LASER-DSR

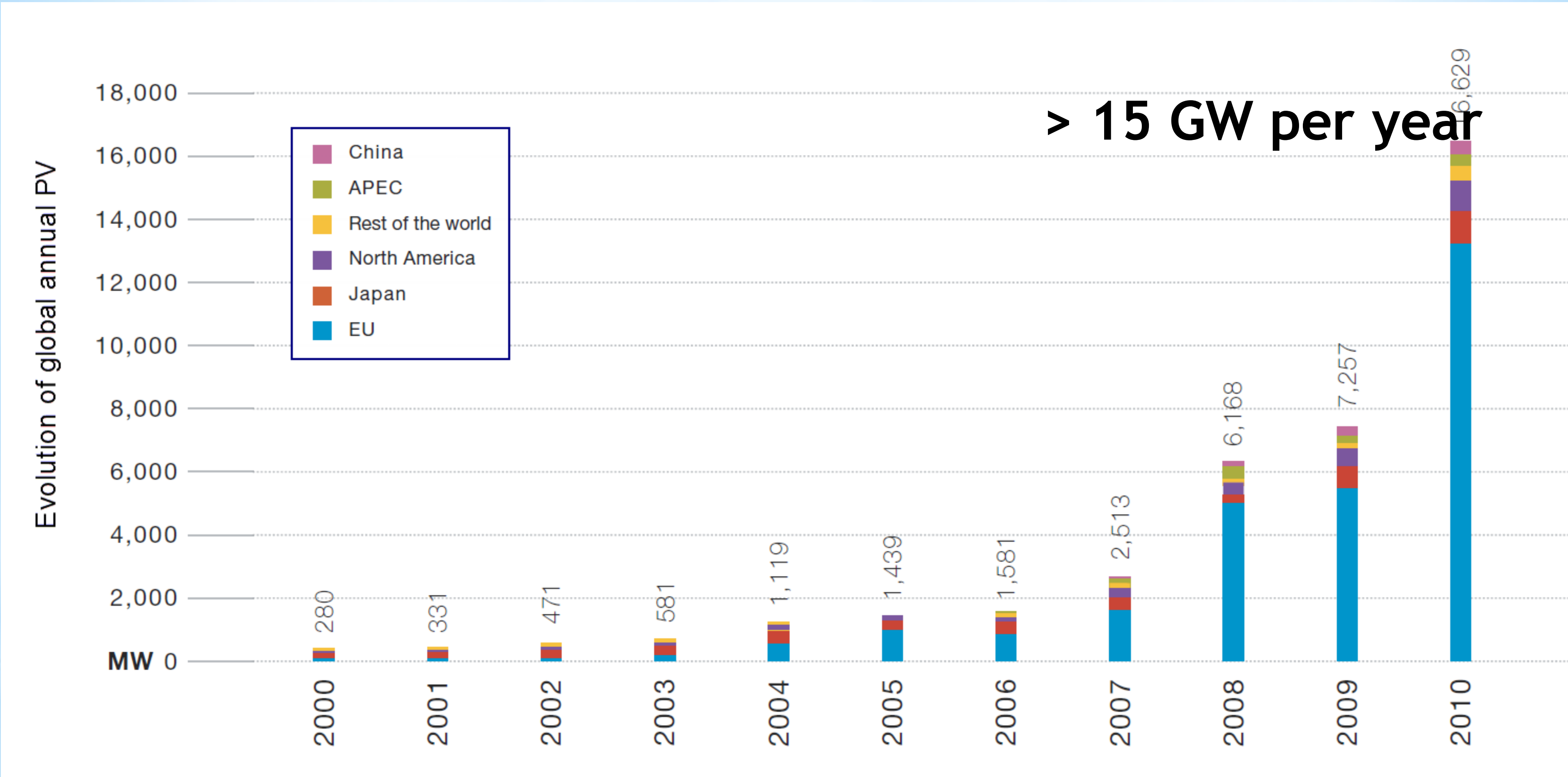
Enabling solar cell and detector calibrations with fs pulses

Stefan Winter, Thomas Fey, Dirk Friedrich, Ingo Kröger
Physikalisch-Technische Bundesanstalt PTB
Working Group 4.14 – „Solar Cells“

Overview

- Demand for high accuracy solar cell calibrations
- Solutions and their problems
- The new PTB setup: Advantages and disadvantages
- How we solve the disadvantages
- Measurements results
- Outlook

Demand for high accuracy solar cell calibrations



Jan. 09 Juli 09 Jan. 10 Juli 10 Jan. 11 Juli 11

Source: EPIA

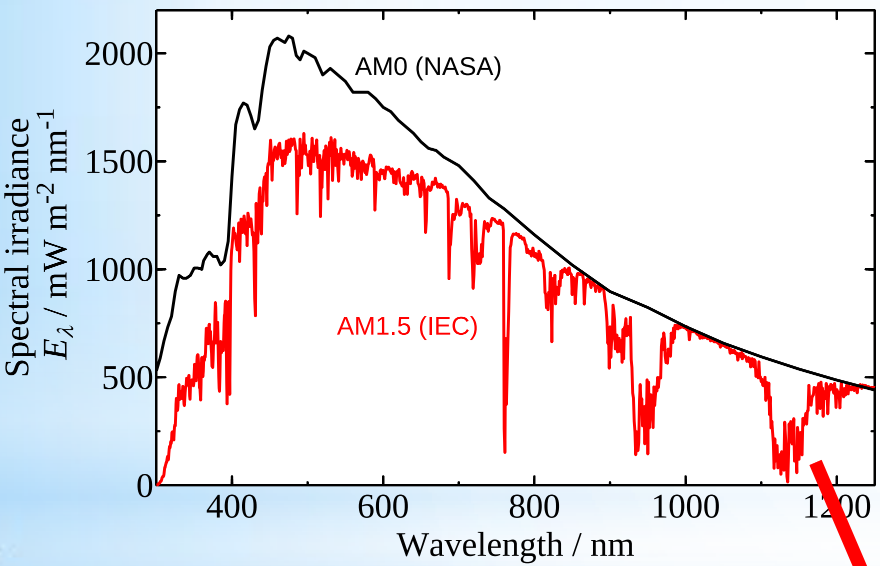
Source: pvXchange

Calibration methods for solar cells

<table>
<tr><td colspan="3">Integral</td><td>Spectral</td></tr>
<tr><td colspan="2">Outdoor, with solar radiation</td><td colspan="2">Indoor</td></tr>
<tr><td>Space (>=40km) AM0</td><td>On the earth AMn</td><td>Solar simulator</td><td>DSR-Method</td></tr>
<tr><td rowspan="3">Very expensive</td><td>n>=1, direct, total, global radiation</td><td colspan="2">Good reproducibility, independent of place and time</td></tr>
<tr><td>Appropriate and stable weather conditions needed</td><td>large cells and modules</td><td rowspan="2">absolute method without spectral mismatch; cell size <= 15x15 cm^2</td></tr>
<tr><td colspan="2">Spectral Mismatch correction where required</td></tr>
</table>

Metrological background

Standard solar spectrum
on earth (AM1.5) or in space (AM0)



