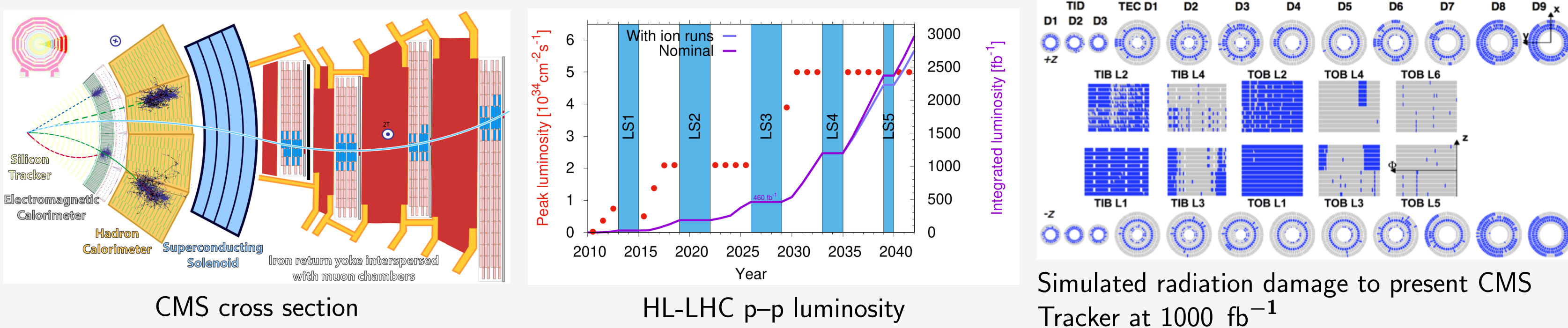


**Abstract:** To cope up with enhanced interaction rates during the High Luminosity operation of the LHC (HL-LHC), the CMS Outer Tracker (OT) is being upgraded with specialized strip-strip (2S) modules with capability of track selection at the hardware level. The assembly of such silicon strip tracker modules consist a multi-step procedure with the usage of several machineries and precision fixtures. Within the CMS, these modules are being built and tested at different institutes/universities across the world passing uniform quality control criteria. In this presentation, vivid procedure and/or the subsequent functionality tests would be highlighted.

## LHC & CMS Detector

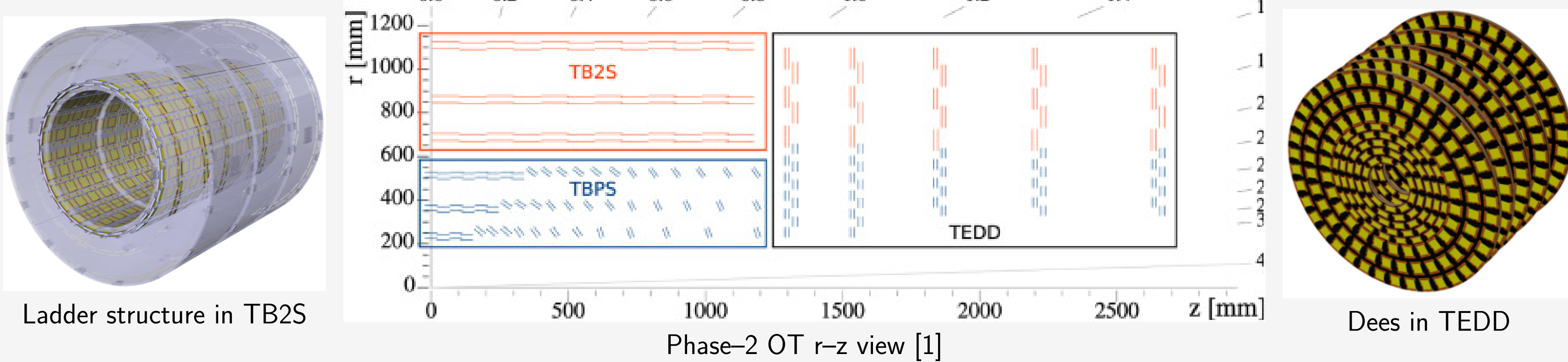
- ▶ The LHC, the world's largest accelerator, collides protons at a center-of-mass energy of 13.6 TeV, allowing precise studies of rare physics processes.
- ▶ During Long Shutdown (LS) 3, the LHC will be upgraded to increase instantaneous luminosity by a factor of 3, enabling significantly larger data collection, with expected delivered integrated luminosity of 3000 fb<sup>-1</sup> during the HL-LHC phase.



