National Center for Photovoltaics

NREL

Cell and Module Level Testing Procedures and Intercomparisons

Keith Emery
ph: (303) 880-2913
email: keith.emery@nrel.gov

International Photovoltaic Reliability Workshop (IPRW) II Removing Barriers to Photovoltaic Technology Adoption: Reliability, Codes/Standards, and Market Acceptance, *July 29-31, 2009, Scottsdale, AZ*

PV Cell and Module Performance Characterization

- Supported by DOE EERE SETP
- Active since 1980
- ISO 17025 accredited
- Traceability path for PV watt rating
- 6174 measurements on 1898 cells and modules for 249 groups in FY08

ACCREDITED

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

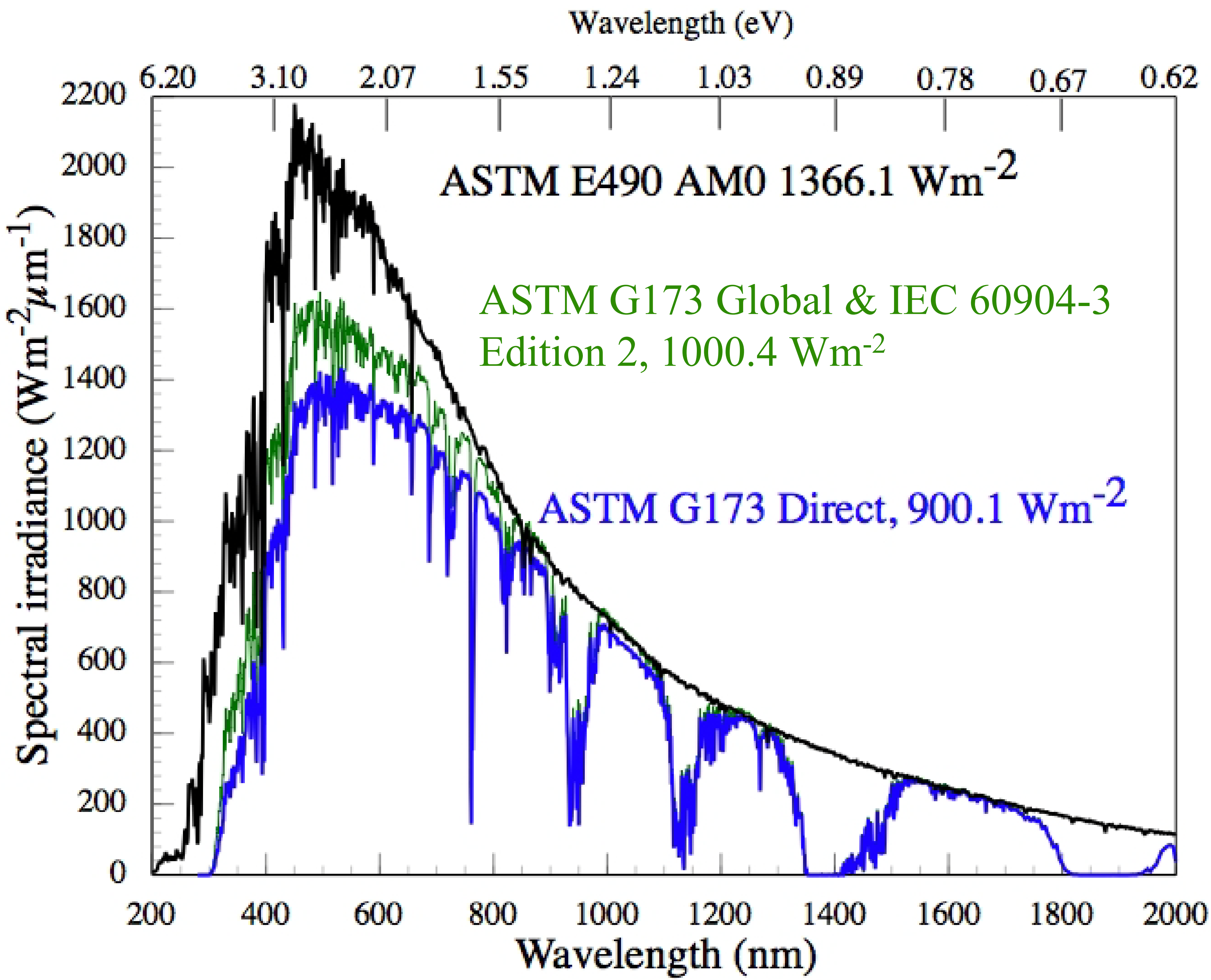
*NRE

Outline

- Reference Conditions
- PV IV theory
- NREL's IV, QE Equipment
- Cell Intercomparisons
- Module Intercomparison
- Artifacts

Standard Reference (Test) Conditions

- Continuous Illumination,
- 25 °C Junction Temperature,
- 1000 W/m^2 Total Irradiance =1-sun,
- ASTM G173 Reference Spectrum
  - Global for flat plate
  - Direct for concentrators
  - Less than 5 suns Global ?
- Area definition for efficiency



Wavelength (eV)
6.20
3.10
2.07
1.55
1.24
1.03
0.89
0.78
0.67
0.62
ASTM E490 AM0 1366.1 Wm-2
ASTM G173 Global & IEC 60904-3
Edition 2, 1000.4 Wm-2
ASTM G173 Direct, 900.1 Wm-2
Spectral irradiance (Wm-2μm-1)
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Wavelength (nm)

Alternative Rating Conditions

- ASTM E2527, PVUSA regression analysis to project test conditions defined by 1000 Wm^{-2} Global or 850 Wm^{-2} direct beam irradiance, 1 or 4 ms^{-1} wind speed, and 20 °C air temperature valid for small modules to large systems ac or dc rating
- Energy based ratings
  - SAM – Typical Meteorological year (Phoenix)
  - IEC 61853 - Typical day
  - Utility kWh / kW where the kW rating is the initial system rating and variable period for kWh

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Reference Cell Method measures with respect to standard reporting test conditions.

$$I^{\text{Test,Ref}} = \frac{I^{\text{Test,Source}} I^{\text{Ref,Ref}}}{I^{\text{Ref,Source}} M}$$

$$M = \frac{\int_{\lambda_1}^{\lambda_2} E_{\text{Ref}}(\lambda) S_{\text{Ref}}(\lambda) \mathrm{d}\lambda}{\int_{\lambda_1}^{\lambda_2} E_{\text{Ref}}(\lambda) S_{\text{Test}}(\lambda) \mathrm{d}\lambda} \frac{\int_{\lambda_1}^{\lambda_2} E_{\text{Source}}(\lambda) S_{\text{Test}}(\lambda) \mathrm{d}\lambda}{\int_{\lambda_1}^{\lambda_2} E_{\text{Source}}(\lambda) S_{\text{Ref}}(\lambda) \mathrm{d}\lambda}$$

IV Procedures

- ASTM Standards
  E948 cells, E1036 modules,
  E2236 Multijunction cells and modules,
  E2527 Concentrator modules & systems
- IEC Standards
  60904-3 IV
  61853-1 thru 4 Energy rating under development
  Draft standard for concentrator rating under development
- Accepted nonstandard procedures
  Sandia / King method
  Performance ratio - kWhr produced / kW peak
  over some time period

Certified Calibration Labs

- ISO 17025 accredited and WPVS Recognized Primary Cell calibration Facility (NREL, PTB in Germany, ESTI JRC in Ispra, AIST in Japan)
- NREL and Fraunhofer ISE are the only available ISO 17025 certified lab in the world with proven proficiency for any PV cell design or technology.
- VLSI standards and Newport Oriel certified for packaged secondary reference cell calibrations
- UL, ASU PTL, and FSEC are ISO 17025 certified for module calibrations as part of their module qualification accreditation

Team's ISO 17025 Accredited IV Procedure

- Approve for Calibration
- 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 normally apply temperature corrections)
- Calculate the efficiency using the total or aperture area.

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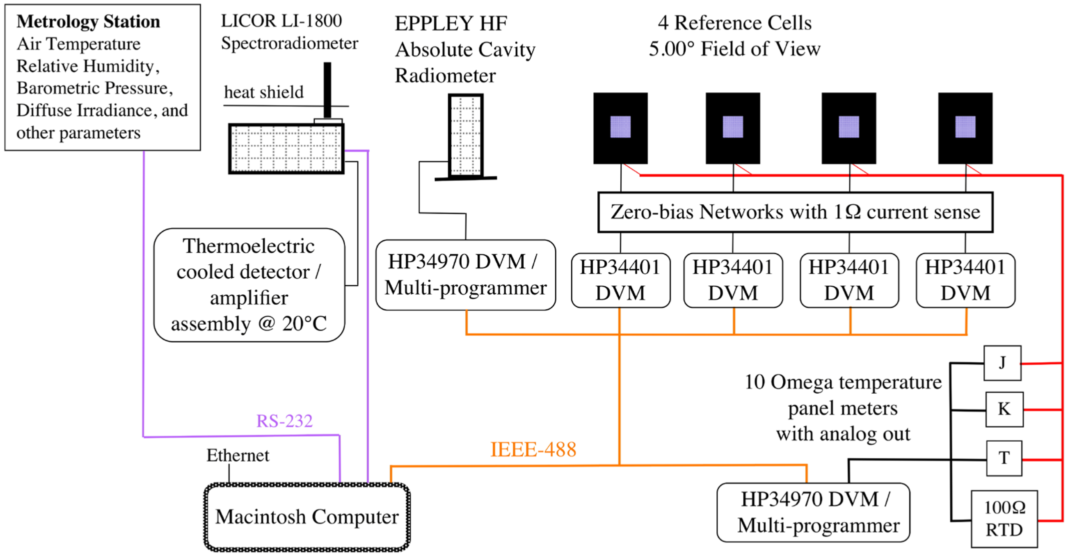
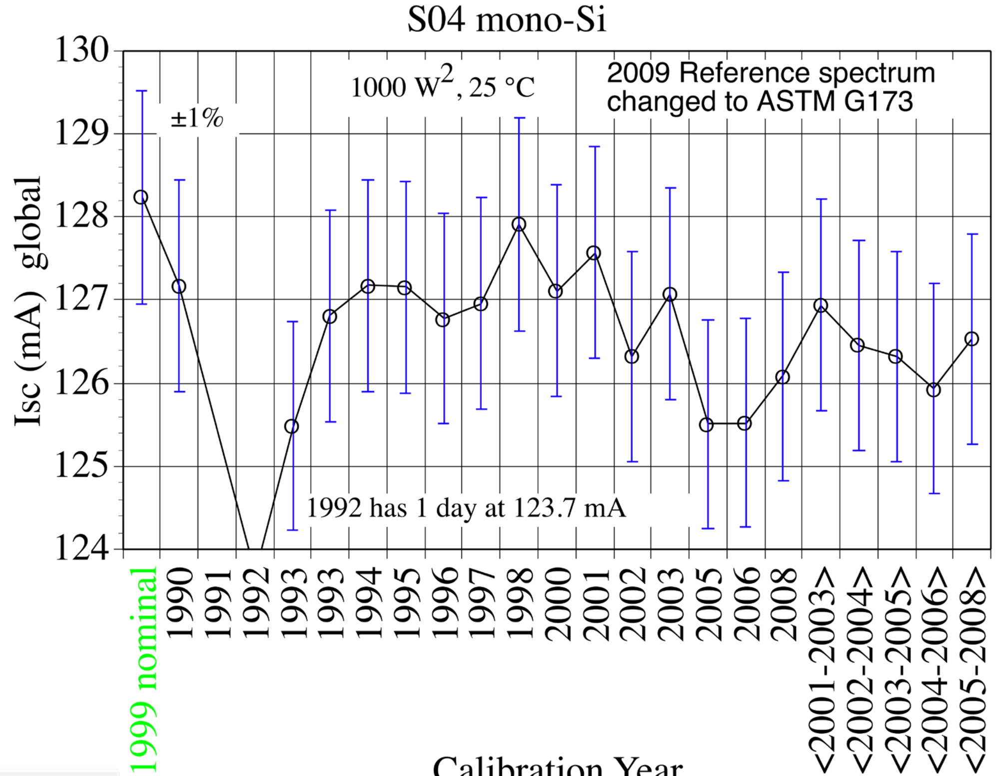
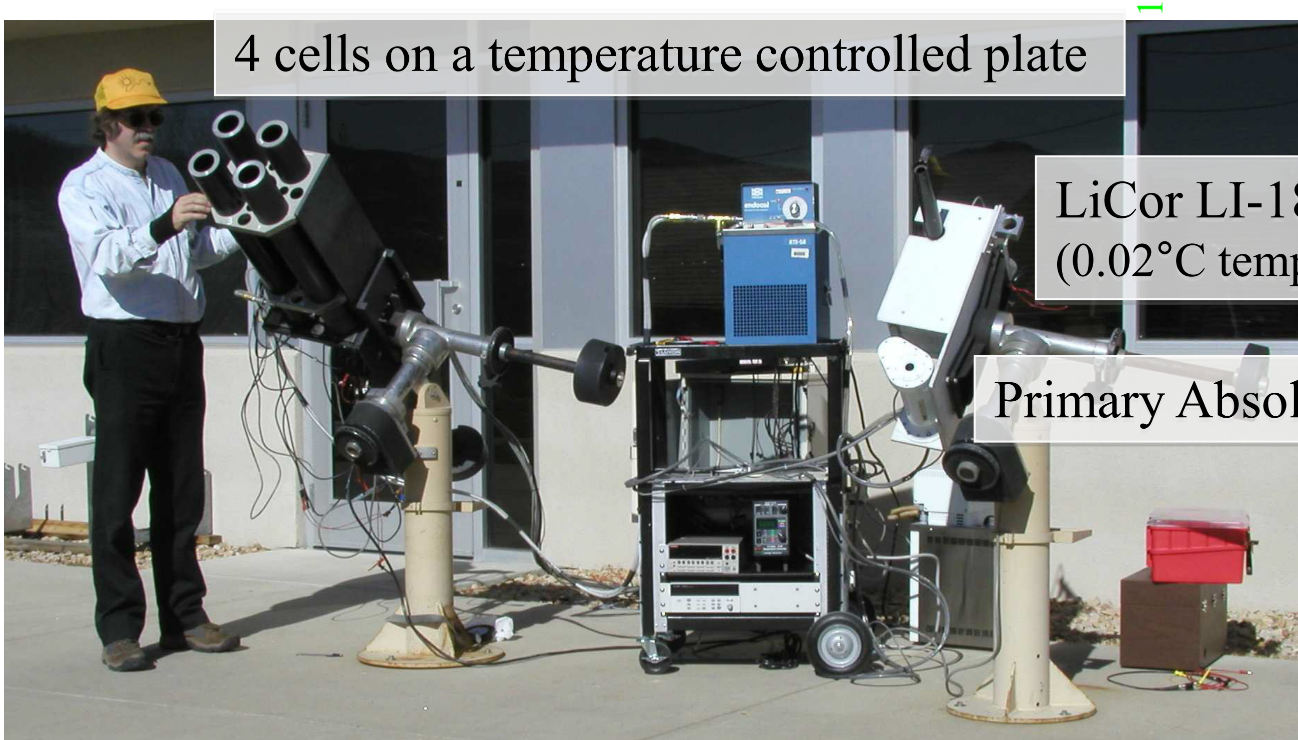
Mission

- Performance measurements for any conceivable PV cell or modules technology of any size or shape
- Primary terrestrial reference cell calibrations for internal use
- 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. Our ISO 17025 quality system applies to all hardware, software, and measurements by team.

