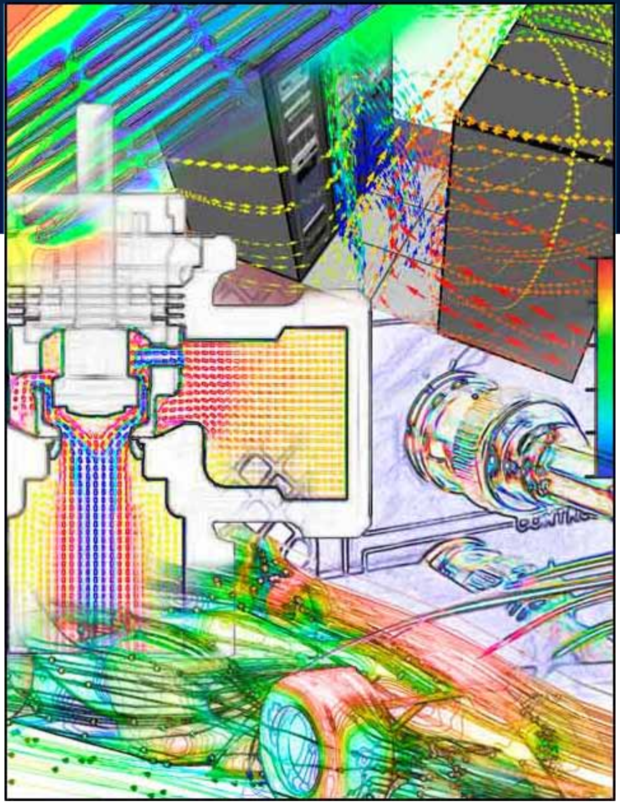
Thermal issues in relation to metrics reported on LED data sheets



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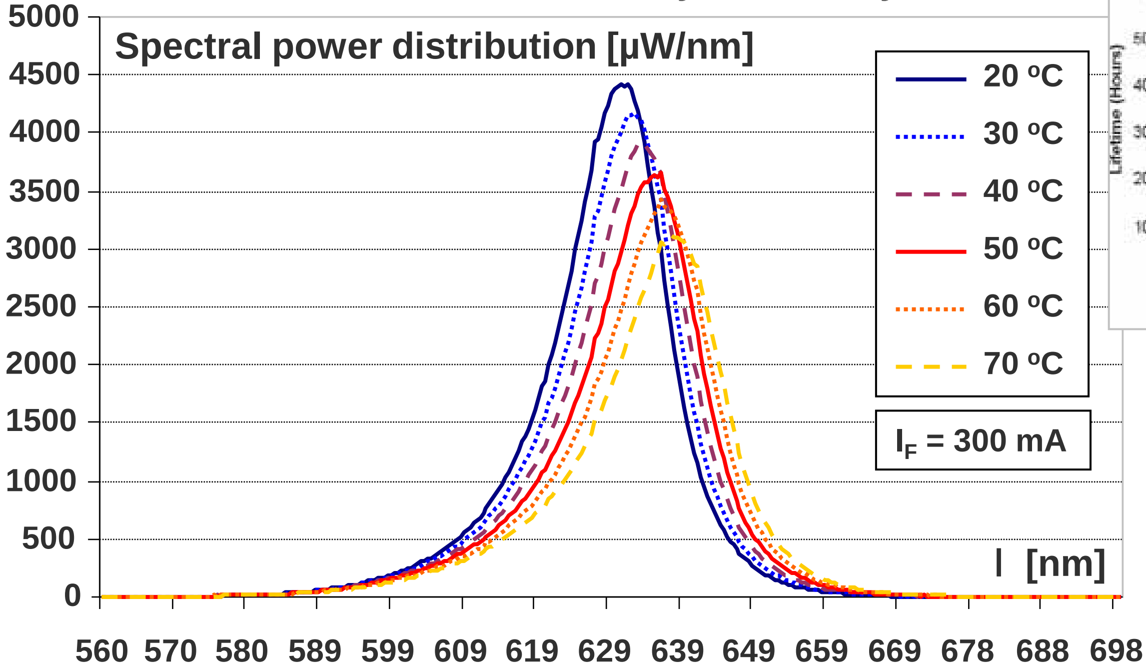
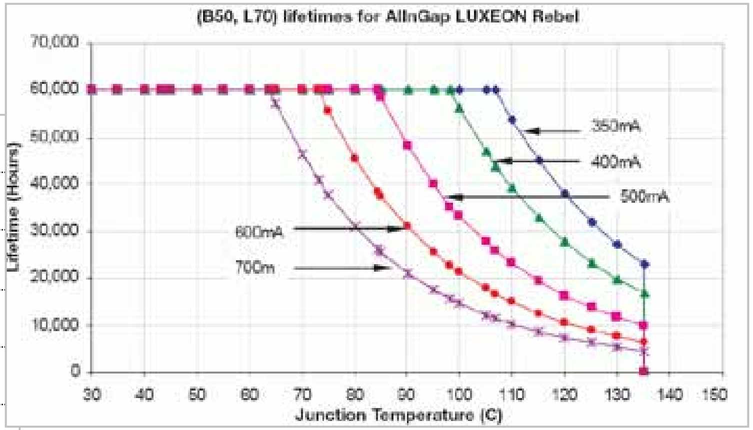
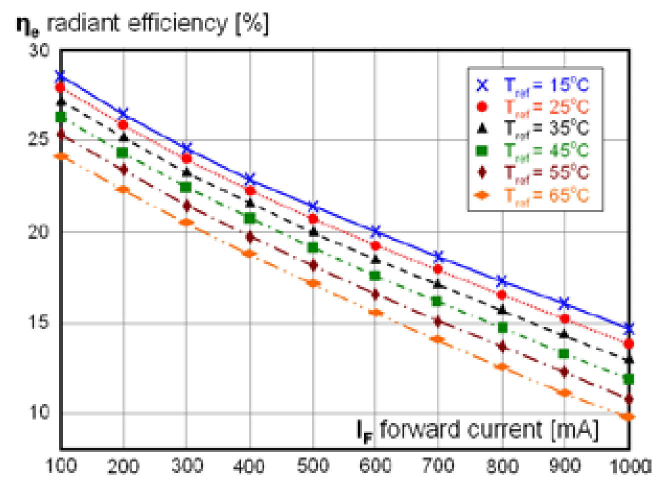
Corrupt file on the USB stick. Please download from
http://www.eet.bme.hu/~poppe/CORM2011/

Introduction: thermal issues in case of LEDs?

- Reliability is connected to thermal issues
  - life time (failure mechanisms are thermally assisted)
  - mechanical stress
- Properties of emitted light strongly depend on temperature
  - spectra / T_{cc}
  - emitted flux / efficiency / efficacy /







Unfortunately thermal related information is not reported in an unambiguous and straightforward way (e.g. real R_{th}, η_e, $d\Phi_V/dT$)

What are the problems with today's LED data sheets?

- R_{th}:
  - **Usually reported**, but **not clear if the radiant flux is considered** in calculating this
    - If not considered, the value is valid for a given forward current and junction temperature only
    - Should be a unique property of the LED package, must not depend on operating conditions
  - Dynamic thermal properties usually not reported
- Luminous flux
  - Reported but often unclear, at what operating conditions it is valid
    - T=25 ^{o}C – but what is at 25 ^{o}C?
  - Luminous flux **depends on current and temperature** – how?
    - Reported only through relative light output diagrams
- Efficiency:
  - **No efficiency data** (F_e/P_{el}) provided
    - Without efficiency information one can not perform proper thermal design
  - Efficiency is not a single number
- Efficacy:
  - Usually reported, but typically indirectly
  - Efficacy is not a single number
  - Not enough, one hardly can calculate efficiency from this

The JEDEC JESD51-1 electrical test method and its applicability to LEDs

R_{th} / Z_{th}

A few words about thermal resistance of LEDs

- Original definition in the JEDEC JESD51-1 document

EIA/JEDEC Standard No. 51-1
Page 3

2. MEASUREMENT BASICS

The thermal resistance of a semiconductor device is generally defined as:

$$R_{JX} = \frac{T_J - T_X}{P_H}$$

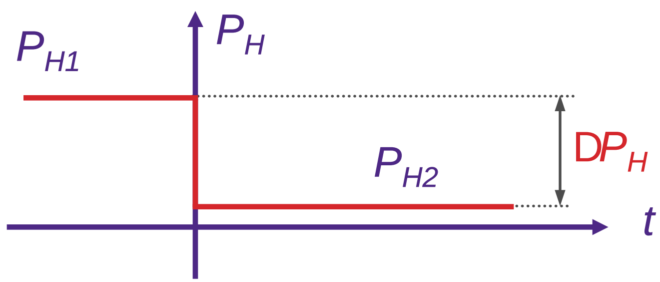
where $R_{\theta JX}$ = thermal resistance from device junction to the specific environment (alternative symbol is θ_{JX}) [°C/W]
T_J = device junction temperature in the steady state test condition [°C]
T_X = reference temperature for the specific environment [°C]
P_H = power dissipated in the device [W]

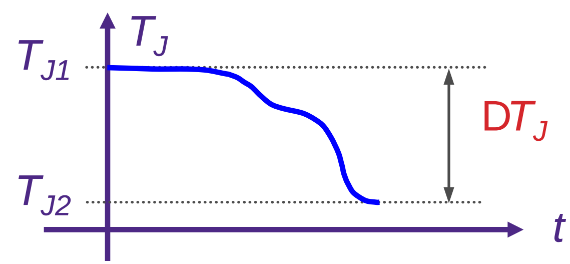
- Classically, for Si semiconductor diodes: $R_{th\text{-}el} = \Delta T_J / (I_F \times V_F)$
  Accurate; the questions are:
  - what is the dissipated power of an LED? — *Subtract radiant flux*
  - what is the T_X reference temperature — *Use cold plate!*
- For LEDs, consider the radiant flux: $R_{th\text{-}r} = \Delta T_J / (I_F \times V_F - P_{opt})$
- Both $R_{th\text{-}el}$ and $R_{th\text{-}r}$ are correct, if proper power is used to calculate T_J

Differential formulation of the thermal resistance

- Instead of spatial difference (temperature values at junction and reference point) temporal difference of the junction temperature can be used

$$\cancel{R_{thJ-X} = \frac{T_J - T_X}{P_H}} \quad \Rightarrow \quad \boxed{R_{thJ-X} = \frac{\Delta T_J(\infty)}{\Delta P_H}}$$

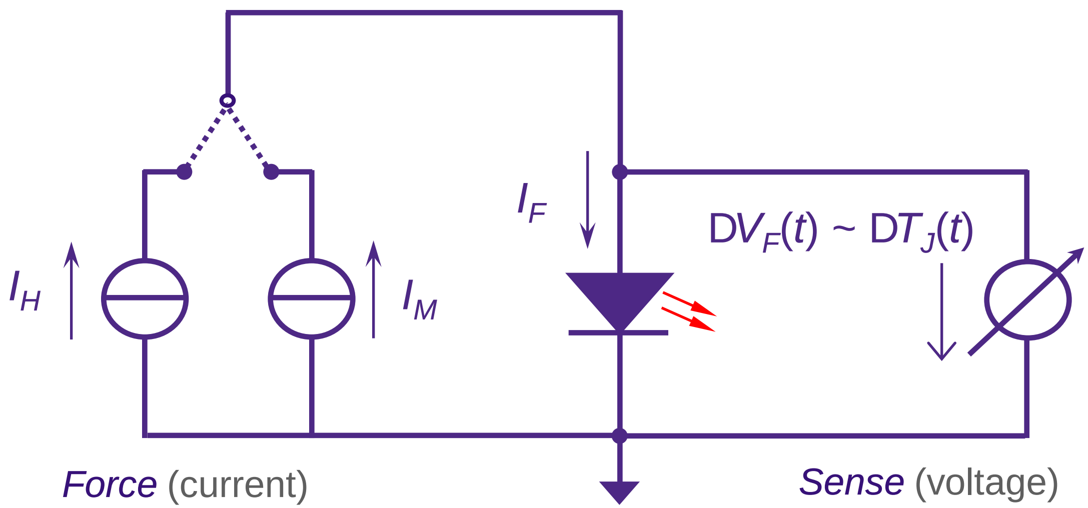




- ***Instead of absolute values*** of temperature and power only the temperature difference and power difference are used
- In case of LEDs the radiant flux must be subtracted from the supplied electrical power to yield heating power

