LASER APPLICATIONS FOR SPACE INSTRUMENTATION

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on behalf of the JUICE laser altimeter GALA team

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INTERPHOTONICS 2025

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AGENDA

Bildquelle hier angeben

Outline

1. Benefits of Laser Altimeter for Space Exploration
2. Conceptual Design, optical Challenge and Link Budget
3. Design and Composition of the JUICE GALA Laser Altimeter
4. GALA Instrument Analysis and Test Results
5. AIV and End to End Test Results

BENEFITS OF LASER ALTIMETER FOR SPACE EXPLORATION

Bildquelle hie angeben

- The question of extraterrestrial life is one that is asked not only by astronomers and scientists
- Mars is considered the more promising candidate, as the conditions on the surface of Venus deviate significantly from those required for life as we know it
- With the beginning of the exploration of the outer solar system, particularly through planetary space probes, it became clear to us that the icy moons of the large outer planets (Jupiter, Saturn, Uranus, and Neptune) are so strongly influenced by the tidal forces from their parent planets that liquid water could exist in large quantities beneath their icy surfaces
- ESA‘s JUICE mission was launched in 2023 and will reach the Jovian system in 2031
- For GALA the most important phases of the mission are the flybys of Europa, Ganymede and Callisto, the pericenter passages of the elliptical orbital phase around Ganymede, and the final low-altitude orbits around Ganymede at altitudes of 500 km
- GALA objectives for Ganymede will contribute to topography, surface roughness and reflectivity, to the interior of the moon, topography combined with gravity field data, tides, rotational state, and to the geodetic definition of reference systems

Science Background

- GALA will provide a high-resolution global shape model of Ganymede while in orbit around this moon based on at least 600 million range measurements from altitudes of 500 km and 200 km above the surface

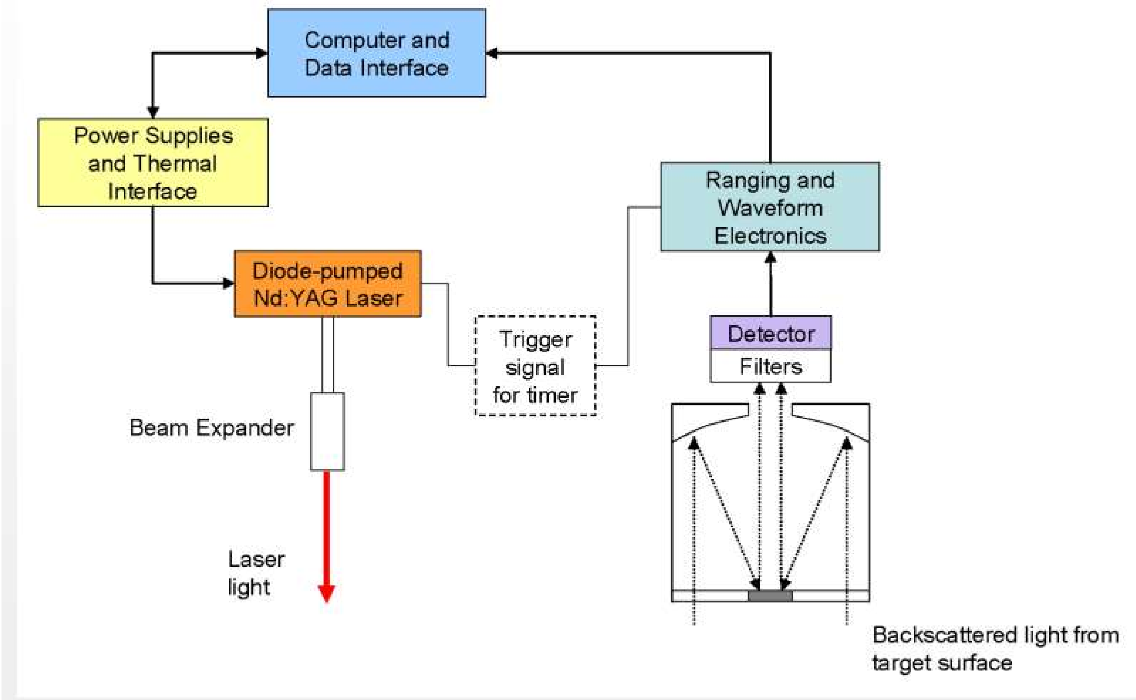
- By measuring the daily tidal deformation of Ganymede, which crucially depends on the decoupling of the outer ice shell from the deeper interior by a liquid water ocean, GALA will obtain evidence for (or against) a subsurface ocean on Ganymede and will provide constraints on the ice shell thickness above the ocean

- In combination with other instruments, it will characterize the morphology of surface units on Ganymede, Europa, and Callisto providing not only topography but also measurements of surface roughness on the scale of the laser footprint, i.e. at a scale of about 50 m from 500 km altitude, and albedo values at the laser wavelength of 1064 nm.

- GALA uses a Nd:YAG laser to generate pulses with pulse lengths of 5.5 ± 2.5 ns

- The return pulse is detected by an Avalanche Photo Diode (APD) with 100 MHz bandwidth and the signal is digitized at a sampling rate of 200 MHz providing range measurements with a sub-sample resolution of 0.1 m

Architecture Design of the Laser Altimeter GALA



Time of Flight Concept

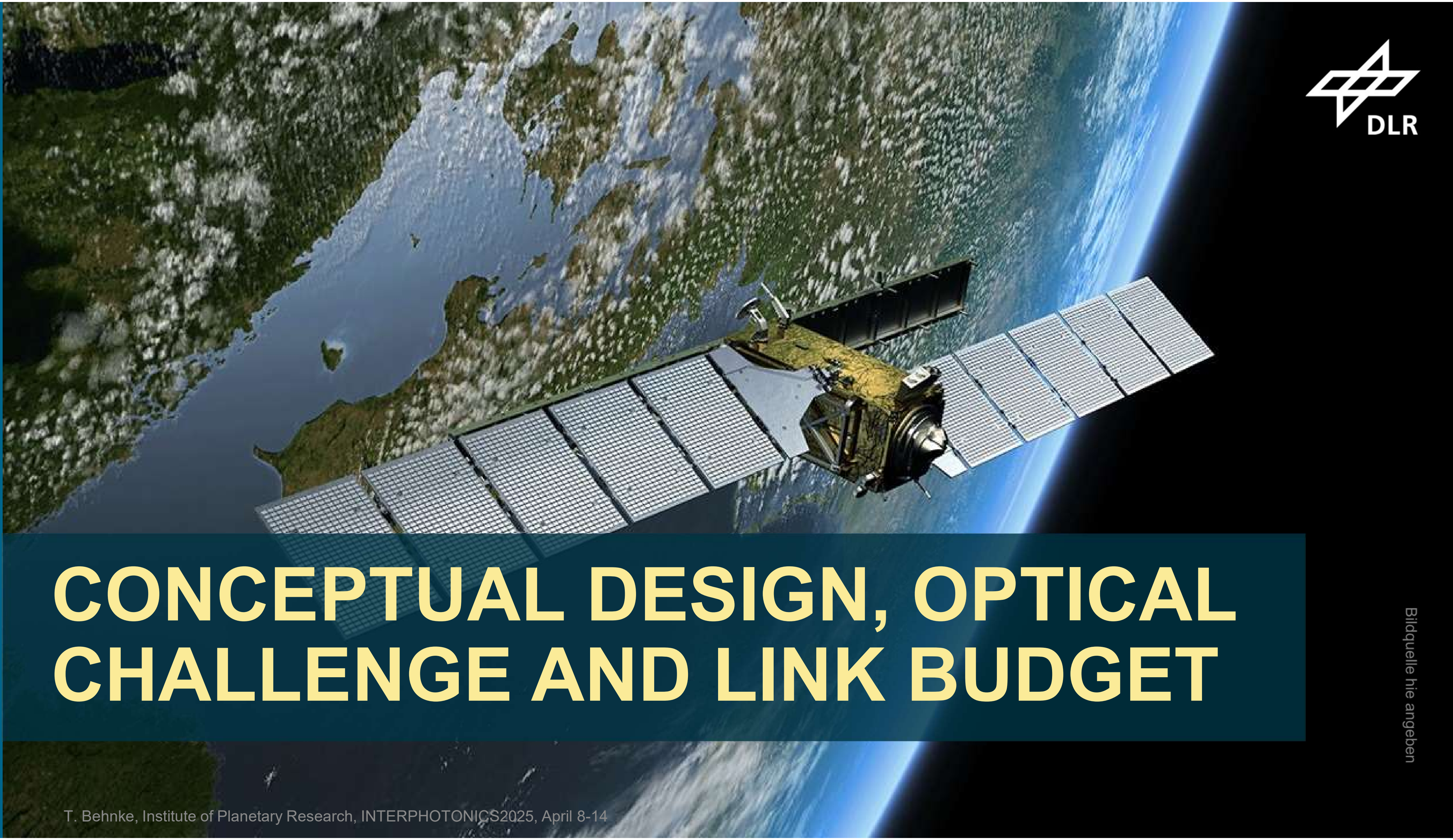
- Nd:YAG laser at 1064.57 nm
- 30/50Hz laser repetition rate
- Puse energy 17/8mJ
- Telescope aperture: 25 cm
- Rx pulse sampling frequency: 200 MHz

