Perovskite characterisation

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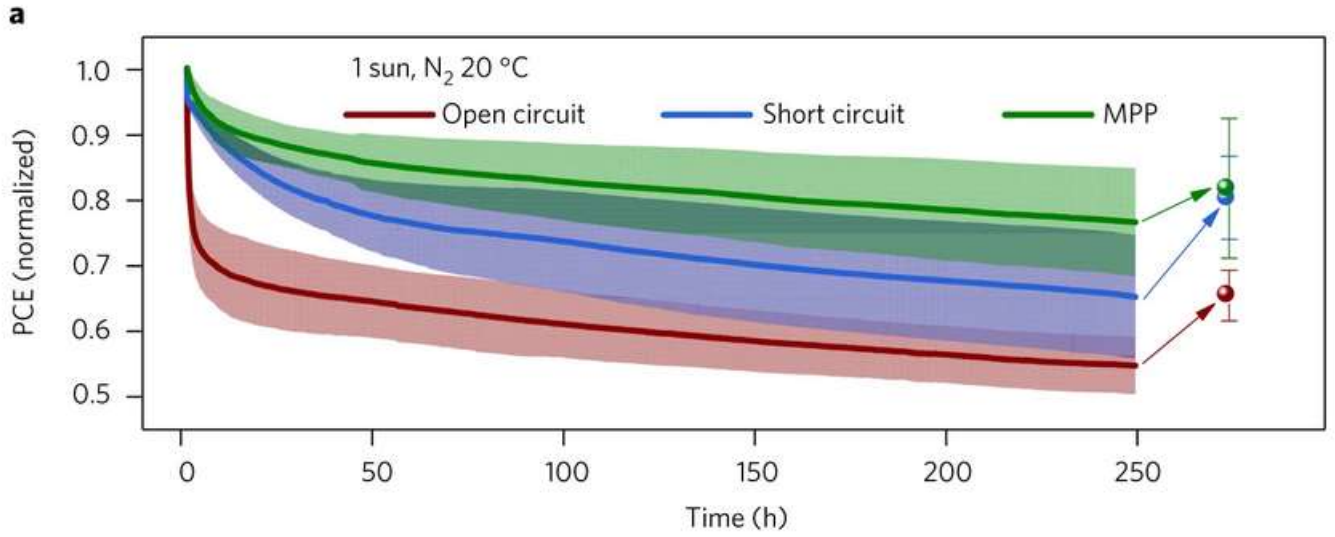
Previously on …

- Measurement challenges of PSK devices and their mitigation
  - Degradation
  - Hysteresis
  - Slower meta-stabilities

Perovskite cell degradation

- Intrinsic and/or extrinsic degradation on short timescales for research scale devices.
- The degradation rate under STC can be a function of the voltage bias conditions.

