The Versatile Link+ Transceiver Story

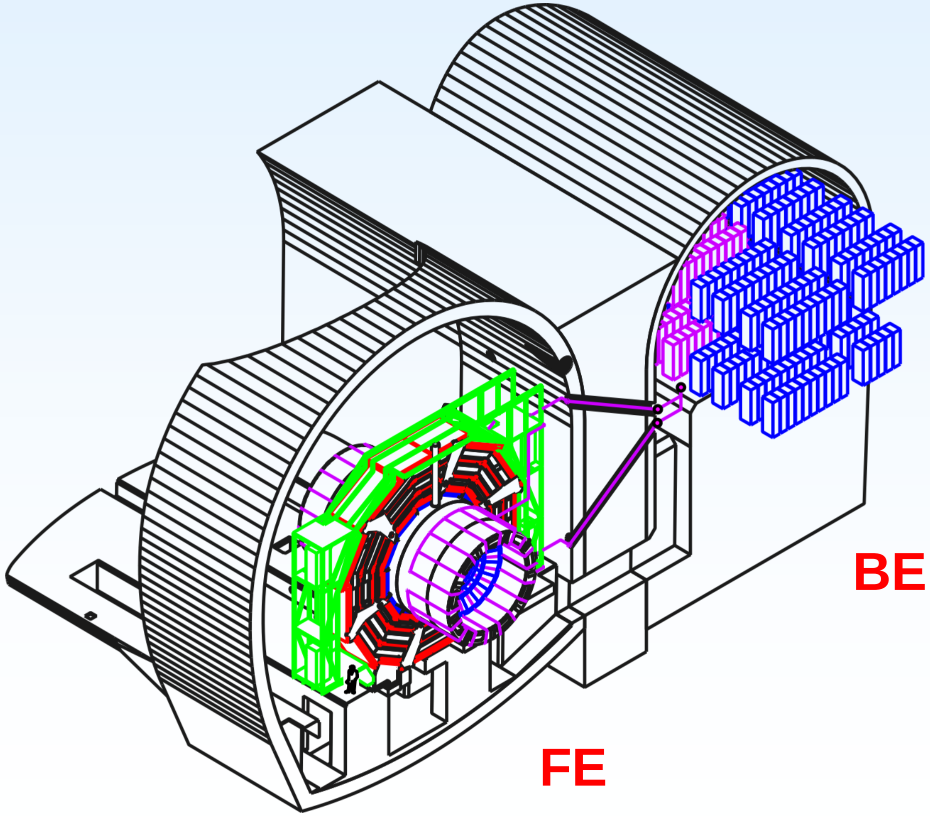
EP-ESE Electronics Seminar

Csaba Soos

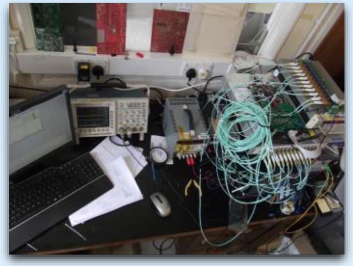
October 8, 2024

Long time ago …

- The Versatile Link PLUS project (VL$^+$) targets the phase II upgrades of the ATLAS and CMS experiments
- VL$^+$ was officially announced at ACES 2014 and started on 1 Apr 2014. The project was subdivided in three phases:
  - Phase 1: proof of concept
  - Phase 2: feasibility demonstration
  - Phase 3: pre-production readiness
- Bi-directional Optical Link
  - Up-stream (FE -> BE): up to 10 Gb/s
  - Down-stream (BE -> FE): up to 5 Gb/s
  - When used with lpGBT:
    - Up-stream: 5.12 or 10.24 Gb/s
    - Down-stream: 2.5 Gb/s

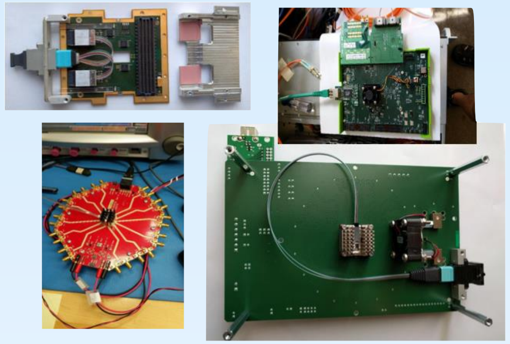


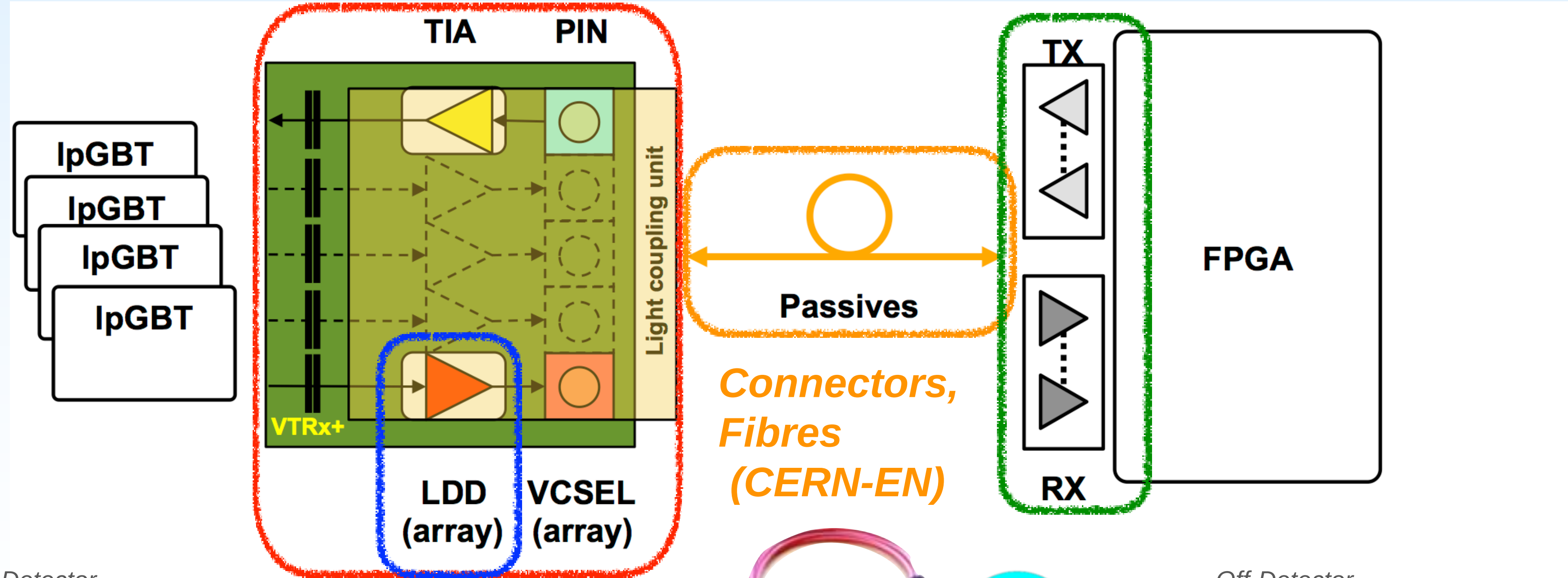
VL$^+$ system architecture



Reliability (Oxford, Academia Sinica)

Commercial Array TRx (FNAL)





Connectors, Fibres (CERN-EN)

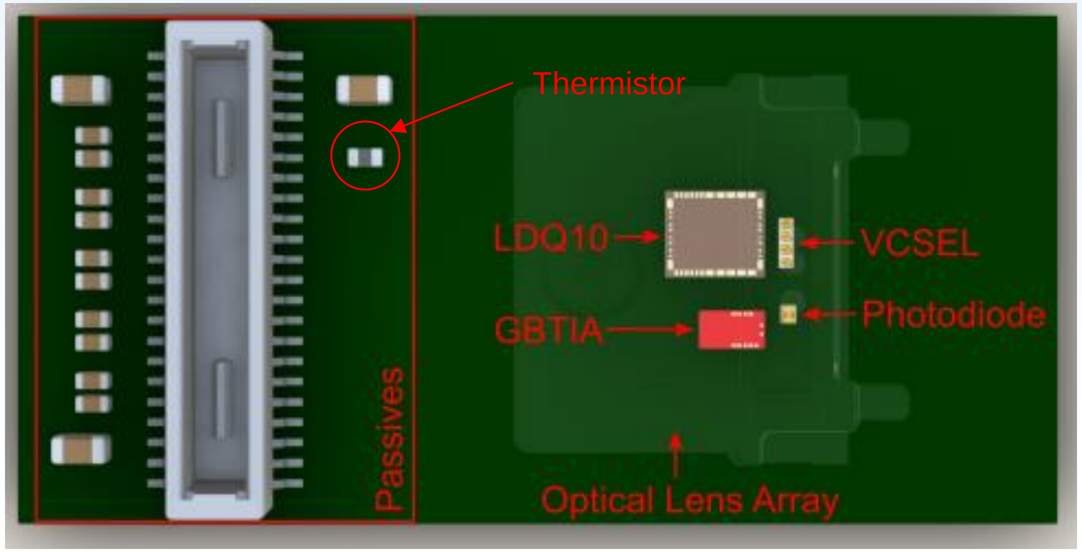
Laser Driver (SMU)

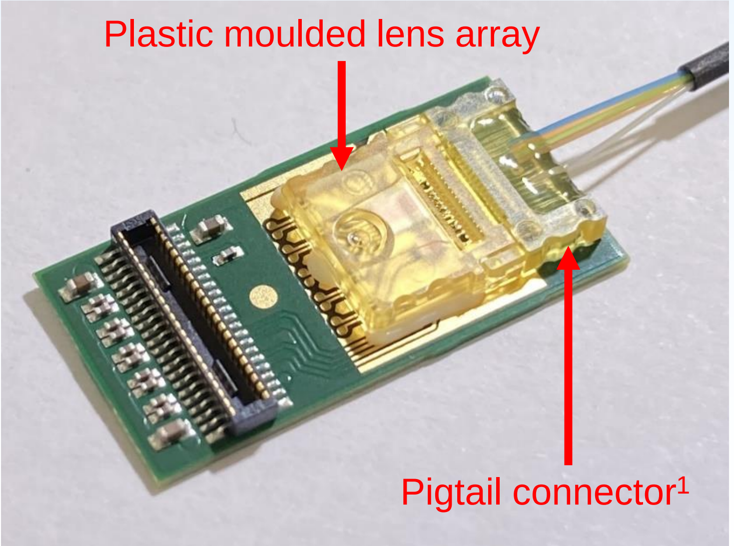
On-Detector
Custom Electronics & Packaging
Radiation Hard

Off-Detector
Commercial Off-The-Shelf (COTS)
Custom Protocol

VL+ transceiver (VTRx+)

- 4Tx + 1Rx, configurable by disabling channels
- Dimensions: 20mm x 10mm x 2.5mm
- Pluggable electrical interface
- Data-rate: TX up to 10Gb/s, RX up to 2.5Gb/s
- Specifications on EDMS
  - https://edms.cern.ch/document/1719329/1





[1] Mated only once during the assembly

VTRx+ design: custom vs customised

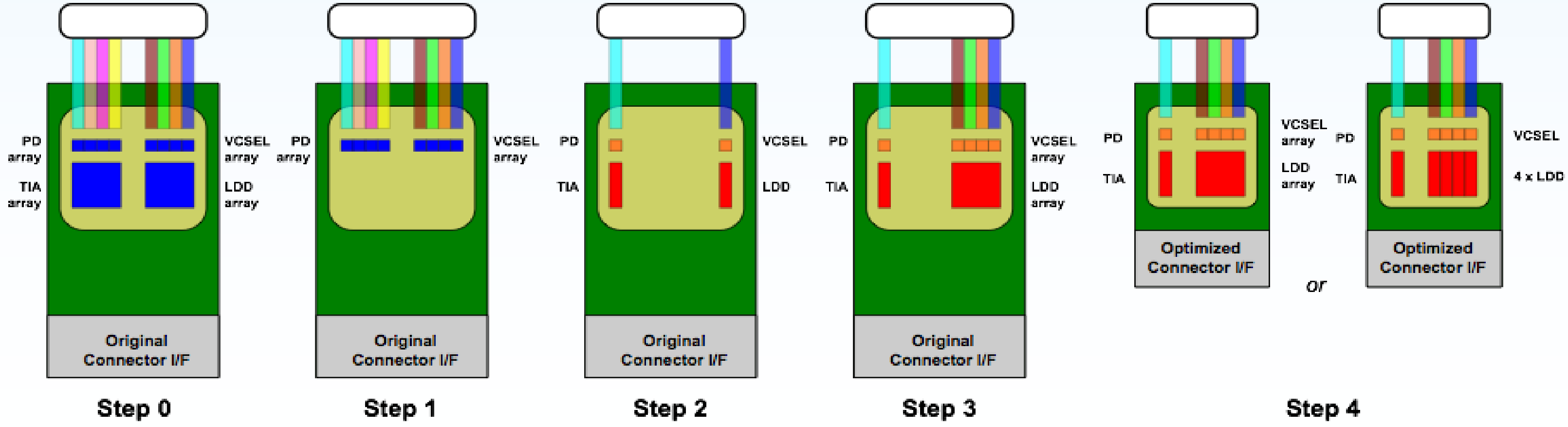
Versatile Link+

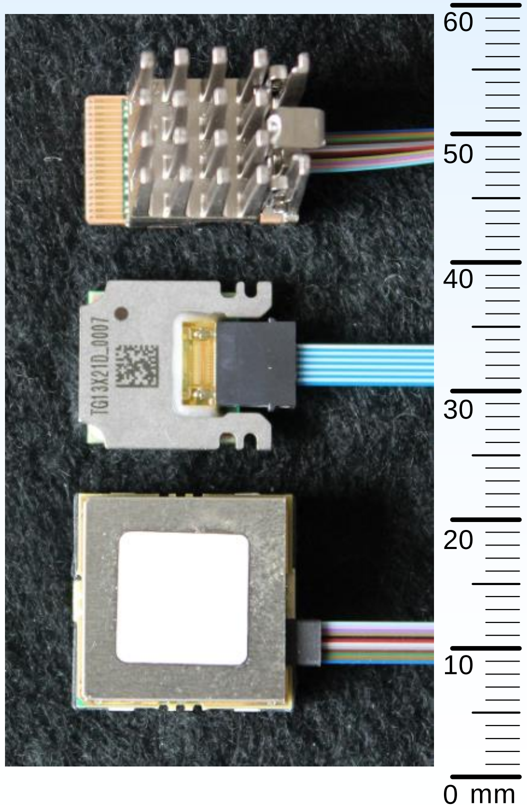
- The VL+ project investigated two options
- Option 1: Find companies that already manufacture optical transceivers and ask them to integrate CERN ASICs in their design
  - Existing know-how
  - Minimise customisation to retain cost benefit from volume production
  - Could be expensive
- Option 2: Design a custom transceiver based on suitable optical coupling block, and find an industrial partner that can manufacture the modules
  - More freedom in design choices
  - Potentially cheaper
  - Could be more difficult to find an industrial partner

Option 1

- Customisation carried out in steps
- Market survey
  - Commercial module “as is” (Step 0)
  - Samples without ASICs (Step 1)
  - CERN ASIC drop-ins to existing parts for evaluation (Step 2/3)
  - Qualified companies bid for development (Step 4)
- Price Enquiry for development and budgetary estimate for production cost
  - Two height variants: A (2.5mm), B (4mm)
- Final step would be a competitive tender for a production contract

Candidate commercial modules





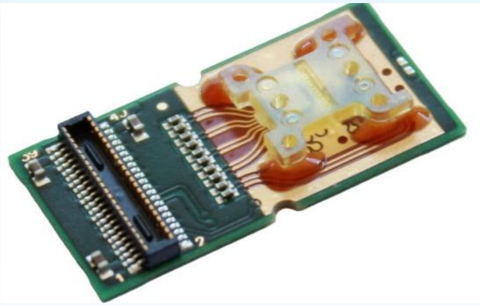
Option 2

- Several VTRx+ prototypes were built to find a suitable optical coupling block
- Prototypes were also used to evaluate electrical interface connectors and to test ASICs, VCSELs and photodiodes

Version 4

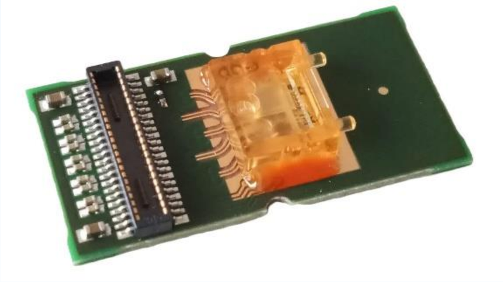
- End of 2017
- Low-profile optical coupling with 2+2 channels (TX/RX optimized)

Version 5



- Early 2018
- US Conec MOI with 12 channels

Version 7



- Early 2019
- Low-profile optical coupling with 8 identical channels

Production version

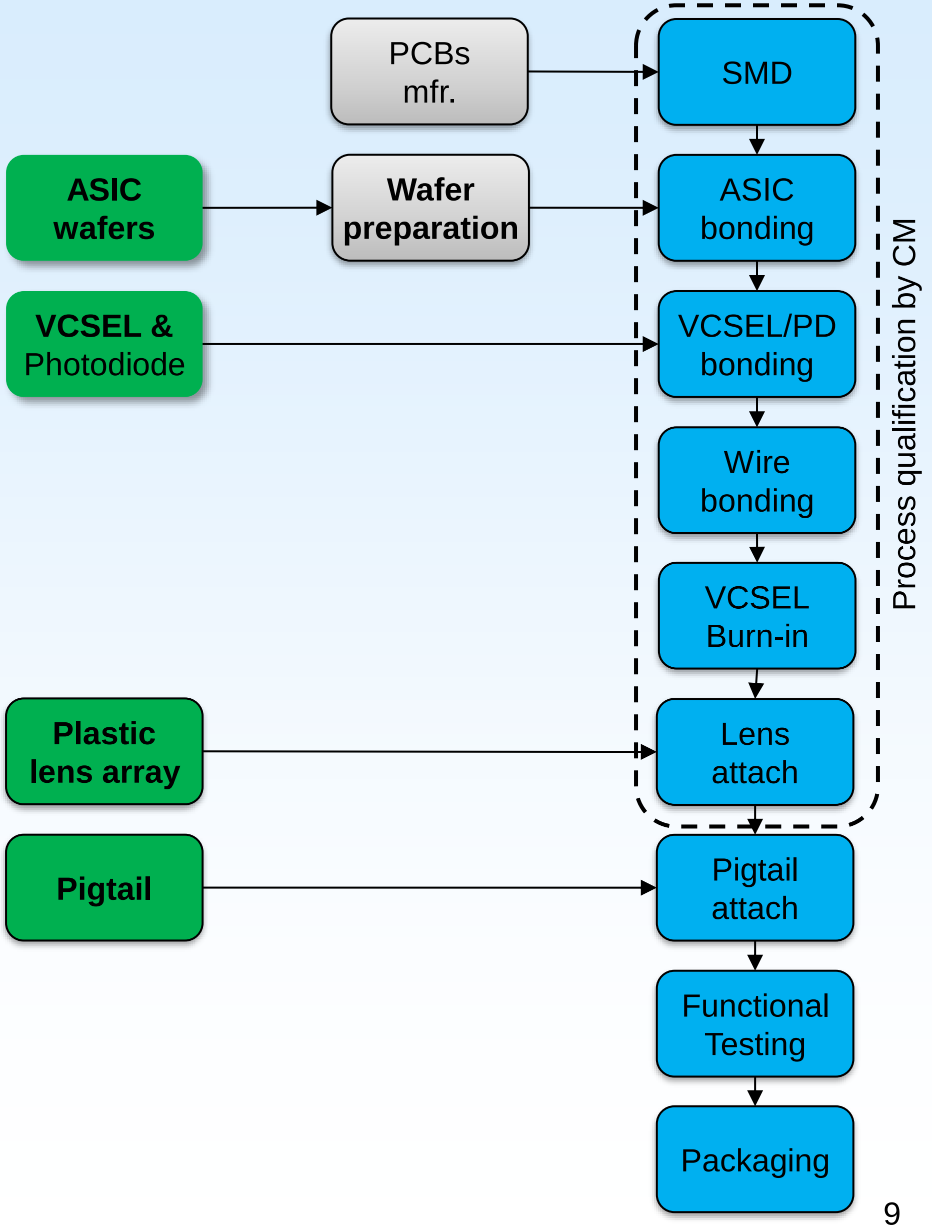
- Early 2020
- Low-profile optical coupling with 16 identical channels

Decision to go with option 2

- Option 1 and 2 developments were carried out in parallel (2017-2018)
- Budgetary estimates for manufacturing option 1 known by end of 2017
- In-house development was favoured as lowest overall cost, particularly in volume production
  - Option 1 as “safety net” in case of complete failure of in-house development
- Final decision to continue with in-house development was taken in 2019

