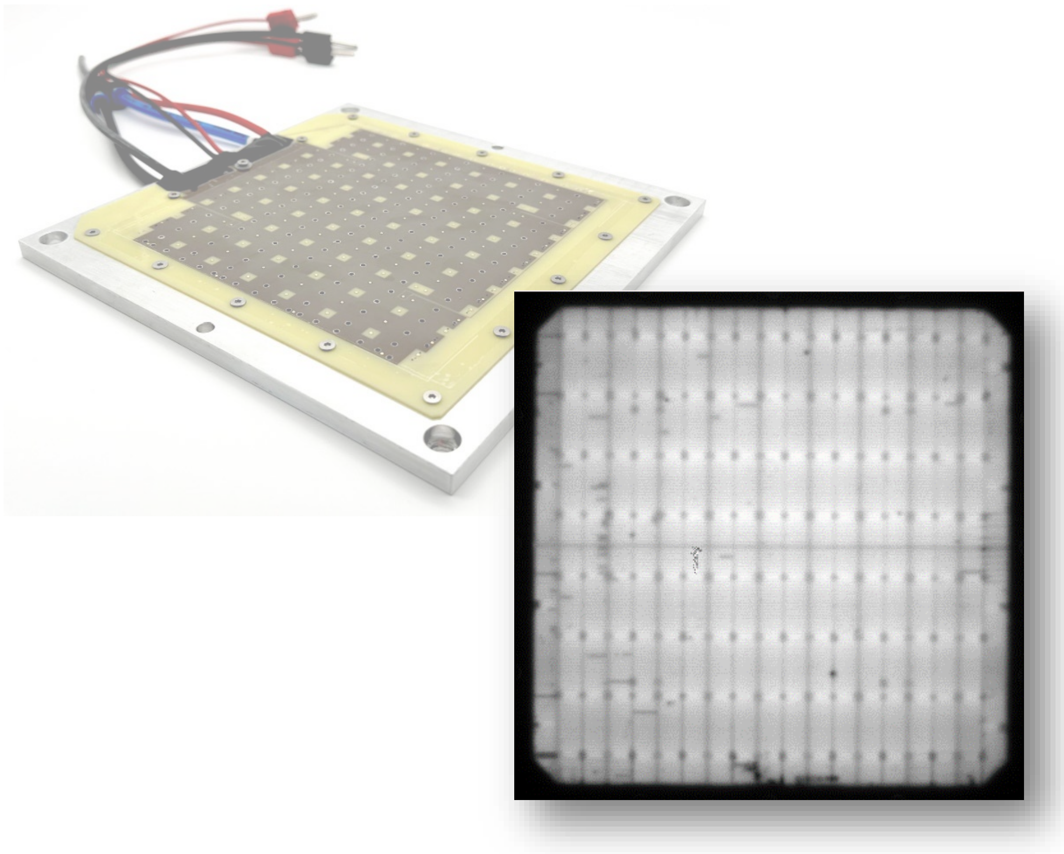
12th Back Contact Workshop
Delft, the Netherlands; December 4–5, 2024

ISFH CalTeC

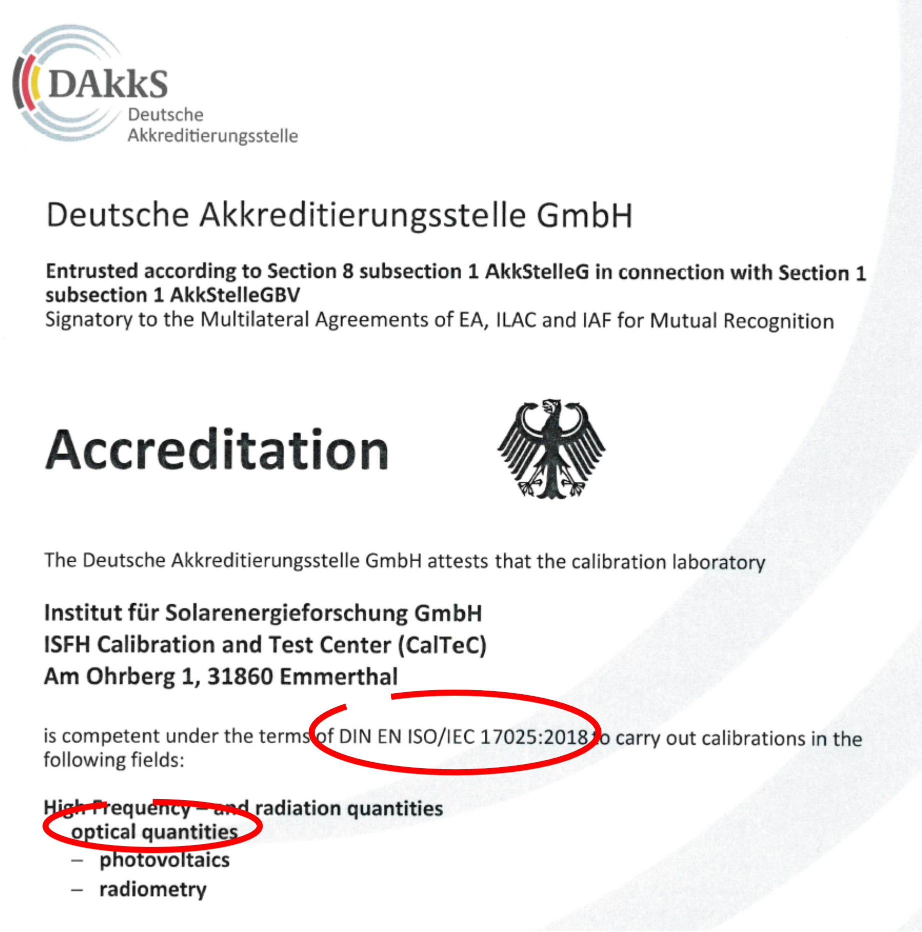


Precise IV testing of BC solar cells: Challenges and status at ISFH

Karsten Bothe and David Hinken

Leibniz Universität Hannover

ISFH Calibration and Test Centre (CalTeC)



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The Deutsche Akkreditierungsstelle GmbH attests that the calibration laboratory

Institut für Solarenergieforschung GmbH
ISFH Calibration and Test Center (CalTeC)
Am Ohrberg 1, 31860 Emmerthal

is competent under the terms of DIN EN ISO/IEC 17025:2018 to carry out calibrations in the following fields:

High Frequency – and radiation quantities
optical quantities
- **photovoltaics**
- **radiometry**

- ISFH CalTeC is ISO/IEC 17025 accredited
- The solar cell calibration laboratory is accredited by the Germam accreditation body DAkkS since 2016

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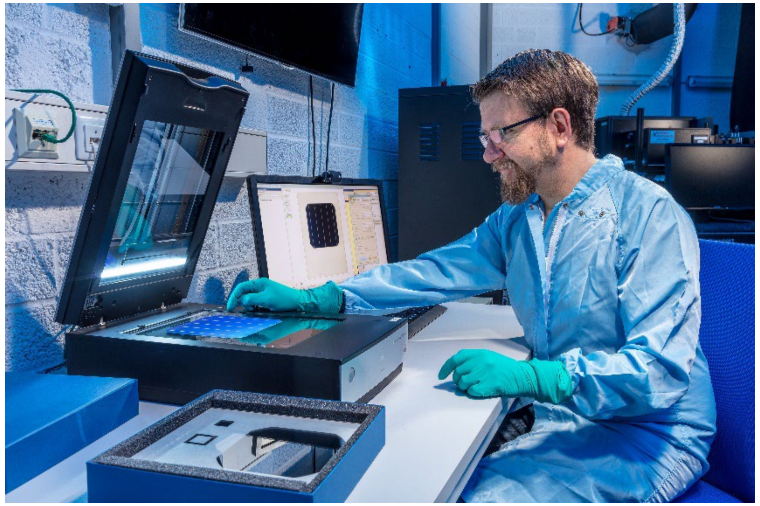
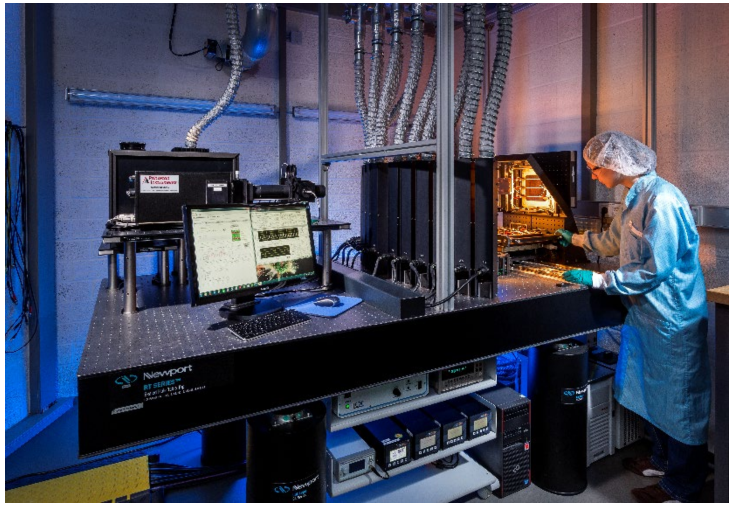
Calibration of solar cells in three steps

Area (cell (TA) or mask (DA)) → Spectral Responsivity → Current-Voltage Chracteristic





- Required for efficiency calculation

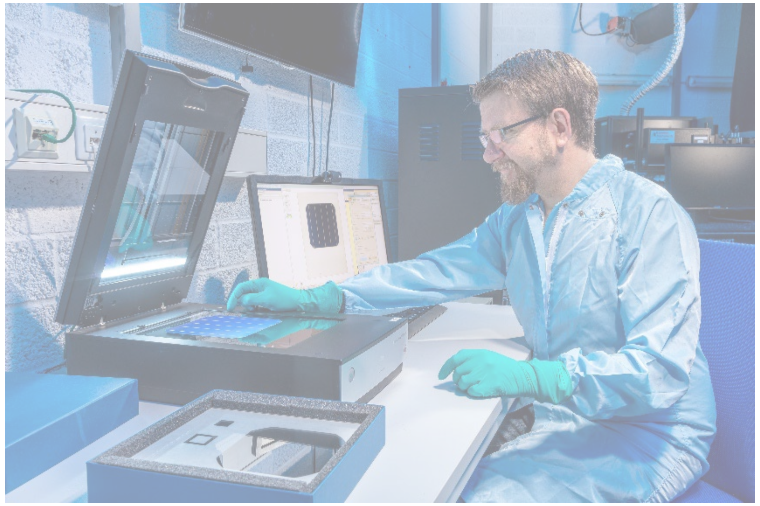
- Required for spectral mismatch correction
- Provides information about linearity

- Required for determination of characteristic parameters I_{sc}, V_{oc}, P_{max}, *FF* and efficiency

Calibration of solar cells in three steps

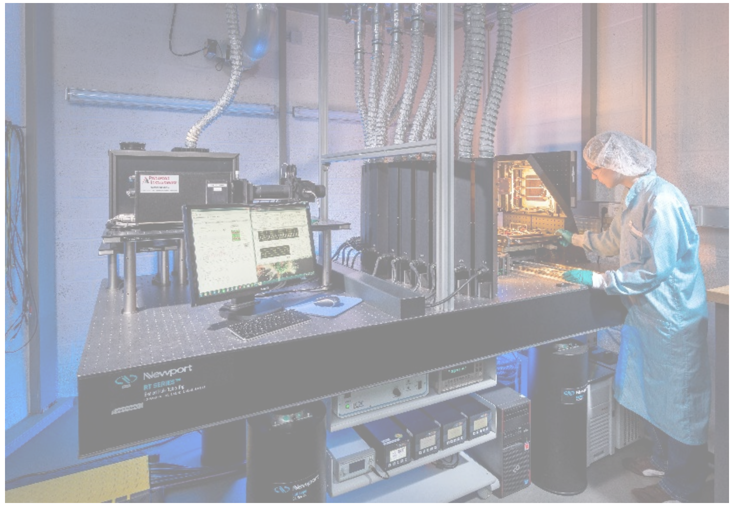
1.

Area (cell (TA) or mask (DA))



- Required for efficiency calculation

Spectral Responsivity



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Calibration of solar cells in three steps

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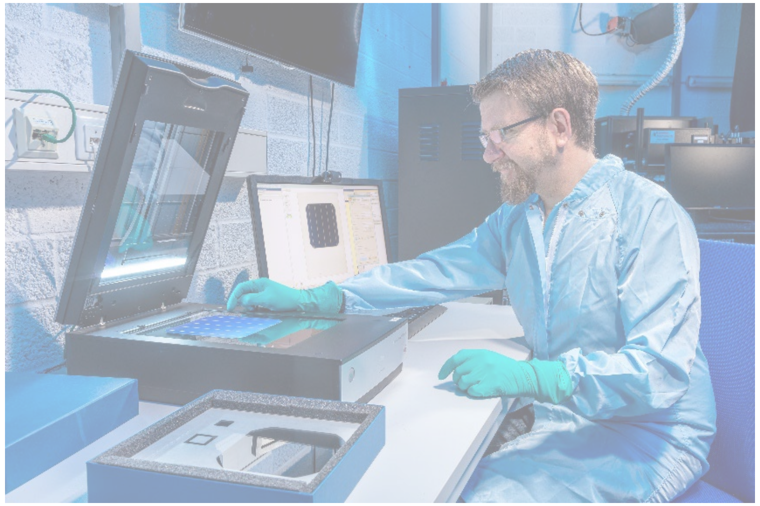
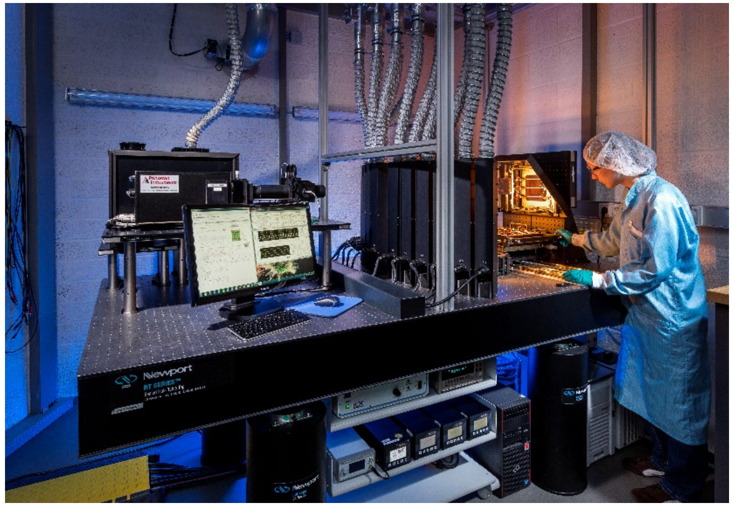


- Required for efficiency calculation

2.

