Design and construction of the CMS Outer Tracker for the Phase-2 Upgrade

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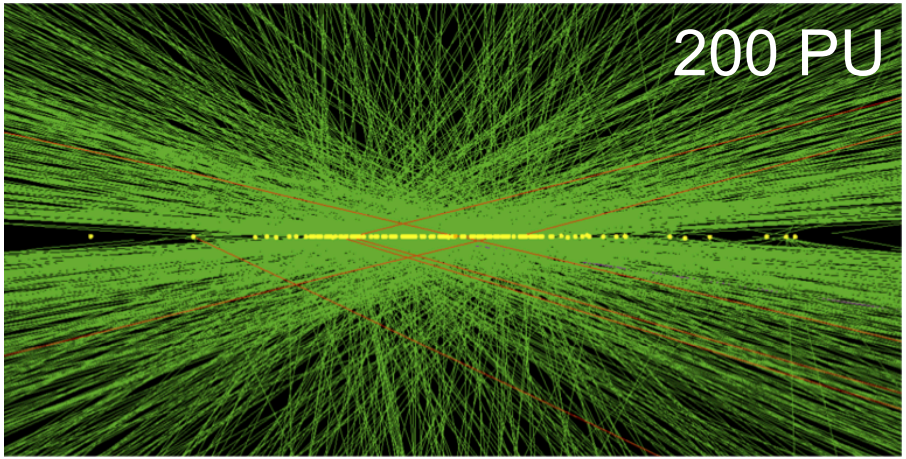
17th October 2023

Vertex 2023, Sestri Levante (Italy)

The Phase-2 Outer Tracker upgrade at HL-LHC

HL-LHC

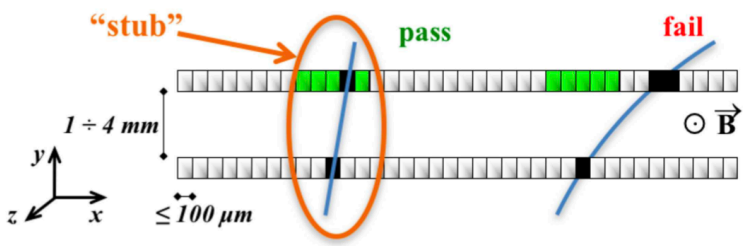
- Instantaneous peak luminosity: 5-7.5x10^{34} $cm^{-2}s^{-1}$ → 3000-4000 fb^{-1} of data!
- $\sqrt{s}$ ~ 14 TeV
- High pileup up to 200 events/25 ns
- High radiation environment



Phase-2 Outer Tracker upgrade

- The whole tracker will be replaced
- Increase granularity: channel occupancy around or below the per cent level
- Provide tracking information in the L1 event selection
- Reduced material

The p_T-module concept

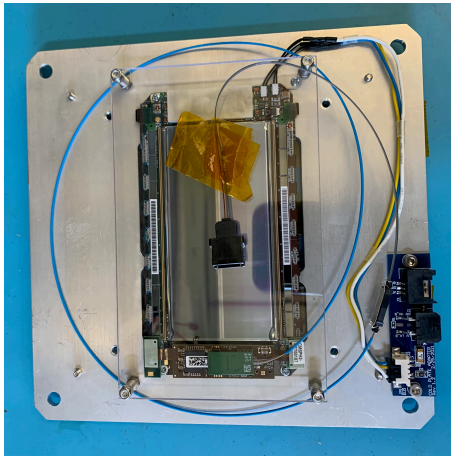


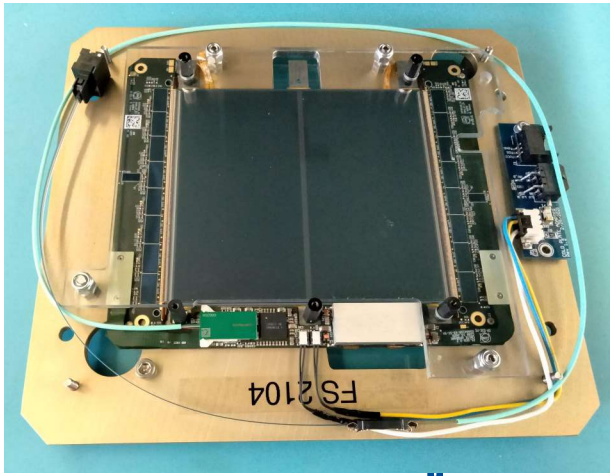
Tracking at L1
40 MHz

- **Stubs** (hits from tracks with p_T>2 GeV) sent to the back-end electronics at 40 MHz to build L1 track primitives

More on the L1 Track Finder in Christopher Brown's talk

- two p_T module versions
  - **PS** (pixel + strip) modules r < 60 cm
  - **2S** (strip + strip) modules r > 60 cm





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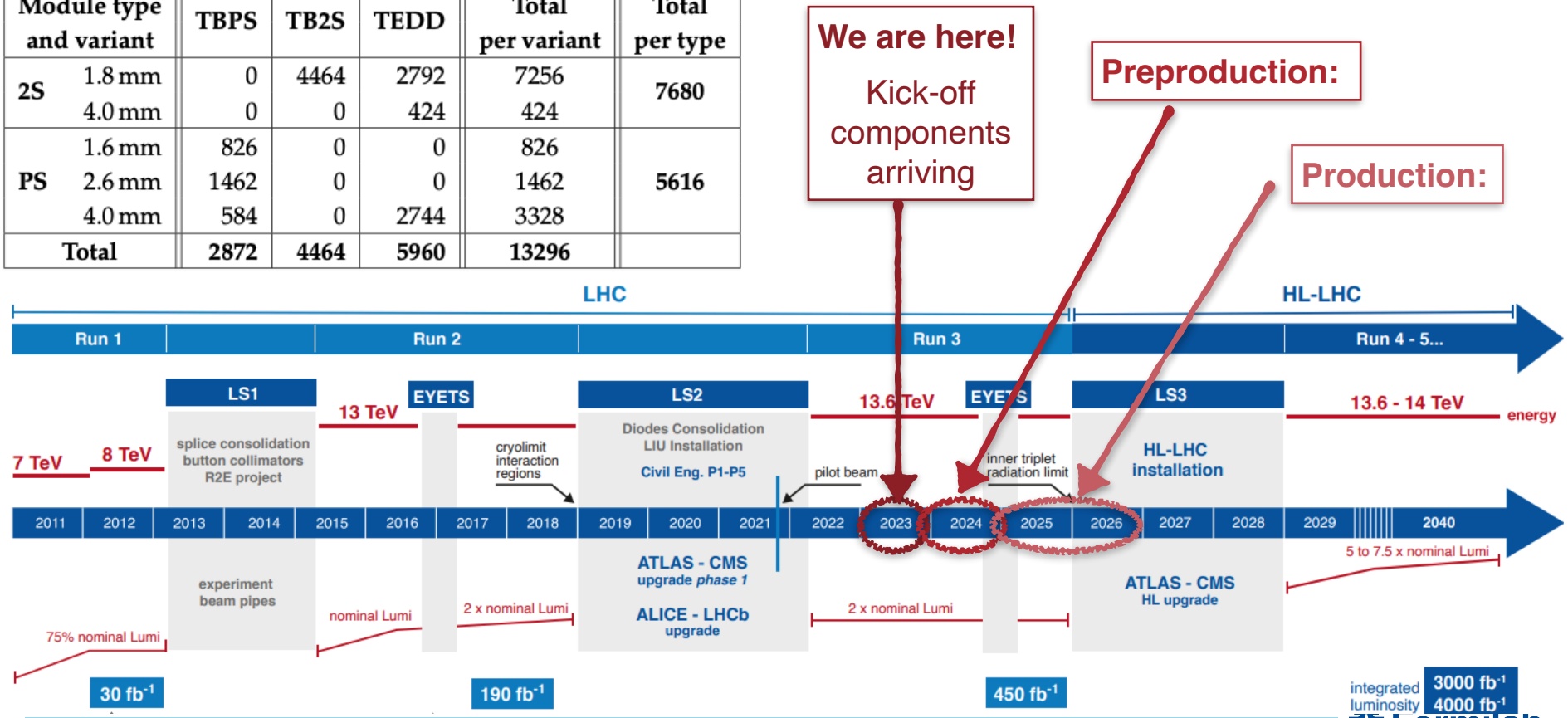
Module production

Module type and variant		TBPS	TB2S	TEDD	Total per variant	Total per type
2S	1.8 mm	0	4464	2792	7256	7680
	4.0 mm	0	0	424	424	
PS	1.6 mm	826	0	0	826	5616
	2.6 mm	1462	0	0	1462	
	4.0 mm	584	0	2744	3328	
Total		2872	4464	5960	13296	



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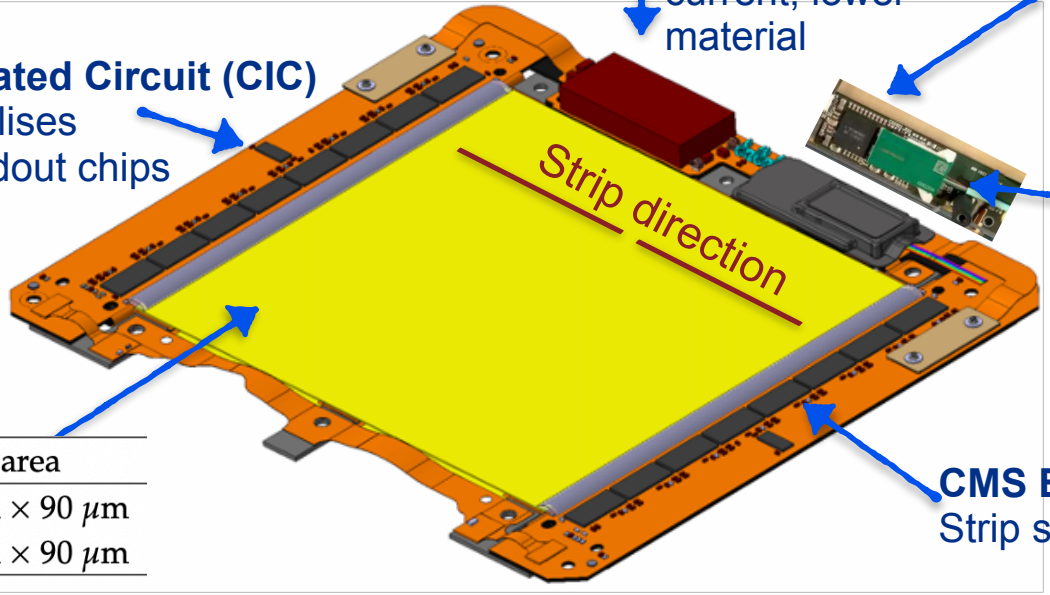
The Strip-strip (2S) module

DC/DC converter
10V input: lower current, lower material

Low-power GigaBit Transceiver (LpGBT)
CERN development for data transfer at HL-LHC

Concentrator Integrated Circuit (CIC)
Aggregates and serialises the data from the readout chips



VTRx+ electrical-optical converter
5Gb/s optical readout

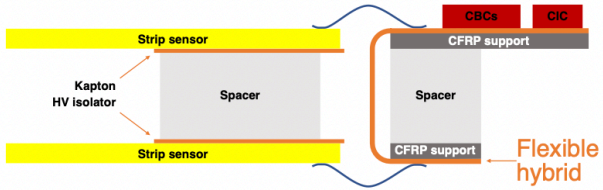
Strip sensors

$\sim 2 \times 90$ cm^2 active area	
2×1016 strips:	~ 5 cm $\times$ 90 μm
2×1016 strips:	~ 5 cm $\times$ 90 μm

