A Benchtop Light Simulator for Standards-based Characterisation of Indoor Solar Cells and Sensors

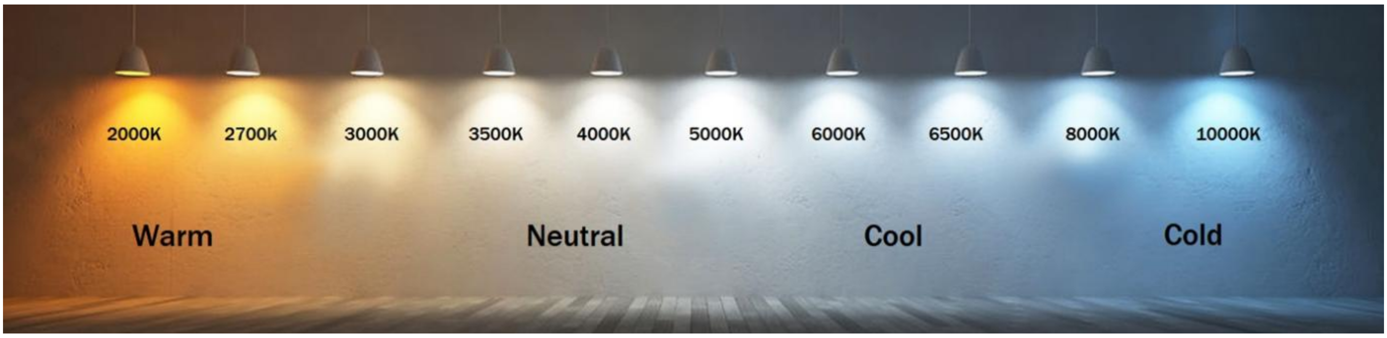
Executive Summary

With the growing adoption of photovoltaic cells designed specifically for use under indoor ambient light conditions, there is an increasing demand for an accurate method to compare the performance of cells using different materials systems or from different suppliers. Despite this requirement there are few light simulators available that have been designed specifically for the characterisation and performance measurement of indoor solar cells. As recently reported by PV Magazine International, Oxford-based Lightricity has recently launched its benchtop "LightBox Indoor Light Simulator". It enables the accurate and reproduceable characterisation of indoor solar cells under a range of light levels from below 10 lux to 50,000 lux and is available in two sizes. The light uniformity of the Lightbox has been measured by the UK's National Physical Laboratory (NPL), as part of an A4i grant from Innovate UK. The LightBox STD and LightBox XL are available now.

Introduction:

With the continued growth of low energy wireless sensors enabling the IoT world, there is great interest in developing alternatives to batteries for powering these devices. Energy harvesting technologies have been shown to be reliable and able to power these sensors thereby enabling more sustainable systems and solutions. The use of indoor ambient light as an energy source is growing in popularity, however, there are numerous different technologies used in photovoltaic systems, including a variety of material systems, chemistries, processing routes and module designs. The variety of solar energy harvesters on the market offers a challenge to designers. How do you compare the performance of the different technologies available? What are the parameters and conditions that need to be considered when evaluating and characterising the performance of a PV cell under indoor light conditions?

Consideration needs to be made for the Correlated Colour Temperature (CCT) and the Colour Rendering Index (CRI) as they impact not only the light quality but also on the energy that can be generated when harvesting light under different light sources. The figures below illustrate the range of colour temperatures (from 2000K to 10’000K) and CRI (from 70 to 90) available.



For indoor applications, the recent IEC specification “IEC TS 62607-7-2:2023” stipulates that CIE LED B4 (5108K) should be used as the reference spectrum for LED illumination.

There are very few characterisation tools available on the market that are: calibrated, reliable, accurate and can replicate a range of different indoor light conditions. This problem has been solved with the introduction of the **LightBox Indoor Light Simulator**. This compact device can characterise the performance of indoor solar energy harvesters, enabling engineers to compare different cell technologies and geometries under a variety of controllable and reproduceable light conditions. Furthermore, it is available in two different sizes: 110mm x 110mm x 80mm incorporating a 5 x 5 array of white LED lights

LightBox STD (110mm x 110 mm x 80mm)

and a larger version 185mm x 185mm x 85mm incorporating an 11 x 11 array of white LED lights. Moreso, the compact and modular design provides the required flexibility, for example the bottom plate can be removed so that the samples can be placed on a hot plate enabling the performance to be measured at elevated temperatures. The LightBox from Lightricity offers a cost-effective alternative to in-house design and build of a custom light simulator.

