PV Cell and Module Calibrations at NREL

PV Asia Pacific Expo

October 23-25, 2012

Keith Emery

Symposium: Accurate Measurements of PV Cells and Modules

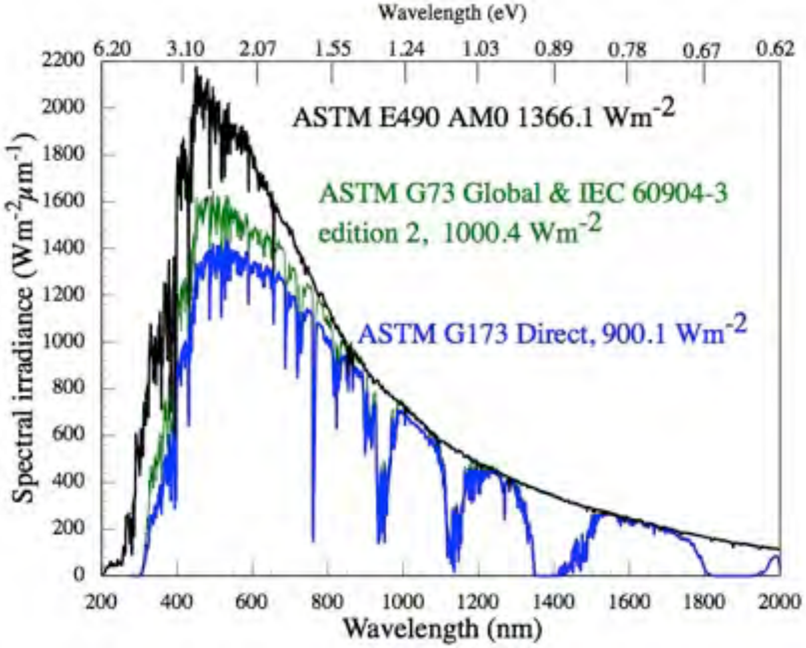
NREL/PR-5J00-65072

Outline

- Mission
- Primary Refenerce Cell Calibrations
- Secondary cell calibrations
  - QE Measurement
  - Linearity Measurement
  - Temperature Coefficient Measurement
  - I-V
    - single junction
    - Multijunction
- Concentrator cell
- Concentrator Moudle
- Flat Plate module
- Summary

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 (Test) 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
NATIONAL RENEWABLE ENERGY LABORATORY

A2LA ACCREDITED

certificate number 1239.02
Accredited for photovoltaic secondary cell, secondary module, and primary reference cell calibration

Calibration – Peak Watt Rating

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

To be uniquely specified:

P_{max} = maximum electrical power produced when illuminated at standard reference (test) conditions defined by a temperature, spectral and total irradiance

A = area of the device

E_{tot} = total irradiance at standard reference (test) 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:

$I^{R,R}$, ($I^{R,S}$) = reference cell short-circuit current under reference (source) spectrum

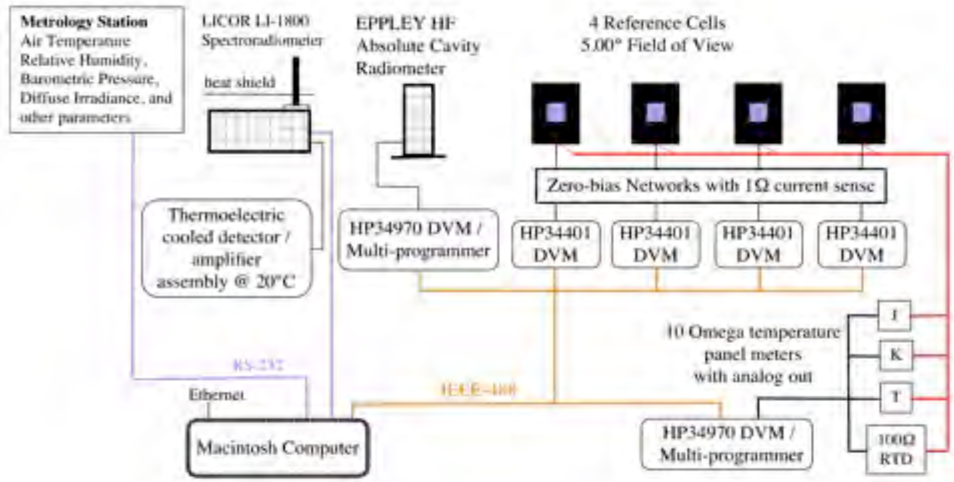
$E_{Ref}(\lambda)$ = reference (photon flux) spectral irradiance

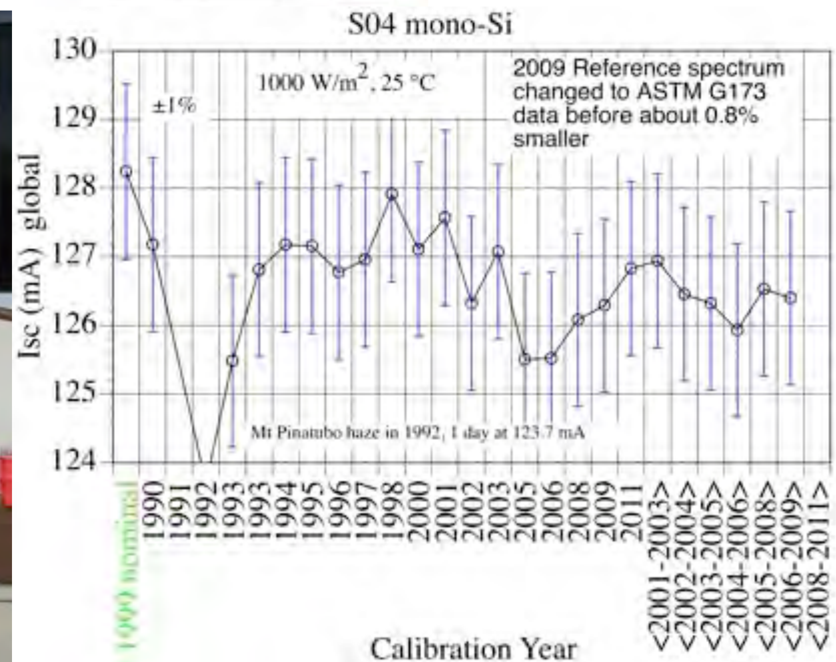
$E_S(\lambda)$ = simulator (photon flux) spectral irradiance

$S_{Ref}(\lambda)$ = reference (quantum efficiency) spectral responsivity

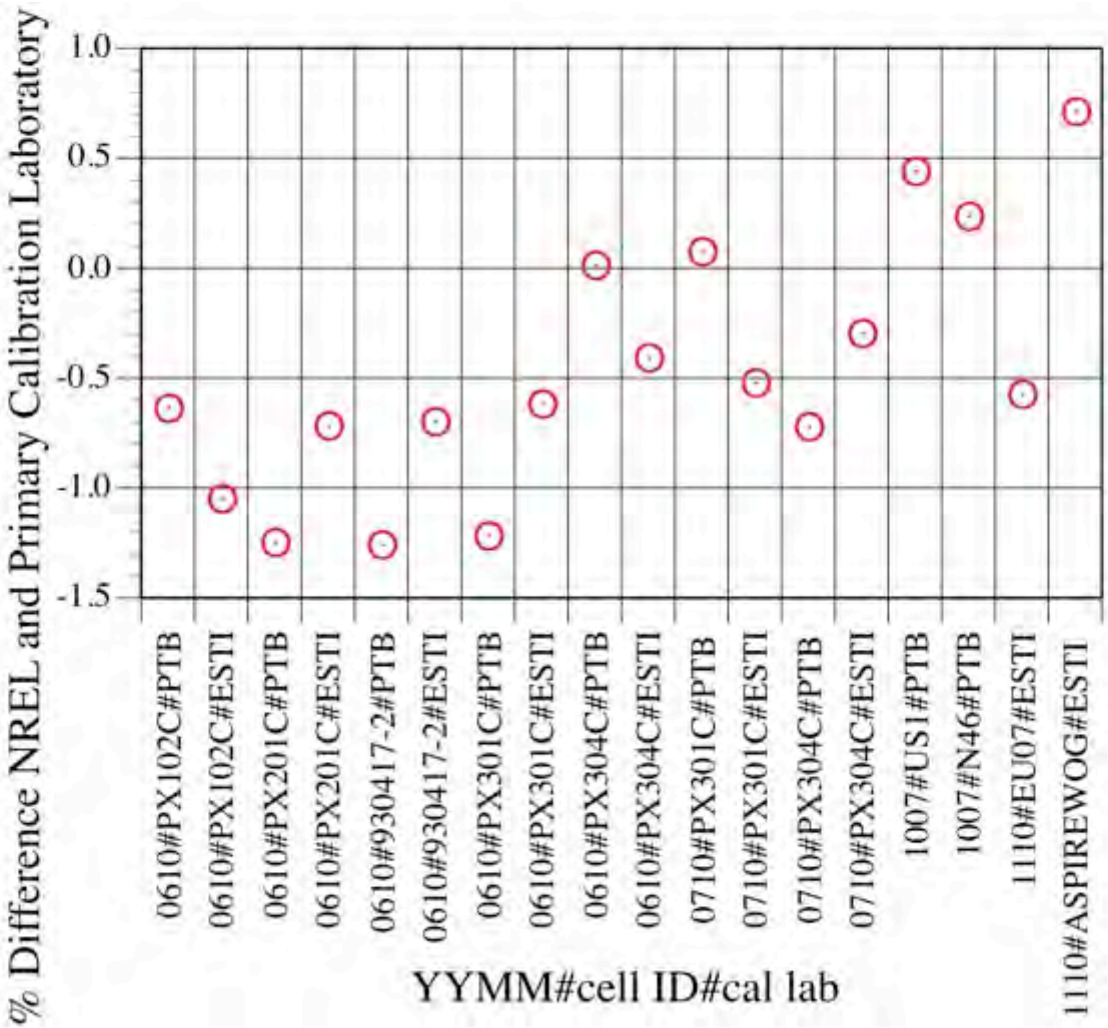
$S_T(\lambda)$ = test cell (quantum efficiency)

