# QUANTUM EFFICIENCY MEASUREMENT SYSTEM

## Includes IV Testing, Spectral Response, Quantum Efficiency System/ IPCE System and Upgrade

Spectral range 250 - 2500 nm

- Monochromatic light power up to 125 mW total
- Keithley 2400 series source meter (Measurement of large capacitance solar cell is possible.)
- Stanford SR800 series lock-in amplifier
- Light-tight measurement chamber
- DC and AC mode measurement capability

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## A. Overview

Photovoltaic devices are so called since they rely upon the photovoltaic effect that was first discovered by a French experimental physicist, Edmund Becquerel, in 1839 to generate a current/voltage upon exposure to light. However, the history of practical PV devices did not begin until 1954 when Bell Laboratory first demonstrated a silicon solar cell with a conversion efficiency of 6%.

Sciencetech Inc. has been designing and manufacturing modular optical spectroscopy instruments and components for over 30 years. They are widely used all over the world in research laboratories, universities and companies. Sciencetech instruments are designed with the researchers in mind and feature fully adjustable controls for research flexibility. All Sciencetech systems incorporate modular design and adherence to industry standards for easy integration with other supplier's instruments and components.

Sciencetech Inc. designs and fabricates four different variants of Photovoltaic Testing System (PTS), as shown in the following table, for implementation of different experimental methods.

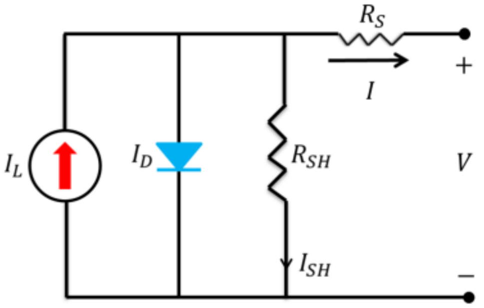
| Model | IV | SR | EQE | CPM | DBP | SSP | IQE | PDS |
|---|---|---|---|---|---|---|---|---|
| PTS-2-QE | X | X | X | | X (upgrade) | | X (upgrade) | |
| PTS-3-CPM | X | X | X | X | X (upgrade) | | X (upgrade) | |
| PTS-3-PDS | X | X | X | | X (upgrade) | | X (upgrade) | X |
| PTS-4-SSP | X | X | X | | X (upgrade) | X | X (upgrade) | |

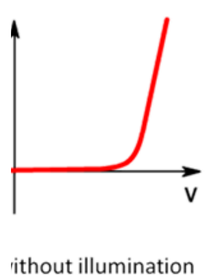
This technical note provides the specific description and features of Sciencetech PTS-2-QE / IPCE system. The PTS-2-QE / IPCE system provides all the capabilities of measuring IV curves, SR, EQE as well as IQE (based on the requirements for upgrading from the customers). Readers interested in CPM, DBP, PDS and SSP can refer to our technical notes on PTS-3 and PTS-4 systems, respectively.

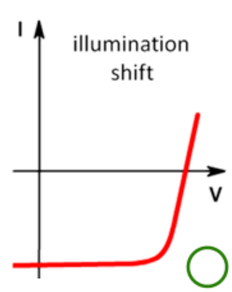
### The quantities our PTS-2-QE / IPCE system measures are:

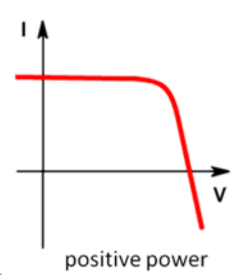
### - Current-voltage characteristics (IV)

The photocurrent running through a solar cell is the superposition of the current generated by the solar cell under illumination and the current of the solar cell diode in the darkness. The illuminating light has the effect of shifting the IV curve down into the fourth quadrant, where power can be extracted from the diode. The basic equation and IV curves are shown in the figures below.