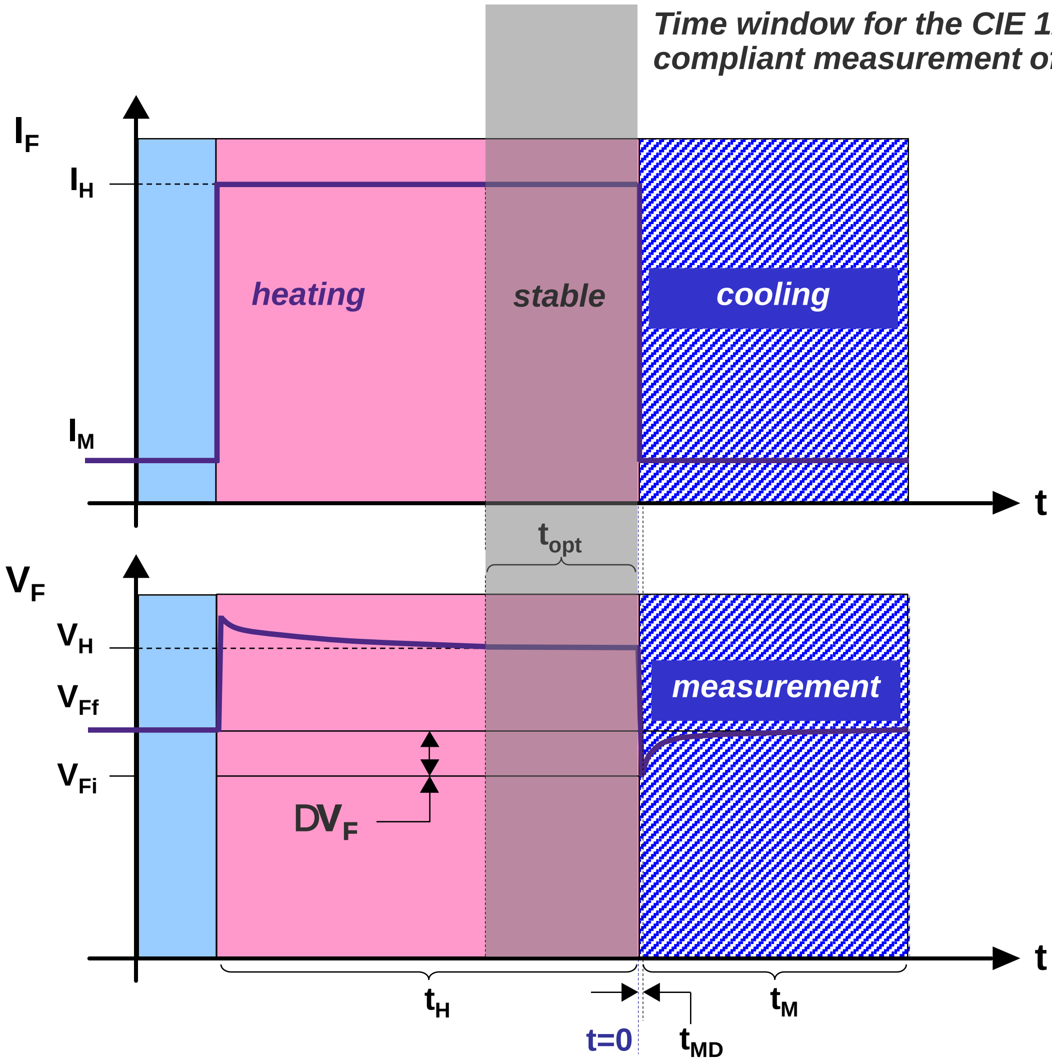
How do we know $DT_J(t)$?

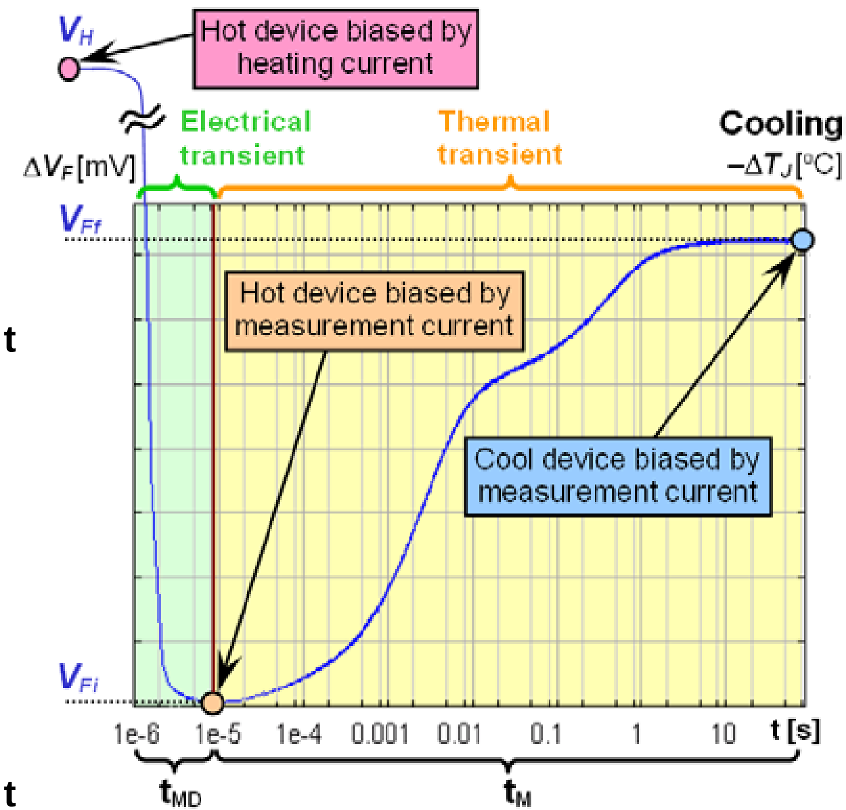
- The LEDs' forward voltage under forced current condition can be used as a very accurate thermometer
- The change of the forward voltage (TSP – temperature sensitive parameter) should be carefully calibrated against the change of the temperature (see JEDEC JESD51-1 and MIL-STD-750D)
  - In the calibration process the S_{VF} temperature sensitivity of the forward voltage is obtained



- Forward voltage change due to temperature change is measured using a 4 wire setup (Kelvin setup)

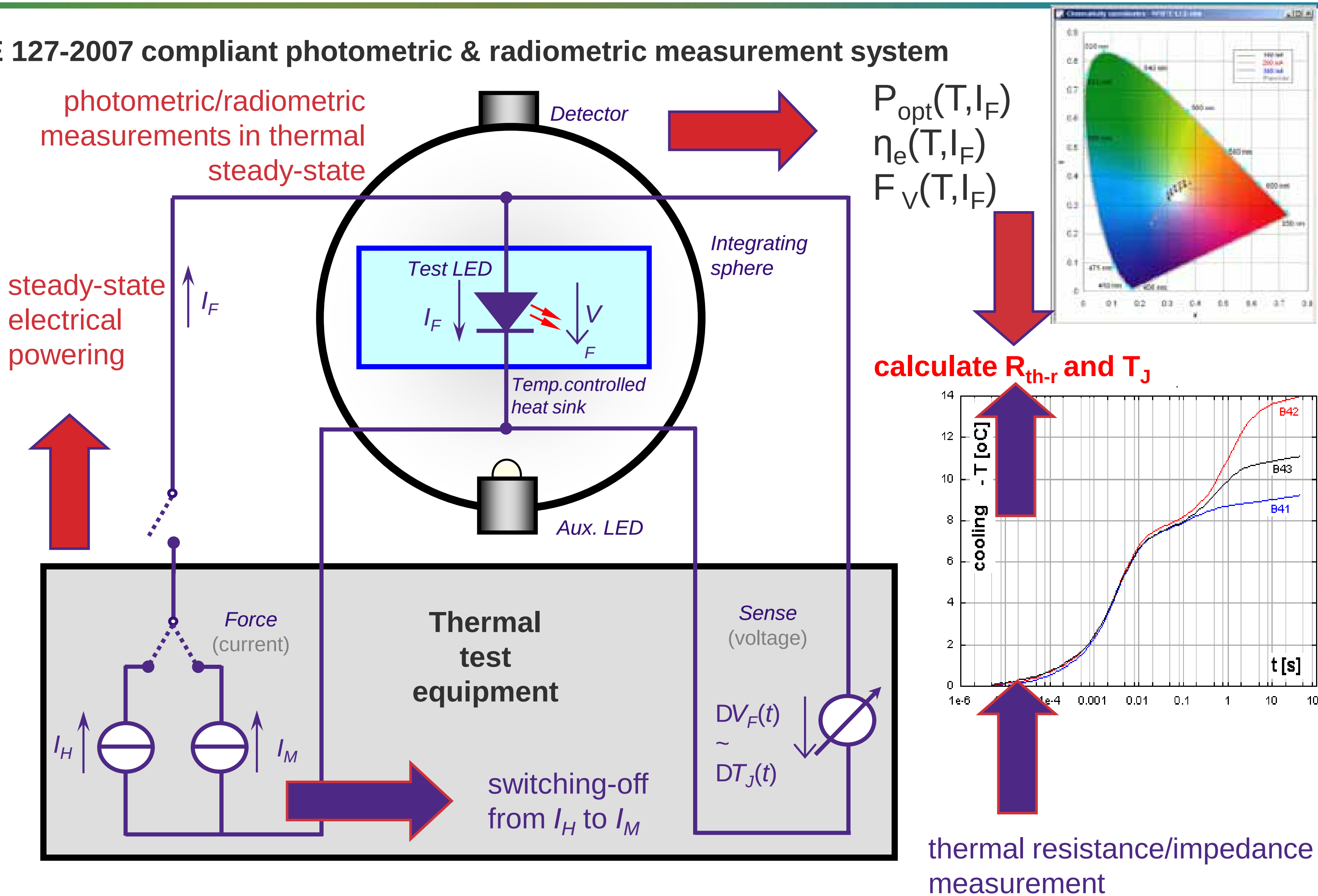
The measurement waveforms





Comprehensive LED testing solution:

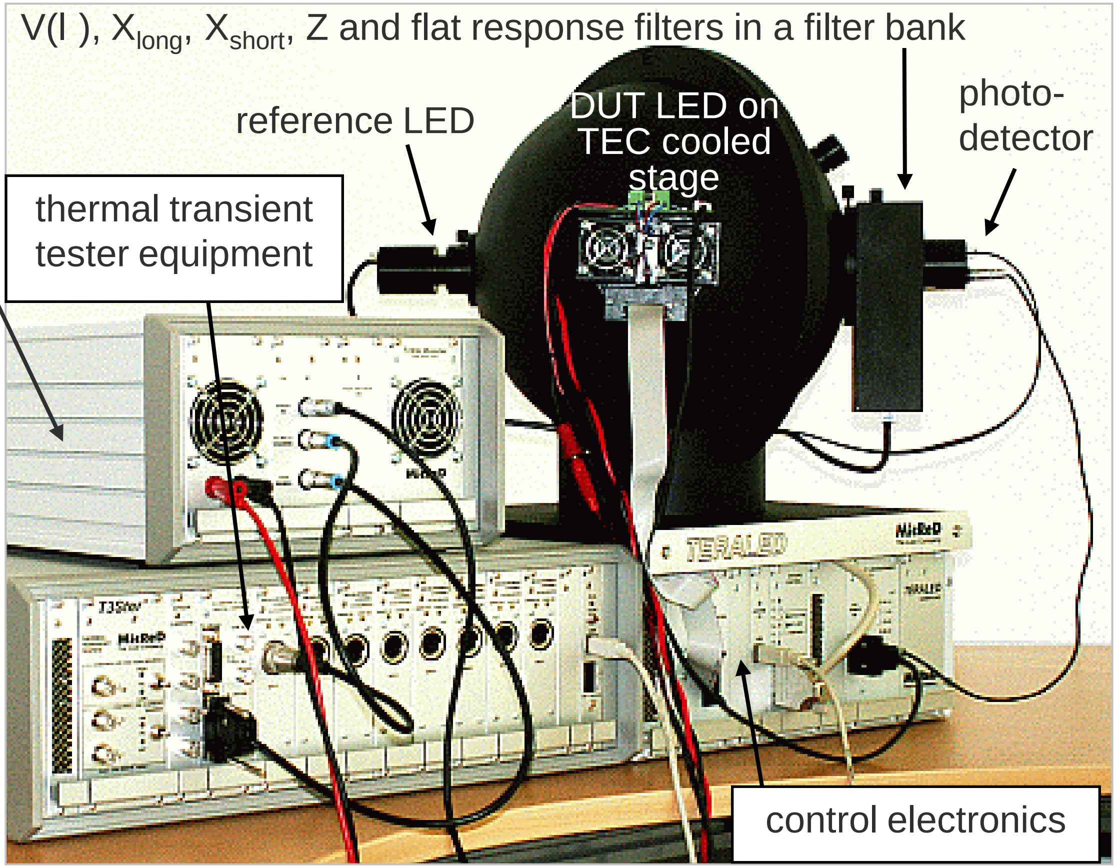
CIE 127-2007 compliant photometric & radiometric measurement system



