NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Rating PV Power and Energy: Cell, Module, and System Measurements

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Part 1

Rating PV Power and Energy - Cell, Module, and System Measurements

June 18-24, 2011

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Testing PV modules used to power the IR telescope on Mt. Evans at 14,264 feet, 4348 m

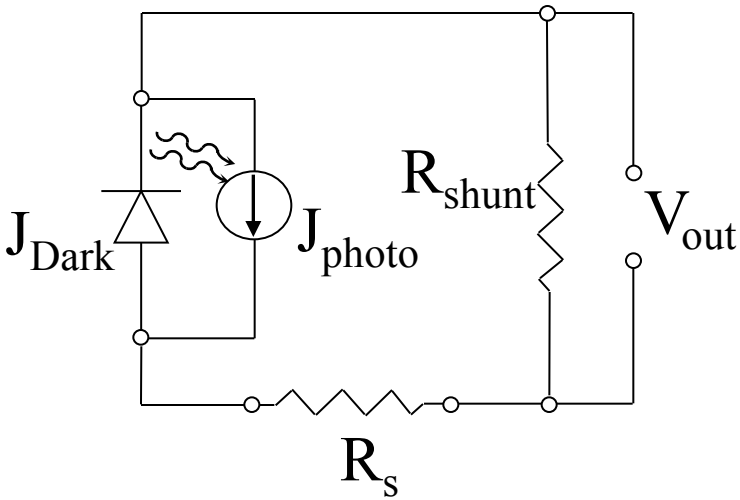
The contents of this tutorial/short course packet are not for sale or distribution, and are solely for educational purposes

Outline

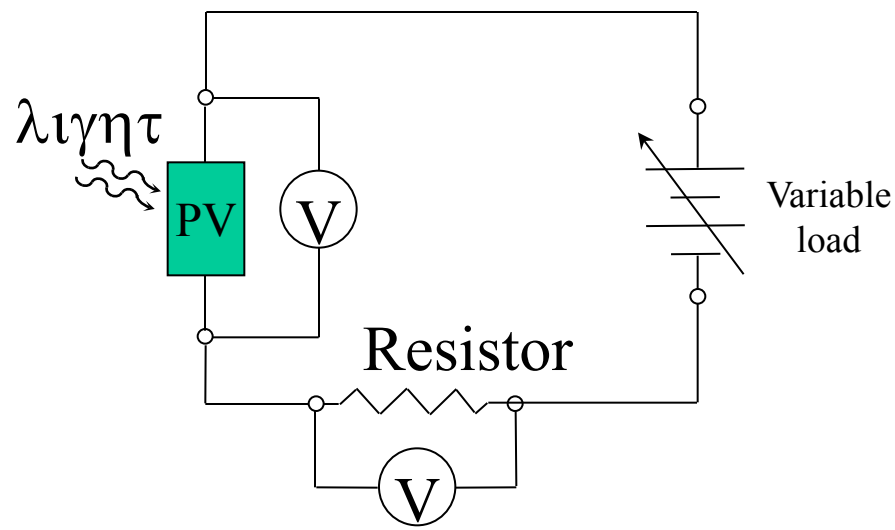
- Current *vs.* Voltage Measurement Theory
  - Basic PV operation, Equivalent Circuit
  - I-V functional dependence
  - Concept of Spectral Error
- PV Power Performance
- PV Measurement Artifacts
- Intercomparisons
- Alternative rating methods

PV Current *vs.* Voltage

Equivalent circuit PV cell



Block diagram IV system

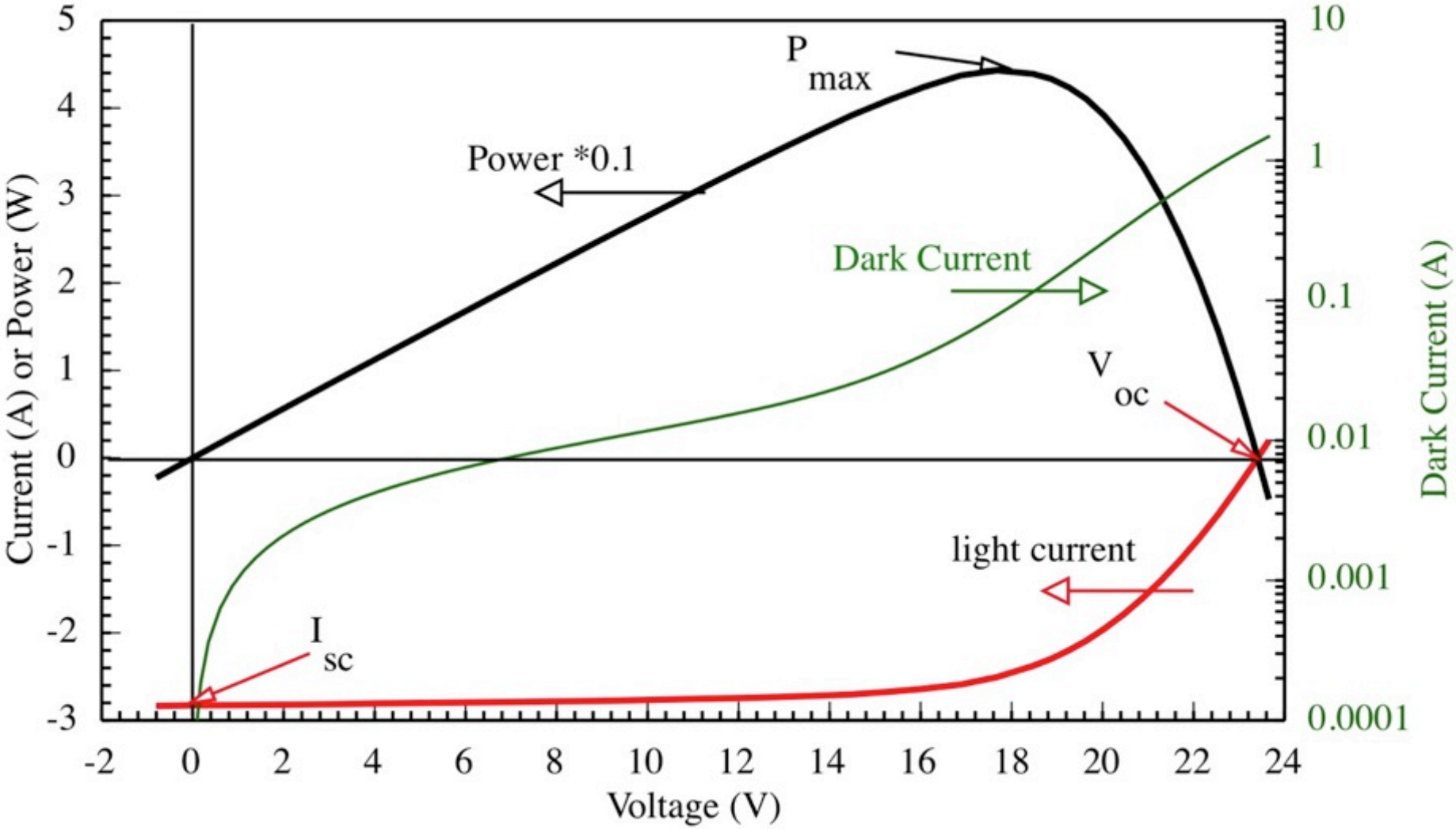


$$J_{Out} = J_{photo} - J_{Dark} - V / R_{shunt}$$

$$J_{Dark} = J_{01}\left[e^{qV/n_1 kT} - 1\right] + J_{02}\left[e^{qV/n_2 kT} - 1\right]$$

$$V_{out} = V - J_{out} R_s$$

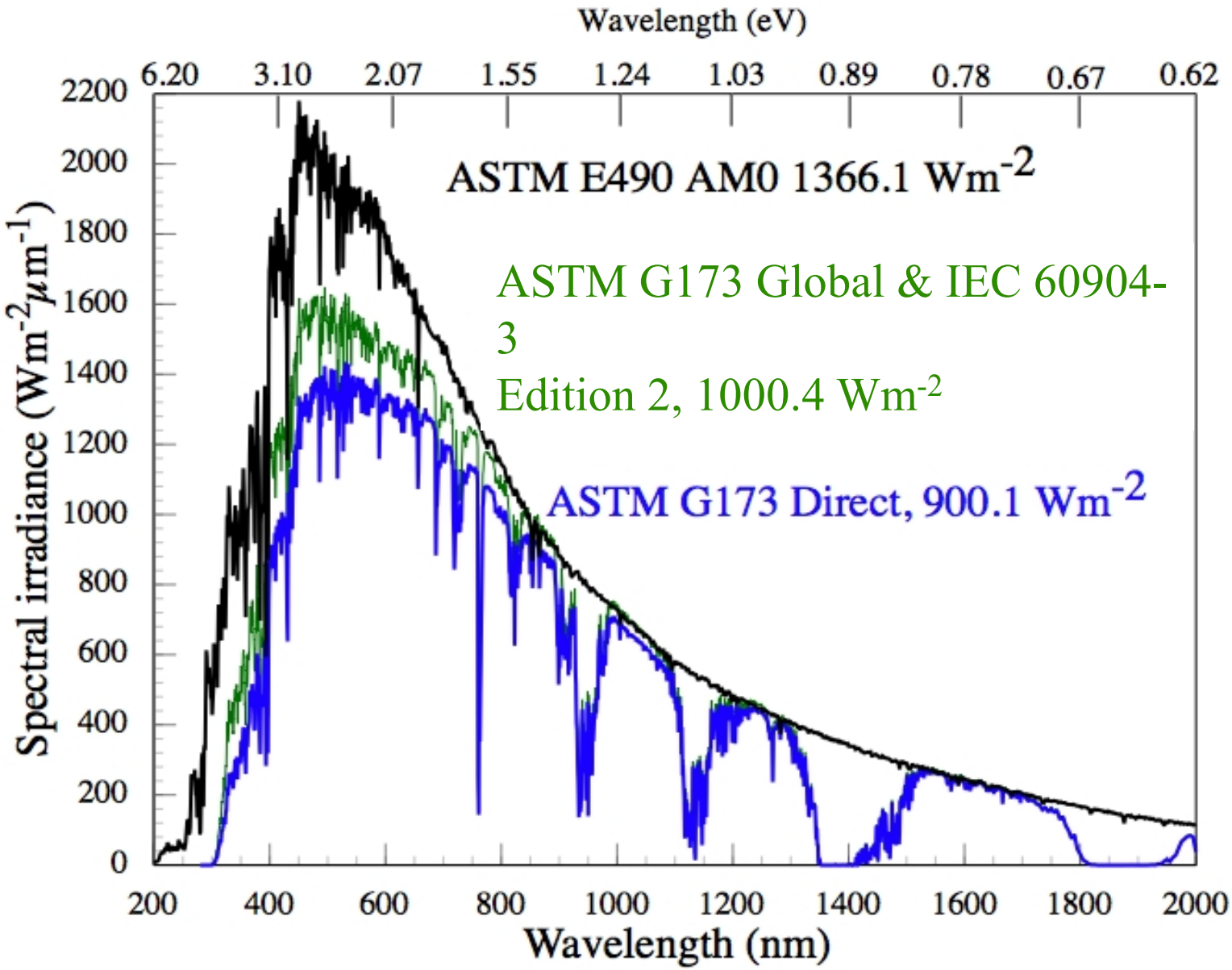
Module Current vs. Voltage Characteristics



Standard Reference (Test) Conditions

- Continuous Illumination,
- 25 ° C Junction Temperature,
- 1000 W/m^2 Total Irradiance=1-sun,
- ASTM G173 Reference Spectrum (direct only for concentrators)
- Area definition for efficiency (mesa area minus peripheral bus bars)

Reference Spectra



Theory

$$Efficiency \equiv \eta \equiv 100 \frac{P_{\max}}{E_{tot} A}$$

To be uniquely specified:

P_{max} is the maximum electrical power produced when illuminated standard reference (test) conditions given by:

25 ° C junction temperature, 1000 Wm^{-2} total irradiance,
IEC 60904-3 ed. 2 or ASTM G173 global reference spectrum

A is the total area of the device including contacts and peripheral bus bars

E_{tot} is the total irradiance at standard reference conditions, 1000 Wm^{-2}

$$1 = \frac{I^{R,R}}{I^{R,S} M}$$

$$M = \frac{\int_{\lambda_1}^{\lambda_2} E_{Ref}(\lambda) S_{Ref}(\lambda) \mathrm{d}\lambda}{\int_{\lambda_1}^{\lambda_2} E_{Ref}(\lambda) S_T(\lambda) \mathrm{d}\lambda} \frac{\int_{\lambda_1}^{\lambda_2} E_S(\lambda) S_T(\lambda) \mathrm{d}\lambda}{\int_{\lambda_1}^{\lambda_2} E_S(\lambda) S_{Ref}(\lambda) \mathrm{d}\lambda}$$

Where:

Reference (photon flux) spectral irradiance, $E_{Ref}(\lambda)$

Simulator (photon flux) spectral irradiance, $E_S(\lambda)$

Reference (Quantum efficiency) spectral responsivity, $S_{Ref}(\lambda)$

Test cell (Quantum efficiency), $S_T(\lambda)$

Multi-junction IV theory

- A reference cell ($I^{R_i,R}$) for each junction is required.
- The reference cell should 'match' the spectral response of that junction.

$$I^{R_1,S} = \frac{I^{R_1,R}}{M_1}$$

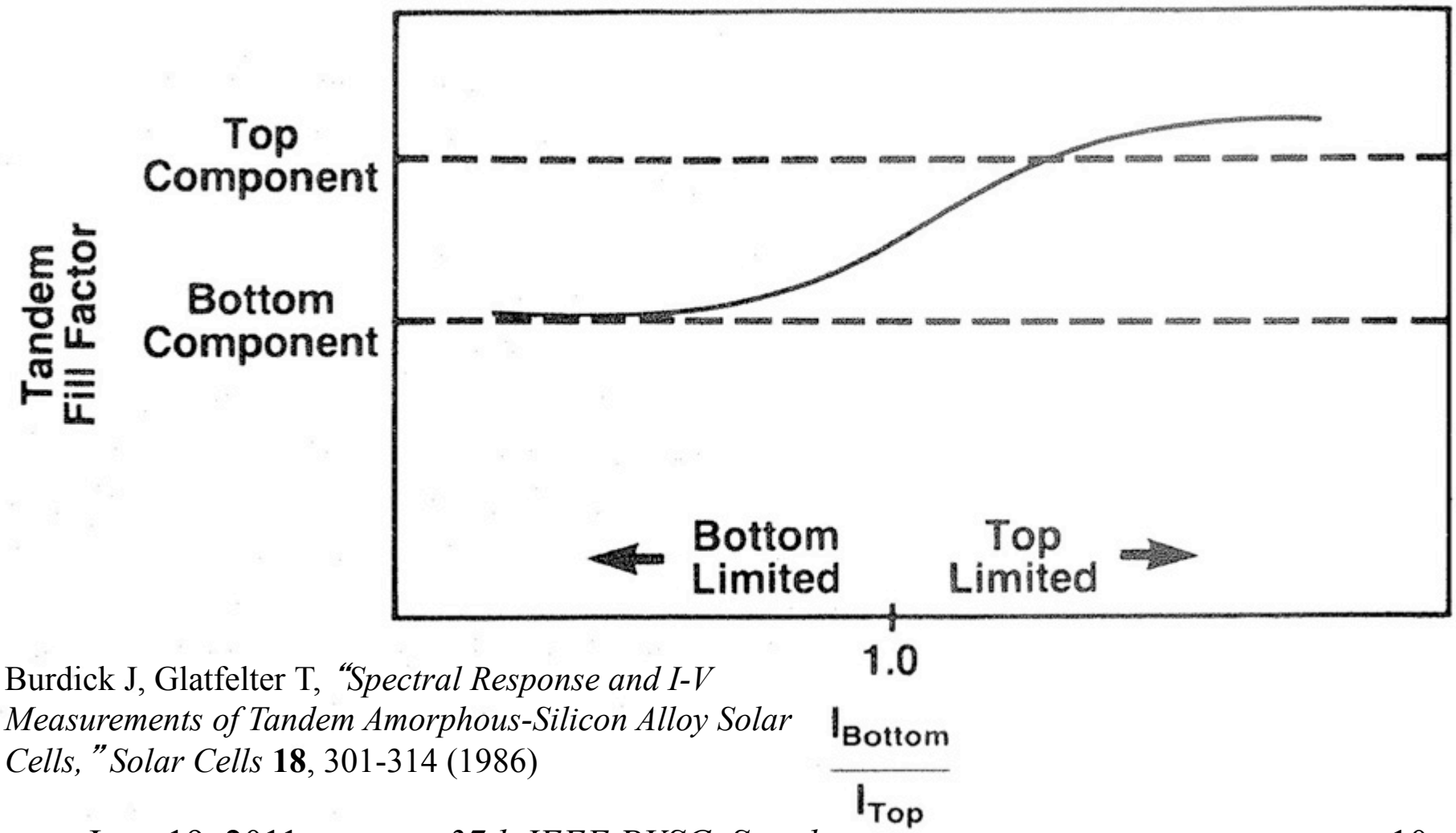
$$I^{R_2,S} = \frac{I^{R_2,R}}{M_2}$$

$$\vdots \qquad \vdots \qquad \vdots$$

$$I^{R_n,S} = \frac{I^{R_n,R}}{M_n}$$

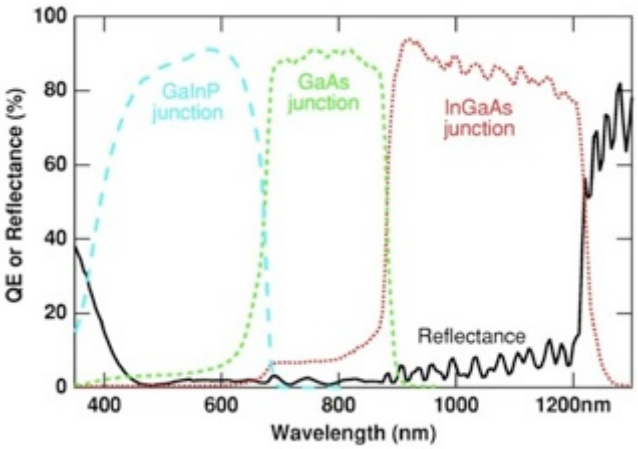
- Calculate M_i using the composite spectrum
- Adjust source(s) until the above equations are true
- Recalculate M_i to verify that mismatch has not changed
- Measure the I-V characteristics

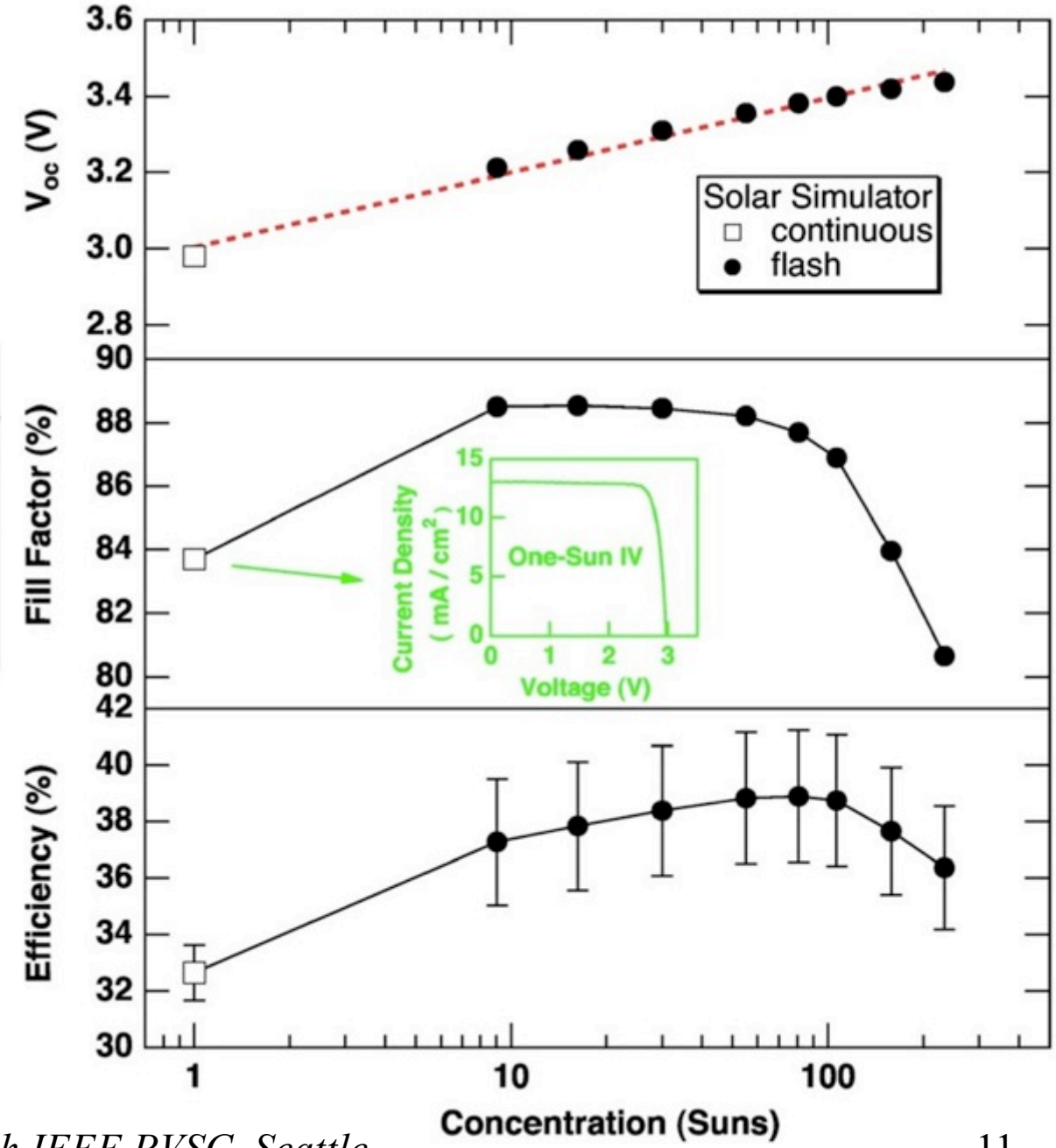
Multijunction Fill Factor vs. Photo-current ratio



Burdick J, Glatfelter T, *"Spectral Response and I-V Measurements of Tandem Amorphous-Silicon Alloy Solar Cells,"* *Solar Cells* **18**, 301-314 (1986)

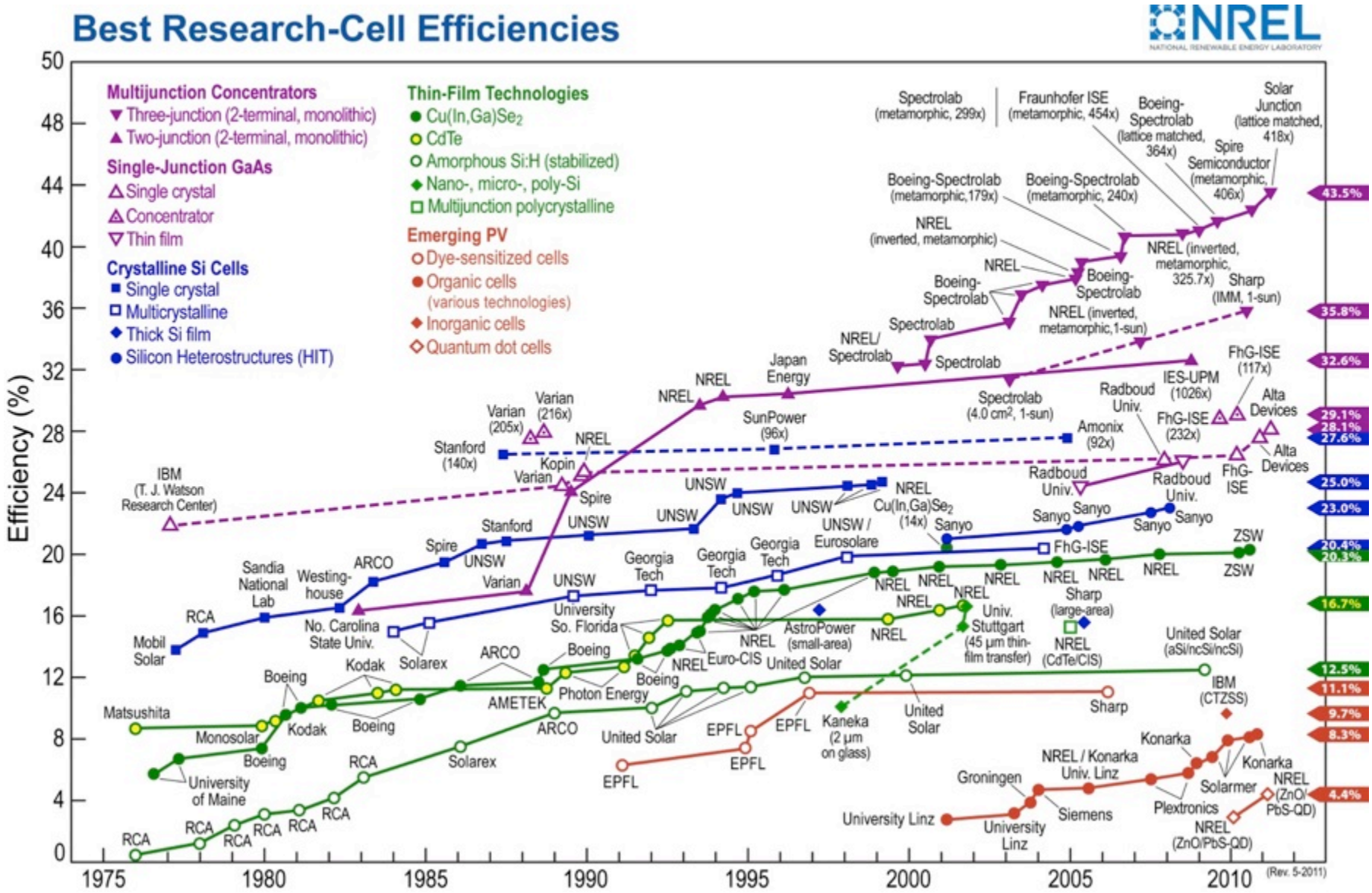
Multijunction I-V





J. F. Geisz, et al, Appl. Phys. Lett. vol. 91, 123505 (2007)

Improvements in Cell Efficiency



Accredited Calibration Labs

- ISO 17025 accredited and WPVS Recognized Primary Cell calibration Facility (NREL, PTB in Germany, ESTI JRC in Ispra, AIST in Japan)
- NREL, AIST and Fraunhofer ISE are the only available ISO 17025 certified lab in the world with proven proficiency through >20 years of intercomparisons for **any** PV cell design or technology.
- VLSI standards and Newport Oriel certified for secondary reference cell calibrations. Intercomparisons with Si wafer, Organic, and various reference cell packages
- UL, ESTI, TUV, JET, and FSEC and many other module qualification labs around the world are ISO 17025 certified for module calibrations

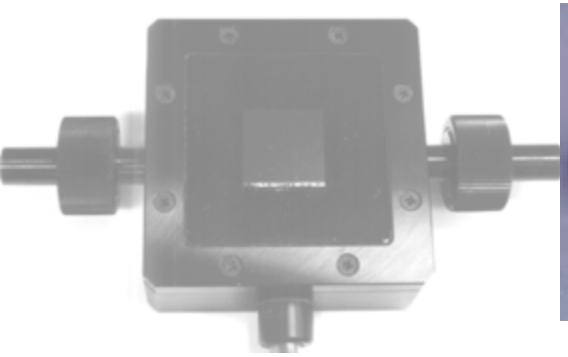
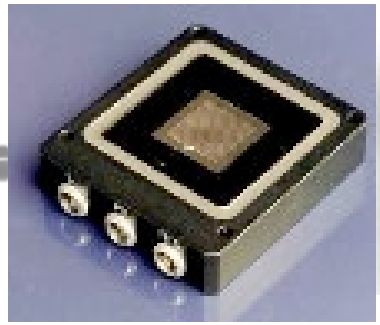
Outline – Irradiance Sensor

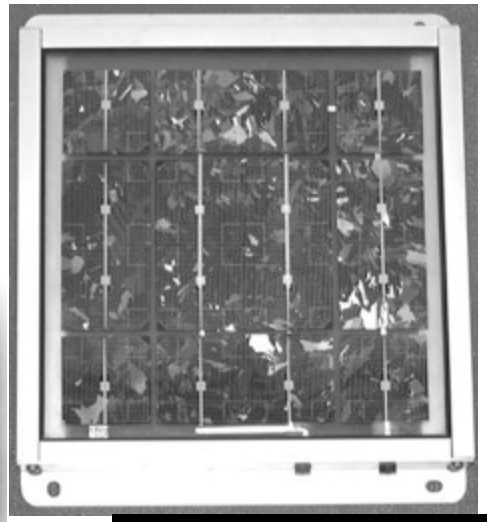
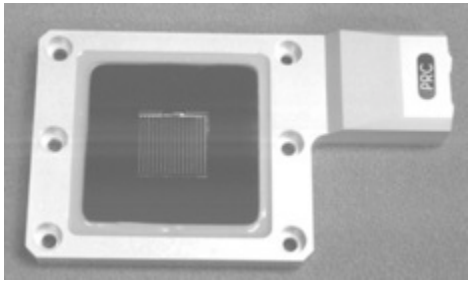
- Current *vs.* Voltage Measurement Theory
- PV Power Performance
  - PV Irradiance Sensor
  - Simulators
  - Commercial and Generic I-V systems
  - Contacting
- PV Measurement Artifacts
- Intercomparisons
- Alternative rating methods

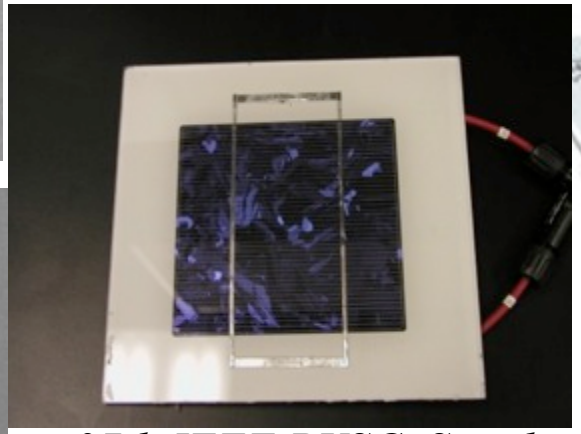
Reference Cell Packages

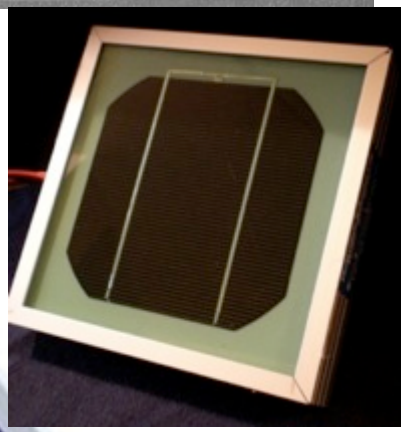
K. Emery and R. Smith, "Monitoring System performance, Proc. PV Module Reliability Workshop", Feb. 11, 2011

- Encapsulated
- Temperature sensor attached or other means to correct for temperature
- Packaged cell or cell in module package





PV Irradiance Sensor

Reference Cells in metal package

- Uncertainty in measuring the total irradiance of ± 1.5% provided that I_{sc} is temperature corrected and size is less than 2 by 2 cm
- Corrects for spectral effects to the reference spectrum. Exact correction if relative quantum efficiencies of reference and PV system identical
- Multiple intercomparisons among ISO 17025 accredited calibration labs suggest uncertainty less than ±2% for Si reference cells at 25 ° C
- Short-circuit temperature coefficient of Si is 500 to 850 ppm/° C depending on spectra measured under. In systems the temperature range may exceed 60 ° or a 3% error in irradiance if temperature not corrected for.
- Regression analysis of field data has a lower mean square error (less noisy)
- Time constant comparable to PV
- Temperature can be controlled potentially giving lower error in calibration

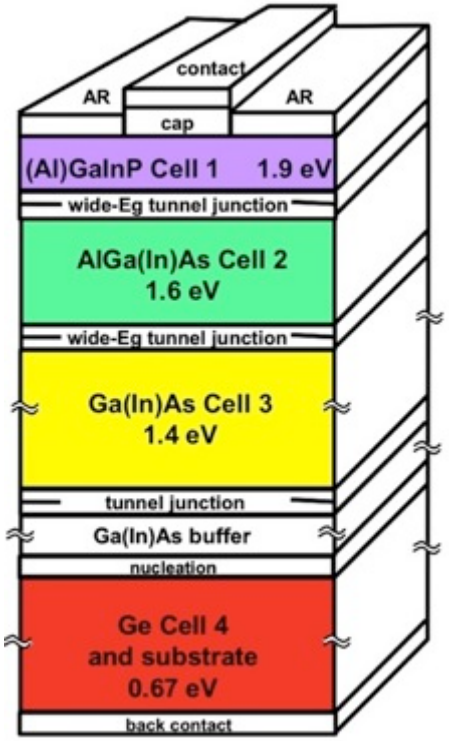
PV Irradiance Sensor

Cell in Module package

- Angular response similar to PV in system
- Quantum efficiency closer to module because packaging similar
- Thermal characteristics similar to PV system
- Slightly higher uncertainty than small area cells.

Concentrator reference cell

Desirable features packaged isotype cell for each junction with an integral reverse bias protection diode rated for operation above the maximum desired intensity.



An isotype cell has all layers above and below it be the same semiconductor type. This shorts all other cells in the device but preserves the optical properties. This gives the isotype cell almost the same QE as the corresponding junction in the multijunction cell.

Pyranometer

- Wide range of uncertainties depending on how calibrated (indoors using a sphere vs. outdoors, how mounted, and if corrections for temperature and angular response applied
- 1.5 % to >5% for WMO first class, potentially >20% for other units.
- "**WMO GUIDE TO METEOROLOGICAL INSTRUMENTS AND METHODS OF OBSERVATION**" http://www.WMO.int/pages/prog/www/IMOP/publications/CIMO-Guide/CIMO_Guide-7th_Edition-2008.html
- U_{95} for pyranometer calibration at NREL on a horizontal surface ±3 to 4% depending on multiple factors. Often different from indoor based calibrations by over 5%.

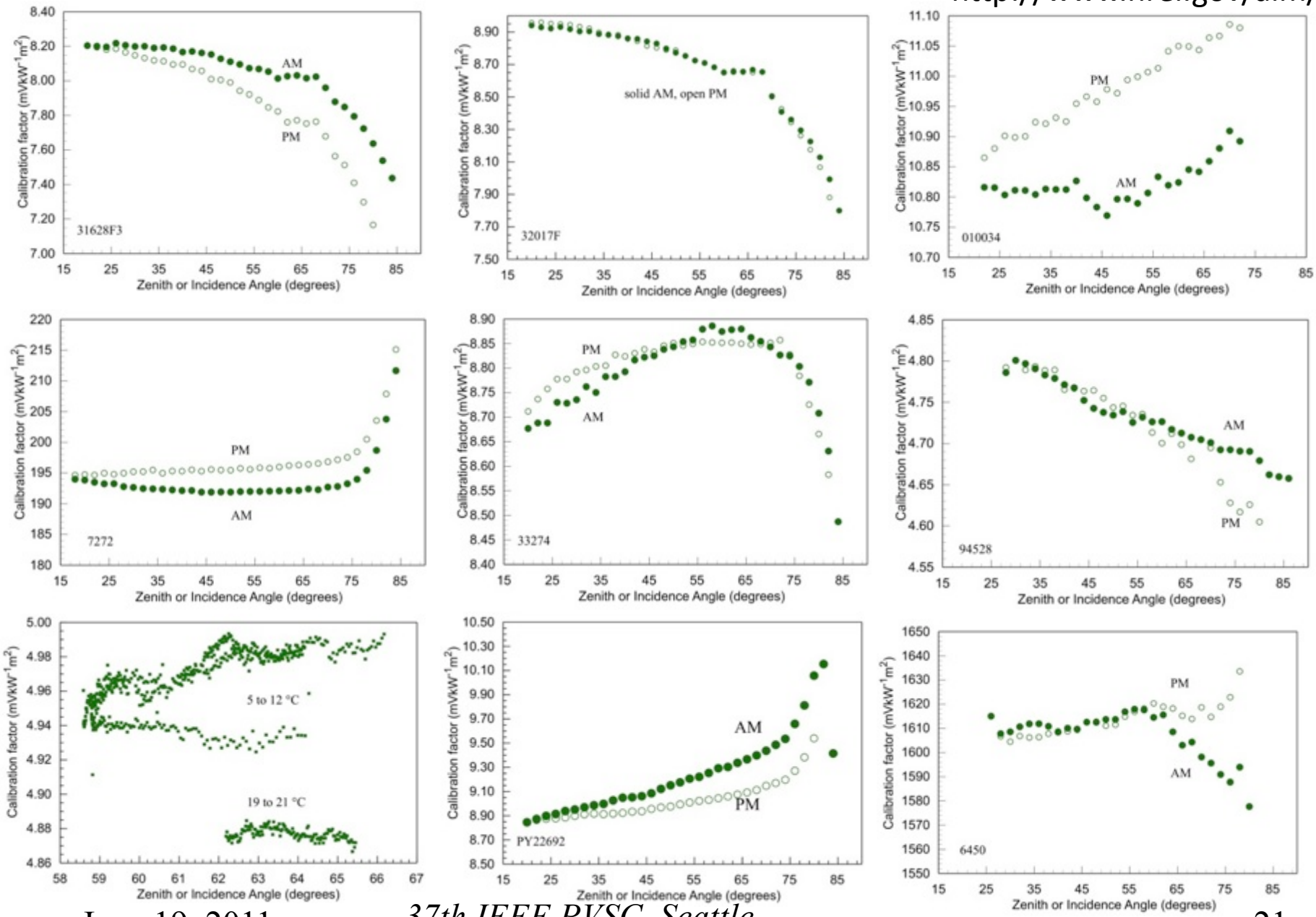
Pyranometer

- Calibrated outdoors with respect to incident spectrum so the calibration is **not** with respect to a reference spectrum. The spectral error for Si pyranometer larger then for thermopile based units.
- Si reference cells calibrated with respect to a reference spectrum can be more accurate than pyranometers even with .
- Usually calibrated on a horizontal surface. Calibration varies with tilt angle.
- Calibration dependent on cable orientation. Cable should face to north away from sun in northern hemisphere.
- Manufacturers often calibrate indoors with integrating sphere against a reference pyranometer.

NREL Single Day Pyranometer Calibrations

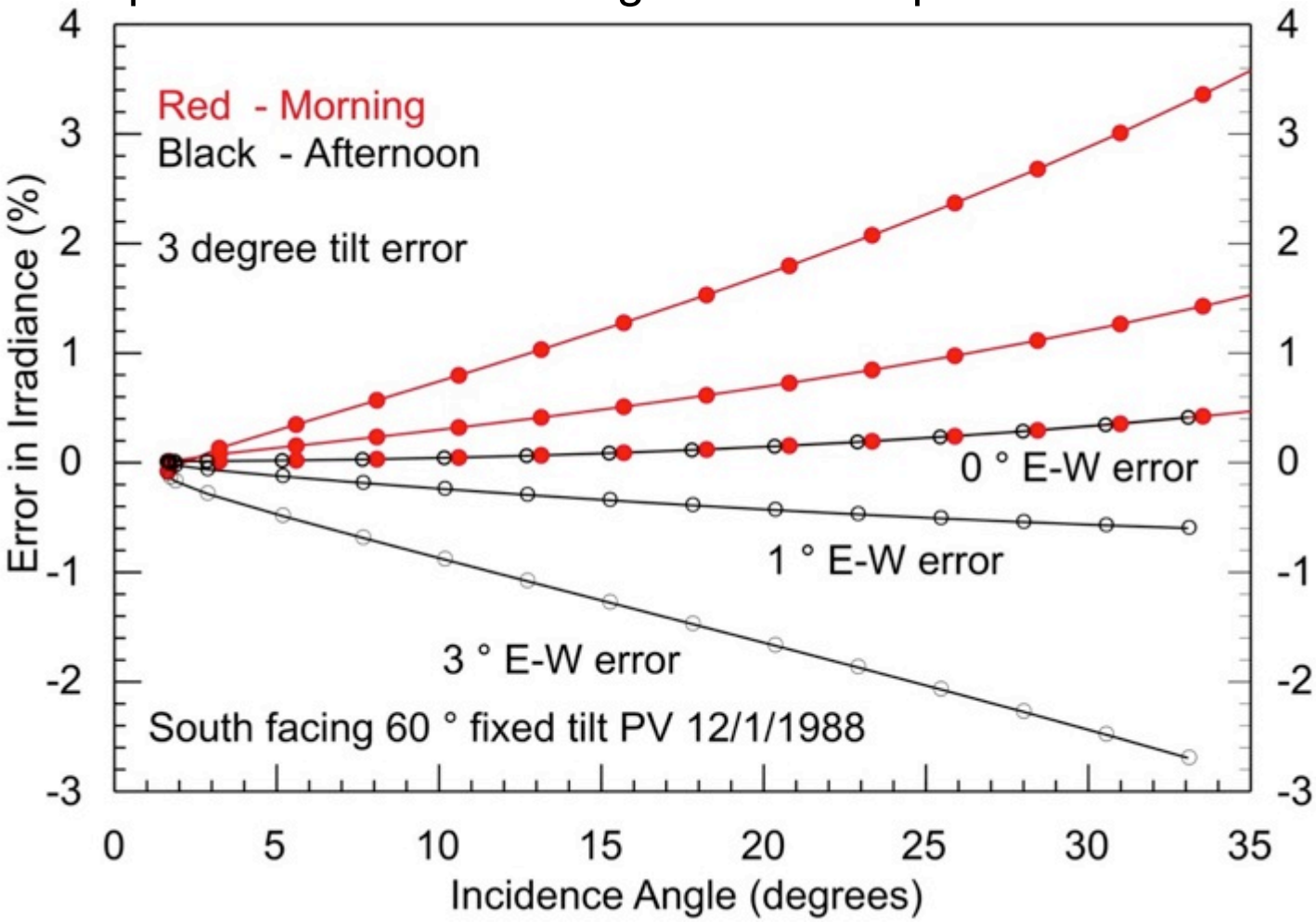
2 degree bins

http://www.nrel.gov/aim/



Leveling Error

How closely must irradiance sensor be aligned to PV array?
What is impact of modules misaligned with respect to each other?



K.A. Emery, et al, "SERI Results from the PEP 1987 Summit Round Robin and a Comparison of Photovoltaic Calibration Methods," SERI tech. rep. TR-213-3472, March 1989.

Outline – Simulators

- Current *vs.* Voltage Measurement Theory
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  - Commercial and Generic I-V systems
  - Contacting
- PV Measurement Artifacts
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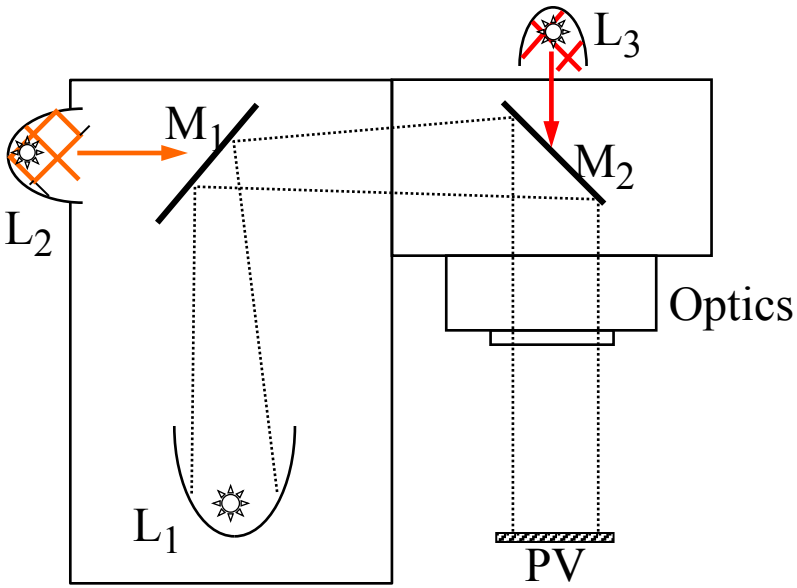
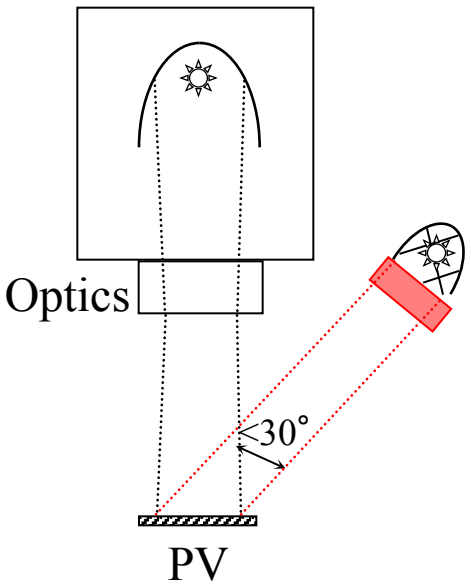
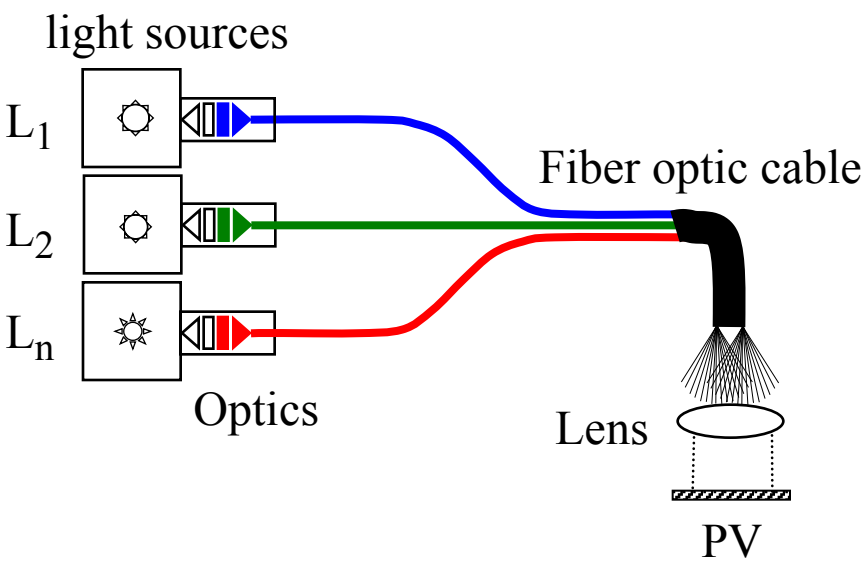
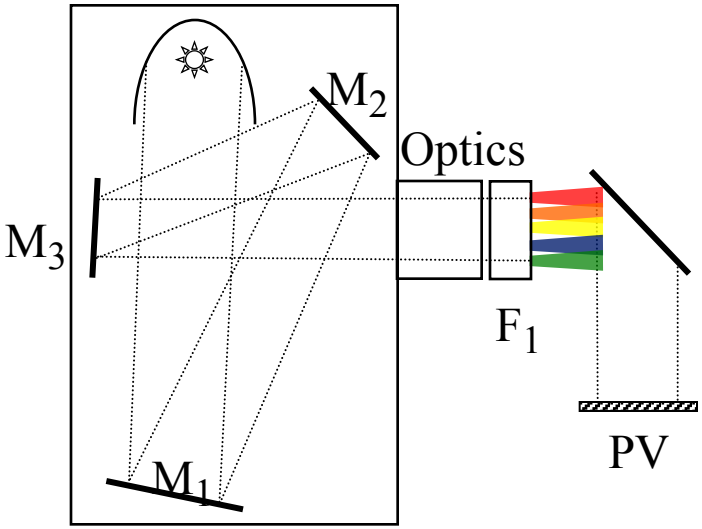
Cell Solar Simulators

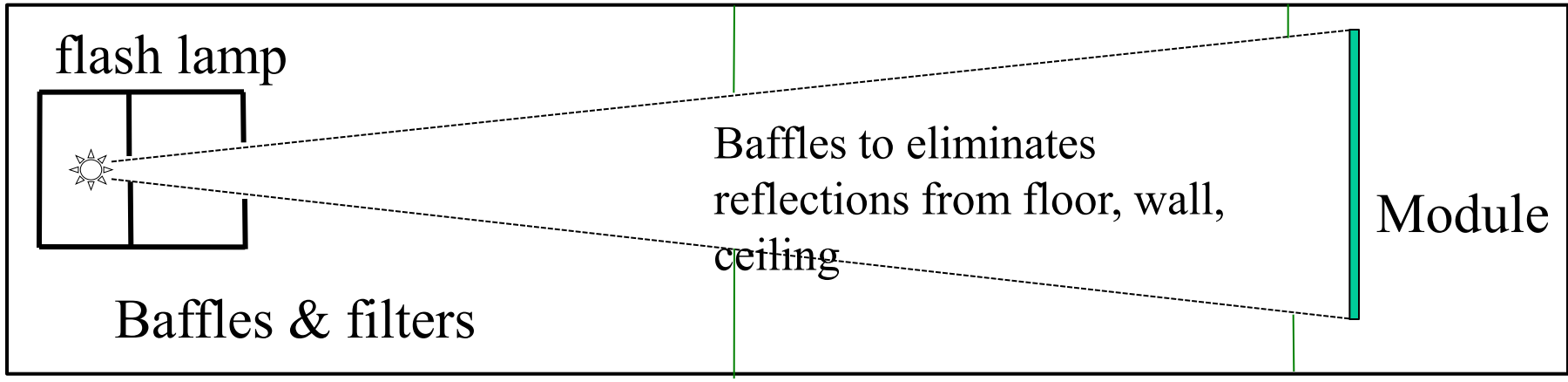


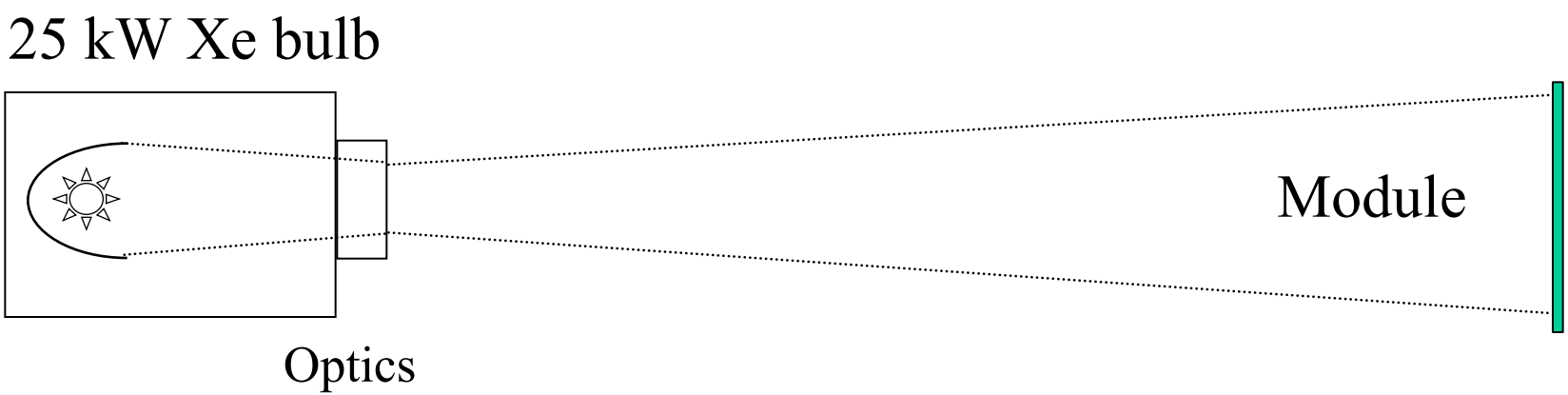






Module Simulators





Simulator Classification

ASTM E927 or IEC 60904-9

Classification	Spectral match in Intervals	Nonuniformity of Irradiance (%)	Temporal Instability	
			Short Term (%)	long term (%)
A	0.75-1.25	2	0.5	2
B	0.6-1.4	5	2	5
C	0.4-1.2	10	10	10

Notes: ASTM only long term instability.

