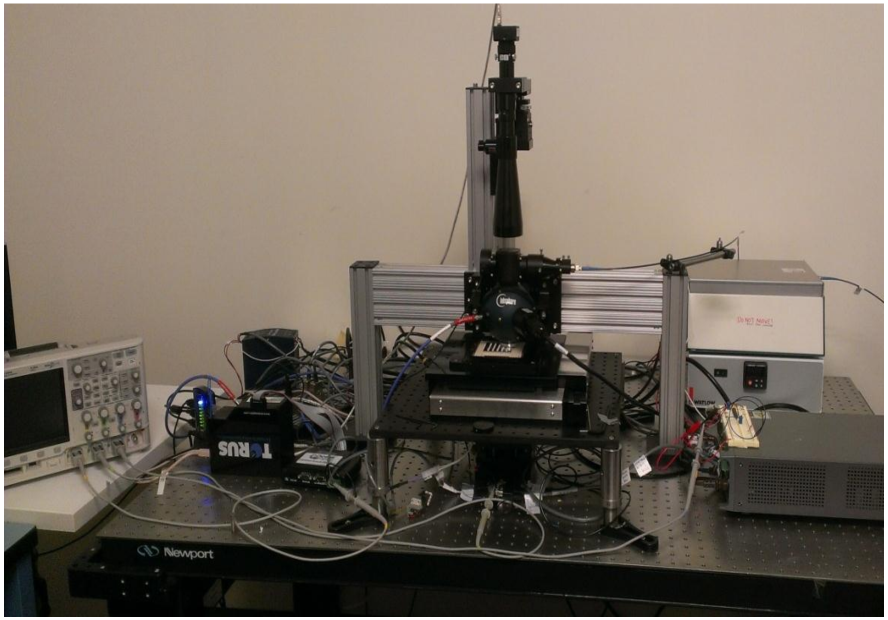
HBLED Hot Testing

2014 Building Technologies Office Peer Review



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Project Summary

Timeline:

Start date: 9/20/12

Planned end date: Early 2015 (3 or 4 month ext. request planned)

Key Milestones:

1. Initial maps of CIE variation vs phosphor and film temperature variations 7/18/2013 actual 9/19/2013
2. LED partner crosscheck 2/24/2014 actual 1/13/2013
3. Conceptual Design for high throughput tool 7/28/2014

Budget: $3,994,729 DOE, $4,626,422 Ind.

Total DOE $ to 3/31/14: $1,717,039 (prelim.)

Total future DOE $: $2,277,690 (prelim.)

Target Market/Audience:

The target market are the manufacturers of HBLEDs for the general lighting industry

Key Partners:

Major U.S. LED manufacturer
Halma plc-Ocean Optics, Inc
Halma plc-Labsphere, Inc

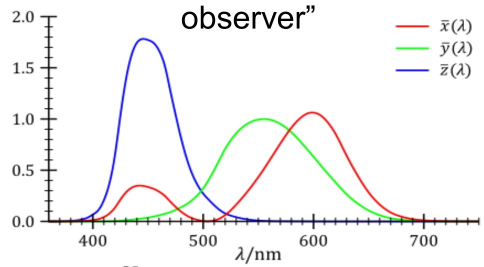
Project Goal:

The project focus is to a) determine the needs of the SSL industry for high quality color coordinate and flux characterization of HBLEDs and to b) demonstrate and test a cost effective tool which achieves and serves the needed requirements.

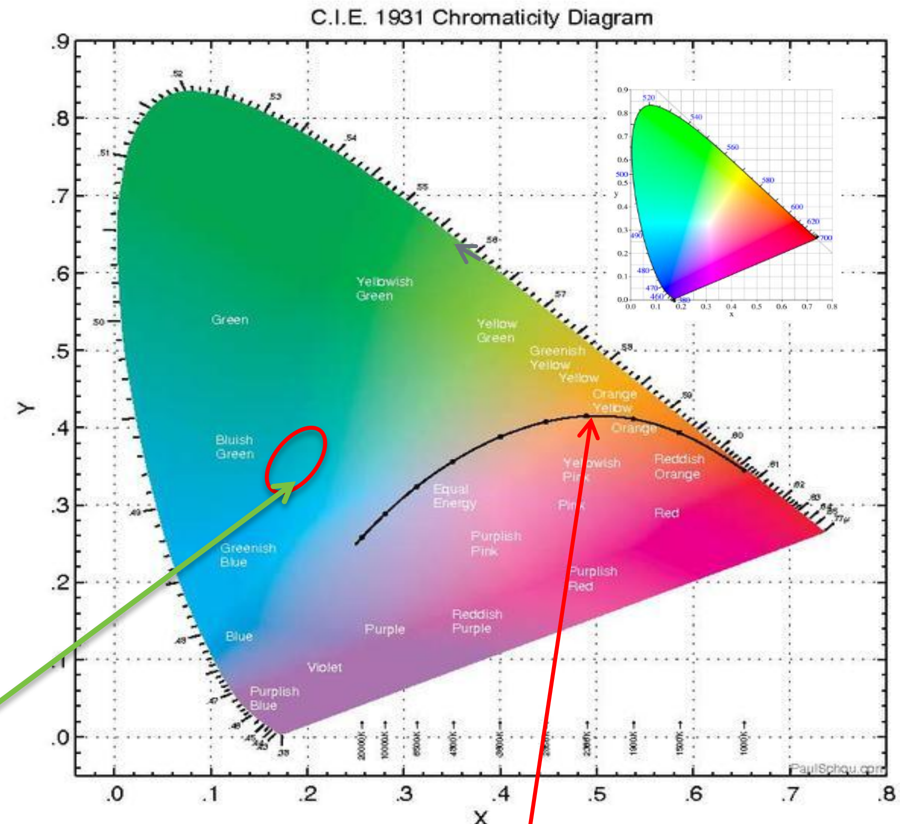
Background on what we are doing and why

The <u>temperature sensitive</u> color of a light source can be specified by two values, x- and y- for example, due to the way in which the eye perceives color