JEDEC JSD51-1 static test method compliant thermal measurement system

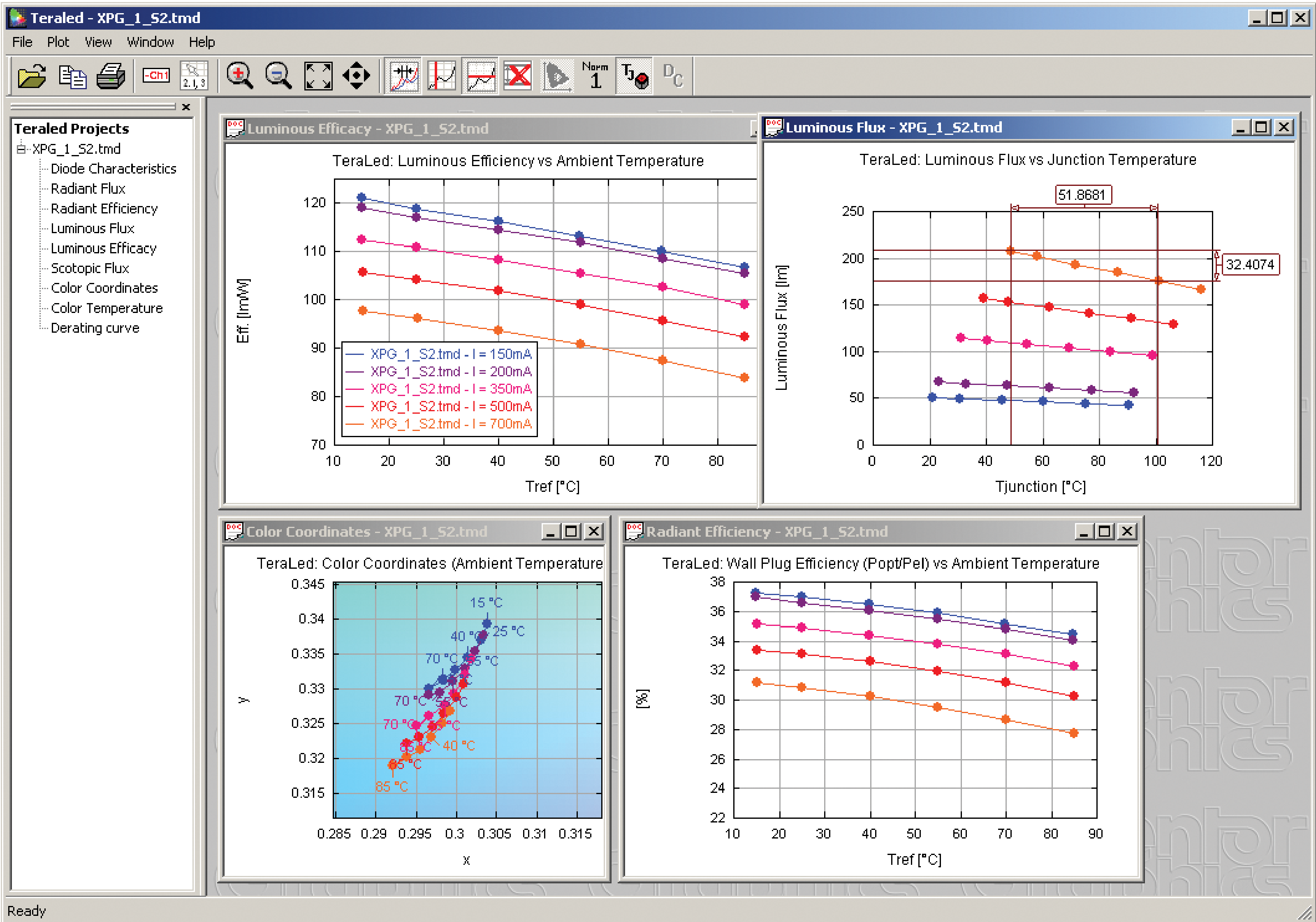
Our implementation:

Special LED booster: allows high voltage across a LED line (overall forward voltage can reach 280V – needed for AC mains driven LEDs).



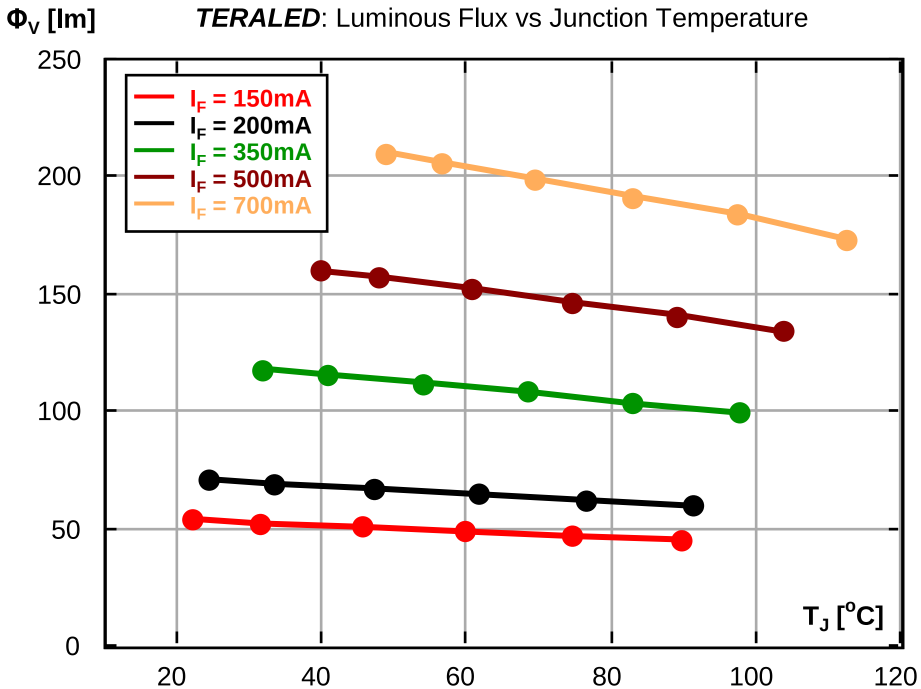
Developed in 2005 in co-operation with the University of Panniona, Veszprém, Hungary (team of prof. J. Schanda) and TENZI Ltd. 30+ users of the combined setup, including leading SSL companies world-wide

Besides R_{th}/Z_{th} we obtain e.g. $\Phi_V(I_F,T_J)$ $\eta_e(I_F,T_J)$ plots

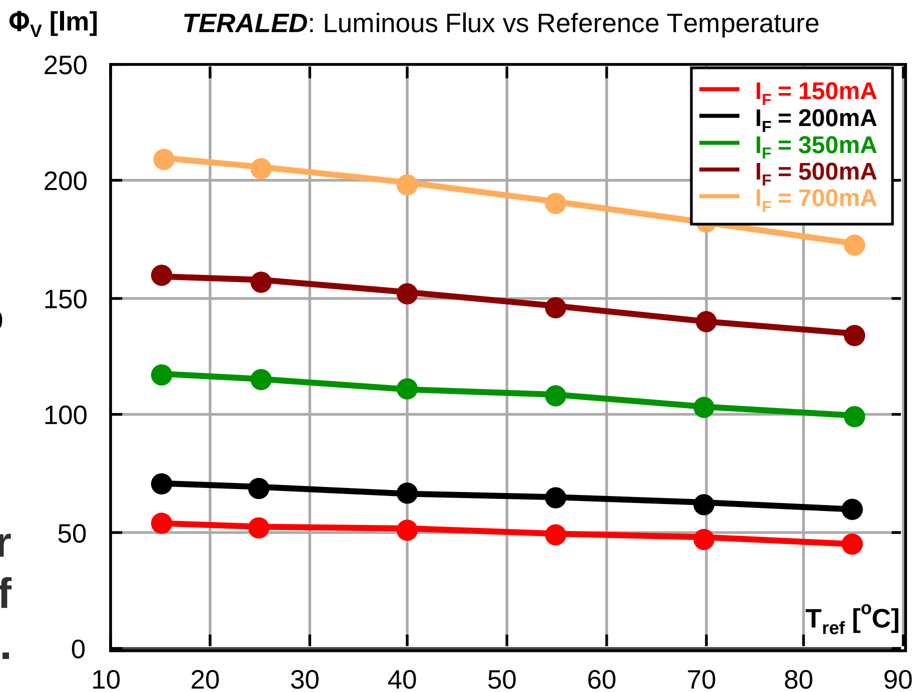


What temperature to report?

- The same luminous flux measurement results shown as function of reference temperature and junction temperature

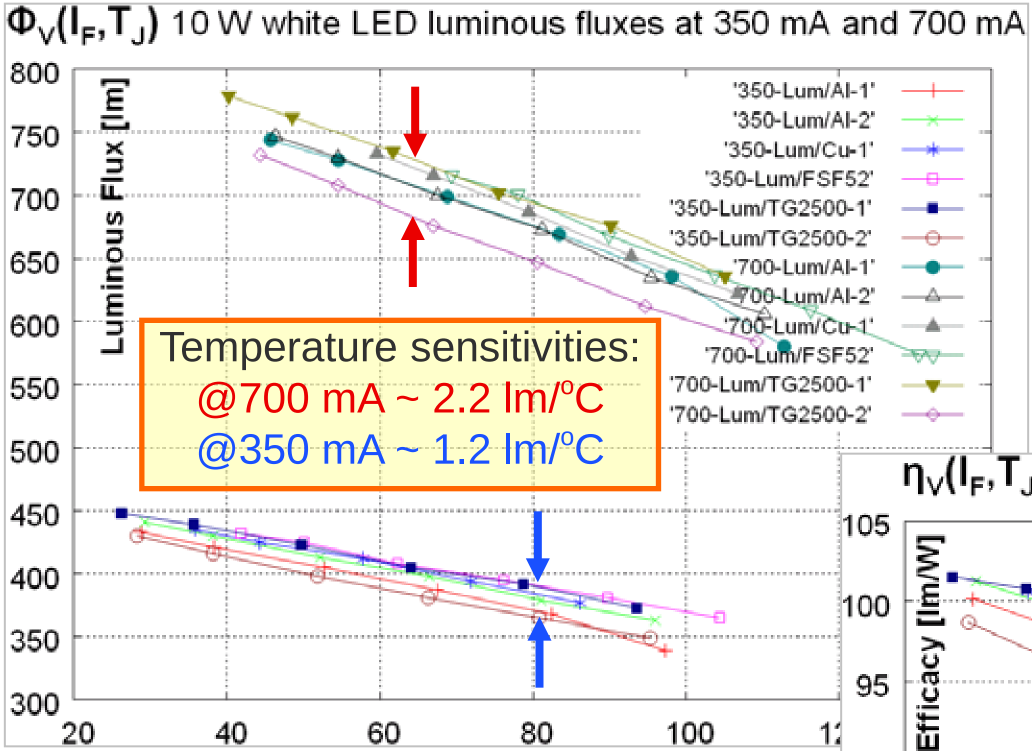


Data as function of *junction temperature* is to be used for physical, multi-domain modeling of LEDs as well as for "hot lumen" estimates.



