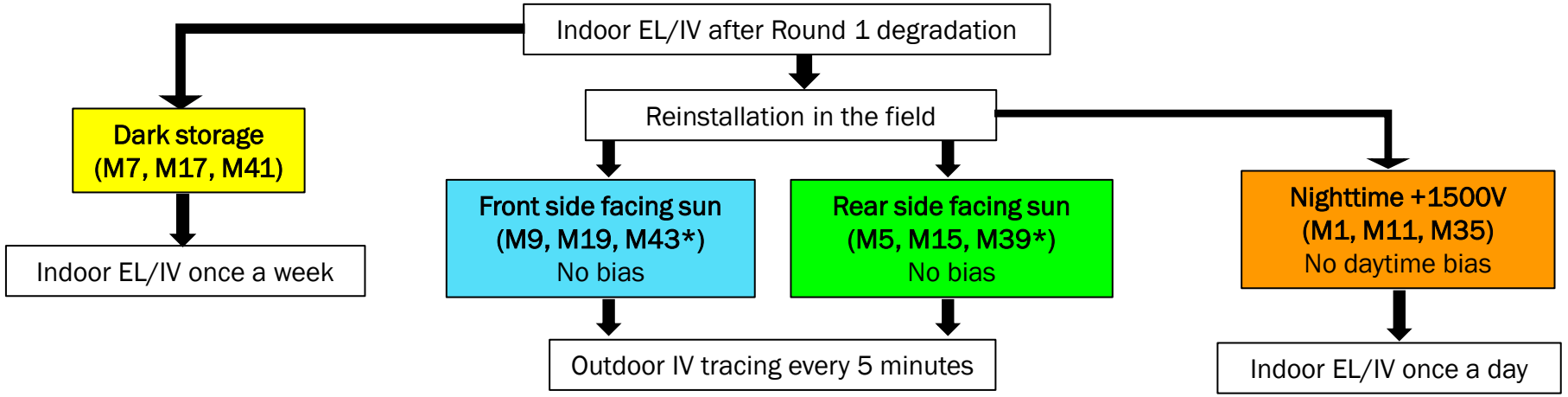
- PID-p evidenced at lower voltage (-600V)
- Light impact confirmed (++ UV component)
- 2.5 x Voltage → 1.45 x P_{max} degradation rate

Round 1 Vs Round 2

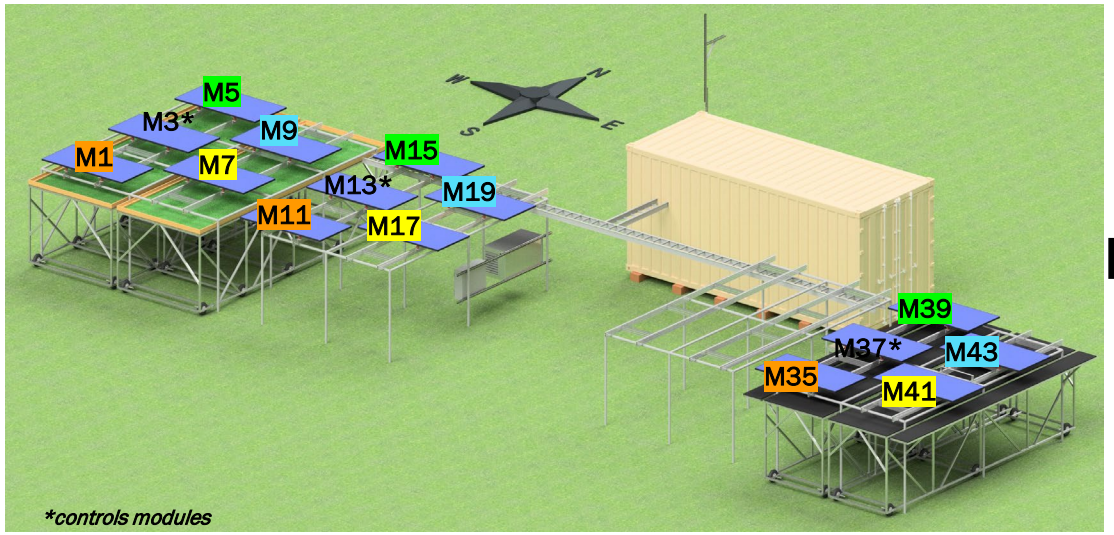
	Degradation rate (%Pmax loss/day)	Licor Albedo dose (W/m²/day)	UV Albedo dose (W/m²/day)	Mean ambient temp (°C)	Mean RH (%)	% "Wet" reading
OPEN RACK -1500V Round 1	-0,249	710.6	0.615	28.16	69.53	64
OPEN RACK -1500V Round 2	-1.486	307.92	0.407	28.89	77.95	84
Ratios	6	2.3	1.5	1	1.1	1.3

