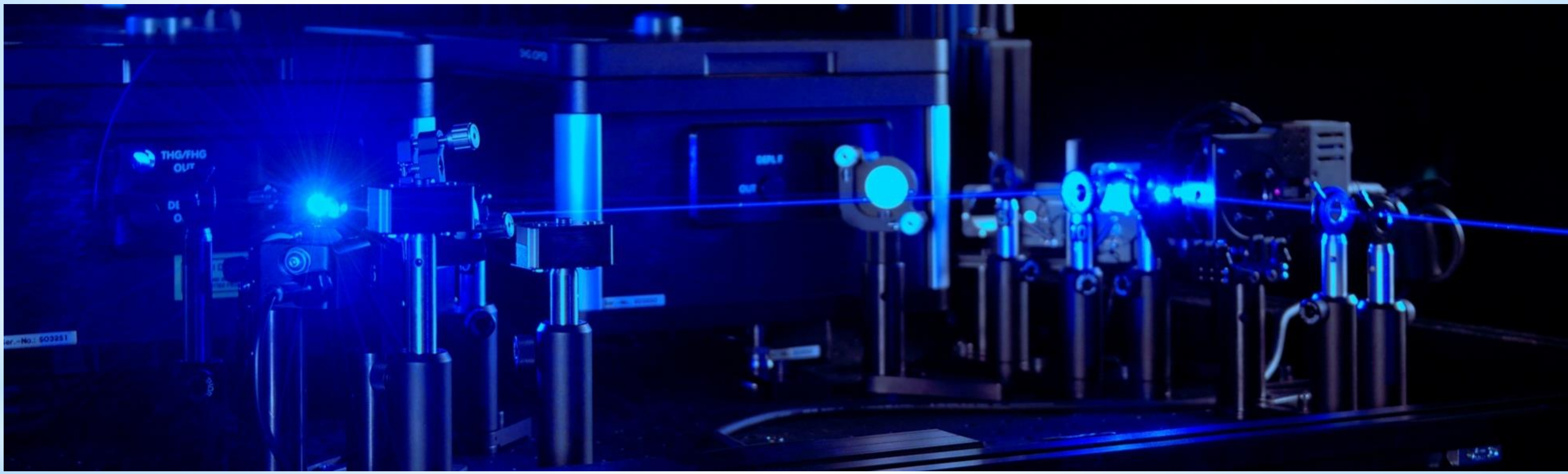
The Laser-DSR Method



New Developments in the Field of Primary Calibrations of Reference Solar Cells

29.10.2015

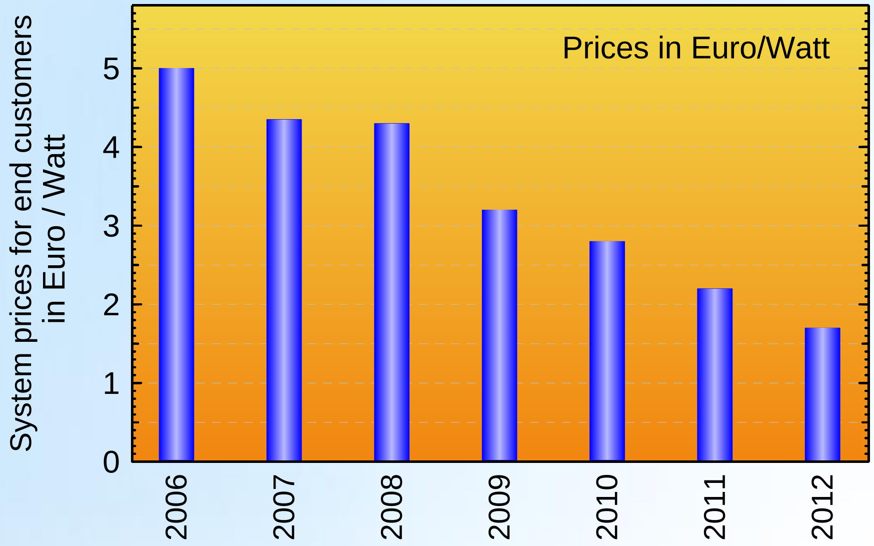
Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin

Overview

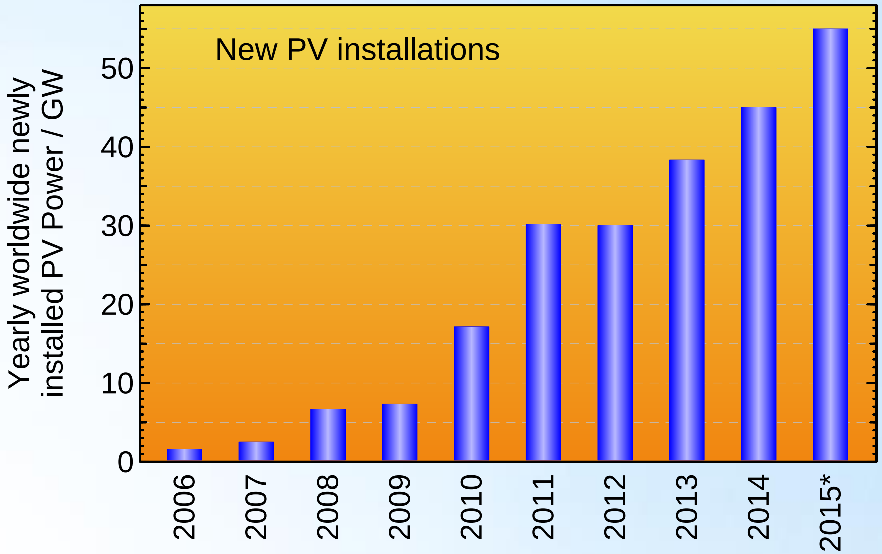
- Demand for high accuracy solar cell calibrations
- Standard Test Conditions
- DSR Method
- The new PTB setup: Advantages and disadvantages
- Validation by International Comparisons => WPVS

Economic Impact of Measurement Uncertainty for Photovoltaics

PTB



Source of data: www.solarwirtschaft.de/preisindex



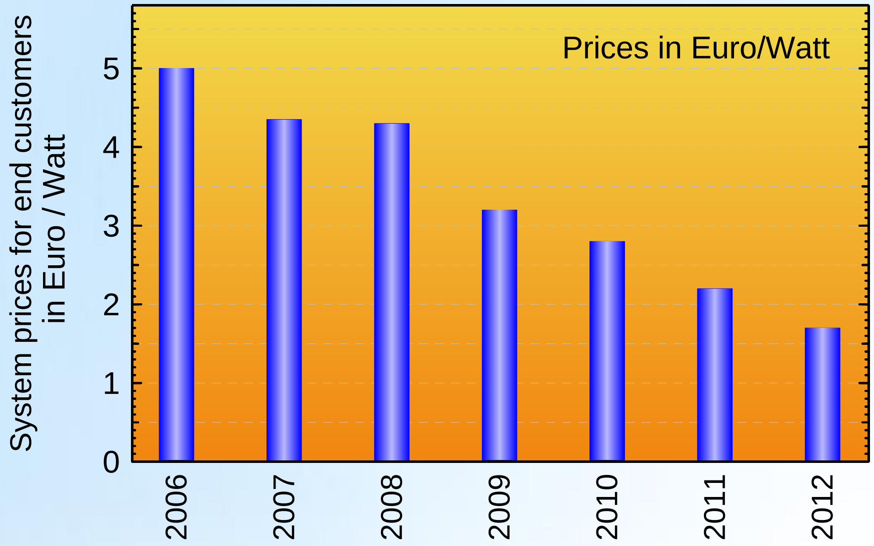
Source of data: EPIA (European Photovoltaic Industry Association) and for 2015 according to IHS market research institute

- Financial uncertainty = Global annual installation × Price × Uncertainty
- 2012: **Financial uncertainty** = 30 GW/year × 1.7 €/W × 1 % = **500 M€/year**

⇒ A measurement uncertainty of 1% leads to a financial uncertainty of 500 M€/year
⇒ **High demand for high accuracy solar cell calibrations**

Solar parks are financed from banks, who add the financial uncertainty arising from measurement uncertainty to the total amount to be financed. A low uncertainty leads to competitive advantage.