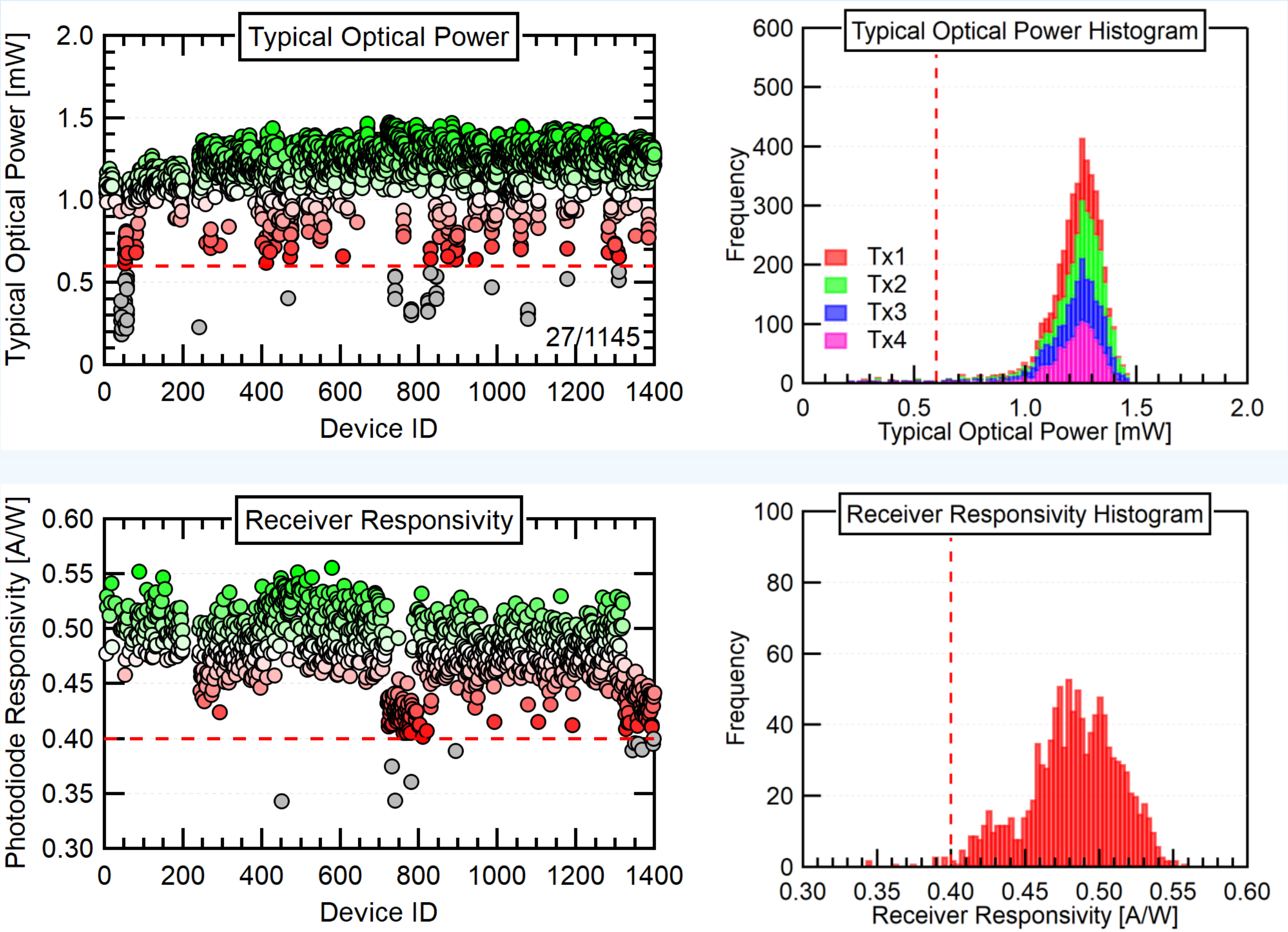
Idustrialisation and assembly process validation

- To move to volume production the process steps had to be validated
- Agreed with CM to use pre-series for validation and then set price for final volume production
- 1200 modules manufactured in smaller batches in 2020-2021
  - Some modules have been given to users
- Production test systems were developed by CERN
  - Pre/Post burn-in test
  - Burn-in monitoring
  - Functional test
- Manufacturing contract preparation
- Contract signatures by end of 2021
- Aimed at starting production in 2022



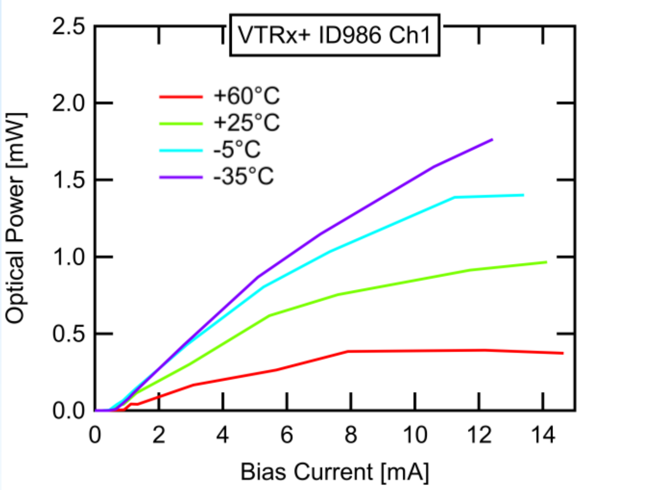
Pre-series performance

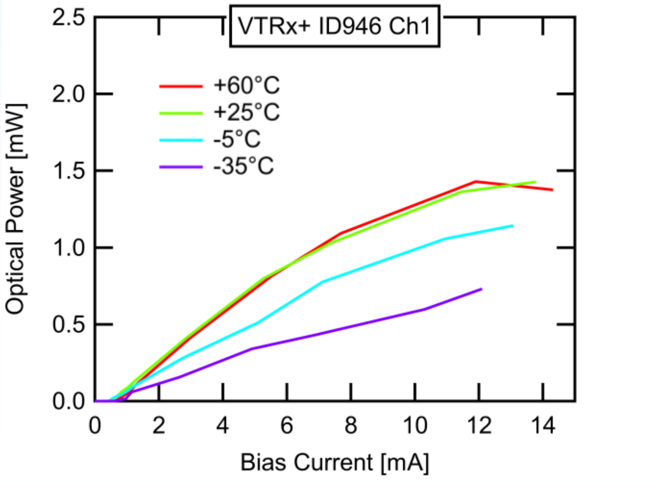
- Room-temperature functional tests show distribution tails



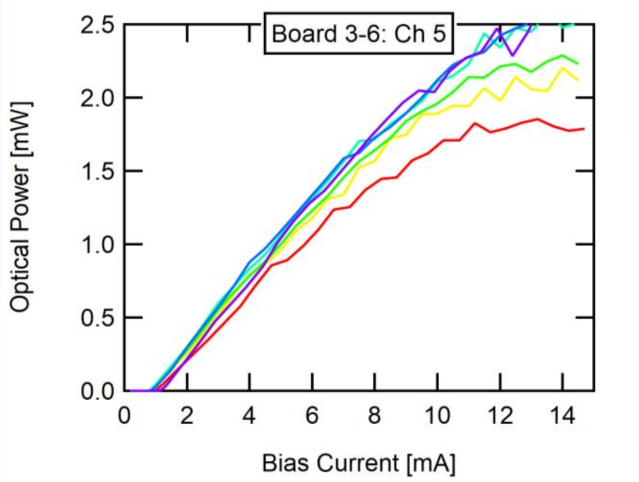
Pre-series performance

- Modules present significant loss of performance at ends of operating temperature range

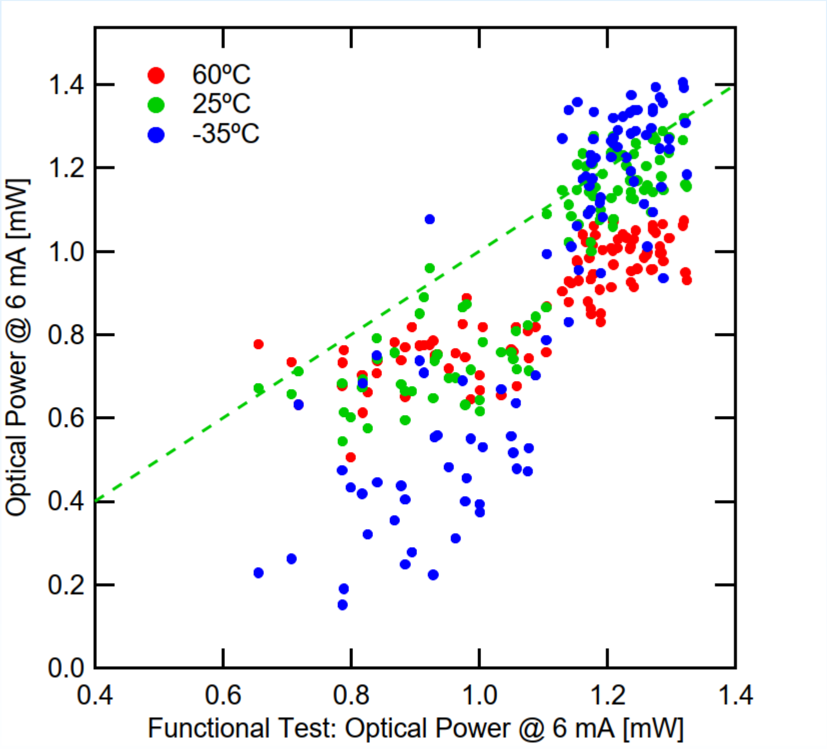




Expected VCSEL behavior:



Thermal rollover happens when the bias current causes self-heating, which in turn reduces the efficiency. This rollover happens at lower bias currents when ambient temperature is higher. Therefore, lower output power is expected in warm, but this penalty occurs significantly only with high bias currents.



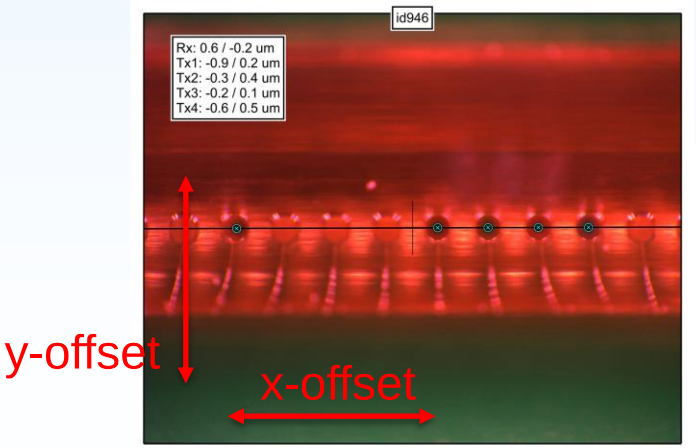
Pre-series outcome

- CERN decided to postpone the production and start root cause analysis
- Checking the free-issued components
  - Pigtail
  - Laser driver
  - VCSEL
- Verifying optical alignment accuracy
  - VCSEL – Photodiode
  - Lens – VCSEL/Photodiode
- Optimise assembly process

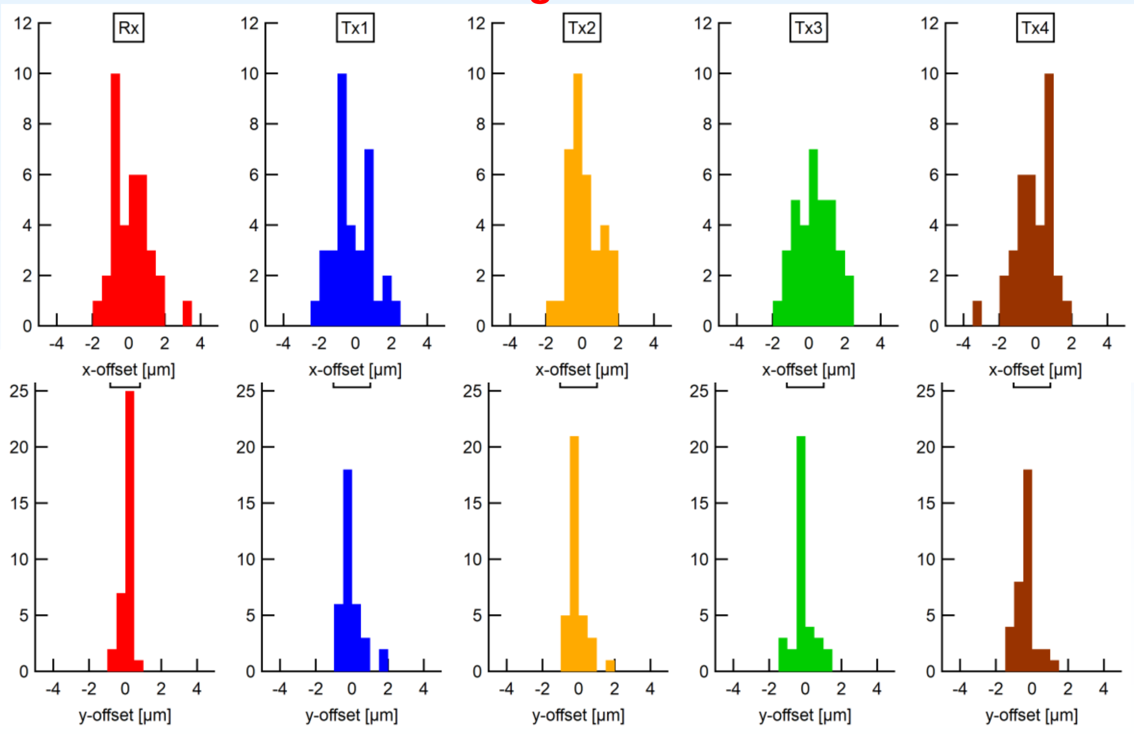
Free-issued components

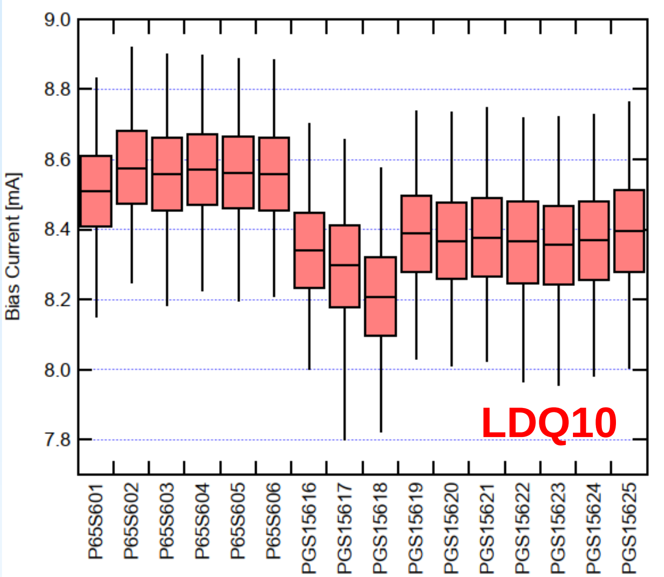
Versatile Link+

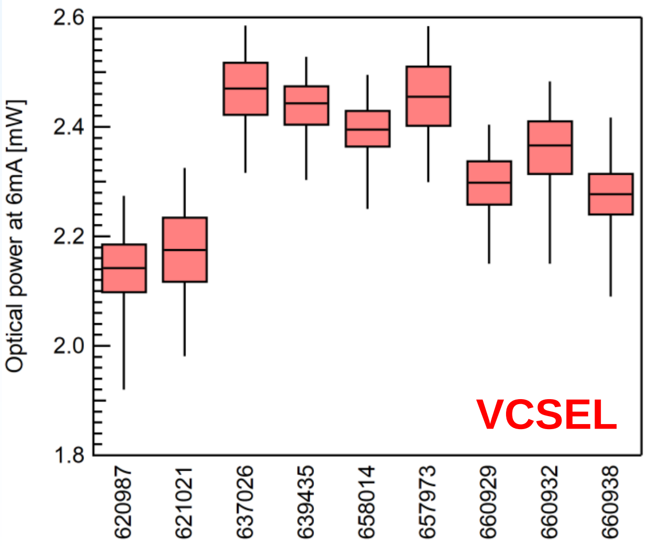
- LDQ10 and VCSEL wafer test data show tight distributions with some wafer-to-wafer variation
- Pigtail samples were inspected, and the results are within ±2 um
- No evidence found for tail coming from components



Pigtails

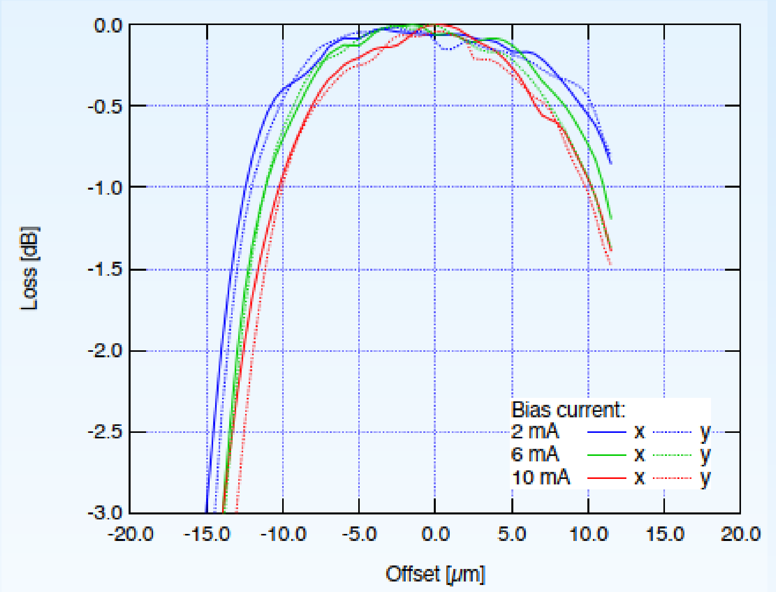


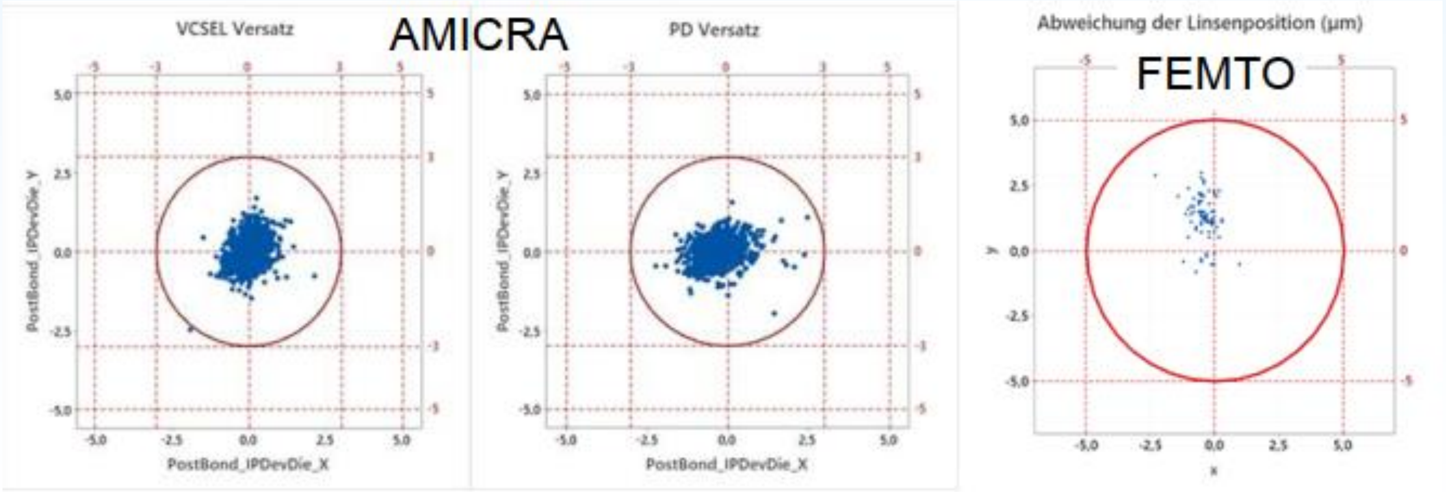


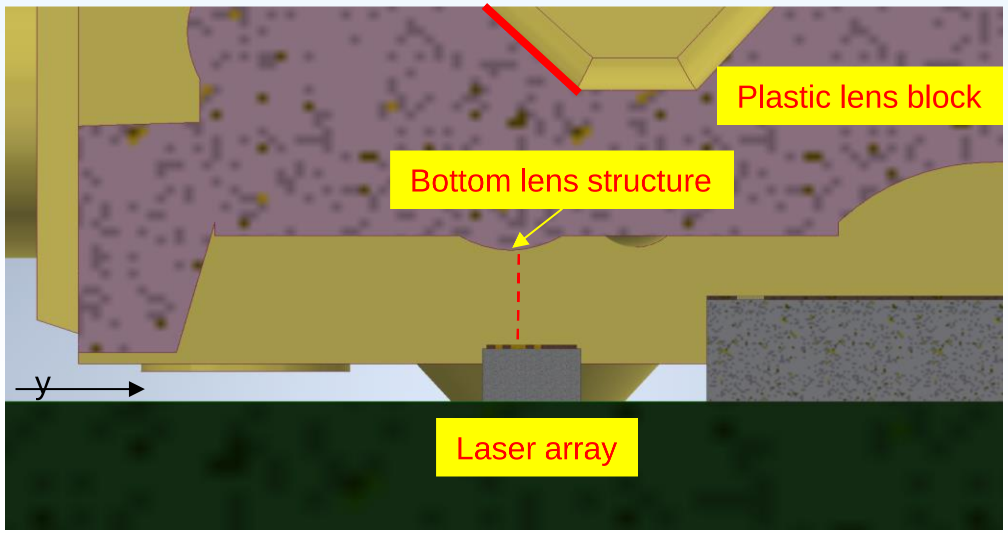


Placement accuracy

- The coupling loss depends strongly on the placement accuracy
  - ±5µm placement accuracy specification
- Good alignment will provide margin for movements caused by temperature due to CTE mismatch
- Manufacturer placement data shows perfect alignment
  - How to verify/calibrate the placement process?
- Measuring the post-placement accuracy is difficult