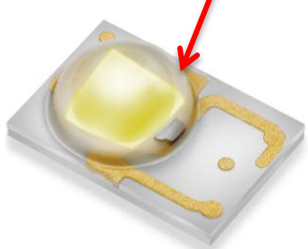
The "standard observer"



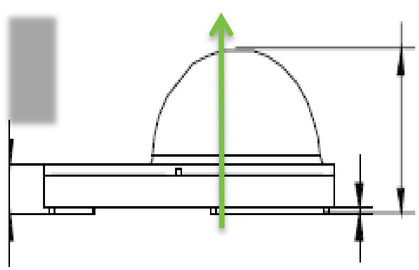
$$X = \int_0^\infty I(\lambda)\,\overline{x}(\lambda)\,d\lambda$$
$$Y = \int_0^\infty I(\lambda)\,\overline{y}(\lambda)\,d\lambda$$
$$Z = \int_0^\infty I(\lambda)\,\overline{z}(\lambda)\,d\lambda$$
$$x = \frac{X}{X+Y+Z}$$
$$y = \frac{Y}{X+Y+Z}$$
$$z = \frac{Z}{X+Y+Z} = 1 - x - y$$

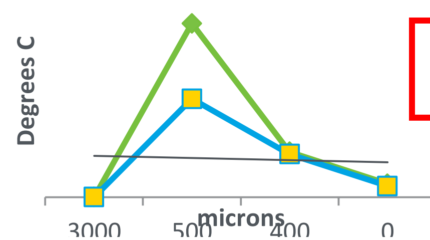


An HBLED which changes color -for 20 minutes- when run at typical use conditions



A "MacAdam ellipse" or SDCM step (10X)





The blackbody curve

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Purpose and Objectives

Problem Statement: The Hot Test project provides more accurate color coordinate and flux characterization of HBLEDs and does so quickly and at a lower cost of ownership than existing approaches.

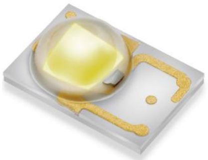
Target Market and Audience: HBLED manufacturers are the target market. HBLEDs in 2013(2017) which are 25%(15%) of the lighting market by units and well over 50%(30%) by lumens. The market is the general lighting market, specifically those sectors demanding good lighting quality (not outdoor).

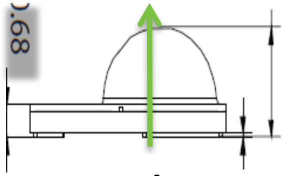
Planned Contribution to Energy Efficiency: The overall potential is to completely serve the HBLED sector.

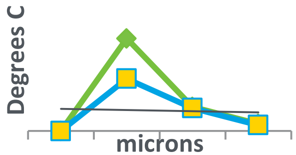
1. The end point would be hot test tools sold to HBLED manufacturers (2 quads energy savings at full adoption)
2. The measured achievement will be the number of tools sold.
    a. In the near term the primary opportunity is estimated to be those HBLED manufacturers currently not hot testing (est. 15-30 tools)
    b. The mid-term opportunity is the retooling in the industry driven by abandoning tile fabrication pathways plus growth in HBLED (est. 120-200 retooling plus 20-40 tools expansion)
    c. The long term opportunity would be growth only (est. 10 tools per year for total of 20-40 tools)

Approach

Approach: The approach is laser non-equilibrium heating followed by full light collection in msec to measure temperature sensitive color and flux



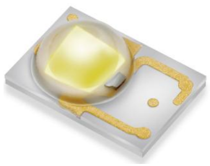


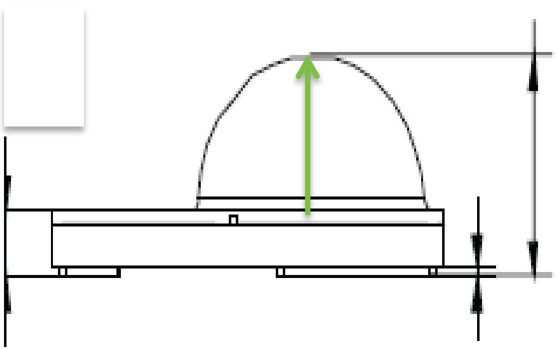


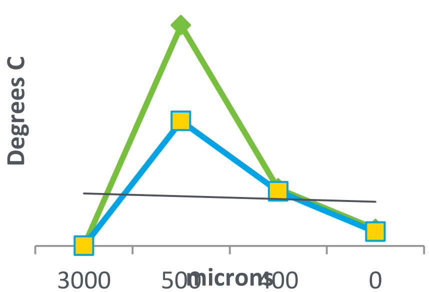
Key Issues: Current hot testing approaches only approximate actual cw HBLED use conditions. They are very slow (typically 4500 UPH due to thermal soak timescales used) and require correction factor application to each die obtained from separate tooling from harvested samples of full population. Result today typically 3-4 steps SDCM color variation and +/- 7.5% flux bins. Also, tool down times significant due to need for frequent recalibration.