NREL Primary PV Calibration



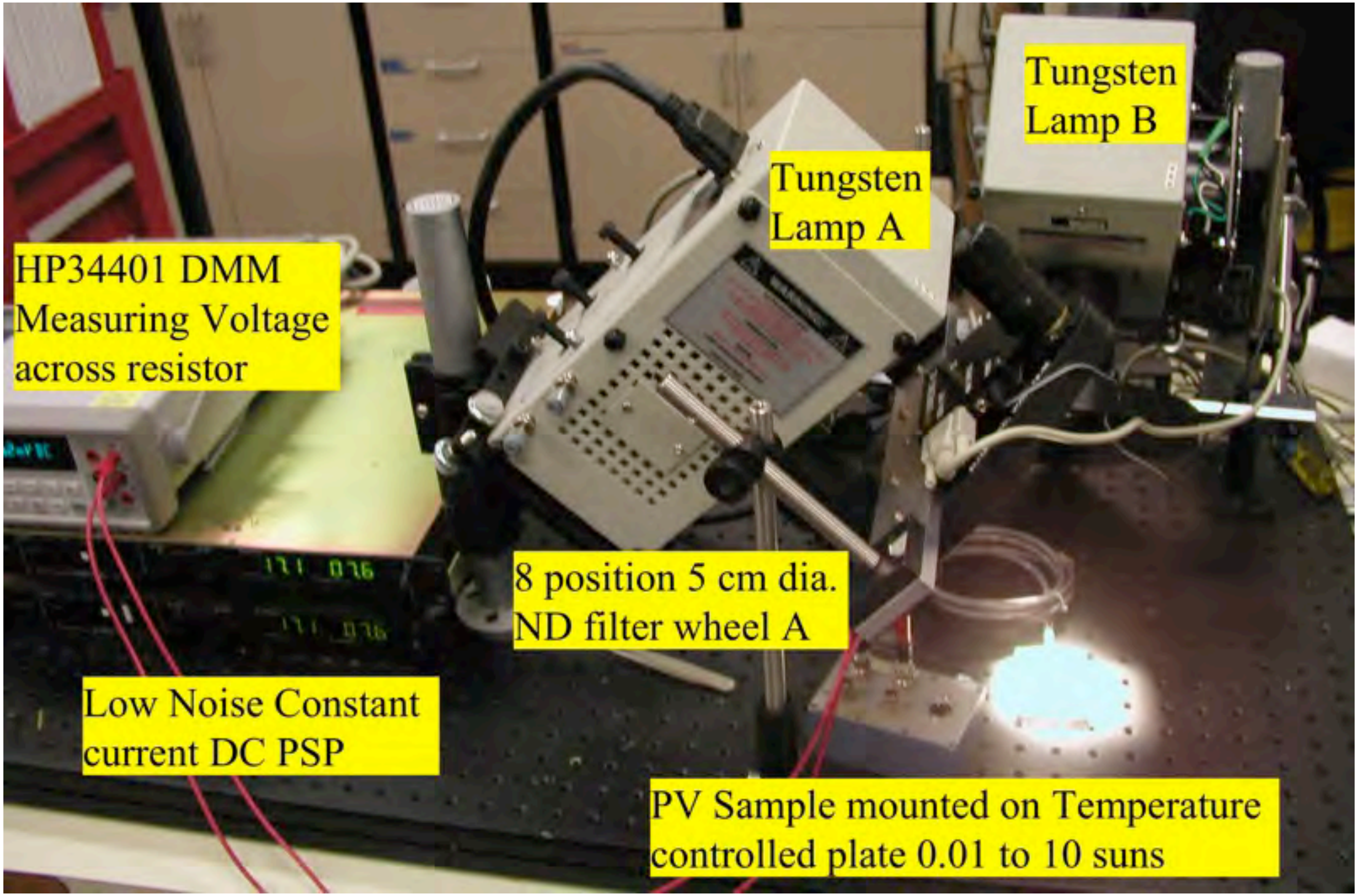


External Intercomparisons are Critical



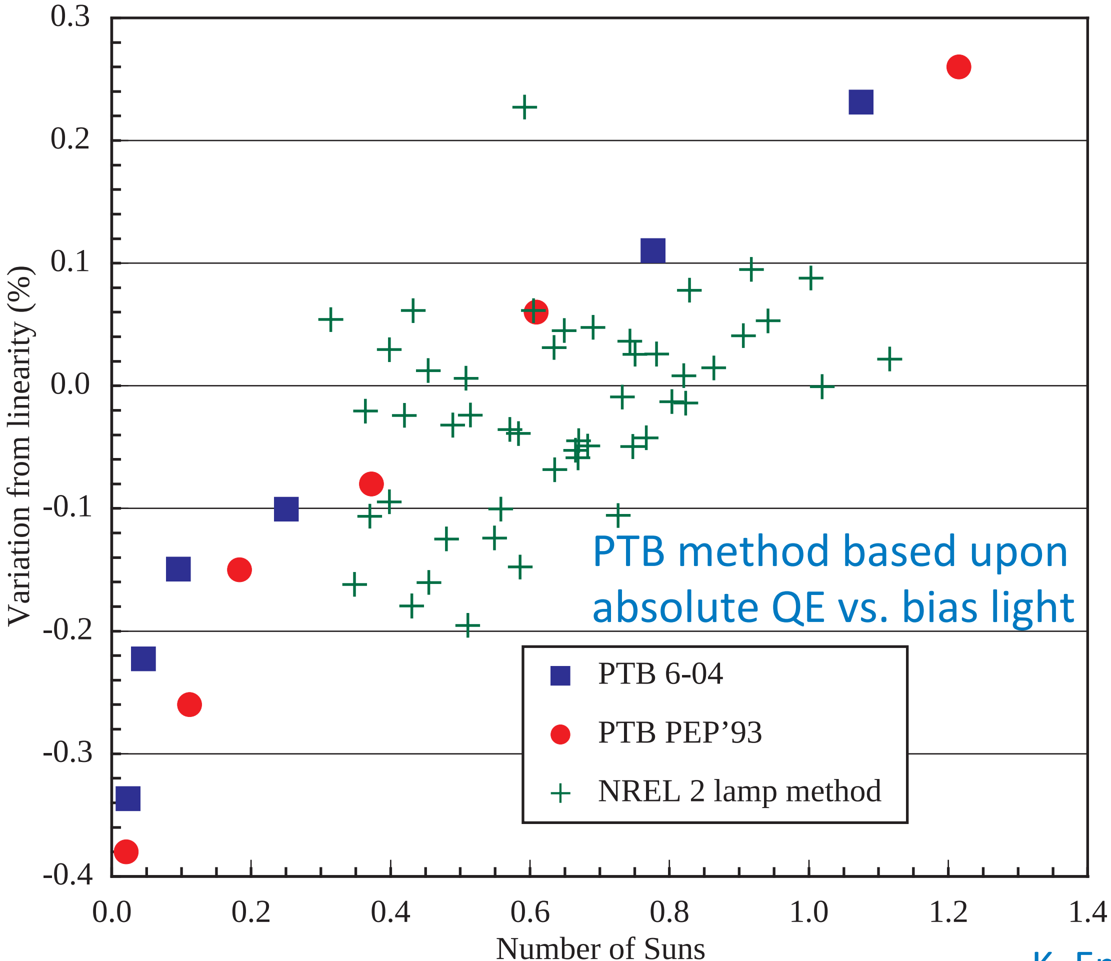
- Compare your results:
- As many labs as possible
- As often as possible
- As many different samples as possible