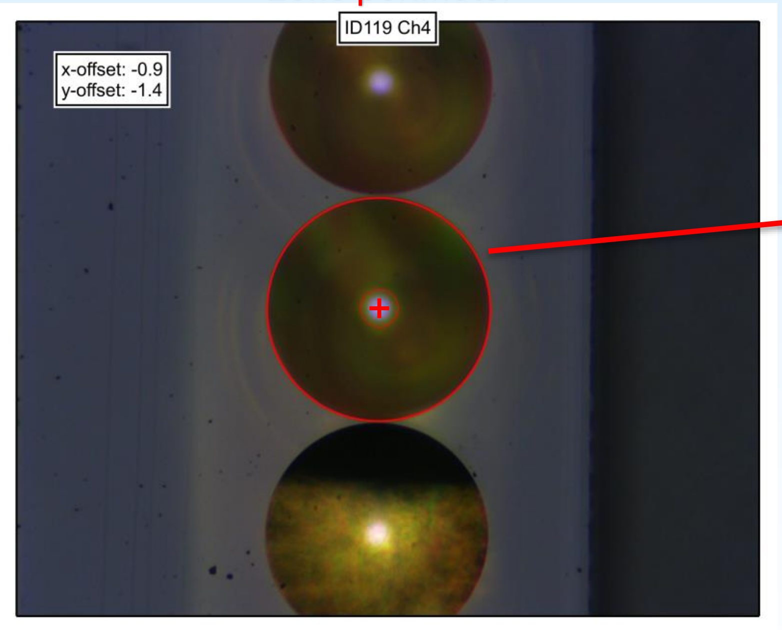




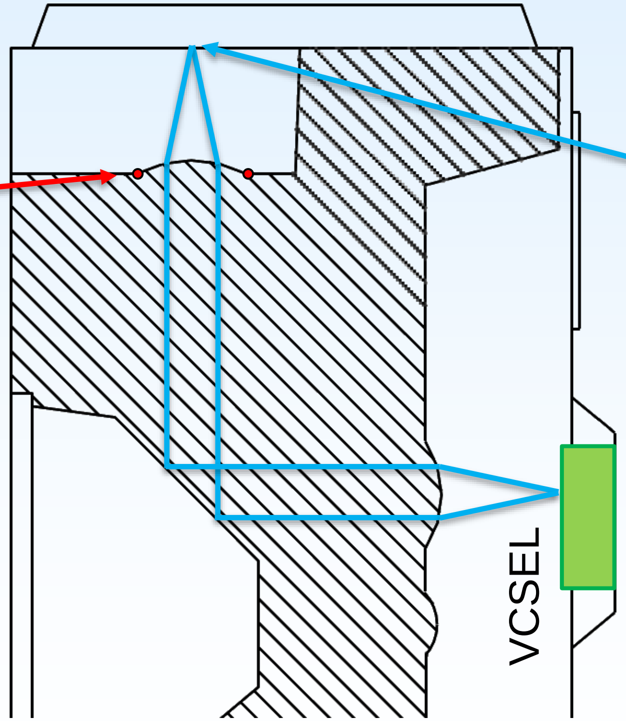
Visual inspection

- CERN developed a non-destructive test method for checking the placement accuracy
- Imaging concept based on the idea of following the light path through the lens

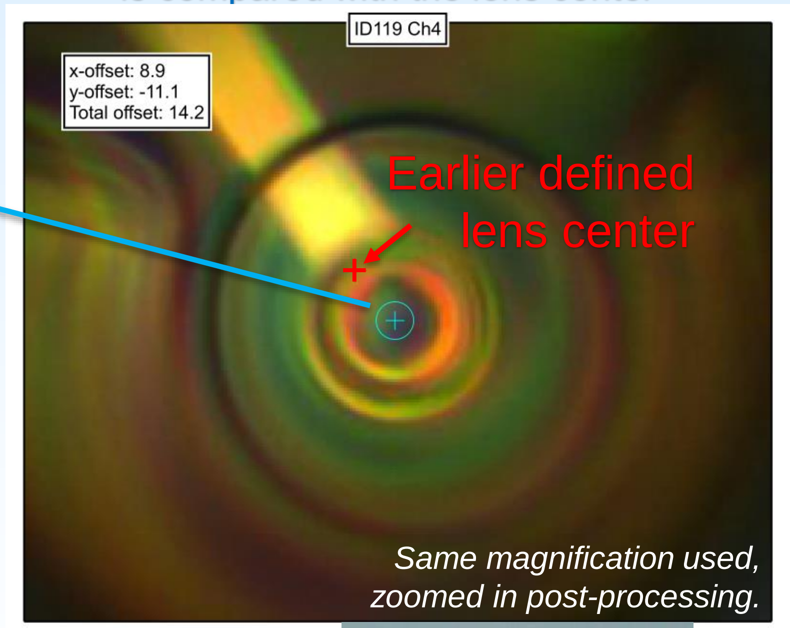
Lens perimeter

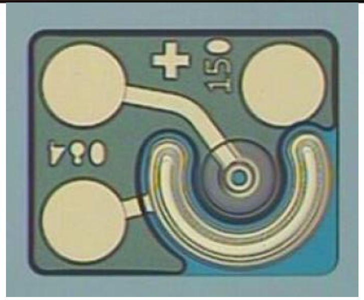


Focus on the image of the VCSEL active area



The center of the active area is compared with the lens center

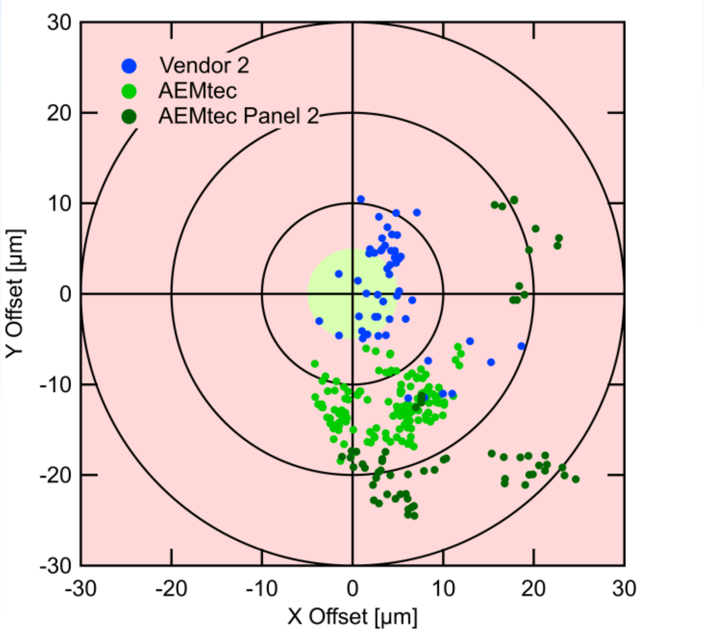


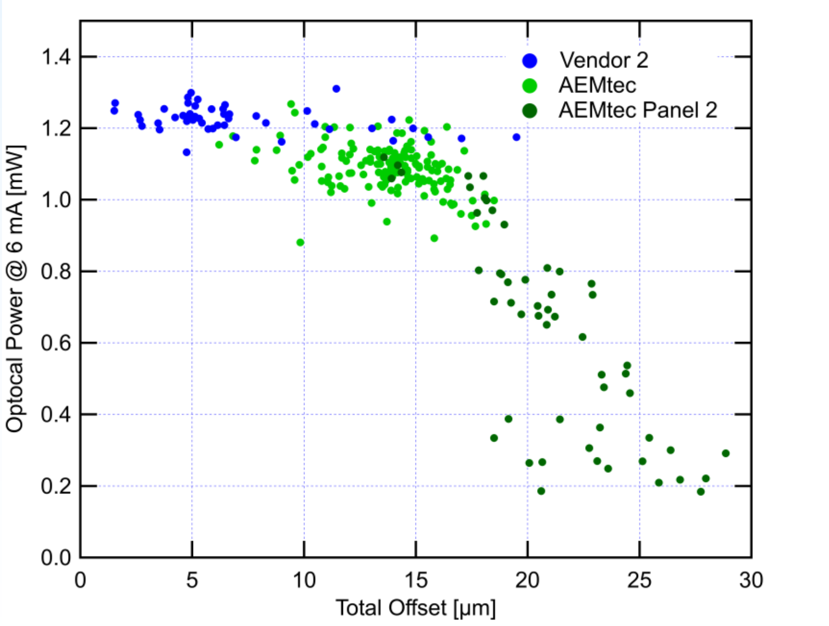


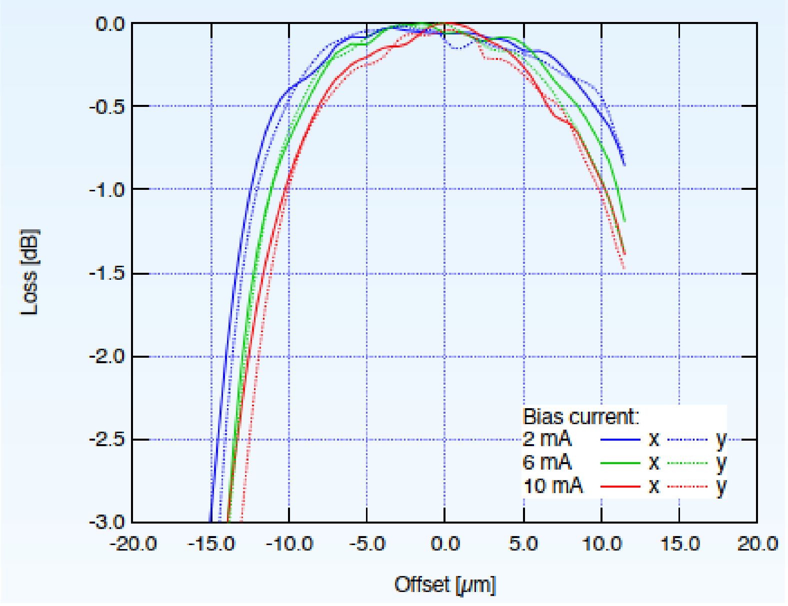
We are looking at the VCSEL active area with part of the anode and cathode contacts in the view.

Visual inspection

- Modules from different panels were inspected and the results were compared with the measured optical power
- Good match with the measured alignment tolerance of the lens array
- The absolute accuracy of the inspection method is few µm, but it provides good relative performance and can be used to detect excessive misalignments
- There is no good correlation with the alignment data provided by the placement machine

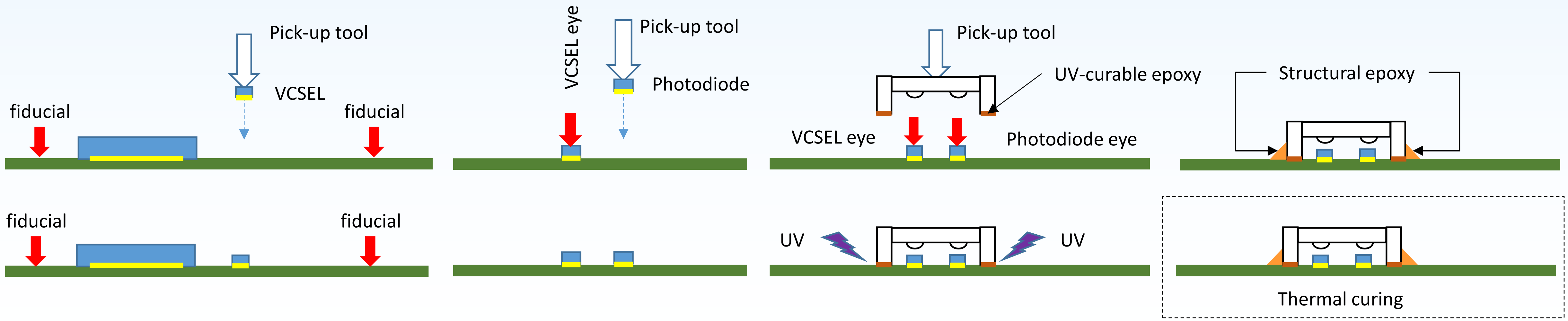






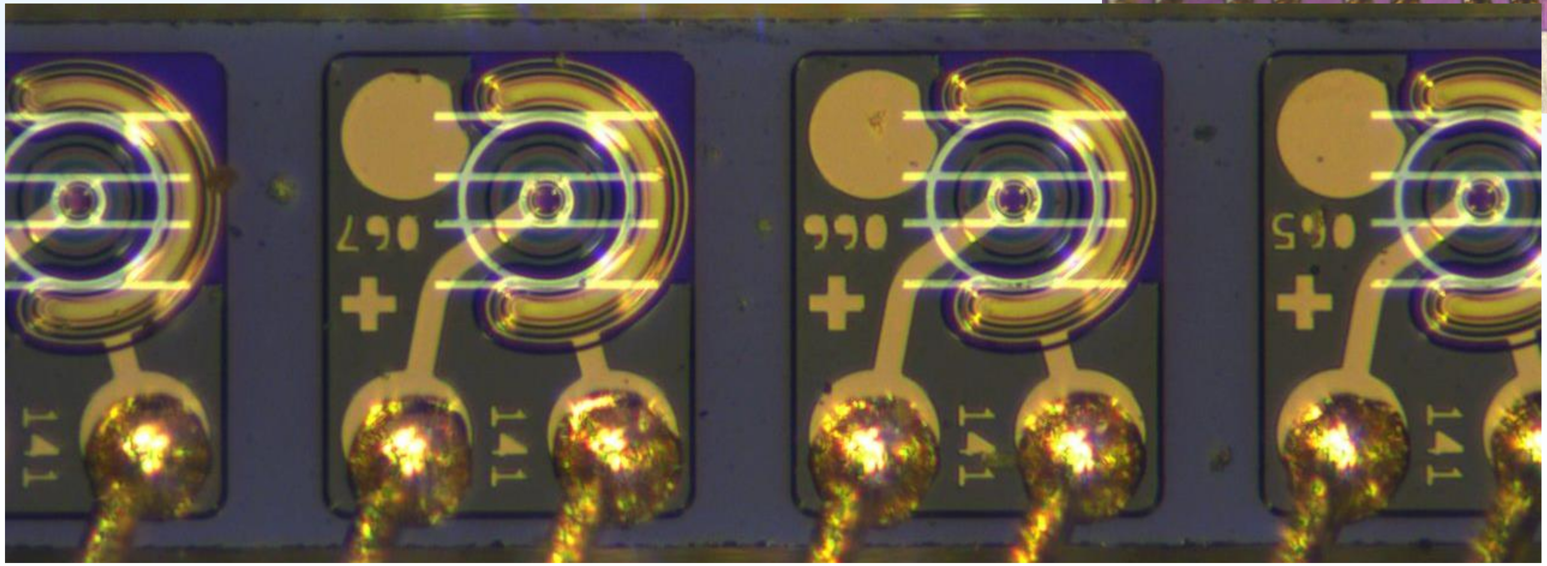
VTRx+ assembly steps

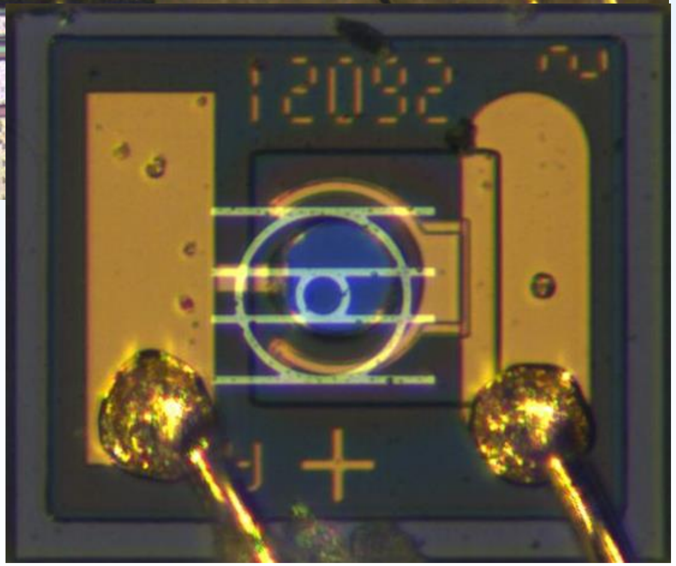
- ASICs and the VCSEL are placed using PCB fiducials
- Photodiode is placed using VCSEL eyes as reference
- Lens block is aligned using the VCSEL eyes as reference
- The lens is tacked using a UV-curable epoxy and cured in batch oven
- Structural epoxy is applied for improved strength and cured in batch oven
- Pigtail is attached as the last step before functional testing



VCSEL and photodiode placement accuracy

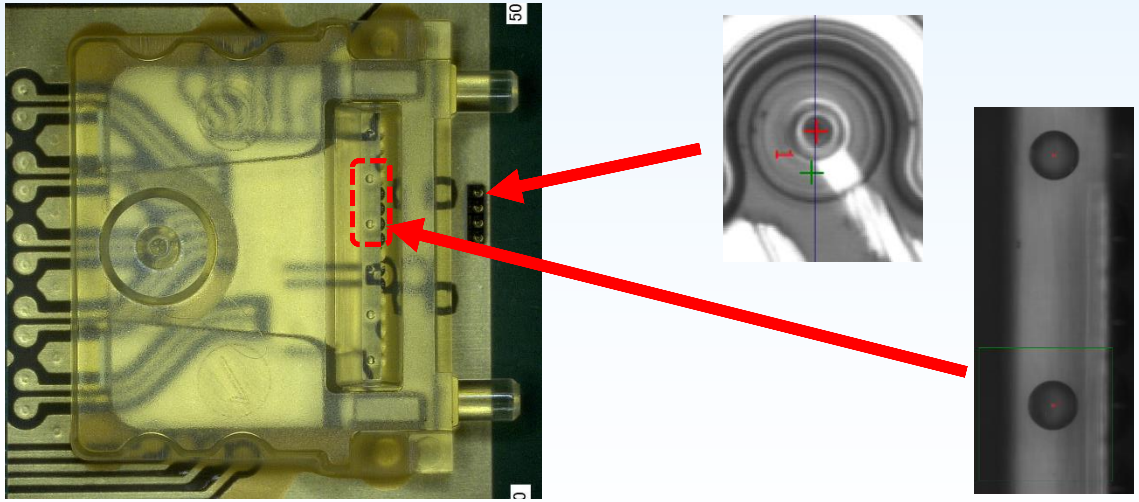
- The VCSEL/Photodiode used as reference for lens alignment; placement accuracy is important
- Incorrect machine calibration led to misalignment
  - Confirmed and fixed by manufacturer
- Process change: photodiode is not used as lens alignment reference
  - No performance hit due to larger active area





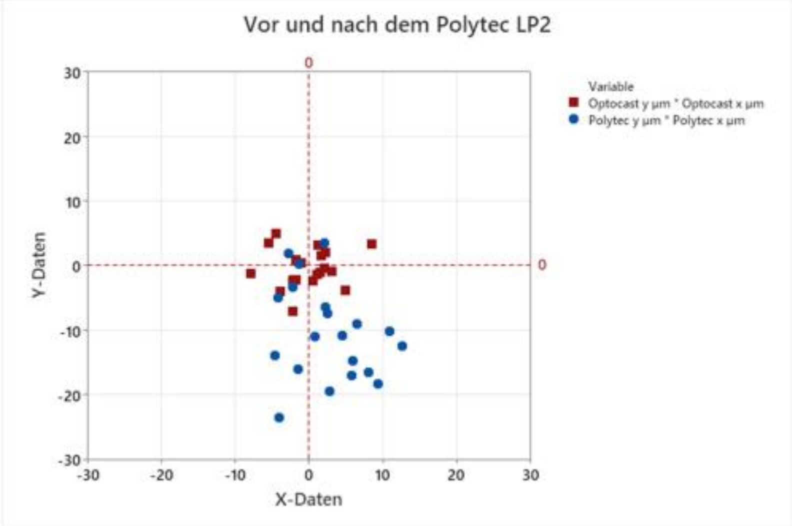
Lens placement accuracy

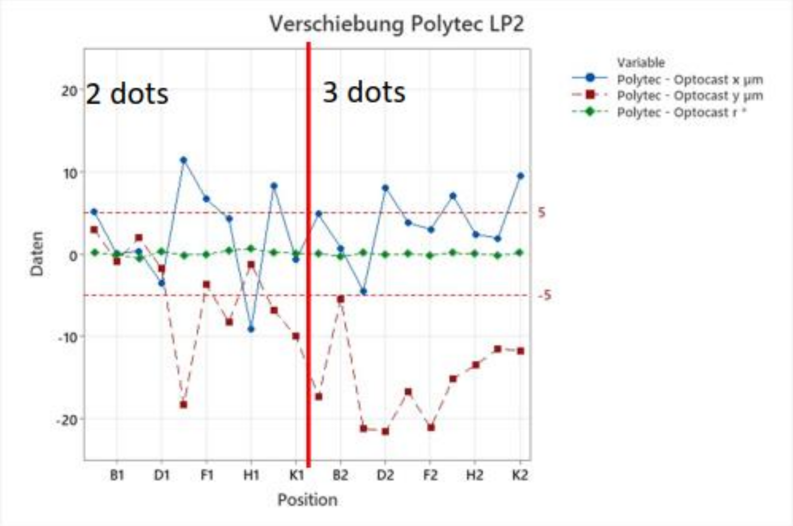
- Placement data provided by the machine suggested good alignment
- However, measured performance and visual inspection results did not confirm that
- What if the placement data is not reliable indicator of the final alignment accuracy
- CM assembled test panels using different gluing strategies
- VCSEL placed outside the lens block used as reference to measure the alignment accuracy