LightBox XL (185mm x 85 mm x 85mm)

The LightBox Indoor Light Simulator:

In designing an indoor light simulator, there were a number of design criteria that needed to be achieved, these were:

- Complying with the most recent standards IEC TS 62607-7-2:2023
- For the light source to be calibrated and easily interchangeable
- For the simulator to be compact and suitable to operate from a laboratory benchtop
- To be operable from a laptop or PC utilising a connection via a USB cable
- Allows the automatic acquisition of current-voltage and power-voltage curves
- Is compatible with standard source meters for example Keithley, Keysight via a GPIB-USB interface
- Affordable

There was also a great deal of consideration of what light conditions would need to be simulated in order for the LightBox to replicate light conditions typically found in practice. The typical light level in an office will be in the range 500 to 1000 lux, however, if one considers a hospital environment then the light levels will generally be lower at between 400 and 800 lux. In the home a living room may have light levels below 100 lux when watching television. The Table below provides a guide to typical light levels in different environments.

Hence, you can see that the light simulator must be capable of reproducing a wide range of light intensities and for this reason a system has been developed that can operate between below 10 lux and 50k lux; covering most light conditions that will be found in the majority of use cases. The illuminance level is controlled by 4 in-built lux sensors with an accuracy of above 99% and to enable temperature compensation the temperature is monitored at up to 3 locations within the LightBox chamber.

Lighting Conditions	
Environment	**Typical *lux* Value**
Dim corridor	50-100
Restroom	100-300
Homes	200-400
Office – Open	300-500
Kitchen	300-750
Hypermarket	1000
Outside under tree shading	3000-10000
Bright sunlight	>100000

CCT	Environment	Application
2700K to 3000K	Relax and comfortable	Residential, Hospitality
4000K	Balanced illumination	Kitchen, Bathroom, Commercial, Retail, Office
> 5000K	Precision and focus	Industrial, Warehouse, Workshop, Garage

CRI	Colour Accuracy	Application
70 to 79	Fair	Outdoor lighting, warehouses, and industrial spaces
80 to 89	Good	Residential and commercial spaces (e.g., homes and offices)
90+	Excellent	Art galleries, photography studios, design workspaces

Light conditions and light intensities for typical indoor environments

Applications:

Indoor PV cells first came into public use in the late 1970's with the invention of the light powered electronic calculators from the likes of Sharp and Casio. Around the same time light powered digital watches were introduced by Seiko, Citizen, Casio and others; both calculators and wristwatches were powered by silicon cells. However, the advent of the Internet of Things and low-power wireless communications has generated renewed interest in indoor PV and the research and development on new material systems. Recent progress in the development of dye Sensitised Cells (DSC), organic PV (OPV), perovskite-based technology and compound semiconductor cells is opening up new application opportunities.

A range of sensors can now be powered by light energy harvesters; these include sensors for monitoring the indoor environment, measuring light level, temperature, relative humidity and CO_2 level for example. In warehouses, hospitals and chemical plant light energy harvesting powered sensors can track assets, whether they be people working in hazardous environments such as lone worker alarms in chemical plants, or portable medical equipment in hospitals where knowing asset location can improve productivity and welfare.

The LightBox has already found widespread use in universities as a tool to characterise the performance of new indoor PV cells during their development. Similarly, industry has adopted the LightBox as an easy to operate and reliable tool for comparing the performance of commercially available indoor PV cells, enabling product designers and engineers to select the best cells for their specific application and the ability to replicate the indoor light environment helps ensure the products are fit for purpose and there intended application.

Those designing IoT systems that incorporate sensors powered by indoor light have found the LightBox XL to be an ideal tool for characterising the performance of sensor units under a range of light conditions. The larger format enables complete sensor units to be evaluated.