I_{sc} Linearity



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

Isc linearity with irradiance



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

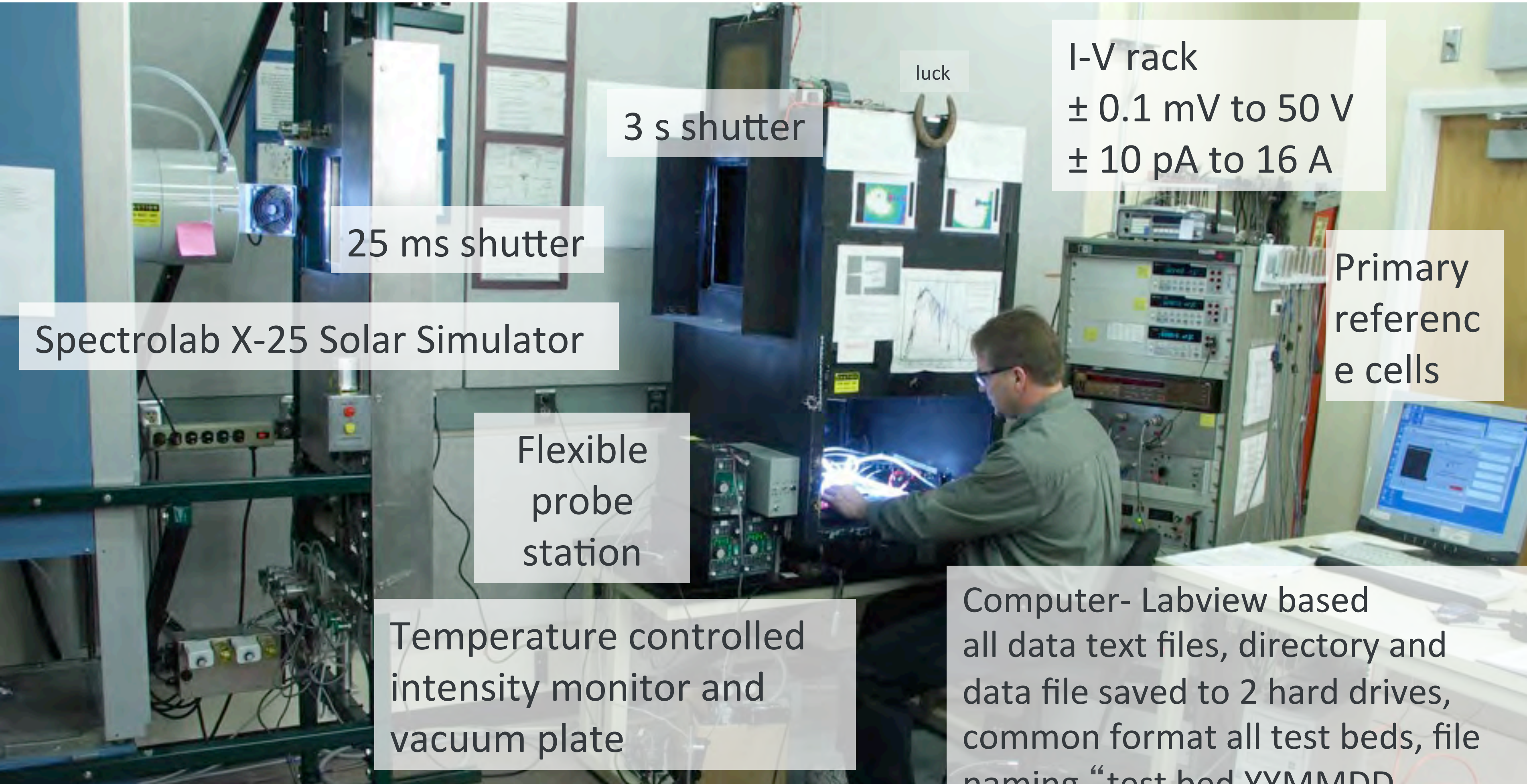
Cell I-V Equipment

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

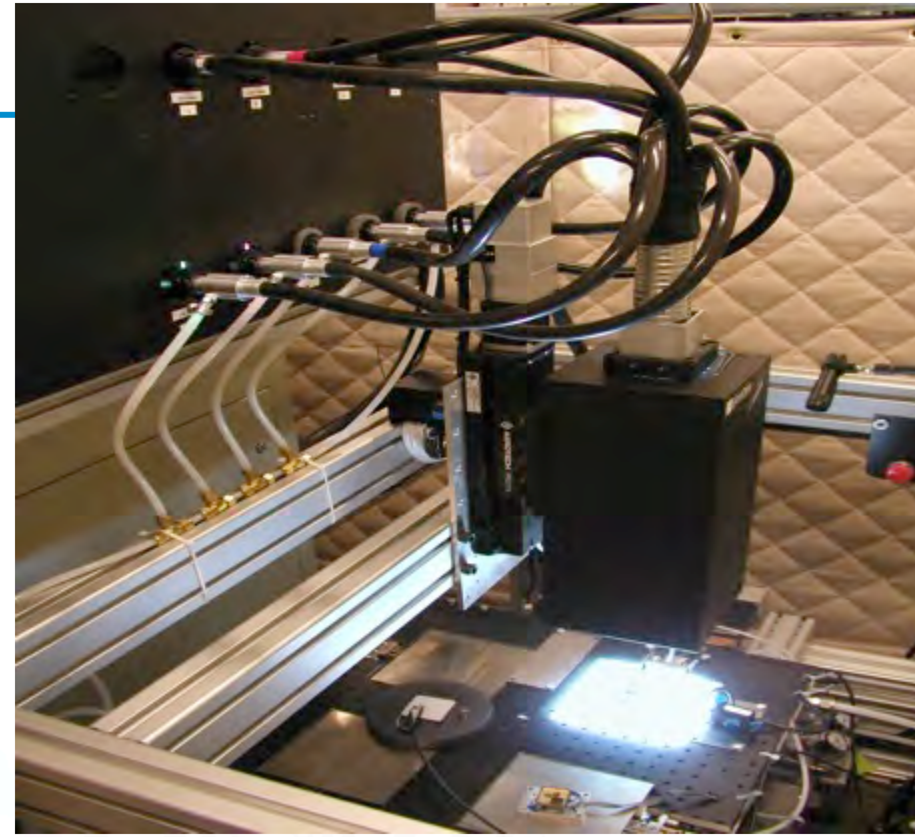
Multi-source spectrally adjustable 0.1 to 1-sun operational. Demonstrated for 6 junctions that can set photocurrent within 1% for each junction.

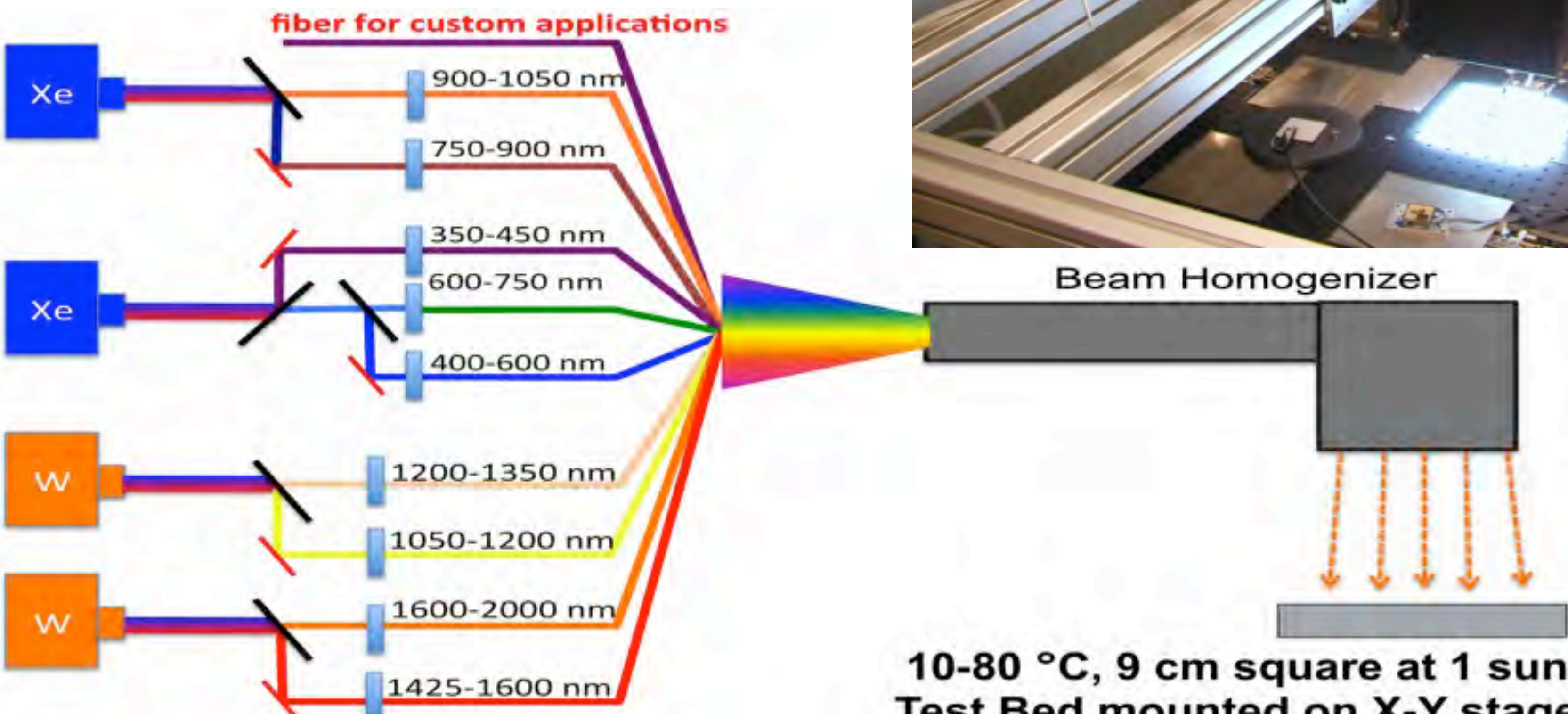
Spectrally adjustable concentrator Spectrolab THIPSS operational in 6 months.