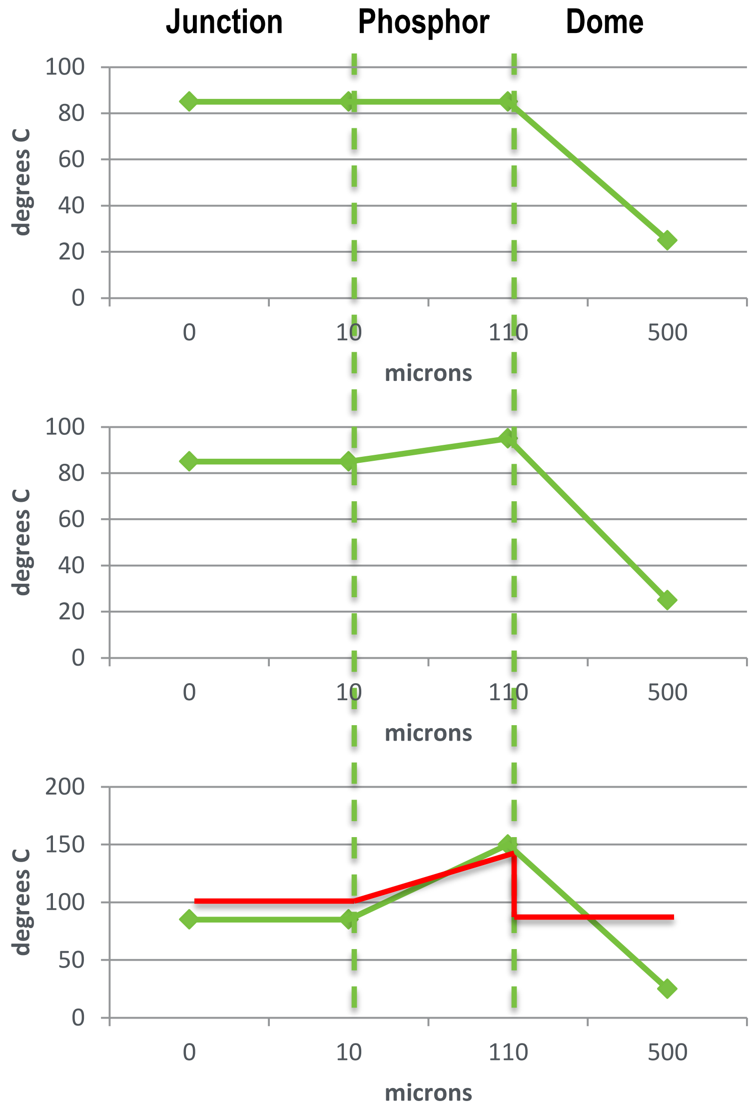
Distinctive Characteristics: Laser heating of phosphors achieves within roughly 1 msec timescale EXACT temperature profile of phosphors under cw use conditions resulting in extremely accurate color coordinates (<0.2 step relative, <1.5 step absolute) and flux (<0.5%). Our tool also collects all light (~2π) and is self-calibrated to an internal reference (resulting in up to 50% improvement in up time). Higher throughput than existing hot test techniques (thermal soaking) can be achieved.

Current Industry Test Procedures









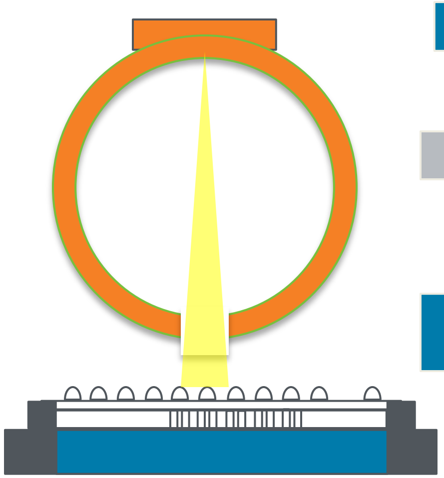
Industry Hot Test: Junction and phosphor at 85 degrees C

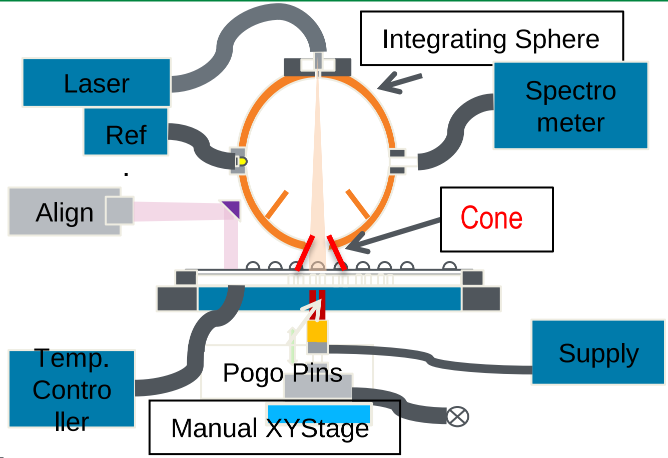
Industry "Soak" Test: Junction at 85 degrees C, LED on for 20 msec

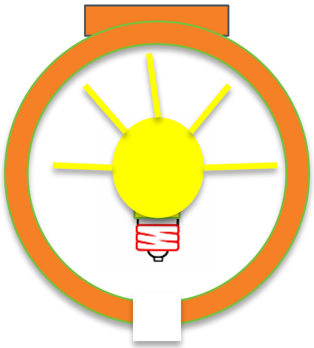
KT Hot Test (LED operating conditions): Junction at 85 degrees C and phosphor 85 to >> 85 degrees C near dome w/ 1msec laser

Current Best Practice for Industry Hot Test

A.