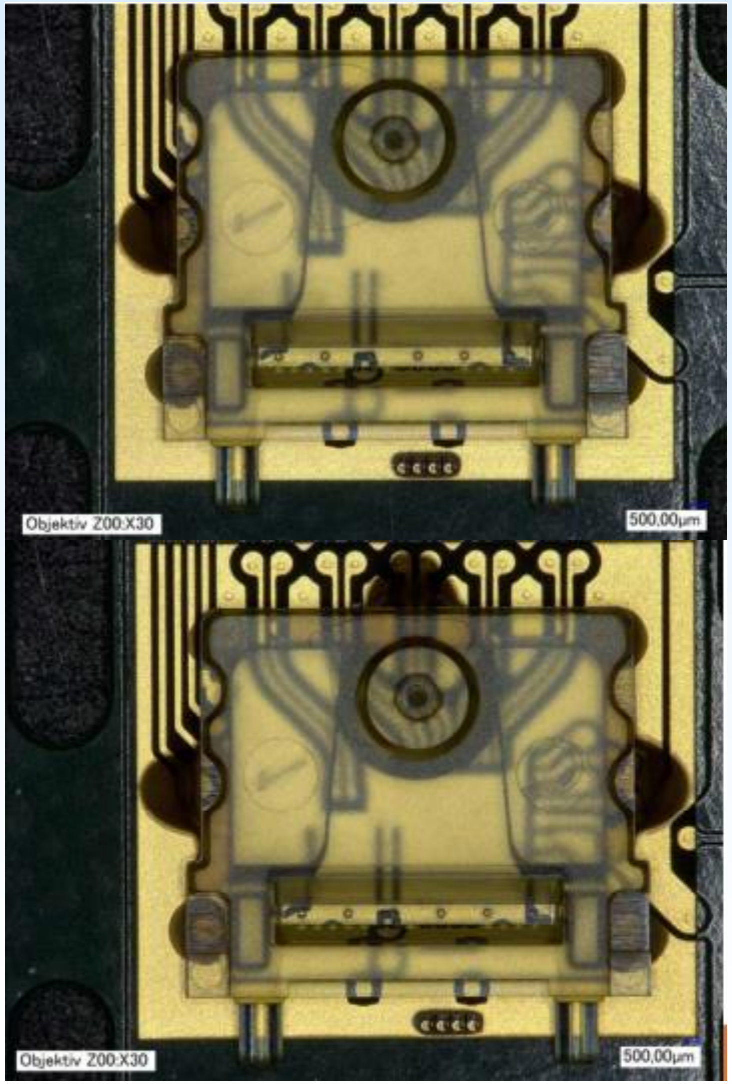


Lens placement accuracy

- UV-curable epoxy at corners and structural epoxy dots (2 or 3) along the edges
- Thermal curing 1h @ 80°C with 1h up/down ramp from/to RT
- Measurements show that lens block moves during adhesive curing
- Most of the samples are outside the ±5µm specification
  - Samples with 2 dots are slightly better



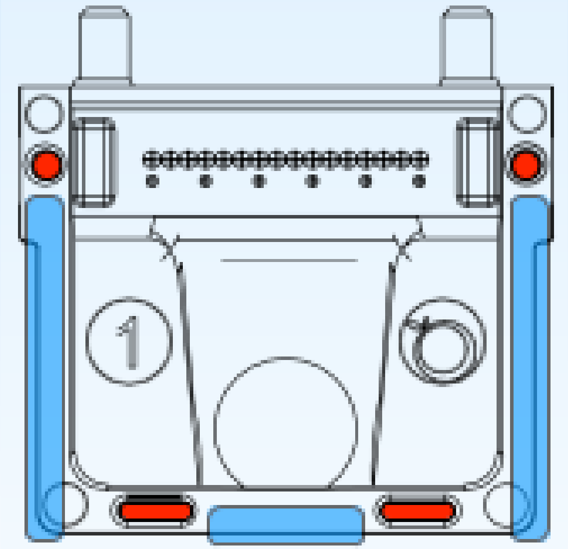




Process optimisation

Versatile Link+

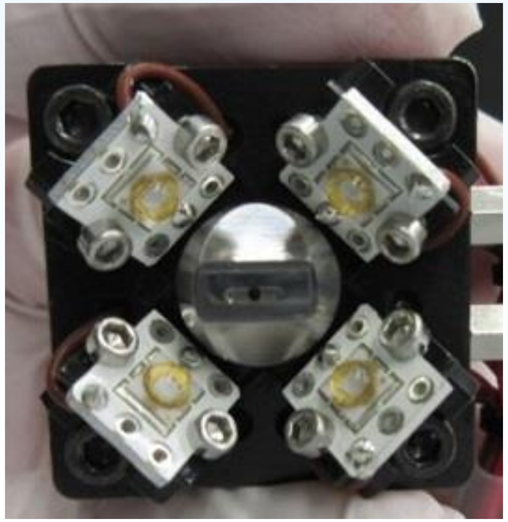
- Based on previous experience (VTRx ROSA) the root cause was suspected to be the first gluing step (UV-curing) of the plastic lens block
  - Insufficient UV curing may lead to movements during thermal curing
- CERN proposed the following changes
  - Adjust glue locations and epoxy quantity; keep-out zone around lens feet
  - Optimise UV parameters (power, wavelength, exposure time)
  - Eventually change epoxy type
- Verify the quality of the UV curing step by measuring the shear strength
  - Difficult to specify minimum shear strength (2.5, 5, 10kg ?)
  - Try to achieve the required shear strength using only one epoxy (no structural epoxy)
- Verify the alignment using the “best” curing parameters
  - Measure after UV-curing
  - Measure after thermal curing
- Qualify the process
  - Temperature cycling and damp-heat test
  - Re-measure the alignment

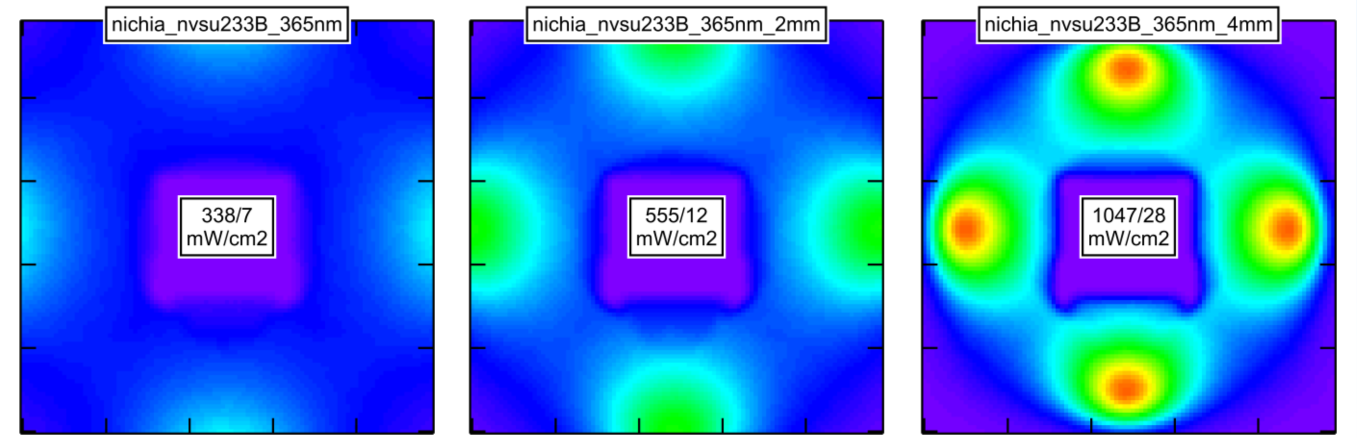


Dispensing path
Keep-out zone

UV source optimisation

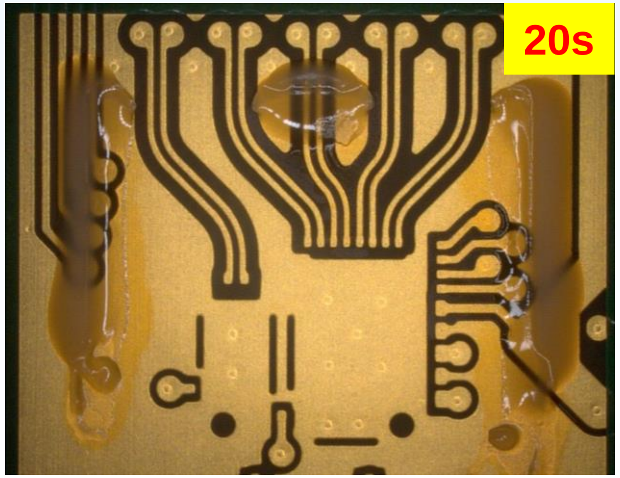
- CERN carried out output power/irradiance pattern simulations to find the best UV source
  - Good agreement with AEMtecs' measurements
- Output power is lower than UV adhesive datasheet recommendation
  - Tool optimisation required to achieve higher power density
- Longer wavelength sources (>410nm) are not working
  - Wavelength conversion system is inefficient
- Curing under the lens is not needed (or possible)
  - Thermal curing step is necessary to complete the polymerisation

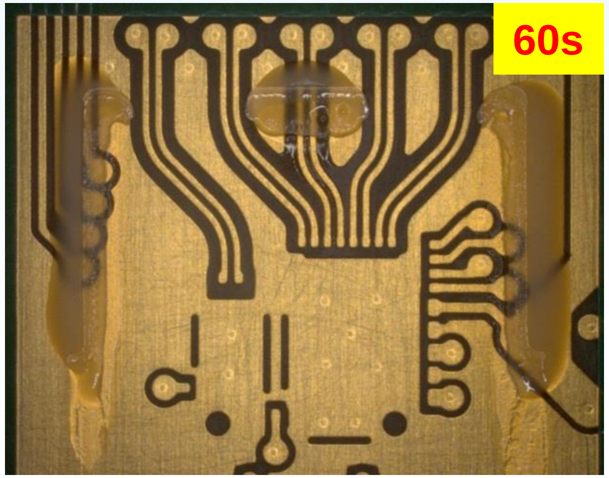


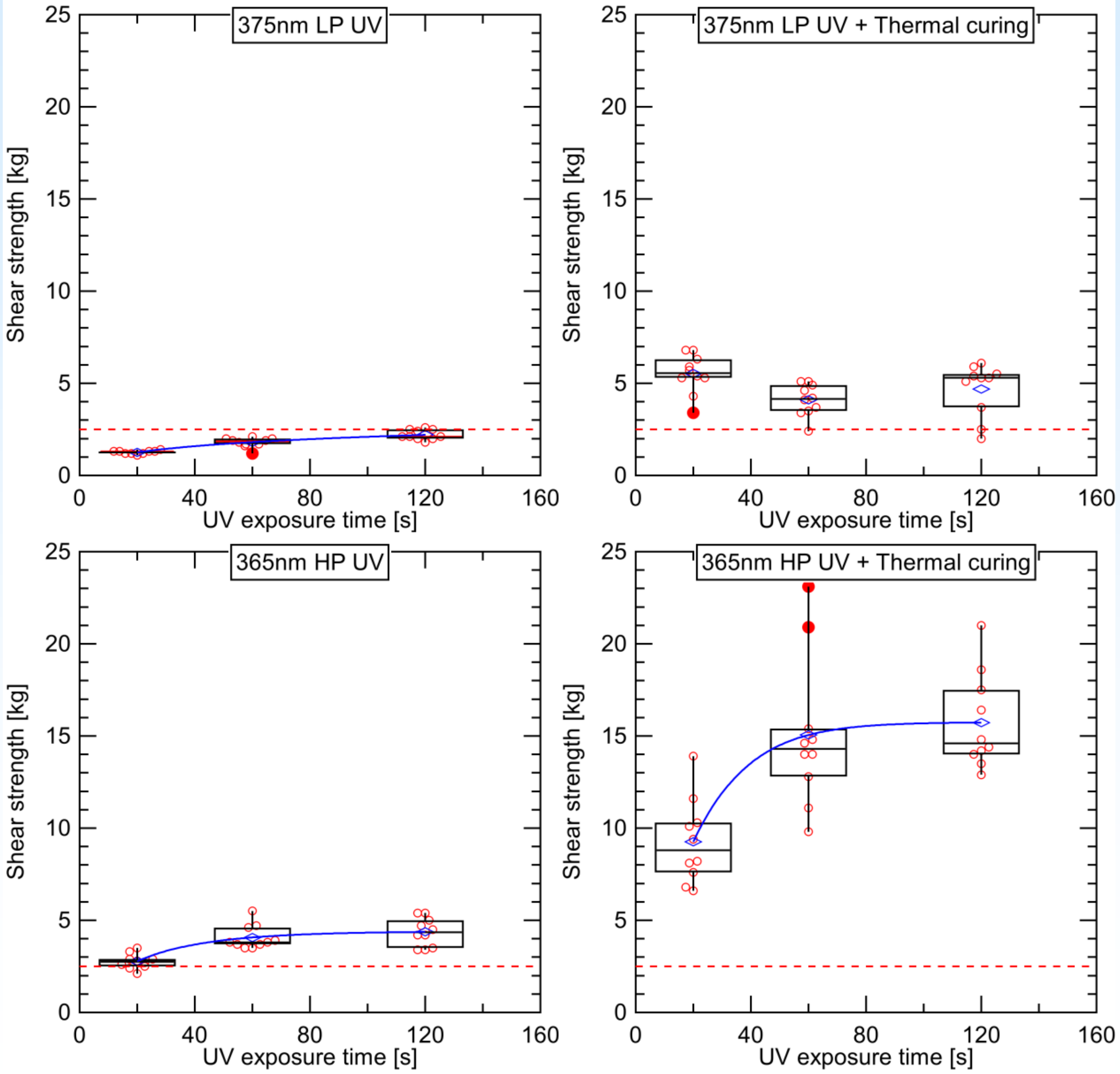


UV exposure time and shear strength

- Using Optocast 3410-VM epoxy and different UV sources
  - 375nm low-power LEDs
  - 365nm high-power LEDs
  - 450nm LEDs (epoxy did not cure properly)
- Shear strength significantly improves when using the high-power UV source
  - Thermal curing increases bonding strength
- Lens block material is very hard to bond to

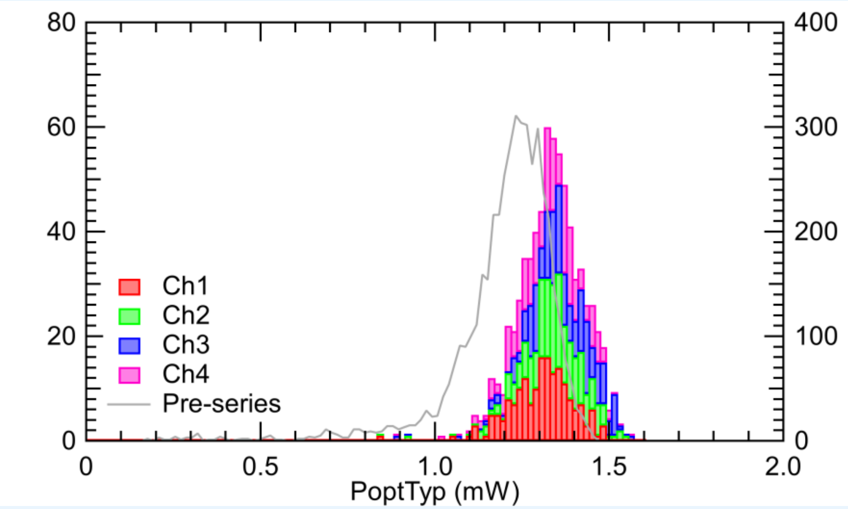


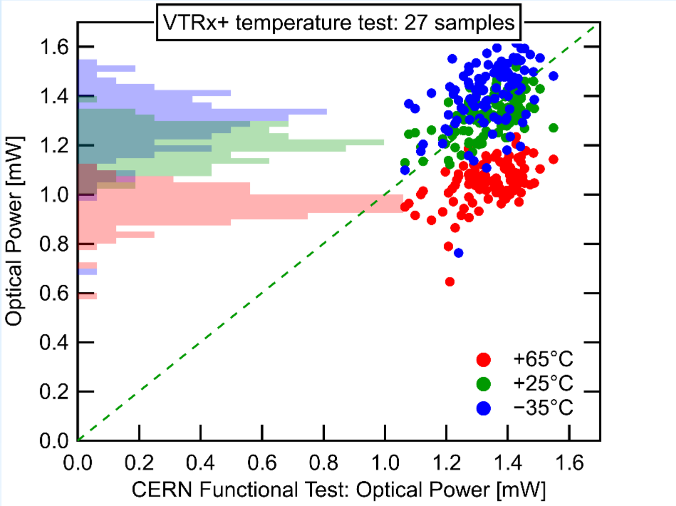




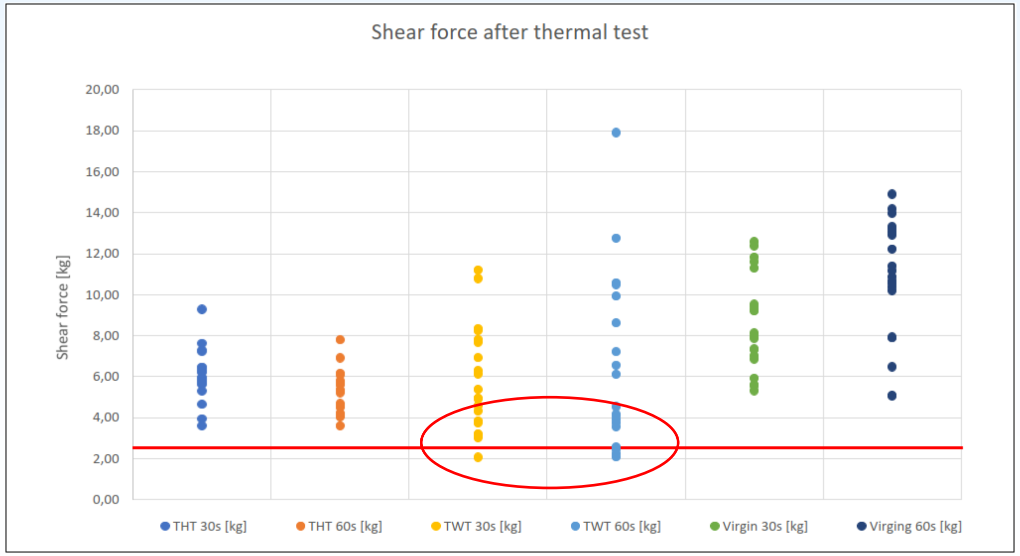
Process validation

- Improved optical coupling at room temperature
- Operating temperature tests confirm better coupling



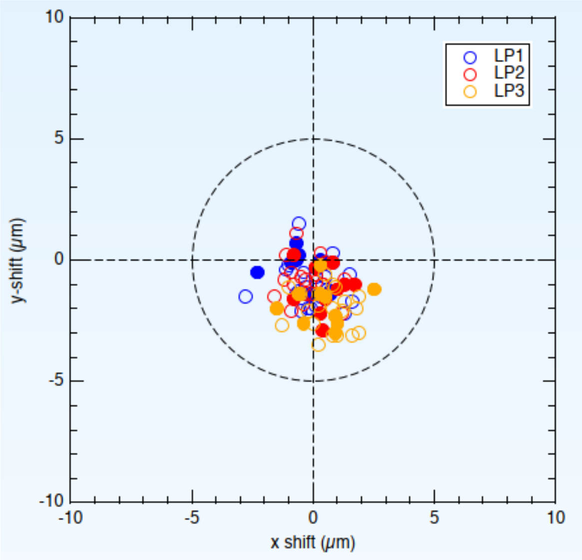


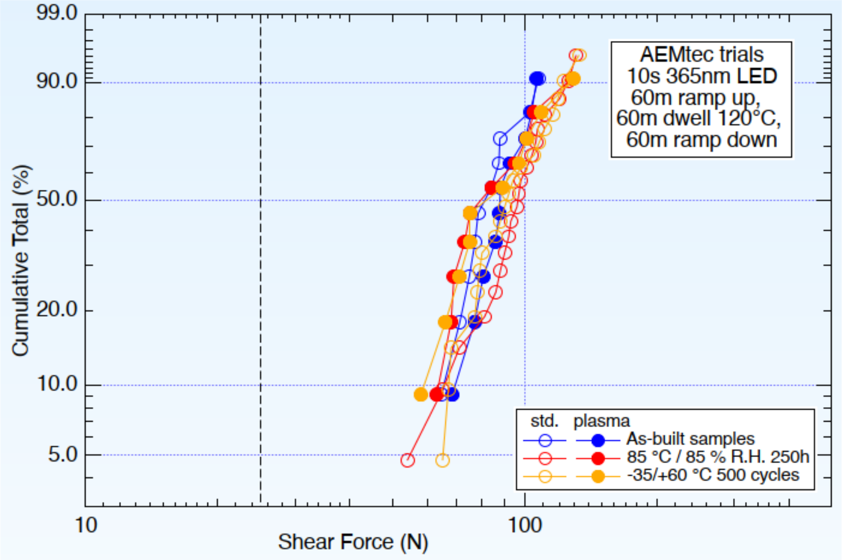
- Process qualification
  - THT (85 C/ 85%, 250hr)
  - TWT (-30C/+60C, 500 cycles, 2 cycles/hr)
- Shear strength too low after temperature cycling



Changing the epoxy

- Based on lens vendor’s recommendations CERN proposed a new dual-cure epoxy
  - Sunbond SB 8410-V1
  - Better adhesion to ULTEM
- CM measured the alignment precision (!) using a dummy VCSEL
  - Shift is less than 5µm
- Gluing process was successfully qualified
  - Shear strength higher than 25N after damp-heat and temperature cycle tests