$\Delta t = 2*s/c$ with

c = Speed of light in vaccum
s = Distance to target

Instrument Challenges

- Complexity between Transmitter(Tx) and Receiver(Rx) Electronics and Optics
- Optical Alignment between Tx and Rx pointing
- Timing Requirements for ranging measurements (short and long time accuracy)
- Signal to Noise constraints
- Space instrument constraints (mass, power, volume)
- EMC budget between Tx and Rx
- Laser induced damage threshold (LIDT)
- Cosmic radiation effects



CONCEPTUAL DESIGN, OPTICAL CHALLENGE AND LINK BUDGET

Bildquelle hie angeben

Signal Consideration

$$N_{ph} = E_{Tx} * \frac{\lambda}{h * c} * \alpha_N * \xi_{Tx} * \xi_{Rx} * T_A^4 * A_{Rx} * \eta_{APD} * \frac{1}{R^2}$$

N_{ph} = number of return photons at λ
E_{Tx} = 17 mJ transmitter optical output power
α_N = normal albedo
ξ = transmitter and receiver losses
T_A = loss of optical power through atmosphere (if applicable forward and return)
η_{APD} = APD quantum efficiency
$A_{RX} = \pi * \left(\frac{D}{2}\right)^2$ Rx aperture area
R = range to target (500 km)

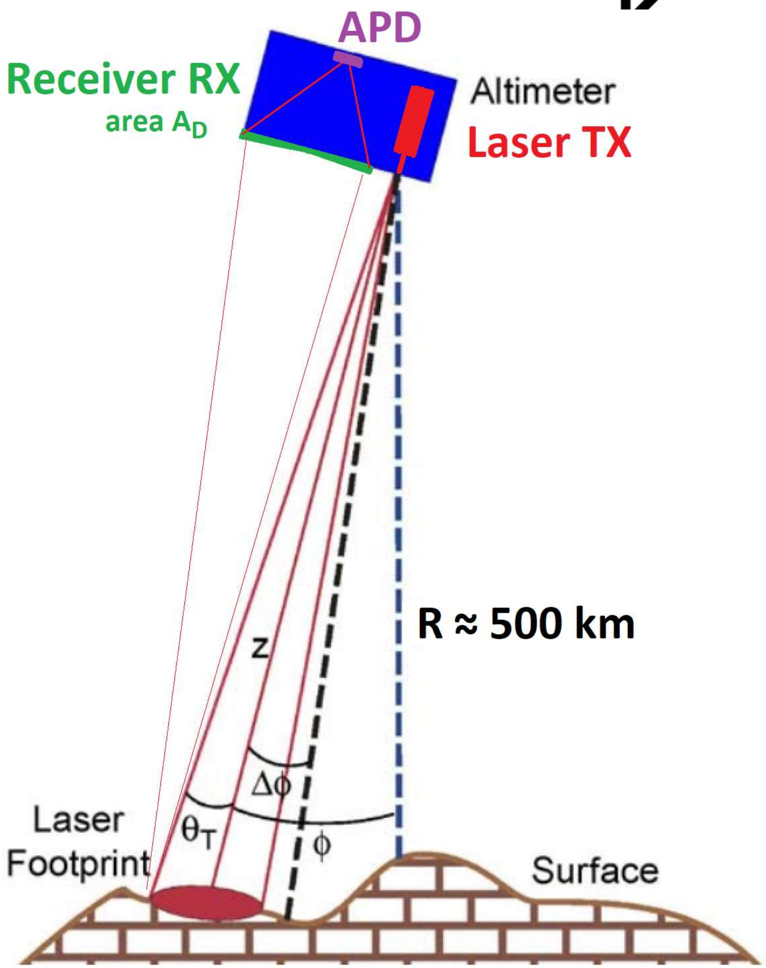
Link Budget

$$E_{Rx} = \kappa * E_{Tx} * A_{Rx} \frac{1}{R^2}$$

$$61\ aJ = \frac{\kappa}{0.018} * \frac{E_{Tx}}{17mJ} * \frac{A_{Rx}}{0.05m^2} * \left(\frac{500\ km}{R}\right)^2$$

$$\kappa = \xi_T * \ \xi_R * T_A^2 * \frac{\rho_s}{\pi} * \eta_{APD} \ \approx 0.8 * 1^4 \ * 0.35 * \frac{\rho_s}{\pi} \ \approx 0.018$$

And 61 aJ corresponds to 330 photons at λ = 1064 nm



Signal to Noise Ratio

Transmitter pulse width: $\approx 3 \ldots 5$ ns

Return pulse widths:
up to 25 ns depending on surface roughness and slope

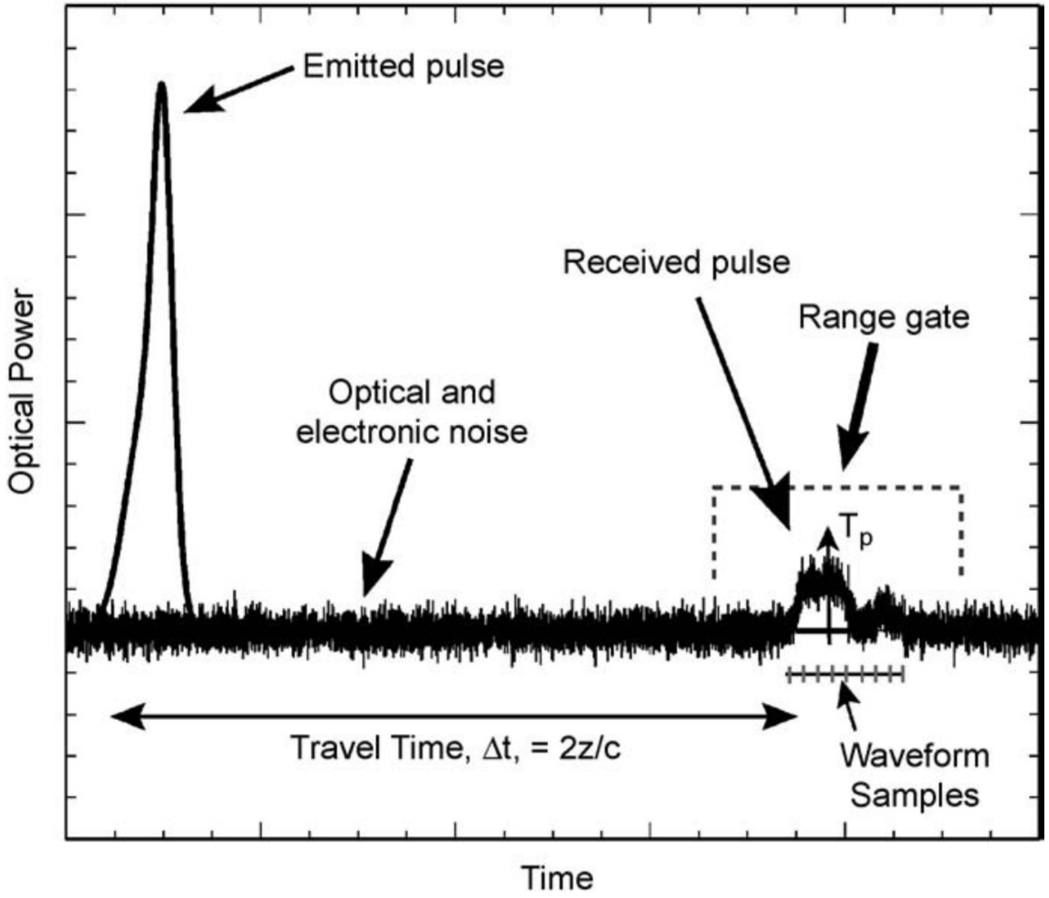
Return signal power: $\frac{61 \text{ aJ}}{25 \text{ ns}} \approx 2.5 \text{ nW}$

