Characterization of back contact solar cells and modules

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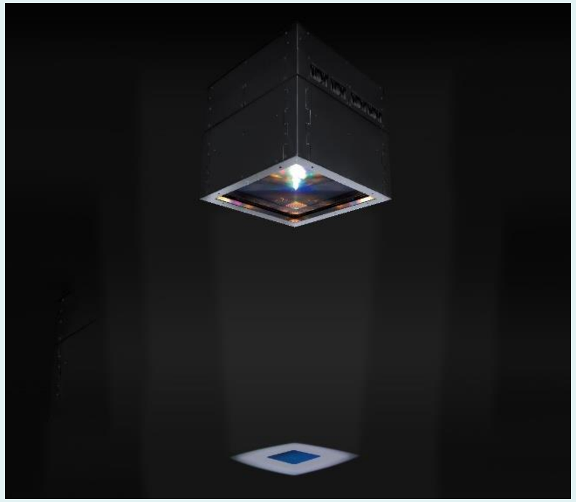
Content

- Characterization Equipment
- Steady-State *IV* measurements on highly capacitive cells and modules
- Module Temperature Analysis under partial shading conditions
- Beyond Si – *IV* measurements on Perovskite and Perovskite-Si Tandem cells

Characterization equipment

- Solar cell sun simulators with Xenon and LED light sources
  - Electroluminescence
  - Thermography
  - Numerous data evaluation options
  - Grid resistance
  - Temperature controlled dark chamber for lab-systems
  - 240 x 240 mm² homogeneously illuminated area



Characterization equipment

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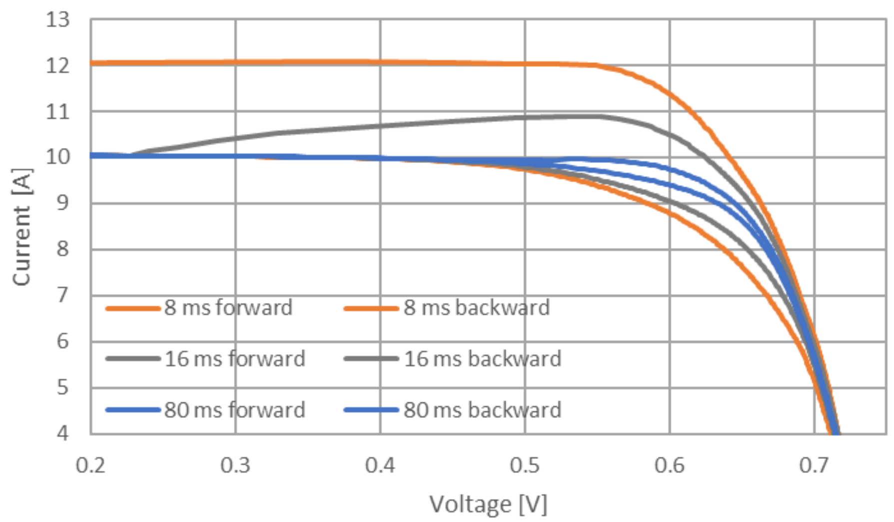
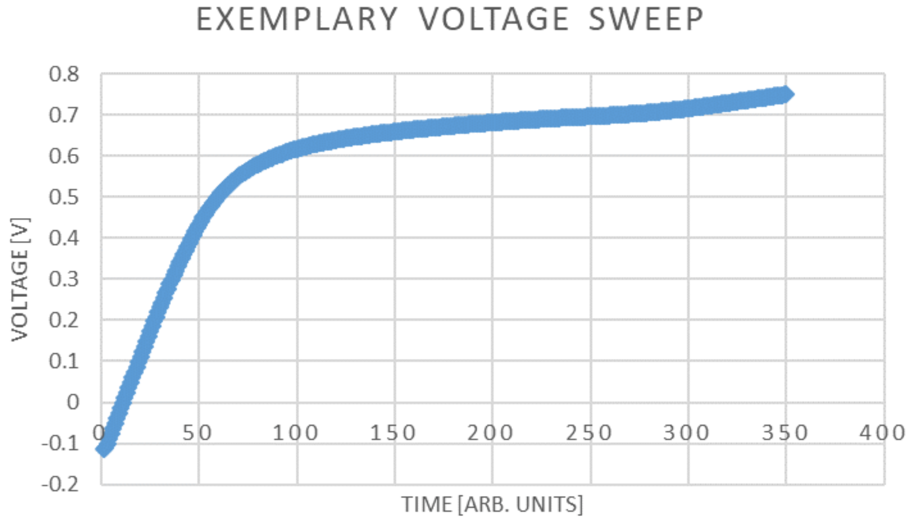
- Solar module sun simulators with Xenon and LED (coming soon) light sources
  - Up to 280 cm x 170 cm homogeneously illuminated area
  - Electroluminescence
  - UV Fluorescence
  - Numerous data evaluation options
  - Temperature controlled measurement chamber

