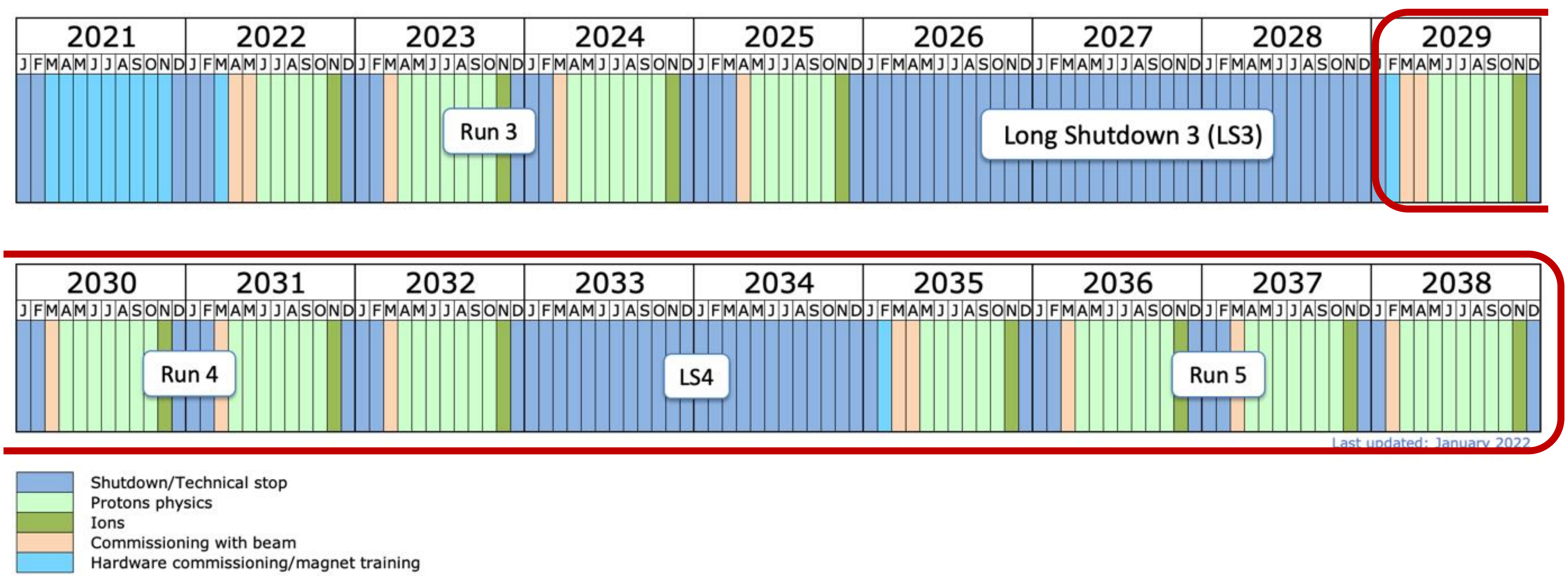
The CMS Outer Tracker for the HL-LHC

ALESSANDRO ROSSI FOR CMS COLLABORATION

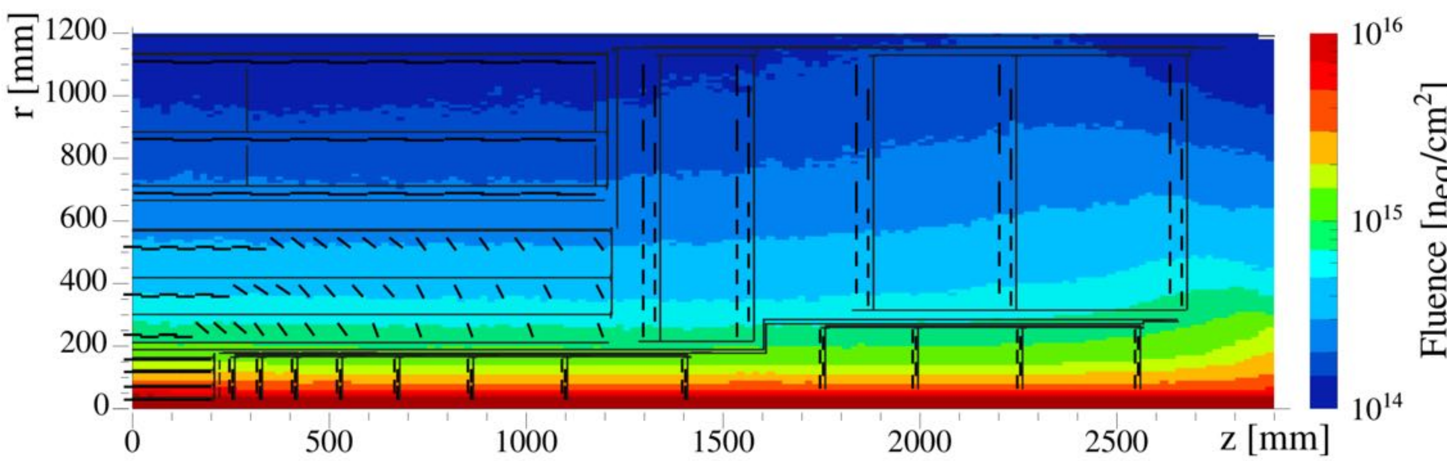
LHC Schedule

- High Luminosity upgrade after LS3
- Peak Luminosity ~$7.5 \times 10^{34} cm^{-2}s^{-1}$
- Expected Pile-up ~200
- Higher rates and radiation dose wrt Run3



High Luminosity Requirements

- ***Increased granularity:*** In order to ensure efficient tracking performance with a high level of pileup
- ***Reduced material in the tracking volume:*** The exploitation of the high luminosity will greatly benefit from a lighter tracker
- ***Contribution to the level-1 trigger:*** The selection of interesting physics events at the first trigger stage becomes extremely challenging at high luminosity
- ***Extended tracking acceptance:*** The overall CMS physics capabilities will greatly benefit from an extended acceptance of the tracker
- ***Radiation tolerance:*** The upgraded tracker must be fully efficient up to a target integrated luminosity of $3000 fb^{-1}$
    - Outer layers “far away” from interaction point will see $>10^{14}$MeV neutron equivalent fluence
        - more than innermost strip tracker layers at 20 cm for today's trackers after 10 years of LHC running

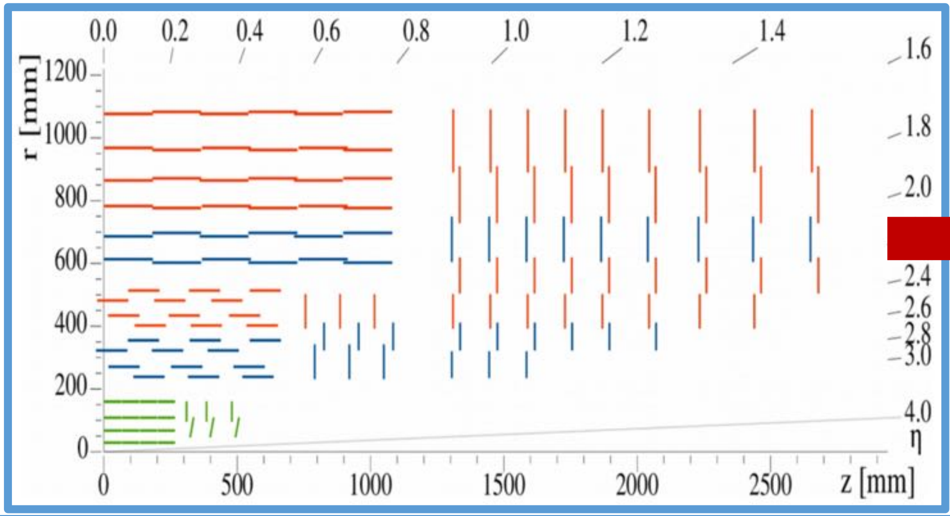


Why change the current Tracker

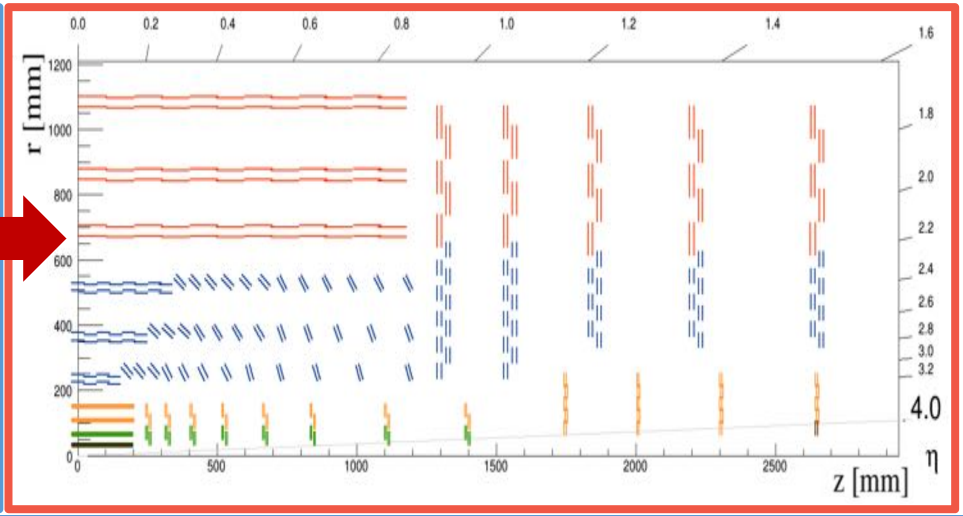
- Radiation damage at the end of Run3
  - A big part of current strip tracker will become completely in-operational due to either leakage current or full depletion voltage limitations at 1 ab^{-1}
  - Pixel detector need to handle a factor 6 higher hit rate (from 0.58 to 3.2GHz/cm^2) and need an higher granularity

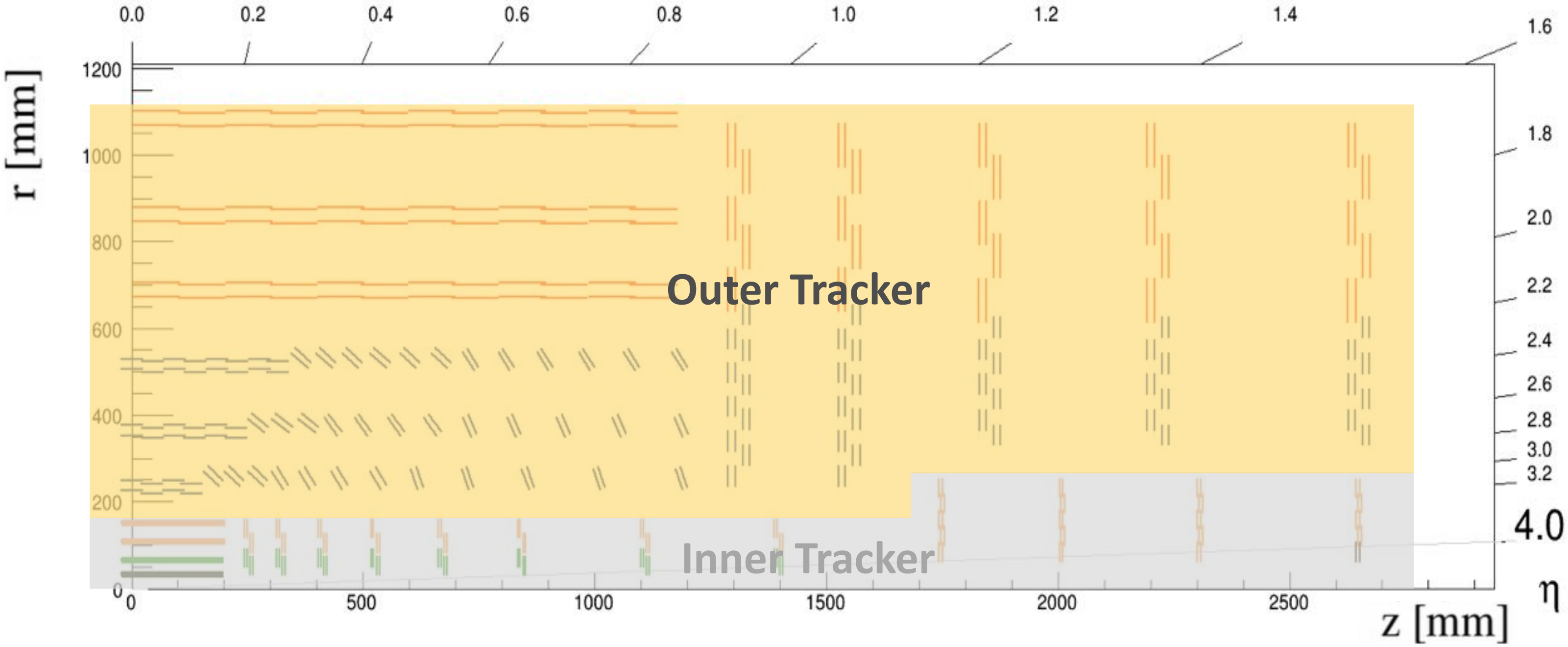
- Full tracker replacement needed for HL-LHC program