ASTM class C spectral match intervals 0.4 to 2.0.

ASTM for >30 by 30 cm 3% nonuniformity allowed for class A.

Simulator Spectral Classification

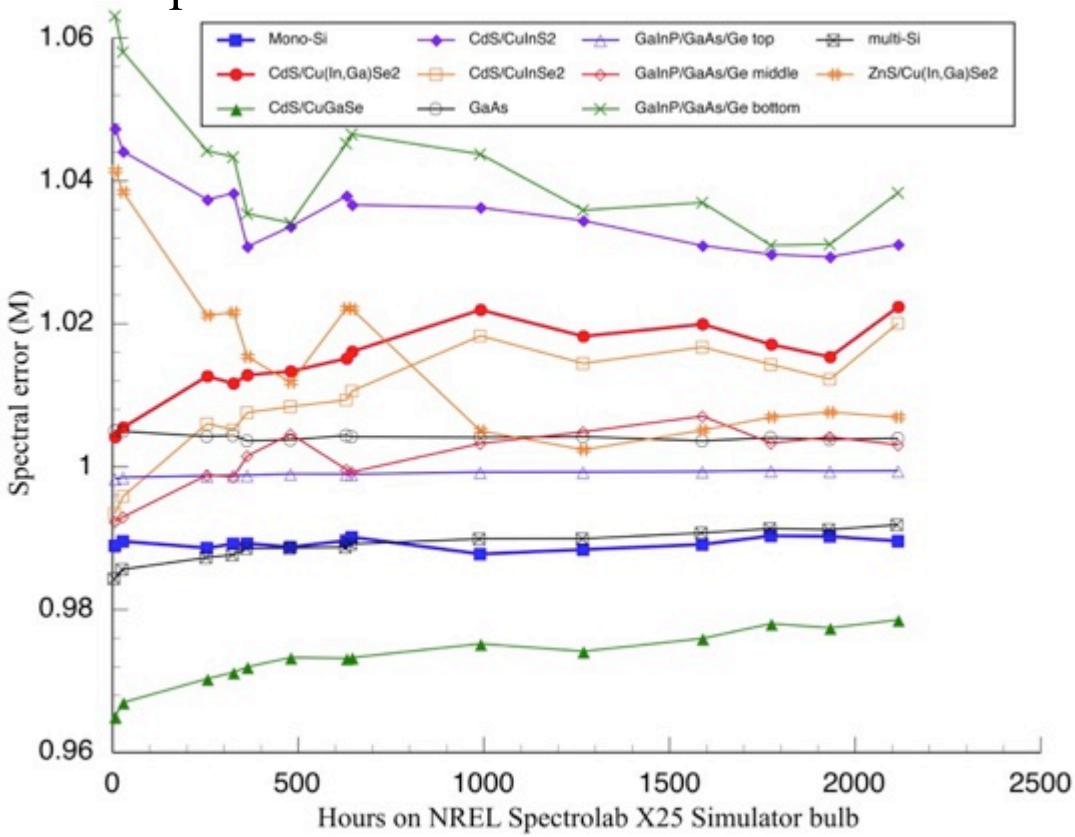
Percentage of the total irradiance in the 400 to 1100 nm wavelength range (300-1400 nm for AM0)

Wavelength interval	Direct	Global	Space
(μm)	AM 1.5	AM 1.5	AM 0
0.3 to 0.4	Not Specified	Not Specified	8.0
0.4 to 0.5	16.9	18.4	16.4
0.5 to 0.6	19.7	19.9	16.3
0.6 to 0.7	18.5	18.4	13.9
0.7 to 0.8	15.2	14.9	11.2
0.8 to 0.9	12.9	12.5	9.0
0.9 to 1.1	16.8	15.9	13.1
1.1 to 1.4	Not Specified	Not Specified	12.2

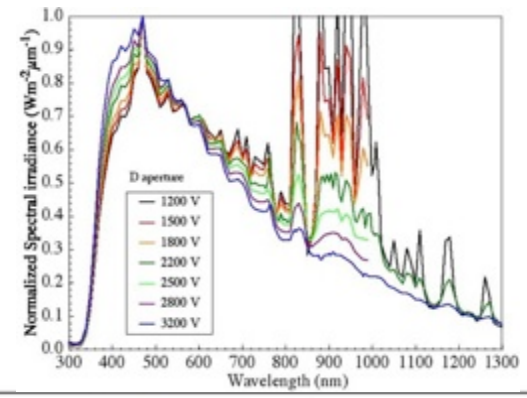
Simulator Spectral Classification

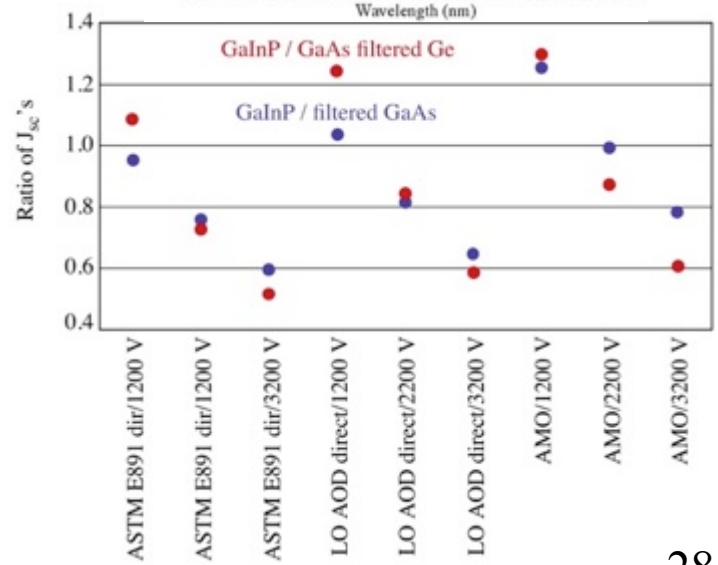
- Spectrum changes with Bulb age – larger for continuous then pulsed simulators
- For flash and filament simulators the spectrum changes with lamp voltage
- For may short pulse simulators the spectrum changes during the flash

Spectrolab X25 3.5 kW Xe continuous

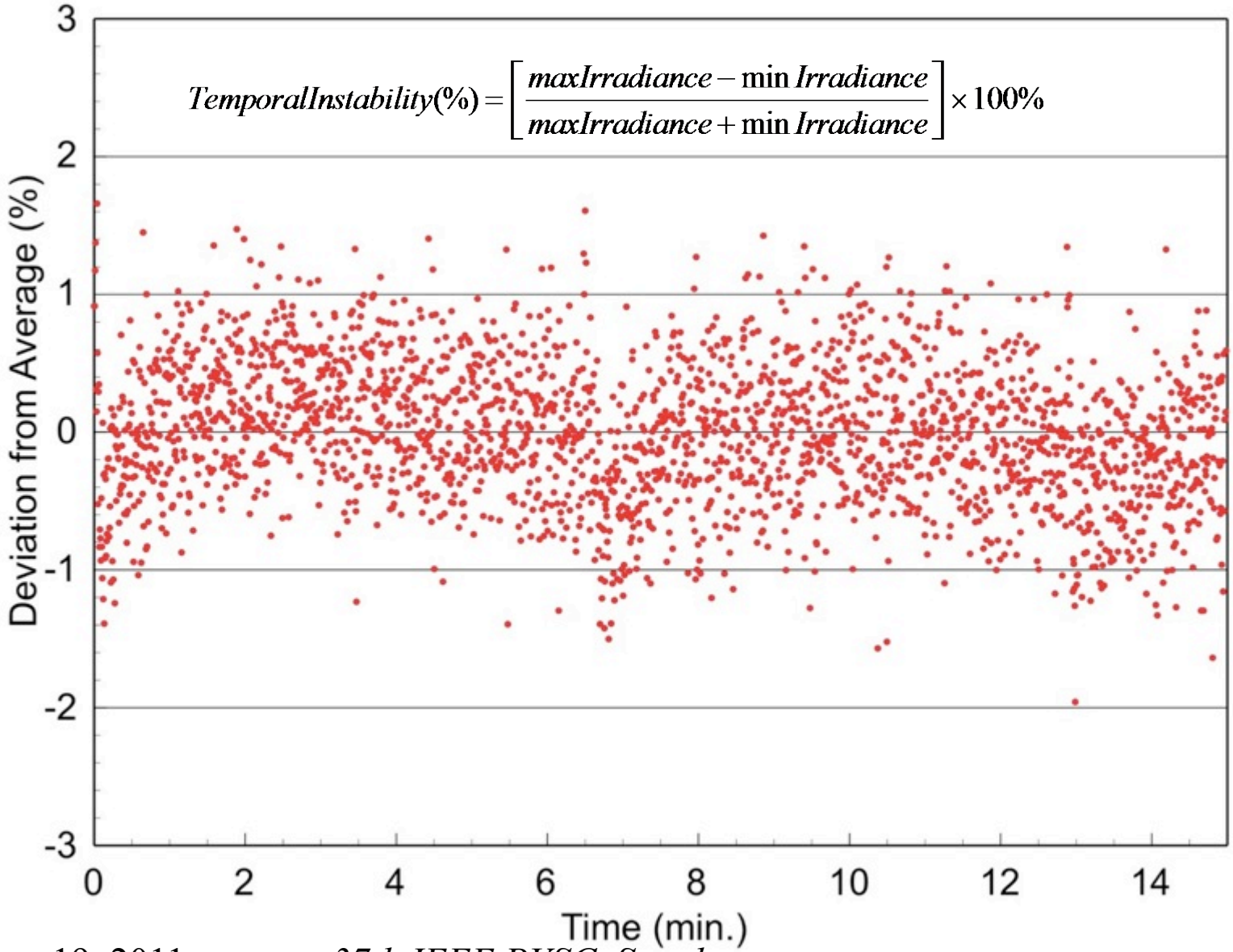


Spectrolab HIPSS 1.5 ms flash



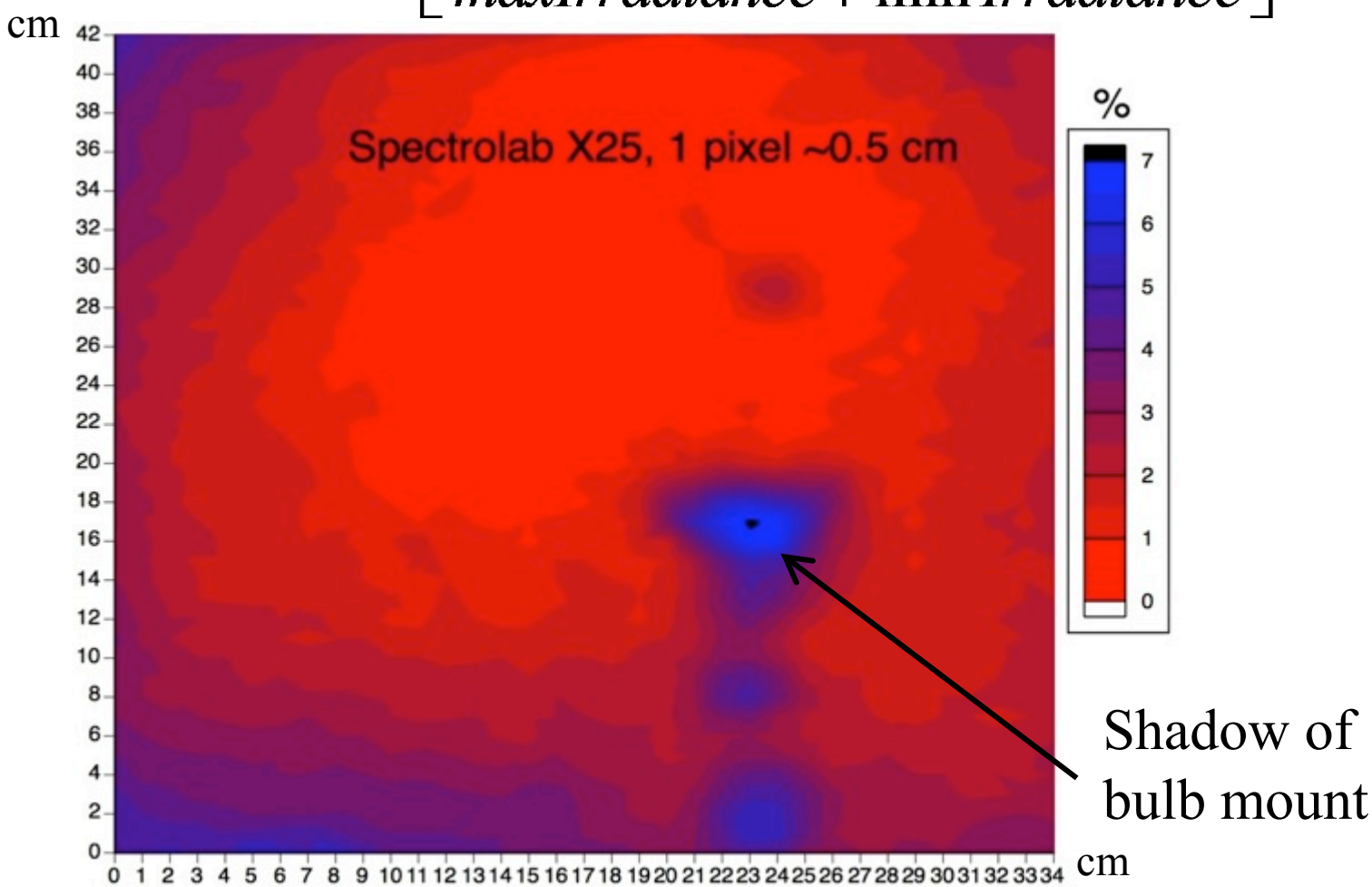


Simulator Temporal Instability

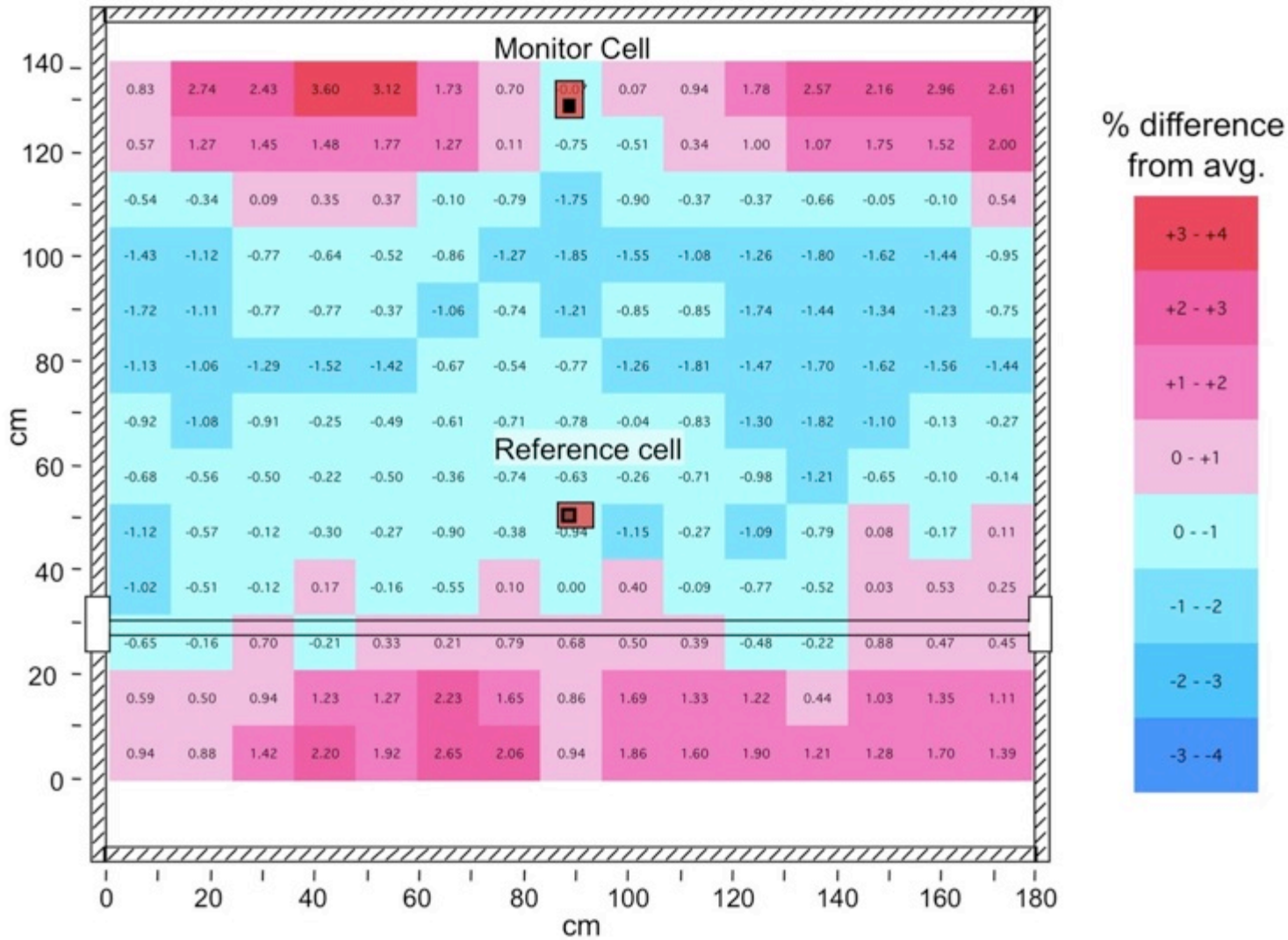


Simulator Spatial Nonuniformity

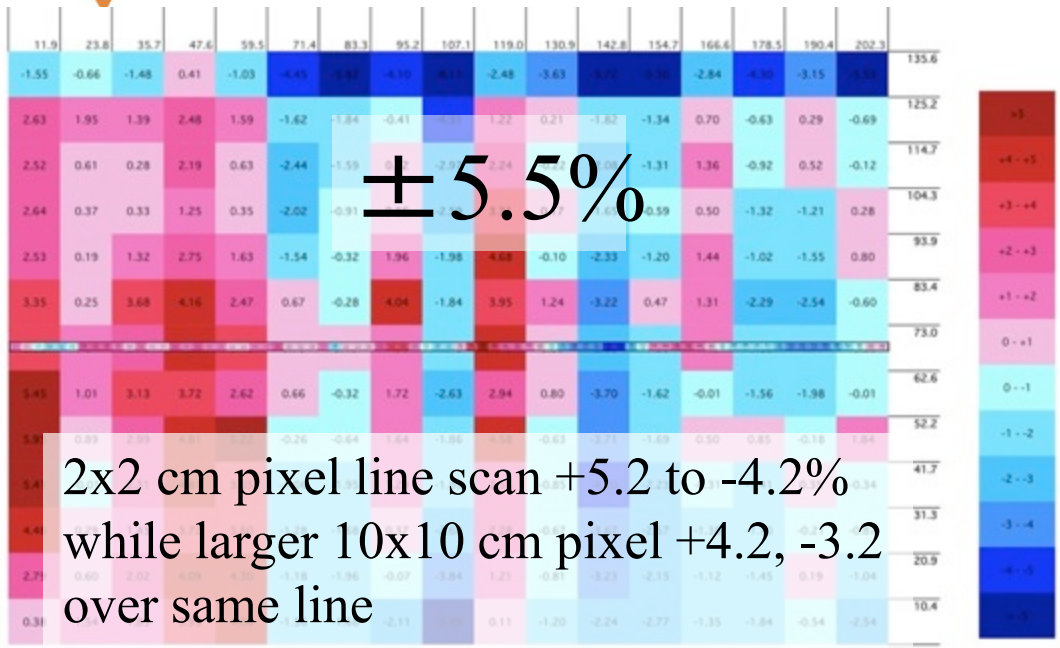
$$Nonuniformity(\%) = \left[\frac{maxIrradiance - \min Irradiance}{maxIrradiance + \min Irradiance} \right] \times 100\%$$



Simulator Spatial Nonuniformity



Simulator Spatial Nonuniformity



The same simulator gives different uniformity maps depending on the pixel size.

Spatial Nonuniformity Pixel size

ASTM E927 – >36 equal area pixels. Pixel area * number of pixels must be > 25% of test area. detector no larger than pixel.

IEC 60904-9 – >64 equal area pixels. Maximum detector area is test area divided by 64 or 400 cm^2.

Word of Caution: For module simulators Class A spatial nonuniformity might not be good enough. This is especially true for simulators where the bulb is close to the sample. This can be an issue for thin-film modules where the cells can be long and narrow because the nonuniformity map will average over small area variations.

Outline – I-V Systems

- Current *vs.* Voltage Measurement Theory
- PV Power Performance
  - PV Irradiance Sensor
  - Simulators
  - Commercial and Generic I-V systems
  - Contacting
- PV Measurement Artifacts
- Intercomparisons
- Alternative rating methods

Features in I-V System

- Lowest uncertainty – (Calibration lab) Voltage and currents measured to 0.02% accuracy. So out of tolerance is not a significant error source (>0.1%).
- Standards call for V_{oc}, I_{sc} measured to 0.02% resolution, 0.1% accuracy!
- Fast testing (production)
- Flexibility for all possible current and voltages and not just what is currently being evaluated
- Lowest Random error (Reliability and other studies where % change vs. time is measured

Features in I-V System

- Ability to control premeasurement history including bias point and light level
- Control over sweep rate to make arbitrarily slow and the ability to sweep in both directions.
- Management of data

  Save data to a data base *versus* save data to a directory and individual I-V files that can be imported into a data base.

  Automatic file naming vs. user selected file names.
- Ability to examine and modify the source code to meet changing needs.

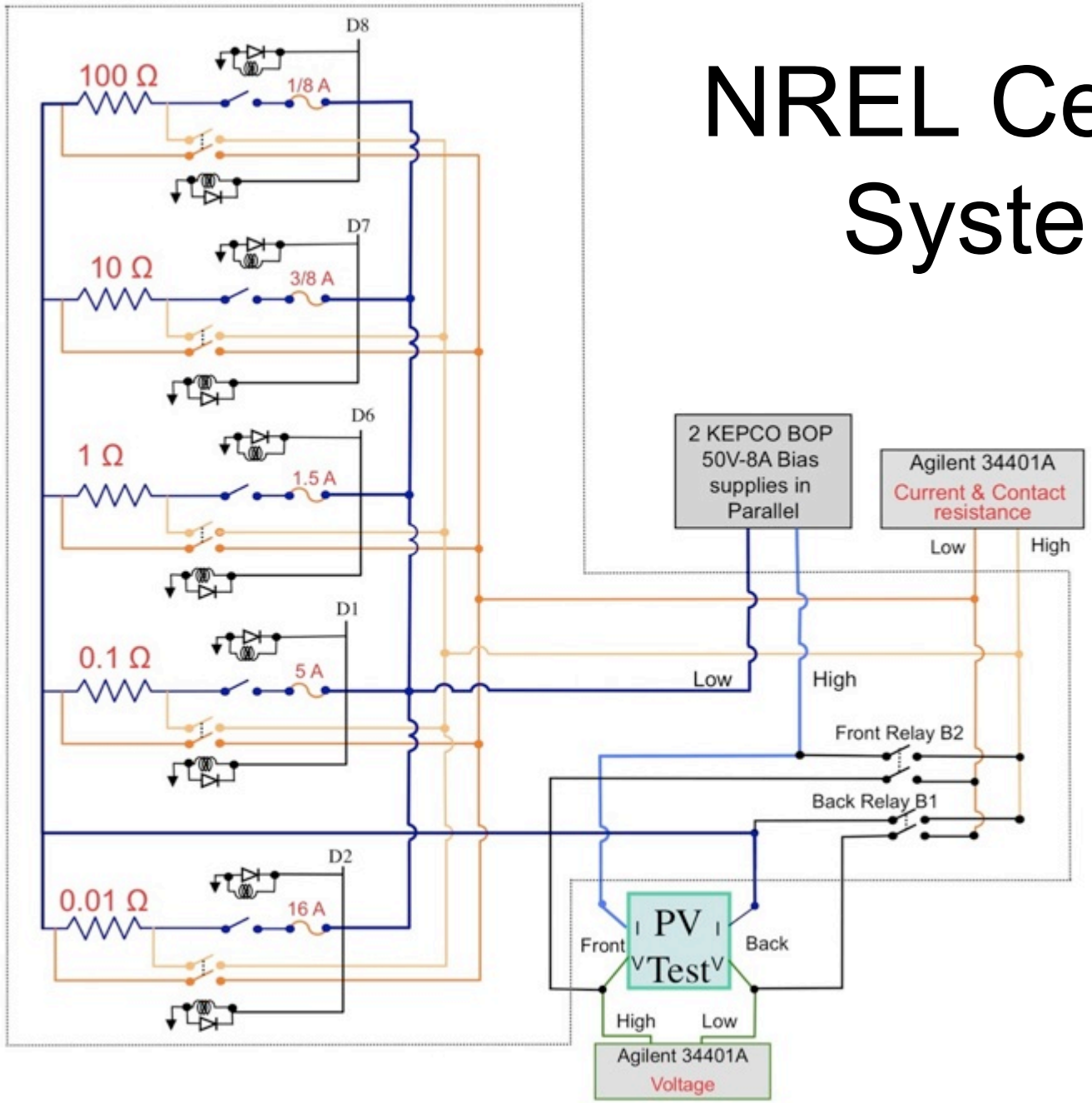
NREL I-V System Features

- Measure resistance between voltage and current on IV systems to verify a good contact before testing. Manually measure with ohm meter for commercial systems, automatically or manually for custom systems.
- Hardware is PV polarity independent – use sign on V_{oc} to determine polarity and bias ranges.
- High and low current and voltage connections to device are isolated from ground. Shielded twisted pair or coax for connections to sample with the shield tied to ground. This gives you 1 free pass for a stealth ground. Commercial system usually make the low negative and tie it to ground. which require

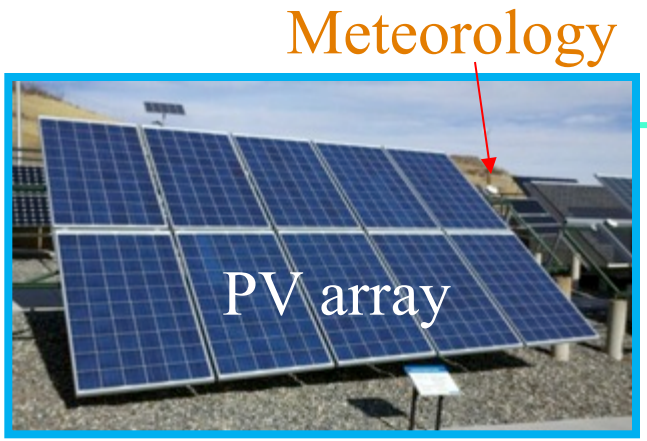
I-V Systems

	Strengths	Weakness	features	examples
Commercial SMU	software easy to use	limited max. current , <few hundred watts	bipolar operation nA to A	Keithley 24XX Agilent 4155
Commercial Load	wide range of max I &V, W to many kW	limited number of I or V ranges	unipolar, small box,	Amrel PEL150 Agilent N3300
Commercial PV tester	easy to use	few can do light and dark. User interface predetermined	ready to go for PV light I-V	Abet, Atonometrics, Daystar, EKO, Wacom, Spire, Nat. Instruments, PV Measurements
Capacitive load	small foot print	power quadrant only, 0 to Voc bias direction	mW to >100 kW	Daystar, PV Measurements, custom circuit
Custom	complete flexibility in software, I &V	difficult to maintain code. No customer support	Any desired features	Calibration labs

NREL Cell I-V System



NREL PV System Monitoring



DC Disconnect

DC Monitoring (V, I)

Utility-Interactive Inverter

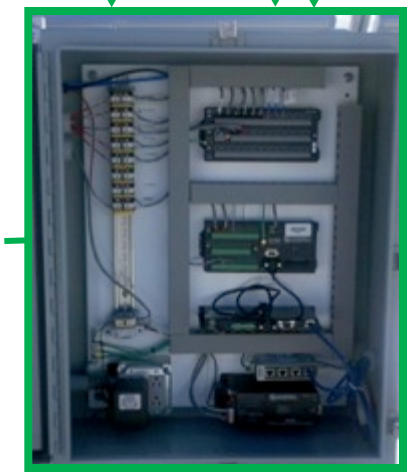
AC Monitoring (V, I, P, PF)

Meteorology
- Module Temp
- Ambient Temp
- Irradiance

AC Disconnect

Network

Utility Grid Or Load



Data Acquisition System

K. Emery and R. Smith, "Monitoring System performance, Proc. PV Module Reliability Workshop", Feb. 11, 2011

IEC 61724 "**Photovoltaic System Performance Monitoring – Guidelines for measurement data exchange and analysis**"

Meteorology

- Total irradiance, in the plane of the array
- Ambient air temperature
- Wind speed

Photovoltaic array

- Output voltage
- Output current
- Output power
- Module temperature
- Mounting / tracker characteristics

Load

- Load voltage
- Load current
- Load power

Energy storage

- Operating voltage
- Current to/from storage
- Power to/from storage

Utility grid

- Utility voltage
- Each phase - Current to/from utility grid
- Power to/from utility grid

Back-up sources

- Output voltage
- Output current
- Output power

System Level Testing

- AC or DC power measured at inverter
  - ac or dc current and voltage transducers
  - data logger
  - Pyranometer (prevailing) or reference cell giving first order spectral correction to reference spectrum
- I-V curve of system
  - Typically a capacitive based IV system because the system can be damaged by holding it at 0V for an extended period of time. Daystar and others manufacturer units rated to 50 kW.
    http://www.zianet.com/daystar/

IEC 61724 "**Photovoltaic System Performance Monitoring – Guidelines for measurement data exchange and analysis"**

- Total Irradiance –
  - Measured in plane of array
  - Uncertainty including including Instrumentation < 5%
  - Pyranometer
  - Reference cell or cell in Module Package or Module (IEC 60904-2)
- Ambient Temperature –
  - Representative of Array Location
  - Uncertainty including Instrumentation < 1° C
- Wind Speed –
  - Measured at Height and Location Representative of Array
  - Uncertainty including Instrumentation < 0.5 m/s for Speeds < 5 m/s, and <10 % of the reading for Speeds > 5 m/s

IEC 61724 "**Photovoltaic System Performance Monitoring – Guidelines for measurement data exchange and analysis**"

- Module Temperature –
  - Measured on back of 1 or more modules in representative of location
  - Uncertainty including Instrumentation < 1° C
  - location on module given in IEC 61829 method A (center of back surface of module in center of array field)
  - Based upon V_{oc} and equivalent Cell temperature (IEC 60904-5)
- Voltage and Current –
  - ac and or dc
  - Uncertainty including Instrumentation < 1% of reading
- Power
  - DC Calculated based upon instantaneous and not averaged readings or directly measured with wattmeter
  - AC power accounts for power factor and harmonic distortion
  - Uncertainty including Instrumentation < 2%

System Monitoring Recommendations

Topic	Recommendation	Reason
Measurement Interval	5-sec scans into 1-min averages	15-minute data (standard) cannot capture many system issues; 1-minute data provides the resolution needed for capturing transient system events such as inverter shutdown. 1-minute data also supports analysis which require more data points (degradation rate calculations, for instance). With the cost of hardware and storage decreasing there is no reason to avoid 1-minute (or sub-minute) data collection.
Analog Signal Lines	High quality PTFE Jacket; Shielded w/ drain wire	Experience has shown that PTFE jacketed signal lines are less susceptible to noise when going between different temperature environments. Also, PTFE has superior resistance against weather (UV, moisture, temperature) when used outdoors.
Outdoor Connectors	Rated for the environment; Use of protective boots.	Use all means to limit connector corrosion. Sunlight resistant boots must be used; unrated boots can crack and actually trap moisture within the connector housing.
Equipment Temperature Ratings	-55° C to 85° C	Equipment enclosures can see dramatic temperatures, especially if exposed to direct sunlight. Equipment must handle these extremes.

System Monitoring Recommendations

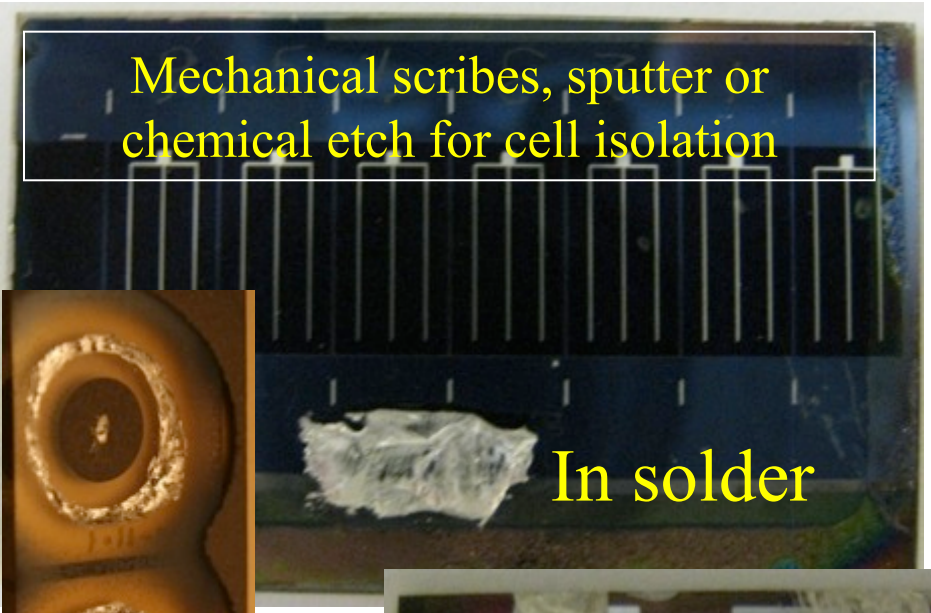
Topic	Recommendation	Reason
Enclosure Locations	In the shade	Direct exposure to sunlight can raise the interior temperature of an enclosure dramatically.
Thermocouple Attachment	Clean location and hands; Silicone adhesive; Round shape	Silicone adhesive has withstood outdoor testing very well. Limit contamination of the adhesive by cleaning the attachment location (w/ IPA) and your hands. Avoid touching the adhesive by using tape with a split carrier film. Square corners are prone to lifting; round dots limits lifting.
Inspection Interval	Visual checks quarterly	Check for: 1)Thermocouple detachment or tape embrittlement 2)Damage to exterior sensors (pyranometers, ambient temp sensors) 3)Evidence of moisture or vermin in enclosures 4)Loose connections at DAS / sensors
Calibration Interval	End-to-End Calibration Annually -Ambient temp above 15° C -Wind speeds below 3 m/s	Bench calibrations are done in an atypical environment (indoor is not equivalent to outdoor conditions). Calibration equipment can be affected by the surrounding environment. Limit temperature extremes and high winds which may cause offsets in the calibration hardware. End-to-end calibrations are necessary to limit uncertainties and systematic errors.

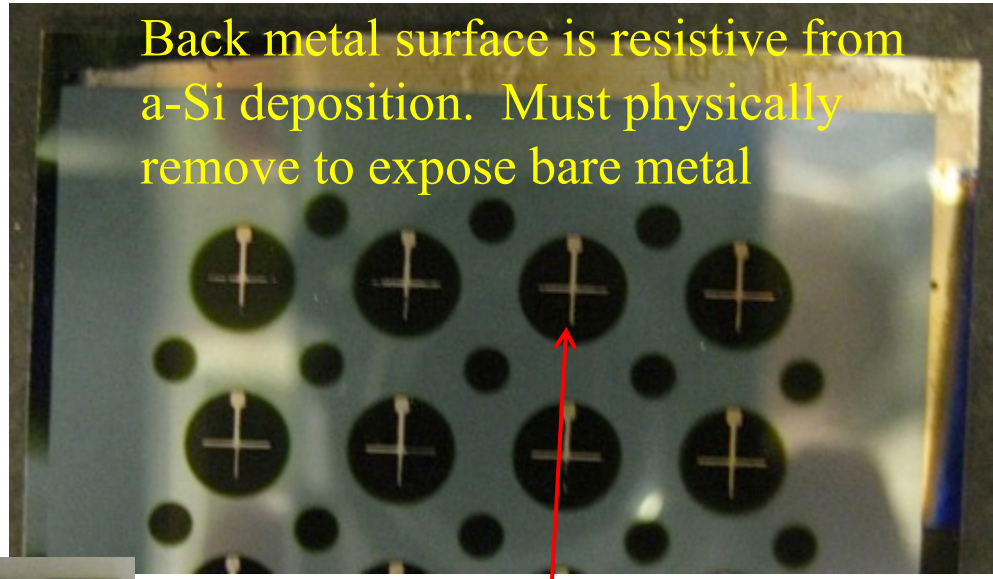
Outline – Hardware

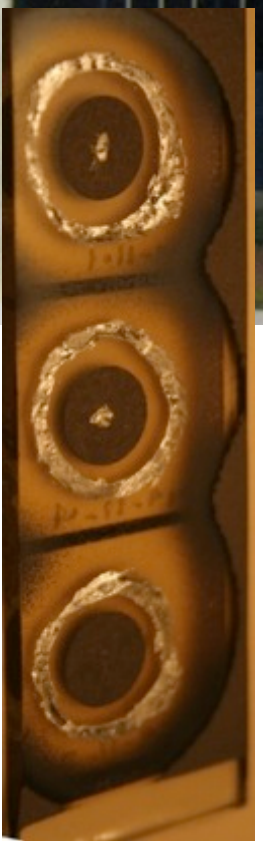
- Current *vs.* Voltage Measurement Theory
- PV Power Performance
  - PV Irradiance Sensor
  - Simulators
  - Commercial and Generic I-V systems
  - Contacting
- PV Measurement Artifacts
- Intercomparisons
- Alternative rating methods

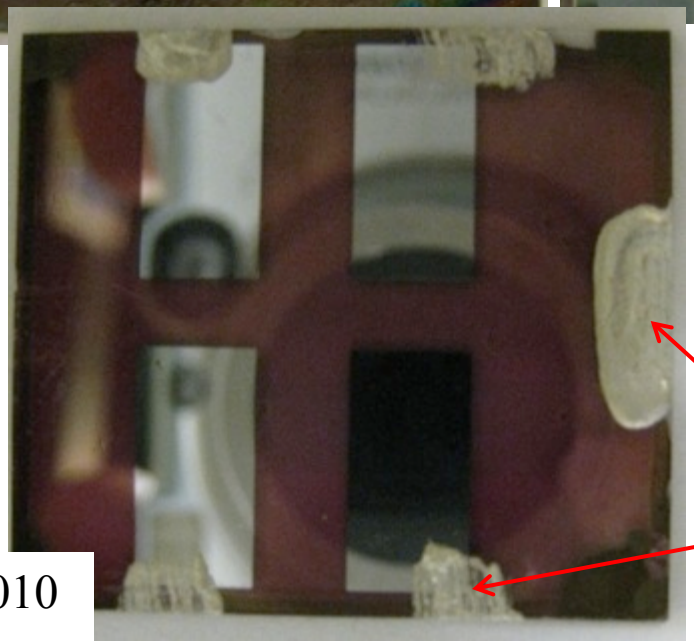
Probing to thin-film Cells

Examples of cells with large distance between contact and cell





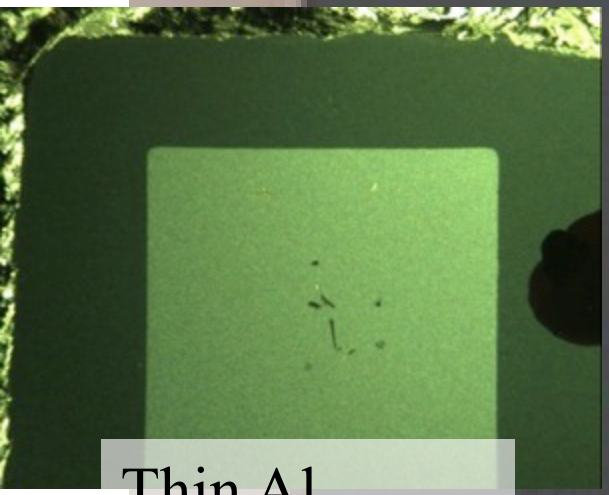




TCO defines cell area even though PV whole surface active. Assumes 0 diffusion length or infinite sheet resistance.

Silver paste will increase resistance with time. Adds to cell area?