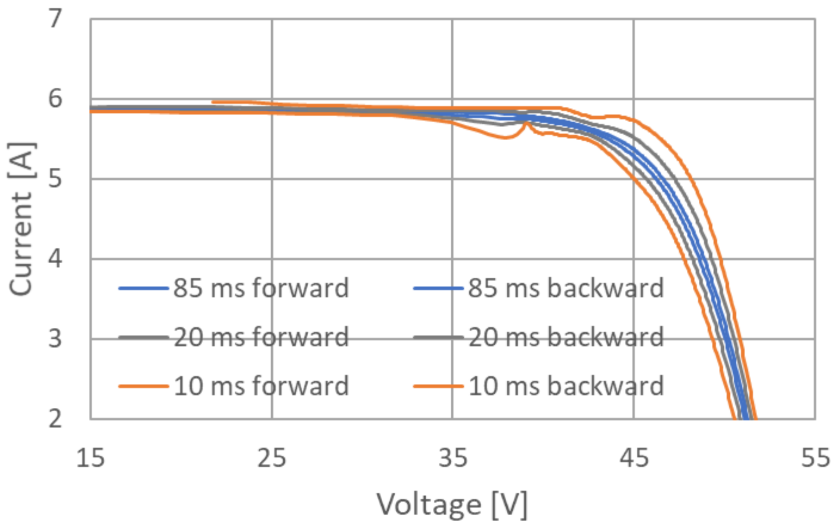
Transient effects in *IV* curves – cell and module

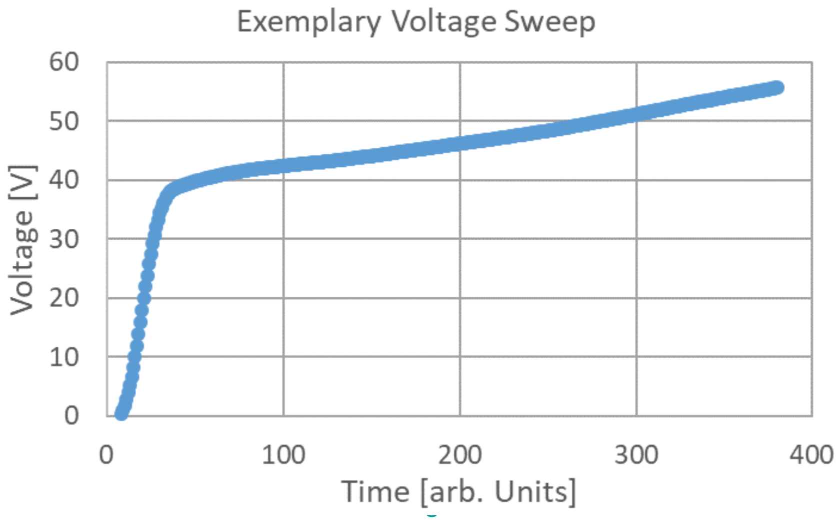




- *IV* curves of a Si-solar cell with 743 mV V_{OC} (upper) and voltage sweep form for this measurement (I_{SC} → V_{OC} sweep shown, lower)
- Strong splitting of forward and backward sweep for very short measurement times even reaching down to I_{SC}
- Even for 80 ms sweep time with optimized sweep form, 3.4% relative hysteresis in P_{MPP} is observed

Transient effects in *IV* curves – cell and module





- *IV* curves of HJT-Module - splitting of forward and backward sweep is much lower, but higher voltage splitting towards V_{OC}
- Sweep form was adjusted similar as for a single cell
- Some disturbances especially for low sweep time in the curves are caused by the reduction of sweep speed somewhat below 40 V
- Curve splitting at 85 ms sweep time is only 1.1 % or 2.65 W