***Ambient temperature* is relevant for thermal designers since this is one of the input parameters of their designs.**

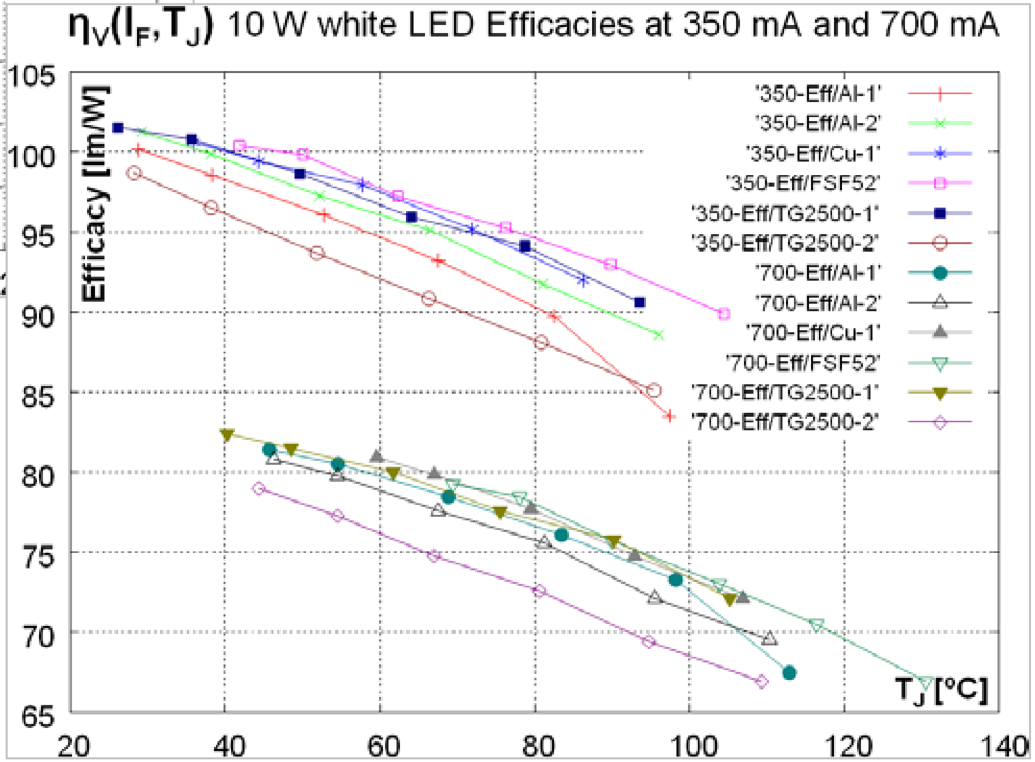
$\Phi_V(I_F,T_J)$ & $\eta_V(I_F,T_J)$ plots for 7 different samples



Luminous flux plots [lm]

Results for 10 W white LEDs

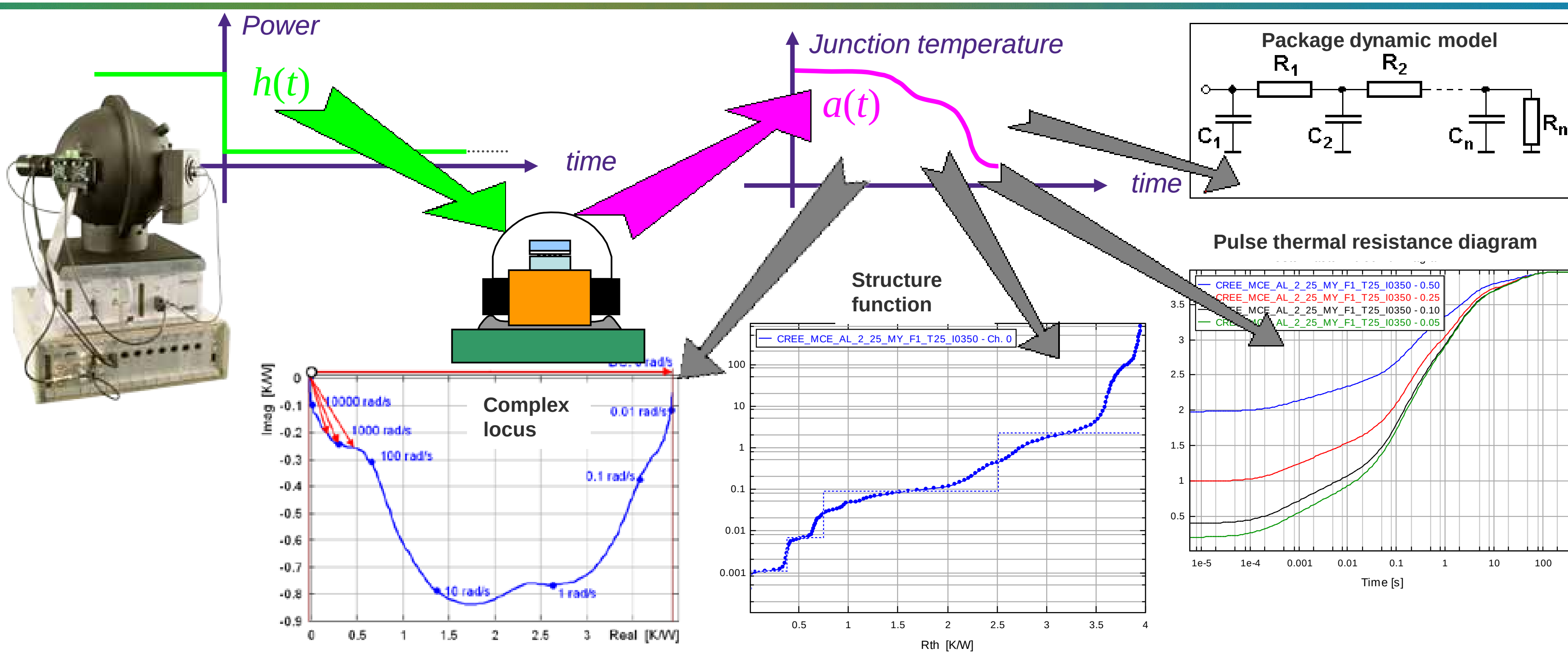
Efficacy plots [lm/W]



We shall use this example also at highlighting some problems of short pulse testing and LM80 tests

What are the benefits of measuring the complete junction temperature transient with 1ms / 0.01 ^{o}C resolution?

Different representations of the thermal impedance



n Thermal transient testing:

— The *h(t)* step-wise change in heating is applied at the junction (abrupt switching)

— The *a(t)* temperature response at the junction is being measured (unit-step response function) while linearity is assumed. Typical resolution is 1ms / 0.01 ^{o}C

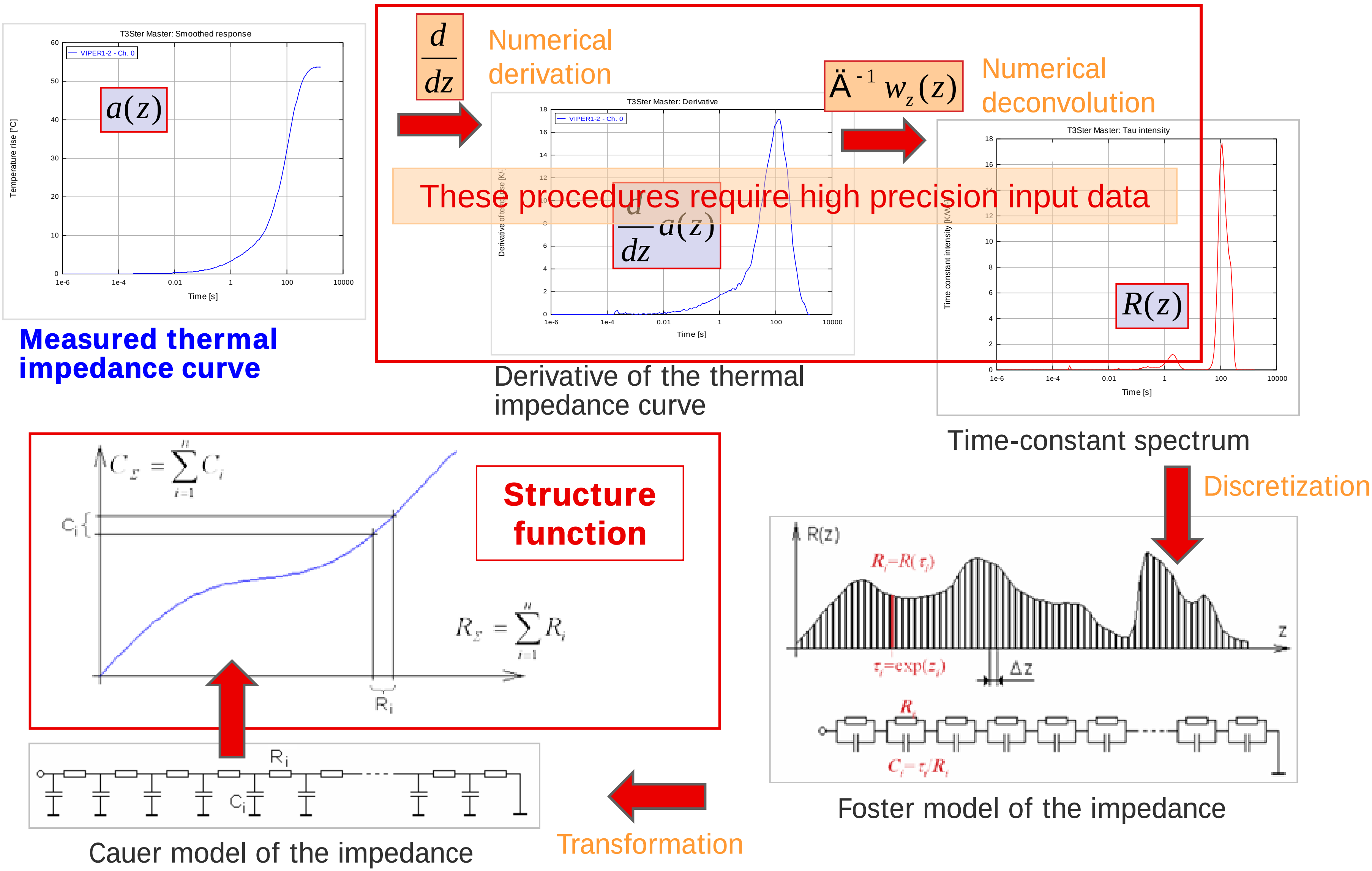
n All available information is extracted from *a(t)* using sophisticated mathematical procedures:

— structure functions è **structural analysis, failure detection**

— pulsed thermal resistance è for thermal design of PWM dimming

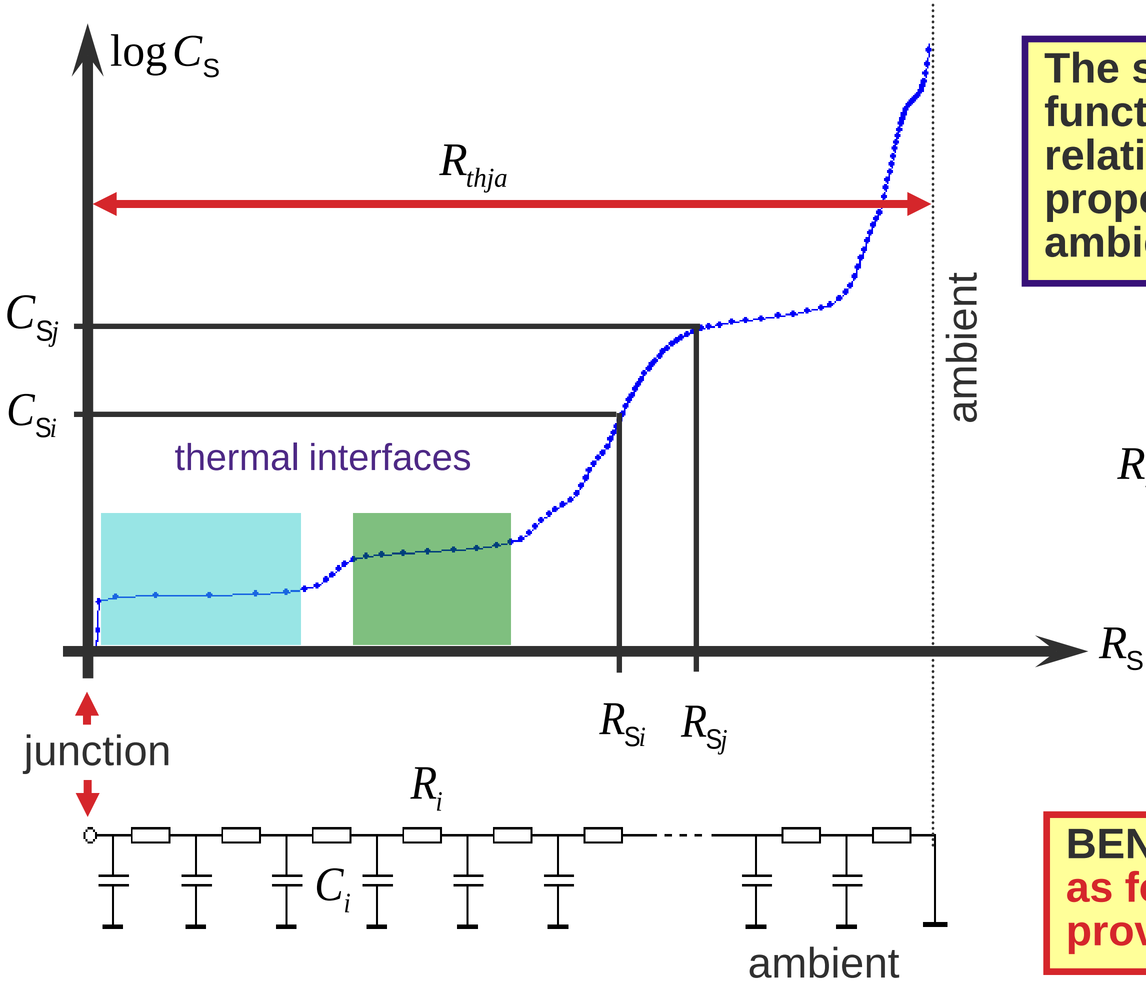
— complex locus (frequency domain rep.) è **for thermal design of AC LEDs**

Converting Z_{th} curves to *structure functions*



The Cumulative Structure Function

The *cumulative structure function* is the *graphical representation* of the *network model of the thermal impedance* of the junction-to-ambient heat-flow path.