Spectrolab X25 Solar Simulator



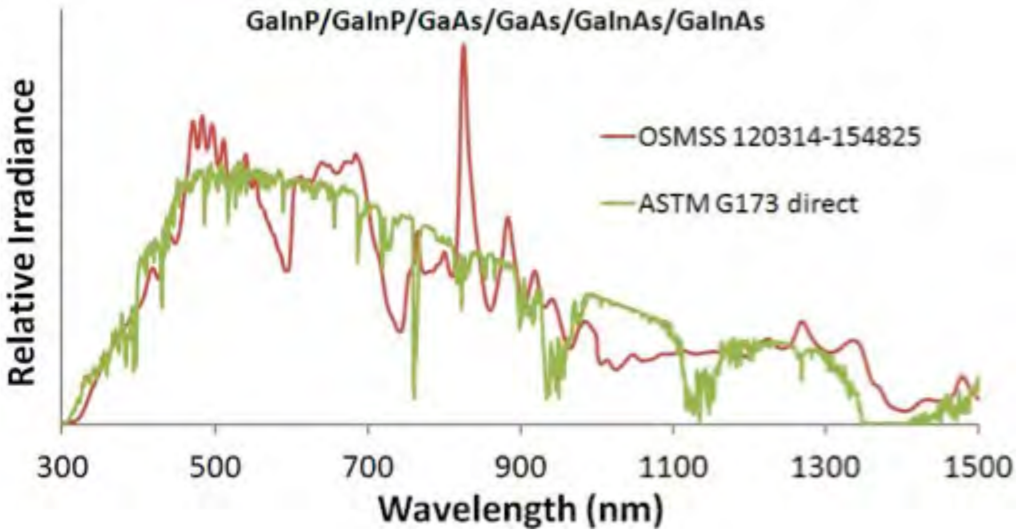
10-Channel One-Sun Solar Simulator

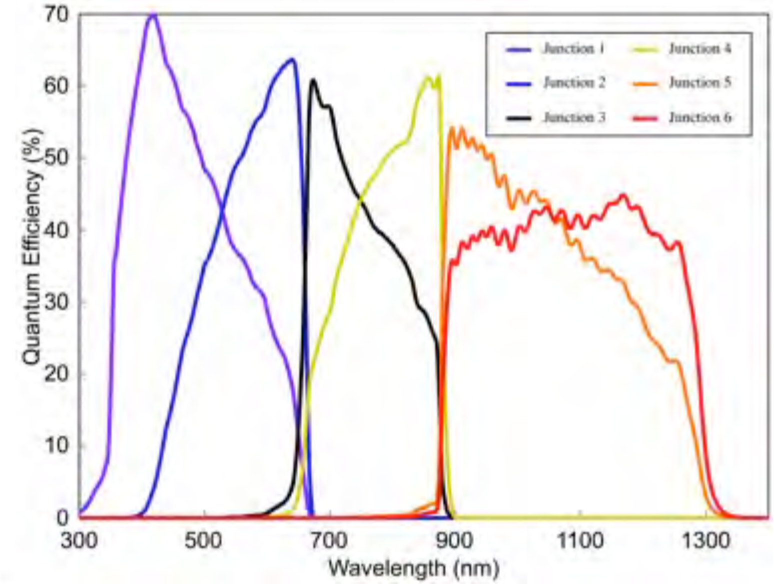


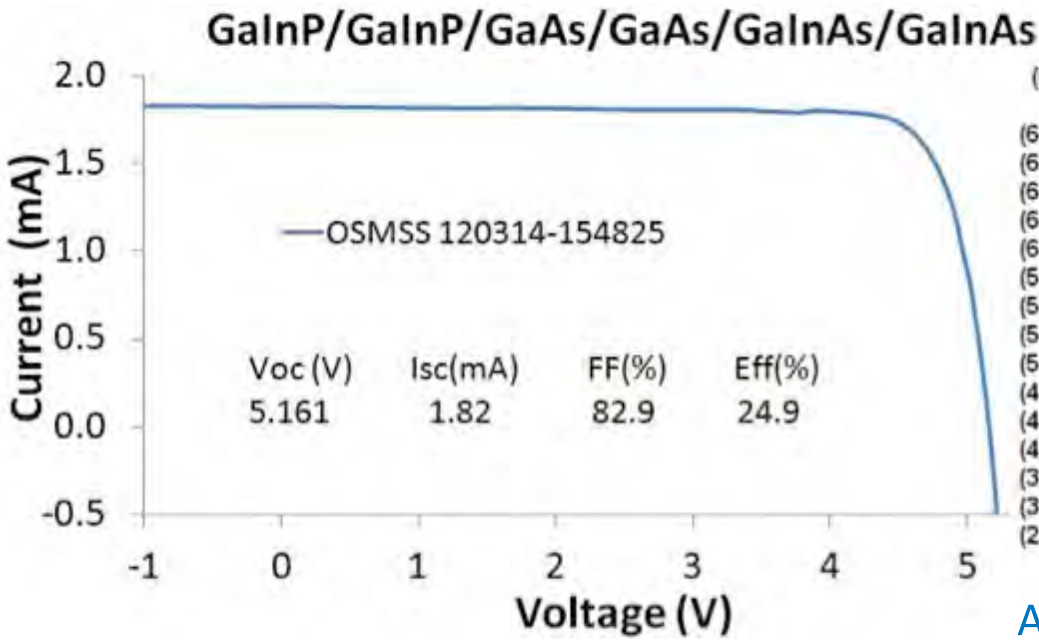


10-80 °C, 9 cm square at 1 sun
Test Bed mounted on X-Y stage

6-junction result





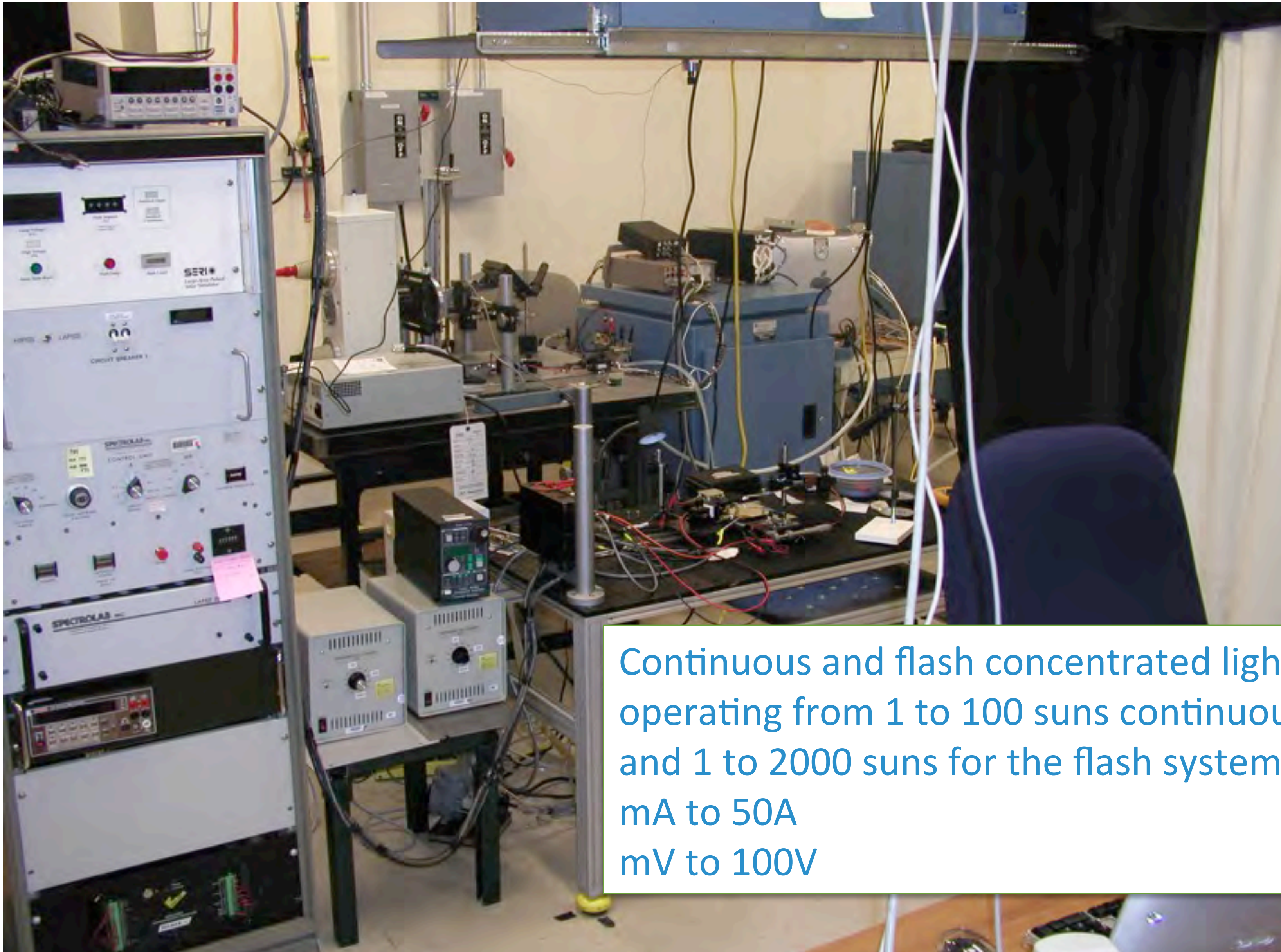


(i,j)	R_{ij}
(6, 5)	1.0001
(6, 4)	0.9968
(6, 3)	0.9961
(6, 2)	0.9973
(6, 1)	0.9976
(5, 4)	0.9967
(5, 3)	0.9960
(5, 2)	0.9972
(5, 1)	0.9975
(4, 3)	0.9993
(4, 2)	1.0005
(4, 1)	1.0008
(3, 2)	1.0012
(3, 1)	1.0015
(2, 1)	1.0003

Tom Moriarty, Joe Jablonski, Keith Emery ,"Algorithm for Building a Spectrum for NREL One-Sun Multi-Source Simulator," 38th IEEE Photovoltaic Spec. Conf., Austin, TX, June 3-8, 2012.

