CFV Labs

DECEMBER 19, 2022

Flash Testing Capability

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Main Takeaways

- CFV Labs has a Class $A^+A^+A^+$ tunnel-type h.a.l.m. indoor flasher, nearly identical to the flasher at Fraunhofer ISE CalLab.
  - 2.4m x 1.3m module capacity
  - Maximum current = 21A, Maximum voltage = 260V
- Accurate measurements of PV modules require precise calibration and characterization of test equipment as well as rigorous measurement process control.
- CFV follows the industry-best practices to achieve top-tier uncertainty in its I-V measurements.
  - Precision calibrated reference cells for in-plane irradiance measurements
  - Separate flasher room continuously maintained at 25°C
  - Quarterly measurement of the flasher spectrum and uniformity
  - Daily quality control with p-type Si modules
  - Weekly quality control with n-type Si and CdTe modules
  - Quarterly checks with reference p-type, n-type (IBC and n-PERT), and CdTe modules
  - Routine interlaboratory measurement comparisons with modules of varied technologies

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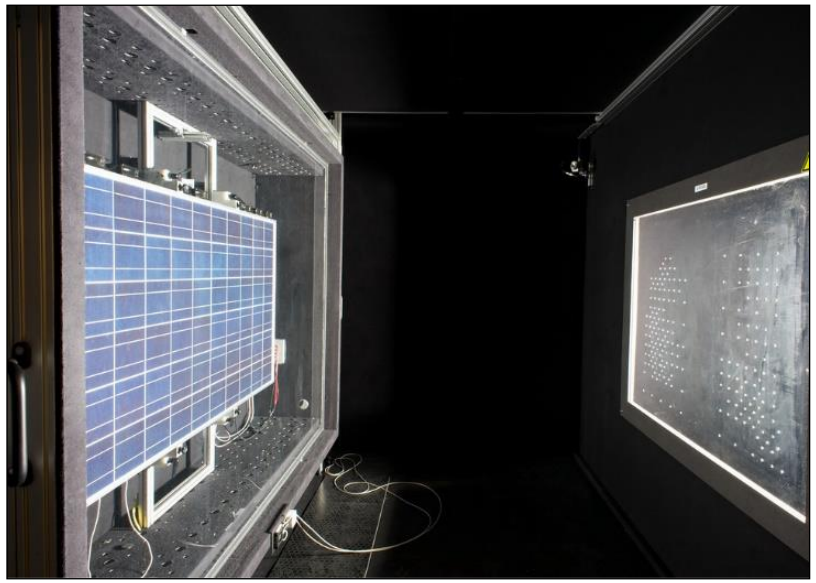
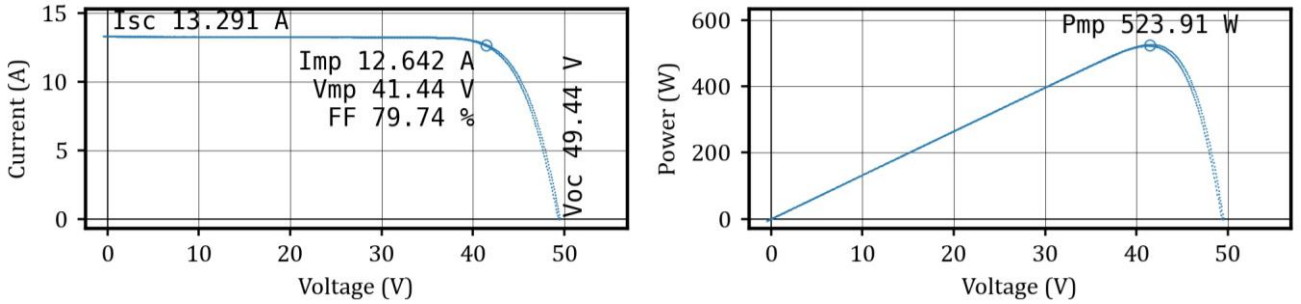
Class $A^+A^+A^+$ Halm Flasher

- Class $A^+A^+A^+$ flasher with the latest optics upgrades
- Single flash is 40ms with a 25ms measurement window. By default, CFV takes three forward- and reverse-sweep measurements and averages the data.
- Sectional sweeps allow accurate analysis of n-type modules.