For example, a group based at the University of Oxford led by Prof. Robert Hoye is developing next-generation inorganic light harvesters for indoor PV. They worked with Lightricity to customise the LightBox to be compatible with the standard device layout adopted by many groups working on photovoltaics in Oxford. This platform is now ideal for reliably screening devices rapidly and accurately. With this setup, there is a calibrated light source, enabling accurate and publishable measurements of device efficiency across the whole range of illuminances relevant for powering Internet of Things electronics. The maximum power point can also be tracked to obtain the stabilised power output, and the hysteresis of the current-voltage scans, depending on scan rate and direction, can also be quantified.

Prof. Robert Hoye: “This is now a valuable tool that should be used across all labs working on indoor photovoltaics.”

The LightBox can also find applications in material degradation studies, whereby the impact on materials, either in the PV cell architecture or deployed in the device packaging from soaking under prolonged light conditions can be evaluated.

Technical Specification and Software:

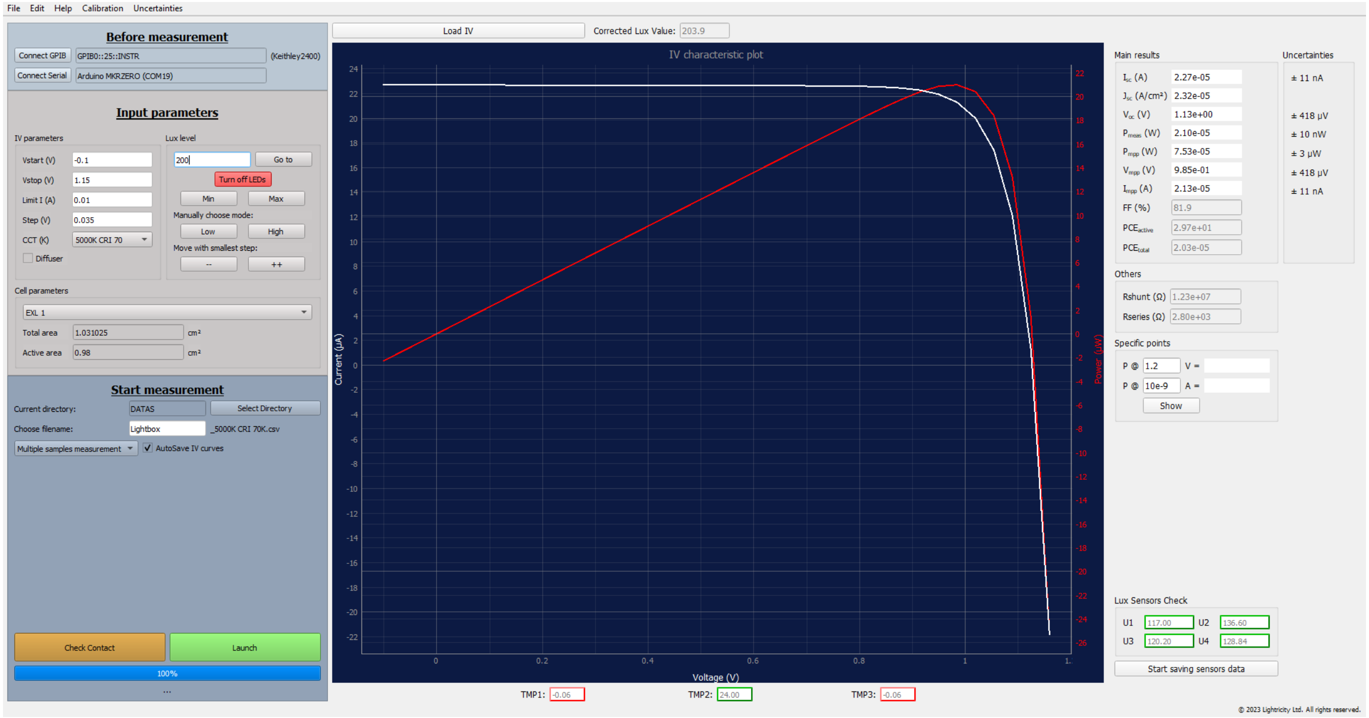
- In-house calibrated benchtop apparatus for the characterisation of solar cells under indoor light within typical measurement uncertainty <5 % (1 standard deviation)
- SA compliance with the standard IEC TS 62607-7-2:2023
- Automated acquisition of Current-Voltage and Power-Voltage curves (via external SMU)
- Fine control of illuminance between 0 lux and 50k lux intensity (depending on LightBox version, and LED CCT and CRI)
- Array of white LEDs with excellent light uniformity (ranging between 99% to 95% in DUT position)