Spectral Responsivity



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Current-Voltage Chracteristic

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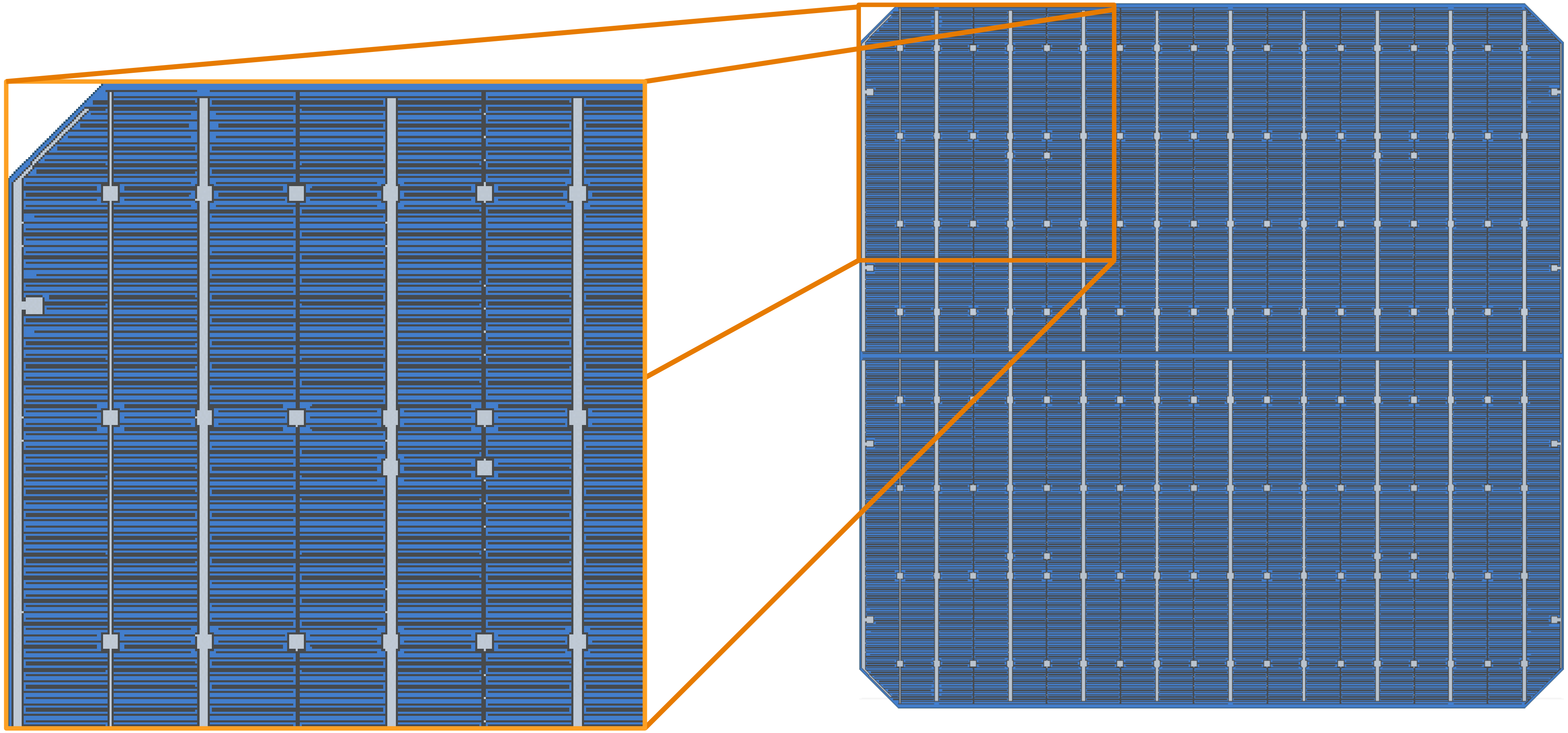
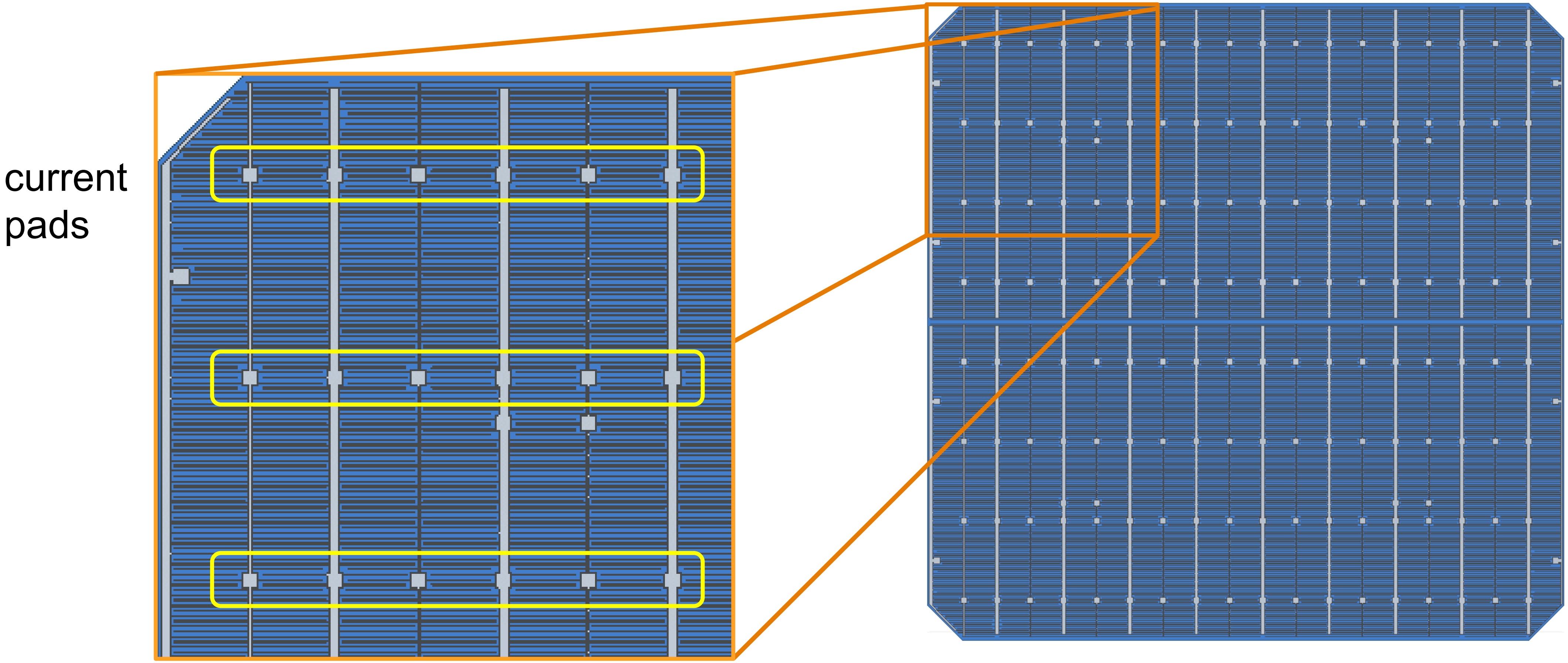
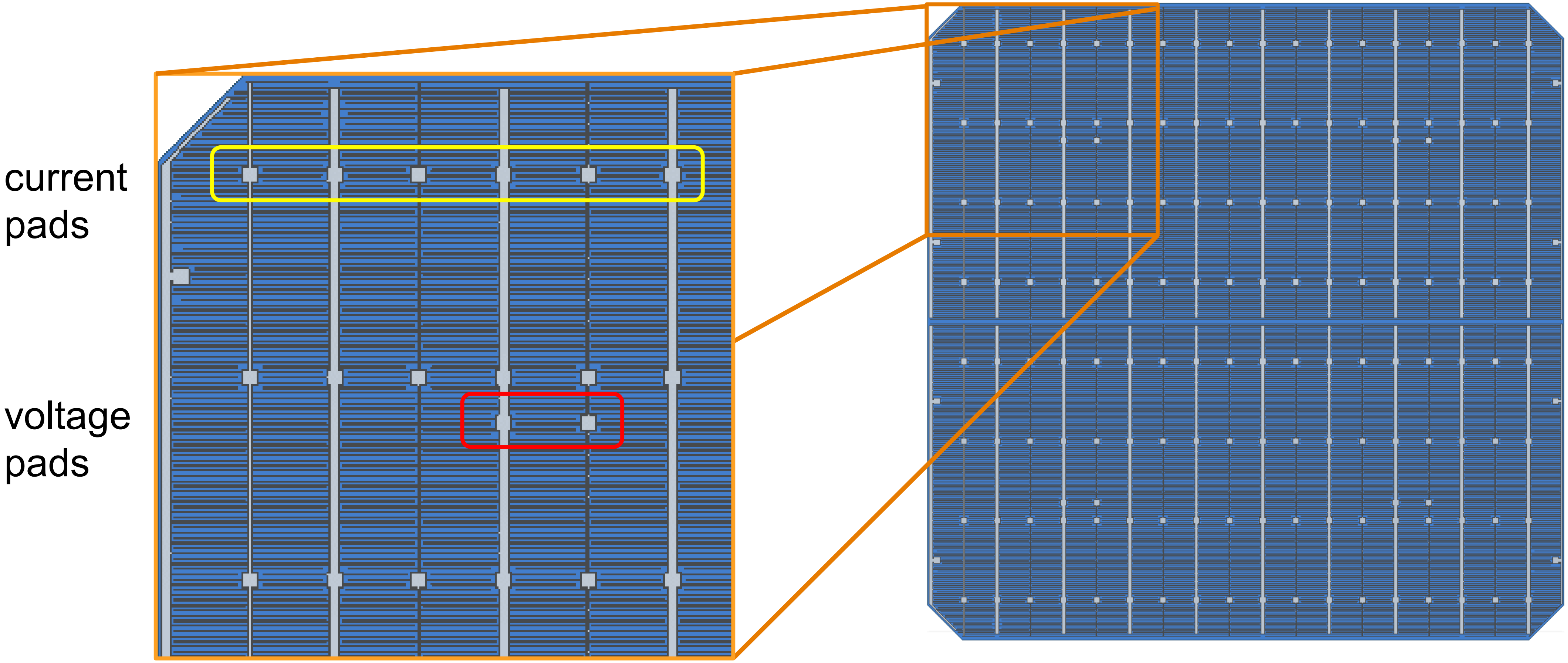
Metallisation layout



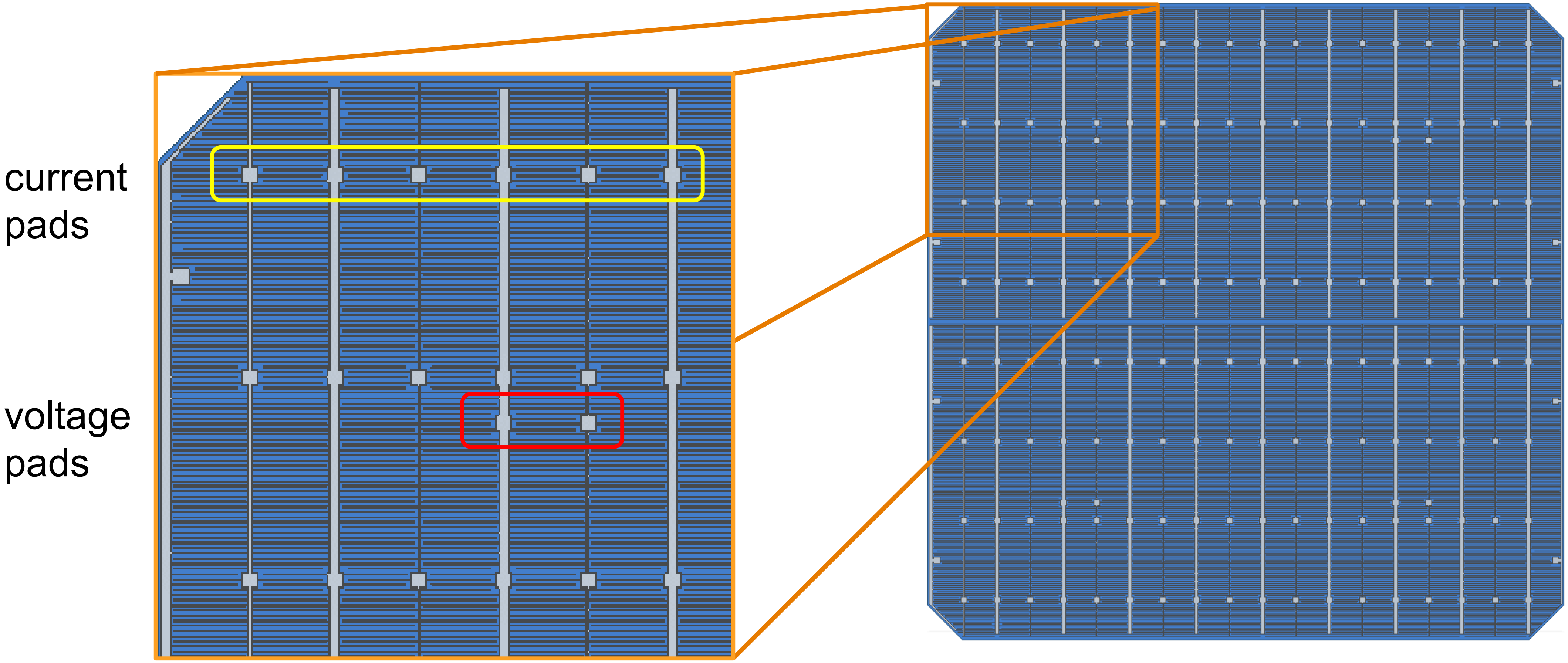
Metallisation layout



Metallisation layout



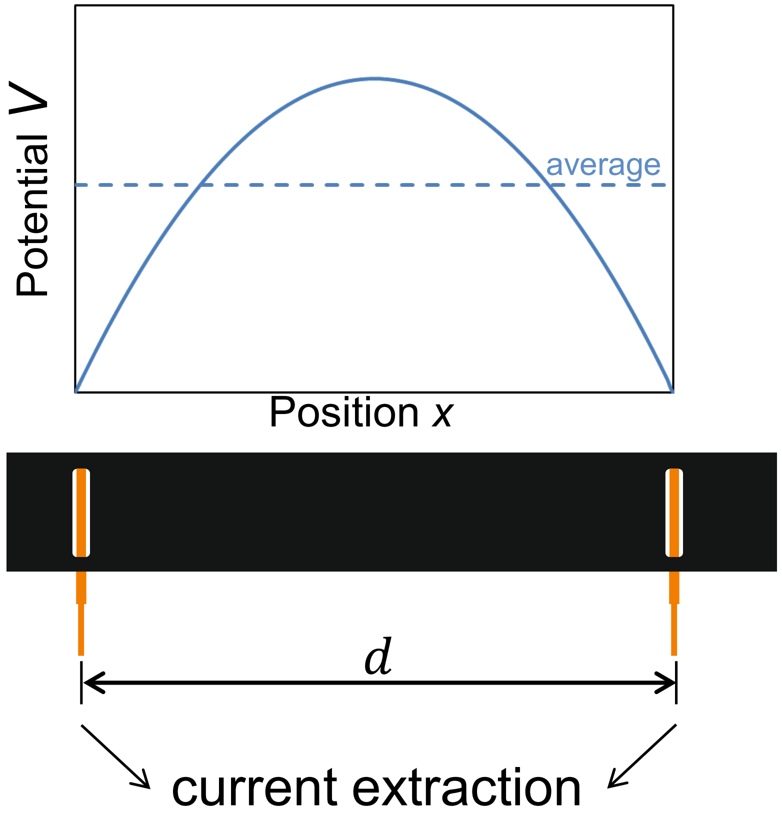
Metallisation layout



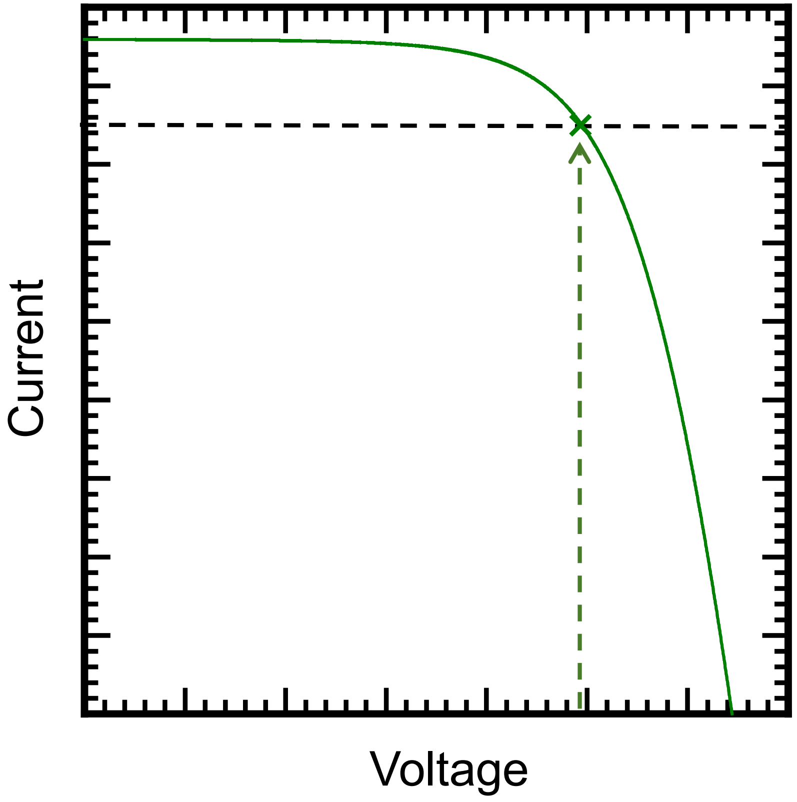
Where to place voltage pads for correct sensing?