NREL Primary PV Calibration





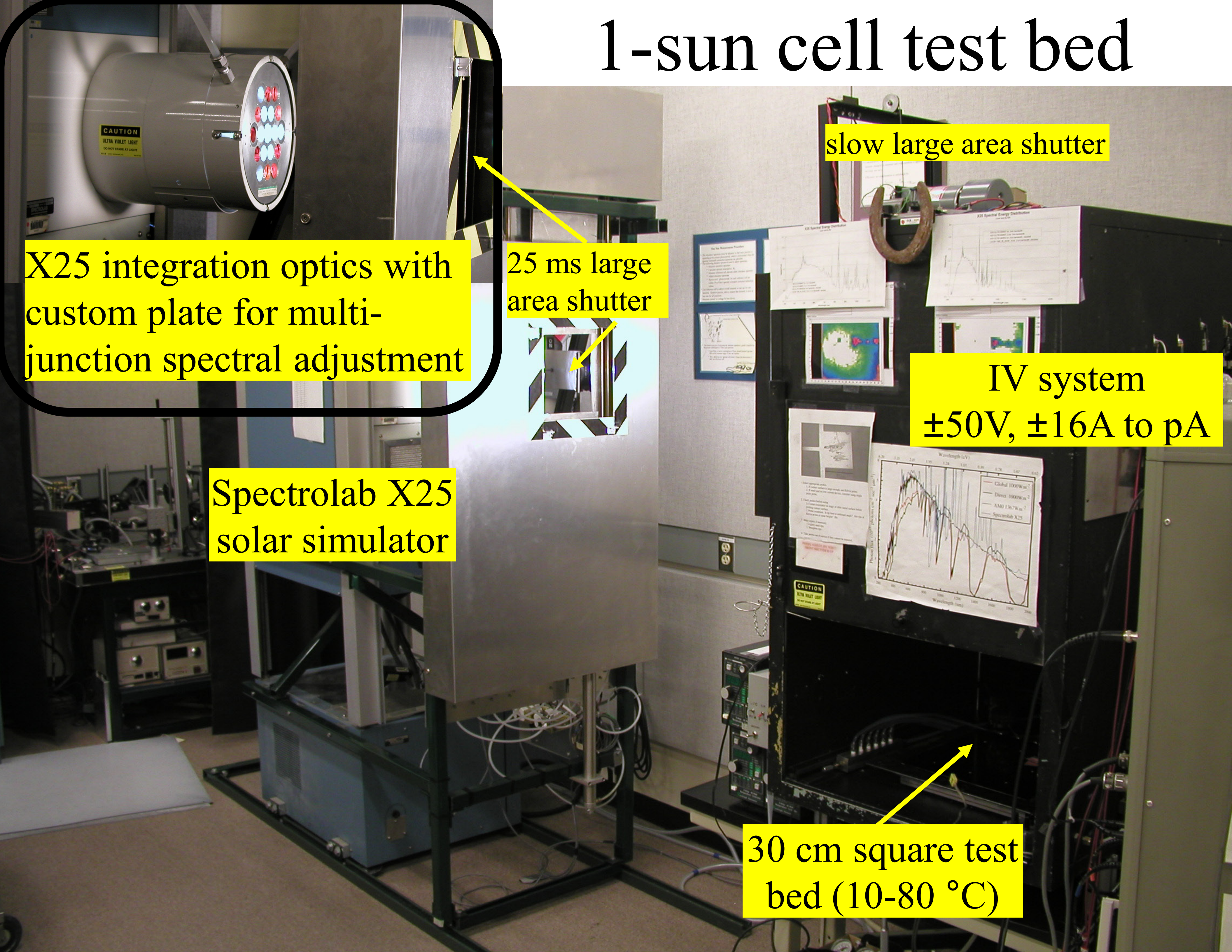


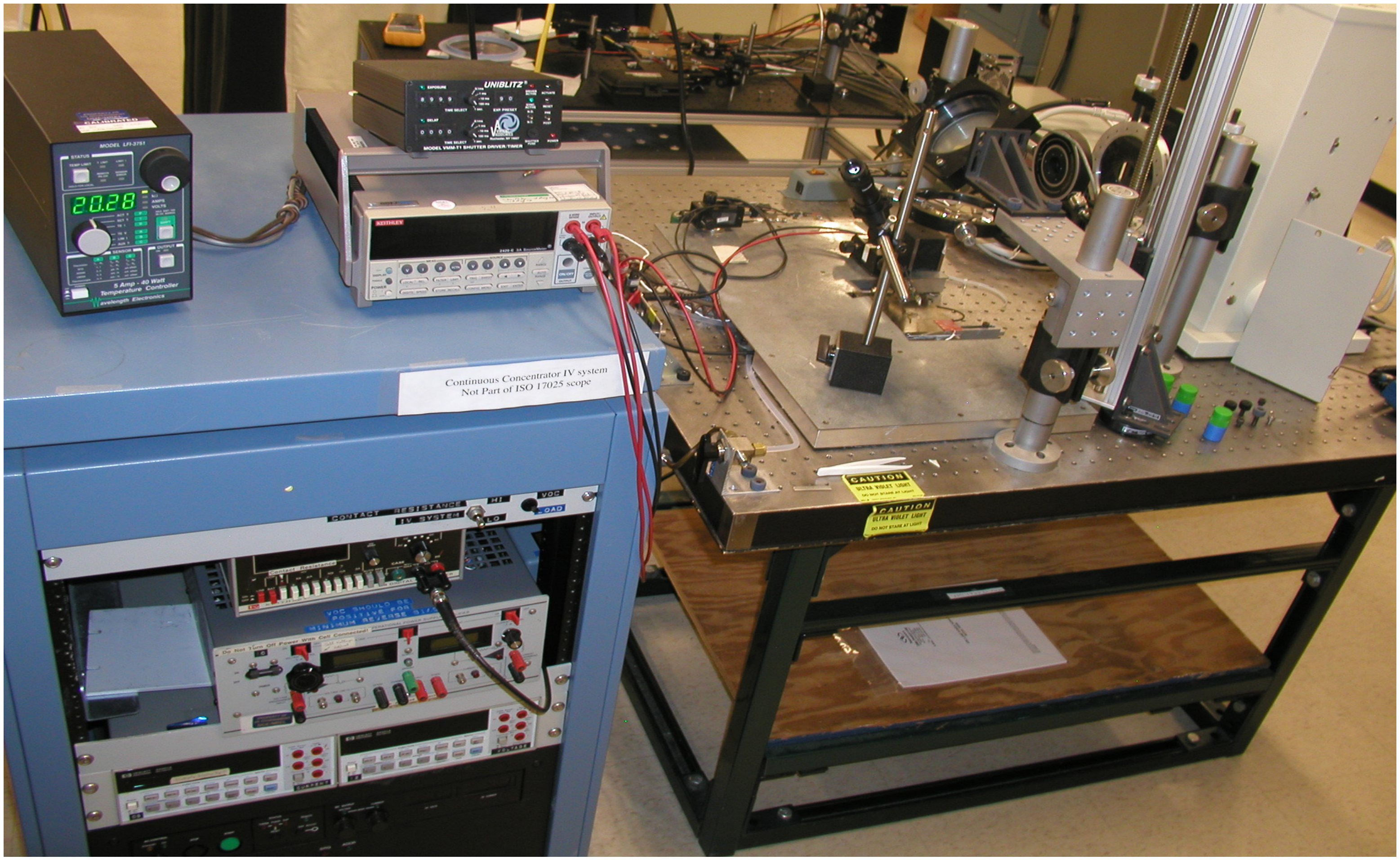
Cell I-V Equipment

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	~ 1cm 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

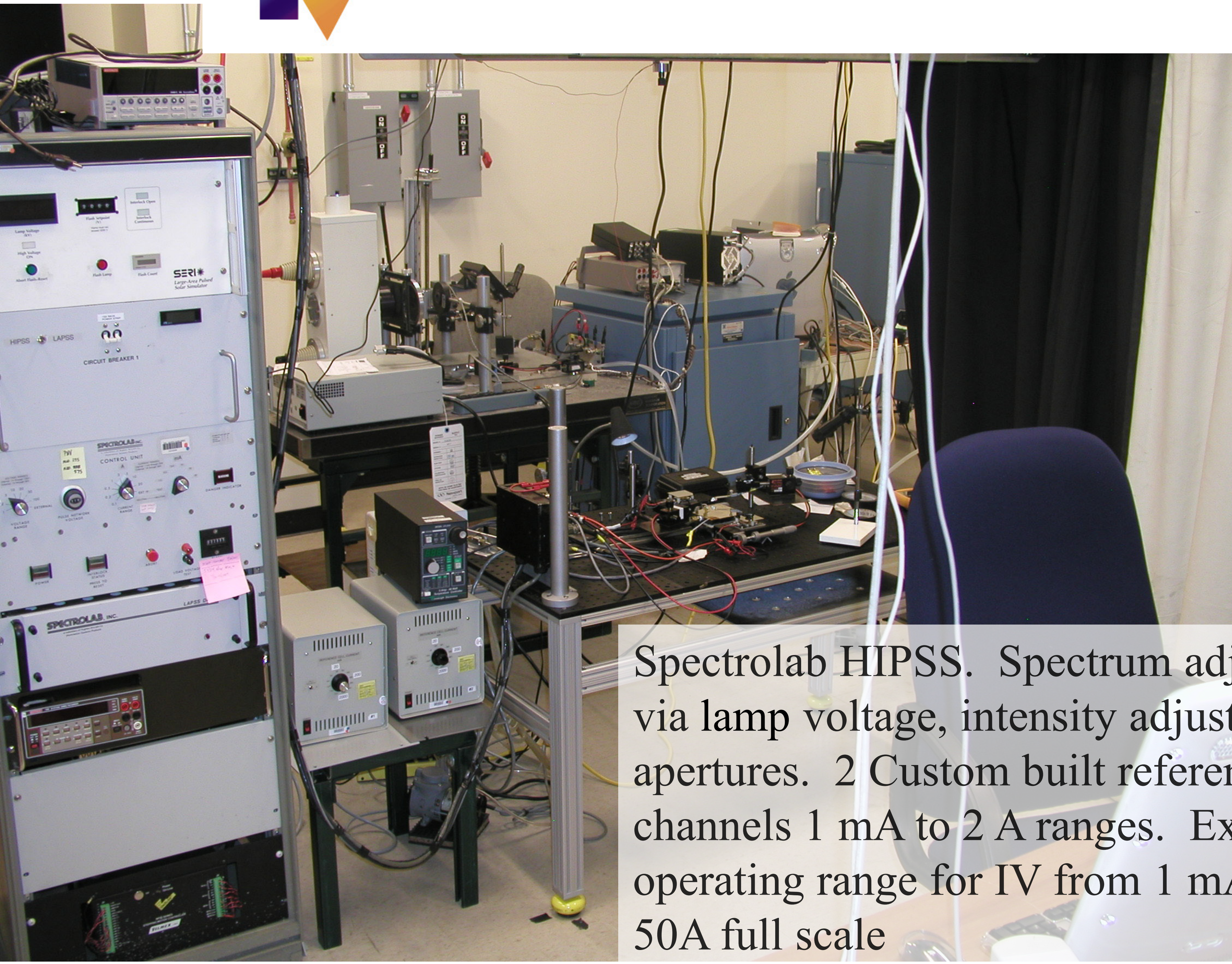
- Multi-source spectrally adjustable 0.1 to 1-sun operational by years end. Unit delivered this week
- Spectrally adjustable concentrator Spectrolab THIPSS ship by years end.

1-sun cell test bed



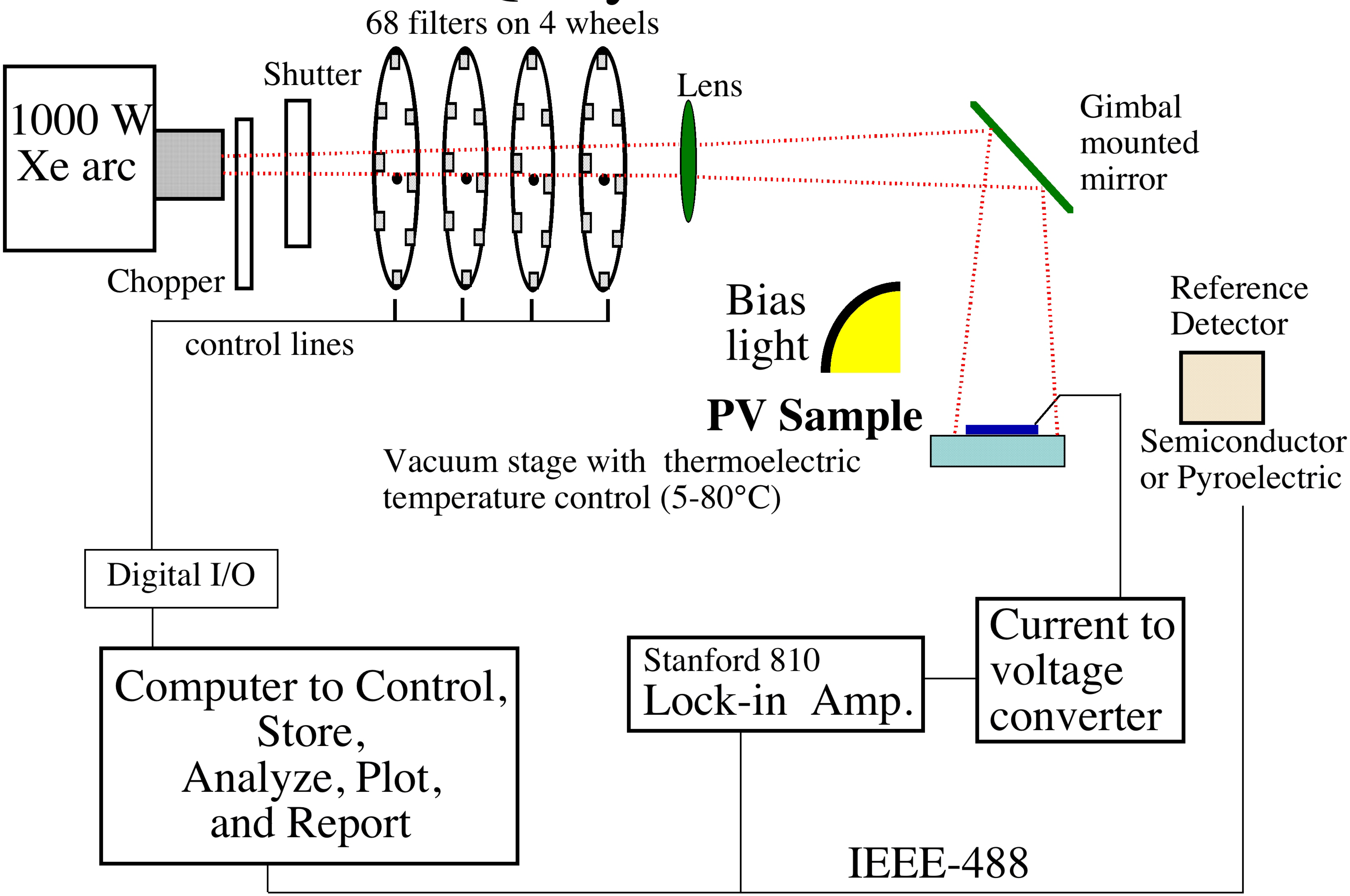


1 to 100 suns continuous concentrator used for samples that are sensitive to bias rate like CIGS concentrators and other test where continues concentrated light is desired