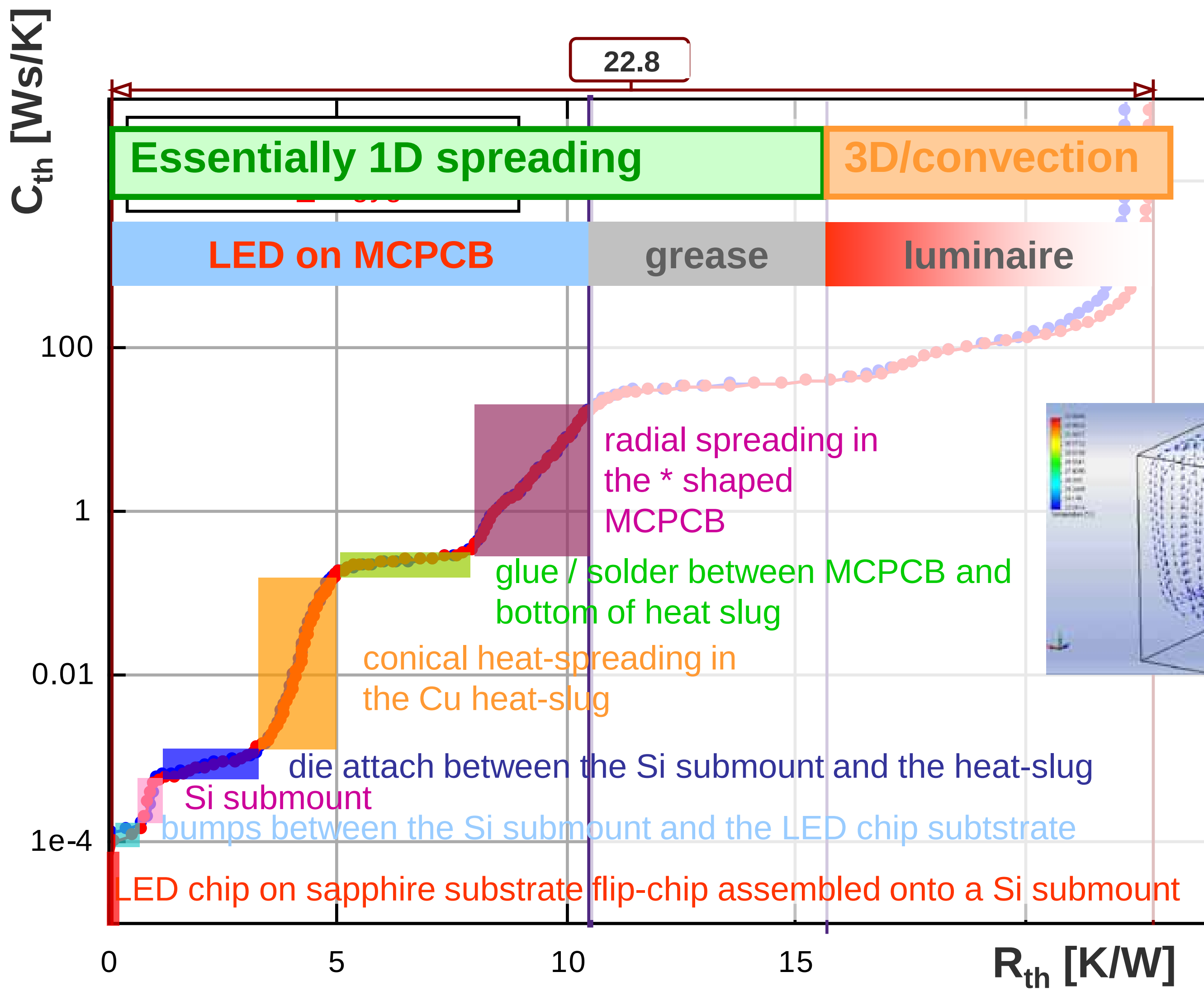
The shape of the structure function is in a one-to-one relationship with the properties of the junction-to-ambient heat-flow path.

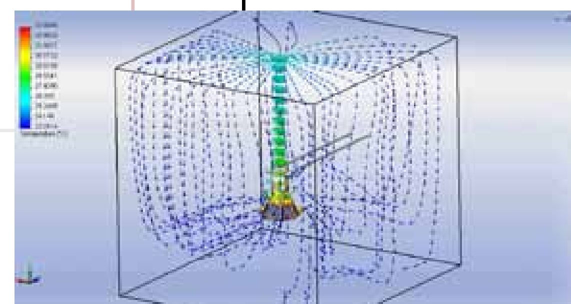
$$R_{Sn} = \sum_{i=1}^{n} R_i \qquad C_{Sn} = \sum_{i=1}^{n} C_i$$

BENEFIT: same testing time as for steady-state, but provides much details…

The *cumulative structure function* illustrates the way how heat flows though a package.

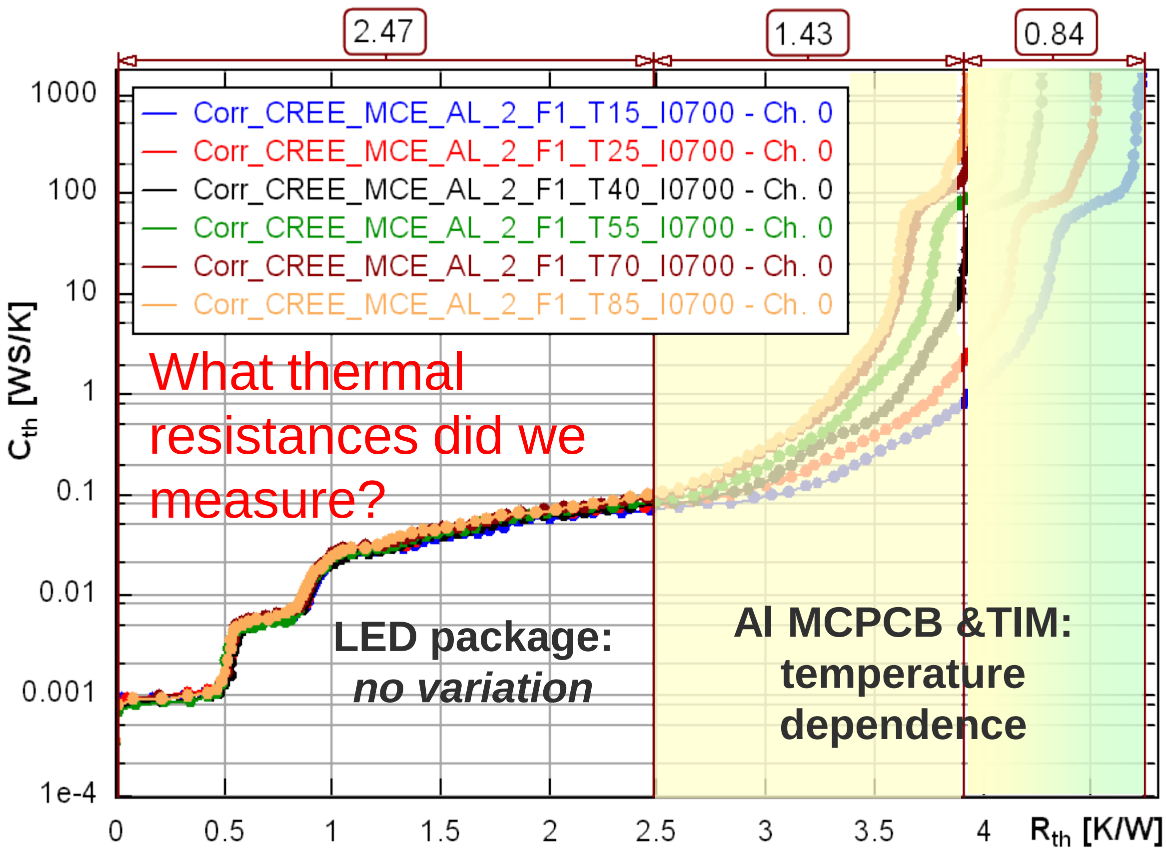
Details of an LED on MCPCB in an MR16 lamp





Results for 10W white LEDs

- Measured at 350/700 mA & between 15 ^{o}C and 85 ^{o}C
  - Structure functions, scaled in $R_{th\text{-}real}$, corrected with P_{opt}



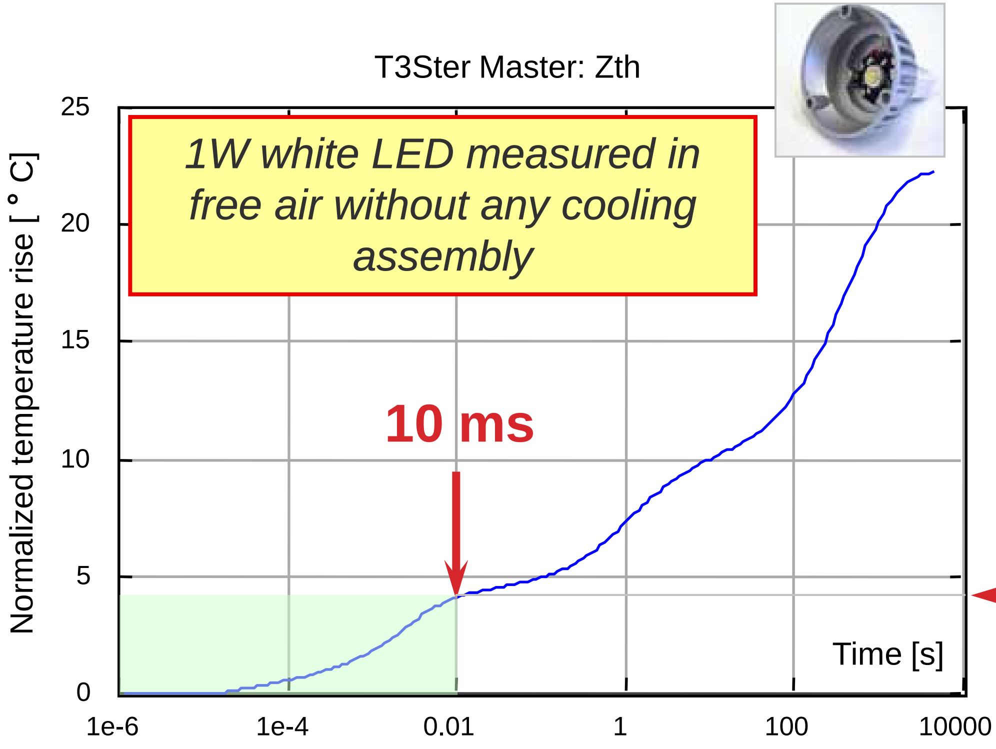
Changes in TIM quality contribute to light output variations

In the next section we shall see, how.