Economic Impact of Measurement Uncertainty for Photovoltaics



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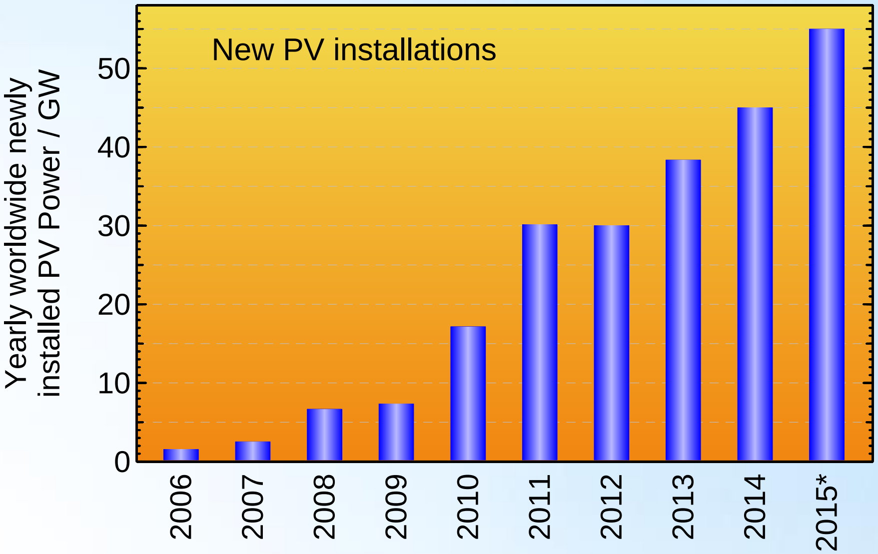


Source of data: EPIA (European Photovoltaic Industry Association) and for 2015 according to IHS market research institute

To achieve lower uncertainties, in addition more realistic standards are needed

⇒ Energy rating instead of Maximum Power for PV classification (EMRP-Project PhotoClass)

⇒ Energy rating approach needs much more parameters

- Temperature dependence
- Non-Linearity
- Angular dependency

} **Demand for a multifunctional calibration facilities**

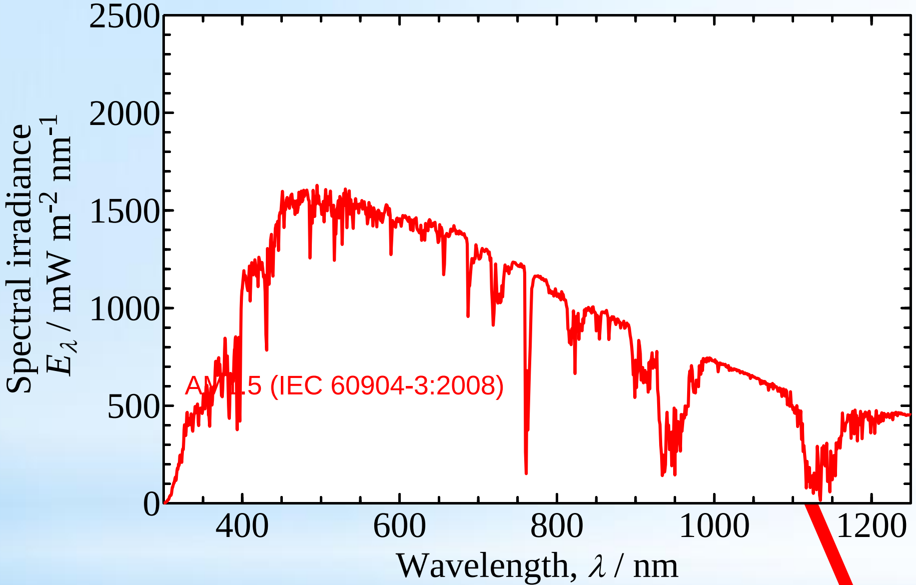
Standard Test Conditions

- Reference solar spectrum AM1,5
- Irradiance E_{STC} = 1000 W/m²
- Cell-Temperature (25°C)
- Angular distribution important, but not defined

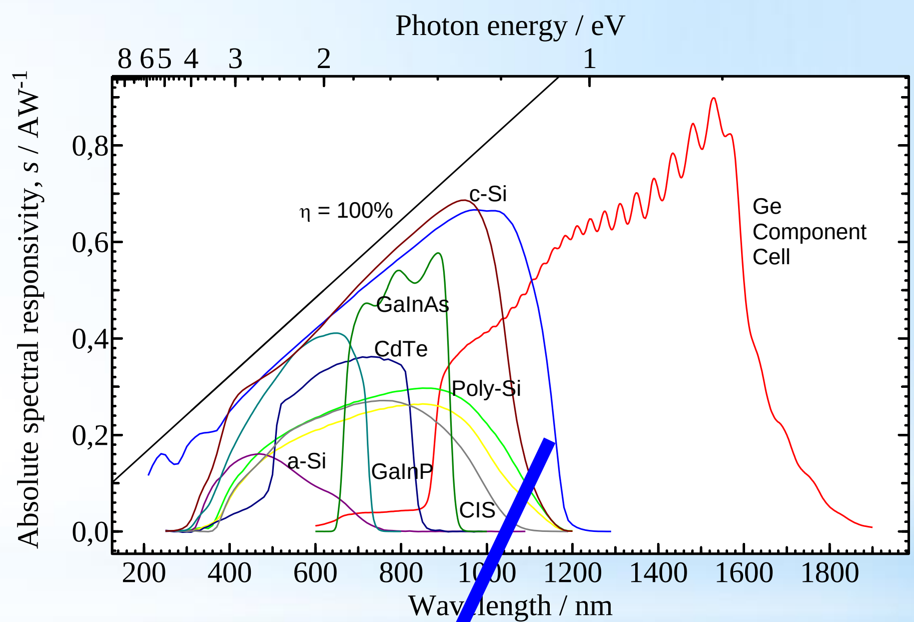
The calibration procedure must **take into account** these STC according to IEC 60904-3.

Metrological background

Reference solar spectrum AM1.5 according to IEC 60904-3:2008



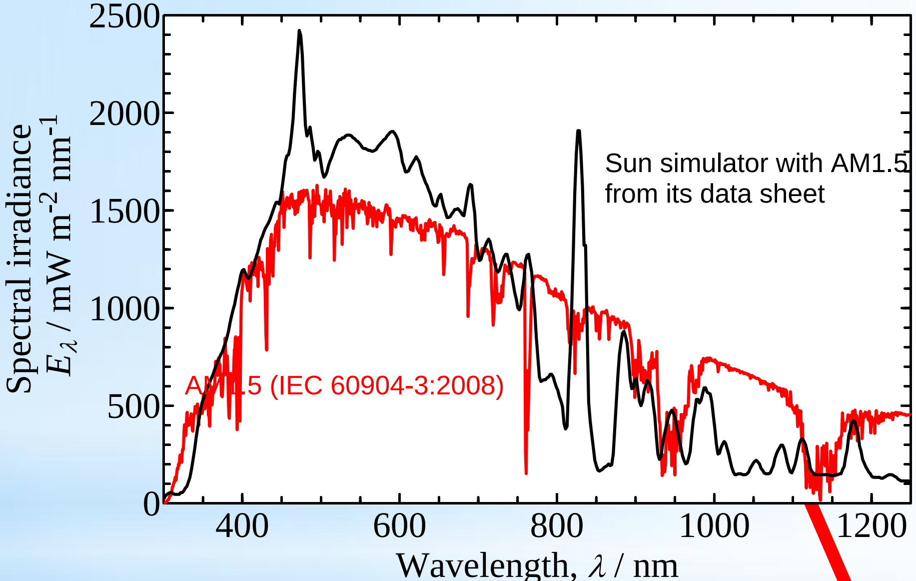
Spectral responsivity of different solar cells



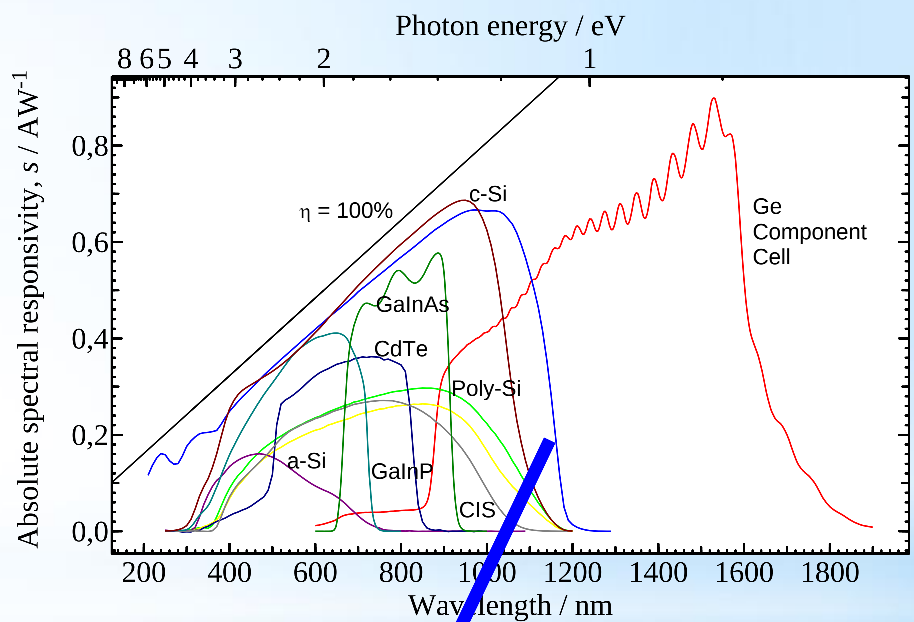
$$\text{Photocurrent:} \quad I = \int E_{\lambda,\mathrm{Norm}}(\lambda) \cdot s(\lambda)\, \mathrm{d}\lambda$$