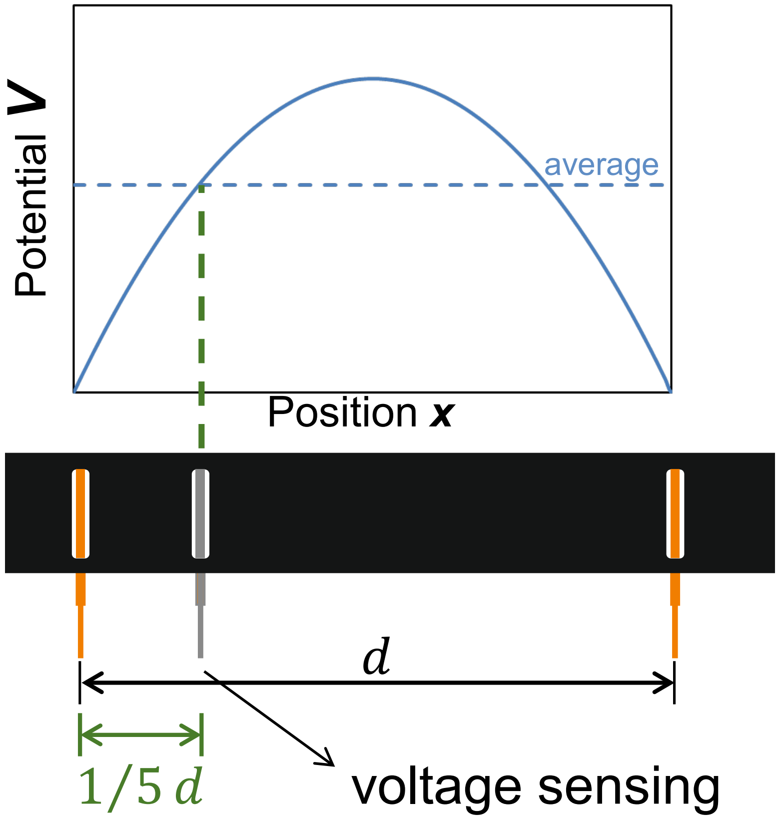
FF over- and underestimation

- The sensing aims at probing the average busbar potential



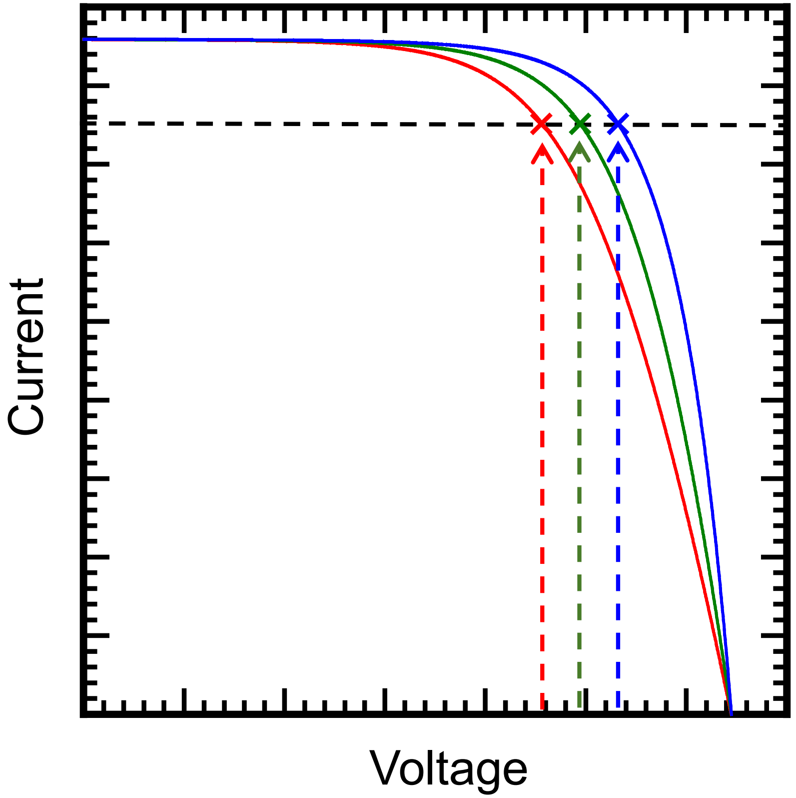
FF over- and underestimation

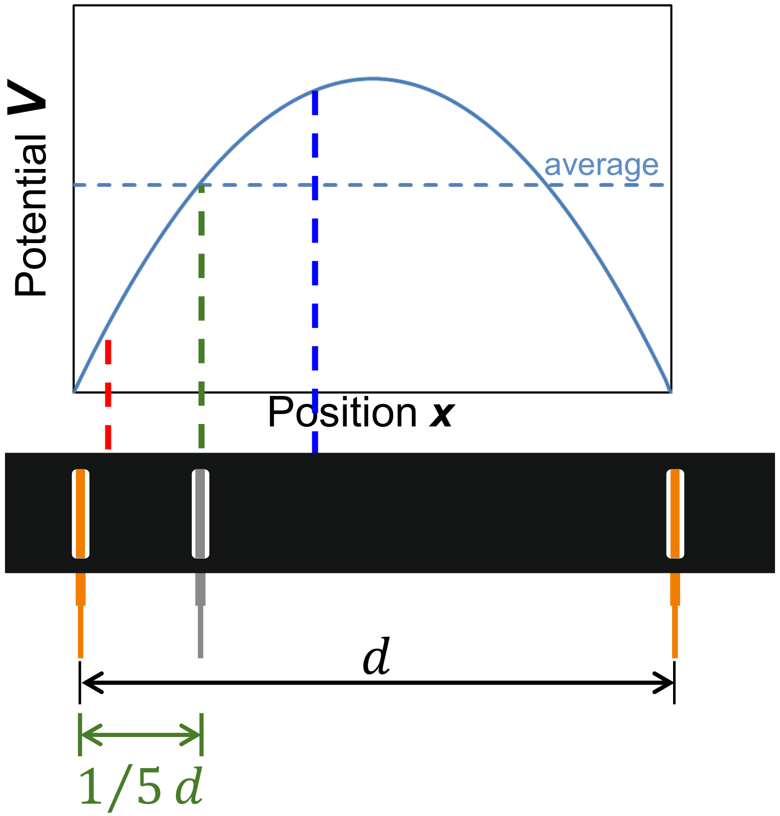




$$\frac{3-\sqrt{3}}{6}d \approx 0.211\, d \approx 1/5\, d$$

FF over- and underestimation

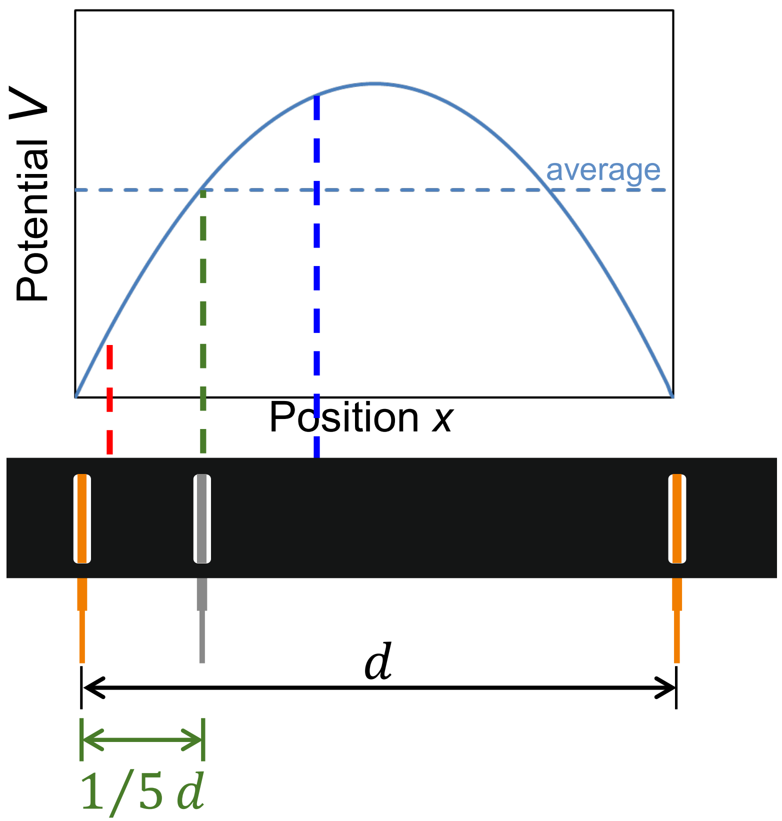




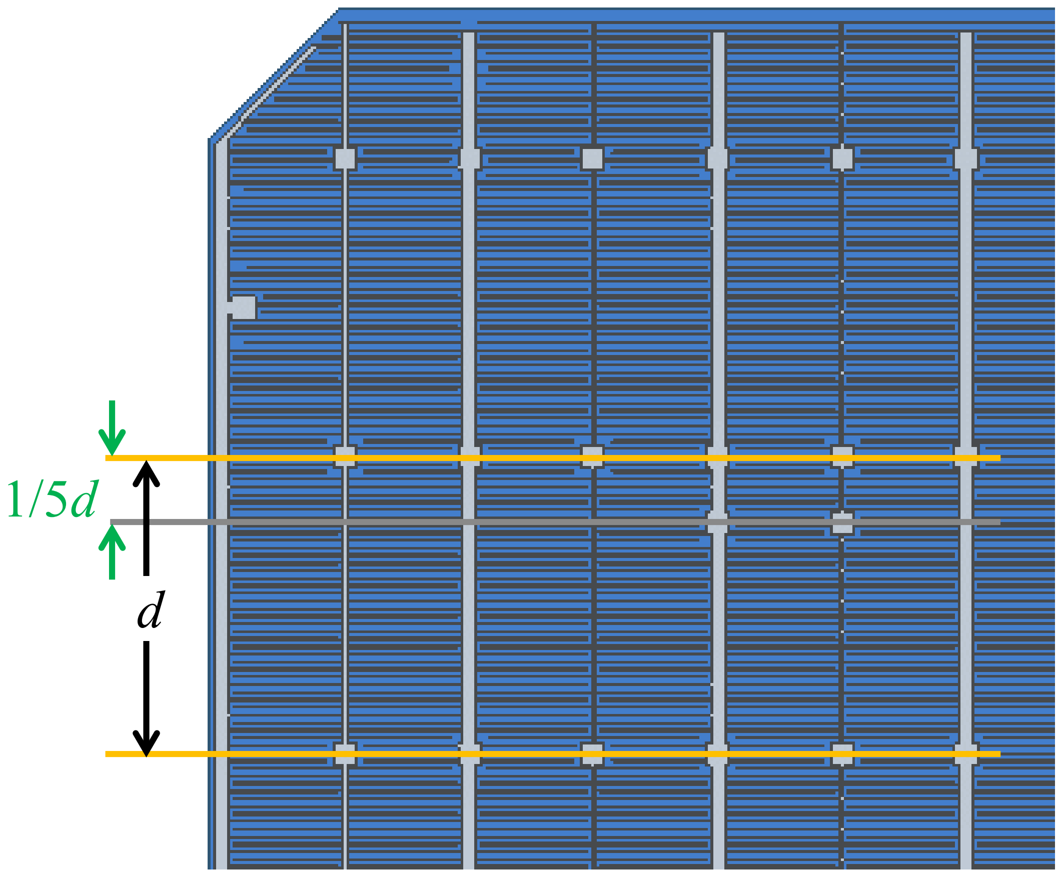
FF over- and underestimation

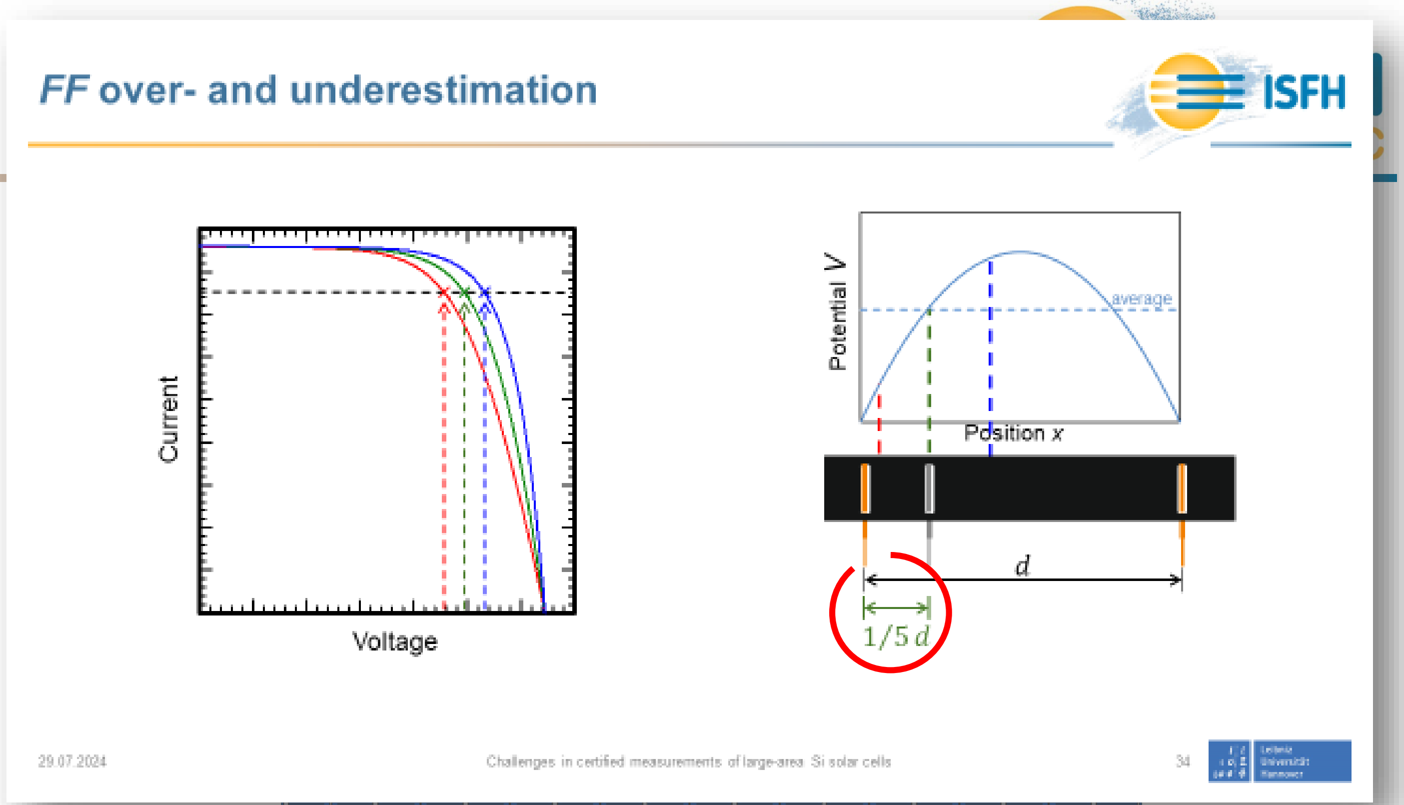
- The sensing aims at measuring the potential that would be measured if the entire busbar were contacted
  - Sensing on busbar with at 1/5th of the distance of two adjacent contacting probes
  - The measured *FF* is independent of the actual busbar resistance and number of probes

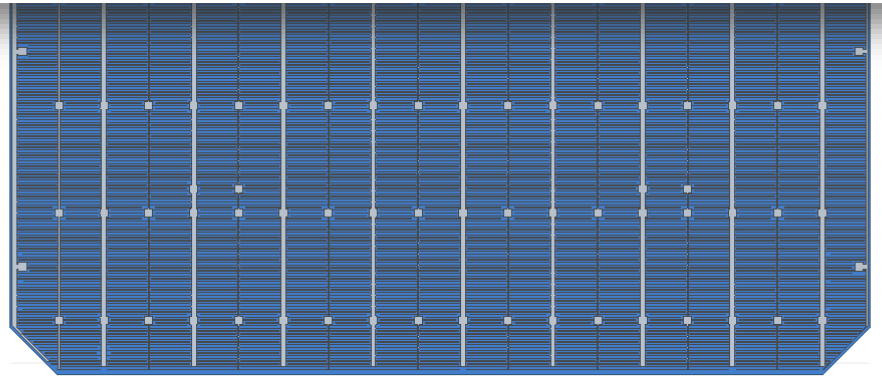
→ Busbar-resistance neglecting (brn) contacting