CMS Phase-1 Tracker



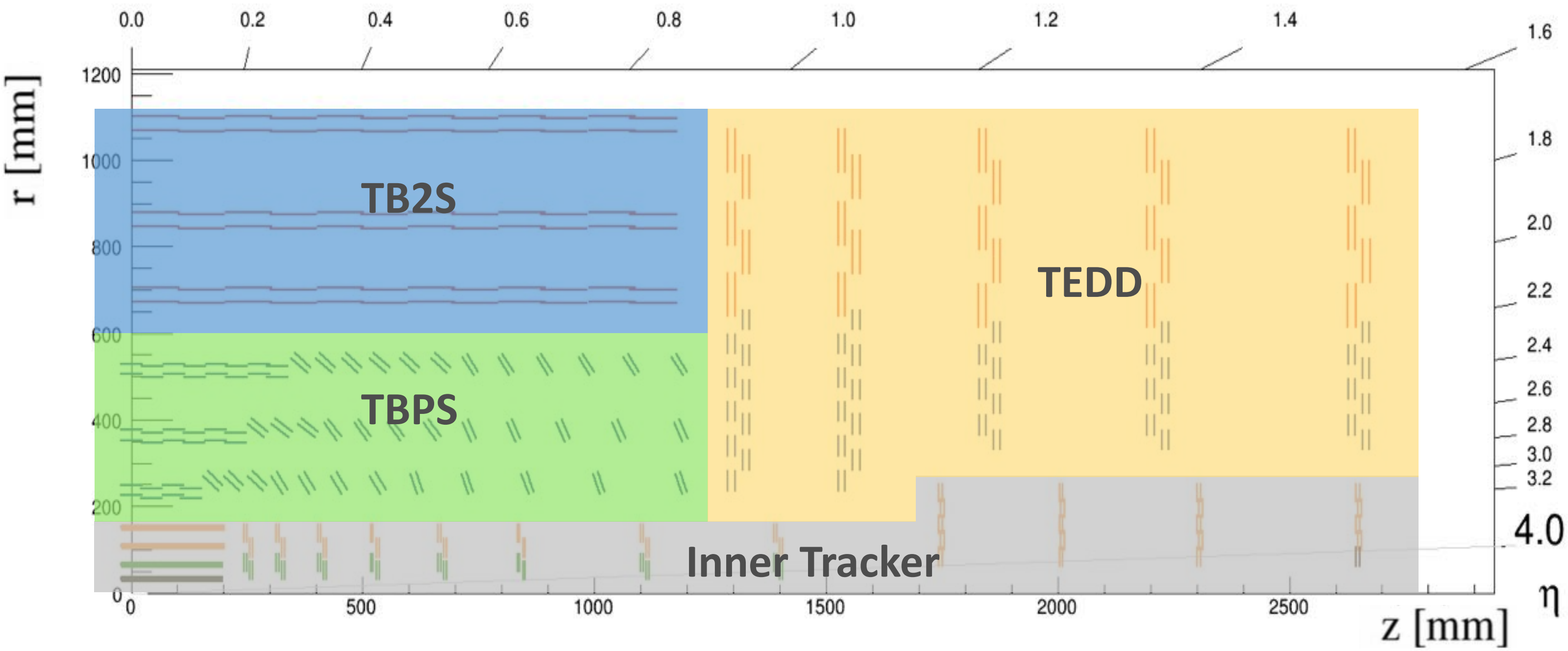
CMS Phase-2 Tracker





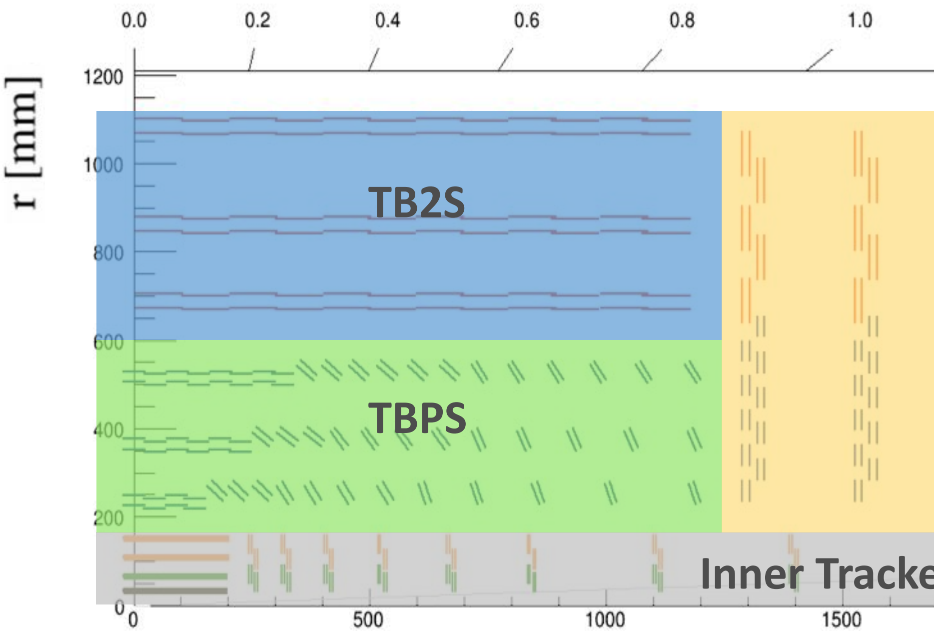
OUTER TRACKER

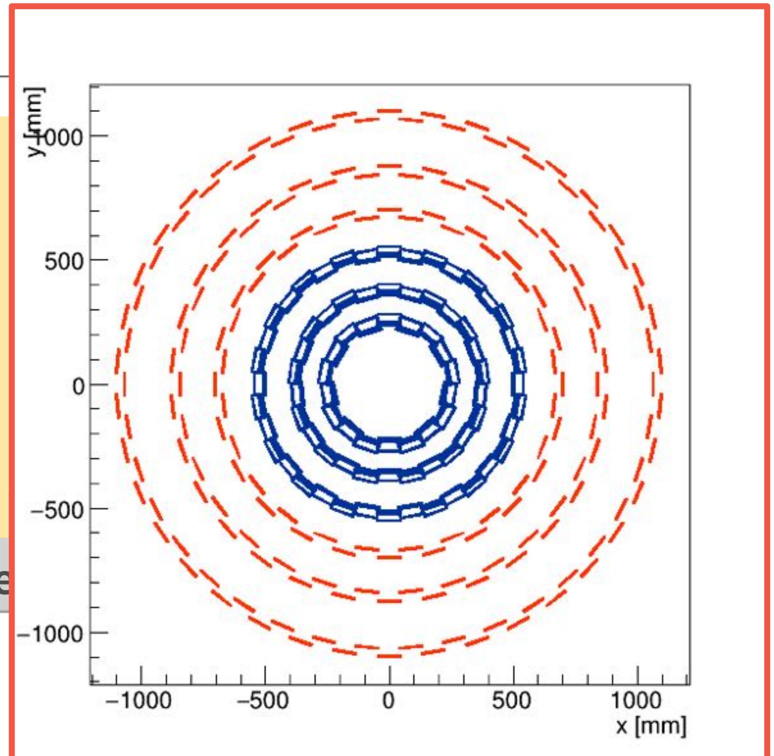
Phase-2 CMS Outer Tracker



- **TBPS** : **T**racker **B**arrel with **PS** modules
- **TB2S** : **T**racker **B**arrel with **2S** modules
- **TEDD** : **T**racker **E**ndcap **D**ouble **D**isk

Phase-2 CMS Outer Tracker





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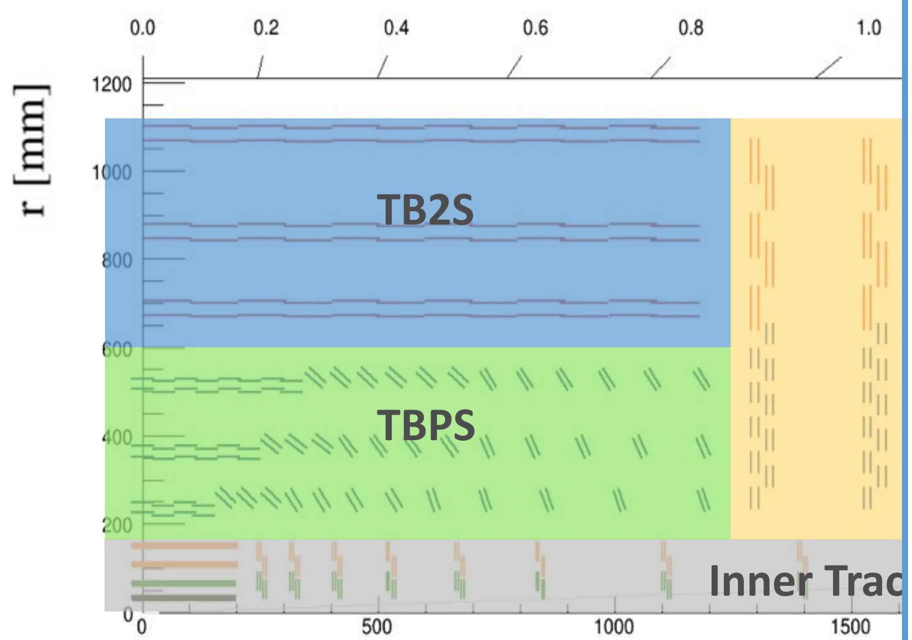

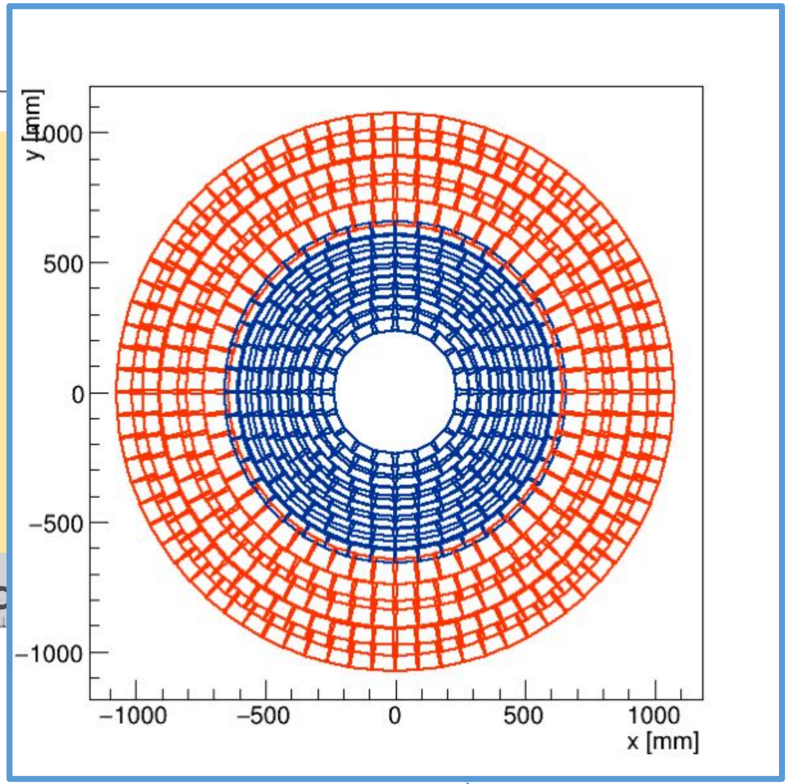

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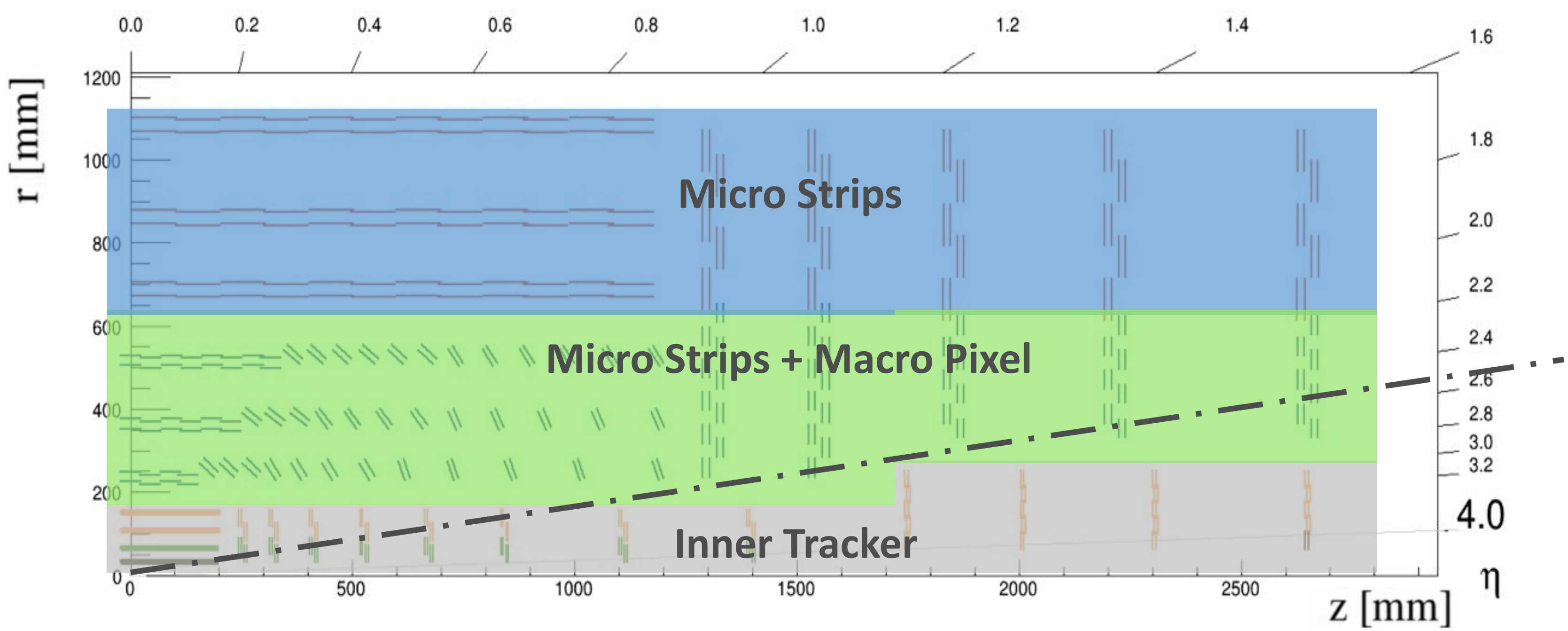


- Outer Tracker coverage up to η~2.5
  - Tracking up to η~4 thanks to InnerTracker
- Two different type of technology: micro-strips and macro-pixels
- Tilted barrel geometry
  - Better trigger performances
  - Reduction on number of modules

Tracks for L1 Trigger

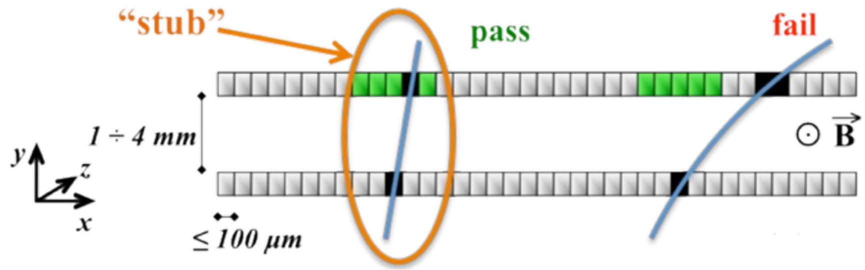
- HL-LHC will deliver an high instantaneus luminosity with a high PileUp
  - It's fundamental to be more selective at L1 trigger in order to keep data rate under control

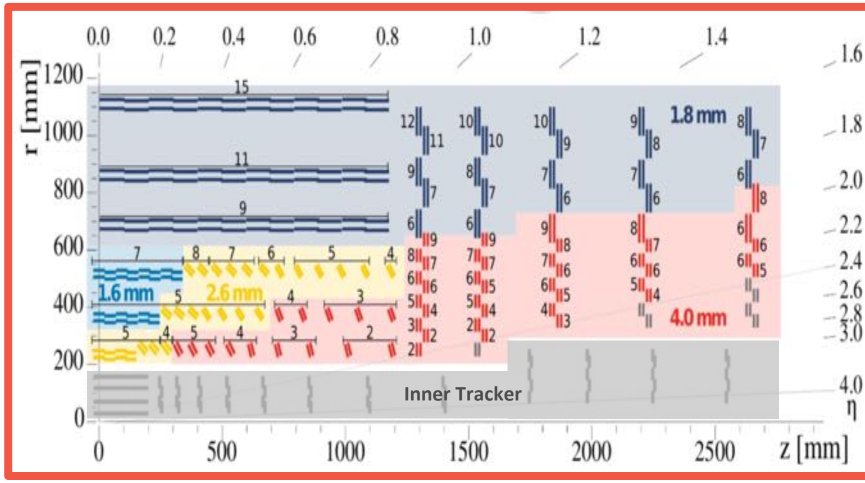
Include Tracks on L1 decision

- Most of charged particles have low p_T
- Perform a p_T selection at readout level in order to reduce the L1 tracking input data size

pT Modules

- Two silicon sensors with small spacing in a module
- Flex hybrid in order to get data from both sensors to one ASIC → Select track «stubs»
- Different sensor spacing for different detector region
- Tunable correlation windows