Spectral responsivity
of different types of solar cells

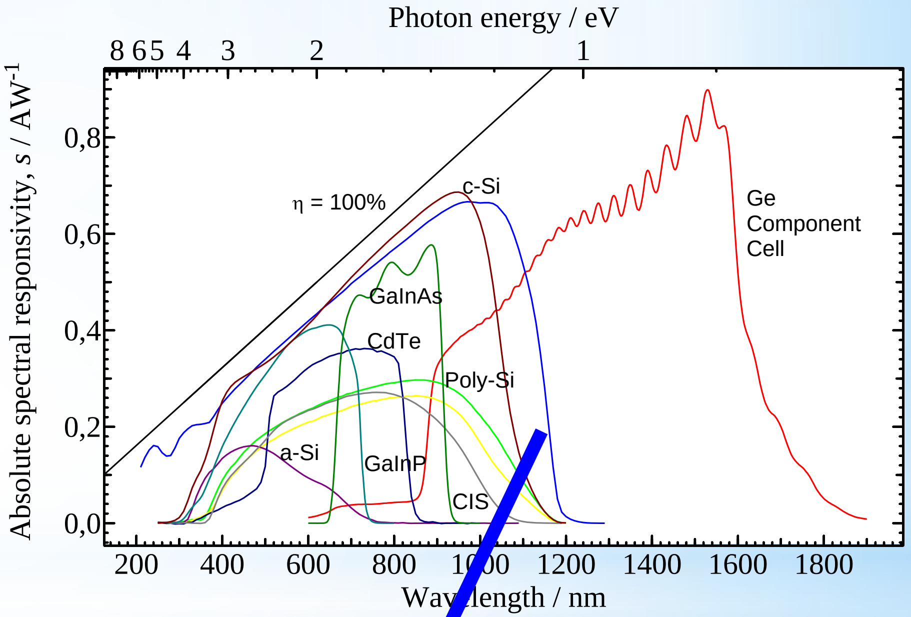
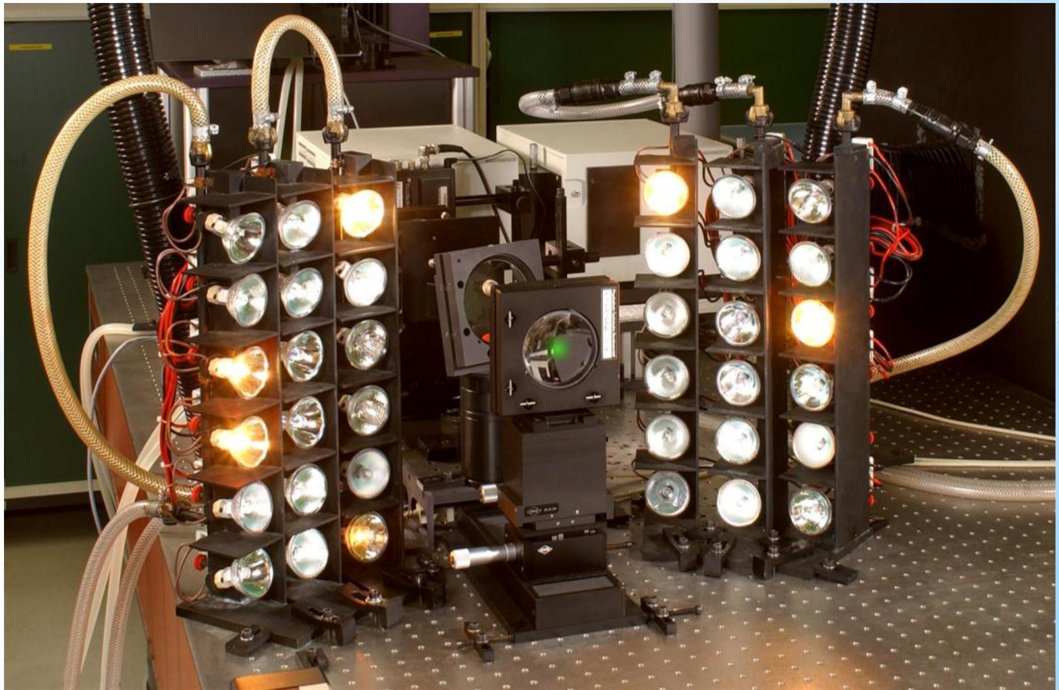


Photo current: $I = \int E_{\lambda,\mathrm{Norm}}(\lambda) \cdot s(\lambda)\,\mathrm{d}\lambda$

How to measure the spectral responsivity

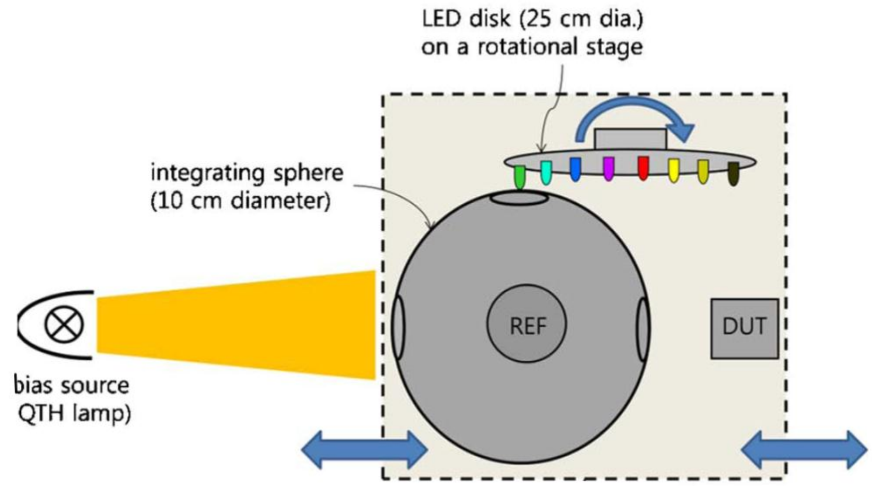
- **Xenon or quartz halogen lamp based system** (DSR, SCF)
  (or laser-driven xenon lamps or supercontinuum systems)
  - + Easy to use
  - – Low Power (100 µW) with subsequent problems ⇒
    - – Uniformity
    - – Bandwidth
    - – Signal-To-Noise especially at high bias levels
    - – Rel. & abs. measurement
    - – Size of the solar cells is limited



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

How to measure the spectral responsivity

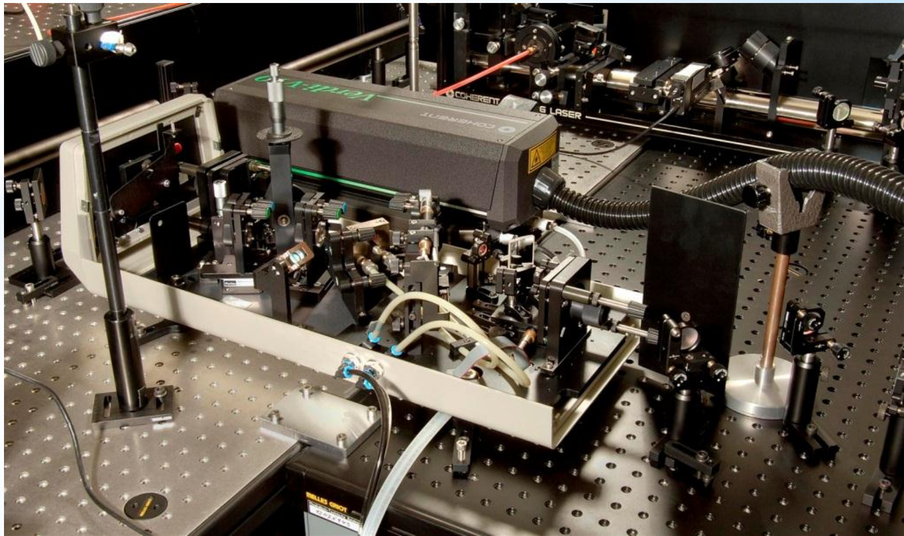
- **LED based systems** (KRISS)
  - \+ High Power level (depending on the setup)
  - \+ Low priced, as no monochromator is needed
  - – Wavelength stability (temperature dependent),
  - – High Bandwidth
  - – No wavelength tuneability



Source: Zaid G., Park S-N., Park S., Lee, D-H., Appl. Opt. 49(35), 6772-6783, 2010

How to measure the spectral responsivity

- **cw-laser based systems** (TULIP, SIRCUS)
  - \+ Very low bandwidth
  - \+ High power levels
  - – Automation is difficult
  - – Interference effects
  - – Gaps in the spectral range



See:
Session 4a, INV 7: Armin Sperling:
“Tuneable lasers for photometry and radiometry”
Poster-Session B: DBR_PO_017, Michaela Schuster:
“Correction algorithm for interference affected measurement data”