CMS Binary Chip (CBC)
Strip sensors readout

Radiation hardness: 5×10^{14} n_{eq}/cm^2

1.8 or 4.0 mm



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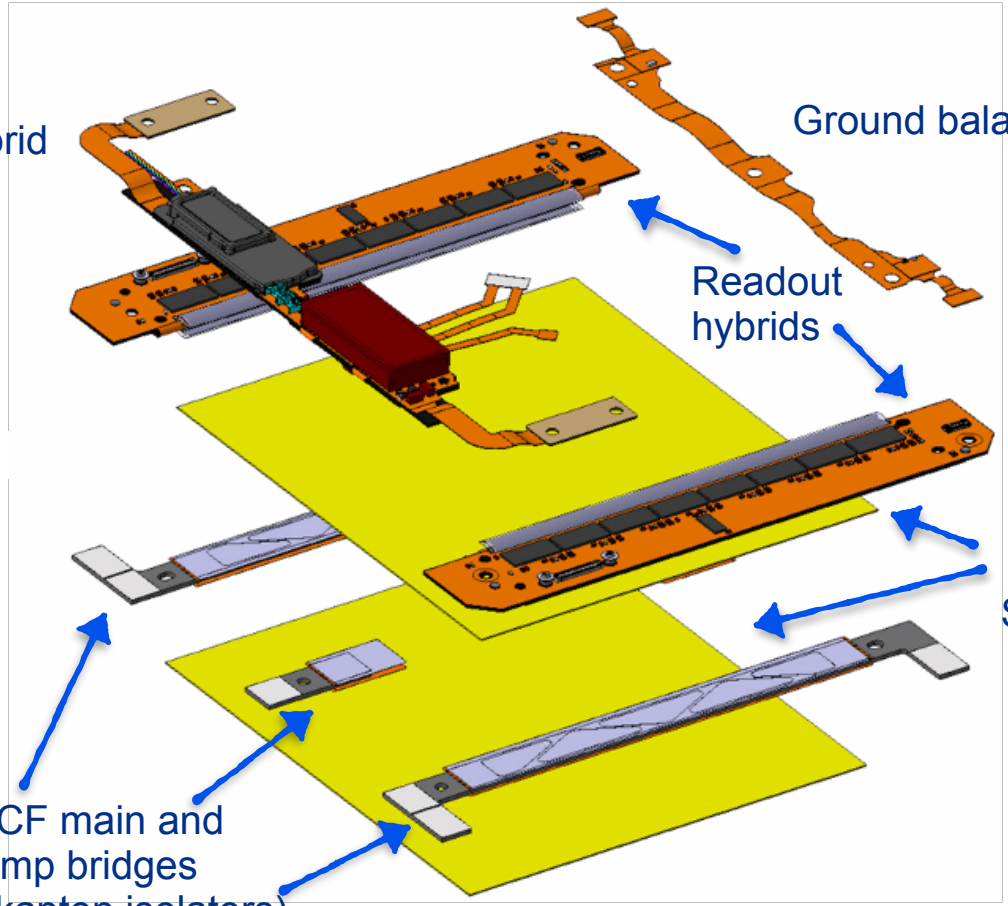
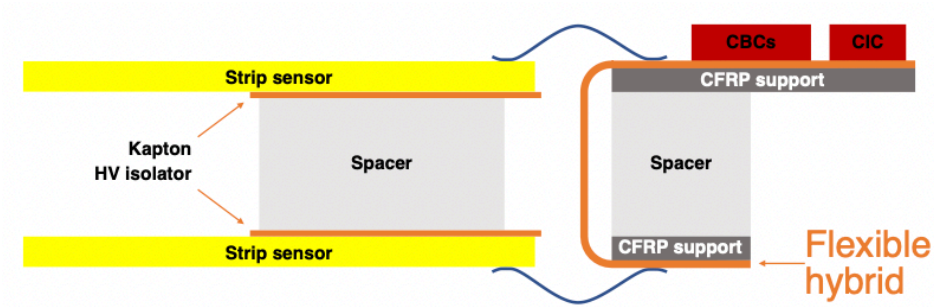
2S module assembly

- 7608 2S + spares needed
  - 7 production centers in Europe, US, India and Pakistan



Requirements on hybrids' fold-over

- Allow to wirebond both sensors to the same hybrid
- Provide adequate stiffness for wire bonding
- Minimize material
- Avoid stress and deformation when operating cold



Complicated fabrication and delicate part!

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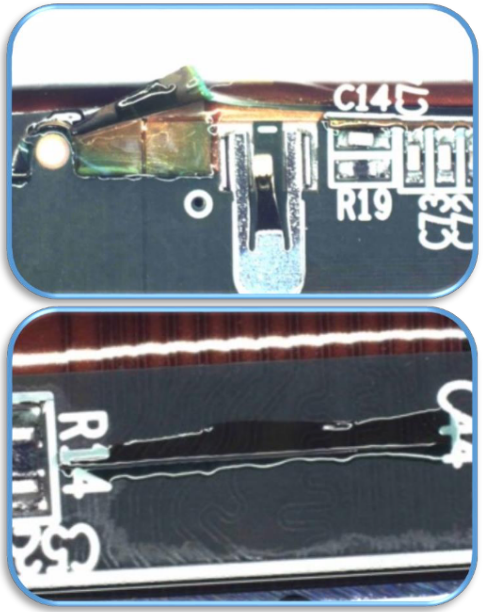
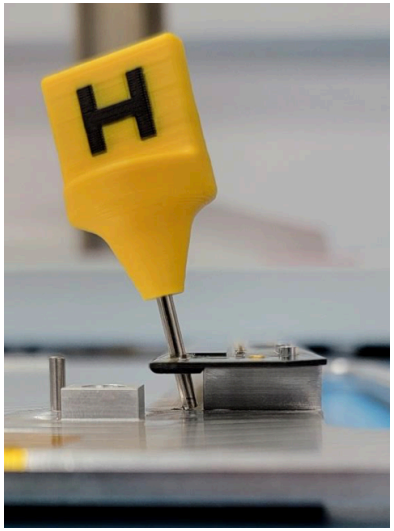
Fold-over hybrids

- We had problems with the lamination and cracks
- Alignment holes blocked in some prototypes



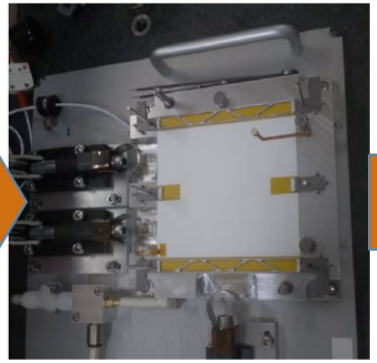


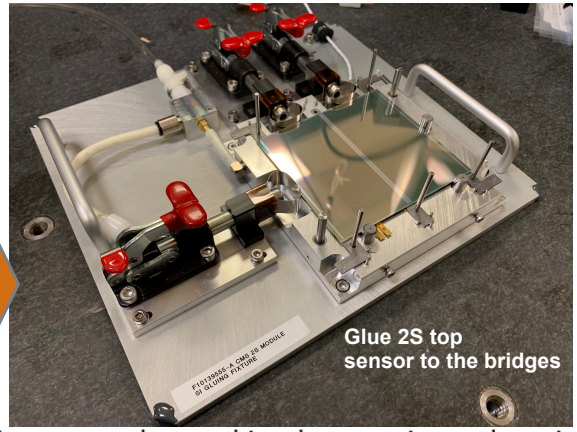
- Coverlay area is enlarged
- Increased distance between coverlay area and surface-mounted components
- New alignment holes and slots placed in the fold-over cut-outs

2S module assembly workflow

Apply epoxy to the bridges

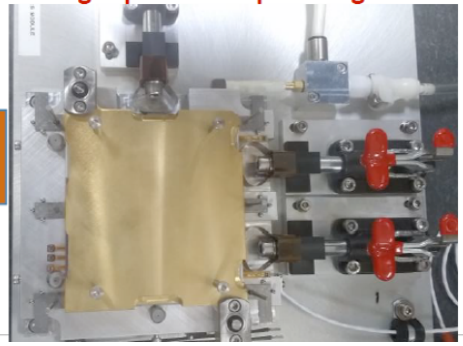
Glue bridges to the 2S bottom sensor





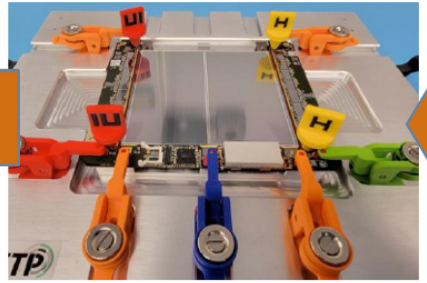
Top sensor located in place against edge pins
Pushers re-engaged

With weight plate on top while glue cures

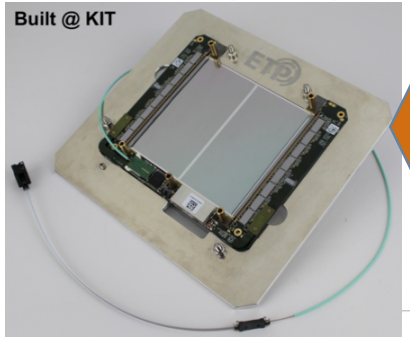


With bridges in place, offset edge pins help loading to the correct location

Attaching Hybrids: SEH and 2FEH



After wirebonding & encapsulation



- Specs:
- rotation < 400 μrad,
- strip parallel (perpendicular) offset < 100 (50) μm

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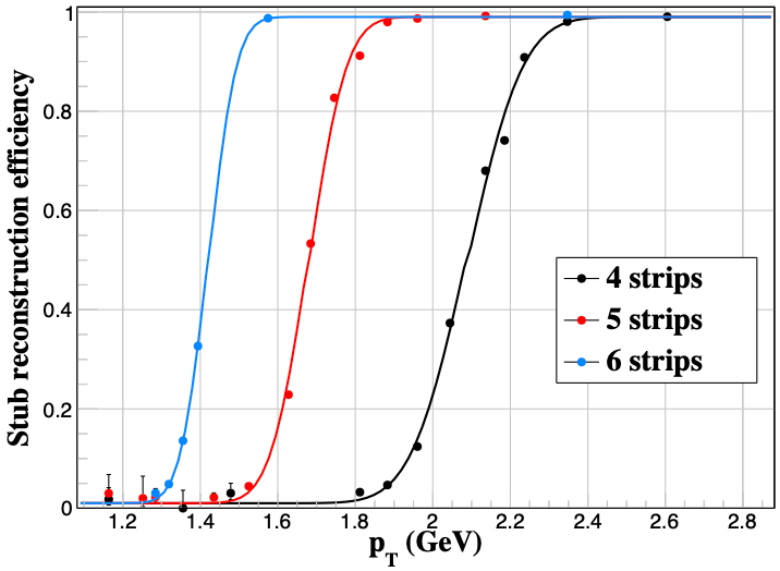
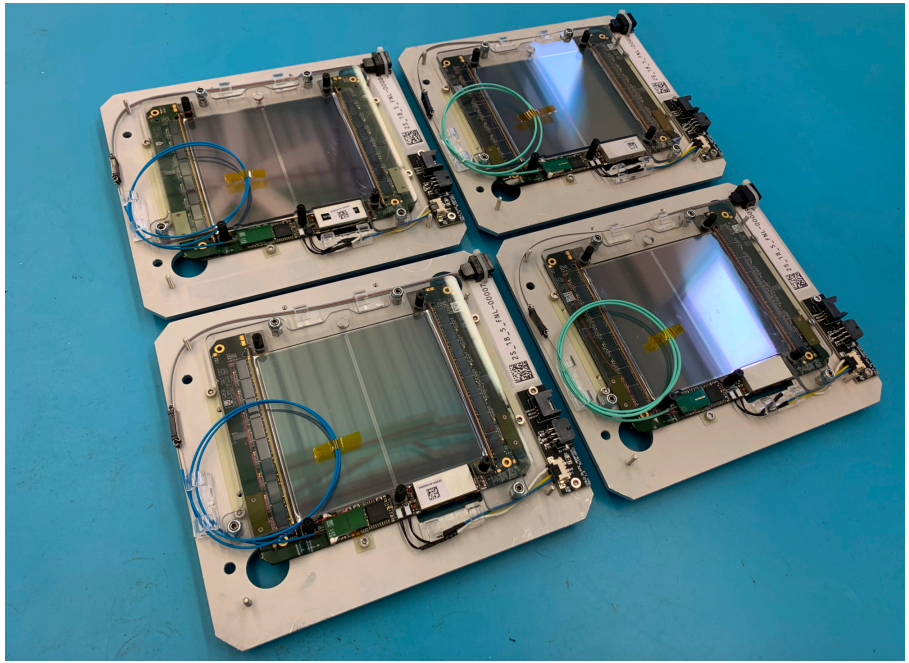
2S prototypes

- More than 60 modules built across the various production centers
- Several laboratory and beam/magnet tests carried out before and after irradiation, expected performance confirmed

[2023 JINST 18 P04001]





Parallel production of 4 modules @ FNAL at production rate

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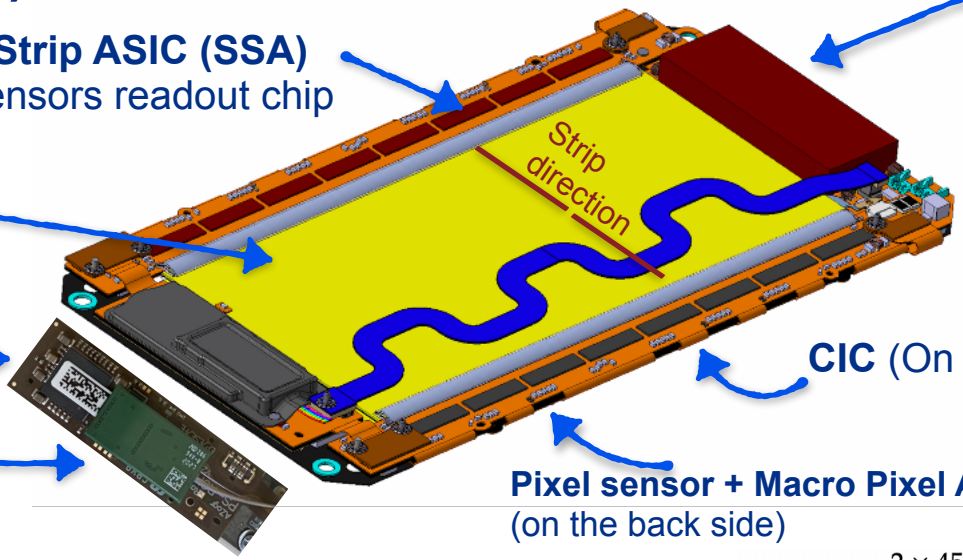
The Pixel-strip (PS) module