Further problems:
Thermal issues in short-pulse testing
and in LM80 tests

Short pulse measurements

- During in-line testing photometric/colorimetric properties are measured with a short pulse
- We can study what happens during in-line testing with high resolution junction temperature transients captured off-line
  - $T_J = T_{ref}$ = constant is assumed, ***THIS IS NOT TRUE:*** In 10 ms significant junction temperature change may take place

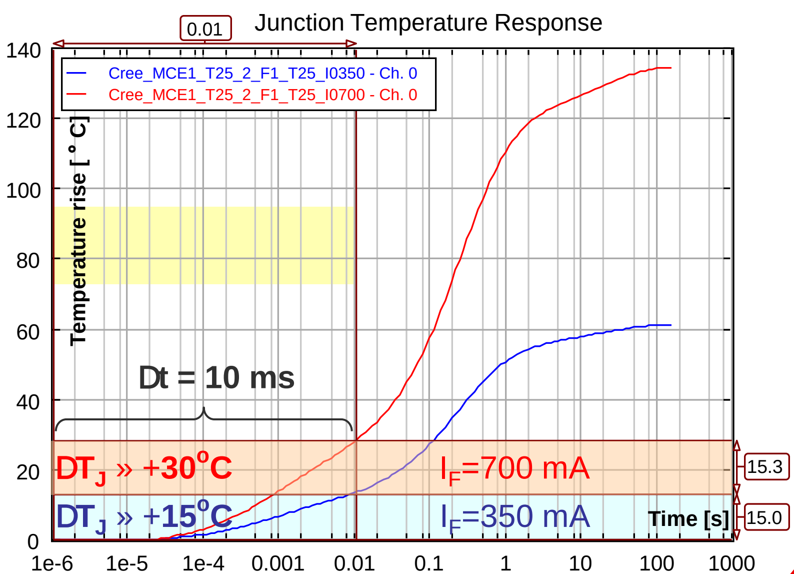


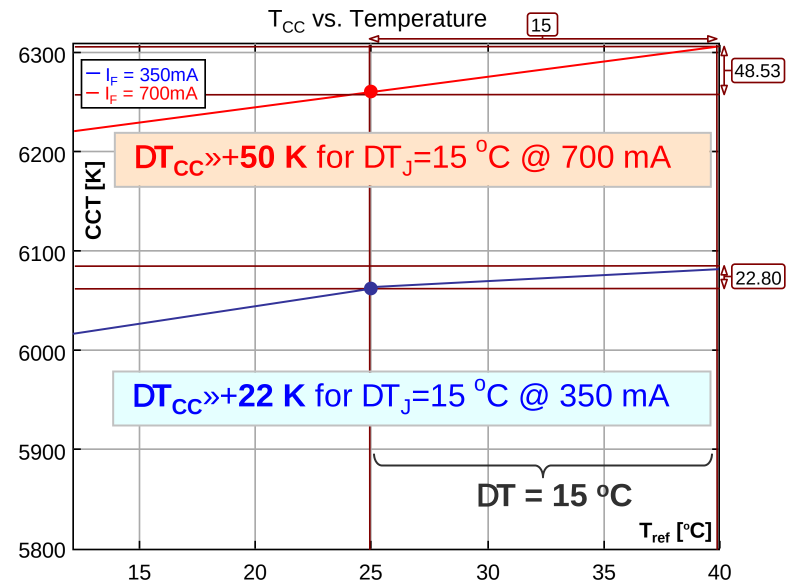
~5 ^{o}C

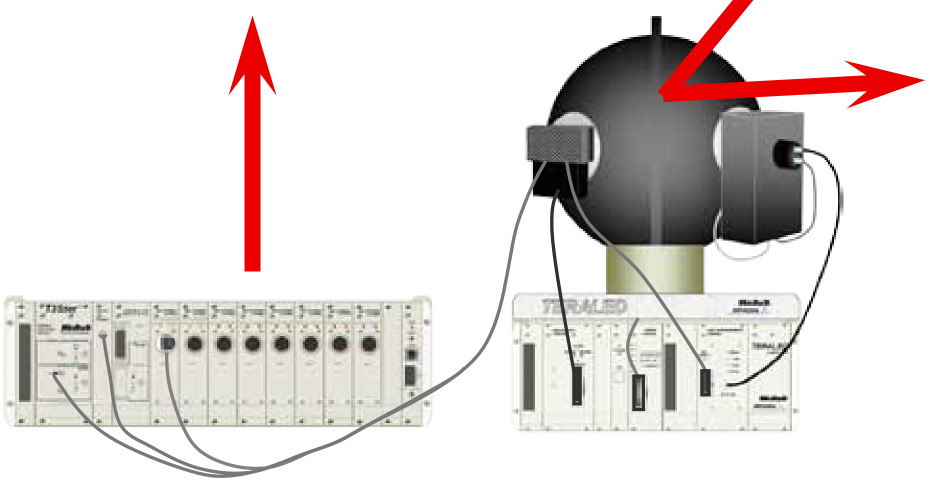
Question is if this causes big problems or not…

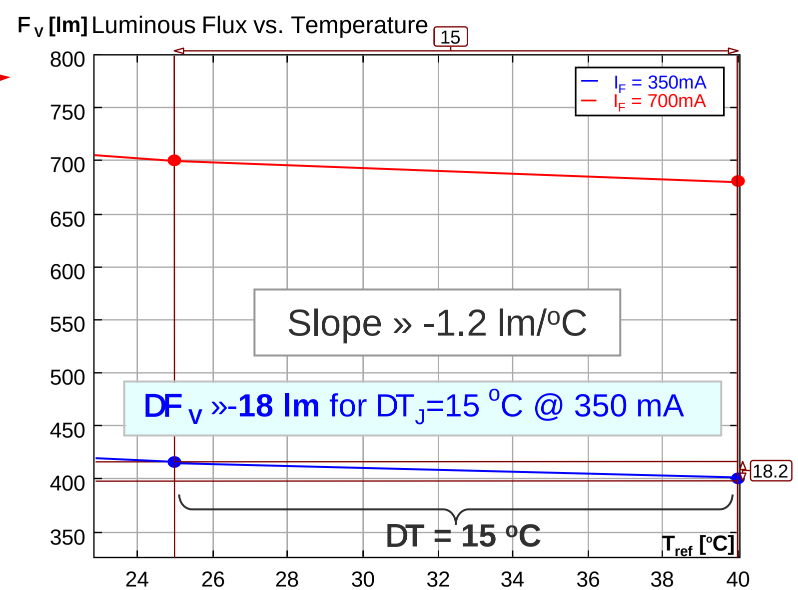
Depends on the temperature sensitivity of light output properties

Example: 10W white LED

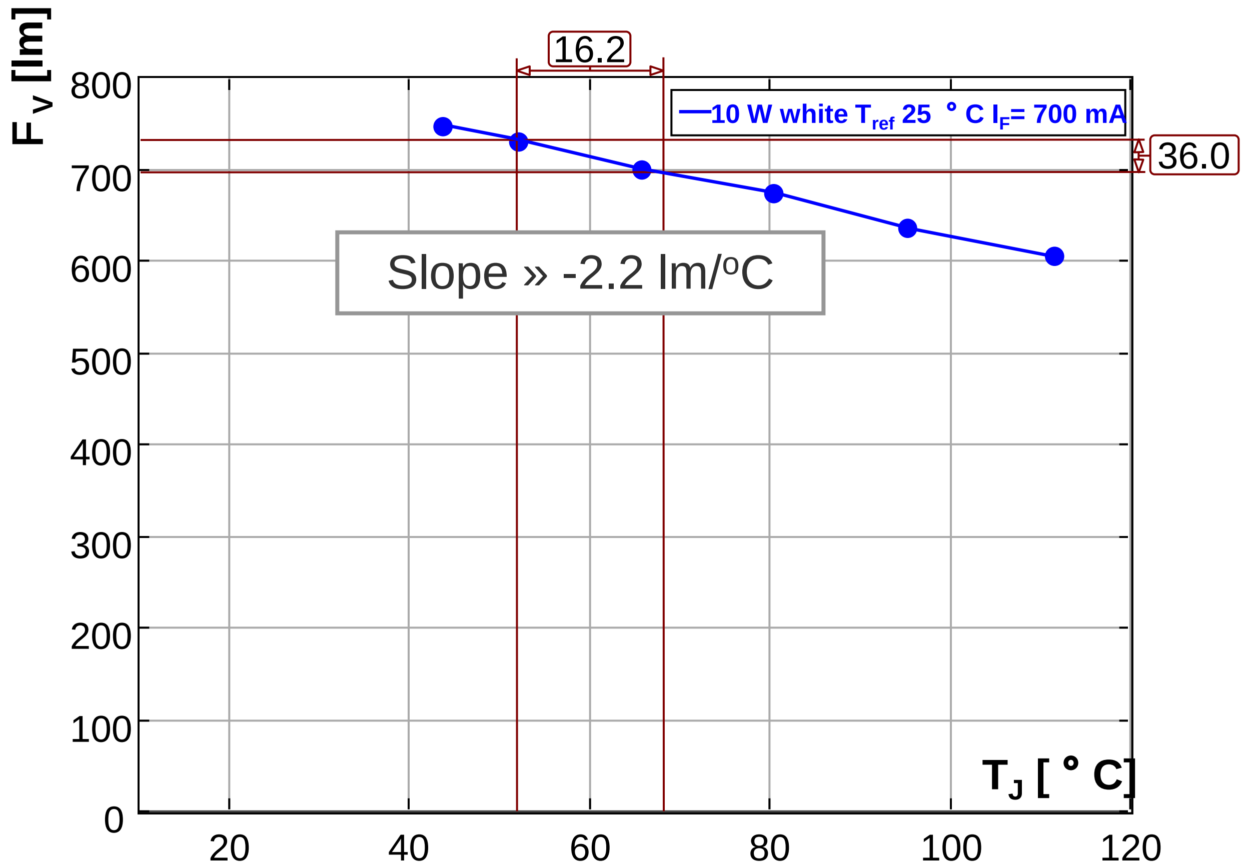








Results for the same LED: $\Phi_V(T_J)$ at I_F = 700 mA



Thermal drift of the luminous flux during 10 ms would be

DF_V = -2.2 lm/^{o}C ✕ 30 ^{o}C = **-66 lm**

8.9% drop with respect to the nominal 740 lm value

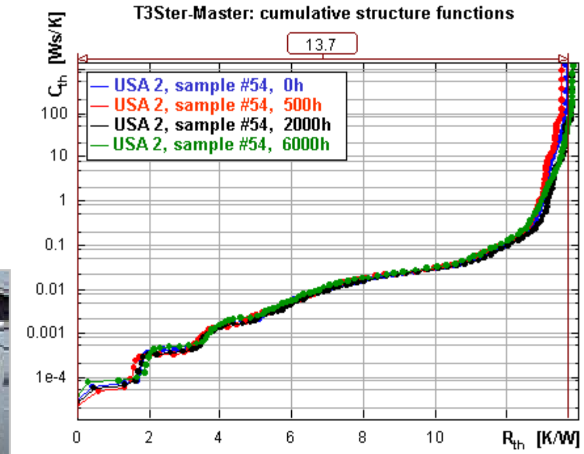
Thermal impedance measurements during LM80 tests

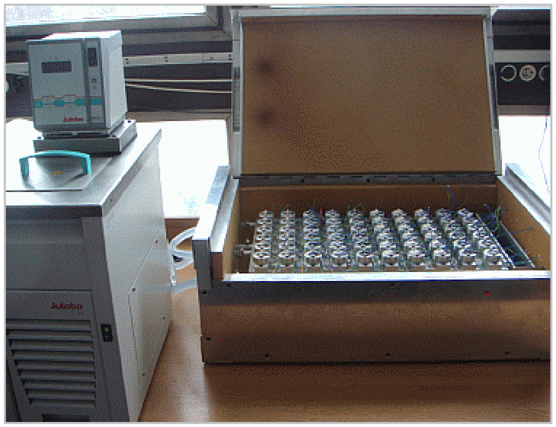
In-situ thermal measurements during LM80 tests

Experiments in co-operation with the research team of prof. J. Schanda (Veszprém, Hungary)

- 8000 h burning time elapsed
- 8 LED types from EU, US, AP
- in-situ measurements