Probing to Superstrate Cells

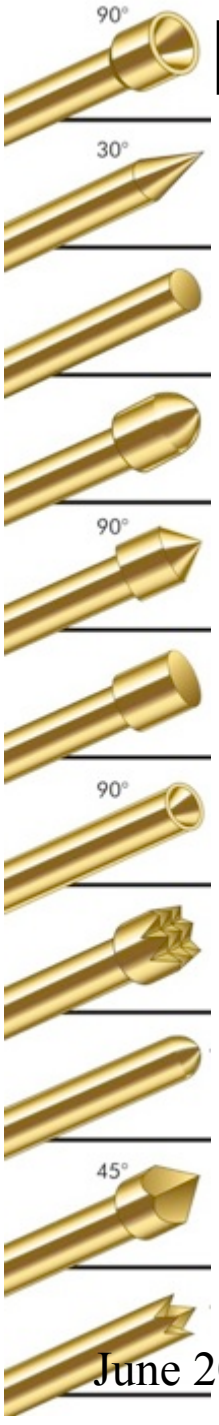


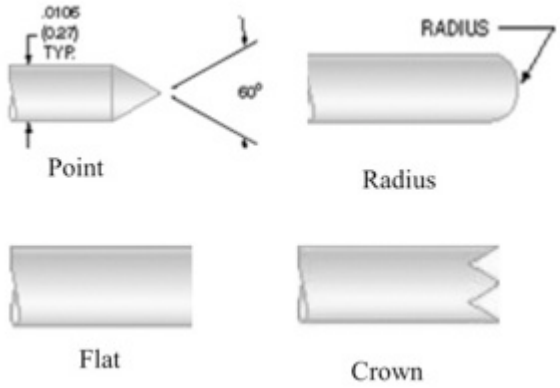
Thin Al sensitive to probe damage

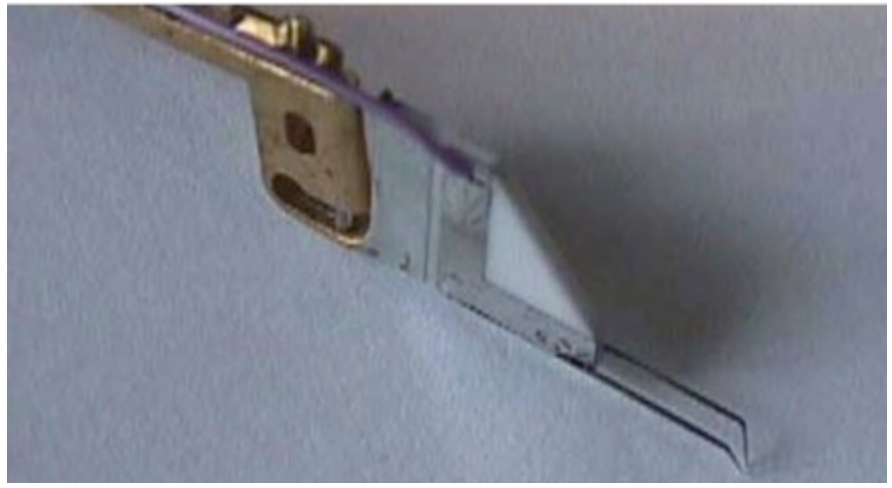
In solder bordering cell minimizes sheet resistance losses

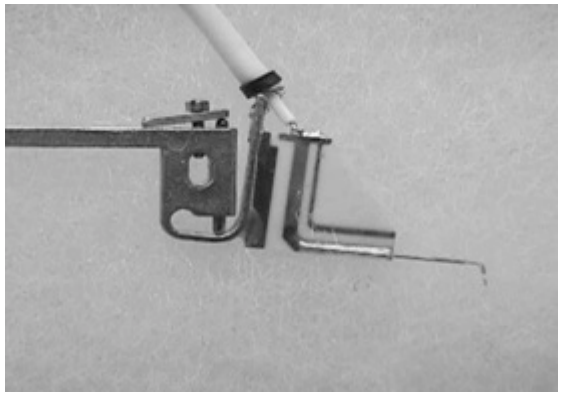
Metalized rubber contact to TCO if In not present

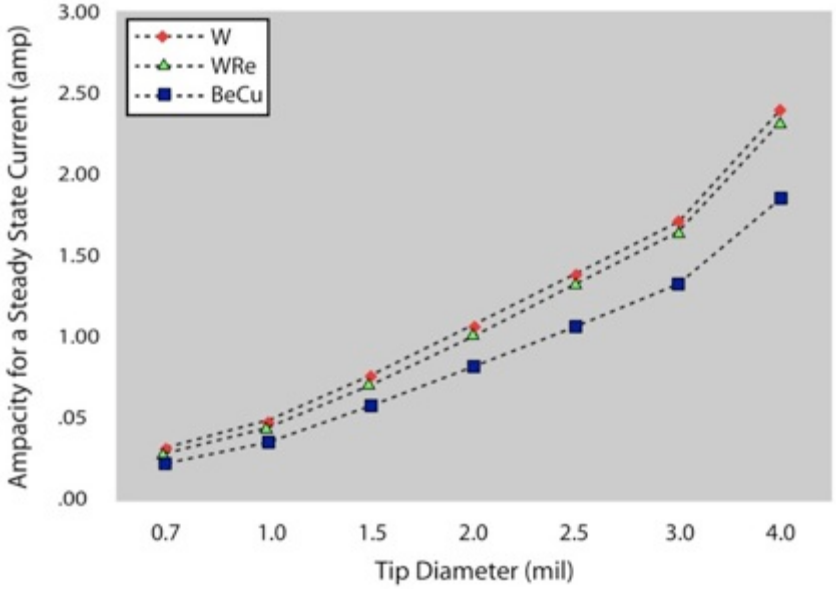
Probing to Cells











Accuprobe (http://www.accuprobe.com/) tips are used because of the large range of diameters (12.7 to 381 microns, 0.5 to 15 mils) and come assembled with wires for current and voltage

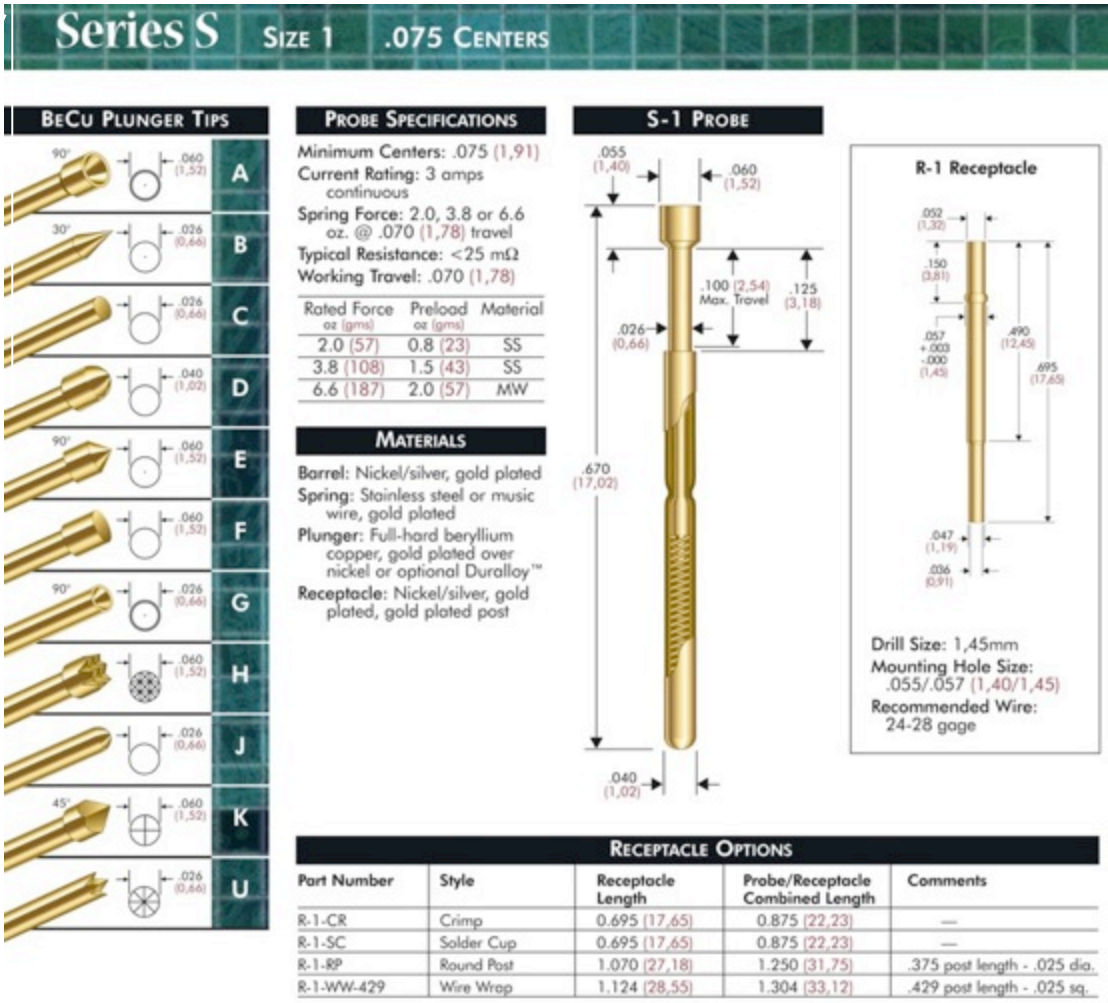
Voltage Probing to back of wafer

- My preference is for Ni or hard Au plated vacuum plate / chuck with a voltage probe. Cleaned with DI water and submicron polish

For voltage we use;

Interconnect Devices
www.idinet.com
Everett Charles Technologies
http://www.ectinfo.com

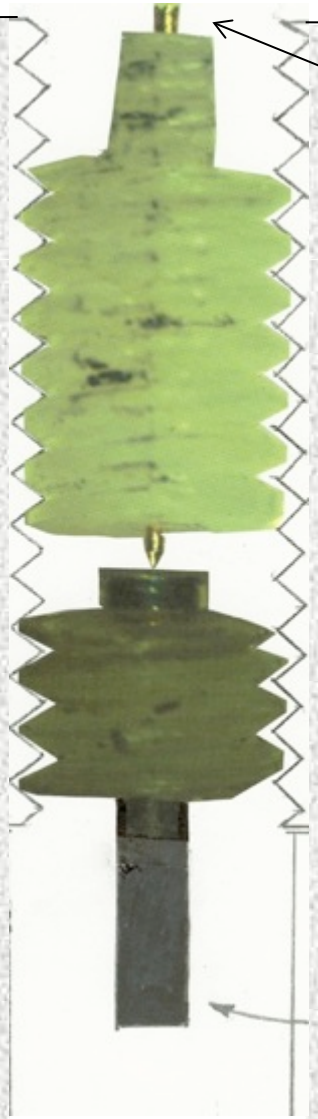
Low force (approx. 1 oz.) spring, single- or multi-pointed tip. Use of receptacle makes drop in replacement possible and height can be adjusted by raising / lowering receptacle.



Probing to back of wafer

top of plate

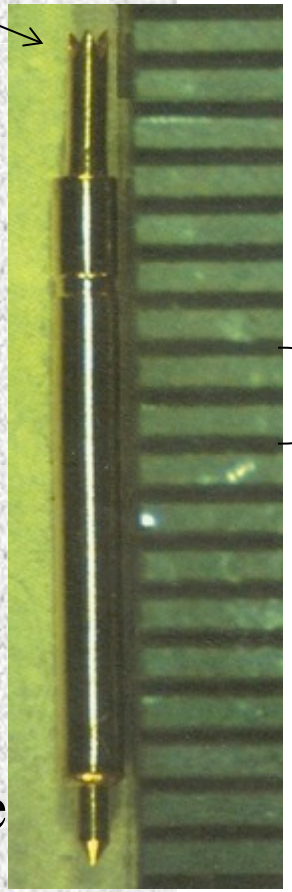
Temperature controlled Vacuum Plate



receptacle mounted in plastic sleeve

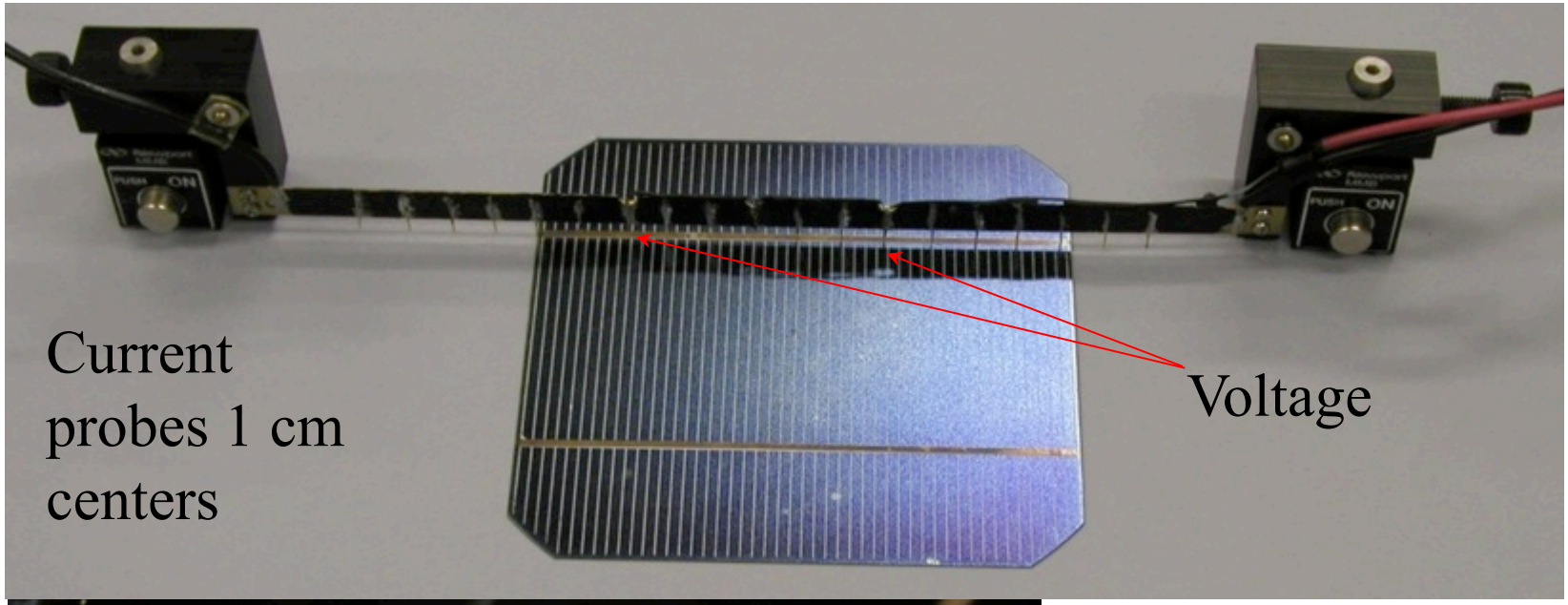
wire for V sense

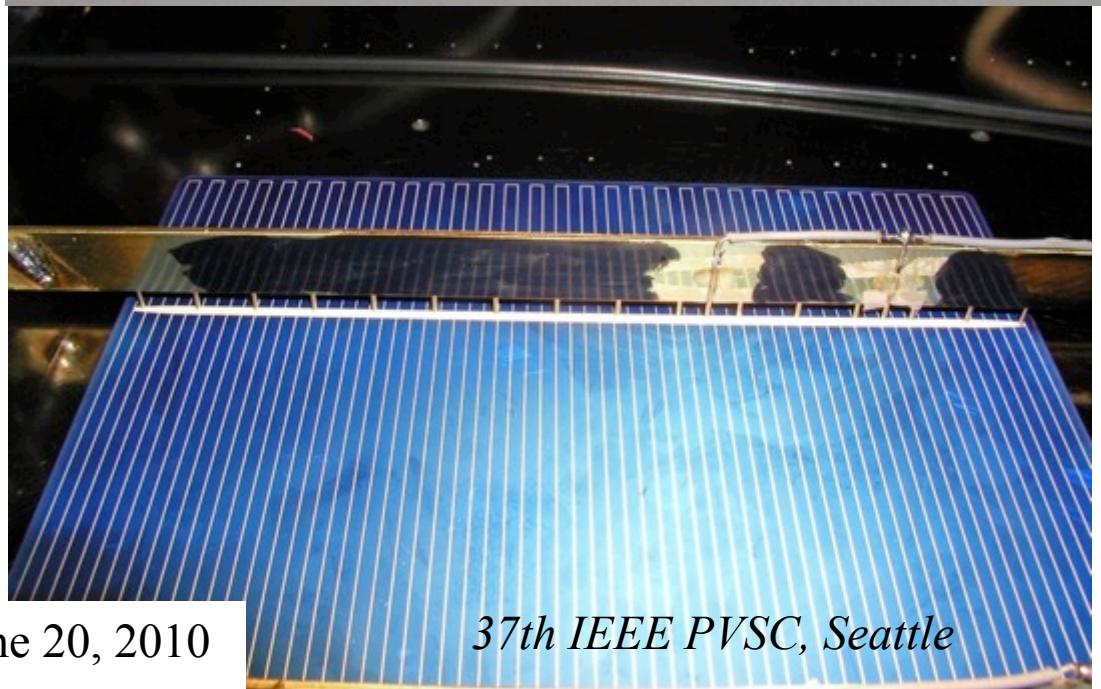
Everett Charles pogo part CSP-25LCBC



1mm

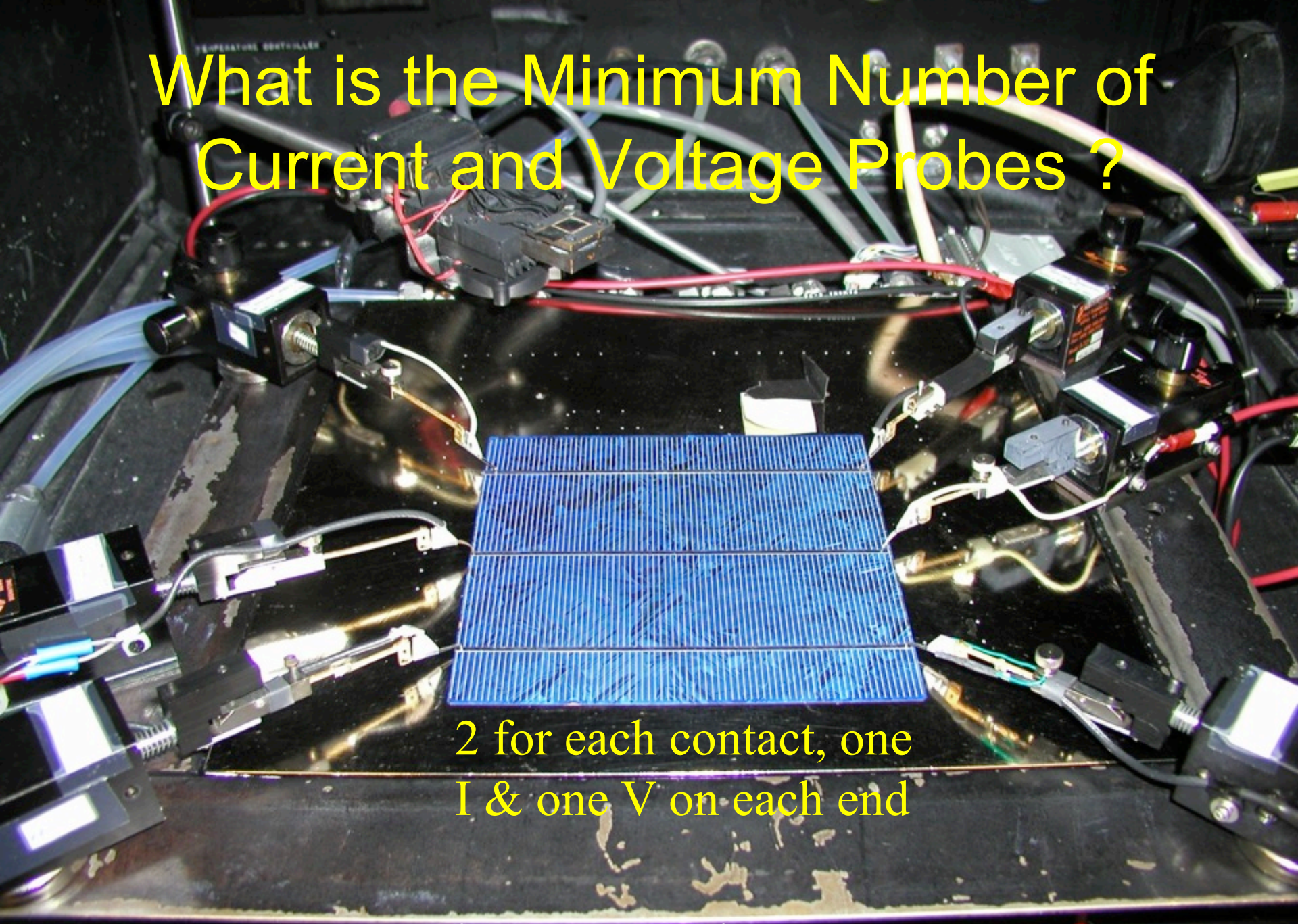
Probing to Wafers





Probe shading will differ between groups

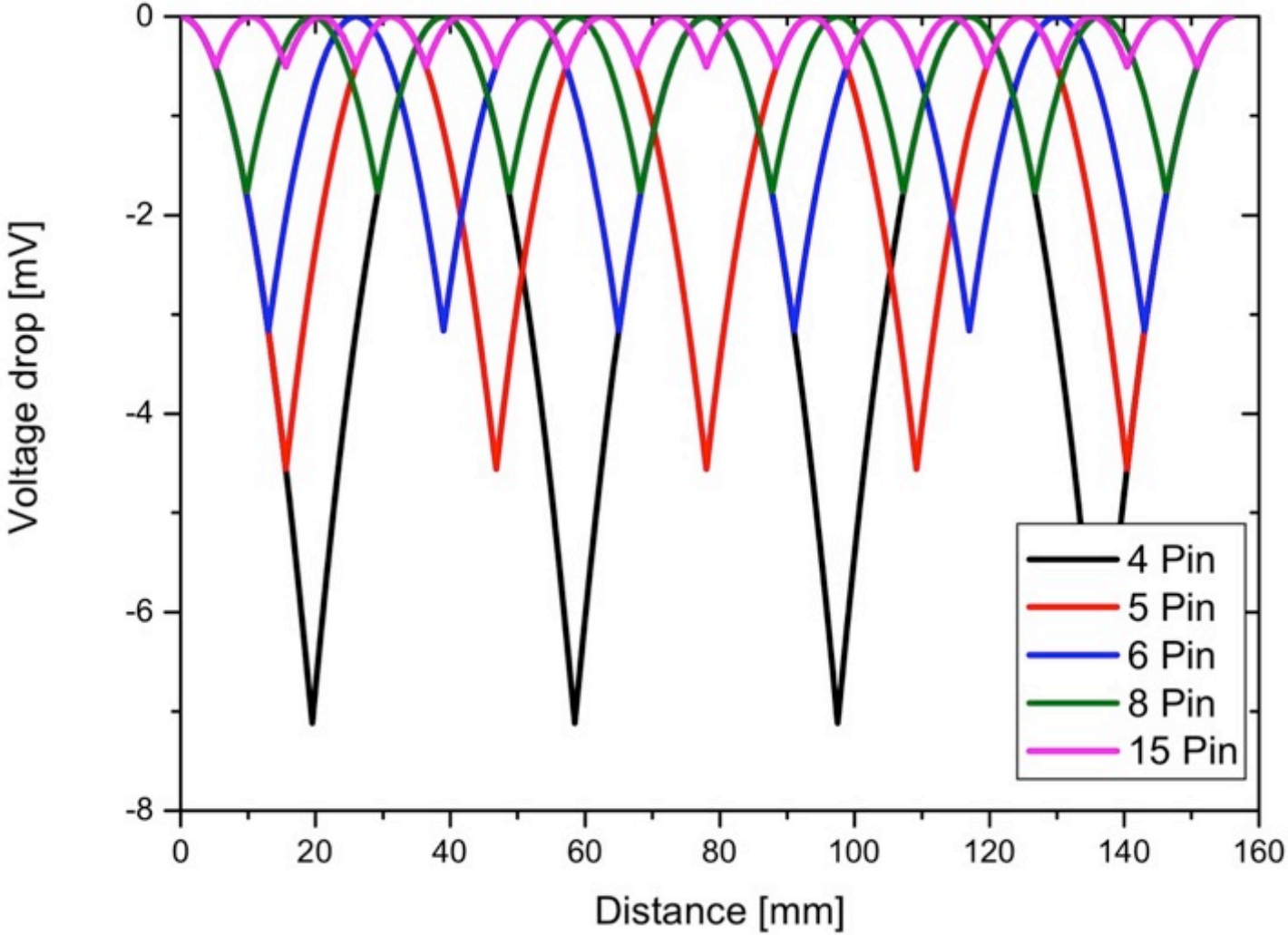
What is the Minimum Number of Current and Voltage Probes ?



2 for each contact, one I & one V on each end

Probing Si Bus bar

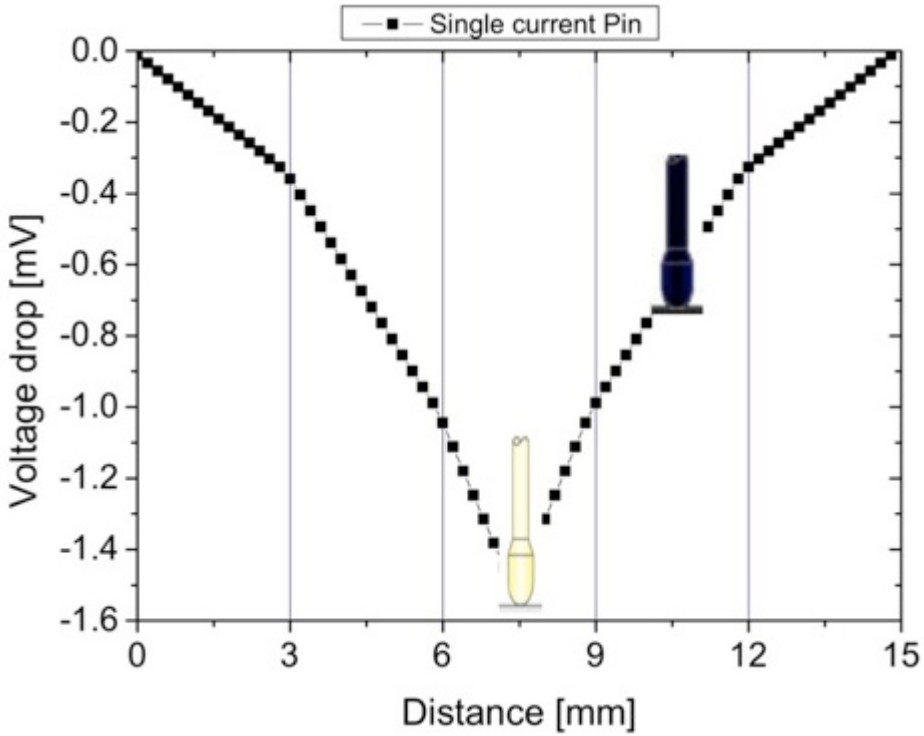
6” wafer, 30 mA cm^{-2}, *vs.* number of probes

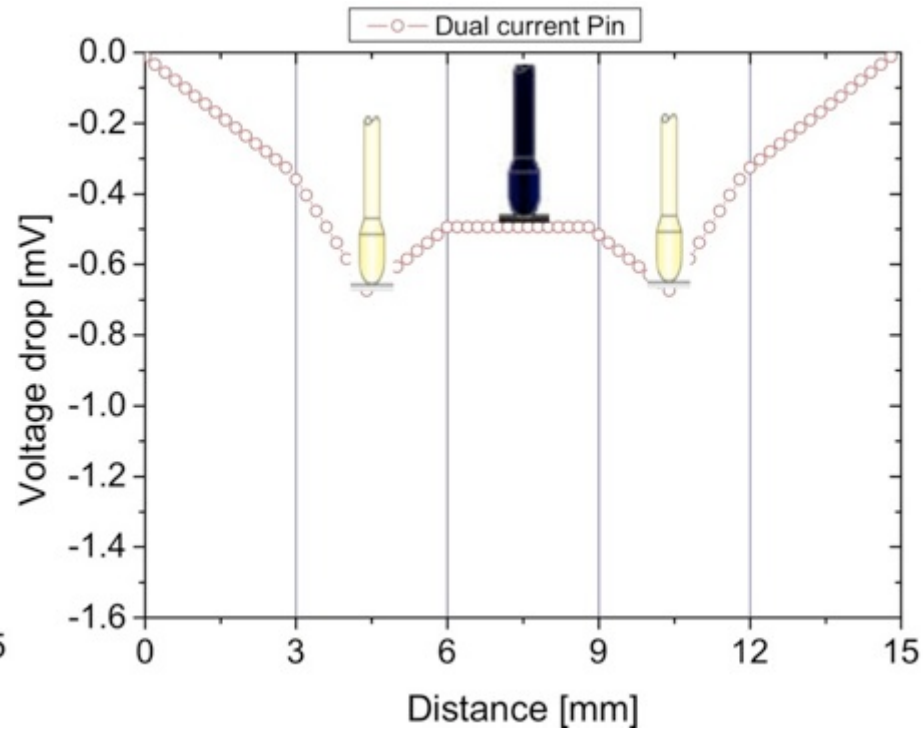


J. Hohl-Ebinger, D. Grote, B. Hund, A. Mette, W. Warta, “Contacting Bare Solar Cells For Stc Measurements,” 23rd European Photovoltaic Solar Energy Conference, 1-5 September 2008, Valencia, Spain

Contacting - single vs. dual current

Goal Simulate zero sheet resistance (superconducting) bus bar

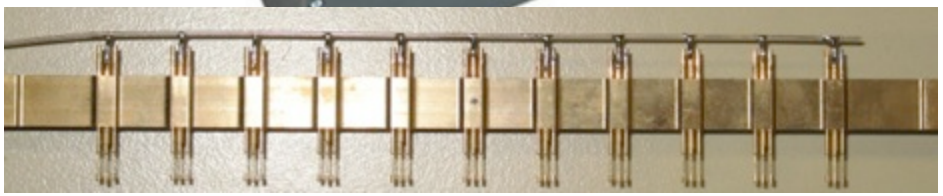




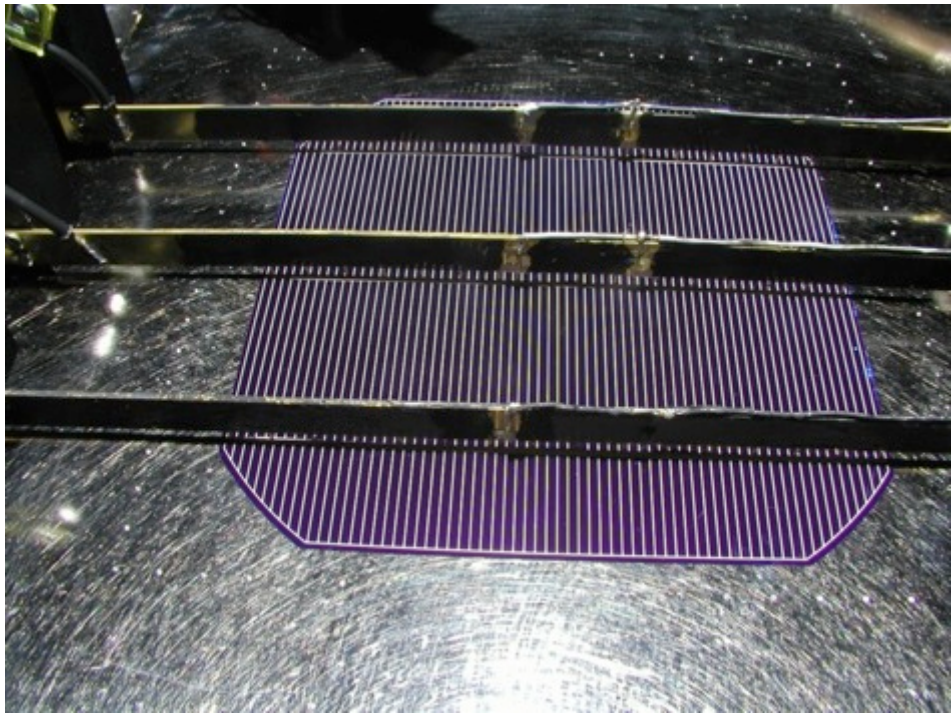
Potential distribution for a single current pin and a dual current pin with a period of 15 mm. Distance to the voltage pin 3 mm. Current pins are yellow and voltage pins are black.

J. Hohl-Ebinger, D. Grote, B. Hund, A. Mette, W. Warta, "Contacting Bare Solar Cells For STC Measurements," 23rd European Photovoltaic Solar Energy Conference, 1-5 September 2008, Valencia, Spain

Probing to Si Cells



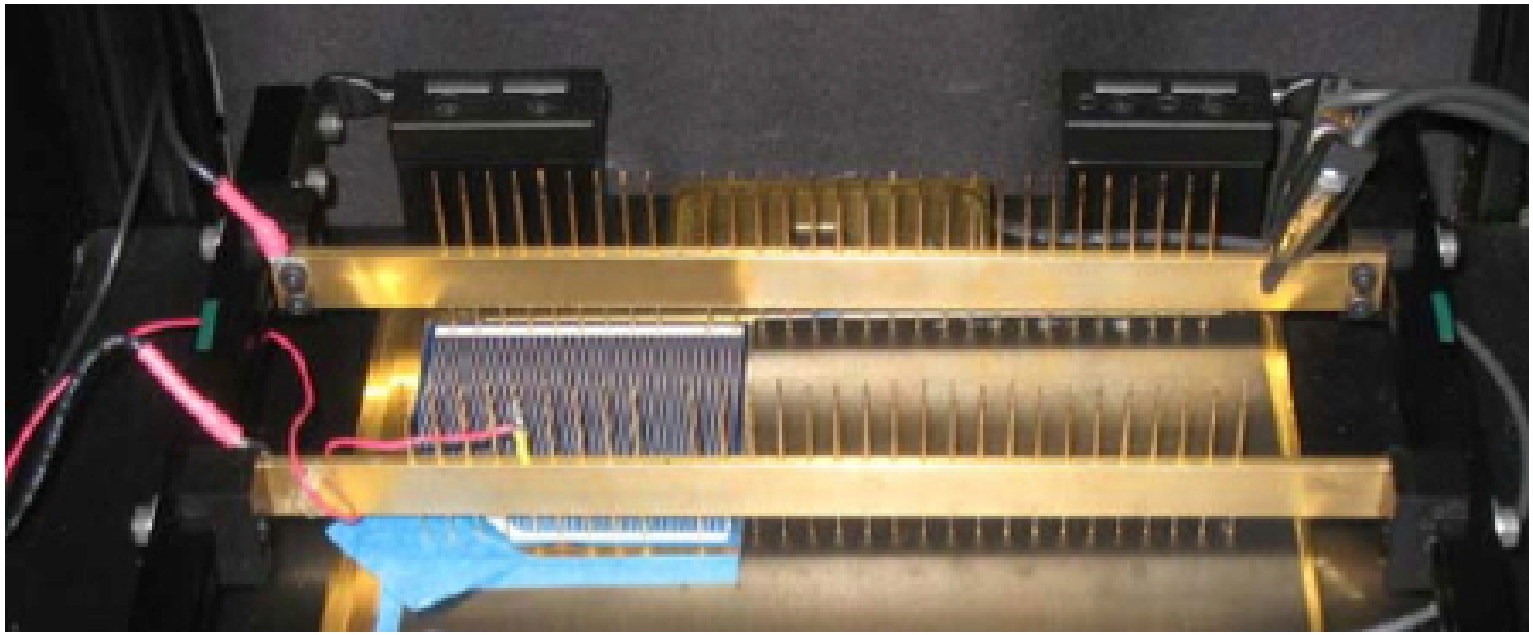
http://www.halm.de/

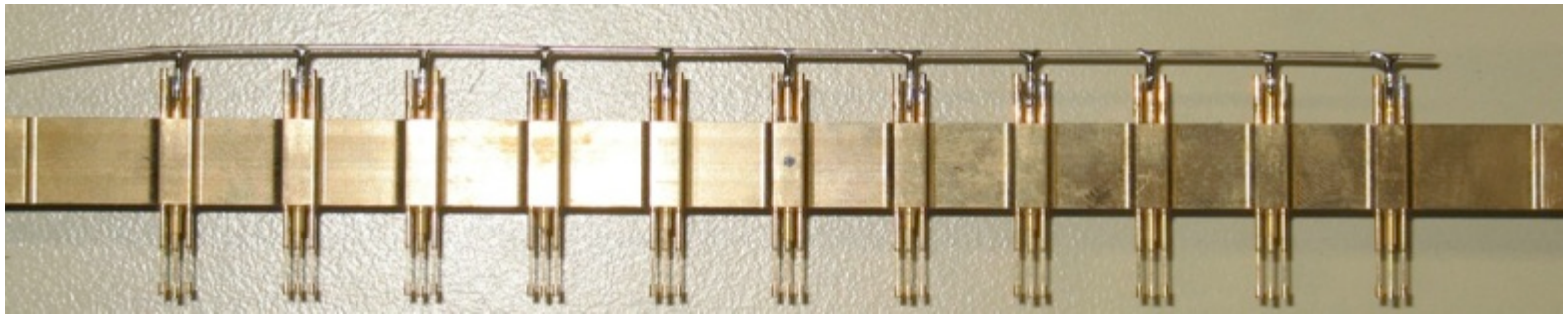


NREL Custom

Removable multipoint probes to facilitate replacement and to accommodate different wafer sizes

Probing to Si Cells



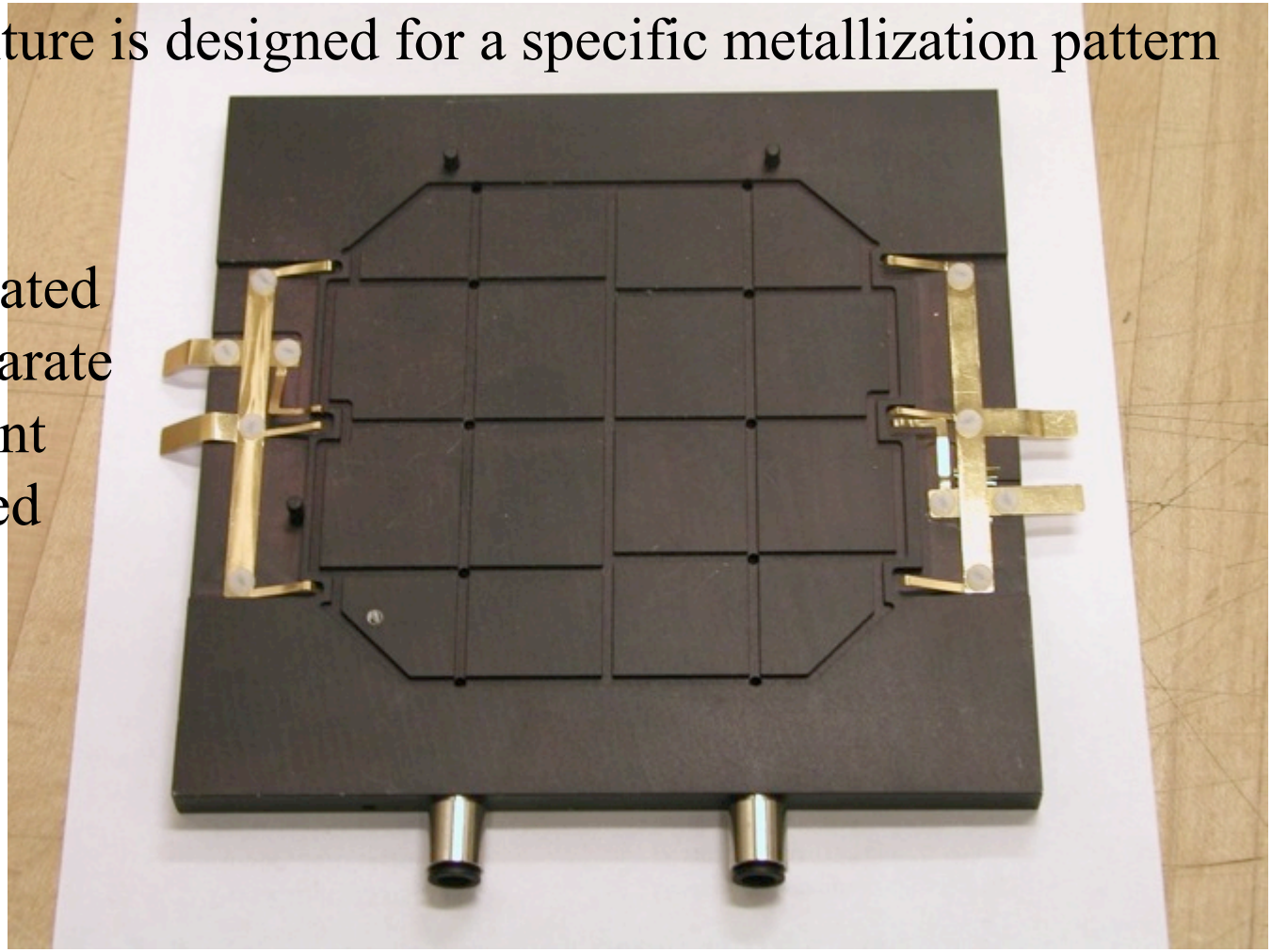


Removable multipoint probes to facilitate replacement and to accommodate different wafer sizes

Back Contact cells

Probe Fixture is designed for a specific metallization pattern

Hardened gold plated leaf springs. Separate voltage and current contacts collocated



Multiple slots and holes for vacuum hold-down. Tradeoff with temperature control

Break

Part 2

Rating PV Power and Energy - Cell, Module, and System Measurements

June 18-24, 2011

Keith Emery
NREL
303-880-2913
keith.emery@nrel.gov

The contents of this tutorial/short course packet are not for sale or distribution, and are solely for educational purposes

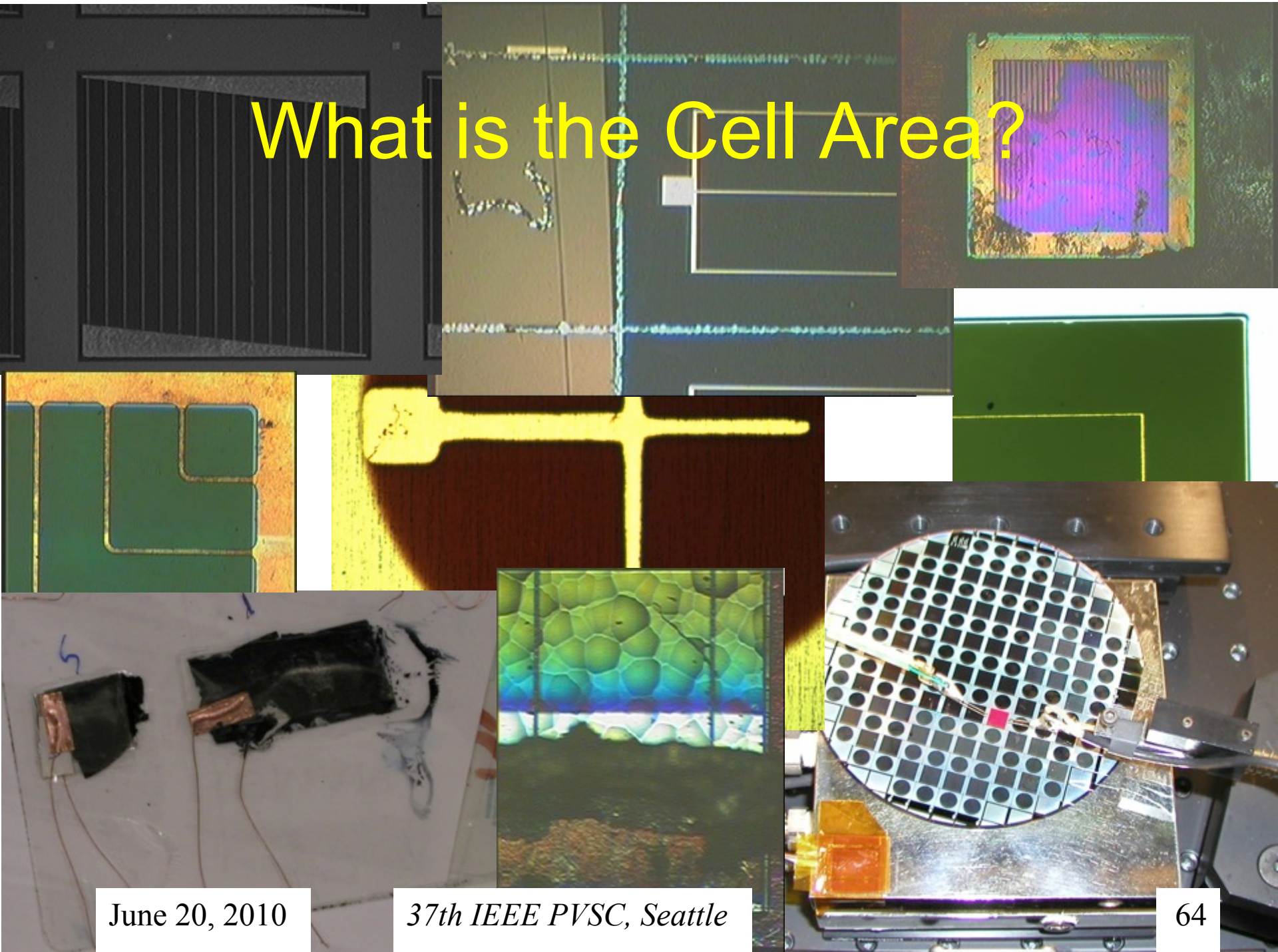
Outline

- Current *vs.* Voltage Measurement Theory
- PV Power Performance
  - PV Irradiance Sensor
  - Simulators
  - Commercial and Generic I-V systems
  - Contacting
- PV Measurement Artifacts
- Intercomparisons
- Alternative rating methods

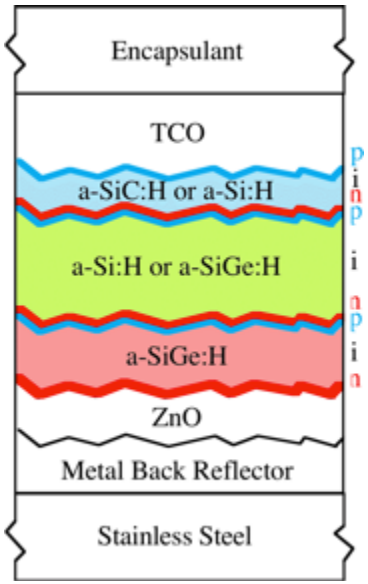
Artifacts

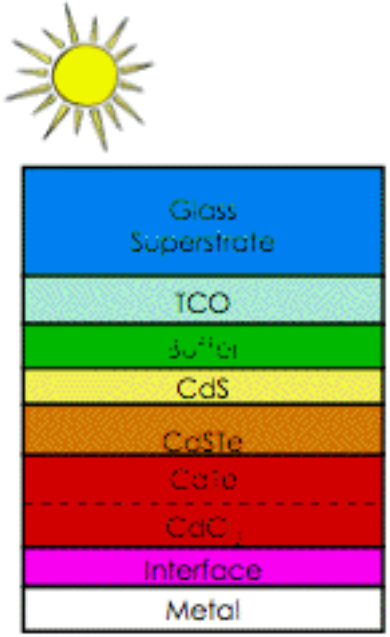
- Device Fabrication and Processing
  - Adjust the electrolyte achieve a greater voltage at expense of life.
  - High initial efficiency can be achieved for amorphous silicon by adjusting the i-layer thickness with same stabilized efficiency.
  - The most common processing change or package design that results in an artificial increase in the efficiency is to have **current collected outside of the defined area**.
  - Reported module efficiencies may not reflect short-term degradation because of the encapsulant or intrinsic processes.
  - Unstable AR coatings
  - Sample unstable in air

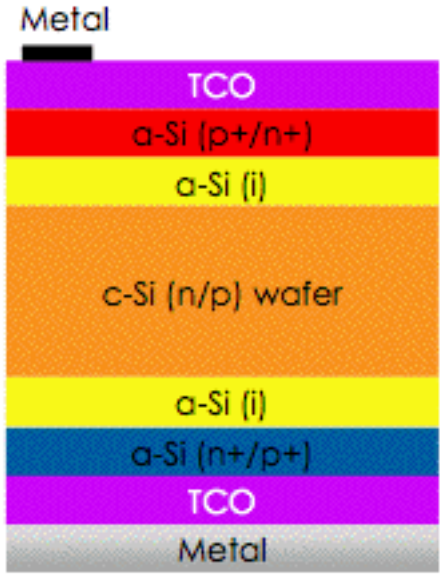
What is the Cell Area?