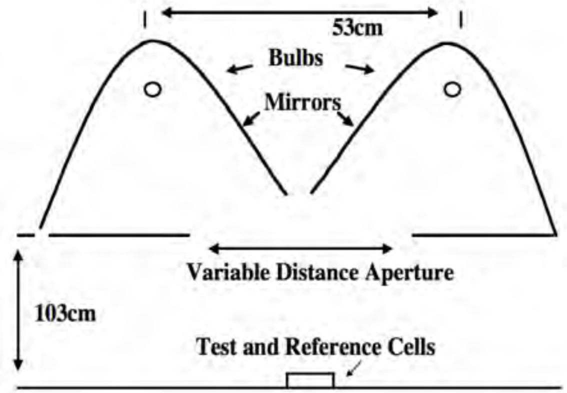
All photo-current ratios less then 0.5%!

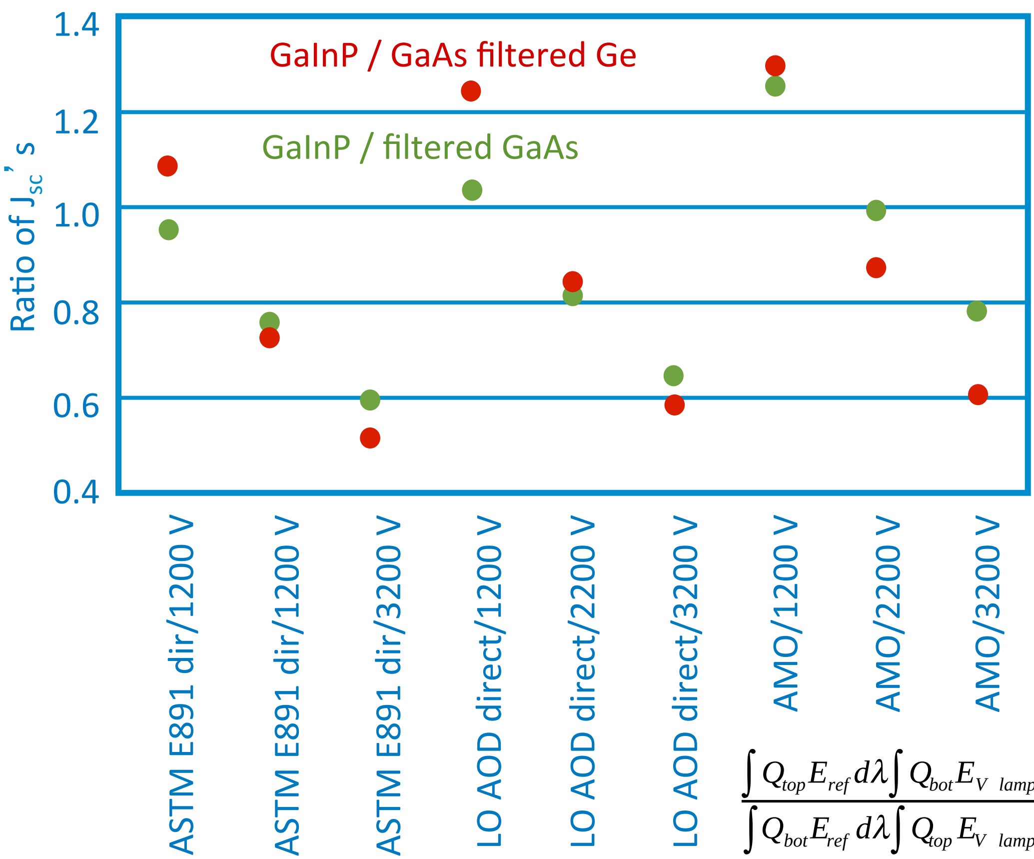
Concentrator Cells



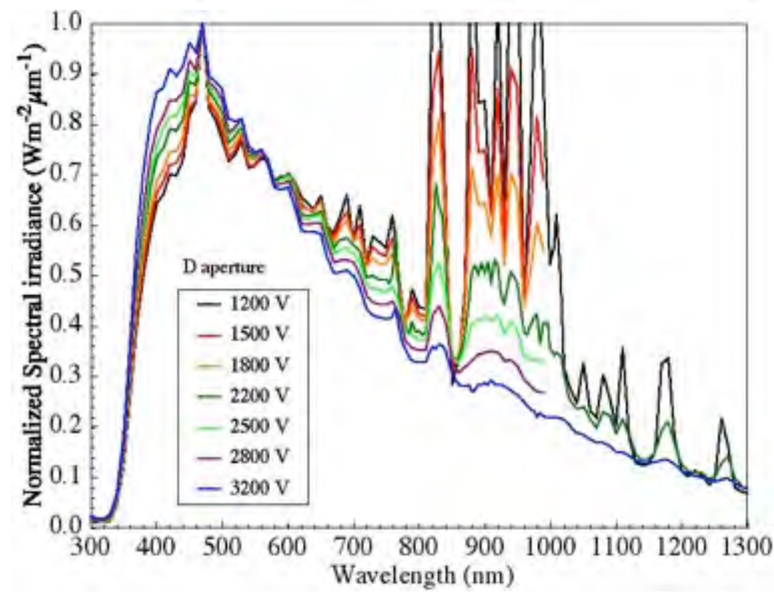
Continuous and flash concentrated light operating from 1 to 100 suns continuous and 1 to 2000 suns for the flash system
mA to 50A
mV to 100V

Concentrator cells





$$\frac{\int Q_{top}E_{ref}\,d\lambda \int Q_{bot}E_{V\ lamp}\,d\lambda}{\int Q_{bot}E_{ref}\,d\lambda \int Q_{top}E_{V\ lamp}\,d\lambda}$$