Transient effects in *IV* curves – cell and module

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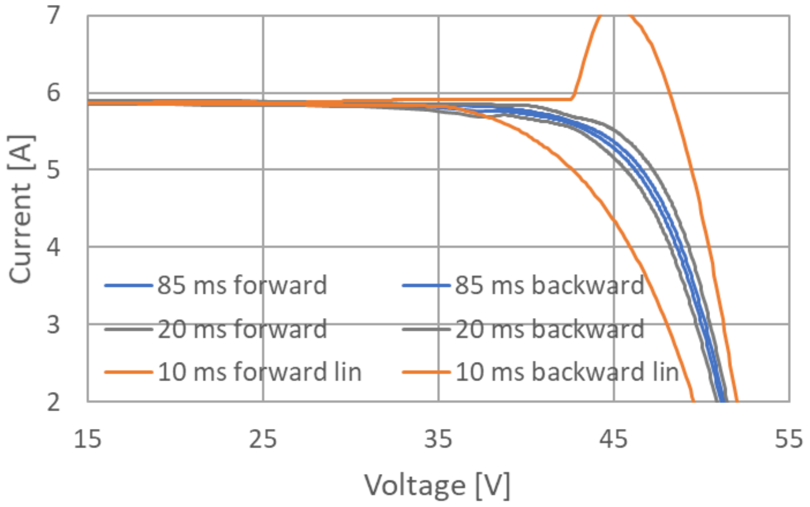
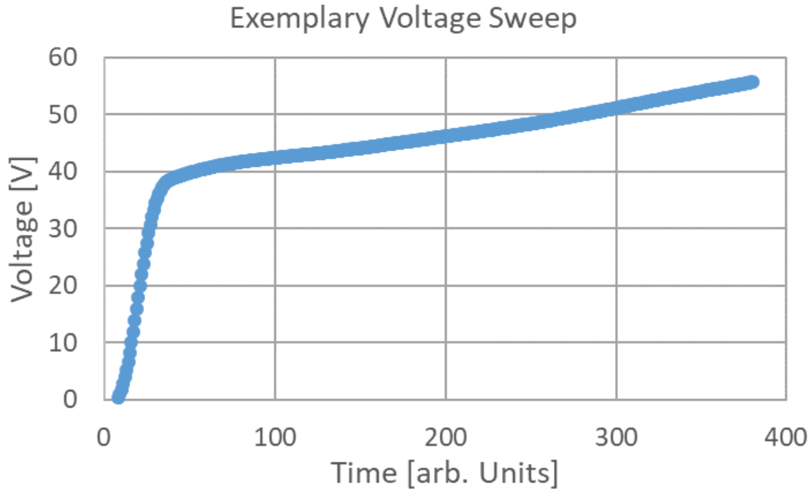
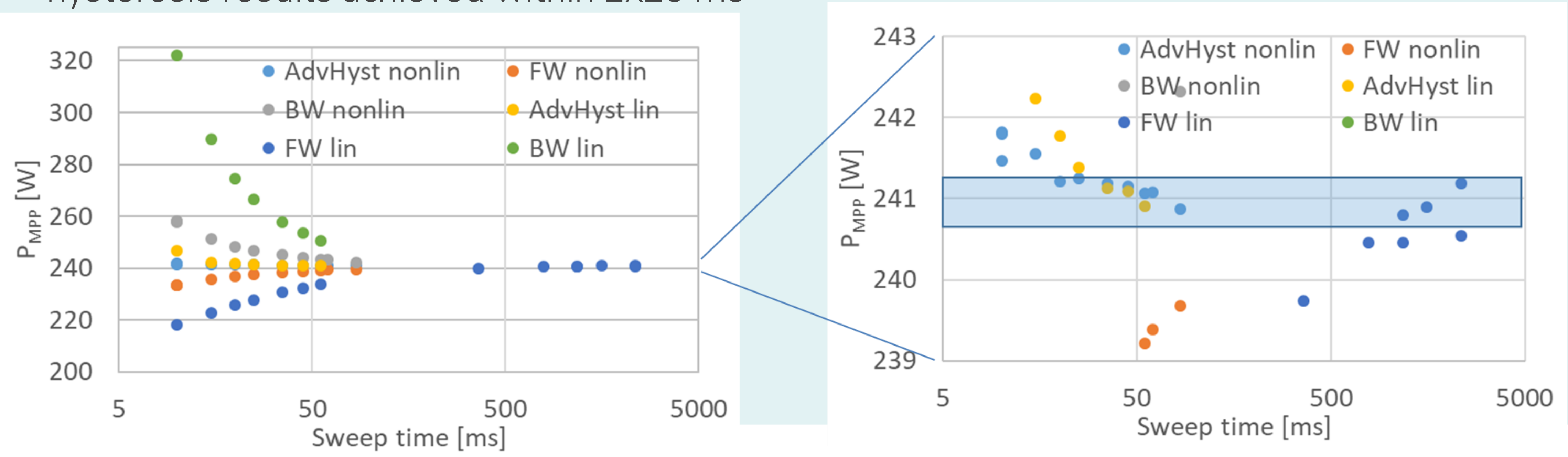




- Changing the 10 ms sweep to a linear voltage ramp leads to much higher curve splitting
- $P_{MPP\_fw} - P_{MPP\_bw}$ increases from 24.6 W to 103.7 W
- Optimization of sweep form is thus already a first effective measure to reduce hysteresis effects

Compensation of hysteresis

- Advanced Hysteresis exemplarily shown for a HJT solar module with appr. 241 W steady-state power output
- Single sweep measurements of several seconds required to meet the precision of advanced hysteresis results achieved within 2x25 ms



Partial shading conditions

- Reasons for shadows a numerous – birds are amongst the most arbitrary ones
- In lab measurements, shadows may be caused by module frames when measuring rear-side power output of bifacial modules

https://www.sv-photovoltaik-ws.de/anlagenfehler/

https://www.ibc-blog.de/wp-content/uploads/2011/09/Beispiele-Verschattung_300dpi.jpg

https://calvatis-bionik.com/leistungen/pv-reinigung-beschichtung/wie-funktioniert-biosol/

https://strahlkraft.org/verschattung-schmaelert-die-solarstromproduktion/

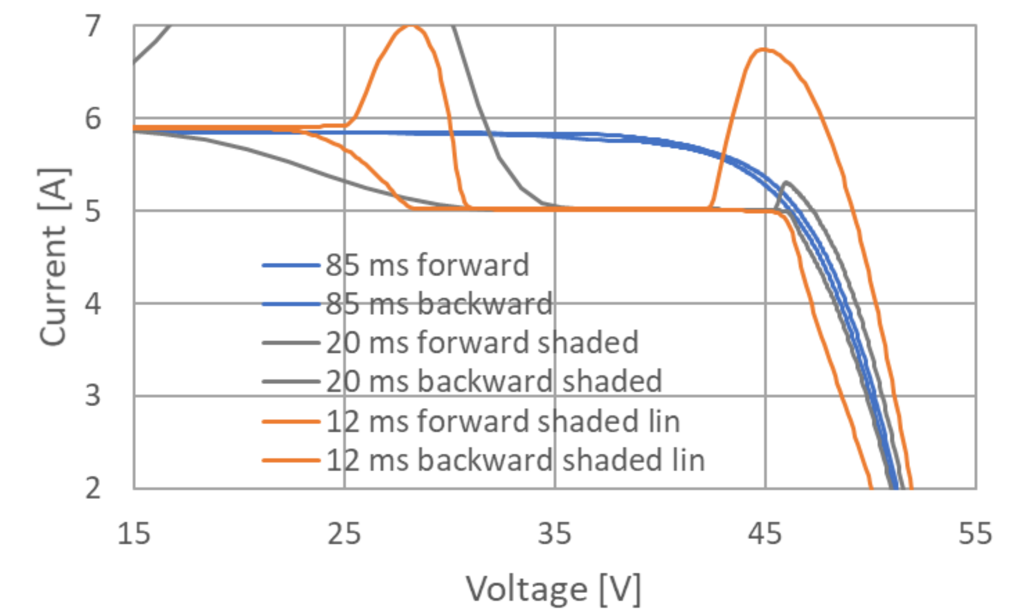
https://www.rechnerphotovoltaik.de/photovoltaik/voraussetzungen/verschattung

How does the *IV* curve look like if the module is partially shaded?

