The CMS Tracker for the High Luminosity LHC

ALESSANDRO ROSSI FOR CMS COLLABORATION

PM2021 – 15th Pisa Meeting on Advanced Detectors – Edition 2022

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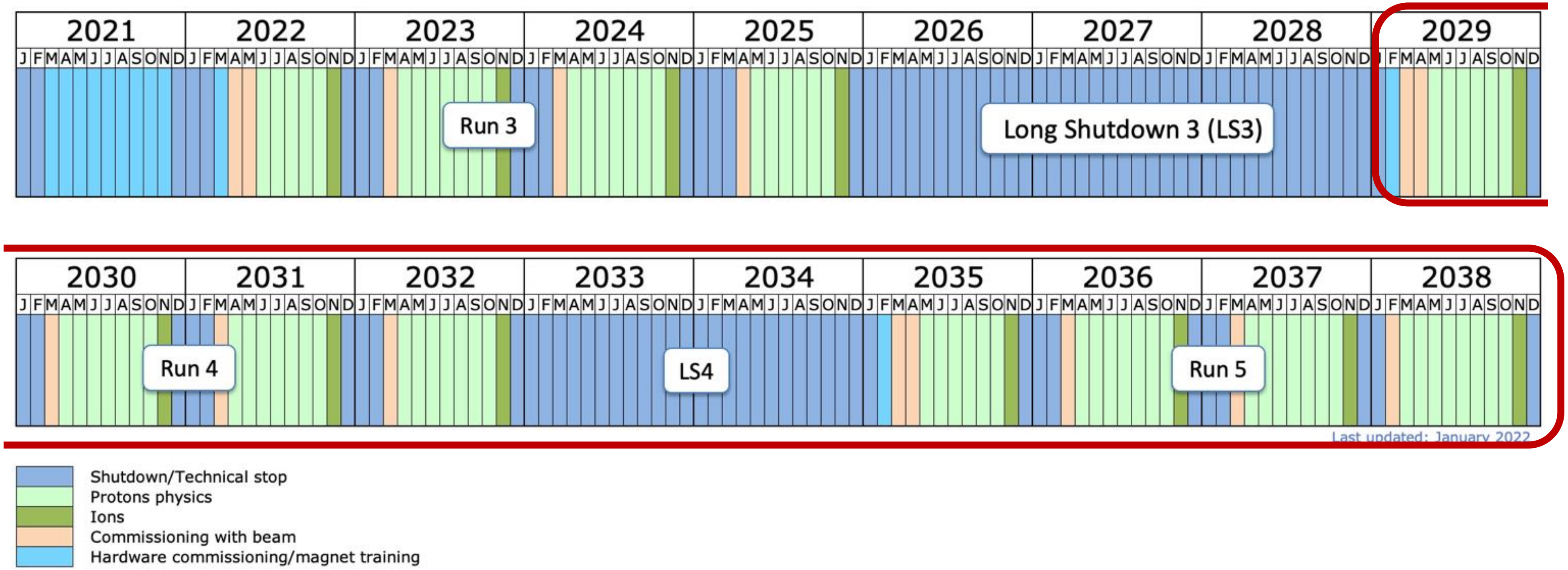
La Biodola – Isola d'Elba (Italy)