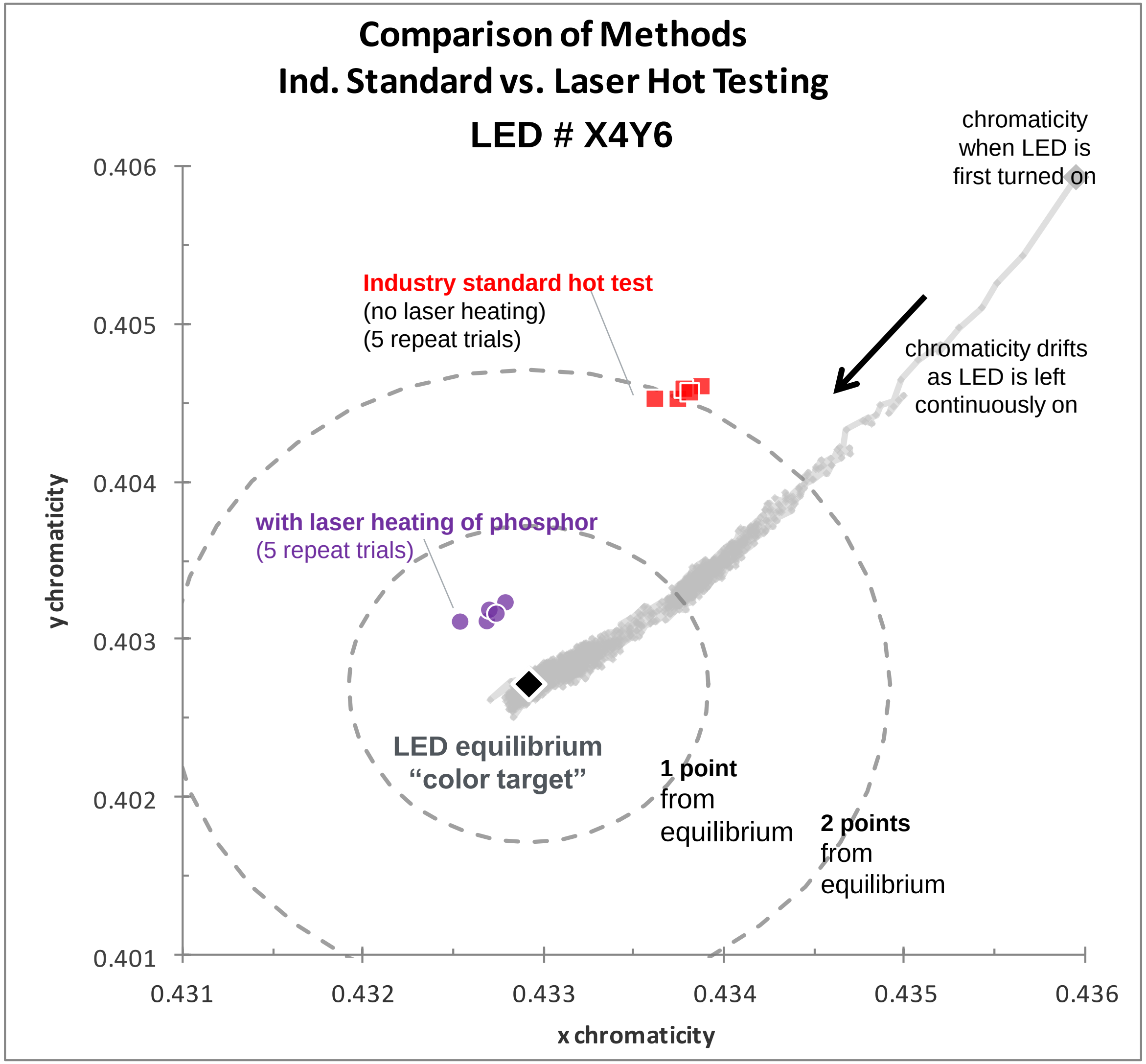


B.

1) LED on "tiles"
2) Not all of 2π emission is collected (f(Φ))
3) Phosphor at incorrect temp.
4) Spectrometer periodically calibrated

1) LEDs assembled in A19 bulb
2) Phosphor at correct temperature
3) All light collected
4) "Correction factor" applied to full batch
5) Separately calibrated

Laser heating brings LED to <0.001 of "target"



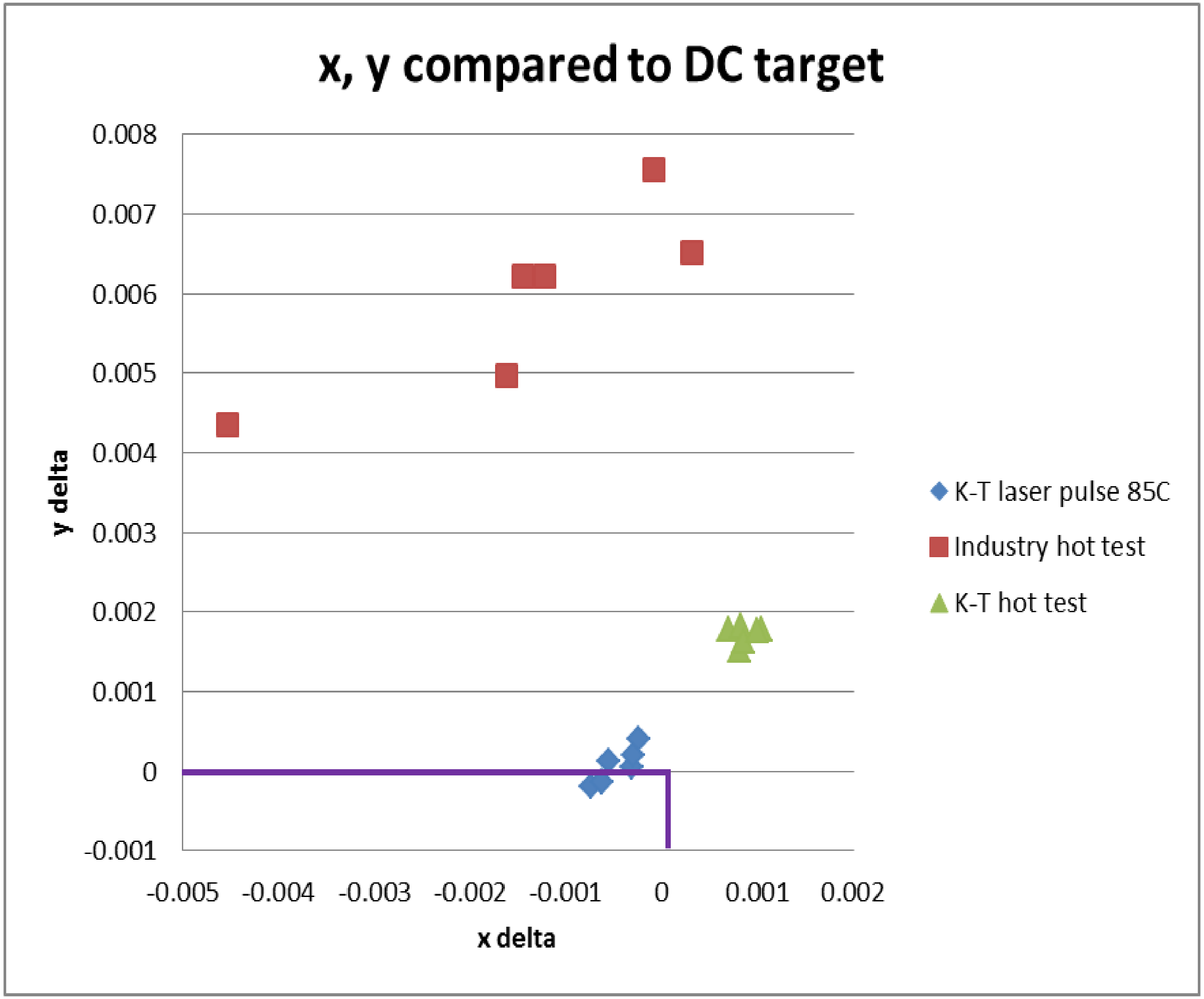
Method for creating 20 ms MP Proxy:

- To establish equilibrium, LED on 20 minutes and monitored Vf to determine 85°C junction reached. 700 mA drive
- Simulate conventional hot test: pogo heat junction, fire LED with increasing durations of drive current (0 to 20 ms).
- KT laser test via pogo junction heating and laser phosphor heating. Junction monitor Vf

Conclusion:

- KT hot tester lands well within 1 point of continuously on LED equilibrium "target".
- Measurement is relatively stable with tight cluster of 5 repeat trials.
- 20 ms MP Proxy is at the edge of 2 points from equilibrium "target".