Cell voltages in a module are far from being all identical – current is identical for all cells

For partial shaded modules that means:

- Adapted voltage ramps might be unusable
- Inhomogeneous voltage distribution between cells may interfere with advanced hysteresis evaluation – longer measurement time required!



Partial shading – what happens besides interesting *IV* curve splitting?

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- Shaded cells can be reverse biased in module operation
- In such cases, high power is applied to unshaded parts of shaded cells
- Additional power may be dissipated locally in case of hot spots
- **IMPORTANT: *IV* curves under reverse bias can only be measured on cell level! However they act on module level only.**
  - What may happen in a module and what does that imply for module design?

Calculation of reverse voltages to be considered

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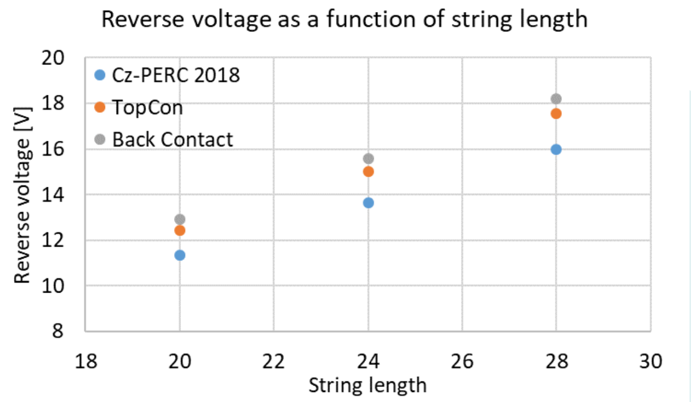
- Voltage:

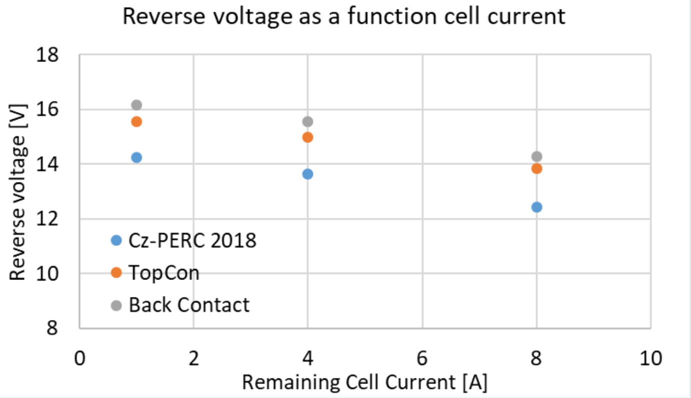
$$V_{rev} = (n-1) \cdot V(T, I, \Phi) + V_{diode}$$

  - With n, the number of cells in a string, $V(T,I,\Phi)$ the cell voltage at the cell temperature T, irradiance Φ and remaining cell current I and V_{diode} the forward voltage of the bypass diode at $I_{MPP} - I$.

- The resulting reverse voltage thus depends on:
  - cell quality and string length
  - temperature and irradiance
  - the remaining current
  - the forward voltage of the bypass diode used

- In unshaded parts of a reverse biased cell, the power density equals $P_{ill} = \Phi + V_{rev} * J_{SC}$





Parameters fixed:
T = 50 °C; I = 4 A
Φ = 1000 W/m²; n = 24

Some examples

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- $P_{ill} = \Phi + V_{rev} * J_{SC}$
  - 1 sun, I = 4 A, 72 cell module, 50 °C module temperature, T_{ku} = 1.8 mV/K, J_{SC} = 42.5 mA/cm²:
    P_{ill} = 1000 W/m² + 15.57V * 42.5 mA/cm² = 7671 W/m²
  - 1.1 suns, I = 4.4 A, 72 cell module, 60 °C module temperature, T_{ku} = 1.8 mV/K, J_{SC} (1sun) = 42.5 mA/cm²:
    P_{ill} = 1100 W/m² + 15.27V * 46.75 mA/cm² = 8239 W/m²
- Under such conditions, what temperature will the module reach?
- Which shadowing condition is most critical?
- Which impact do additional localized reverse currents have?
- How do cell layout or wafer thickness affect this?