- Lab-free: compatible with standard source meters (e.g., Keithley 2400 & 2600, and Keysight 2900) via GPIB-USB interface
- Closed looped illuminance control ensured by 4 lux sensors
- Temperature monitored at up to 3 different points

	LightBox STD	**LightBox XL**
Outer dimensions (mm) (including legs and connectors)	100 × 105 × 85	185 × 195 × 85
LED array	5 × 5	11 × 11
Correlated colour temperature (CCT)	From 2200 to 6500K (default 5000K)	
Colour rendering index (CRI)	From 70 to 90 (default 70)	
Illuminance range[1,2]	<10 to 50,000 lux	<10 to 40,000 lux
Light uniformity at DUT[3]	~ 95%	~ 95%
Spectral coincidence (5000K CRI70)[4]	SA	SA
Temporal stability (200lx and 1000lx)	SA	SA
Spatial Uniformity at DUT position	SA (Ø5.0mm)	SA (Ø5.2mm)
Spatial Uniformity at centre	SA (Ø15.8mm)	SA (Ø26.4mm)
Recommended max DUT sample size[5]	5 cm × 5 cm	10 cm x 12 cm

[1] Light intensities < 200 lux reach with neutral density, included in LightBox 1.0 and XL.
[2] Upper limit depends on LED CCT and CRI.
[3] Light uniformities tested in lab for both LightBox STD and XL.
[4] Spectral coincidences without neutral density.
[5] DUT stage customisation available upon request.

The LightBox is controlled via a software application (Windows, perpetual license) that has been developed to interface the LightBox with an external source-meter for data acquisition. The light intensity within the LightBox can be controlled between below 10 lux to 50,000 lux. The system can support single, multiple samples or lux sweep measurements. A summary of the measurements can be saved in a csv file locally in the user laptop or PC. In addition, the measurement uncertainty of each PV parameter is displayed in the main window providing more details about the measurement quality to the users. The software can also display the total uncertainties of the measurement if the user is using a compatible source meter.



