Solar Simulation Standards and QuickSun® Measurement System

Antti Tolvanen

Endeas Oy

Endeas in Brief

- QuickSun® Solar Simulators
- Technology invented 1996 in Fortum (www.fortum.com)
- Endeas Oy licenses technology 2001
- Endeas today:
  - ✓ > 200 simulators delivered
  - ✓ turnover ~ 4 M€

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Solar simulation

- Measurement of the electrical characteristics (most important P_{max}) of solar cells and modules at comparable and repeatable conditions
- International and national standards specify simulator performance requirements and measurement methods and conditions
- Done mainly to verify quality of solar cells and sort according to power, and to inspect and sort final products in PV module manufacturing. Important also in R&D.
- Standard testing conditions (STC)
  - 1000 W/m^2
  - 25°C
  - AM1.5G spectrum
- Correction procedures for temperature and irradiance

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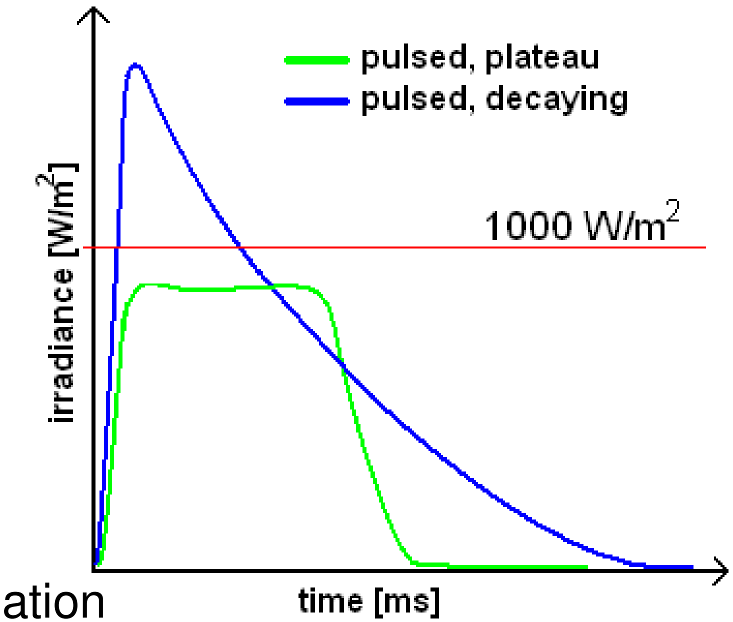
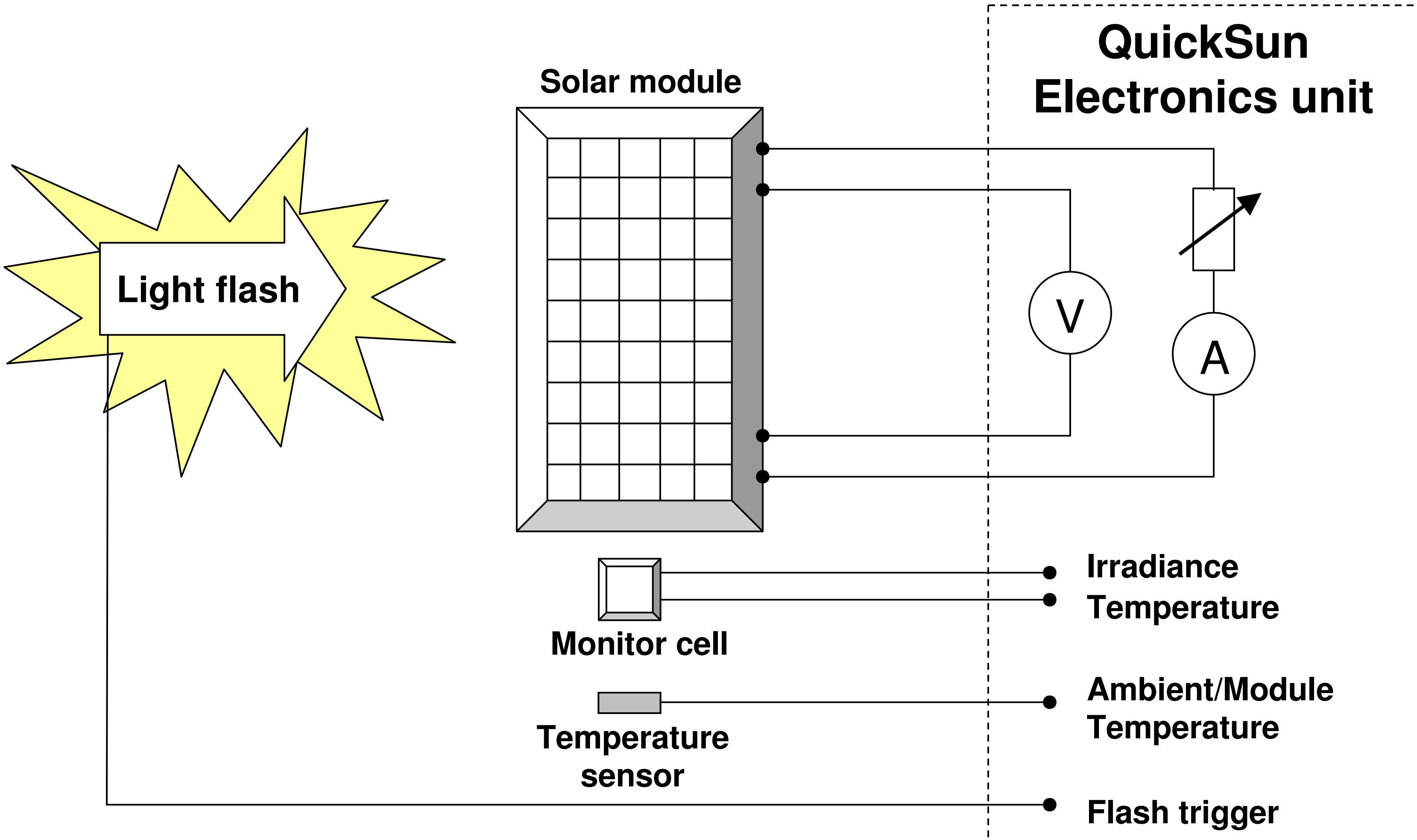
Simulator types

- Steady state / constant light
  - Heat load, cooling, high power consumption
- Pulsed light
  - No heating of the sample
  - Fast measurement, no temperature leveling
- Pulsed light, decaying
  - Can measure easily at different irradiation levels
    - ➢ Measurement of series resistance
  - High peak irradiance easily reached
  - More refined analysis possible (IDCAM)