I-V data of a 20.23%-efficient module;
Graph shows an overlay of forward and reverse sweeps of 1 section each.

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Measurement Uncertainty Drivers for PV Module Measurements

- Identification, quantification, and mitigation of uncertainty drivers is crucial for understanding the accuracy of PV module measurements.
- Primary uncertainty drivers for measurements of PV modules include:
  - Test plane irradiance and uniformity
  - Spectral mismatch effects
  - Module temperature and uniformity
  - Test equipment measurement accuracy
  - Test reproducibility

Precision Calibrated Reference Cells

- CFV uses Fraunhofer's WPVS (World PV Scale) reference cells for the in-plane and real-time irradiance measurement.
- Each data point in the I-V curve is individually corrected with the simultaneously measured reference cell Isc data, to correct errors from temporal instabilities of the flasher (short-term instability < 0.5%).
- Using a calibrated reference cell for the irradiance measurement is superior to using a reference module in terms of the measurement uncertainties.
- The reference cells are calibrated at regular intervals with uncertainties <0.7%.

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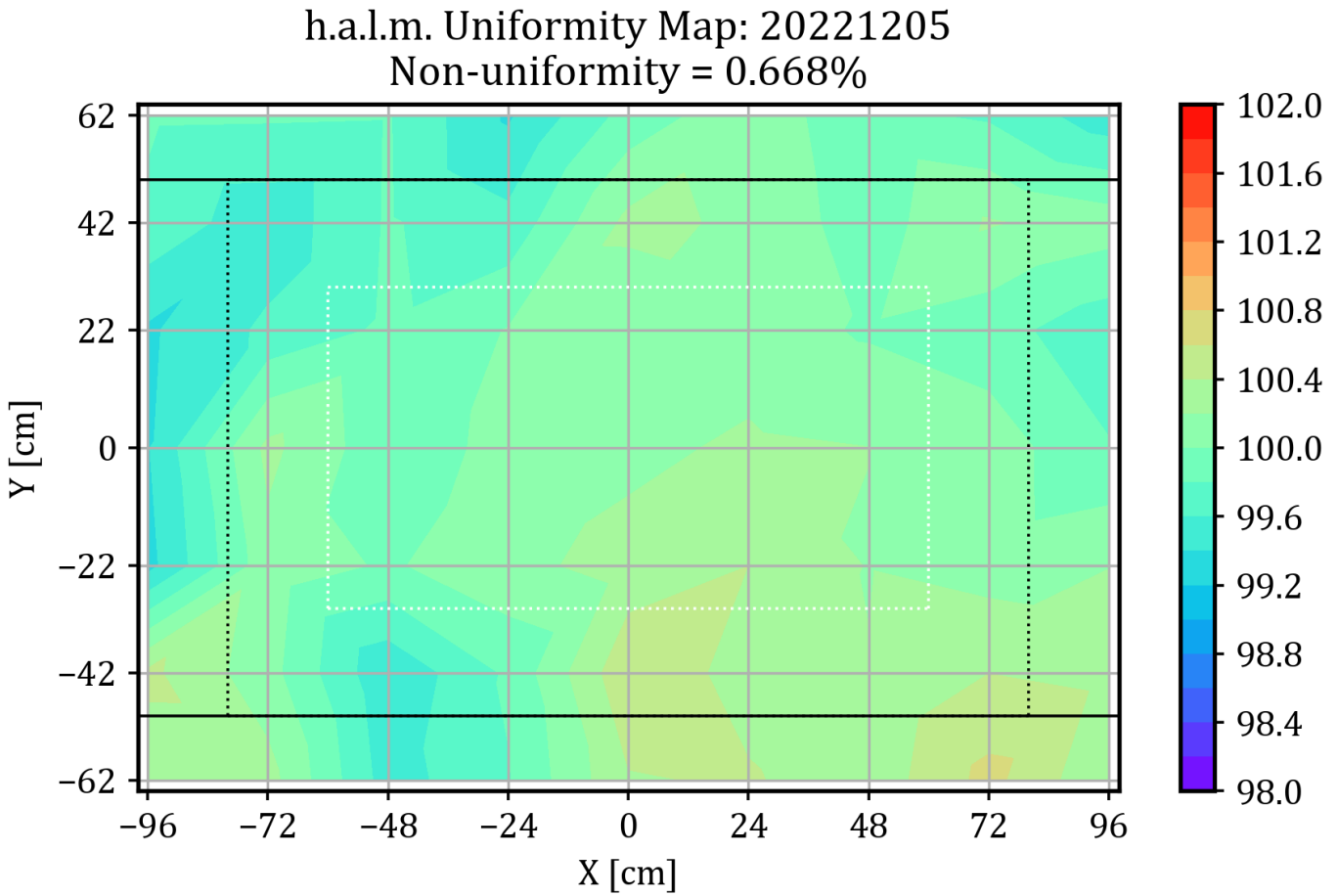
Test Plane Irradiance Uniformity