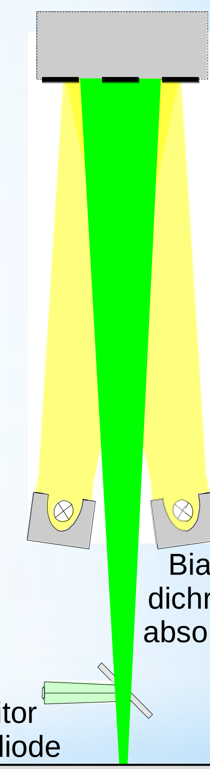
How to measure the spectral responsivity

PTB

- **Quasi cw laser based systems with modelocked Ti-Sapphire** (Quasi-cw-TULIP, LASER-DSR)
  - \+ Very high power (up to > 3500 mW)
  - \+ Fully tunable
  - \+ Wavelength range from 190 nm to 4000 nm
  - \+ Complete automation possible from 210 nm to 4000 nm
  - – Unknown behavior of short fs pulses to semiconductor detectors, especially in the UV and blue wavelength region
    Every 12 nm a 120 fs pulse hits the surface: Duty cycle 1/100.000
    ⇒ Integrating spheres are used for pulse stretching
    ⇒ fluorescence effects + high power losses

The new LASER-DSR setup

- Laser substitutes lamps
  - Power increases up to a factor 1000
    - + Good uniformity
    - + Low bandwidth possible
    - + No interpolation between relative and absolute measurement



Pulsed with 80 MHz

CW signal

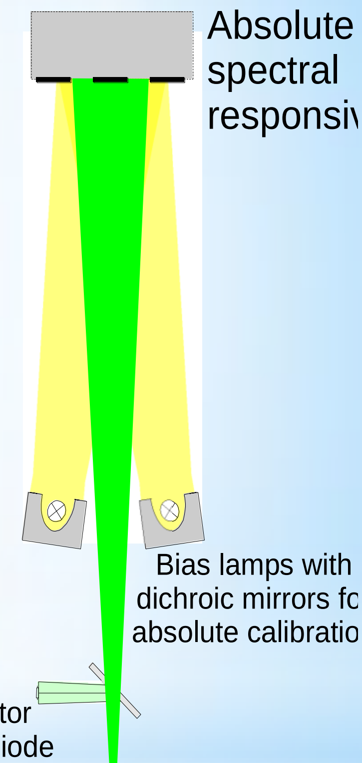
Modelocked Ti:Sapphire laser → Optical parametric Oscillator (OPO), SHG, THG, FHG → Pulse-to-CW converter → Bandpass limitation (monochromator)

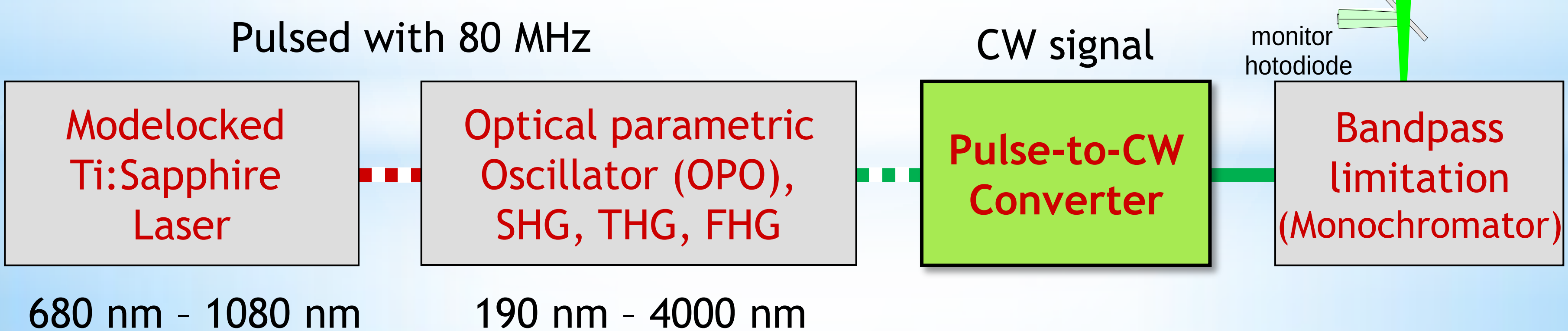
680 nm – 1080 nm

190 nm – 4000 nm

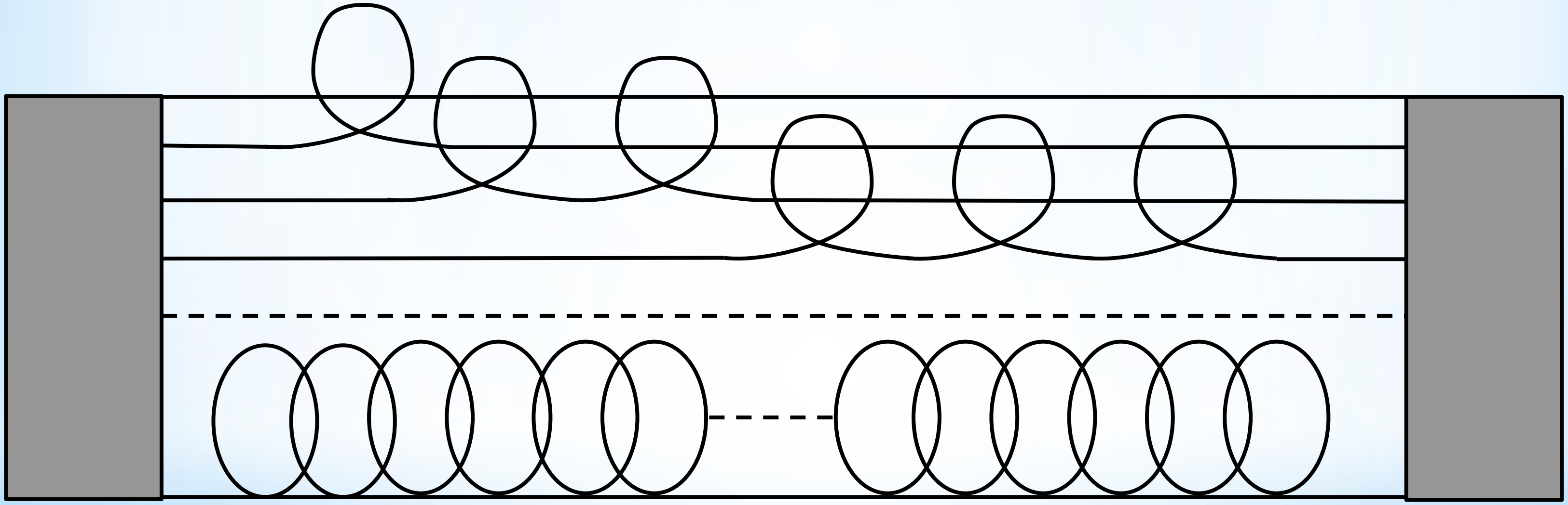
The new LASER-DSR setup

- Laser substitutes lamps
  - Power increases up to a factor 1000
    - + Good uniformity
    - + Low bandwidth possible
    - + No interpolation between relative and absolute measurement