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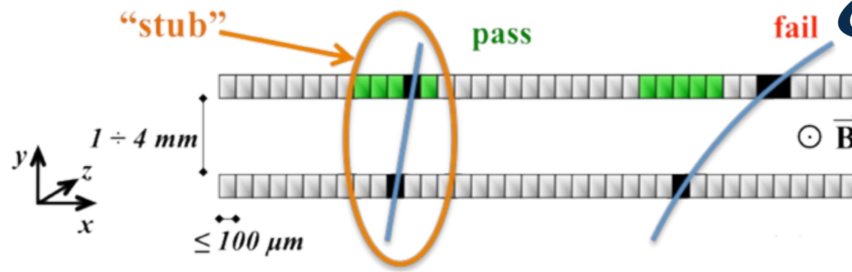
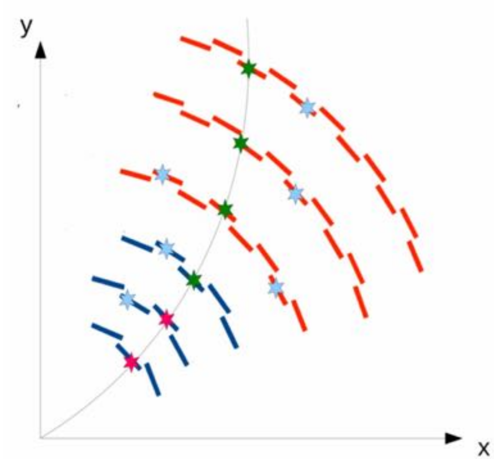
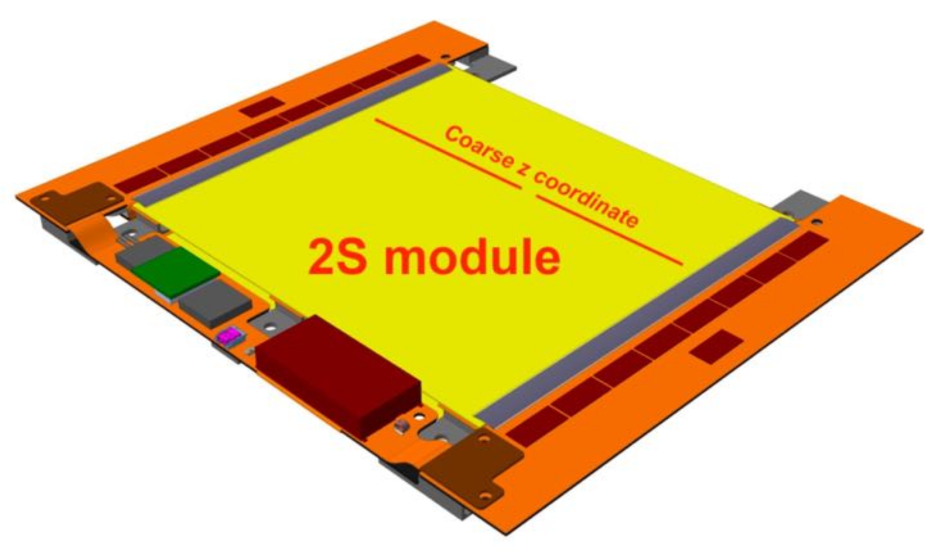


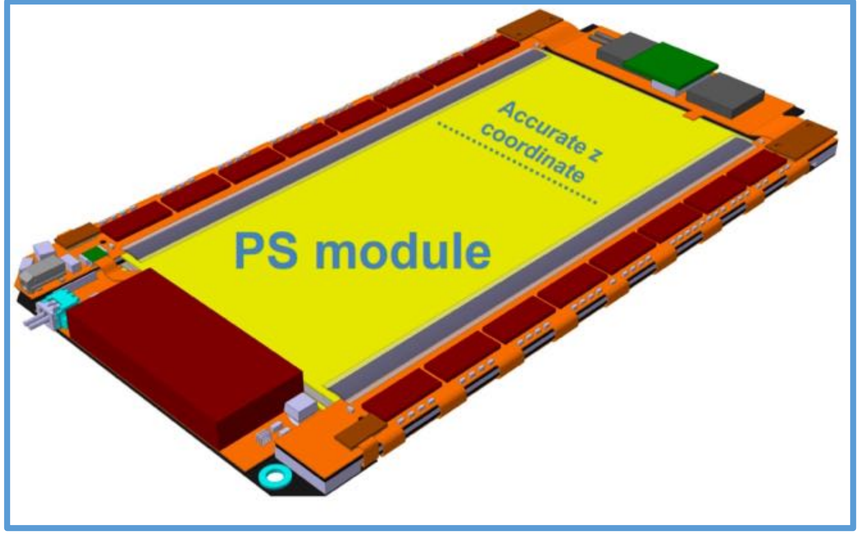
Track Trigger

- Associate track to stubs from OT layers and extract pT measurement
- Trigger events based on track pT at L1



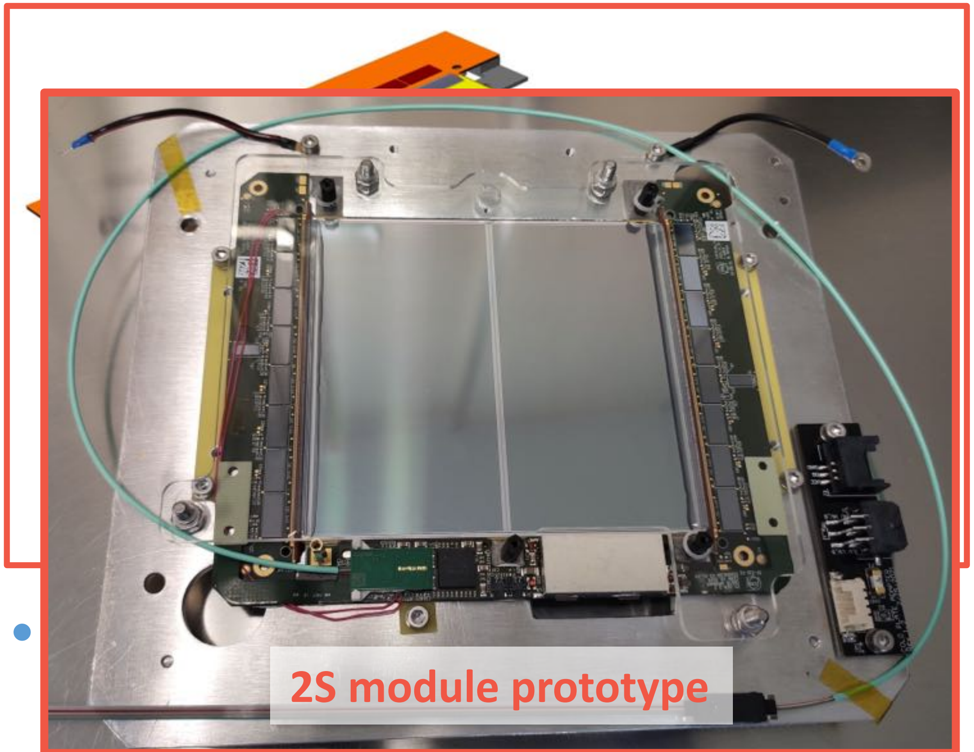
Phase-2 Tracker Modules



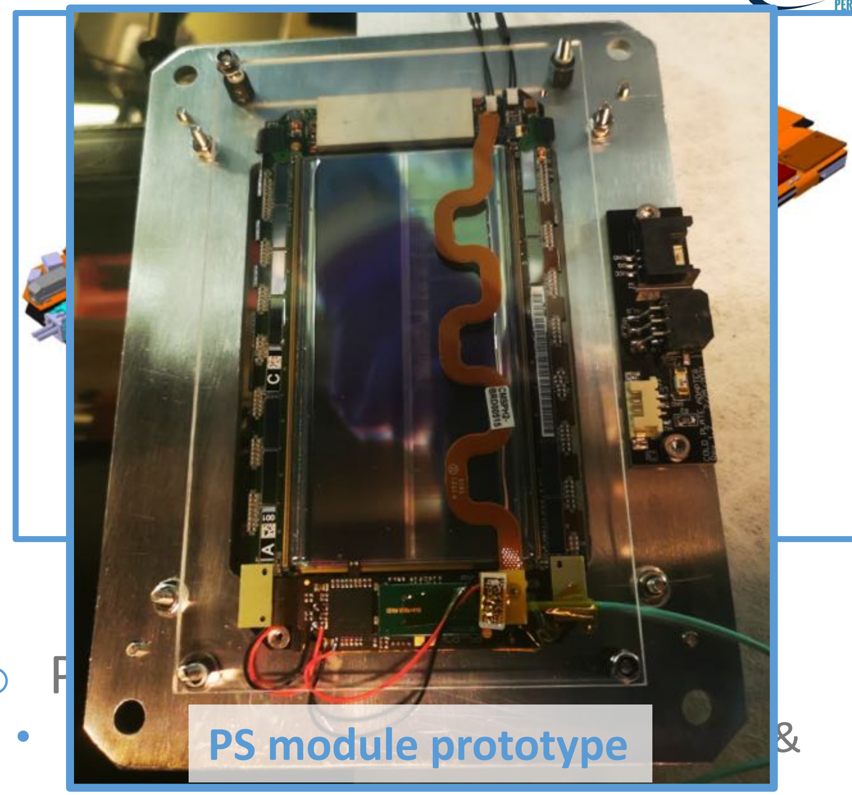


- Two type of modules:
  - 2S Modules
    - 2 different spacing : 1.8mm & 4mm
    - 2 micro strip sensors with 5cm x 90µm strips
    - Sensor dimension are 10cm x 10cm
      - two column of 1016 strips
  - PS Modules
    - 3 different spacing : 1.6mm & 2.6mm & 4mm
    - One strip sensor: 2.5cm x 100µm strips
    - One macro Pixel sensor : 1.5mm x 100µm pixels
    - Sensor dimension 5cm x 10 cm
      - two column of 960 strips
      - 32x960 pixels

Phase-2 Tracker Modules



- 2 different spacing : 1.8mm & 4mm
- 2 micro strip sensors with 5cm x 90µm strips
- Sensor
  - two c



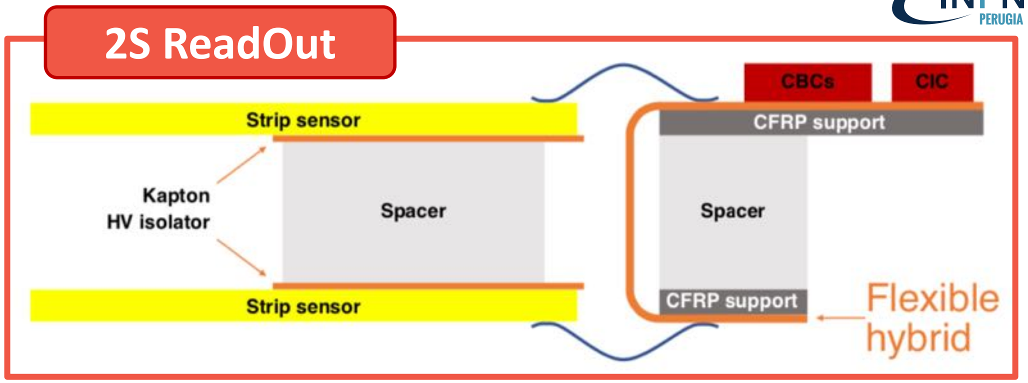
- P
  - &
  - One strip sensor: 2.5cm x 100µm strips
  - m x 100µm
  - m
    - two column of 960 strips
    - ~30k pixels

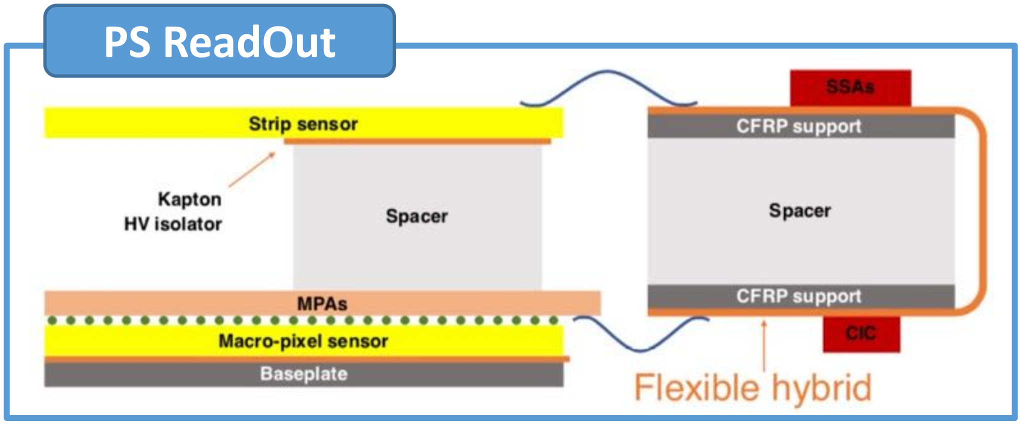
Many prototypes assembled 2022 → First modules with final components by the end of 2023

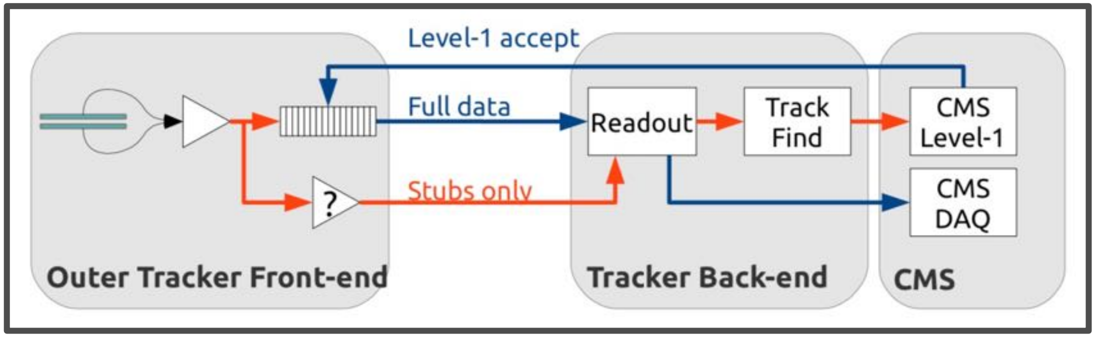
Modules ReadOut

- 2S Module ASICs
  - CMS Binary Chip (CBC) for readout and stub finding for L1
    - both sensors read out by same chip
  - 254 channels per chip
    - 127 from each sensor
  - Implemented in 130 nm technology
- PS Module ASICS
  - Macro-Pixel ASIC (MPA) and Short-strip ASIC (SSA) for readout of sensors
  - Stub finding performed by MPA
    - SSA sends cluster and L1 information to MPA to enable match in space and time
  - Both chips done in 65 nm technology
- Common ASIC:
  - CIC concentrator chip
    Receives L1 information and readout data
  - "Data hub" to service hybrid
  - Done in 65 nm technology

