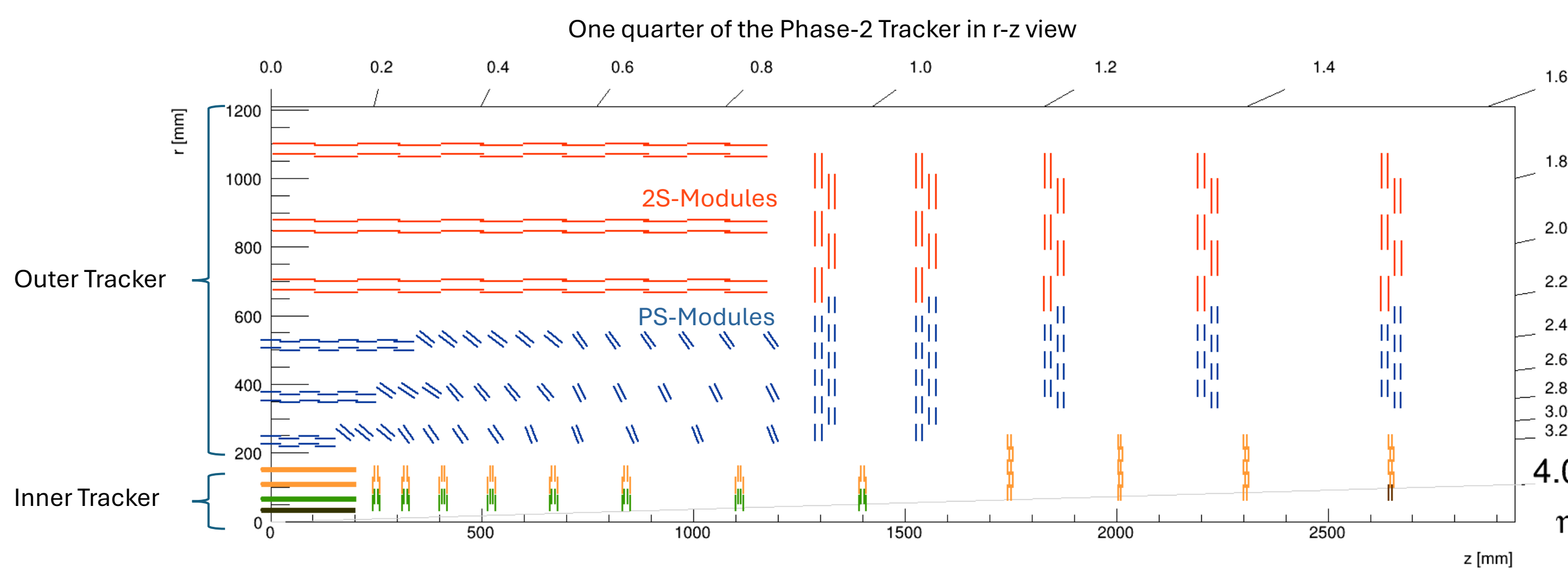


## 1. The CMS Phase-2 Tracker Upgrade



During the Long Shutdown 3 from July 2026 to June 2030, the LHC will be upgraded to the High-Luminosity-LHC, increasing the instantaneous luminosity from  $\sim 2 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$  to  $5\text{-}7.5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ .

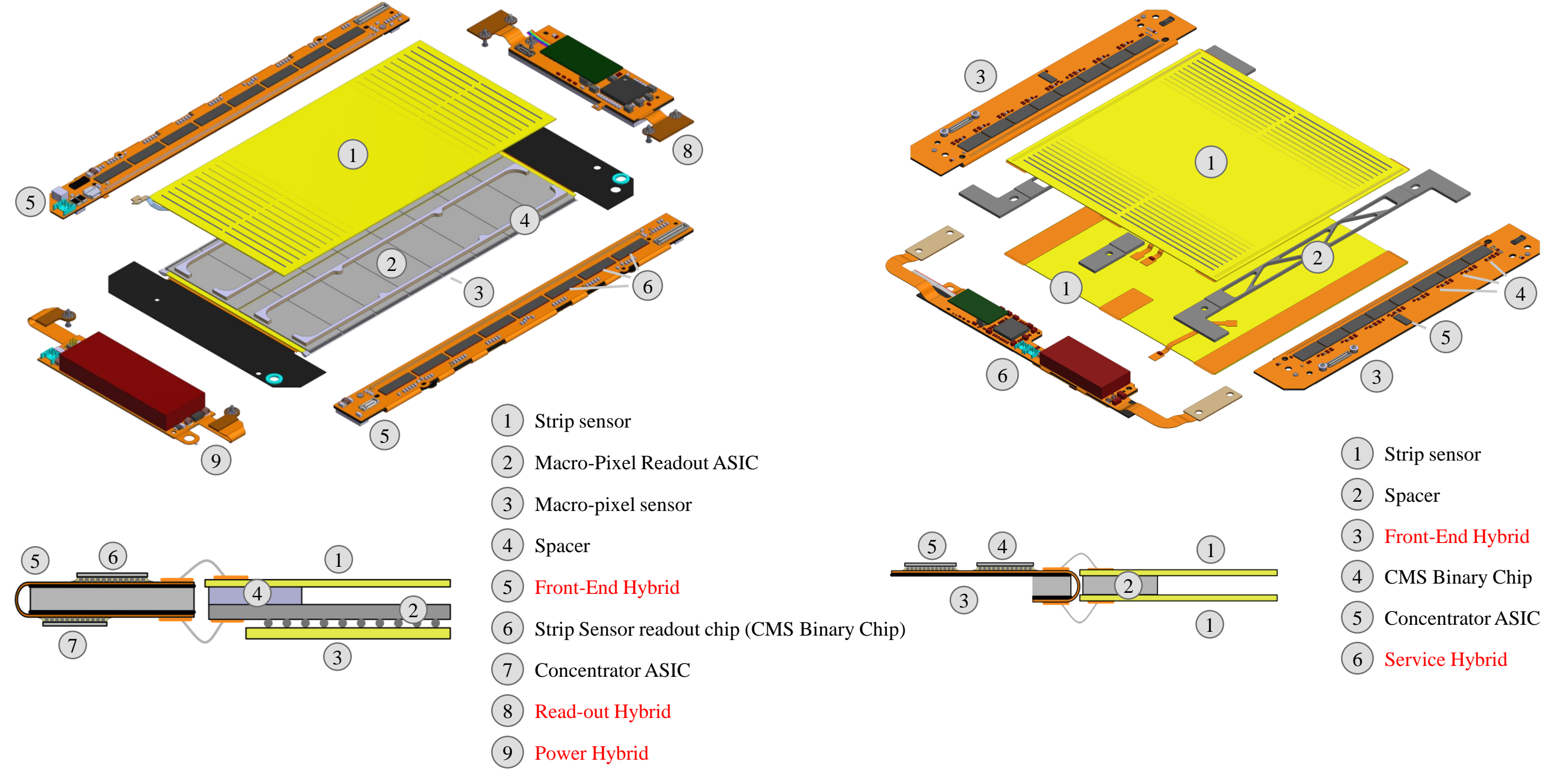
A new silicon tracker is currently being built that can endure the HL-LHC conditions. The tracker must be radiation tolerant up to an integrated luminosity of  $3000 \text{ fb}^{-1}$  and capable of distinguishing up to 200 pileup events. The Outer Tracker (OT) is built of silicon modules that contain two sensors placed on top of each other, allowing for on-module rejection of low  $p_T$  ( $< 2 \text{ GeV}$ ) tracks.

The tracker will be operated at  $-35^\circ\text{C}$ . The expected lifetime will be about 10 to 15 years, with no access to perform repairs possible. Careful quality control of all components is therefore essential to ensure that only perfectly functioning parts are installed in the detector, thus enabling high efficiency.

## 2. Phase-2 Outer Tracker modules

The Outer Tracker will be composed of two types of silicon modules:

- Pixel-strip (PS) modules: 1 strip sensor with  $(5 \times 10) \text{ cm}^2$  size and  $90 \mu\text{m}$  pitch, 1 pixel sensor with  $(1467 \times 100) \mu\text{m}^2$  pixel size
  - Strip-strip (2S) modules: 2 strip sensors with  $(10 \times 10) \text{ cm}^2$  size and  $90 \mu\text{m}$  pitch
- All hybrids are made of flex PCBs that are glued to carbon-fiber or FR4 stiffeners. The Front-End hybrids are folded and glued to a spacer, so that both sensors are read out on the same hybrid.



## 3. Hybrid production

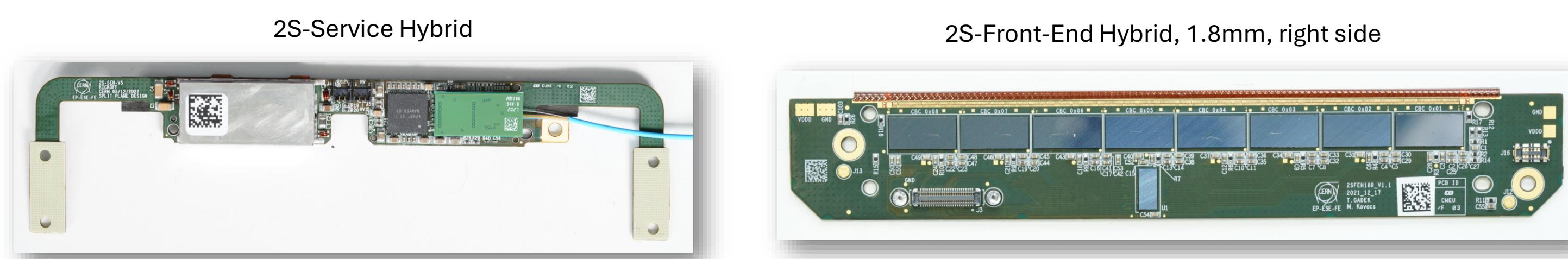
The prototyping phase of hybrids ended in summer 2023. The mass production is expected to finish in Q1 2026 and is split into three batches:

- Pre-series batch – to finalize the hybrid designs, and to identify manufacturing issues
- Pre-production batch – to verify the design and assembly process changes
- Series production phase

Required numbers of hybrids, including approximately 5% spares:

- 24 000 hybrids for 8 000 2S modules
- 23 520 hybrids for 5 880 PS modules

There are 5 main types of hybrids with different thickness variants (PS: 1.6 mm, 2.6 mm, 4.0 mm, 2S: 1.8 mm, 4.0 mm), resulting in 18 variants.



## 4. Visual inspection

Every delivered hybrid is visually inspected at one of the two VI centers (CERN and Wigner Research Centre for Physics).

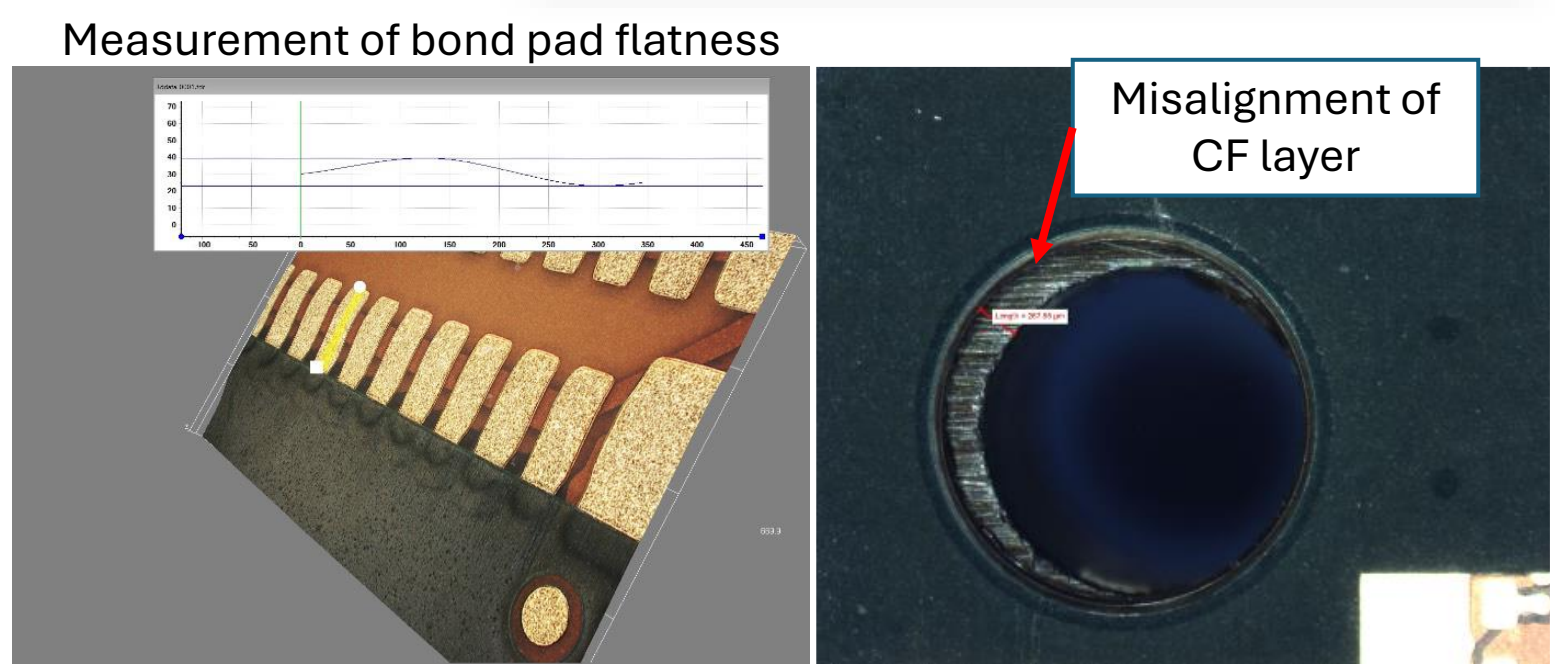
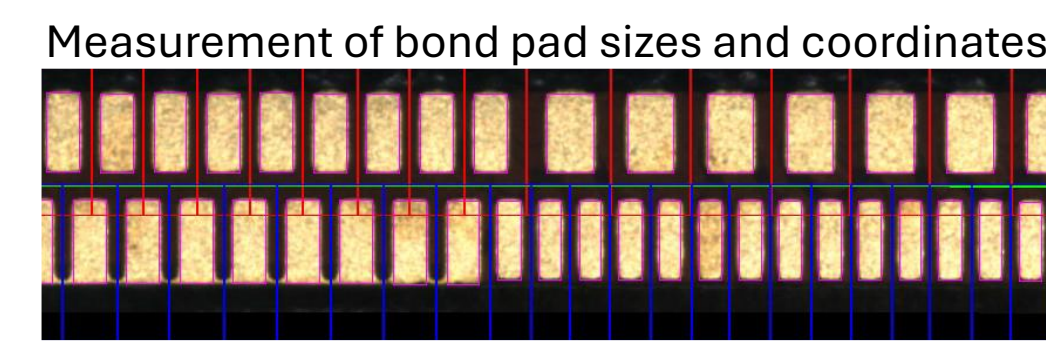
- Inspection of a hybrid takes 10-15 minutes
- VI Reports are made available to module production centers via a web tool