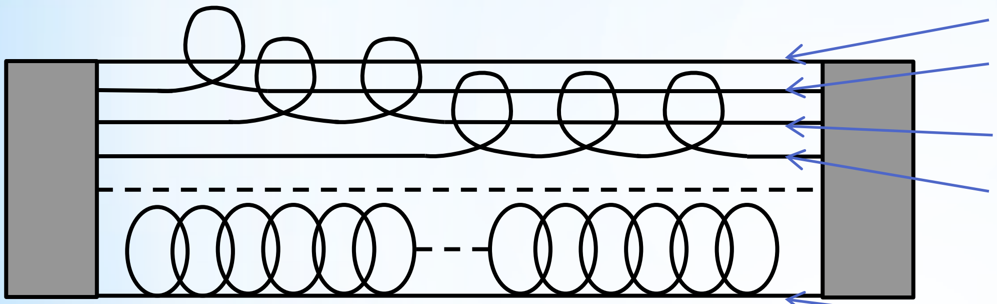


Pulse to cw converter



Pulse to cw converter

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



$L_0 = l_0$ — $t_0 = t_0$

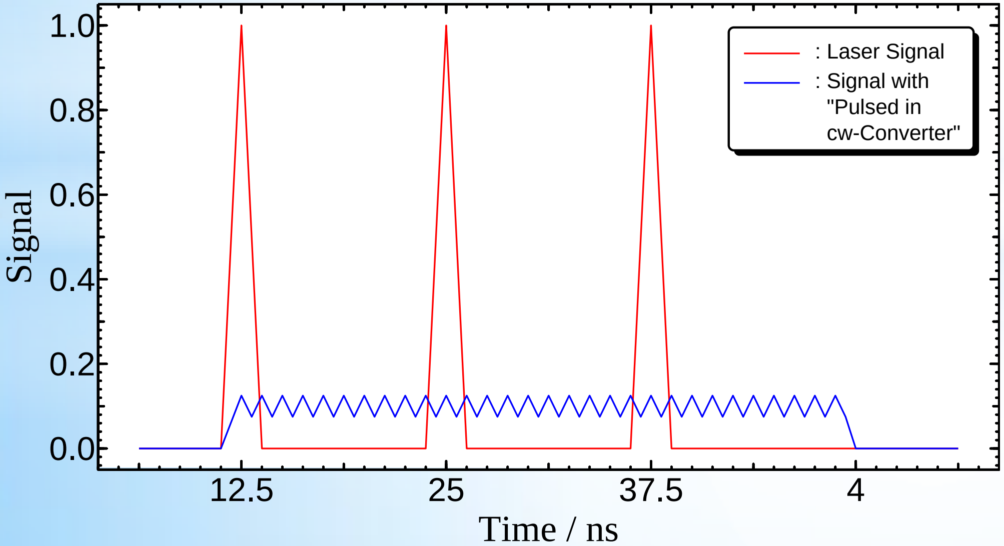
$L_1 = l_0 + 2.5$ cm — $t_1 = t_0 + 0.125$ ns

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

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

… — …

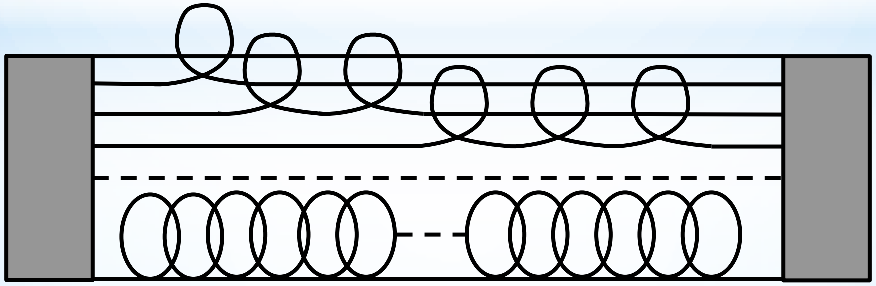
$L_{99} = l_0 + 247.5$ cm — $t_{99} = t_0 + 12.375$ ns



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

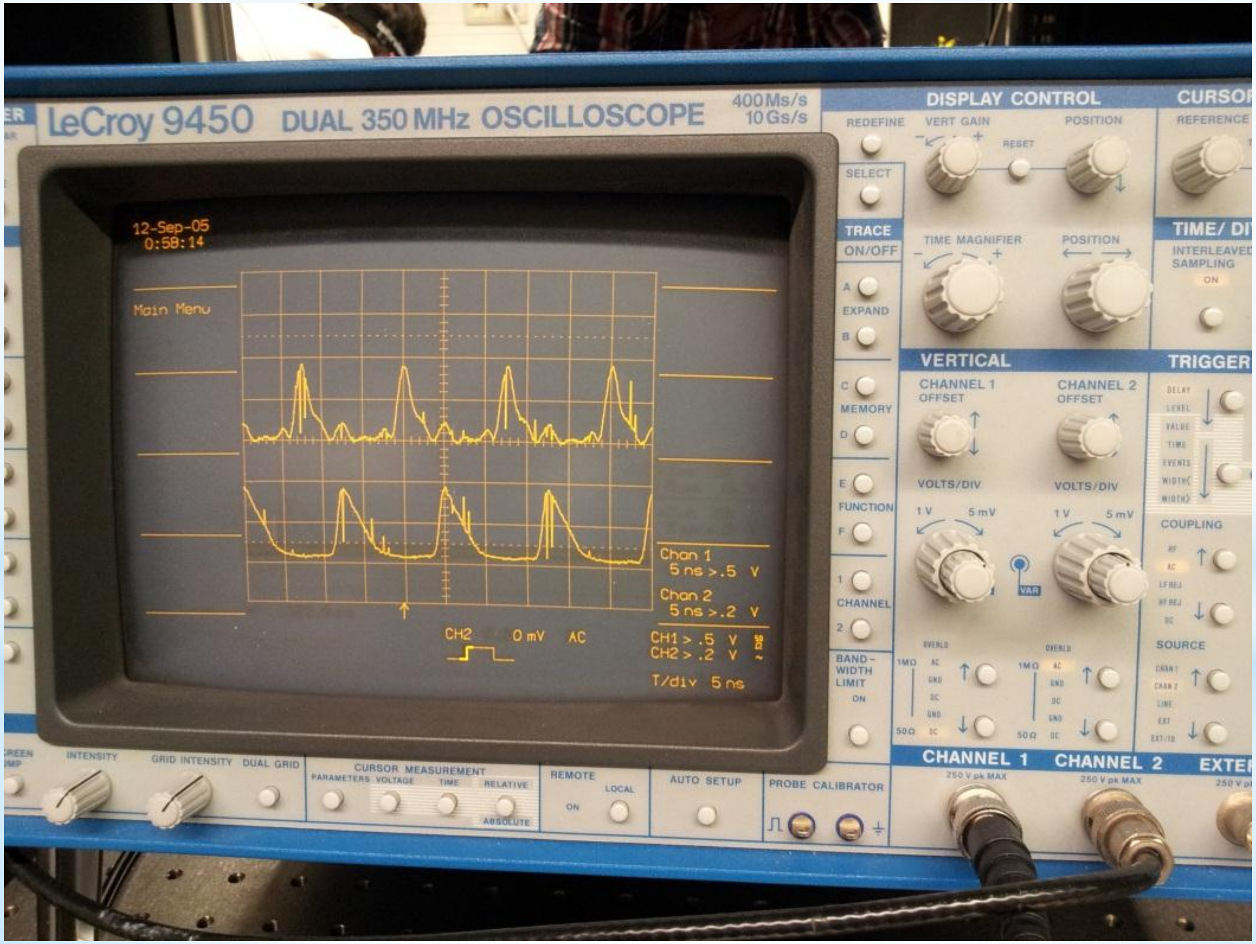
Pulse to cw converter

- Fiber bundle with different length of the single fibers
- The laser is pulsed with 80 MHz
  - ⇒ every 12.5 ns a pulse appears
  - ⇒ During this time the light moves 3 m in air and about 2 m in the fiber
  - ⇒ The distance between the shortest and longest fiber must be 2m
- We need in any case a fiber to couple into the monochromator
- To improve efficiency the ends of the fibers are fused