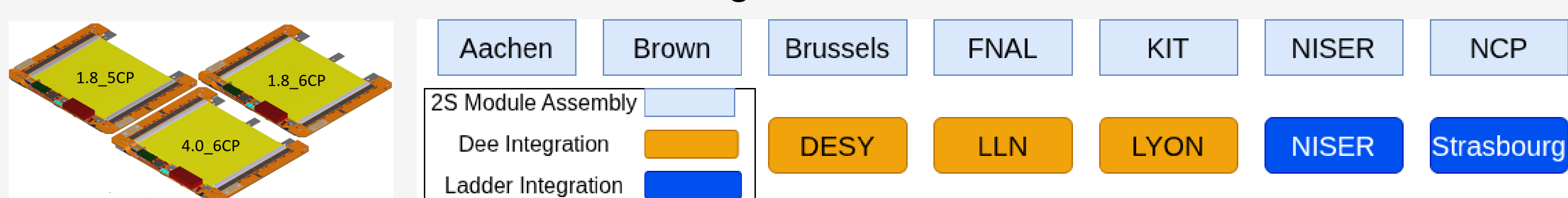
- ▶ The CMS detector is a sophisticated, general-purpose hermetic detector, containing various sub-detectors to optimize particle detection.
- ▶ CMS Phase-2 upgrade is planned to handle high data rates of HL-LHC operation to maintain the unique physics goals.

## Tracker & 2S Modules

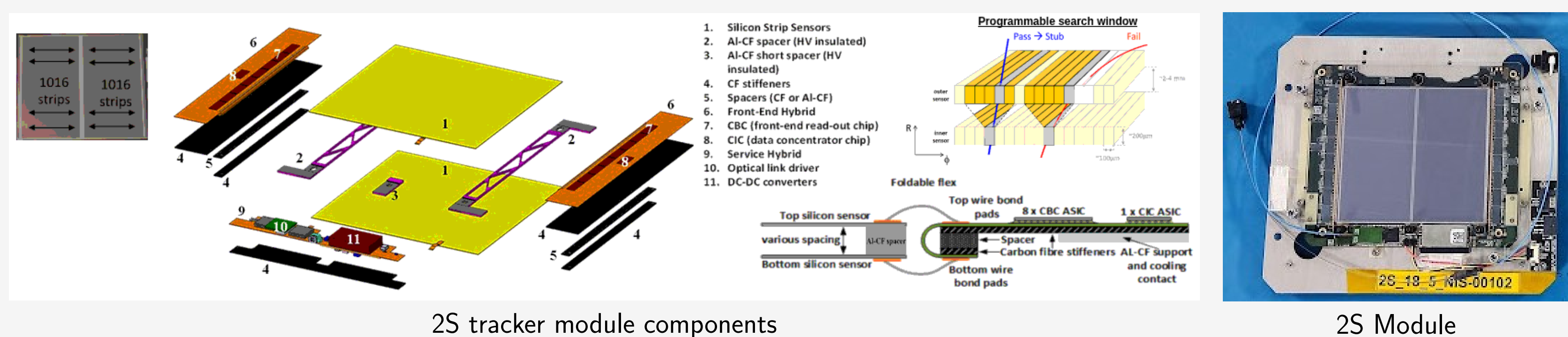
- ▶ The Tracker, at the core of CMS, operates in a 3.8T magnetic field, measuring particle momentum via trajectory curvature. It must be lightweight to avoid disturbing the particle while maintaining accuracy.
- ▶ The CMS Tracker is made entirely of silicon for high-precision tracking. Current Outer Tracker (OT) consists of strips measuring 10cm × 180μm, and thickness of 300μm.
- ▶ The Phase-2 CMS detector will feature an upgraded OT with pixel-strip and strip-strip (2S) modules, equipped with unique feature of hardware level track triggering capabilities for the first time in any HEP experiment.