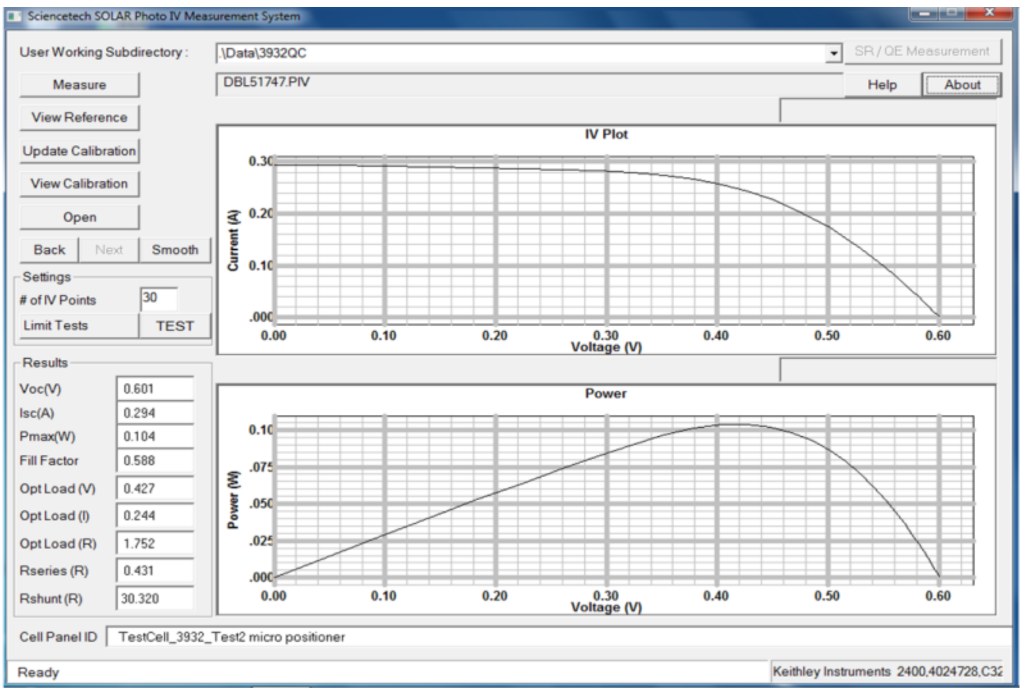




$$I = I_L - I_{SH} - I_D = I_L - \frac{V - V_S}{R_{SH}} - I_0\left(e^{\frac{e(V-V_S)}{nkT}} - 1\right)$$

Parameters are: $I_L$ , the photo current generated by the solar cell that can be used for an external load under illumination; $I_D$, the net current flowing through the diode; $I_0$, the diode's leakage dark saturation current in the absence of light; $R_{SH}$, a current consuming resistor parallel to the solar cell diode due to manufacturing defects; $R_S$, a resistor in series with the solar cell circuit due to contact between different metal parts in a solar panel circuit; $I_{SH}$, the current flowing through the shunt resistor; I, the total output current from the solar panel; V, the voltage across the cell terminals; T, the temperature in Kelvin; e and k, constants for charge of a single electron and Boltzmann constant, respectively; Finally, n is the ideality factor and Vs is the voltage across Rs.

The effect of a shunt resistance is to consume the cell-generated current so the total output current drops due to this diversion. The effect of a series resistance is to reduce the fill factor, which is a drop in the output power from the solar cell.

A source meter (Keithley 2400) used as an active load permits operating the solar cell under test at various load conditions, including short-circuit, compensating for a series resistor required to sense the current produced by the solar cell from the bias light.

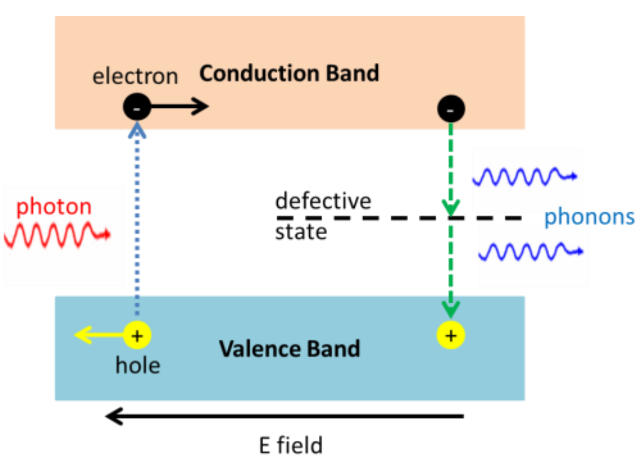



The software controls the source meter to automatically measure the following IV characteristics (an example shown on the left):

- Dark IV
- Open-circuit voltage Voc (as well as Voc slope)
- Short-circuit current Isc
- The maximum power Pmax (Vmax and Imax)
- Fill factor
- Forward and reverse sweep features
- The shunt resistance $R_{SH}$ and $R_S$

## - Spectral response (SR)

The spectral response is the ratio of the current generated by the solar cell to the power incident on the solar cell, thus in the unit of A/W. The measurement of SR should be performed using a monochromatic probe beam under simultaneous illumination by a Solar Simulator (SS, i.e., bias light) (ASTM E 1021).