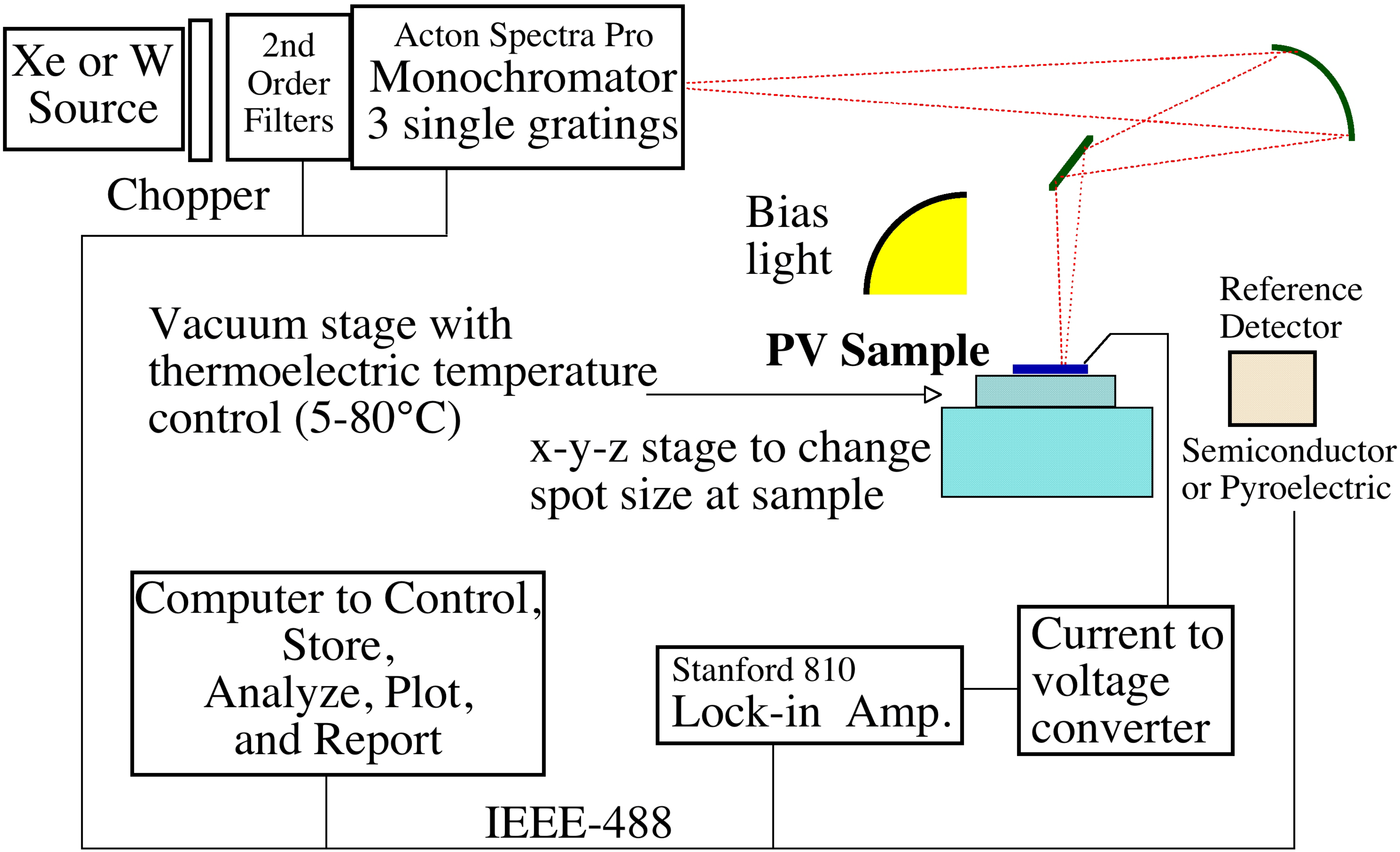


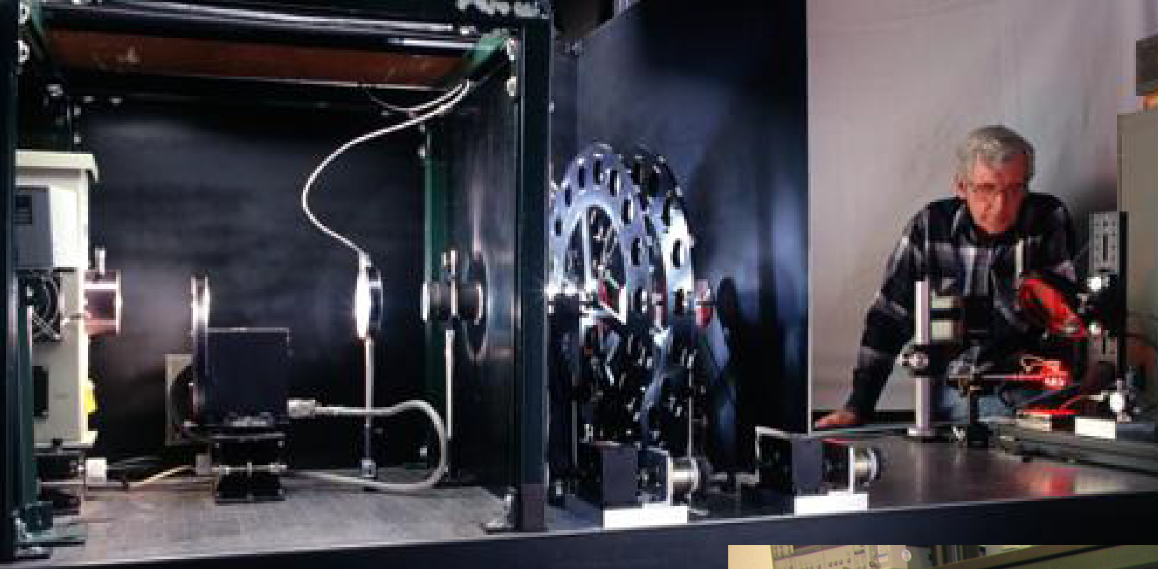
Spectrolab HIPSS. Spectrum adjusted via lamp voltage, intensity adjusted via apertures. 2 Custom built reference cell channels 1 mA to 2 A ranges. Extended operating range for IV from 1 mA to 50A full scale

NREL Filter QE system 280 - 2,000 nm

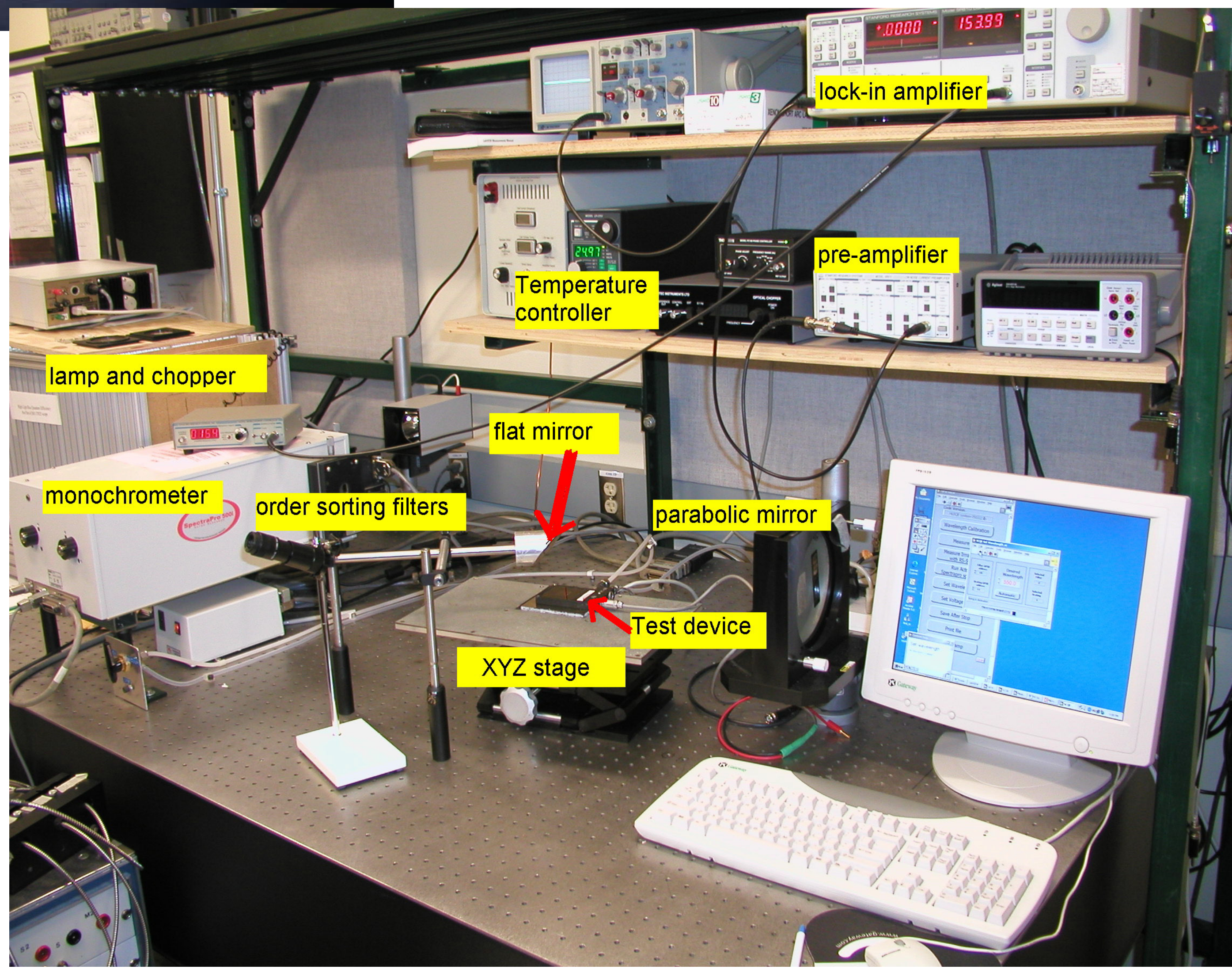


NREL Grating QE system 350 - 2800 nm





The spectral responsivity is measured with a filter based system (298-1800 nm) or a grating based system 350-2800 nm



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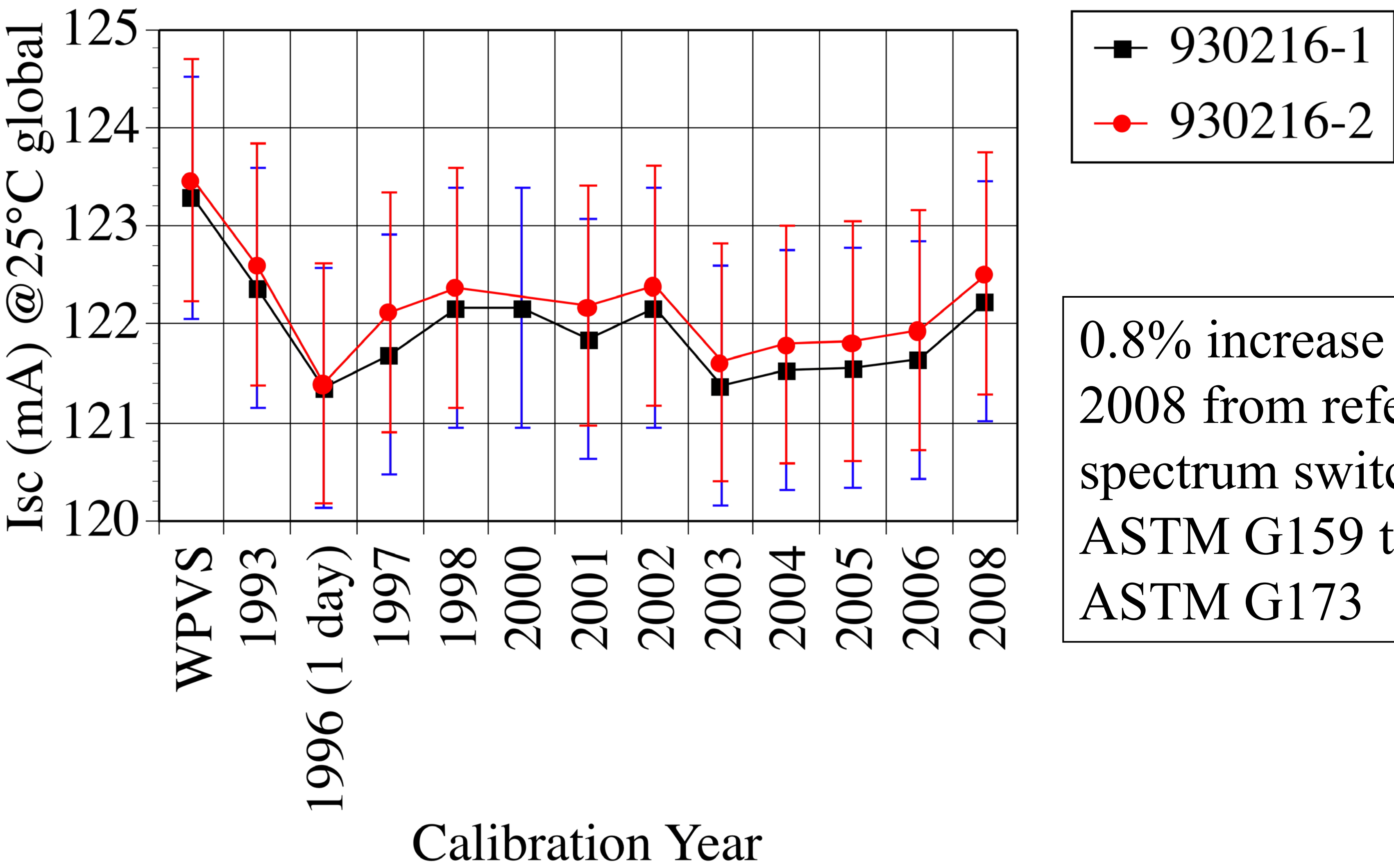
How do my Calibrations drift from Year to Year ?