DC/DC converter
10V input: lower current, lower material

Short Strip ASIC (SSA)
strip sensors readout chip

Strip sensors
strip: ~2.4 cm x 100 μm
module area: ~10 x 5 cm2



LpGBT

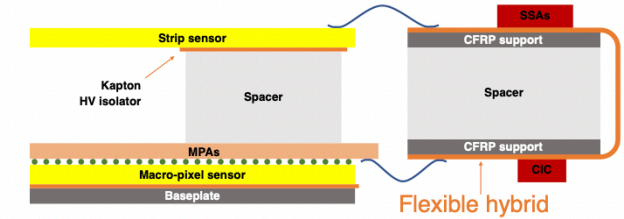
CIC (On the back)

VTRx+
5 or 10 Gb/s optical readout

Pixel sensor + Macro Pixel ASIC (MPA) = MaPSA
(on the back side)

$\sim 2 \times 45$ cm^2 active area	
2×960 strips:	~ 2.4 cm $\times$ 100 μm
32×960 macro-pixels:	~ 1.5 mm $\times$ 100 μm

1.6, 2.6 or 4.0 mm



Radiation hardness: 1.4x10^{15} n_{eq}/cm^2

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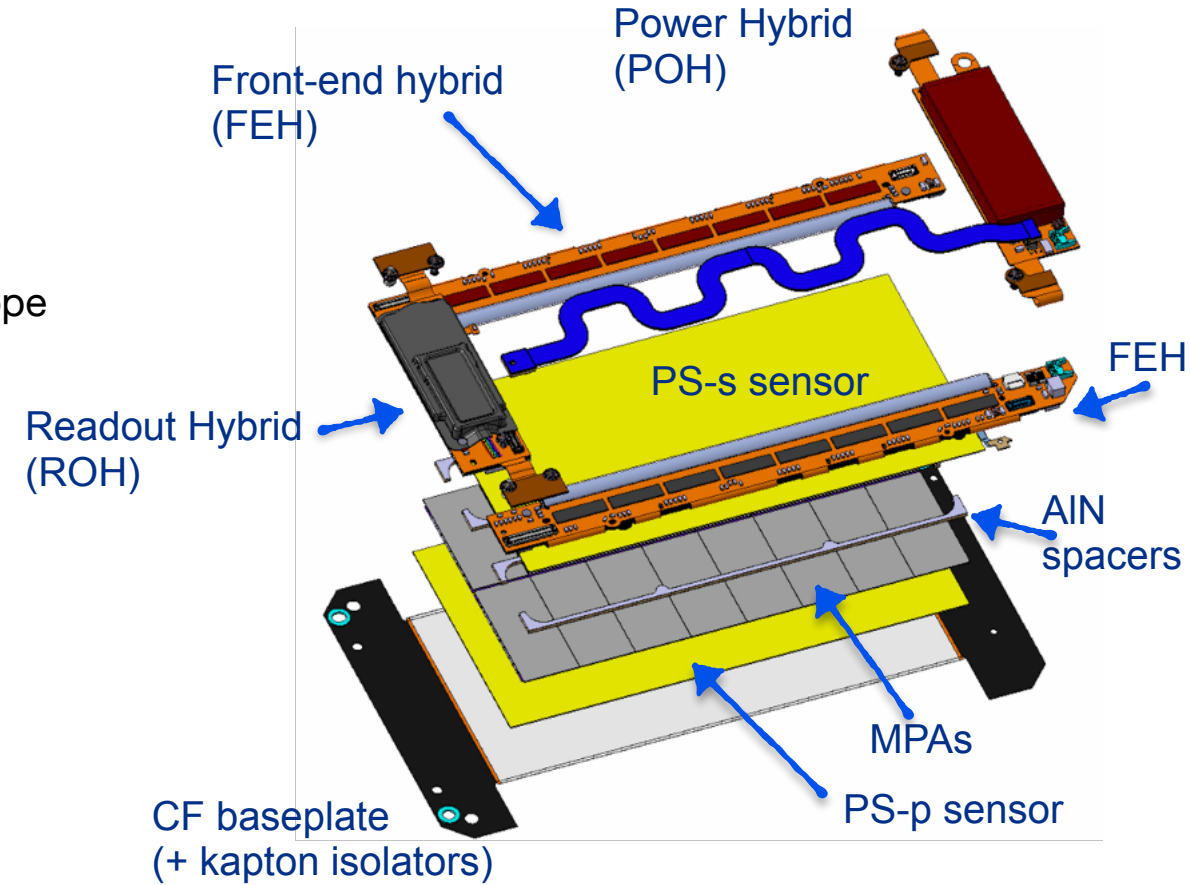
PS module assembly

- 5592 PS + spares needed
  - 5 production centers in Europe and US



More on the PS assembly and performance
in Ilirjan Margjeka's talk

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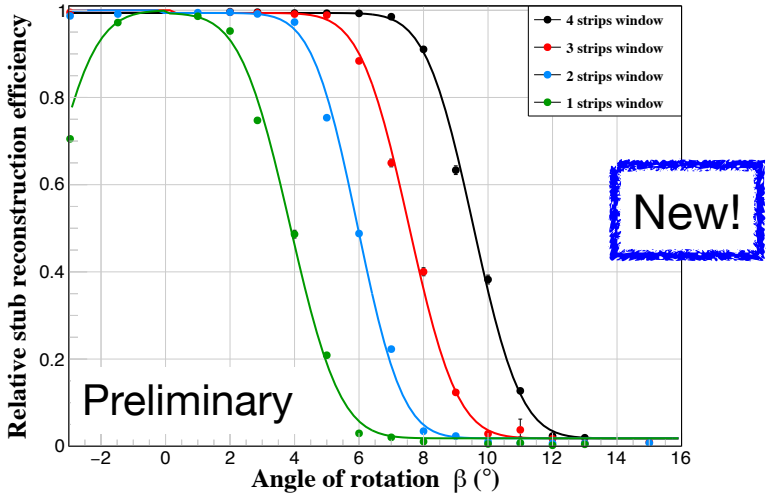
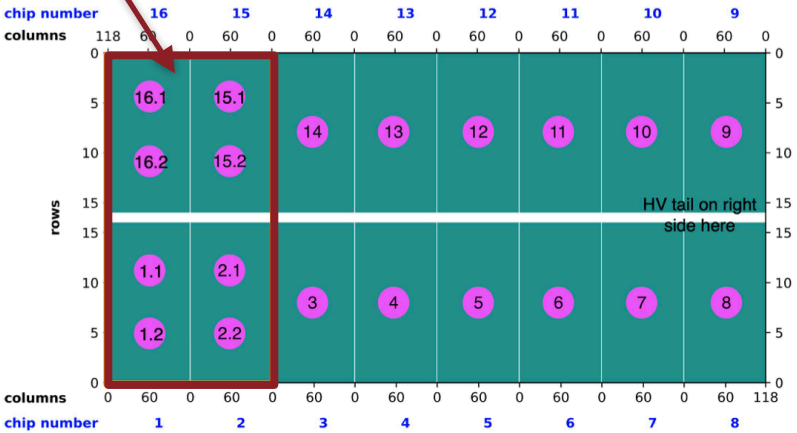
PS prototypes

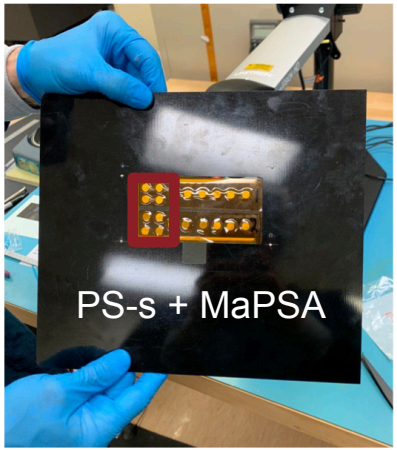
- More than 30 modules built across the various production centers
- Several laboratory and beam/magnet tests carried out before and after irradiation
  - Latest beam test this summer: stay tuned!

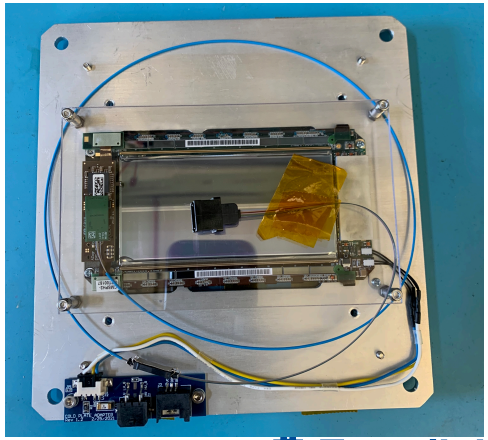


1.4x10^{15} MeV n_{eq}/cm^2

Non irradiated







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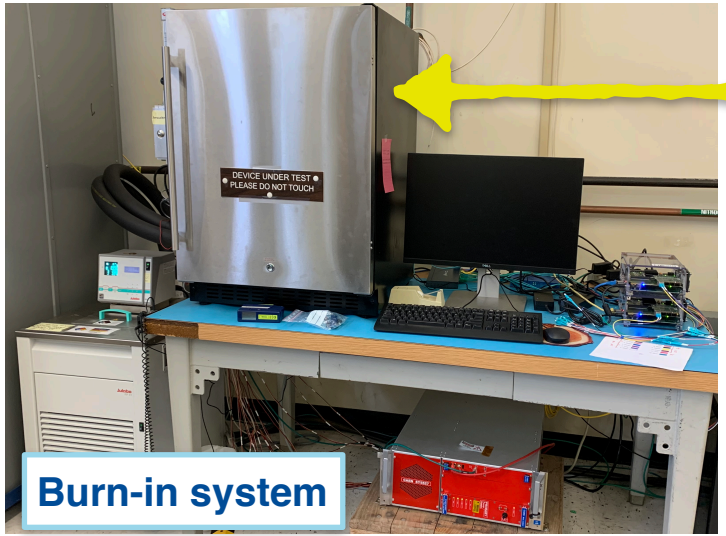
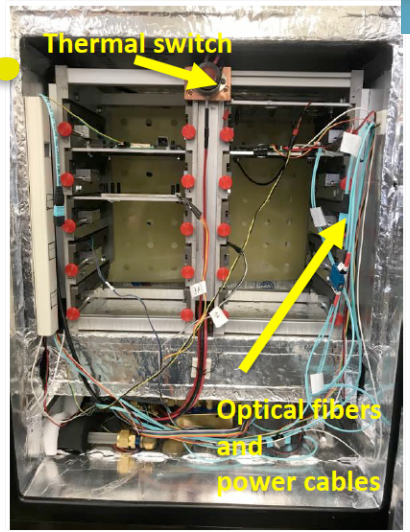
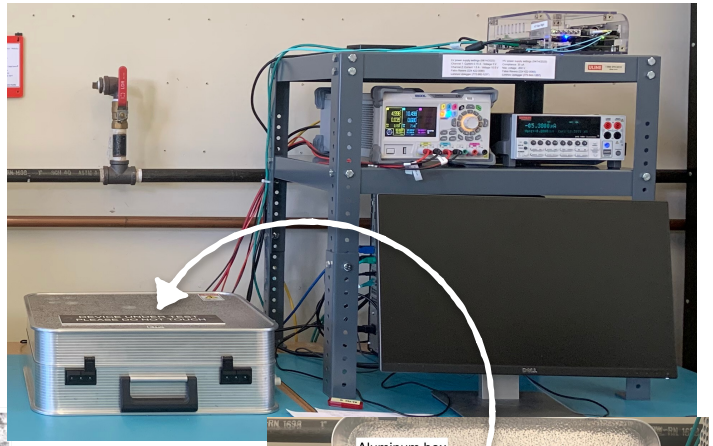
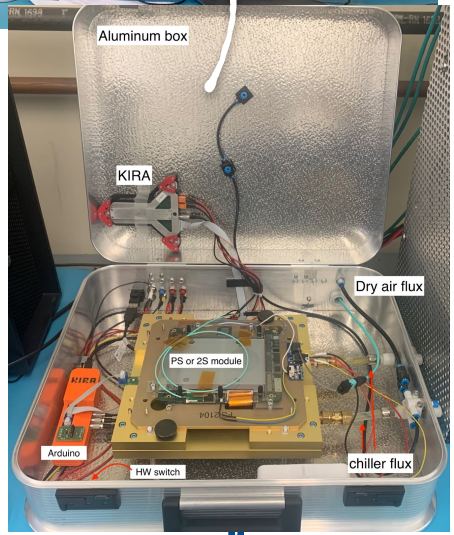
Test setup at production centers

- Reception test of sensors
- Basic functionality test of hybrid assembly (2S only)
- Module test before encapsulation
- Thermal cycles for 24h from RT to -33 ˚C