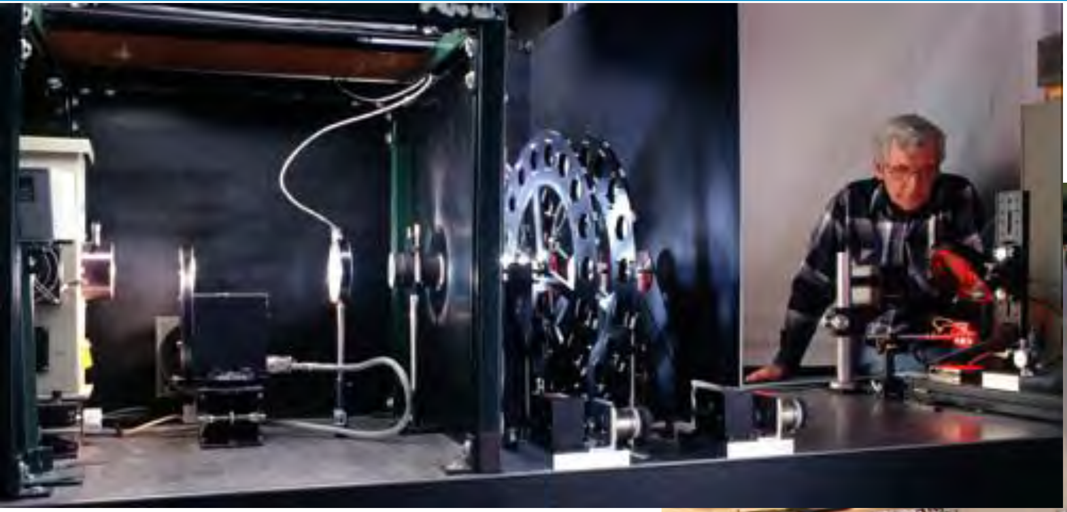


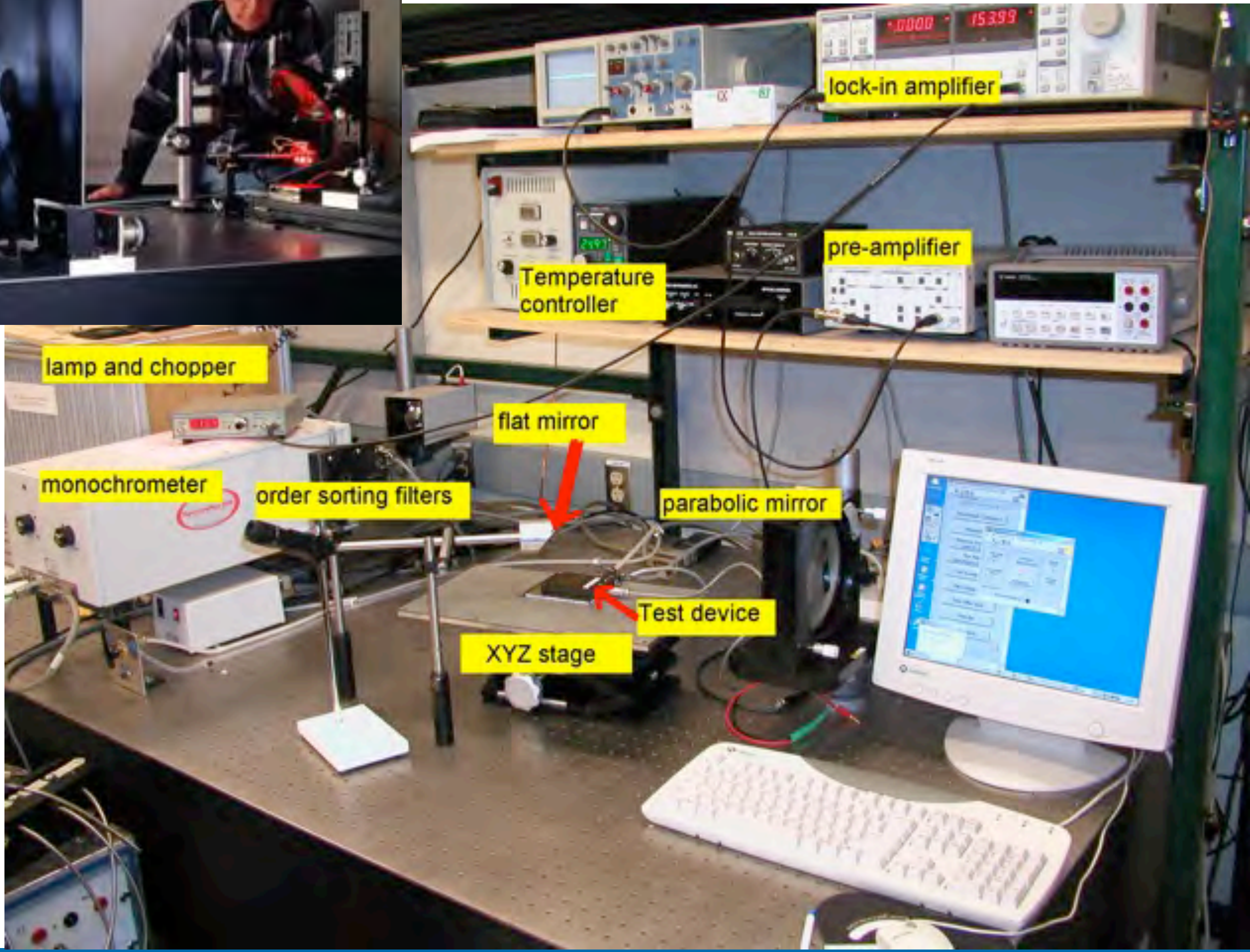
J. Kiehl, K. Emery and A. Andreas, "Testing Concentrator Cells: Spectral Considerations of a Flash Lamp System," *Proc. 19th EU PVSEC*, Paris, June 7-11 2004.

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	150 W Xe	350-2800 nm 3 - gratings	1 by 3 mm minimum

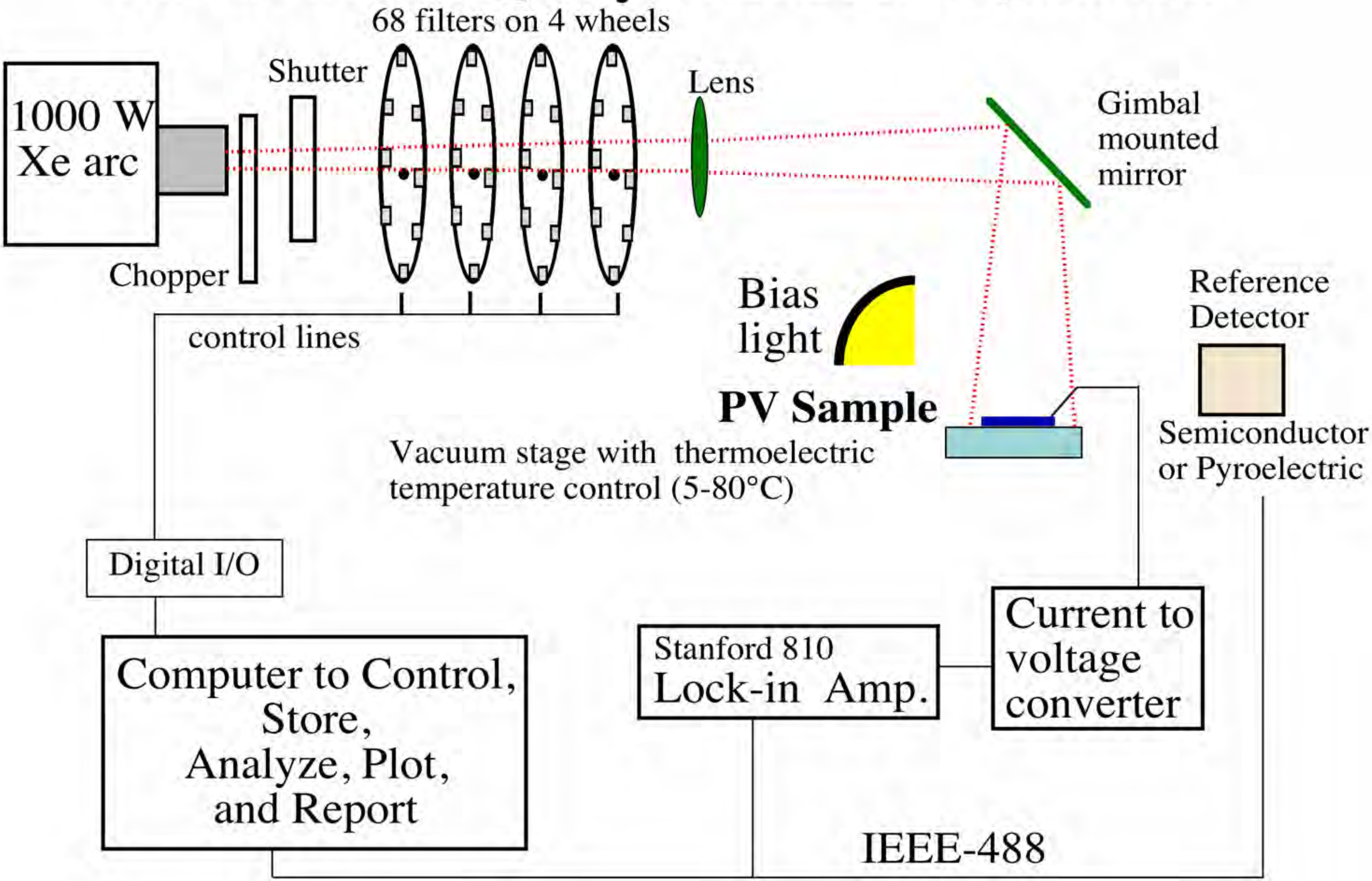
NREL QE systems



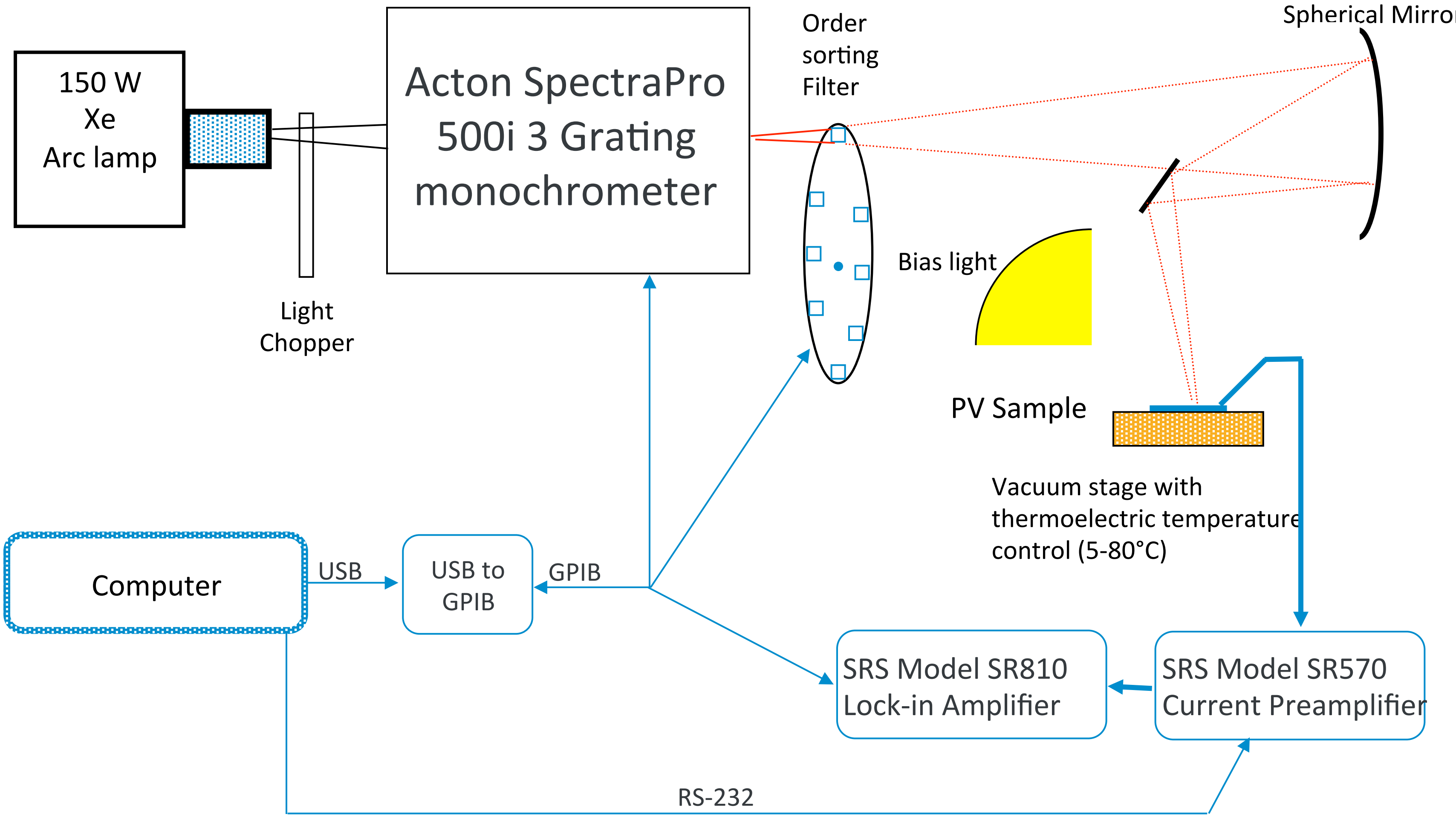


The spectral responsivity is measured with a filter based system (280-1800 nm) or a grating based system 350-2800 nm