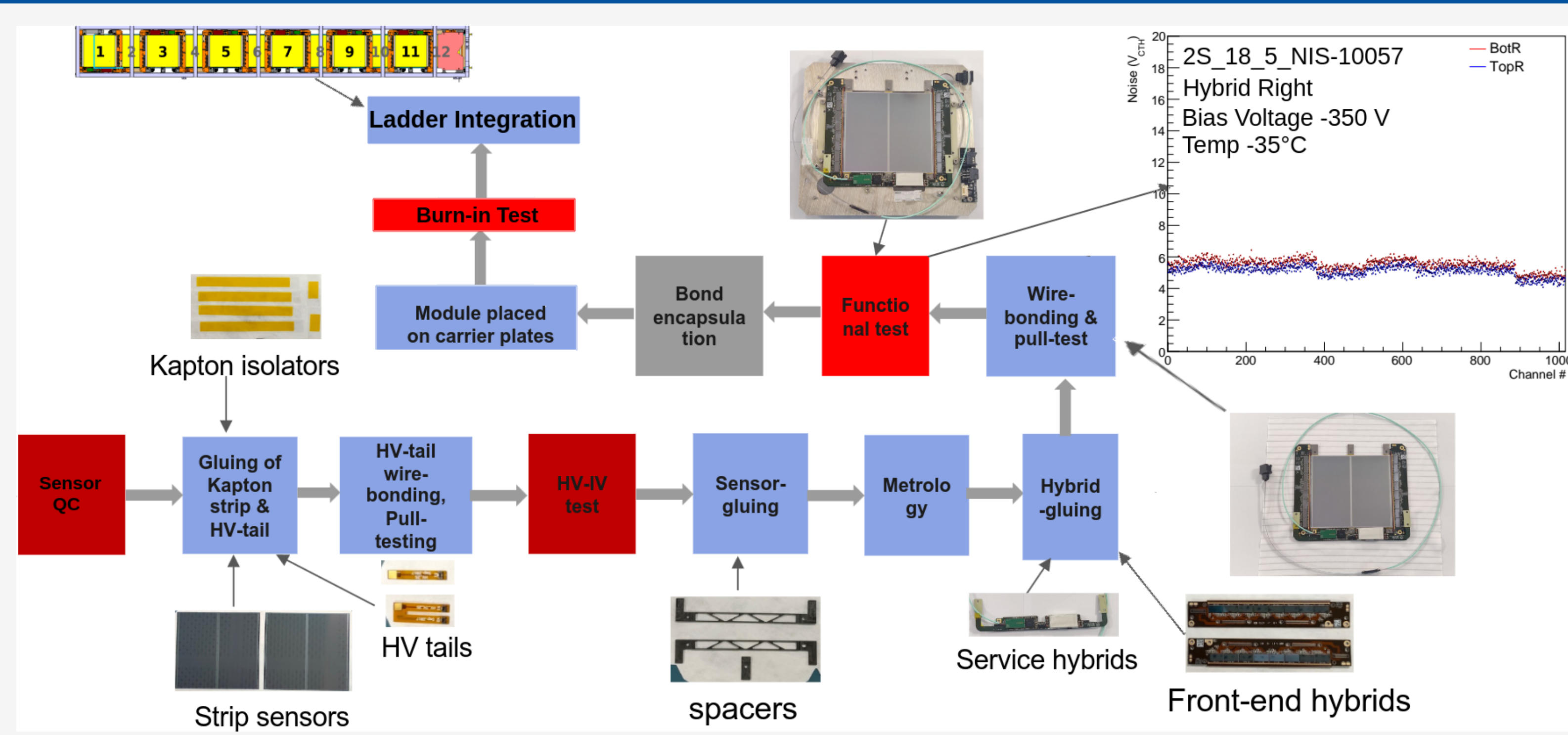
- ▶ Three different flavours of 2S modules exist: 1.8mm 5CP, 1.8mm 6CP and 4.0mm 6CP
- ▶ Total 7680 2S modules will be installed in the tracker, with 4464 in TB2S and 3216 in TEDD, which will be assembled and integrated at various sites across the world.