X, Y Chromaticity Target accuracy (six die)



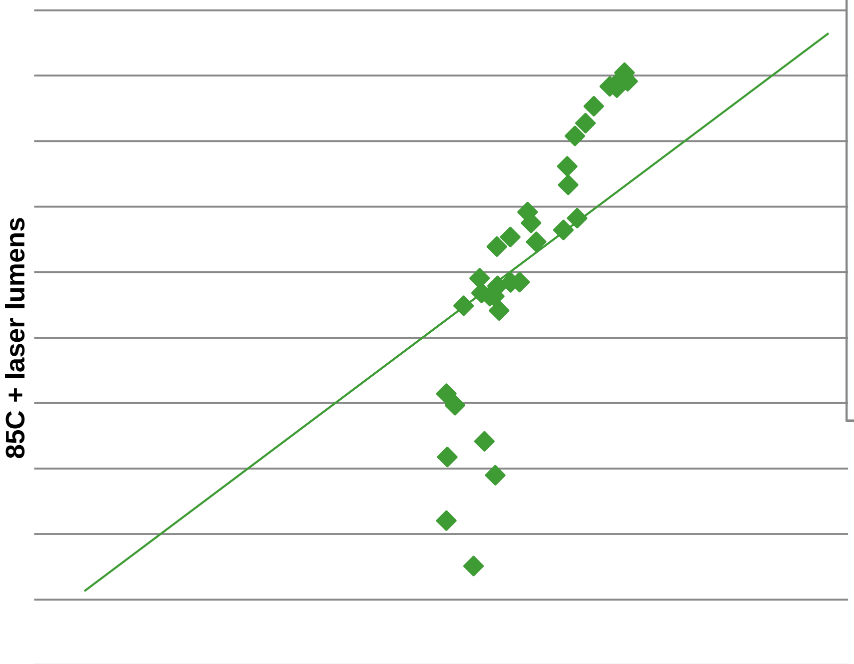
Conclusion:

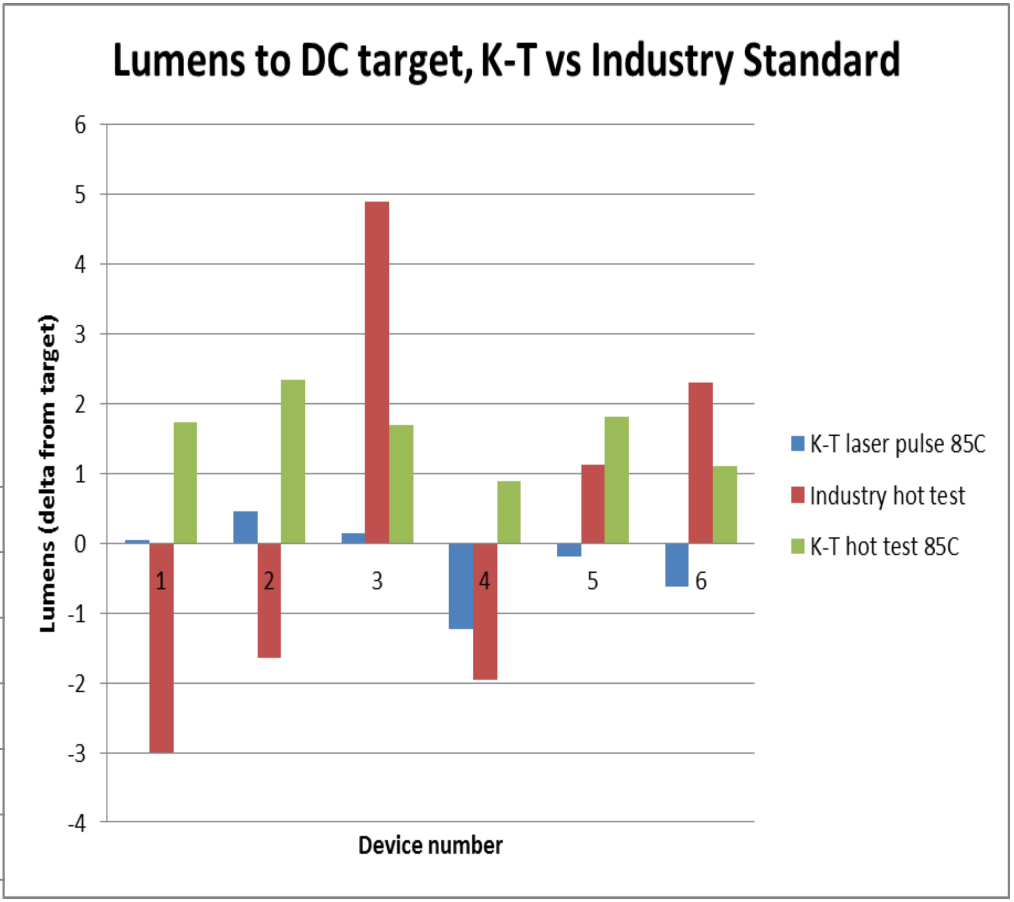
- K-T hot tester has much better x-,y- accuracy and precision than commercial hot test tool
- Correct temp distributions
- Full angular light collection

Lumens: Target accuracy

- Chart shows lumens measured at 85C compared to RT
- Data taken on K-T's laser hot test bench
- If RT data predicted operating temperature performance, data would fall on the straight line
  - Therefore, hot testing is key to accurate measurement of LED performance