NREL Filter QE system 280 - 2,000 nm



NREL Grating QE system



Module I-V Equipment

Test bed	area	min / max V	min / max I
Large Area Continuous Simulator (LACSS)			
filtered 25 kW Xe	150 x 120 cm	±0.1 mV	±10 μA
Continuous CLASS AAA		±300 V	±60 A
Spatial nonuniformity dominant error			
±3.9% uncertainty in P_{max} with 95% confidence limit from formal error analysis			
Error in Pmax dominated by error in I_{sc}			
Standard Outdoor Measurement System (SOMS)			
fixed tilt adjusted monthly,	No constraints	±0.1 mV	±1 μA
Adjustable azimuth & elevation		±300 V	±60 A
lowest error in Isc because zero uniformity error			
temperature related errors dominant			
Spire model 4600SLP	200 x 137 cm	0.08 mV	0.1 mA
2 Xe flash lamps		150 V	20 A
50 to 80 ms pulse duration			
Pulsed CLASS AAA			

Spatial nonuniformity dominant is error source. This can be minimized by a reference module of the same size and cell arrangement as what is being tested.

Excellent repeatability (<0.5% over many days)

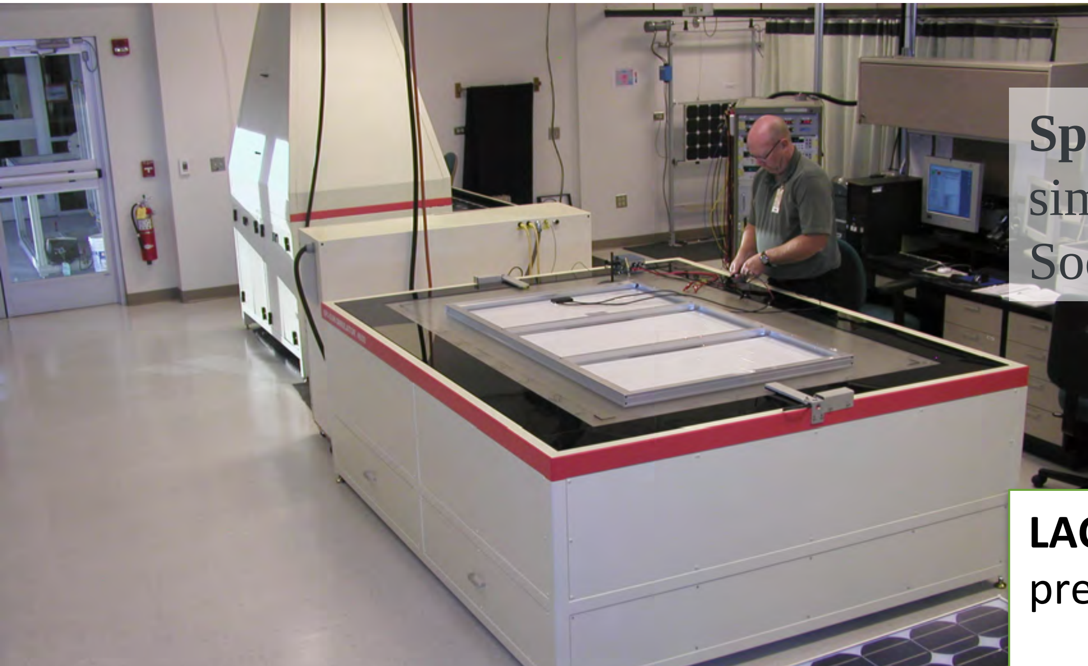
±5.0% uncertainty in P_{max} with 95% confidence limit from formal error analysis

Error in Pmax dominated by error in I_{sc}

SOMS

Good spectrum and spatial nonuniformity, poor temperature control. Spectral irradiance measured to correct for spectral error. Si cell in module package is reference for irradiance and spectral corrections. Pyranometer is for comparison only.

Module Simulators

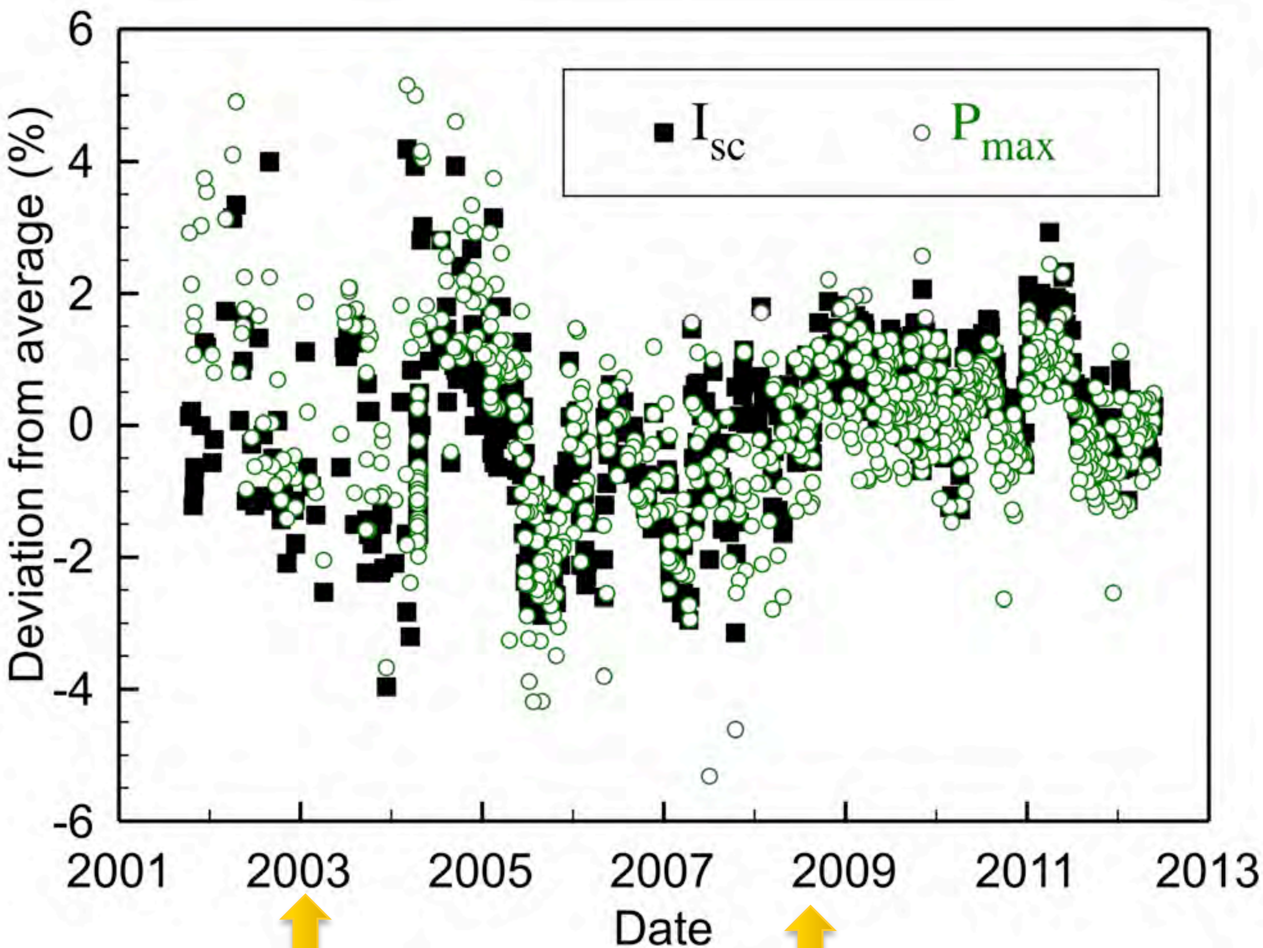


Spire SLP 4600 pulsed module simulator in recently expanded OTF
Soon to be replaced by Spire 6500