- P_{max} degradation 6 times faster in Round 2 : lower irradiance conditions AND more rainy days.

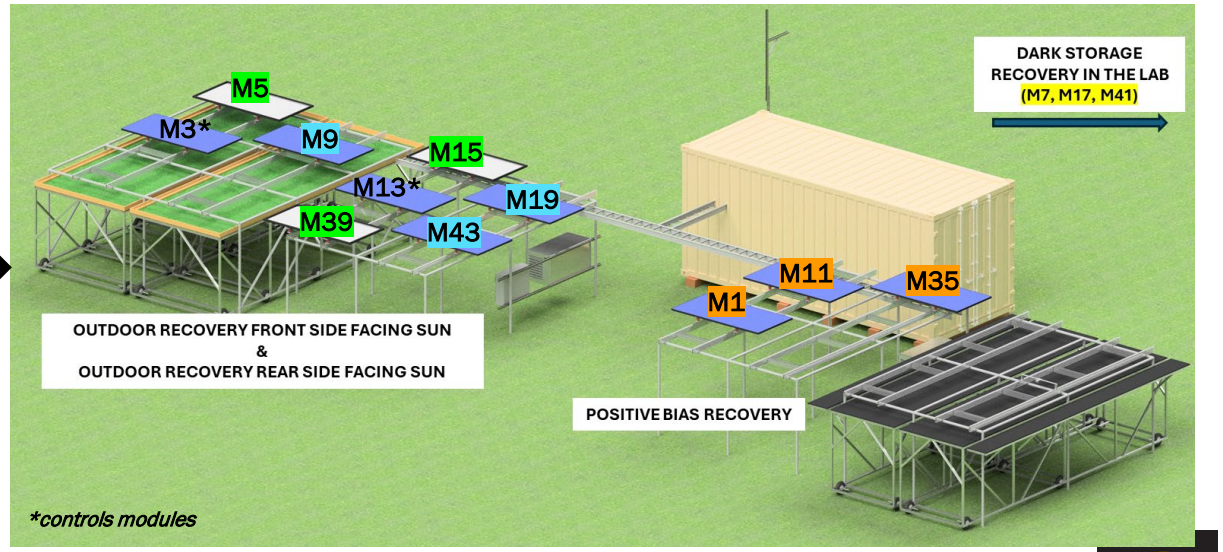
5. Recovery experiments : Experimental plan



**IV tracing not possible on SIM Roof → recovery done on Open rack*



Layout modules after Round 1 (-1500V degraded modules only)