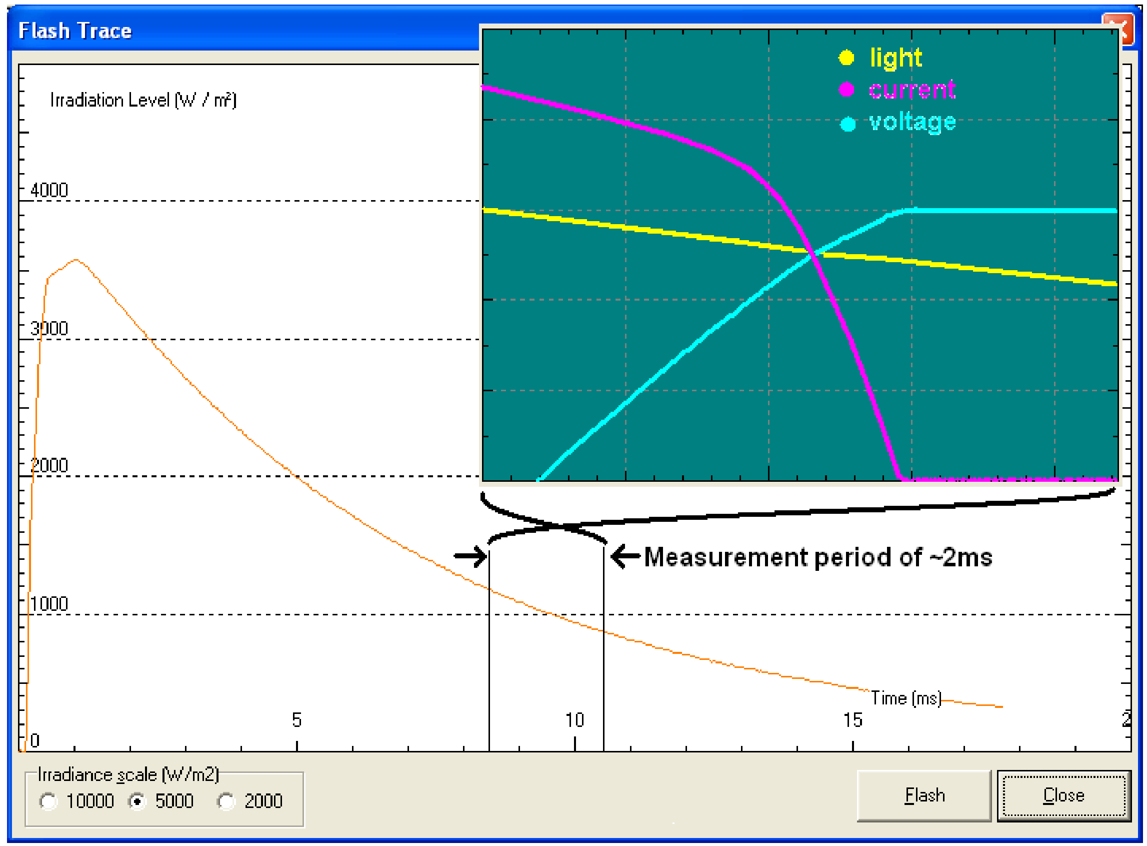


Measurement principle



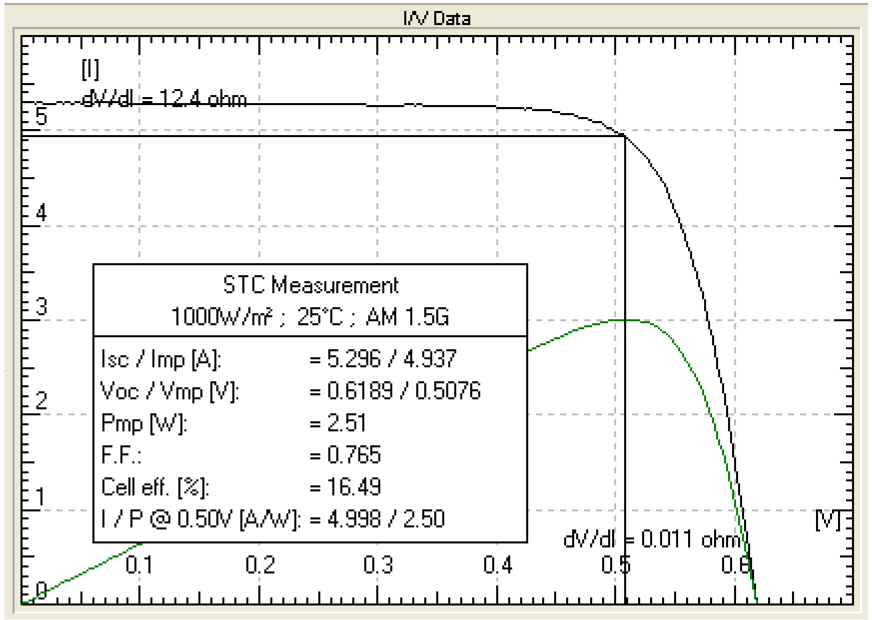
Measurement principle, cont.

- Flash pulse is triggered, irradiance measured with monitor cell.
- When target irradiance level is reached, I-V measurement initiated. Typically at 1200 W/m².
- Module is swept from short circuit to open circuit during the following approx. 2 ms. Voltage, current and irradiance signals are recorded simultaneously.



Measurement principle, cont.

- QuickSun measures 4096 raw data points for each signal; current, voltage and irradiance
- Data is averaged in groups of eight to obtain 512 I-V graph data points. This reduces measurement noise.
- Measured I-V data is corrected for irradiance and temperature to defined conditions.
- The I-V curve is obtained, with relevant measurement parameters.



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International Standards for solar simulation

- Solar simulator performance requirements
  - IEC 904-9 (2nd ed.)
- Cell and module measurement procedure
  - IEC 904-1 (2nd ed.)
- Irradiance and temperature correction procedures and coefficients
  - IEC 891

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Other relevant standards

- IEC 904-2 Requirements for reference solar devices
  - requirements for selection, packaging, calibration, marking and care of reference solar cells and modules
- IEC 1215 Crystalline silicon terrestrial photovoltaic (PV) modules – Design qualification and type approval
  - type approval: visual inspection, performance@STC, insulation test, determination of α and β, NOCT, performance@NOCT, performance@low irradiance...
- IEC 1646 Thin-film terrestrial photovoltaic (PV) modules – Design qualification and type approval
- IEC 904-3 Measurement Principles for Terrestrial PV Solar Devices with Reference Spectral Irradiance Data
- IEC 904-7 Computation of Spectral Measurement of a PV Device
- IEC 904-8 Guidance for Spectral Measurement of a PV Device

IEC webstore: http://webstore.iec.ch/

Solar simulator performance requirements

- Standard IEC 904-9 describes the requirements for solar simulators.
- The three key aspects of solar simulator performance:
  - Positional non-uniformity
  - Spectral match
  - Temporal instability (short term, long term)
- Can be applied to all PV technologies, but spectral match criteria designed for c-Si
- For performance measurements a class CBA simulator is the minimum
  - (C = Spectrum, B = Non-uniformity, A = STI)
- LTI Specification for Irradiance exposure tests

Characteristic	Class A	Class B	Class C
Spectral match (ratio of the actual percentage of total irradiance to the required percentage specified for each wavelength range)	0,75 – 1,25	0,6 – 1,4	0,4 – 2,0
Non-uniformity of irradiance	< ± 2%	< ± 5%	< ± 10%
Temporal instability, short term, STI	< ± 0.5%	< ± 2%	< ± 10%
Temporal Instability, long term, LTI	< ± 2%	< ± 5%	< ± 10%

Minimum requirements (highlighted: Class C spectral match, Class B non-uniformity, Class A STI)

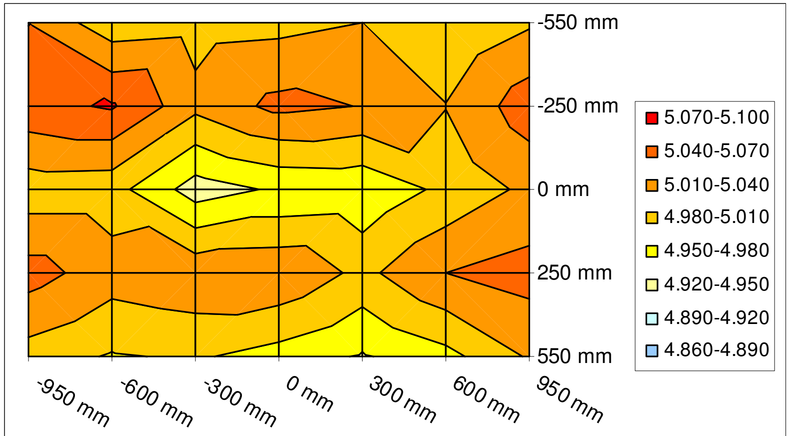
Positional non-uniformity

- Class A requirement: < ± 2%
- In practice, measured using the short circuit current of a single solar cell:

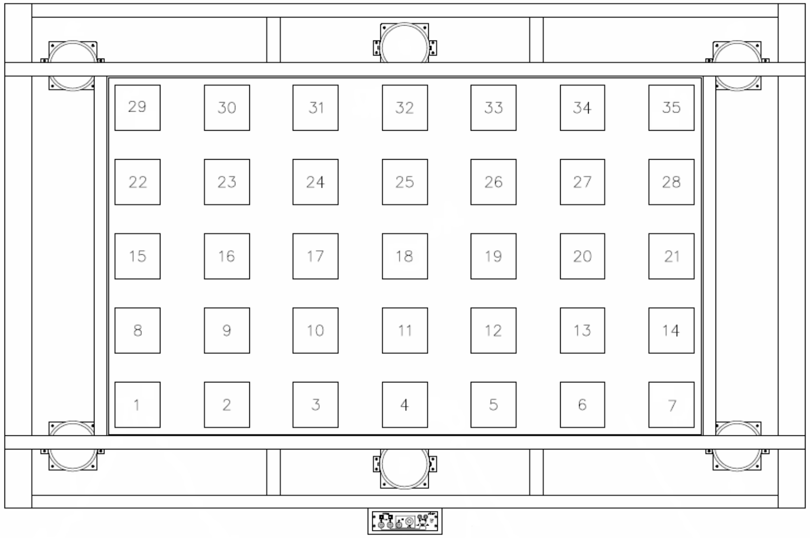
$$\Delta E = \frac{E_{max} - E_{min}}{E_{max} + E_{min}} \cdot 100\%$$

ΔE = positional non-uniformity of irradiance
E_{max} = maximum value of irradiance (maximum I_{SC})
E_{min} = minimum value of irradiance (minimum I_{SC})

- Non-uniformity of QuickSun simulators is routinely checked and easily adjusted and maintained
- The positional non-uniformity of all QuickSun solar simulators is class A



Non-uniformity: ± 1.36 %



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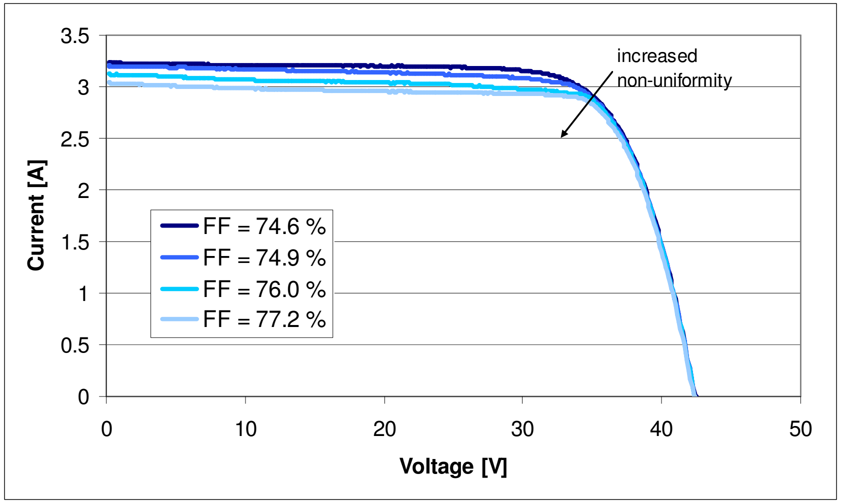
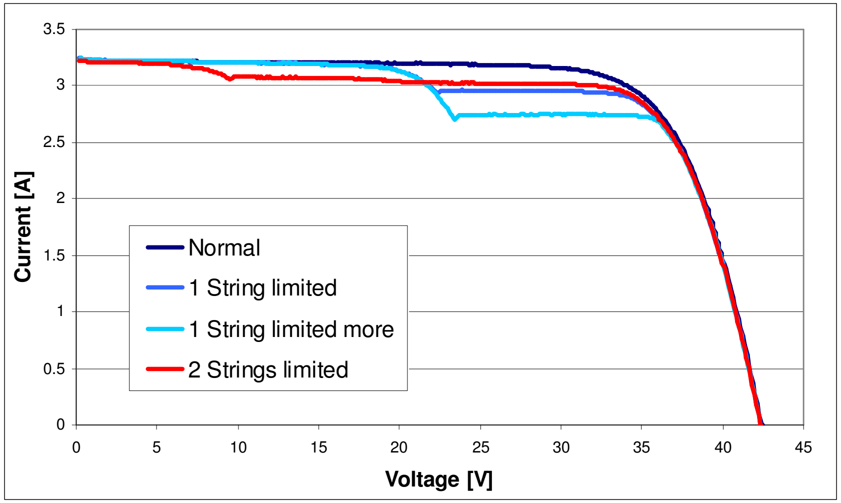
Effects of non-uniformity