The use of the SS mimics the true operating conditions and is also related particularly to the quality of the material. In poor quality material, the crystal has defective states, where generated carriers lose their energy on phonons and return back to the valence band, leading to incorrect measurement of spectral response, as shown in the figure below. Light from the SS generates a large amount of carriers which help fill/pump the defects/traps so that those carriers generated by the probe beam are not lost.

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# QE / IPCE SYSTEM

To distinguish the photocurrent generated from the weaker probe beam from the photocurrent generated from the stronger SS beam, the probe beam is amplitude modulated with the use of an optical chopper. Finally, the SR measurement is performed by focusing a monochromatic beam onto the sample and registering the photocurrent generated as a function of wavelength (as shown in the first figure on page 8). This sensed current plus a reference signal at the frequency of the light modulation (amplitude modulation from the chopper) are both fed into the lock-in amplifier to allow measurement of the photocurrent generated by the modulated monochromatic light.

Unless a different request is made, the geometry of the light from the Monochromator is controlled to illuminate only a small section of the solar cell (typically 3mm diameter), ensuring that 100% of the monochromatic irradiance contributes to the output signal. Sciencetech's QE system also allows users to switch from this "automatic mode" to the "manual mode" for setting their own measurement conditions based on the research requirements.

## - External Quantum Efficiency (EQE / IPCE)

External Quantum Efficiency is defined as the ratio of the number of carriers generated and collected by the solar cell to the number of photons of an incident beam without considering the losses due to reflection, transmission, or absorption from the sample. It is usually given as a function of wavelength and has a straightforward relationship with SR as follows:

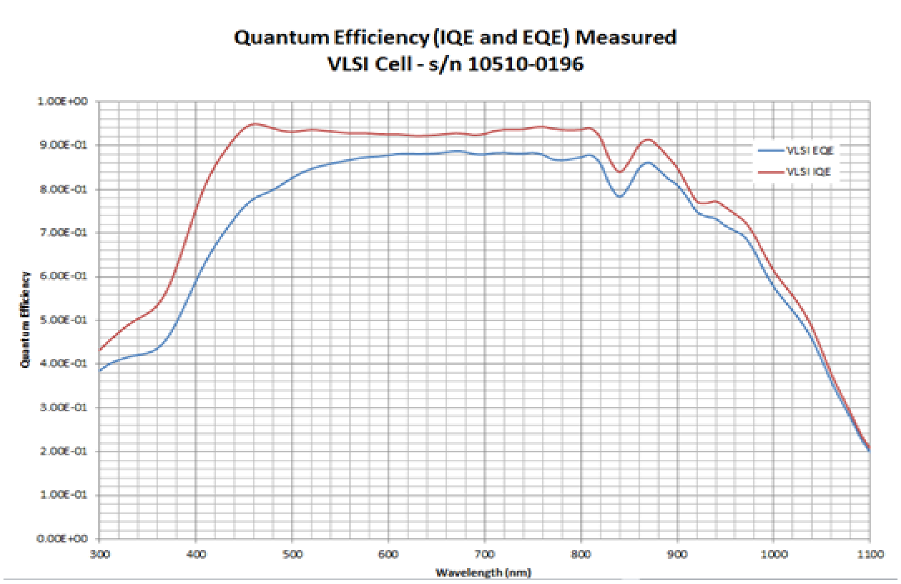
$$\mathrm{QE} = \frac{hc}{e\lambda}\mathrm{SR} = \frac{\mathrm{SR} * 1240}{\lambda}$$

where the wavelength is in the unit of nm and SR is in A/W.

## - Internal Quantum Efficiency (IQE)

Internal Quantum Efficiency is a calculation of the QE with consideration of the losses at the sample, i.e., the ratio of the number of carriers generated and collected by the solar cell to the number of photons that are truly converted by the solar cell.