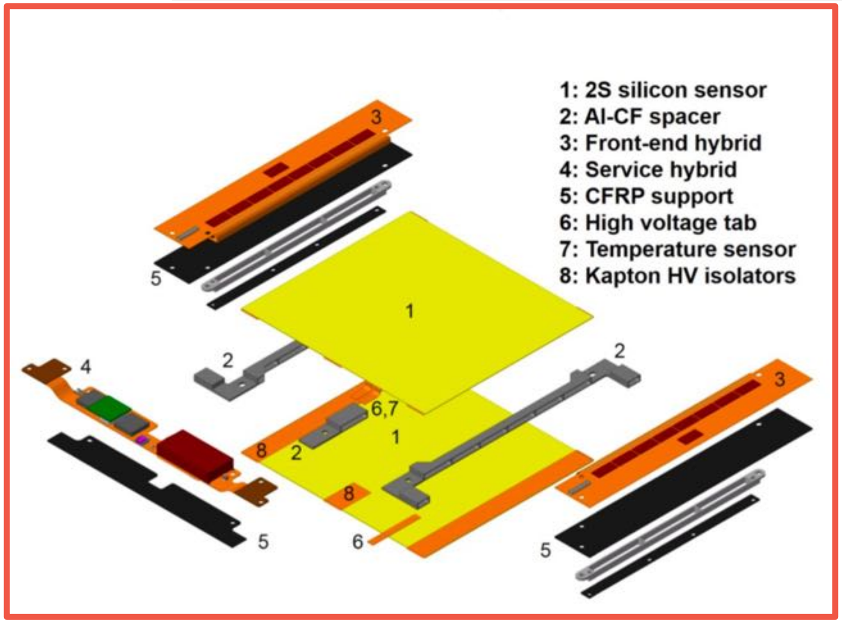
Electronics need to manage 12.5μs latecy before L1 trigger come back

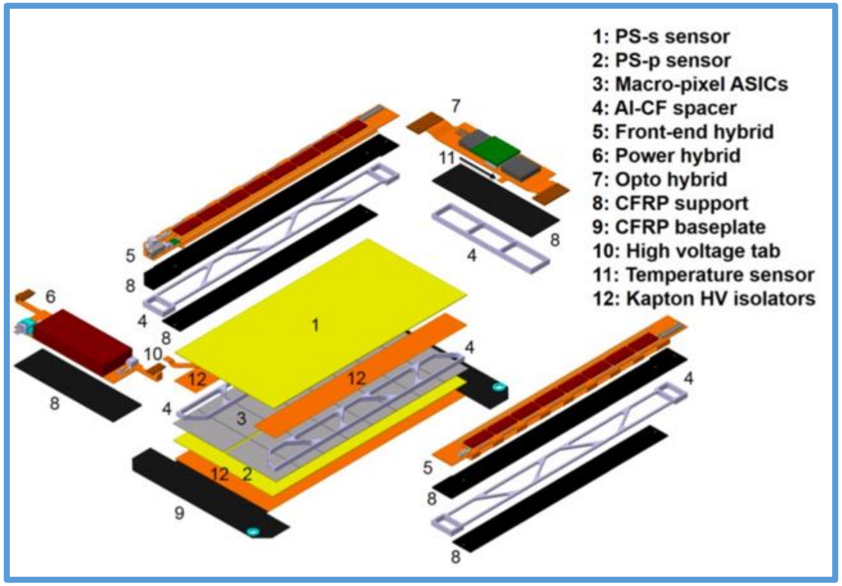






Modules Service Systems



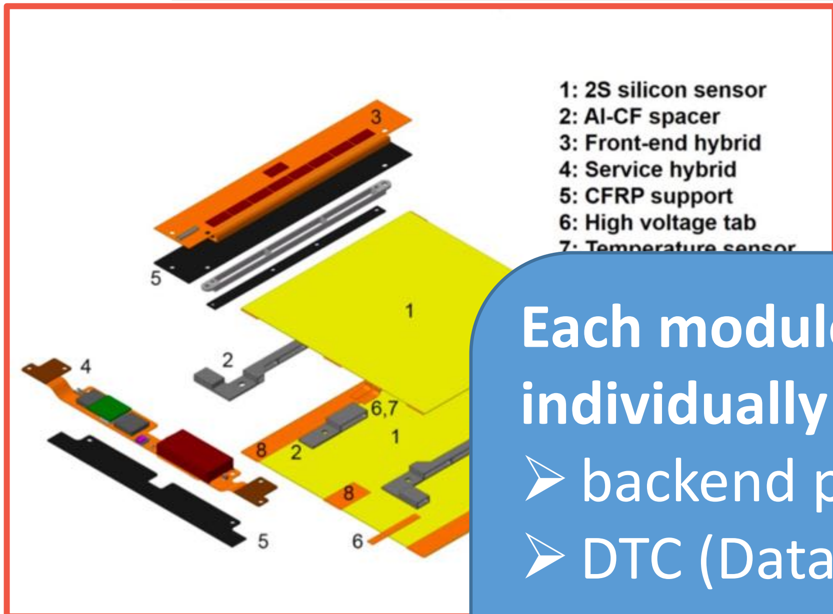


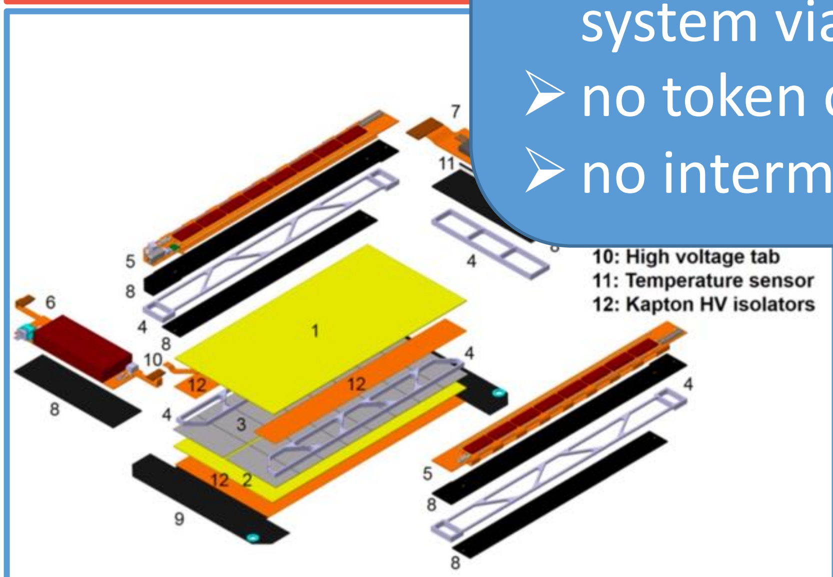
- Module houses both frontend and service hybrids
- Service hybrid(s) has:
  - lpGBT
  - VTRx+
  - DCDC converters

HL-LHC common development

- Frontend hybrids have readout chip and data concentrator

Modules Service Systems





- Module houses both frontend and service hybrids

s:

ave readout chip and data concentrator

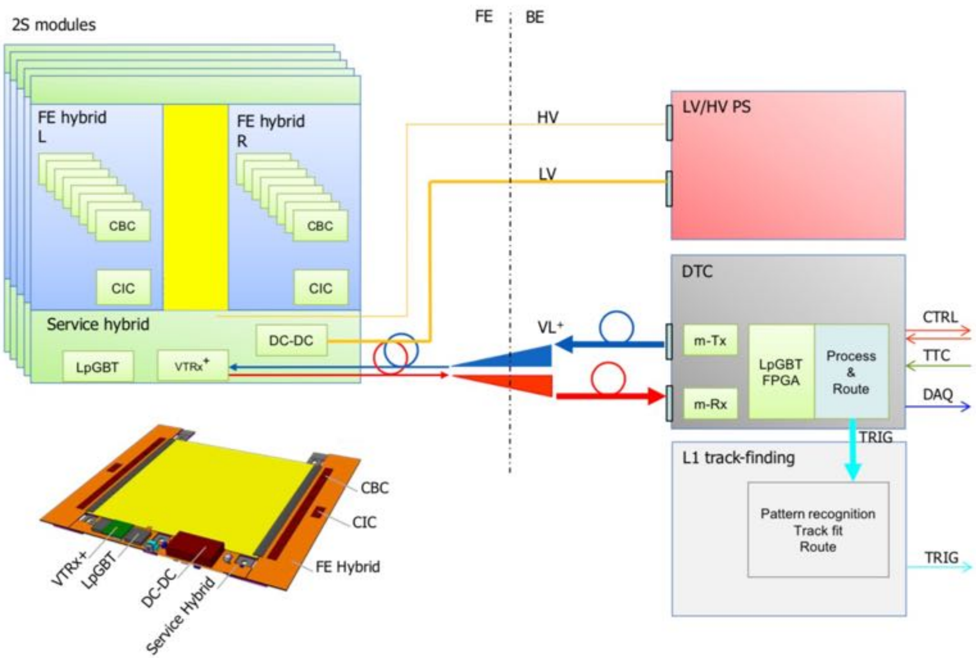
Each module is a functional unit individually connected to:

- backend power system
- DTC (Data, Trigger and Control) system via Optical link
- no token control rings
- no intermediate power grouping

HL-LHC common developmen t

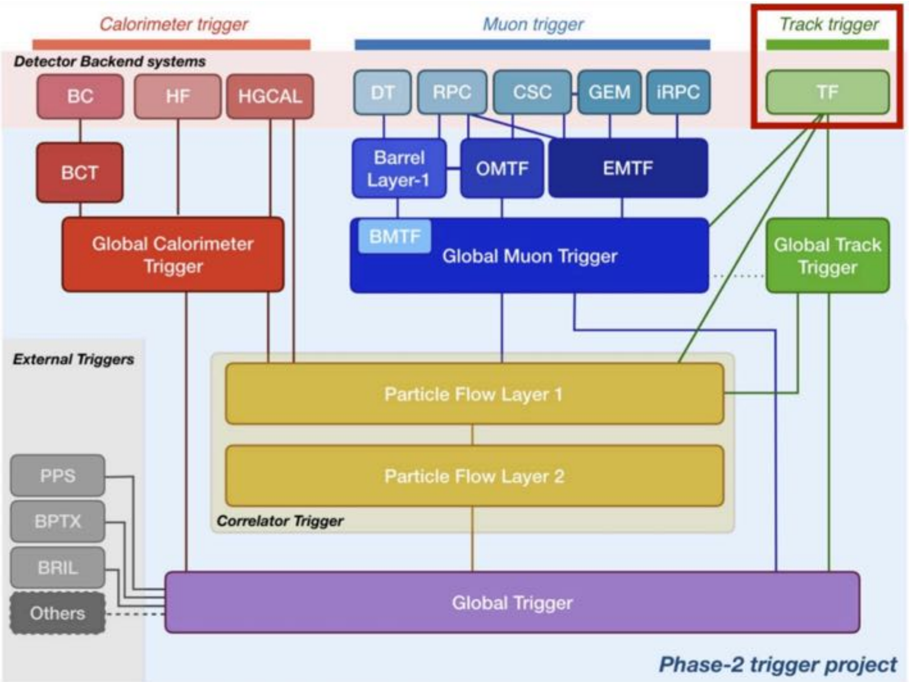
Backend

- DTC (**D**ata, **T**rigger and **C**ontrol) boards readout and control module
  - ACTA standard
- Each Module equipped with a lpGBT and a VTRx+
- Bi-directional optical links
  - **2.56 Gb/s DTC → Module**
    - clock, trigger, fast-commands and programming
  - **5.12 or 10.24 Gb/s Module → DTC**
    - L1 and DAQ data
- L1 data at 40 MHz
- DAQ data (after L1) at 750 kHz



Track Trigger

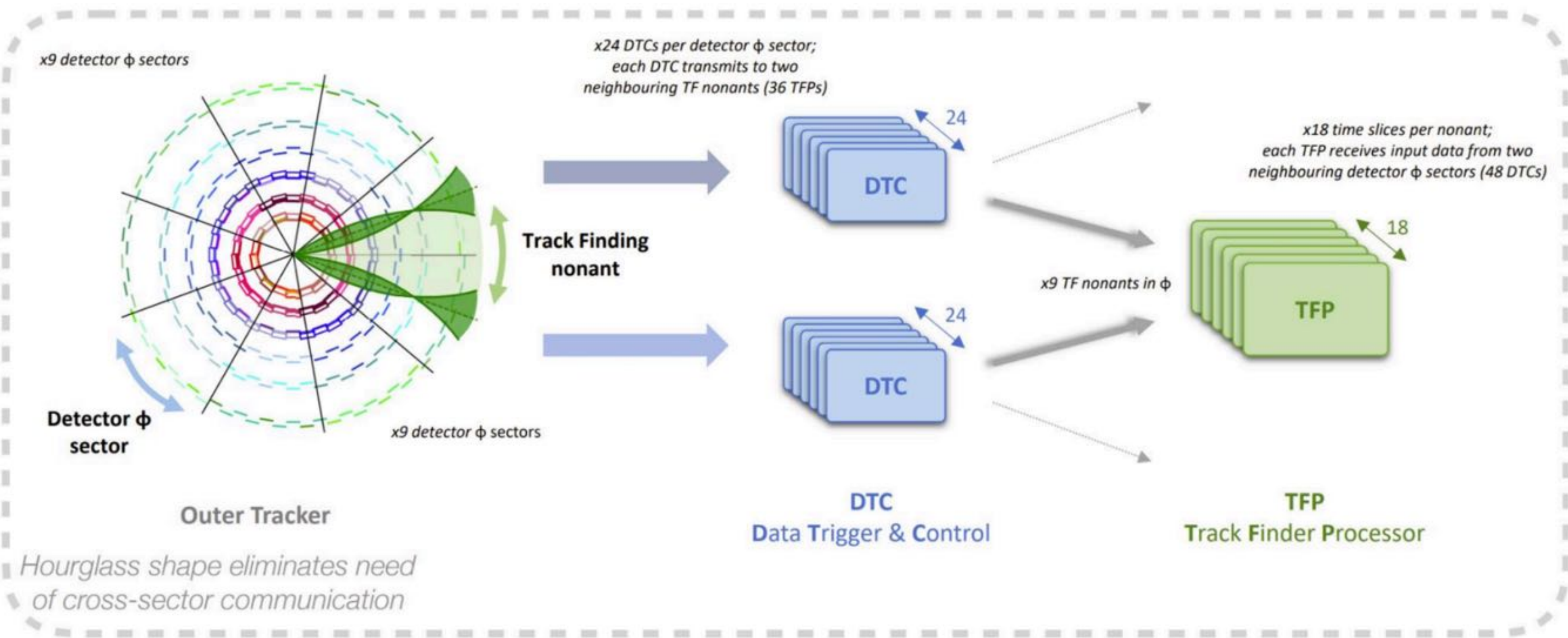
- Main issue: how to keep reasonable threshold at Level 1 trigger?
  - Tracking!