Metrological background

Reference solar spectrum AM1.5 according to IEC 60904-3:2008

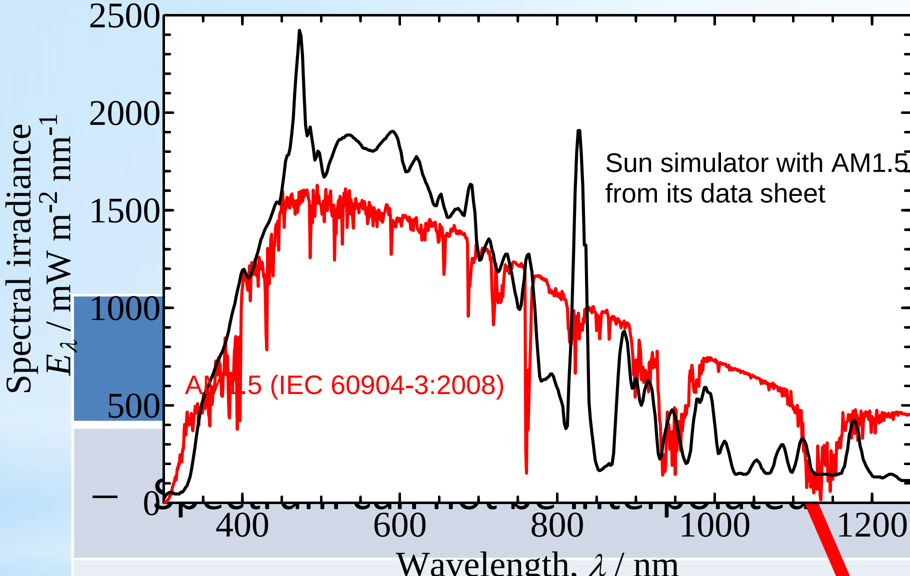


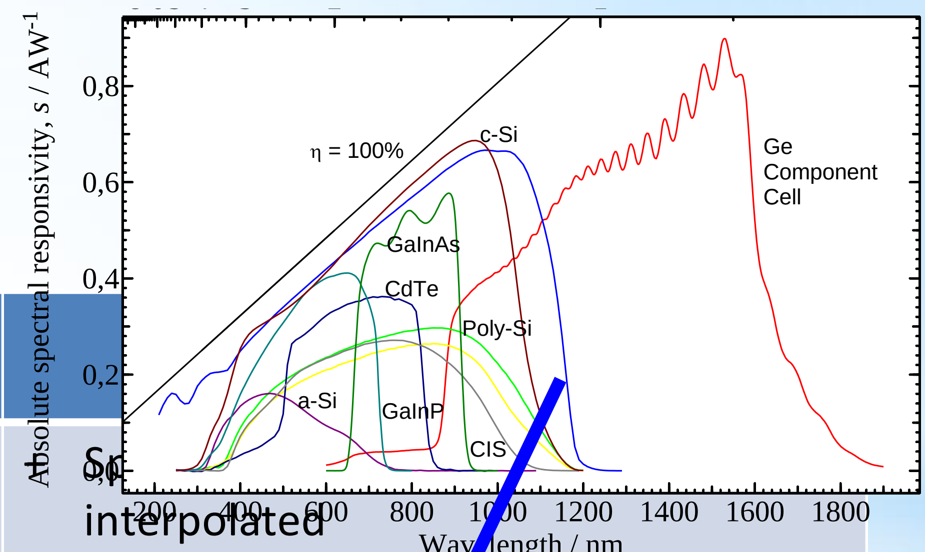
Spectral responsivity of different solar cells



$$\text{Photocurrent:} \quad I = \int E_{\lambda,\mathrm{Norm}}(\lambda) \cdot s(\lambda)\, \mathrm{d}\lambda$$

Comparison of integral and spectral measurements





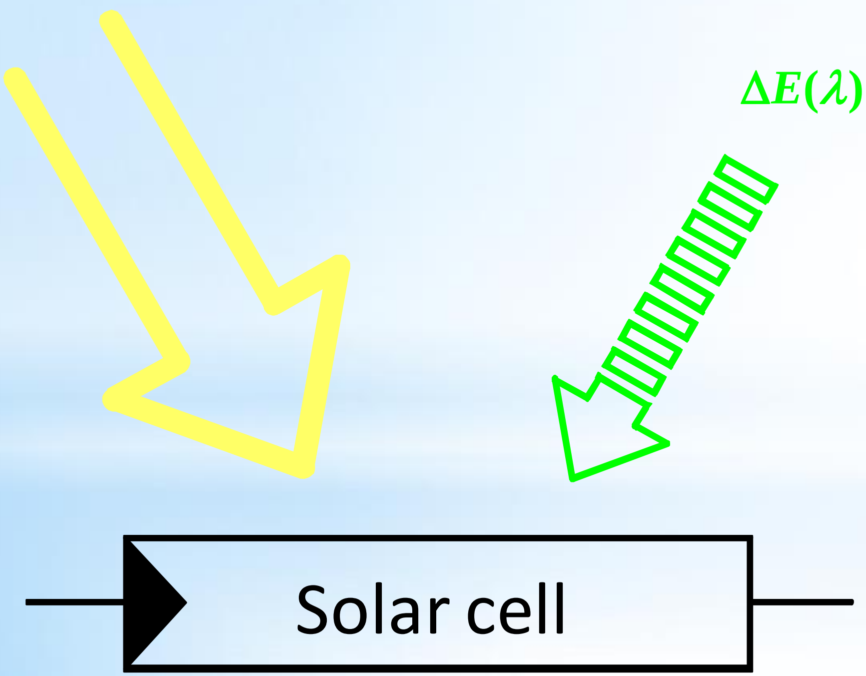
– Spectrum can not be interpolated	+ Sp[illegible] interpolated
– Uncertainty due to the measurement of the spectrum, e.g. spectral straylight within the spectroradiometer	+ The AM1.5 spectrum of the standard can be used directly => No uncertainty component
+ High signal	– Low signal

$$\text{Photocurrent:}\quad I = \int E_{\lambda,\mathrm{Norm}}(\lambda)\cdot s(\lambda)\,\mathrm{d}\lambda$$

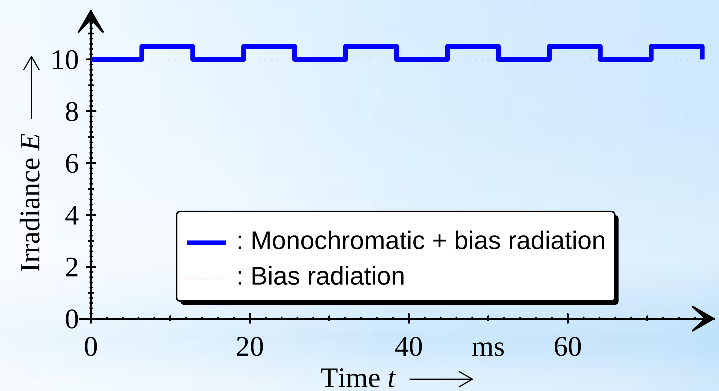
DSR-Method
Differential Spectral Responsivity