Instead of attempting to measure the losses directly using an integrating sphere, Sciencetech determines total QE losses by making two QE measurements under different conditions which emphasize external surface effects, allowing losses due to reflection and scattering to be inferred more accurately than would normally be possible to measure. This allows a wider range of sample sizes, and provides accurate, precise information on IQE.




Once the losses are determined the Internal Quantum Efficiency can be simply calculated through the following expression:

$$\mathrm{IQE} = \frac{\mathrm{EQE}}{1 - \mathrm{losses}} = \frac{\mathrm{EQE}}{\mathrm{absorption}}$$

where losses we measured include the reflection from and the transmission through the sample. Absorption rate is the portion that converts photons to carriers in the sample.

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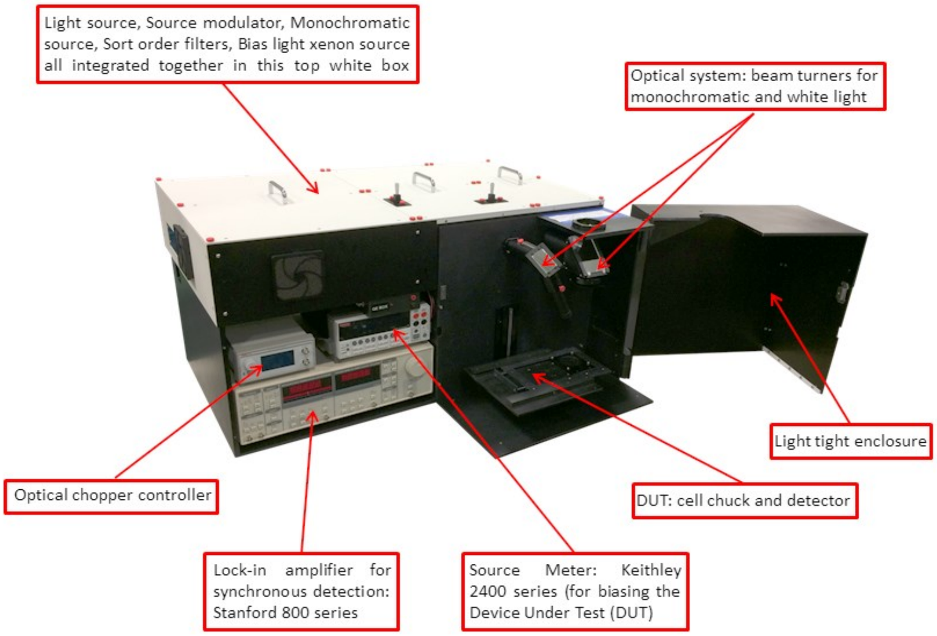


## B. Specifications

- Complete SR, QE, IQE and IV measurement system with software: The system includes the bias light source, monochromator with automated order sorting filters, steady-state solar simulator Class AAA, measurement electronics, computer, and software required to measure solar cell characteristics.
- Light tight sample enclosure
- All components are assembled on Sciencetech's integrated optical and electronic mounting system with 54 cm x 92 cm desktop footprint.
- 1 Sun low-noise bias light source with AM1.5G filter is included for QE and IV measurements.
- Can include intensity attenuation features upon request.
- Filter holder is mounted in the optical path, which allows two filters to be mounted in series.
- Manually controlled shutter is included to regulate the light exposure time.
- Bias voltage range is available from 0 to 200 V.
- Photocurrent measurement resolution ranges from 10 picoampere to 10 microampere depending on the range.
- Sample enclosure with adjustable dual cell holder and target table of 150 mm height adjustment.
- Power system, single phase, can be configurable for 230 VAC, 50 Hz or 110 VAC, 60 Hz.
- Shielded and light tight test area enclosure has convenient removable cover allowing access from top, front and sides.