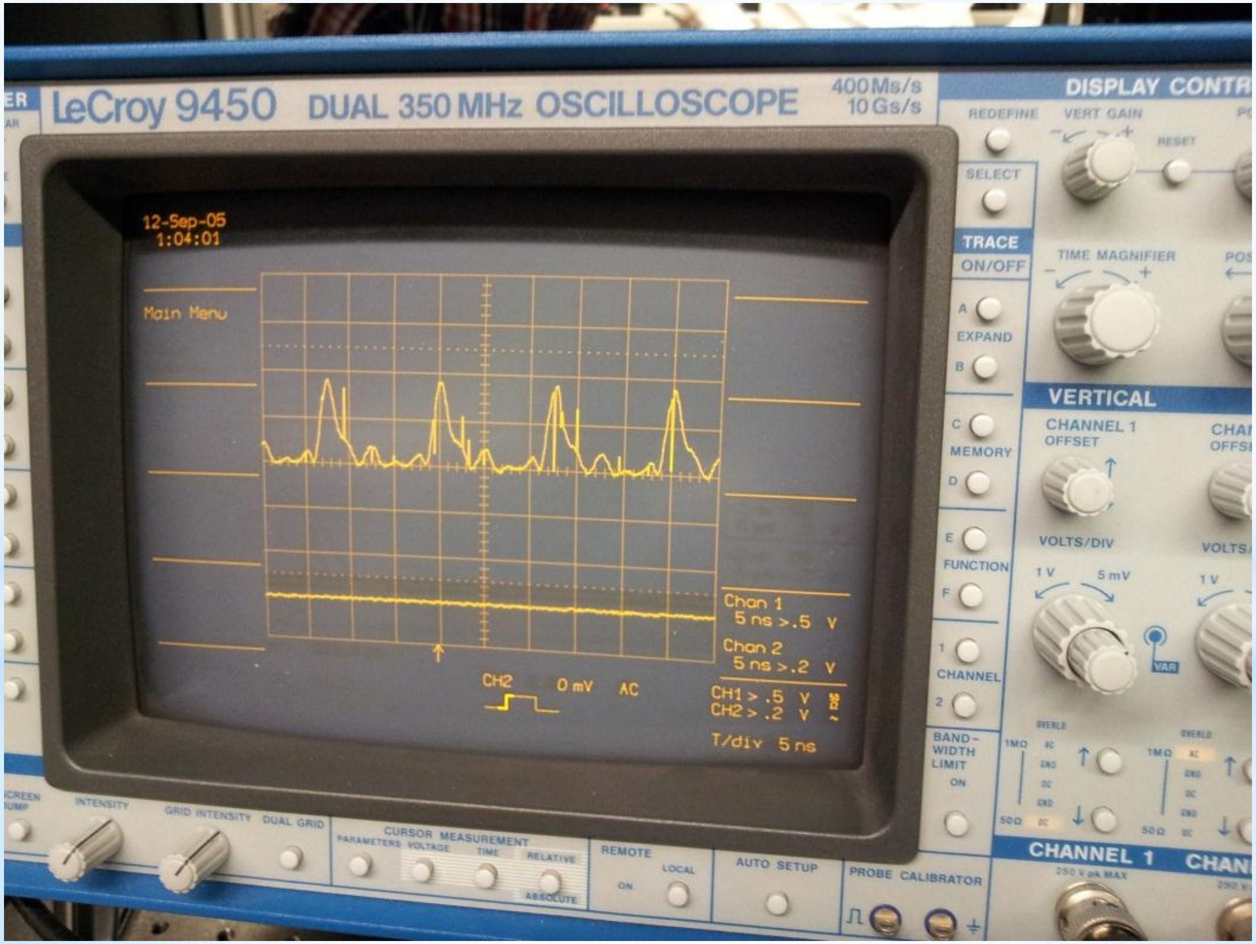
Pulse to cw converter

- Experimental prove: Signal behind a standard fiber



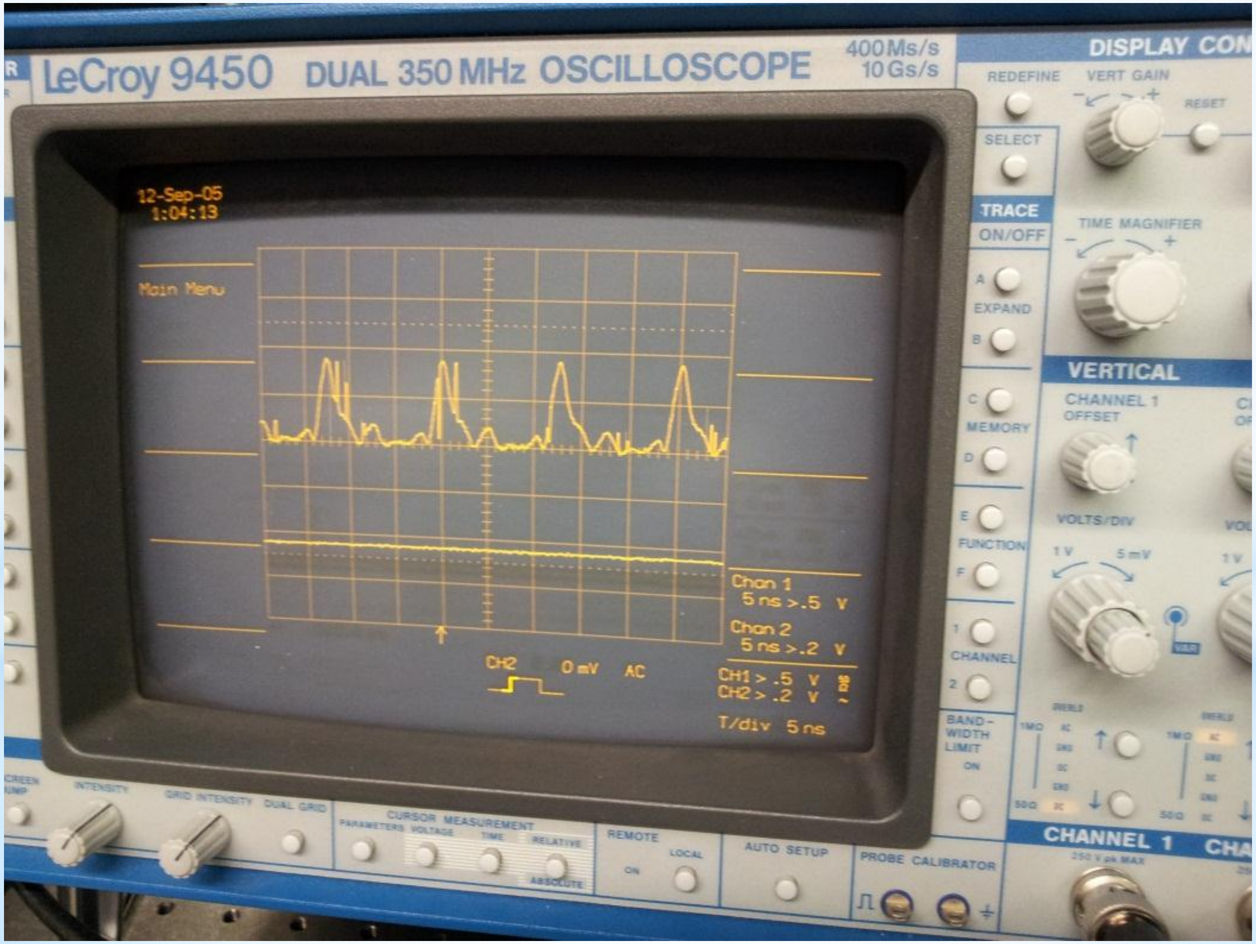
Pulse to cw converter

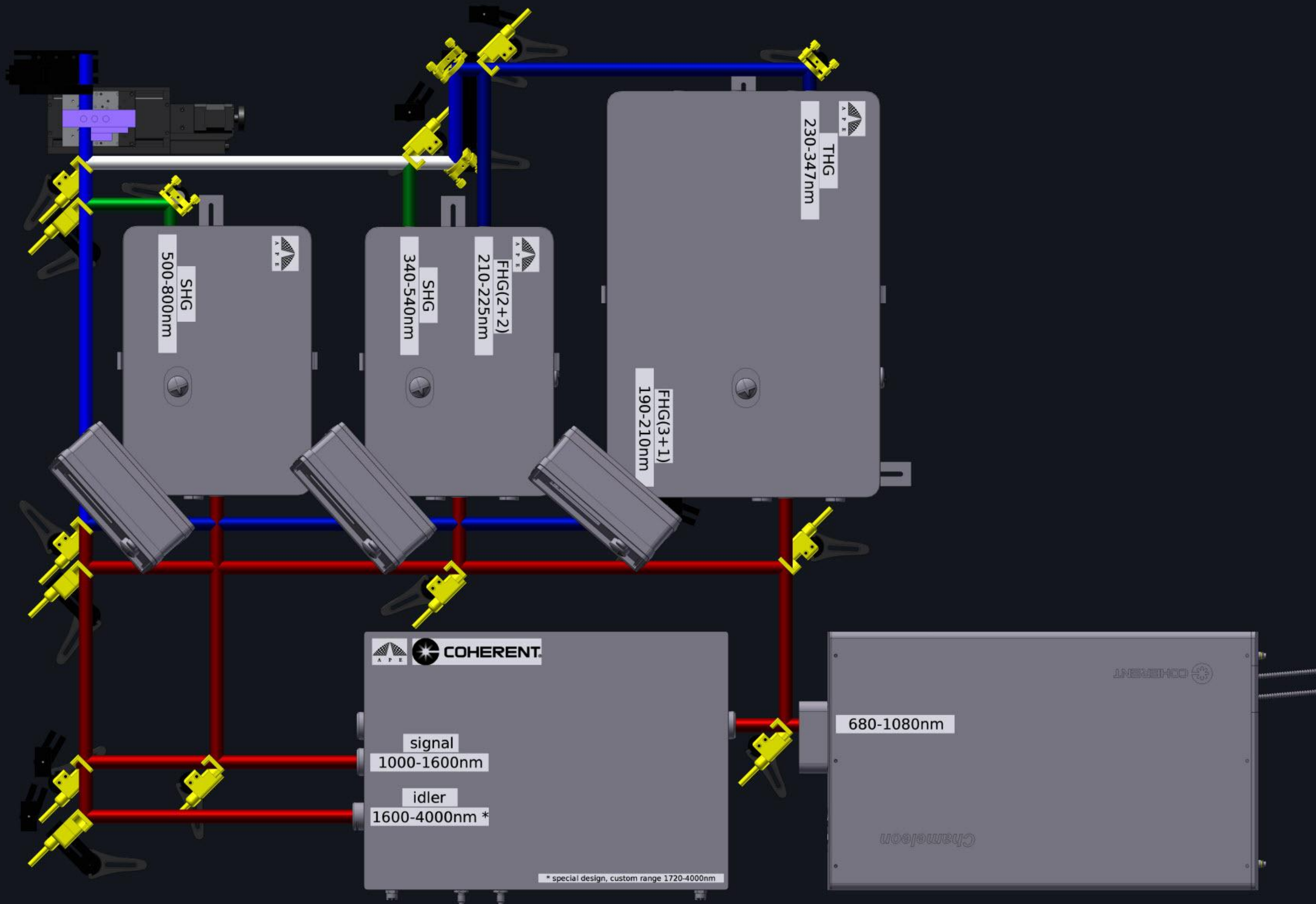
- Experimental prove: Zero line without signal