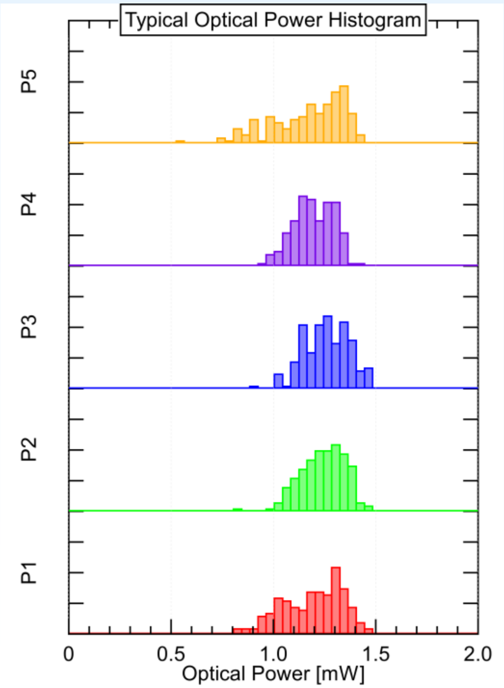




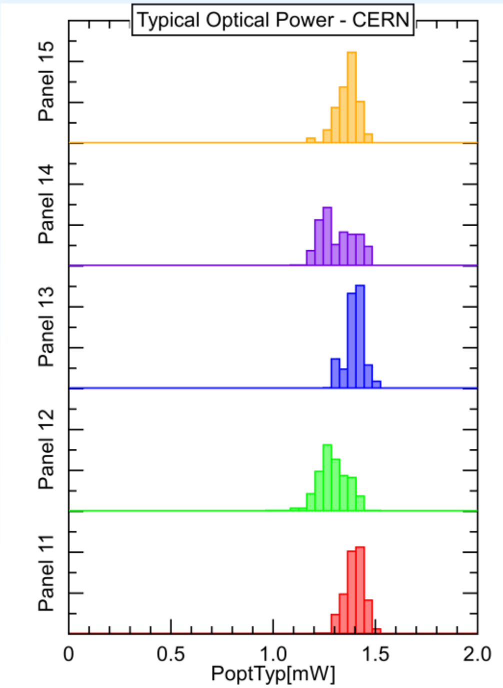
Ready to launch the production

- CM assembled 2 batches using the qualified assembly process
- Found some low-power outliers in the first batch
- CERN proposed to use only VCSEL eyes for alignment in the second batch
- Second batch had better coupling performance confirmed also by temperature tests

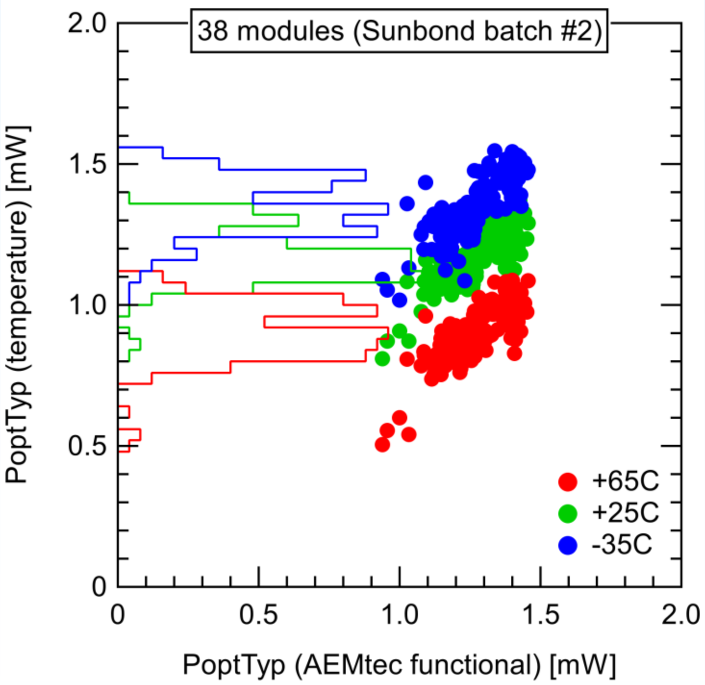
Batch 1



Batch 2

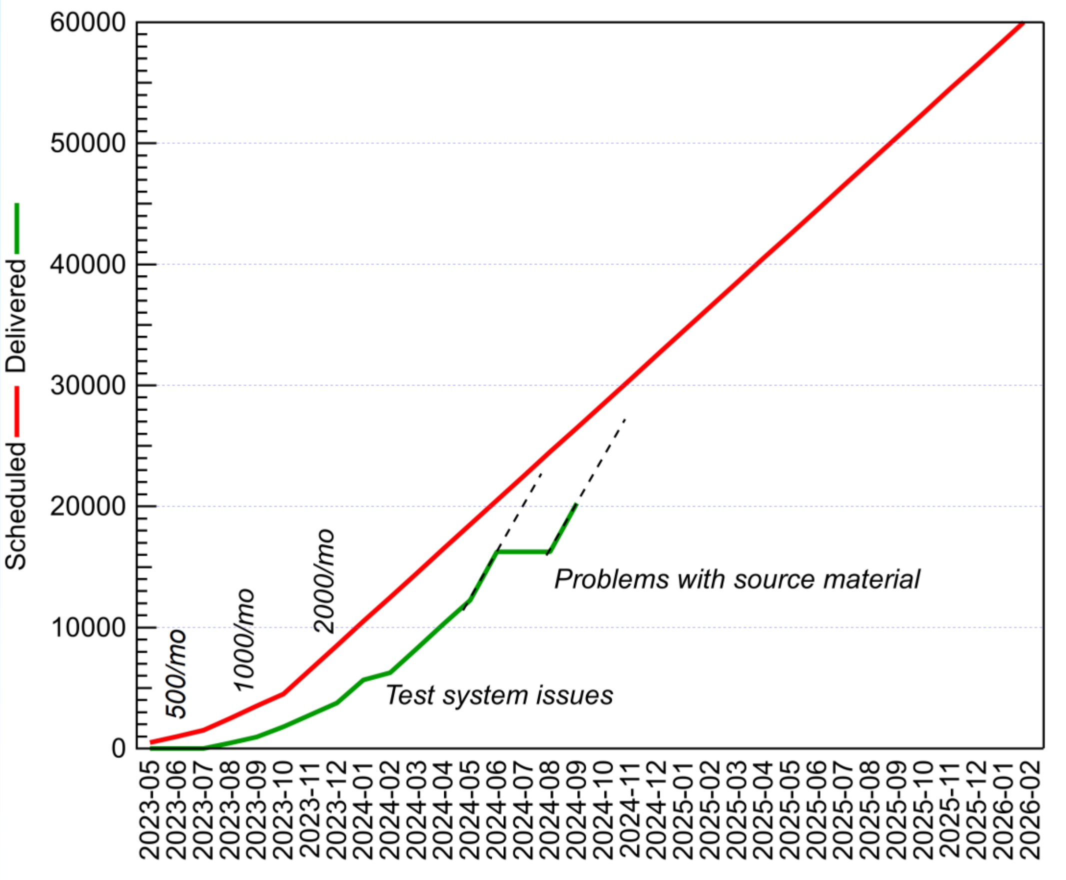


Batch 2

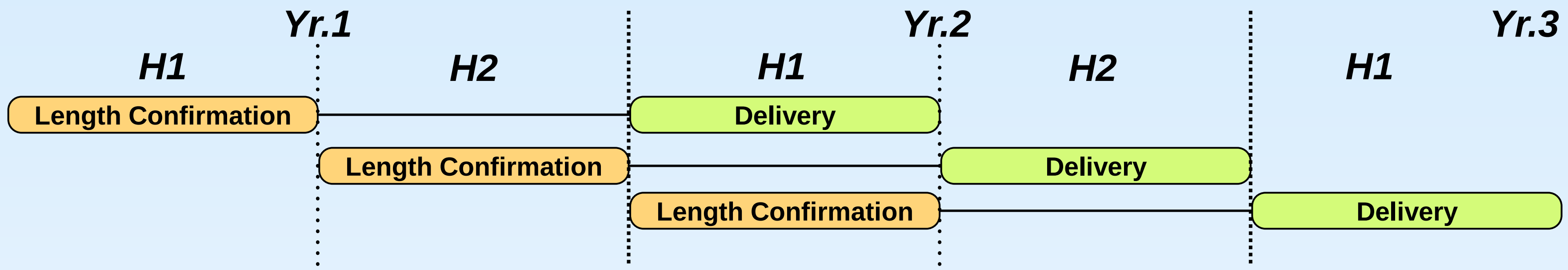


Production ramp-up

- Ramping-up the production presented its own challenges
- CERN's expectations had to be aligned to CM's mfr. culture
  - Order N => receive M<N, strict lot concept at CM
  - Yield (sharing the cost and responsibility)
- Production related issues
  - Batch 1 non-conformity (witness VCSEL)
  - Test system adjustment
  - Source material issues

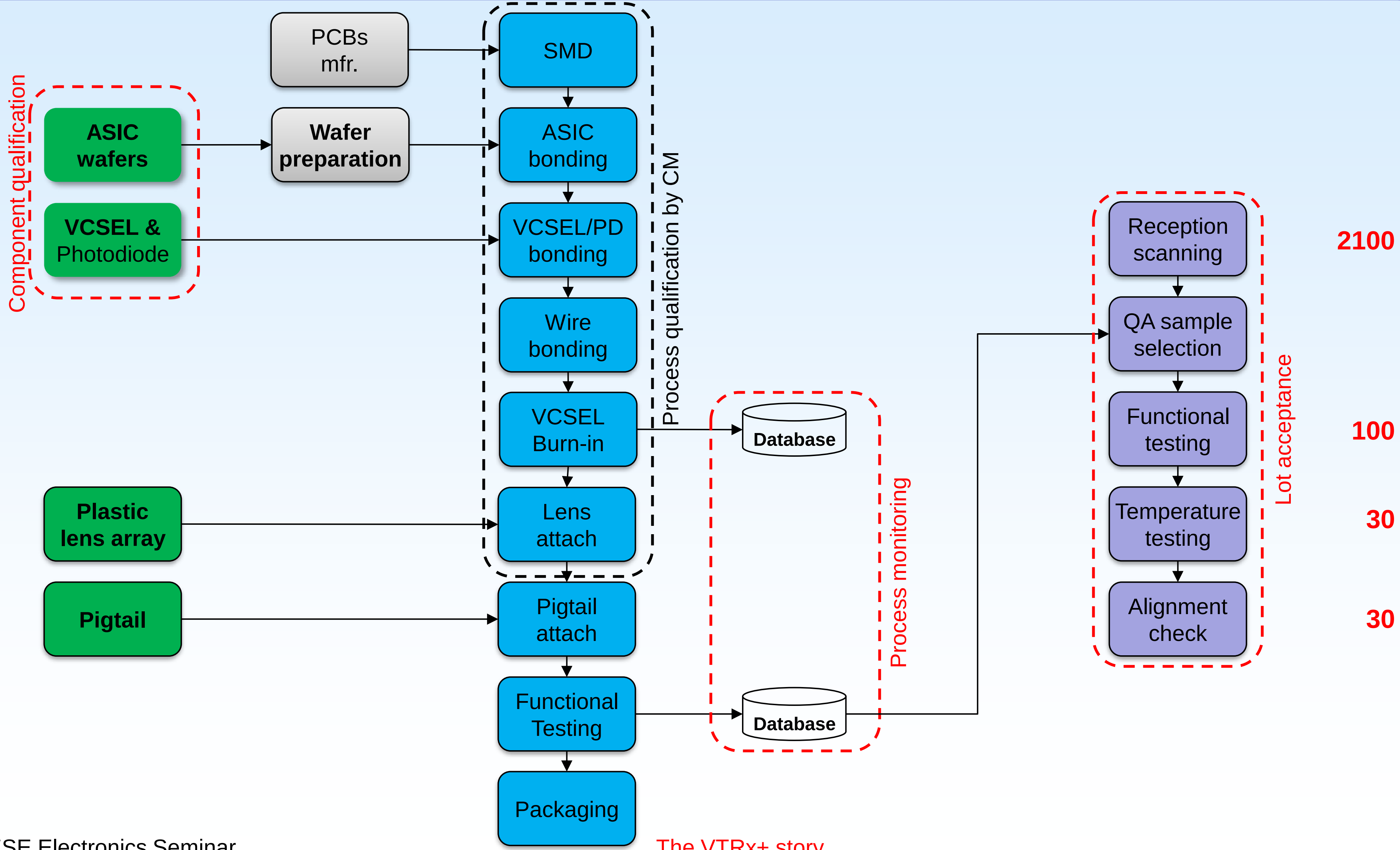


Pigtail ordering



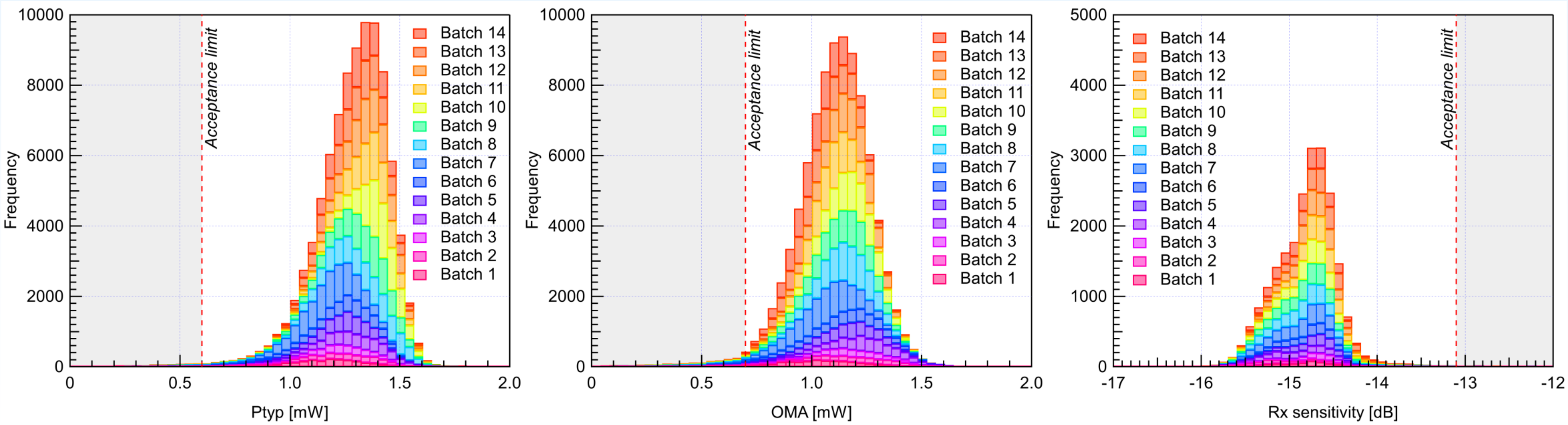
- Rolling pigtail ordering schedule
  - Collect requests and prepare orders to optimise production capacity
- Lately justified by long lead times
- Logistics overhead
  - ~14k pigtails/6 month
  - Acceptance, storage, transport
  - Towers of Hanoi

Assembly and QA



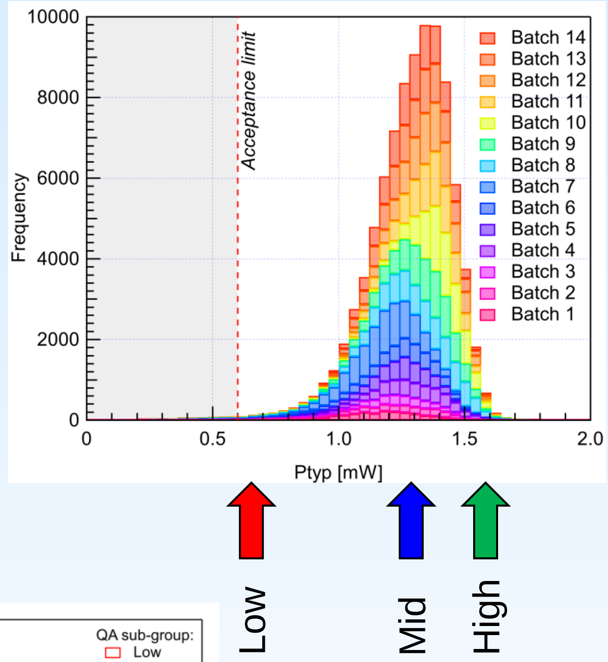
Production test results

- Overall manufacturing yield is ~90%
  - The functional test yield stabilised around 95%
- Acceptance limits are tighter than system specifications
  - Provides additional margin

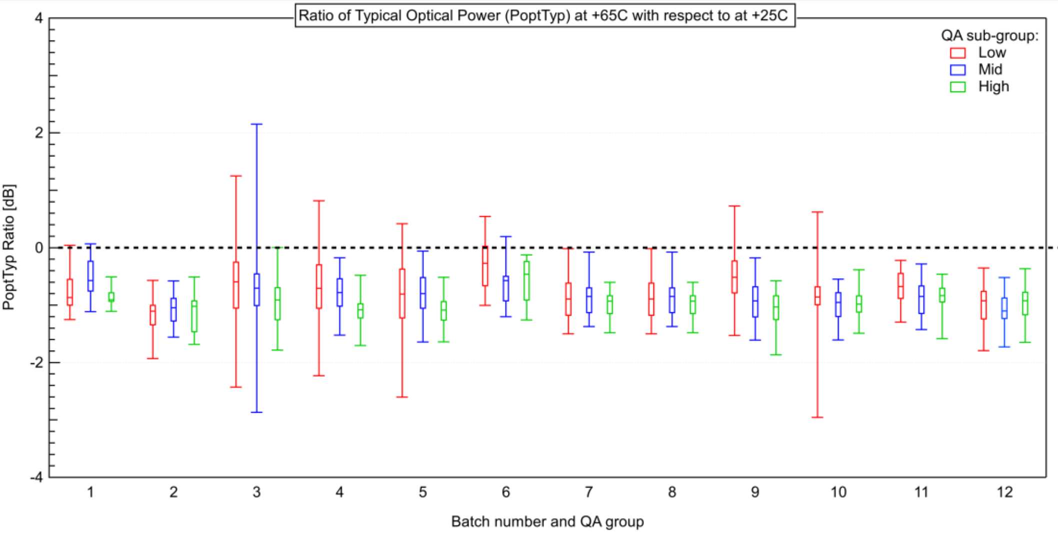


Operating temperature tests

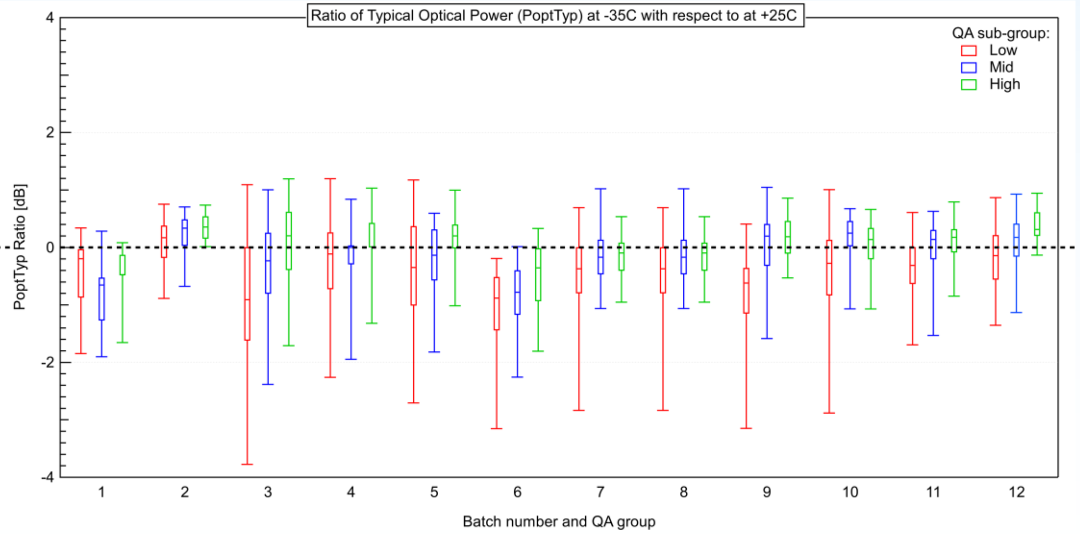
- Directed module selection covering the tails as well as the middle portion of the distribution
- Selection criteria defined based on typical optical power
  - Corresponds to (approximately)
    - lowest 10%
    - mid 10%
    - highest 10%