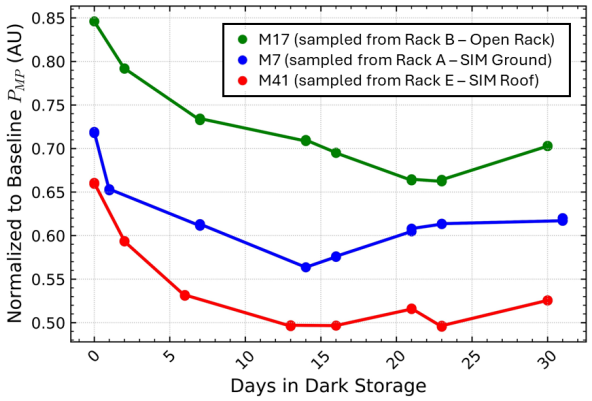


Layout modules for recovery experiments

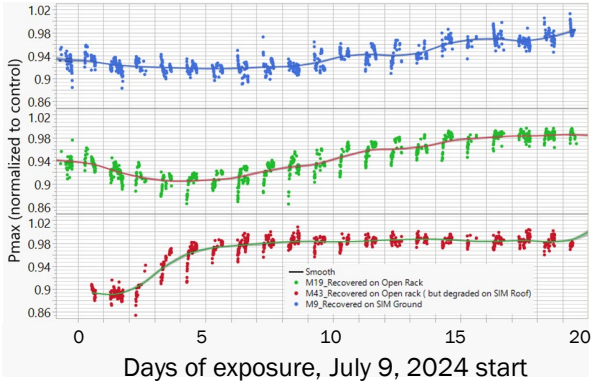
5. Recovery experiments : Results

Recovery rate

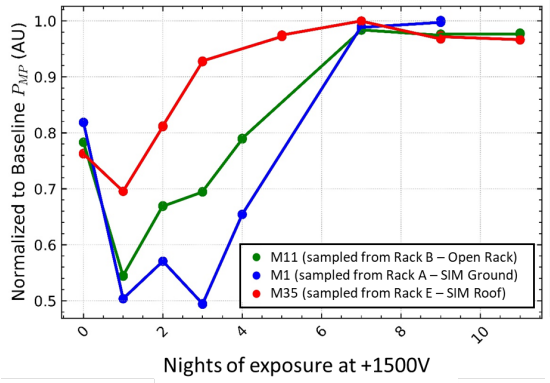
P_{max} indoor data
Dark storage, V = 0



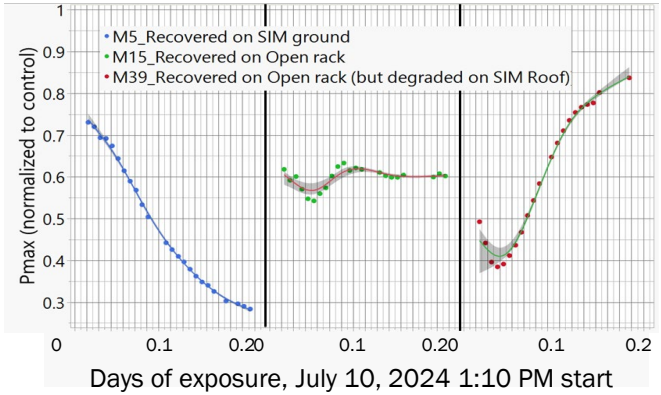
P_{max} outdoor data
Outdoor front side facing sun, V = 0

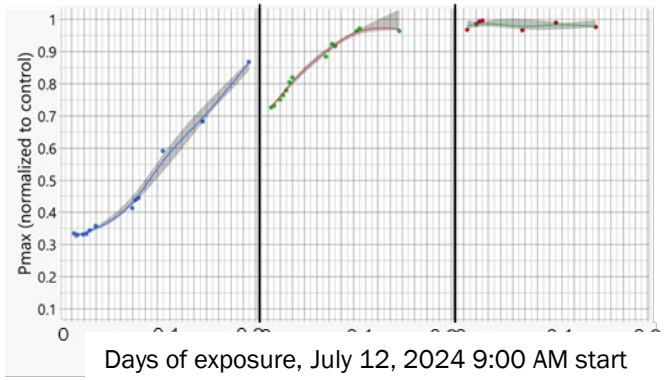


P_{max} indoor data
Positive bias, V = +1500V



P_{max} outdoor data
Outdoor rear side facing sun, V = 0





	Dark storage	Outdoor front side facing sun	Nighttime positive bias	Outdoor rear side facing sun
Time to full recovery	N/A	10 to 20 days	4 to 8 nights	2 to 7 hours