Hot test vs Room temperature lumens





Conclusion:

- K-T hot tester has much better flux accuracy and precision than current commercial hot test tools

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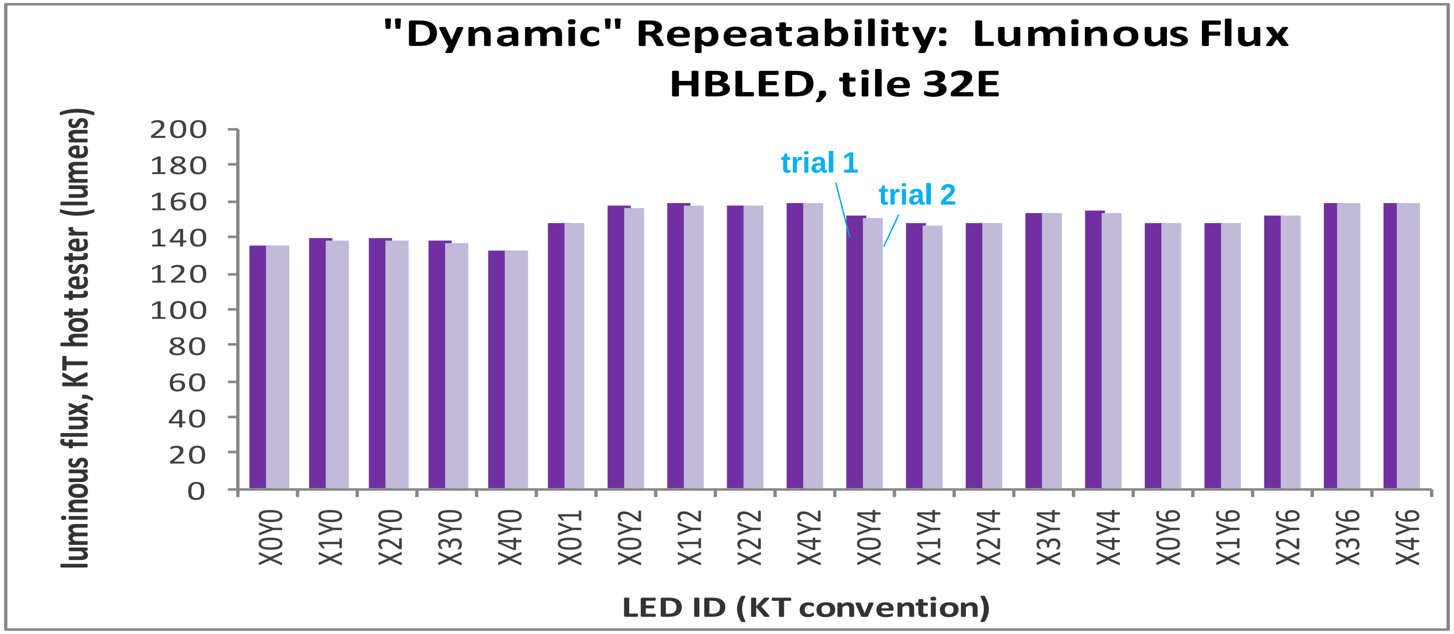
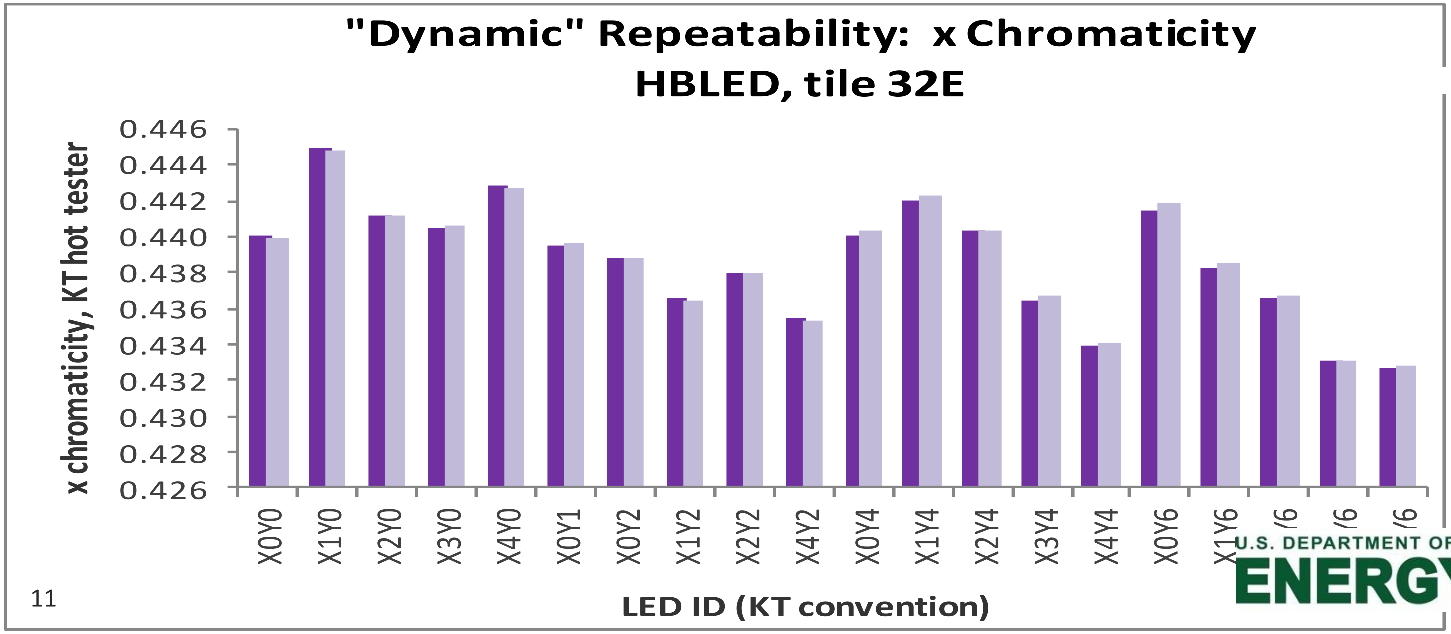
Initial results show good "dynamic" repeatability