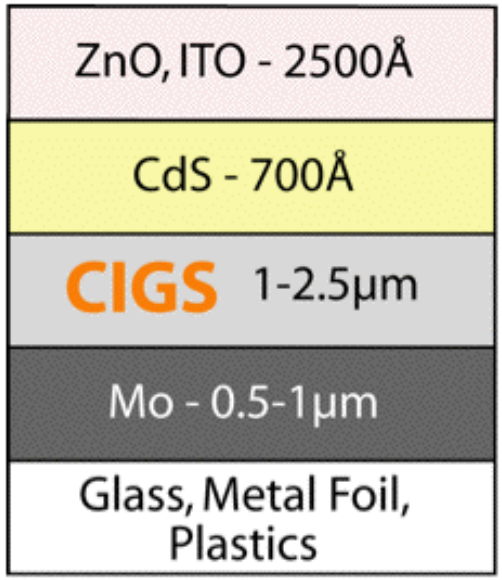


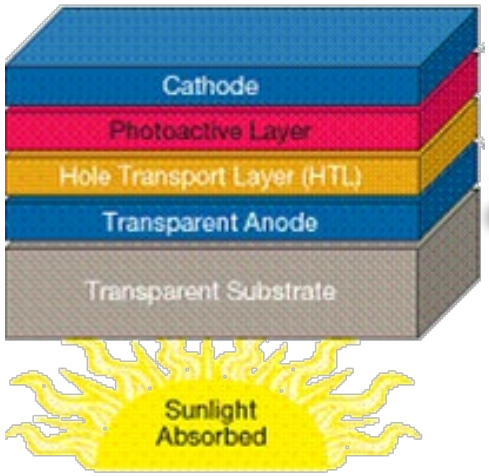
No Standard PV Design

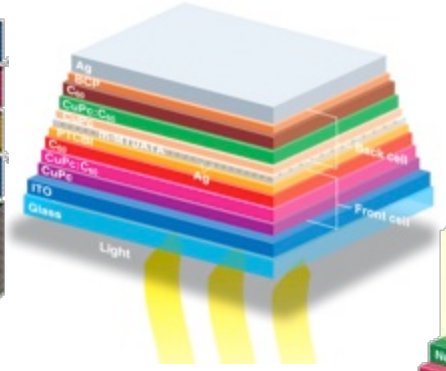


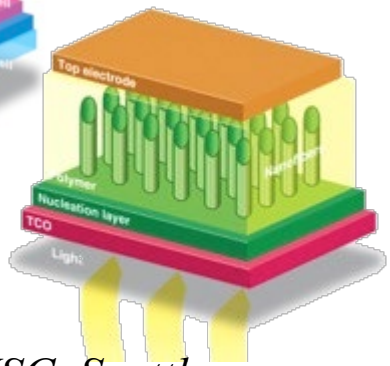


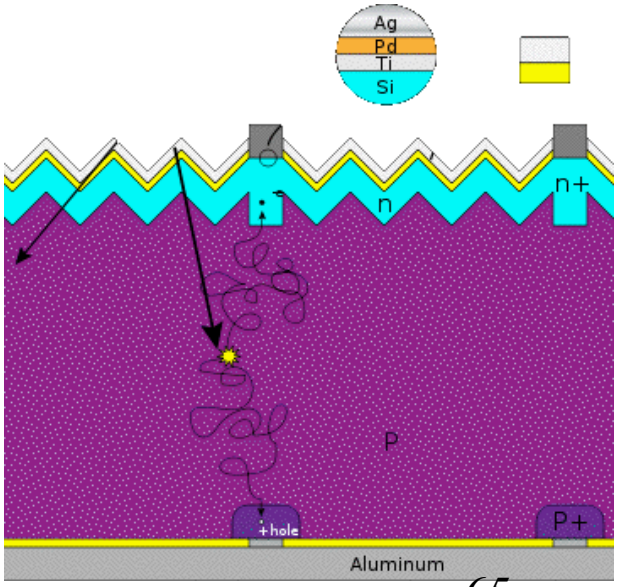






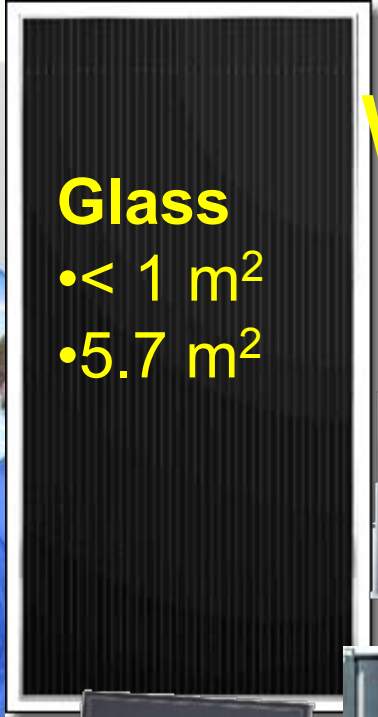


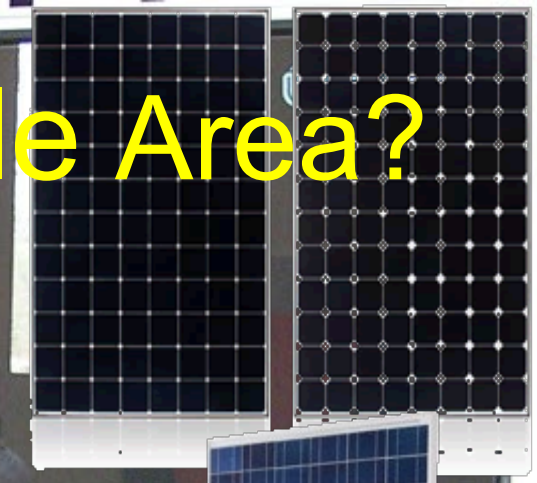




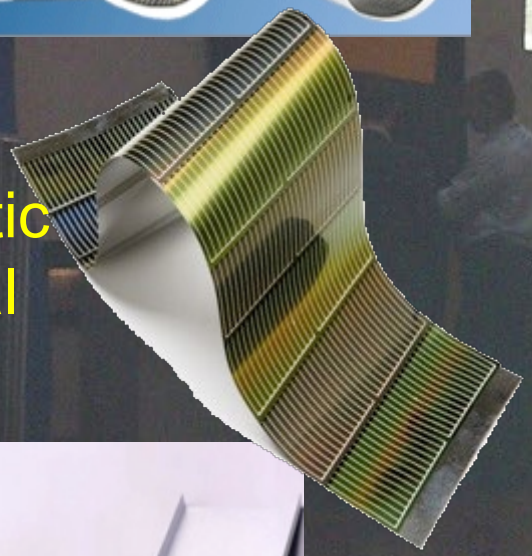
What is the Module Area?

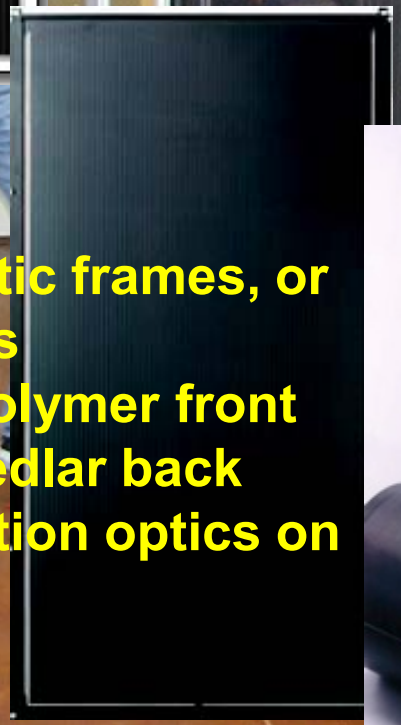
Glass
- < 1 m^2
- 5.7 m^2



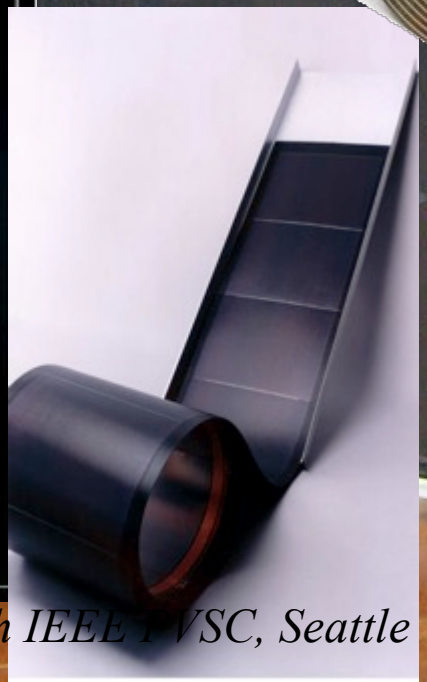


Foils
- Plastic
- Metal

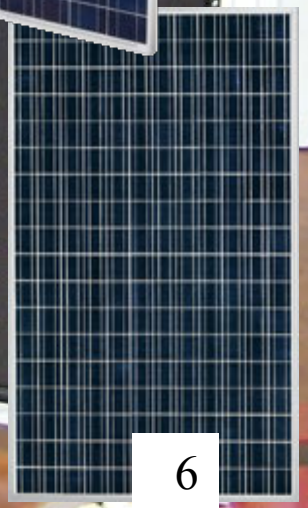




Metal, plastic frames, or frameless
Glass or Polymer front
Glass or Tedlar back
Low contrition optics on the front



Wafers
- Round
- Square
- Rectangular



Area – Definitions

Cell - The basic photovoltaic device which generates electricity when exposed to light.

Reference Cell - A solar cell meant for irradiance measurement.

Concentrator Cell - A cell designed for irradiances exceeding one sun.

Submodule - A photovoltaic device incorporating two or more cells meant to demonstrate photovoltaic material and interconnect technology. It does not need to be environmentally protected, and it doesn't have to incorporate all aspects of final product design.

Module - An environmentally protected solar photovoltaic device.

Note regarding encapsulated cells measured at NREL:

Environmentally protected cells meet the definitions for both "Module" and for "Cell." They will be referred to as "Modules" in our test reports if their apparent purpose is for power generation or commercial production, or "Cells" if their apparent purpose is for use as a calibration device.

Environmentally Protected - Capable of surviving without damage: 1. A fingernail dragged across the front surface of the device, 2. Brief immersion in water, 3. Exposure to rain for one day, with front or back of device facing up.

Area – Definitions

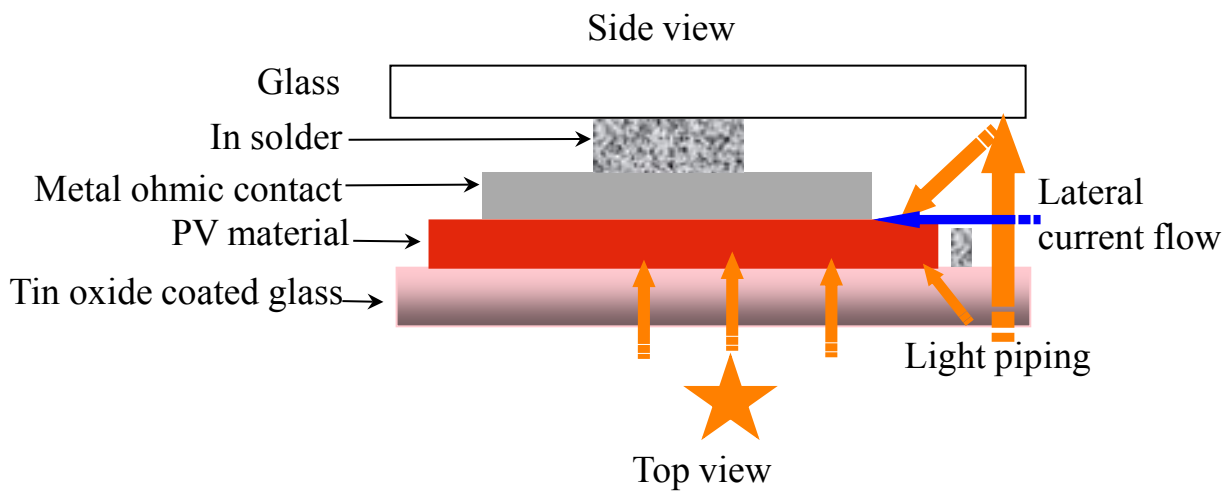
Cell Total Area - The total surface area of the electrically active region of the photovoltaic device, including grids and contacts. External wires and contacts are not included.

Concentrator Cell Area - The total surface area of the region of the solar cell meant to be illuminated. This generally does not include the peripheral bus bars. When testing a concentrator cell with active regions outside the bus bars, these regions are included in the area measurement or masked off.

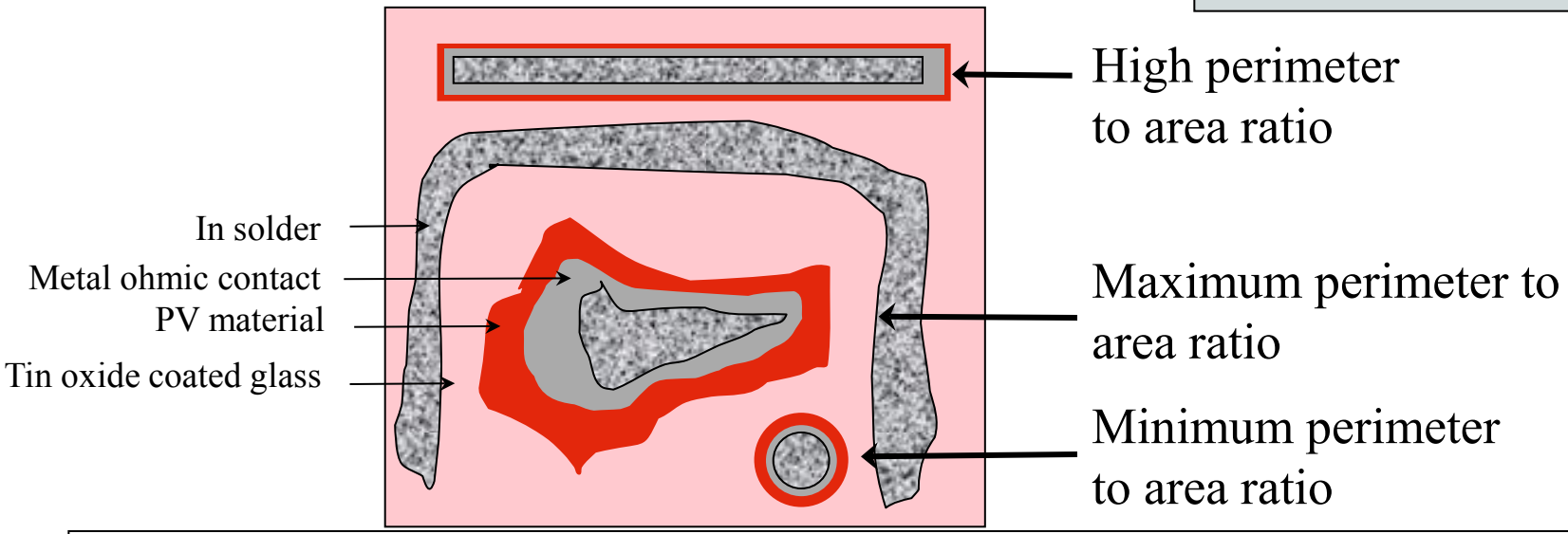
Module/Submodule Aperture Area - The total surface area of a module or submodule, excluding frame. If the module includes an aperture, then the area of the aperture is used. If the aperture is not a quadrilateral or a circle, then the area of the smallest quadrilateral, circle, or other polygon is used.

Module/Submodule Total Area - The entire projected area of the module, including frame and borders, if any. Equal to aperture area in the case of a frameless module with no aperture supplied.

Cell Area



Vary perimeter to area ratio to determine if edge generation or recombination significant



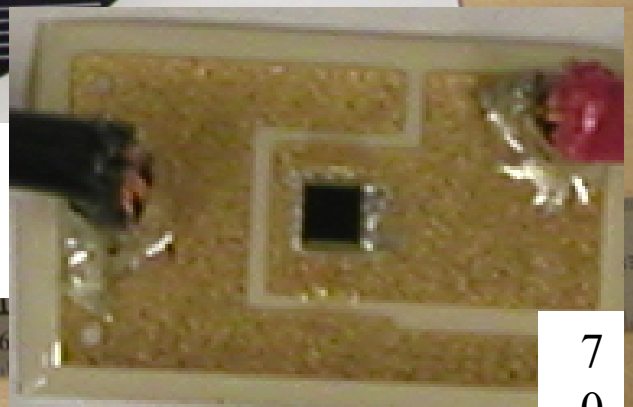
Require an aperture if collection outside the defined area

Light trapping

A mono-crystalline solar cell's efficiency improves when encapsulated because the encapsulation utilizes a white border providing additional light to the cell via internal reflections.

Aperture area, cm^2	Border mm	Voc mV	Isc A	FF %	Efficiency
unmasked	--	603.3	1.346	60.63	14.1
82.8	32	602.4	1.298	61.39	13.7
64.0	21	601.7	1.265	61.36	13.3
51.8	13	600.8	1.222	61.86	13.0
37.2	2	597.8	1.147	62.39	12.2
34.8	0	597.8	1.095	62.95	11.8

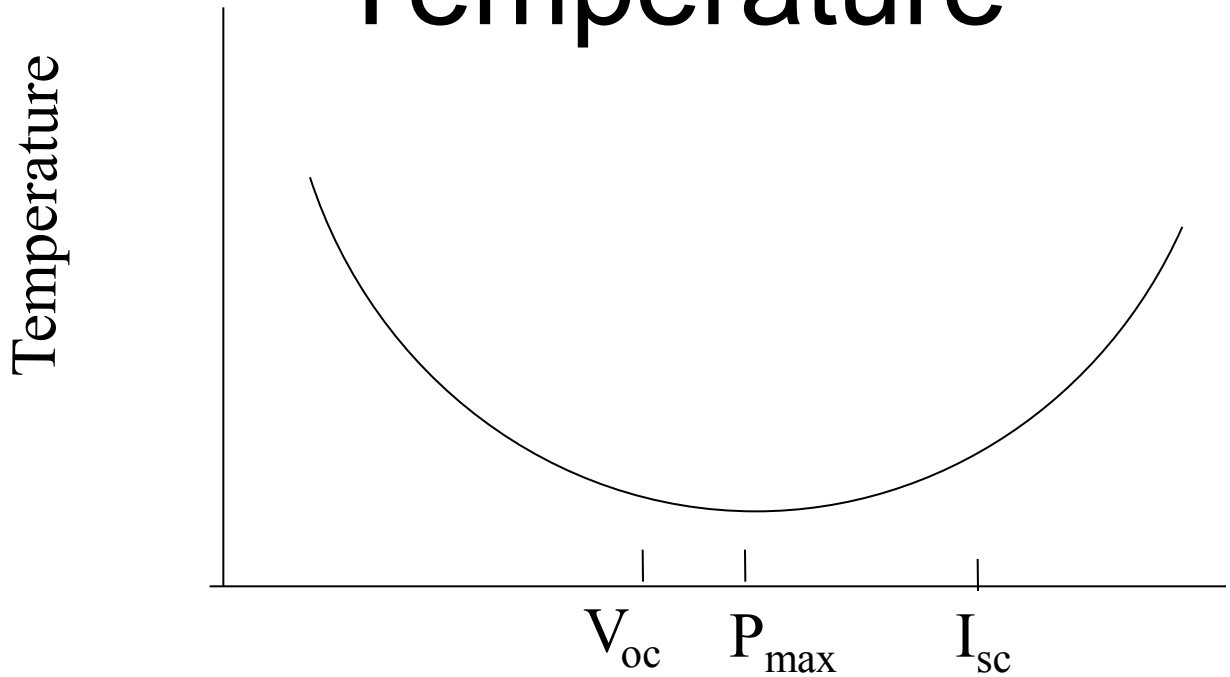
30% boost in Isc from light outside cell area because cell coated with silicone



Artifacts

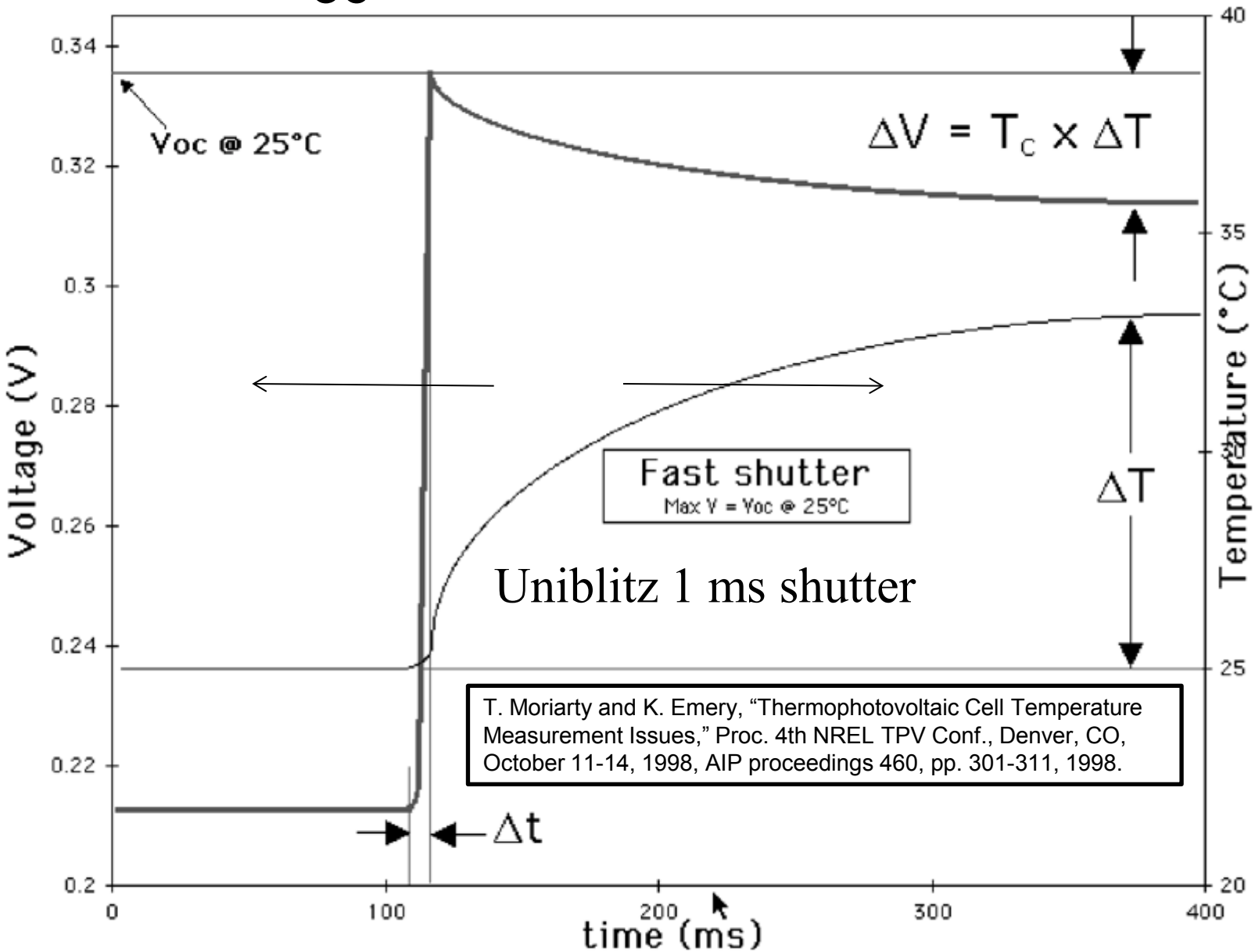
- Procedural
  - Apply a static charge to the surface of a MIS device to temporarily charge up an inversion layer.
  - Bias the device prior to measurement to charge transient states.
  - Too small of a current contact (grids, junction box, ribbons) , resulting in localized cell, cell to probe contact or wire heating, causing a reduced fill factor.
  - Reflections off the probes or operators white lab coat causing an enhanced Isc.
  - Sense the voltage at a location different from where the current is collected giving artificially high fill factors
  - Sense the current at many locations on a device to minimize losses from a large sheet resistance.
  - Set the temperature too low.

Temperature



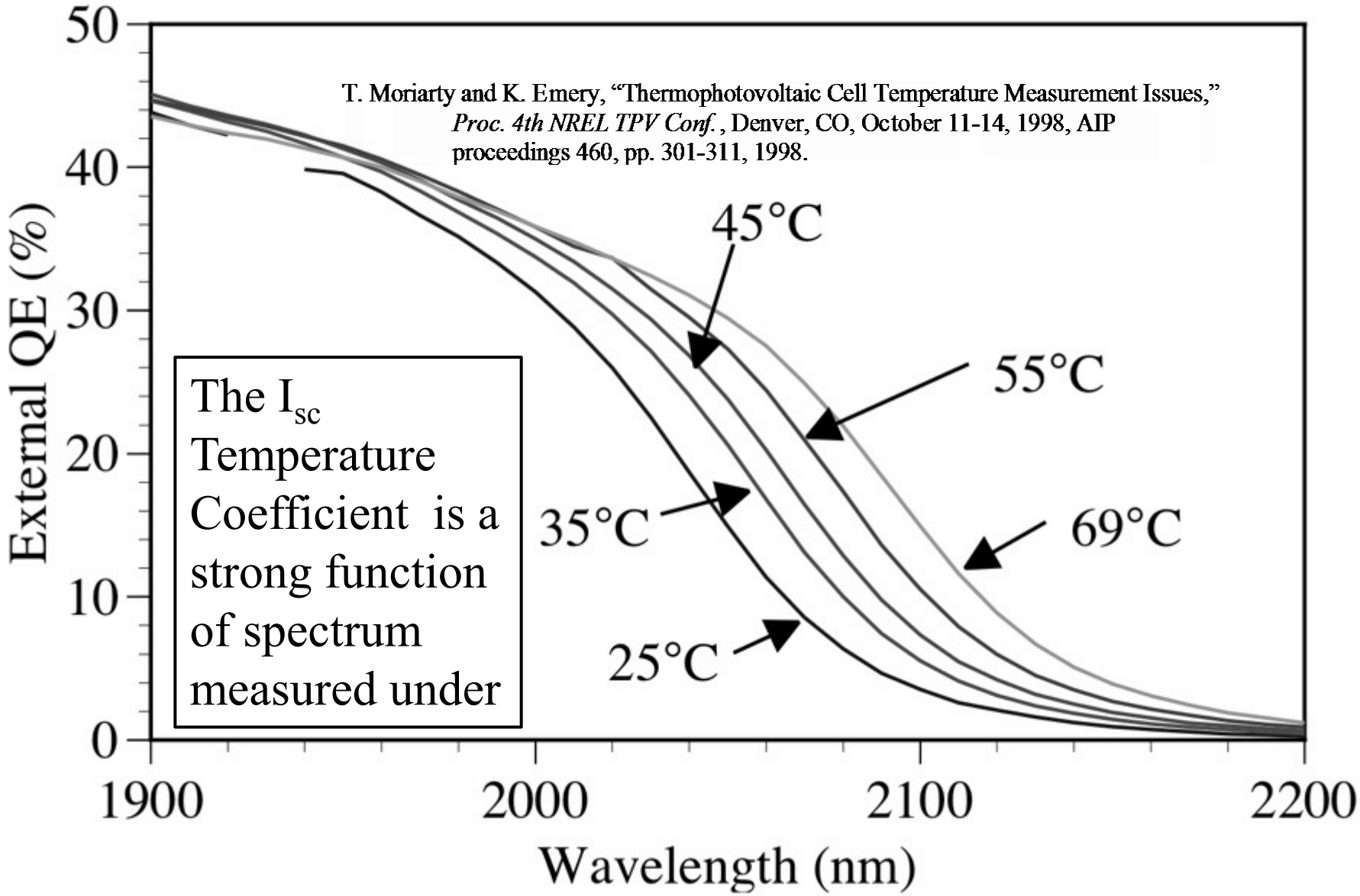
You can not directly measure junction temperature
Temperature gradient between back surface & junction are a function of light level, air temperature, wind speed
Sensor error >±2° C for thermocouple/meter

V_{oc} *vs.* Temperature



T. Moriarty and K. Emery, "Thermophotovoltaic Cell Temperature Measurement Issues," Proc. 4th NREL TPV Conf., Denver, CO, October 11-14, 1998, AIP proceedings 460, pp. 301-311, 1998.

QE *vs.* Temperature

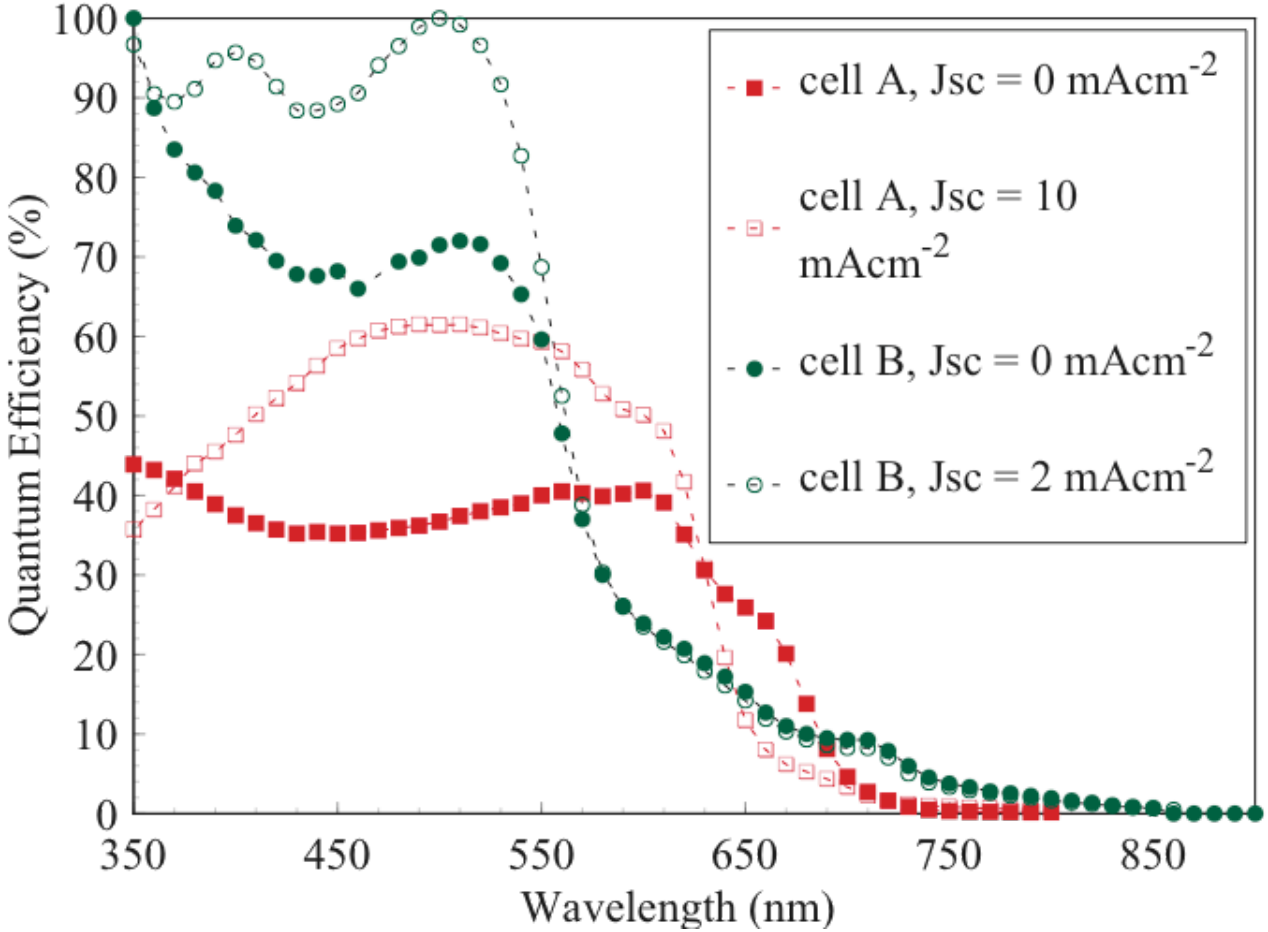


The I_{sc} Temperature Coefficient is a strong function of spectrum measured under

QE Artifacts

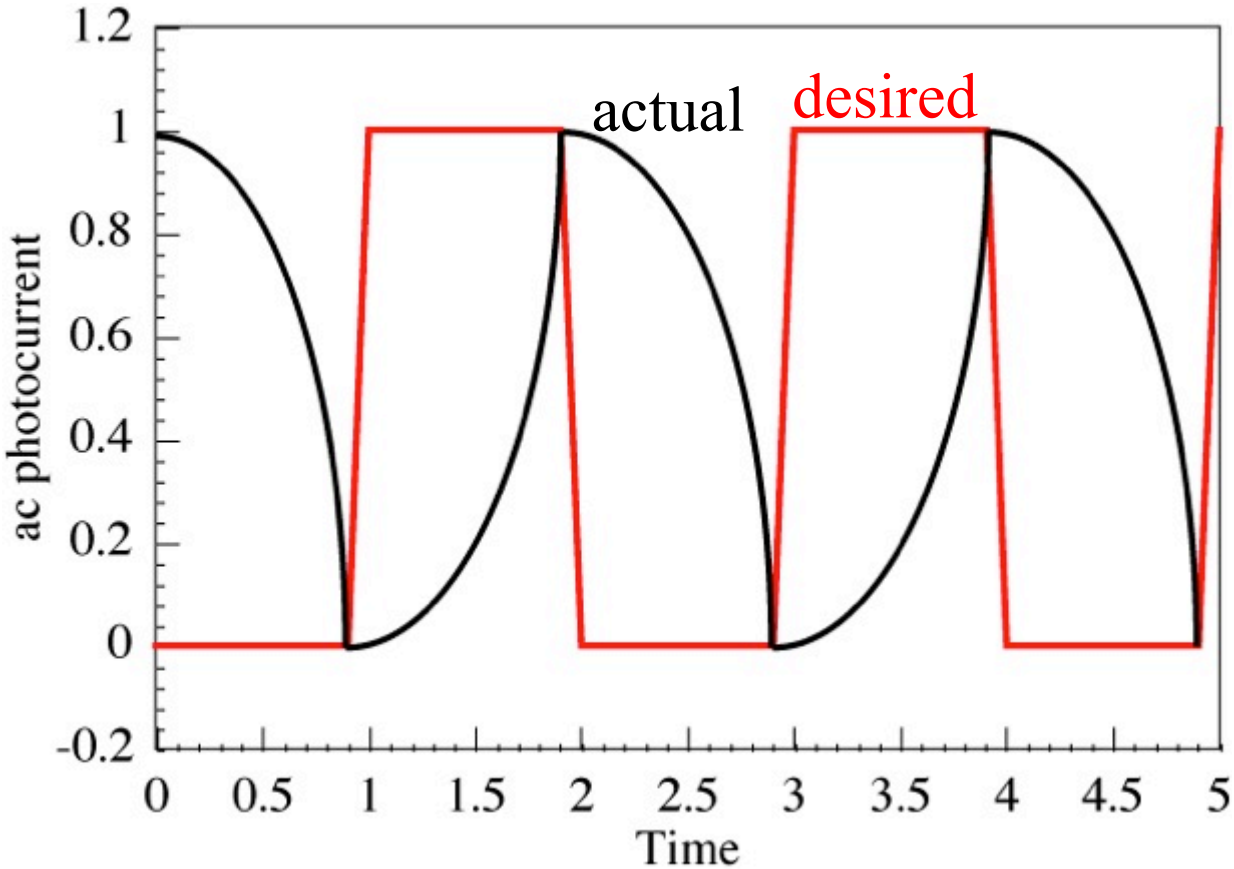
- Response time too slow for chopping
- QE without bias light used to calculate 1-sun Jsc or M
- monochromatic light nonuniform
- Partial illumination vs. complete illumination of sample with monochromatic beam.
- If real time calibrations are used with a grating monochromator (monochrometer) then the reference detector may see different polarization then test device.
- Signal from the bias light reflected off the chopper will introduce an error in the QE. – So place the chopper at the entrance slits
- Stray light. Increases rapidly in the UV. Normally a bandpass filter is required for 300 to 400 nm light with a single grating monochrometer. The light is broadband.
- Incomplete filter blocking.
- Damaged or improper order sorting filter causing the sample to see multiple wavelengths of light at a given wavelength setting.

QE bias light effect



The absolute and even the normalized QE is a function of the bias light level

Slow Response time QE

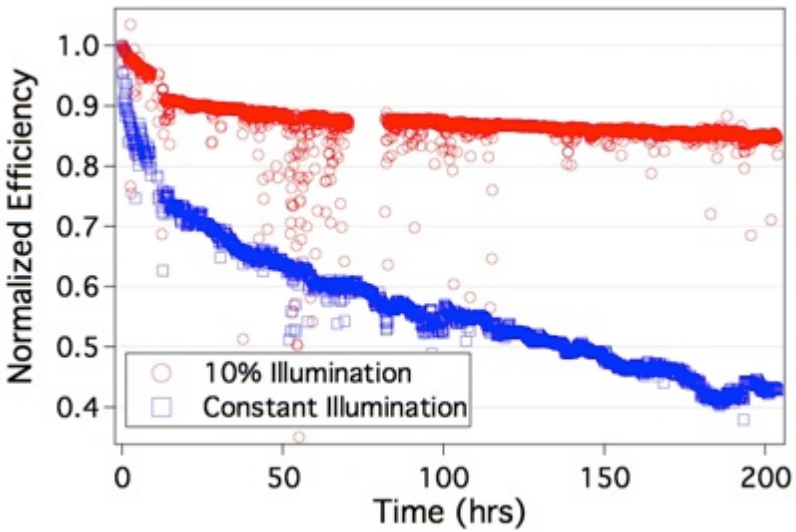


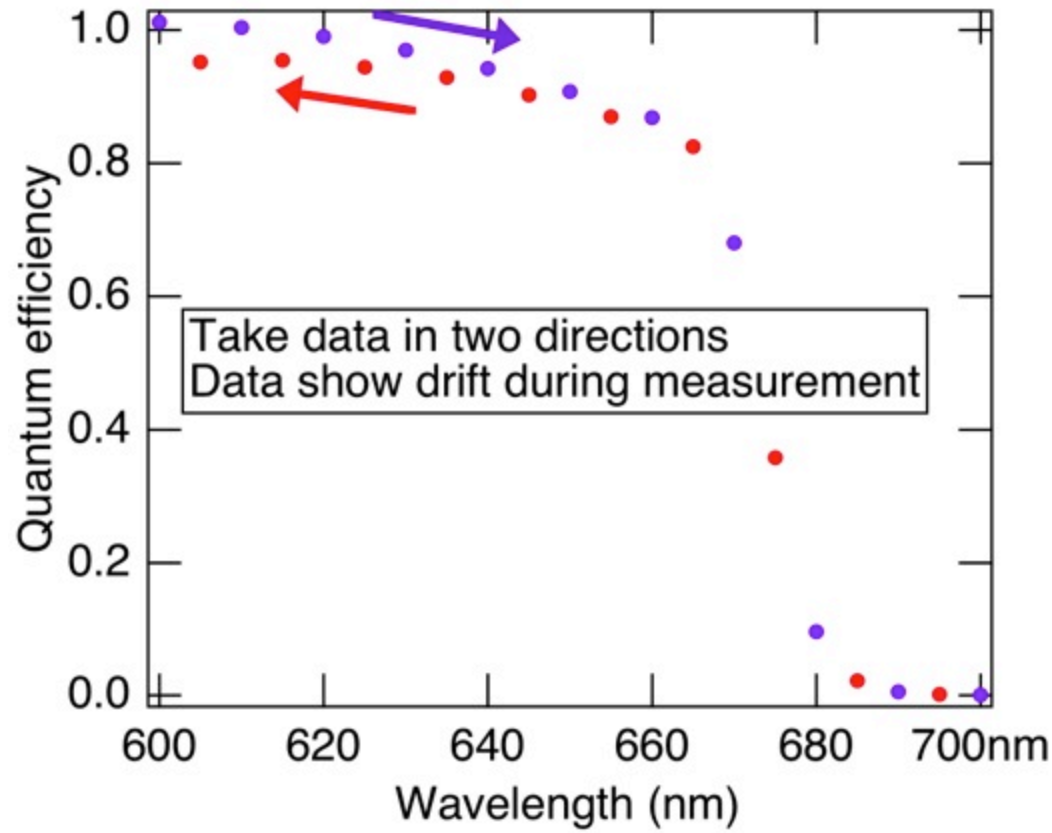
Monitor chopped waveform during QE. Reduce chopping frequency until square. Higher bias light helps. Effect is greater in IR for some samples. Noisy contacts also evident in waveform if present.

Stability during QE

How do I know cell did not degrade during QE measurement?

Take every other data point going one wavelength direction and the complementary points going the other



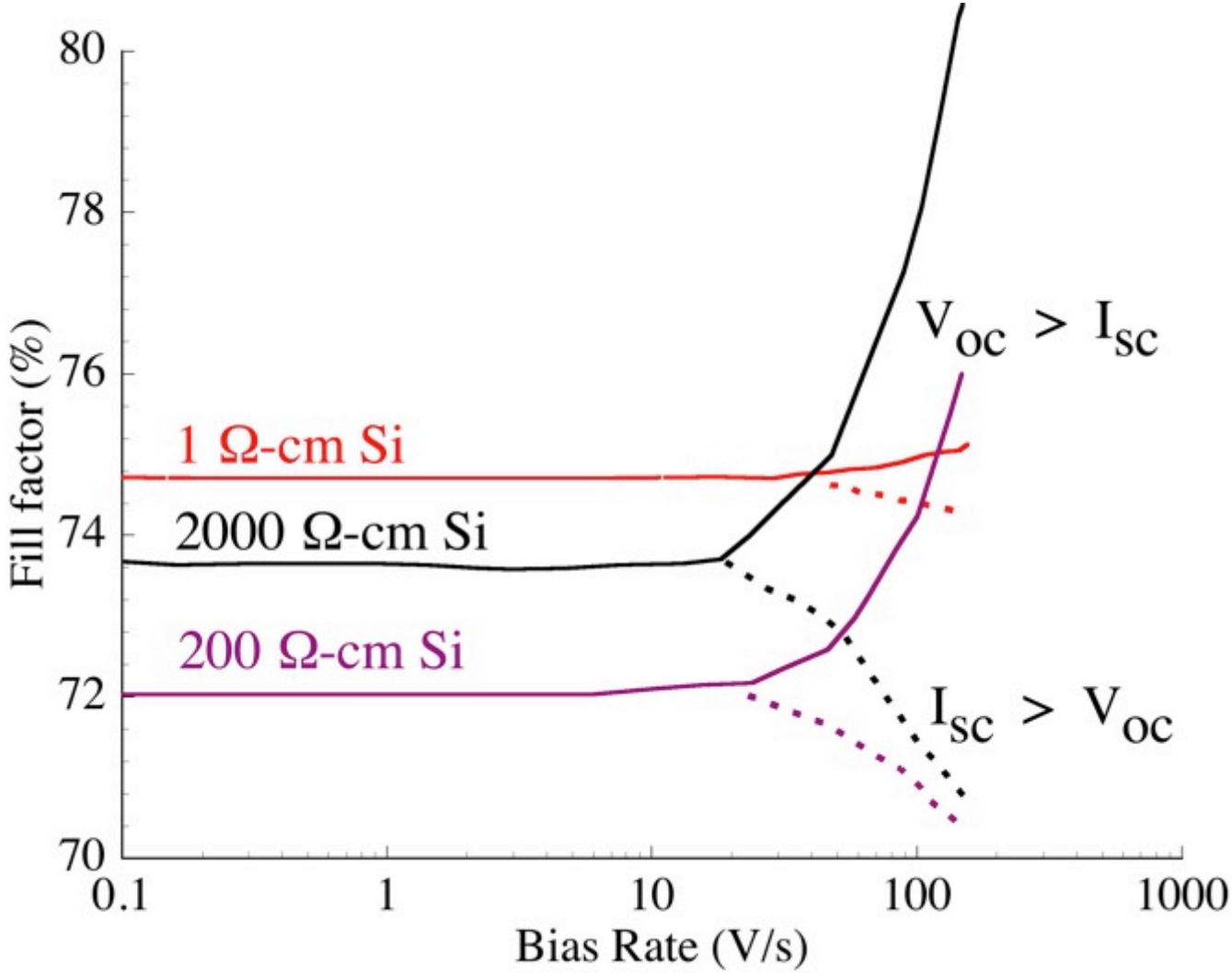


data courtesy Matthew Reese Solar Energy Matr. & Solar cells **92** (2008) 746

I-V equipment Artifacts

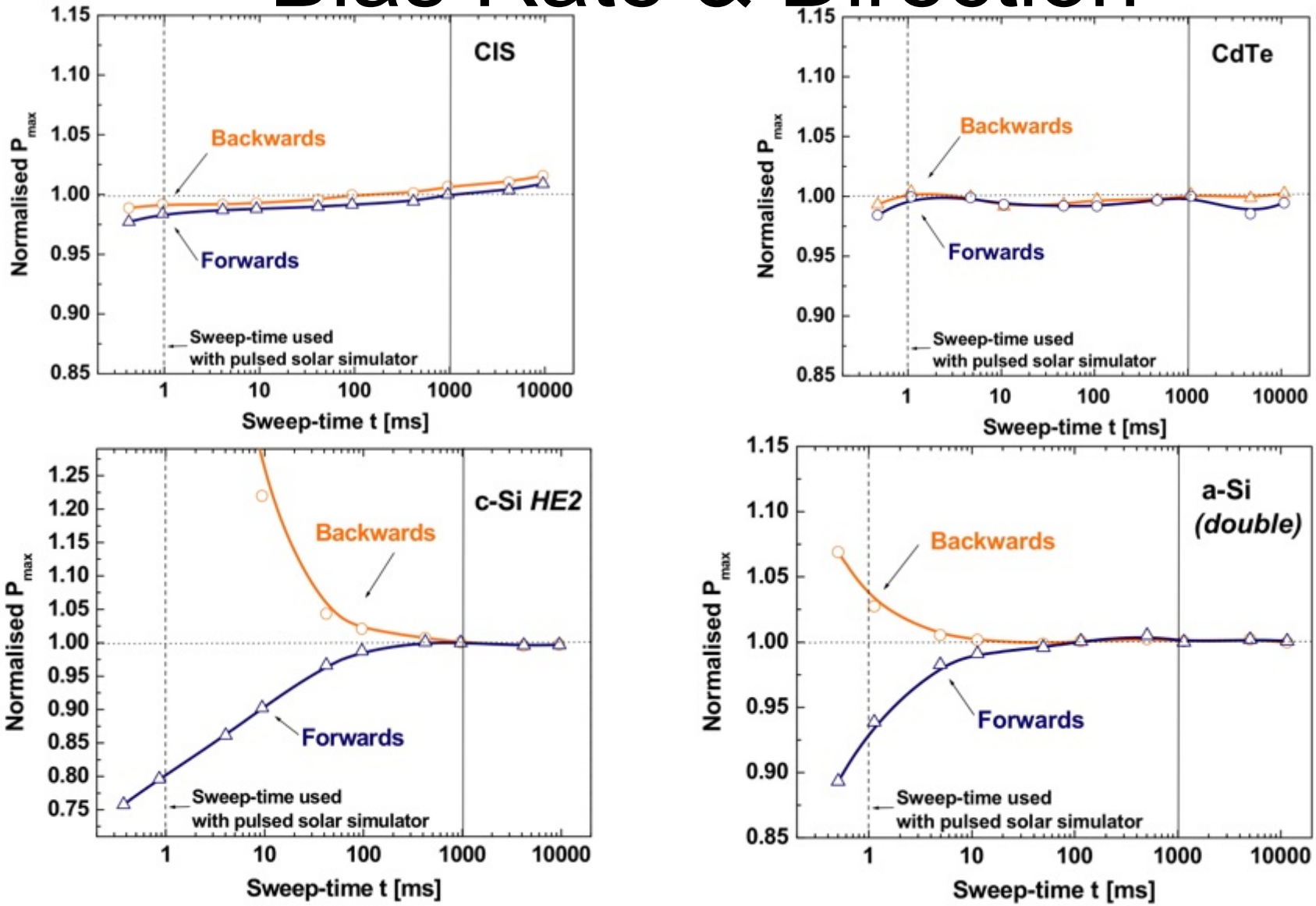
- Bias the device at too large of a rate. Bias rate problems by measuring the I-V at different bias rates or directions
- Drift in the equipment calibration
- Not correcting for the spectral mismatch error. A spectral correction is required for each junction in a multi-junction cell or module
- Drift in the reference cell or radiometer calibration. (1 year minimum calibration interval, multiple reference cells)

Bias rate & direction



D.L. King, J.M. Gee, and B. R. Hansen, "Measurement Precautions for High-Resistivity Silicon Solar cells," proc. 20th IEEE PVSC, 1988, p. 555.