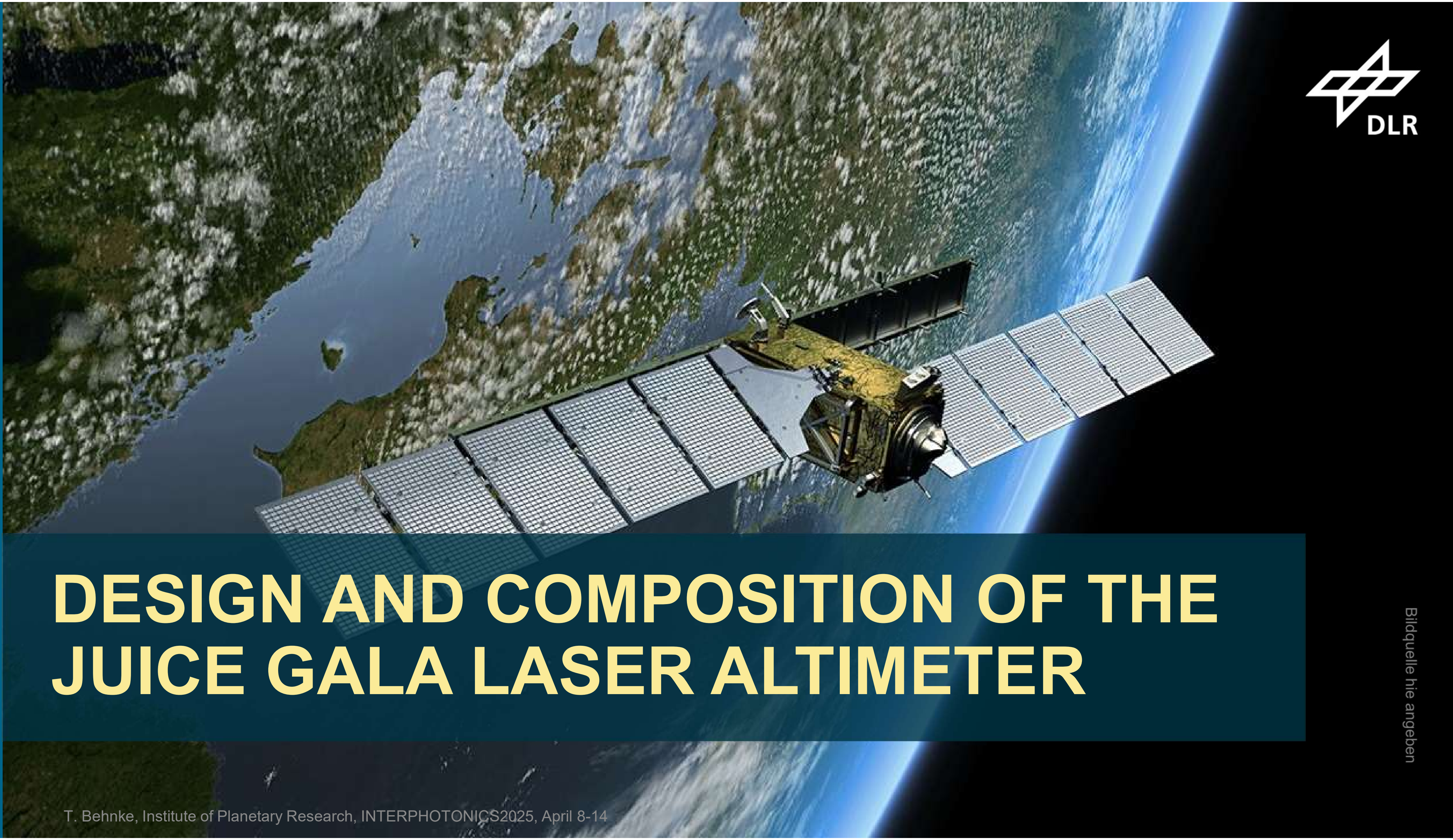
Responsivity APD module of Excelitas:

$R = 750 \text{ kV/W} \Rightarrow 1.875 \text{ mV}$ signal amplitude

Noise floor APD in a bandwidth of 100 MHz:

$$\frac{40 \text{ fW}}{\sqrt{\text{Hz}}} \Rightarrow \frac{30 \text{ nV}}{\sqrt{\text{Hz}}} \Rightarrow 0.3 \text{ mV RMS}$$