Bias radiation
E_b

Modulated monochromatic radiation, measured with Ref.-PD



$I_b + \Delta I_{sc}(\lambda, E_b)$

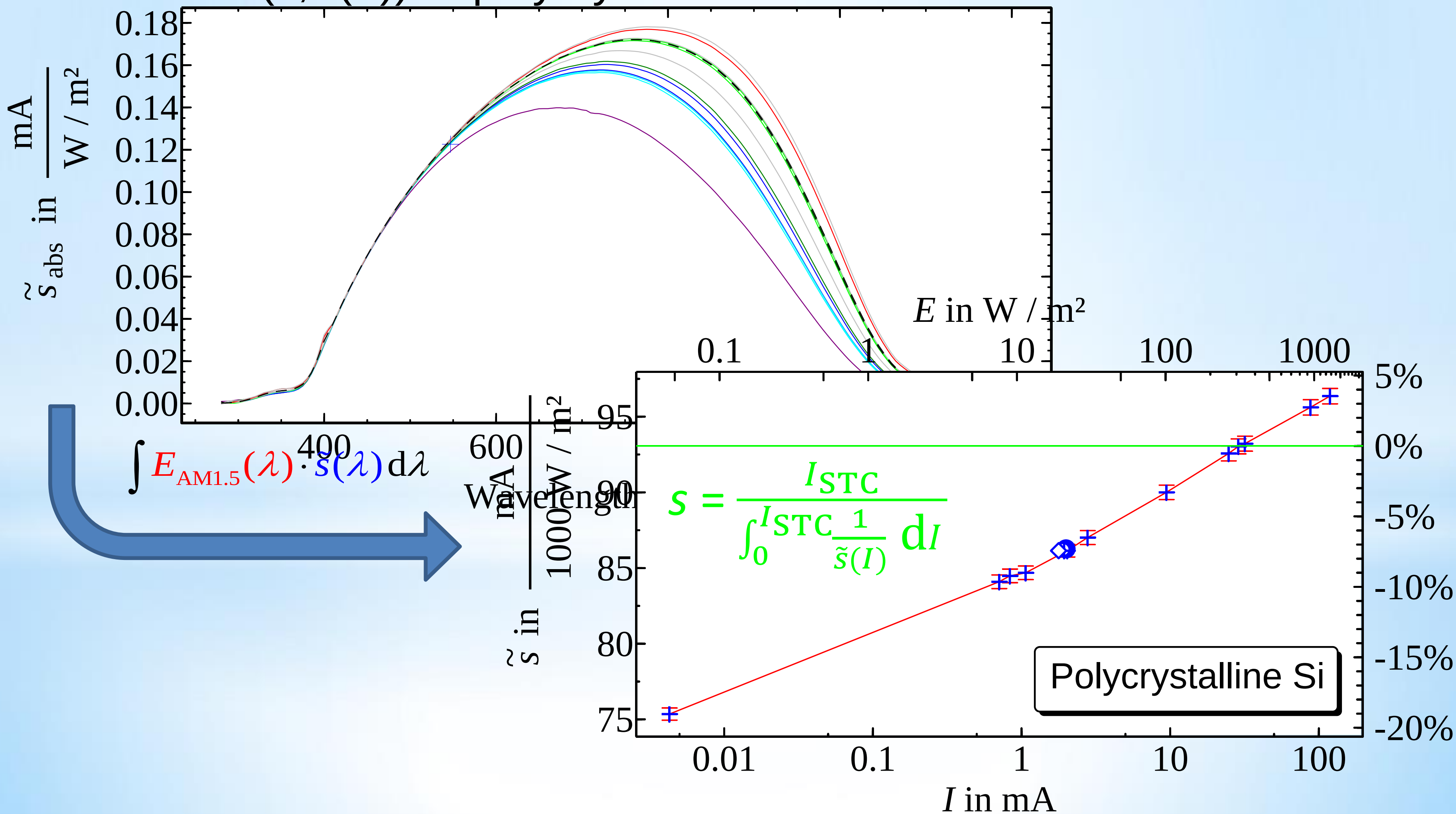


$$\tilde{s}(E_b) = \frac{\Delta I(\lambda, E_b)}{\Delta E} \overset{\Delta E \ll E_b}{=} \frac{\mathrm{d}I}{\mathrm{d}E}$$

DC-Multimeter + Lock-In-Amplifier

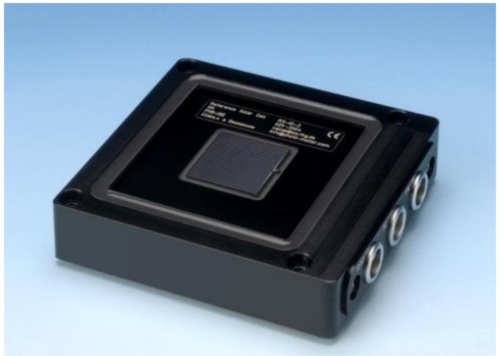
Result of DSR measurement

Absolute differential spectral responsivity
$\tilde{s}(\lambda, I(E))$ of polycrystalline Si solar cell

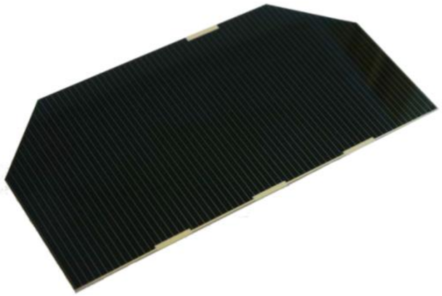


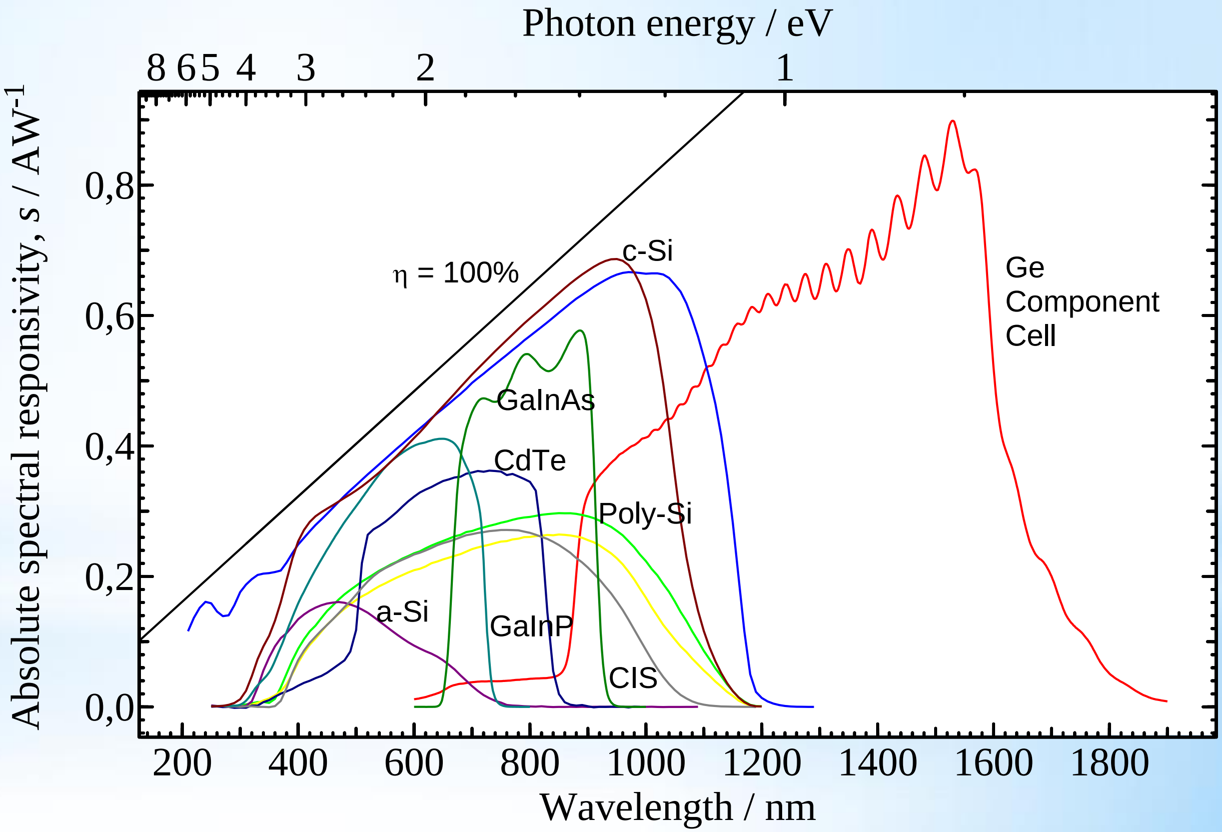
Calibration objects

Reference solar cells



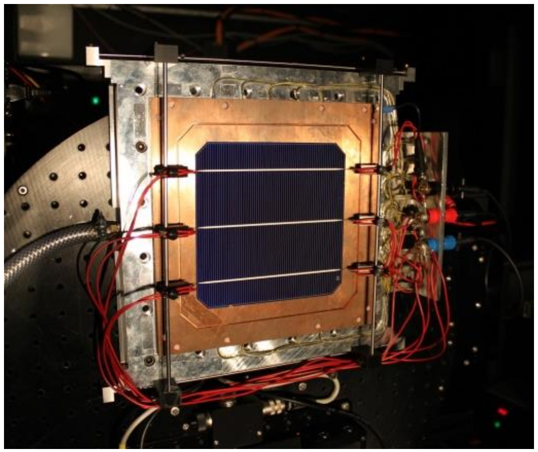
Component solar cells
for Space Application
Laboratory method instead of balloon flight