Example test criteria for the visual inspection:

- Quality and correctness of components soldering
- Cleanliness of the PCB and connectors, bond pads
- Gluing quality of the stiffeners and compensators
- Fold-over accuracy
- Alignment of PCB layers, components

Example metrology studies:

- Hybrid flatness and guiding pins measured with dedicated jigs
- Hybrid thickness, weight
- Stretch of bond pattern



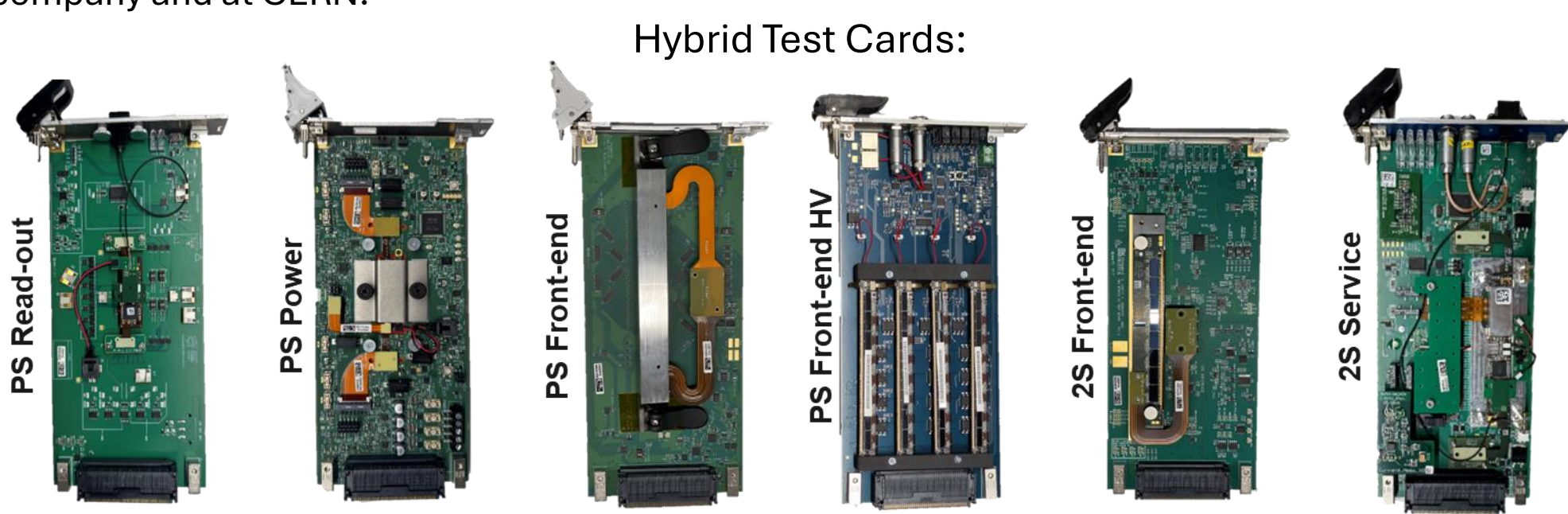
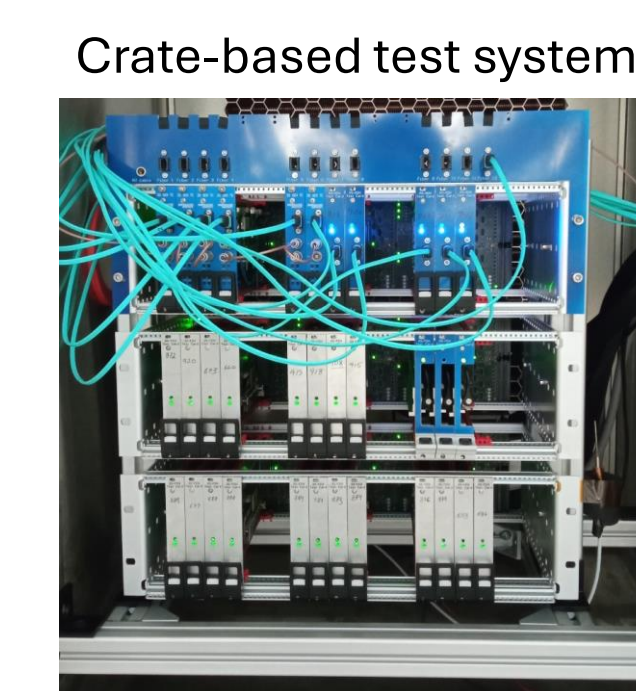
## 5. Functional testing