Method:

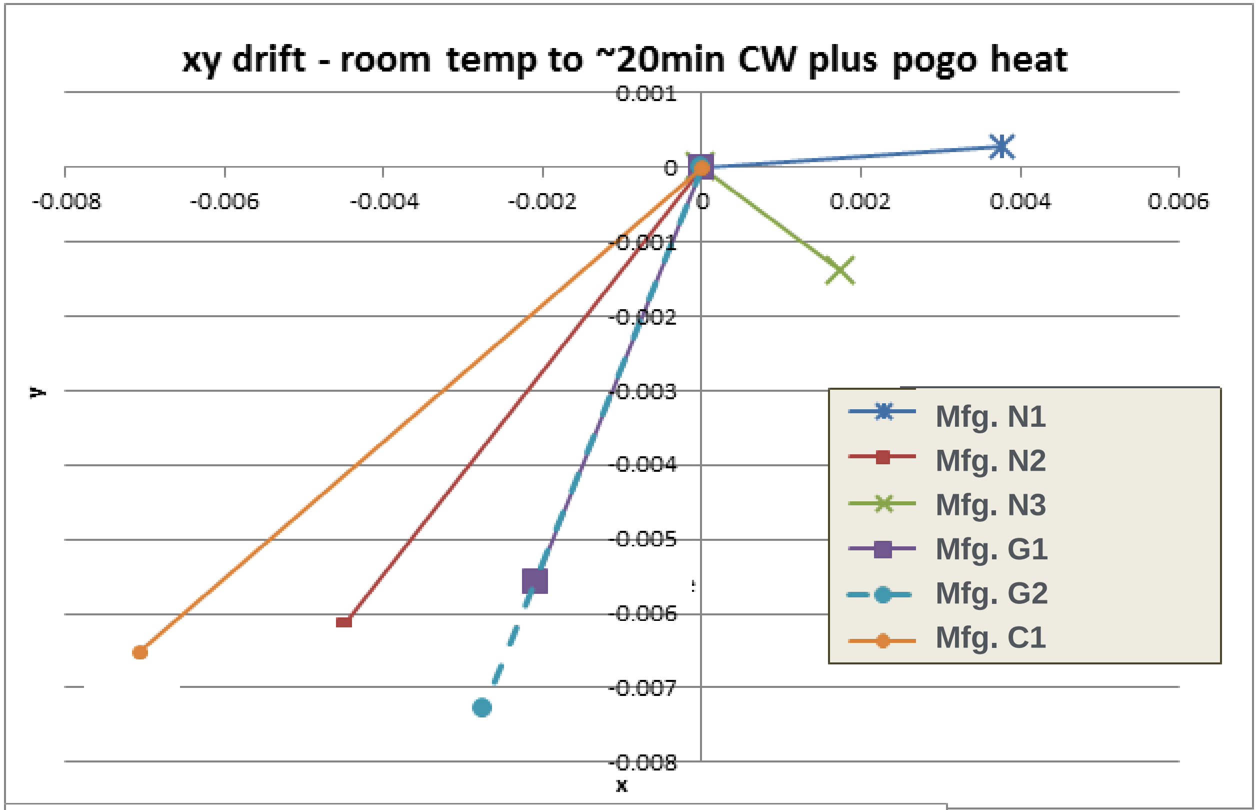
- Using hot tester recipe (pogo heating with laser at 20.5 W for 5 ms), took two trials. Time between trial 1 and trial 2 is approximately 2 days. Removed tile from tester between trials.

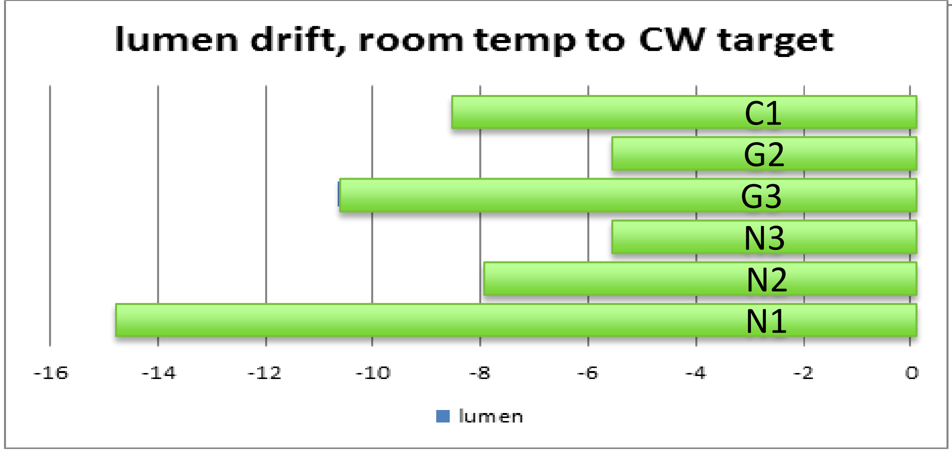
Conclusion:

- The "dynamic" repeatability is very good.
  - σ, luminous flux = 0.29 lumens
  - σ, x chromaticity = 0.00016
  - σ, y chromaticity = 0.00013

Industry currently reports x- and y- to roughly 0.01 (two steps) and flux to +/-7.5%

Example Coordinate and Lumen Changes Across Suppliers





- **We have evaluated a broad range of die across various manufacturers and observe that our results are applicable across the board**