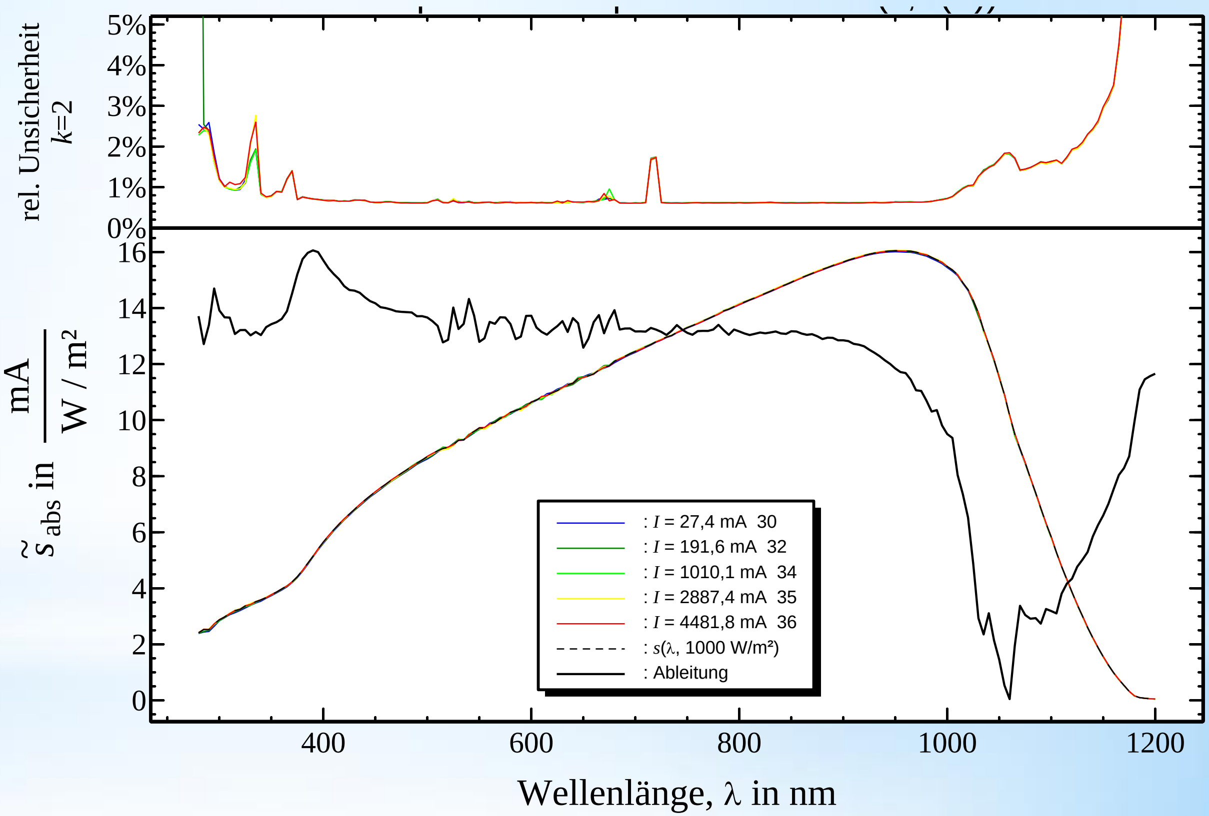




Calibration objects

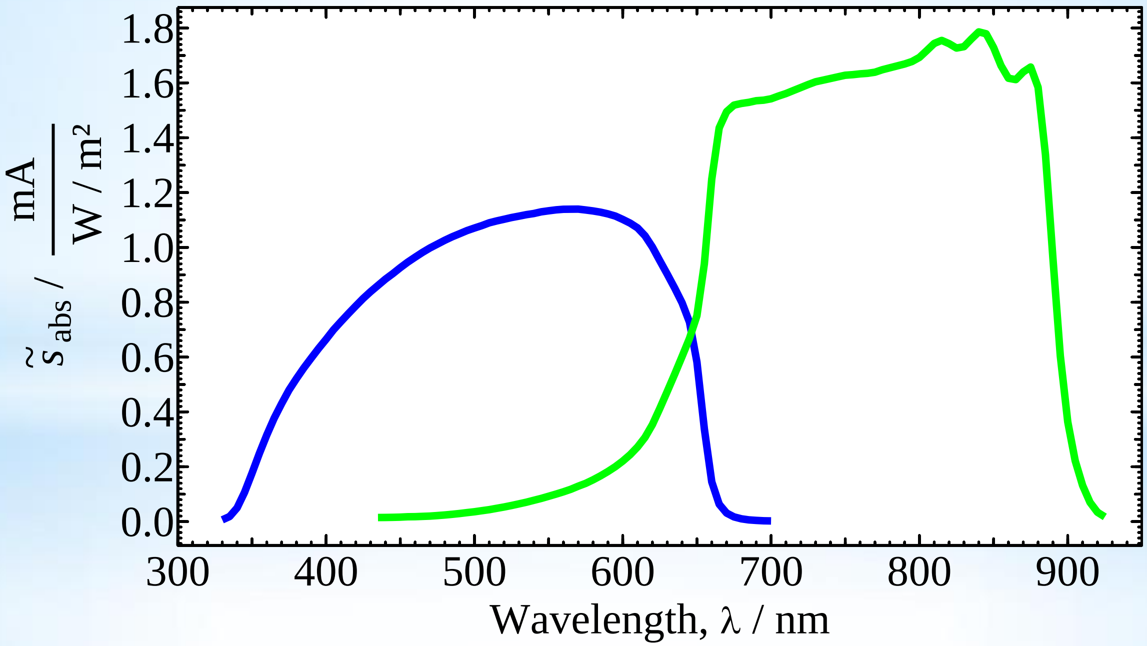
Industry solar cells





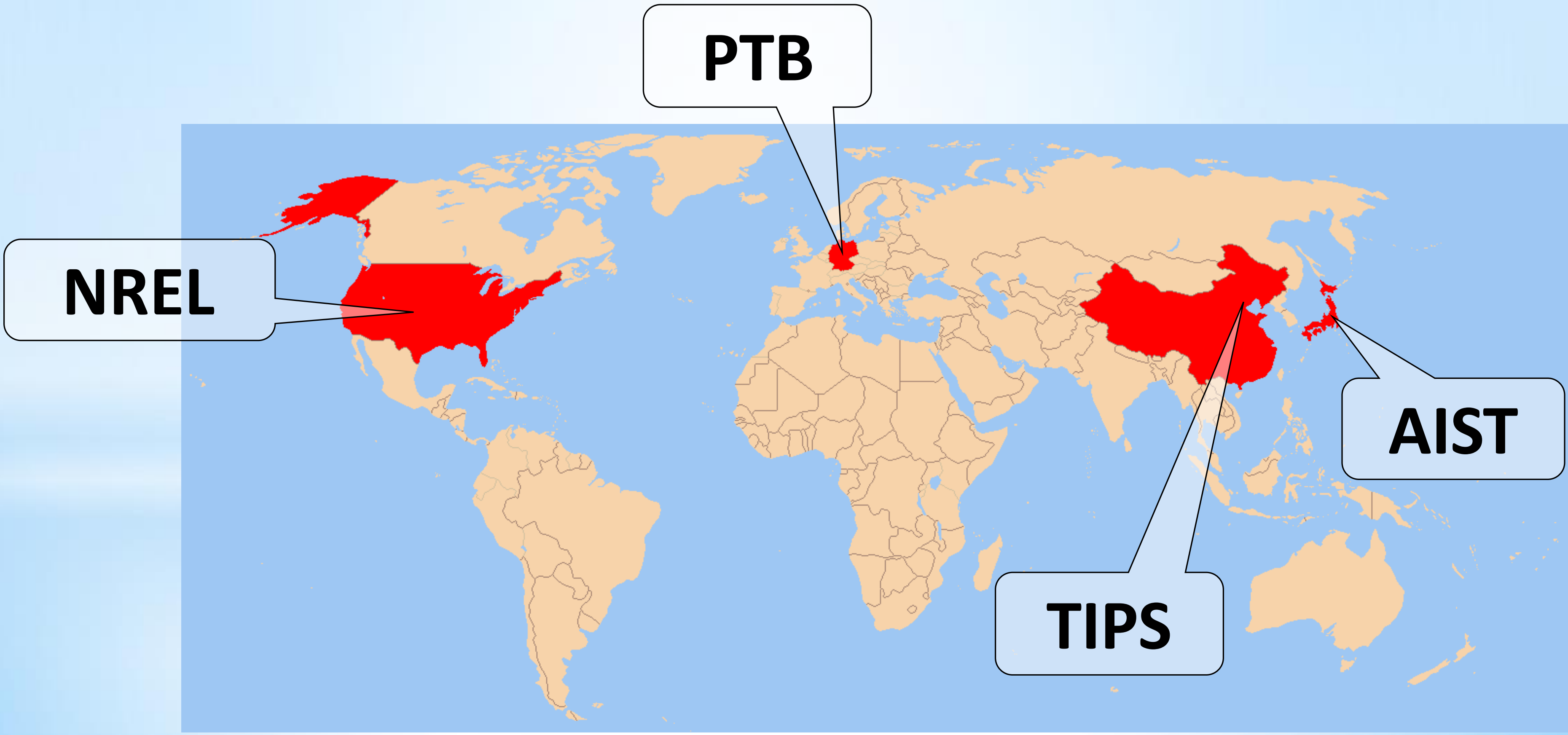
Validation of the DSR method for non Si responsivities

- Comparison of component solar cells with "extraterrestrial" calibration by ESA
- The results agree within 0.4% and 0.6%.