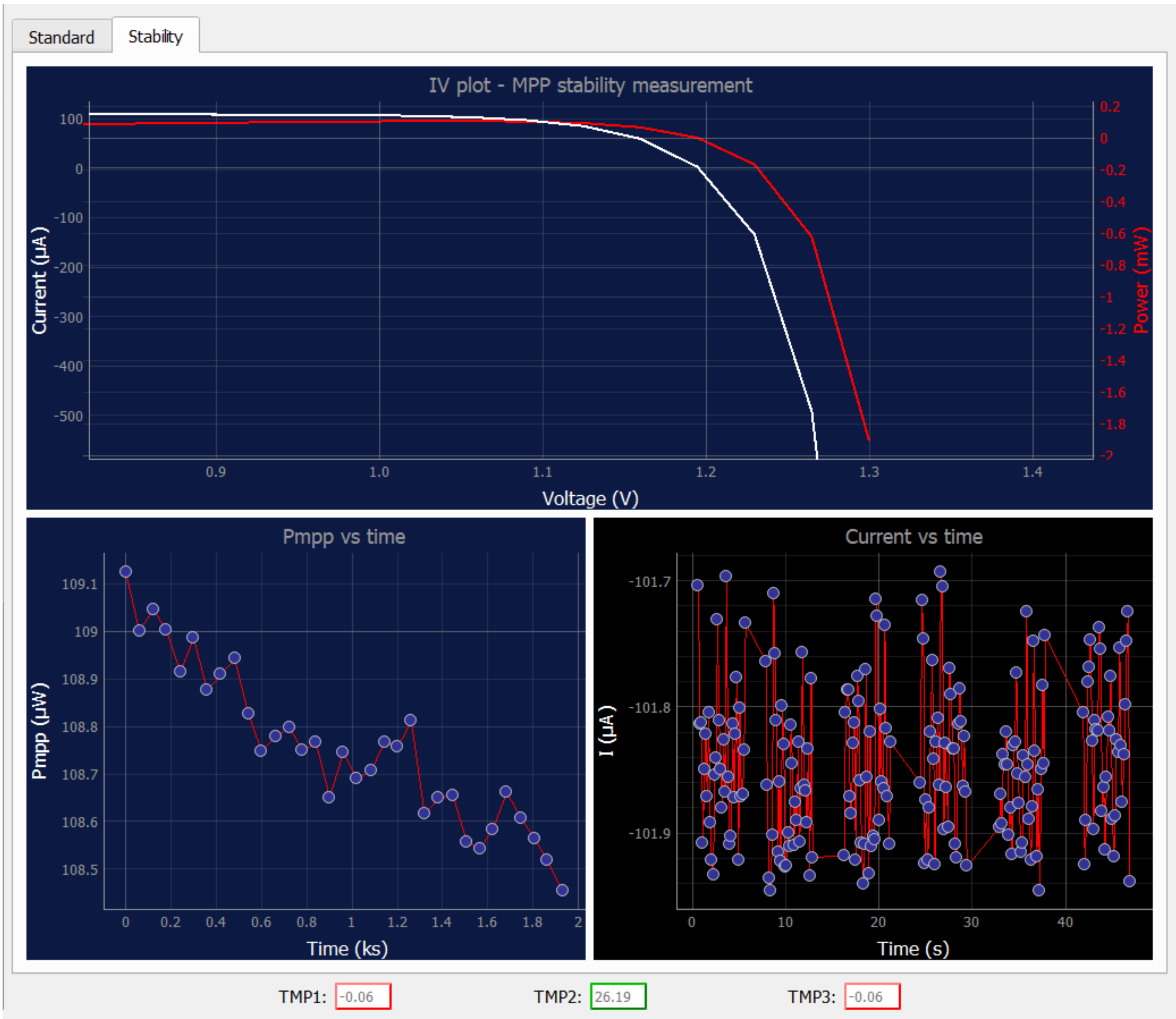
LightBox software: User interface (main screen)

The main PV device characteristics measured by the LightBox are:

- Current-Voltage I(V) curve – white curve
- Power-Voltage P(V) curve – red curve
- The software will then extract the photovoltaic operating parameters:
  - Short-circuit current: Isc (A)
  - Open-circuit voltage: Voc (V)
  - Current at maximum power point: Imp (A)
  - Voltage at maximum power point: Vmp (V)
  - Power at maximum power point: Pmp (W)
  - Fill Factor: FF (%)
  - Shunt resistance (Ω)
  - Series resistance (Ω)
  - Power conversion efficiency (%)

Additional software modules especially for the R&D of new classes of indoor PV materials, such as perovskites, are available, including:

- Voltage scan speed
- Forward & backward voltage scan
- Maximum power point tracking (please see figure below)
- Open circuit voltage stability
- Short circuit current stability
- Application of voltage bias before voltage scan