- ▶ Each 2S module consists of silicon strip sensors with 2032 strips per sensor, totaling 4064 channels, and with each strip having dimension of 5cm × 90μm. For each row, strips are read out by 8 CMS binary chips (CBC).
- ▶ Common CBC reads out both top and bottom sensors, CBC searches for hit correlation from first to second layer within a programmable window. The detection of hit within this window is called a stub, which does hardware triggering.
- ▶ Stubs and hit data are sent at 320 MHz to Concentrator IC (CIC), which aggregates the data and performs clustering and zero suppression. Data are then converted to optical signal and sent to back-end electronics.



## 2S Tracker Module Assembly Procedure



## 2S Tracker Module Assembly

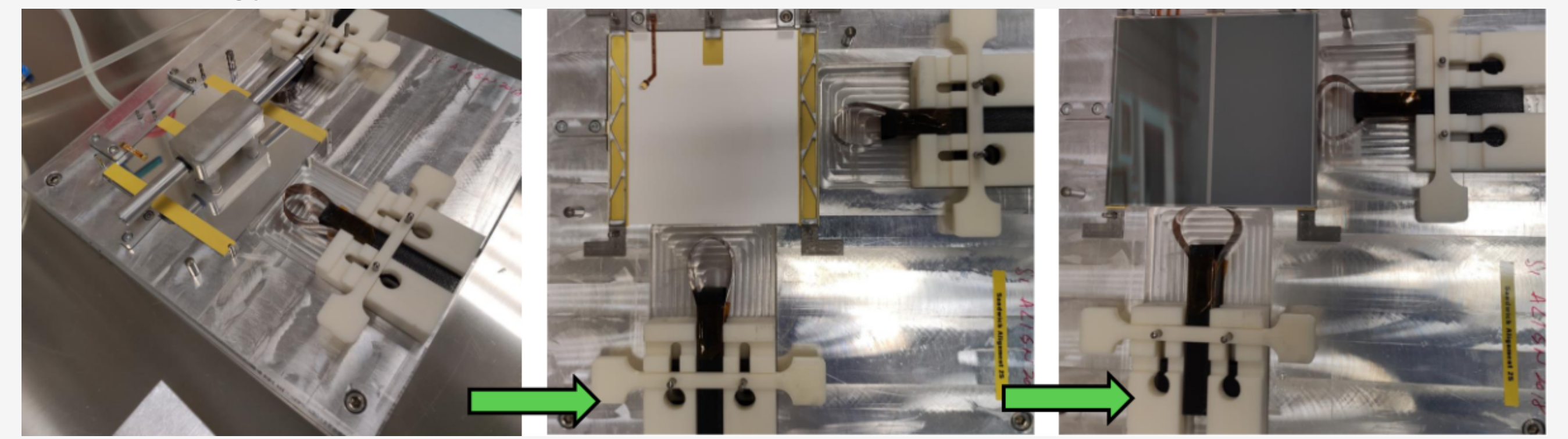
To assemble modules, a class 10,000 cleanroom is essential to avoid contaminating sensors, hybrids, and electronics.