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

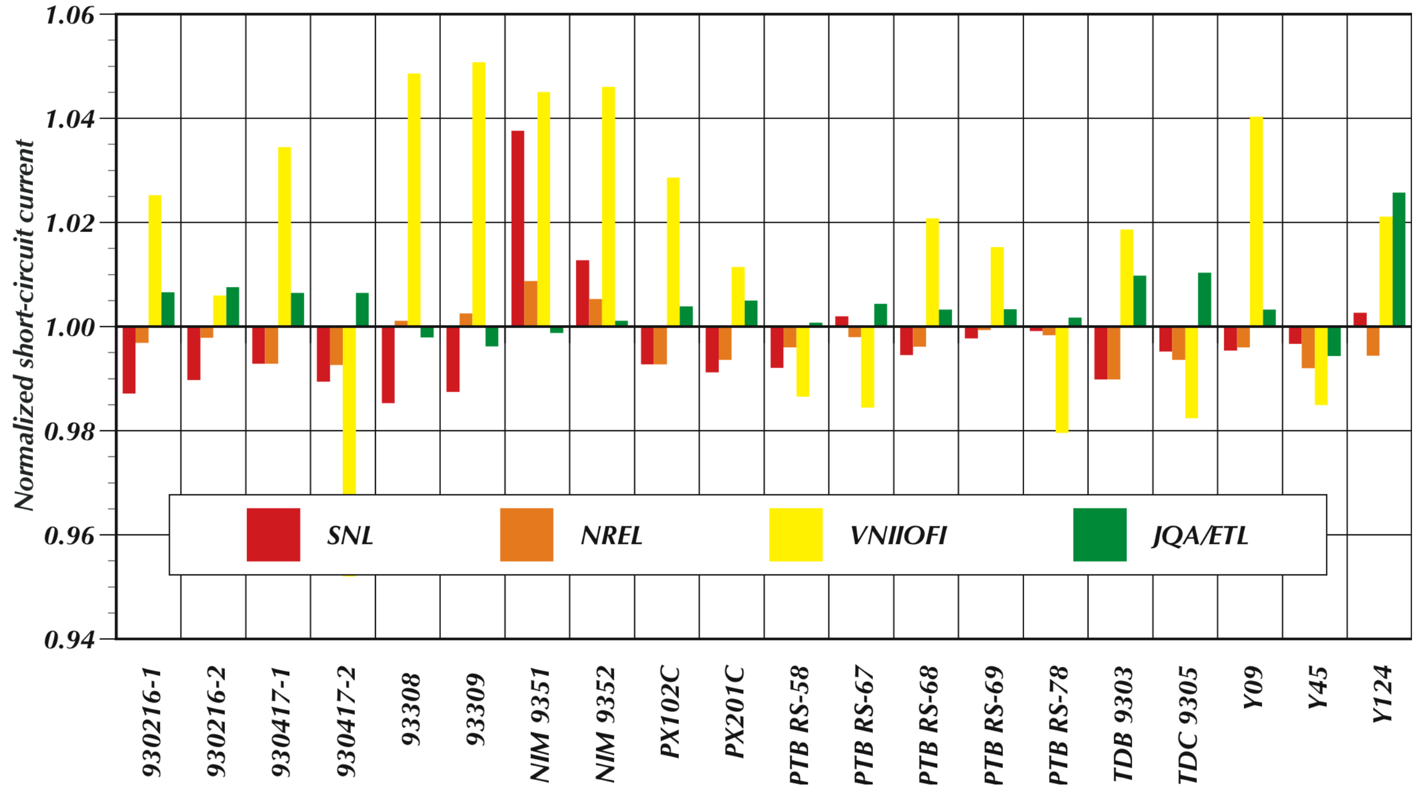
  C.R. Osterwald et al, *25th IEEE PVSC*, p.126, 1996

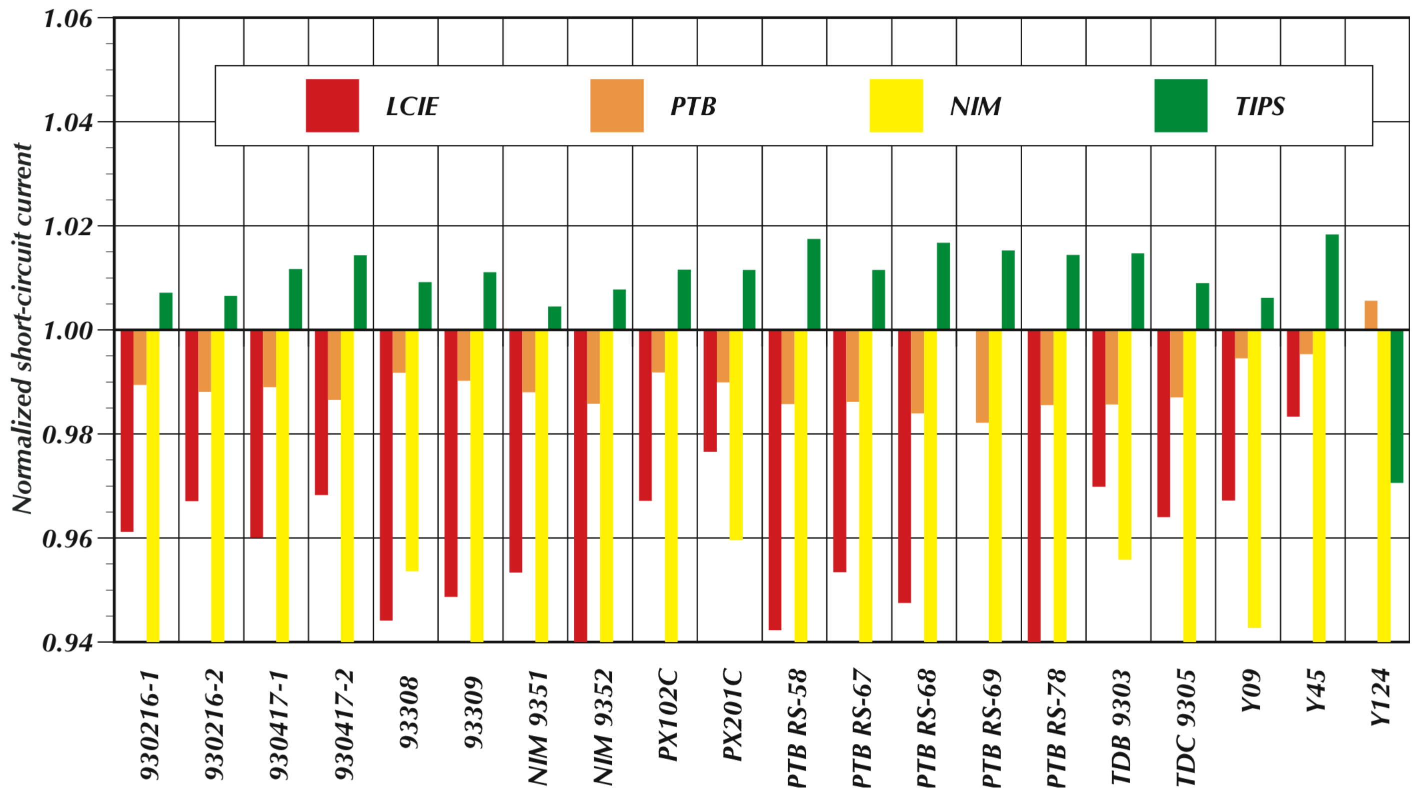
  C.R. Osterwald et al, Progress in PV, **7**, p.287-, 1999
- PEP' 2000 WPVS Recalibration – NREL host

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

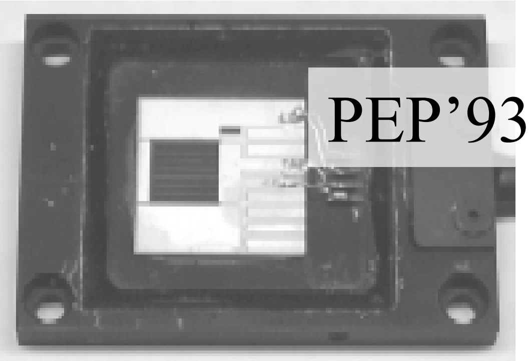
  S. Winter, et al, 31st IEEE PVSC, p.1011, 2005.

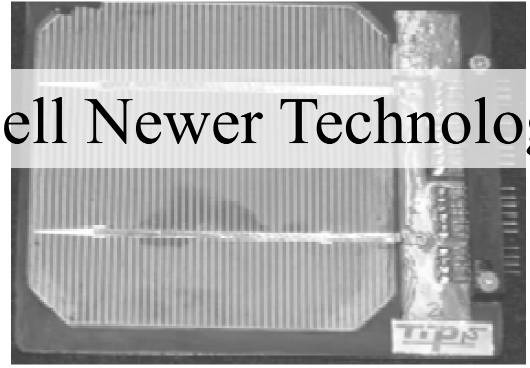
PEP'93 Si cell Intercomparison

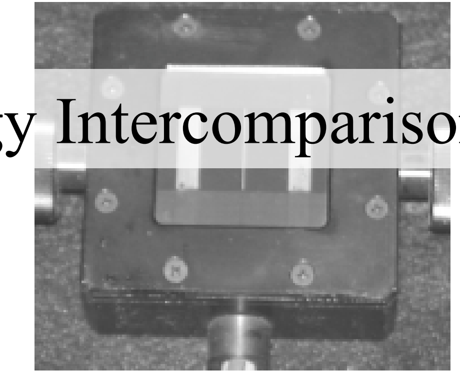


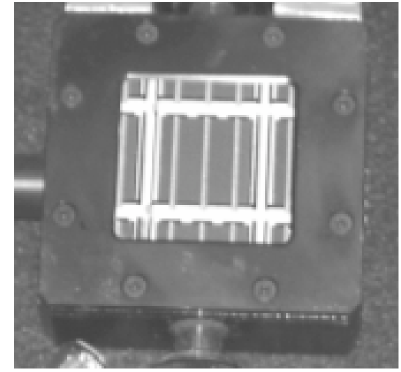


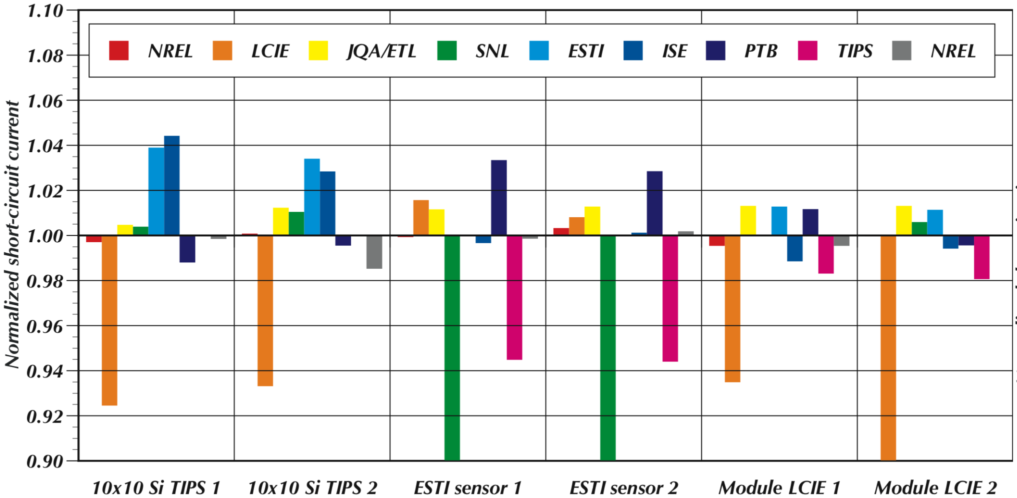
PEP'93 cell Newer Technology Intercomparison

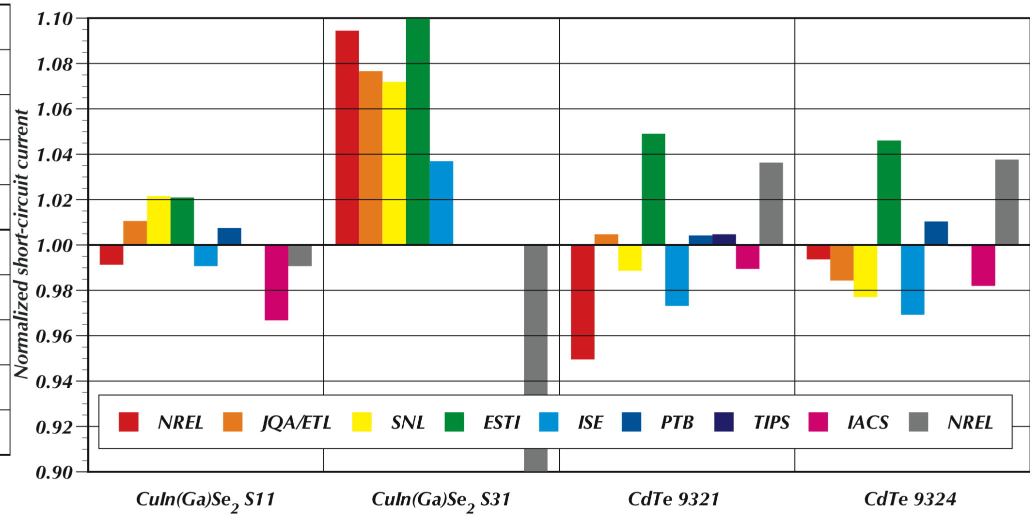


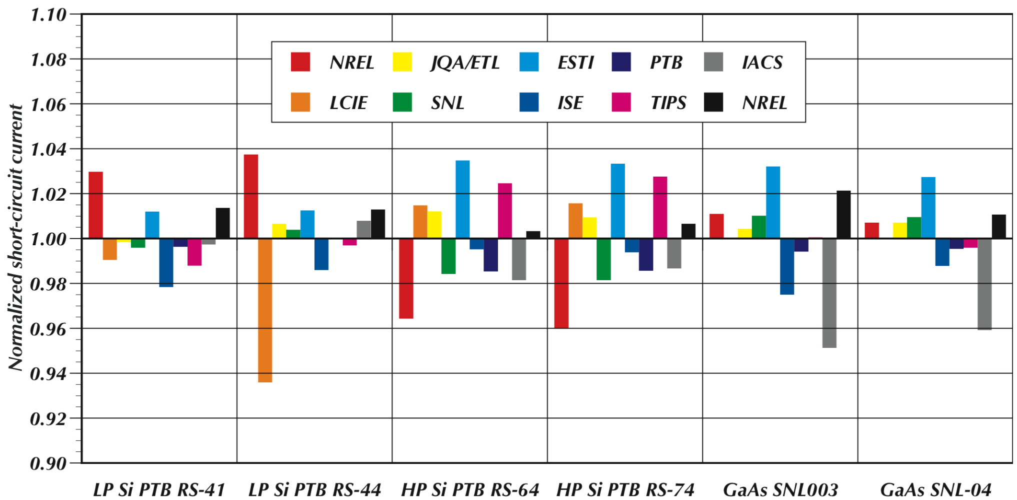


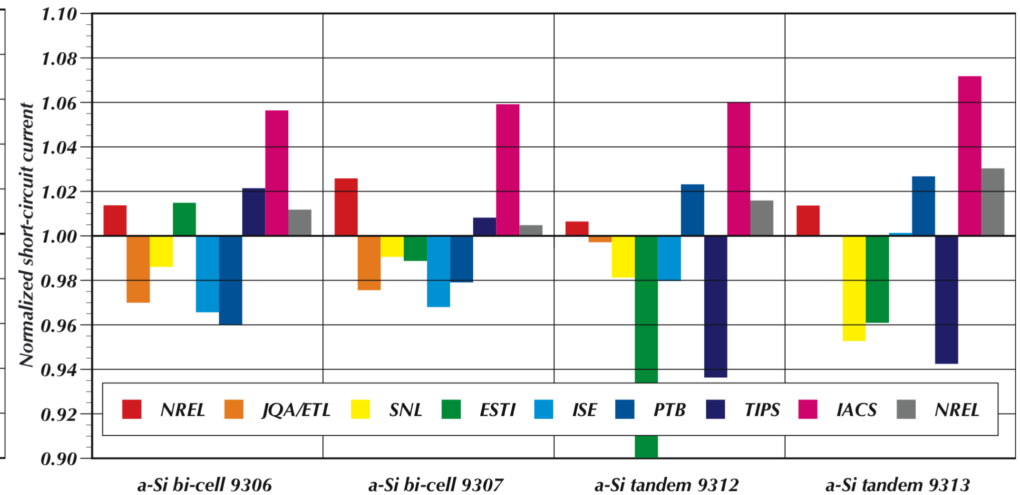










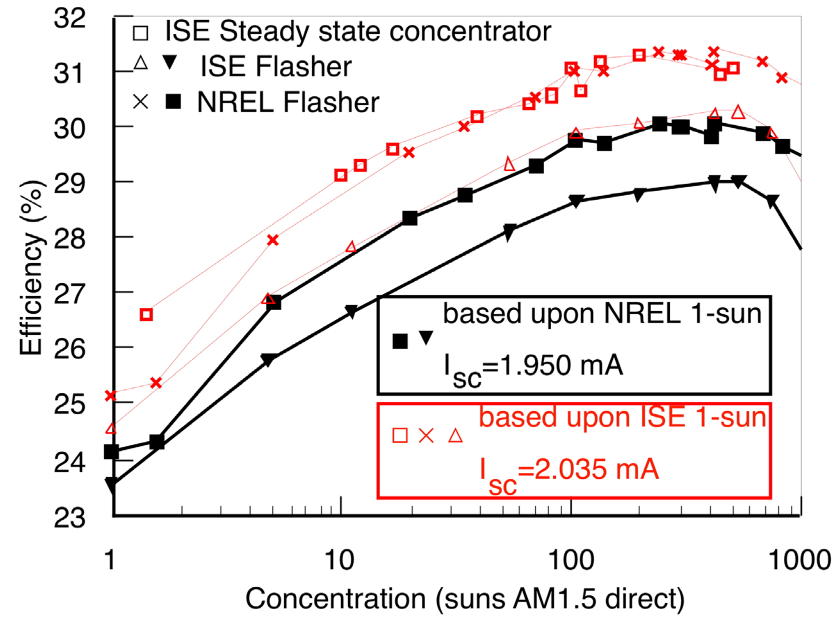


Published Informal Intercomparison

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.