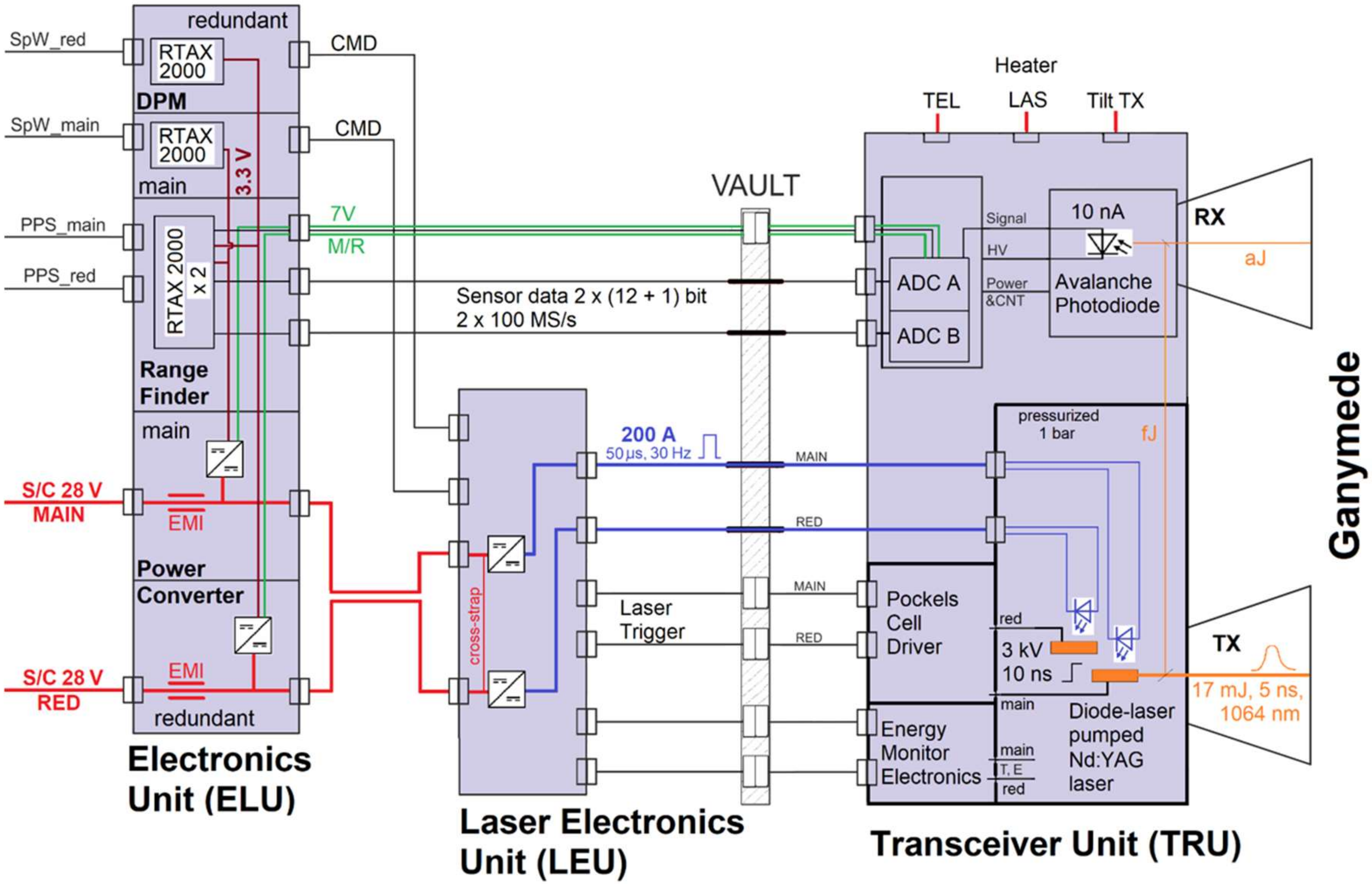
DESIGN AND COMPOSITION OF THE JUICE GALA LASER ALTIMETER

Bildquelle hie angeben

T. Behnke, Institute of Planetary Research, INTERPHOTONICS2025, April 8-14

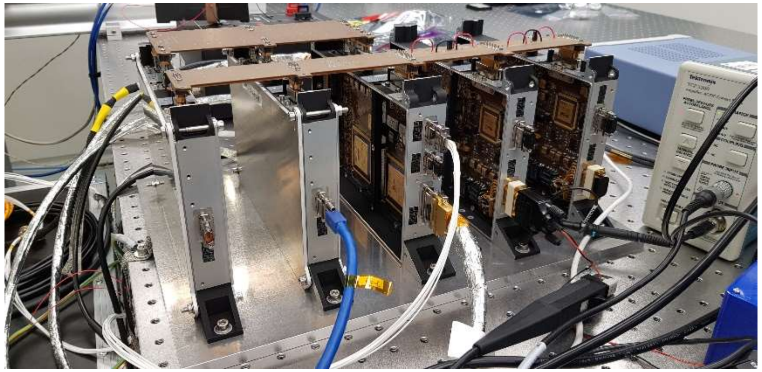
GALA, the electrical view

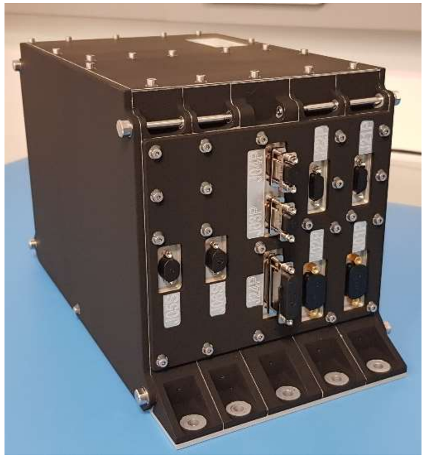
DLR



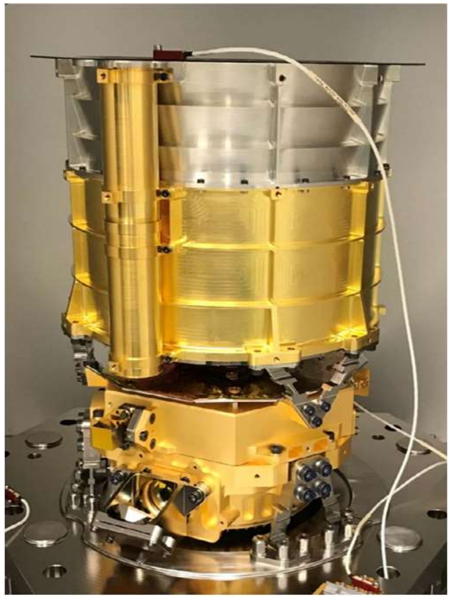
Pices of Hardware

ELU PFM on testbench and integrated



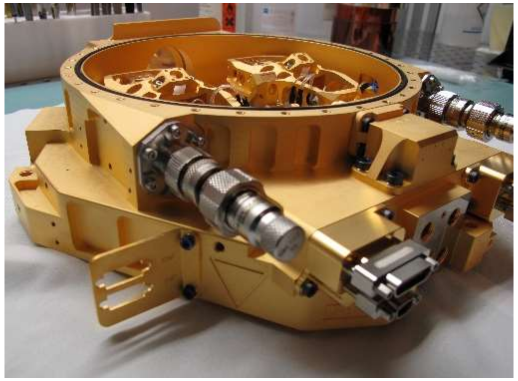


LEU PFM

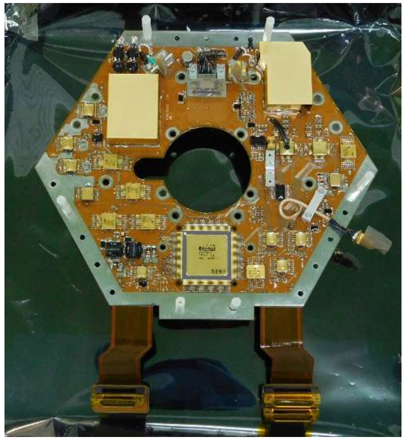


TRU PFM
integrated

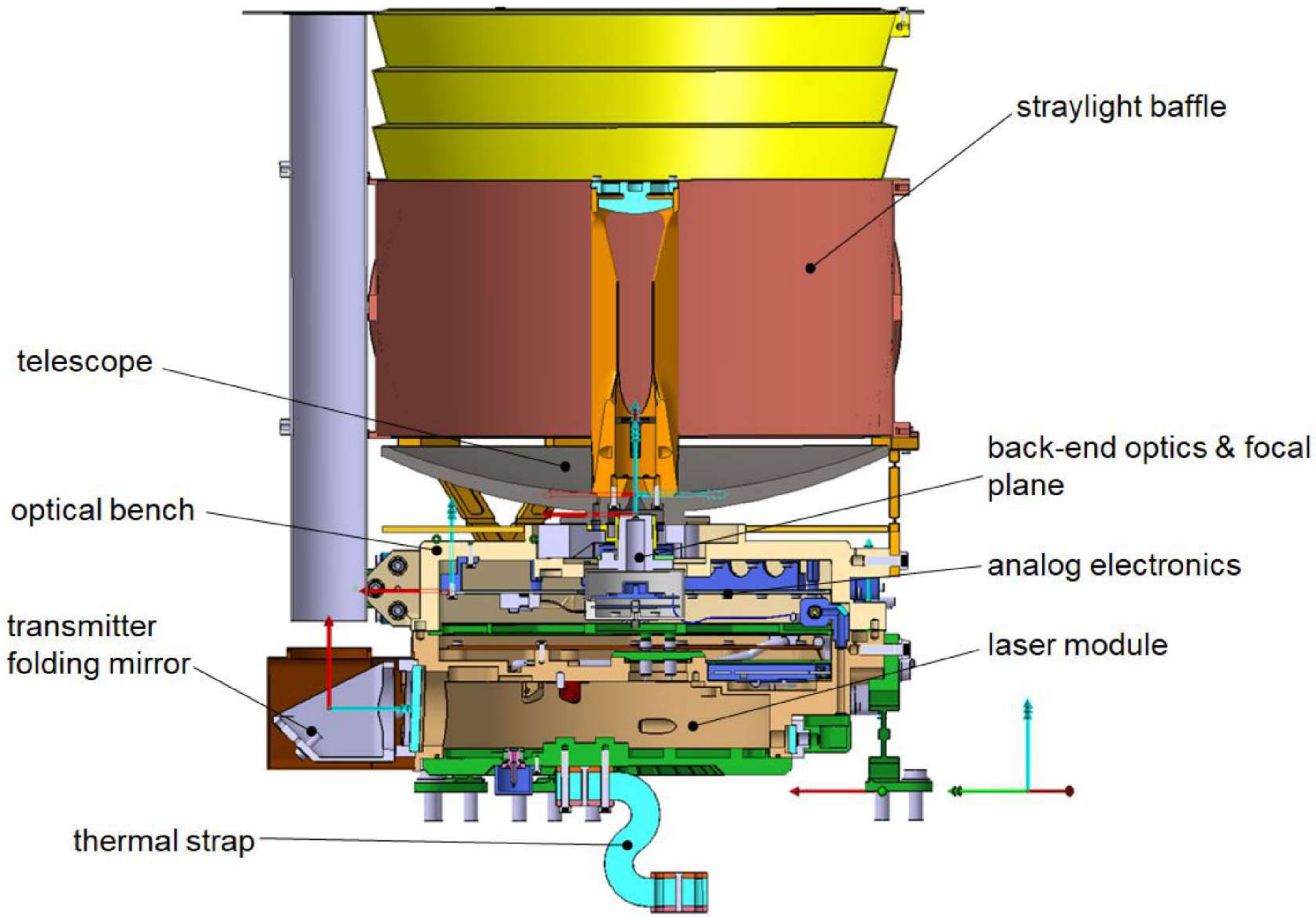
Laser housing of TRU PFM

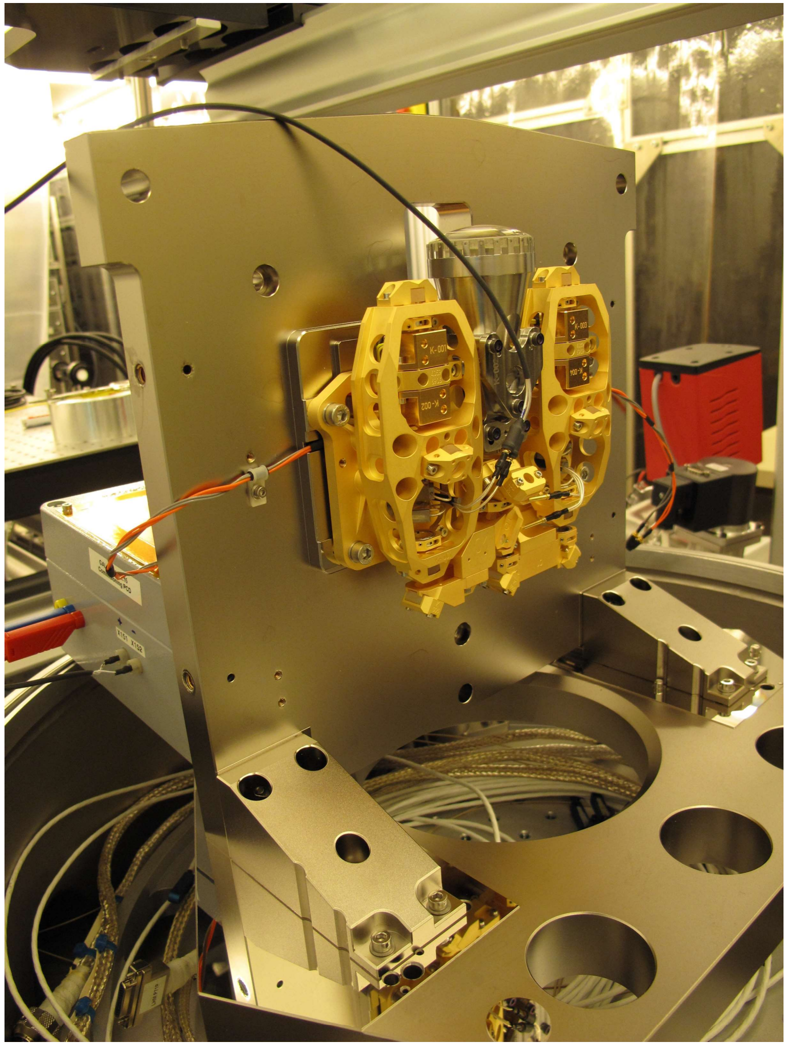


AEM PFM



BEO/FPA PFM


straylight baffle
telescope
back-end optics & focal plane
optical bench
analog electronics
transmitter folding mirror
laser module
thermal strap