- Full FPGA approach
  - Two stage processing:
  - Data Trigger & Control (DTC)
    → TrackFinder
  - 15k-25k stubs per bunch crossing (25ns)
  - Need tracks within 5 μs after collision
  - ~300 tracks with pT > 2 GeV

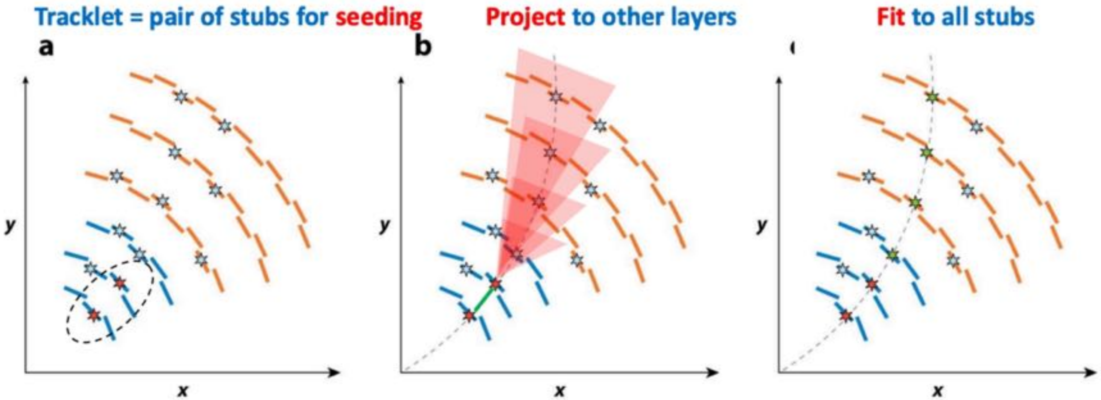
Track Trigger (II)

- Track Finder uses hourglass-shaped nonant
- To avoid cross-sector communication
- 18 time slices per nonant: 9 x 18 = 162 TFP boards
- Each TFP board: 48 input, 6 output optical links @ 25 Gb/s

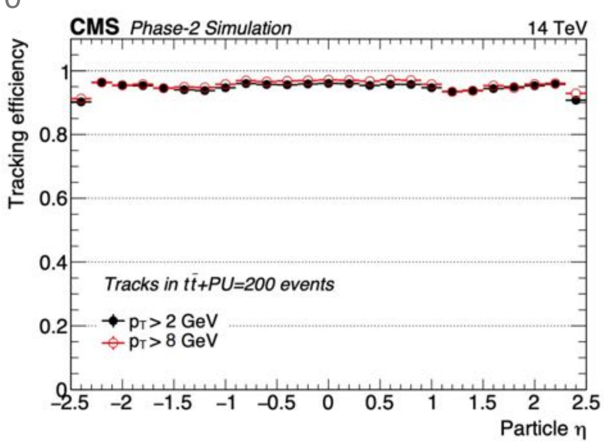


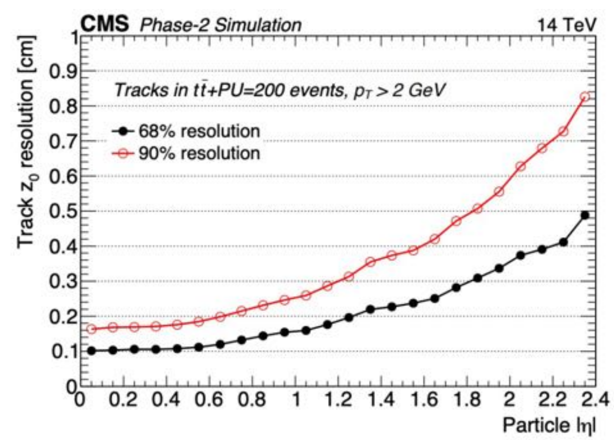
Track Trigger (III)

- Three major steps to tracks:
  - Seeding → Projection → Fitting



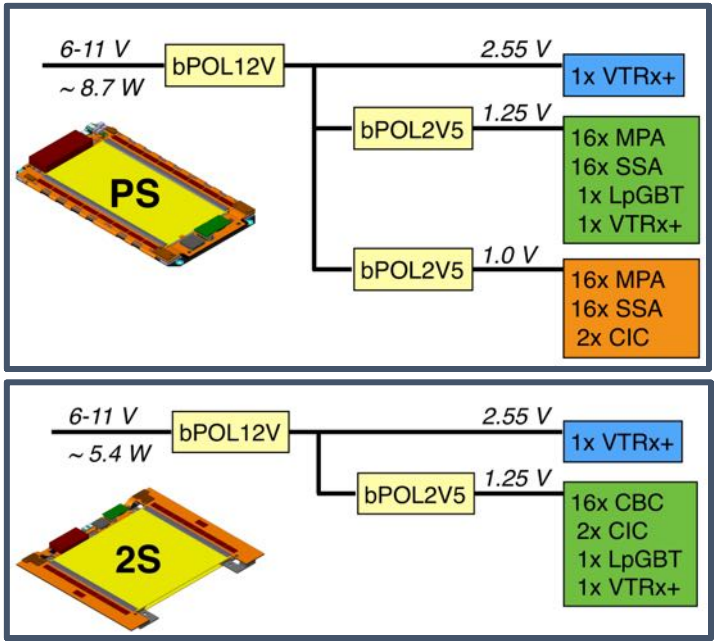
- Expected tracking performance based on simulation
  - High efficiency across pT/η
  - Precise z_0 resolution for vertex association



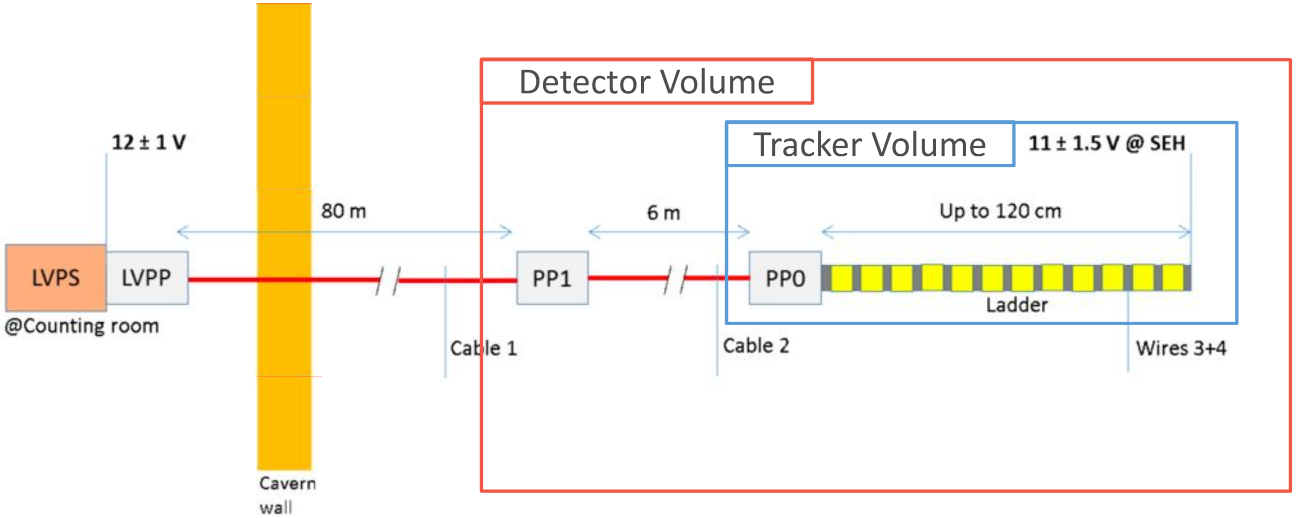


Powering & Cooling

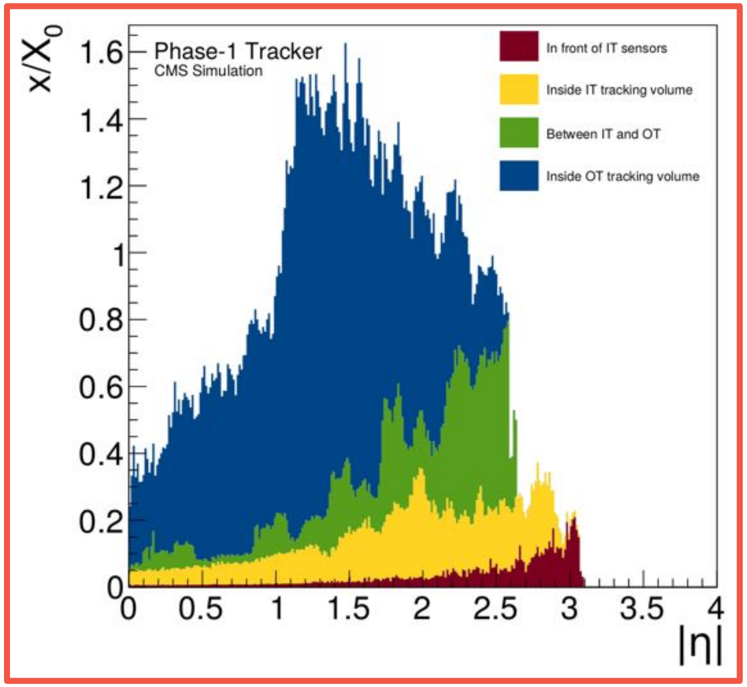
- **Large Area + High Granularity**
  - **High Power Budget : <u>Outer Tracker ~100kW</u>**
    - **<u>Parallel Powering with on-module conversion</u>** *(DCDC converters)*

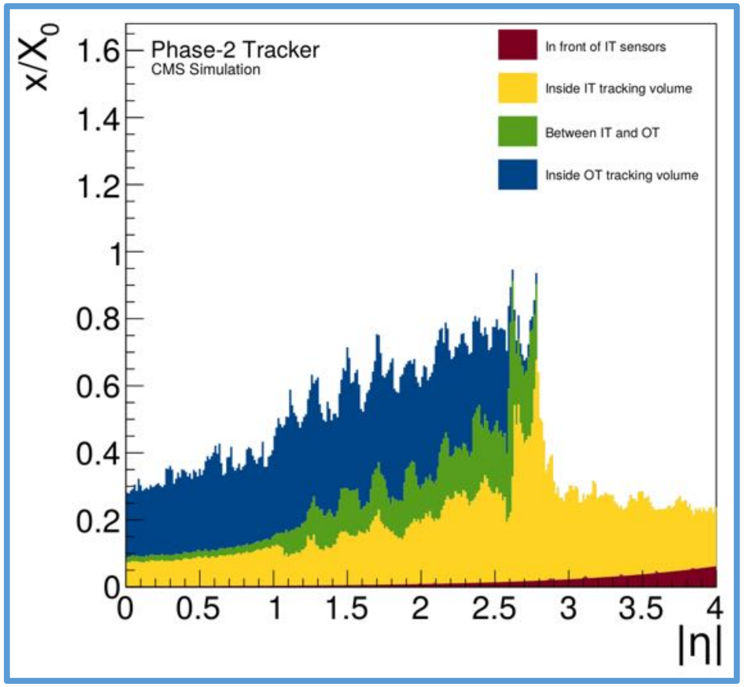


Powerful cooling system:
- (4+1) x 50W cooling plants
- based on two-phase CO_2 cooling system (-35°C set point)
- small pipes



Material Budget





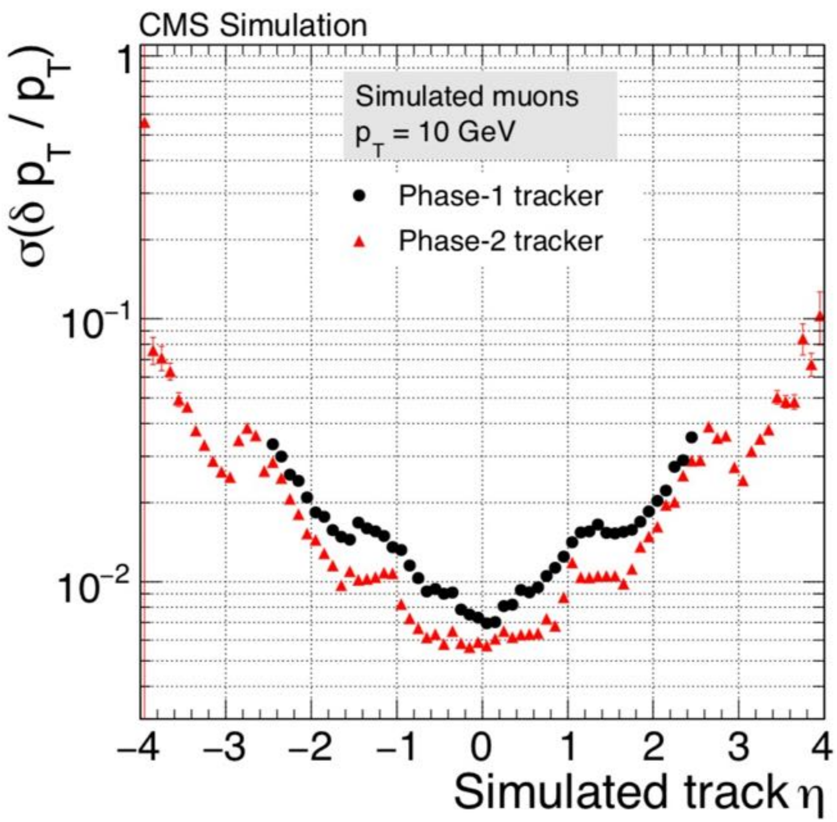
- Material budget much reduced wrt Phase0/1 detector despite an increase in the number of channels

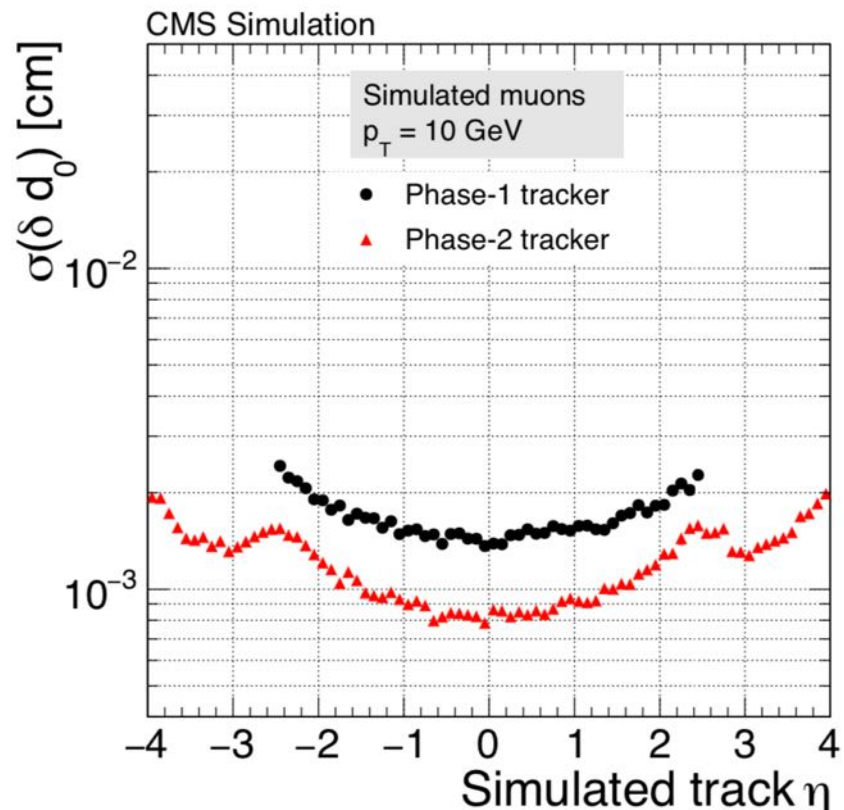
- *DCDC converters*
- *Fewer layers*
- *Lighter materials*
- *Optimized service routing*
- *CO2 cooling*
- *Inclined geometry*