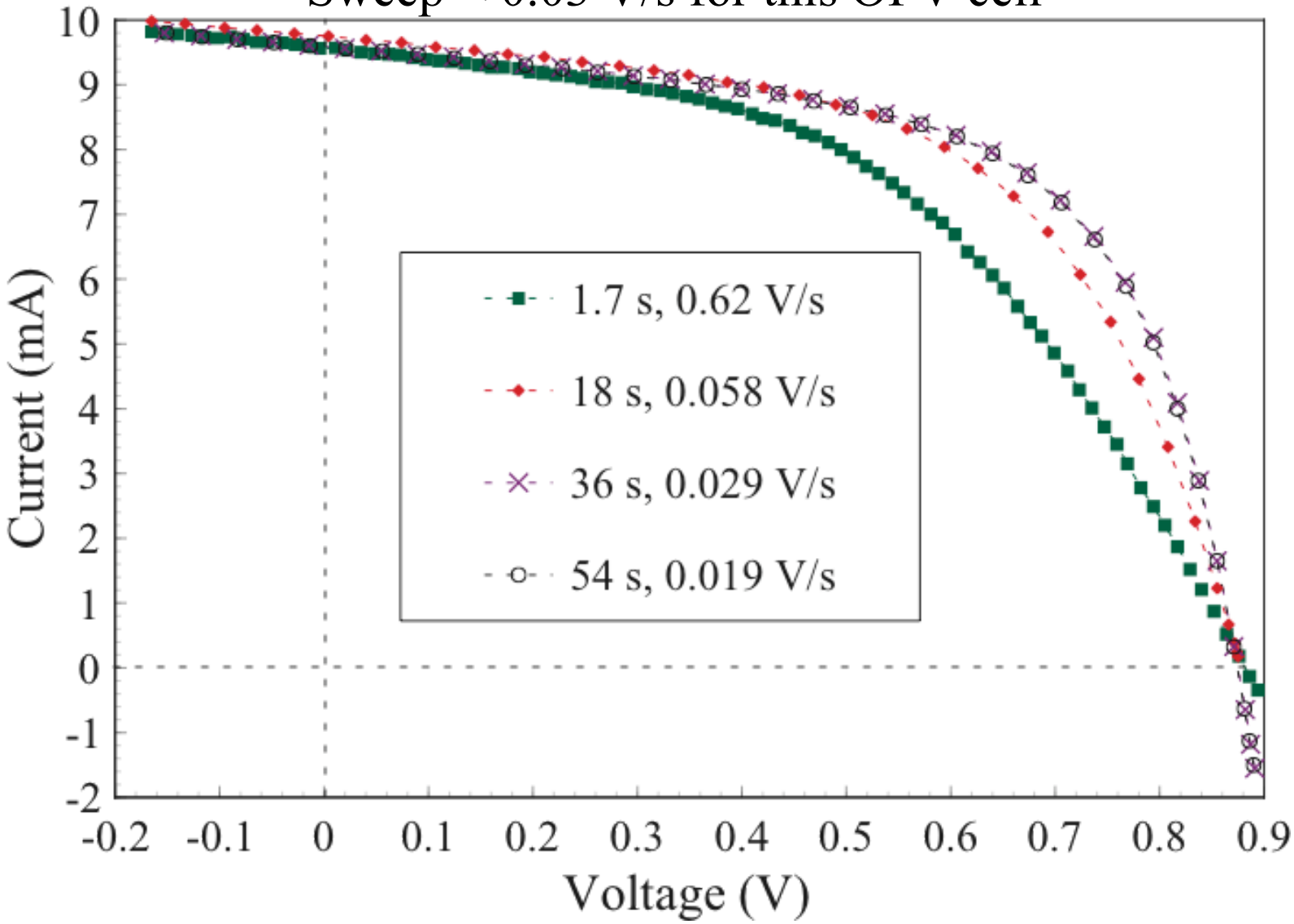
Bias Rate & Direction



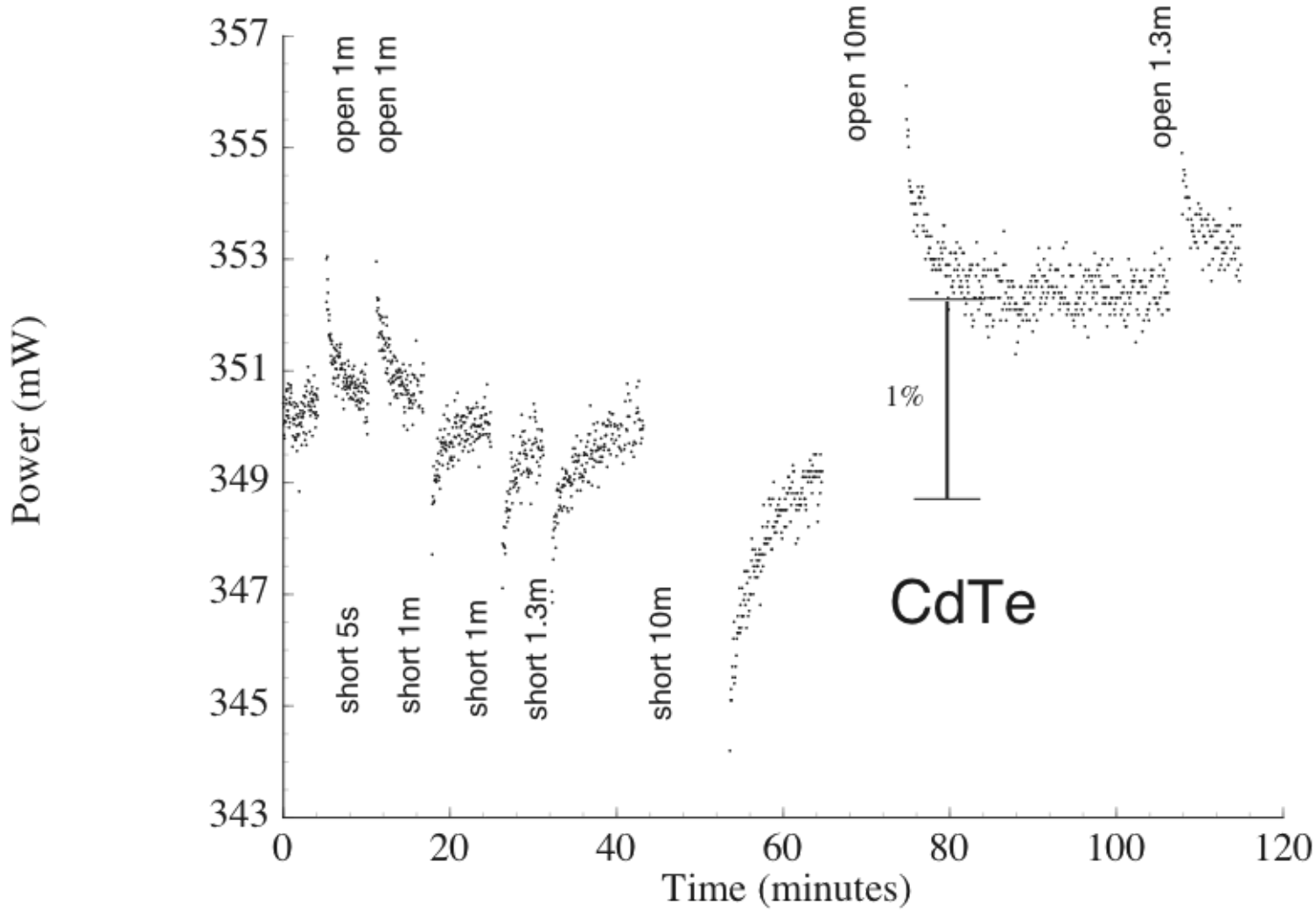
A. Virtuani, H. Muellejans, F. Ponti, and E. Dunlop, ¨Comparison of Indoor and Outdoor Performance Measurements of Recent Commercially Available Modules,” proc. 23rd EU PVSEC, 2008, ,p. 2713.

Bias Rate Artifact

Sweep < 0.03 V/s for this OPV cell



CdTe transients



Transients in CIS No changes in I_{sc}

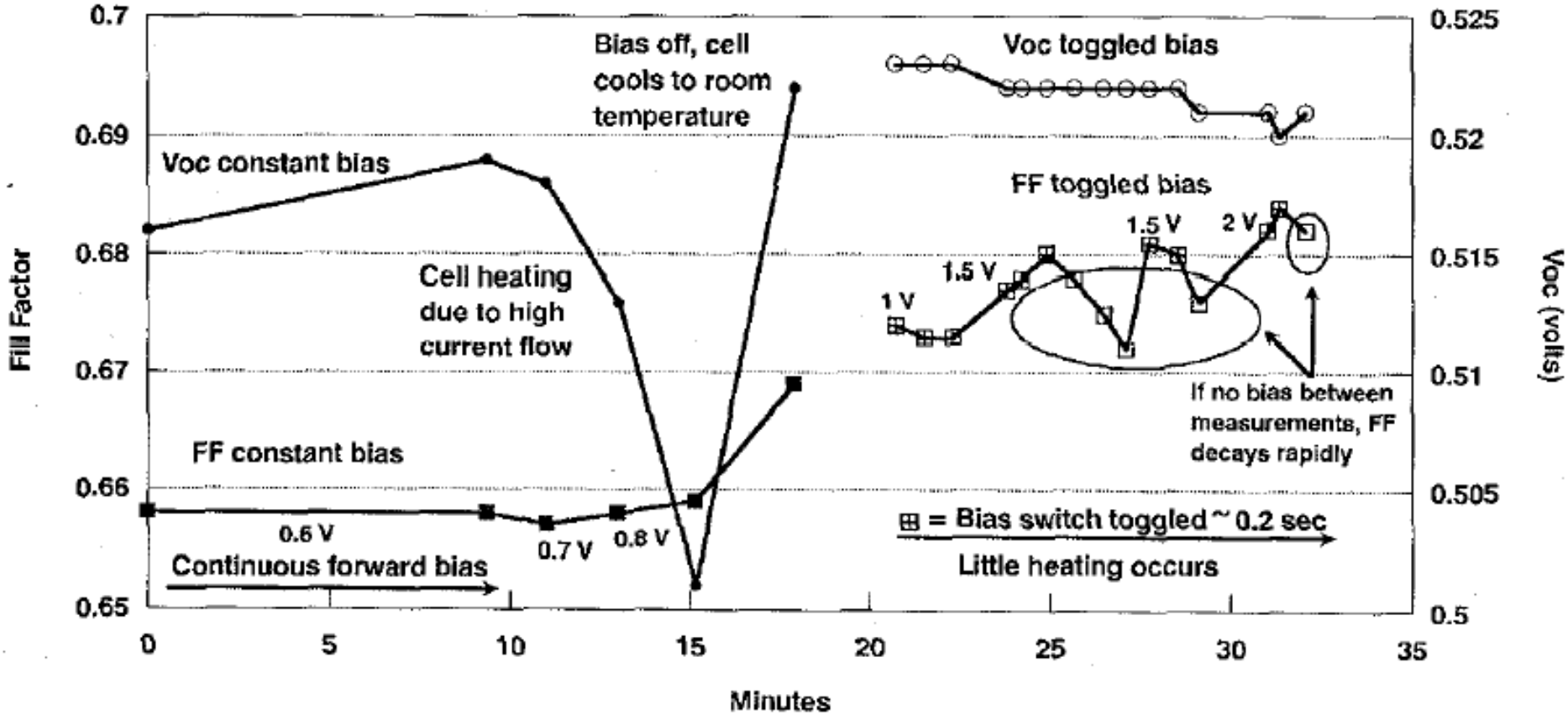


Fig. 3. Different dark forward bias methods applied to a cell that had previously been light soaked until the efficiency stopped increasing.

What should be done so that a result can be trusted?

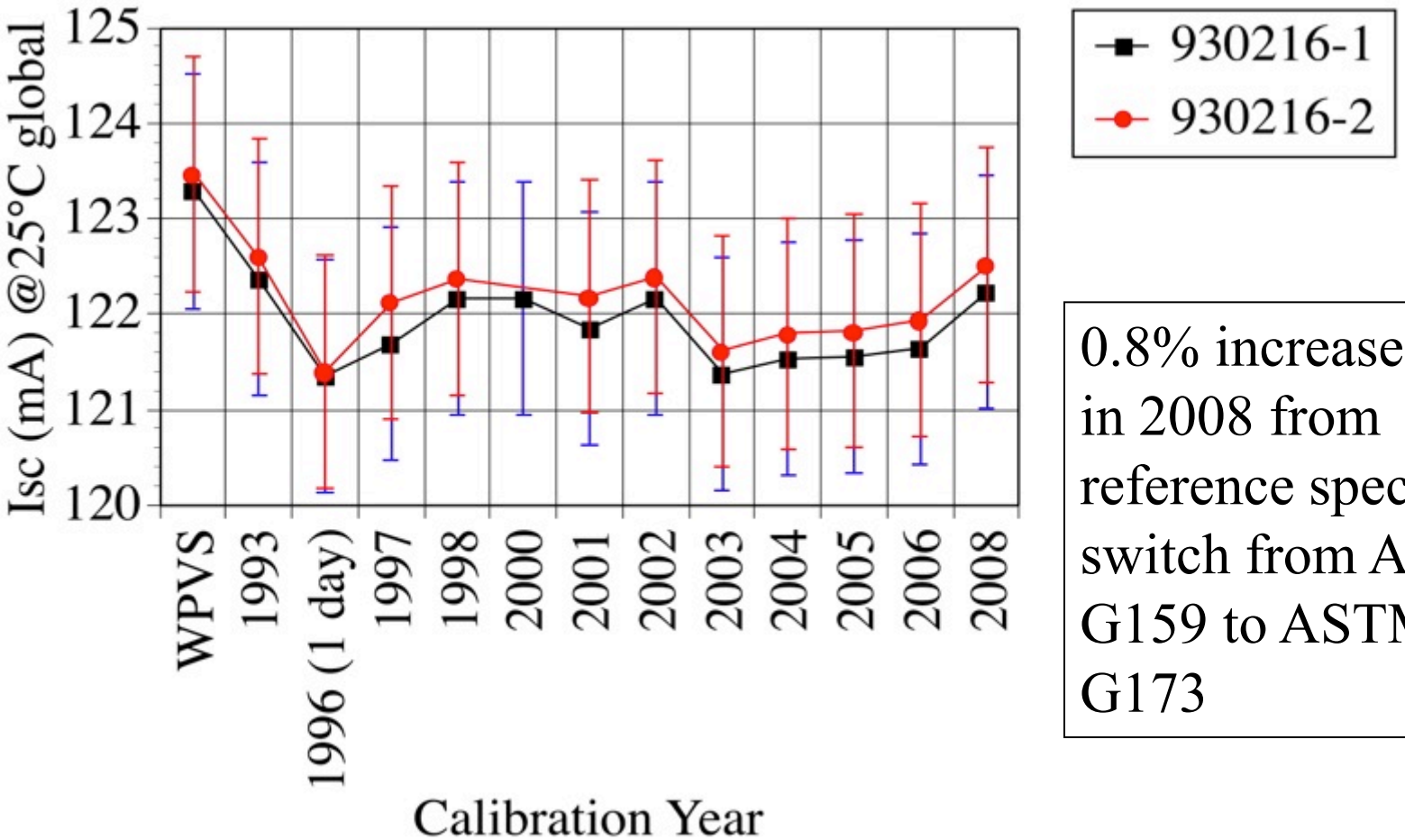
- Check J_{sc} from integrated external QE
- Participate in round robin/independent verification
- Give enough information so others can reproduce your results
- Example references that are linear in different intensity ranges
- Make sure that cells are not electrically connected (Incomplete mesa isolation. Any device where the area is defined by the contact and not the actual PV area can be shorted together at times)
- Verify J_{sc} is independent of area or perimeter to area ratio
- Measure light levels before and after if not during IV.
- Check for hysteresis in JV sweeps
- TANDEMS ARE HARD TO MEASURE CORRECTLY. Single junction procedures for each junction.

Outline - Performance

- PV Theory
- PV Technology
- PV Performance
  - Measurement Theory
  - Primary calibration
  - IV systems
  - QE systems
  - Multi-junction issues
  - Artifacts
  - Intercomparisons
  - Alternative rating methods

How do my Calibrations drift from Year to Year ?

Track All Calibrations over Time



0.8% increase in I_{sc} in 2008 from reference spectrum switch from ASTM G159 to ASTM G173

Formal Cell Intercomparisons

- PEP' 84 – ESTI host

  H. Ossenbrink et al, 18th IEEE PVSC, p.943, 1985
- PEP' 87 Cells and modules – PTB host

  J. Metzdorf et al, *21st IEEE PVSC*, p.952, 1990.
- ASTM 1992 – NREL host

  C. Osterwald, *23rd IEEE PVSC, p.110, 1993*

  PEP' 93 Wide variety of cells – NREL host

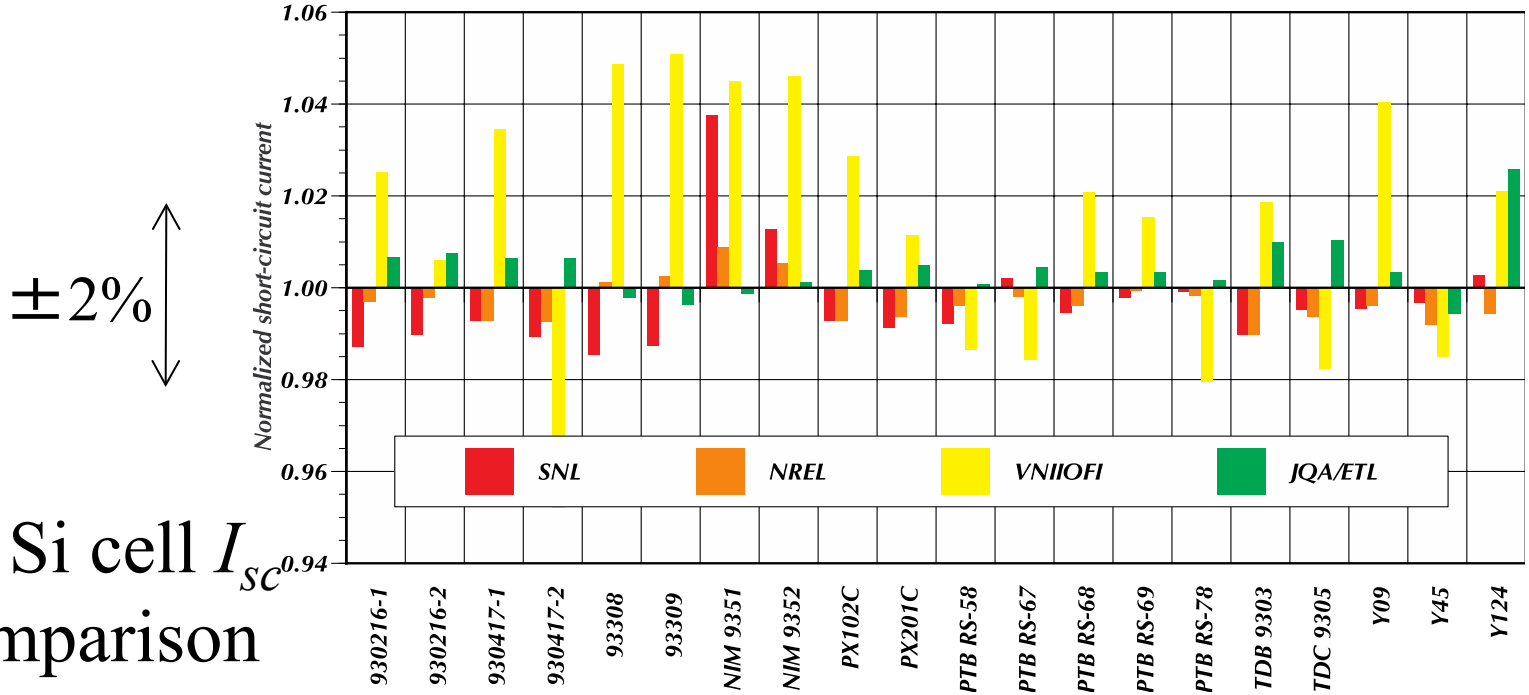
  C.R. Osterwald et al, *25th IEEE PVSC*, p.126, 1996

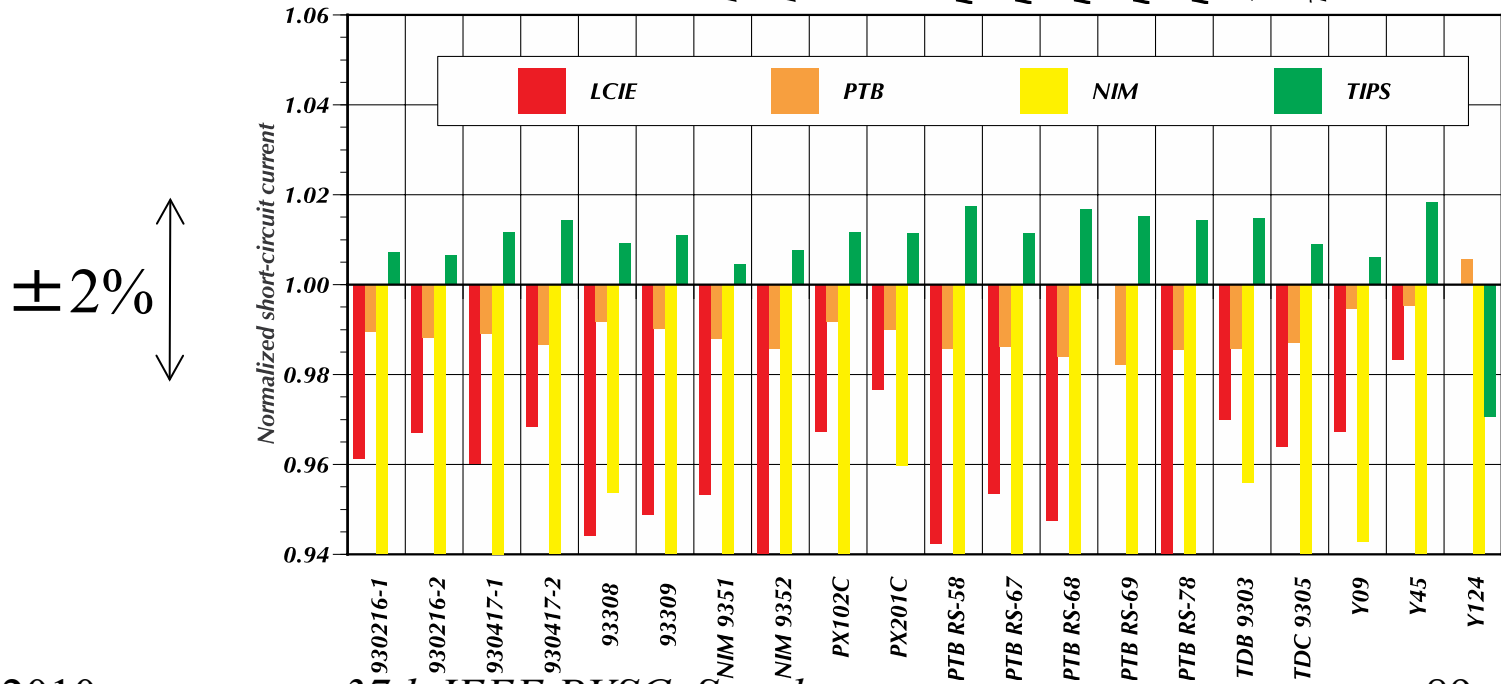
  C.R. Osterwald et al, Progress in PV, **7**, p.287-, 1999
- PEP' 2000 WPVS Recalibration – NREL host

  Keith Emery, " NREL tech. Rep. NREL/TP-520-27942, March 2000
- PEP' 2005 WPVS Recalibration – PTB host

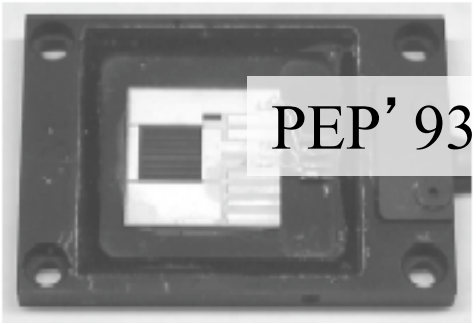
  S. Winter, et al, 31st IEEE PVSC, p.1011, 2005.

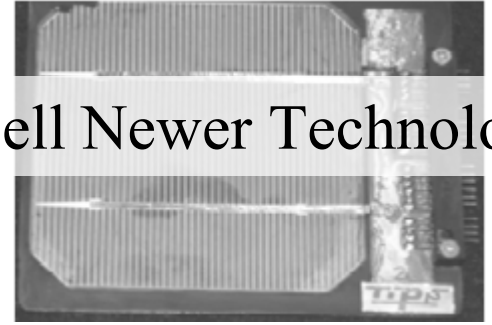
PEP' 93 Si cell I_{SC} Intercomparison

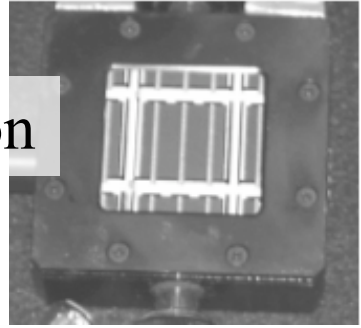


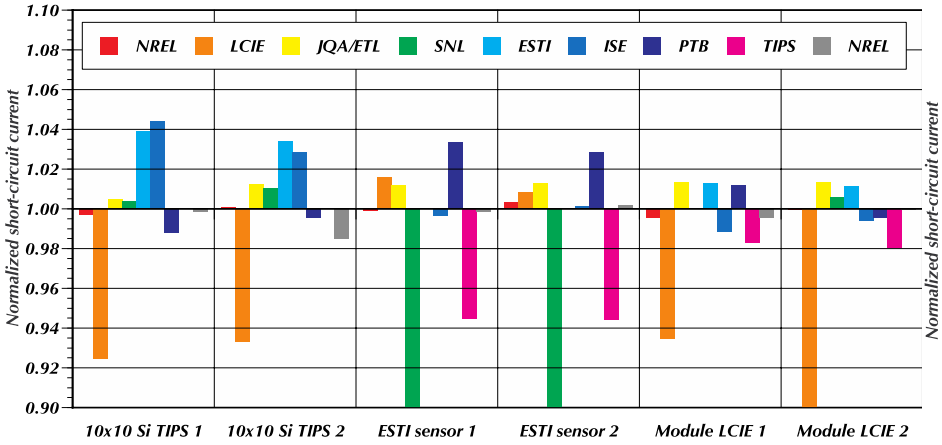


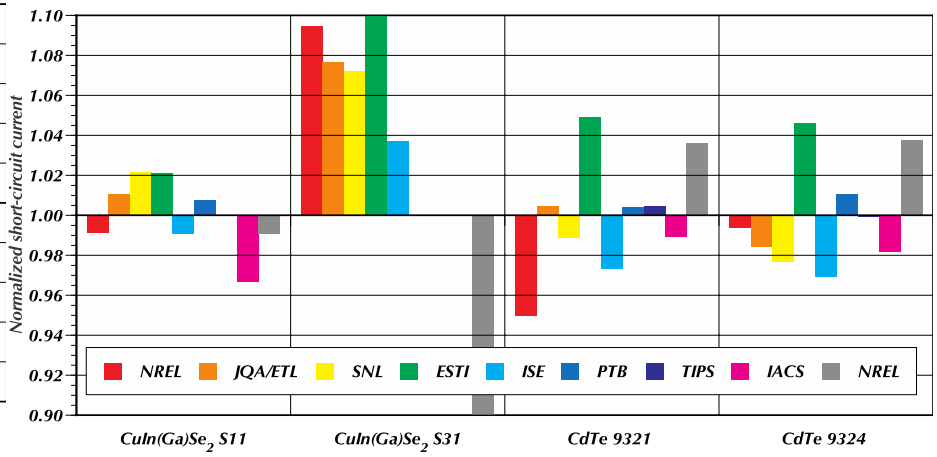
PEP' 93 cell Newer Technology Intercomparison

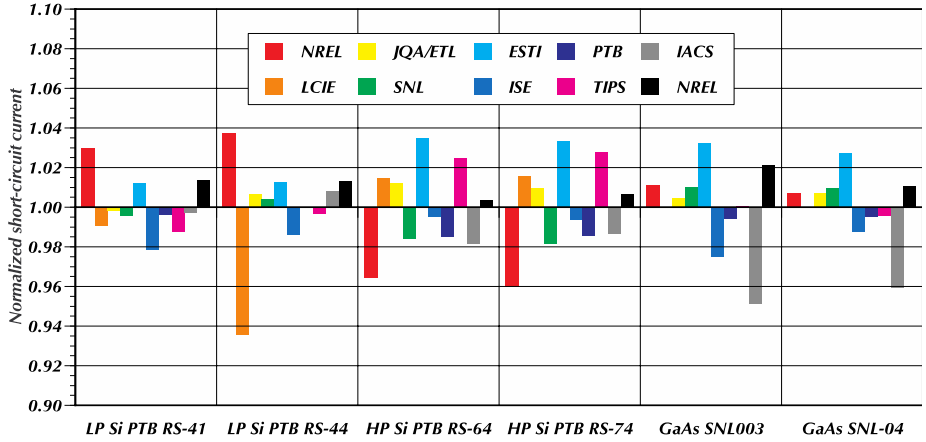


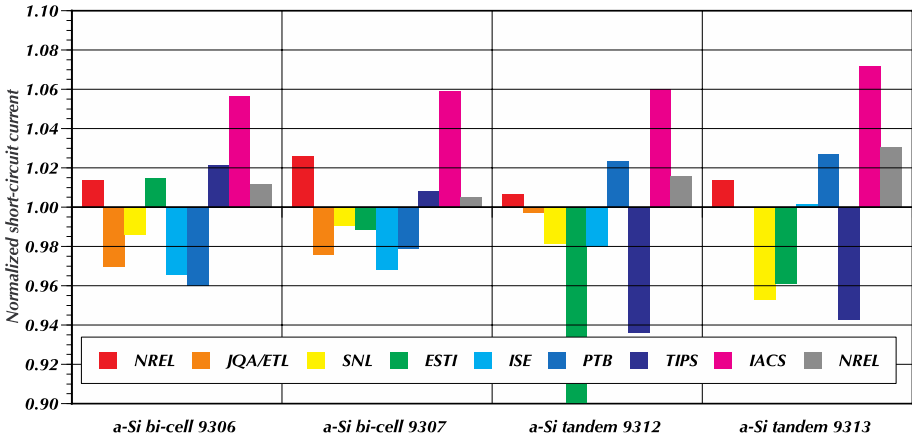












Unpublished Informal Intercomparison

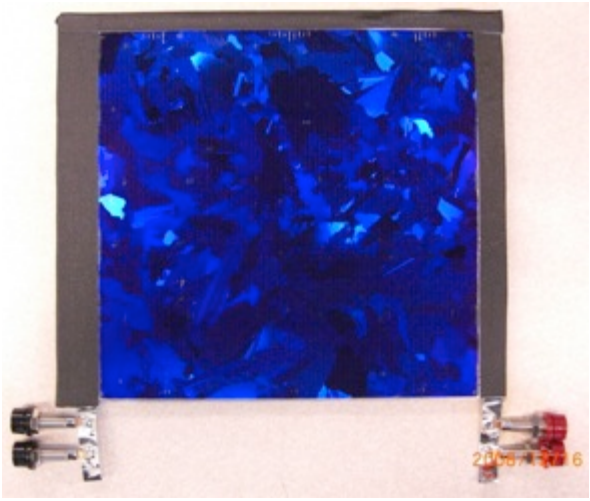
NREL PV calibration team required to show intercomparisons to ISO 17025 auditor on annual basis. Often conducted without our knowledge. Most major groups have done this.

In 2007-2008 Advent hosted NREL Sandia, and ISE intercomparison

	Site								
	Lab1			Lab2			Adv post		
	Cell #			Cell #			Cell #		
Parameter	18	36	52	18	36	52	18	36	52
Efficiency [%]	-3.5	-3.5	-2.3	-0.7	-0.9	0.0	-0.1	-1.2	-0.8
FF [%]	-0.5	-2.2	-2.0	-1.0	-0.5	-0.4	-0.3	-0.6	-0.3
Isc [A]	-0.9	-1.3	-0.3	-0.3	-0.4	-0.4	0.3	-0.0	-0.2
Pmax [W]	-3.4	-3.5	-2.3	-1.8	-1.3	-0.6	-0.1	-1.2	-0.9
Voc [mV]	-2.1	0.0	0.0	-0.6	-0.3	0.2	-0.1	-0.5	-0.4

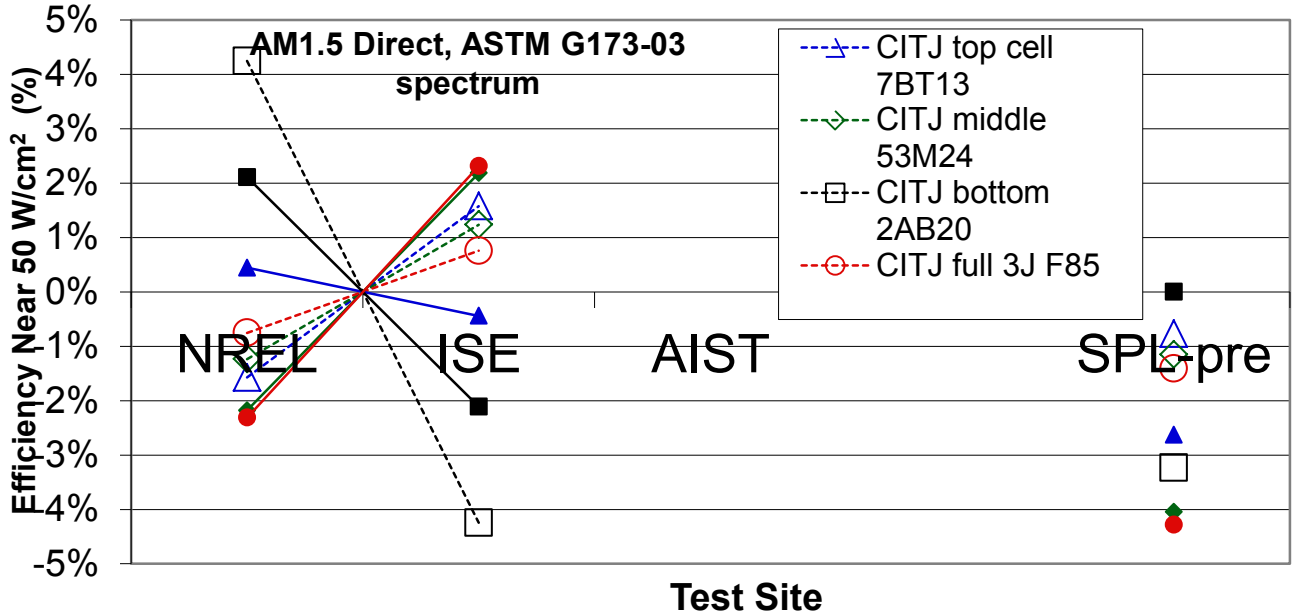
Test Data for Laminated 156x156mm EWT Cells

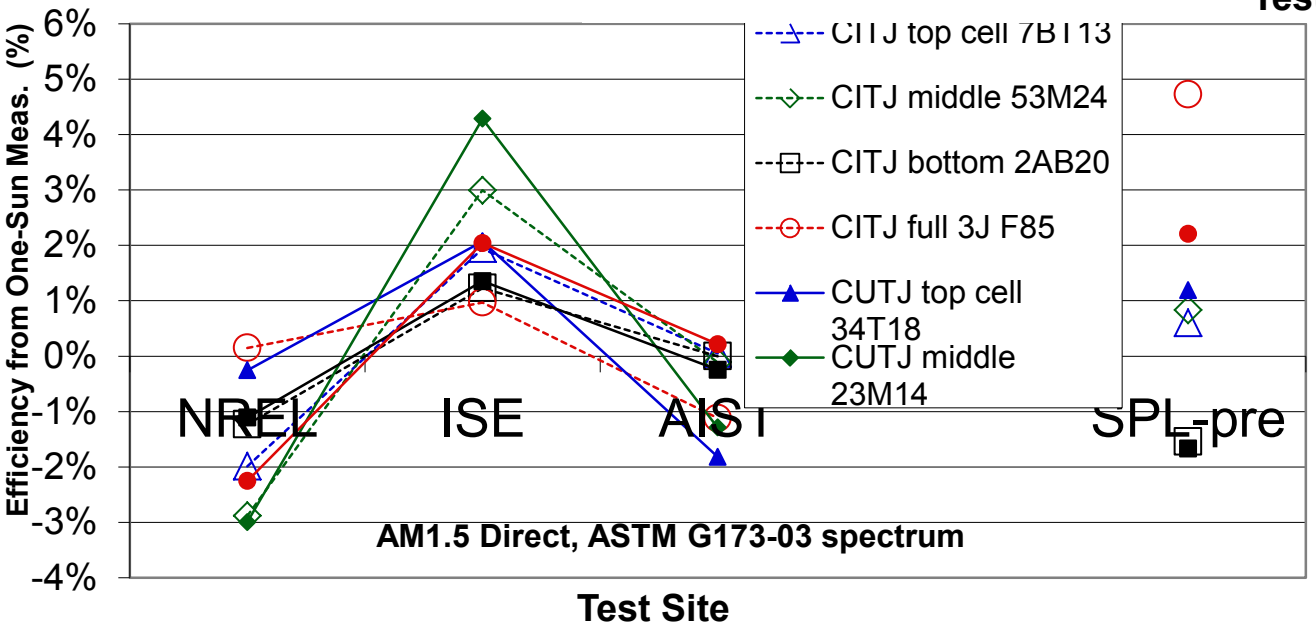
Cell ID	Laboratory/Tester/TestDate	Isc (A)	Voc (V)	FF	Eff (%)	Pmax (W)	Imax (A)	Vmax (V)	Area (cm^2)
Pair Average	SNL Outdoor Module Test 2007-04-18	8.070	0.589	0.687	13.390	3.260	7.283	0.448	243.40
	NREL Cell Laboratory SpectroLab X25 2007-05-02	7.584	0.588	0.685	13.105	3.058	6.795	0.450	233.30
	NREL Module Lab Spire 240A 2007-05-30	7.910	0.592	0.699	13.600	3.274	7.235	0.452	361.85
	NREL Module Lab SpectroLab X200 2007-06-01	7.874	0.584	0.686	13.100	3.154	7.042	0.448	361.85
	NREL Module Lab SOMS Outdoor 2007-06-08	7.947	0.587	0.686	13.300	3.198	7.170	0.448	361.85



Unpublished Informal Intercomparison

2007 Spectrolab hosted an intercomparison with NREL, Fraunhofer ISE, and AIST in Japan.





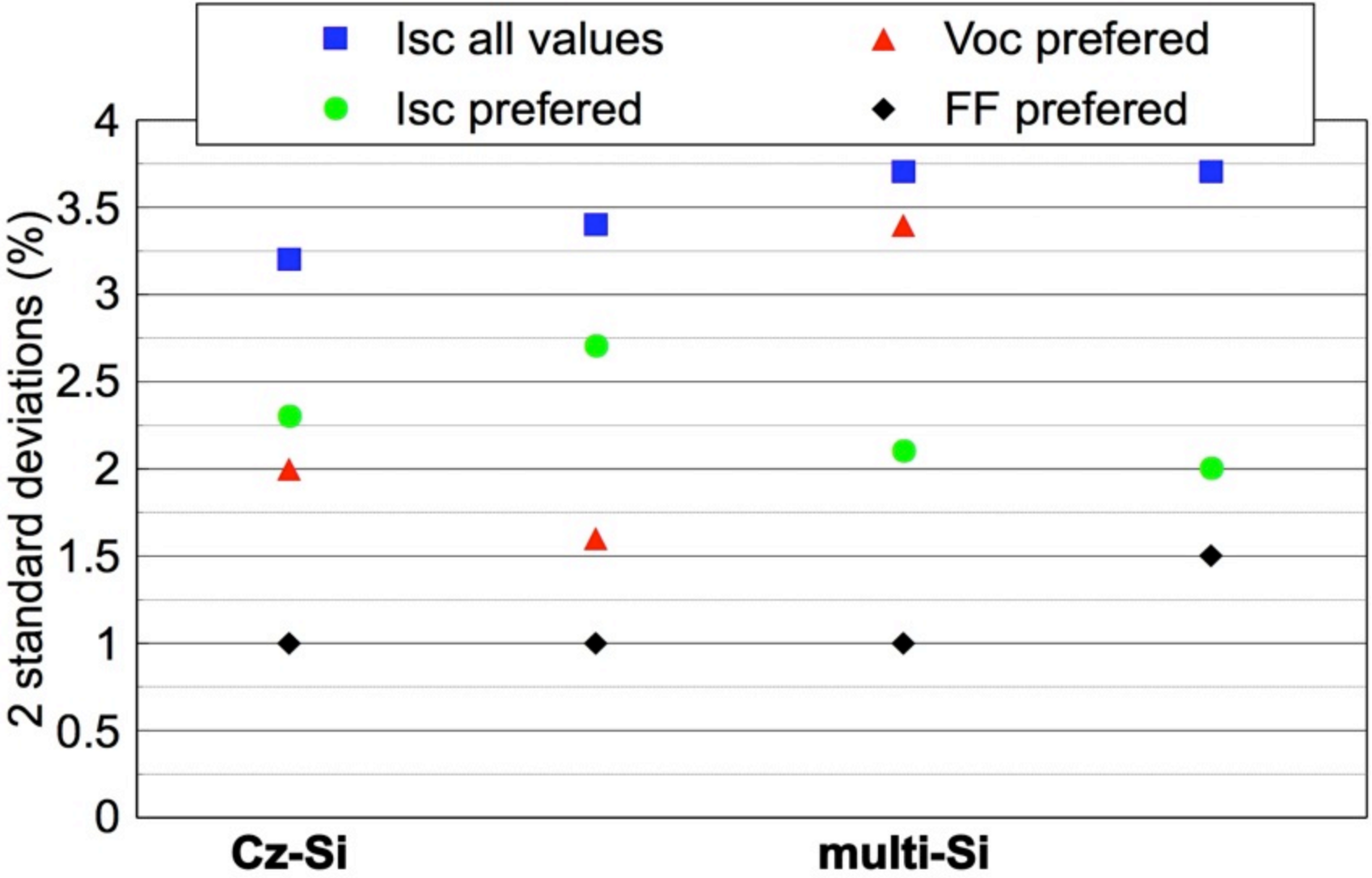
Formal Module Intercomparisons

- PEP' 87 Si modules & with cells – PTB host
- ASTM 1992 Si modules E1036 – NREL host
- NREL 2004 Selection of modules – NREL host 10 labs

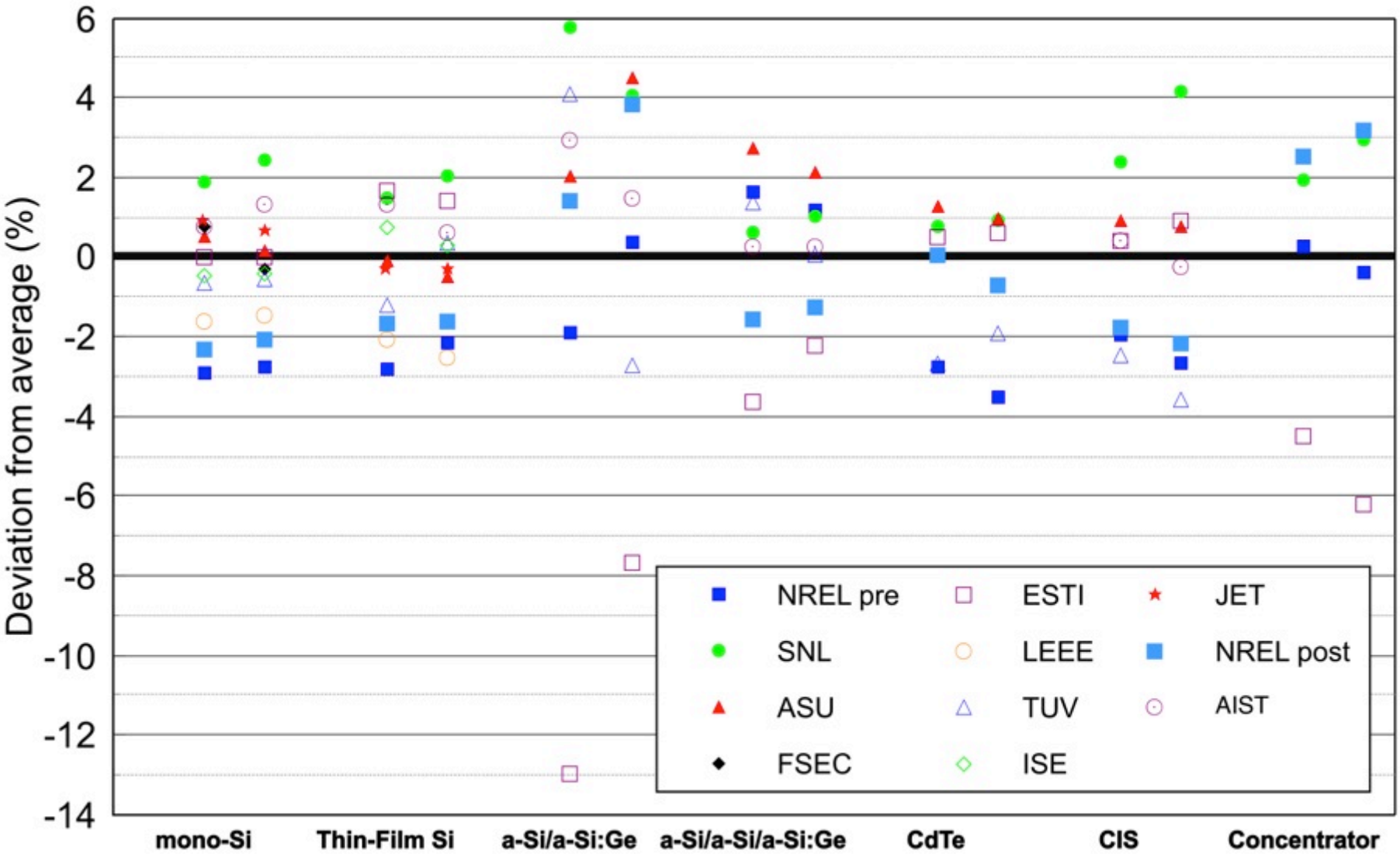
  S. Rummel et al, *4th World Conference on PV Energy Conversion, p.2034, 2006*
- 2006-2008 EC PERFORMANCE project – 7 labs

  T. Betts et al, 21st EU PVSEC, p.2447, 2006
  W. Herman et al, 22nd EU PVSEC, p.2506, 2007
  W. Herman et al, 23rd EU PVSEC, p.2719, 2008