- Increasing non-uniformity affects IV curve
- Situation can be identified from elevated FF

- If non-uniformity affects only a part of the module, IV curve is deformed (when module has bypass diodes)

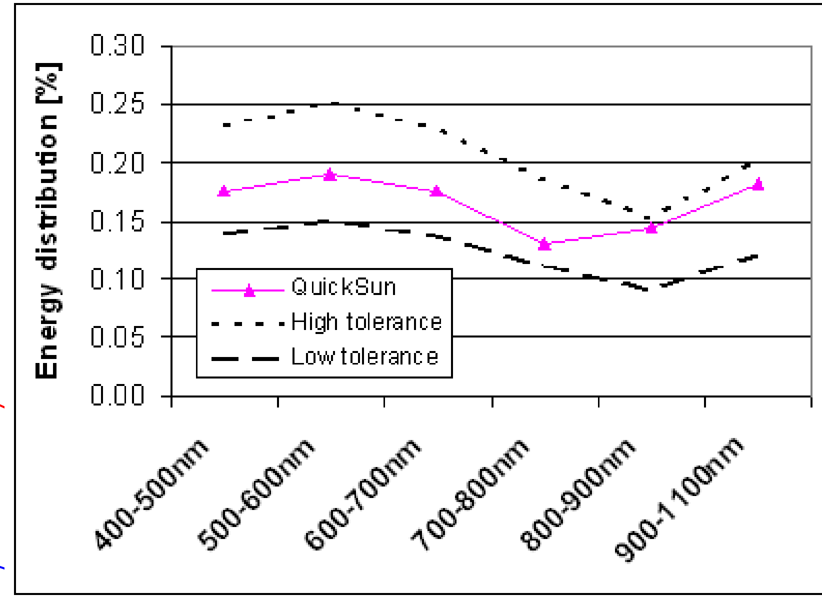




- Current mismatch of cells/strings causes same effects as non-uniform irradiance
- Poor non-uniformity causes problems with irradiance calibration. Module position and orientation affect result.
- If there are no bypass diodes, the effect is always as in left picture

Spectral match

- Defined as the ratio of actual irradiance to the percentage of total irradiance of reference spectrum in distinct wavelength ranges.
- Reference spectrum is AM1.5G
- QuickSun spectrum measured with OceanOptics spectrometer. TÜV using same technology.
- Measurement is triggered at the same instant as the actual I-V measurement, integration time is 3 ms.



Wavelength interval [nm]	Percentage of total irradiance between 400 – 1100 nm, AM1.5G	Typical spectrum of QuickSun solar simulator [%]	ratio, class A: 0.75 – 1.25
400 – 500	18.5	17.6	0.95
500 – 600	20.1	19.0	0.94
600 – 700	18.3	17.6	0.96
700 – 800	14.8	13.1	0.89
800 – 900	12.2	14.5	1.19
900 – 1100	16.1	18.2	1.13
400 – 1100	100	100	⇒ **Class A**

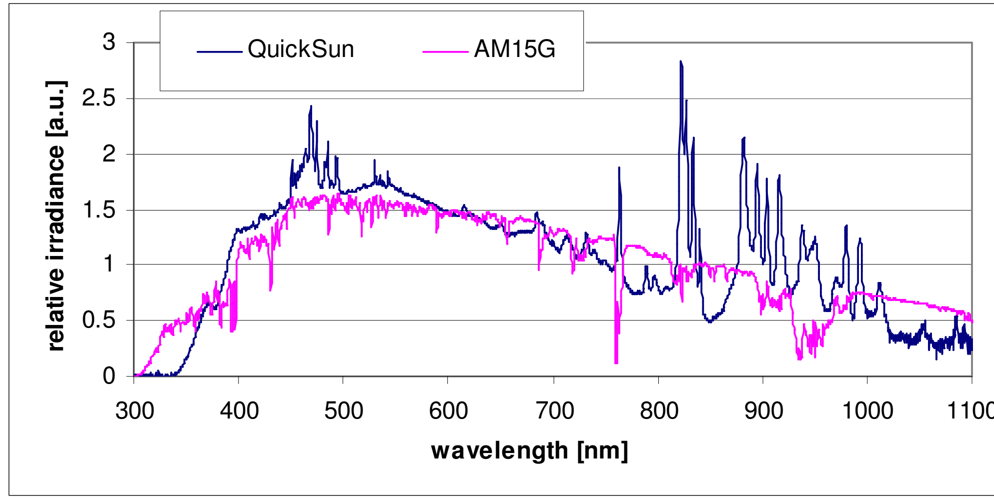
Spectral match, cont.

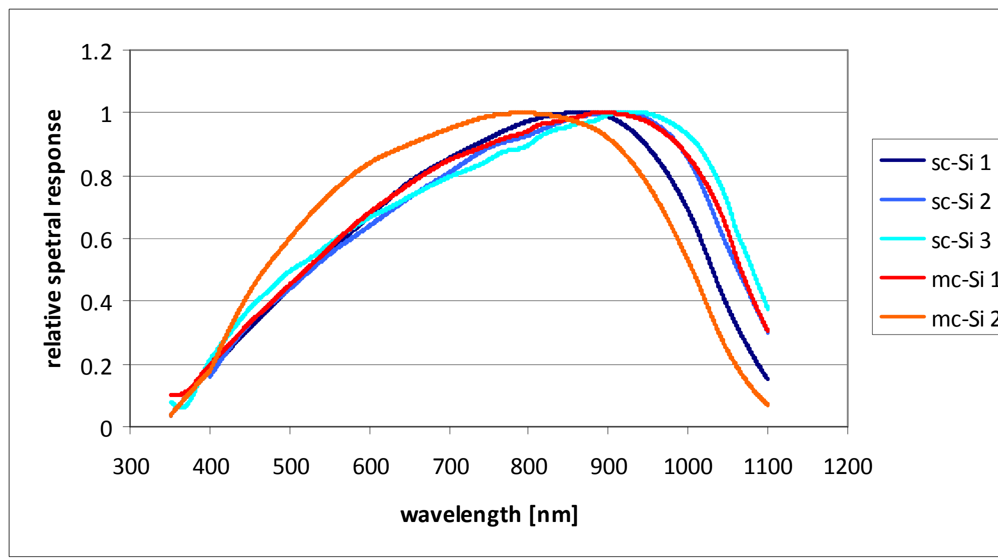
- Spectral effects can be corrected with Mismatch factor

$$M = \frac{I_{\text{ref, AM1.5G}}}{I_{\text{ref, Simulator}}} \frac{I_{\text{Cell, Simulator}}}{I_{\text{Cell, AM1.5G}}}$$

$$I_{\text{ref, AM1.5G}} = \int SR(\lambda) E(\lambda) d\lambda$$

- Typically, the correction is small, only performed at institutes for reference measurements
- In practice, effects eliminated by using a matched reference cell/module





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Temporal instability

- Short term instability (STI) refers to the change in light intensity during the acquisition of single data point.
- If irradiance is measured simultaneously with current and voltage, STI is class A
- Long term instability (LTI) on pulsed solar simulators refers to the change in light intensity during the measurement of IV graph.
- Only STI of class A is required for performance measurements of solar devices.

Cell and module measurement

- Specifications in standard IEC 904-1
- Current and voltage measurement accuracy ± 0.2 %
  - In QuickSun systems data point averaging and software calibration improve accuracy
- 4-wire measurement
  - Standard feature of QuickSun
- Temperature measurement accuracy ± 1 °C
  - QuickSun measures monitor cell and ambient temperature with a precision IC sensors with 0.1 °C resolution and ± 1 °C accuracy
- Temperature within 25 ± 2 °C, if not, a correction to be made
  - Always corrected to desired temperature
- Bias voltage to enable measurement of true short circuit current
  - QuickSun measurement starts at zero voltage