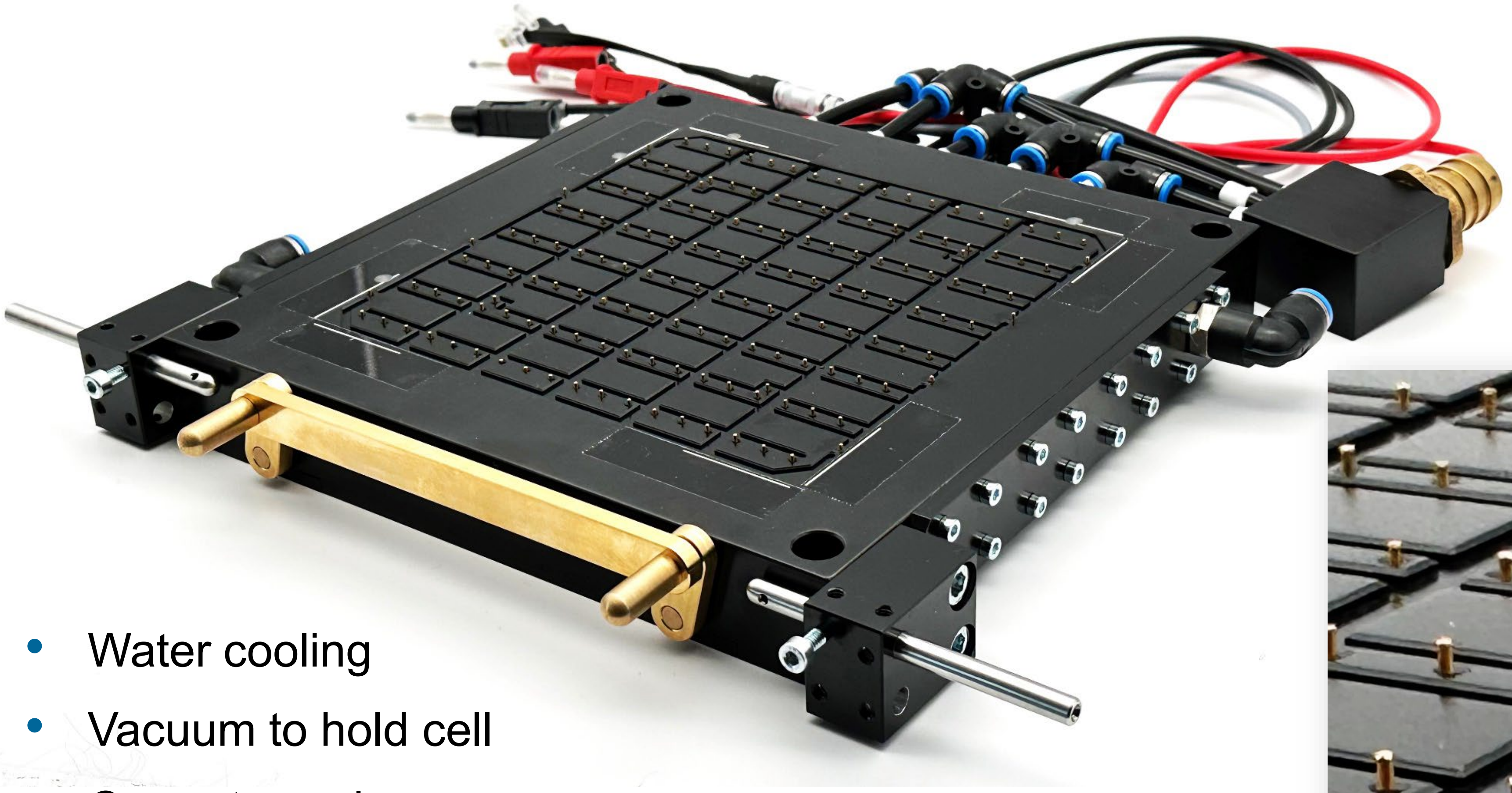
Back contact cells

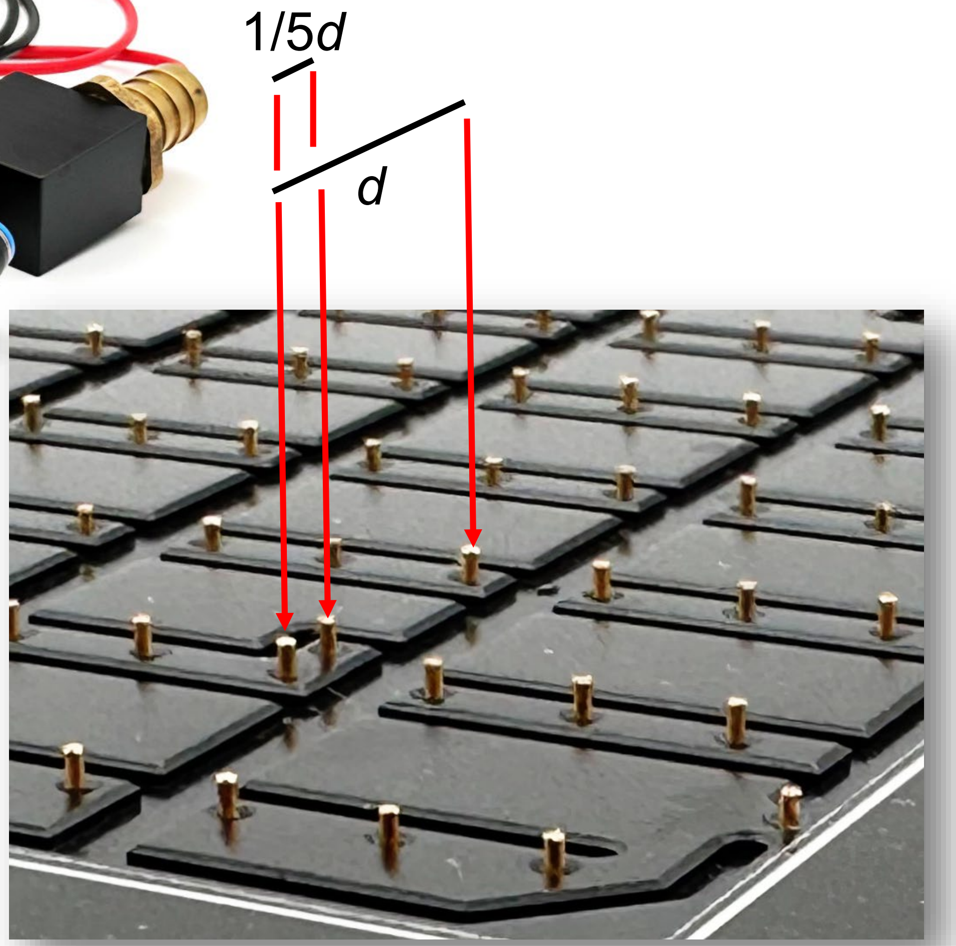






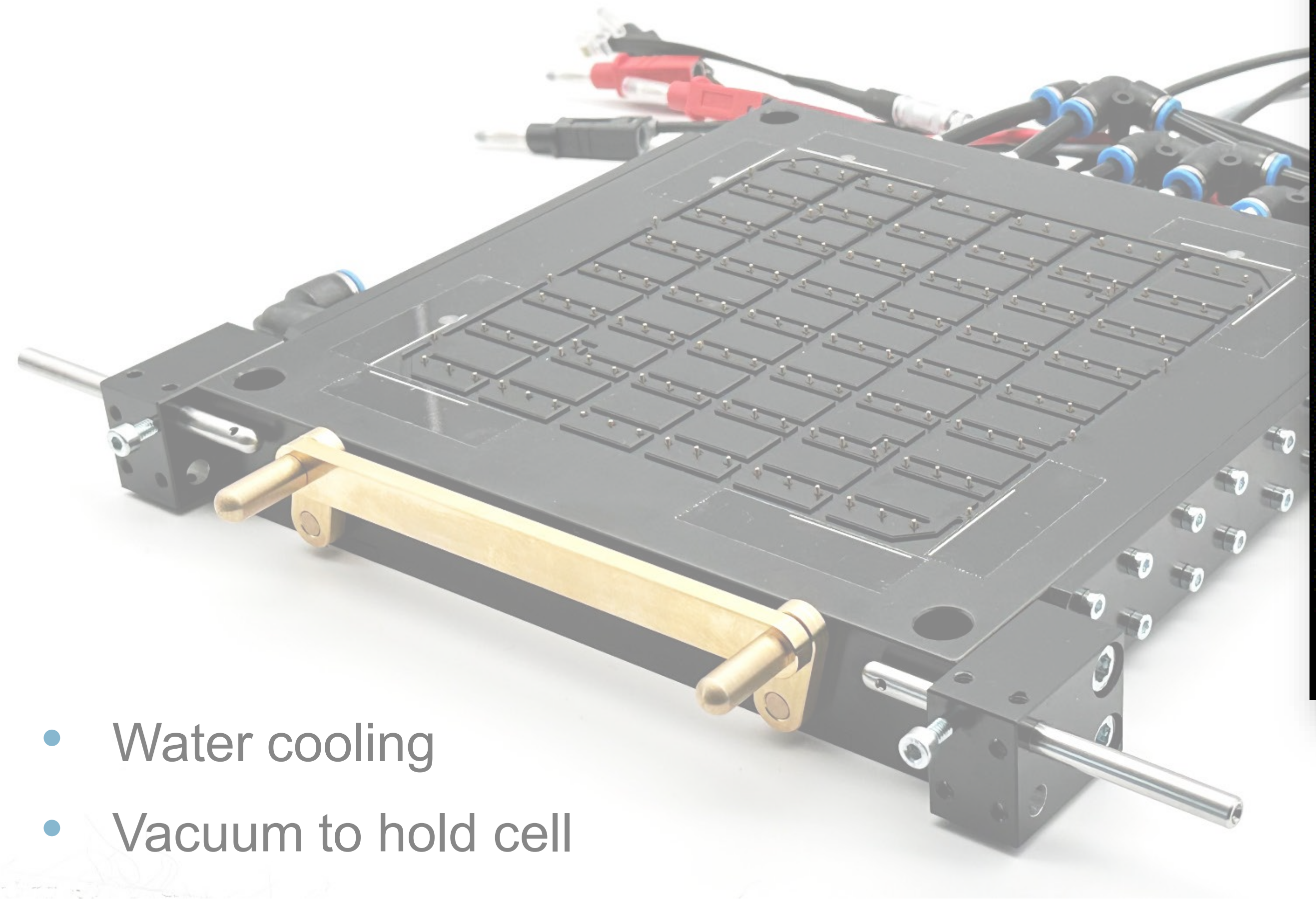
Contacting bare back contact cells – fakir chuck