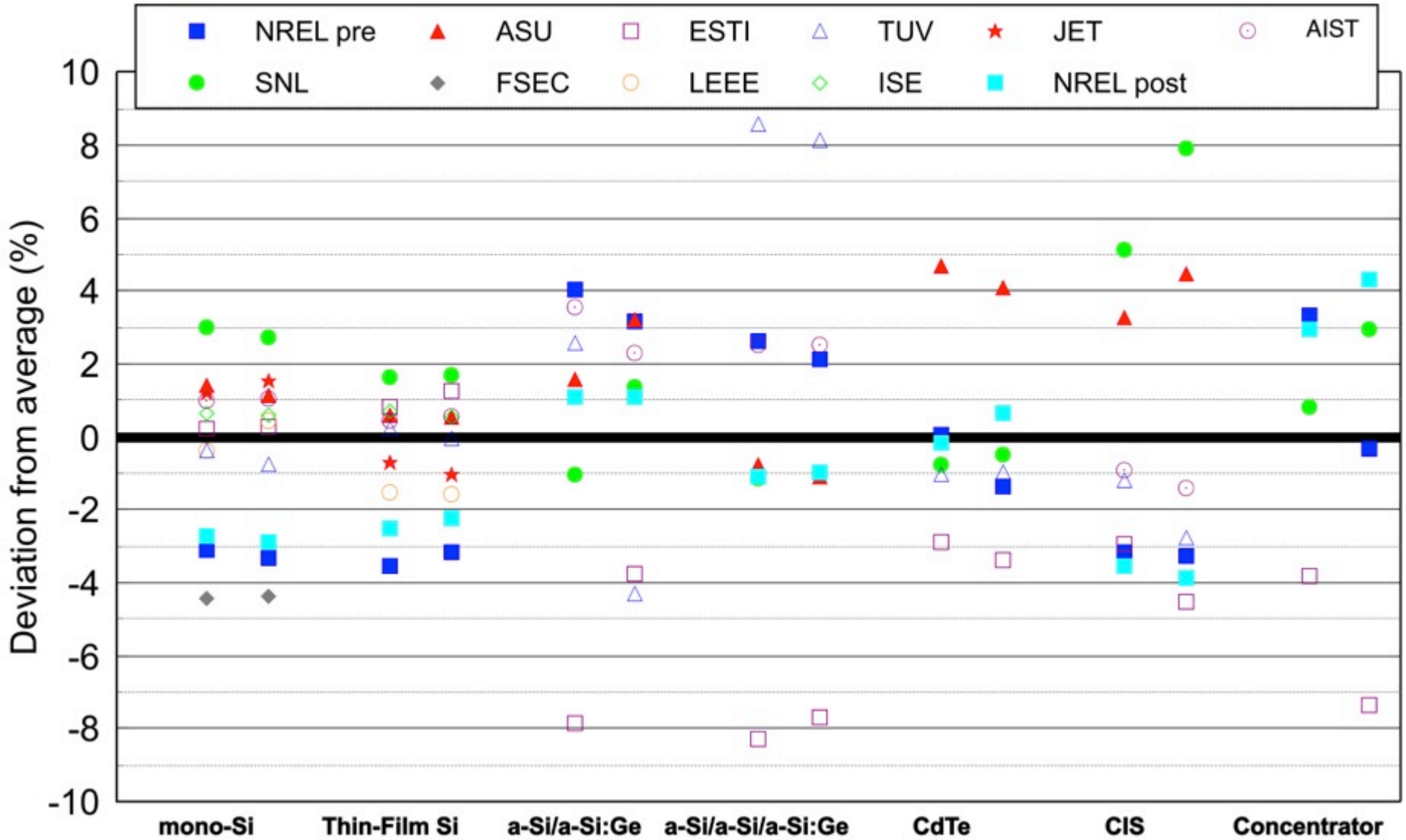
PEP’87 Module Intercomparison



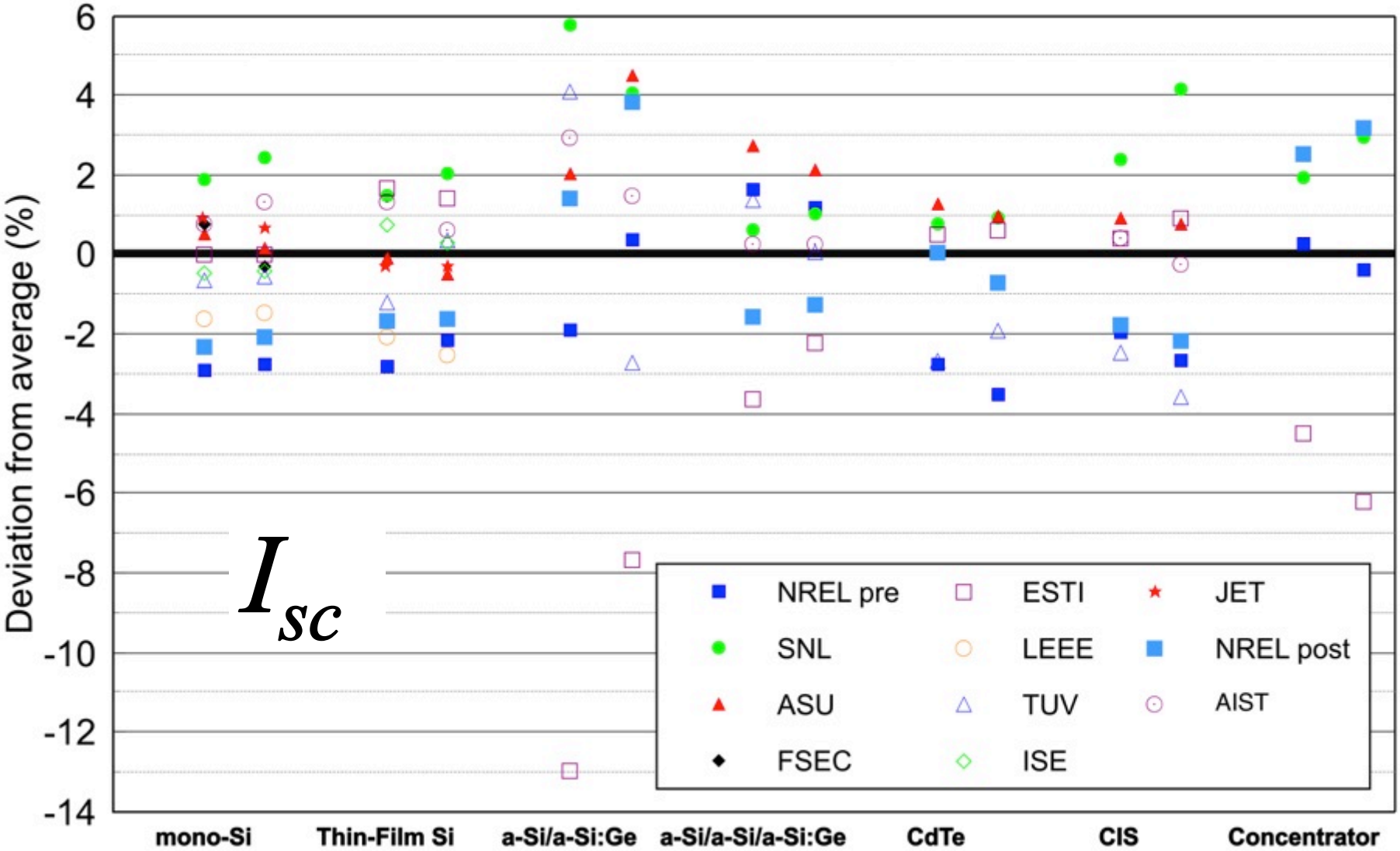
Results - I_{sc}


Deviation from average (%)
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
mono-Si
Thin-Film Si
a-Si/a-Si:Ge
a-Si/a-Si/a-Si:Ge
CdTe
CIS
Concentrator
NREL pre
ESTI
JET
SNL
LEEE
NREL post
ASU
TUV
AIST
FSEC
ISE

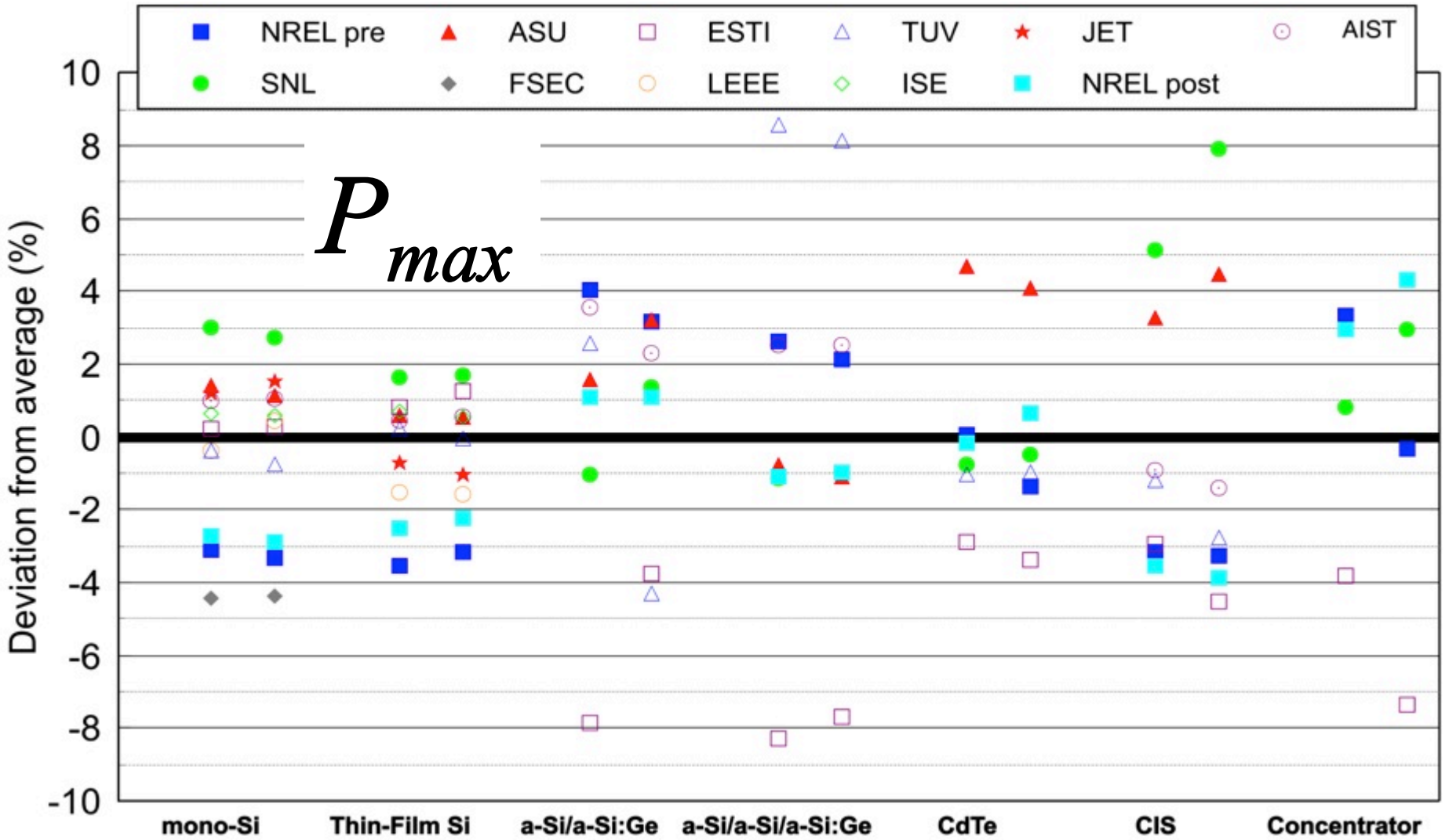
Results - P_{max} @ 25 C, 1000 Wm^{-2}, IEC Global Reference spectrum



NREL 2004 Intercomparison

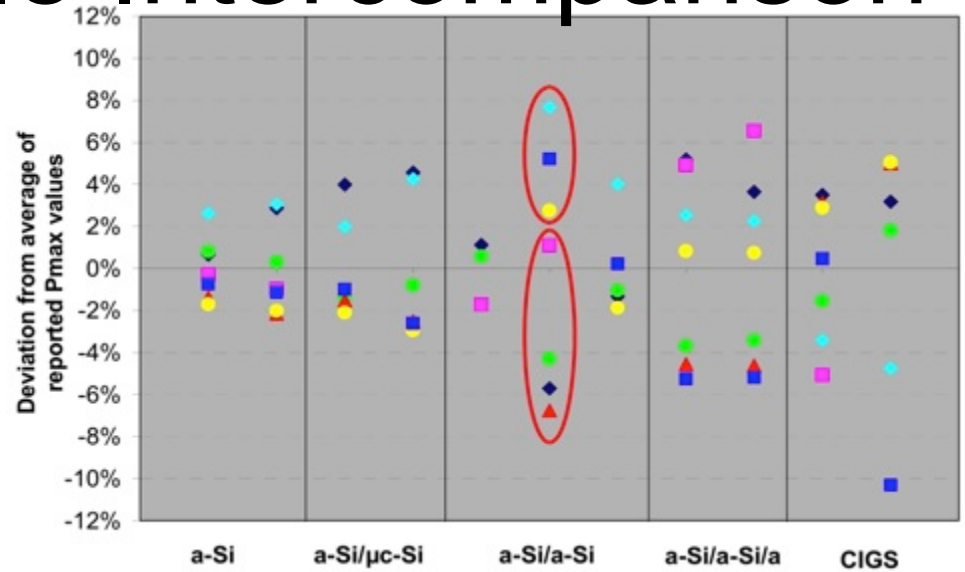


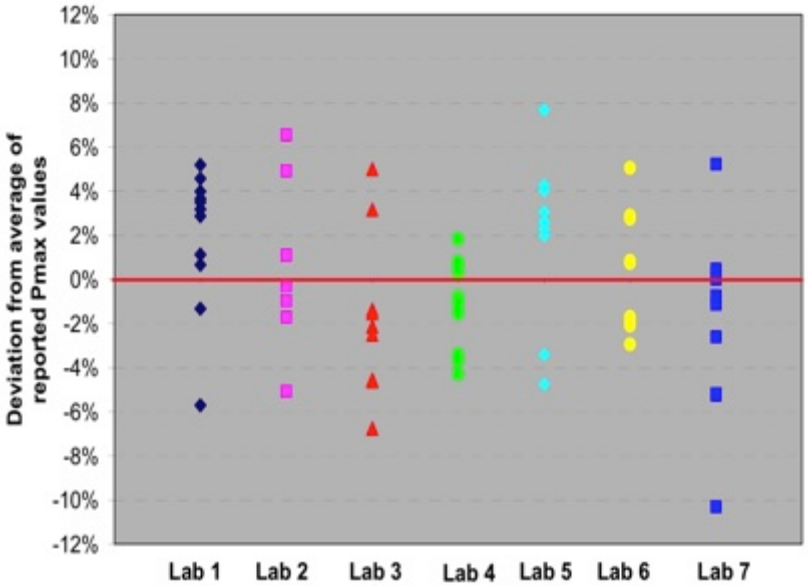
NREL 2004 Module Intercomparison

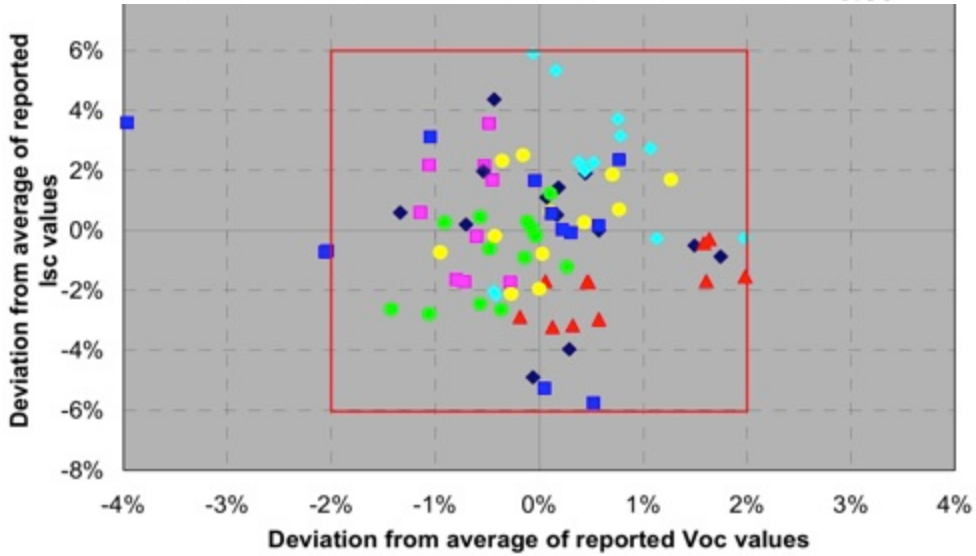


2008 EU Module Intercomparison

Arsenal research, Vienna (Austria)
Ciemat, Madrid (Spain)
EC DG Joint Research Centre, Ispra (Italy)
ECN, Petten (The Netherlands)
Fraunhofer-ISE, Freiburg (Germany)
SUPSI, Lugano (Switzerland)
TÜV Rheinland, Cologne (Germany)







W. Herrmann, S. Zamini, F. Fabero, T. Betts, N. van der Borg, K. Kiefer, G. Friesen, W. Zaaiman, "**RESULTS OF THE EUROPEAN PERFORMANCE PROJECT ON THE DEVELOPMENT OF MEASUREMENT TECHNIQUES FOR THIN-FILM PV MODULES**", proc. 23rd EU PVSEC, 2008, p. 2719

Outline - Performance

- PV Theory
- PV Technology
- PV Performance
  - Measurement Theory
  - Primary calibration
  - IV systems
  - QE systems
  - Multi-junction issues
  - Artifacts
  - Intercomparisons
  - Alternative rating methods

“Ideal” Rating

Ideally the rating should be relevant to the application

PV-System Configuration	**Critical Operation Period**
Grid-connected, fuel-saving mode, hydrogen production	The whole year
Peak demand supply	During peak demand
Remote system for cooling	At high temperatures
Remote system with storage	During months with low irradiance
Pump system for agriculture	During growth time (period when water needed)

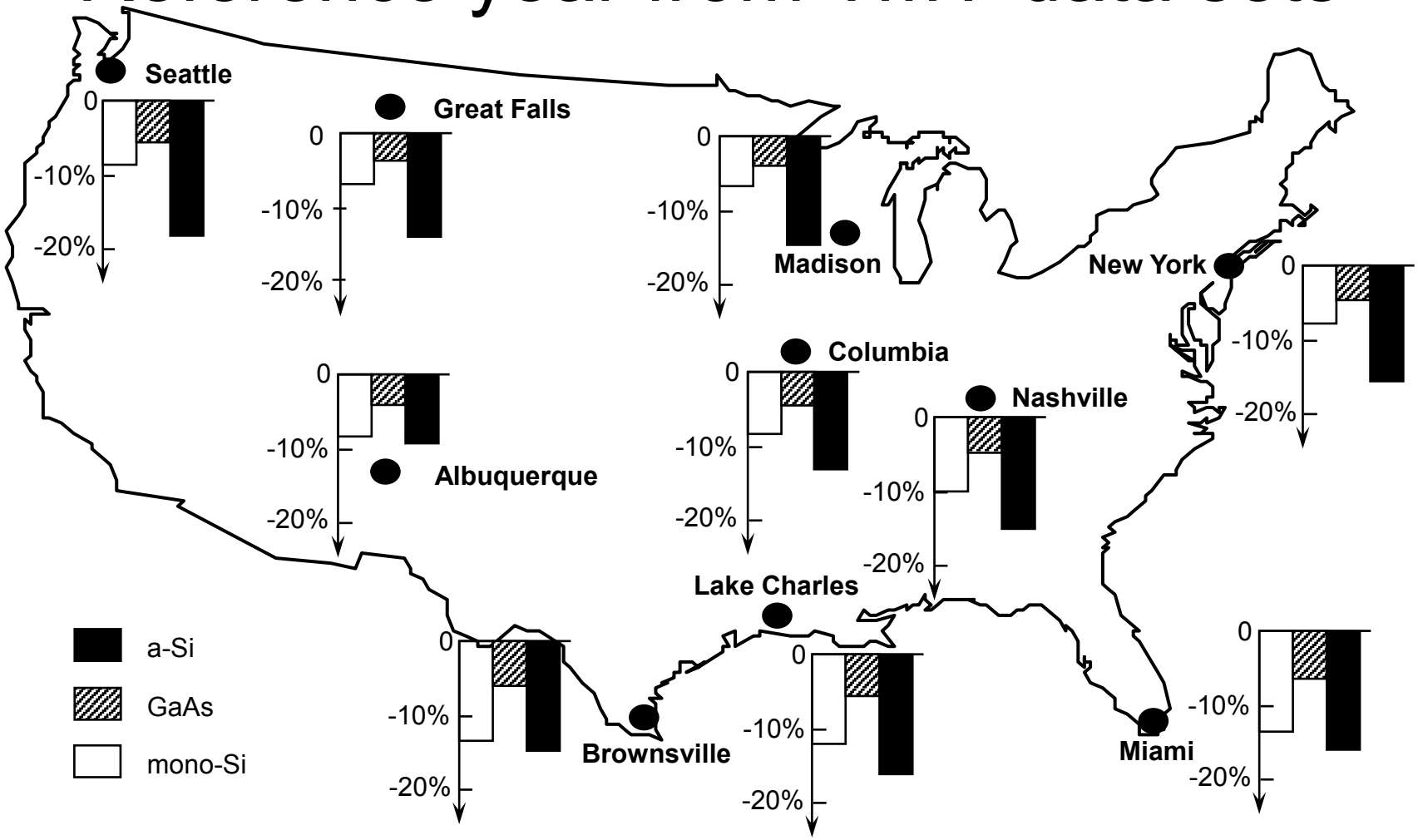
Alternative Rating Conditions

- Regression based upon air temperature
  - ASTM E2527, PVUSA regression analysis to project test conditions defined by 1000 Wm^{-2} Global or 850 Wm^{-2} direct beam irradiance, 4 ms^{-1} wind speed, and 20 ° C air temperature valid for small modules to large systems ac or dc rating.
  - ASTM is extending this to flat-plate technologies.
- Performance ratio P_{max} at some site specific location divided by P_{max} at standard reference conditions.
- Current at some load voltage for battery charging

Performance Ratio

- Site specific value normalized value useful in comparing multiple technologies.
- May artificially bias to lower light levels because resource data is averaged over an hour and in partly cloudy conditions the data is a combination of high and low light levels but is hourly averaged giving an average low light conditions. Modules with shunting problems do less well than expected when using resource data.
- Spectral and seasonal effects present.

Calculated Performance ratio for Reference year from TMY data sets



S. Nann and K. Emery, "Spectral Effects on PV-Device Ratings," Solar Energy Materials Vol. 27, pp. 189-216, 1992.

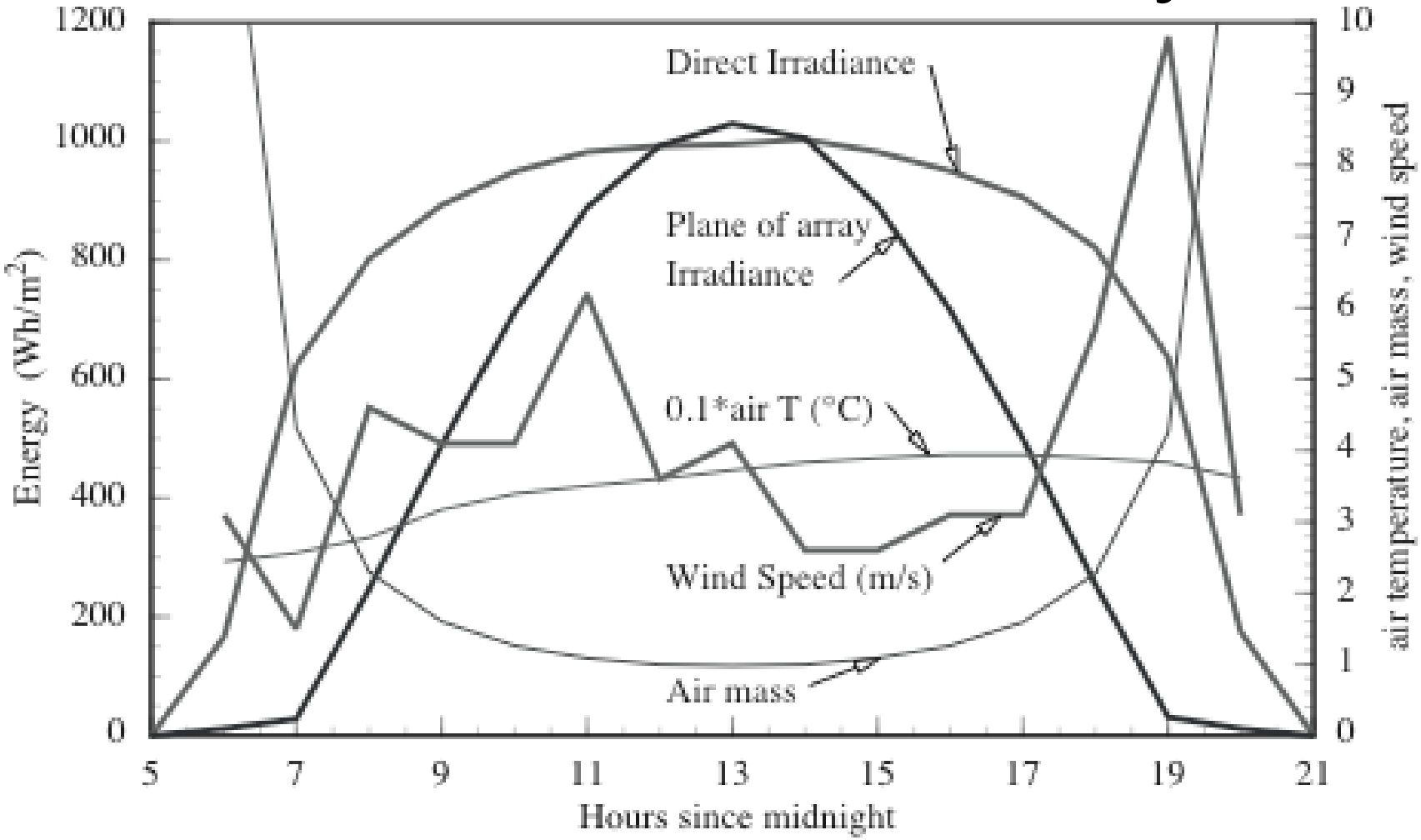
Outline

- Current vs. voltage Theory
- PV Power Performance
- PV Energy Performance
  - Theory
  - Standards Development

PV Energy Performance

- This is the ultimate ideal rating but there is little consensus. IEC 61853 under development for many years with some recent progress.
- The energy rating can be as simple as a utility level rating of KWhr produced at the inverter divided by the peak watt rating or the total incident irradiance
- The energy can also be rated with respect to a reference day, month or year. AM/PM first attempt.
- Energy with respect to a reference year part of the levelized cost of energy metric. The reference years are not uniquely specified for multi-junction technologies. Resource data is typically hourly averaged data.

AM/PM Reference day



C. Gay, J. Rumburg, and J. Wilson, (1982), "AM/PM" – All-Day Module performance Measurements, *Proceedings of the 16th IEEE PV Spec. Conf.*, San Diego, pp. 1041-1046.

Typical Reference days

Subjective Parameter Estimates for Reference Day Parameters

Profile	Peak Wm^{-2}	Daytime °C	Wind Speed ms^{-1}	%	Humidity %	Cloud Cover .
Hot Sunny	> 1000	>35	Low	Low	0	
Cold Sunny	>900	Max 0	Avg	High	<30	
Hot Cloudy	<400	>30	Avg	High	>50	
Cold Cloudy	200-400	Max 0	High	High	>90	
Nice	800-900	20	Avg	Avg	<30	

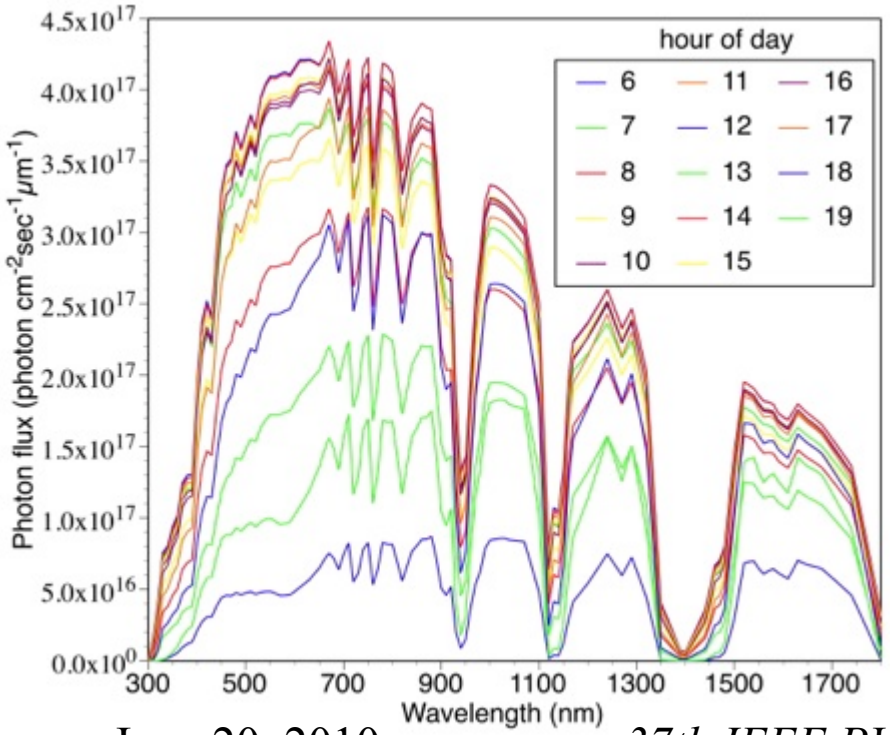
Profile	Global Horiz. Whr/m²	Direct Whr/m²	Diffuse Whr/m²	Temp °C	Relative Humidity %	Wind Speed m/s	Cloud Cover % .
Hot Sunny	9144	11876	999	36.3	6.3	3.9	0.0
Cold Sunny	4340	9440	330	-0.6	50.9	2.2	4
Hot Cloudy	3465	292	3265	32.1	59.8	7.9	90
Cold Cloudy	1319	8	1317	-0.1	93.4	3.7	100
Nice	7117	8347	1529	17.3	65.4	5.0	47

B. Kroposki, D. Myers, K. Emery, L. Mrig, C. Whitaker, and J. Newmiller, "Photovoltaic Module Energy Rating Methodology Development," *Proc. 25th IEEE PVSC*, May 13-17, 1996, pp. 1311-1314.

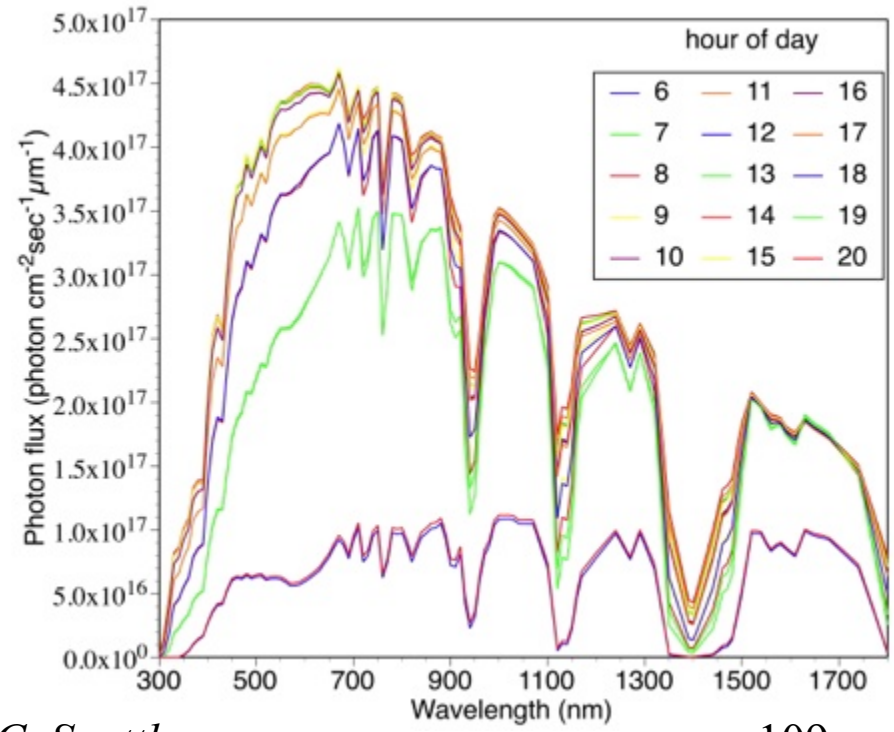
Global Normal Spectra generated for the reference days

With spectral information multi-junctions and narrow response range technologies can be accurately modeled. Translation equations that account for spectral effects can be used. Spectral information is not required for Si, CdTe or CIGS technologies at the +/-3% level.

Nice



Hot-Sunny

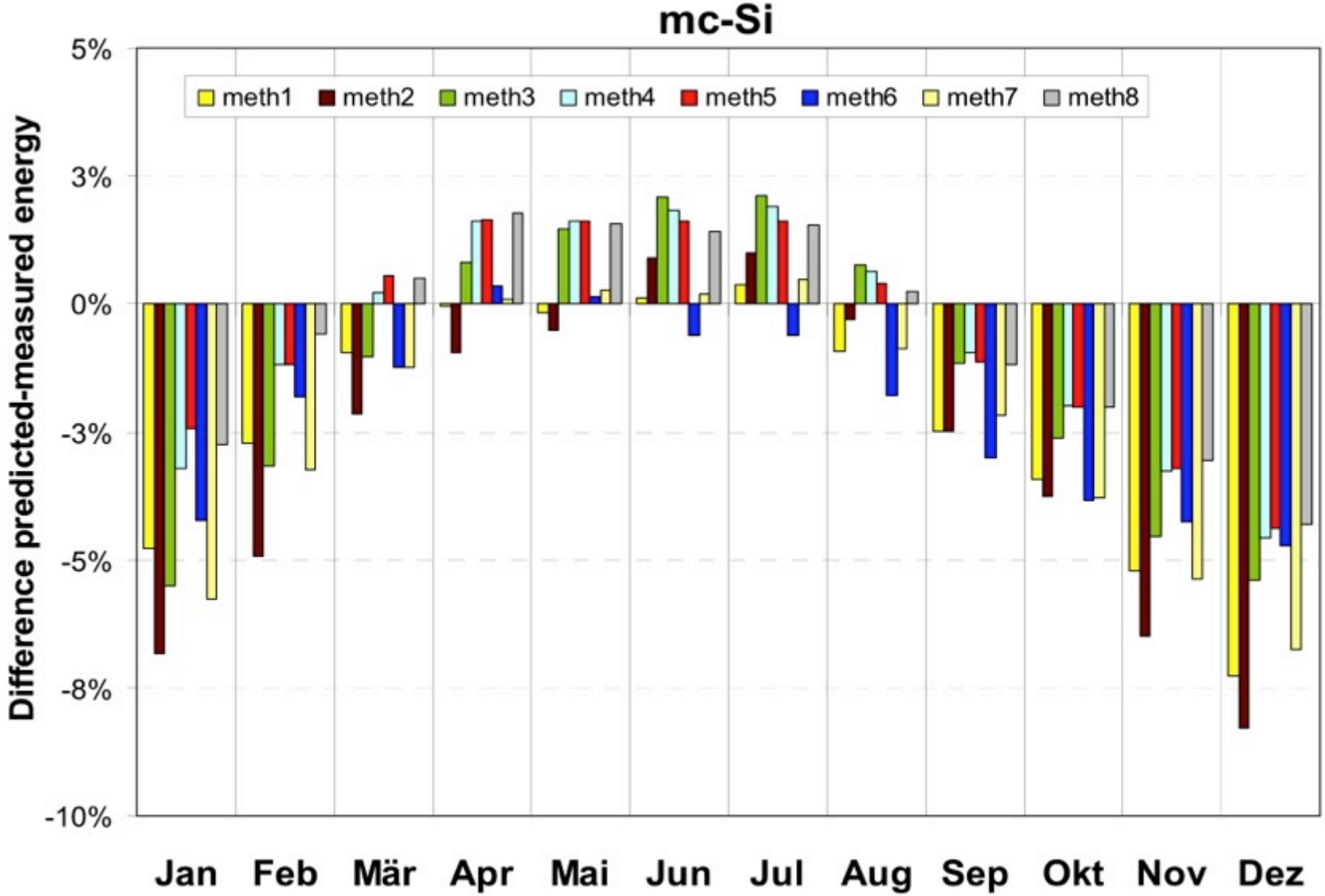


EU Comparison of Energy Rating methods

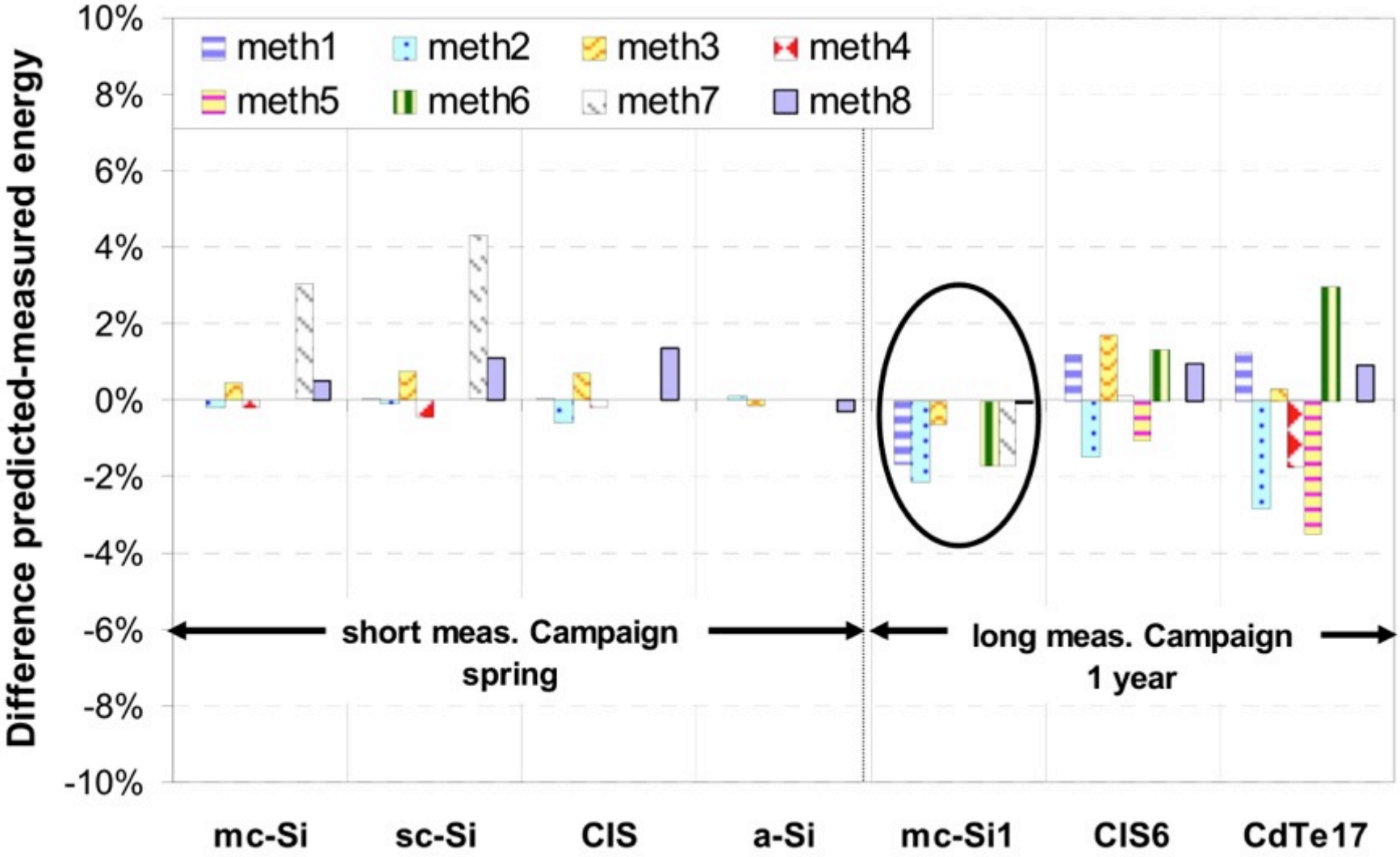
name of method	institute	extracted information	raw data handling	power or efficiency equations	temperature coefficient(s)
SSE	CREST	η(G,25°C), TC	T=24-26°C → η(G,25°) G=950-1050W/m² → TC AOI ≤ 30°	$\eta(G,25°) = C_0+C_1G+C_2\ln G$	TC@1000W/m²
Yield Simulator	ECN	η(G,25°C), TC	binning P(G,T) G bins= 50W/m² Tm bins=5°C	avg η(G,25°)	average TC (250,500,750,1000W/m²)
Somes	UU	η(G,25°C), TC	binning η(G,25°) G bins= x±5W/m² x=0,200,400…1000W/m²	$P_t = P_{nom} \cdot \frac{\Theta(G)}{\Theta(1000)} \cdot \frac{G}{1000}$	TC=0.4%/°C (default value)
MotherPV	INES	η(G,25°C), TC	binning η(G,T) G bins= 20W/m²	avg η(G,25°)	TC(G)
PV-SAT	H2M	η(G,T)	data from 9:00-15:00	$\eta_{MPP}(G,T) = a_1 + a_2G + a_3 \ln(G * m^2/W) \cdot (1+\alpha(T_{Module} - 25))$	
Matrix method 1	SUPSI	P(G,T)	binning P(G,T) G bins= 10W/m² Tm bins=1°C StDev<20%	$I_m = I_{m,stc} \cdot G/1000 \cdot [1+\alpha_{Im} \cdot (\Delta T + T - 25)]$ $V_m = V_{m,stc} + C_0 \cdot \ln(G/1000) + C_1 \cdot (\ln(G/1000))^2 + \beta_{Vm} \cdot (\Delta T \cdot + T - 25)$	
Matrix method 2	JRC	P(G,T)	$0.7 \leq P_{m,stc} \times G/1000 \leq 1.4$	$P(G,T) = I_{m,stc} \cdot G/1000 \cdot [1+\alpha_{Im} \cdot (T - 25)] \cdot (V_{m,stc} + C_0 \cdot \ln(G/1000) + C_1 \cdot (\ln(G/1000))^2 + \beta_{Vm} \cdot (T - 25))$	
ZENIT	ISE	P(G,T)	G>30W/m²; Pm/G>0.02 or data from 10:00-18:00	$P(G,T) = a \cdot G^2 + b \cdot \log(G+1) \cdot G + c \cdot \left(\frac{(\log(G+e)^2)}{G+1} - 1 \right) \cdot G + d \cdot (TMOD - 25)$	

Gabi Friesen, "From Module Performance to Module Energy Delivery: the Path to the Definition of Energy Rating," from *International Workshop on Standardization in the Photovoltaic Sector; 23 July 2007; Brussels*

EU Comparison of Energy Rating methods at the same site



Gabi Friesen, "From Module Performance to Module Energy Delivery: the Path to the Definition of Energy Rating," from *International Workshop on Standardization in the Photovoltaic Sector; 23 July 2007; Brussels*



Gabi Friesen, "From Module Performance to Module Energy Delivery: the Path to the Definition of Energy Rating," from *International Workshop on Standardization in the Photovoltaic Sector; 23 July 2007; Brussels*

Questions?

Supplementary materials

Bibliography

First derivation of M

C.R. Osterwald, (1986), Translation of Device Performance Measurements to Reference Conditions, *Solar Cells*, 18, pp. 269-279.

First use of M

K.A. Emery, C.R. Osterwald, T.W. Cannon, D.R. Myers, J. Burdick, T. Glatfelter, W. Czubatyj, and J. Yang, "Methods for Measuring Solar Cell Efficiency Independent of Reference Cell or Light Source," *Proc. 18th IEEE Photovoltaic Spec. Conf.*, Las Vegas, NV, October 21–25, 1985, pp. 623–628, IEEE, New York, 1985.

Uncertainty Analysis

D.R. Myers, K.A. Emery, and T.L. Stoffel, "Uncertainty Estimates for Global Solar Irradiance Measurements Used to Evaluate PV Device Performance," *Proc. SERI 9th Photovoltaics Advanced Research and Development meeting*, May 24-26, 1989, Solar Cells, vol. 27, pp. 455-464, 1989.

K.A. Emery, C.R. Osterwald, and C.V. Wells, "Uncertainty Analysis of Photovoltaic Efficiency Measurements," *Proc. 19th IEEE Photovoltaic Specialists Conf.*, New Orleans, LA, May 4-8, pp. 153-159, IEEE, New York, 1987.

H. Field and K. Emery, "An Uncertainty Analysis of the Spectral Correction Factor," *Proc. 23rd IEEE Photovoltaic Specialists Conf.*, Louisville, KY, May 10-14, 1993, pp. 1180-1187, IEEE, New York, 1993.

K. Emery, "Uncertainty Analysis of Certified Photovoltaic Measurements at the National Renewable Energy Laboratory," August 2009, NREL tech rep. NREL/TP-520-45299.

K. Whitfield and C.R. Osterwald , Procedure for Determining the Uncertainty of Photovoltaic Module Outdoor Electrical Performance, Progress in PV., vol. 9, pp. 87-102, 2001

Independent record efficiency

M.A. Green, K. Emery, Y. Hishikawa, and W. Warta, "Solar Cell Efficiency Tables (version 37)," Progress in Photovoltaics Research and Applications, vol. 19, pp. 84-92, 2011.

I-V and QE

K.A. Emery, "Measurement and Characterization of Solar cells and Modules," Handbook of Photovoltaic Science and Engineering, second edition, Chap. 18, pp. 797-840, A. Luque and S. Hegedus editors, John Wiley & Sons, W. Sussex, U.K., ISBN -0-470-72169-8, 2011.

Standards

WWW.astm.org

PV standards can be found in Annual Book of ASTM Standards, Vol. 12.02. American Society for Testing and Materials, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, United States.

WWW.iec.ch

IEC working group 2 PV cell and module IV and QE, IEC 60904-1 thru -10, IEC 60891

ISO 15387:2005, Space systems – Single-junction space solar cells – Measurement and calibration procedures, International Organization for Standardization, Geneva, Switzerland.

History of PV Efficiency

1975, 1976 Baton Rouge Workshops

Workshops developed "Terrestrial Photovoltaic Measurement Procedures," NASA Tech. Report TM 73702, June 1977. (25 ° C, total area, reference spectrum)

1976-1984 Multiple AM1.5 spectra referenced by community with no group actually measuring with respect to their claimed tabular reference spectrum

1984 spectral mismatch error developed and implemented at NREL to measure WRT arbitrary reference spectrum*

*K.A. Emery, et. al, "Methods for Measuring Solar Cell Efficiency Independent of Reference Cell or Light Source," Proc. *18th IEEE PV Spec. Conf.*, 623–628 (1985).

History of PV Efficiency

1985

- ASTM E892, now retired as ASTM G159 reference spectrum adopted internationally and in use until 2009.
- ASTM E948, IEC 60904 standards under development
- Community starts to reach consensus on reference conditions and procedures.
- A Spectral error M exists for all indoor or outdoor measurements if the goal is with respect to a reference spectrum

1985-1986

- Multijunction QE procedures developed
- J. Burdick and T. Glatfelter, "Spectral response and I-V measurements of tandem amorphous-silicon alloy solar cells," Solar Cells, **18**, pp. 301-314, 1986.