- CFV carries out quarterly uniformity measurements.
- Latest non-uniformity was ~0.7% (Class A^+ limit: 1%)
- After the irradiance uniformity mapping, the calibrated reference cell is placed at a location that matches the average irradiance of the test plane.



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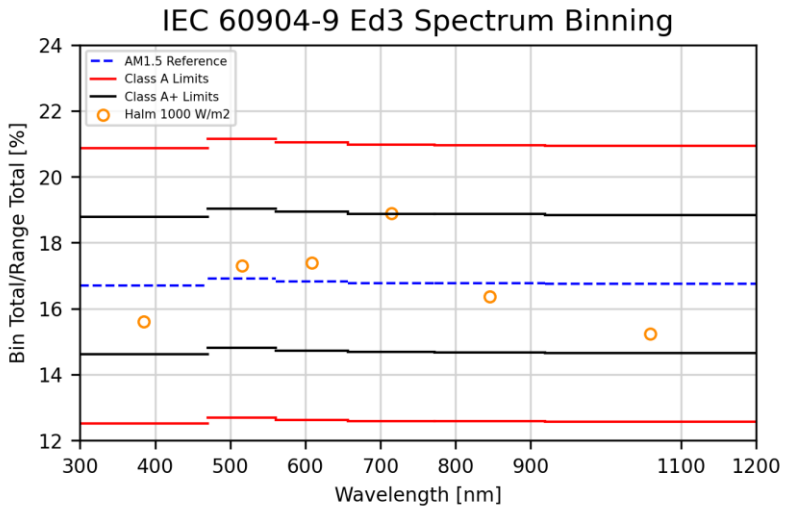
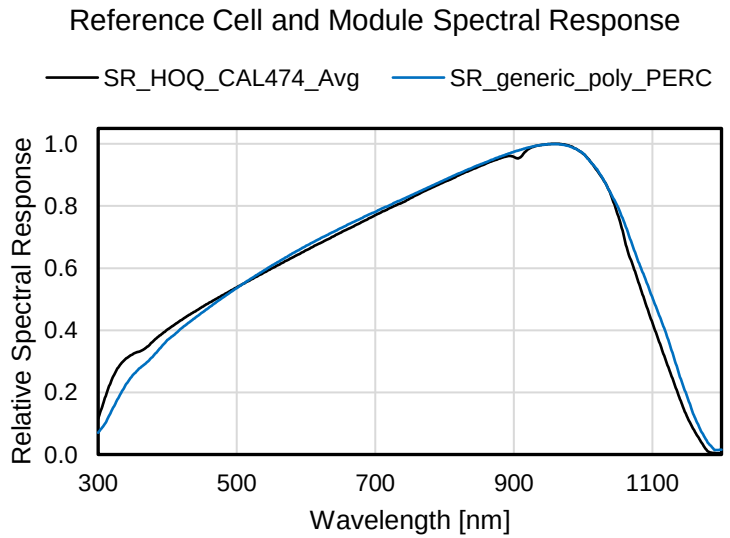
Spectral Mismatch Effects – Module EQE Data

- CFV carries out quarterly spectrum measurements with a calibrated spectroradiometer at better than 1nm wavelength resolutions.
- Latest spectrum measurement shows Class A^{+} spectral match.
- Measurement uncertainties are generally higher in the absence of module EQE or SR data.
- CFV has partnerships with Fraunhofer ISE and NREL for module EQE/SR measurements.