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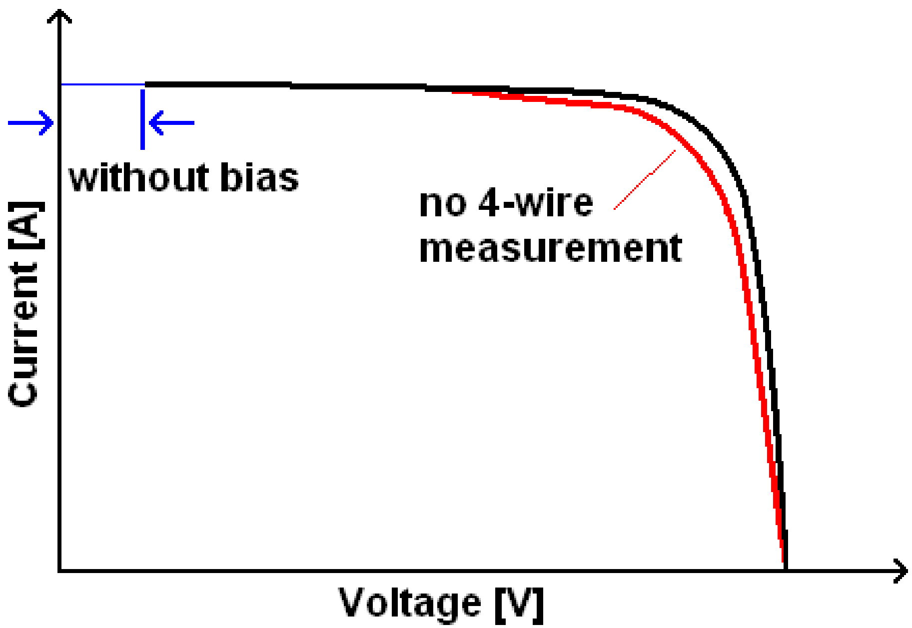
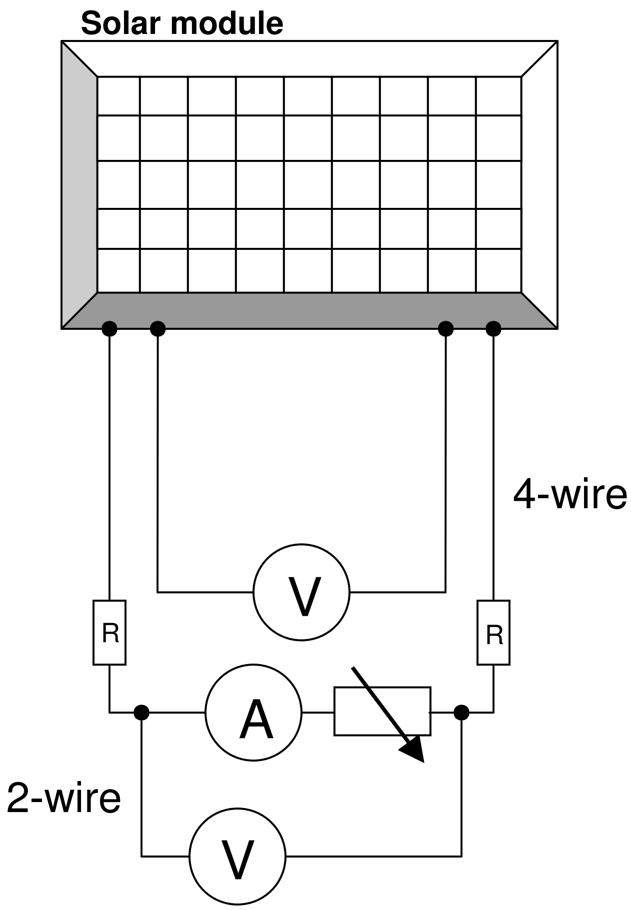
Effect of bias voltage and 4-wire measurement





Cell and module measurement, cont.

- Calibration of the irradiance signal dominates the total accuracy in cell and module measurements.
- Absolute accuracy is determined by the accuracy of the I_{SC} of the reference cell/module.
- Usually I_{SC} measured by an institute (such as NREL, ISE, JQA, ESTI) has an accuracy of only 2 % (at best)
- Spectral response varies ⇒ Each cell type requires own reference
- The irradiance level is set and calibrated in the QuickSun system with better than 1 W/m^2 resolution
- With factory calibration the guaranteed accuracy of QuickSun irradiance measurement is ± 3 % for silicon solar cells.

Calculation and correction of measured data

- Correction formulas given in IEC 891
- Current:

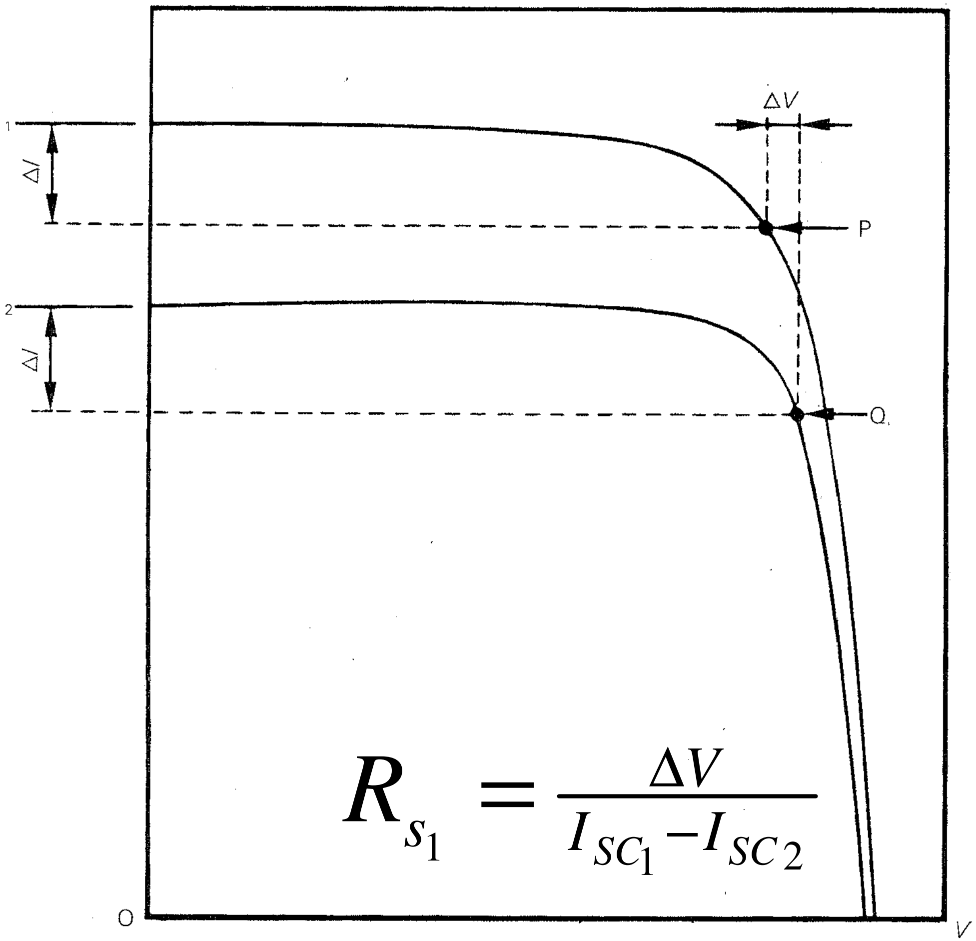
$$I_2 = I_1 + \underbrace{I_{SC}\left[\frac{E_2}{E_1} - 1\right]}_{\text{irradiance correction}} + \underbrace{\alpha(T_2 - T_1)}_{\text{temperature correction}}$$

- Voltage:

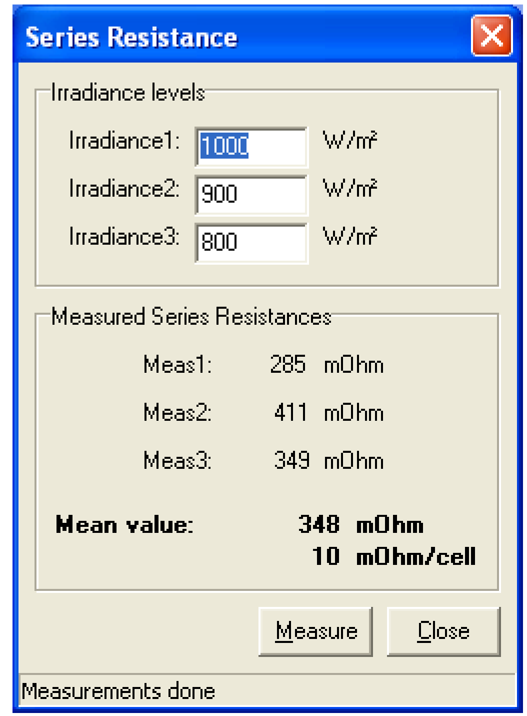
$$V_2 = V_1 + \underbrace{\beta(T_2 - T_1)}_{\text{temperature correction}} - \underbrace{R_S(I_2 - I_1)}_{\text{series resistance}} - \underbrace{KI_2(T_2 - T_1)}_{\text{curve correction}}$$

- V_1, I_1, E_1, T_1 are actual measured voltage, current, irradiance and temperature
- V_2, I_2, E_2, T_2 are the corrected characteristics
- α and β are temperature coefficients for current and coltage
- R_S is the series resistance
- K is the curve correction factor

Series Resistance (IEC 891)



$$R_{s_1} = \frac{\Delta V}{I_{SC_1} - I_{SC_2}}$$



QuickSun Complience with IEC standards

- IEC 904-9
  - QuickSun simulators comply with AAA classification
  - Performance report is given with every simulator
- IEC 904-1
  - Measurement uncertainty complies with standard
  - Special requirements are standard features (e.g. 4-wire measurement, bias voltage)
- IEC 891
  - Correction is performed automatically

QuickSun Solar Simulators

- QuickSun 120CA Cell Solar Simulator
- QuickSun 700A Large Area Solar Simulator
- QuickSun 540LA In-Line Solar simulator

QuickSun® 120CA Cell Solar Simulator

- Single flash measurement system
- Class A spectrum
- < 2% non-uniformity
- Throughput:
  - Manual model 360 cells/hour
  - Automated model 1200 cells/hour
- Average flash lamp lifetime 500 000 flashes
- IDCAM option for detailed cell analysis
- Heating option for temperature coefficient measurements
- Option for Dark IV at reverse voltages