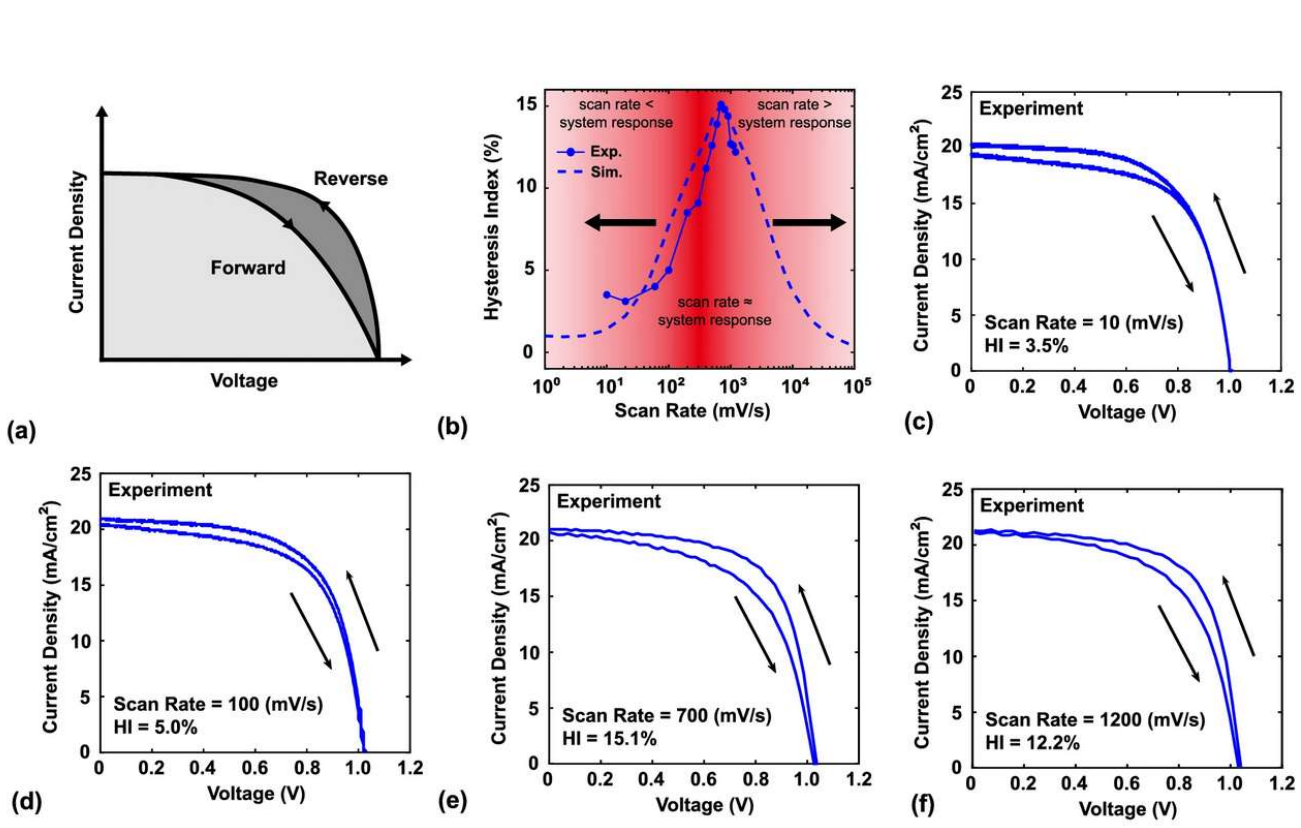


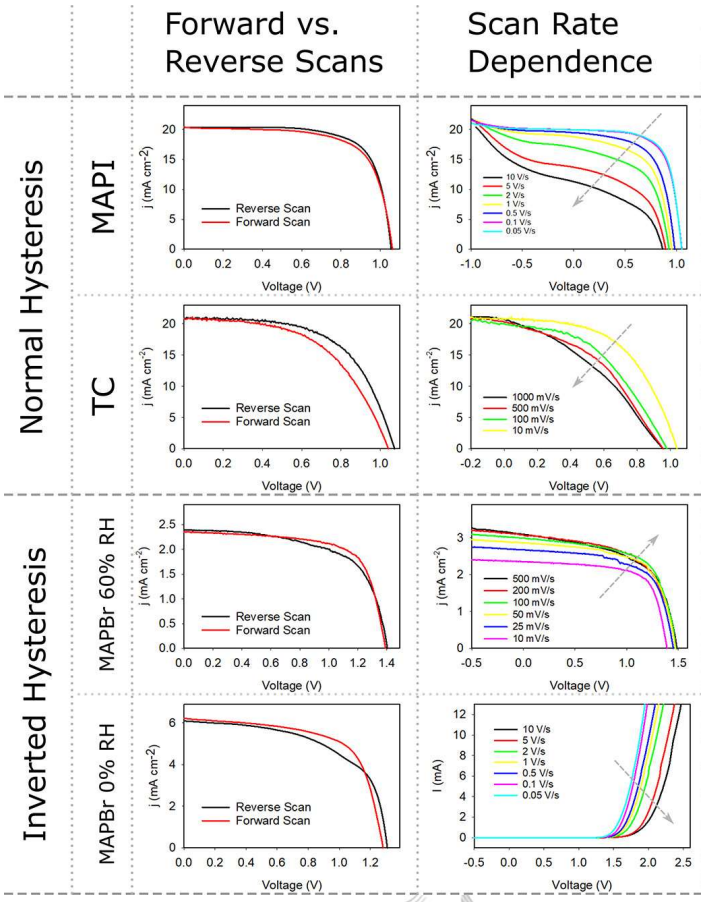
Domanski, K. et al. 'Systematic investigation of the impact of operation conditions on the degradation behaviour of perovskite solar cells.' Nat Energy 3, 61–67 (2018). https://doi.org/10.1038/s41560-017-0060-5

Our experience

- Device stability has improved significantly. We still observe strong meta-stability.
- Do we receive only ‘good’ devices due to our prolonged measurement protocol?
- Degradation currently not a major problem for a single calibration measurement.
    - Manufactured, screened, characterised, shipped, verified at ESTI.
- On some devices repeat measurements are consistent.
- For inter-comparisons between multiple laboratories degradation is still a problem.