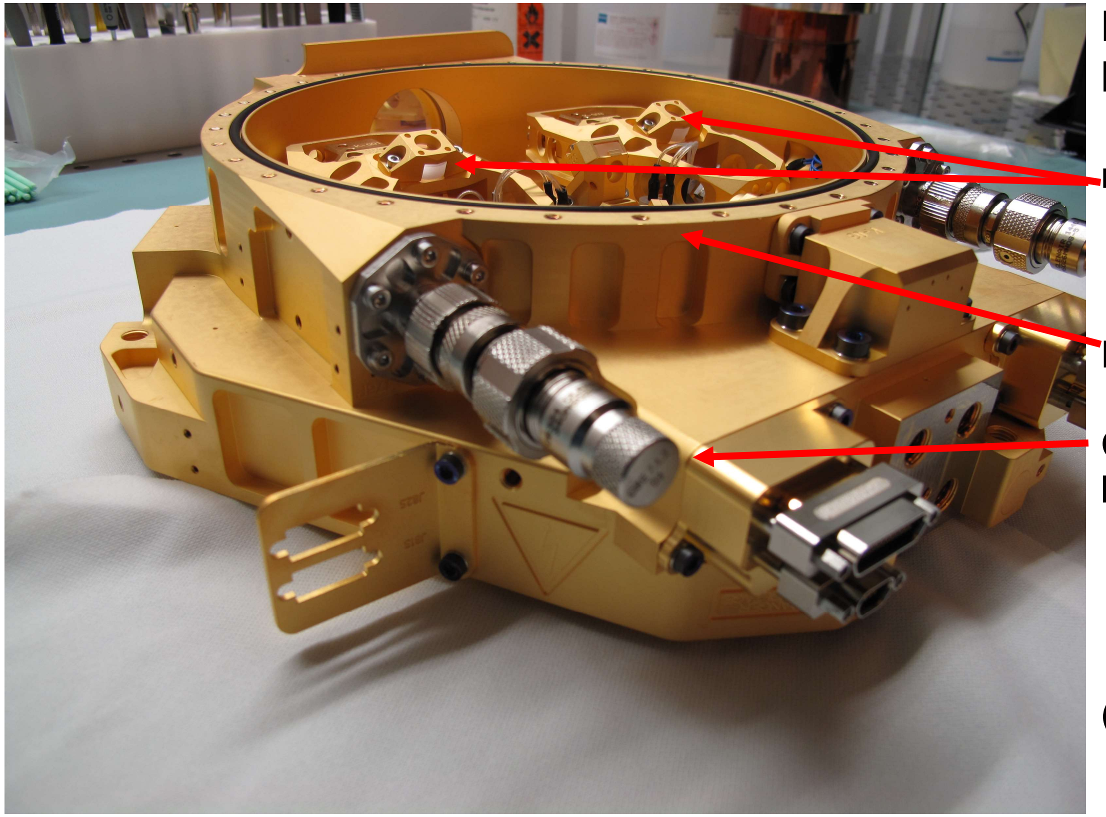


Laser Head Module

Main & redundant lasers with beam expander, mounted on alignment test stand

(DLR/Hensoldt)

Transmitter Part of the Transceiver Unit



Bottom part of TRU housing

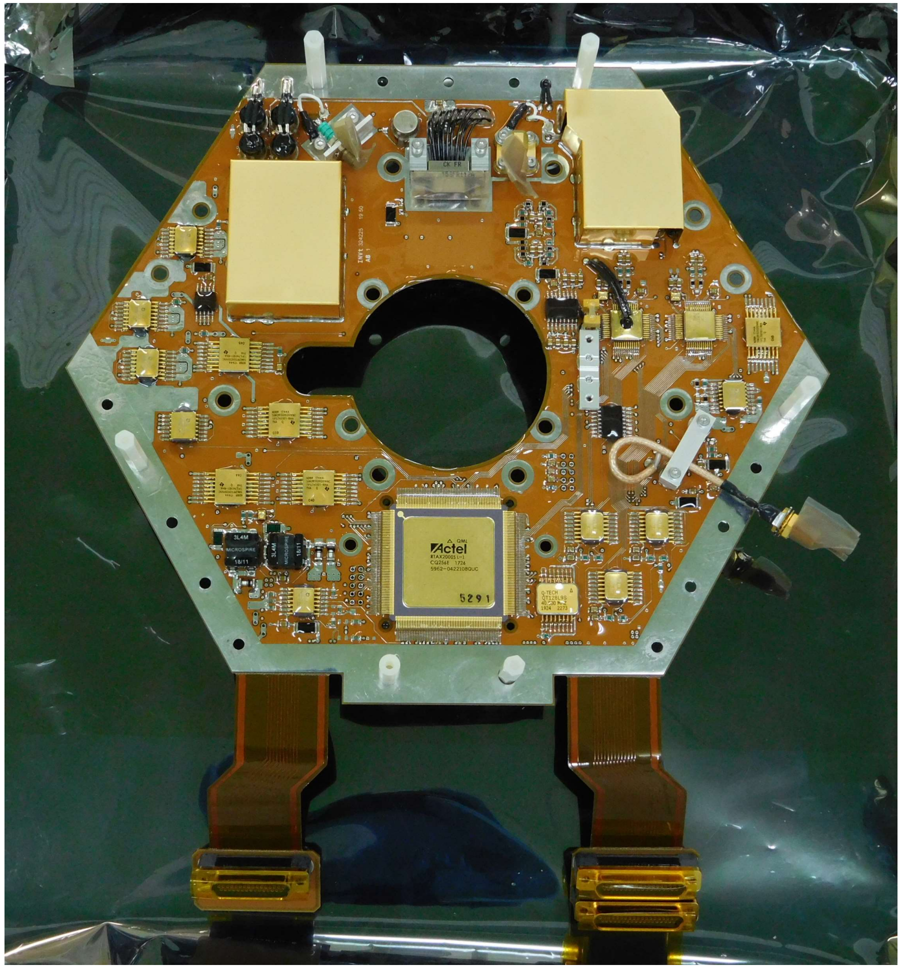
main & redundant lasers

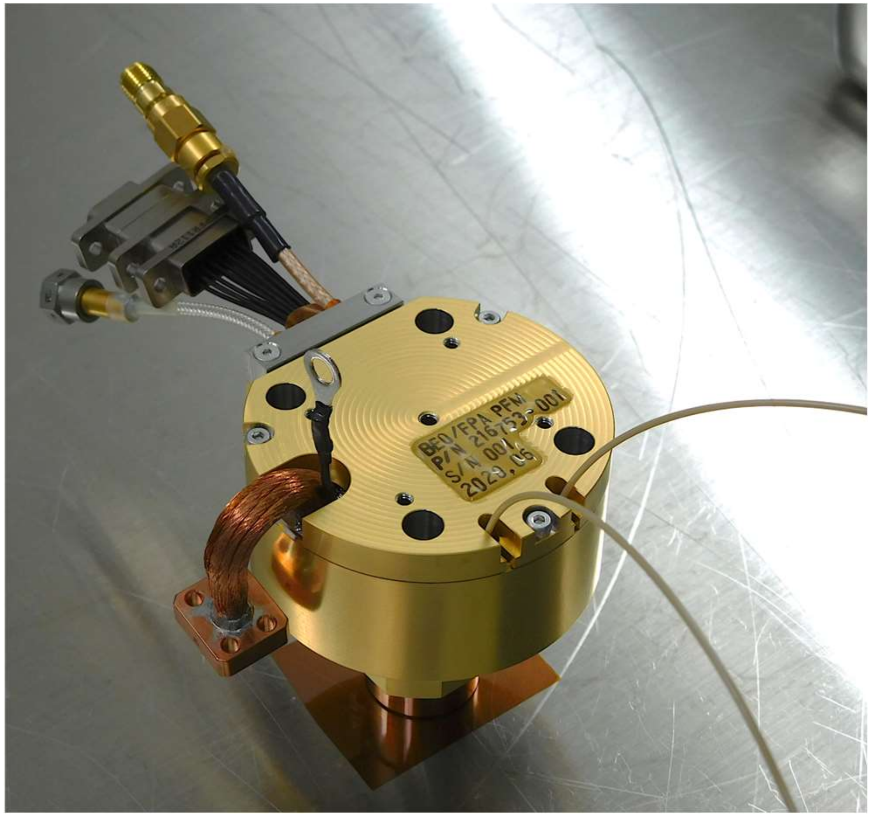
Flange for hermetic sealing

Connectors for 200 A of laser diode pump current

(DLR/Hensoldt)

BEO/FPA and AEM PFM (Receiver assemblies inside the TRU)





BEO/FPA and AEM PFM manufacturing JAXA/MEISEI.

GALA INSTRUMENT ANALYSIS AND TEST RESULTS

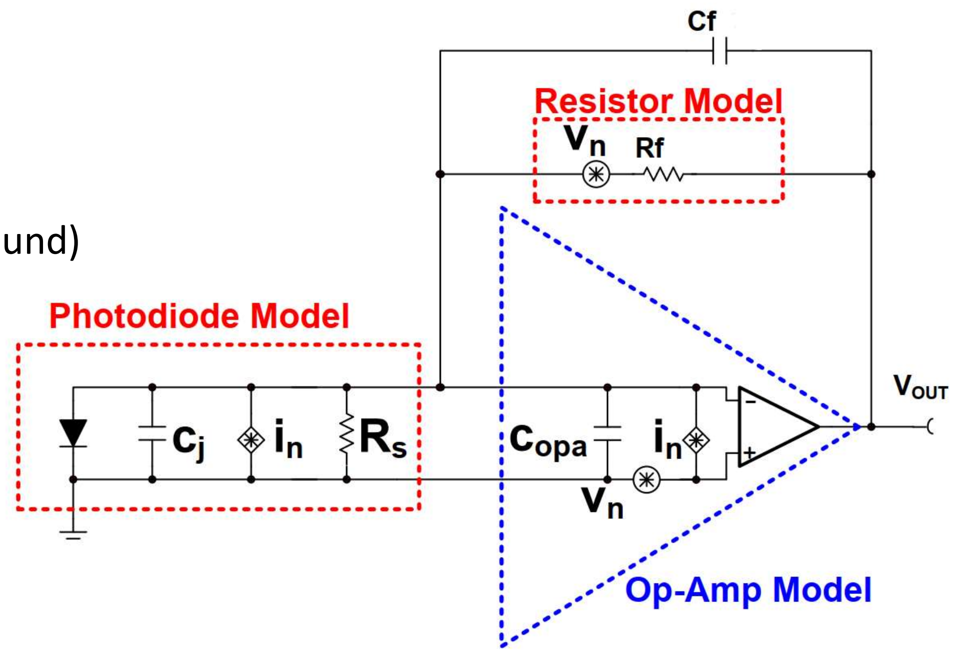
Bildquelle hie angeben

EMC Challenge between Transmitter and Receiver

- TRU combines Transmitter and Receiver hardware in a compact housing
- 4 modulators pump 50A during 50 … 70 µs into a laser diode array. The total current amounts to 200 A into the summing node.
- An active Q-switch activates the outgoing laser pulse by charging 10 pF within 10 ns with 3 kV
- typically 1000 photons are transmitted onto the Si Avalanche Photodiode detector (APD) which yields, with a nominal responsivity of 685 kV/W and a typical return pulse width of 30 ns, signals of about 6 nW, respectively 4 mV amplitude.