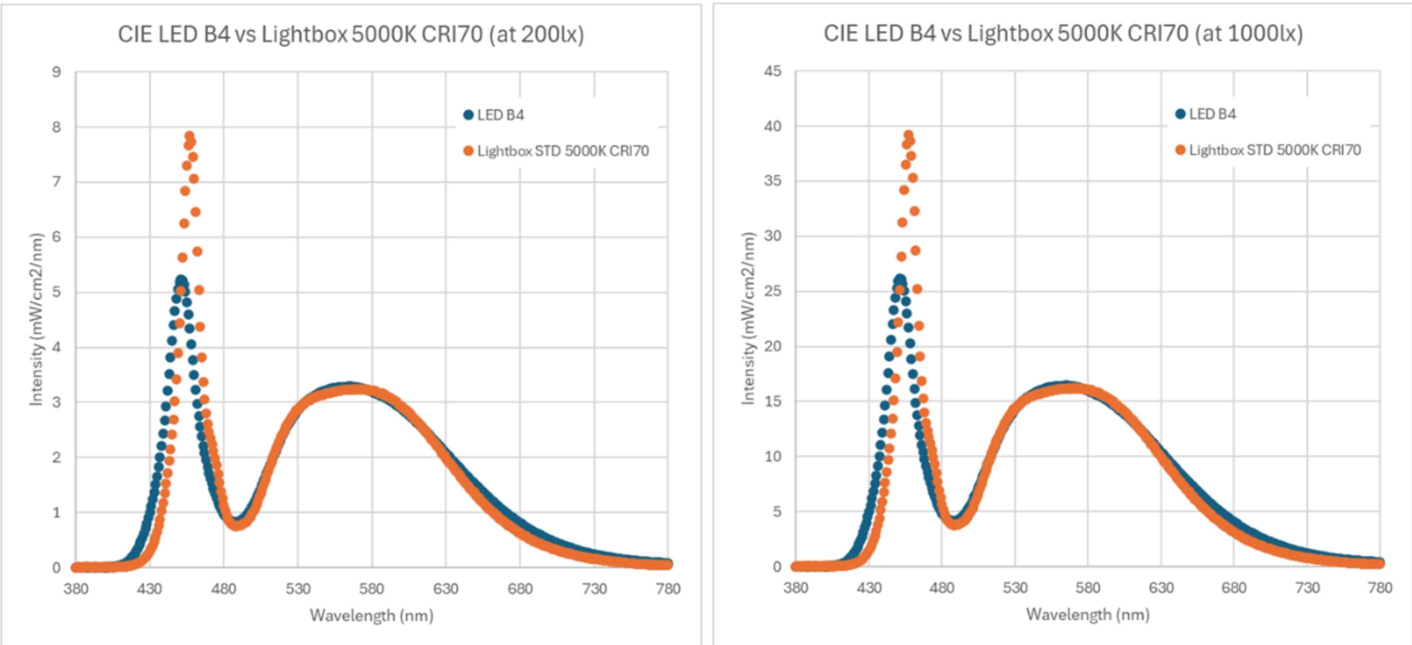
LightBox software: Maximum power point tracking

Standards-based Device Characterisation under IEC TS 62607-7-2:2023

Three main aspects of a light simulator must be evaluated under the standard IEC TS 62607-7-2:2023:

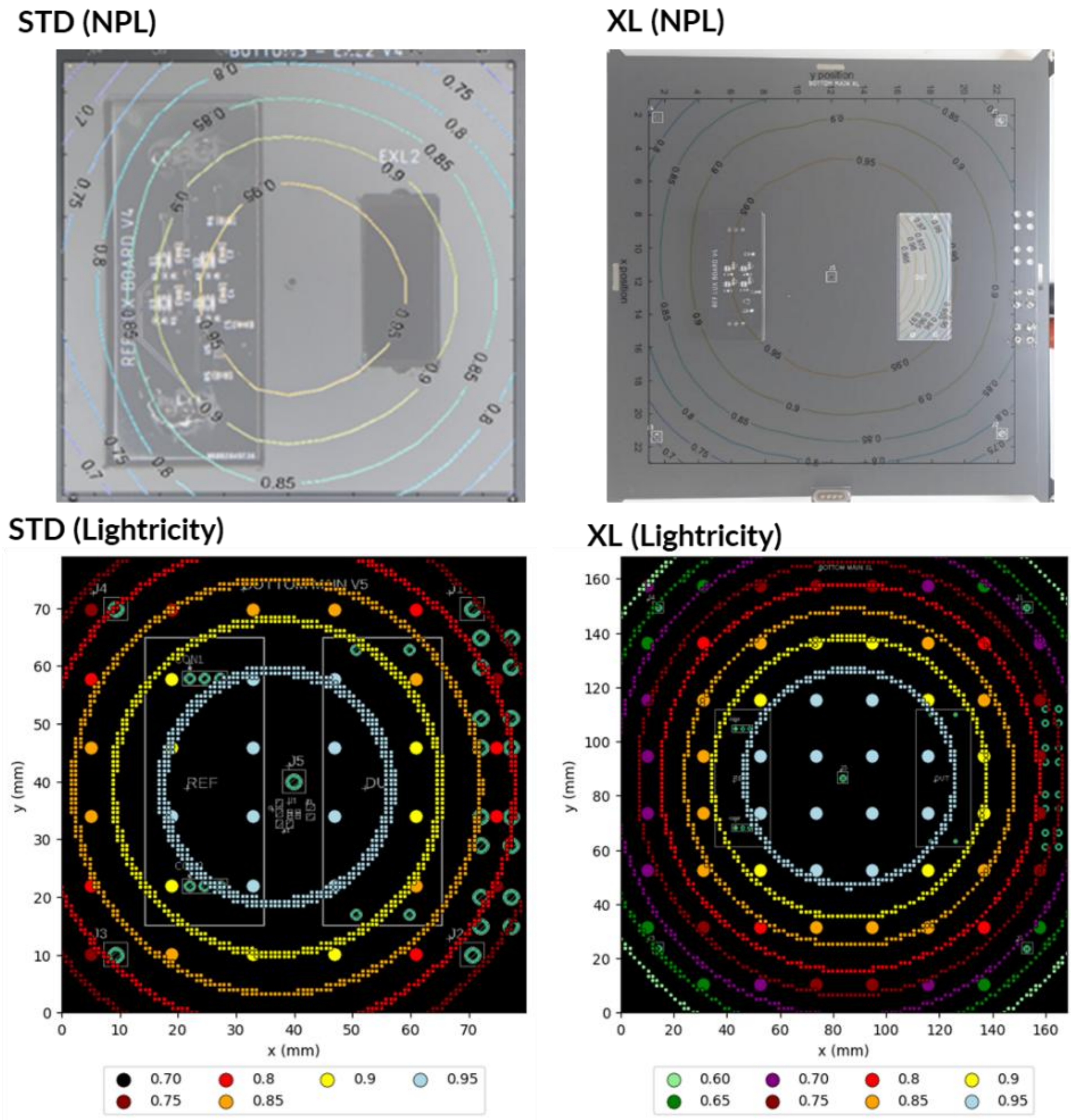
1. Spectral coincidence
2. Temporal stability, and
3. Spatial uniformity

The simulator light source must reach a certain close-match spectral coincidence (±5%) compared to the CIE LED B4 to achieve SA classification at 200 and 1000 lux with a temporal stability (i.e., peak-to-peak intensity variation) less than 0.5% over time. Both LightBox STD and XL are fitted as default with white LED CCT 5000K CRI 70 with a spectral coincidence SA, as shown in the figure below, with SA temporal stability (<0.1%, not shown here).