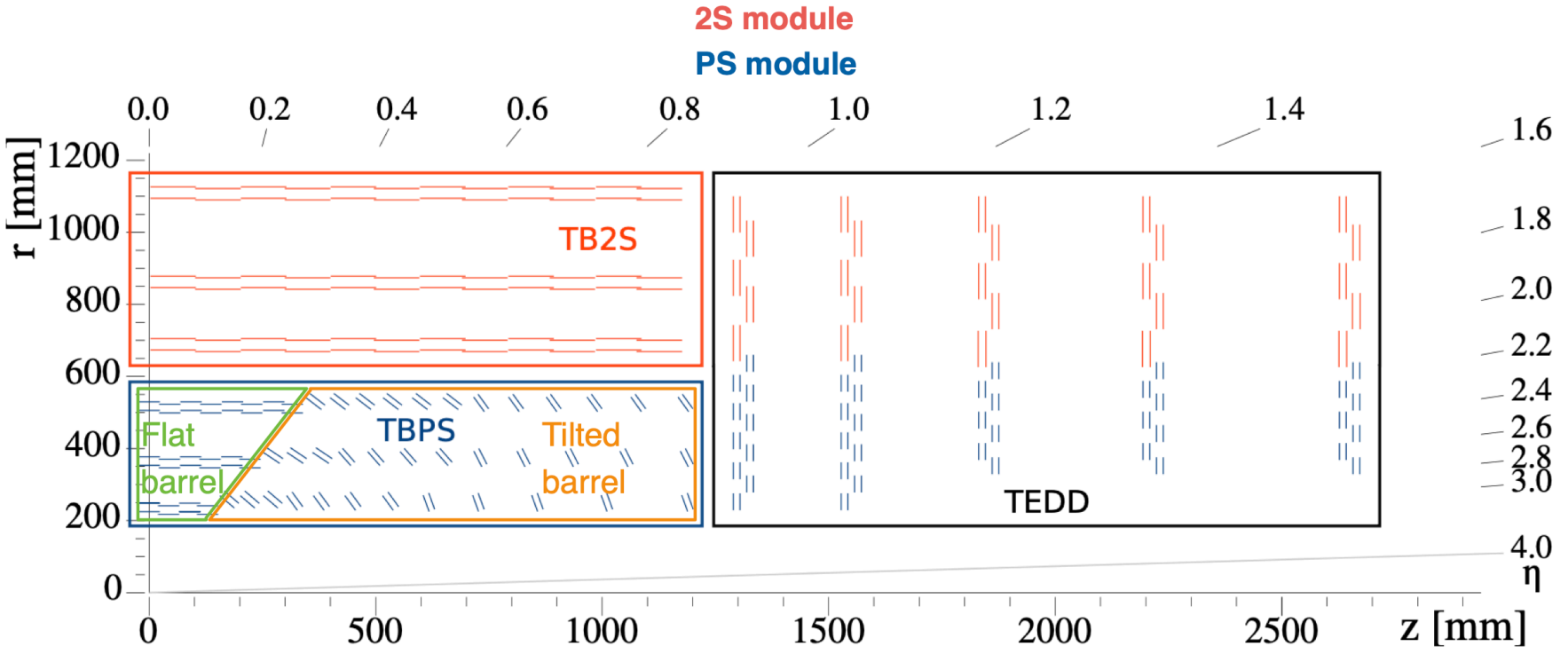






Tracker geometry

Minimum # of sensitive layers to ensure robust track finding at L1 trigger



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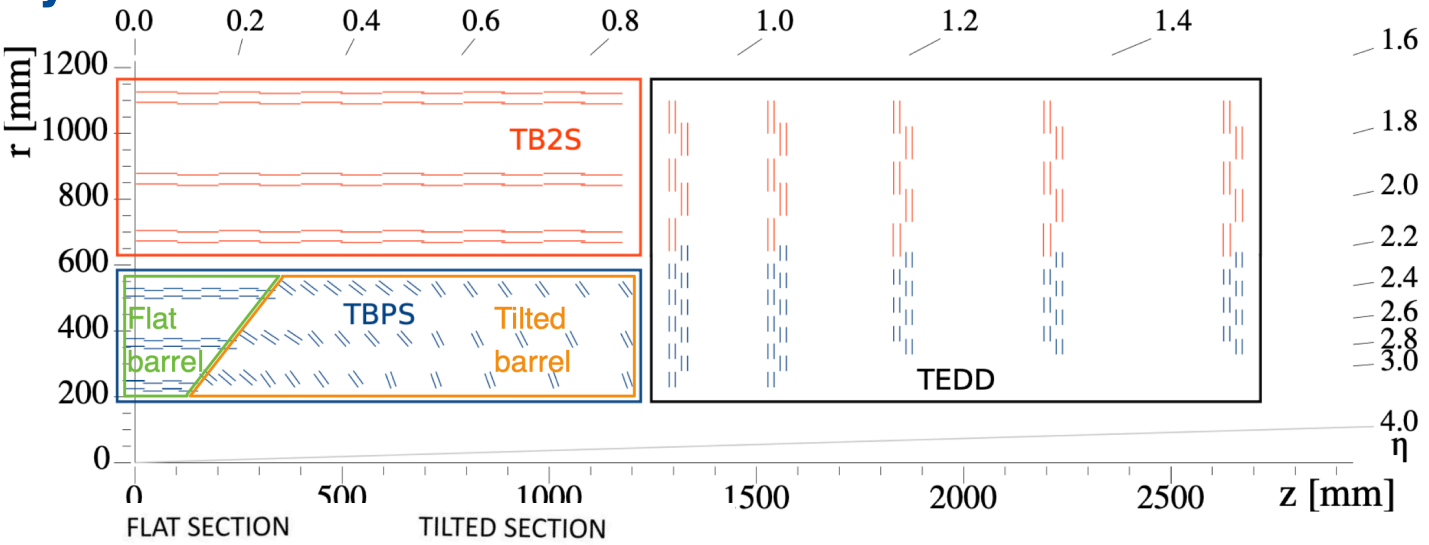
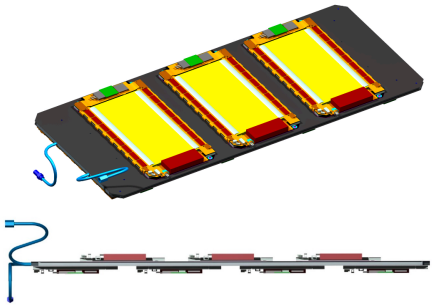
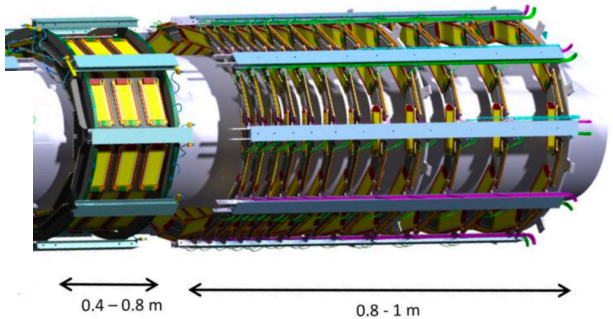
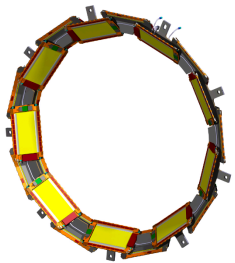
Tracker geometry









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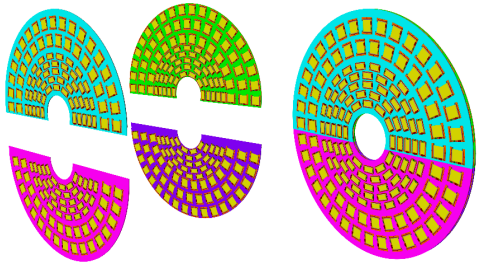
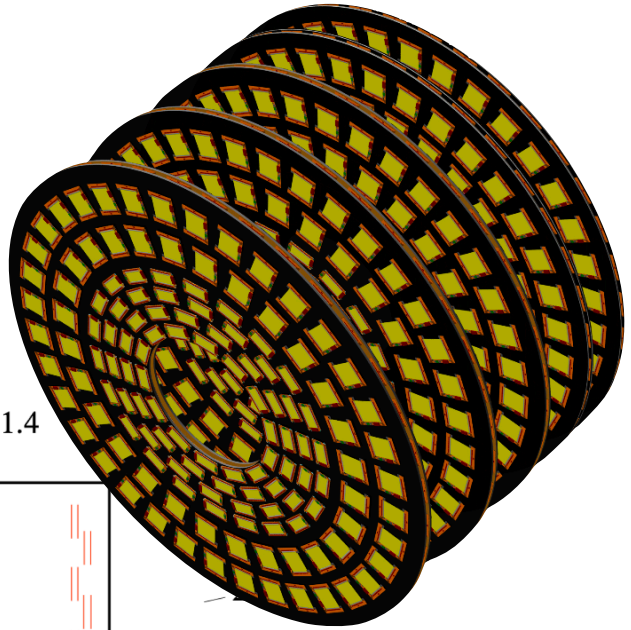
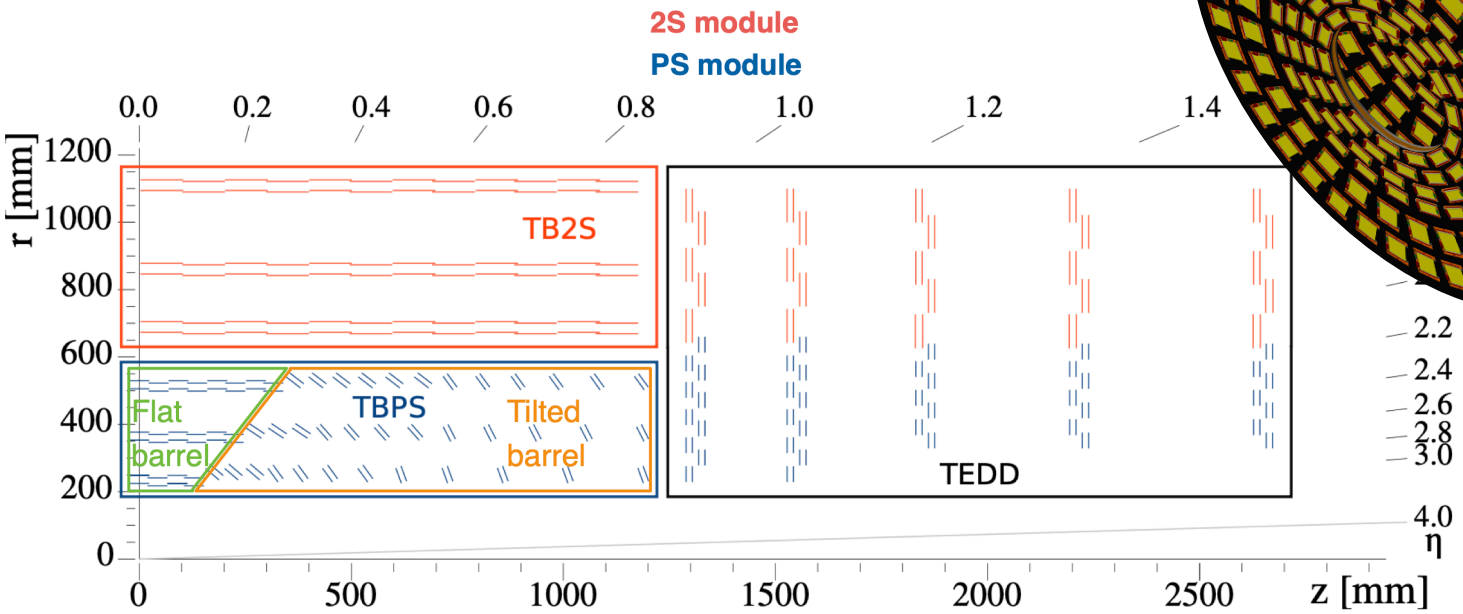
Tracker geometry







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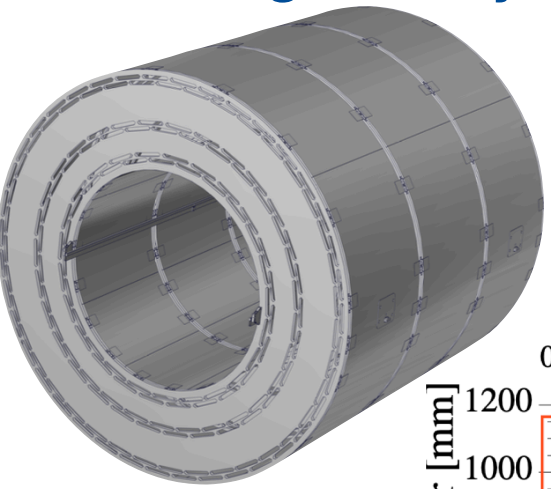
Tracker geometry



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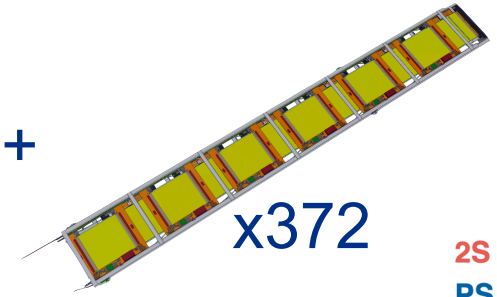