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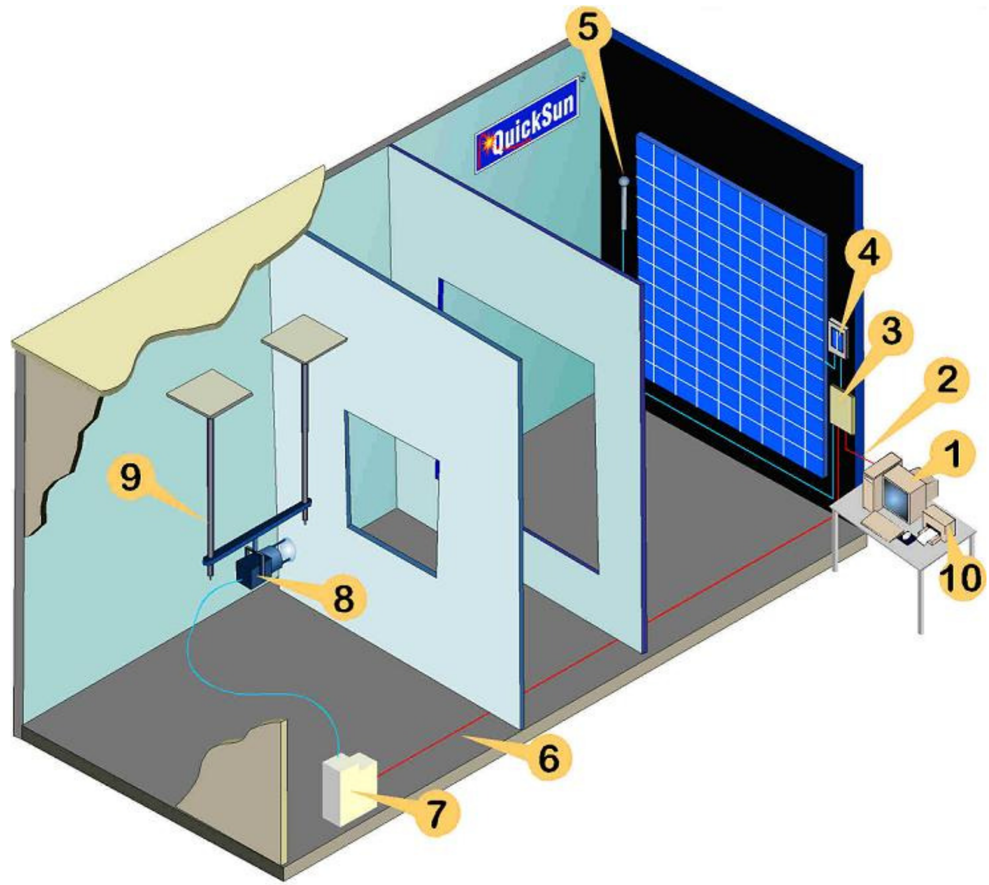
QuickSun 700A Large Area Simulator

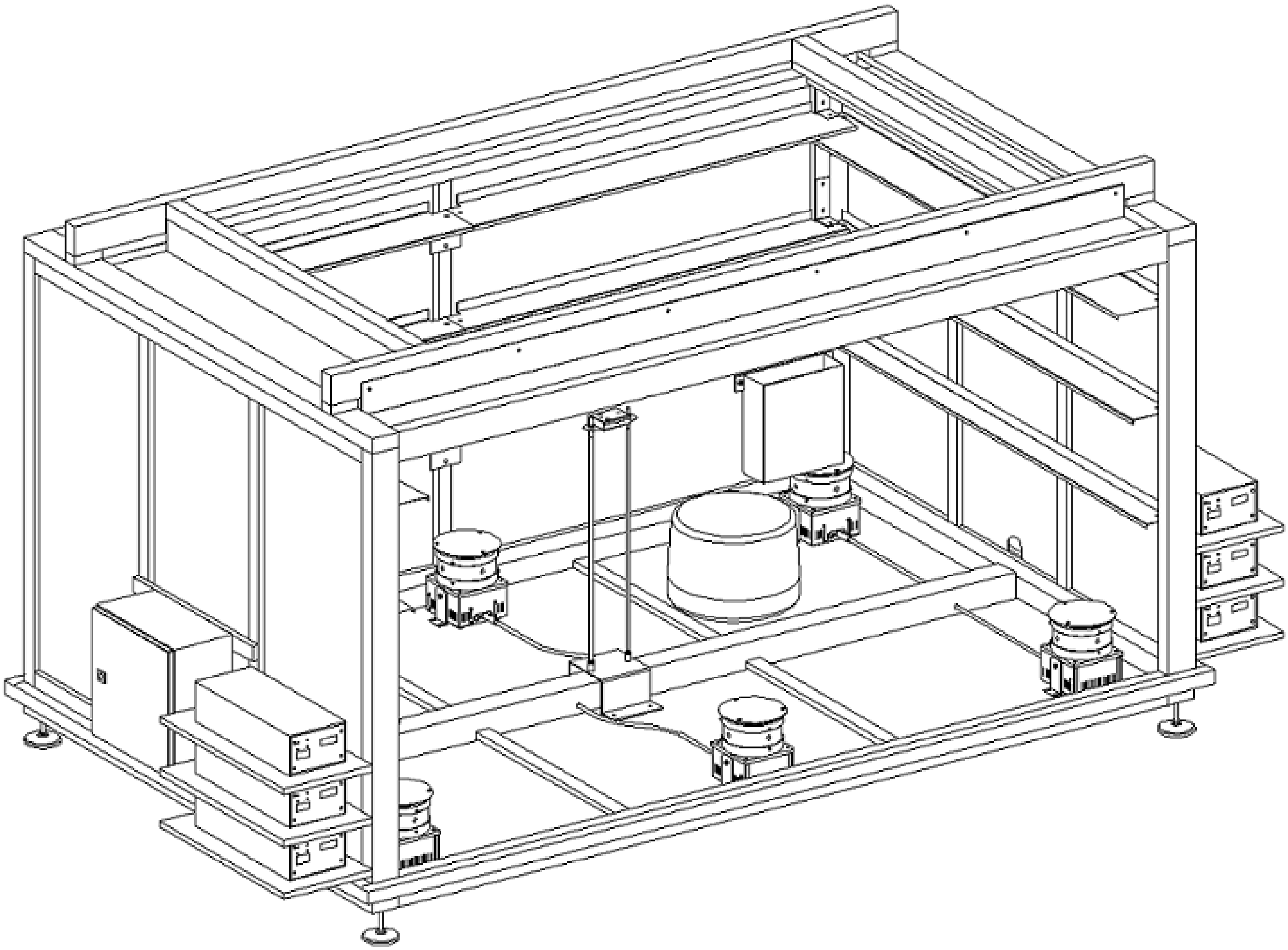
- Ideal for manual module handling
- Measurement area of up to 160cm x 220cm with non-uniformity < 2%
- Length of flash tunnel only 5.5 m / 4.5 m thanks to proprietary optics
- Throughput depends on area:
  - 60 modules/hour (160x220cm^2)
  - 120 modules/hour (130x160cm^2)
- Can also be assembled vertically as a tower with module face up



QuickSun® 540LA In-Line Solar Simulator

- In-line simulator with high throughput, 180 modules per hour
- Modules measured face down for easy production line integration
- Non-uniformity of the 190 cm x 110cm test area < 2 %
  - Special model for larger modules, max area 205 cm x 135 cm
- Compact, factory footprint saving size (1.6 x 1.7 x 3.0 m^3)
- Class A Spectrum

QuickSun® 540LA In-Line Solar Simulator



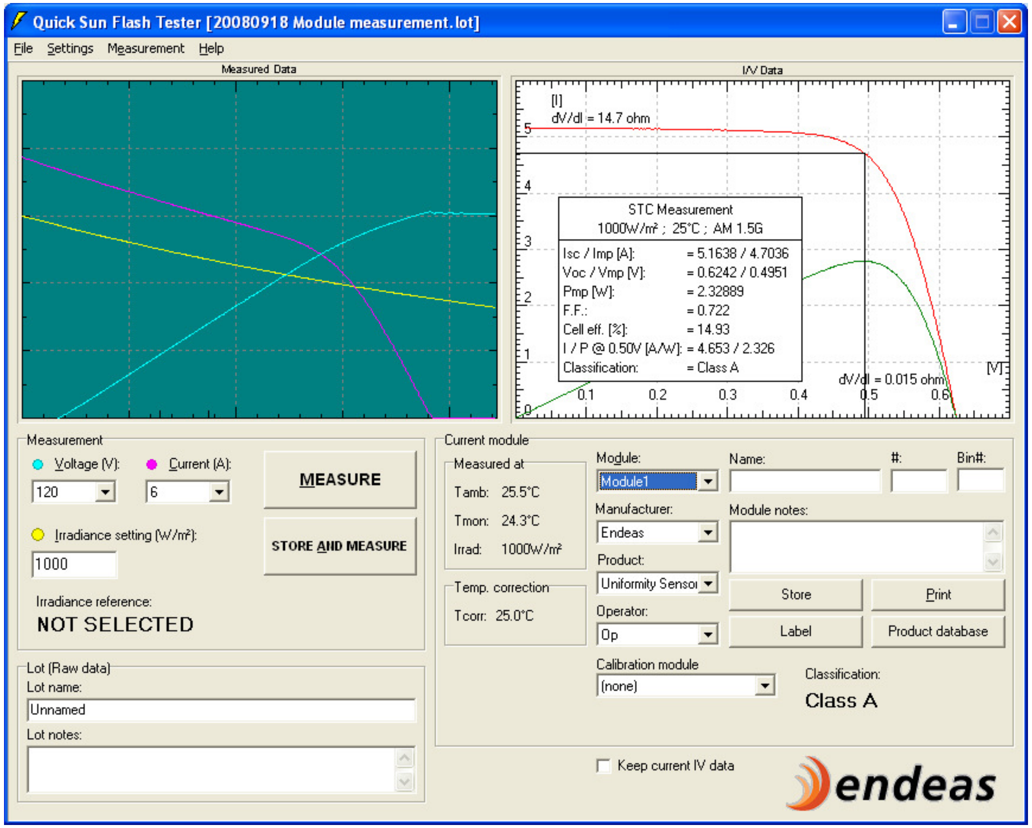
Common features of QuickSun simulators

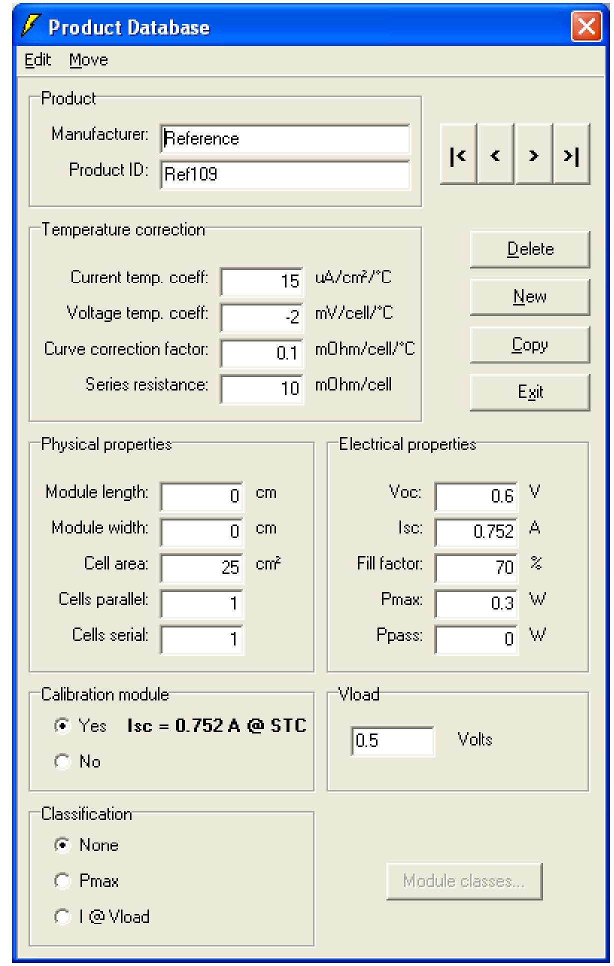
- Single flash measurement
- Class AAA simulator (spectrum, non-uniformity, STI)
- Irradiance level adjustable, 200 – 1200 W/m^2, 1 W/m^2 resolution
- Current and voltage scales adjustable to any value, internal hardware optimizes measurement accuracy accordingly
- Good measurement reproducibility (< 0.25 %)
- Measurement of series resistance
- Proprietary 2-diode analysis option (IDCAM)
- User friendly Windows® software