Thermal model for hot spot calculation - topview

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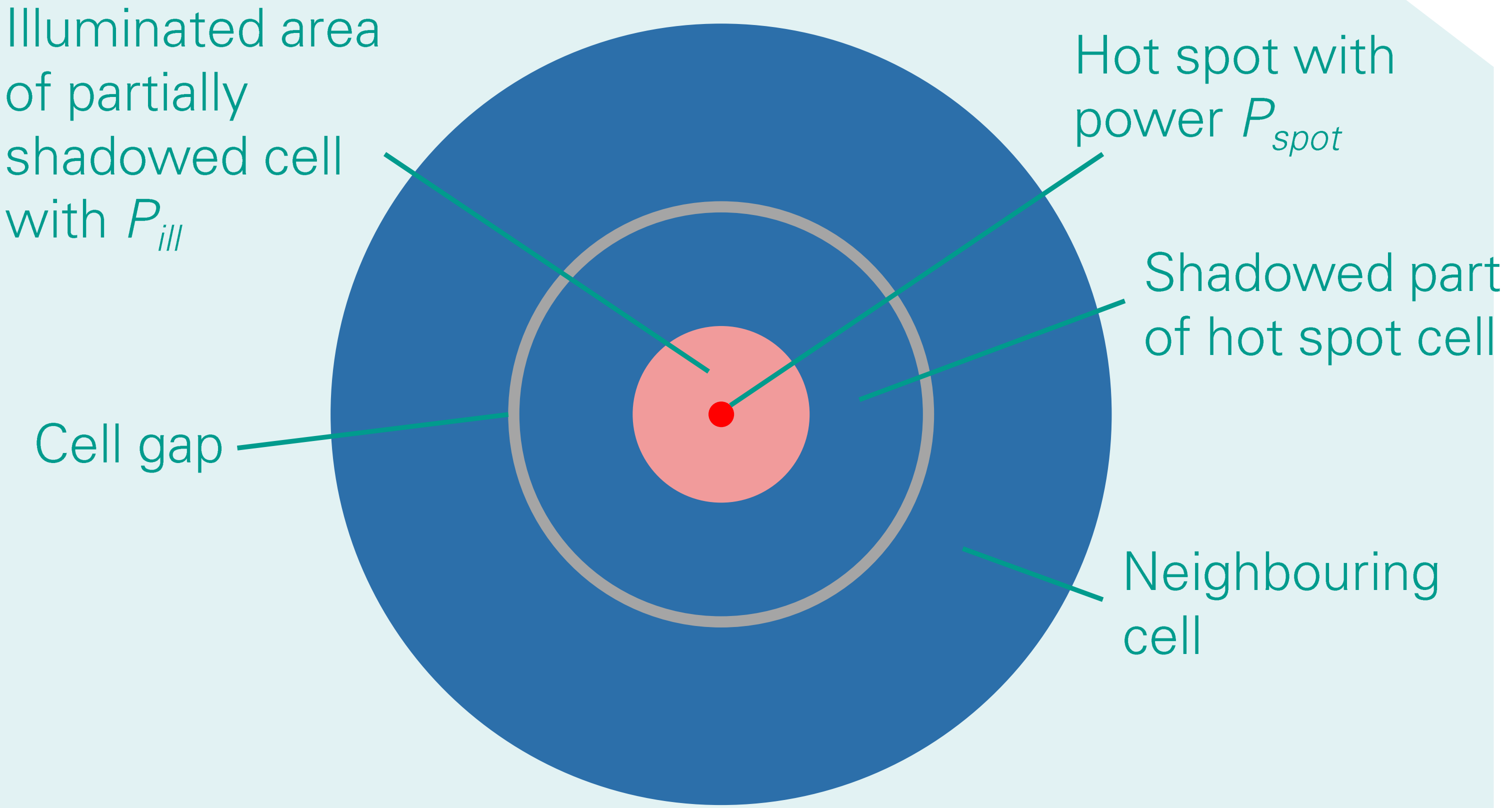
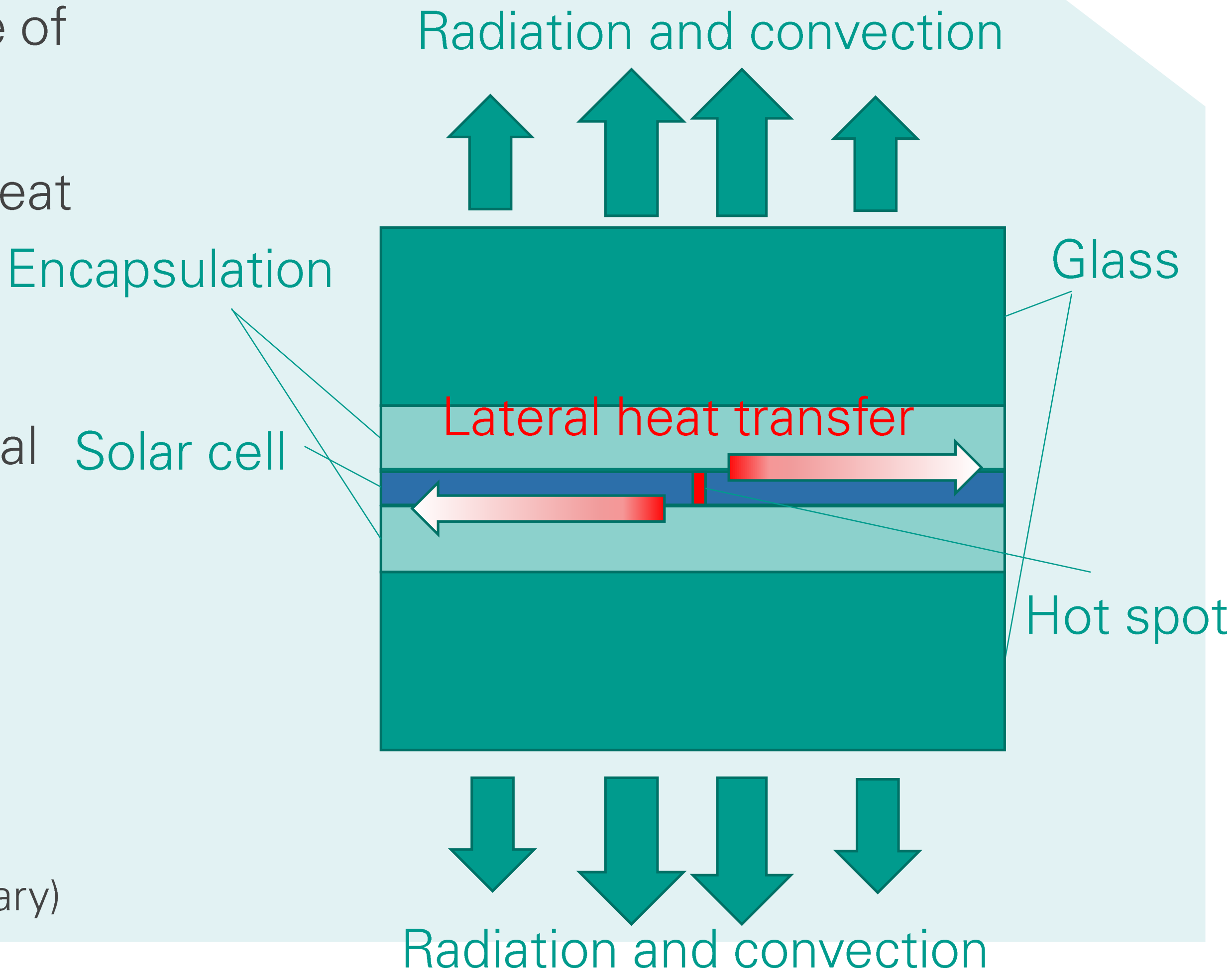
- Due to radial symmetry, all regions are circular in topview
- Reddish areas in the center may have source terms for power
- All areas consume heat by vertical dissipation
- Different areas have different lateral heat conductivity