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2S module

PS module

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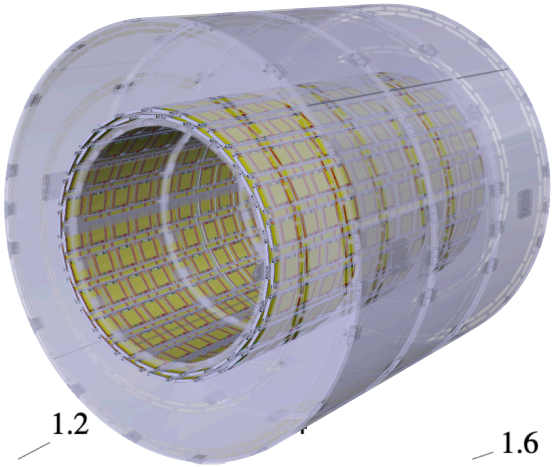

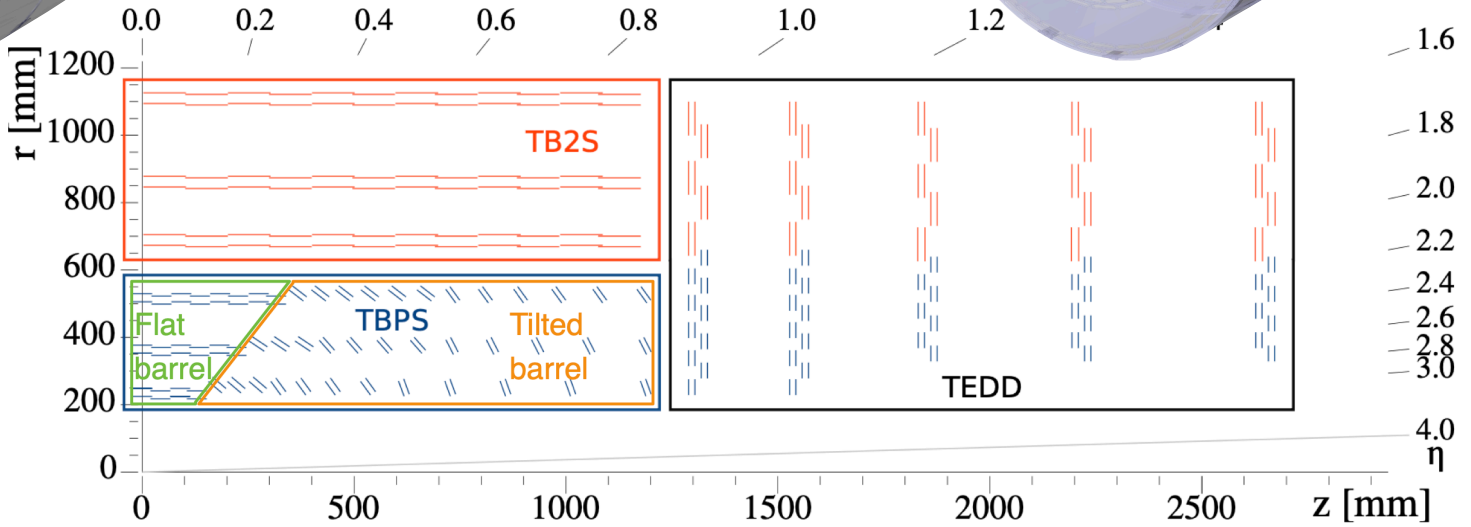

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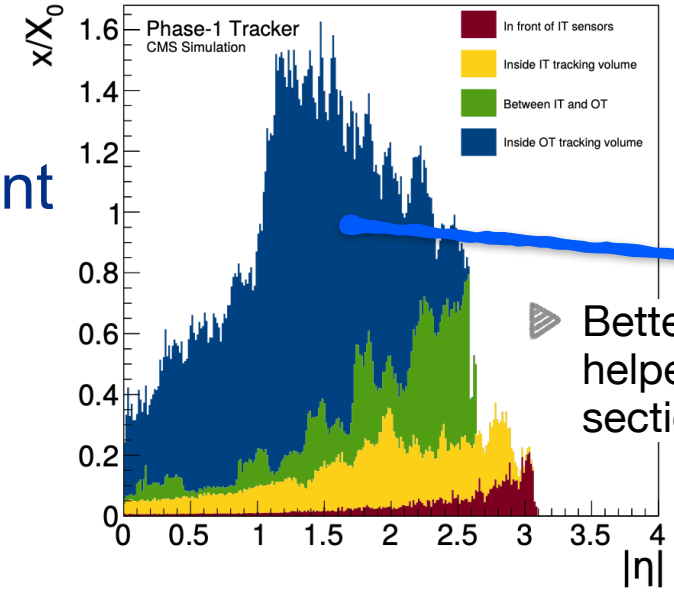
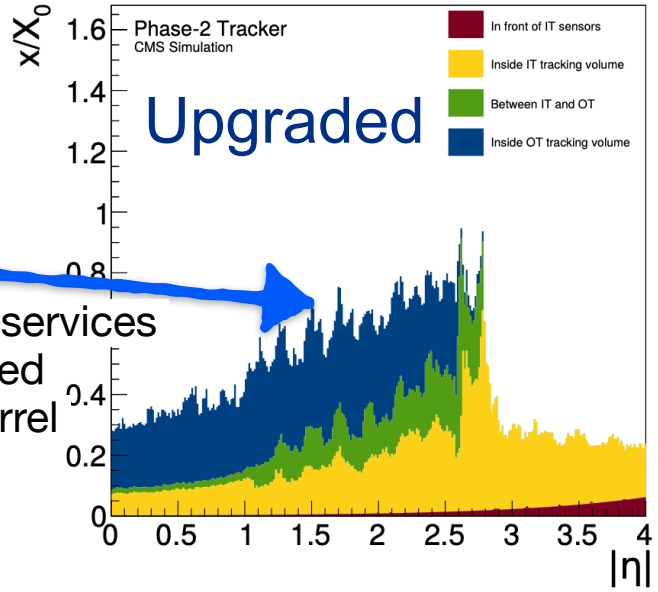
Mechanics, cooling and material budget

Current





- Better routing of services helped by the tilted section of the barrel

- Modules mounted on carbon fiber/carbon foam support structures
- 2-phase CO_2 cooling at -33 ℃
  - Smaller pipes wrt C_6F_{14} coolant currently used

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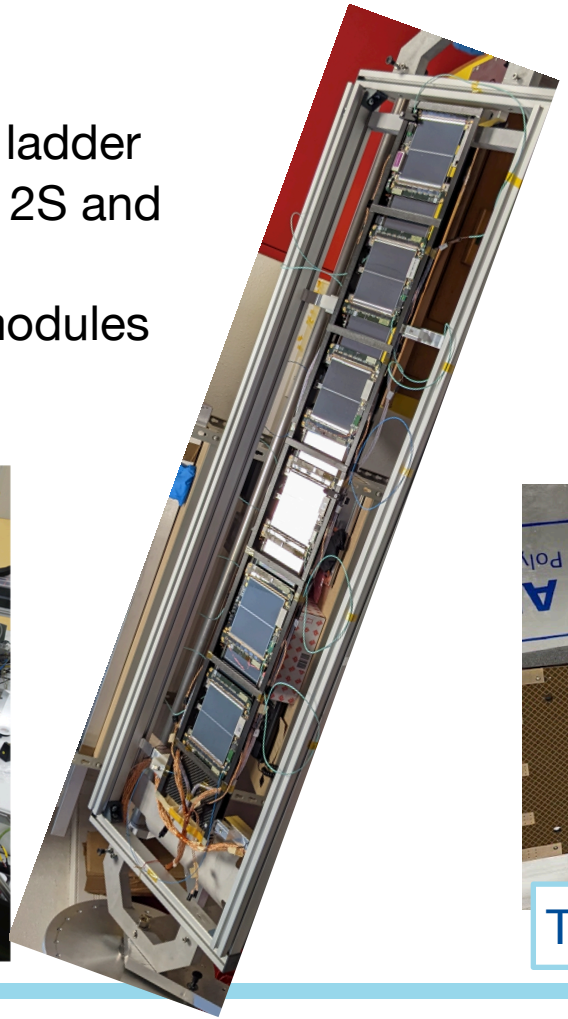
Integration tests

- On TEDD Dee and TB2S ladder
- First integration test with 2S and PS prototype modules
- First time mounting 2S modules on a dee prototype



- First vacuum backed module installed on a plank
- CO_2 cooling system for integration tests is fully functional
- Plank at -28° C

TBPS flat barrel

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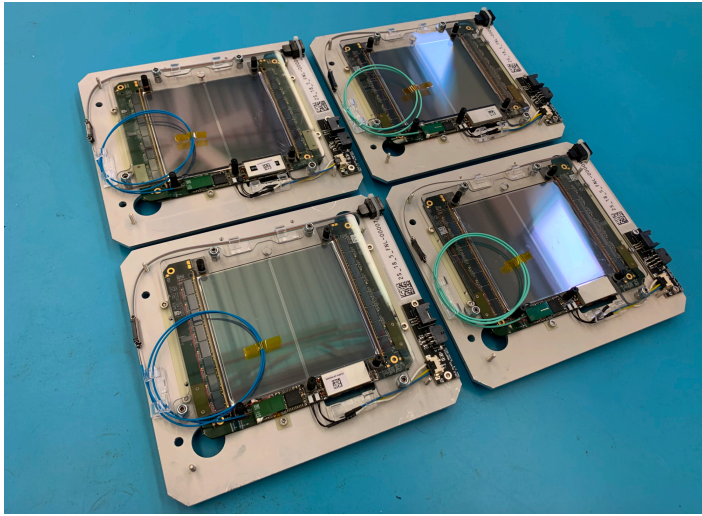
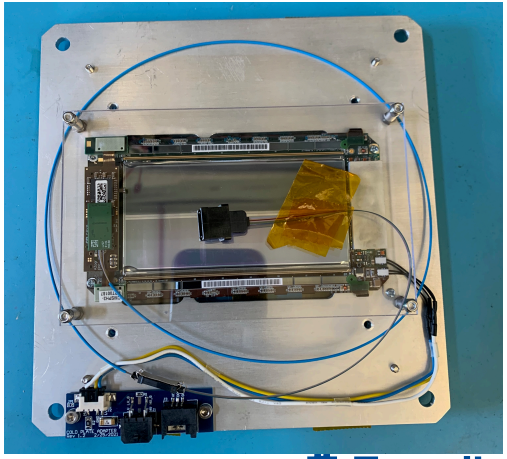
Summary

- The CMS tracker will be fully replaced for HL-LHC
- The new Outer Tracker features
  - Tracking at L1 thanks to the p_T modules
    - 2S and PS
  - Reduced material budget



- Module production centers are getting ready
  - Several prototypes successfully assembled and tested
  - Pre-production: 2024
  - Production: ~2025-2026



We are preparing the kick-off production as we speak!
Stay tuned!

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VERTEX 2023

Thank you!

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Module Assembly Centers and Expected Number of Modules

Center	Institutions	2S modules	PS modules
Aachen	RWTH Aachen	800	
Karlsruhe	KIT	1288	
Belgium	ULB, VUB, Antwerp	1512	
India	NISER, IIT-BBS, IOP Bhubaneswar, SINP Kolkatta, IITM	1104	
Pakistan	NCP Islamabad	1104	
US Midwest	Bethel, Fermilab, Iowa, Purdue, UC Davis, Wayne State	900	1242
US Northeast	Brown, Princeton, Rutgers	900	1310
DESY	DESY		1120
Bari	Bari		960
Perugia	Perugia		960
Total (w/o spares)		7608	5592

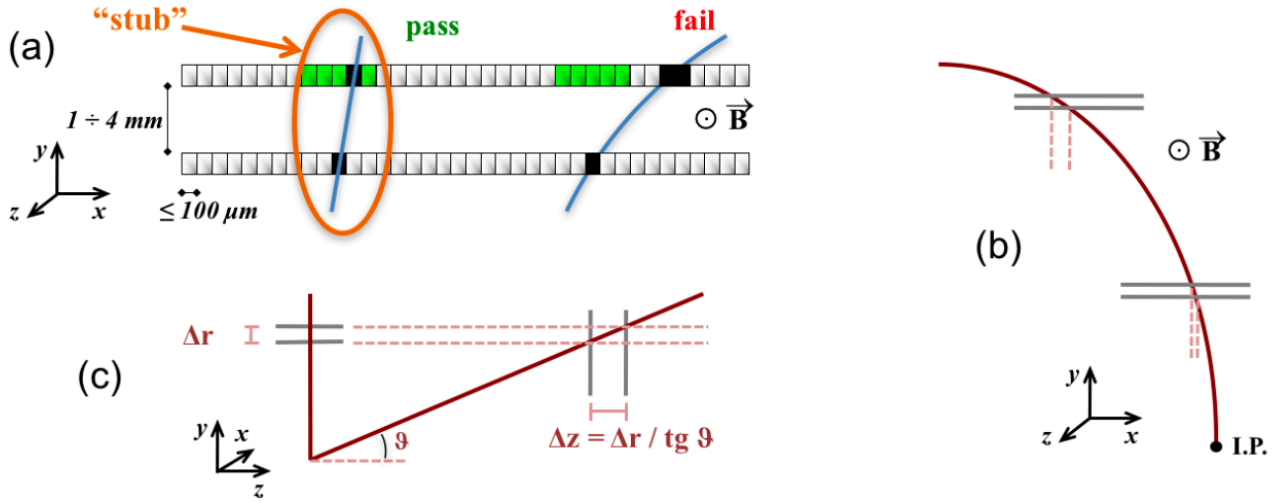


Figure 2.5: Illustration of the p_T module concept. (a) Correlation of signals in closely-spaced sensors enables rejection of low-p_T particles; the channels shown in green represent the selection window to define an accepted stub. (b) The same transverse momentum corresponds to a larger distance between the two signals at large radii for a given sensor spacing. (c) For the endcap discs, a larger spacing between the sensors is needed to achieve the same discriminating power as in the barrel at the same radius.

concept is therefore applicable in the Outer Tracker, and limited in angular acceptance to about $|\eta| < 2.4$.