Perovskite cell hysteresis vs sweep rate





DOI:10.1038/s41598-022-11899-x

DOI: 10.1021/acsphyschemau.1c00009

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‘Solving’ hysteresis

Hysteresis can be ‘solved’ with (quasi) steady-state/settled measurements:

Single point measurements (1-15 min):

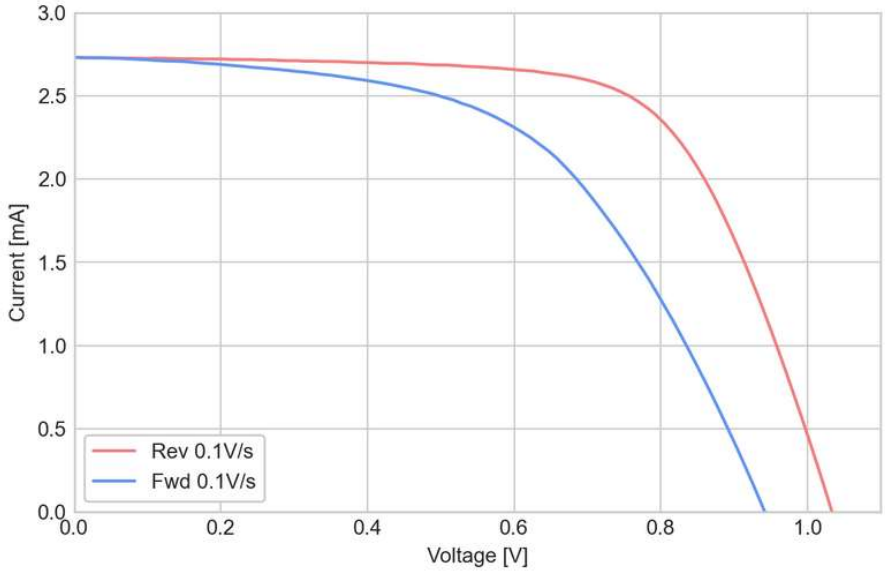
- SPO/SCFV (may not be at Vmpp)
- MPPT (the algorithm my affect the end result)

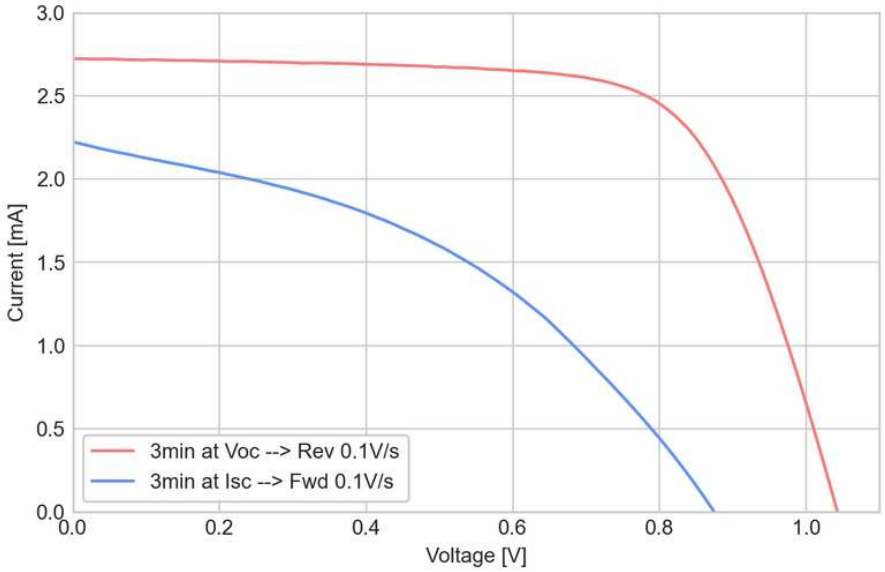
Partial or full I-Vs (based on some settling and time criteria):

- Dynamic I-V
- Asymptotic I-V
- Time-resolved I-V
- Real-Time One Sweep
- Manual I-V (ESTI)

All practically ‘remove’ hysteresis for some devices.