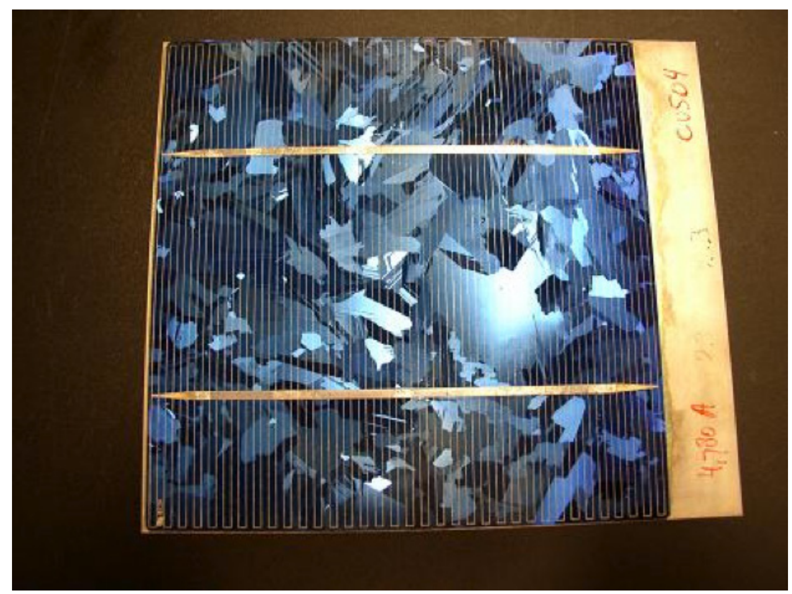
Fraunhofer ISE $Ga_{0.35}In_{0.65}P/Ga_{0.83}In_{0.17}As$

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



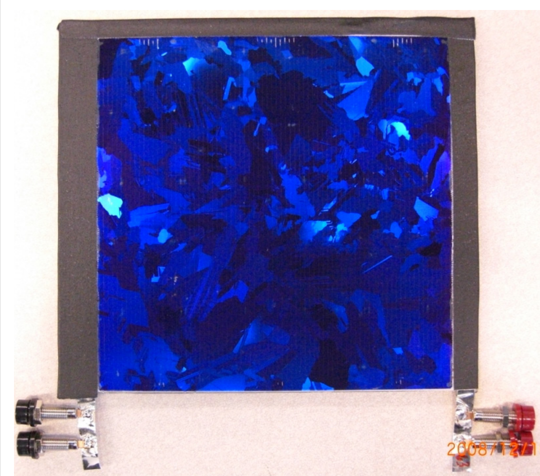
Unpublished Informal Intercomparison

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

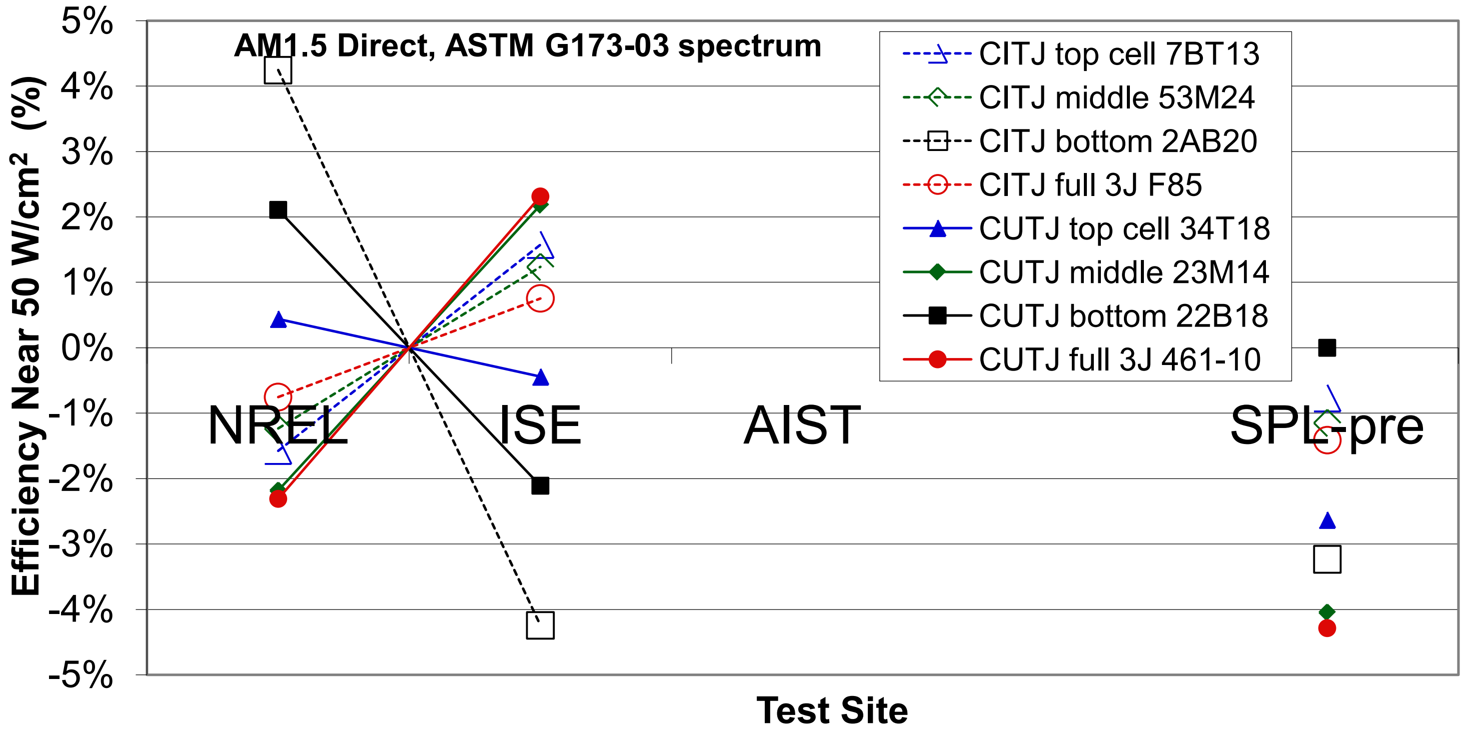
In 2008 Calisolar hosted an intercomparison with Fraunhofer ISE and NREL

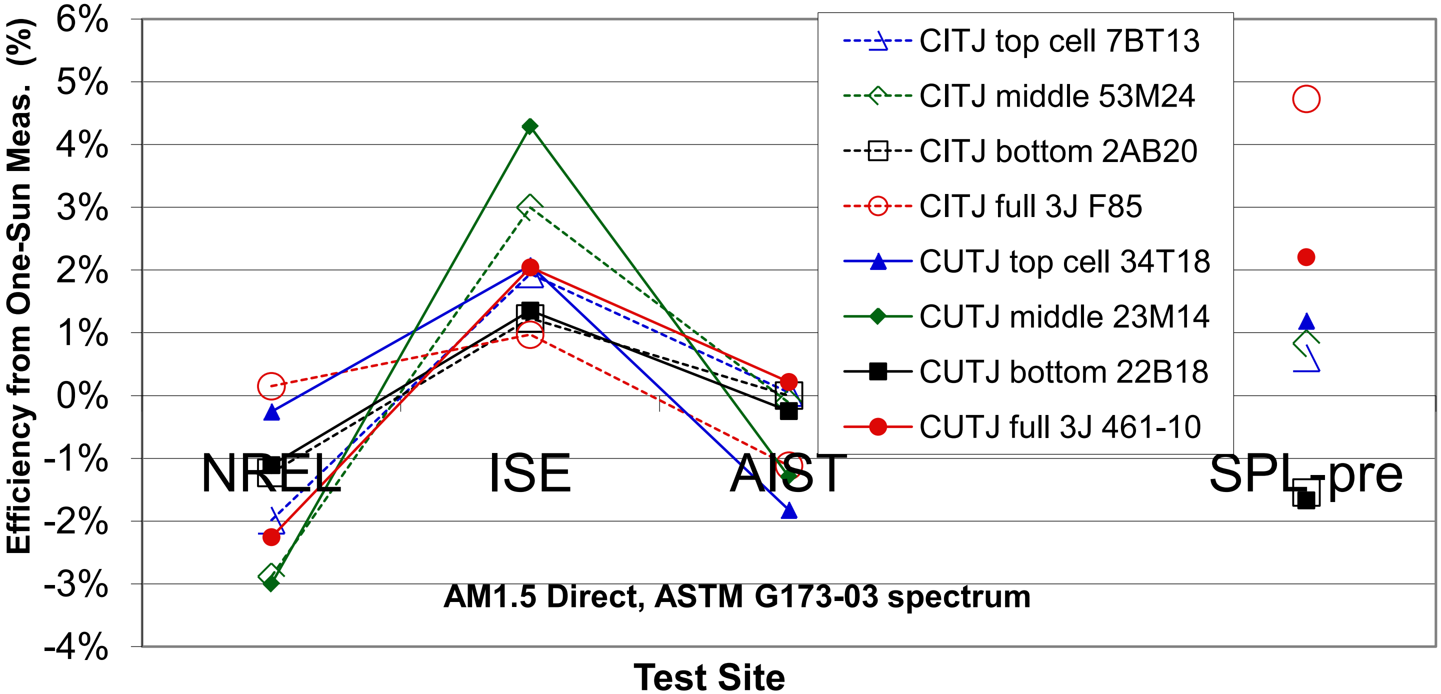
Percentage difference between NREL and ISE. Positive numbers indicate NREL lower than ISE.

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

Unpublished Informal Intercomparison

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





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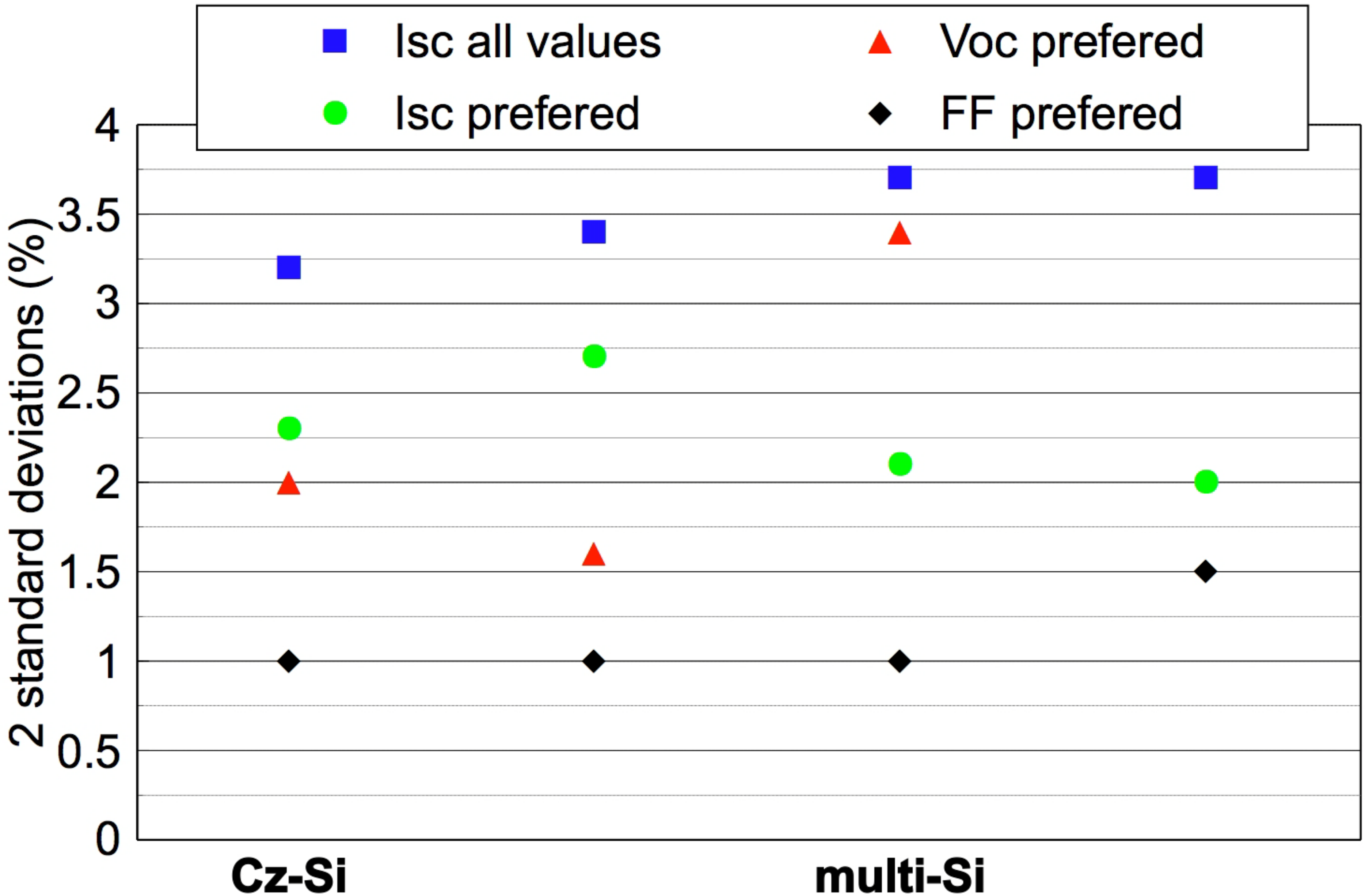
Formal Module Intercomparisons