Hot



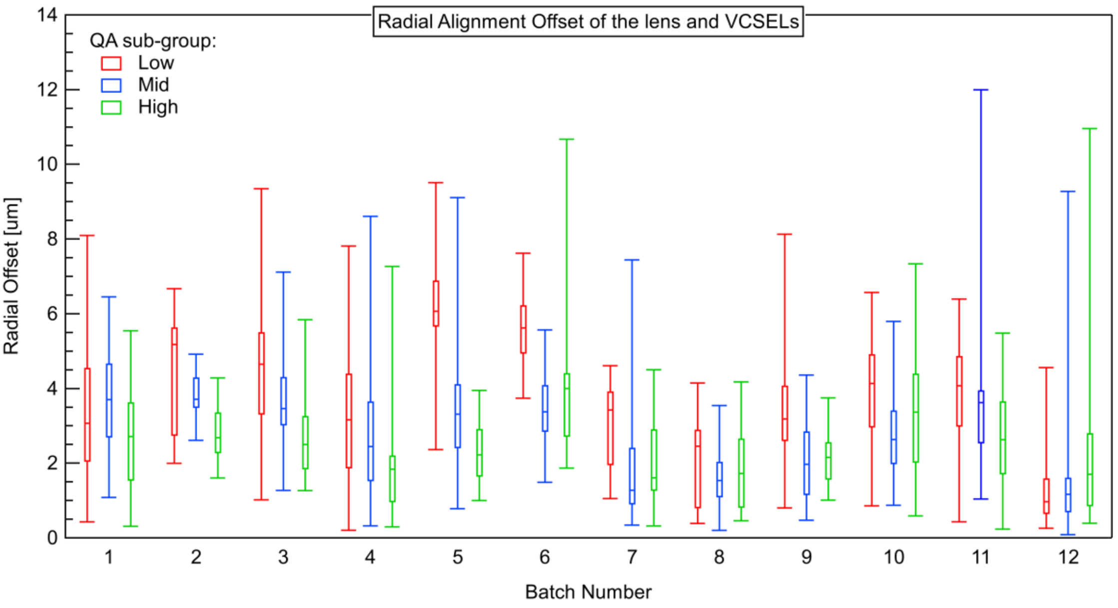
Cold

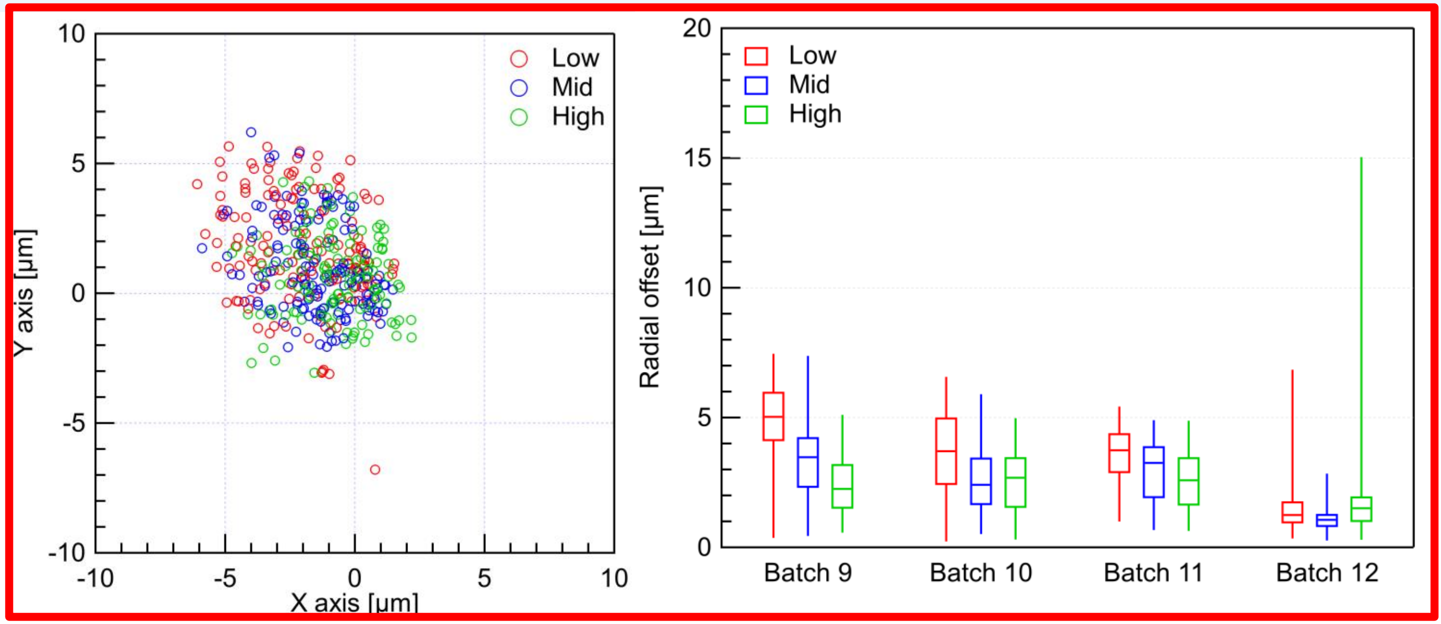


Alignment verification

- Alignment check implemented as part of the lot acceptance procedure
  - Method proposed by CERN based on image recognition
  - Pictures are taken without removing the pigtail
- Absolute accuracy (0,0 location) depends on lens features
  - Fiducial location vs lens centre
- Image recognition is not perfect, hence the outliers

Data from last four batches processed with improved software





Lessons learnt

- There is a whole world between “building prototypes” and “manufacturing high quality products”
  - It is challenging to select/rank companies based on prototyping experience
  - Company may (will) change attitude when switching to production mode
- Understanding the process steps is a key to success
  - Need to invest time and money
- How to adapt CERN’s procurement process to such projects?
  - Specification of object vs specification of process
  - Finding many vs finding none
  - Selecting the “best” vs selecting the “cheapest”
- Building and maintaining production test systems should not be underestimated
  - Experimental test and measurement vs operator-proof 100%-uptime production tester
- In industrial terms 50k parts is a pre-series

Conclusion

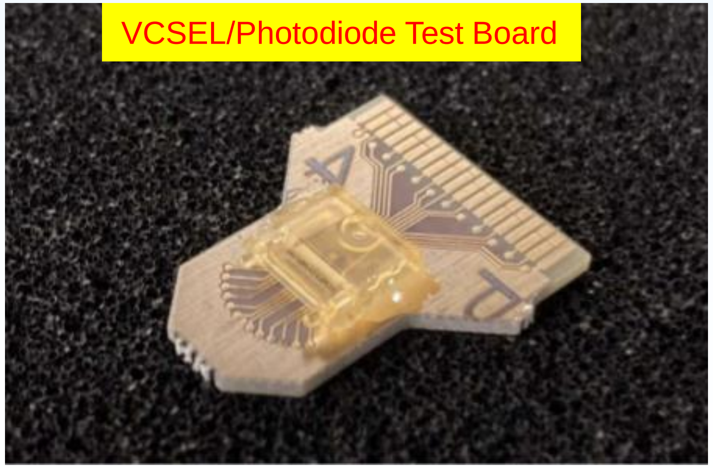
- Designed custom transceiver module that meets challenging requirements
- Carried out assembly process optimisation with industrial partner
- Now one third of the way through VTRx+ production
- We will keep monitoring the performance
- In honour of “The Curious Case Of The VTRx Receiver Failures”:

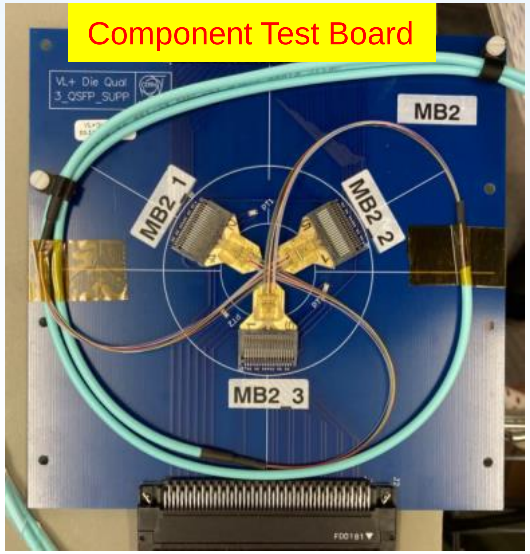
Don’t assume!

Spare slides

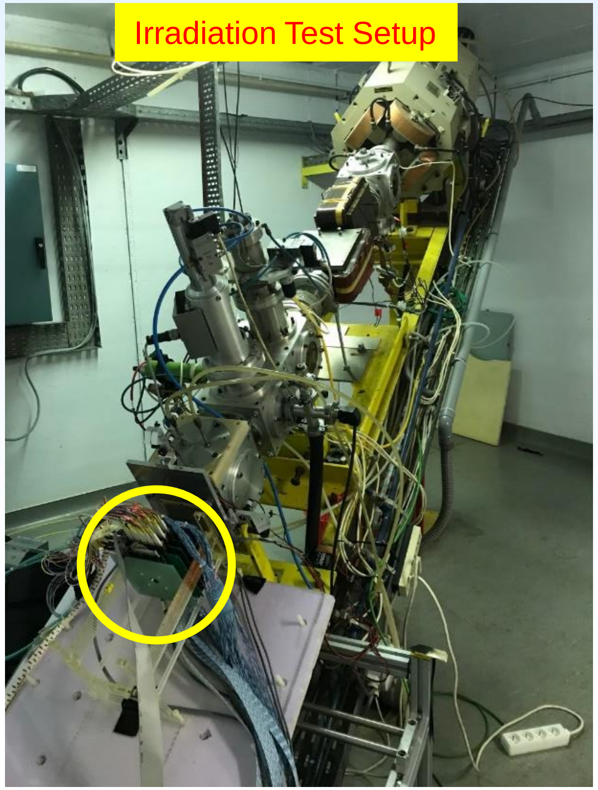
Component qualification

- VCSEL and Photodiode
  - Environmental tests: temperature and irradiation (neutron)
  - All photodiode wafers (2) and 6 VCSEL wafers have been tested
- GBTIA
  - Qualified in the framework of the Versatile Link project
- LDQ10
  - Irradiation tests: neutron, heavy ions

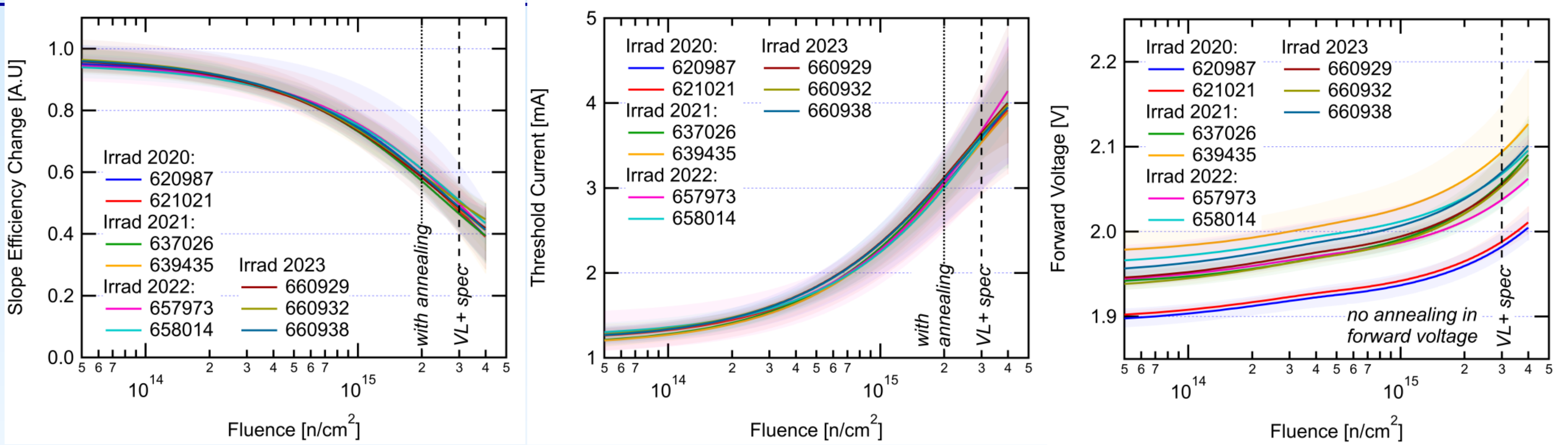

VCSEL/Photodiode Test Board

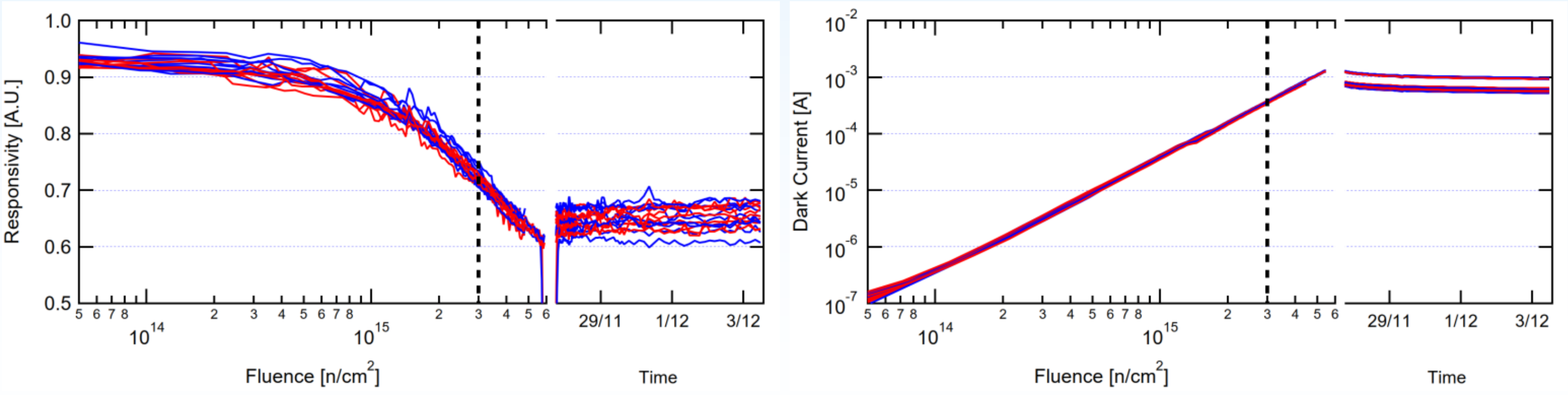


Component Test Board


Irradiation Test Setup

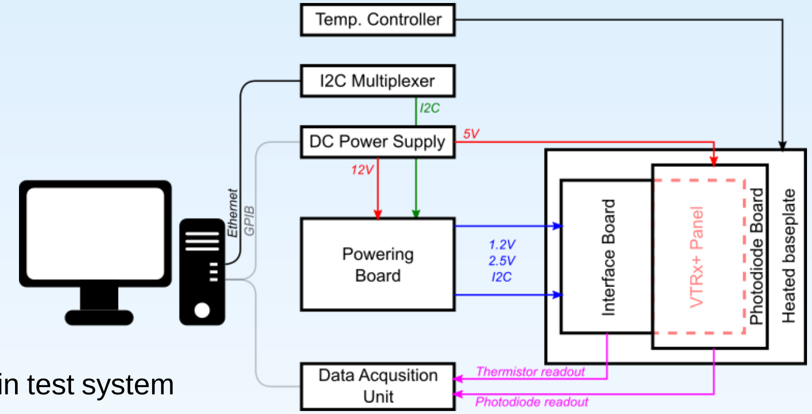
Component qualification



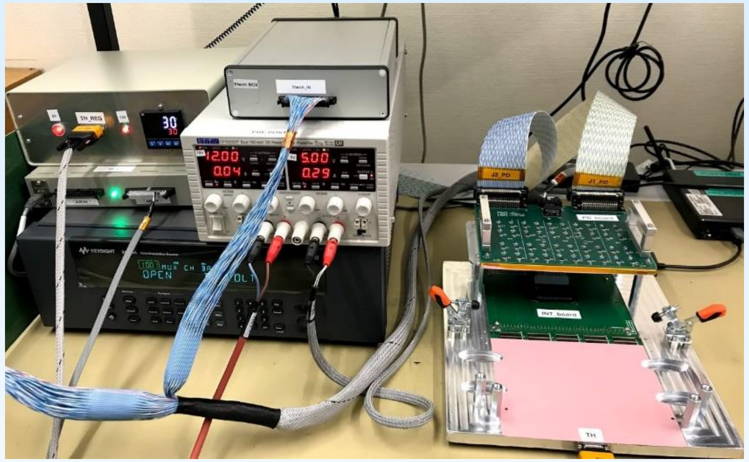


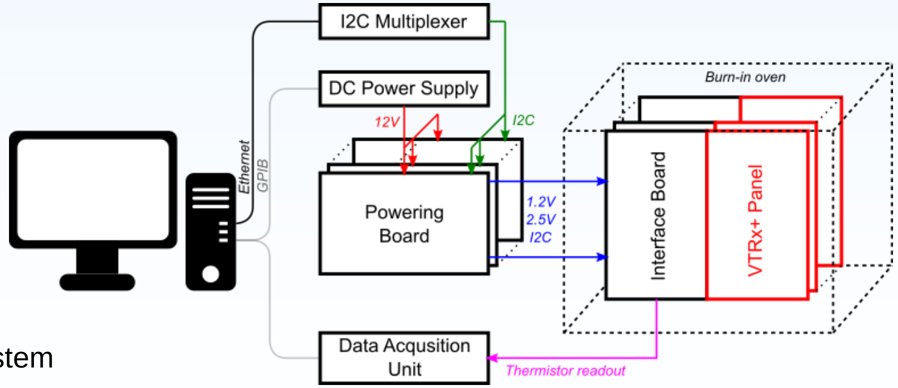
Burn-in test systems

- Used for finding infant mortalities and to stabilize VCSEL
- Carried out on VTRx+ panels during the assembly



Pre-, and post-burn-in test system



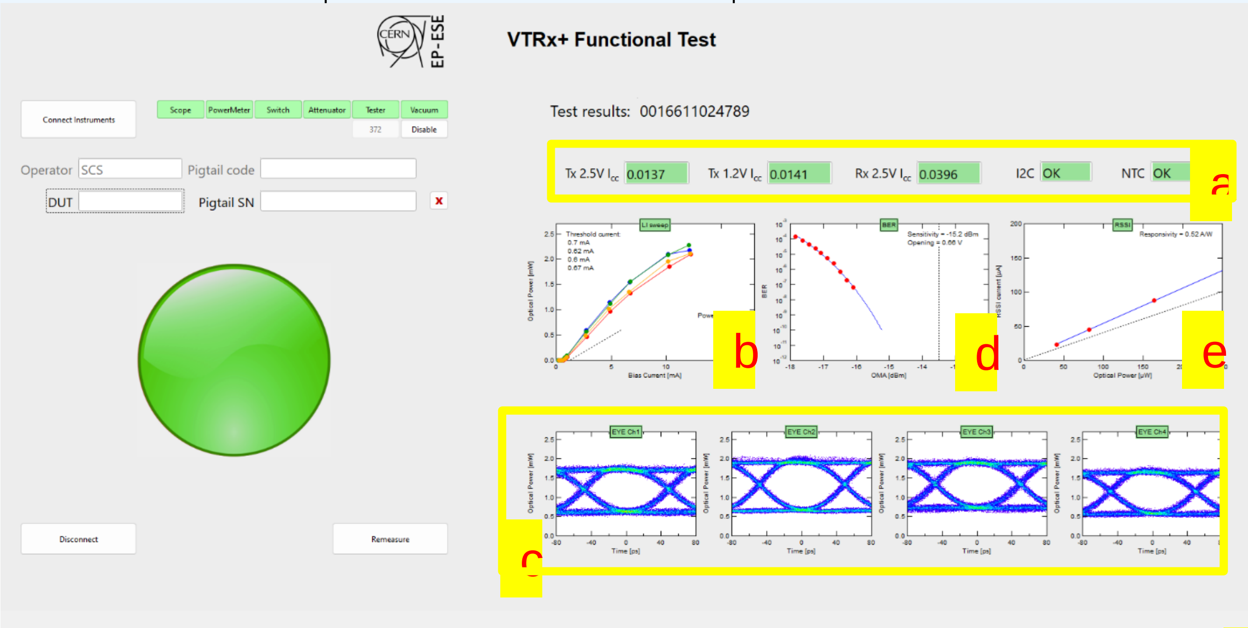


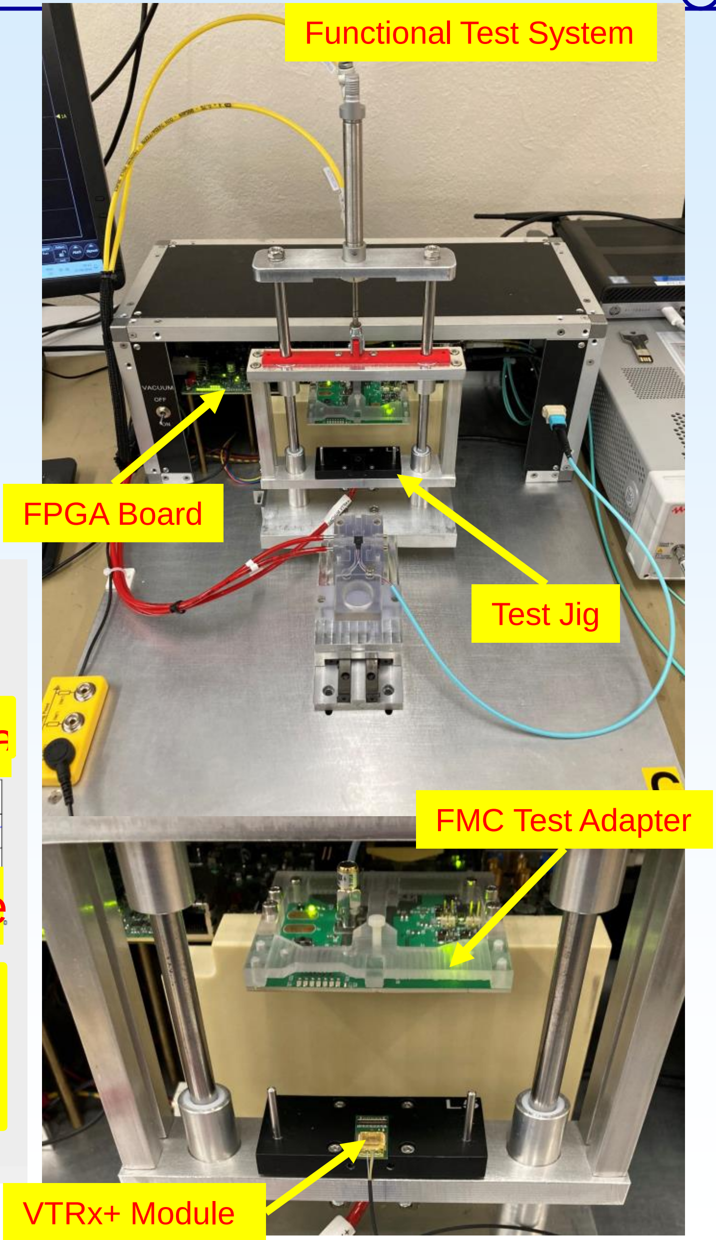
Burn-in test system

Functional test system

Power-on test: supply currents, I2C communication, thermistor (a)