Every hybrid will be electrically tested at  $+40^\circ\text{C}$  and at  $-35^\circ\text{C}$ , at the assembly company and after reception at CERN to find assembly related issues. A scalable test system was developed to quickly test up to 12 hybrids in sequence. It consists of:

- Dedicated test cards for each hybrid type that verify the complete functionality of the hybrid
  - e.g., for the 2S-Service Hybrid testcard: LV voltages, HV integrity, analog signals, 320 Mbps data links, clocks, I<sup>2</sup>C communication, connection to the Front-End hybrids
- A backplane that multiplexes the digital signals and connects the active testcard (one at a time) to a back-end board ( $\mu\text{TCA AMC}$  with Kintex 7 FPGA)
- System is steered by a graphical user interface that gives direct feedback after each test
- Test results are stored in the CMS tracker production database

Target throughput is 108 hybrids per 8h shift (~2300 hybrids per month).

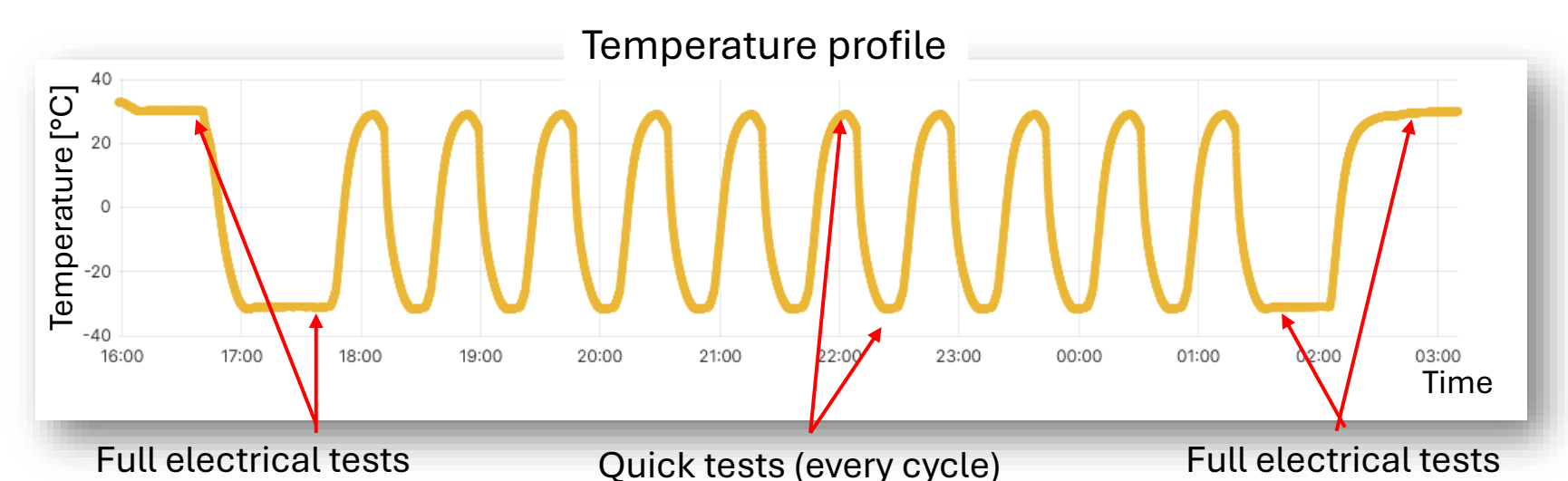
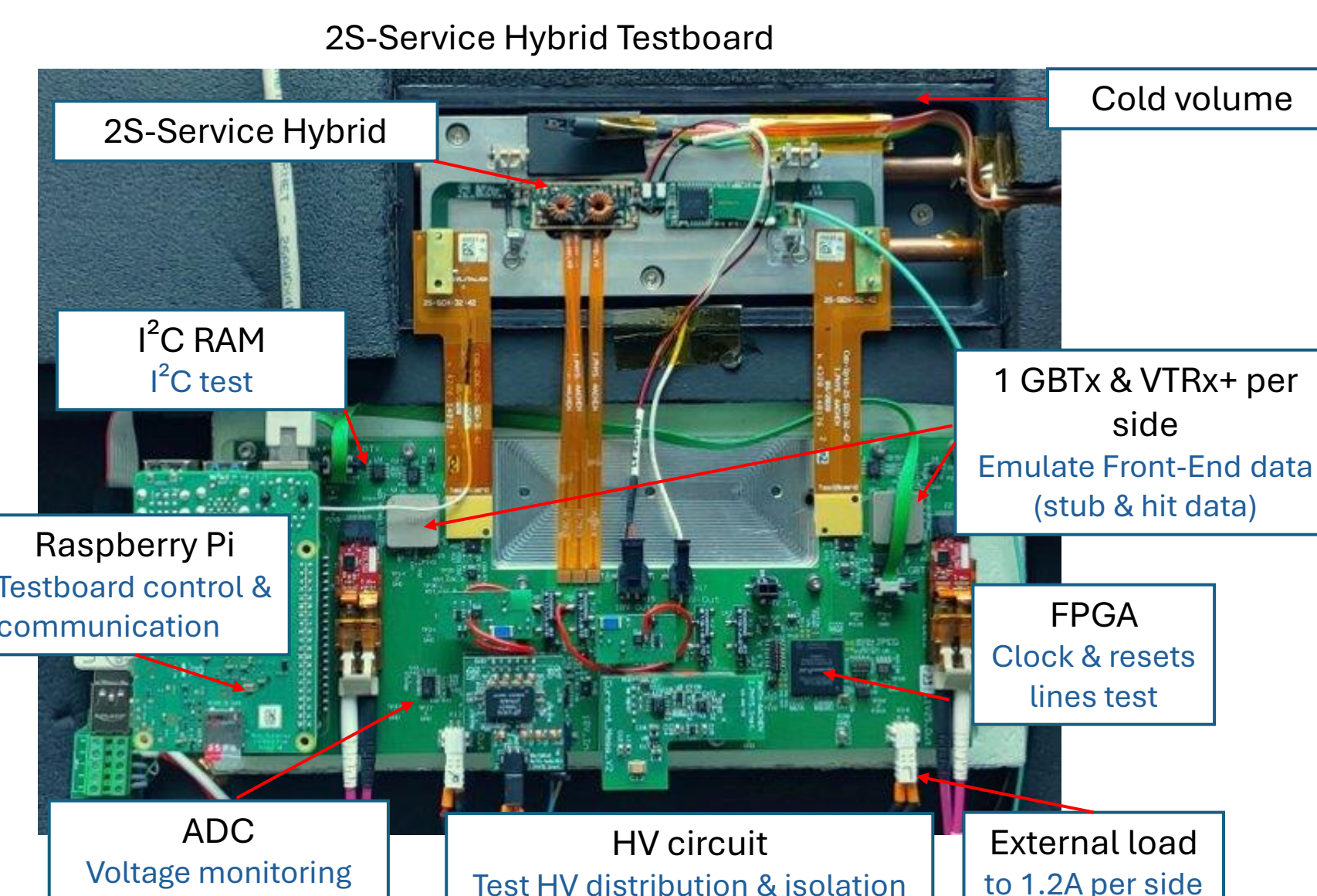
Setups with 3 crates in a climatic chamber have been successfully installed at the assembly company and at CERN.



A subset of 2S-Service Hybrids (~1300 pieces) will undergo an extended testing in a thermal cycling setup at RWTH Aachen University.

- Service Hybrid mounted on aluminum block that is cooled by a liquid chiller
- Testboard was developed for in-depth electrical testing:
  - Measurement of low voltage (for readout ASICs) and high voltage (silicon sensor depletion), currents, turn-on voltages, efficiency, etc.
  - I<sup>2</sup>C communication with the LpGBT ASIC
  - Emulation of clock, trigger, and reset signals (coming from the detector back-end)
  - Emulation of stub and hit data (coming from the detector front-end)
- Active thermal cycling (hybrid is powered all the time) with ten cycles between  $-35^\circ\text{C}$  and  $+30^\circ\text{C}$

Three hybrids can be tested per day (in parallel). A complete test procedure takes 12 hours.



## 6. Main observed issues and measures taken

**Contamination:** Bond pads can be contaminated in several assembly steps at the flex manufacturer and the assembly company (lamination of stiffeners, fold-over gluing, soldering, underfill of ASICs).