C. Baur, G. Siefer, R. Kern, S. Winter: "Primary solar cell standards – comparison of extraterrestrial and synthetic calibration", in Proceedings of "9th European Space Power Conference (ESPC)", (Saint Raphael, Juni 2011)

Realisation und maintainance of the „World Photovoltaic Scale“



EURAMET supplementary comparison S.5

- Started in 2013, Draft A this year
- Star-like order: Participant -> PTB -> Participant
- Calibration of I_{sc} under STC
- Participants
  - PTB (Coordinator)
  - VNIIOFI
  - KRISS
  - A*STAR
  - ITRI
  - NIM
  - Asked for participation in the next round: NIST

How to measure the Differential Spectral Responsivity

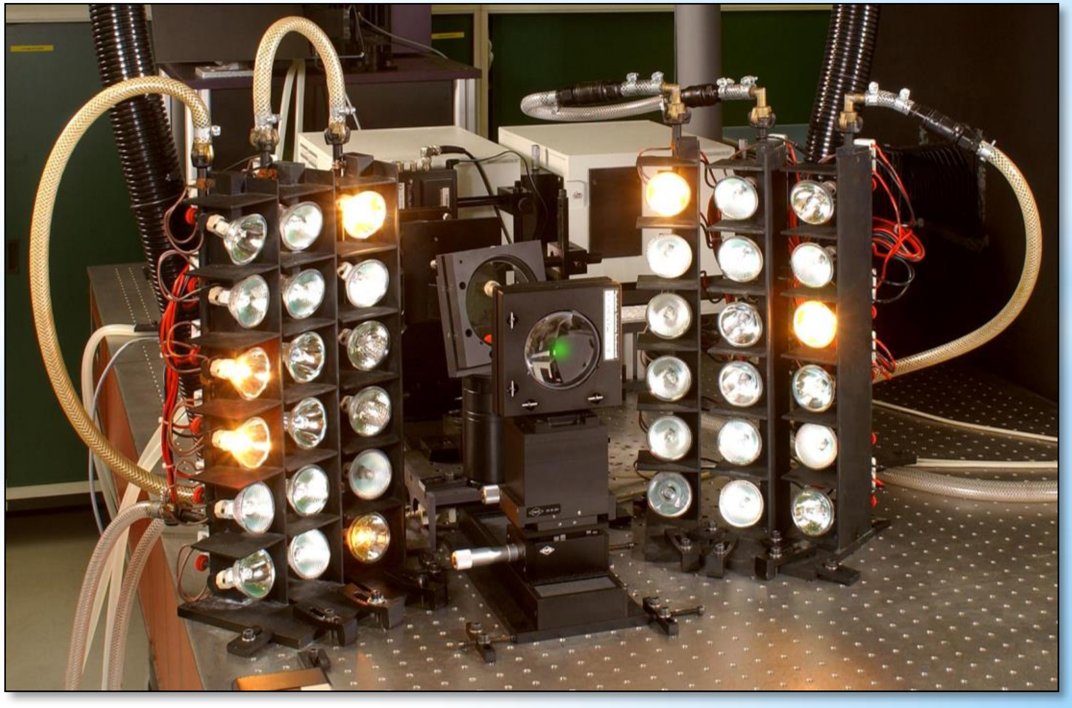
PTB

- **Xenon or quartz halogen lamp based system** (DSR, SCF)

  (or laser-driven xenon lamps or supercontinuum systems)

  \+ Easy to use

  – Low Power (100 µW) with subsequent problems ⇒
    - Uniformity
    - Large bandwidth
    - Bad Signal-To-Noise especially at high bias levels
    - Rel. & abs. measurement needed
    - Size of the solar cells is limited

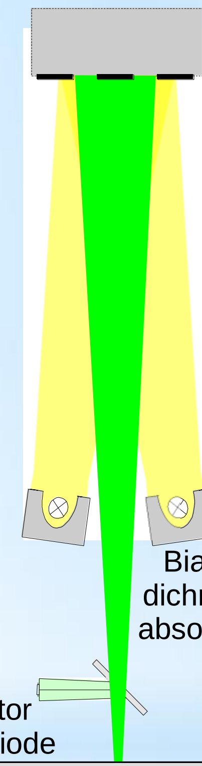


S. Winter, T. Wittchen, J. Metzdorf in Proc. 16th EU PVSEC, (Glasgow 2000)

The new Laser-DSR setup

PTB

- Tunable laser substitutes lamps
  - Power increases up to a factor 100 – 10000
    - \+ Good uniformity
    - \+ Low bandwidth possible
    - \+ No interpolation between relative and absolute measurement



Pulsed with 80 MHz

CW signal

Modelocked Ti:Sapphire laser → Optical parametric Oscillator (OPO), SHG, THG, FHG → Pulse-to-CW converter → Bandpass limitation (monochromator)

680 nm – 1080 nm

190 nm – 4000 nm

Many further improvements in detail

Design of the new Facility

This image cannot currently be displayed.

Electronic

x,y,z-Table

Φ-θ-Goniometer

Biasradiator

Compact Array Spectroradiometer

Scientist

Pulse-to-CW Convertor (Fiber)

Chopper

PhD-Student

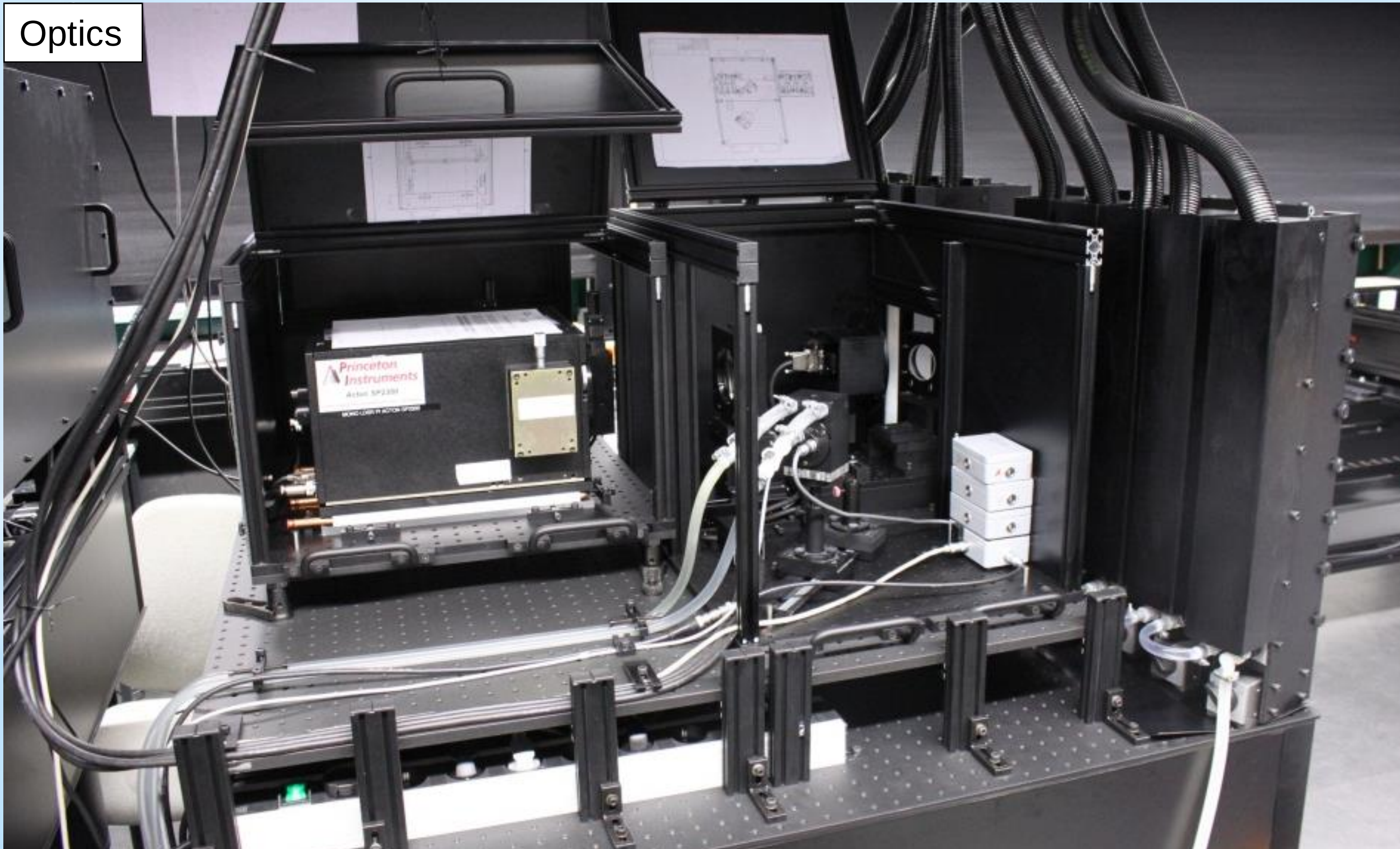
Climate Chamber

Optics (Lenses, Apertures, Monitor phodiode)