### 1. Sensor-kapton isolators gluing

- ▶ Sensor IV measurements are taken using a probe station up to bias voltage of -800 V. Thin kapton strips (25μm) and HV tails are glued to the backplanes for insulation.
- ▶ Multiple layer of 10μm low-viscosity glue is applied uniformly.
- ▶ After curing, HV tails are wire-bonded using a wire-bonder and encapsulated. Final HV and IV tests are conducted to confirm proper connections.

### 2. Sensor-sensor gluing

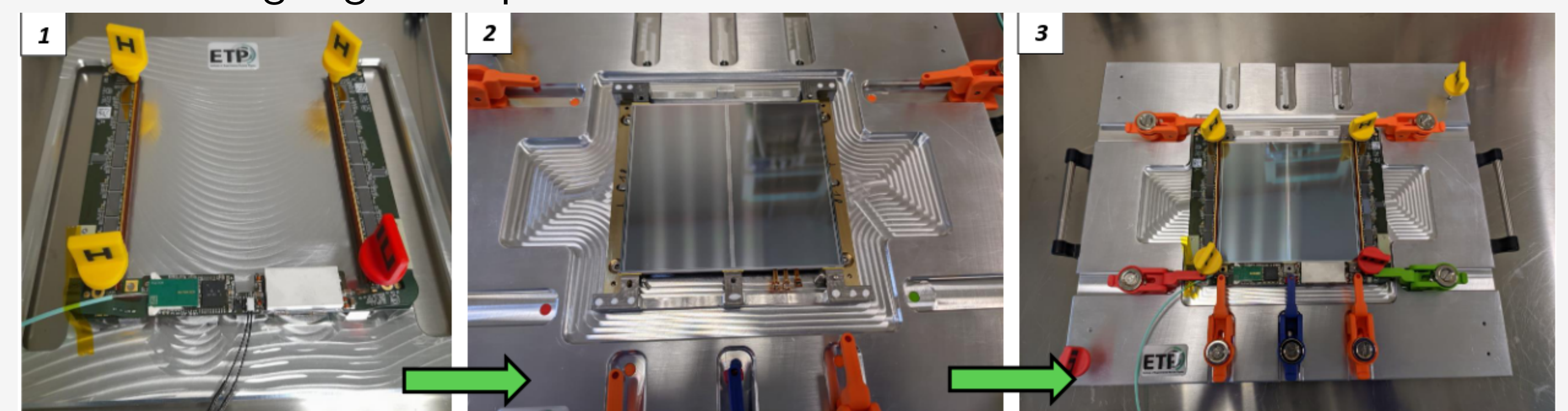
- ▶ AI-CF spacers are used for sensor-sensor gluing, to ensure track curvature above 2 GeV for hardware-level  $p_T$  selection precise tolerances are required: relative rotation < 400μrad, translation along sensor length < 100μm, and along sensor pitch < 50μm.
- ▶ Needle-based vision measurement, double-sided camera or laser-based measurement are used for metrology.



Sensor sandwich steps

### 3. Hybrid gluing

- ▶ Hybrids consisting radiation hard CBC (65 nm) and CIC (130 nm) ASICs are assembled into skeleton. Electronic noise measurements aka functional tests are performed to ensure proper hybrid functionality.
- ▶ Eleven dots of glue are applied to the AI-CF support structure, and the skeleton is aligned and lowered using alignment pins on to sensor sandwich.



Hybrid gluing steps

### 4. Automatic ultrasonic wire-bonding

- ▶ Sensor channels are bonded to hybrids using a wire-bonder, with a total of 4064 bonds (1016 × 4 sides).
- ▶ ~10 bonds are pull-tested using a pull tester to ensure bond quality.
- ▶ Functional tests are performed after bonding, and wirebonds are encapsulated on both sides. Functional tests are repeated after glue curing to ensure consistency.