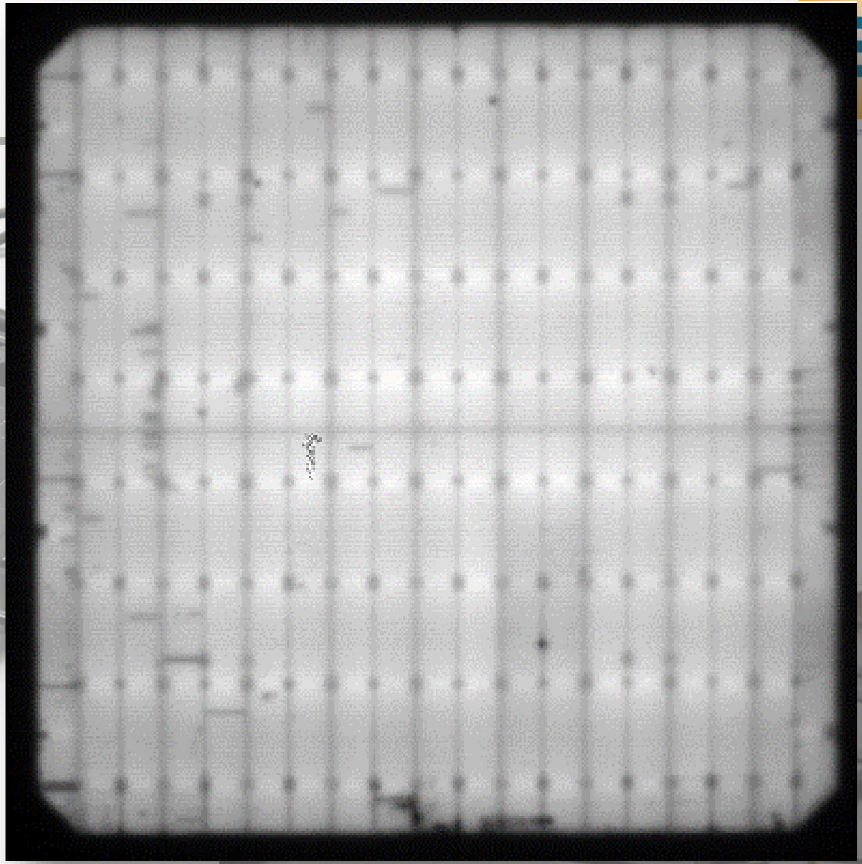


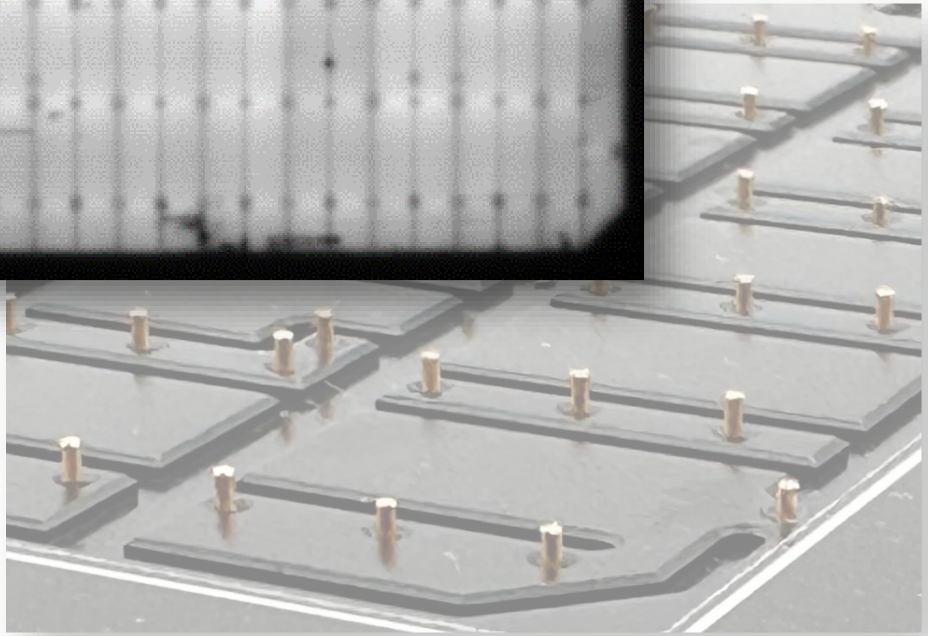


- Water cooling
- Vacuum to hold cell
- Correct sensing
- Homogenous contacting

Contacting bare back contact cells

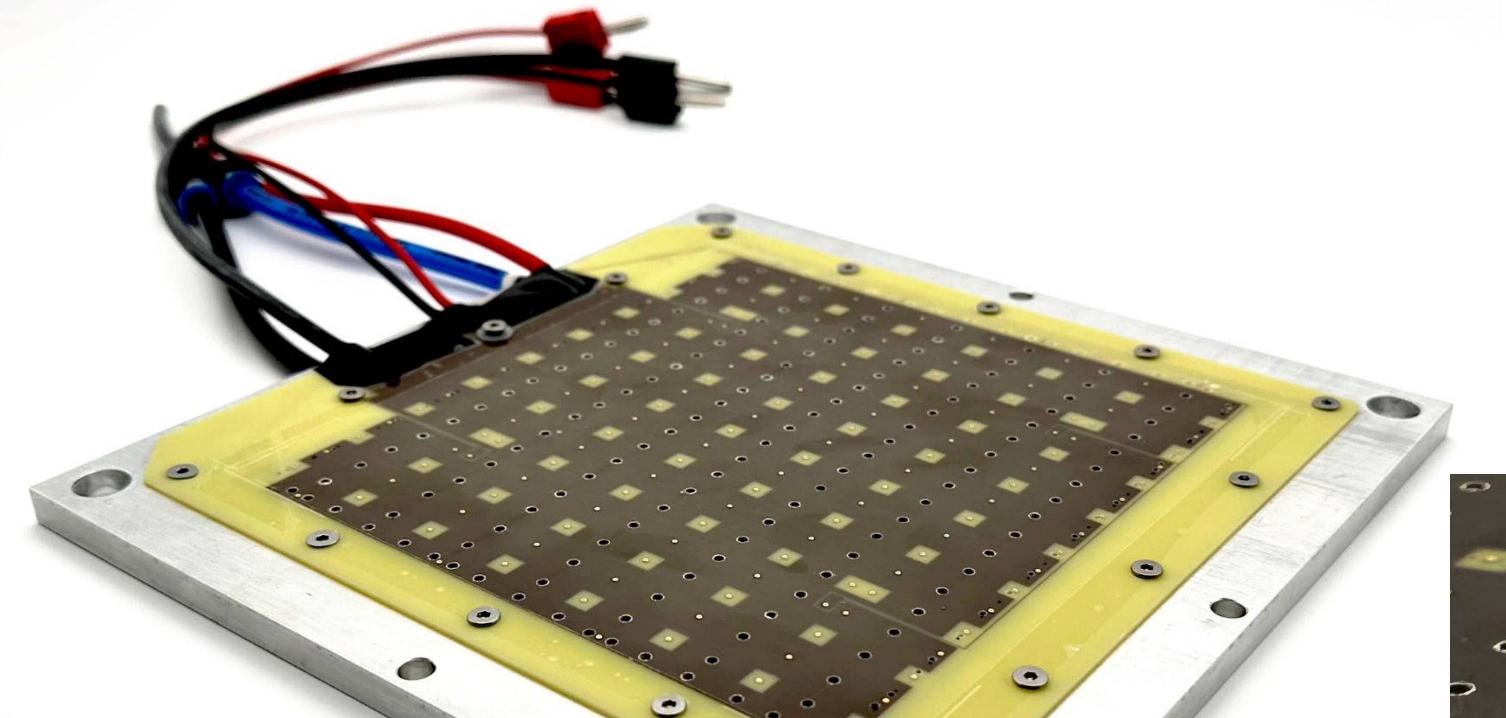




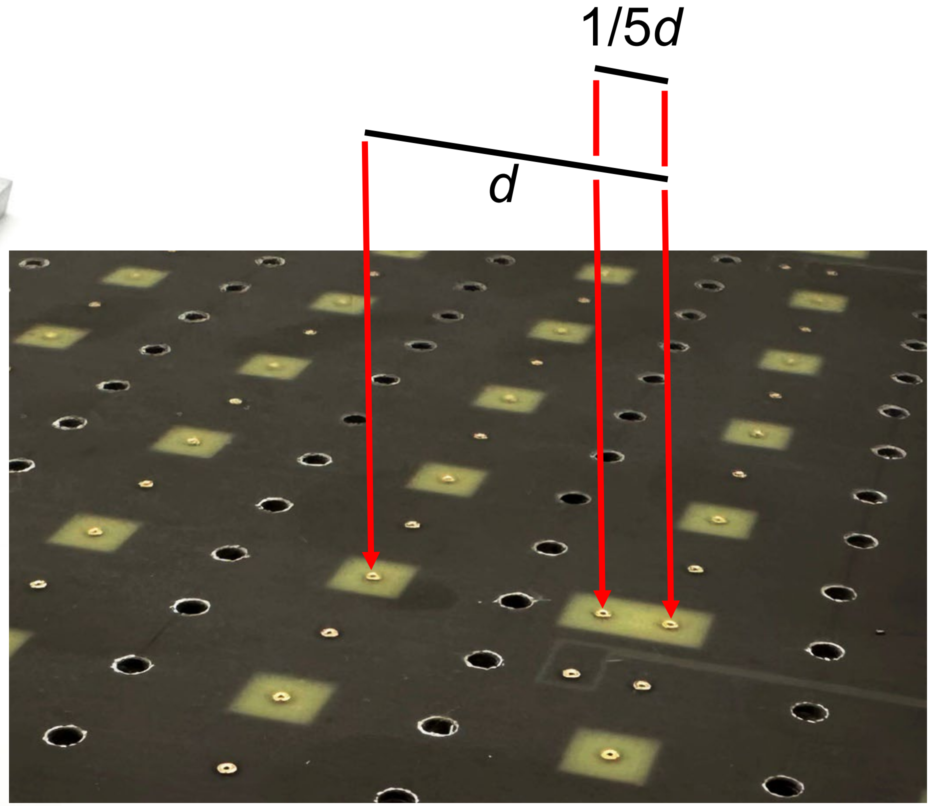


- Water cooling
- Vacuum to hold cell
- Correct sensing
- Homogenous contacting

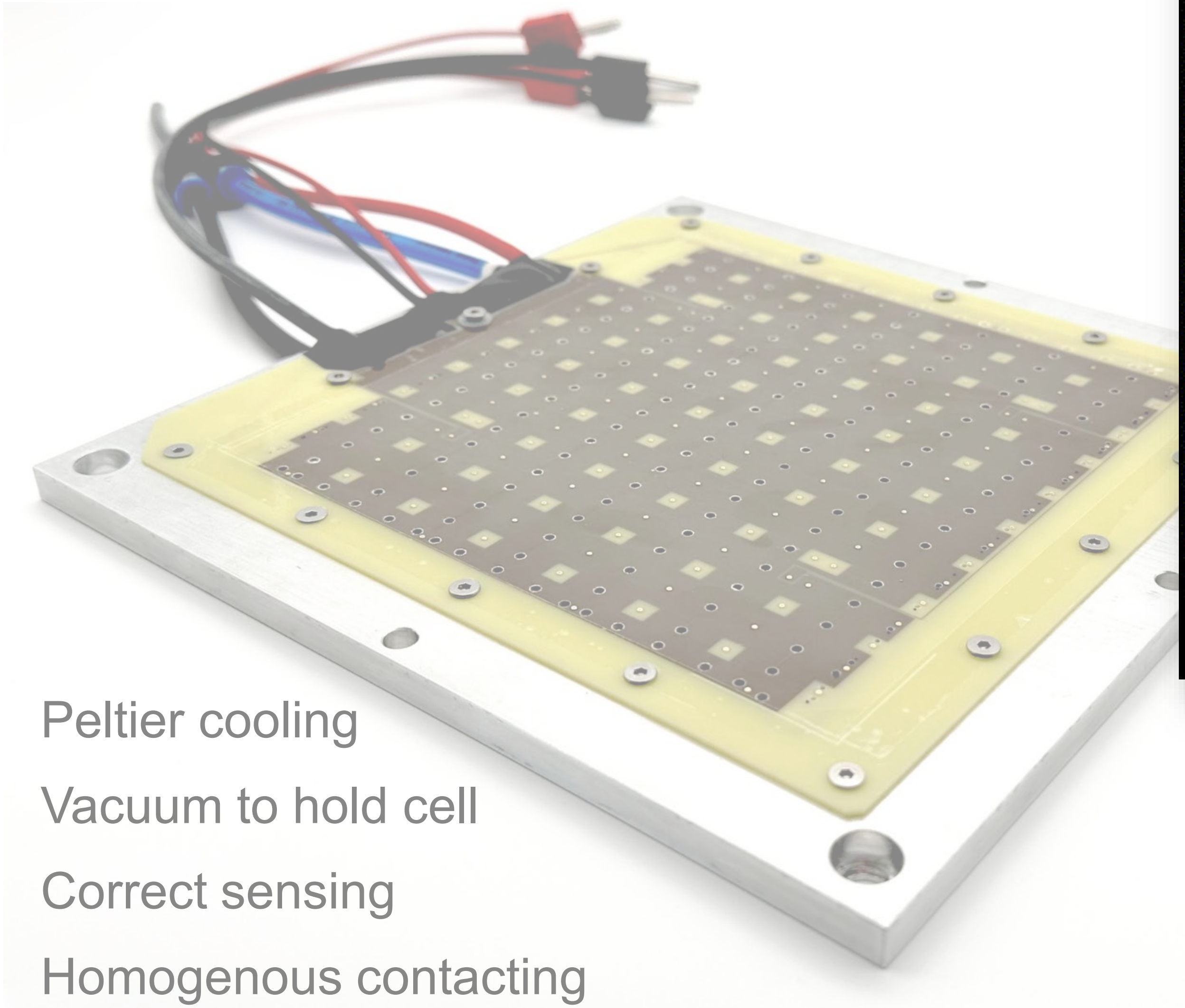
Contacting bare back contact cells – PCB chuck

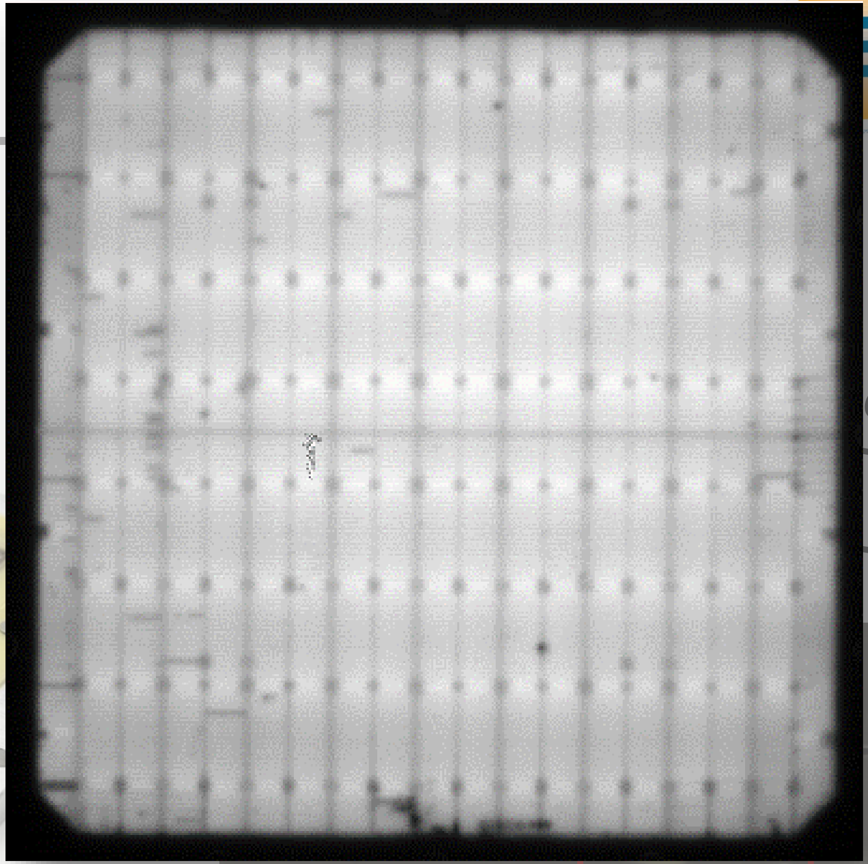


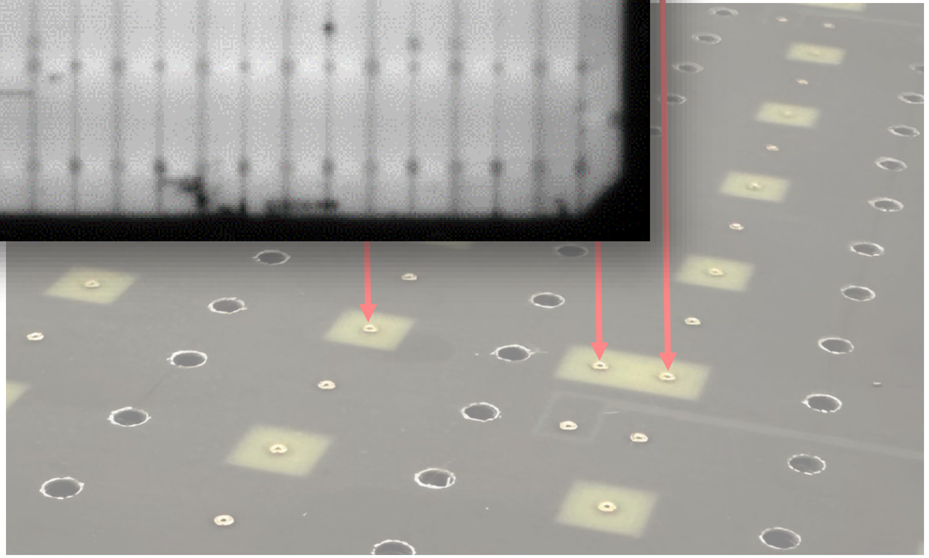
- Peltier cooling
- Vacuum to hold cell
- Correct sensing
- Homogenous contacting



Contacting bare back contact cells

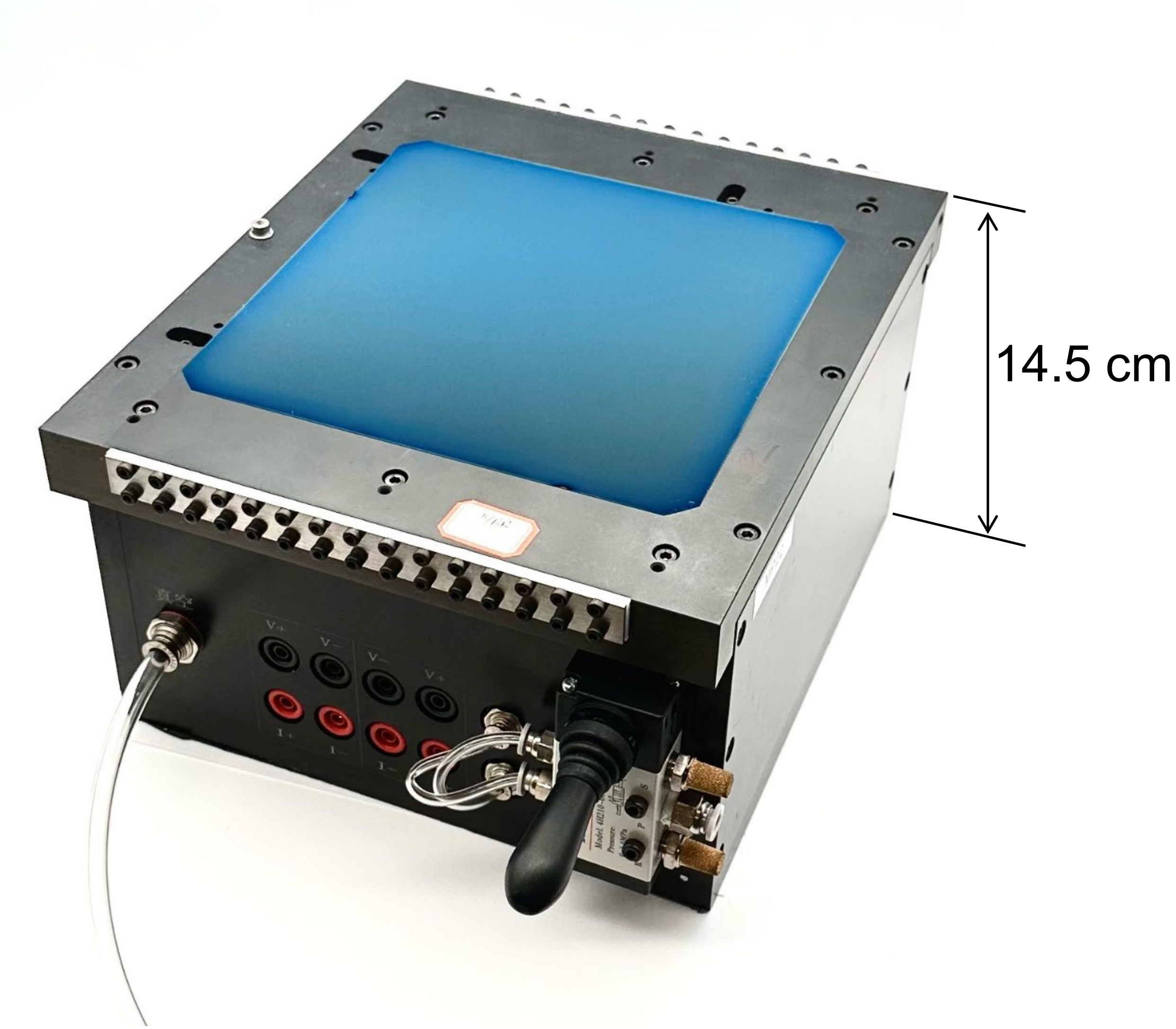






- Peltier cooling
- Vacuum to hold cell
- Correct sensing
- Homogenous contacting