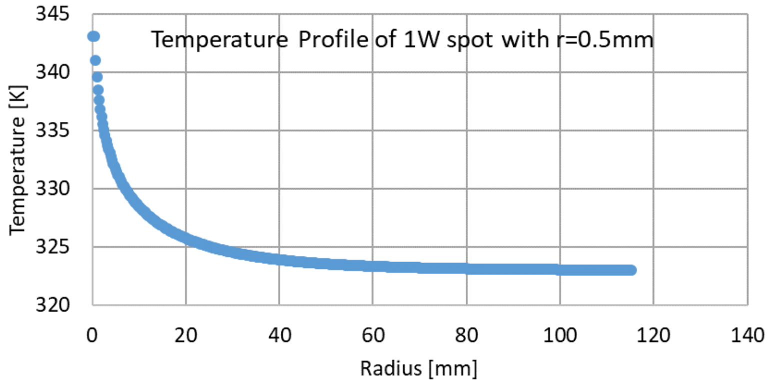
Thermal model for hot spot calculation – cross section

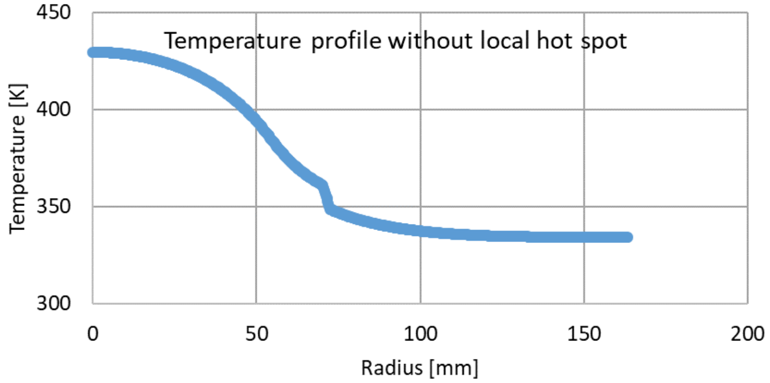
- Calculate radial symetric heat transfer for sake of simplicity
- Vertical heat losses from the module, lateral heat distribution within the module
- Account for radiative and convective losses
- Use one lumped thermal conductivity for lateral heat transfer
- Parameters:
  - Convection: 20 W/m²K on both sides
  - Emissivity: 0.85 on both sides
  - 2.3 mm glass on both sides with λ_{glass} = 1 W/mK
  - 180 µm Si with λ_{Si} = 150 W/mK (cell thickness can vary)

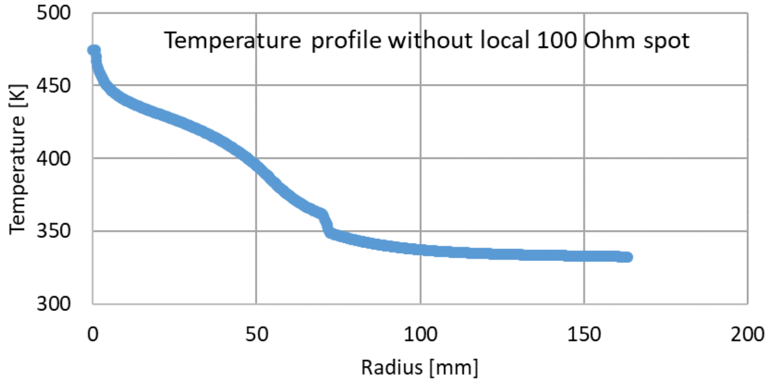


Some exemplary results of thermal calculation

- A 1 W hot spot with r_{spot} = 0.5 mm achieves a local temperature 20 K above ambient
- An illuminated region of 55 mm, a 2 mm cell gap at r_{gap}=70 mm, in a 72 cell IBC module @ 4.4 A, 60 °C module temperature under 1.1 suns illumination achieves a center temperature of 156 °C, without any localized hot spot
- Adding a hot spot of 100 Ω increases T_{max} to 201°C
- Changing the cell thickness to 140 µm increases these values to 160 °C and 214 °C respectively