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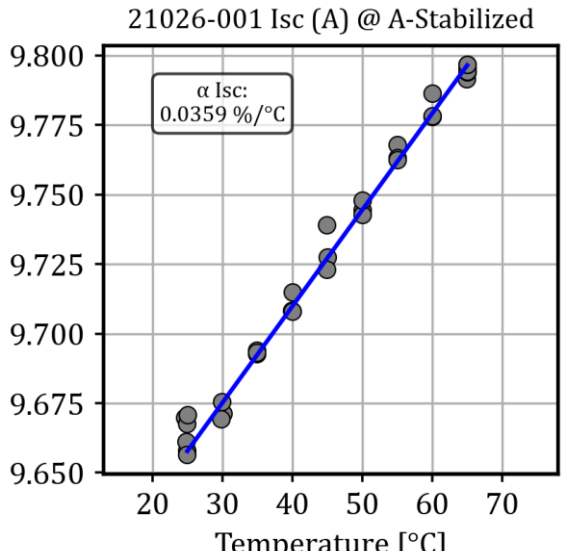
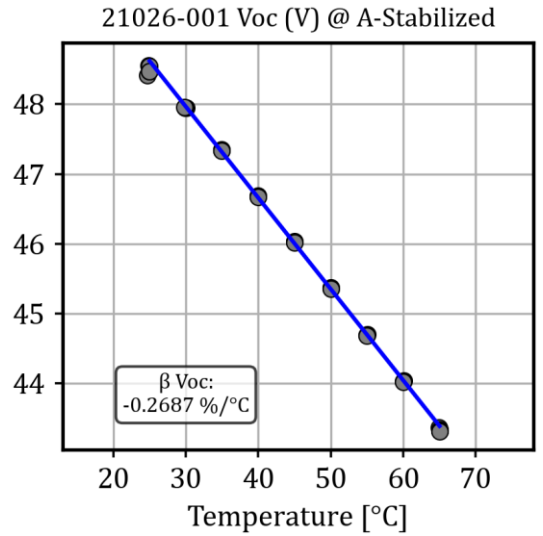
Module Temperature Measurements

- Both voltage and current have measurable temperature coefficients, e.g. for silicon modules.
  - $\alpha_{Isc} \sim +0.04\ \%/°C$
  - $\beta_{Voc} \sim -0.27\ \%/°C$
- Temperature errors arise from several sources
  - Module temperature measurements
  - Module temperature uniformity
  - Module temperature coefficients (because data is corrected to 25°C)
- Flasher room is maintained at a constant 25.0 ± 1.0°C temperature.
- Modules are stored in the flasher room for a minimum of 1 hour prior to measurement to ensure module temperature stability and uniformity.
- Module temperatures are measured with Class A four-wire RTDs with low uncertainties.





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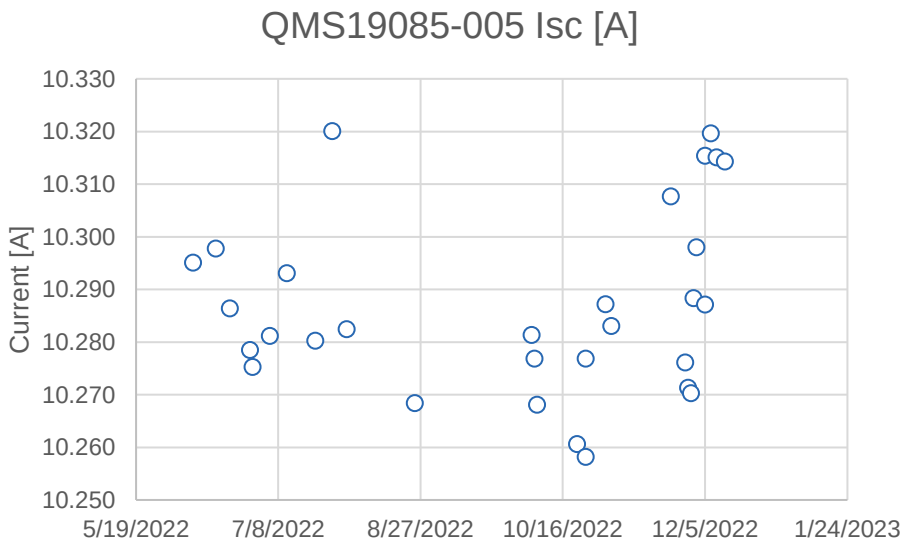
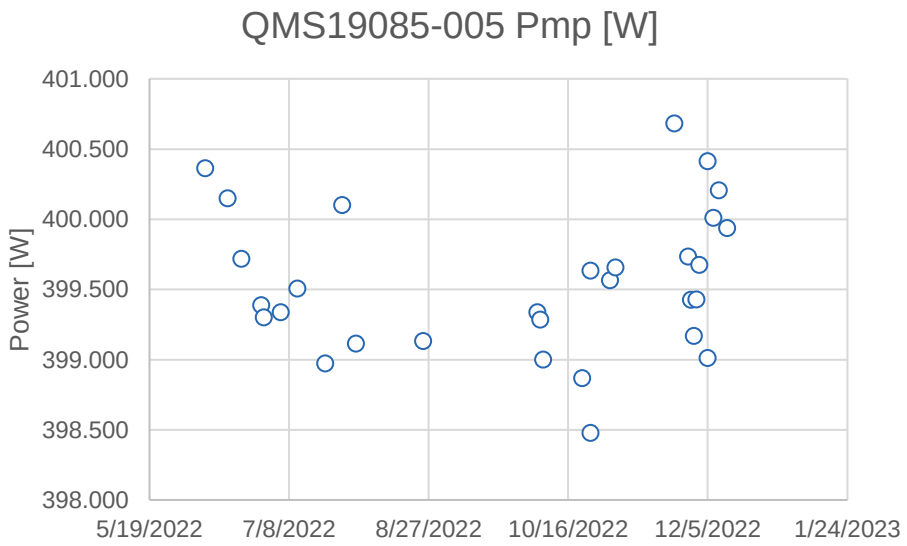
Measurement Repeatability (Silicon Control Module Data)