Customer contacting units

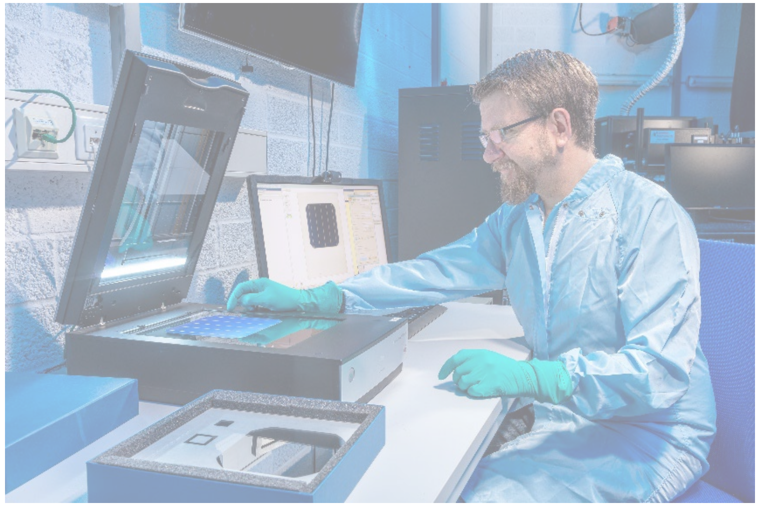


Acceptance tests (selected criteria):

- Temperature:
  - Thermal contact area > 50%
  - Thermalization to 25°C under illumination possible
  - Temperature homogeneity better than ± 0.25 °C
- Electrical contact:
  - 4-wire contacting realized
  - Sense contact position correct
  - Robustness of cables, plugs and sockets OK
  - Lateral EL distribution only due to cell "features" (busbar & finger resistance, wafer inherent or process induced defects) not due to bad contacting pins (inhomogeneous contacting resistance)
  - Reproducibility of V_{OC} better than ± 0.3 mV
  - Reproducibility of FF ± 0.3 $\%_{abs}$

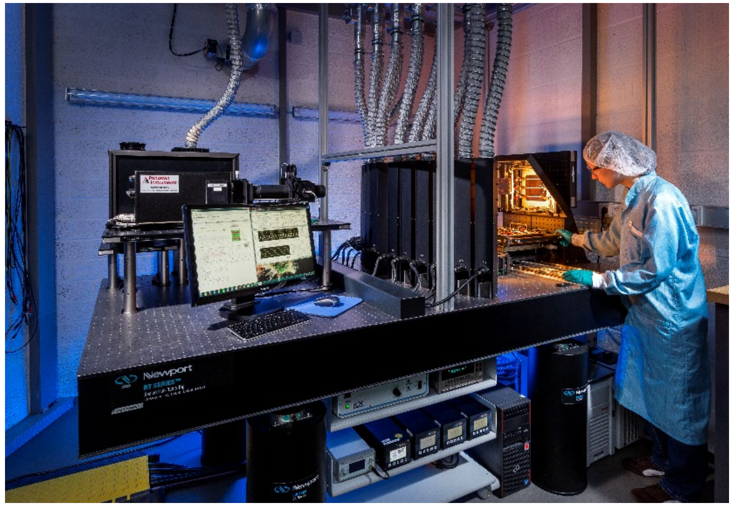
Calibration of solar cells in three steps

Area (cell (TA) or mask (DA))



- Required for efficiency calculation

Spectral Responsivity



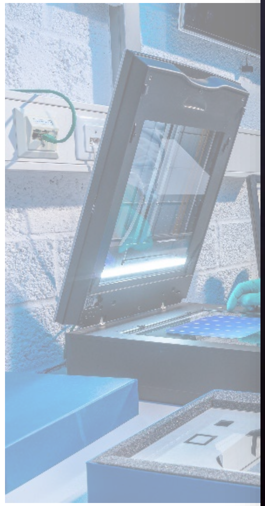
- Required for spectral mismatch correction
- Provides information about linearity

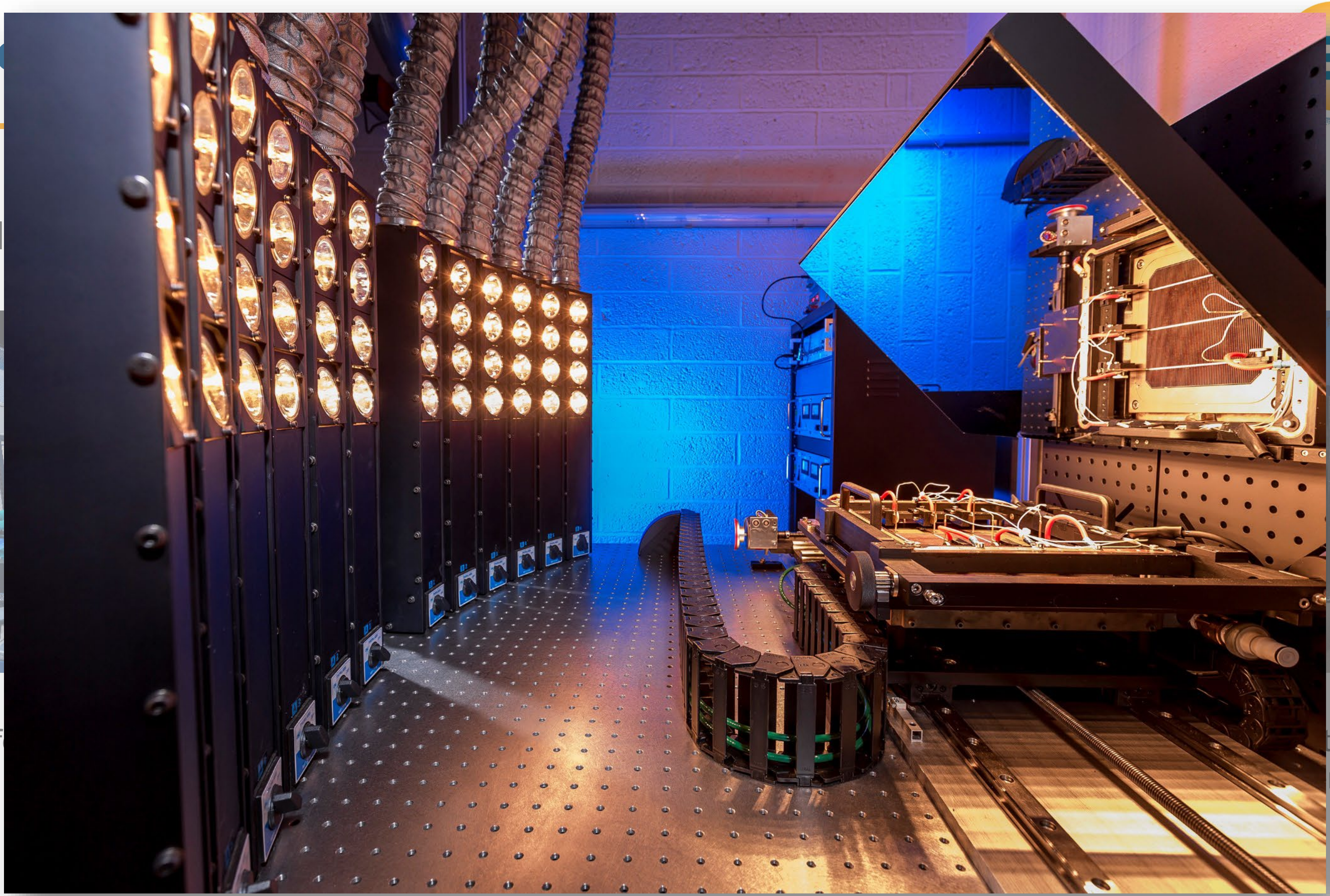
Current-Voltage Chracteristic

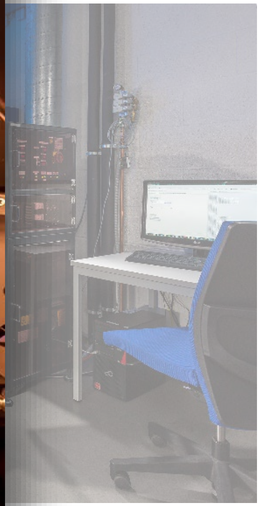
- Required for determination of characteristic parameters I_{sc}, V_{oc}, P_{max}, FF and efficiency