- The production cycle was analyzed in detail to identify critical steps
- Better training of the personnel, new microscopes installed at the manufacturer for improved VI
- Enhanced cleaning procedures
- More realistic specifications have been defined

**Damage of glue joints:** The fold over of the Front-End Hybrids is glued before the reflow soldering. Force due to unavoidable mismatch in the coefficients of thermal expansion can lead to delamination.

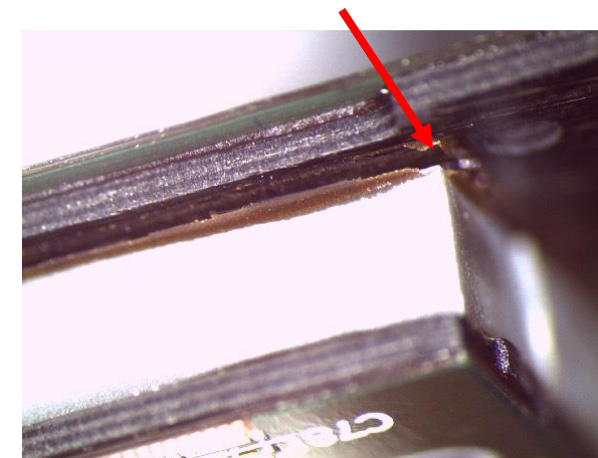
- Increase of the glue curing temperature and time before reflow soldering
- Use of micro ceramic balls to control the glue thickness

**Bump bonding quality:** A single batch showed data line failures consistent with bad bump bonds. 6 affected hybrids were found in the functional test, but a few more cases appeared after thermal cycling in a module.

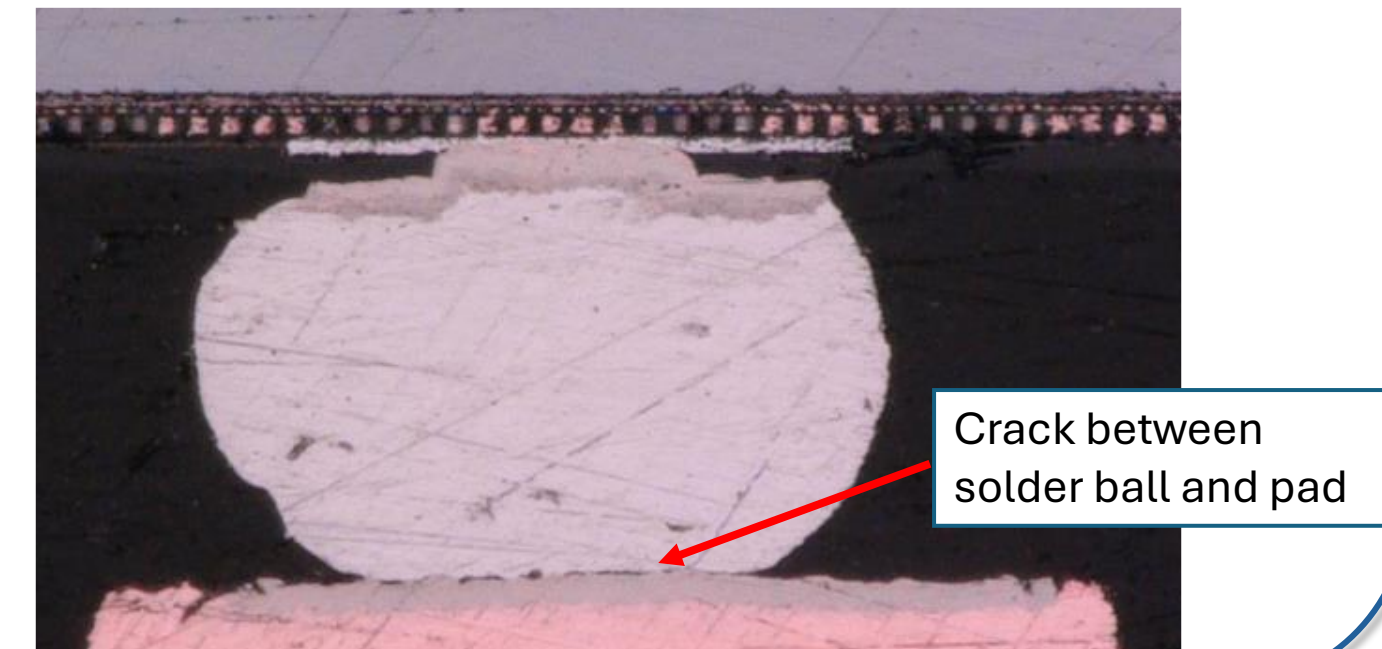
- Identified issues during the flux dipping
- They could be solved by increasing the dipping depth from  $60 \mu\text{m}$  to  $90 \mu\text{m}$