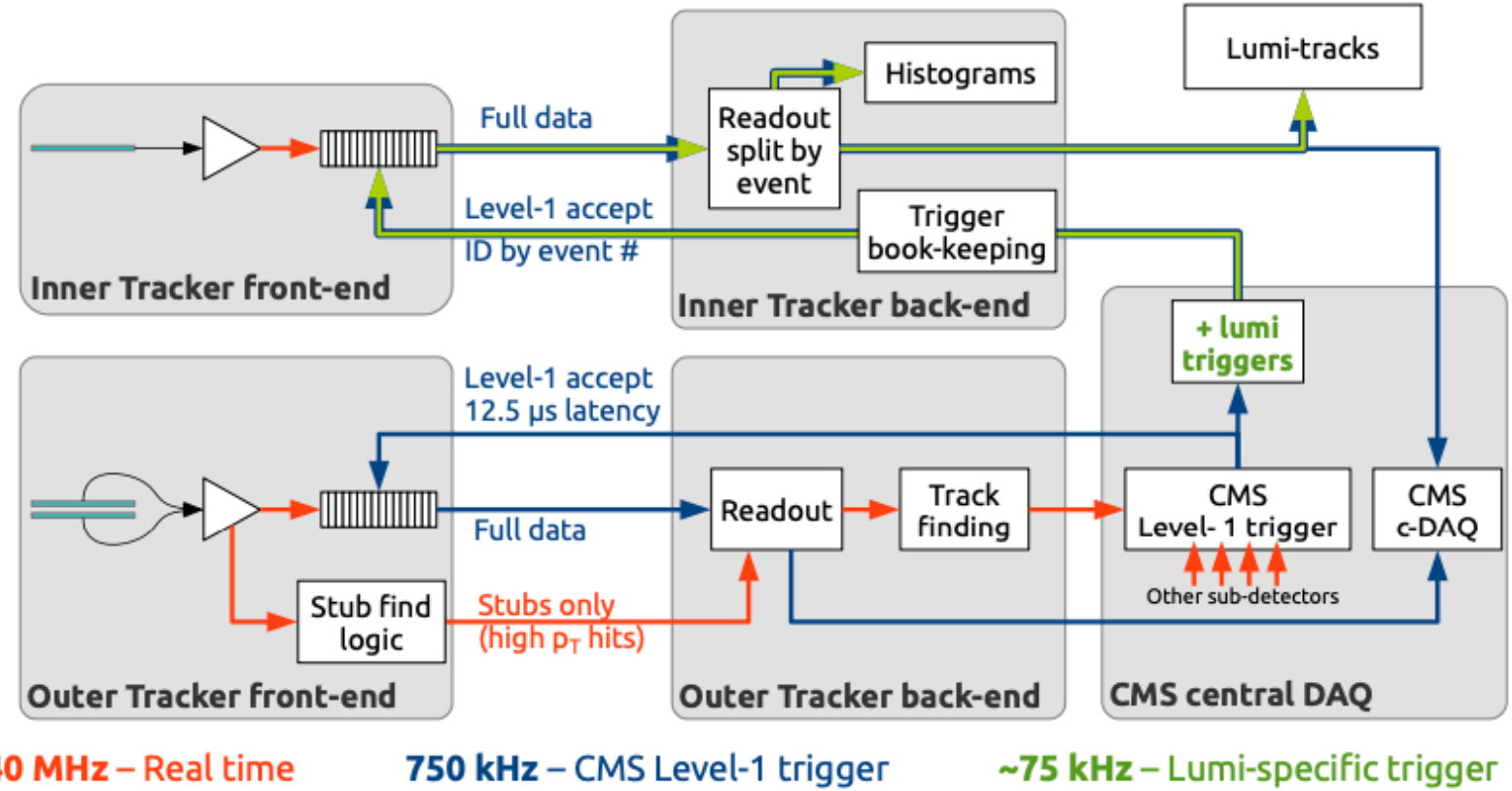
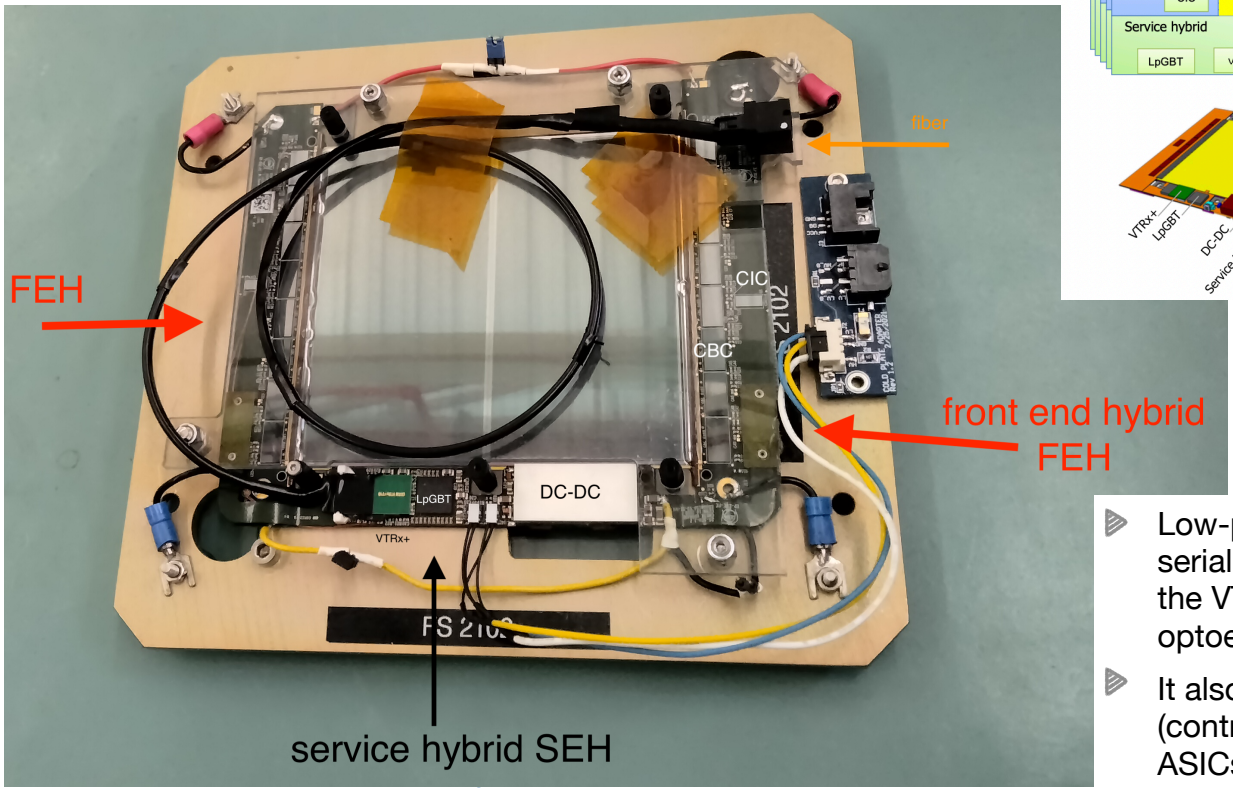


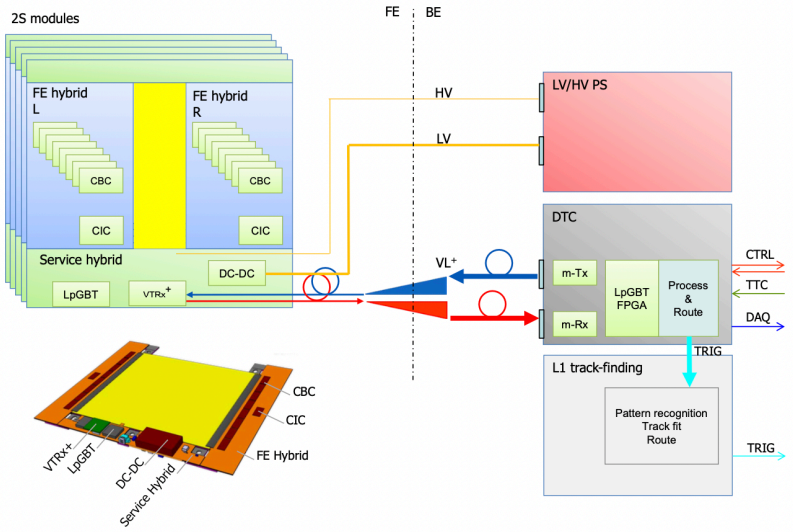
Figure 10.27: Diagram showing a potential distribution of dedicated luminosity triggers to the TEPX front-end and the data flow for luminosity measurements.

milab

2S module components

- CMS Binary Chip, CBC→ reading out the strips
- Concentrator Integrated Circuit, CIC
  →interface between CBCs and readout link

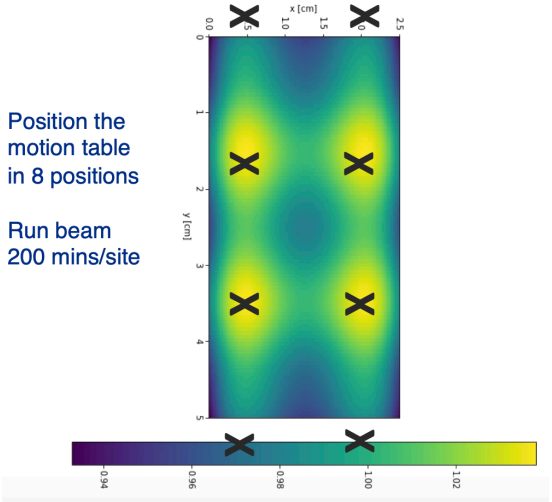


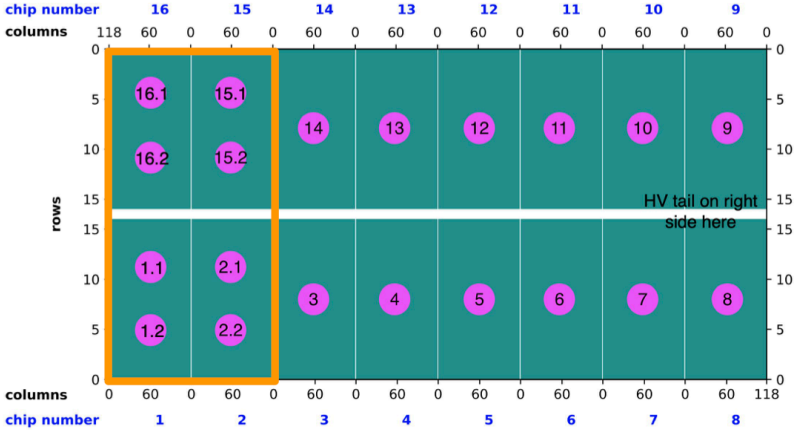


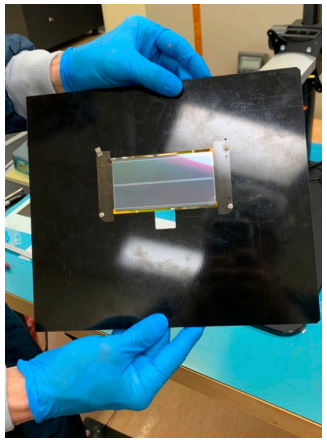
- CIC: aggregate and serialize the data of the readout chips and to distribute clock, trigger, and control signals to them.
- Low-power Gigabit Transceiver (LpGBT) serializes/deserializes data sent to/received from the VTRx+ (Versatile TRansceiver plus) optoelectronic transceiver.
- It also acts as I^2C master of the module (controlling, monitoring and configuring the FE ASICs)

Irradiation

- Sensor sandwich irradiated at Fermilab ITA (March 20-21)
  - 400 MeV protons, sigma = 1 cm, 8 pulses per minute, 32 μs chop time
- Target uniform fluence of 1.4e15 MeV neq/cm2 across MPAs 1-2, 15-16
- Focus irradiation on small area rather than whole sensor to reduce cool-down time and compare with non irradiated region