Perovskite cell hysteresis and voltage bias





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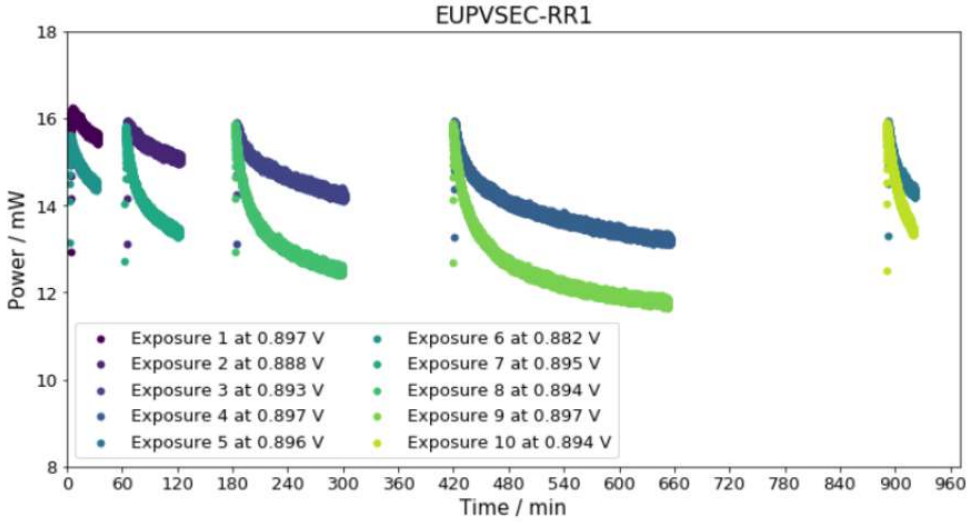
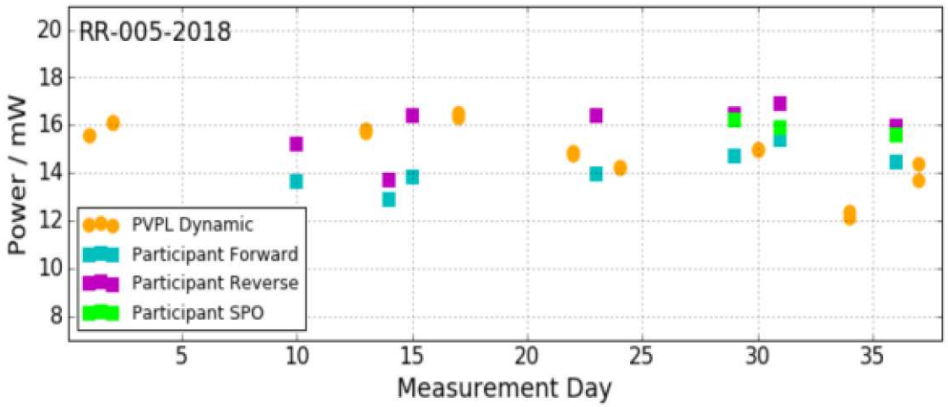
Meta-stability coupling

- There is a coupling of meta-stabilities (reversible change in performance) on different timescales:
  - Fast (seconds to minutes) Responsible for Hysteresis (attributed to halide migration)
  - Medium to Slow (10 min to hours) Affects Reproducibility. (attributed to cation migration)

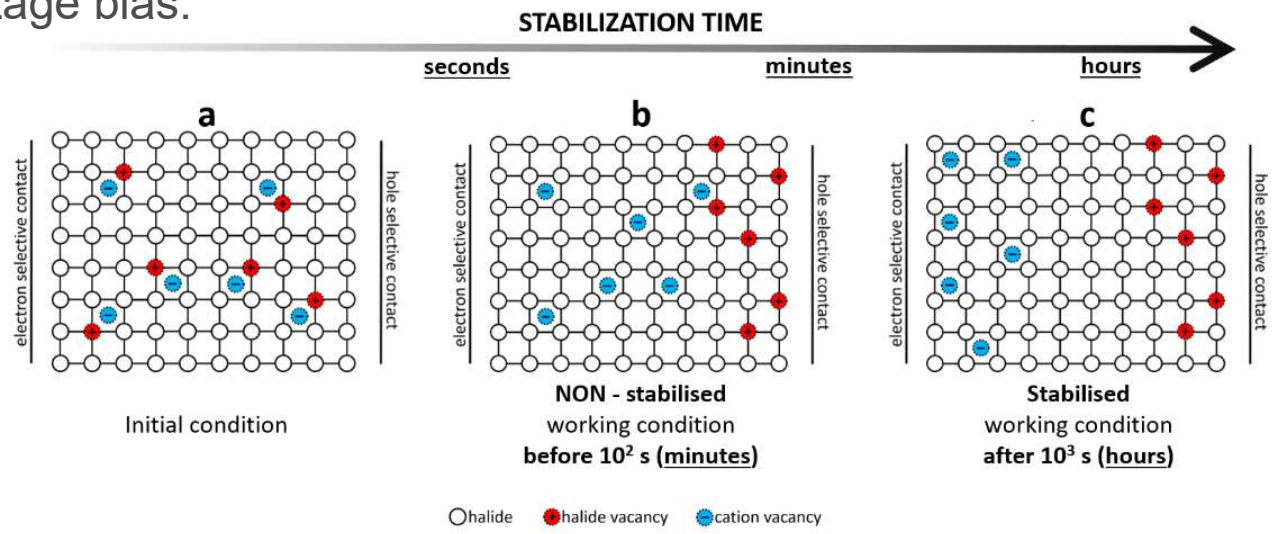




B.Mihaylov et al 'Perovskite Meta-Stability Effects in Hysteresis-Free Measurements ', EUPVSEC 2019 3CO.6.1

Useful mental model – ionic motion

- There is a broad consensus that the motion of ionic species is responsible for meta-stabilities.
- Pmax depends on the distribution of ionic species within the bulk and accumulated at the interfaces.
- A (quasi) steady-state is when this distribution has reached (near) equilibrium conditions at a given external voltage bias.



Domanski, K et al. 'Migration of cations induces reversible performance losses over day/night cycling in perovskite solar cells'.Energy & Environmental Science 2017, 10, 604–613

Solving slow meta-stability (Reproducibility)

Problem:

Settled state is a function of the device history (voltage bias and light exposure).