Common recovery pattern

P_{max} drop → Local minimum → P_{max} increases until full recovery (except for dark storage)

Recovery rate depends on the method used

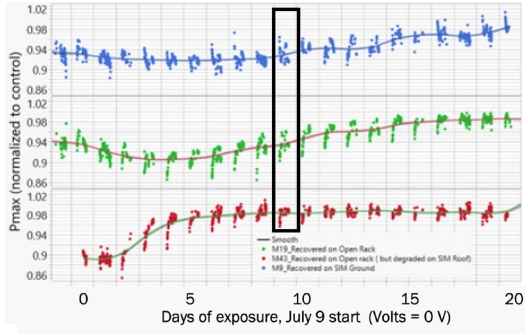
Outdoor rear side facing sun > Positive bias > Outdoor front side facing sun > Dark storage

Recovery rate depends on the degradation history

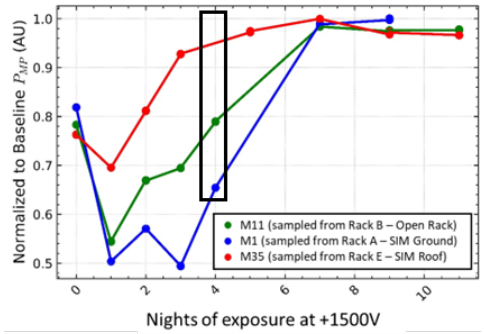
Module degraded on SIM roof > Module degraded on Open rack > Module degraded on SIM Ground