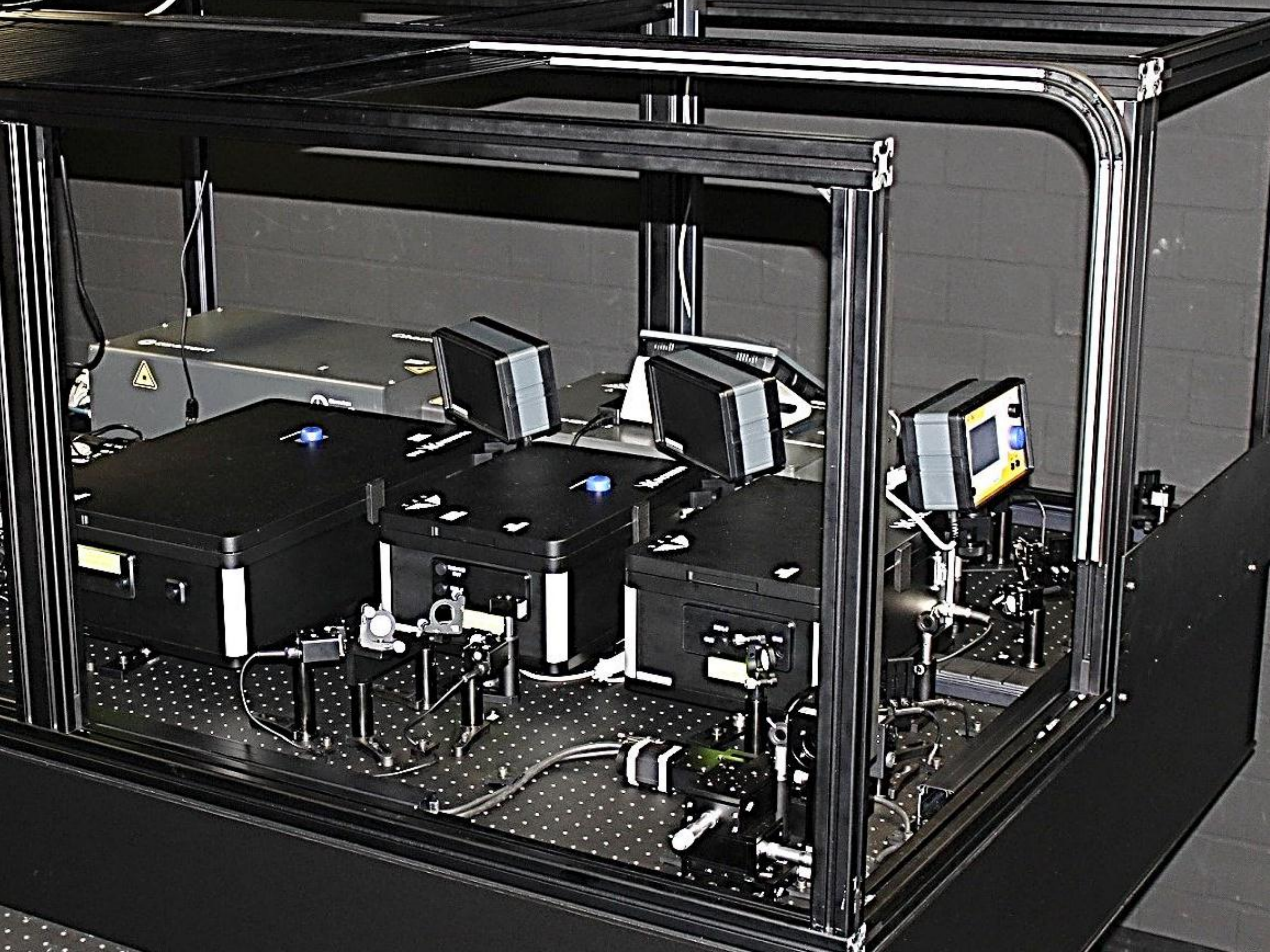


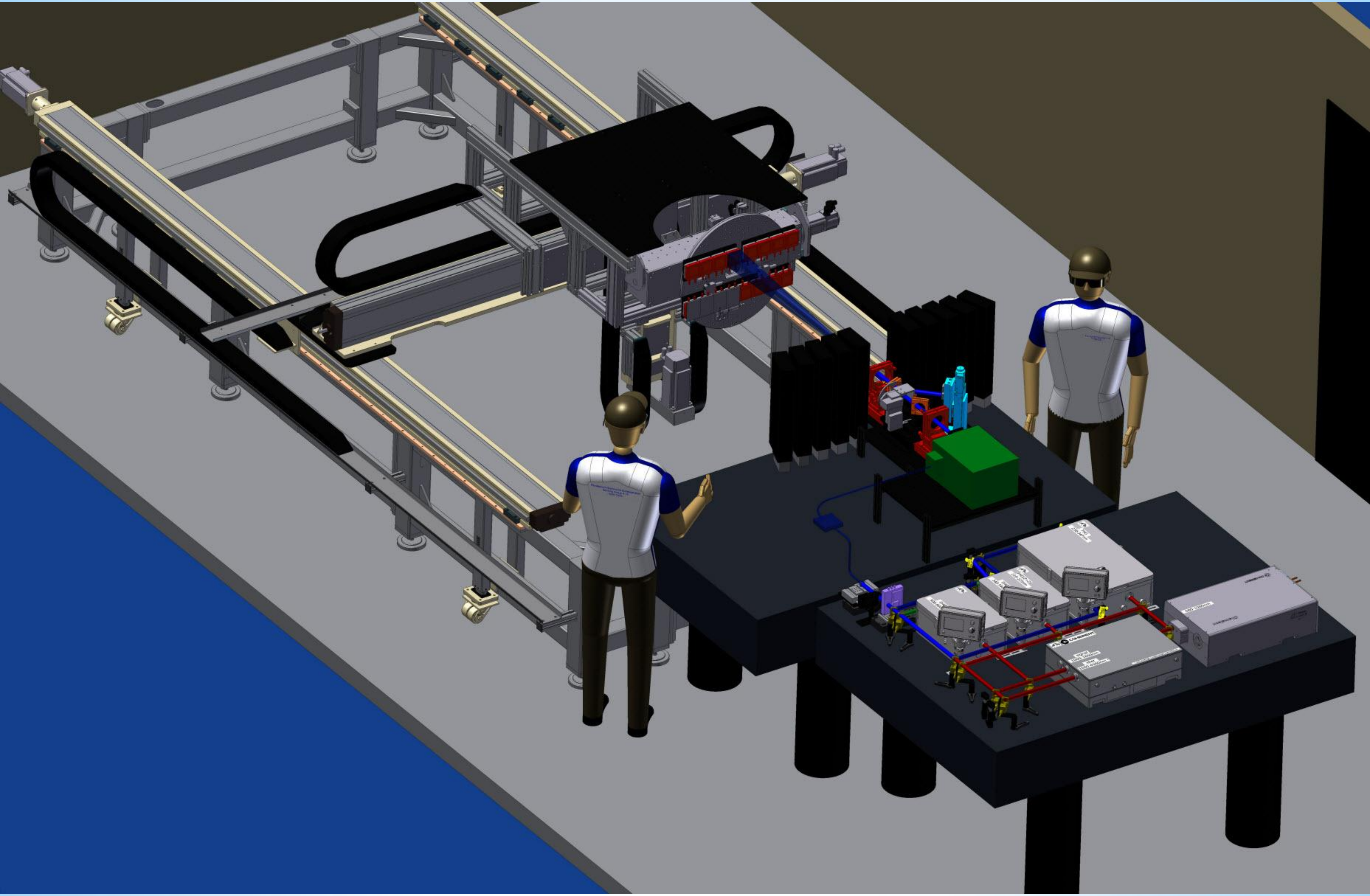
Pulse to cw converter