- The latest six months of control module data shows excellent repeatability. The table below provides the standard deviation of each STC IV parameter for a silicon control module (144 half-cut mono-PERC) over the last six months.

Isc [A]	Voc [V]	Imp [A]	Vmp [V]	Pmp [W]
0.17%	0.06%	0.12%	0.09%	0.13%





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Latest Control Module Measurements (2022 Q4)

Module ID	Cell Technology	Last CFV Measurement Date	Last CFV Measured Pmp [W]	Last Fraunhofer ISE Measured Pmp [W]	Difference (CFV/Fraunhofer) – 1
CFV009	Mono PERC	2022-12-07	260.68	261.20	-0.12%
CFV010	n-PERT	2022-12-07	303.18	301.74	+0.60%
CFV012	IBC	2022-12-07	316.87	315.34	+0.55%
CFV013	Poly Al-BSF	2022-12-07	280.53	281.90	-0.42%
CFV014	CdTe	2022-12-08	109.95	109.78	+0.11%
				Average	+0.15%

CFV014 (CdTe) measurements were carried out after chamber preconditioning procedures specified by the manufacturer, at both CFV and Fraunhofer ISE CalLab.

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CFV's STC I-V Measurement Uncertainties (k=2)

Cell Technology	Isc [A]	Voc [V]	Imp [A]	Vmp [V]	Pmp [W]
Crystalline Silicon, Monofacial*	± 1.4 %	± 0.7 %	± 1.6 %	± 1.2 %	± 1.9 %
Crystalline Silicon, Bifacial*	± 1.6 %	± 0.75 %	± 1.8 %	± 1.3 %	± 2.2 %
CdTe**	± 2.7 %	± 1.6 %	± 2.7 %	± 2.0 %	± 3.3 %
CIS/CIGS*	± 1.7 %	± 1.6 %	± 2.1 %	± 1.8 %	± 2.6 %

*** With module EQE data, uncertainties are higher for measurements in which EQE/SR data is not available**

**** Depends on stabilization method**

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Summary

- CFV has a best-in-class tunnel-type flash tester.
- Starting with the technical guidance of Fraunhofer ISE CalLab, and through ten years of experience, CFV has developed practices to guarantee top-tier measurement uncertainty.
- The quality control practices, and the measurement setup allows sub 2.0% STC Pmp [W] measurement uncertainty for silicon monofacial modules with module EQE/SR data. Measurements of bifacial modules have slightly higher STC Pmp [W] uncertainties of 2.2%.
- CFV uses precision calibrated reference cells for in-plane irradiance measurement.
- Interlaboratory round robin tests on show very good match between CFV and other top-tier labs such as Fraunhofer ISE, NREL and SERIS.

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Thank you.

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