$$i_s = M * R_o(\lambda) * P_s * \mathrm{F}$$

M	= Gain (typ. 150) controlled by high voltage
Ro(λ)	= Responsivity (typ. 0.3 A/W, M=1)
Ps	= Incident optical power (signal and background)



$$v_{out} = (i_s + i_n) * R_f$$

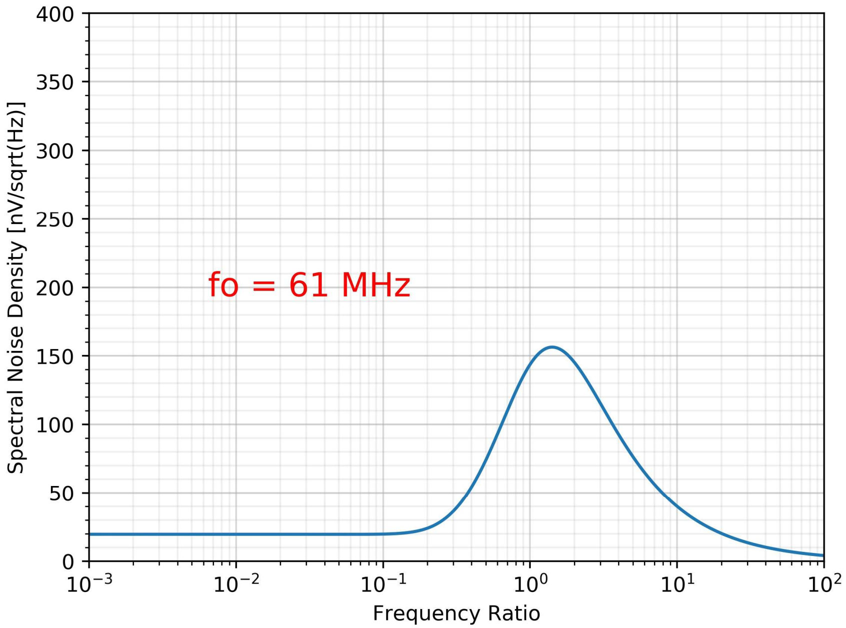
$$i_n = \sqrt{2 * q * \left(i_{DS} + (i_{DB} * M^2 * F)\right) * B}$$

i_{DS}	= surface dark signal
i_{DB}	= bulk dark signal
F	= APD noise factor
B	= Bandwidth

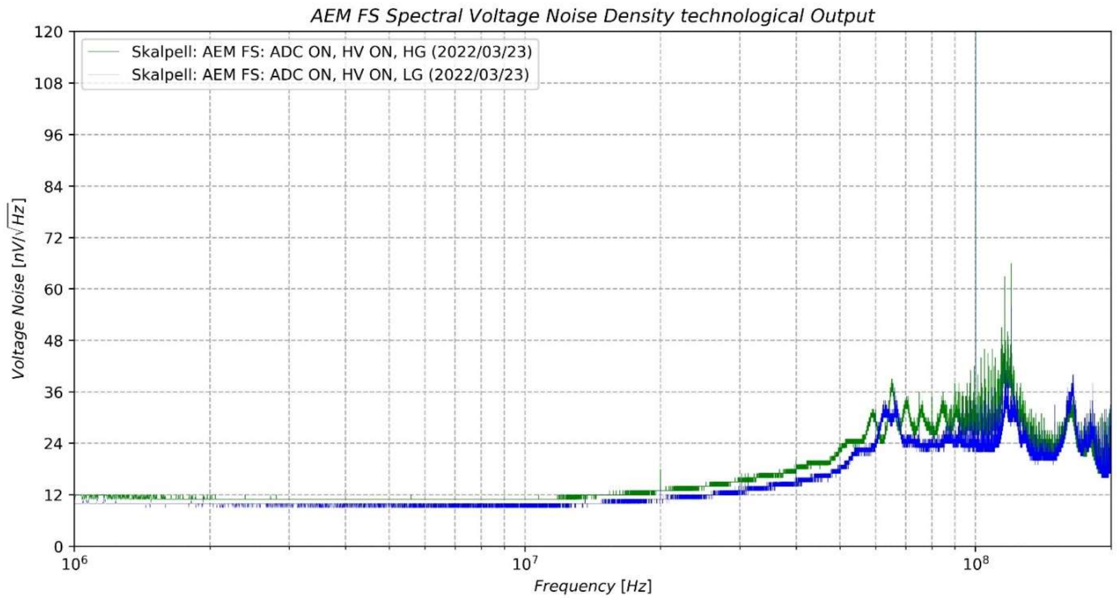
$$v_{out} = \frac{v_n + (i_n * R_f) + v_r + \frac{\omega^2}{\omega_0^2} v_n\left(\frac{C_f + C_{IN}}{C_f}\right)}{1 + \frac{\omega^2}{\omega_0^2}}$$

$$with\ C_{IN} = C_j || C_{opa}$$
$$\omega_0^2 = \frac{1}{C_f^2 * R_f^2}$$

Theory



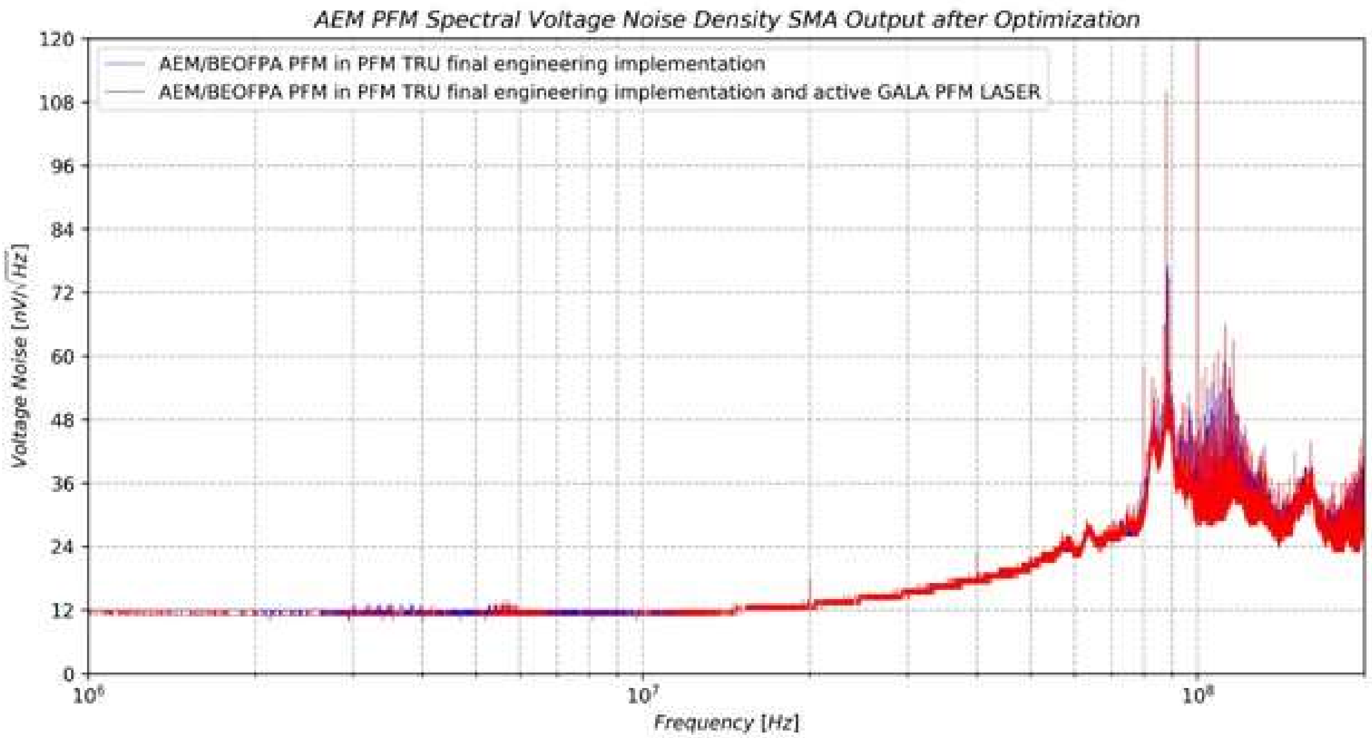
Implementation



- LF noise floor amounts to 12 nV/sqrt(Hz) – equivalent to 33 kΩ thermal noise on 50 Ω input (divider by 2)