Solution:

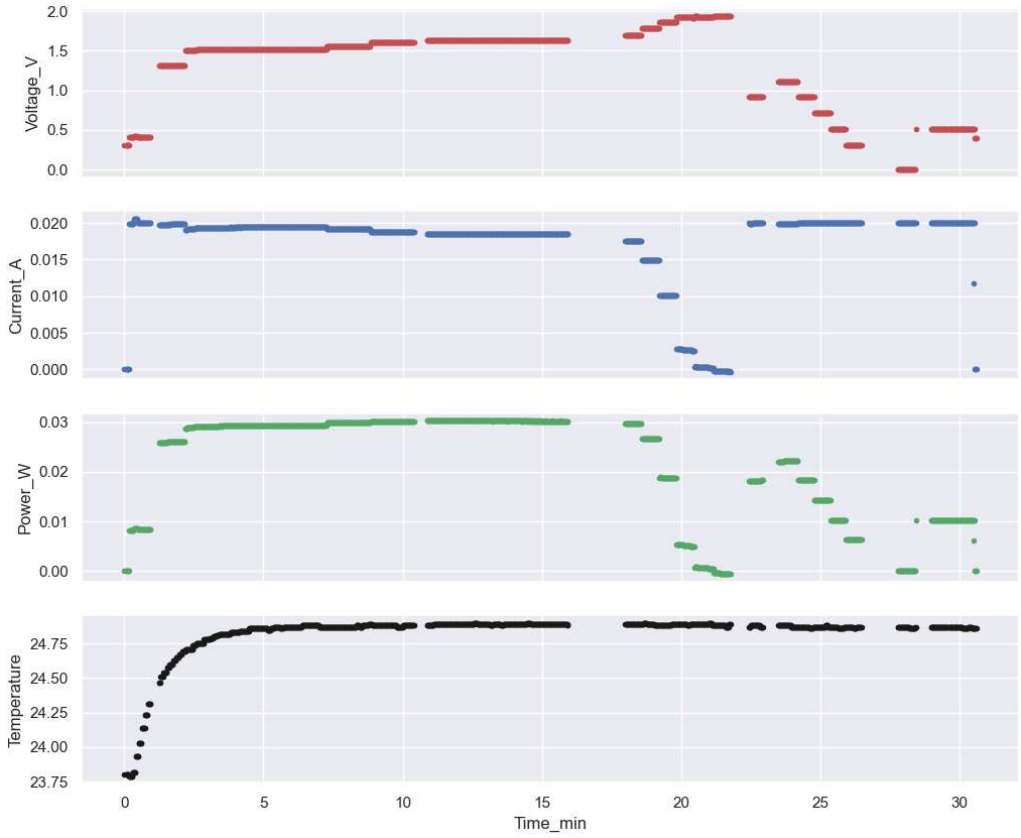
Define the measurand better, i.e. define the pre-conditioning so that the same state is measured.

But:

- How do you ‘reset’ the device state ?
- The function that maps performance to history is unknown a priori.
- Practical limitations of comprehensively investigating this on a case-by-case basis.
- Limitation on maximum measurement times.

Manual I-V at ESTI

- Measure, control and record everything.
- Manually control the voltage set points
- Pre-condition the device at (near) Vmpp under light (minimum of 5 minutes, maximum of 60 minutes).
- Allows for:
  - Temperature stabilisation
  - Validation of settling criteria (e.g. 0.04% relative std. over 90 seconds)