Opened glue joint in a PS-Front-End Hybrid



Cross-section of a bump bond of the 2S-Front-End Hybrid



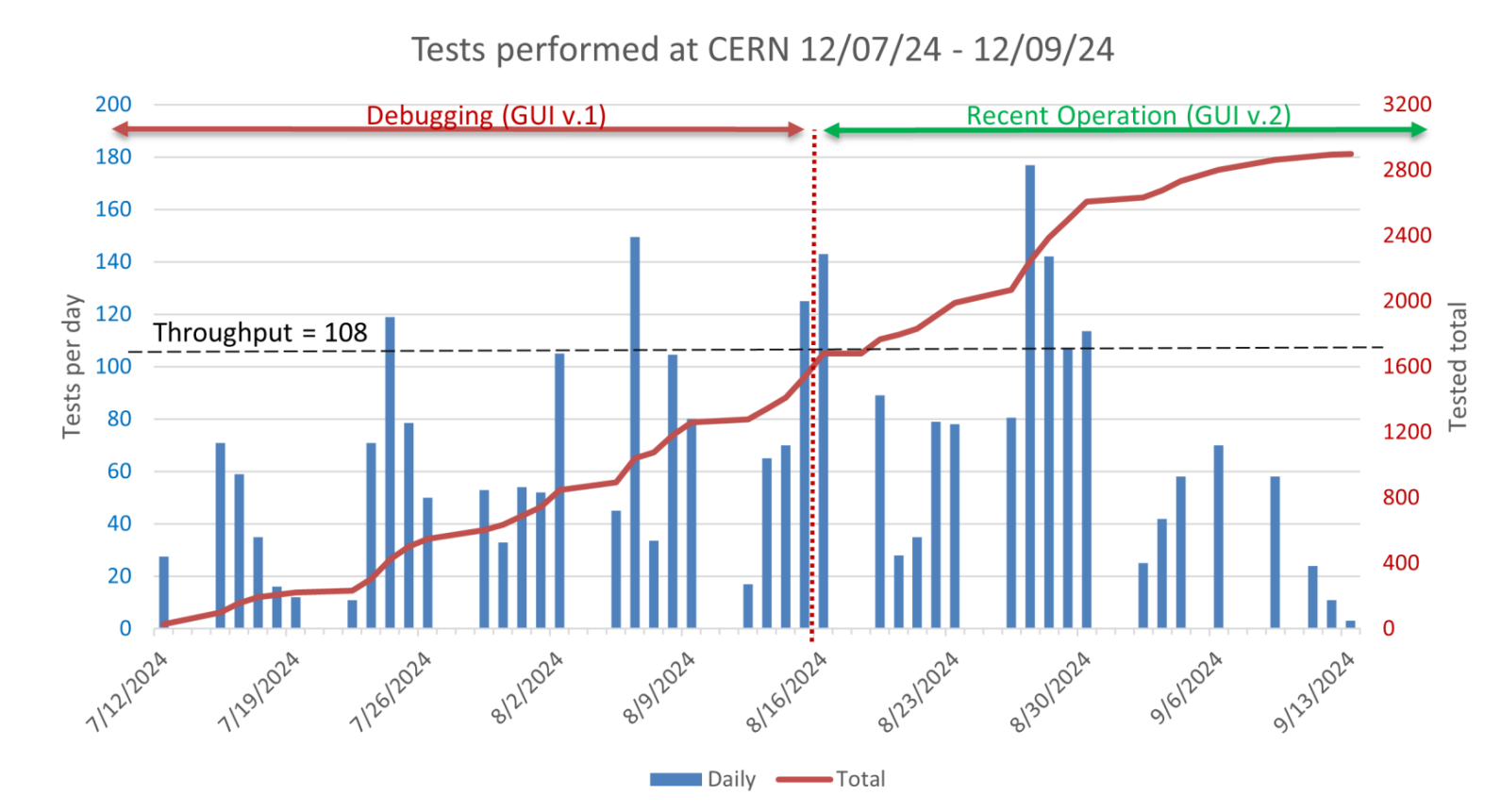
## 7. Quality control results

The pre-production of hybrids for the Outer Tracker has concluded, and the series production has started.

- Yield of the pre-production (about 1400 hybrids of all types):
- 90% of all hybrids passed the visual inspection
  - Out of these, ~96% passed the functional testing
  - Losses are dominated by glue joint openings and bond pad contaminations
  - No design changes are required in any of the hybrid variants

Targeted test throughput of 108 hybrids per day was achieved and even exceeded

- The observed issues are much better under control and several process improvements have been introduced
- The combined yield (VI & functional testing) increased from ~36% in the pre-series batch to 86% in the pre-production batch
- The delivery of hybrids from the series production is ongoing. The production rate still must ramp up.



Example production planning of a variant of PS-Read-Out Hybrids