$$P_n = 4k_B TRB$$

Noise spectral Density during Laser Operation

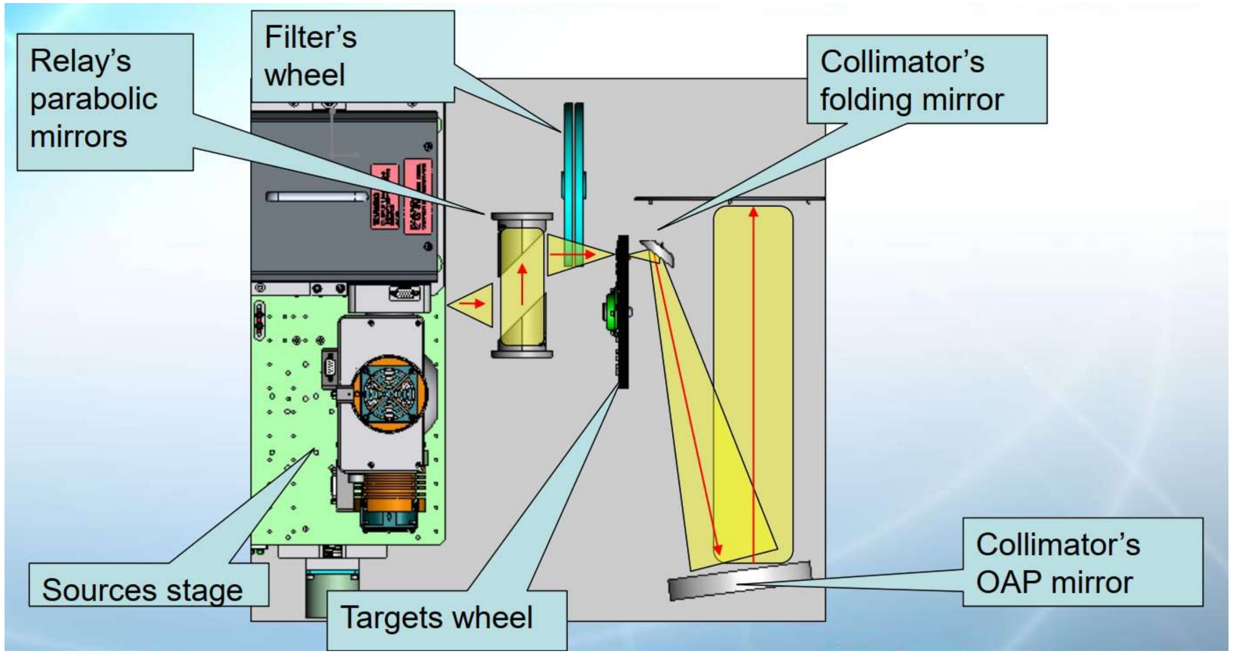


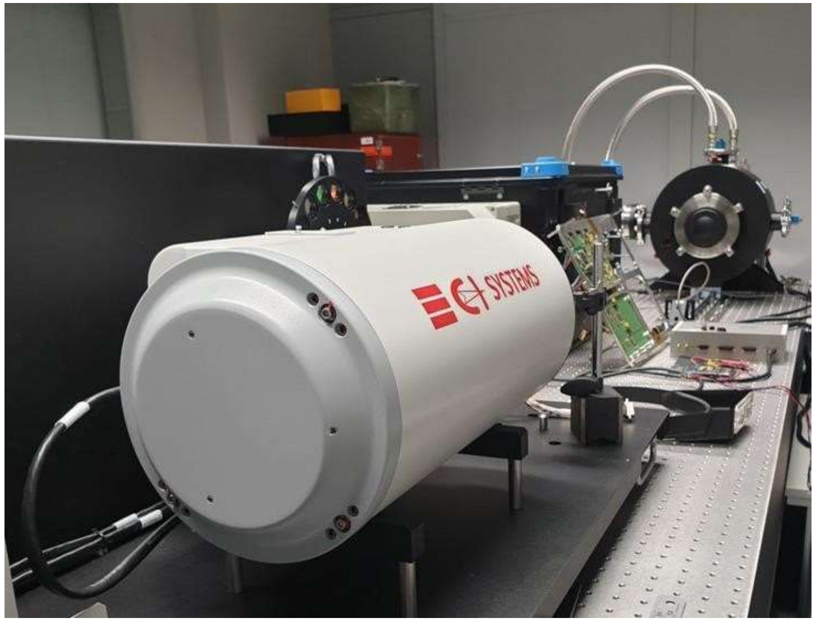
AIV TEST AND END TO END TEST RESULTS

Bildquelle hie angeben

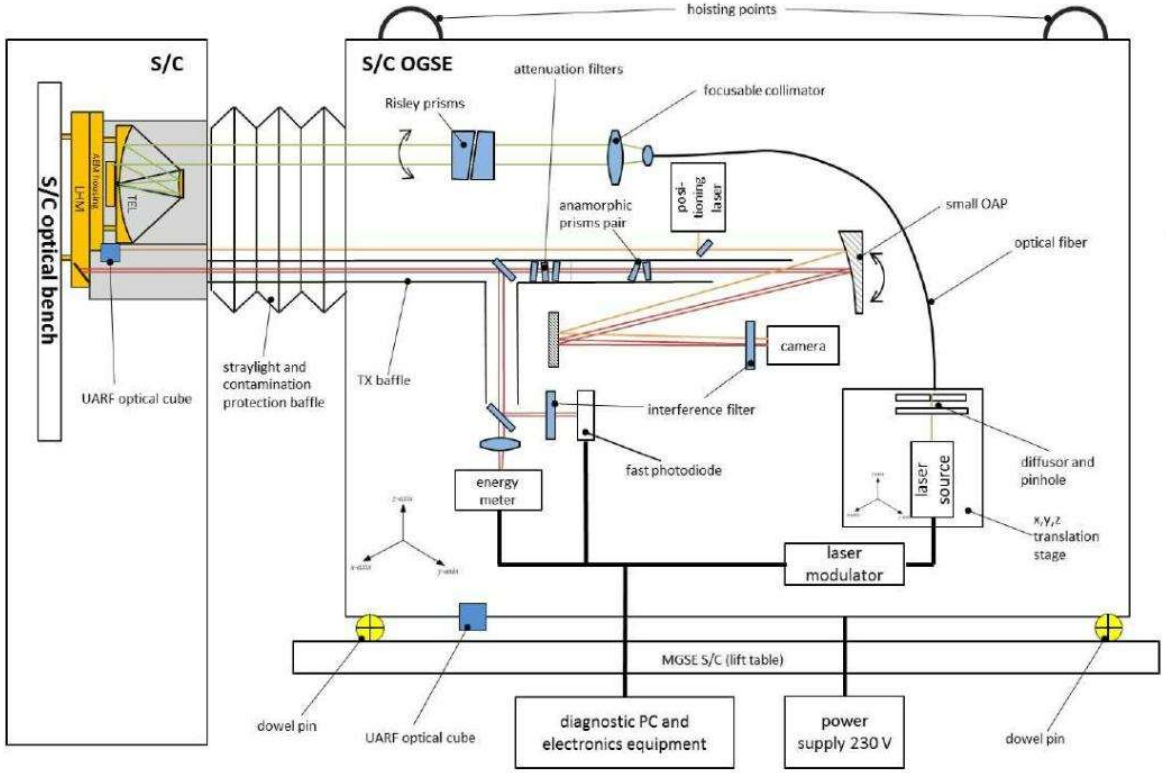
Detector Characterization Lab

Parameter	Range	Parameter	Range
Integrating sphere wavelength	440-2100 nm	Collimator F#	3
Number of filters	2 times 16	Collimator focal length	15 inch
Filter spectral resolution (Δλ/λ)	< 2.5%	Collimator aperture	5 inch
Number of targets	8	Field of view	2 °



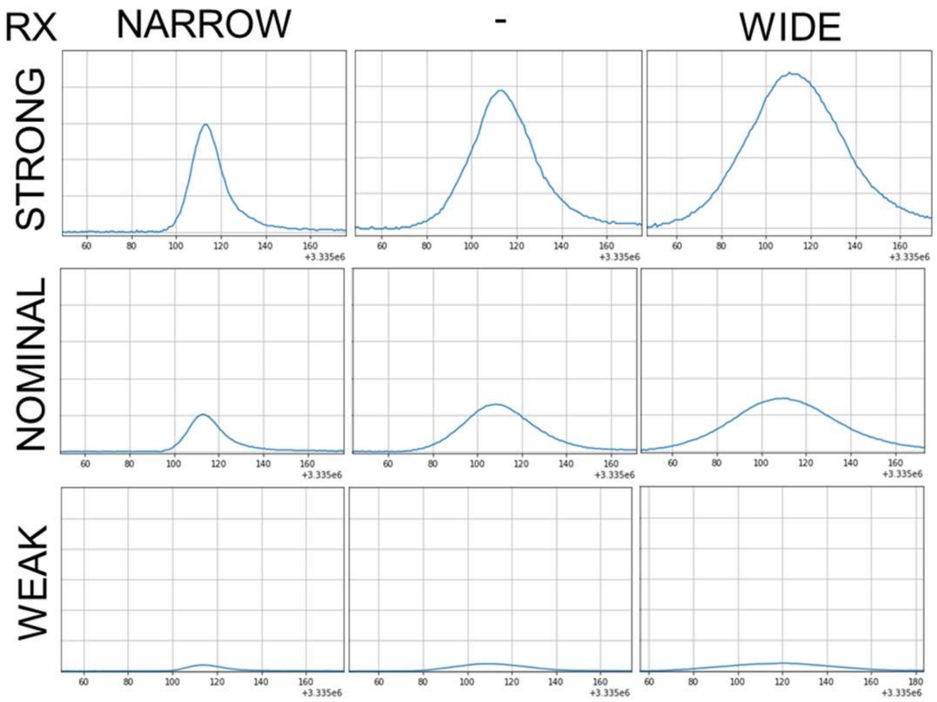


Instrument end to end test setup (orbit simulation)