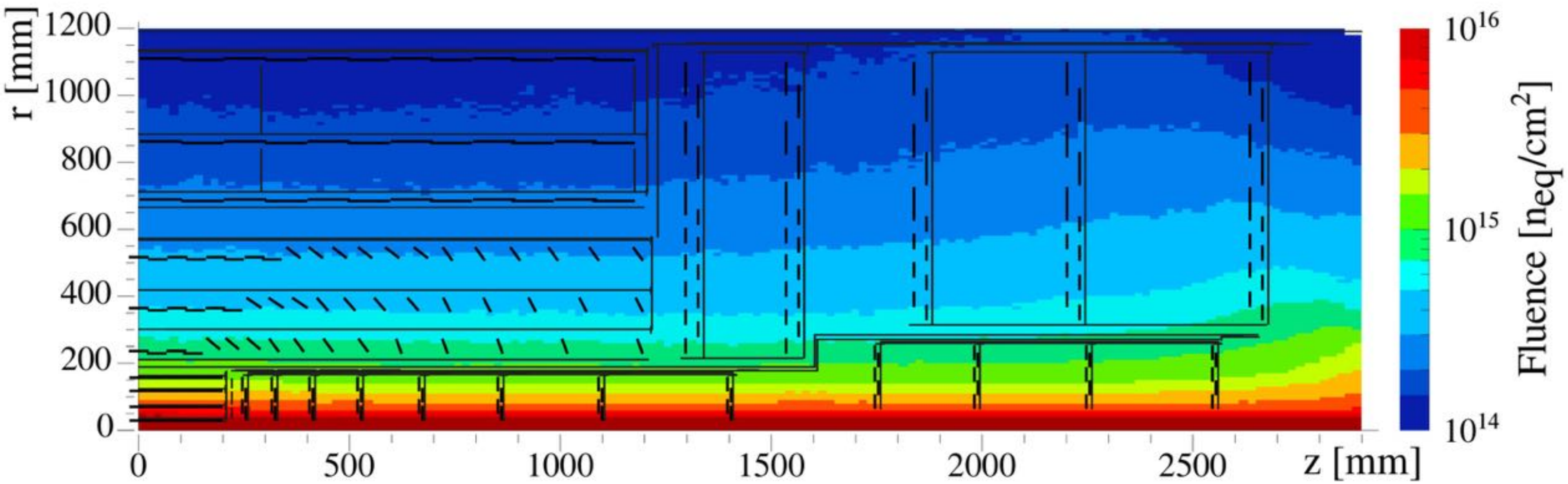
LHC Schedule

- 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
- Crab cavities
- (some) New Magnets (11T)
- Civil engineering:
  - New acces shafts
  - New service tunnels
- ...and more!



High Luminosity Requirements

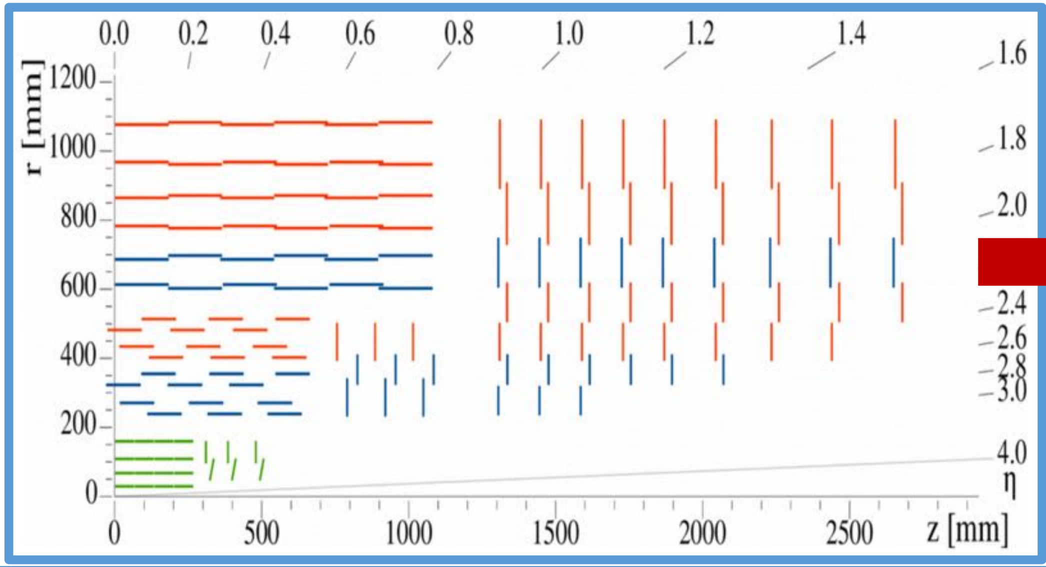
- ***Increased granularity:*** In order to ensure efficient tracking performance with a high level of pileup
- ***Reduced material in the tracking volume:*** The exploitation of the high luminosity will greatly benefit from a lighter tracker
- ***Contribution to the level-1 trigger:*** The selection 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