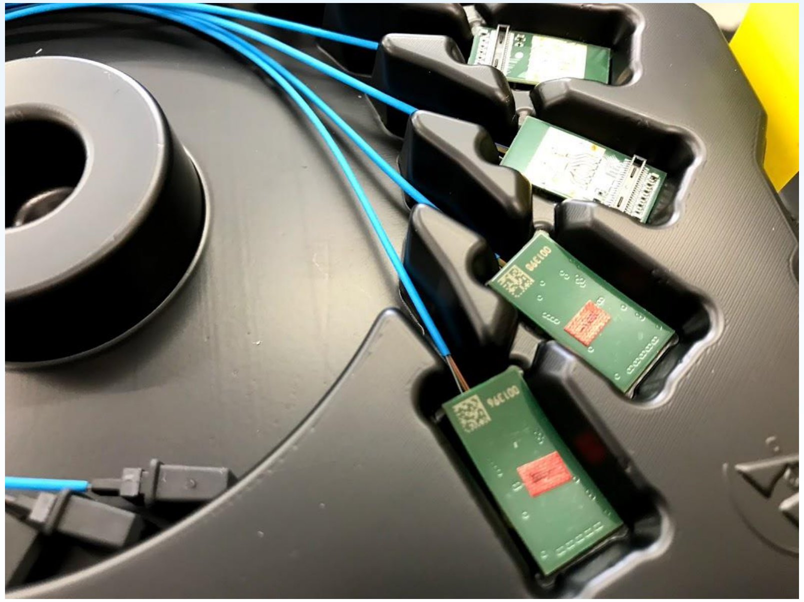
	Static	Dynamic
Transmitter	VCSEL L-I (b)	Tx Eye Diagram (c)
Receiver	Photodiode responsivity (e)	Rx Sensitivity (d)

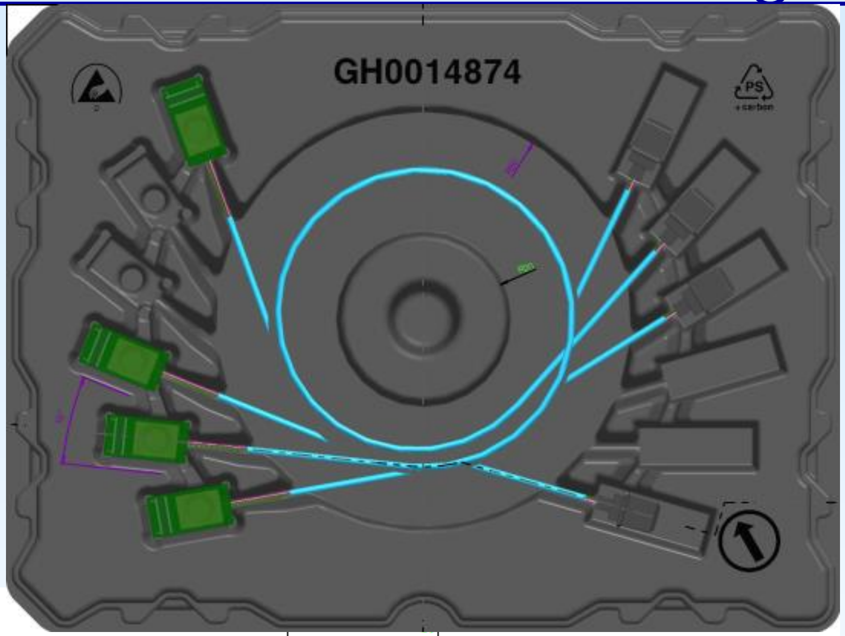


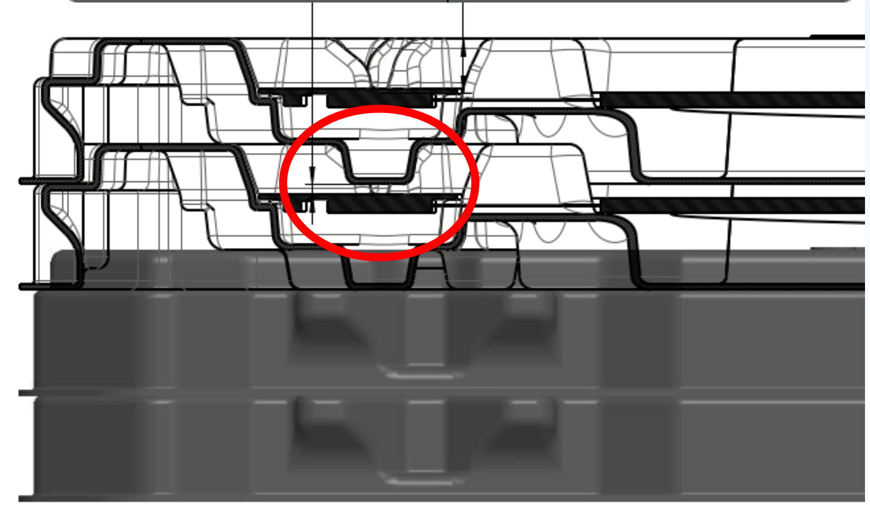


Packaging solution 1

- ESD-safe blister tray
- Trays can be stacked to reduce the packaging volume
- Difficult to coil long pigtails
- Stacked trays can damage modules

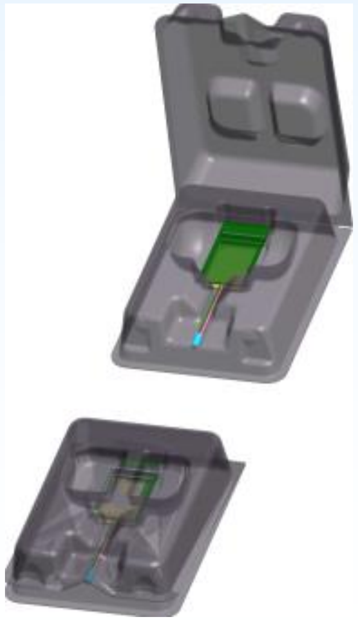


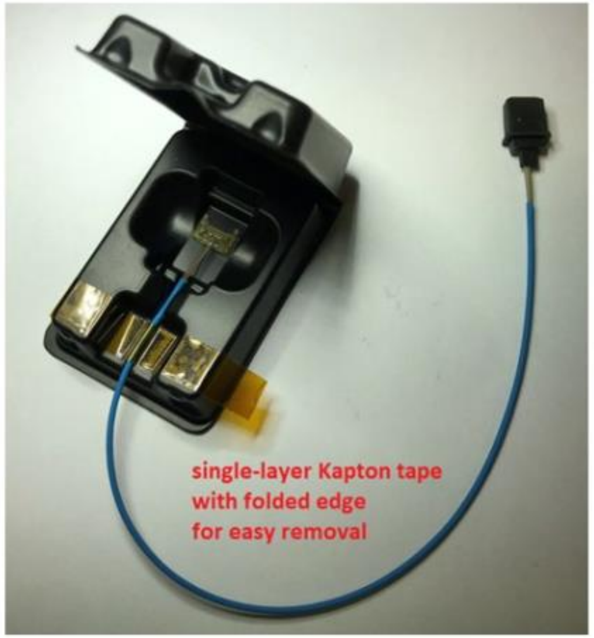




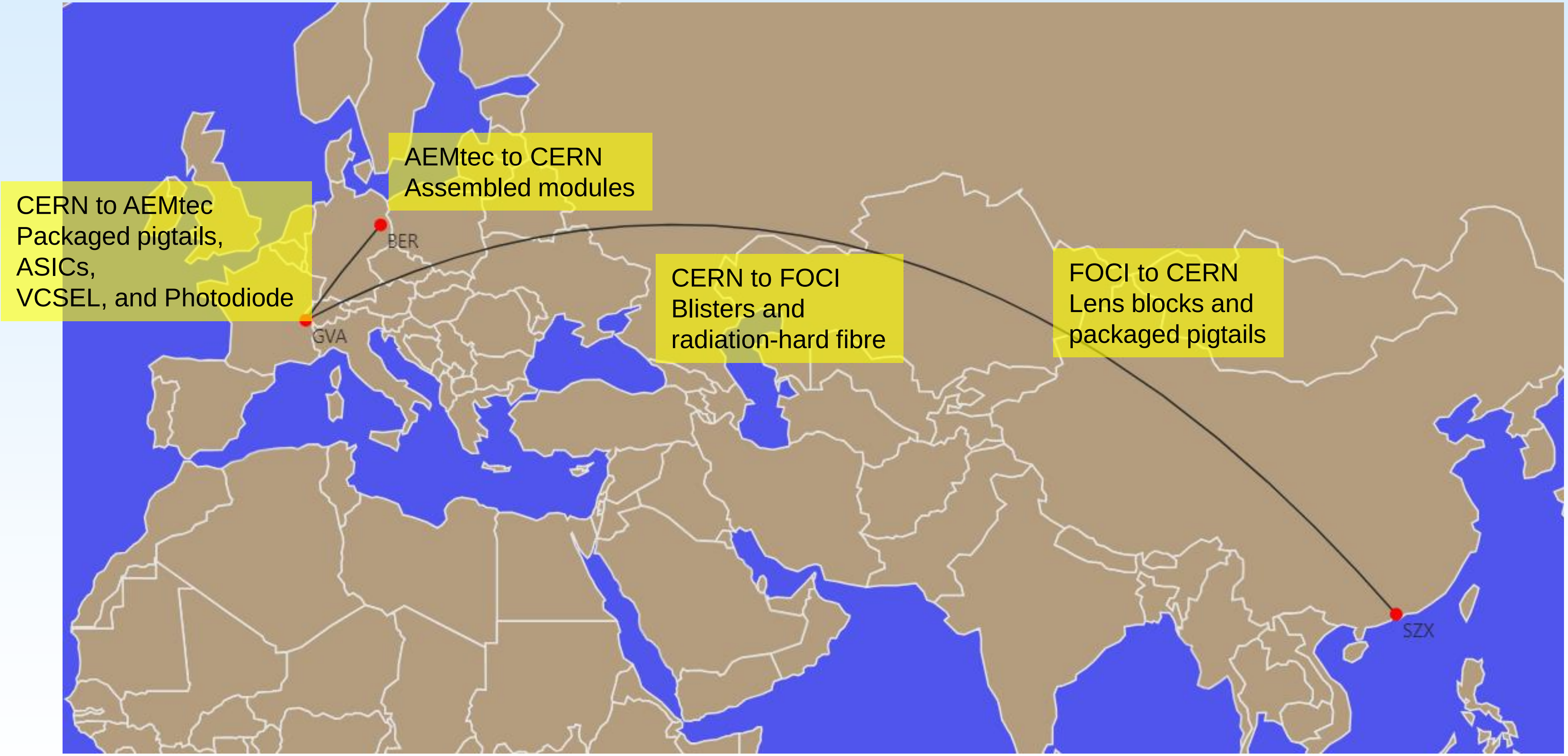
Packaging solution 2

- New blister for packaging single modules
- Blister is also used for protecting the pigtail connector during shipping
- Increased volume and more logistics effort





Carbon footprint

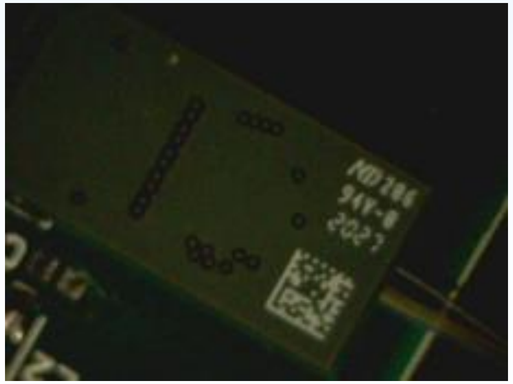


Light leakage – VTRx+ module

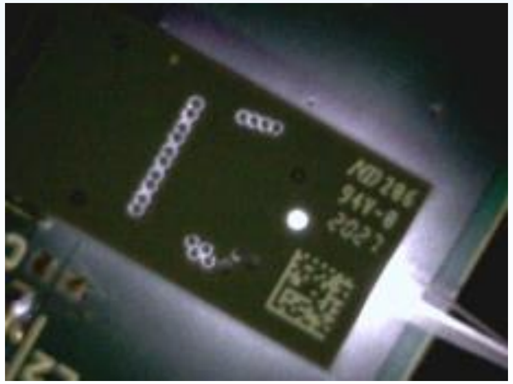
Versatile Link+

- 3D-printed cover (raw and painted) was used for the preliminary test
- Raw material is almost transparent to infrared
- Matte black paint greatly reduces the stray light
  - Depending on the direction the attenuation is 9-15 dB
- Shielding on the fibre side needs to be improved
- Better material (e.g. thermoformed Polystyrene) could improve the shielding performance

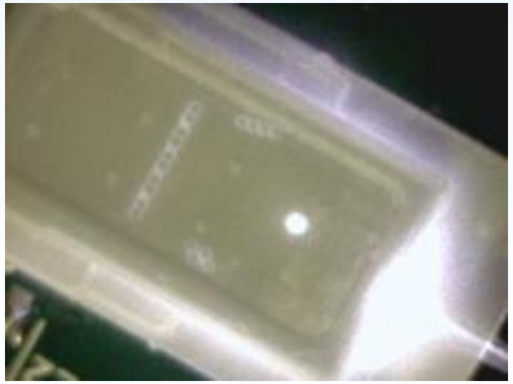
Module OFF



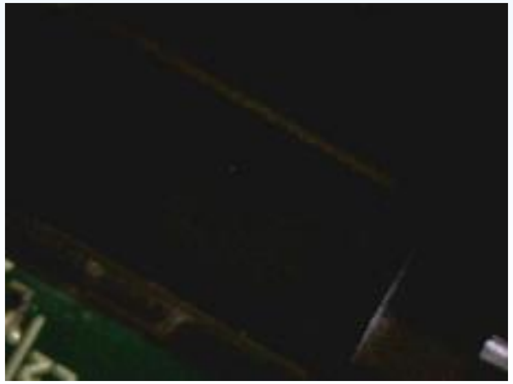
Module ON



Raw cover



Painted cover



Photos taken using an infrared sensitive camera

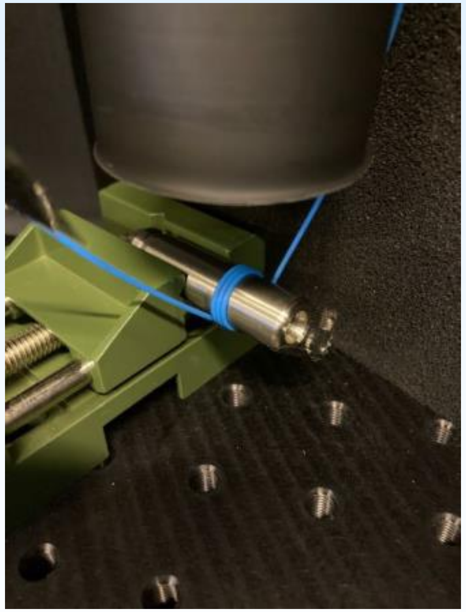
Light leakage – VTRx+ pigtail

Versatile Link+

- The impact of the fibre jacket material/colour

Bare fibre (reference)

89%

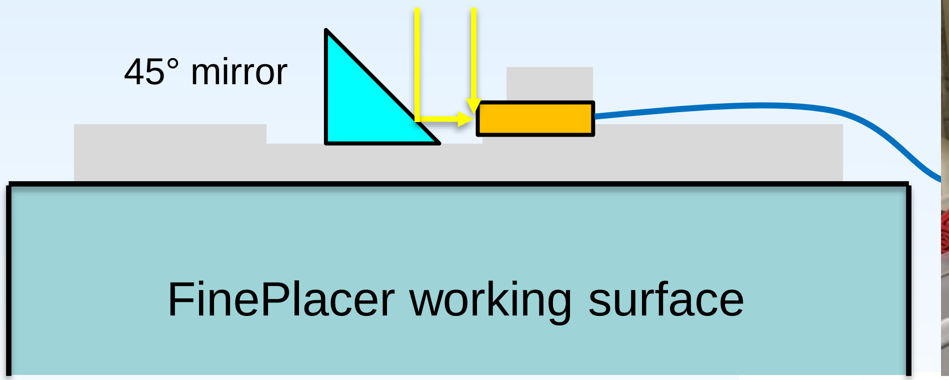


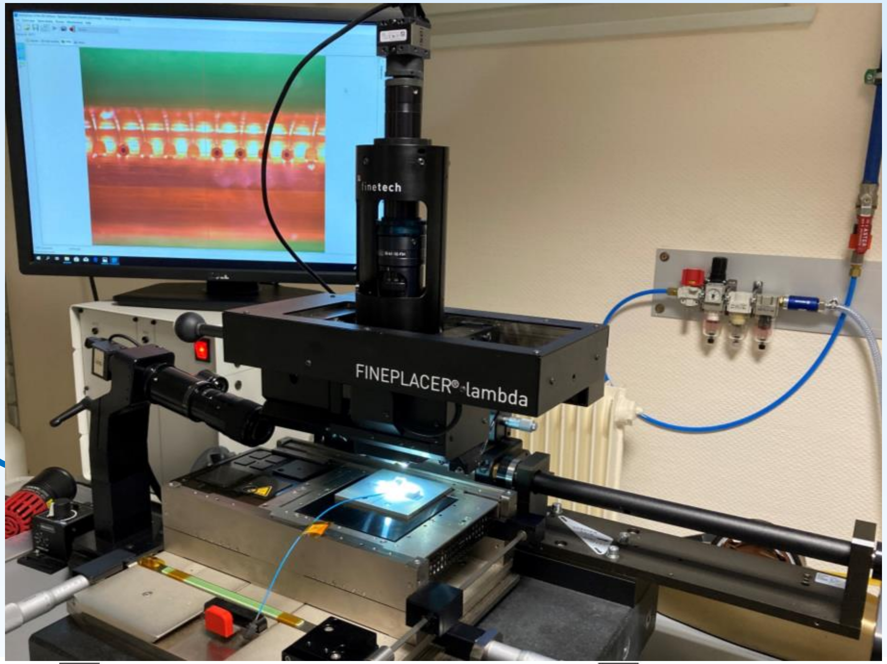
84%

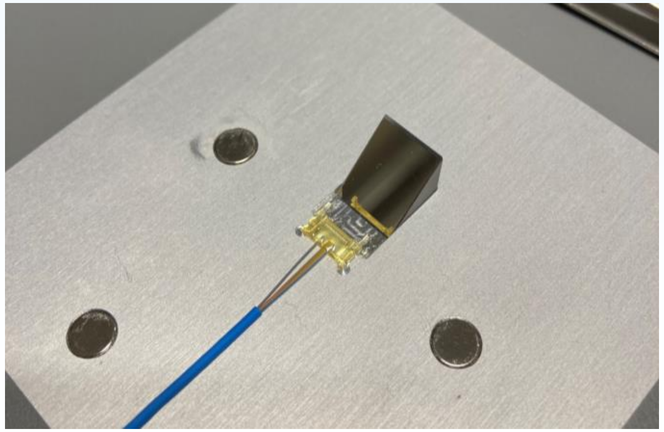
6%

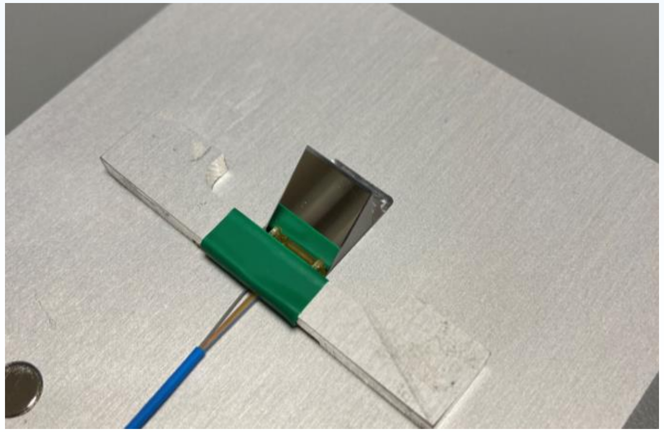
Pigtail tolerances

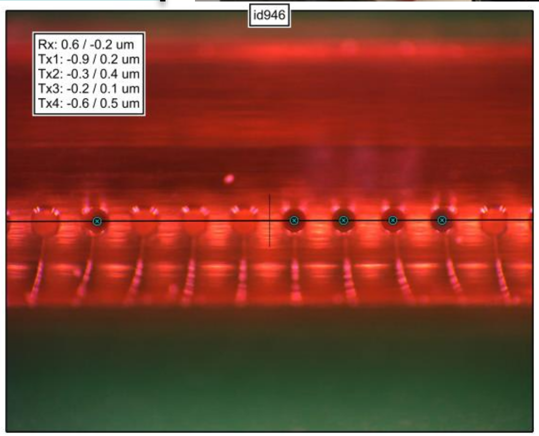
- 45° mirror reflects the front of the connector to the view of the microscope
- Only focus change and a small lateral movement with the FinePlacer stage required between the measurements