2S assembly

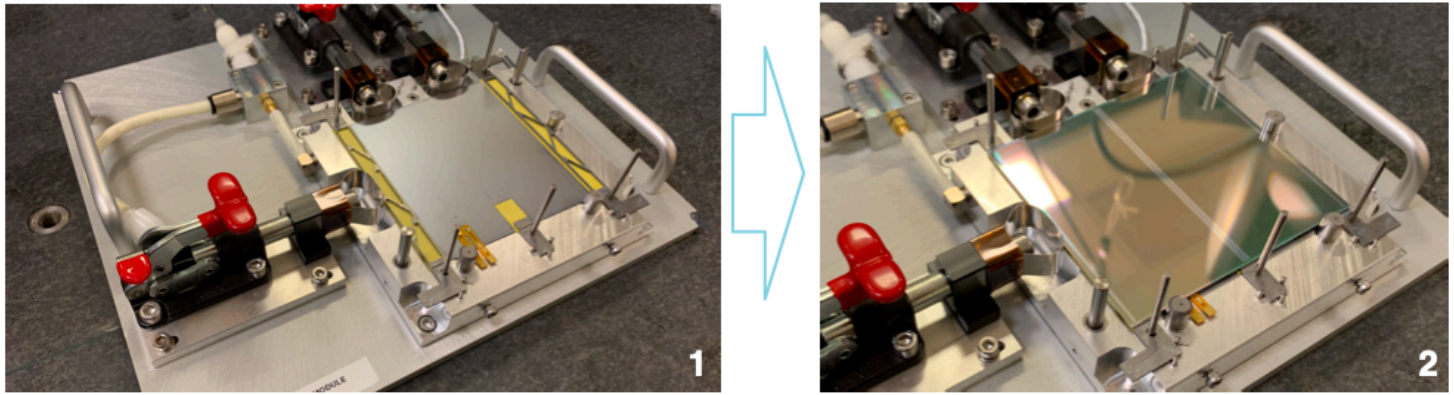
- Sensor preparation
  - Visual inspection and IV
  - Kapton and HV tail gluing
- Hybrid preparation
  - Visual inspection
  - “Skeleton” assembly
- Sensor sandwich production
  - sensor-bridges-sensor gluing
  - sensor-sensor alignment measurement
- Module production
  - Hybrid gluing
  - Wire-bonding and encapsulation

PS assembly

- CF baseplate preparation
  - insert and kapton gluing
- Strip sensor preparation
  - Visual inspection and IV
  - HV tail gluing
- Hybrid preparation
  - Visual inspection
- Sensor sandwich production
  - Strip sensor-spacers-MaPSA gluing
  - Alignment measurement
  - sandwich on CF baseplate gluing
- Module production
  - Hybrid gluing
  - Wire-bonding
  - Wire-bond encapsulation

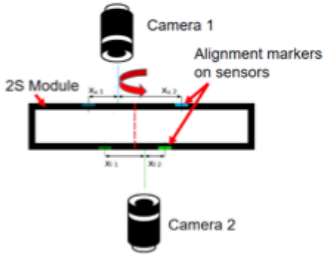
2S assembly - sensor alignment

Sensor-sensor gluing

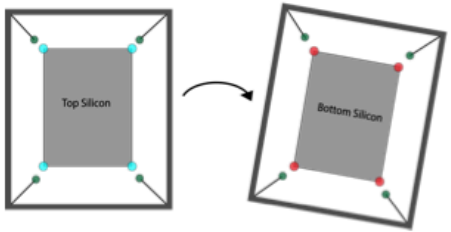


Sensor-sensor alignment measurement

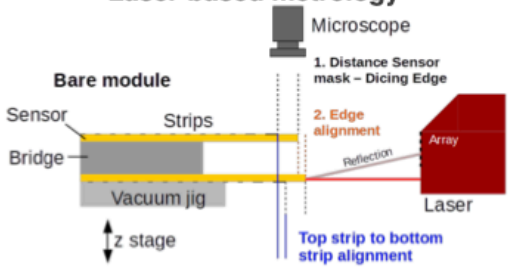
Double-sided metrology



Needle-based metrology



Laser-based metrology



- Specs: rotation < 400 µrad, strip parallel (perpendicular) offset < 100 (50) µm

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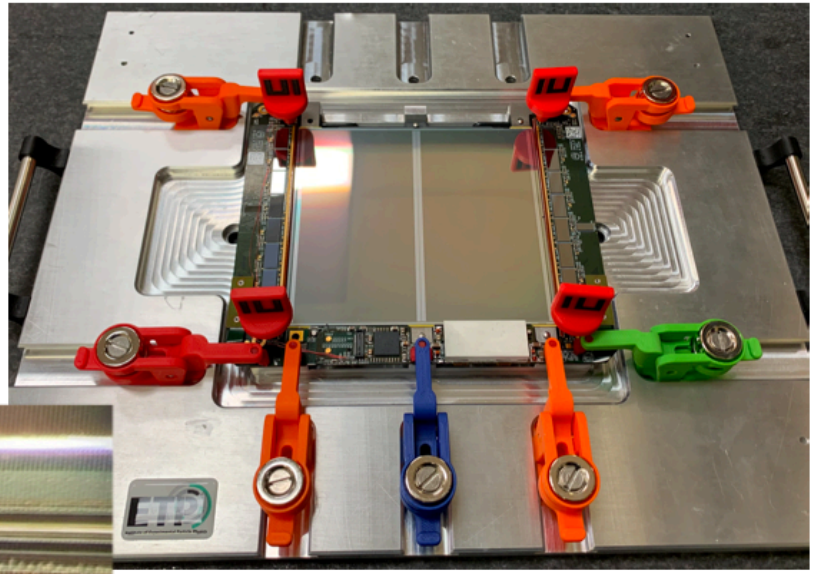
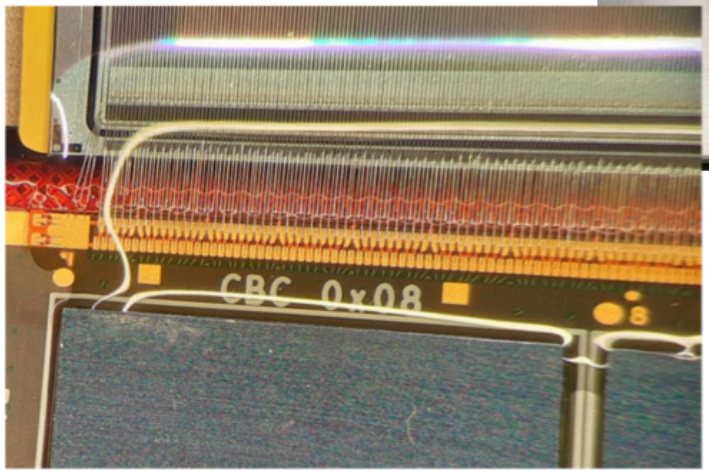
2S assembly - hybrid gluing and wire bonding

- Sensor “sandwich" to hybrid alignment using dowel pins
  - Good alignment required for wire-bonding
- Dedicated fixtures produced for wire-bonding



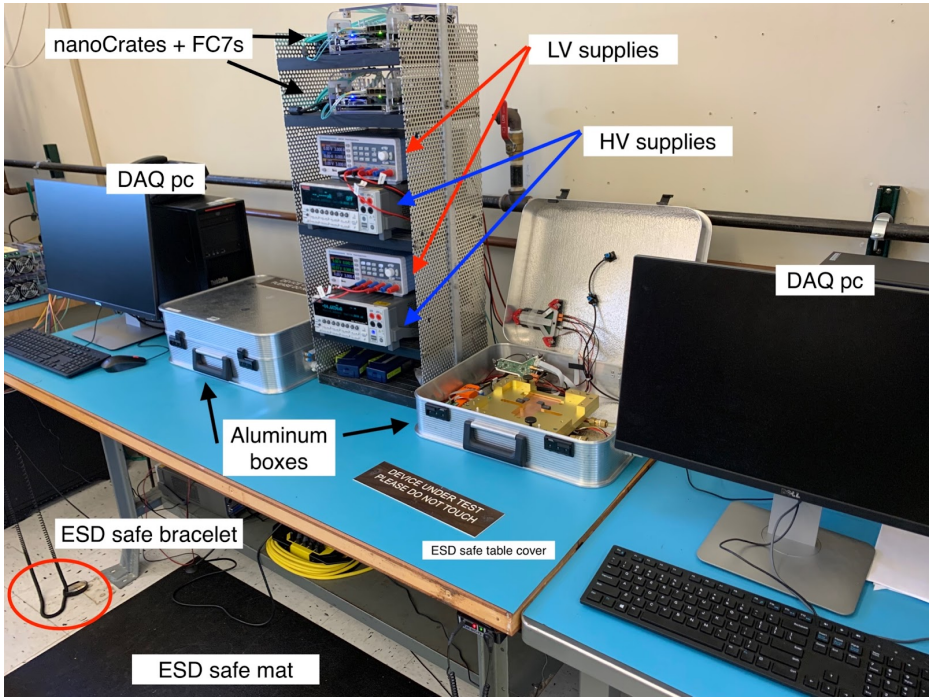


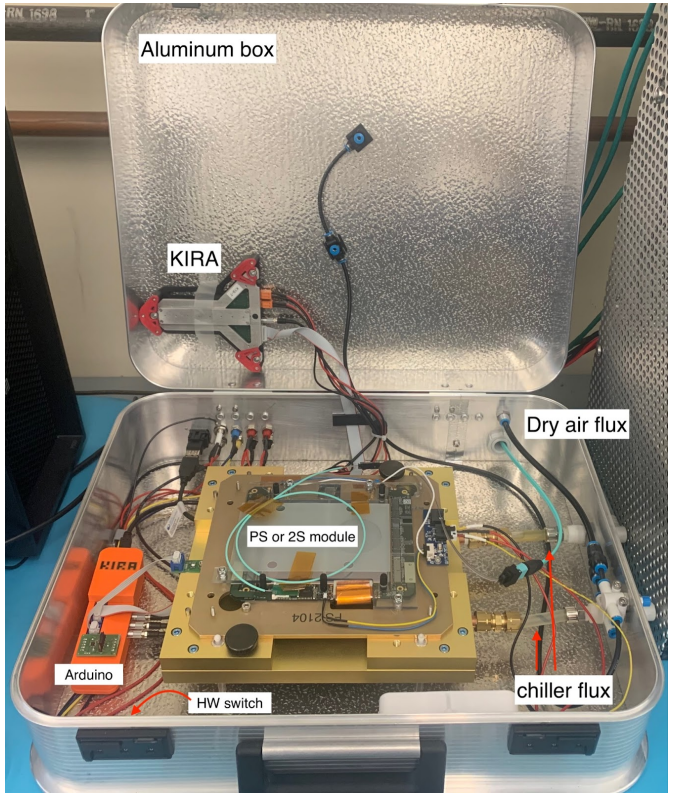
- Wire-bonds encapsulate to protect them and prevent sparking
- Similar approach for PS modules hybrid gluing and wire-bonding