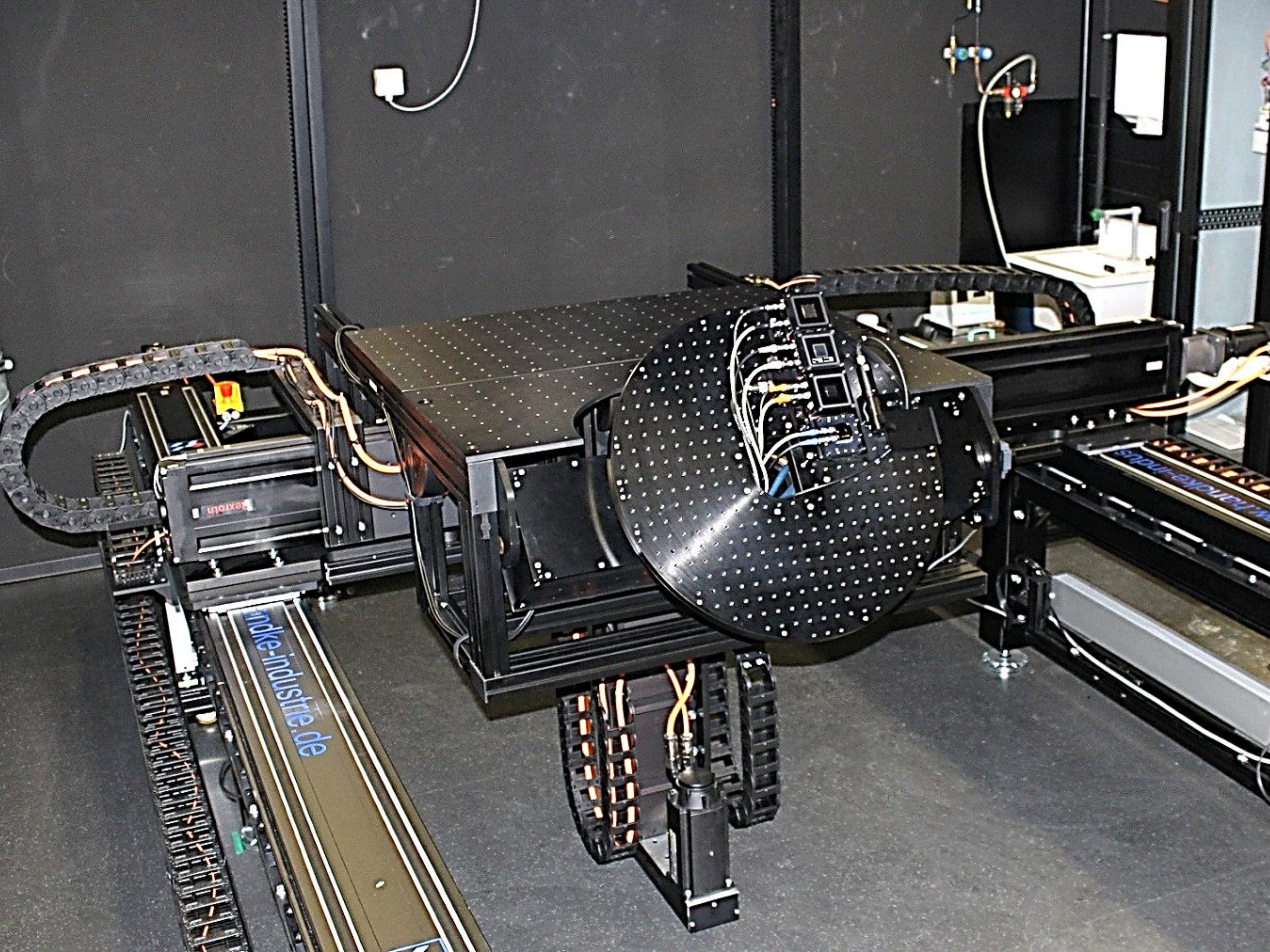
- Experimental prove: Const. Signal behind converter