Features of the QuickSun software

- Database for measurement product information (measurement data correction coefficients, module size, performance characteristics)
- Storing of multiple measurements in single file
- Printing of data sheet of measurement results
- Measurement data easily exported to other applications (CSV files) or directly to an external database (Access, MySQL)
- Measurement results can be corrected to other temperatures
- Label printing, barcode reader as an option
- TCP interface to connect to other factory equipment

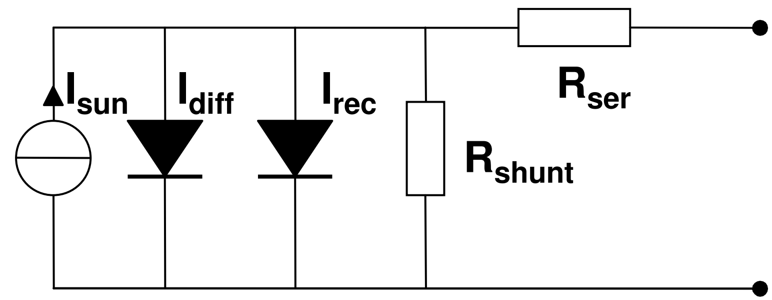
QuickSun software, cont.



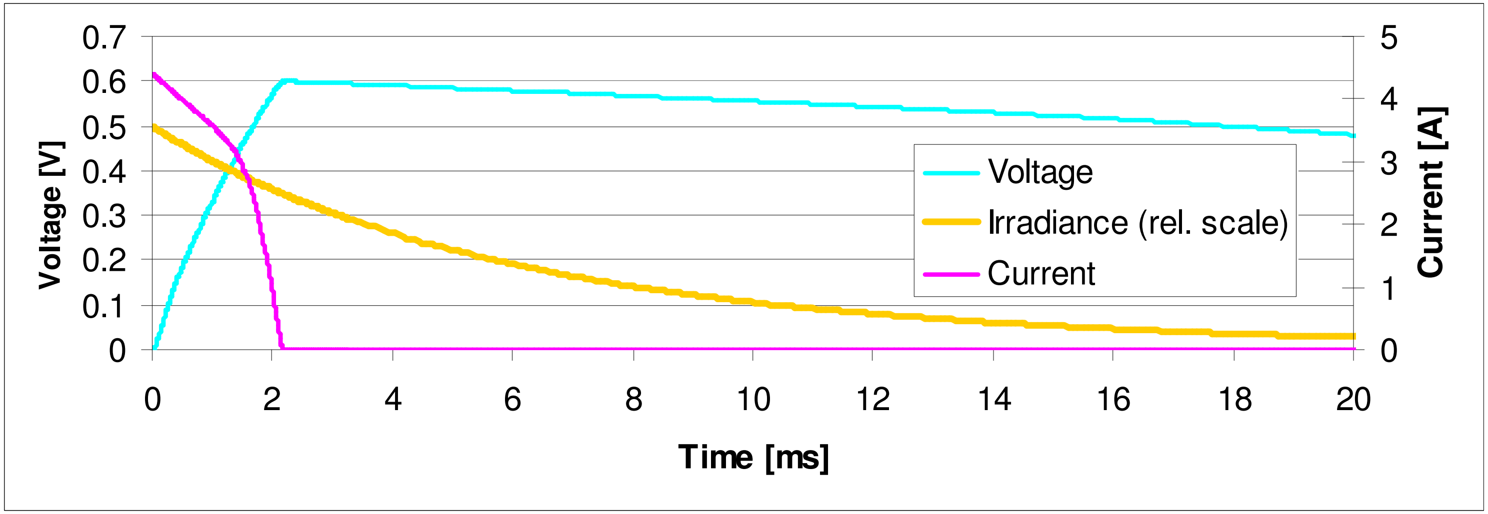


IDCAM

- Irradiance Decay Cell Analysis Method
- Cell parameters of 2-diode model can be extracted from a single measurement



$$I = I_{sun} - I_{diff}\left[e^{\frac{q}{kT}(V+IR_{ser})} - 1\right] - I_{rec}\left[e^{\frac{q}{2kT}(V+IR_{ser})} - 1\right] - \frac{V + IR_{ser}}{R_{shunt}}$$



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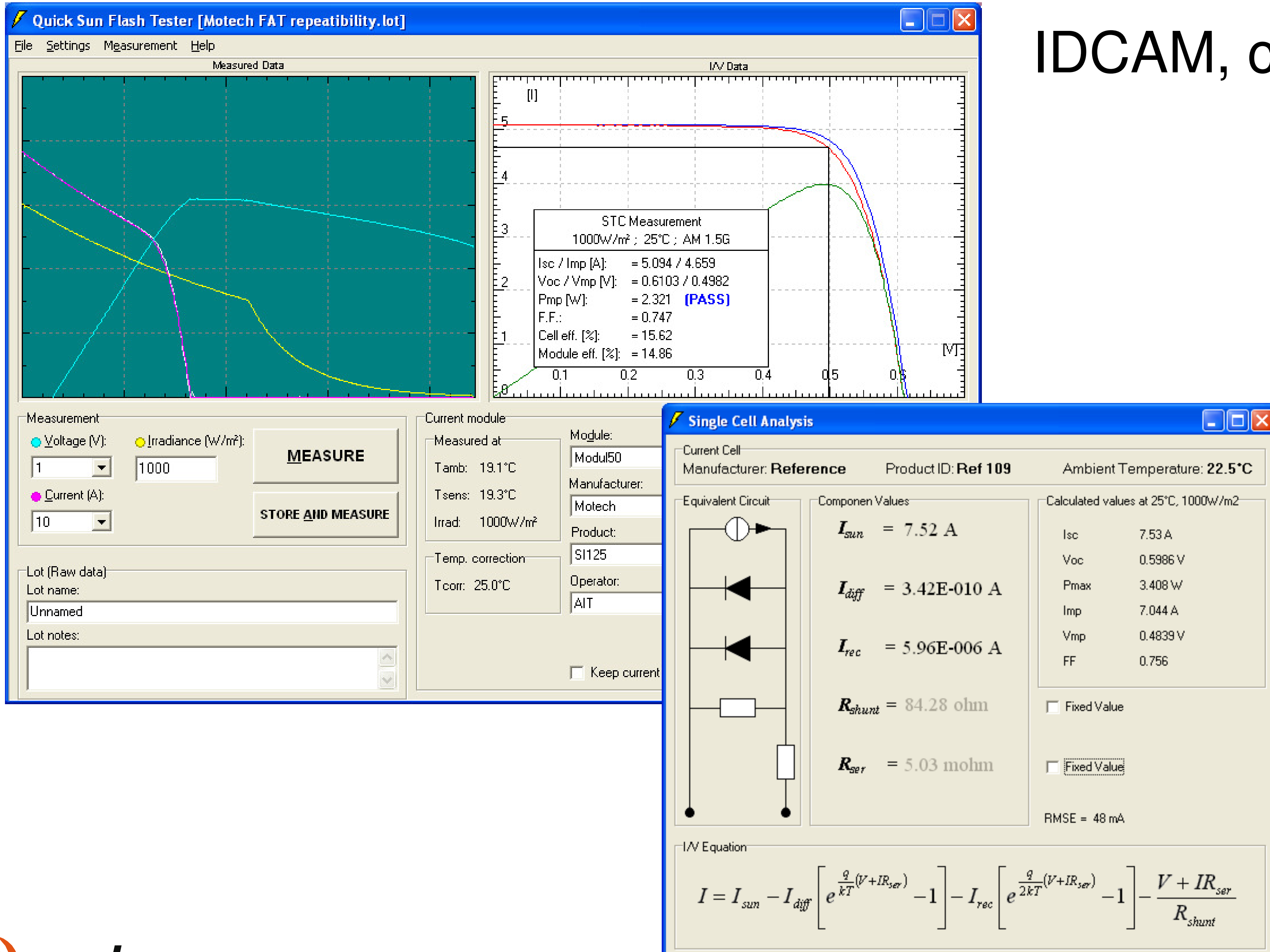
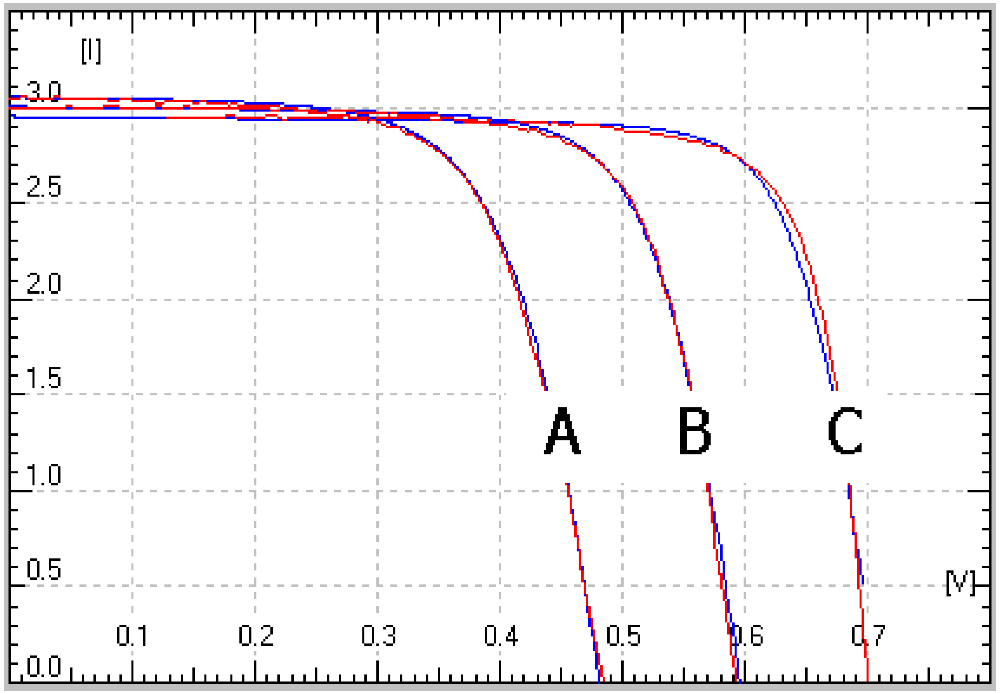
IDCAM, cont.