Representative Return pulse shapes for Peformance Testing

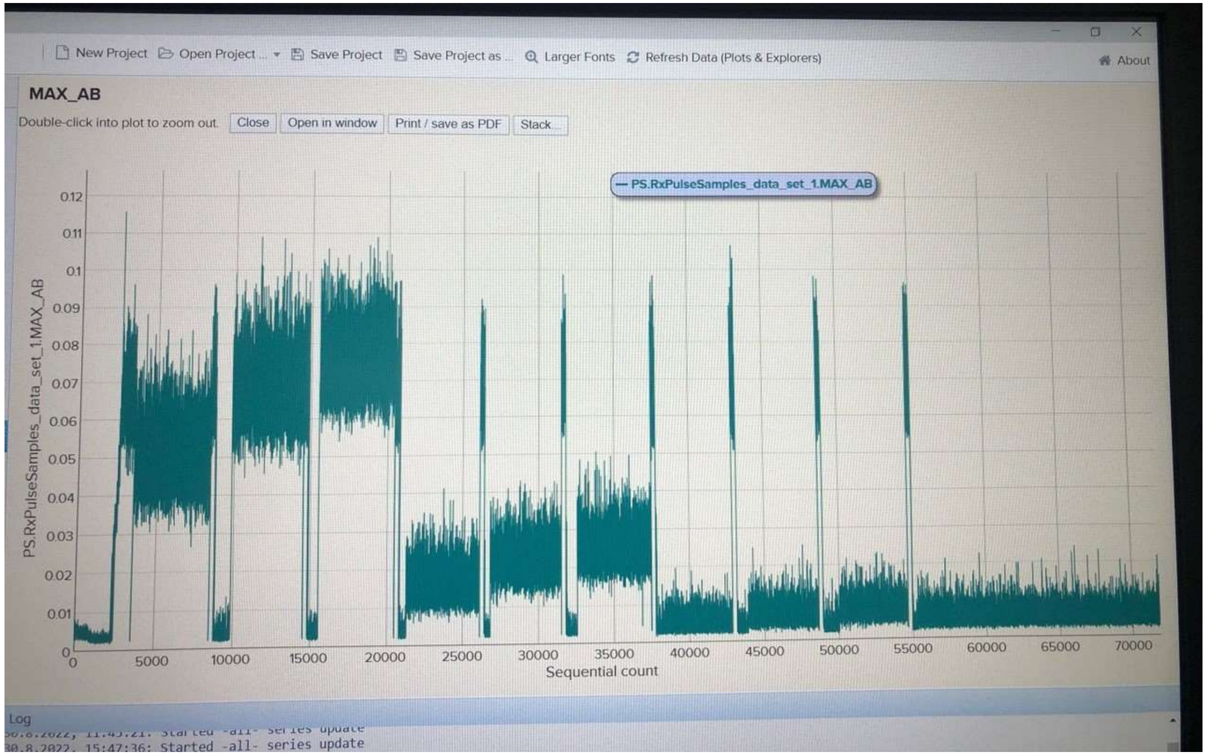
Rx Pulse name	Energy [fJ]	Photons	FWHM [ns]
Strong narrow	0.558	2940	13.7
Strong	1.360	1760	31.0
Strong wide	2.182	11,480	47.6
Nominal narrow	0.134	710	13.7
Nominal	0.327	1720	31.7
Nominal wide	0.518	2730	48.7
Weak narrow	0.054	280	11.4
Weak	0.131	690	26.2
Weak wide	0.207	1090	38.8
Super weak narrow	0.0277160	140	11.4



Instrument scientific performance

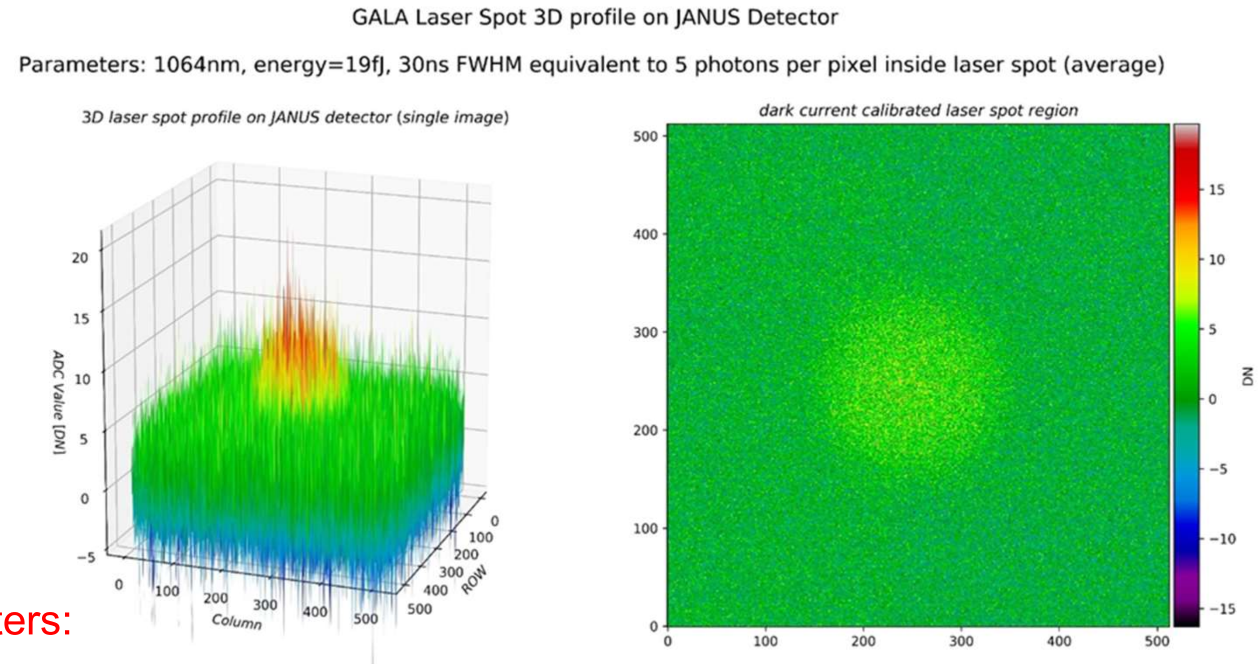
One of three blocks of the GALA E2E test: Different artificial pulse from the OGSE were detected by GALA, even the super-weak pulses: 0.054 fJ pulse energy, 11.4 ns pulse width, approx. 300 photons.

The GALA performance model requires at least 700 photons.



strong pulses | normal pulses | weak pulses | Super-weak pulses Were detected by GALA!

JUICE Laser Altimeter (GALA) Return Pulse Recognition on CIS115 Detector single image



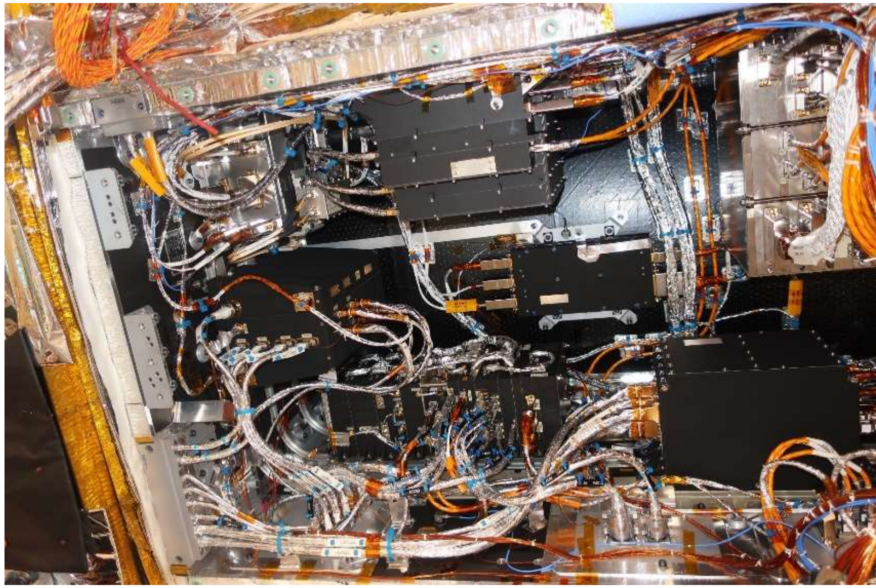
GALA Laser Parameters:

$Laser\ Energy: 19\ fJ, Photon\ Energy@1064nm:\ 1.94 * 10^{-19}\ J, Pulse\ Rate:\ 30\ Hz, Puls\ Width: 30\ ns$

CIS 115 Details:

$QE\ @\ 1064\ nm: < 5\ \%, exposure\ time: 160\ ms, pixel\ size\ 7\ \mu m^2$, spot size diameter: 100 px

CIS115 detector output signal: 6 -7 $e^{-}\ (avg)$ (respectively 3-4 DN)



Thank you for your Attention!