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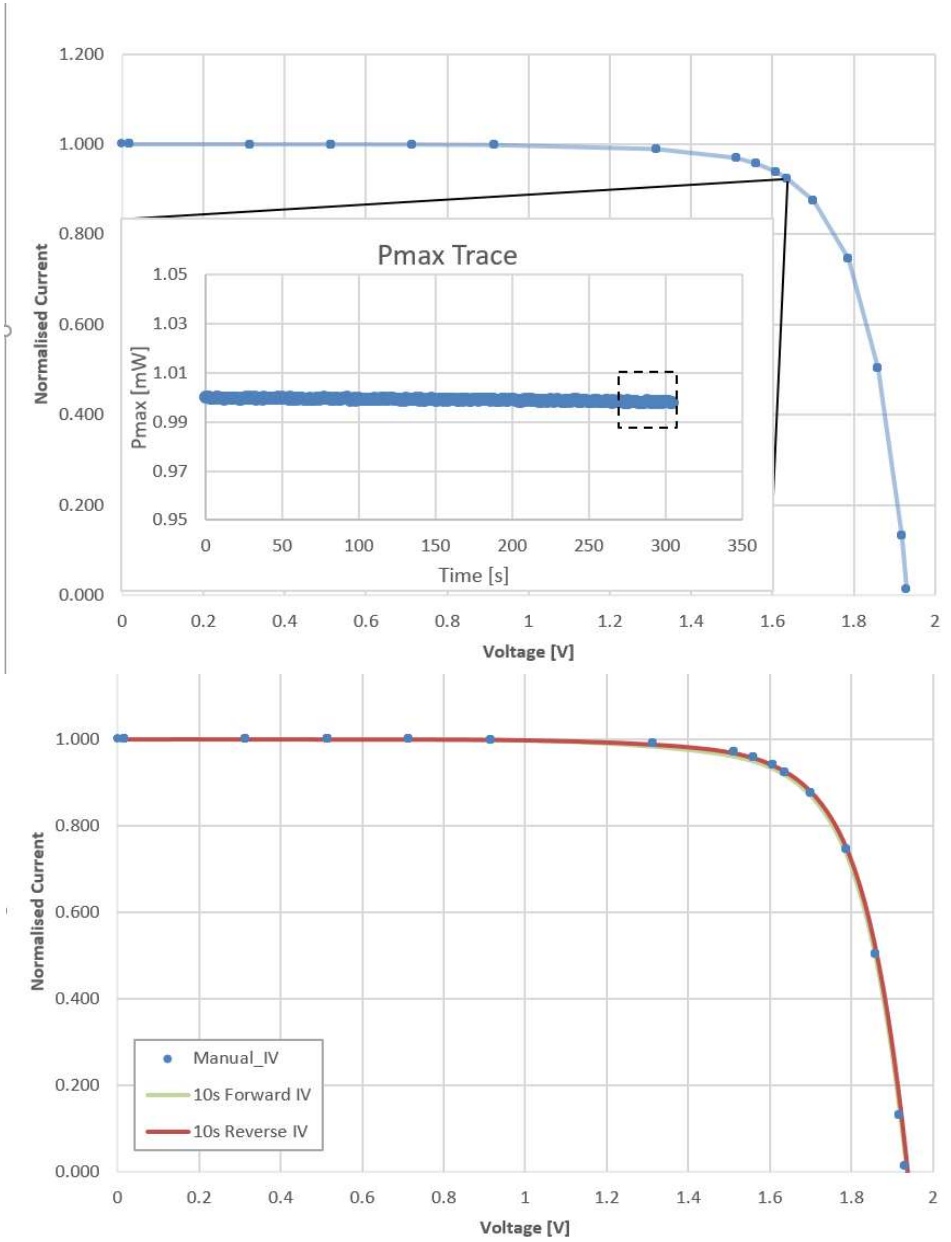
Manual I-V at ESTI

- Find Vmpp and trace for at least 5 minutes.
- Do ‘fast’ I-V sweeps immediately after Vmpp trace. Device is held at Vmpp in between.
- Measure settled Voc and Isc
- Optionally do ‘fast I-V’ curves at each state
- Check Pmax in between