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

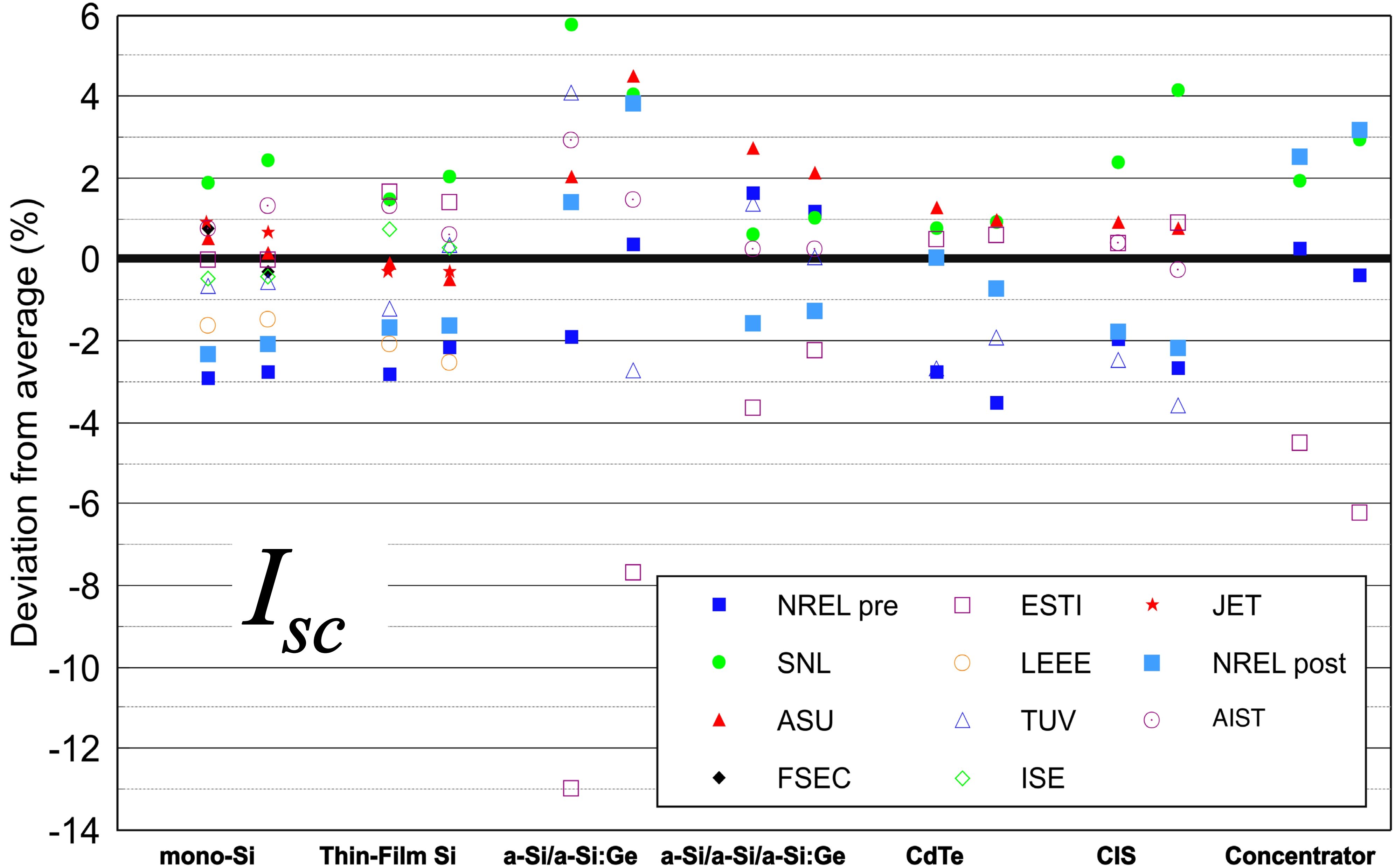
  S. Rummel et al, *4th World Conference on PV Energy Conversion, p.2034, 2006*
- 2006-2008 EC PERFORMANCE project –
  7 labs