KÖZLED project of the Hungarian Goverment

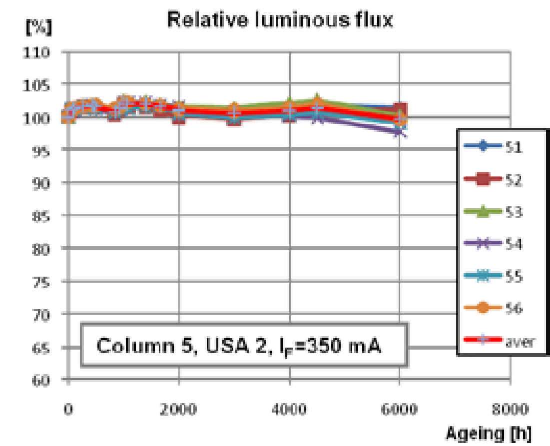


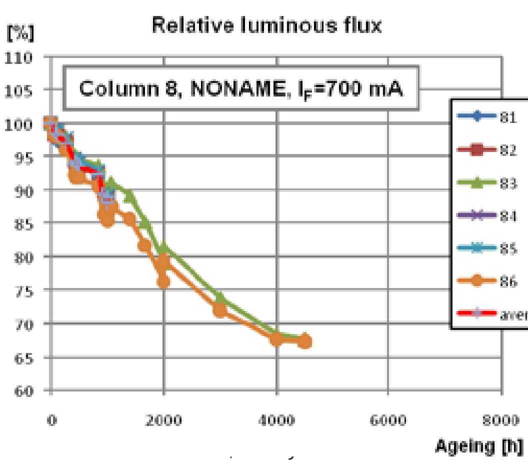


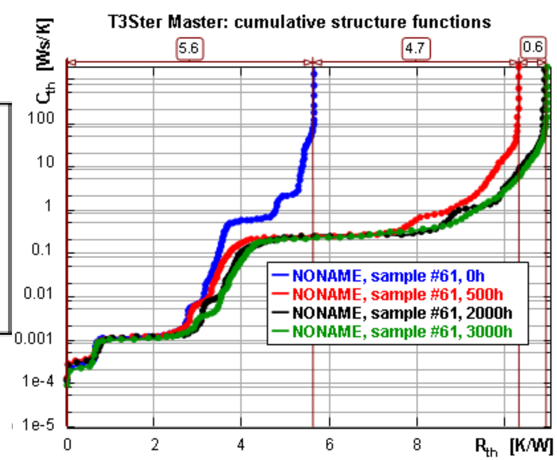
LM80 test chamber with all the LEDs assembled

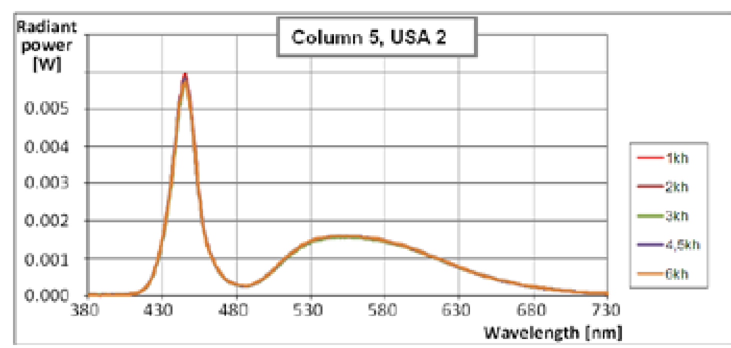
In-situ photometric measurments

In-situ thermal measurements



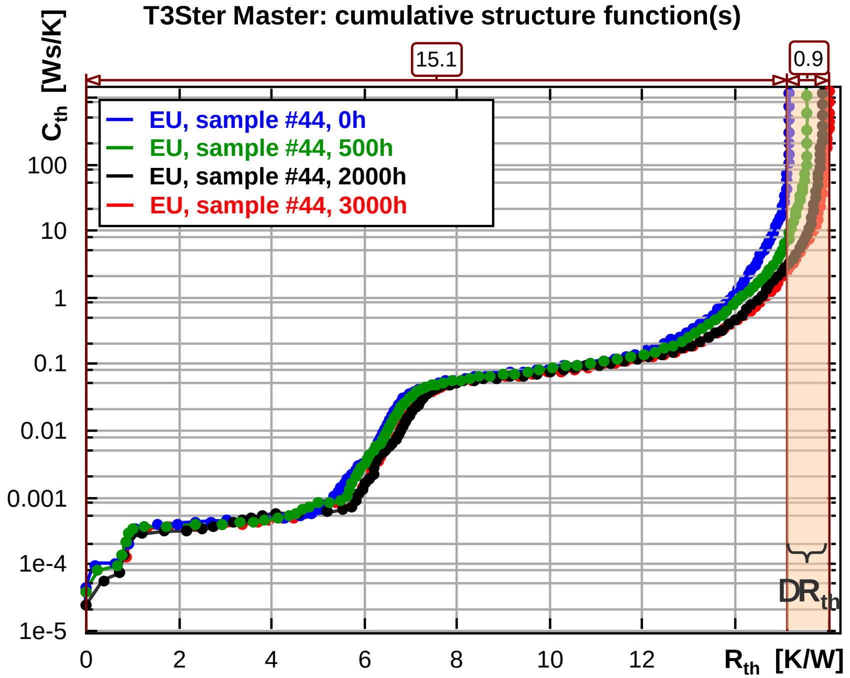


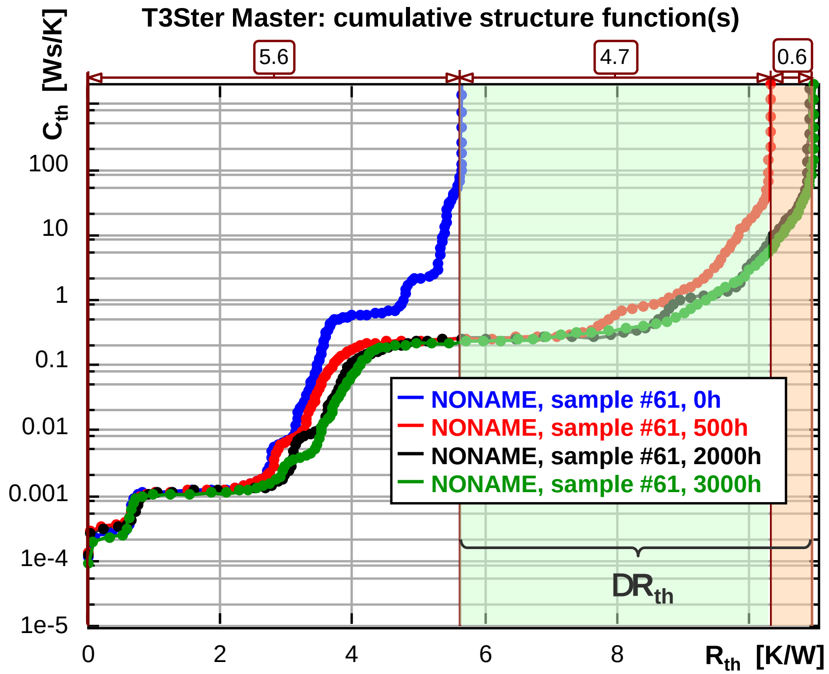




Recent results from LM80 test of different LEDs

- Results after 3000h:





TIM ageing: external to the LED – LM80 results must be compensated for this

Delemination from the MCPCB: a failure inside the LED assembly, its contribution to light output degradation is part of the LM80 test result

- The ~100% increase in thermal resistance in case of NONAME sample #61 is highly correlated with the drastic drop of relative luminous flux but it is not the primary reason

What is the effect of DR_{th} on DF_V?

Ageing [h]	P_{el} [W]	P_{heat} [W]	$R_{th\text{-}el}$ [K/W]	$R_{th\text{-}real}$ [K/W]	T_J [ºC]	DF_v [lm]	F_v [lm]	$F_{v\text{-rel}}$ [%]	**$DF_{v\text{-rel}}$ [%]**	
EU sample #44, with TIM ageing			h_e=17.5 %		**dF_v/dT_J = -0.15 [lm/ºC]**					
0	1.065	0.879	15.1	18.3	41.1	0.00	65.00	100.00	0.00	
3000	1.063	0.877	16.0	19.4	42.0	0.14	64.86	99.79	**0.21**	**0.21%**
NONAME, <u>with TIM ageing</u>			h_e=25.6 %		**dF_v/dT_J = -0.23 [lm/ºC]**					
0	1.045	0.862	5.6	6.8	30.9	0.00	88.00	100.00	0.00	
3000	1.052	0.868	10.9	13.2	36.5	1.26	86.74	98.56	**1.44**	
NONAME, <u>without TIM ageing</u>			h_e=25.6 %		**dF_v/dT_J = -0.23 [lm/ºC]**				**Effect of TIM:**	**0.17%**
0	1.045	0.862	5.6	6.79	30.9	0.00	88.00	100.00	0.00	
3000	1.052	0.868	10.3	12.48	35.8	1.12	86.88	98.73	**1.27**	
									Effect of delam:	**1.27%**
USA 1, 10 W, with TIM ageing			h_e=24.4 %		**dF_v/dT_J = -2.2 [lm/ºC]**					
0	9.53	7.20	3.8	5.04	61.3	0	737.0	100.00	0.00	
3000	9.52	7.20	4.7	6.23	69.8	18.8	718.2	97.46	**2.54**	**2.54%**

n Contribution of thermal resistance increase to drop of the relative luminous flux:
- — In case of samples from vendor EU and NONAME the effect of TIM ageing contributes to relative luminous flux drop by ~0.2% only.
- — In case of LEDs with higher temperature sensitivity this contribution is about **2.5%**

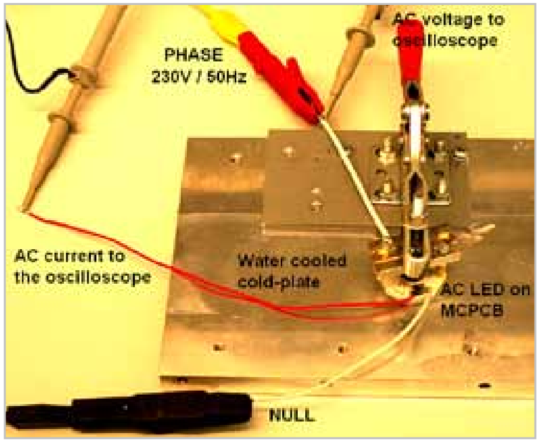
A few words about the AC thermal impedance of LEDs

Problems of testing AC LEDs: dissipation, Z_{thAC}

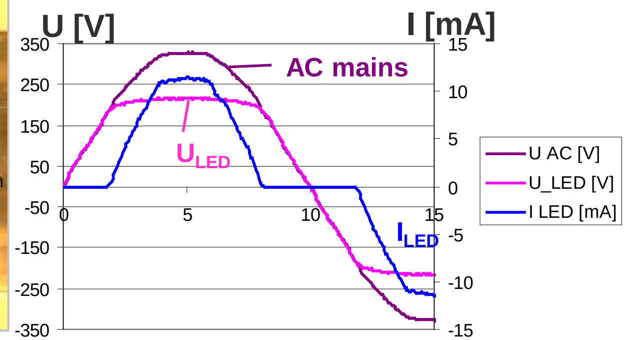
- The AC dissipation for voltage generator driven LED: many harmonics

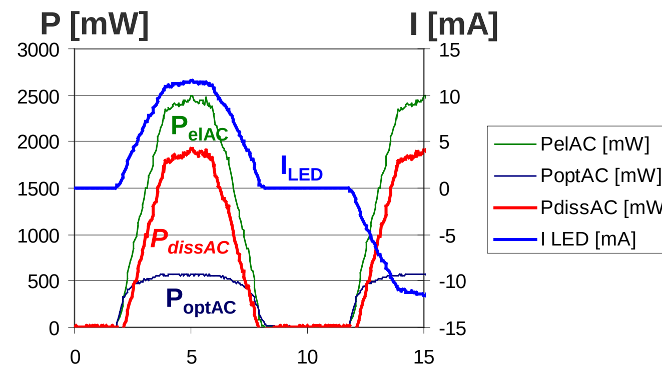
$$P_{dissAC}(\omega) = U_{MAX}^2 \times \frac{I_0}{mU_T} \times \frac{1}{1!} \sin^2(\omega t) + U_{MAX}^3 \times \frac{I_0}{(mU_T)^2} \times \frac{1}{2!} \sin^3(\omega t) + U_{MAX}^4 \times \frac{I_0}{(mU_T)^3} \times \frac{1}{3!} \sin^4(\omega t) + \ldots$$