History of PV Efficiency

1987

ECD publishes multijunction I-V theory in use at NREL and elsewhere today

T. Glatfelter, J. Burdick, and W. Czubatyj, (1987), A Method for Measuring the Conversion Efficiency of Tandem Solar Cells, *Proceedings 2nd PV Science and Engineering Conf.,, Aug. 19-22, 1986, pp. 106-109.*

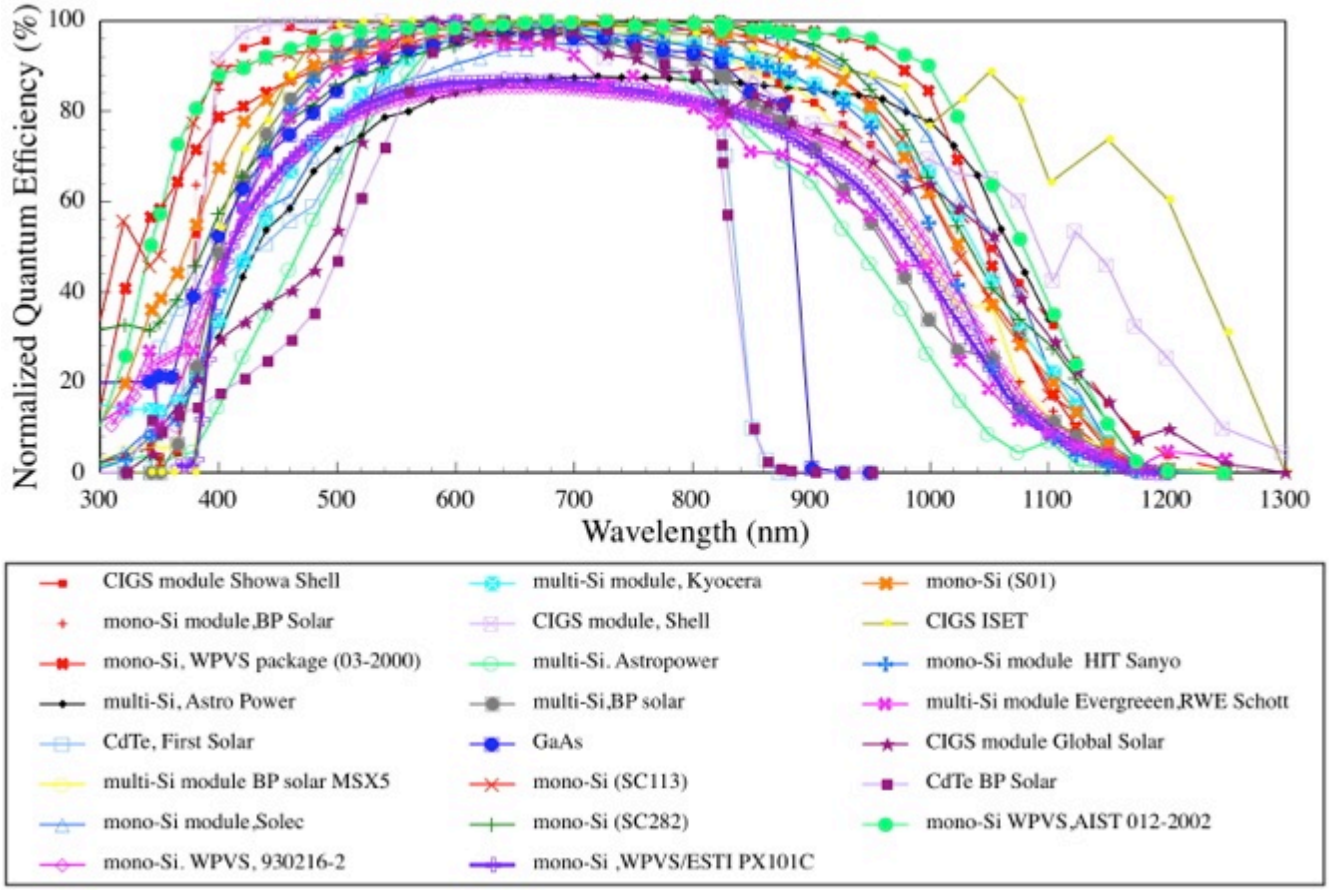
T. Glatfelter and J. Burdick, (1987), A Method for Determining the Conversion Efficiency of Multiple-Cell Photovoltaic Devices, *Proceedings of the 19th IEEE PV Spec. Conf.* New Orleans, pp. 1187-1193.

$$1 = \frac{I_i^{R,R}}{I_i^{R,S} M_i}$$

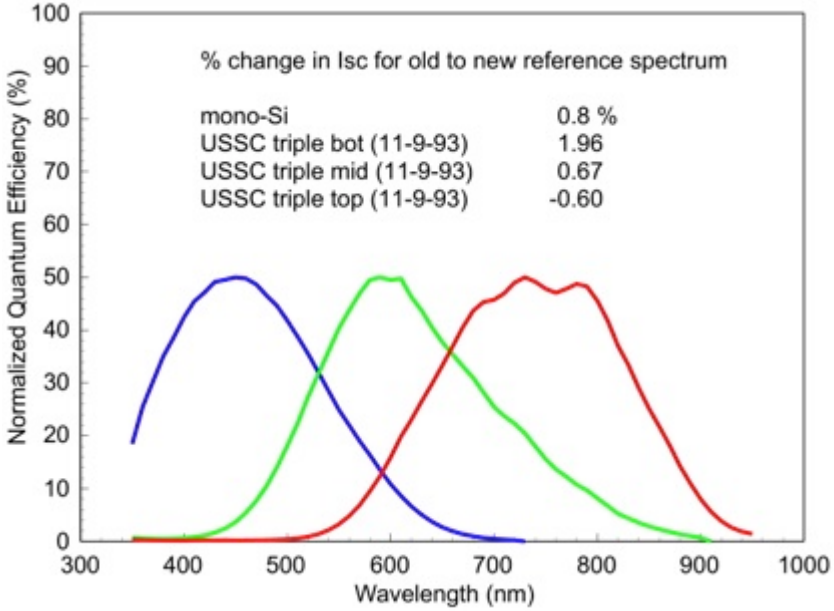
$$M_i = \frac{\int_{\lambda_1}^{\lambda_2} E_{Ref}(\lambda) S_{Ref}(\lambda) \mathrm{d}\lambda}{\int_{\lambda_1}^{\lambda_2} E_{Ref}(\lambda) S_T^i(\lambda) \mathrm{d}\lambda} \frac{\int_{\lambda_1}^{\lambda_2} E_S(\lambda) S_T^i(\lambda) \mathrm{d}\lambda}{\int_{\lambda_1}^{\lambda_2} E_S(\lambda) S_{Ref}(\lambda) \mathrm{d}\lambda}$$

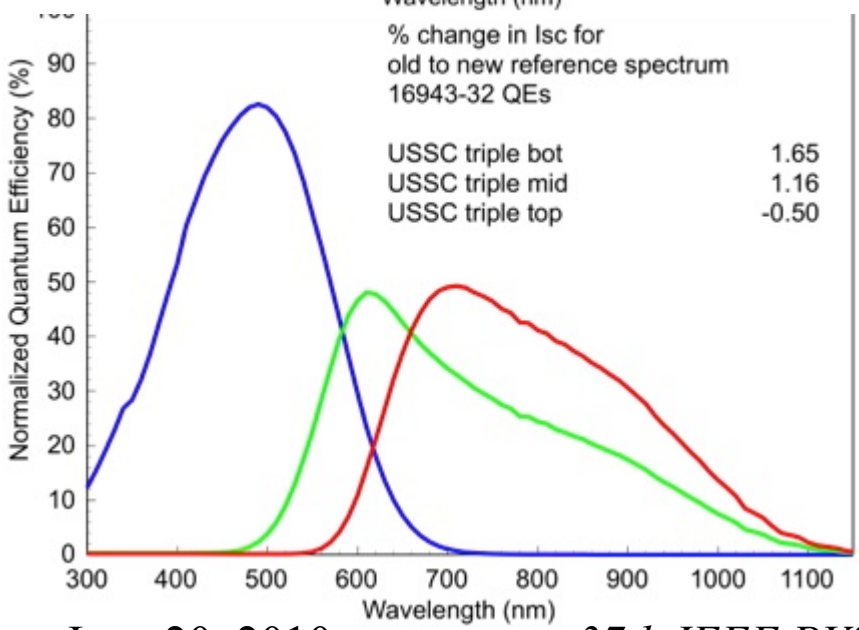
Effect of new Spectra

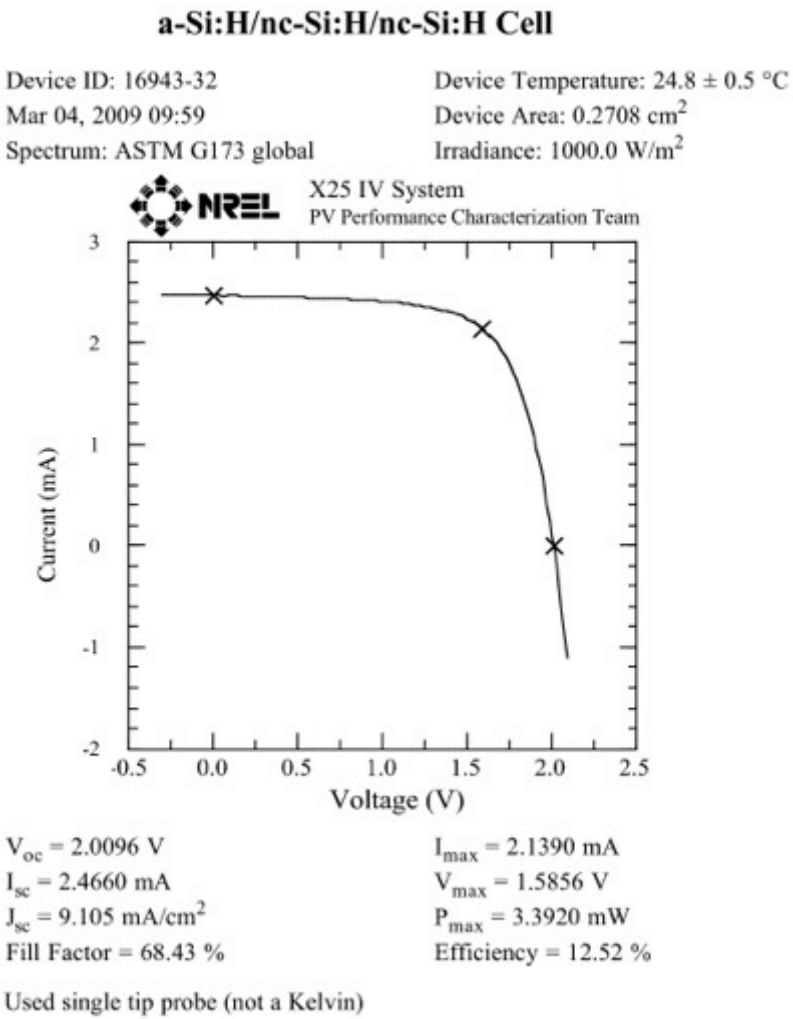
QE	%Jsc ASTM G173 / Jsc ASTM G159 Global
Mono-Si	0.76-0.92
Multi-Si	0.79-0.97
Cu(Ga,In)(S,Se)	0.79- 0.93
CdTe	1.24



Effect of new Spectrum







Publications containing PV Area Definitions

<u>American Society for Testing and Materials (ASTM)</u>
E948: Cells Using Reference Cells Under Simulated Sunlight
E1036: Standard Test Methods for Electrical Performance of Nonconcentrator Terrestrial Photovoltaic Modules and Arrays using Reference Cells
E1328: Terminology Relating to Photovoltaic Solar Energy Conversion

<u>Institute of Electrical and Electronics Engineers (IEEE)</u>
ANSI/IEEE 928: IEEE Recommended Criteria for Terrestrial Photovoltaic Power Systems

<u>International Electrotechnical Commission (IEC)</u>
60904-1: Measurement of photovoltaic current-voltage characteristics
60904-3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data

<u>ERDA/NASA</u>
TM 73702 Terrestrial Photovoltaic Measurement Procedures, ERDA/NASA/1022-77/16, June 1977.

K. A. Emery, "Solar Simulators and *I-V* Measurement Methods," Solar Cells, 18 (1986) p. 251-260.
M.A. Green and K.A. Emery, “Solar Cell Efficiency Tables,” Progress in Photovoltaics Research and Applications, vol. 1, pp. 25-30, 1993.

Area– Progress in PV Efficiency Tables

"Total area. This is the preferred area for reporting of results and equals the total projected area of the cell or module (the area that would be measured by taking a photograph of the device against a white background and measuring the area of the background shaded by the device). For the case of a cell attached to glass, the total area would be the area of the glass sheet.

Aperture area. In this measurement, the device under test is masked so that the illuminated area is smaller than the total cell or module area, but all essential components of the device, such as busbars, fingers and interconnects, lie within the masked area. (Masking is not required if it can be demonstrated that areas outside the aperture area are not responsive to light or are not steering light onto active areas.)

Designated illumination area. In this case, the cell or module is masked to an area smaller than the total device area, but major cell or module components lie outside the masked area. For example, for a concentrator cell, the cell busbars would lie outside of the area designated for illumination and this area classification would be the most appropriate. (Again, masking is not required if it can be demonstrated that areas outside the designated illumination area are not responding to light.)"

M.A. Green and K.A. Emery, "Solar Cell Efficiency Tables," Progress in Photovoltaics Research and Applications, vol. 1, pp. 25-30, 1993.

Supplementary materials

PV Performance Measurements at NREL

PV Cell and Module Performance Characterization

SRRL
Broadband Radiometer Calibrations for U.S.
Spectral Radiometer calibration
Volt, Ohm, Amp, Temperature

OTF
Module calibrations

SERF
Cell calibrations

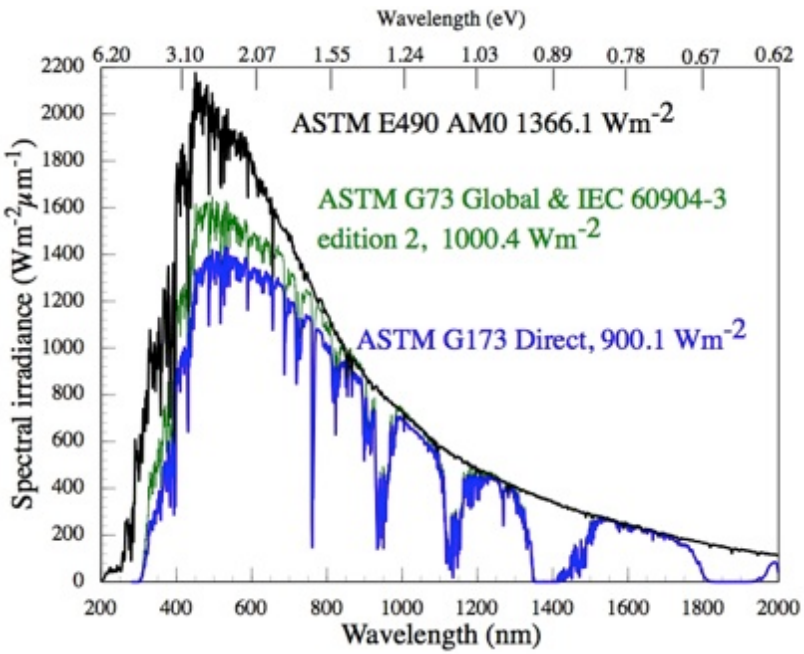
ACCREDITED

certificate number 2236.01 photovoltaic secondary cell, secondary module, and primary reference cell calibration

*NREL

Mission

- Daily PV Performance Measurement Technology transfer to community via emails, phone calls and 1/2 day to several days consulting at NREL
- Assist certified test labs with calibration traceability, uncertainty analysis, procedures and error sources.
- Active in ASTM and IEC photovoltaic standards development

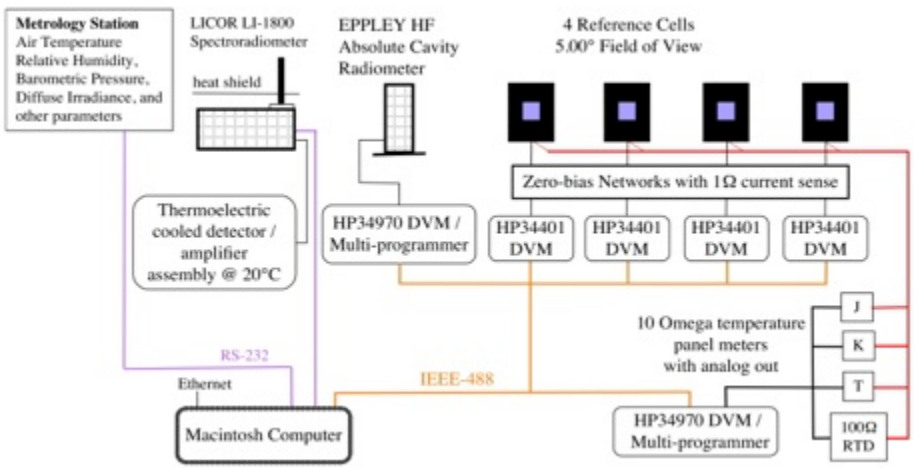


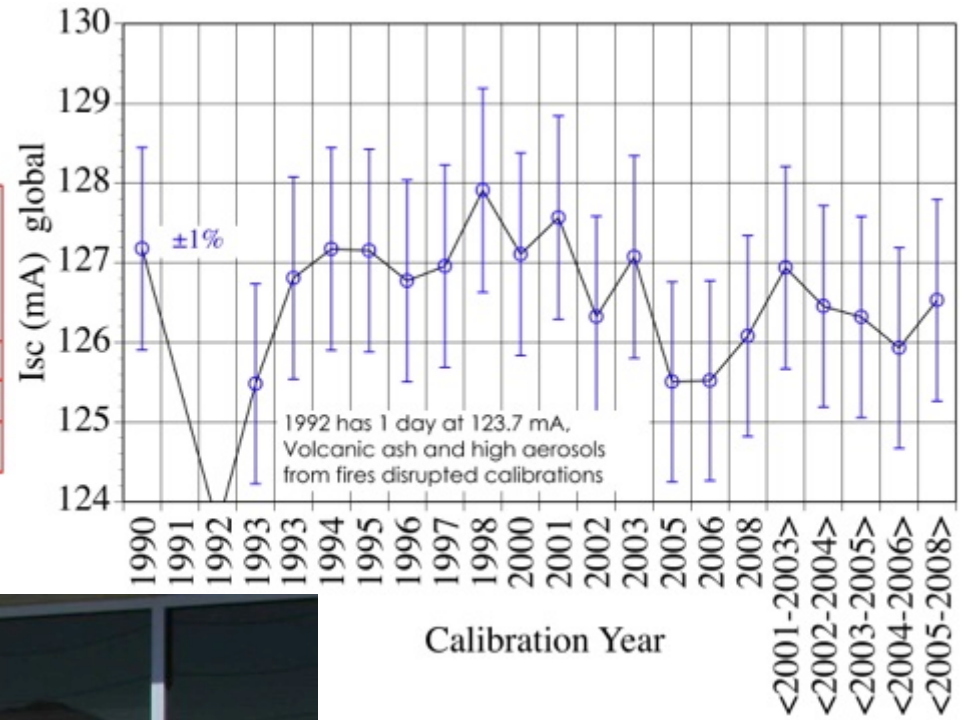
Standard Reporting Conditions
PV Temperature: 25 C
Total Irradiance: 1000 Wm^{-2}
Reference spectrum: Tabular

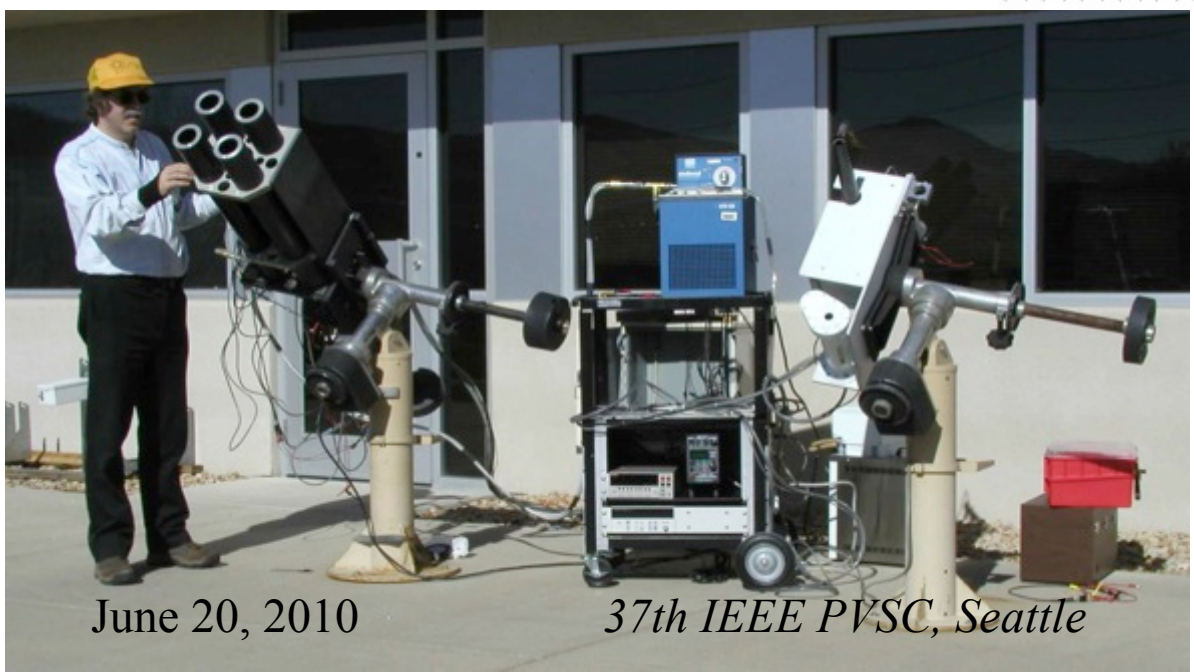
Mission

- Performance measurements for any conceivable PV cell or modules technology of any size or shape
- Primary terrestrial reference cell calibrations
- Secondary reference cell and module calibrations for the PV community
- Independent efficiency measurement for PV community and contract deliverables
- ISO 17025 accreditation applies to a narrow scope of samples. The same hardware, software, and quality system used for all measurements.

NREL Primary PV Calibration



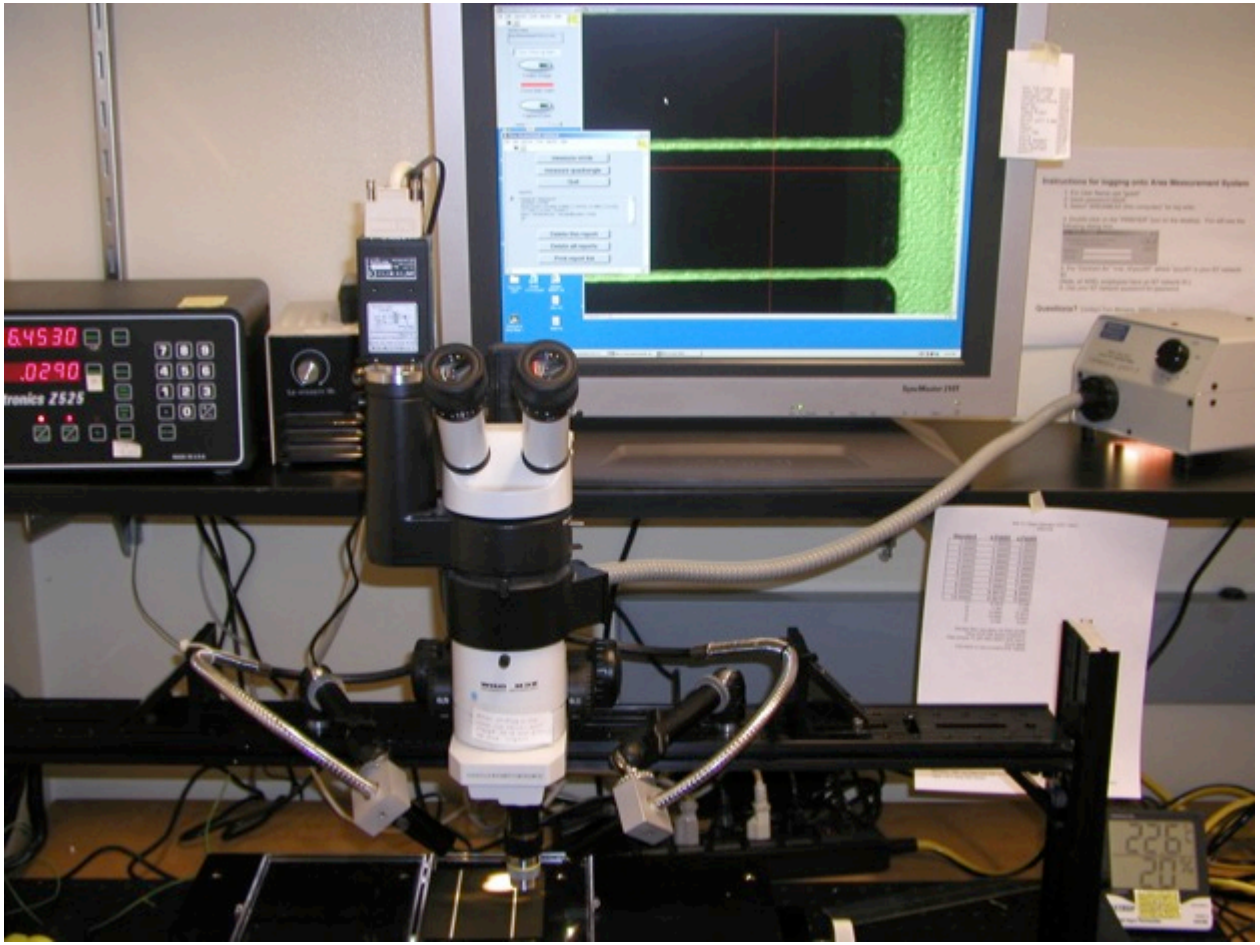




Summary of IV Procedures

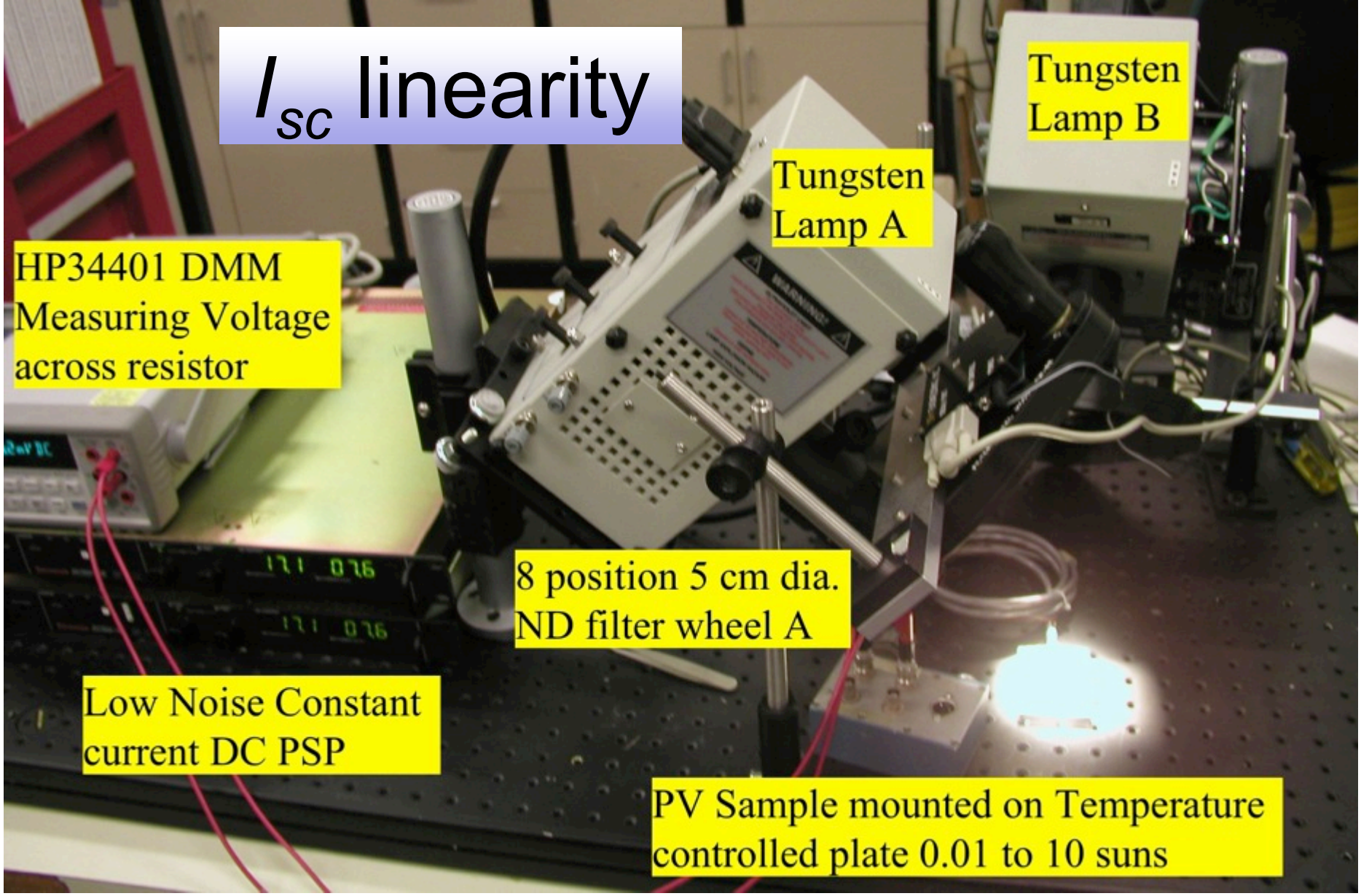
- log the sample in and measure the area
- Measure the QE of the sample with some light bias
- Set or measure the light level using a calibrated PV reference cell that produces a given short-circuit under SRC corrected for spectral error M.
- Mount the sample and set / measure the temperature
- Measure the IV characteristics
- Apply temperature and irradiance corrections if needed. (We do not apply corrections)
- Calculate the efficiency based upon the total or aperture area.

Area Measurement

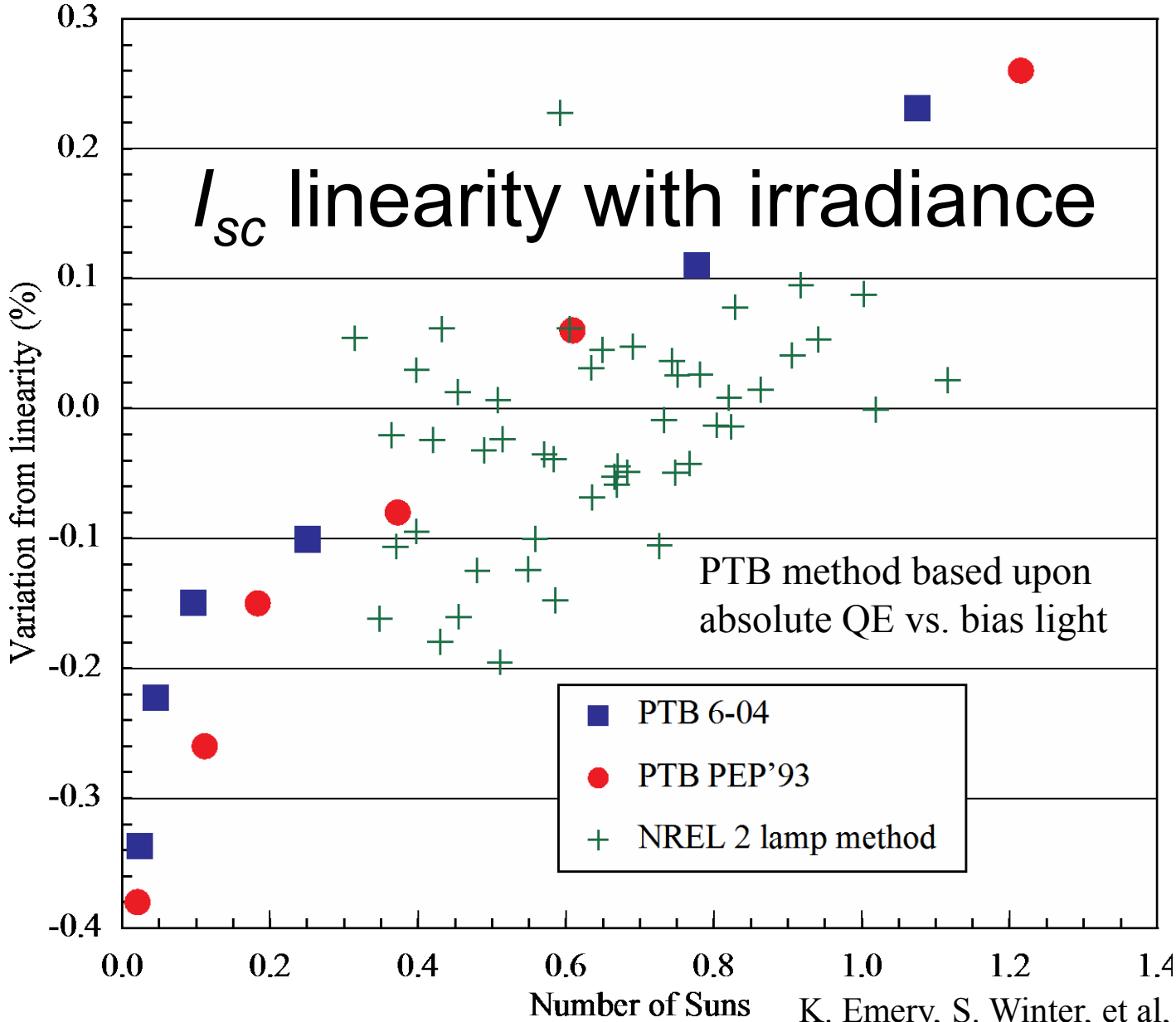


- After sample logged in and approved for measurement the area is measured by digitizing points on the perimeter of a circle, or corners of a general quadrilateral, or a polygon, or a circle with multiple flats.
- Recently upgraded from 4 inch X-Y to 12 inch X-Y stage.

I_{sc} linearity



Linearity test bed to demonstrate that Isc is linear with irradiance as required in reference cell calibration and IV measurement standards.



PTB method is the most correct procedure because it relies on the change Jsc from the absolute QE vs. bias light.

K. Emery, S. Winter, et al, "Linearity Testing of Photovoltaic Cells," Proc. 4th World PVSEC, pp. 2177-2180, 2006

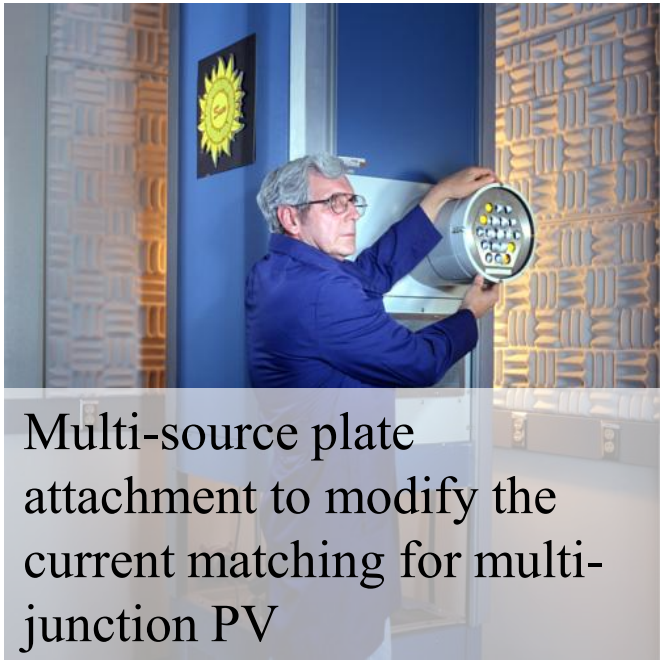
Cell I-V Equipment

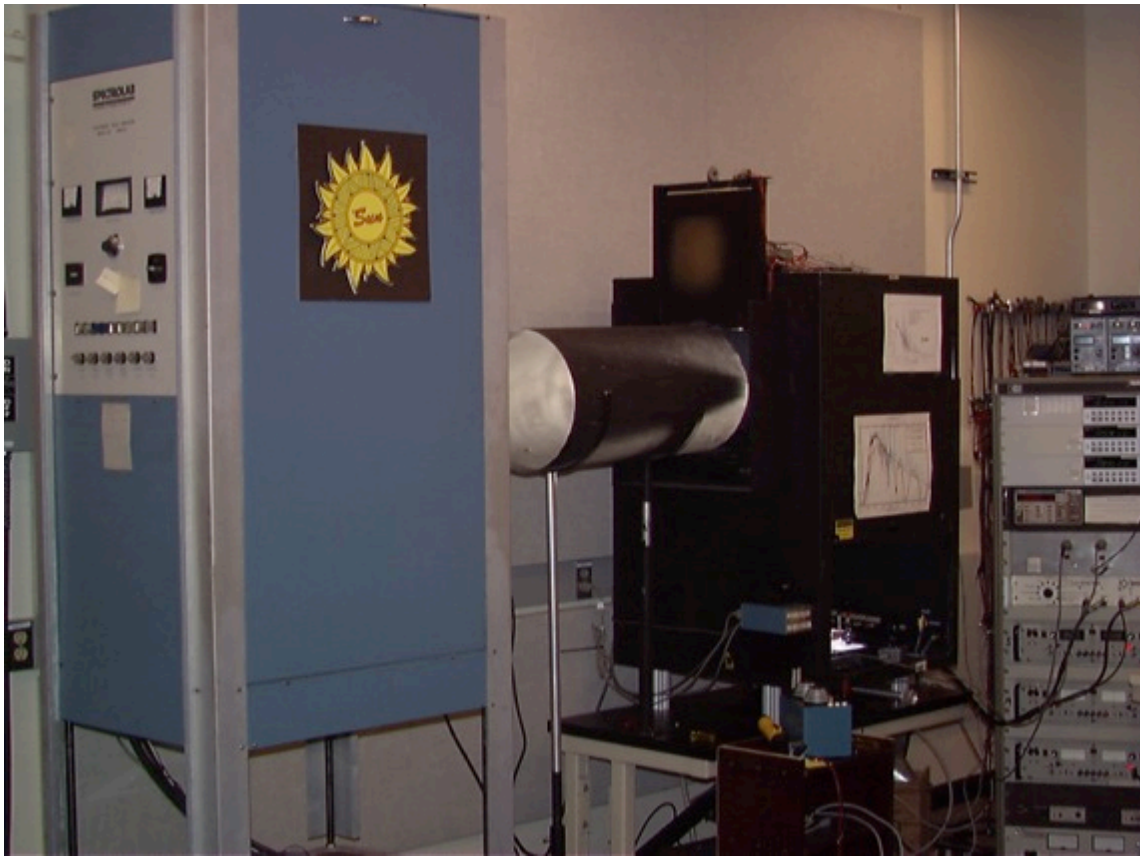
I-V Applications	Light source	size/temperature	Voltage	Current
1-sun Continuous	Spectrolab X25 filtered 3 kW Xe 0.1 - 20 suns	30 cm x 30 cm 5-50 ° C	±0.5 mV ±50 V	±10 pA ±16 A
Continuous Concentrator	1 kW Xe 1 to 200 suns	~ 1 cm diameter 5-80 ° C	±0.1 mV ±10V	±1 μA ±10 A
Pulsed Concentrator	Spectrolab LAPSS Spectrolab HIPSS 2 reference channels	2 Xe flash lamps 2 lamps & mirrors	1 mV 100 V	1 mA 50 A

Multi-source spectrally adjustable 0.1 to 1-sun operational by years end.

Spectrally adjustable concentrator Spectrolab THIPSS delivered by years end.

Spectrolab X25 Solar Simulator

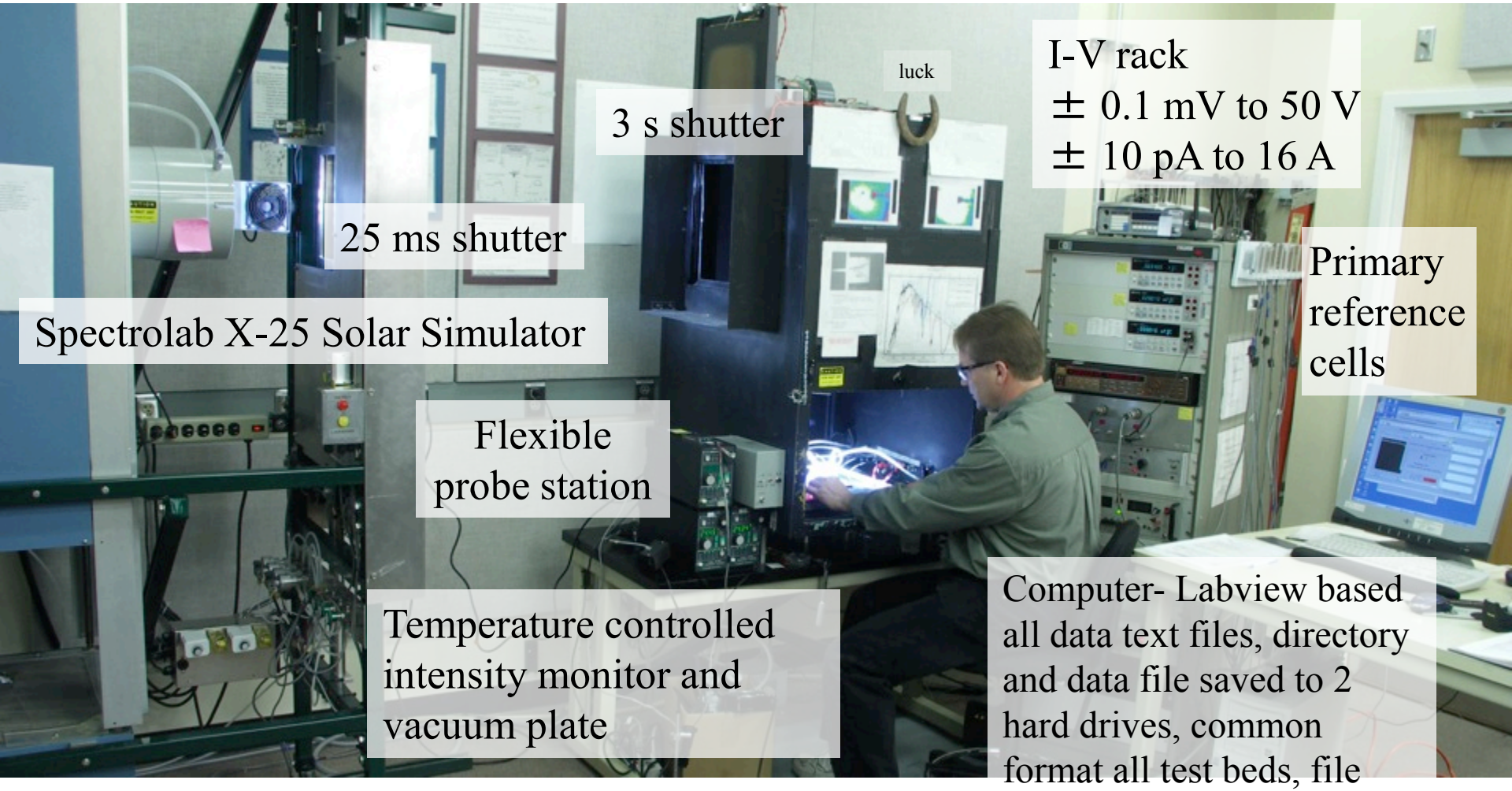




- The spectral mismatch factor is computed and applied to the reference cell calibration.
- The 1-sun I-V at standard reference conditions and optionally the dark I-V is then measured.

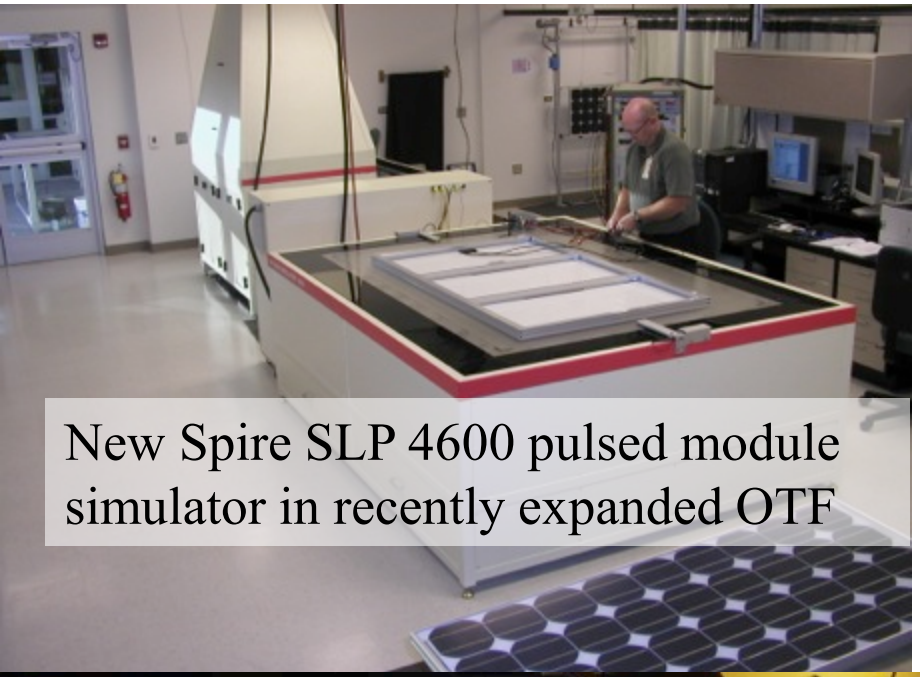
I-V Measurement

PV Performance team's 1-sun simulator



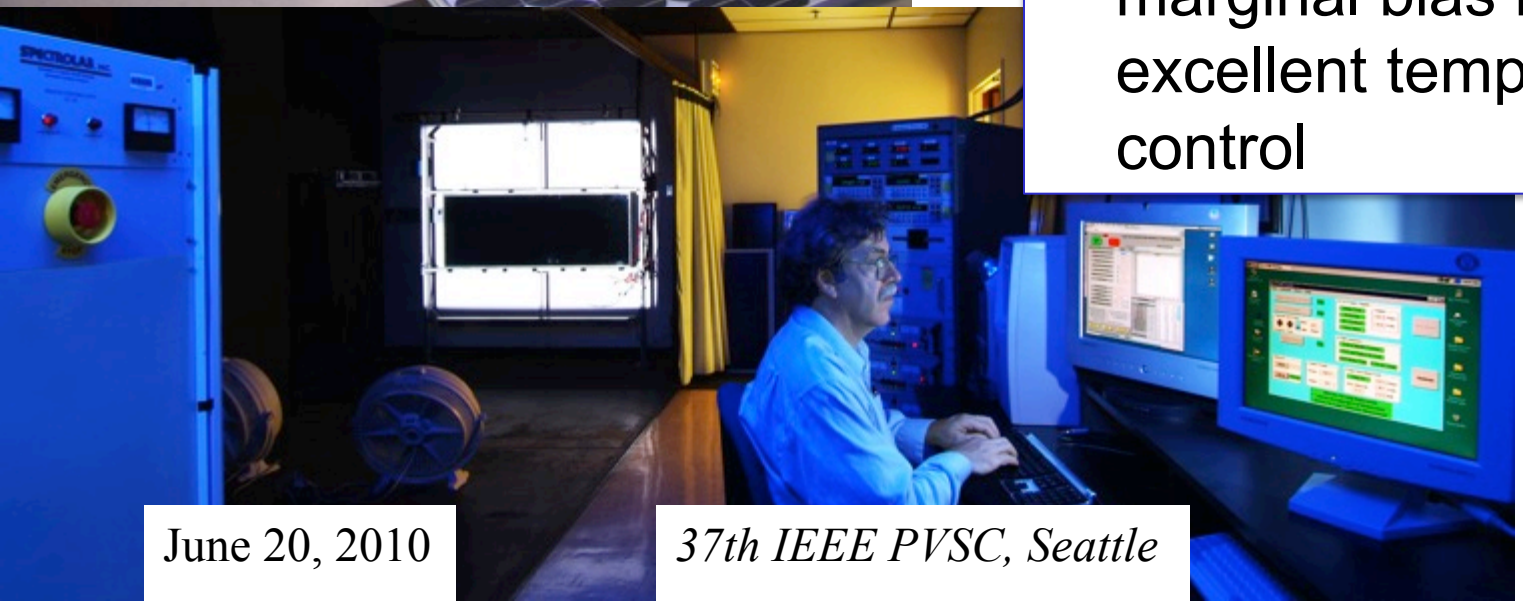
Computer- Labview based all data text files, directory and data file saved to 2 hard drives, common format all test beds, file naming "test bed YYMMDD-HHMMSS"

Module Simulators

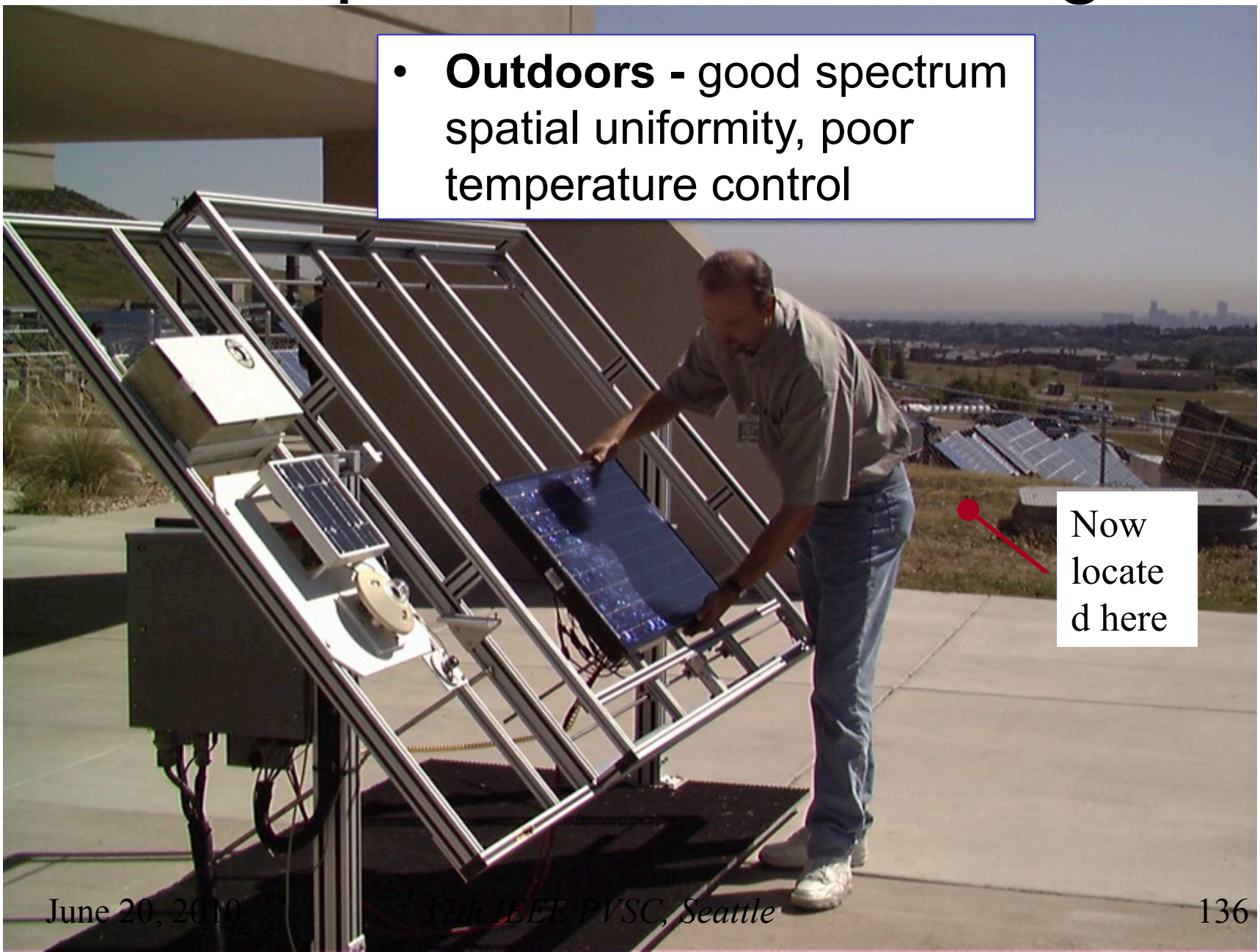


New Spire SLP 4600 pulsed module simulator in recently expanded OTF

- **Continuous Simulator -** light, dark IV, full control of premeasurement conditions and bias rate, poor spatial nonuniformity, good temperature control
- **Pulsed simulator -** good spatial nonuniformity, marginal bias rate control, excellent temperature control