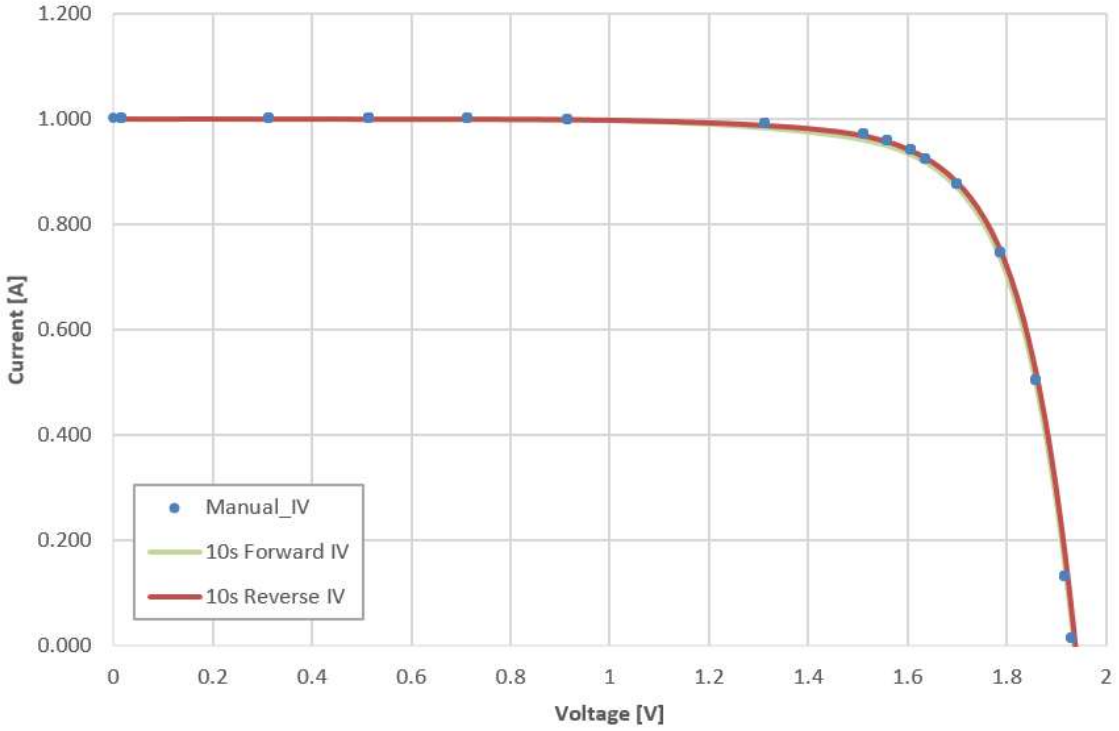


Optimum settled efficiency

- Which efficiency do we certify? →The highest measured settled efficiency
- All are conservative and ‘real’ measurements:
  - Tracked for more than 5 minutes
  - No unrealistic pre-conditioning (voltage or light bias)
- The highest is a local maximum.
- If it is a global maximum it can be ‘found’/reproduced by other methods in other laboratories.
- Reproducible → Representative

How useful are fast I-Vs?

- Validate a sweep rate after pre-conditioning and Pmax tracking to save measurement time.



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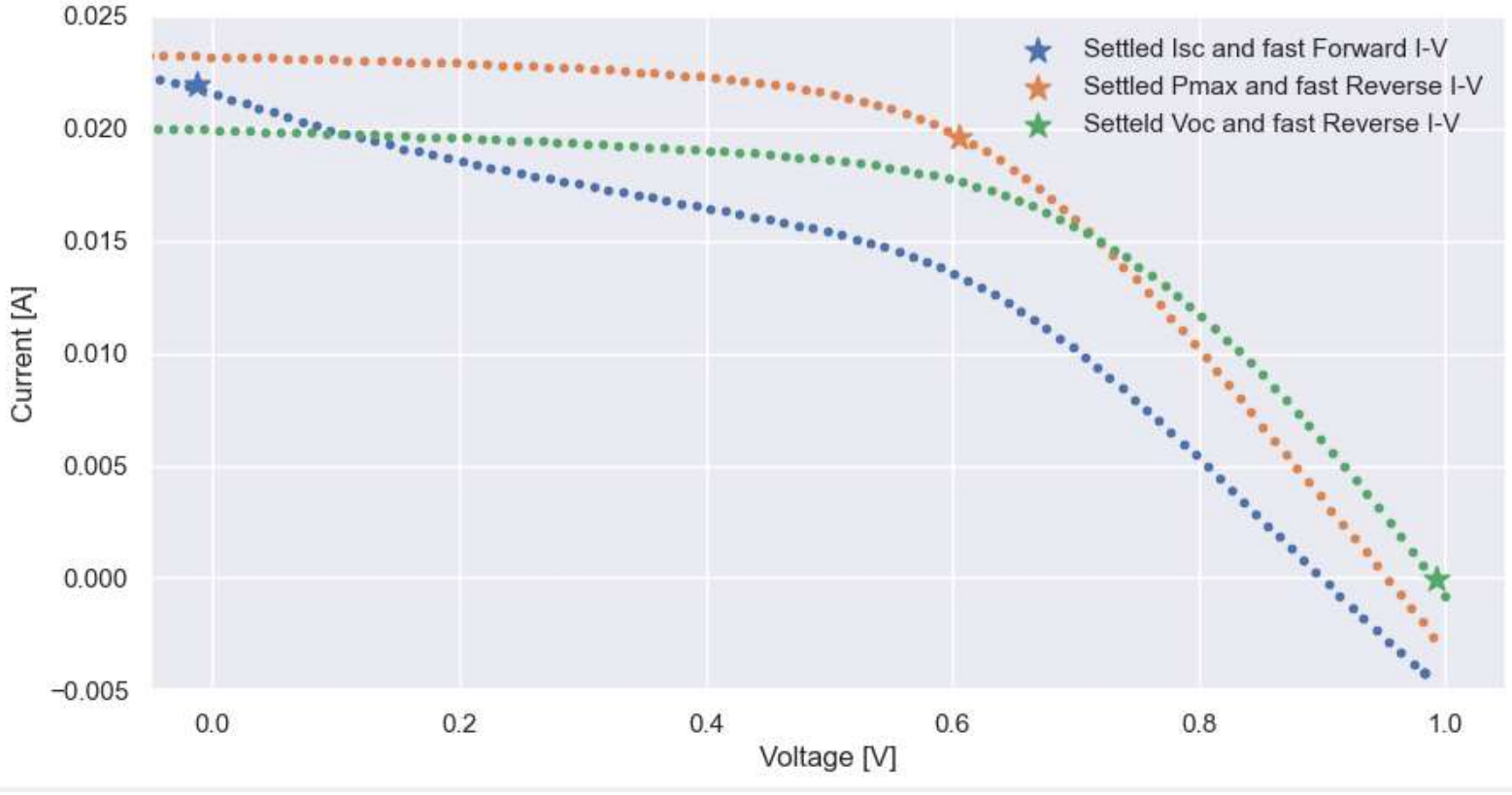
How useful are fast I-Vs?