Resulting module design criteria

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- Cells and modules must withstand up to 200°C
- Not more than 24 cells in series one string (per bypass diode)
- Not less than 100 Ω parallel resistance in a cell → Reverse current @ 15 V should be below 0.15 A
- Higher reverse current only if IR thermography is used on cell level and distribution of reverse current allows a higher total current (no concentration in single spot)
  - Ideally a thermal simulation predicts temperature increase on module level from thermography images to judge on the criticality of the reverse current distribution

New cell types – silicon and beyond

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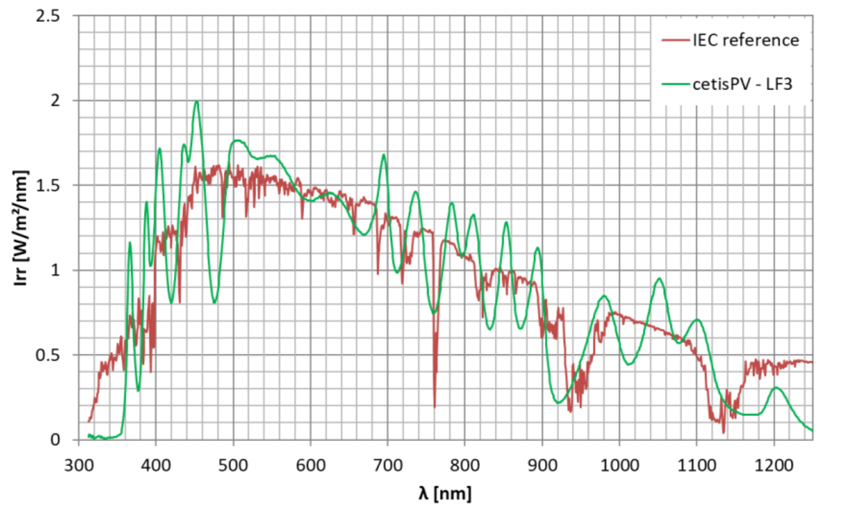
- High efficiency Si-solar cells with >26 % efficiency will dominate in the next 5 – 10 years
- Tandems are rapidly catching up, recently Longi reached 33.9 % certified efficiency
- New materials require spectral variability and new measurement strategies → the new Light-Source cetisPV-LF3 meets this demand
- Measurement strategies for perovskite-Si tandem cells are currently in development

cetis-PV LF3



Spectrum of cetis-PV LF3 as compared with AM1.5G reference spectrum

Perovskite – silicon tandem cells

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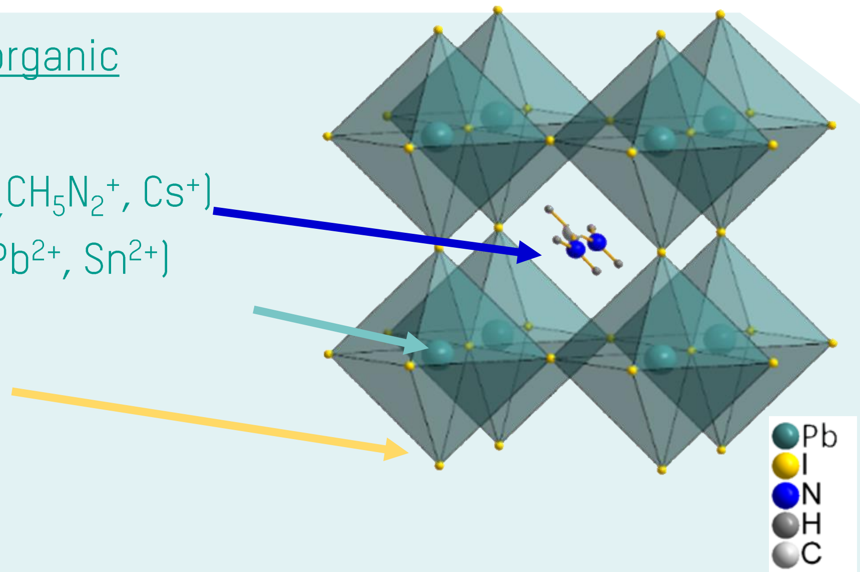
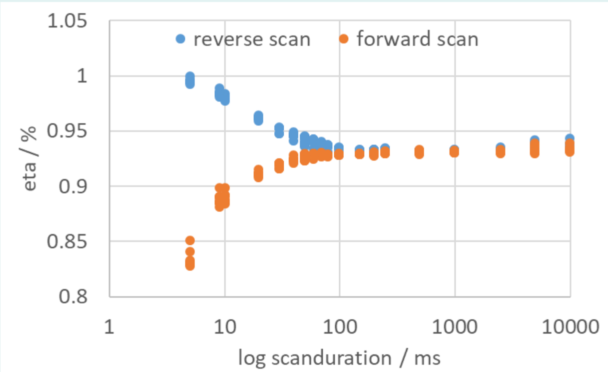
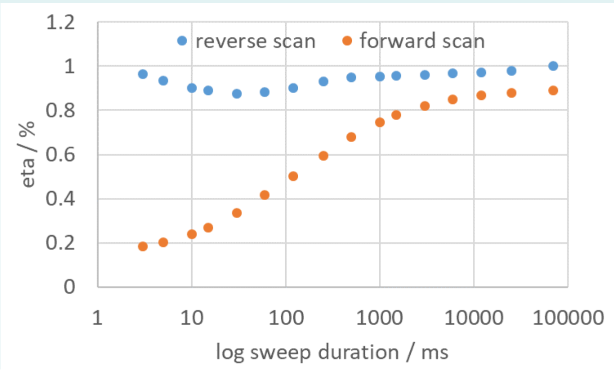
- Perovskite and Si-perovskite tandem cells may show hysteresis
- Root cause is different than to Si cells – new treatment required