F. Ravera, Vertex 2022

Fermilab

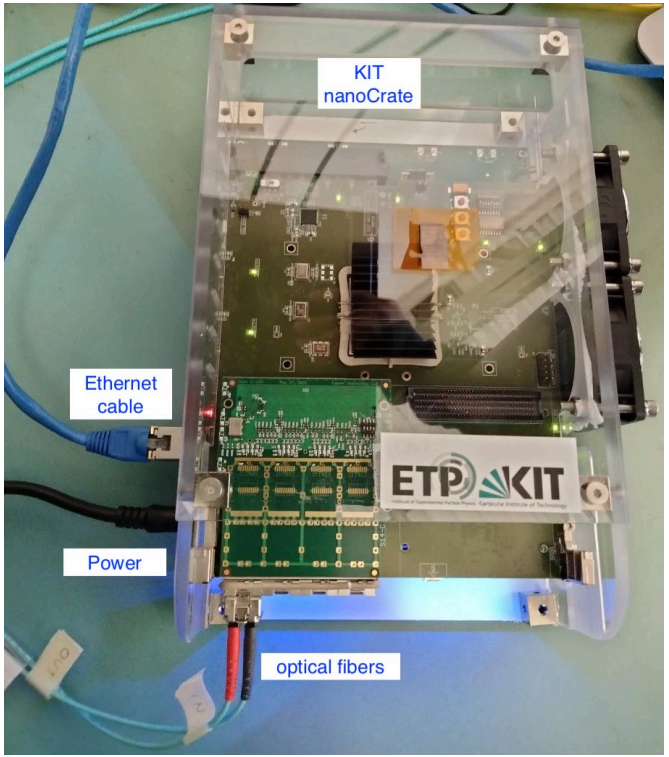
Single test stend

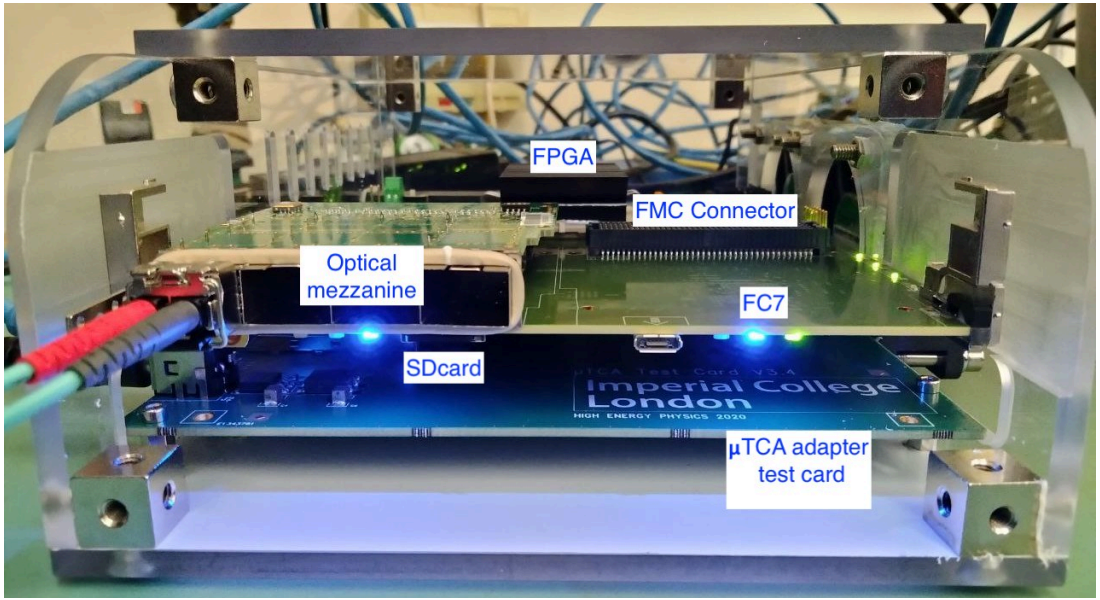




Fermilab

FC7





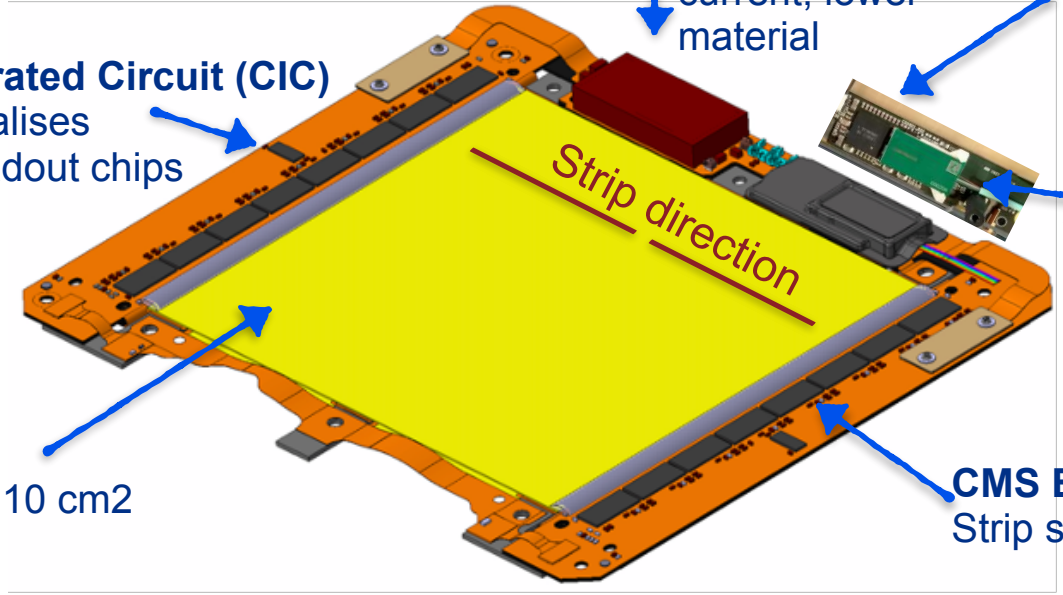
Fermilab

The Strip-strip (2S) module

DC/DC converter
10V lines: lower current, lower material

Low-power GigaBit Transceiver (LpGBT)
CERN development for data transfer at HL-LHC

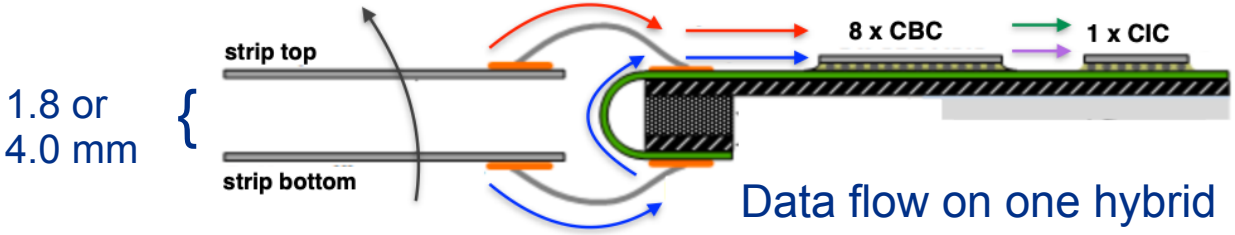
Concentrator Integrated Circuit (CIC)
Aggregates and serialises the data from the readout chips



VTRX+ electrical-optical converter
5Gb/s optical readout

Strip sensors
strip: 5 cm x 90 µm
module area: ~10 x 10 cm2

CMS Binary Chip (CBC)
Strip sensors readout



Data flow on one hybrid

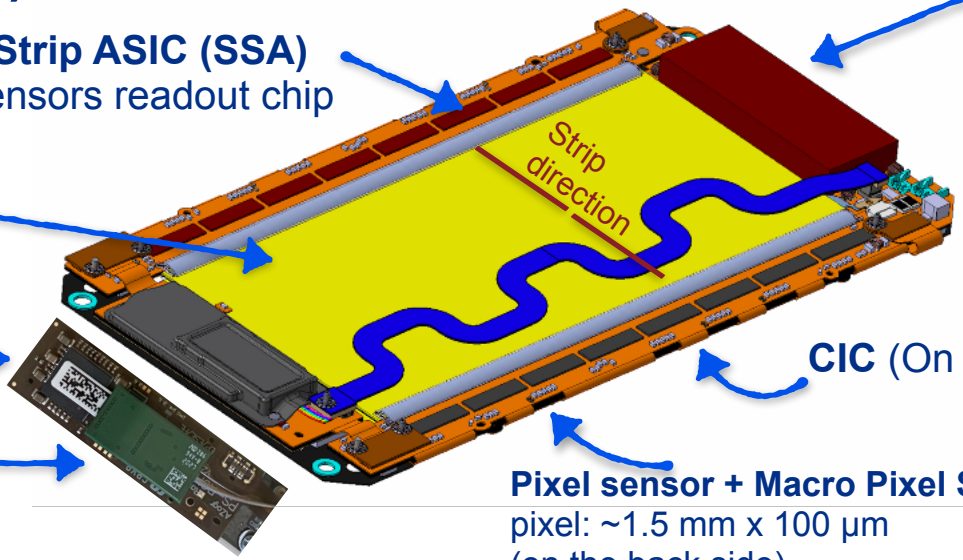
Fermilab

The Pixel-strip (PS) module

DC/DC converter
10V lines: lower current, lower material

Short Strip ASIC (SSA)
strip sensors readout chip

Strip sensors
strip: ~2.4 cm x 100 μm
module area: ~10 x 5 cm2



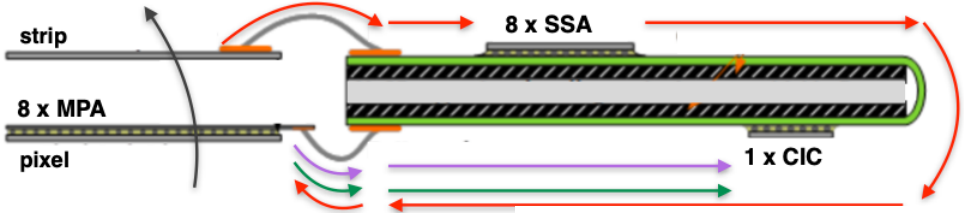
LpGBT

CIC (On the back)

VTRX+
5 or 10 Gb/s optical readout

Pixel sensor + Macro Pixel Sub-Assembly (MaPSA)
pixel: ~1.5 mm x 100 μm
(on the back side)

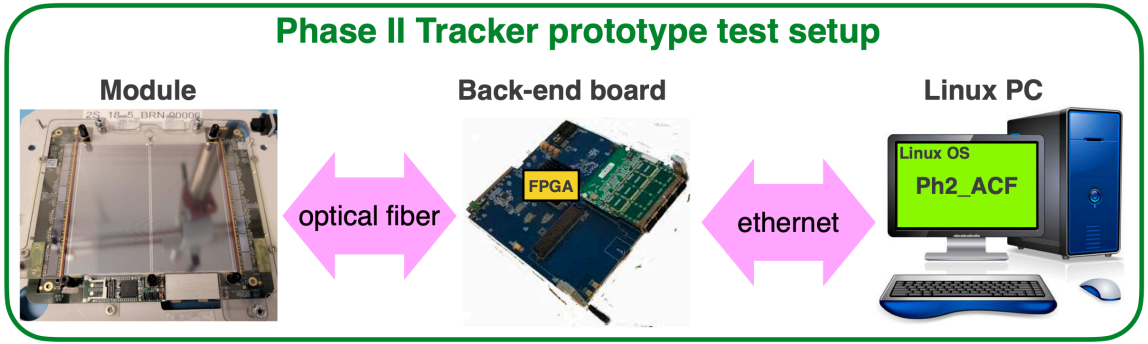
1.6, 2.6 or 4.0 mm



top sensor data
top + bottom data
stub data

Data flow on one hybrid

Ph2_ACF: Phase II Acquisition and Control Framework

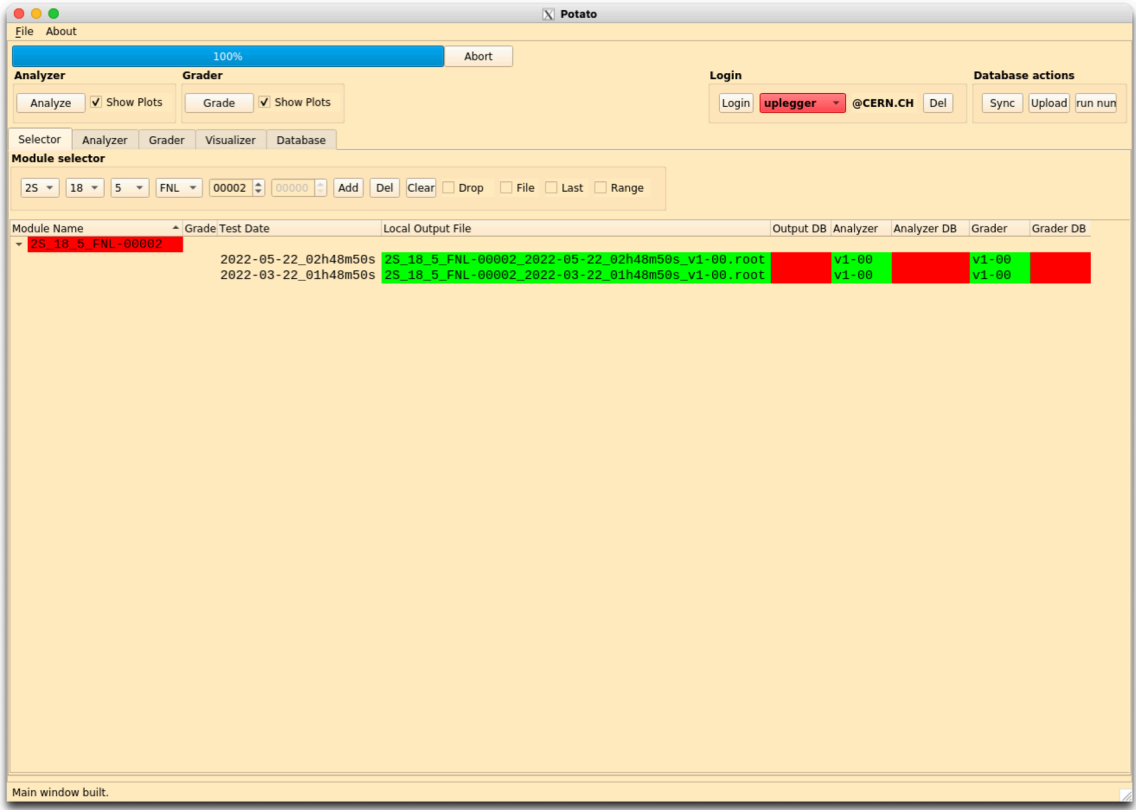


- It is used to characterize and optimize the 2S and PS modules
  - using FC7 based systems
  - In the lab and in test beams
- It will be used to test the modules during production both for the single test stand and burnin box
- Objectives of the development:
  - a DAQ software for the full Tracker (Inner + Outer)
  - a DAQ software for the whole lifetime of the project

Phase 2 Outer Tracker Analyzer of Test Outputs

POTATO!

- A tool that will help the 10 (!) production centers to:
  - keep track of the tests done on modules
    - uploading and downloading data to the **database**
  - **Analyze** the test results from Ph2_ACF
  - Use the test results to **grade** a module to **decide** whether it will be mounted or not on the detector



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