CMS Collaboration, «The Phase-2 Upgrade of the CMS Tracker», 10.17181/CERN.QZ28.FLHW

Performances: Phase1 vs Phase2

- Track parameters resolution of Phase-2 tracker improve wrt Phase-1
  - Higher granularity and less material
- Significant extention at higher η



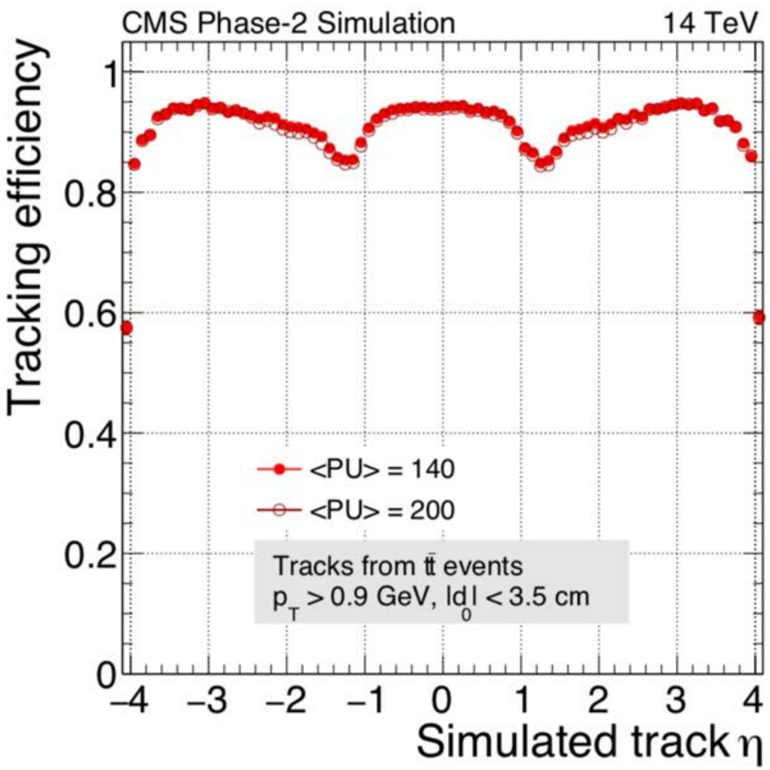


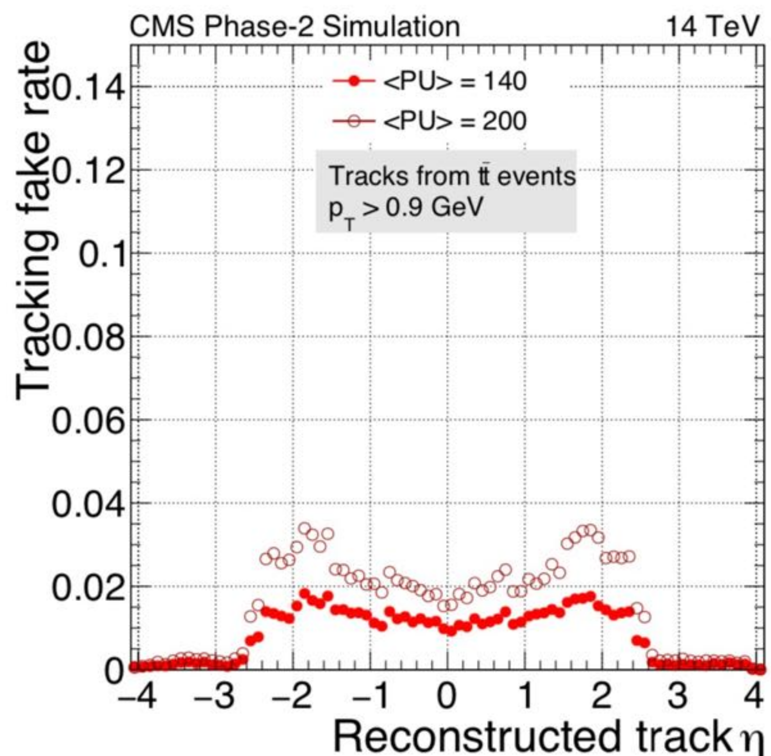
CMS Collaboration, «The Phase-2 Upgrade of the CMS Tracker», 10.17181/CERN.QZ28.FLHW

Performances: High PileUp

- High tracking efficiency (~90%) also at 200PU
  - Fake rate below 2(4)% at 140(200)PU

- *Dip around ±1.2η due to Barrel/endcap transition in Inner Tracker*
  - *Due to an old geometry model, it has been reduced by a factor ~2 with optimized geometry*

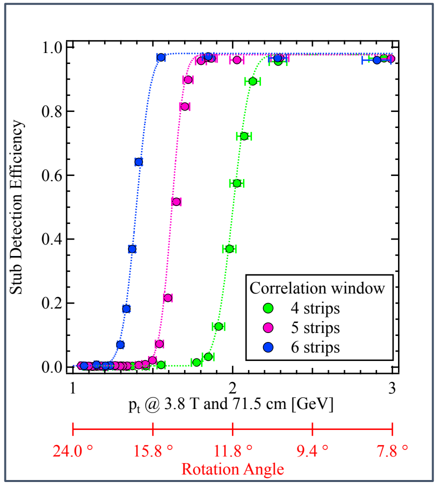


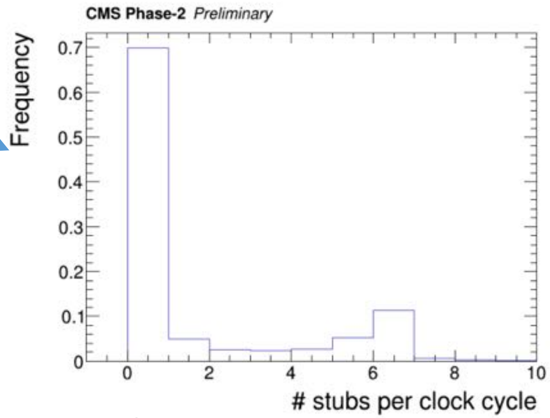


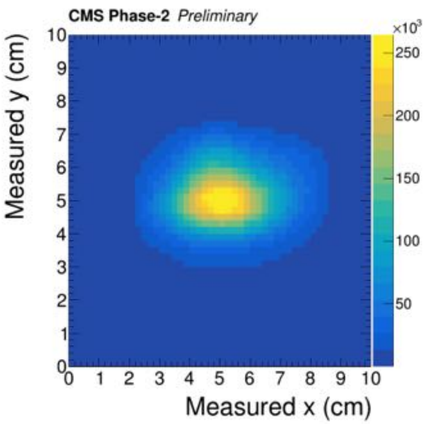
CMS Collaboration, «The Phase-2 Upgrade of the CMS Tracker», 10.17181/CERN.QZ28.FLHW

Some highlights from beam tests

- Different module prototypes tested in particle beam
  - **2S**
    - Full size module and mini-module has been tested
      - Stubs finding capabilities tested
        - Magnetic bending «simulated» with module rotation
    - Beam Test focus on the 40MHz stubs readout also performed
      - High intensity muon beam with Stubs line directly on disk



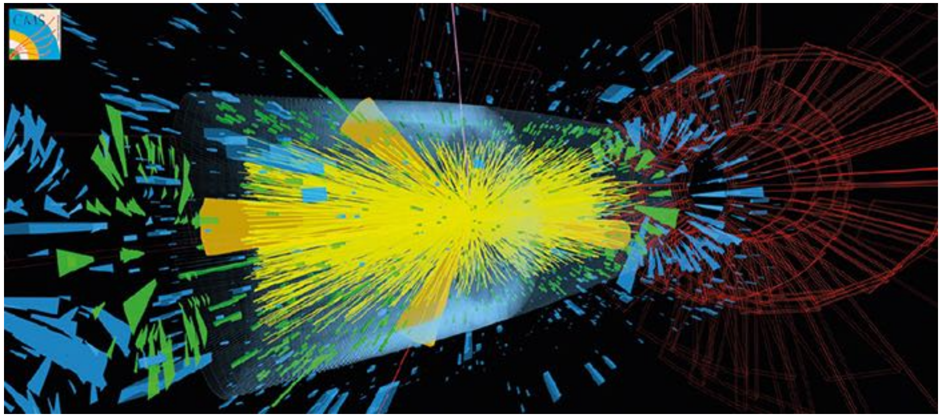




  - **PS**
    - Test on Single sensor (pixel) with MPA readout
    - MPA+SSA intercommunication tested on bench
    - Several beam test activity on full PS modules ongoing

Conclusions

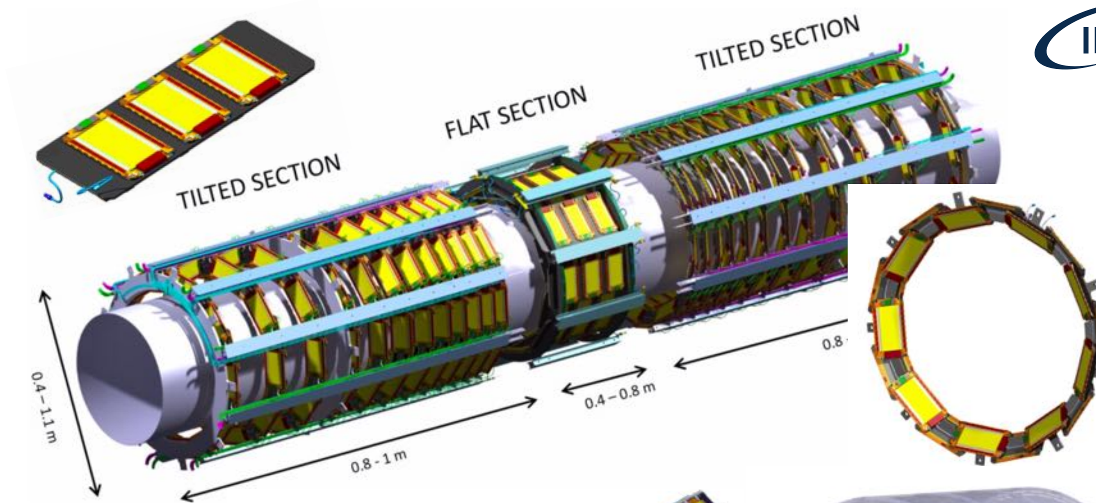
- Ambitious upgrade project underway for the CMS Tracker for the HL-LHC running
  - Designed to maintained or improve tracking performance compared to current system even in the presence of up to 200 pile-up events
  - Tracking capabilities extended to $|\eta|=4$
  - Tracks above 2 GeV as L1 primitives at 40MHz
- Improvements result in the tracker being more performant and yet more light-weight compared to its predecessor
- Advanced layout and integration studies
- First pre-production modules foreseen by the end of the summer…a long way toward HL-LHC!

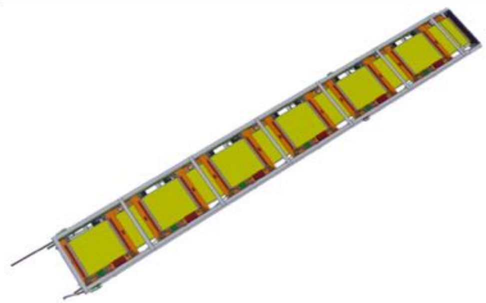


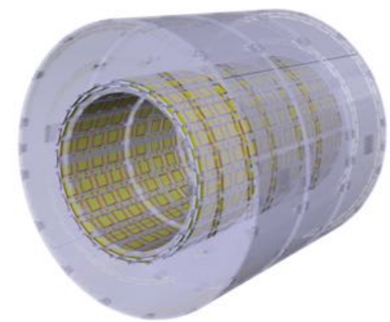
Backup

Mechanics

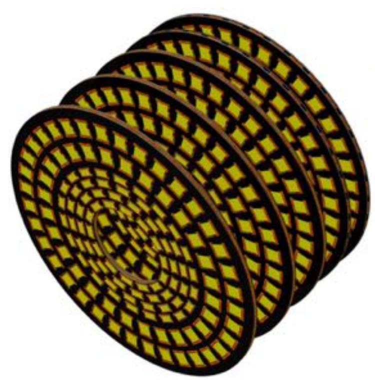
- TBPS
  - Flat Part: planks
  - Tilted Part: rings
- TB2S
  - Ladder support structure
- TEDD
  - Building block: DEE (half disk)
  - Double-Disk to be hermetic also with rectangular modules

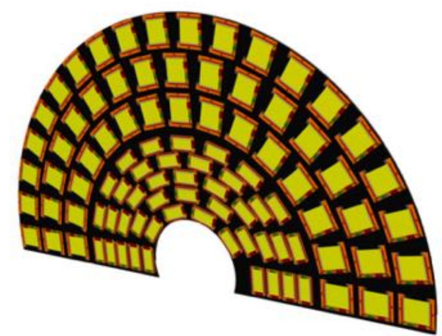






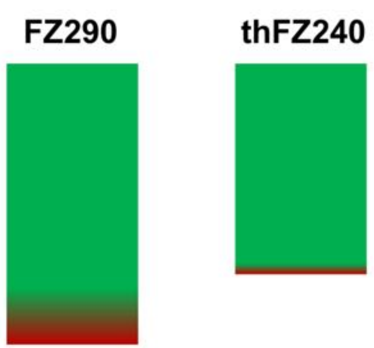
Module type and variant		TBPS	TB2S	TEDD	Total per variant	Total per type
2S	1.8 mm	0	4464	2792	7256	**7680**
	4.0 mm	0	0	424	424	
PS	1.6 mm	826	0	0	826	**5616**
	2.6 mm	1462	0	0	1462	
	4.0 mm	584	0	2744	3328	
Total		**2872**	**4464**	**5960**	**13296**	