# QE / IPCE SYSTEM

| | |
|---|---|
| Light Source for Monochromator | • 150W Xe arc lamp or 250W QTH tunable source, average lifetime 1200 hours<br>• As low as 0.5% instability<br>• 250 - 2500 nm tuning/scanning range (Xenon) |
| Monochromator | • Czerny-Turner design with adjustable bandpass 0.2 to 10 nm<br>• Motorized triple grating system<br>• Monochromatic probe light power<br>• Beam size : (0.1 cm × 0.1 cm) to (0.5 cm × 0.5 cm) |
| Order Sorting Filters | • Filters 1, 2, 3, and 4 with cut-on wavelengths at 280 nm, 475 nm, 850 nm, and 1500 nm<br>• Filter diameter 25.4 mm (1”) |
| Bias Light Source | • 75 W Ultra-stable Xe arc lamp, average lifetime 1200 hours<br>• 2” bias light/ 1” class AAA (ASTM E927) Solar Simulator<br>• Adjustable spot size |
| Reference Detector | • 5mm diameter, broadband pyroelectric<br>• Calibrated range 250 - 2500 nm<br>• Reference solar cells 20 mm x 20 mm<br>• Specialized chuck 76.2 mm x 76.2 mm (3” x 3”) |
| IV Tester | • Source meter Keithley 2400<br>• Maximum electric power reading 20 W<br>• Maximum voltage 200 V and maximum current 1 A<br>• Voltage accuracy 0.015% and current accuracy 0.22%<br>• Measurement time period for 100 IV points is 44 s |
| Data Acquisition | • Stanford Lock-in Amplifier SR800 series (LIA-810)<br>• Collected data exportable as ASCII file compatible with MS Windows<br>• Chopper 1-200Hz |
| Interface | • RS-232 (at least 1 hardware serial port) and USB |
| System Dimensions | • 92cm x 54cm x 54cm (36” x 21” x 21”) |

| | |
|---|---|
| Standards | • IEC 60904-1 Measurement of photovoltaic IV characteristics<br>• ASTM E 1036 Standard test methods for electrical performance of nonconcentrator terrestrial photovoltaic modules and arrays using reference cells<br>• ASTM E 1021-15 Standard test method for spectral responsivity measurements of photovoltaic devices |

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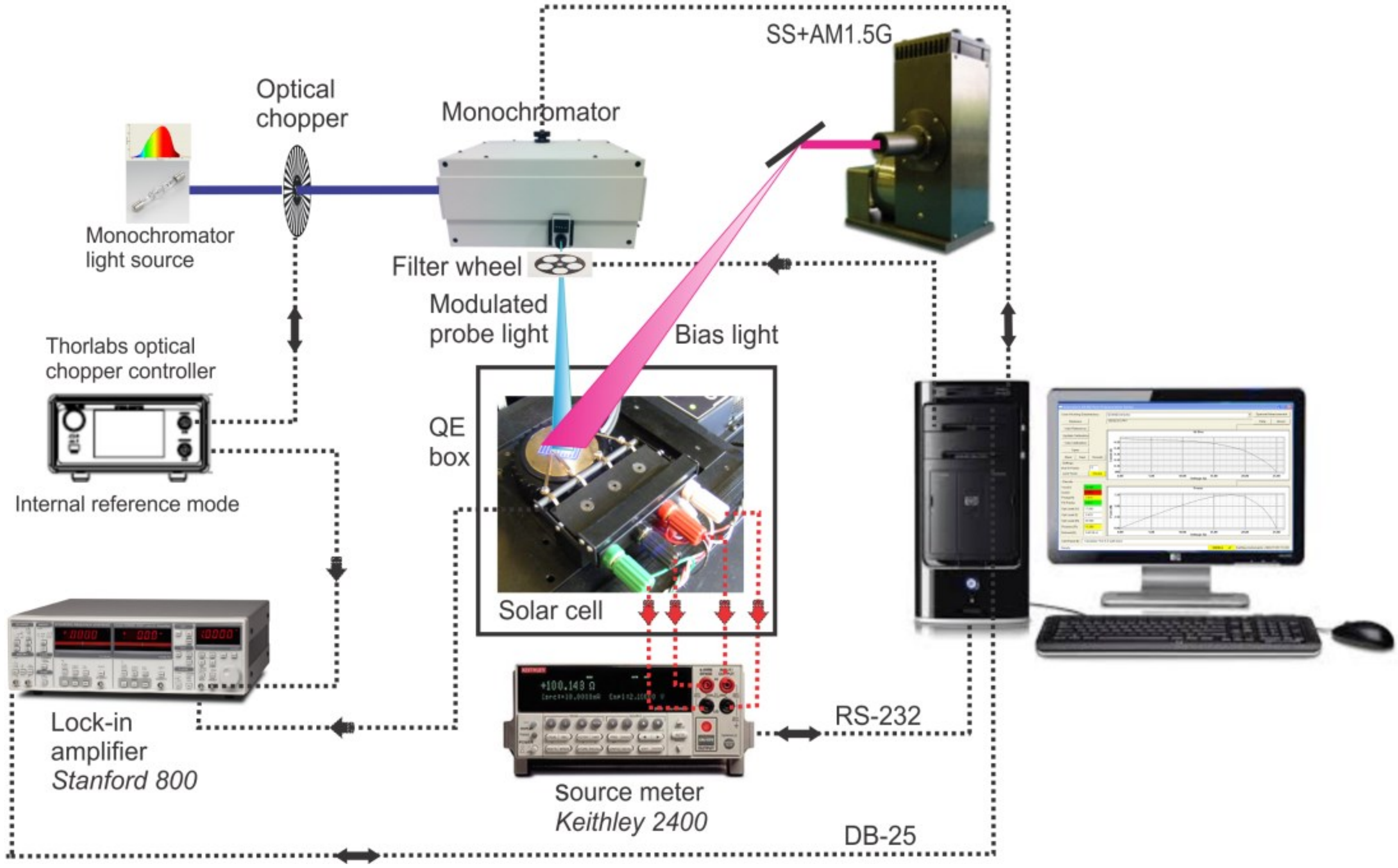
## C. Configuration