LACSS - light, dark IV, full control of premeasurement conditions and bias rate,

Internal Intercomparisons are Critical

mono-Si Check Module on LACSS Module Simulator



new reference cell

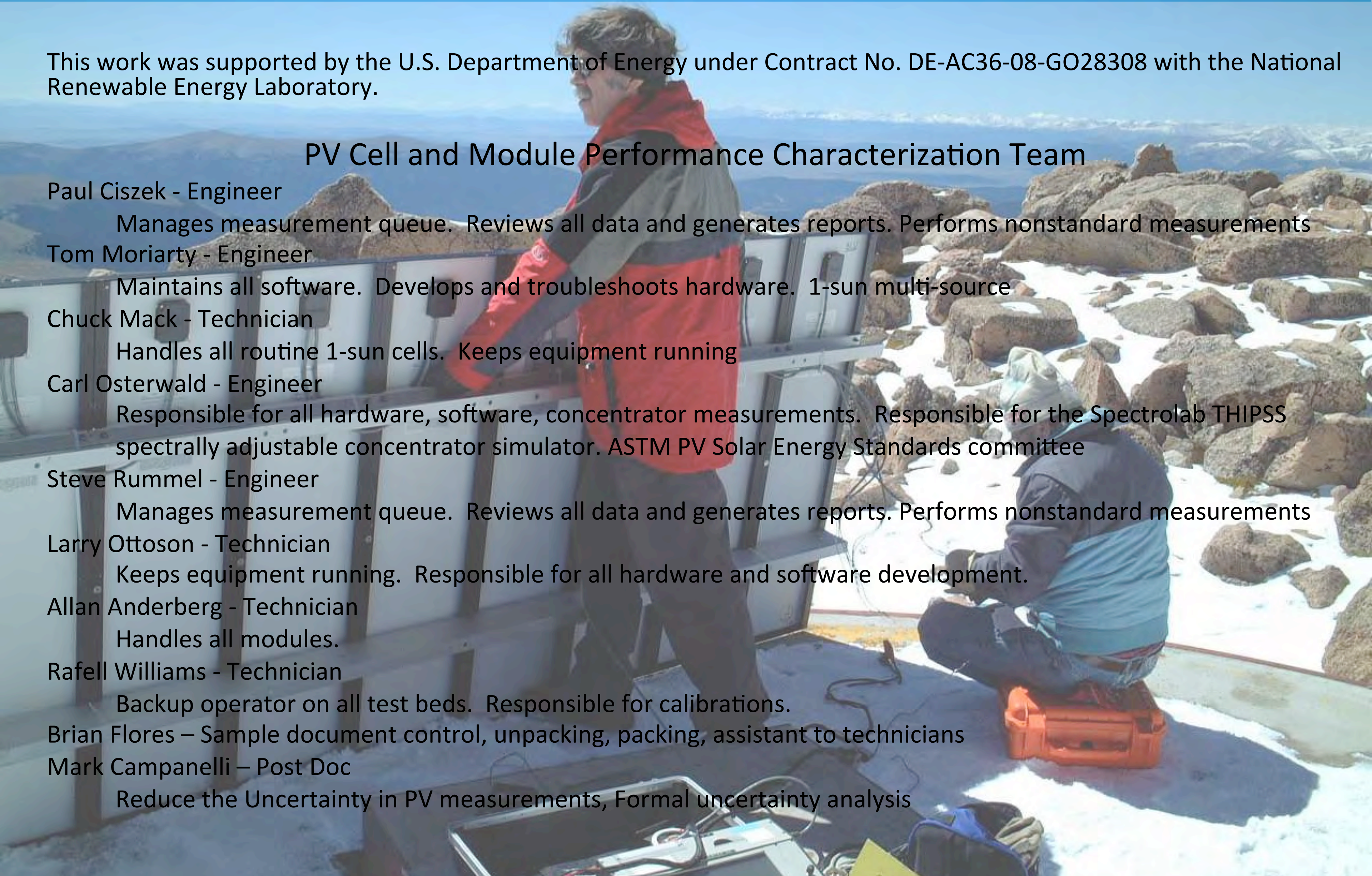
new reference spectrum +0.9% increase in I_{sc}

Concentrator Modules

Summary

- NREL has equipment to measure any conceivable cell or module technology
- Lack of standards for low concentration modules complicates matters
- Spectrally adjustable simulators critical for more then 3 junctions. NREL's 10-channel fiber optic simulator has shown that the light can be set for each junction within 1% of what it would be under the reference spectrum for up to a 5 junction cell.
- Uncertainty in Module simulators dominated by spatial nonuniformity for calibration labs. Manufacturers can mitigate this error by using matched reference modules instead of cells.

Acknowledgements



This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory.

PV Cell and Module Performance Characterization Team

Paul Ciszek - Engineer
  Manages measurement queue. Reviews all data and generates reports. Performs nonstandard measurements

Tom Moriarty - Engineer
  Maintains all software. Develops and troubleshoots hardware. 1-sun multi-source

Chuck Mack - Technician
  Handles all routine 1-sun cells. Keeps equipment running

Carl Osterwald - Engineer
  Responsible for all hardware, software, concentrator measurements. Responsible for the Spectrolab THIPSS spectrally adjustable concentrator simulator. ASTM PV Solar Energy Standards committee

Steve Rummel - Engineer
  Manages measurement queue. Reviews all data and generates reports. Performs nonstandard measurements

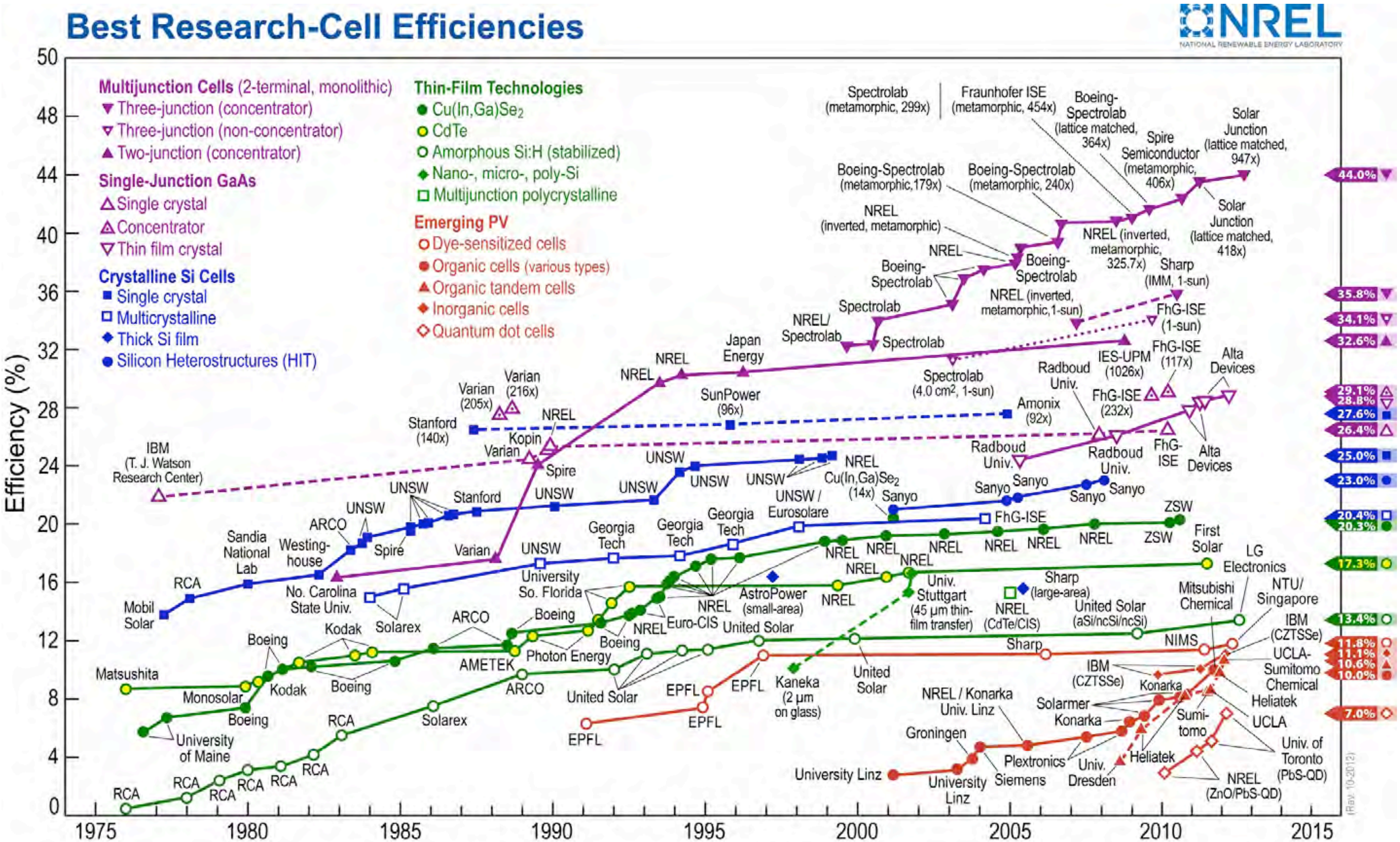
Larry Ottoson - Technician
  Keeps equipment running. Responsible for all hardware and software development.

Allan Anderberg - Technician
  Handles all modules.

Rafell Williams - Technician
  Backup operator on all test beds. Responsible for calibrations.

Brian Flores – Sample document control, unpacking, packing, assistant to technicians

Mark Campanelli – Post Doc
  Reduce the Uncertainty in PV measurements, Formal uncertainty analysis



Record cell efficiencies over time by technology measured by recognized independent test labs.
There are no area or stability constraints beyond testing in air for inclusion in this table.
http://www.nrel.gov/ncpv/ or http://en.wikipedia.org/wiki/Solar_cell_efficiency