Multiple frequencies

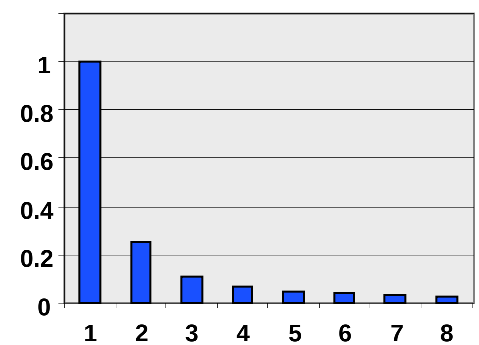


SSC Archie driven by 50Hz mains

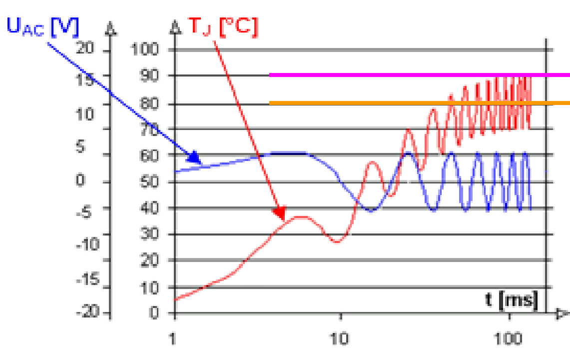




The first 8 harmonics of P_{dissAC}



- How to define a single number thermal metric?



$$Z_{thAC\text{-}max} = T_{JAC\text{-}max} / P_{dissAC\text{-}mean}$$

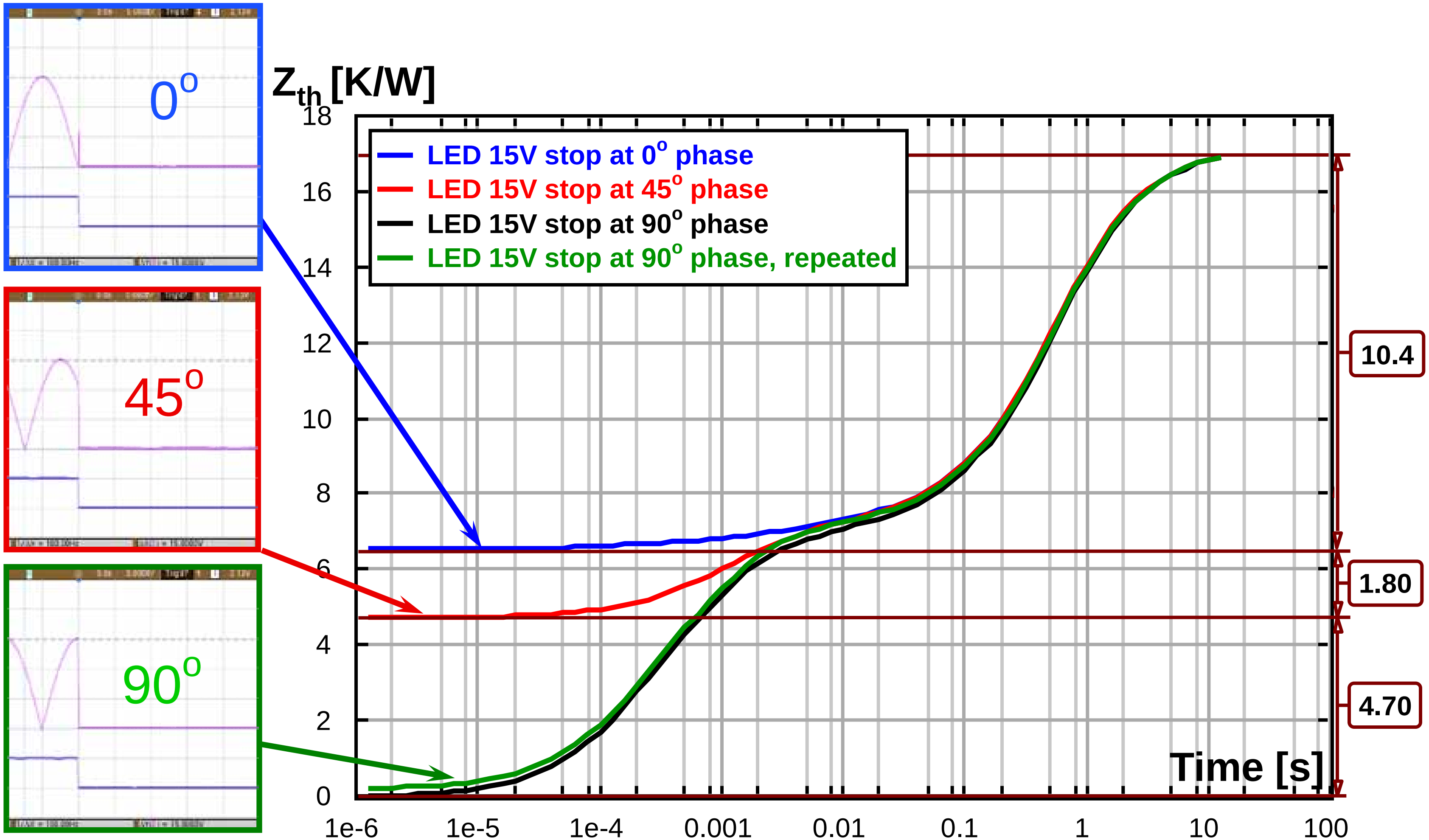
$$Z_{thAC\text{-}mean} = T_{JAC\text{-}mean} / P_{dissAC\text{-}mean}$$

$$T_{JAC}(t) = \sum_{n=0}^{\pm\infty} Z_{th}(n\omega_0) \times P_{dissAC}(n\omega_0) \times e^{jn\omega_0 t}$$

$$Z_{th}(\omega) = \int_0^{\infty} a(t) e^{-j\omega t} dt$$

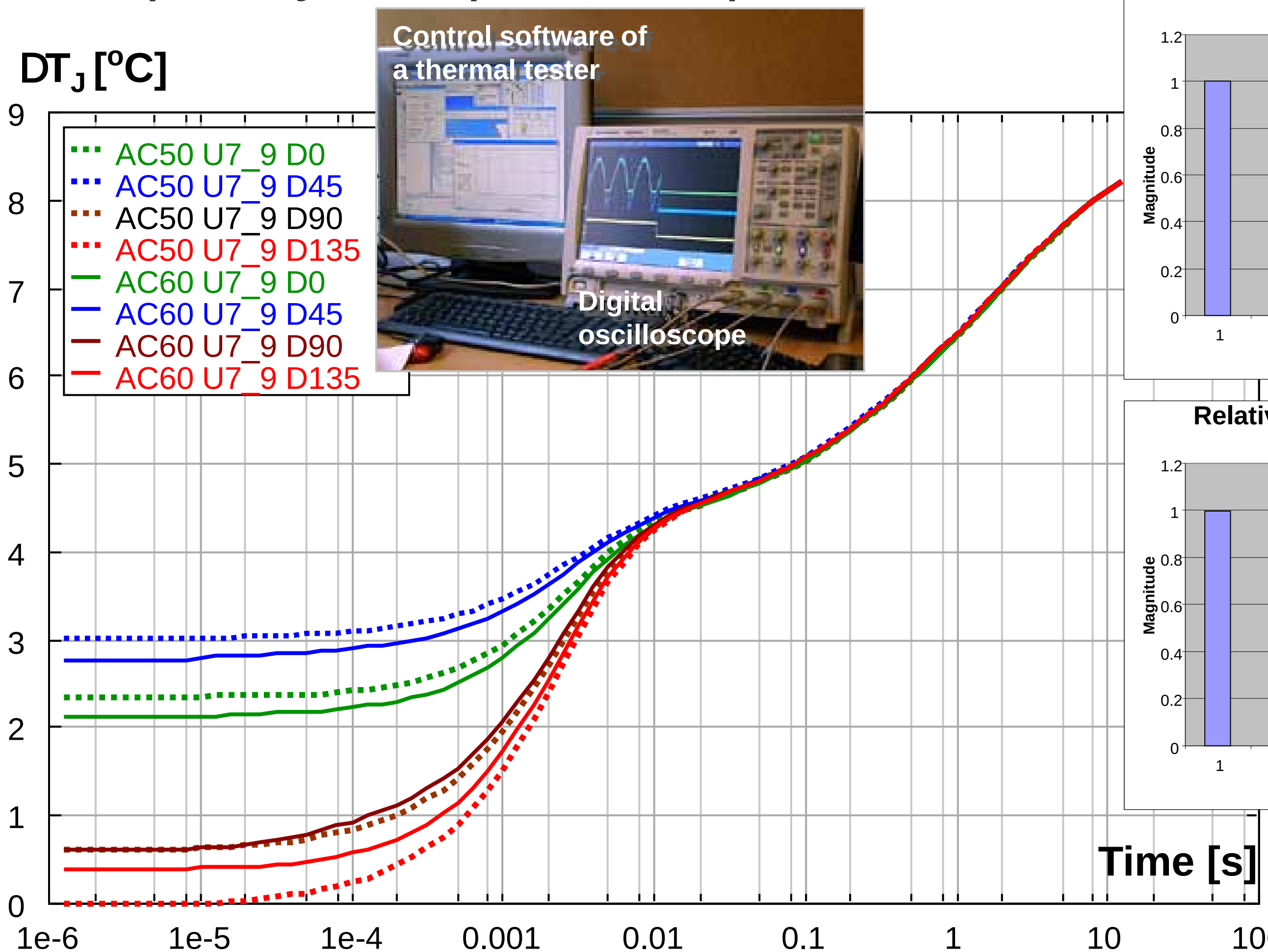
Some measurement results (cooling after AC heating)

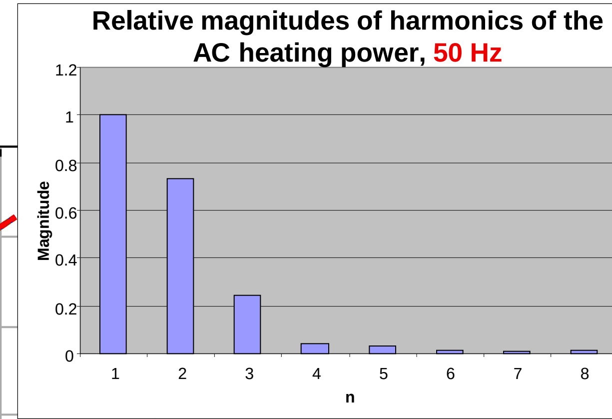
- Switching at 0^o, 45^o and 90^o of phase of a 50 Hz sine-wave
  - — The impedance measured strongly depends on the phase: 16.9 K/W @ 90^o phase vs. 10.4 K/W @ 0^o phase in this example.

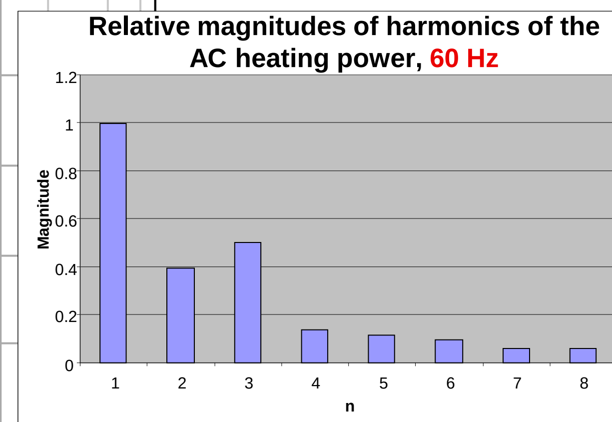


Some measurement results (cooling after AC heating)

- Frequency and phase dependence:







Follows theoretical expectations but the explanation is not straightforward.

Without firm definitions and understanding one may report almost "any" test result.

Summary

- Measurement setup for consistent measurement of thermal and light output metrics of power LEDs was shown
  - Based on existing standards (JEDEC JESD51-1, CIE 127-2007)
  - Therefore with some new measurement guidelines it is easily implemented
- Merits of such a system capable of capturing real transients of the junction temperature were shown:
  - Structure functions derived from these help structural analysis
  - Features "inside the LED package" and "outside the LED package" can be easily identified
- Combined thermal transient and photometric measurements suggest that the constant junction temperature assumption in short pulse in-line testing is not valid
  - Temperature sensitivity of luminous flux can be derived from such measurements; this parameter is relevant e.g. in LM80 tests
- To eliminate effect of variations (ageing) of TIM during LM80 tests, *in-situ* measurements are suggested, combined with thermal transient measurements
- Problems related to the “AC thermal impedance” as a single number thermal metric for AC mains driven LEDs were raised

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Thank you for your attention