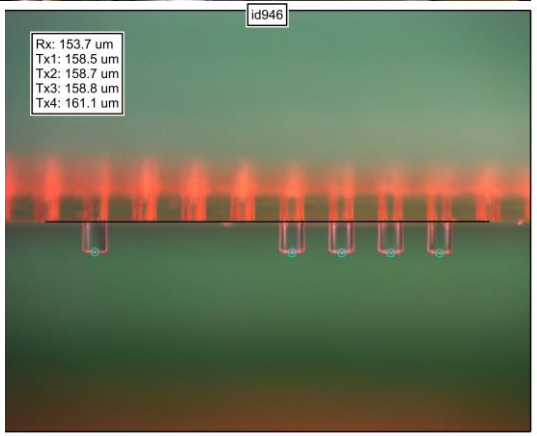






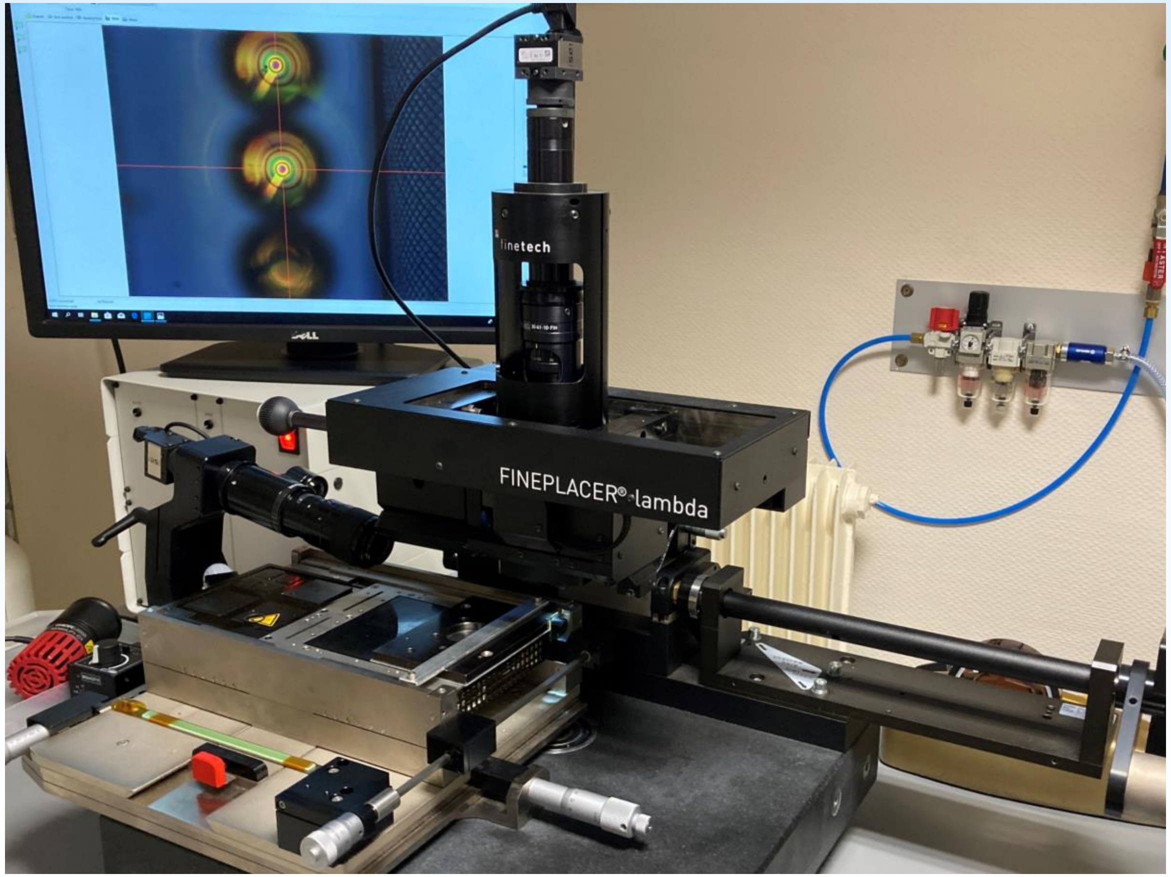


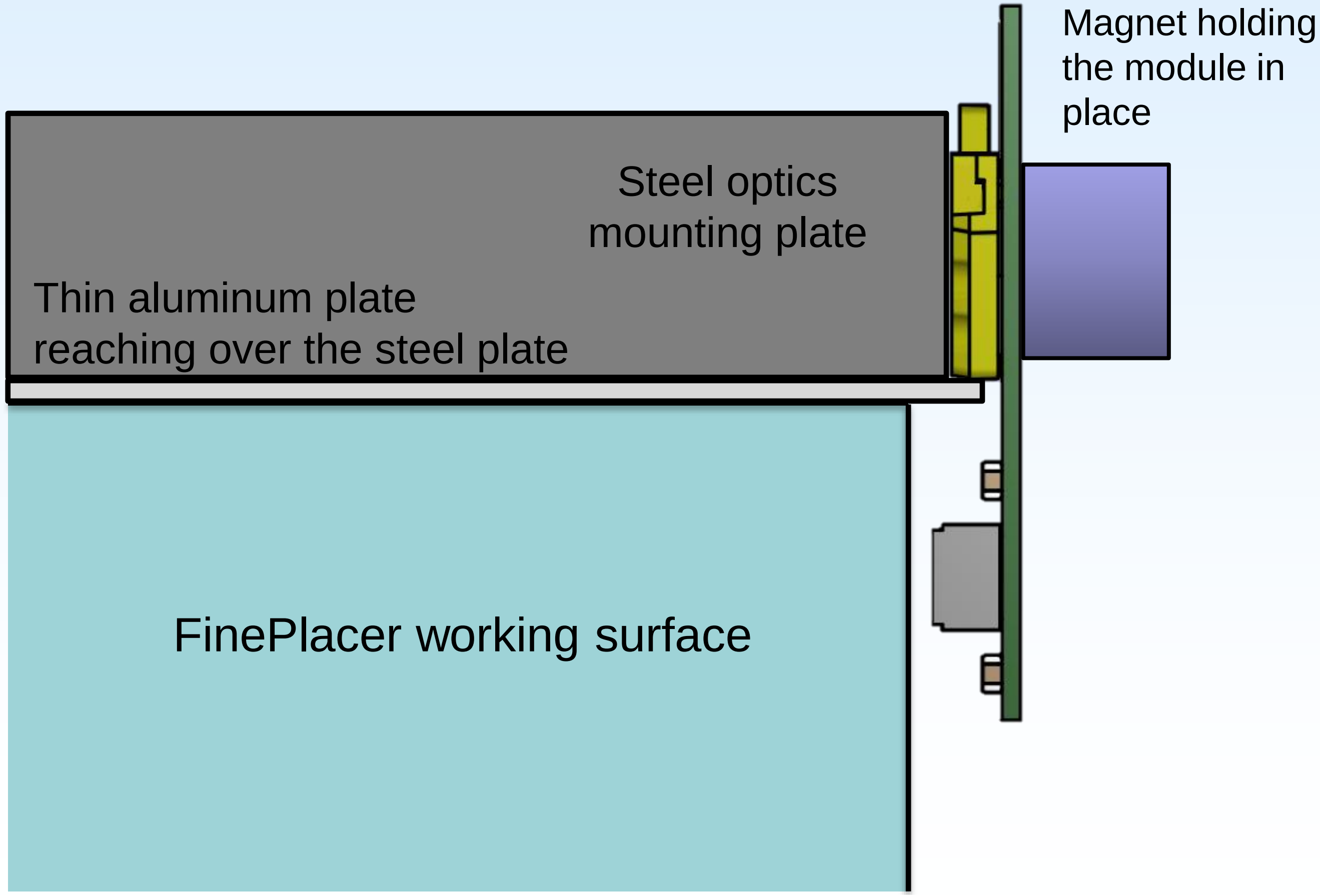




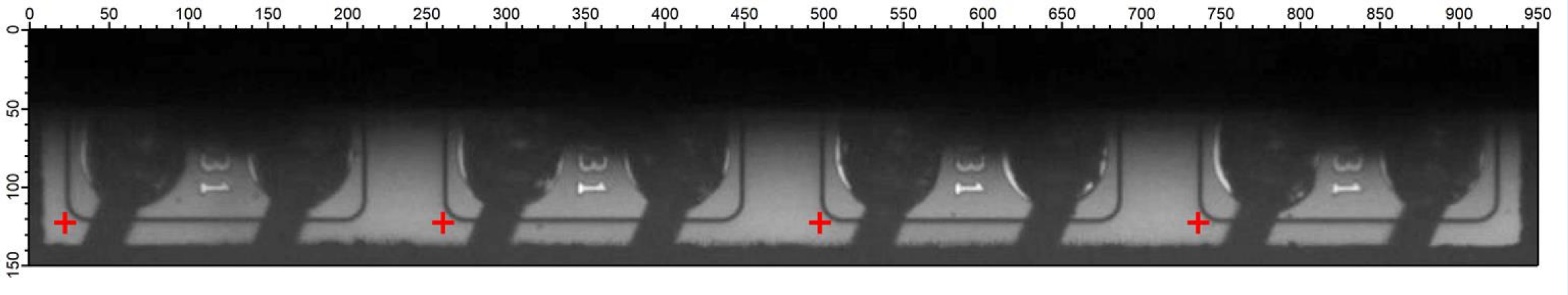
Visual inspection

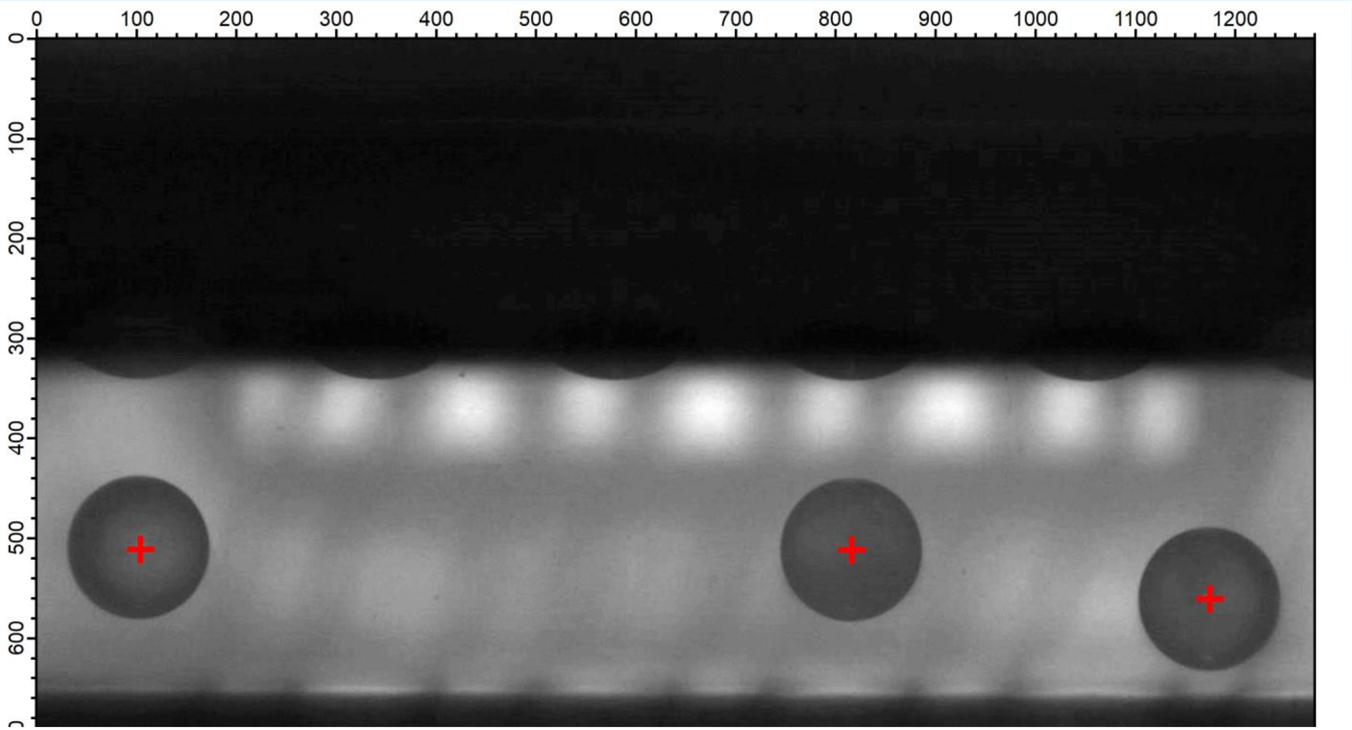
- CERN developed a non-destructive test method for checking the placement accuracy
- Imaging concept based on the idea of following the light path through the lens

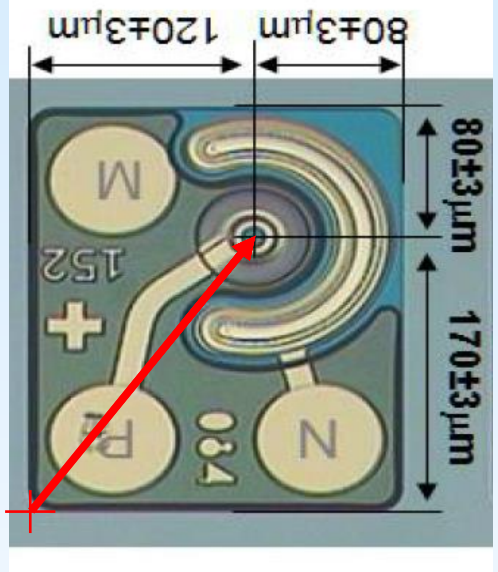




Visual inspection



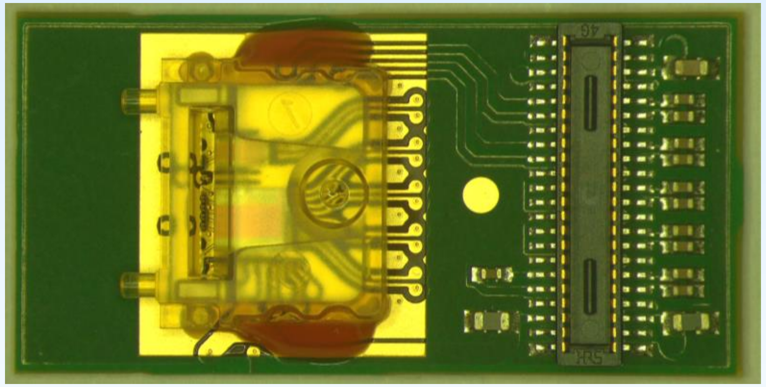




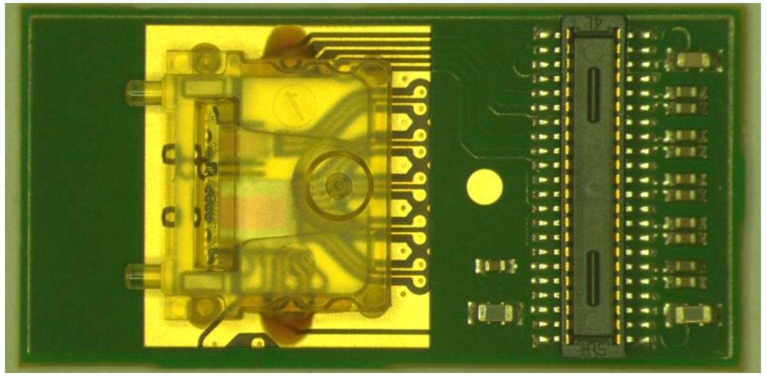
Optimised gluing process (1st attempt)

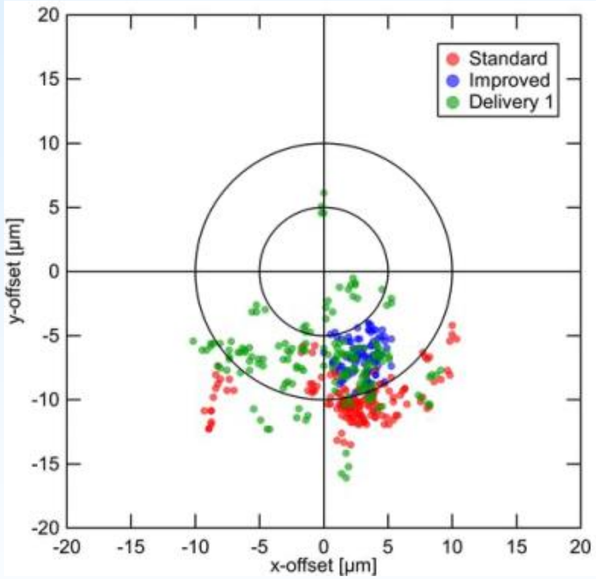
- Functional modules assembled using UV-curable epoxy and structural epoxy dots
- Not stable enough to start the production

Standard gluing process (pre-series)



Improved gluing process

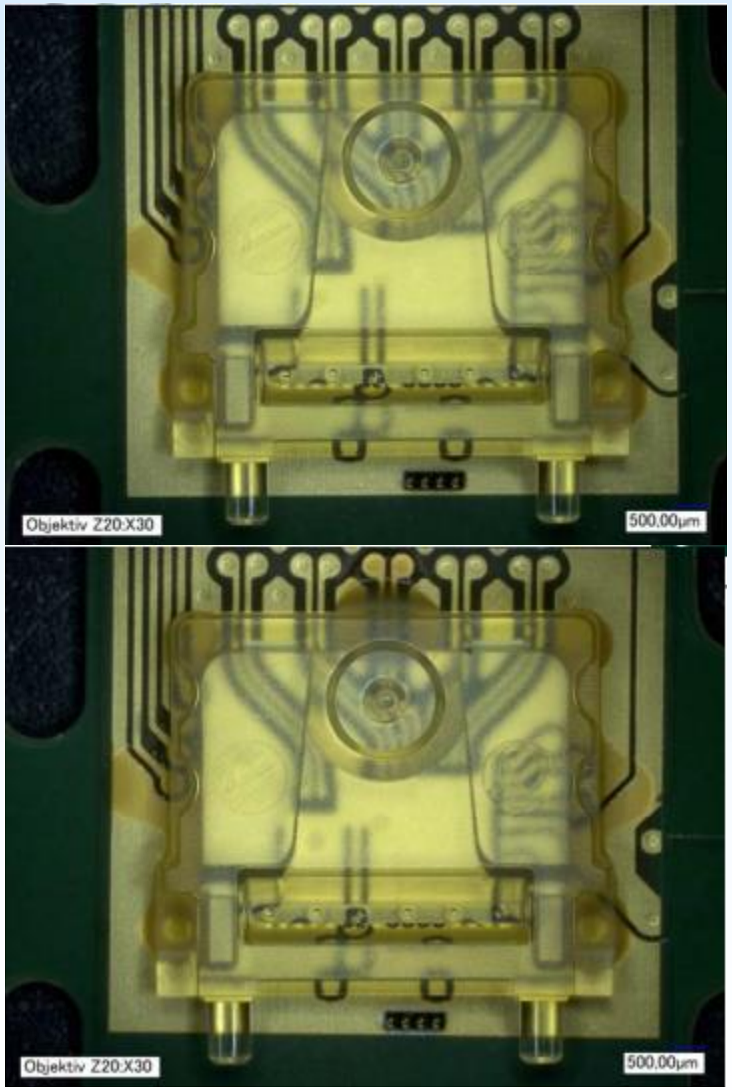


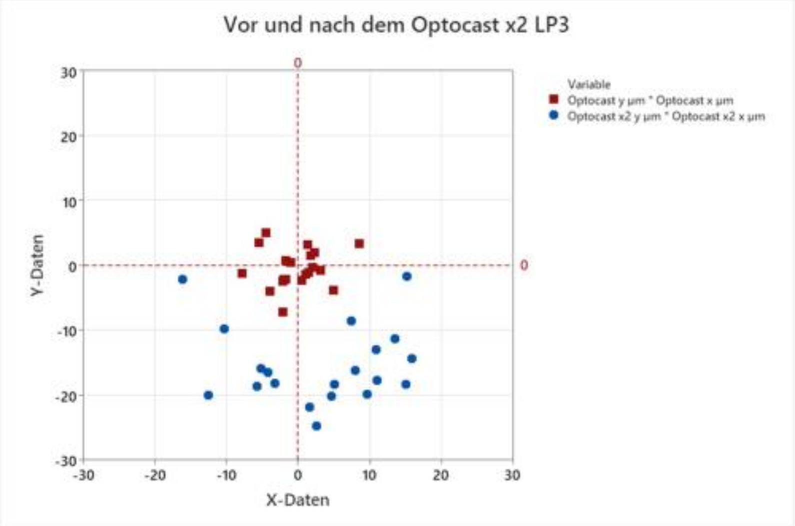


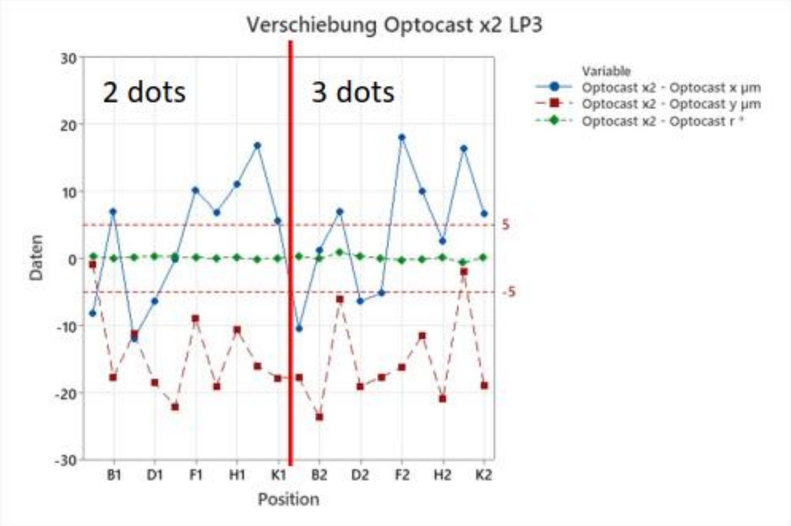
	Lens-attach process used	Modules Delivered	Modules tested AEMtec (yield)	Modules tested CERN (yield)
Panel 1	Same as Pre-series	39 (TBC)	–	18
Panel 2	Improved	22 (TBC)	–	22
Delivery 1 from 4 panels	Improved	100	100 (74%)	100 (91%)

Lens placement accuracy

- Using only UV-curable epoxy at corners and along the edges
- Thermal curing 1h @ 120°C with 1h up/down ramp from/to RT
- Measurements show that lens block moves during adhesive curing
- All samples are outside the ±5µm specification







Difference between VTRx and VTRx+