Calibrati

Area (cell







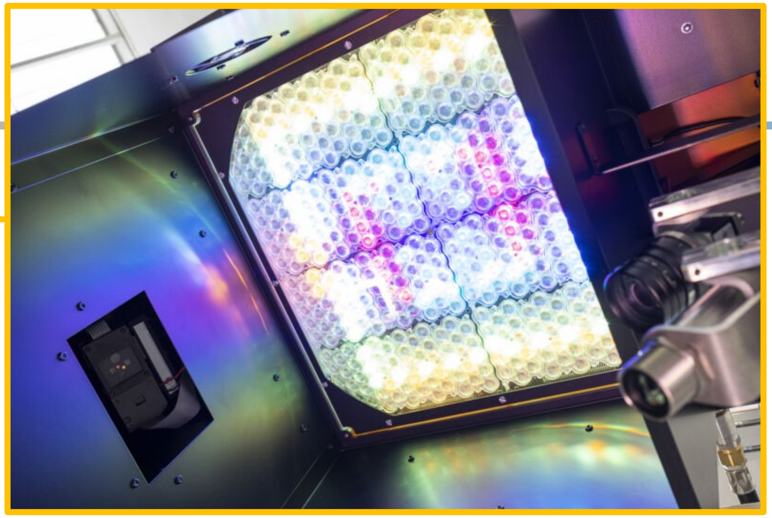
racteristic

- Required f

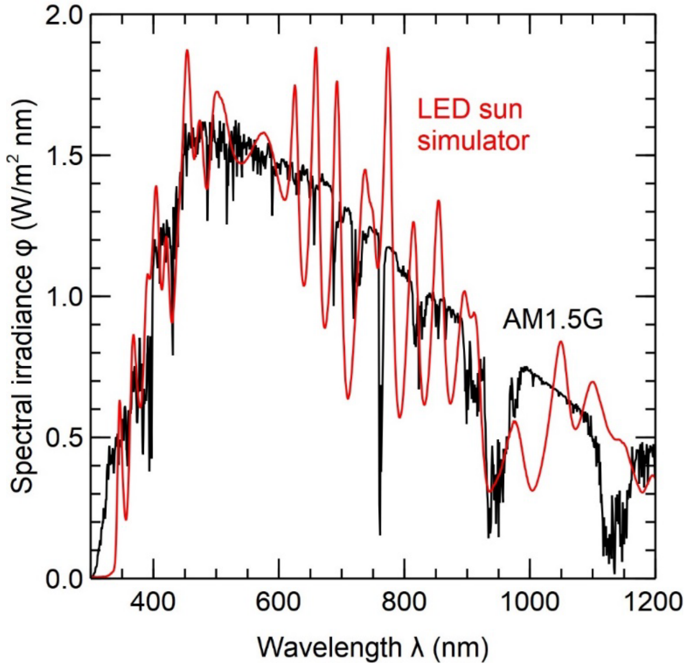
tion of

rs I_{sc}, V_{oc},

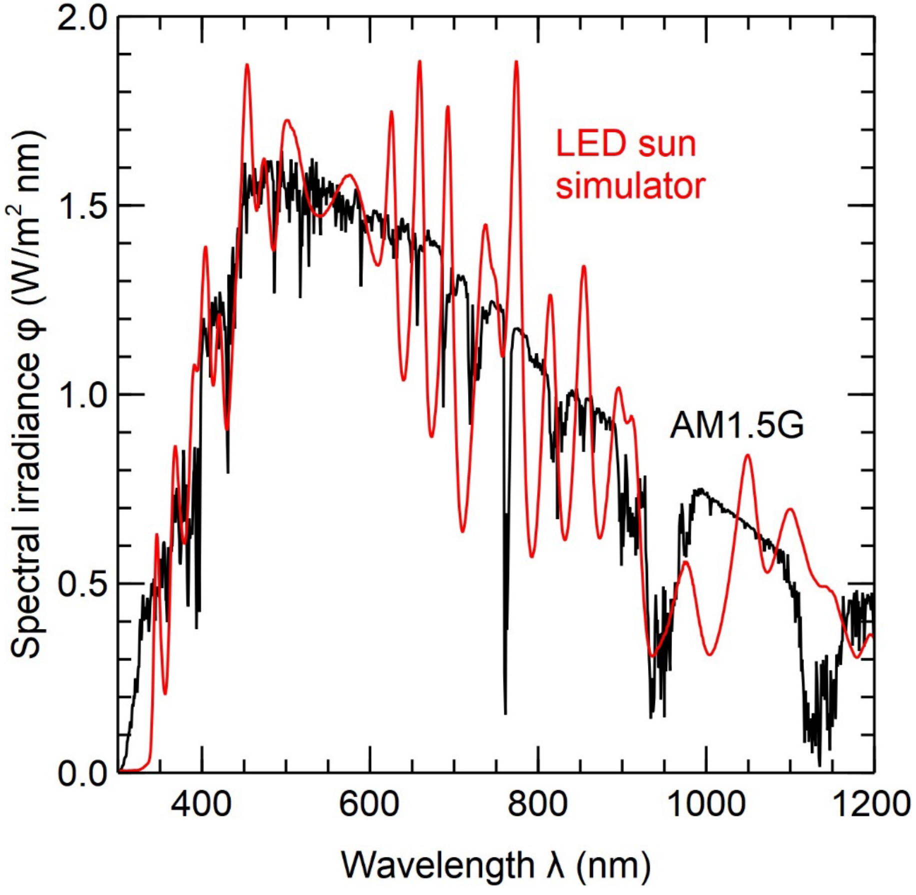
LED sun simulators

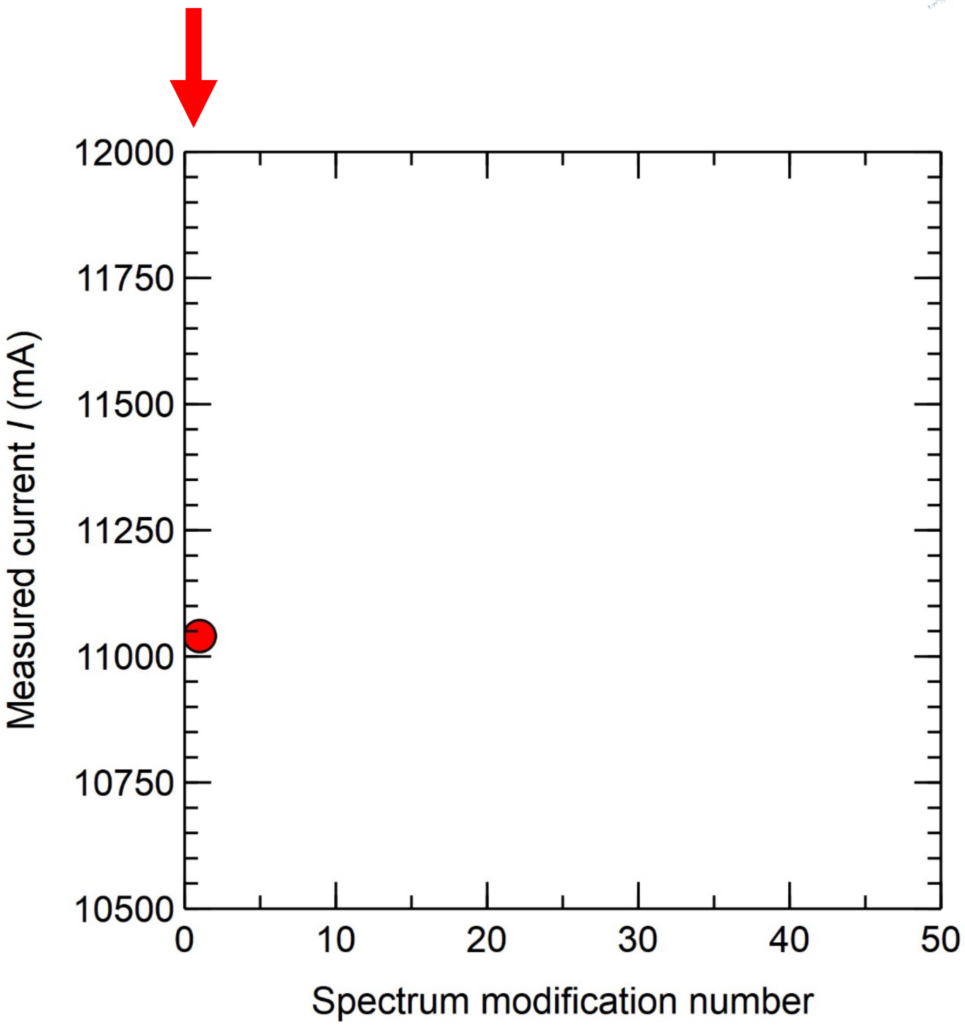


Picture from WAVELABS Solar Metrology Systems GmbH

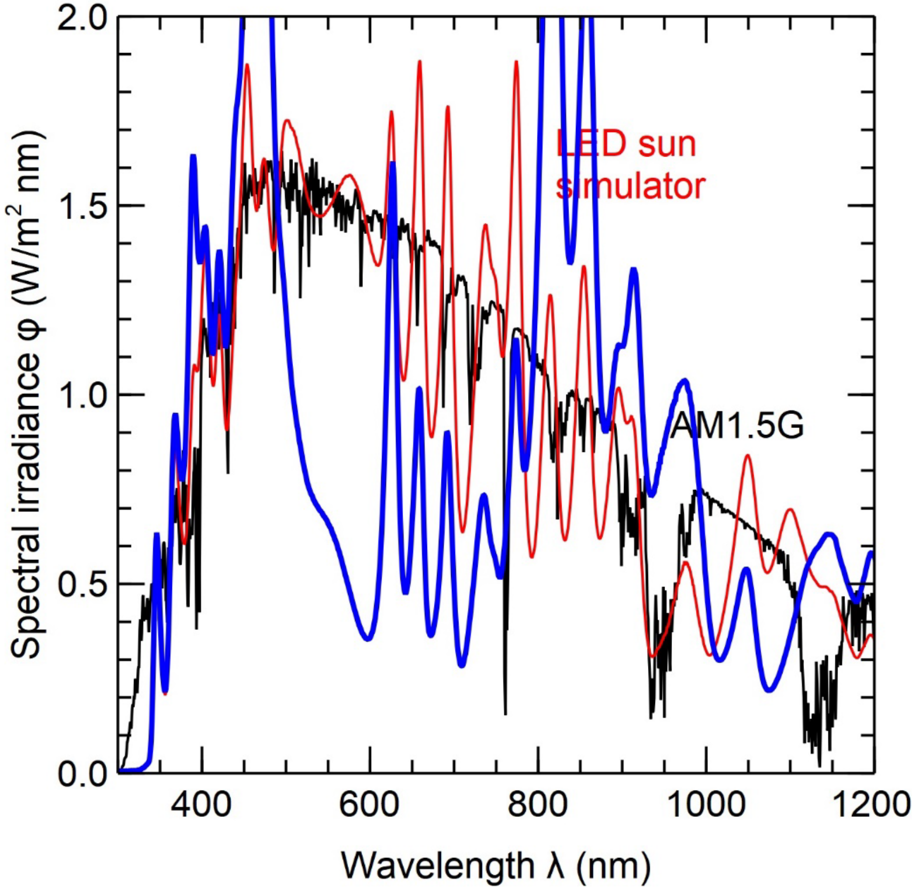


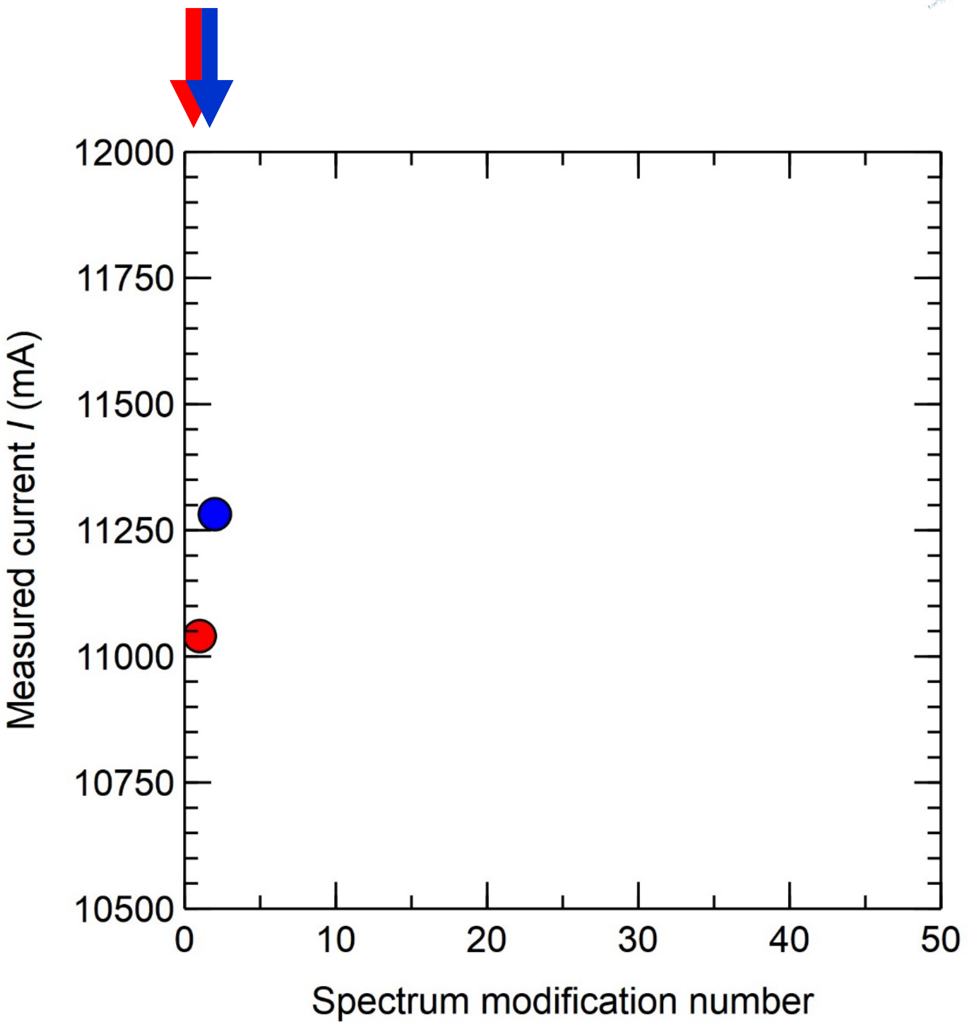
Base spectrum



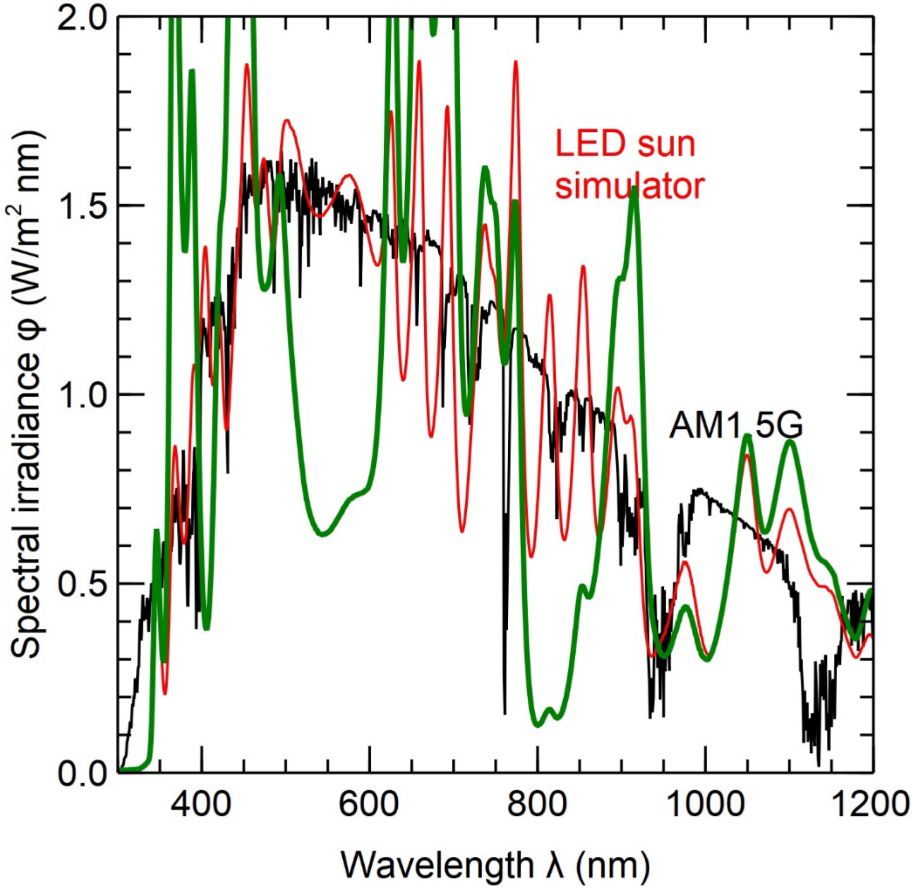


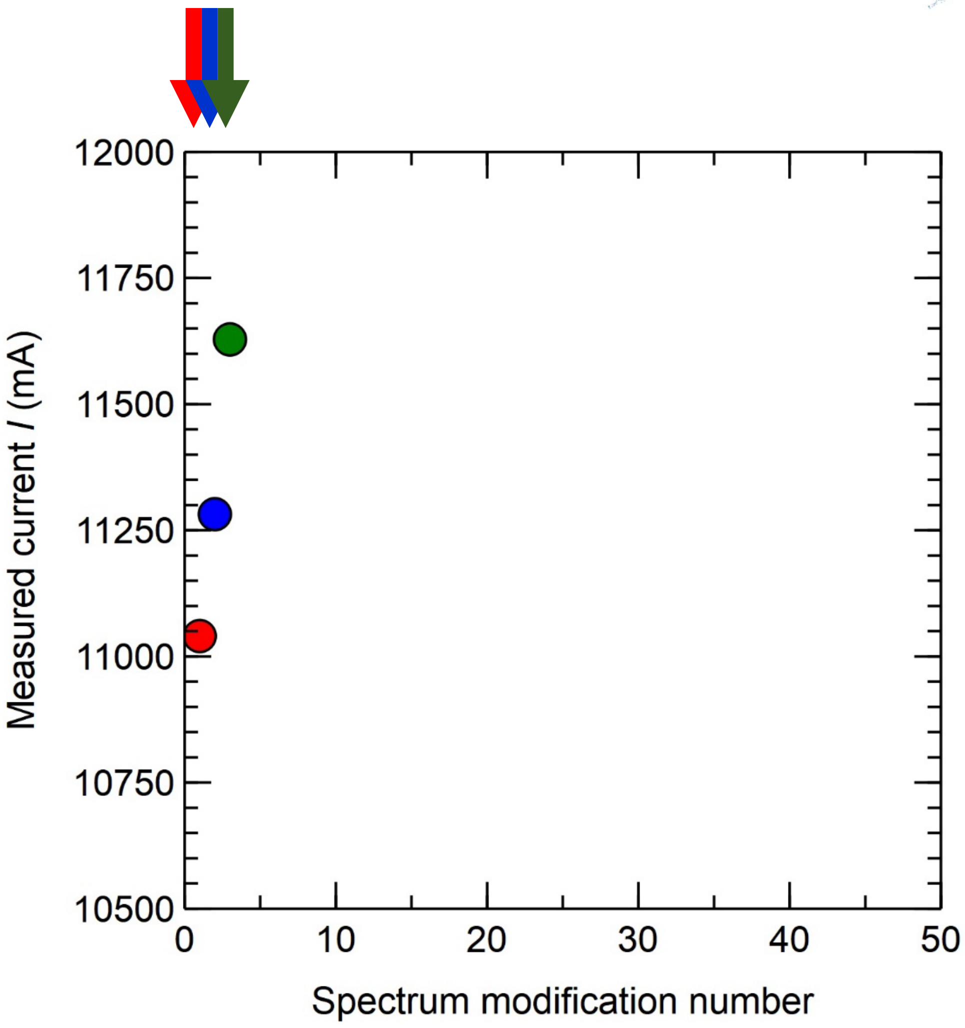
Spectral modification 1



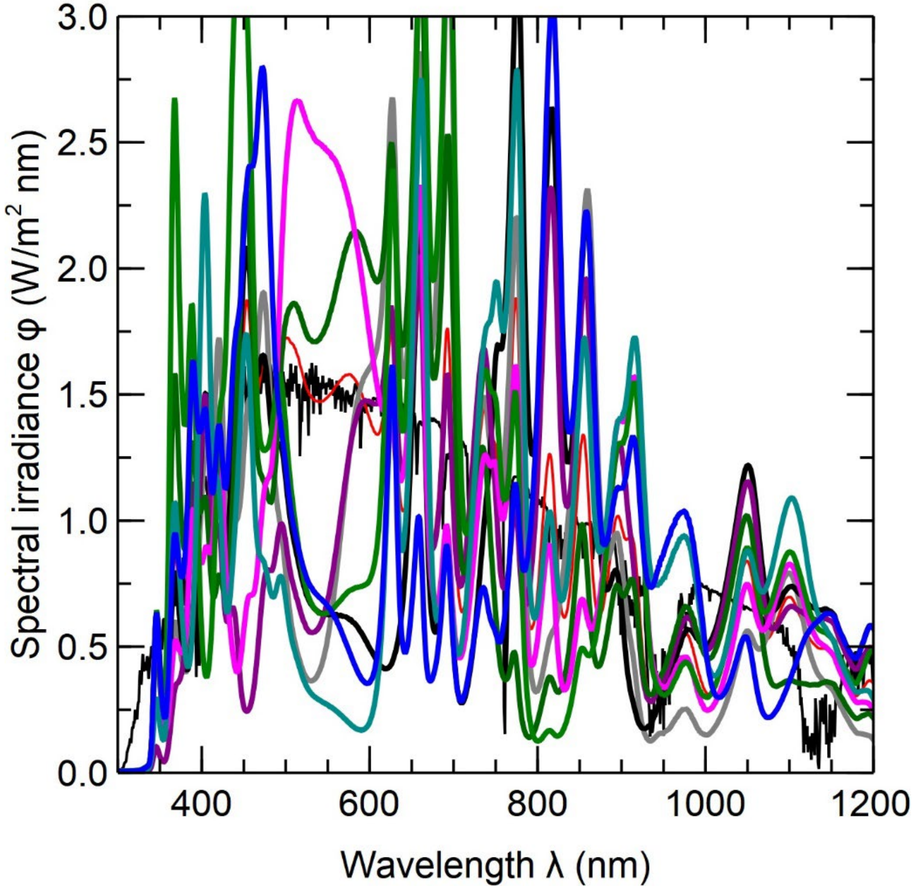


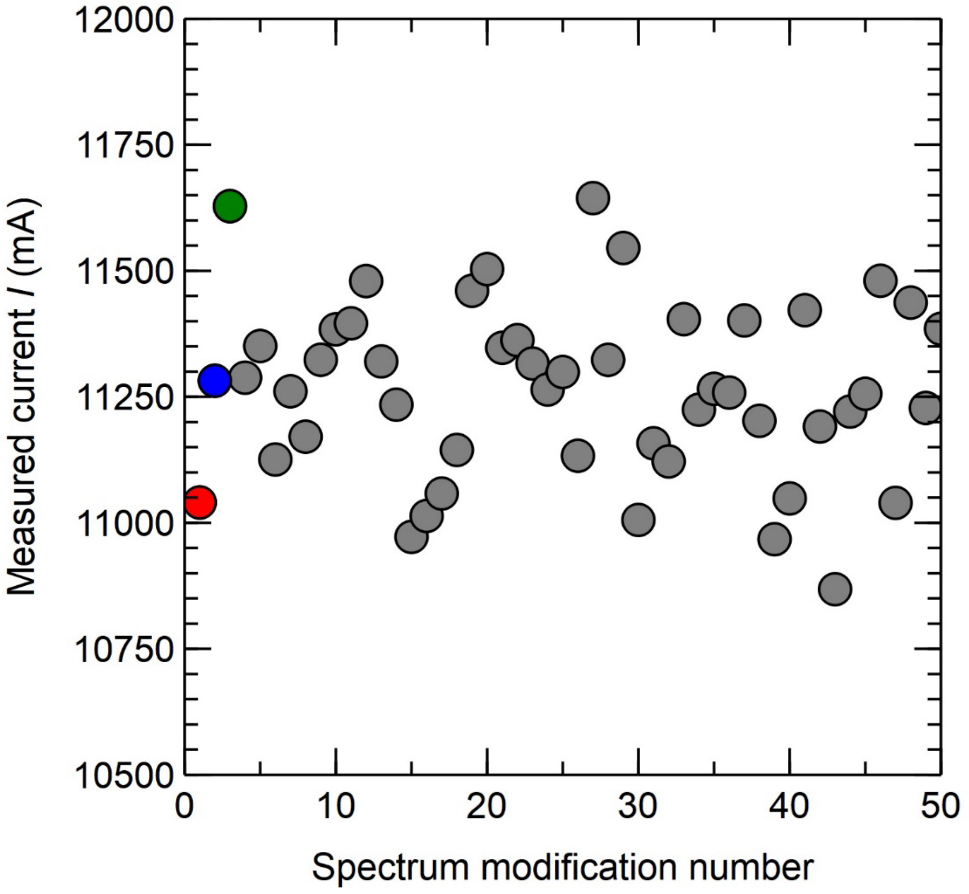
Spectral modification 2



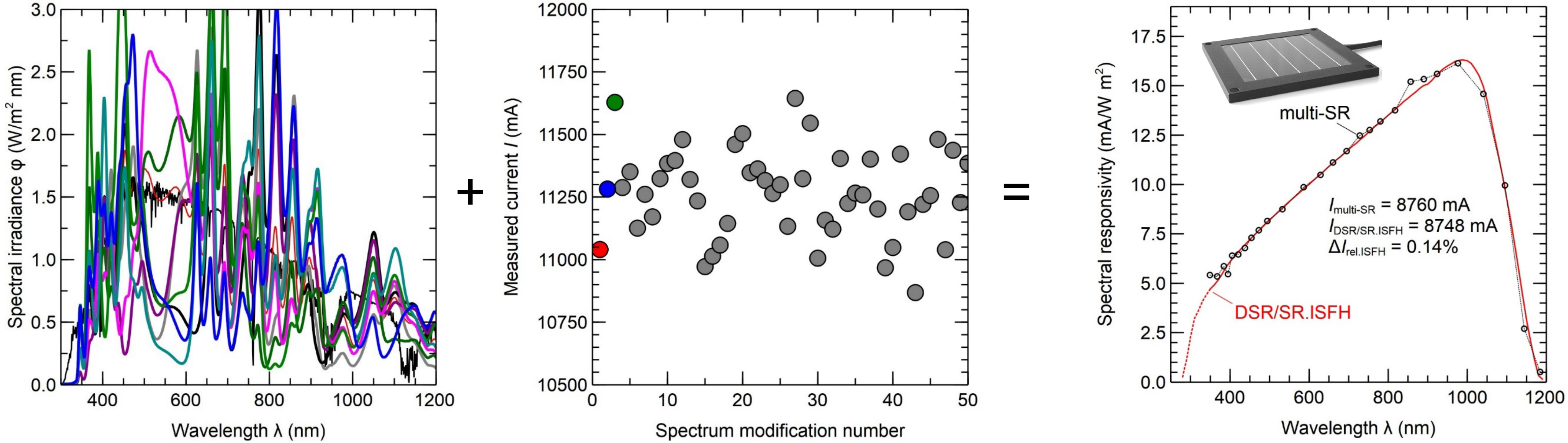


Spectral modification 1 to 50





Multi-spectrum SR using a LED solar simulator



Multi-spectrum SR using a LED solar simulator

ISFH CalTeC

Solar RRL

Research Article

Multi-Spectrum Method for the Determination of the Spectral Responsivity and the Short-Circuit Current of Photovoltaic Devices

David Hinken, Carsten Schinke, Karsten Bothe, Rolf Brendel

First published: 12 May 2023 | https://doi.org/10.1002/solr.202300240

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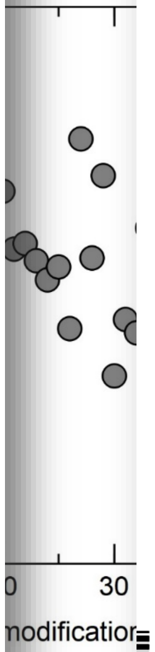
Abstract

Herein, a method for the determination of the spectral responsivity (SR) and the short-circuit current under standard test conditions of photovoltaic devices (e.g., solar cells) is presented. This multi-spectrum SR method requires a spectrally tunable broadband light



(12) NACH DEM VERTRAG ÜBER DIE INTERNATIONALE ZUSAMMENARBEIT AUF DEM GEBIET DES PATENTWESENS (PCT) VERÖFFENTLICHTE INTERNATIONALE ANMELDUNG

(19) Weltorganisation für geistiges Eigentum
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WO 2024/179827 A1

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(21) Internationales Aktenzeichen: PCT/EP2024/053584

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(71) Anmelder: INSTITUT FÜR SOLARENERGIEFORSCHUNG GMBH [DE/DE]; Am Ohrberg 1, 31860 Emmerthal (DE).

(72) Erfinder: **HINKEN, David**; Hauptstr. 53, 30457 Hannover (DE). **BOTHE, Karsten**; Notenstecherweg 5, 31789 Hameln (DE). **SCHINKE, Carsten**; Asternstr. 1, 30974 Wennigsen (DE).

(74) Anwalt: **QIP PATENTANWÄLTE, DR. KUEHN & PARTNER MBB**; Bavariaring 10, 80336 München (DE).

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(54) Title: APPARATUS AND METHOD FOR MULTISPECTRAL DETERMINATION OF SPECTRAL IRRADIANCE SENSITIVITY AND VOLTAGE-DEPENDENT CURRENT BEHAVIOR OF PHOTOVOLTAIC UNITS

Record BC cells calibrated at ISFH

Progress in Photovoltaics: Research and Applications

WILEY

PROGRESS IN PHOTOVOLTAICS

SHORT COMMUNICATION

Solar Cell Efficiency Tables (Version 65)

Martin A. Green[1] | Ewan D. Dunlop[2] | Masahiro Yoshita[3] | Nikos Kopidakis[4] | Karsten Bothe[5] | Gerald Siefer[6] | Xiaojing Hao[1] | Jessica Yajie Jiang[1]

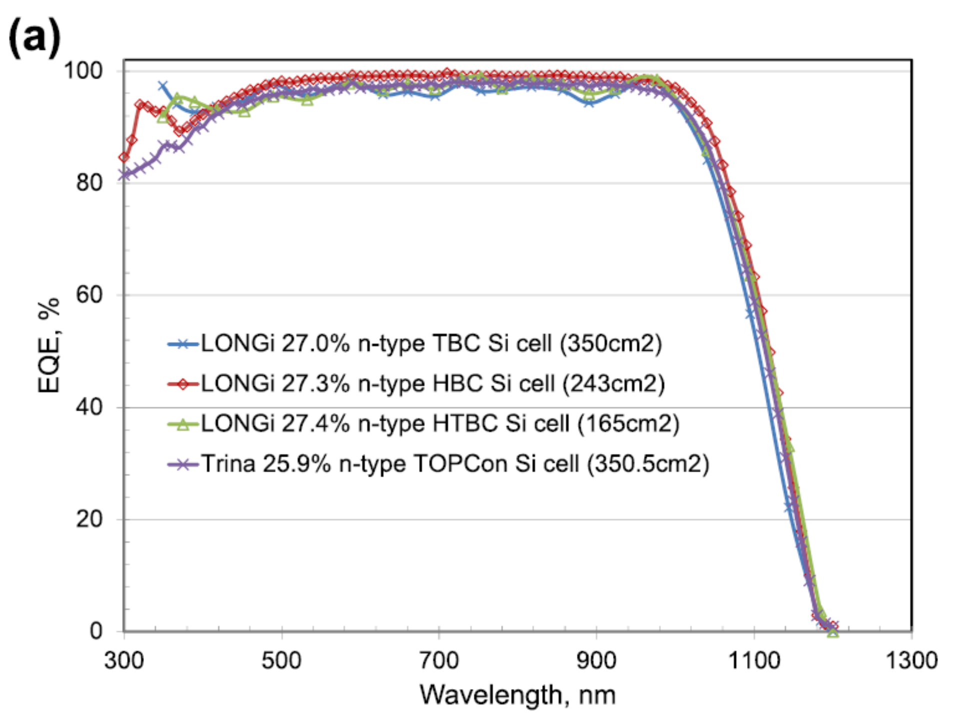