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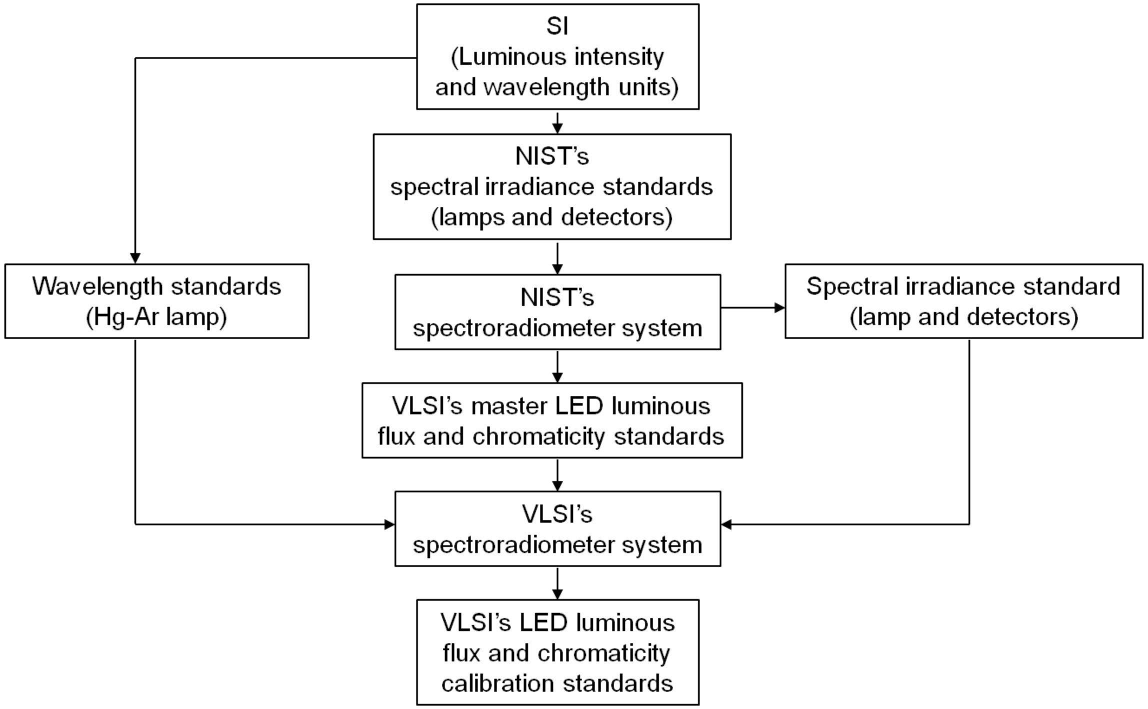
Absolute On-Tool Calibration Standards Developed

- High brightness warm white and cool white LED sources,100 ~ 200 lumens, turn-key devices with integrated temperature and current controllers
- Expanded absolute uncertainty of total luminous flux: ± 1.3%
- Expanded absolute uncertainty of color coordinates: ± 0.002 (less than 1 MacAdam ellipse)
- Traceable to fundamental SI units through NIST (master standards directly certified by NIST)
- ISO 17025 accreditation planned
- <u>Project far greater tool up time</u>



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Progress and Accomplishments

Discoveries: 1. We found that pinpointing "equilibrium conditions" was simple and precise. 2. We proved that collecting 2π emission was essential. 3. 450 nm laser excitation worked-no junction effects 4. Accuracy achieved in coordinates and flux was beyond our expectations. 4. Lead to solid understanding of industry wide (LED mfg and luminaire mfg) protocols for color quality (can be improved)

Accomplishments: We have demonstrated the most accurate and lowest cost of ownership approach to color coordinate and flux accuracy in the industry.

Project Contribution to Energy Efficiency : We are currently constructing and testing prototype at 15000 UPH which will quantify cost effectiveness of approach. We have developed deep understanding of LED characterization/color quality by mfgs and by users and identified clear improvements for HBLED and MBLED. We hope to leverage this project into MBLED sector as well as HBLED.

1. Market outcomes: continued in-process engagement with LED mfgs now moving to hot test plus those moving to CSP LED architectures
2. Measurement results meet/exceed expectations. Market insertion still being determined.

Awards/Recognition: US patent 61/559411 and US patent 61/560614

Project Integration and Collaboration

Project Integration: We meet regularly with leading edge hot testing LED companies today to identify and refine improvements to existing practice and to quantify tooling specifications defined by the industry.

Partners, Subcontractors, and Collaborators: LED mfg., Ocean Optics, and Labsphere are (outstanding) project partners. Ocean Optics and Labsphere developed spectrometer/integrating sphere to our specifications. LED mfg. provided test samples, characterization comparisons, sustained advice on industry architecture directions and detailed issues regarding characterization tools.

Communications: Results and approach have been presented at DOE conferences and in multiple regular meetings with LED mfg. and Ocean Optics (partners), as well as with Osram, Nichia, Seoul Semiconductor, GE, Acuity, Hubbell, PLL, and Soraa.

Next Steps and Future Plans

Next Steps and Future Plans: We are in the process of improving tooling need forecasts by assessing adoption by non-hot testing LED mfgs and by assessing move to CSP architectures and retooling needs. Possibly need to assess application to saturated phosphors.

1. What do we need to do to wrap up the project?
   a. Build and test/validate the fully integrated prototype tool
   b. The key risk to this project is market adoption and market adoption pathways.
   c. Key decision will be final assessment of cost effectiveness and market adoption
2. Once the project is complete what does BTO need to do to ensure significant market outcomes?
   a. BTO might evaluate the consumer adoption effects of non matching (non-concentric binned) products from different mfgs. True for hot tested HBLED as well as MBLEDs.

Project Budget

Project Budget: Below
Variances: Spending has been slower than projected due to staffing
Cost to Date: 44%of funds have been expended as of 3/31/14 (est.)
Additional Funding: Corporate matching funds are 53.6% of overall project costs ($1.16 corporate to every $1 DOE)

Budget History					
8/15/2012– 9/30/2013 (past)		FY2014 (est. to date) current		FY2014 – 9/30/14 (total 2014 planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$1,343,651	$1,589,519	$373,388	$432,432	$2,651,078	$3,036,903

Project Plan and Schedule

Explanation for slipped milestones:

- Primarily due to retooling of staff needed to build prototype

Project Schedule												
Project Start: 8/15/2012		Completed Work										
Projected End: ca. 12/31/2014		Active Task (in progress work)										
		Milestone/Deliverable (Originally Planned) use for missed										
		Milestone/Deliverable (Actual) use when met on time										
	FY2013				FY2014				FY2015			
Task	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Past Work												
Initial bench maps												
LED partner data crosscheck												
Compare calibration data to W calibration lamp												
report accuracy and reproducibility of bench												
Test samples from 3 vendors												
Current/Future Work												
Final review ICOS platform												
Q4 Milestone: Example 7												