## D. Optional specifications and accessories

| | |
|---|---|
| Monochromatic Light Source | • An option to concentrate light spot in a 1mm x 4mm rectangle for rectangular samples. |
| Temperature controlled vacuum chuck with probes | • 15.2cm x 15.2cm (6" x 6") maximum sample size inside standard chamber and minimum cell size 3.8cm x 3.8cm (1.5" x1.5")<br>• For automated stage a specific chuck size could be customized<br>• Brass plated tin; Optional: gold plate, gold or nickel coating<br>• Temperature Controlled range -10 °C - 80 °C |
| Bias Light | • Adjustable irradiance up to 5 Suns |
| Dual light source system | • Combined Tungsten and Xenon lamps for higher light efficiency |
| Automated Stage | • Customized X-Y-Z translation stage and probe station for automated characterization using PTS system |

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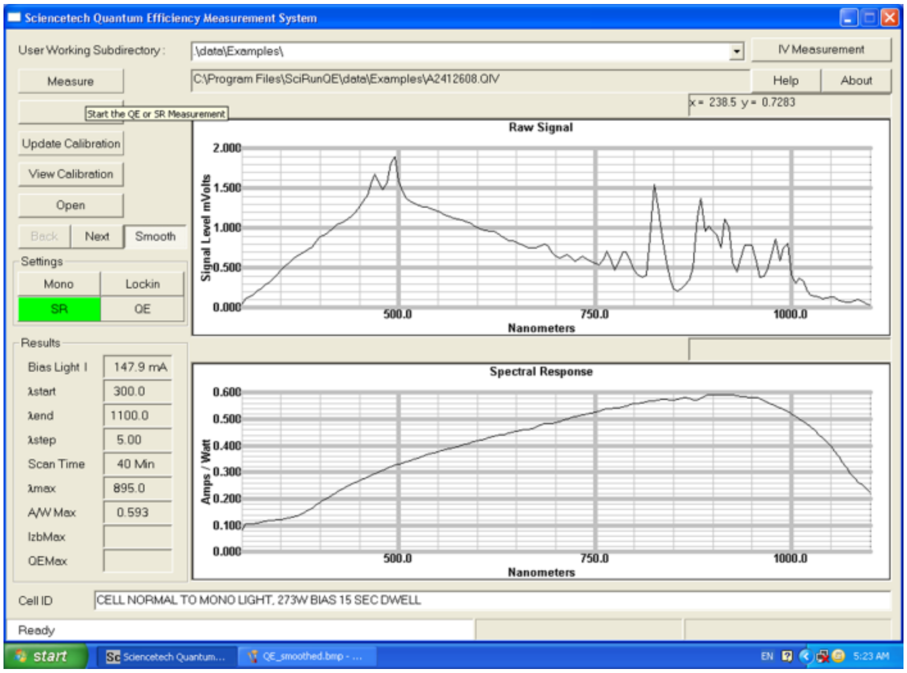