TABLE 1 | Confirmed single-junction terrestrial cell and submodule efficiencies measured under the global AM1.5 spectrum (1000 W/m²) at 25°C (IEC 60904-3: 2008 or ASTM G-173-03 global).

Classification	Efficiency (%)	Area (cm²)	V_{oc} (V)	J_{sc} (mA/cm²)	Fill factor (%)	Test centre (date)	Description
Silicon							
Si (crystalline cell)	**27.4 ± 0.4[a]**	**165.72 (t)**	**0.7456**	**42.35[b]**	**86.7**	**ISFH (9/24)**	**LONGi, n-type HTBC** [4]
Si (thin transfer submodule)	21.2 ± 0.4	239.7 (ap)	0.687[c]	38.50[c,d]	80.3	NREL (4/14)	Solexel (35 μm thick) [5]
Si (thin-film minimodule)	10.5 ± 0.3	94.0 (ap)	0.492[c]	29.7[c,e]	72.1	FhG-ISE (8/07)	CSG Solar (< 2 μm on glass) [6]

TABLE 2 | 'Not… …er the global AM1.5 spec…

Classification							
Cells (silicon)							
Si	25.0 ± 0.5	4.00 (da)	0.706	42.7[a]	82.8	Sandia (3/99)	UNSW, p-type PERC [30]
			0.7241	42.87[c]	83.1	FhG-ISE (7/17)	FhG-ISE, n-type TOPCon [31]
			0.7323	42.05[d]	84.3	FhG-ISE (11/19)	FhG-ISE, p-type TOPCon
			0.7266	42.62[e]	84.3	ISFH (2/18)	ISFH, p-type TBC [32]
			0.6940	41.58[g]	83.3	ISFH (7/19)	LONGi, p-type PERC [33]
			0.7383	**41.70[i]**	**84.1**	**ISFH (10/24)**	**TRINA, n-type TOPCon** [34]
Si (large)	**27.0 ± 0.5[j]**	**350.0 (t)**	**0.7447**	**42.32[k]**	**85.8**	**ISFH (8/24)**	**LONGi, n-type TBC** [4]
Si (large)	26.8 ± 0.4[l]	274.4 (t)	0.7514	41.45[m]	86.1	ISFH (10/22)	LONGi, n-type HJT [35]
Si (large)	26.6 ± 0.4[l]	274.1 (t)	0.7513	41.30[m]	85.6	ISFH (10/22)	LONGi, p-type HJT [36]
Si (large)	**27.3 ± 0.4[n]**	**243.1 (da)**	**0.7434**	**42.60[k]**	**86.2**	**ISFH (12/23)**	**LONGi, n-type HBC** [4]

Thank you for your attention!

Equation system

Equation system 1:

$$I_{\mathrm{sc1}} = \int d\lambda \, \varphi_1(\lambda) SR(\lambda)$$

$$I_{\mathrm{sc2}} = \int d\lambda \, \varphi_2(\lambda) SR(\lambda)$$

$$\vdots$$

$$I_{\mathrm{scM}} = \int d\lambda \, \varphi_{\mathrm{M}}(\lambda) SR(\lambda)$$

Discretization

Equation system 1:

$$I_{sc1} = \int d\lambda\, \varphi_1(\lambda) SR(\lambda)$$

$$I_{sc2} = \int d\lambda\, \varphi_2(\lambda) SR(\lambda)$$

.
.
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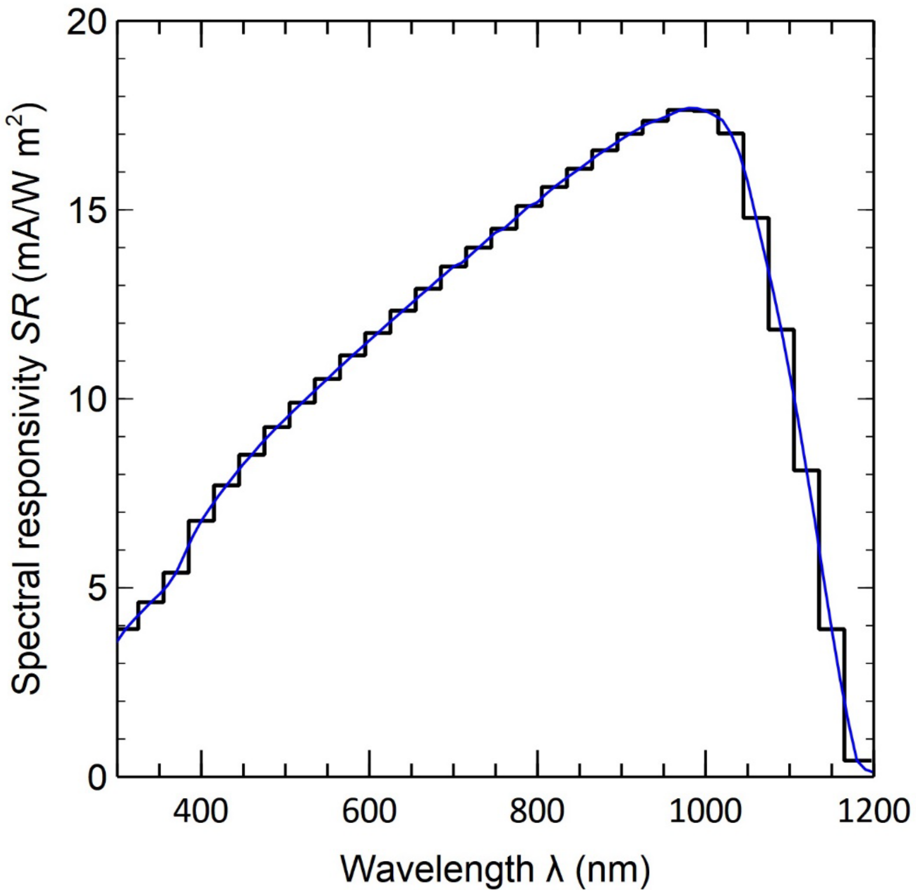
$$I_{scM} = \int d\lambda\, \varphi_M(\lambda) SR(\lambda)$$



- Discretization of SR curve into N intervals
- Obtain second equation system

Solving

Equation system 1:

$$I_{sc1} = \int d\lambda\, \varphi_1(\lambda) SR(\lambda)$$

$$I_{sc2} = \int d\lambda\, \varphi_2(\lambda) SR(\lambda)$$

$$\vdots$$

$$I_{scM} = \int d\lambda\, \varphi_M(\lambda) SR(\lambda)$$

Equation system 2:

$$I_{sc1} = \sum_{k=1}^{N} \int_{\lambda_k}^{\lambda_k} d\lambda\, \varphi_1(\lambda) SR_k$$

$$I_{sc2} = \sum_{k=1}^{N} \int_{\lambda_k}^{\lambda_k} d\lambda\, \varphi_2(\lambda) SR_k$$

$$\vdots$$

$$I_{scM} = \sum_{k=1}^{N} \int_{\lambda_k}^{\lambda_k} d\lambda\, \varphi_1(\lambda) SR_k$$

- Discretization of SR curve into N intervals
- Obtain second equation system
- Solvable with least-square algorithm with N unknowns
- Result: $SR_1, \ldots, SR_N$