- Measure 3 states (Vmpp, Voc and 0V) and their associated I-Vs



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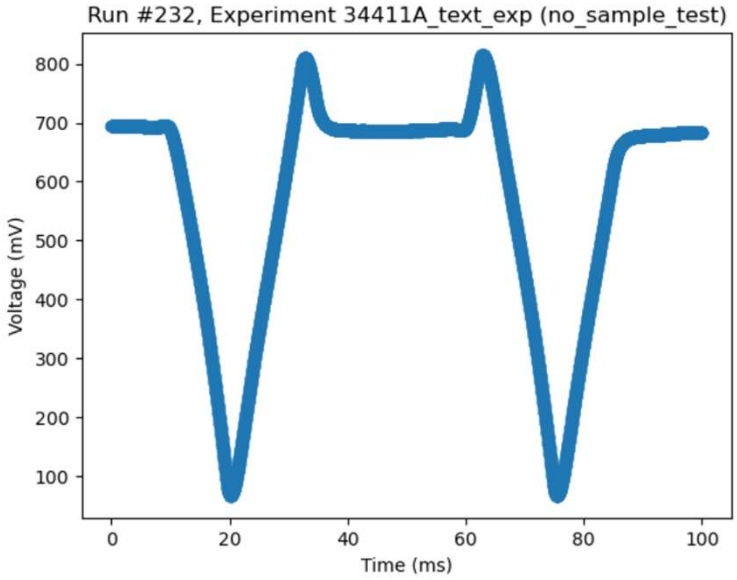
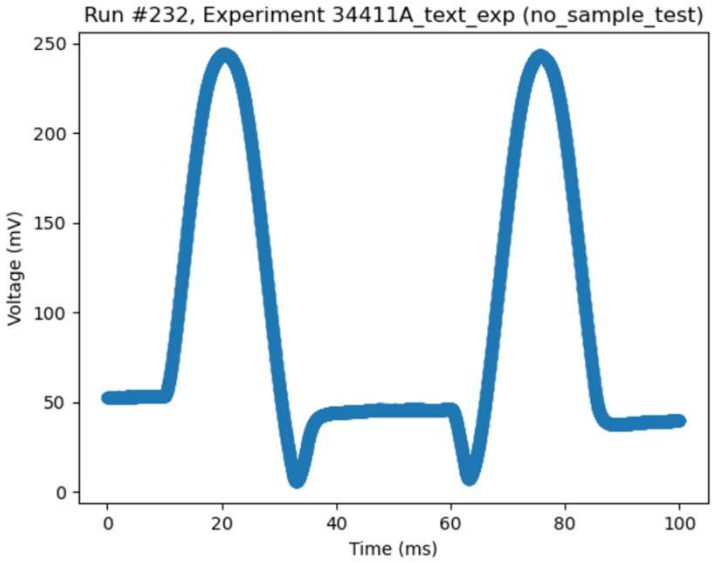
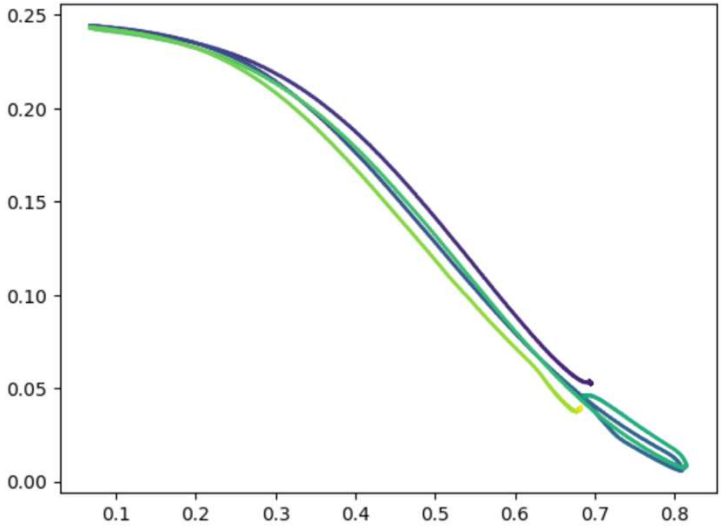
Possibilities for the future

- ‘Batman’ curve
- Function generator plus amplifier allows for many orders of magnitude of sweep rates for each settled point.







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Main points of today

- Different, equally valid device states exist.
- External voltage bias and light bias are the levers to control this.
- Vmpp is probably the state of most interest.
- V=0, Voc and could also be of interest
- Fast I-Vs can be useful, but require sweep rate investigation and voltage control in between.

Thank you

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What about reliability studies ?

- Performing the full protocol at ESTI takes 2-3h.
- In the context of days of aging it may be acceptable.
- It allows to compare all 3 settled Pmax measurements
- Helps to investigate the connection between meta-stability and degradation.
- Shortcut protocol could be validated against it.