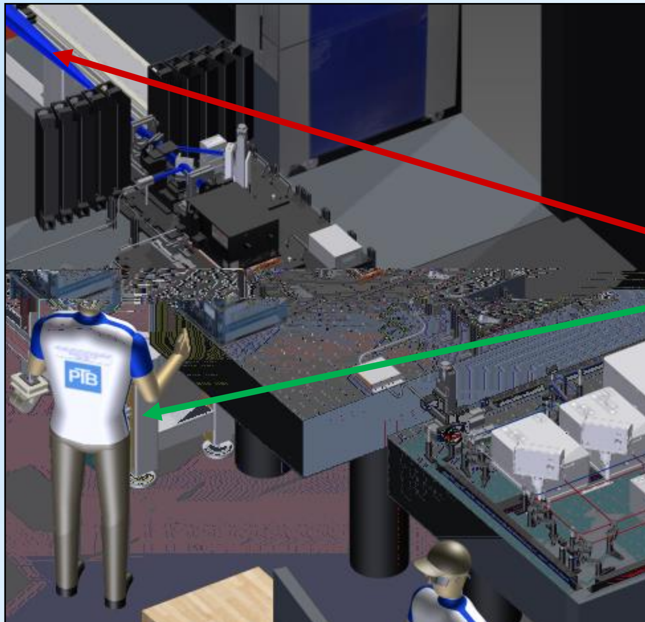
Monochromator

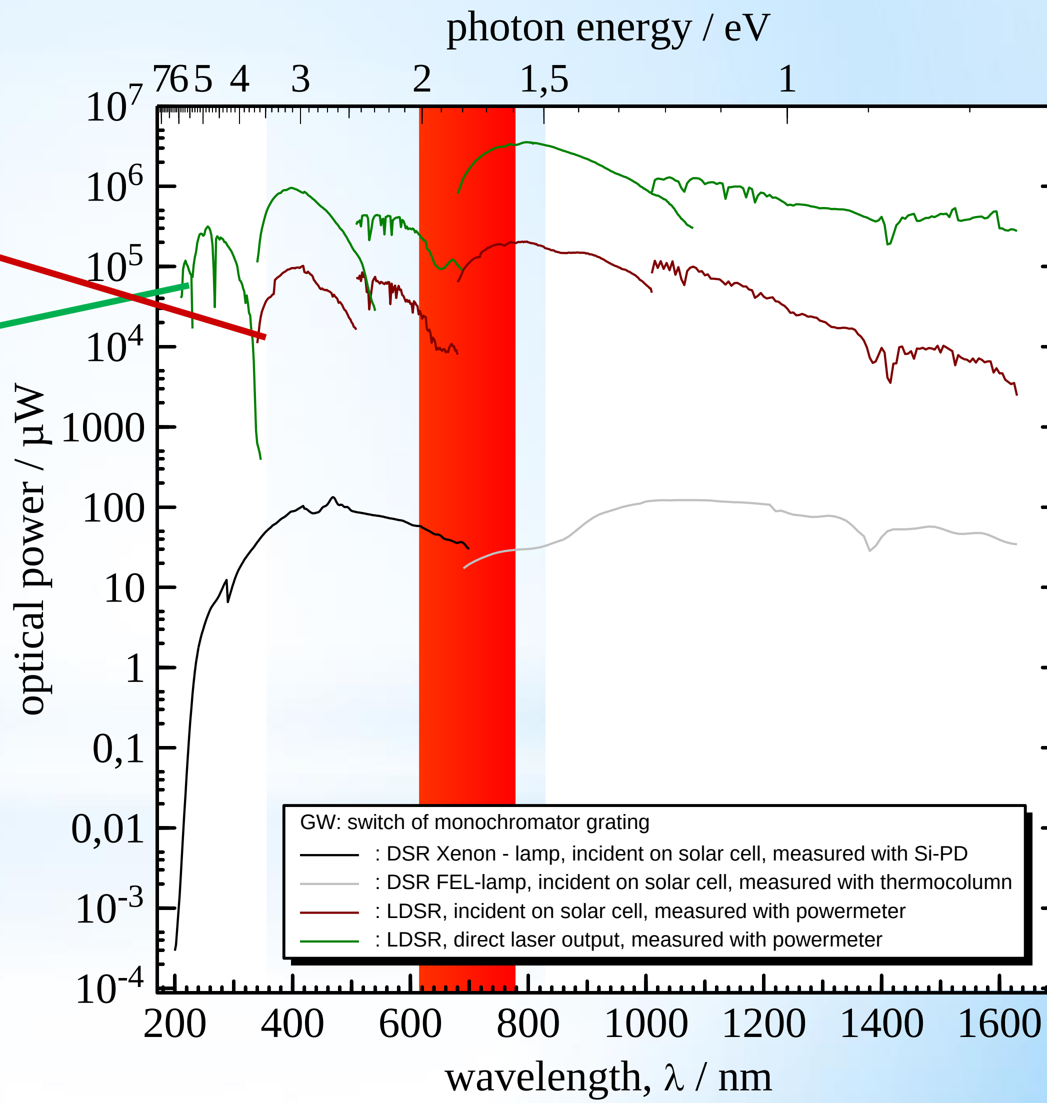
Lasersystem (Ti:Saphir Laser, OPO, SHG, THG, FHG)

Laser-DSR- Facility: From Design to Realisation



Measurement results: Radiation power





- Factor 100-10 000 higher optical power than with the old facility
- Spectral range 200-1600nm

Conclusion

PTB

- DSR method is well suited for the primary calibration of different types of solar cells
- The method is validated for many different stable single junction solar cells
- PTB develops the next-generation of the DSR facility: LASER-DSR
- The high power improves the signal to noise ratio and enables higher resolution and better uniformity
- It is a multipurpose spectral comparison facility.

$$s = s(\lambda, E, f_{\text{Chopper}}, T, x, y, z, \varphi, \theta)$$

Conclusion

Thank you for your attention

A part of the work was funded by EMRP.
The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

“Towards an energy-based parameter for photovoltaic classification”

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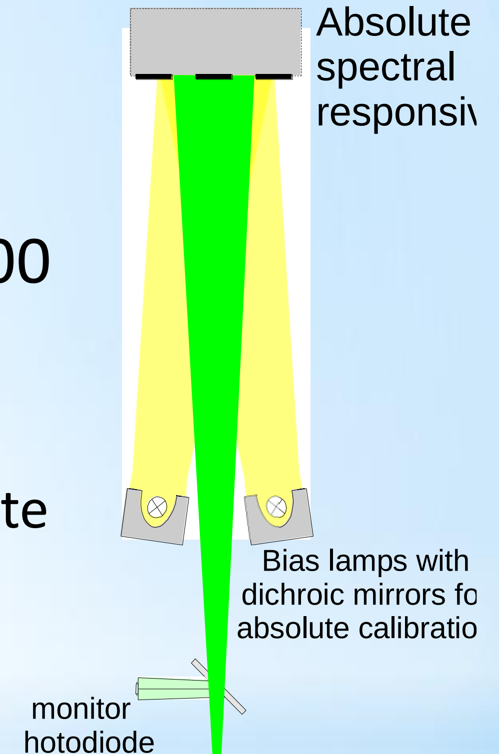

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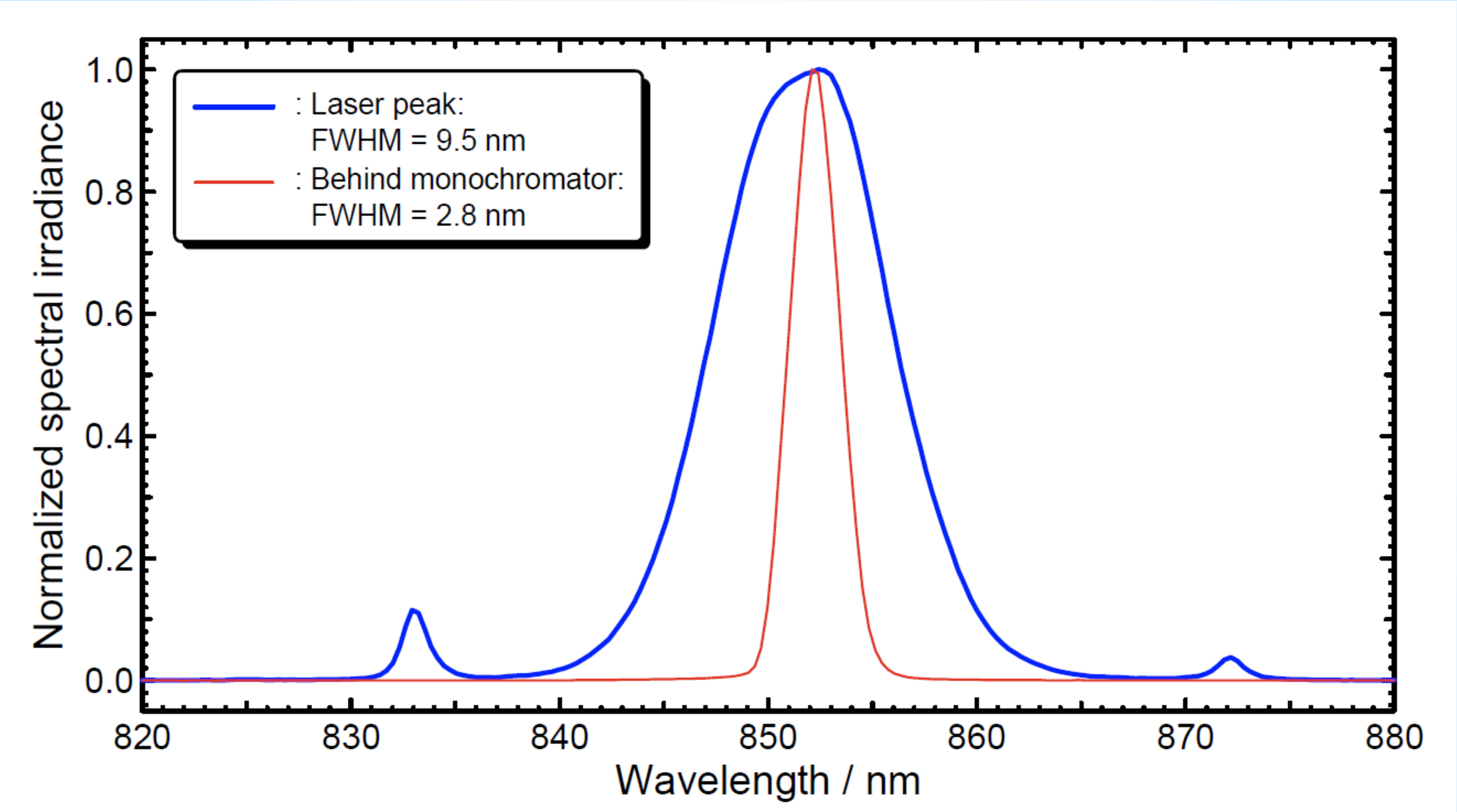
Modelocked Ti:Sapphire laser → Optical parametric Oscillator (OPO), SHG, THG, FHG → Pulse-to-CW converter → **Bandpass limitation** (monochromator)

680 nm – 1080 nm

190 nm – 4000 nm

Why do we need a monochromator behind the laser?