5. Recovery experiments : Results

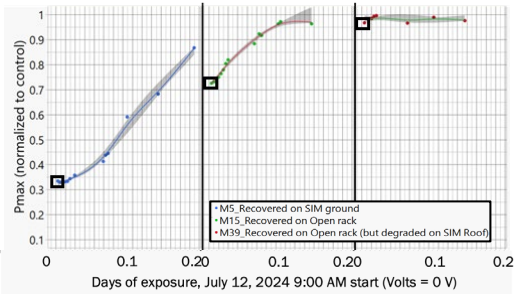
Outdoor recovery front side facing sun



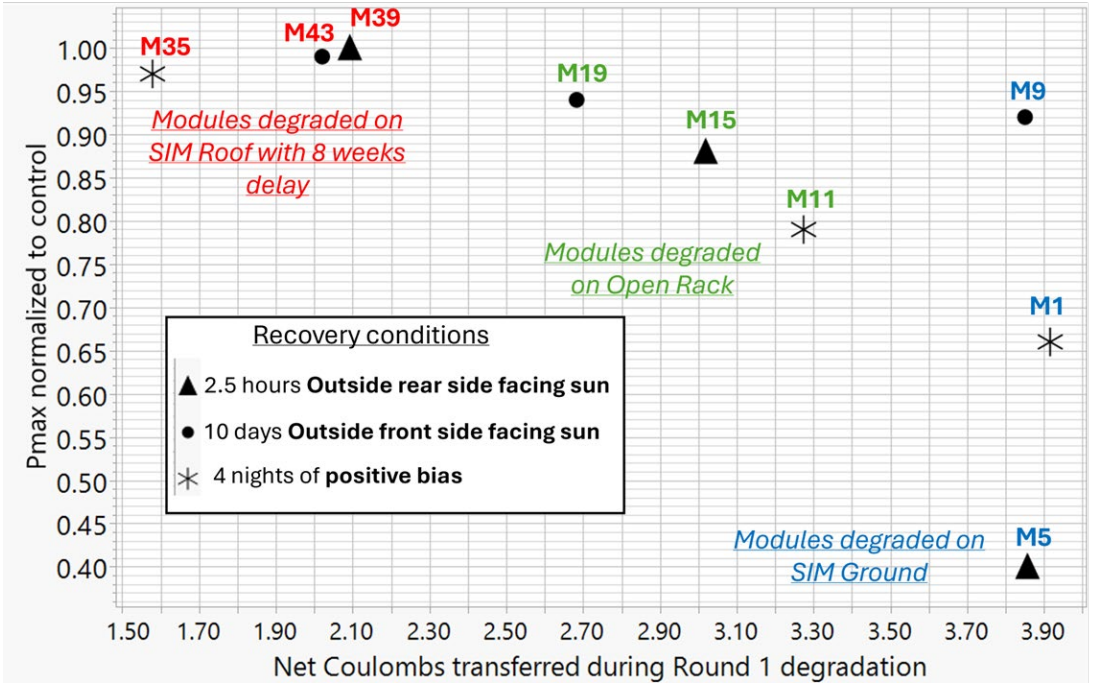
Positive bias recovery



Outdoor recovery rear side facing sun



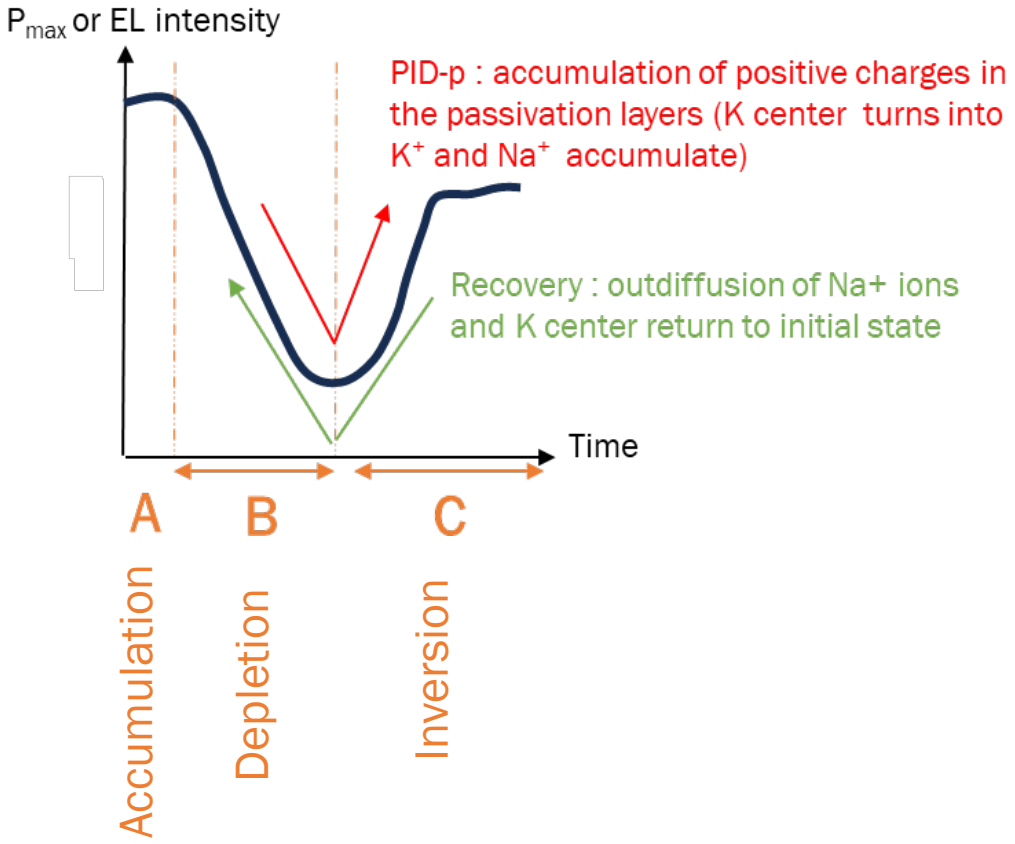
P_{max} after chosen recovery time (such as P_{max} in the increasing phase) plot as a function of Net coulombs transferred during degradation