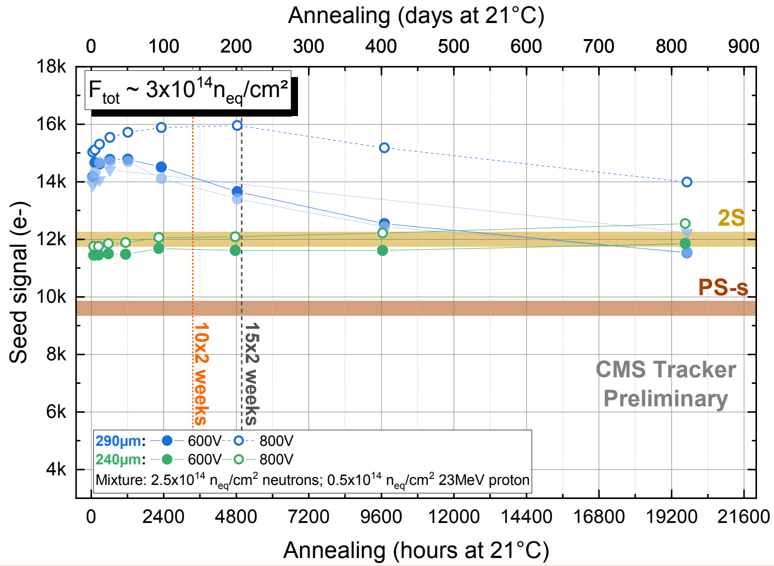
Sensors

- Silicon sensors will be produced by Hamamatsu
  - n-in-p sensors
    - Showed better behavior after irradiation
- HPK lost confidence in deep diffused material as substrate for mass production
  - baseline for TDR
- Options left:
  - standard material: 320µm physical and 290µm active (**FZ290**)
    - same material as in the current tracker
  - thinned material with physical ~ active thickness (**thFZ240**)
    - same substrate as FZ290, but backside ground down to desired thickness, followed by polishing
    - more expensive

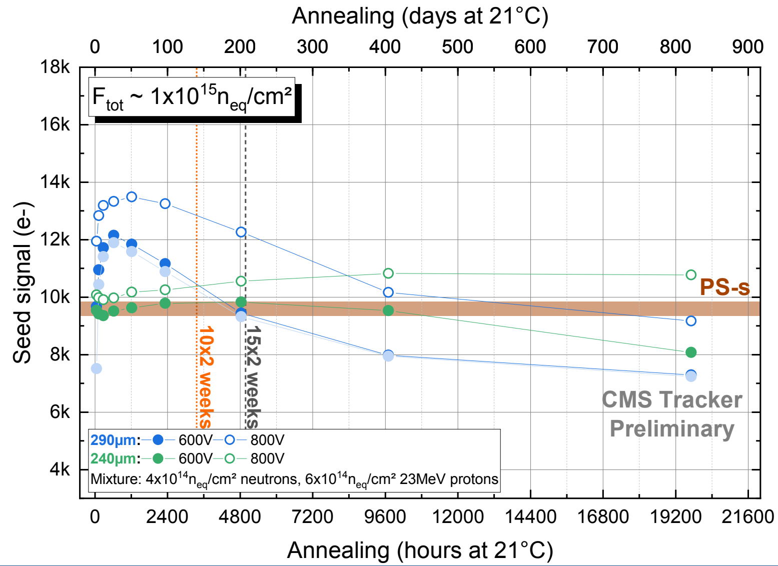


Sensors

- Irradiation campaign to study the sensors behavior and perform a technology choice:
  - Take nominal expected max. fluences for outer (2S) and inner (PS) regions after 3000fb^{-1}
  - Consider the approximate mixture of neutrons and charged hadrons



- Expected max. 2S fluence after 3000fb^{-1}
- Signal measurements:
  - **thFZ240 barely reaches 2S limit**
  - **FZ290 is well above**



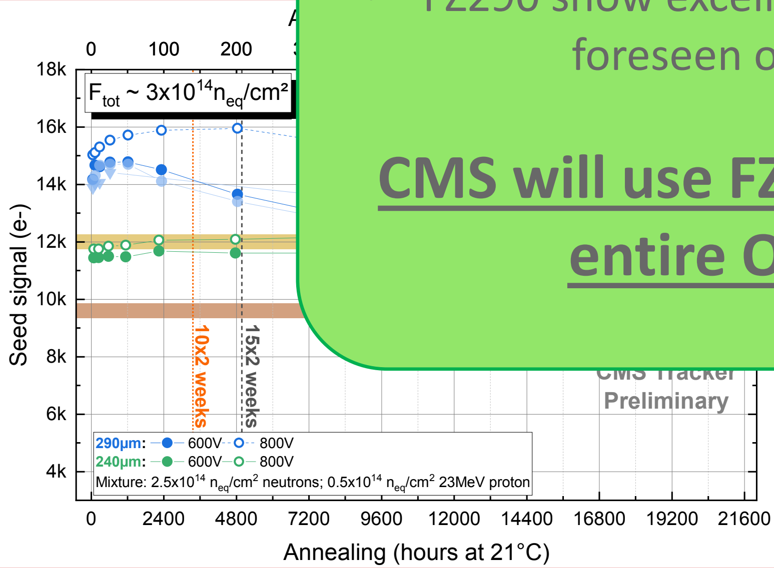
- Expected max. PS fluence after 3000fb^{-1}
- Signal measurements:
  - **thFZ240 only just above PS-s limit**
  - **FZ290 comfortably above with 800V**

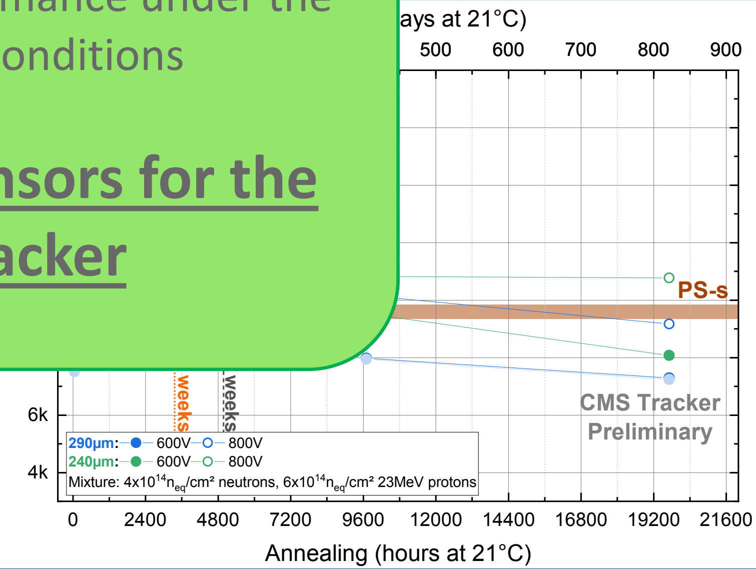
Sensors

- Irradiation campaign to study the sensors behavior and perform a technology choice:
  - Take nominal expected max. fluences for outer (2S) and inner (PS) regions after 3000fb^{-1}
  - Consider the ... adrons

- There is not a clear benefit of thFZ240 over the standard FZ290
- FZ290 show excellent performance under the foreseen operation conditions

CMS will use FZ290 sensors for the entire Outer Tracker





- Expected max. 2S fluence after 3000fb^{-1}
- Signal measurements:
  - **thFZ240 barely reaches 2S limit**
  - **FZ290 is well above**

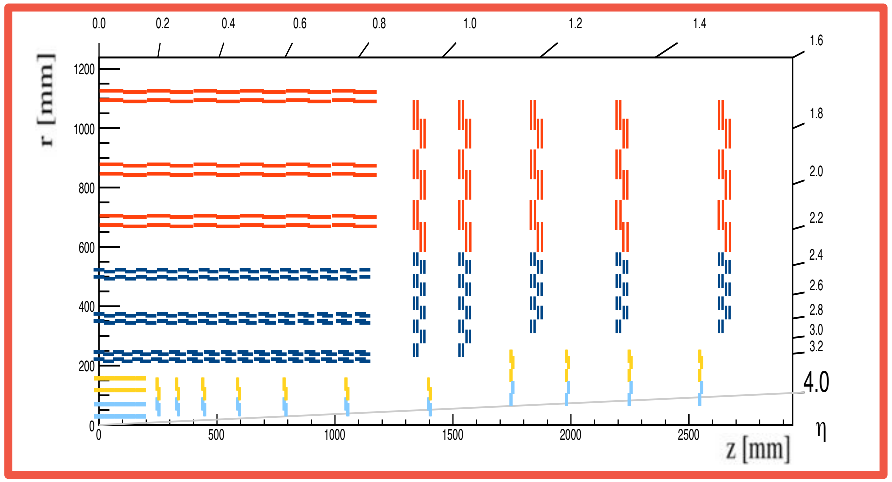
- Expected max. PS fluence after 3000fb^{-1}
- Signal measurements:
  - **thFZ240 only just above PS-s limit**
  - **FZ290 comfortably above with 800V**

Tilted Barrel Geometry

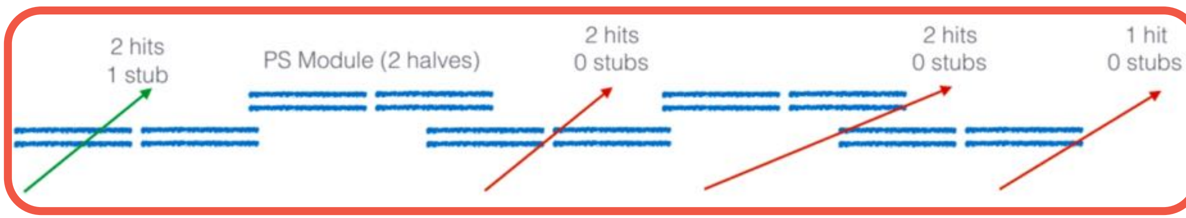
- Stubs generation works only if the charged particle cross the two sensors on the same halve of the same module
- This is not true for (flat) barrel peripheral modules

→ **(increasingly) Tilt peripheral barrel modules**

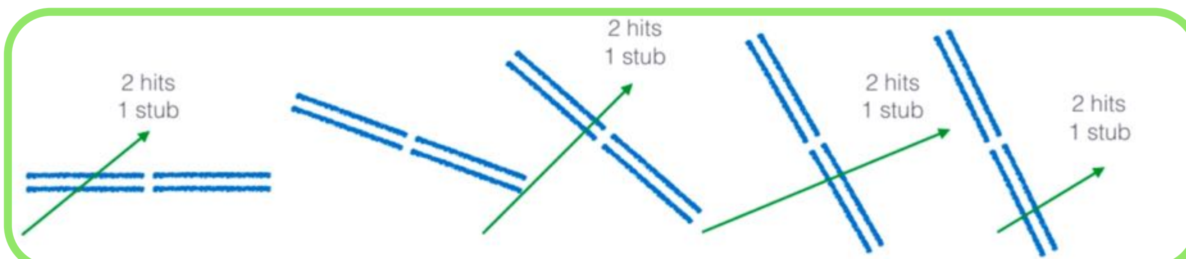
Technical Proposal Geometry



Flat Geometry



Tilted Geometry



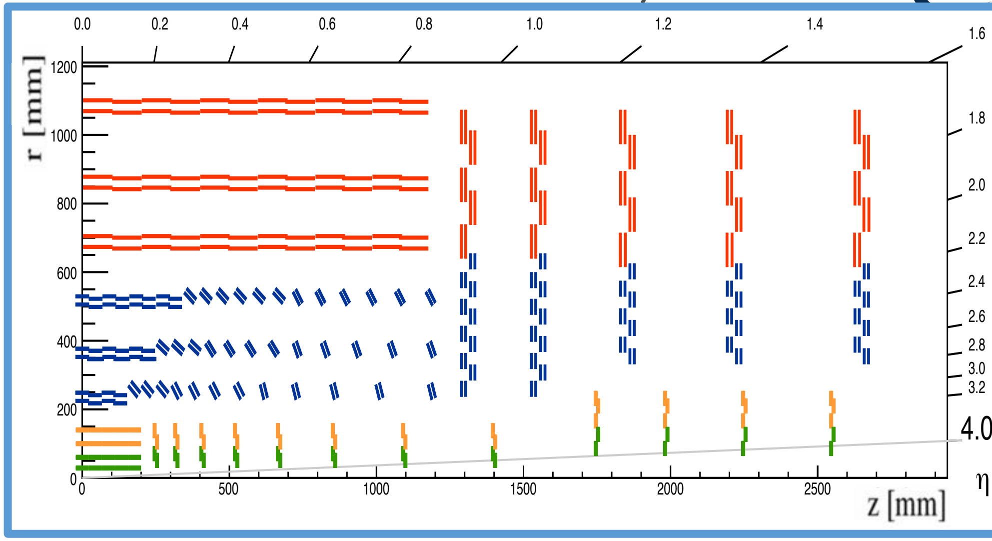
Tilted Barrel Geometry

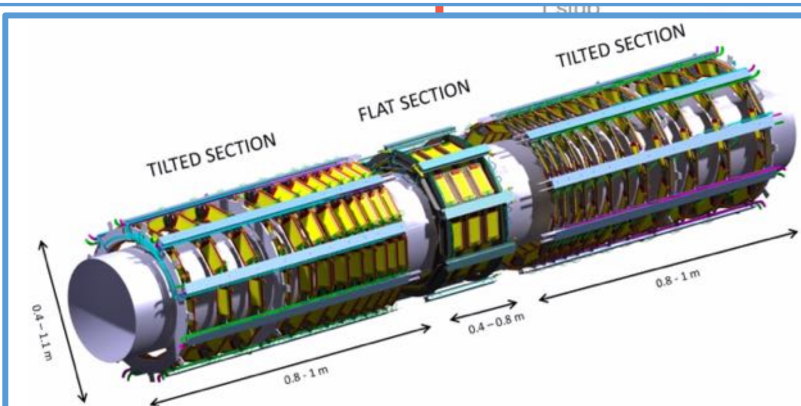
- Stubs generation works only if the charged particle cross the two sensors on the same halve of the same module
- This is not true for (flat) barrel peripherical modules

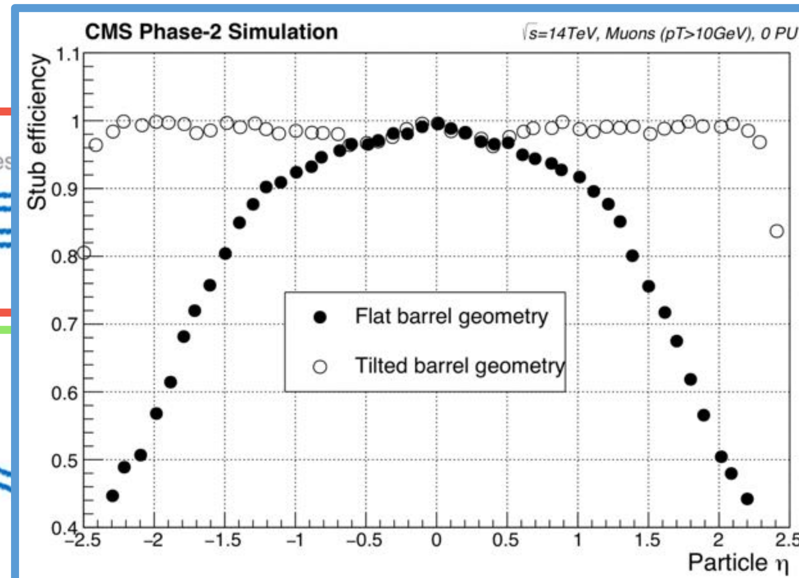
→ **(increasingly) Tilt peripherical barrel modules**