  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

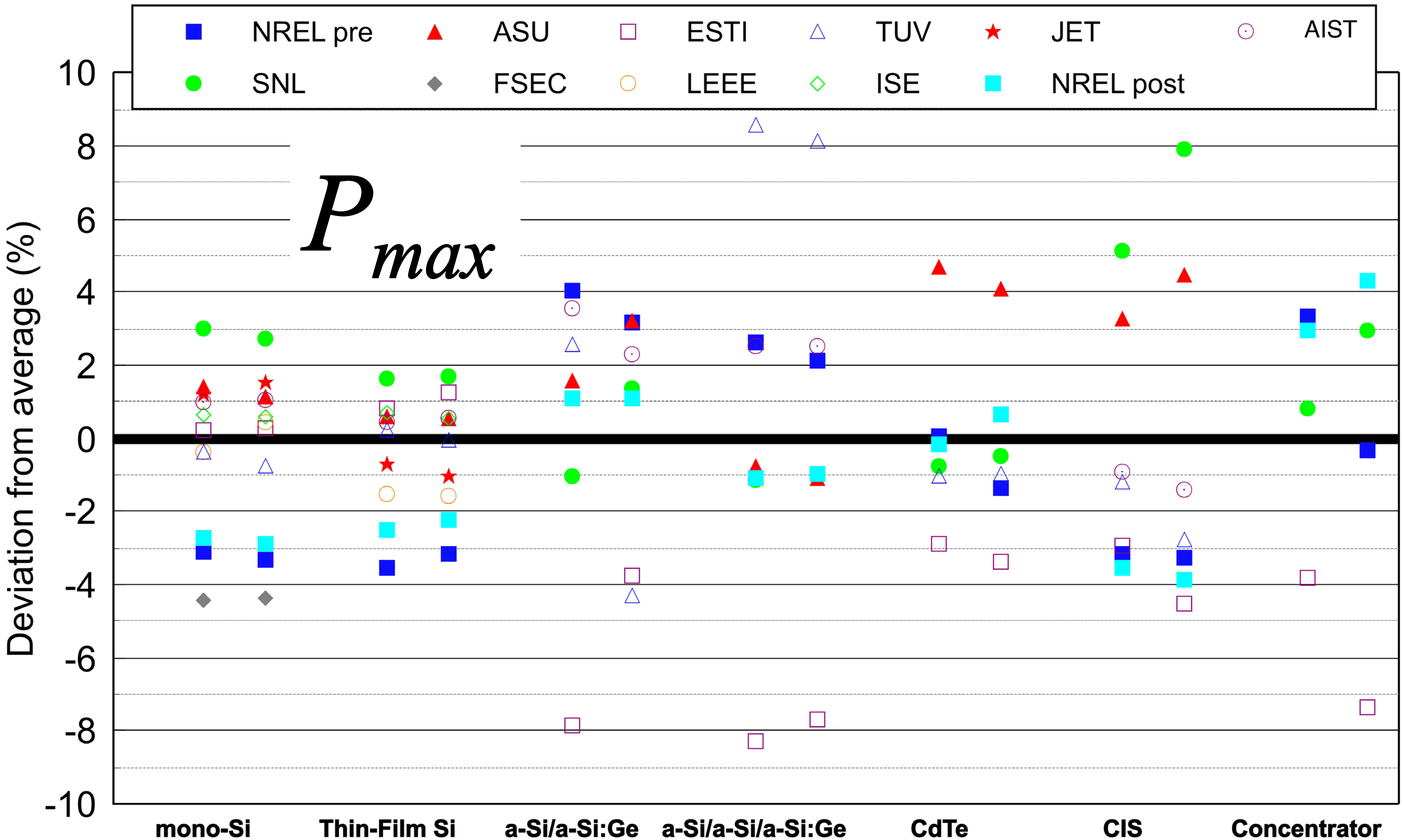
PEP'87 Module Intercomparison



NREL 2004 Intercomparison Results

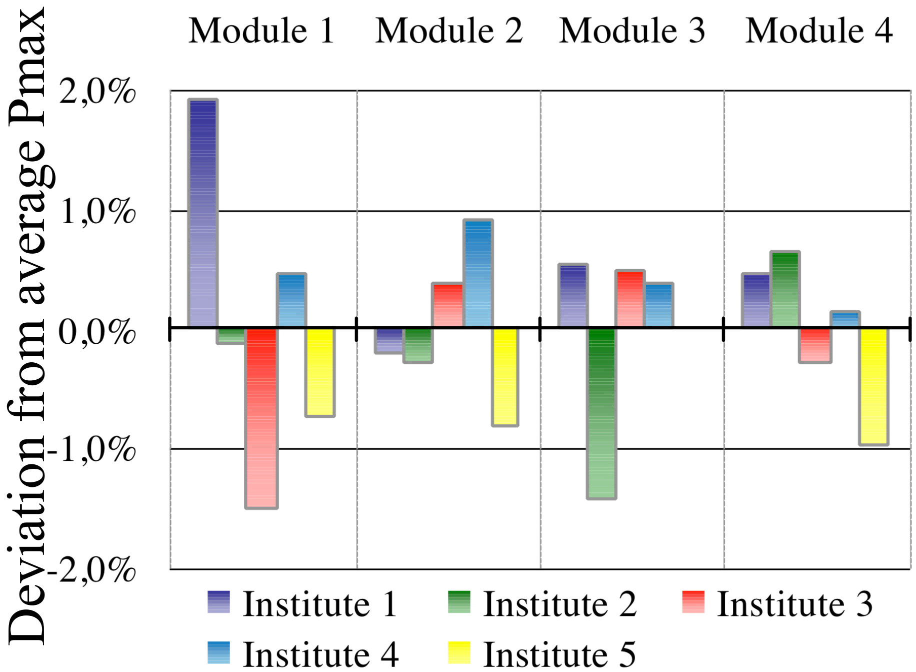


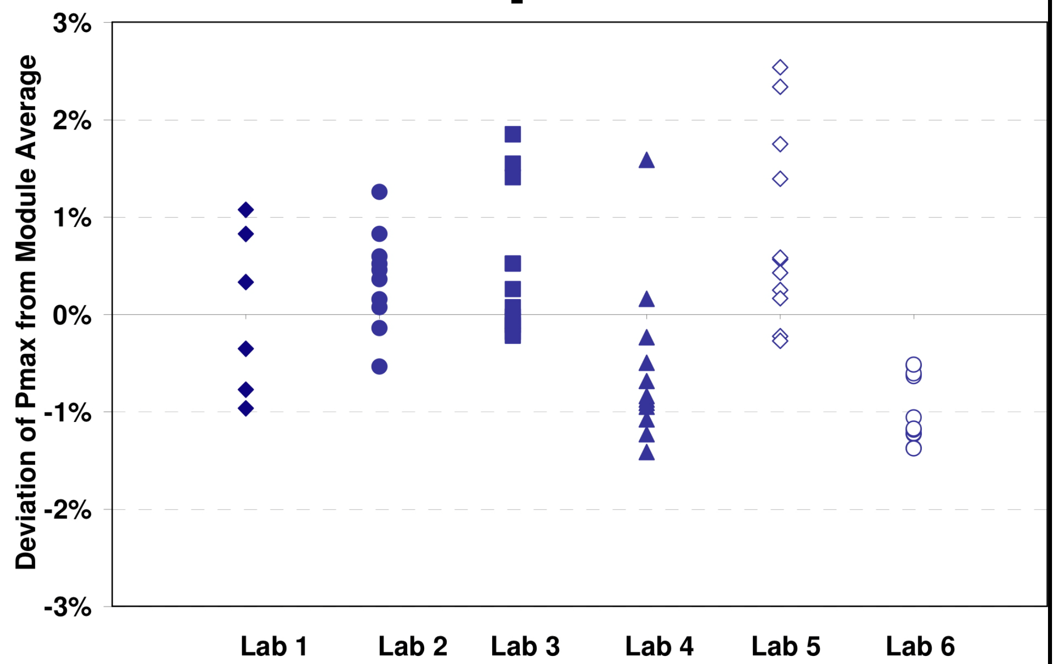
NREL 2004 Intercomparison Results

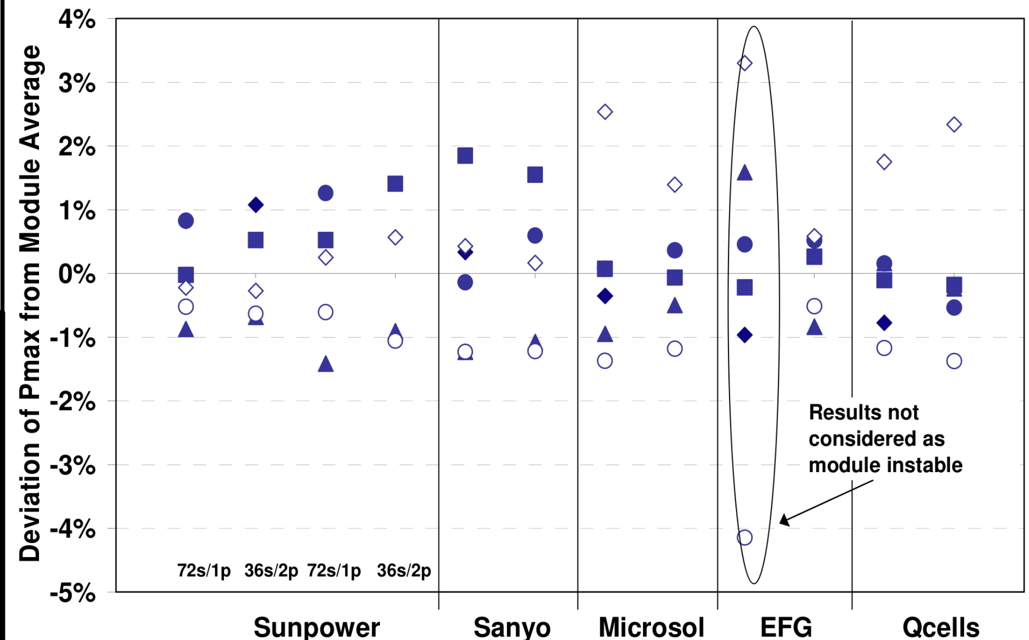


2006 EU Module Intercomparisons

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



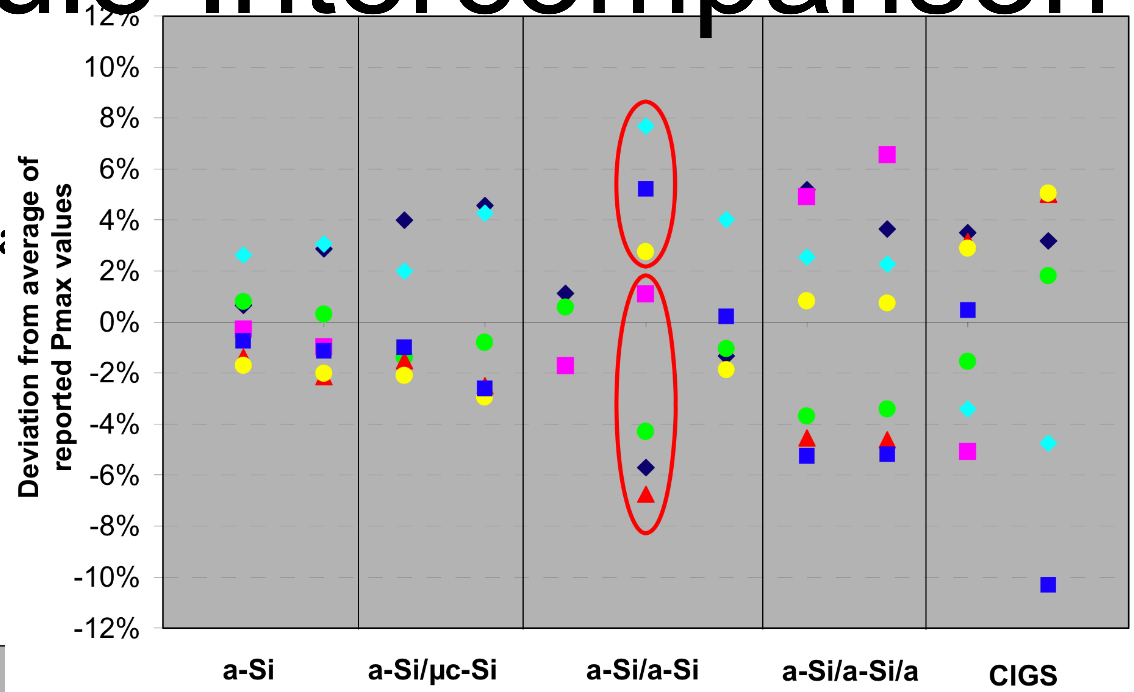


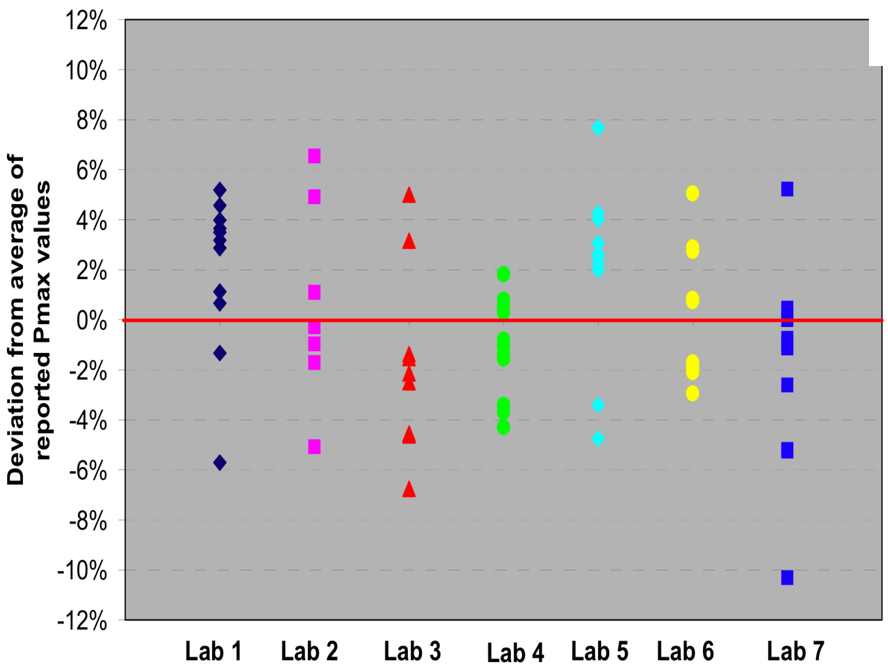


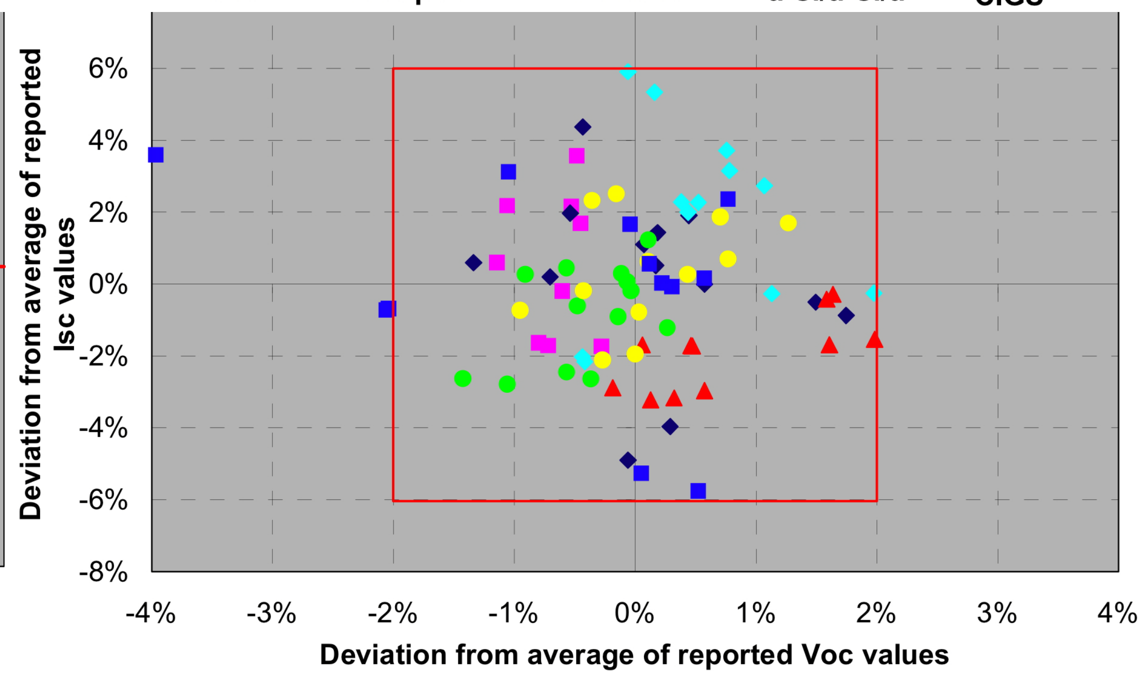
W. Herman, et al, proc. 22nd EU PVSEC, 2007, p.2506
Arsenal research, Vienna (Austria)
Ciemat, Madrid (Spain)
EC DG Joint Research Centre, Ispra (Italy)
Fraunhofer-ISE, Freiburg (Germany)
SUPSI, Lugano (Switzerland)
TÜV Rheinland, Cologne (Germany)

2008 EU Module Intercomparison

Arsenal research, Vienna (Austria)
Ciemat, Madrid (Spain)
EC DG Joint Research Centre, Ispra (Ita
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

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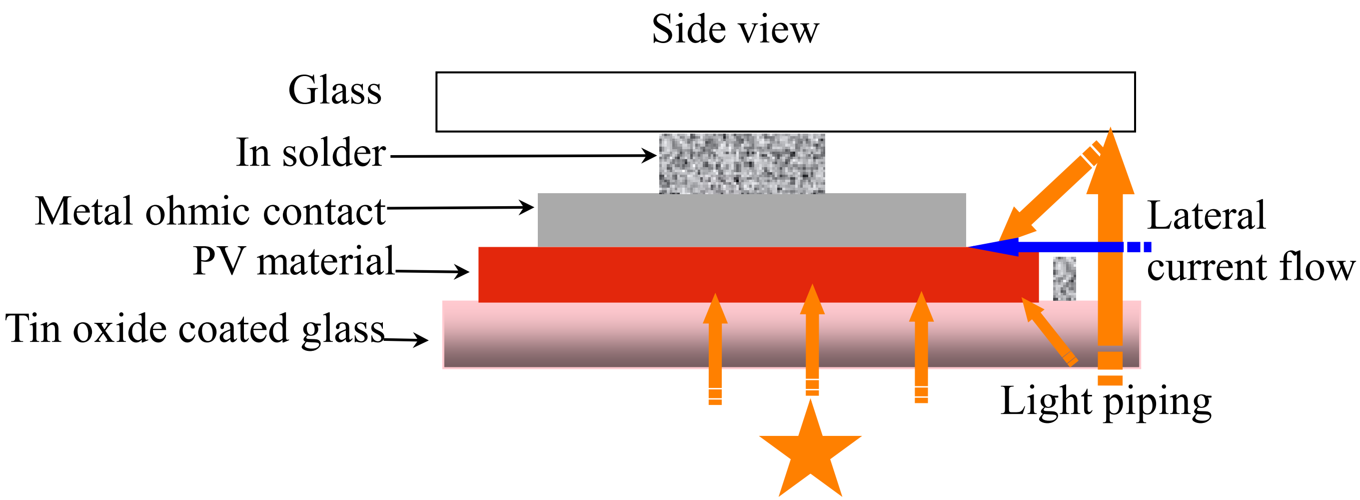
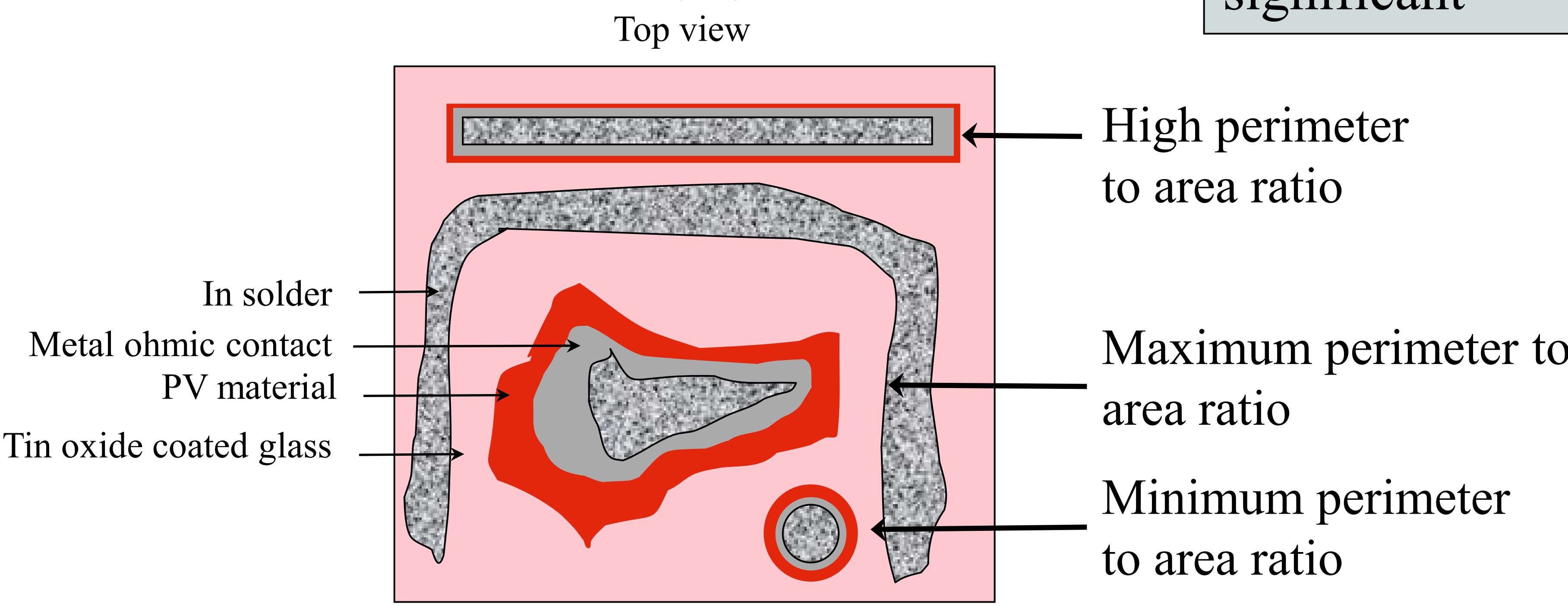
Artifacts

- 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 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

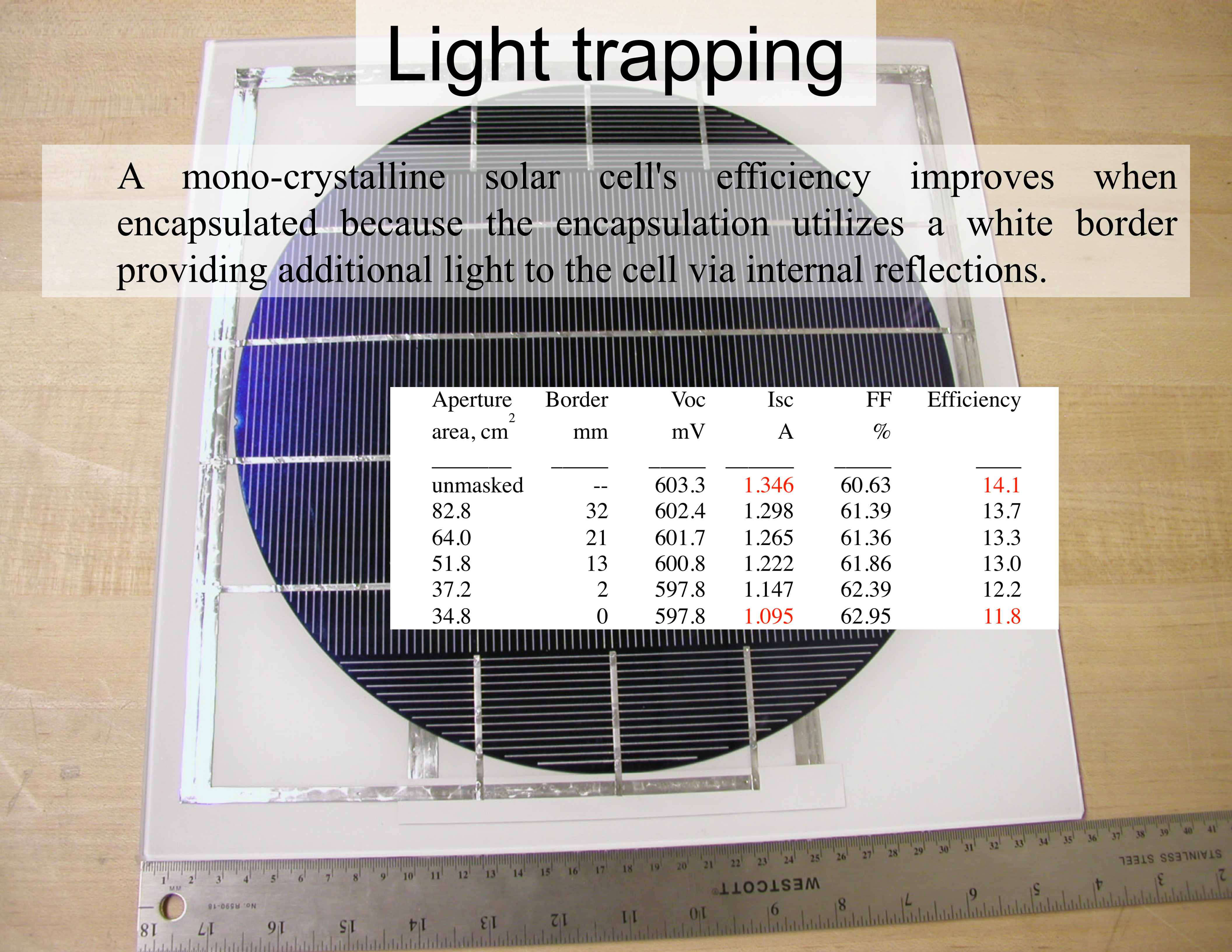
Area



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



Require an aperture if collection outside the defined area



Light trapping

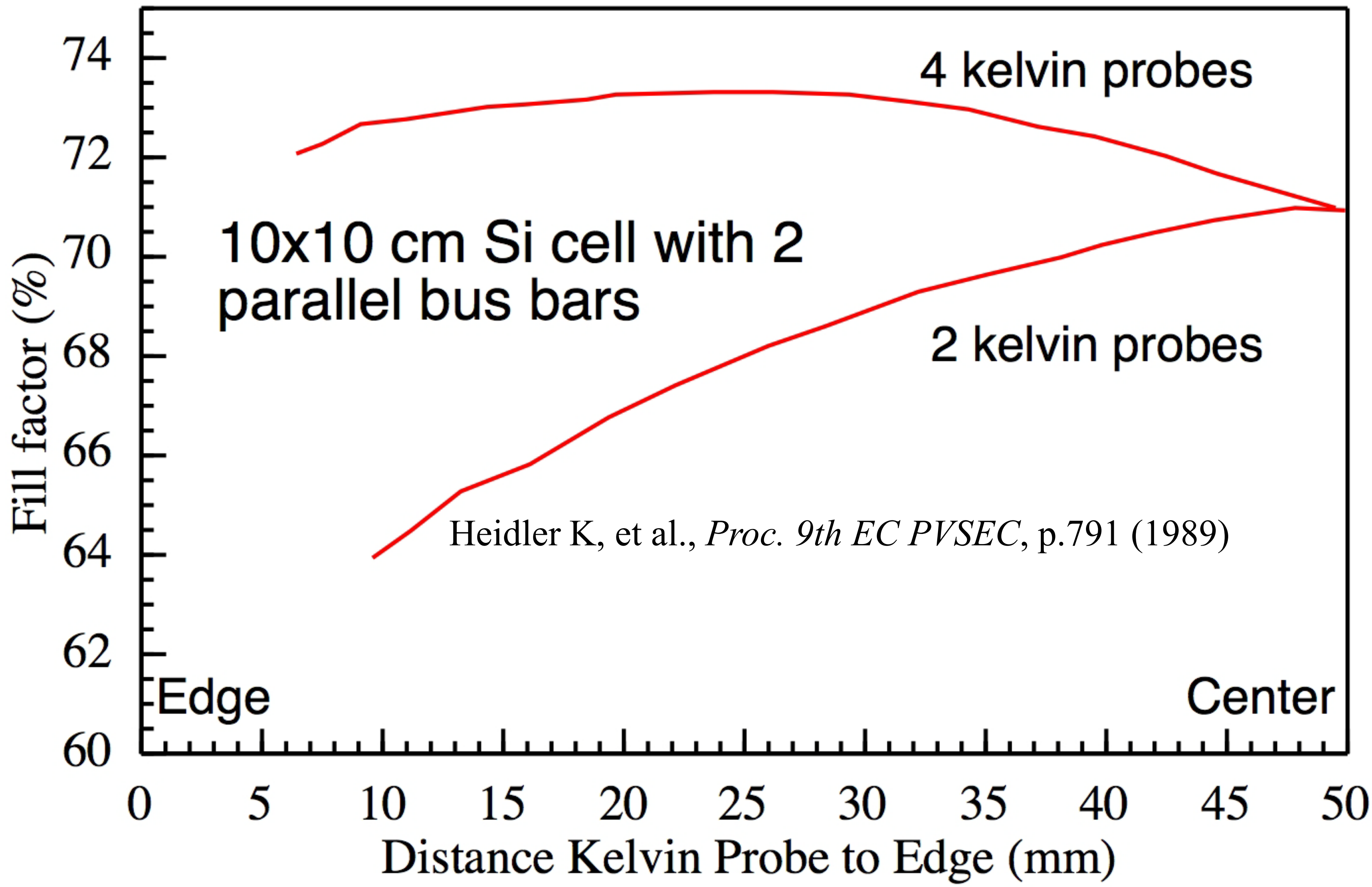
A mono-crystalline solar cell's efficiency improves when encapsulated because the encapsulation utilizes a white border providing additional light to the cell via internal reflections.