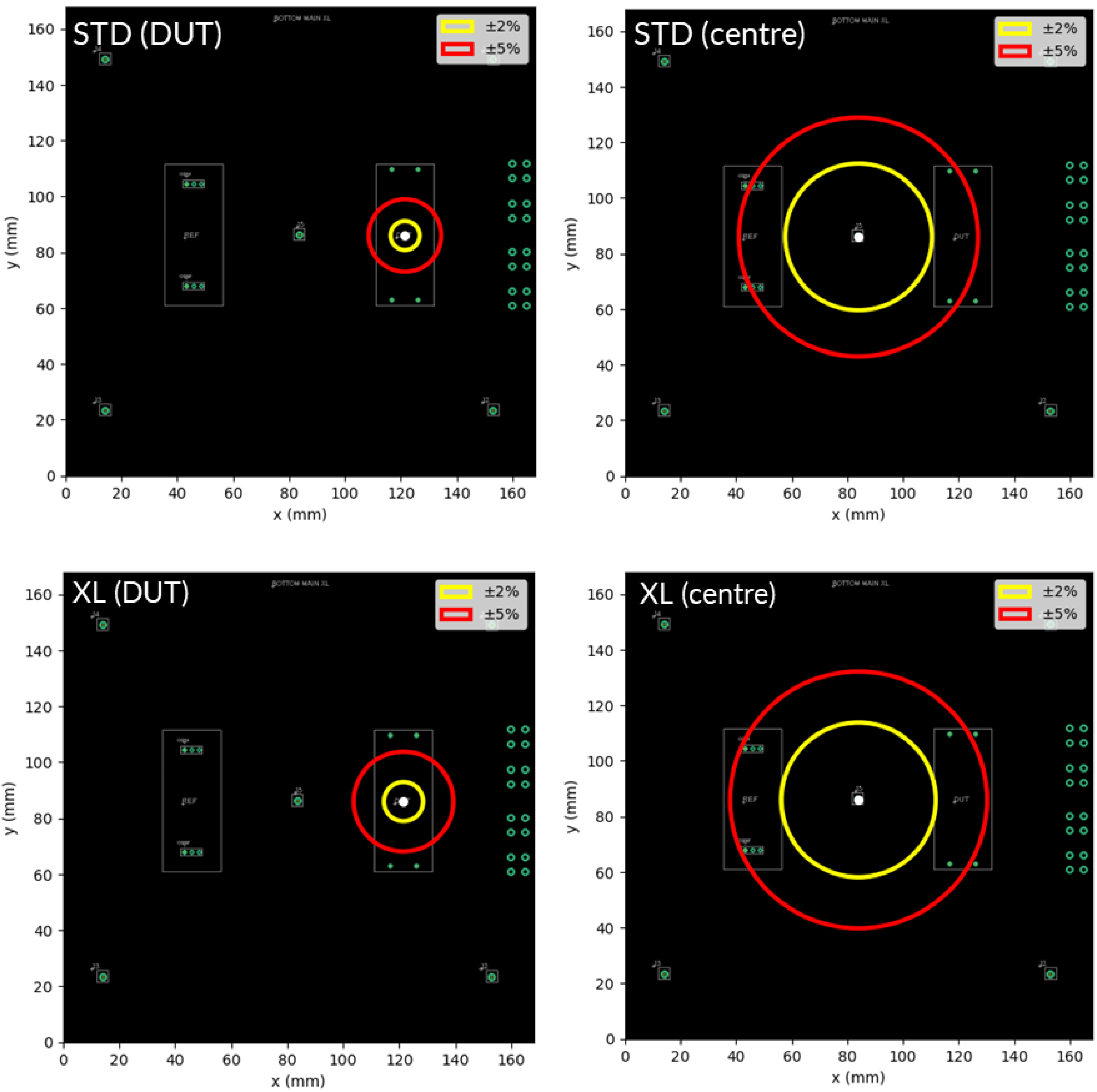
LightBox spectral coincidence according to IEC TS 62607-7-2:2023: Class SA for 200 lux (left); Class SA for 1,000 lux (right)

The light uniformity is crucial for evaluating the spatial uniformity according to the standard. The light uniformity of a selection of our LED arrays was independently measured both by the National Physical Laboratory (NPL), Teddington, London, and by the Lightricity team as shown for the LightBox STD and LightBox XL below. The measurements were carried out on different LED panels at NPL and Lightricity, separately, with consistent agreement between the resulting light uniformity.



LightBox light uniformity for LightBox STD (left) and LightBox XL (right); measured by both NPL (top row) and Lightricity (bottom row).

The IEC standard defines spatial uniformity of ± 2% as SA and A, a spatial uniformity of ± 5% as B. As shown in the figure below, the LightBox can offer different positions within the DUT



LightBox spatial uniformity according to IEC TS 62607-7-2:2023 for LightBox STD (top row) and LightBox XL (bottom row) ; measured at DUT (left) and LightBox centre positions (right).

stage where the user can measure their own devices complying with class SA spatial uniformity (yellow lines), depending on the sample size.

Contact Information:

For further information, LightBox product enquiries and order information please visit: www.lightricity.co.uk