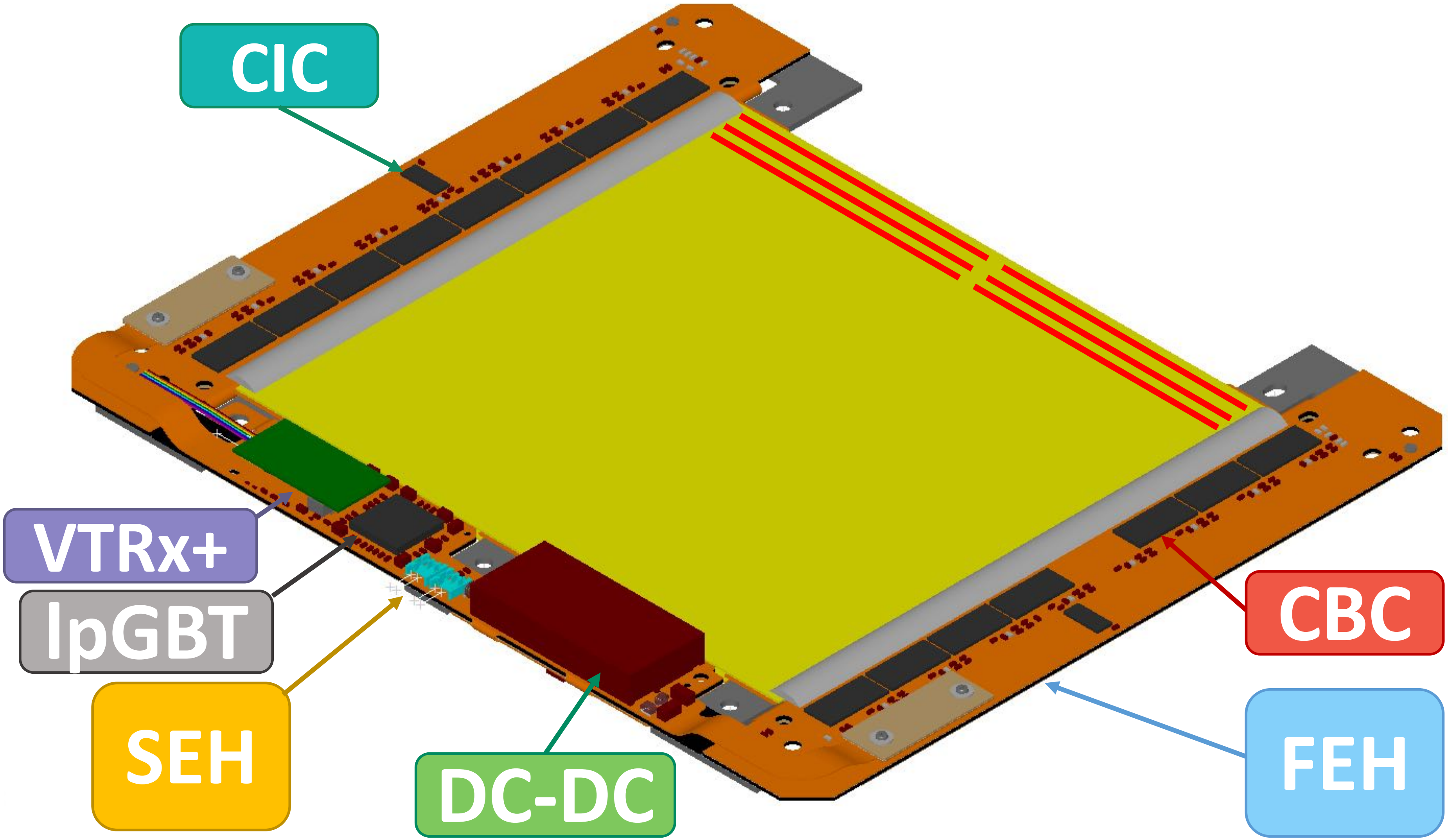
- **Sizable reduction on the number of modules needed**
  - → **From ~15k (flat) to ~13k (tilted)**

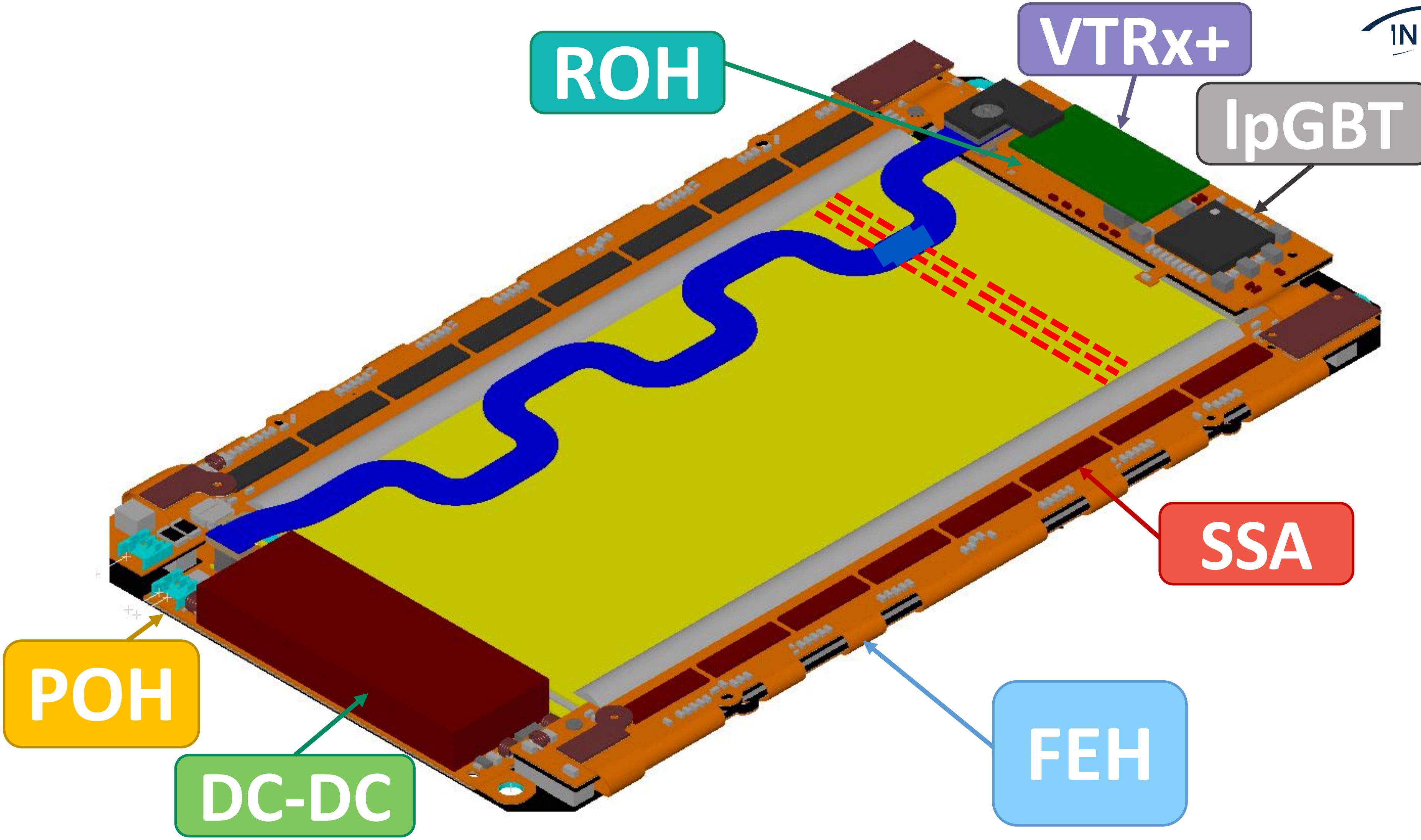
Tilted Barrel Geometry

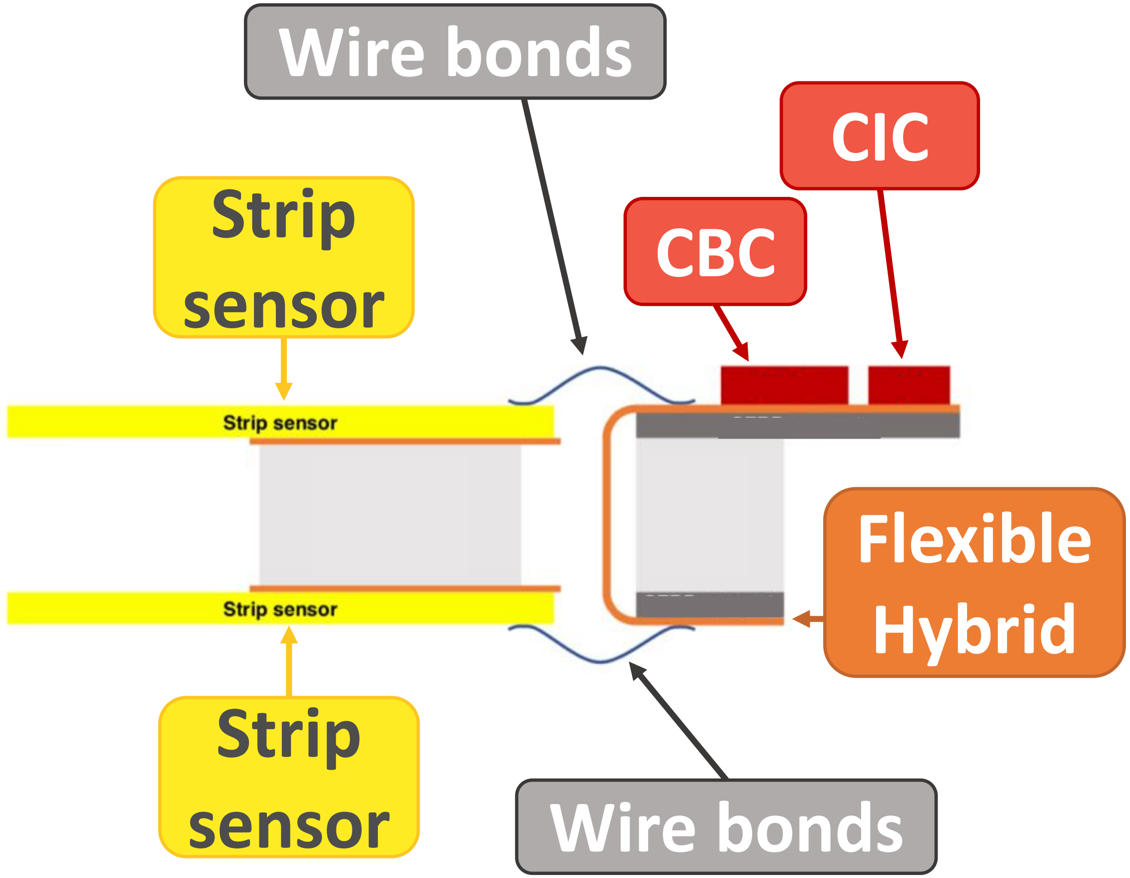


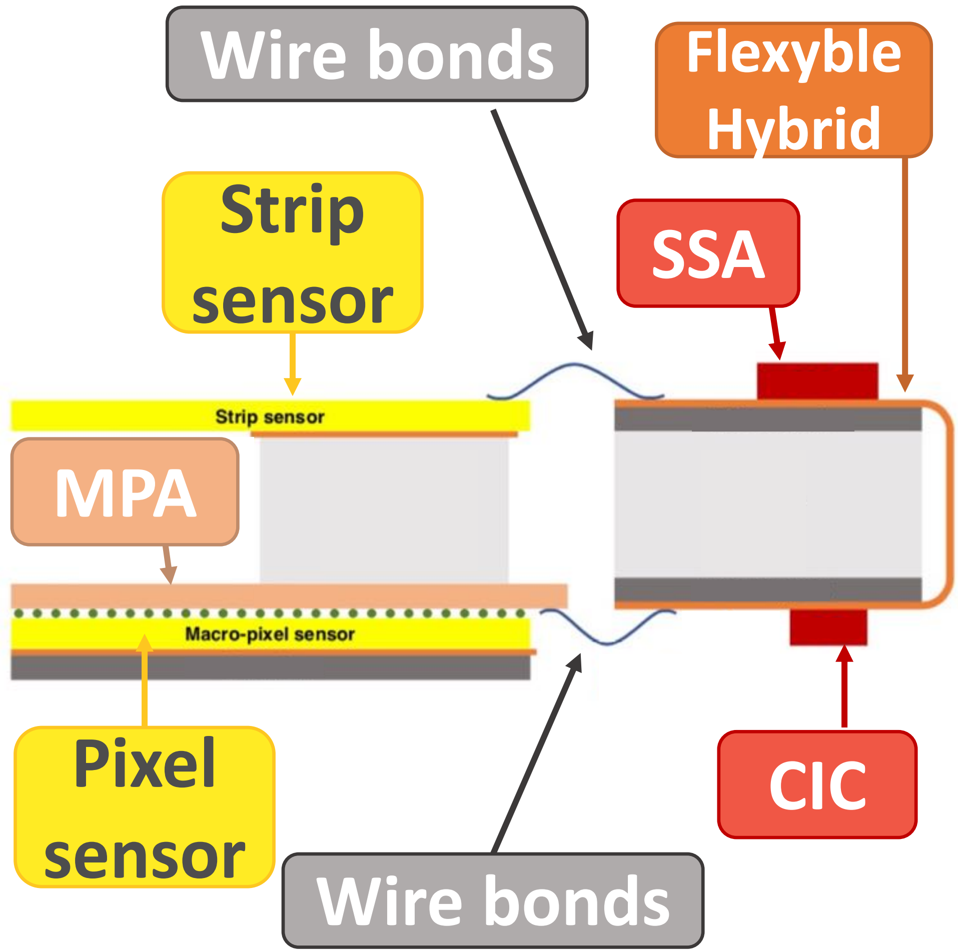





CIC
VTRx+
lpGBT
SEH
DC-DC
CBC
FEH


ROH
VTRx+
lpGBT
SSA
POH
DC-DC
FEH


Wire bonds
CIC
CBC
Strip sensor
Strip sensor
Strip sensor
Flexible Hybrid
Strip sensor
Strip sensor
Wire bonds


Wire bonds
Flexyble Hybrid
Strip sensor
SSA
Strip sensor
MPA
Macro-pixel sensor
Pixel sensor
Wire bonds
CIC

Irradiated Sensors at Beam Test

- Sensor irradiated with neutron only at JSI
- CBC3 readout chip (almost final)
- Charge collection reflected in hit efficiency as a function of threshold
  - FZ290 can tolerate higher thresholds
  - Only after long annealing (200 days) at ultimate $5x10^{14}neq/cm^2$ both materials are comparable
- dark noise occupancy was measured:
  - lower than 10^{-5} while expected hit occupancy is $\sim10^{-2}$
  - Scale with annealing (current) and not with thickness