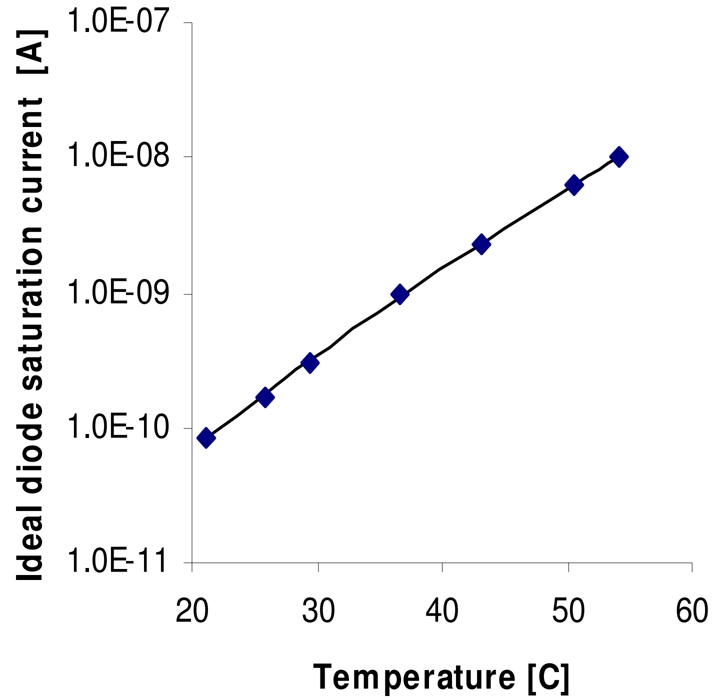


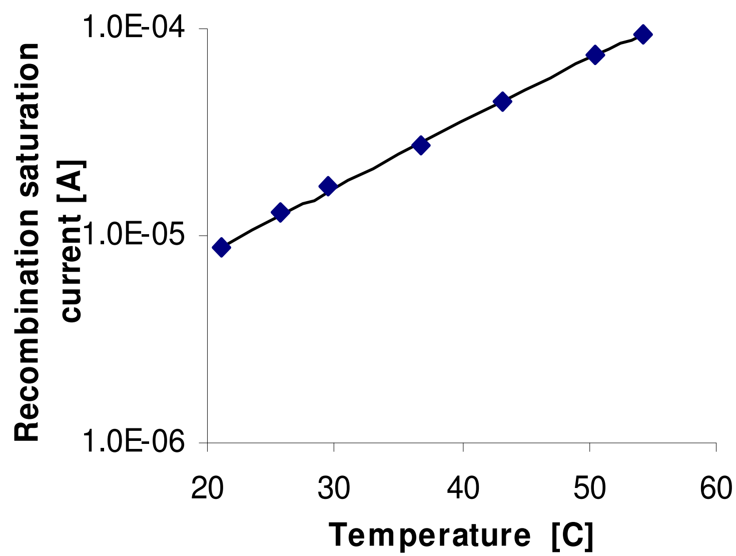
Quick Sun Flash Tester [Motech FAT repeatibility.lot]
File
Settings
Measurement
Help
Measured Data
I/V Data
[I]
[V]
STC Measurement
1000W/m² ; 25°C ; AM 1.5G
Isc / Imp [A]: = 5.094 / 4.659
Voc / Vmp [V]: = 0.6103 / 0.4982
Pmp [W]: = 2.321 [PASS]
F.F.: = 0.747
Cell eff. [%]: = 15.62
Module eff. [%]: = 14.86
Measurement
Voltage (V):
Irradiance (W/m²):
1
1000
Current (A):
10
MEASURE
STORE AND MEASURE
Lot (Raw data)
Lot name:
Unnamed
Lot notes:
Current module
Measured at
Tamb: 19.1°C
Tsens: 19.3°C
Irrad: 1000W/m²
Temp. correction
Tcorr: 25.0°C
Module:
Modul50
Manufacturer:
Motech
Product:
SI125
Operator:
AIT
Keep current
Single Cell Analysis
Current Cell
Manufacturer: Reference
Product ID: Ref 109
Ambient Temperature: 22.5°C
Equivalent Circuit
Componen Values
I_{sun} = 7.52 A
I_{diff} = 3.42E-010 A
I_{rec} = 5.96E-006 A
R_{shunt} = 84.28 ohm
R_{ser} = 5.03 mohm
Calculated values at 25°C, 1000W/m2
Isc 7.53 A
Voc 0.5986 V
Pmax 3.408 W
Imp 7.044 A
Vmp 0.4839 V
FF 0.756
Fixed Value
Fixed Value
RMSE = 48 mA
I/V Equation
$I = I_{sun} - I_{diff}\left[e^{\frac{q}{kT}(V+IR_{ser})} - 1\right] - I_{rec}\left[e^{\frac{q}{2kT}(V+IR_{ser})} - 1\right] - \frac{V+IR_{ser}}{R_{shunt}}$

IDCAM, temperature analysis

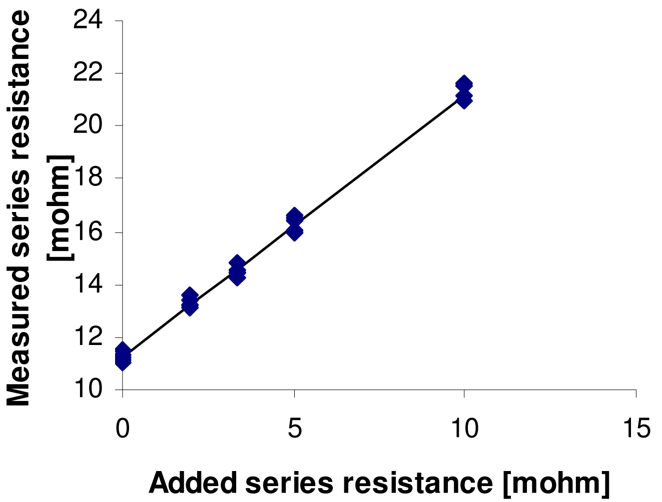


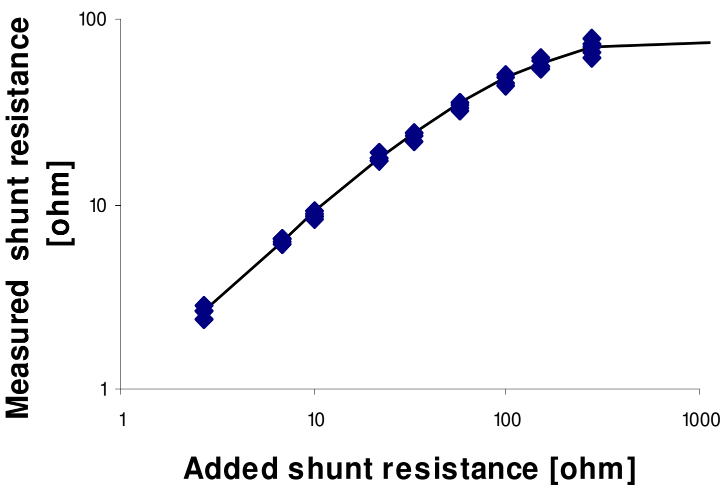
Measured and calculated IV curves at 26.2 °C, graphs B. The same measurement data corrected to +75 °C and –25 °C; graphs A and C, respectively.