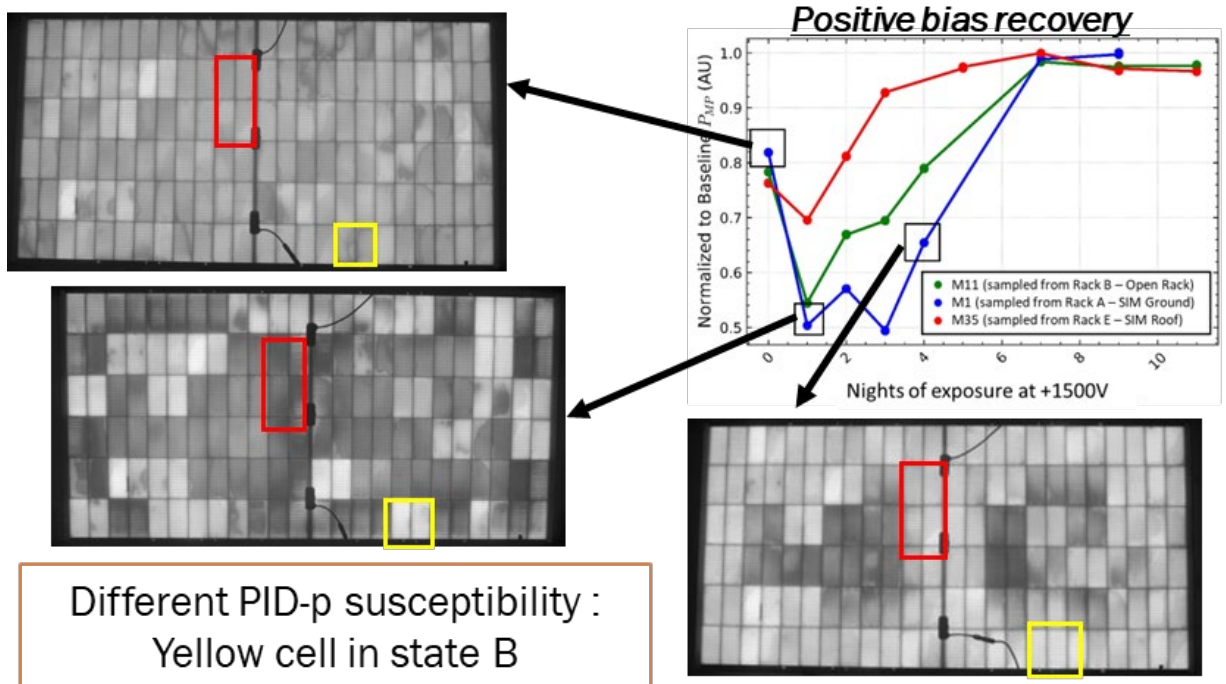
More coulombs transferred during degradation → greater extend of PID-p → more time needed for full recovery

5. Recovery experiments : Results

Correlation recovery pattern and Si/passivation layers interface states



Identification of A/B/C states on EL images



Different PID-p susceptibility :
Yellow cell in state B
Red cells in state C

6. Conclusions

PID-p degradation :

- PID-p is occuring in the field in bifacial PERC modules for voltages as low as -600V
- Higher degradation rate for :
  - Higher voltages
  - When modules are wet
  - Mounting configuration providing less albedo light
- Different PID-p susceptibility of the cells within a module

PID-p recovery :

- More coulombs transfered during degradation → more time needed for full recovery.
- Full recovery under positive bias or illumination
- PID-p recovery pattern → PID-p signature

Thank you for your attention