The new Laser-DSR setup

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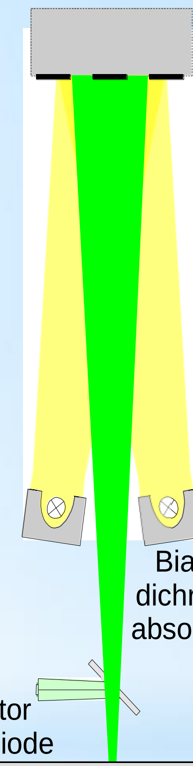

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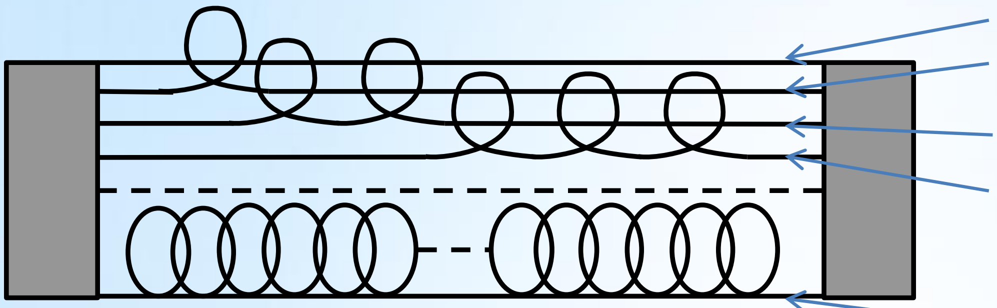
Pulse to cw converter

Fiber bundle with 100 multimode fibers , each with an individual length



$L_0 = l_0$ $t_0 = t_0$

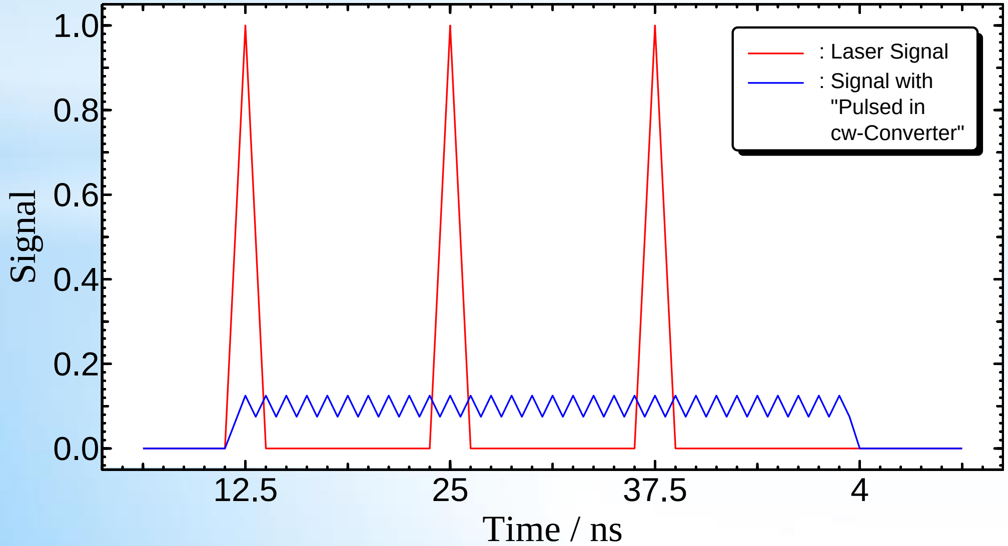
$L_1 = l_0 + 2.5$ cm $t_1 = t_0 + 0.125$ ns

$L_2 = l_0 + 5.0$ cm $t_2 = t_0 + 0.250$ ns

$L_3 = l_0 + 7.5$ cm $t_3 = t_0 + 0.375$ ns

… …

$L_{99} = l_0 + 247.5$ cm $t_{99} = t_0 + 12.375$ ns

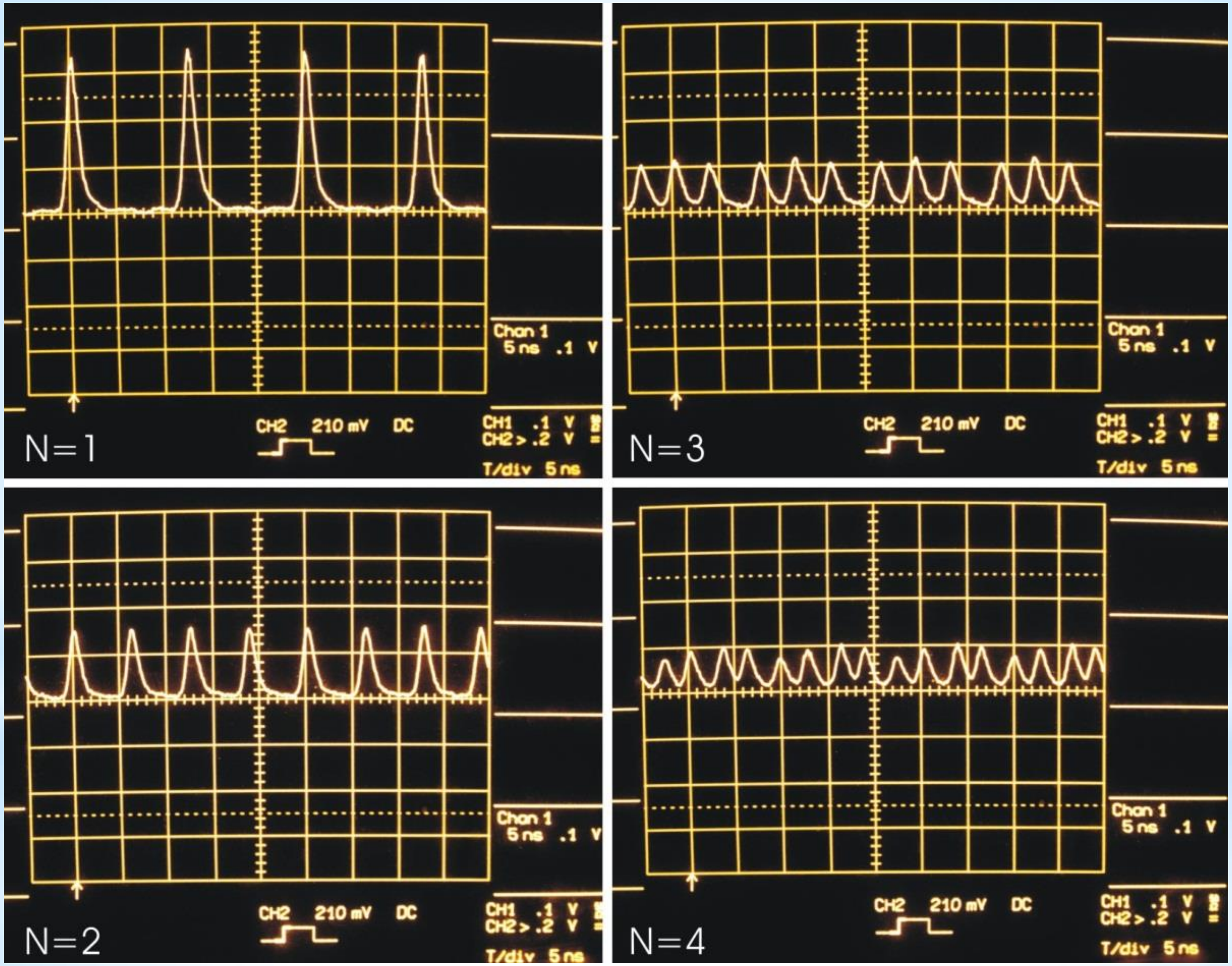


And after 12.5 ns the next pulse from the laser appears.

Pulse to cw converter

Fiber 1

Fiber 1 and Fiber 50



Fiber 1, 33 and 66

Fiber 1, 25, 50 and 75

Pulse to cw converter

All 100
fibers