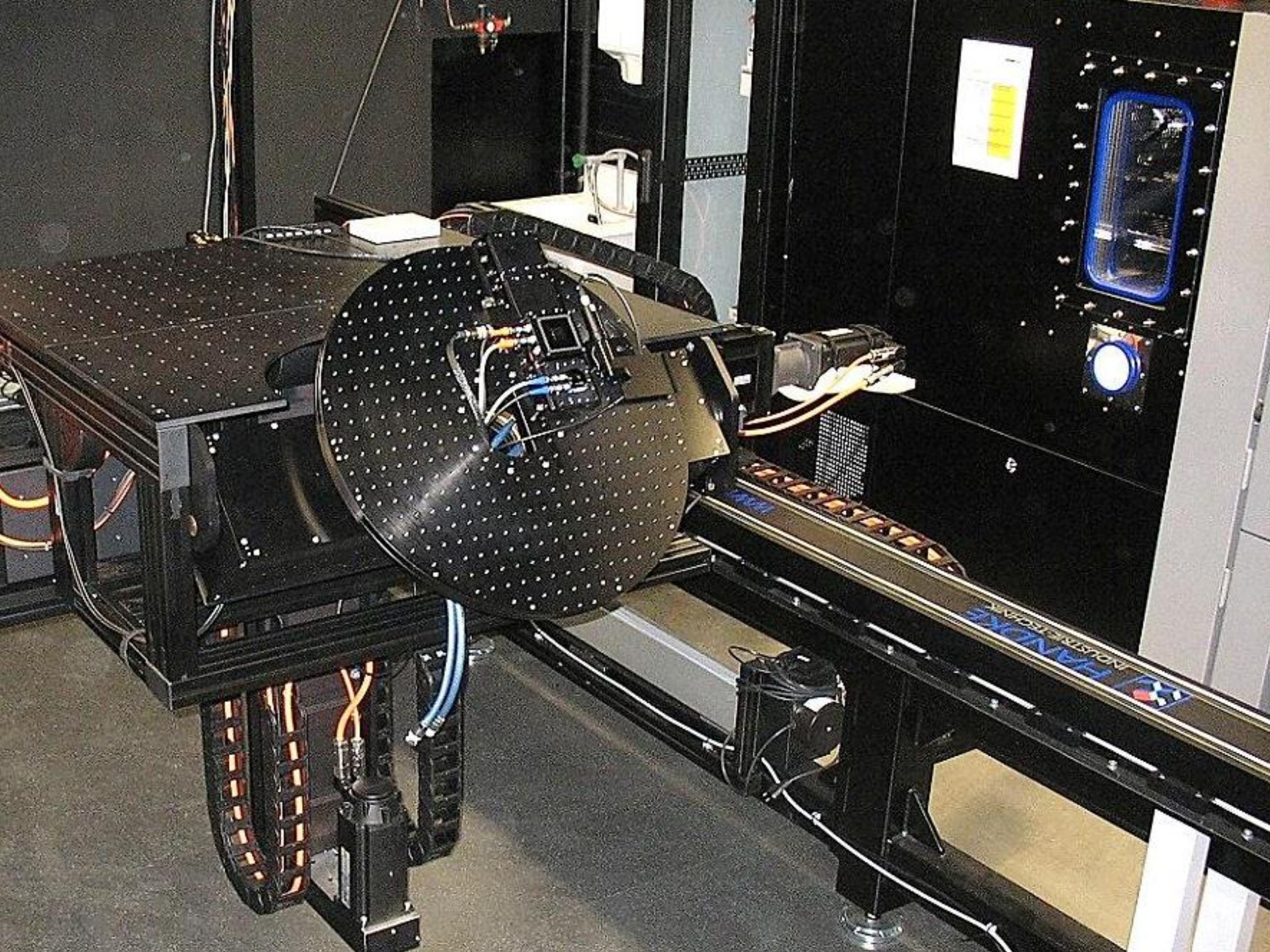



SHG
500-800nm
SHG
340-540nm
FHG(2+2)
210-225nm
THG
230-347nm
FHG(3+1)
190-210nm
COHERENT
signal
1000-1600nm
idler
1600-4000nm *
* special design, custom range 1720-4000nm
680-1080nm

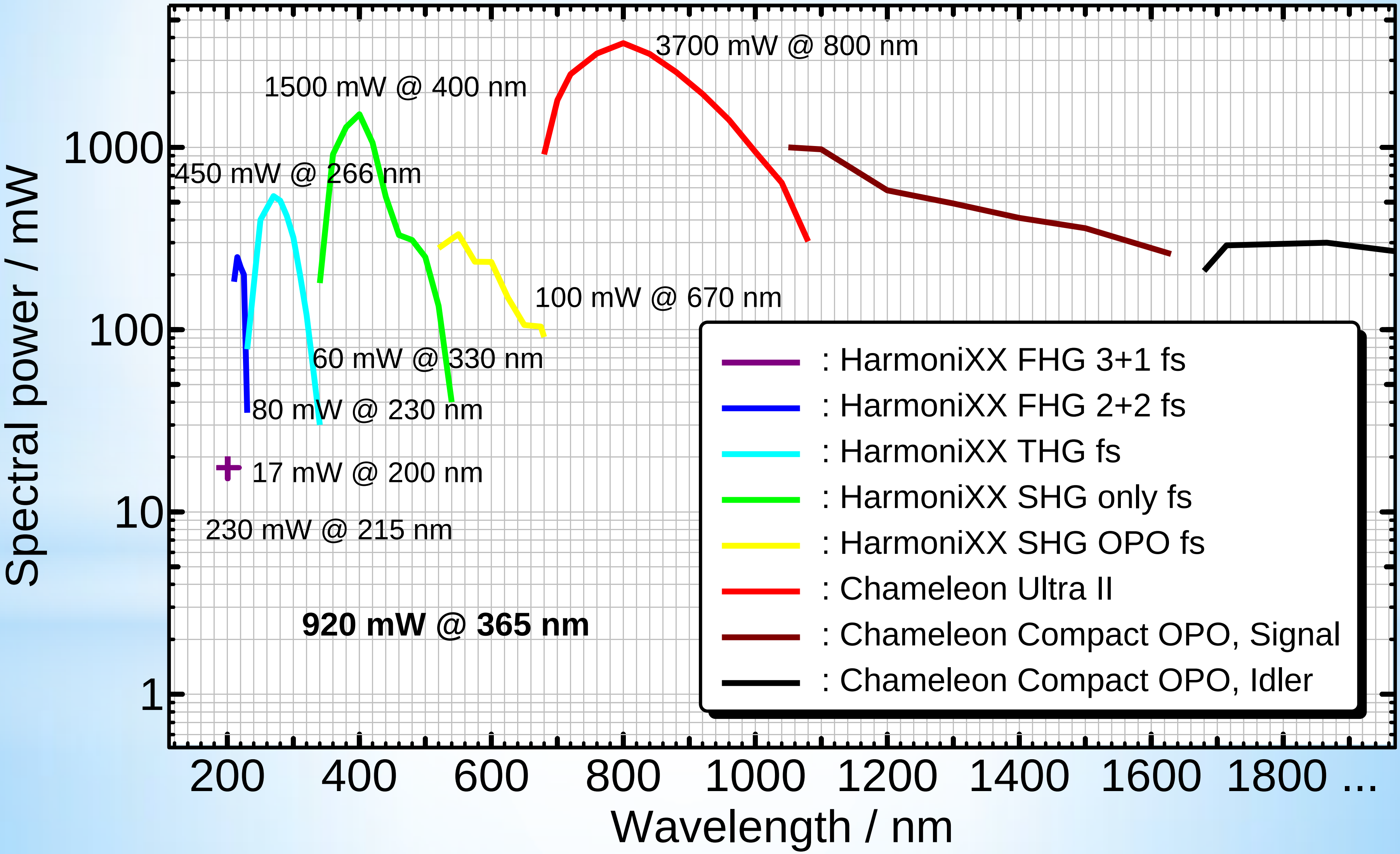





ndke-industrie.de



Measurement results



Conclusion

- PTB develops the next-generation of the DSR facility: LASER-DSR
- It has up to 1000 times more optical power than the old facility
- It is a multipurpose spectral comparison facility.

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

- We expect a reduction of uncertainty from 1.6% to 0.6% for large solar cells
- A fiber bundle with different lengths converts the fs pulses to a const signal
- The Pulse-To-CW converter can be used for all light sources with high repetition rates:

✓ Pulsed Laser	}	Photometry and Radiometry:
✓ Supercontinuum sources		Biology, Medicine
✓ Synchrotron radiation		Chemical Analyses