Flat-plate Module testing

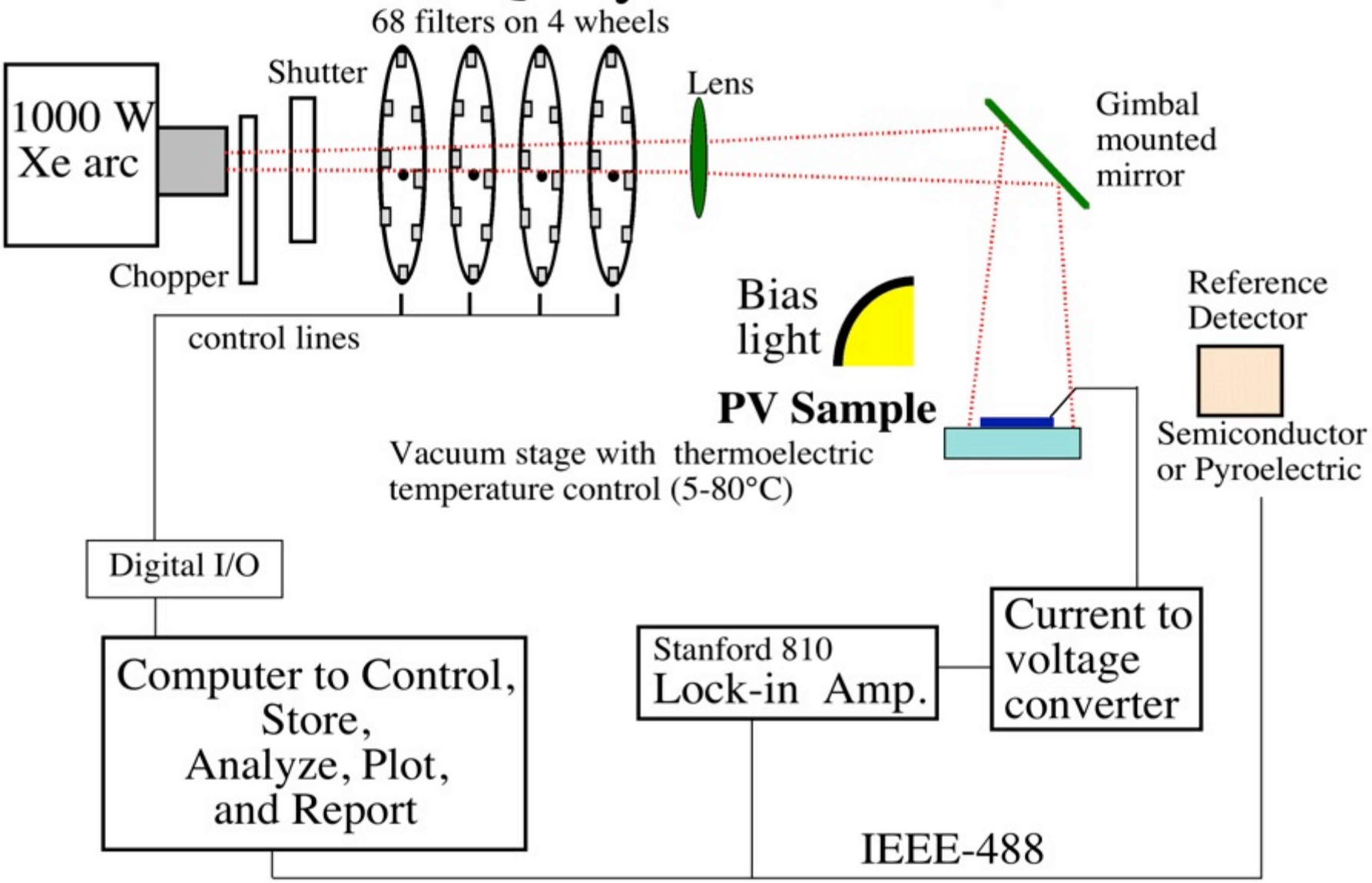


- **Outdoors -** good spectrum spatial uniformity, poor temperature control

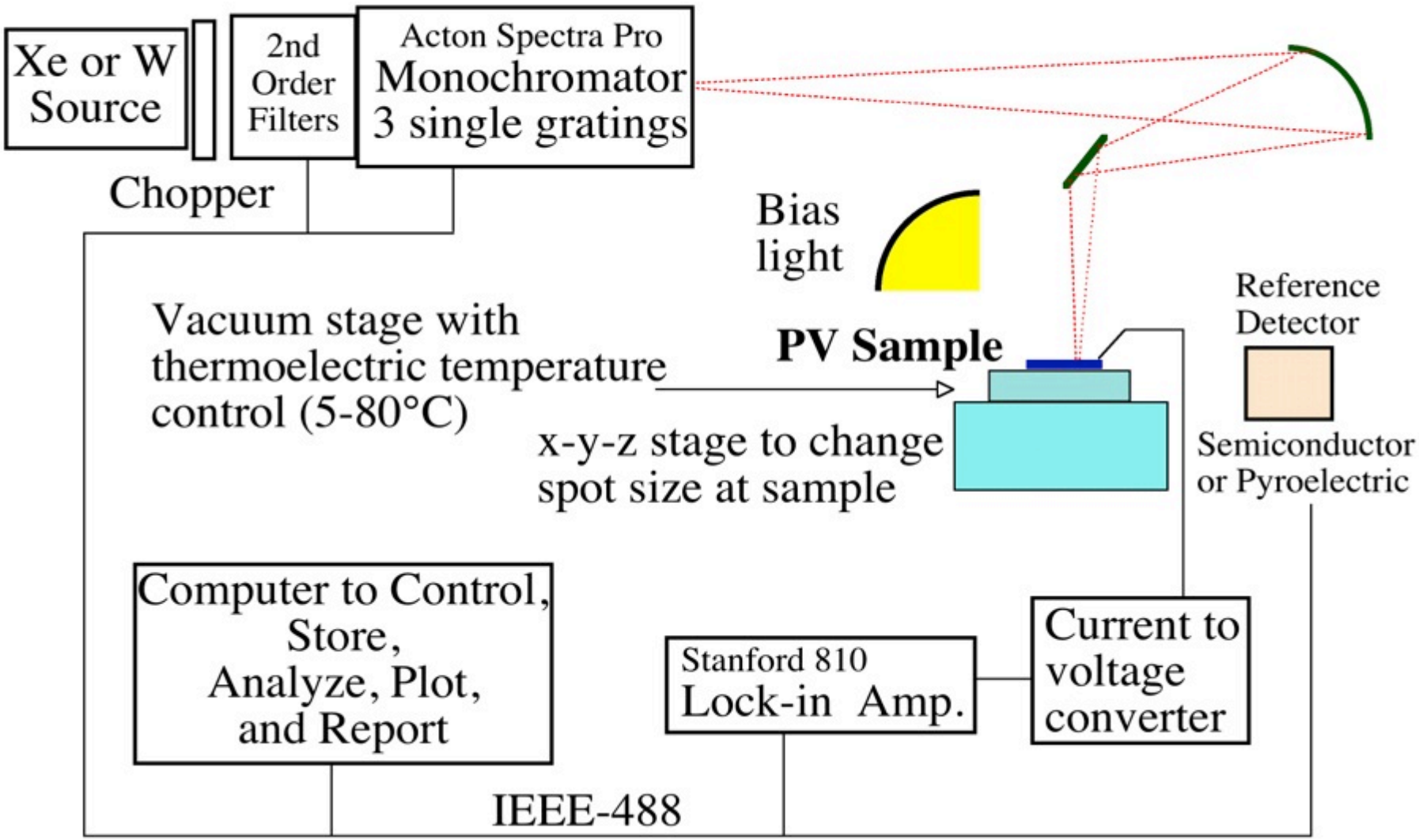
QE Equipment

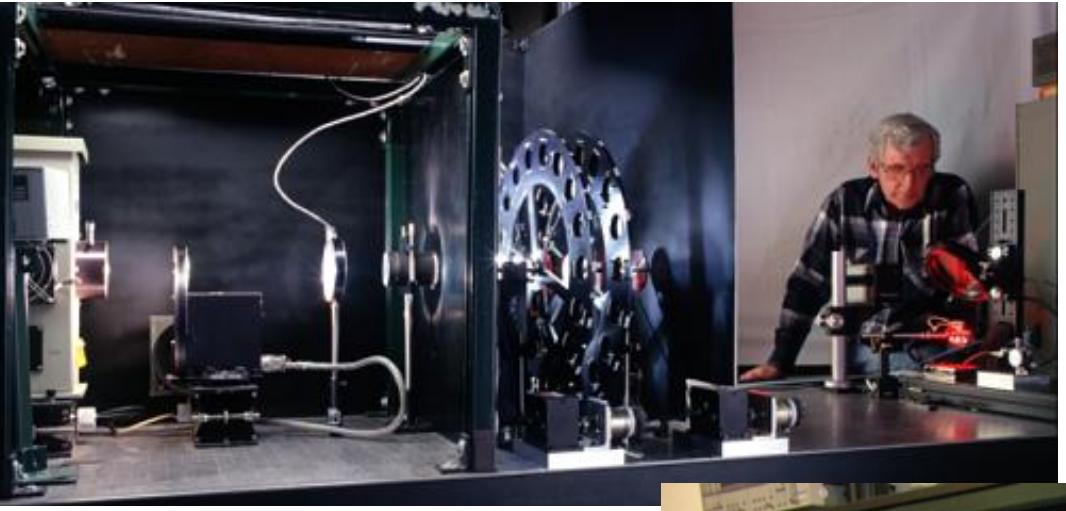
Applications		Light source	Wavelength	Beam
Cells & Modules	1 kW Xe	280-2000 nm 68 - 10 nm bandpass filters	cm to m in diameter	
Cells	75 W Xe	350-3200 nm 3 - gratings	1 by 3 mm minimum	

NREL Filter QE system 280 - 2,000 nm



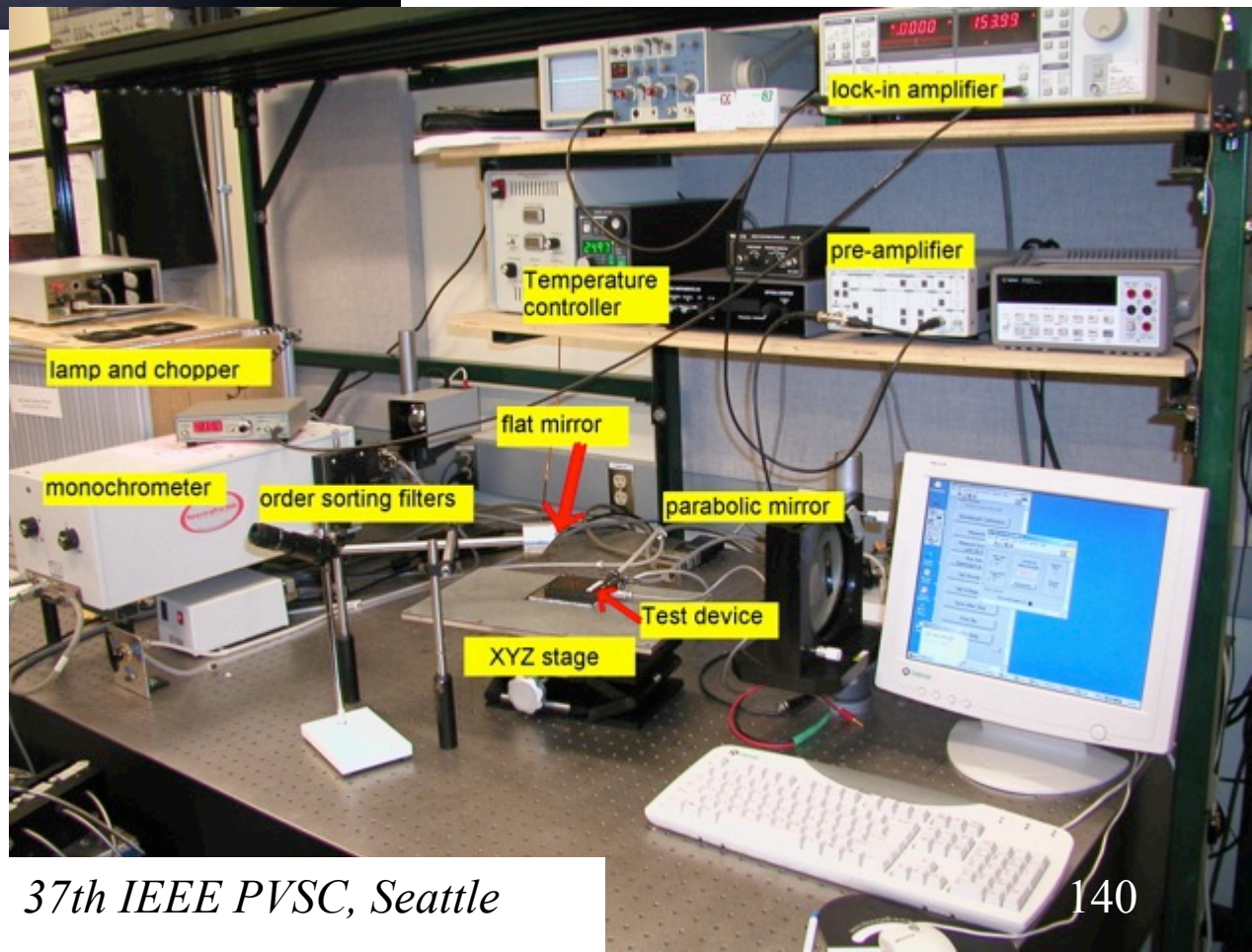
NREL Grating QE system 350 - 2800 nm

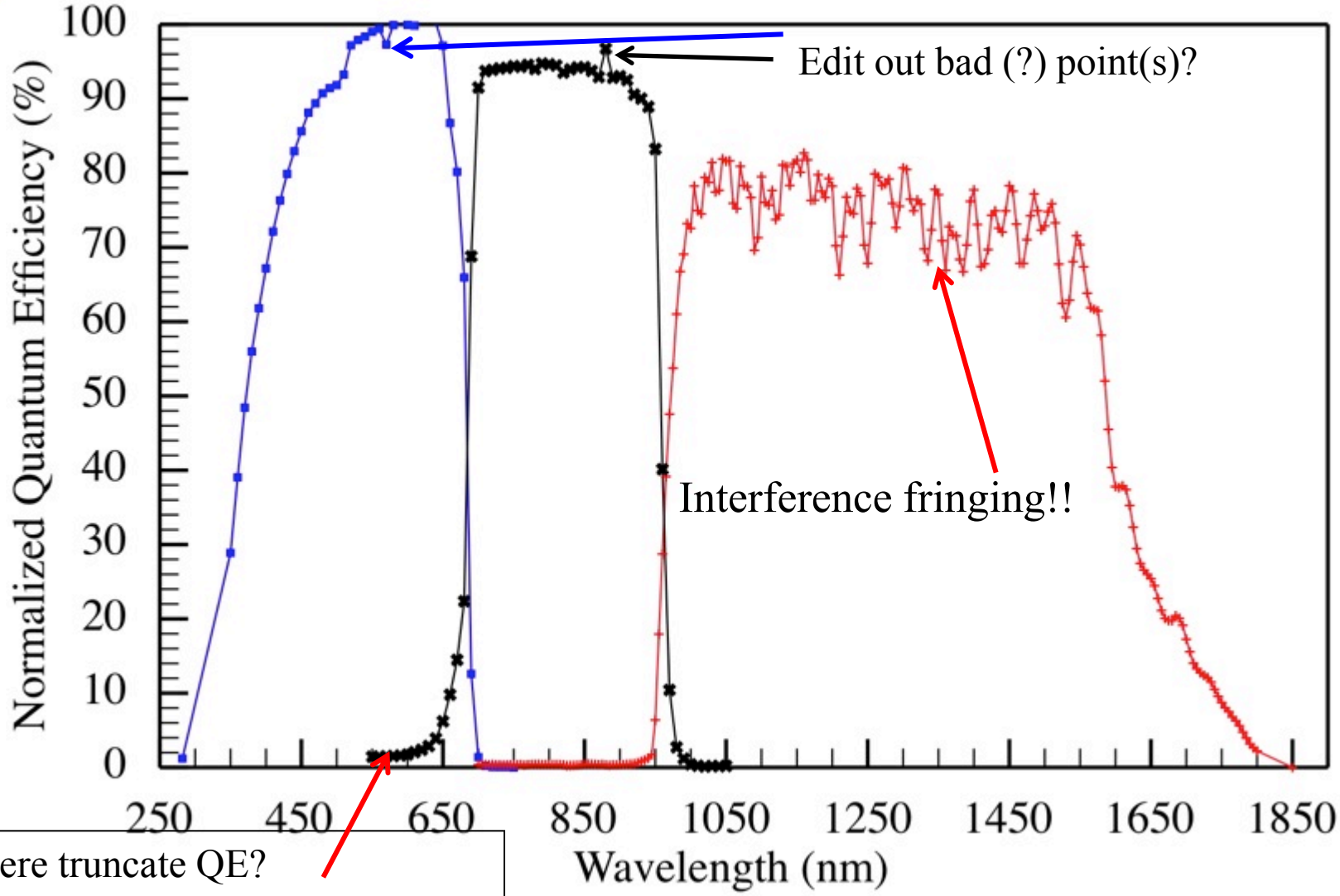




The spectral responsivity is measured with a filter based system (298-1800 nm) or a grating based system 350-3000 nm

NREL QE systems



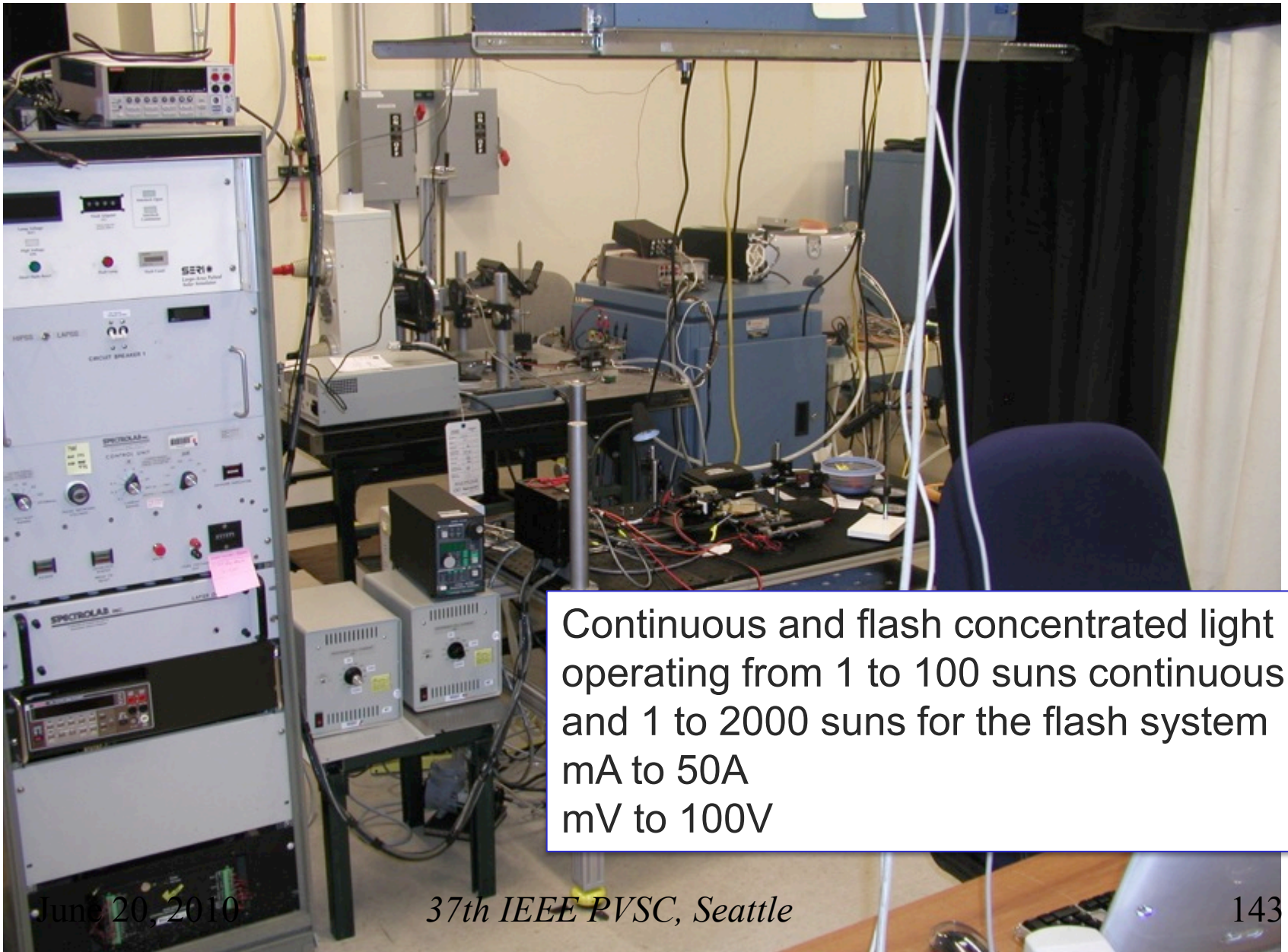


Where truncate QE?
Is this shunt, luminescence, real?

Outline - Performance

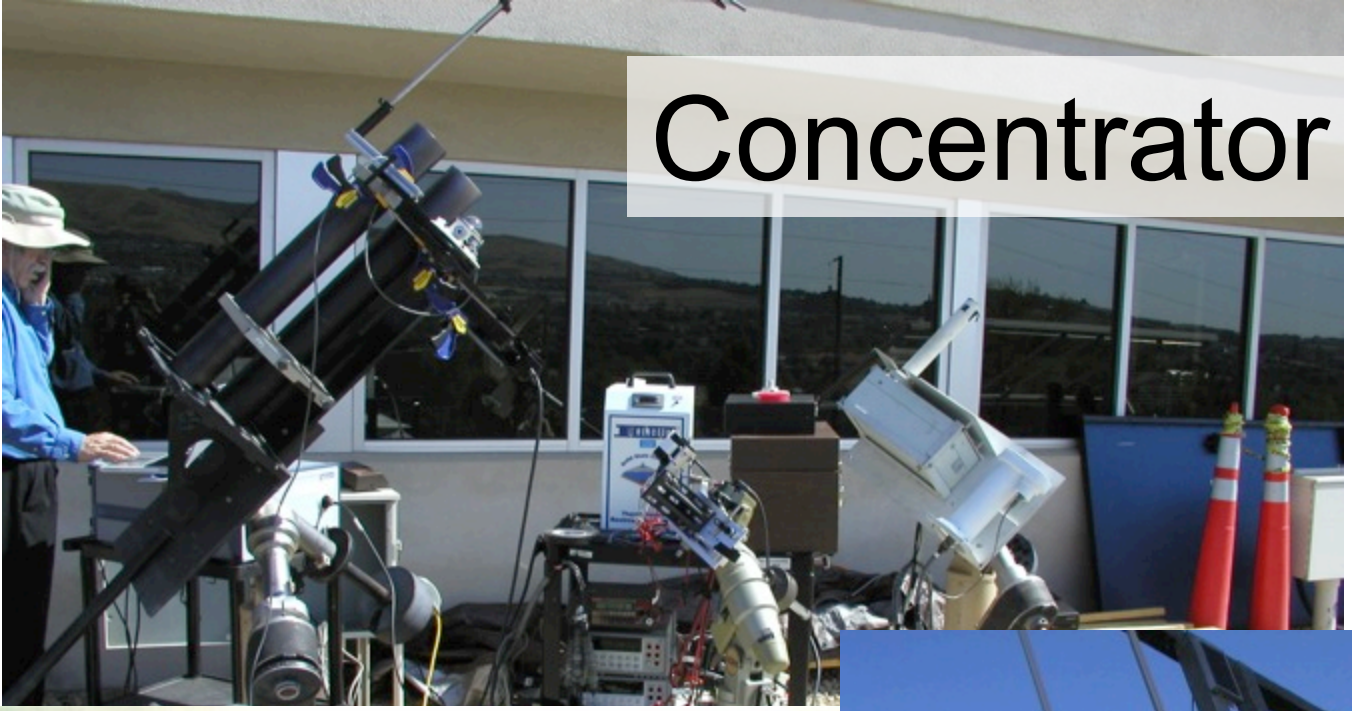
- PV Theory
- PV Technology
- PV Performance
  - Measurement Theory
  - Primary calibration
  - IV systems
  - QE systems
  - Multi-junction issues
  - Artifacts
- PV Reliability
- PV Resource

Concentrator Cells



Continuous and flash concentrated light operating from 1 to 100 suns continuous and 1 to 2000 suns for the flash system
mA to 50A
mV to 100V

Concentrator Modules



PVUSA / ASTM E2527 Regression

$$P_m = a_1 * E + a_2 * E * E + a_3 * E * T_{air} + a_4 * E * v$$

E is total direct or plane of array irradiance

T_{air} is the air temperature near the module or array

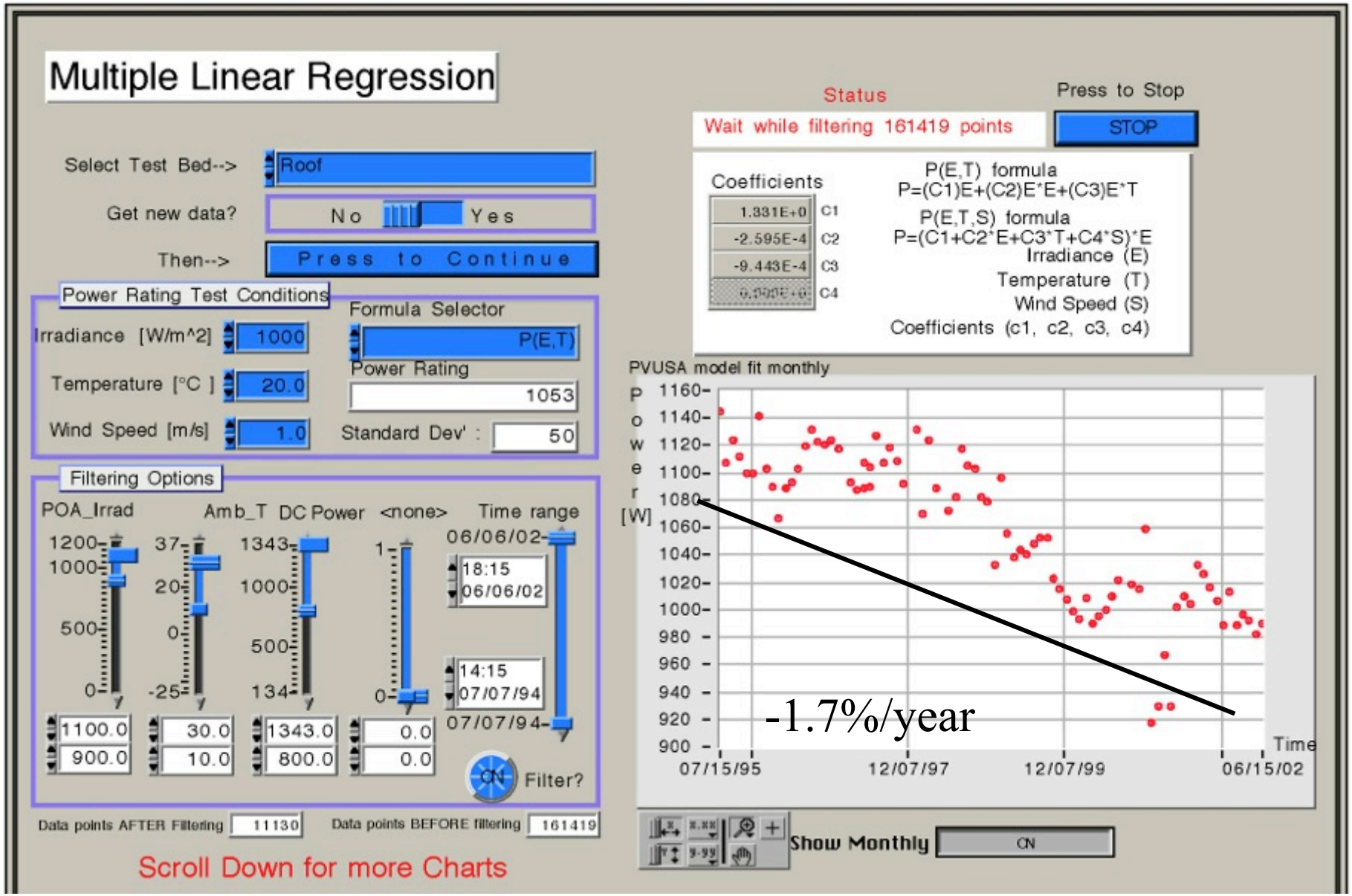
T_{cell} can be used if reliable

v is the wind speed

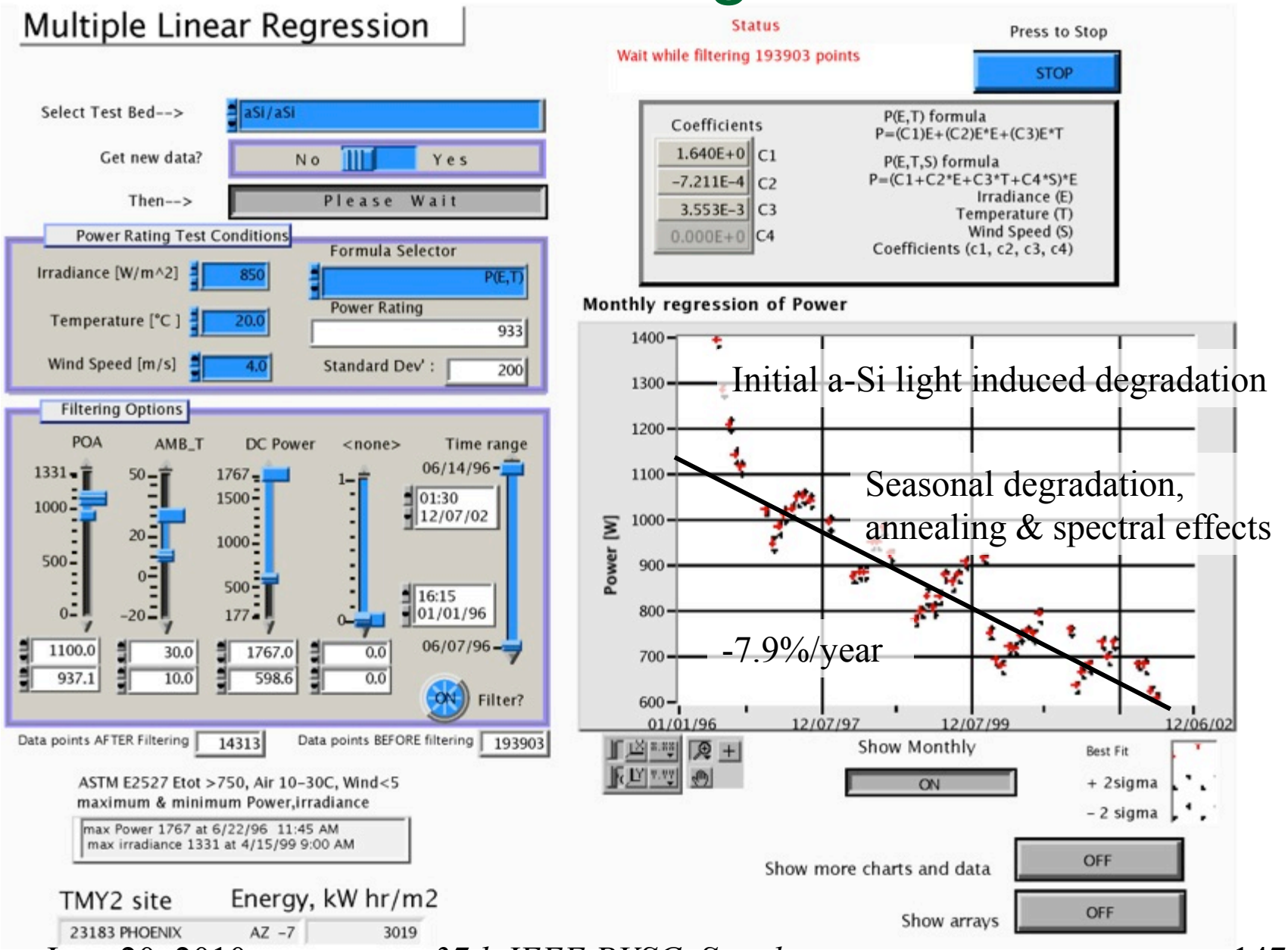
The data is typically reported at 20 ° C air temperature, 1 or 4 m/s wind speed, and

850 Wm^{-2} direct or 1000 Wm^{-2} global irradiance

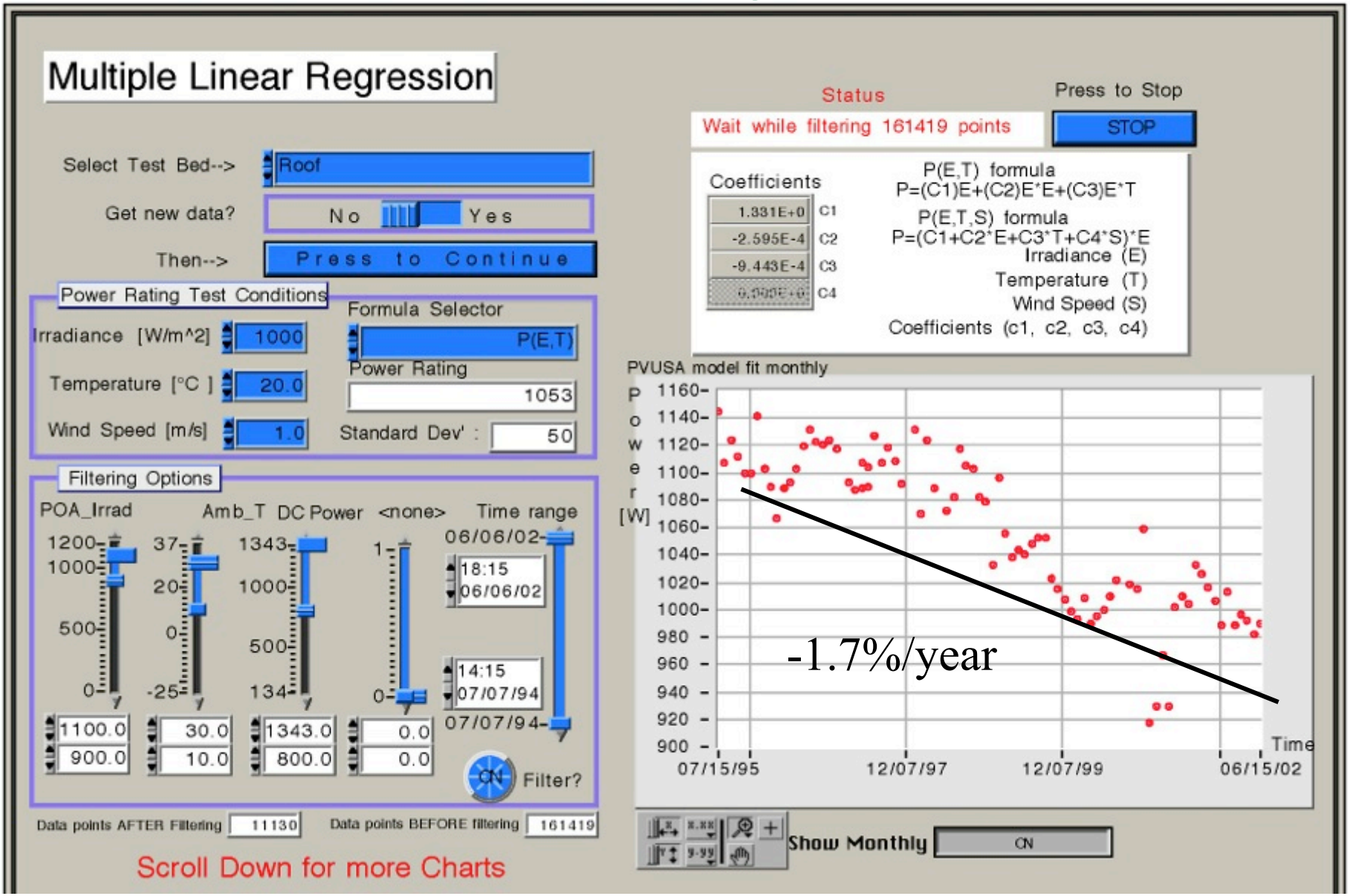
Labview NREL Regression Code



Labview NREL Regression Code



Labview NREL Regression Code

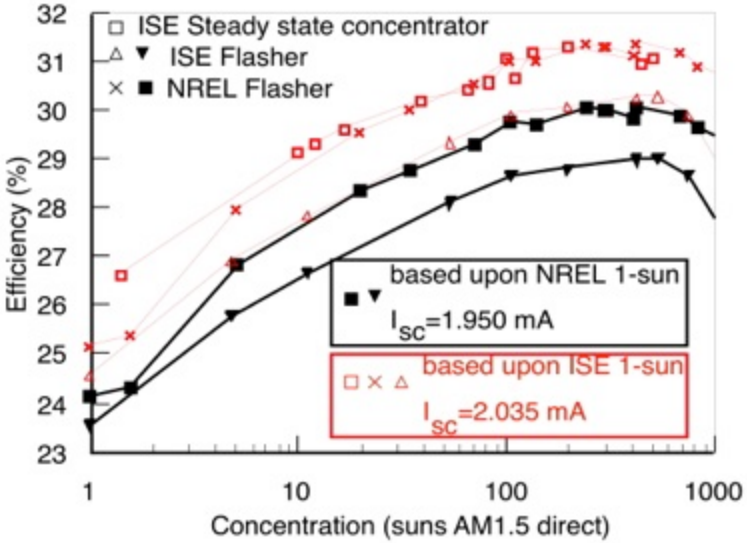


Published Informal Intercomparison

K. Emery, M. Meusel, R. Beckert, F. Dimroth, A. Bett and W. Warta, "Procedures for Evaluating Multijunction Concentrators," *Proc. 28th IEEE PVSC*, Sept. 15-22, 2000, pp. 1126-1130.

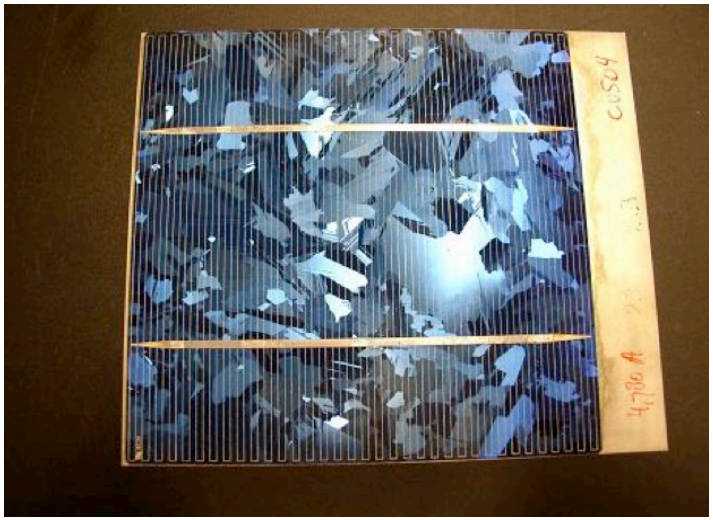
Fraunhofer ISE $Ga_{0.35}In_{0.65}P/Ga_{0.83}In_{0.17}As$

One sun Parameter	NREL	ISE
Isc	1.950 mA	2.035 mA
Voc	1.940 V	1.943 V
Pmax	3.196 mW	3.325 mW
Fill Factor	84.5 %	84.1 %
Efficiency	**22.9 %**	**23.8 %**



Arvid van der Heide, Stefan Winter, Keith Emery, and Wim Zaaiman, "Comparison Between Large Reference Cells Calibrated by ESTI-JRC, NREL and PTB, Performed at ECN", Proc. 20th EU PVSEC, June, 2005.

Cell	Calibrated	Isc,cal	Isc,ECN	ΔI (%)
100-A	ESTI 2002	3.020 ± 1.9%	3.032	+0.4
100-B	ESTI 2002	3.006 ± 1.9%	3.019	+0.4
100-B	NREL 2003	3.023 ± 2.0%	3.019	-0.1
125-A	ESTI 2002	4.780 ± 1.9%	4.816	+0.8
125-B	ESTI 2002	4.731 ± 2.0%	4.716	-0.3
125-C	NREL 2004	5.311 ± 2.0%	5.311	---
125-D	NREL 2004	5.380 ± 2.0%	5.393	+0.2
125-E	PTB 2004	4.752 ± 2.9%	4.724	-0.6
150-A	ESTI 2002	6.858 ± 1.9%	6.808	-0.7
150-B	PTB 2004	7.247 ± 2.8%	7.122	-2.2



Unpublished Informal Intercomparison

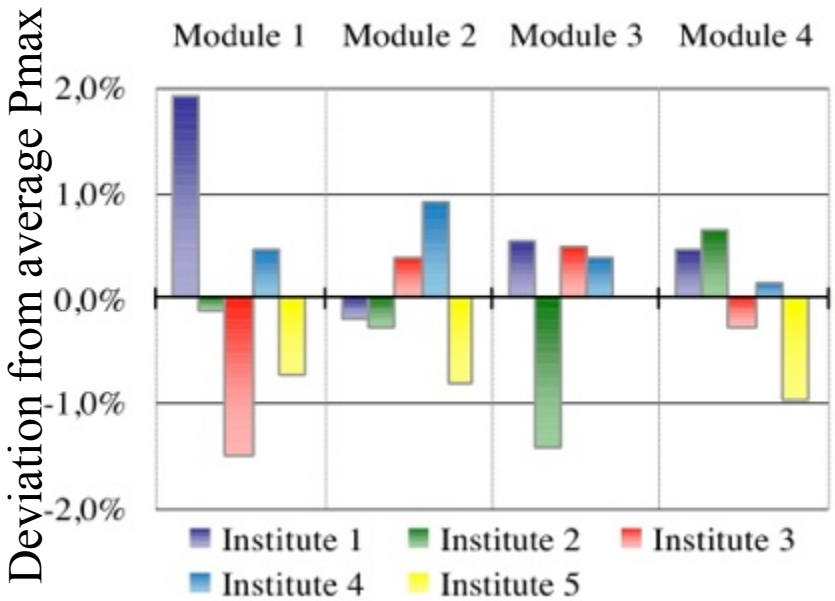
In 2008 Calisolar hosted an intercomparison with Fraunhofer ISE and NREL

Percentage difference between NREL and ISE. Positive numbers indicate NREL lower than ISE.

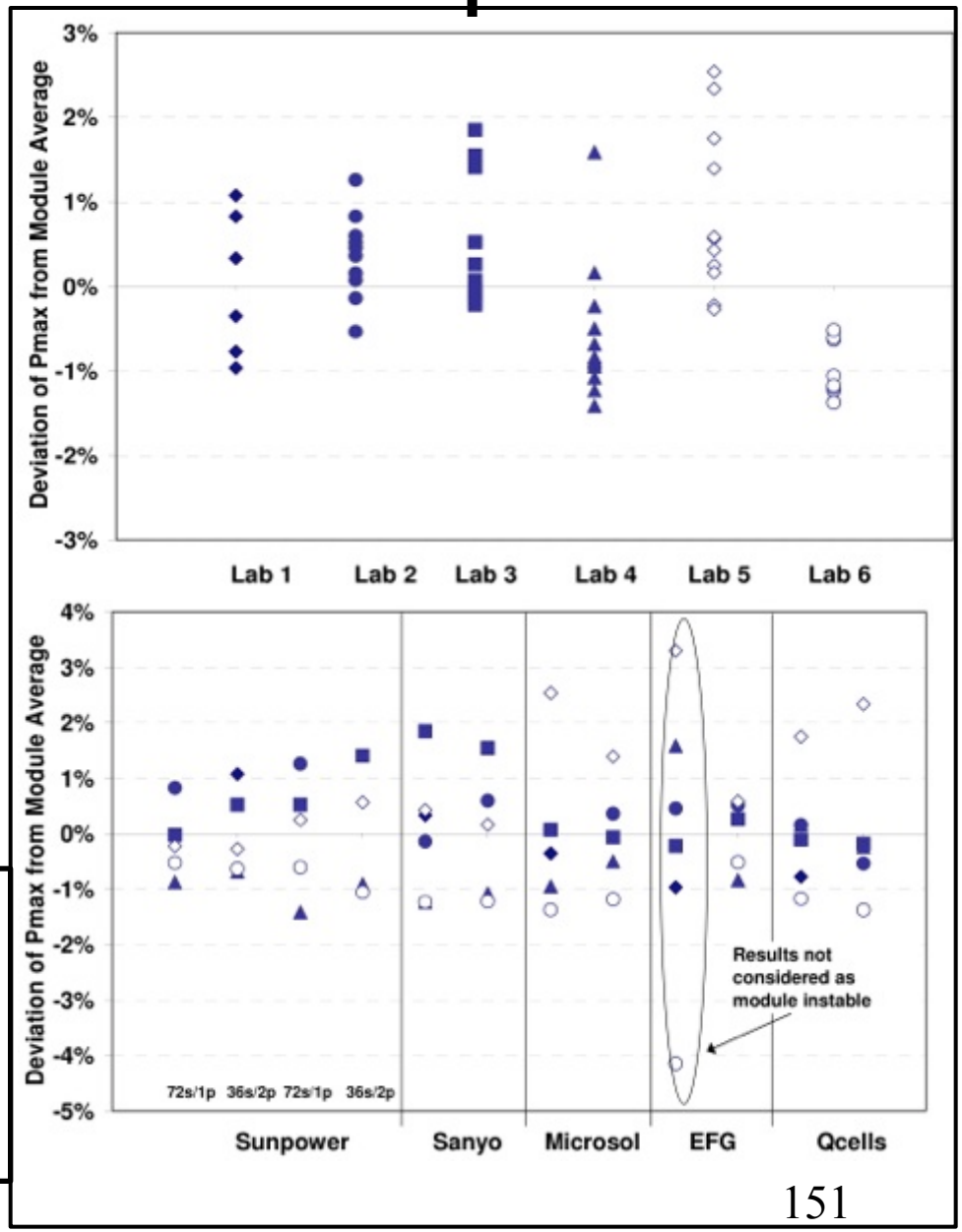
ID	area	Isc	Voc	FF	Pmax	Efficiency
BER6	0.0	1.1	-0.1	1.4	2.3	2.4
BER7	0.1	1.9	-0.2	0.4	2.1	2.1
BER3	-0.1	1.1	-0.4	1.0	1.7	1.9
BER2	0.0	1.7	-0.3	0.8	2.3	2.2
BER1	0.0	2.0	-0.1	0.8	2.6	2.6
BER4	0.0	1.2	-0.2	0.4	1.4	1.4
BER9	-0.1	1.9	-0.1	1.1	2.9	2.9
BER5	0.0	1.6	0.0	1.1	2.7	2.7

2006 EU Module Intercomparisons

K. Keifer, et al, proc. 21st EU PVSEC, 2006, p. 2493.
Fraunhofer ISE, ESTI, TÜV Rheinland, NREL, TISO



W. Herman, et al, proc. 22nd EU PVSEC, 2007, p.2506
Arsenal research, Vienna (Austria)
Ciemat, Madrid (Spain)
EC DG Joint Research Centre, Ispra (Italy)
Fraunhofer-ISE, Freiburg (Germany)
SUPSI, Lugano (Switzerland)
TÜV Rheinland, Cologne (Germany)



www.nrel.gov

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.