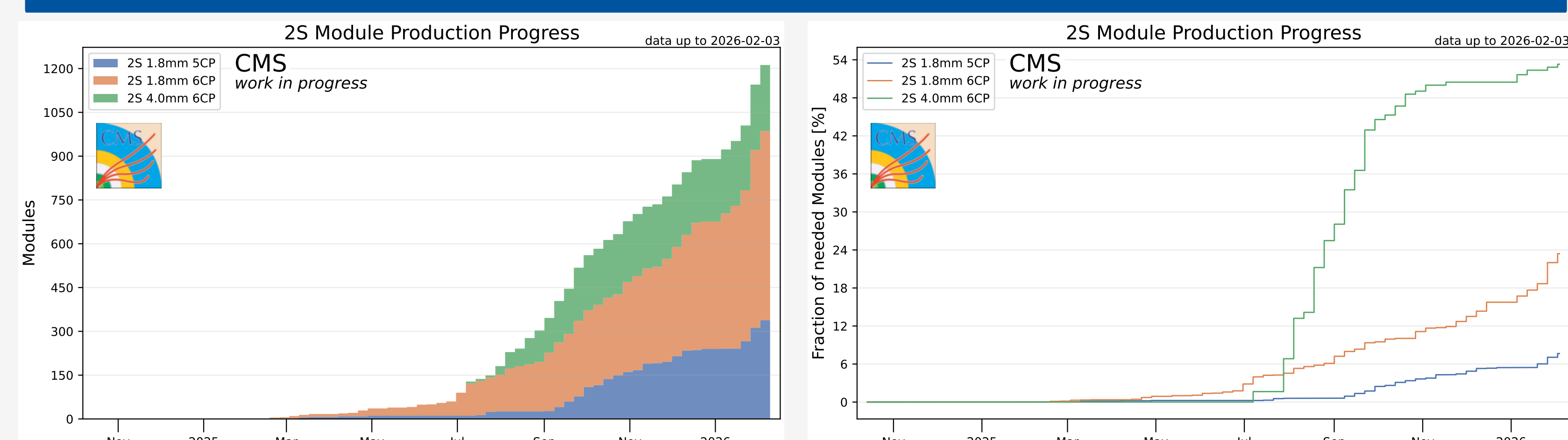
### 5. Multi-module burn-in test

- ▶ Ten modules are assembled in a burn-in setup, where they undergo controlled thermal cycling between 20°C and -35°C. Functional tests are conducted at each temperature.
- ▶ Otsdaq [2] and Phase-2 acquisition and control framework [3] are used to control the temperature cycling and module readout.

### 6. Sub-structure assembly

- ▶ After burn-in modules are integrated in ladders and dees.
- ▶ Ladders will be integrated in tracker barrel (TB2S) and dees will be integrated in tracker endcap (TEDD).
- ▶ CO<sub>2</sub>-based Marta cooling plant is used for temperature cycling for these sub-structures.
- ▶ Collective noise profile of all the modules from ladders and dees are measured at different temperature.

## 2S Module Production Progress



Cumulative number of potentially good 2S modules produced grouped by module variant. The granularity is in weeks.

Fraction of needed 2S modules produced excluding spares grouped by module variant. The granularity is in weeks.

## References

- [1] CMS Collaboration, "The Phase-2 Upgrade of the CMS Tracker," tech. rep., CERN, Geneva, Jun 2017.
- [2] CMS Collaboration, "Otsdaq cms tracker." [https://gitlab.cern.ch/otsdaq/otsdaq\\_cmstracker](https://gitlab.cern.ch/otsdaq/otsdaq_cmstracker), 2026.
- [3] CMS Collaboration, "CMS Tracker Phase2 Acquisition & Control Framework." [https://gitlab.cern.ch/cms\\_tk\\_ph2/Ph2\\_ACF/](https://gitlab.cern.ch/cms_tk_ph2/Ph2_ACF/), 2026.