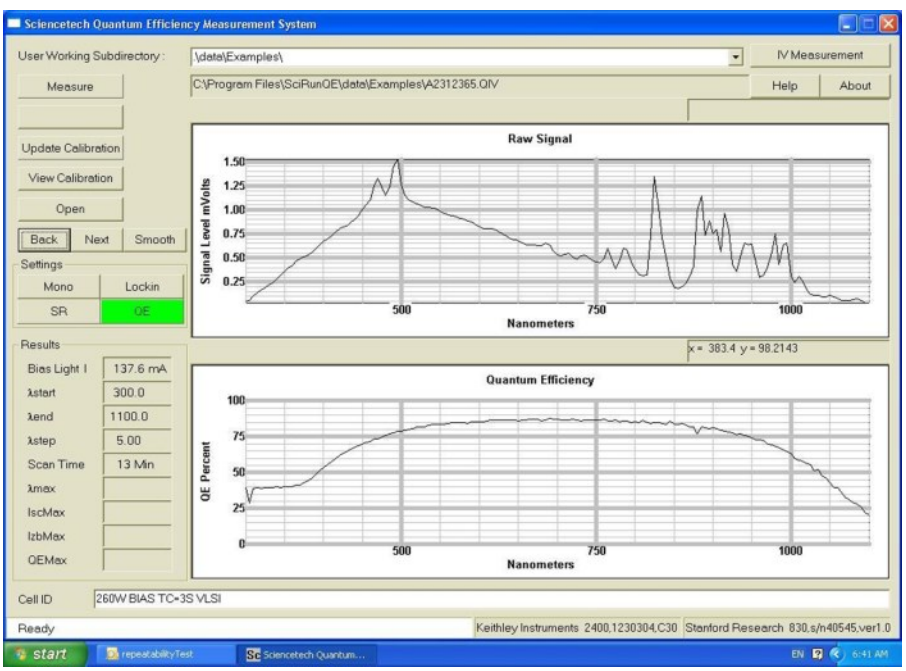
## E. Software features

The PTS-2-QE / IPCE-IQE system comes with a fully integrated software package, capable of controlling every aspect of the system:




- MS Windows based
- Automation of data acquisition with simple command scripts
- Data acquisition and automation log-keeper data stored in ASCII format
- Visualization corresponds to LabVIEW standards.
- Graphical and data output can be in a wide range of file types.
- Sciencetech may supply source code to customers that wish to further modify the system or integrate it into existing computer framework.

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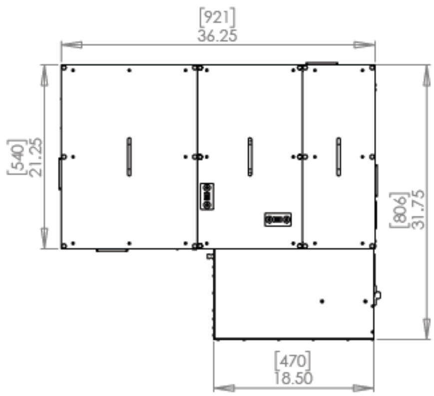
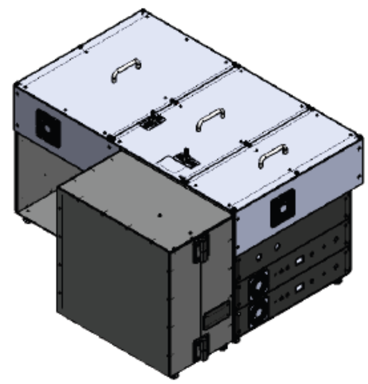
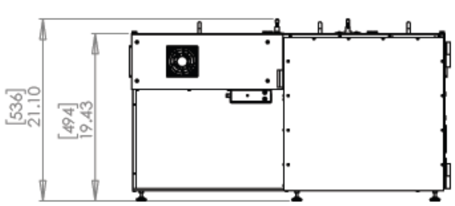
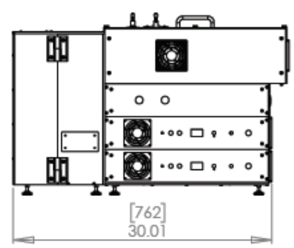
## F. Dimensions: [mm] and inch



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