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

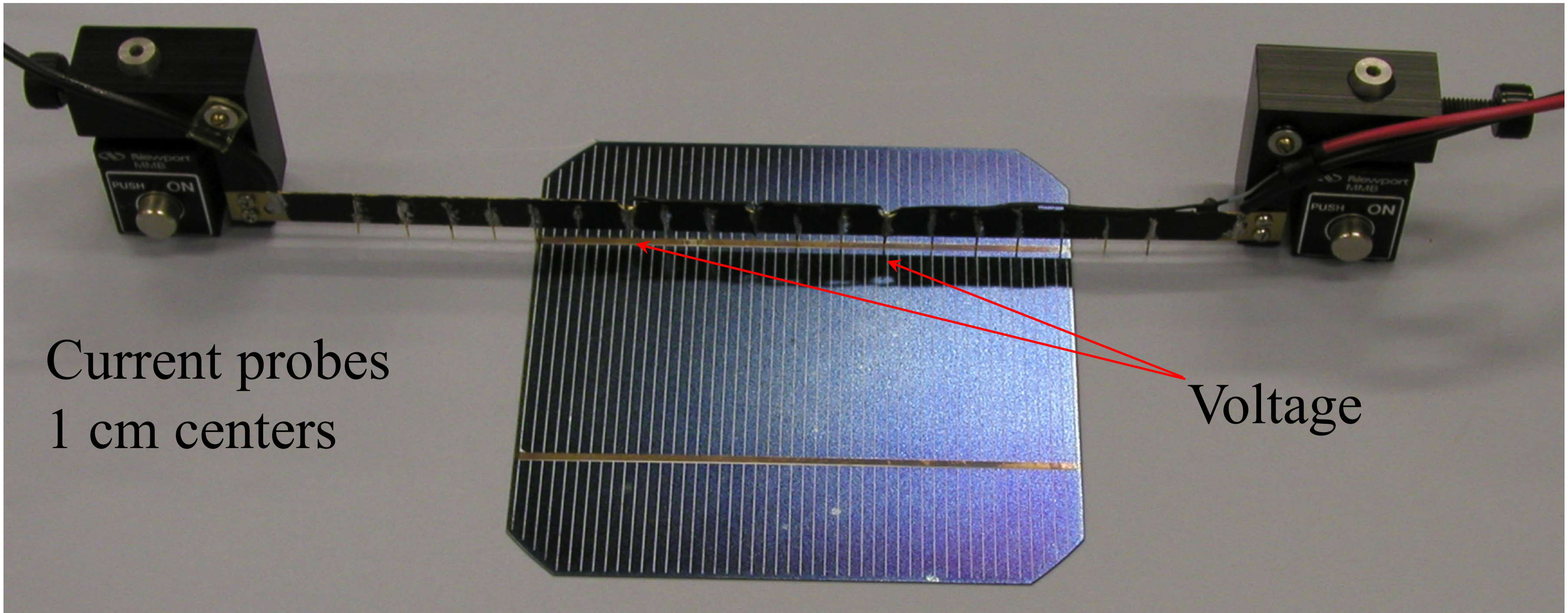
Artifacts

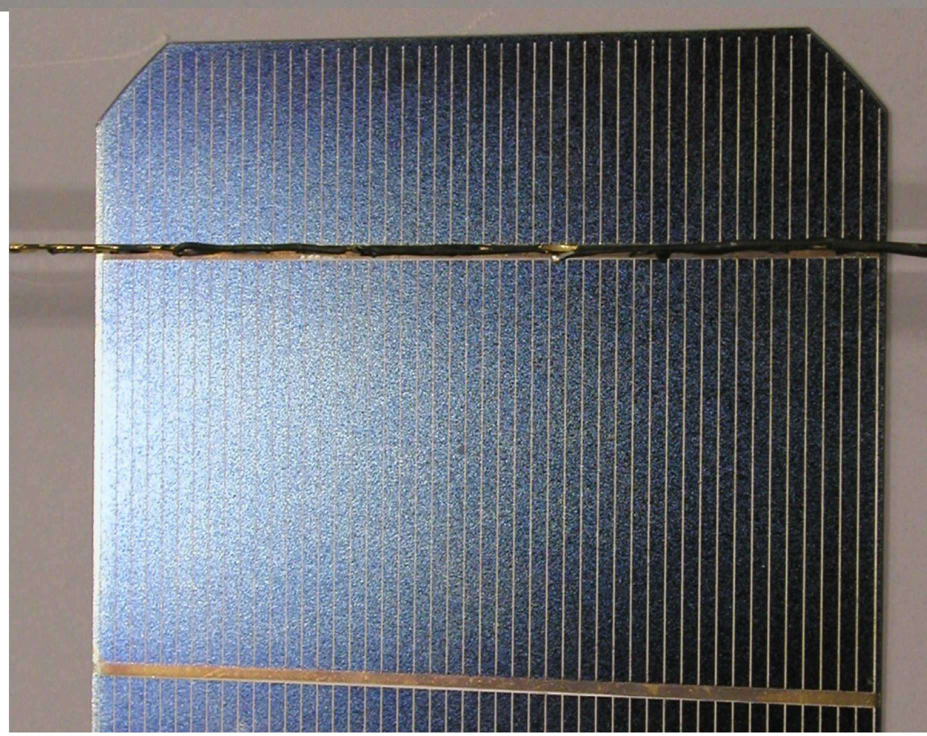
- Procedural
  - Apply a static charge to the surface of a MIS device to temporarily charge up an inversion layer.
  - Bias the device prior to measurement to charge transient states.
  - Too small of a current contact (grids, junction box, ribbons) , resulting in localized cell, cell to probe contact or wire heating, causing a reduced fill factor.
  - Reflections off the probes or operator 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.

Probe Spacing



Probing to Wafers





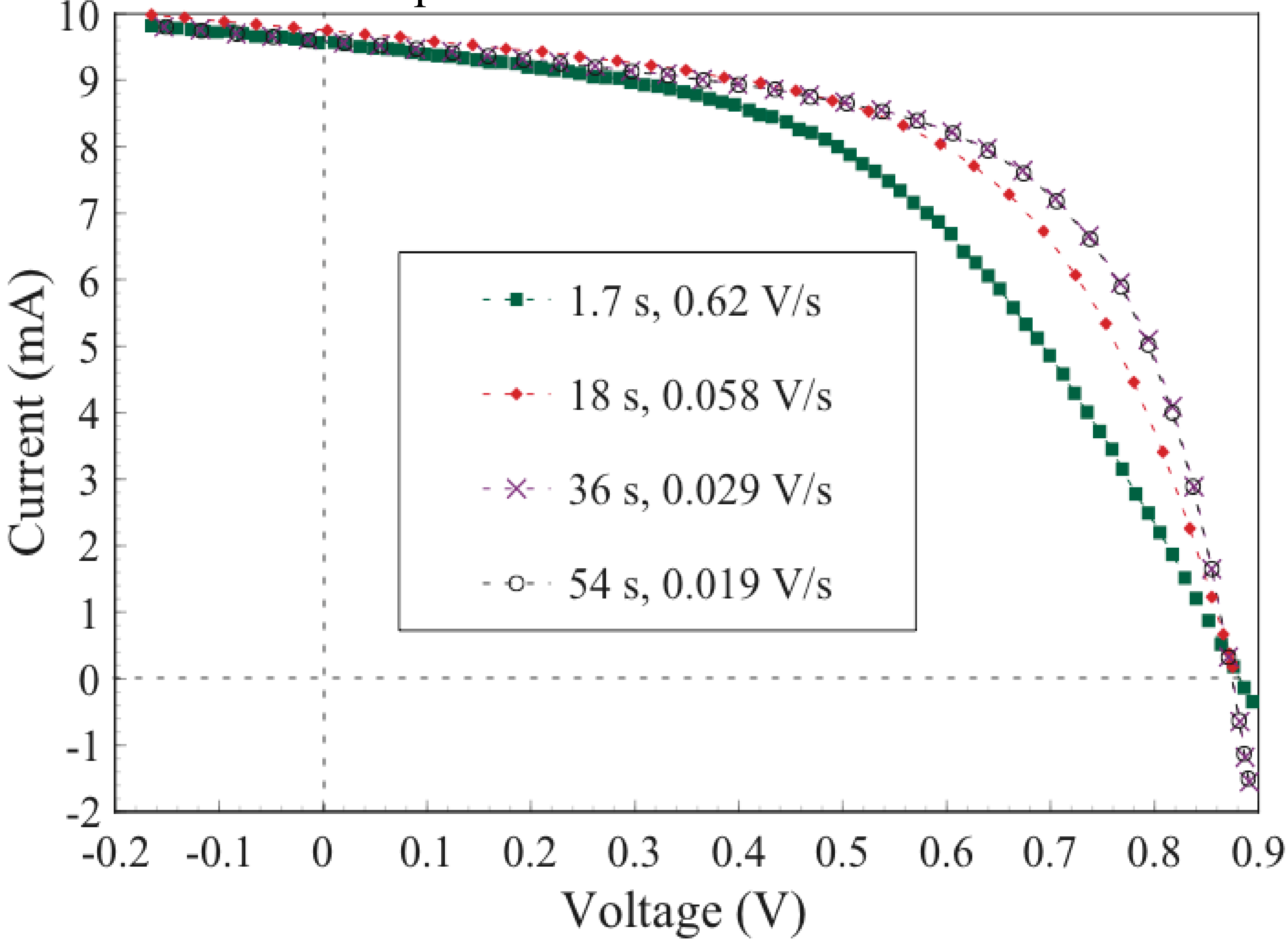
Probe shading can differ between groups

Artifacts

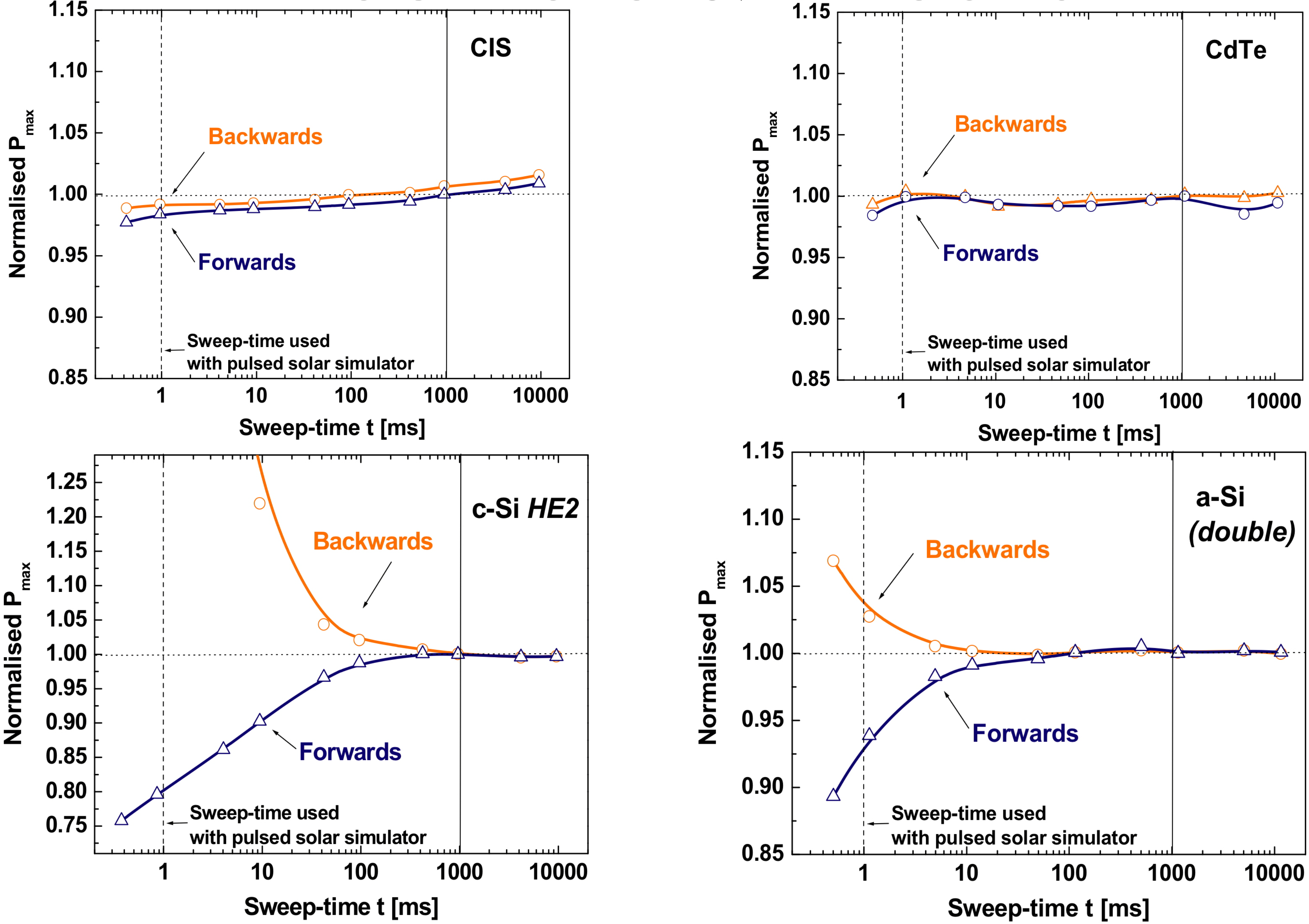
- Data Acquisition System
  - Bias the device at too large of a rate. Bias rate problems by measuring the I-V at different bias rates or directions
  - Drift in the equipment calibration
  - Not correcting for the spectral mismatch error. A spectral correction is required for each junction in a multi-junction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

Bias Rate Artifact

Sweep < 0.03 V/s for this OPV cell



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.

Summary

- NREL IV, QE calibration procedures and equipment are ISO 17025 accredited
- Periodic Intercomparisons are critical to determine if calibrations drifting
- A variety of artifacts exist but can be minimized with proper procedures