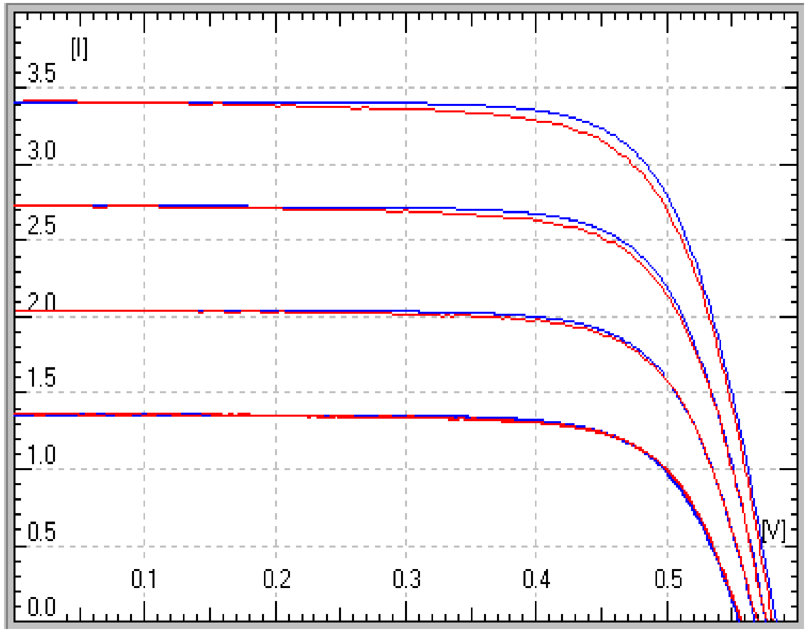




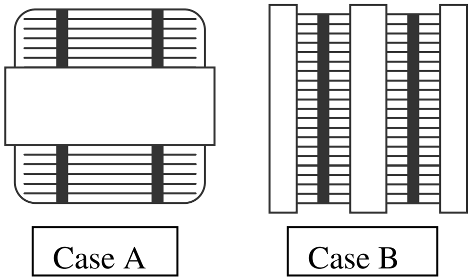
IDCAM, analysis cont.







Calculated and measured IV graphs at 1000, 800, 600 and 400 W/m^2.



Solar-Power report by TÜV (2005)

- Goal of the Solar-Power project was to develop harmonized procedures for PV module output measurements.
- SMEs combined efforts to improve their testing methods
- Improve power control
  - sorting in power classes
- Reduce manufacturing tolerances
  - strenghten market position
- Evaluation of solar simulator performance

1

Solar-Power

Development of Innovative Quality Assurance Measures to Improve the Efficiency of Solar Panel Production

Contract:
CRAFT-1999-72232

FINAL REPORT

Project duration: 1st May 2003 to 30th April 2005

Co-ordinator:
IPEG GmbH
Gewerbegebiet Beerwalde
Windmühlenstr. 2
04626 Löbichau
Germany

SME Project Partners:
Swiss Sustainable Systems AG, Switzerland
Arctic Solar AB, Sweden
Bluenergy Germany AG, Germany
Millennium Electric TOU, Israel
Solarwatt Solar-Systeme GmbH, Germany
Helios Technology SRL, Italy
Enfoton Solar Ltd., Cyprus[1]

R&D Performer:
TÜV Immissionsschutz und Energiesysteme GmbH, Germany

Research funded in part by THE EUROPEAN COMMISSION Within the Fifth Framework Programme

[1] Enfoton Solar has replaced S.W.S (contract amendment No. 1)

Solar-Power report by TÜV, cont.

Participant	Type	Supplier, model
IPEG	Long-pulse	LEC, FS-PSS
3S	Steady-state	Tungsten halogen
Arctic Solar	Long-pulse	ENDEAS, QuickSun
Bluenergy	Steady-state	H.A.L.M., LED array (planned)
Millennium	Short-pulse	SPIRE, SPI-SUN
Solarwatt	Long-pulse	BERGER, PSS-8
Helios	Short-pulse	Self-development
Enfoton	Long-pulse	LEC, FS-PSS

Table 5.1.3: Available solar simulator systems in the project consortium

QuickSun only AAA simulator

- Irradiance non-uniformity: **class A**
- Spectral match: **class A**
- Temporal instability: **class A**

all others: BCA

Only QuickSun's spectrum matches AM1.5G

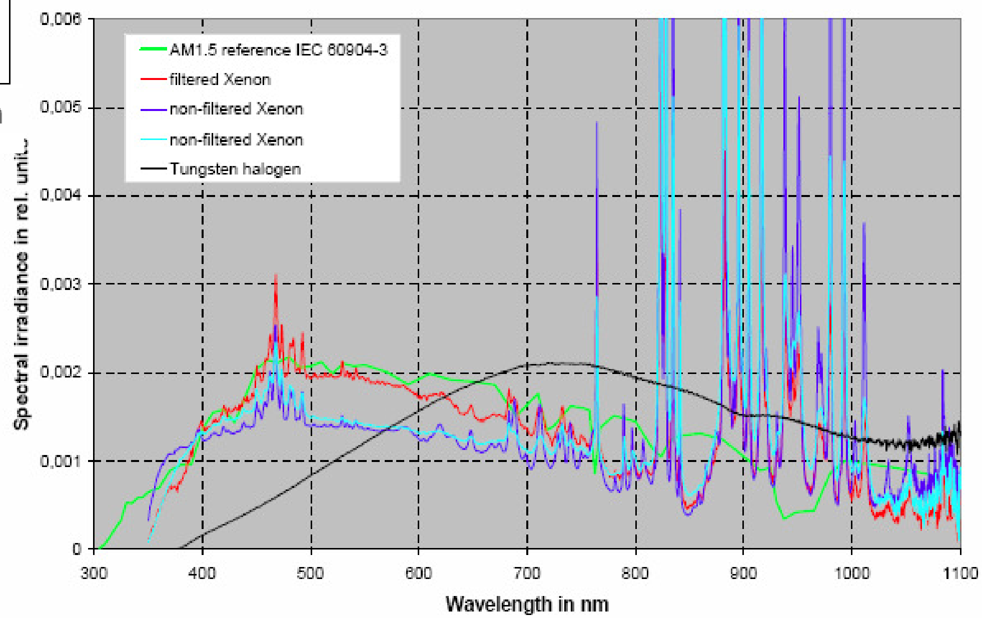
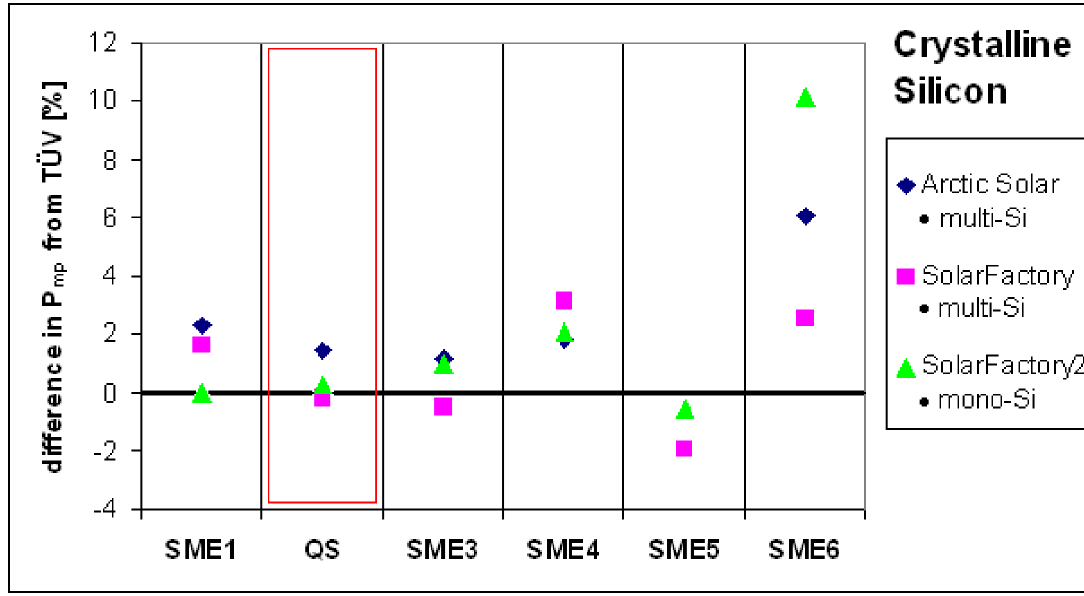
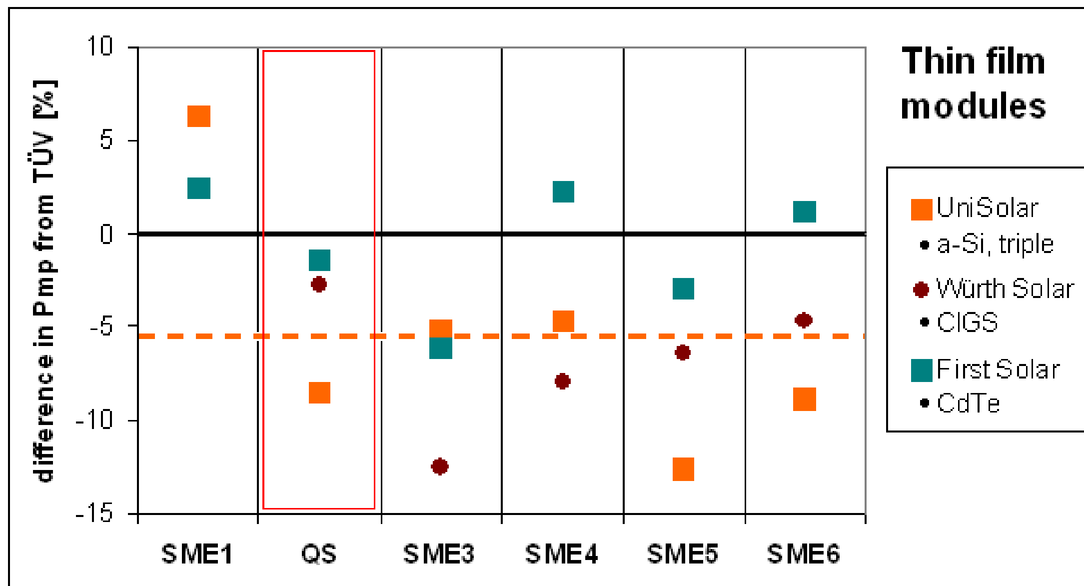


Figure 5.1.8: Spectral irradiance of solar simulators in the SME consortium normalised to AM 1.5 reference spectral irradiance.

Solar-Power, round robin

- Round robin test on all simulators and PV modules of different technologies
- QuickSun was top performer





- - - Power of UniSolar module outdoors, measured by Endeas

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Thank you for your attention

More information: www.endeas.fi

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