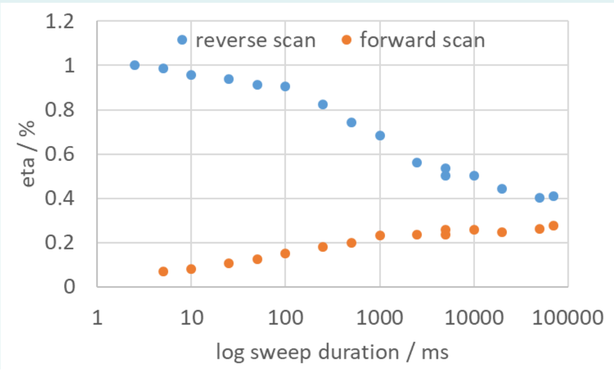
Structure of organic-inorganic perovskite materials

- A = cation, ($CH_3NH_3^+$,$CH_5N_2^+$, Cs^+)
- B = metallic anion (Pb^{2+}, Sn^{2+})
- X = halogen (I^-, Br^-)









Efficiency as a function of sweep time and direction for three different samples

Perovskite – silicon tandem cells

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- Perovskite and Si-perovskite tandem cells may show hysteresis
- Root cause is different than on Si cells – new treatment required
- Metastabilitiy can extend over hours in some cases

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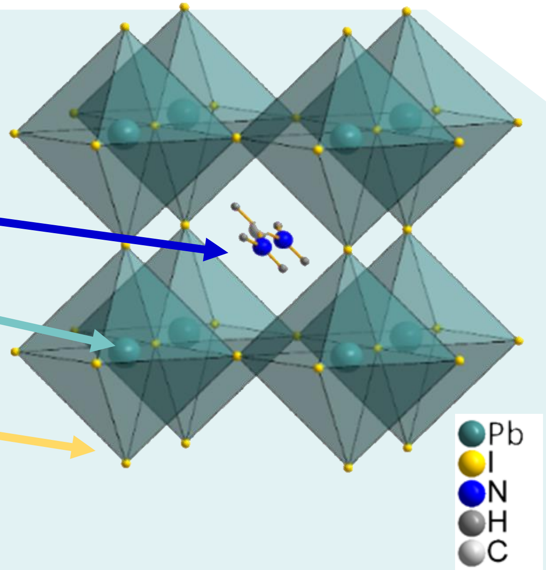

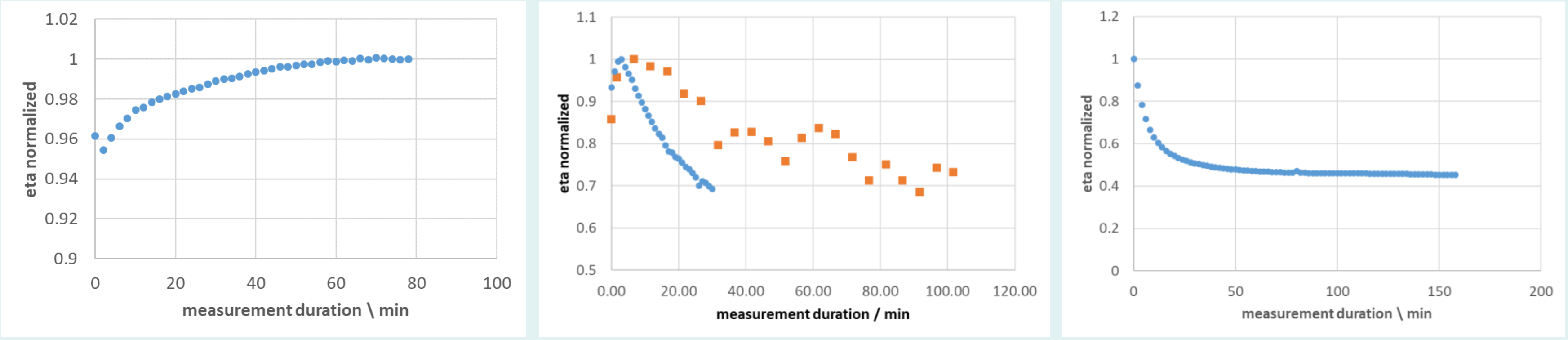

Efficiency as a function of time at repetitive sweeps under continuous illumination

Conclusions

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- Best in class simulators require thourough quality measures in manufacturing and operation
- Besides high quality hardware, data analysis is important for back-contact cells and modules - Advanced hysteresis precisely compensates transient effects for all Si-based devices
- Under partial shading modules should withstand 200 °C and strings should not be longer than 24 cells in series connection
- We are ready to take on your measurement tasks for Perovskite and Tandem cells