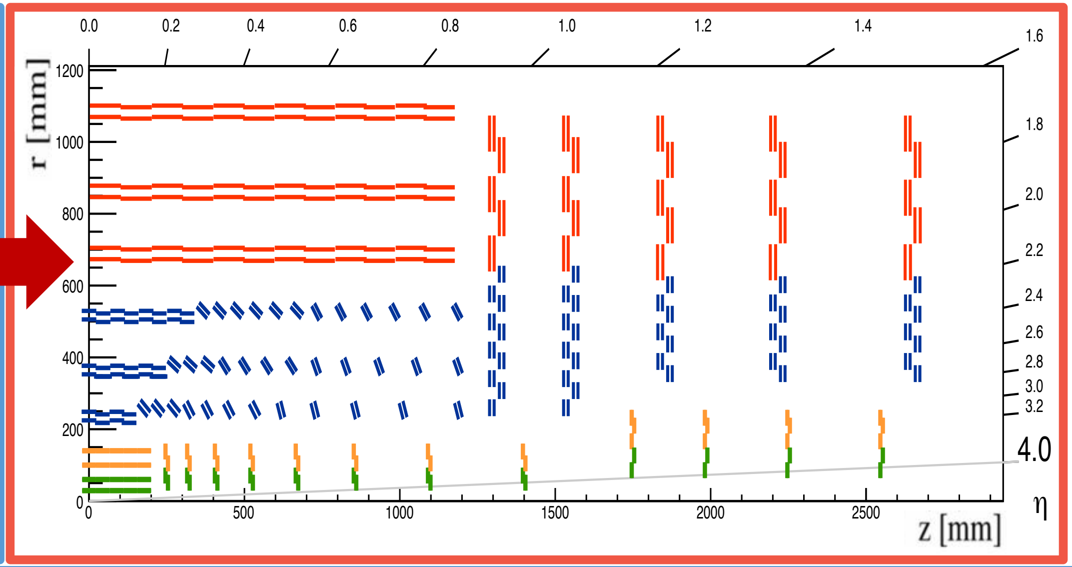
Why change the current Tracker

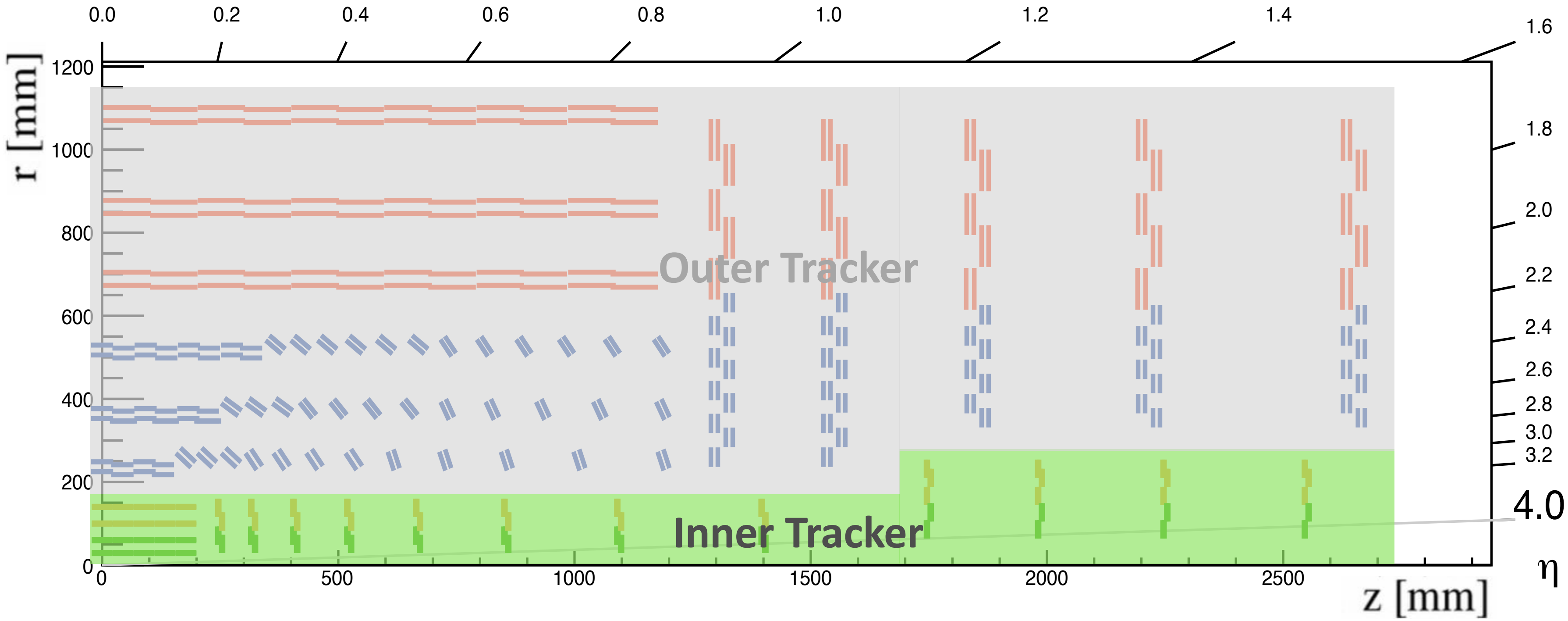
- Radiation damage at the end of Run3
  - A big part of current strip tracker will become completely in-operational due to either leakage current or full depletion voltage limitations at 1 ab^{-1}
  - Pixel detector need to handle a factor 6 higher hit rate (from 0.58 to 3.2GHz/cm^2) and need an higher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

CMS Phase-1 Tracker



CMS Phase-2 Tracker

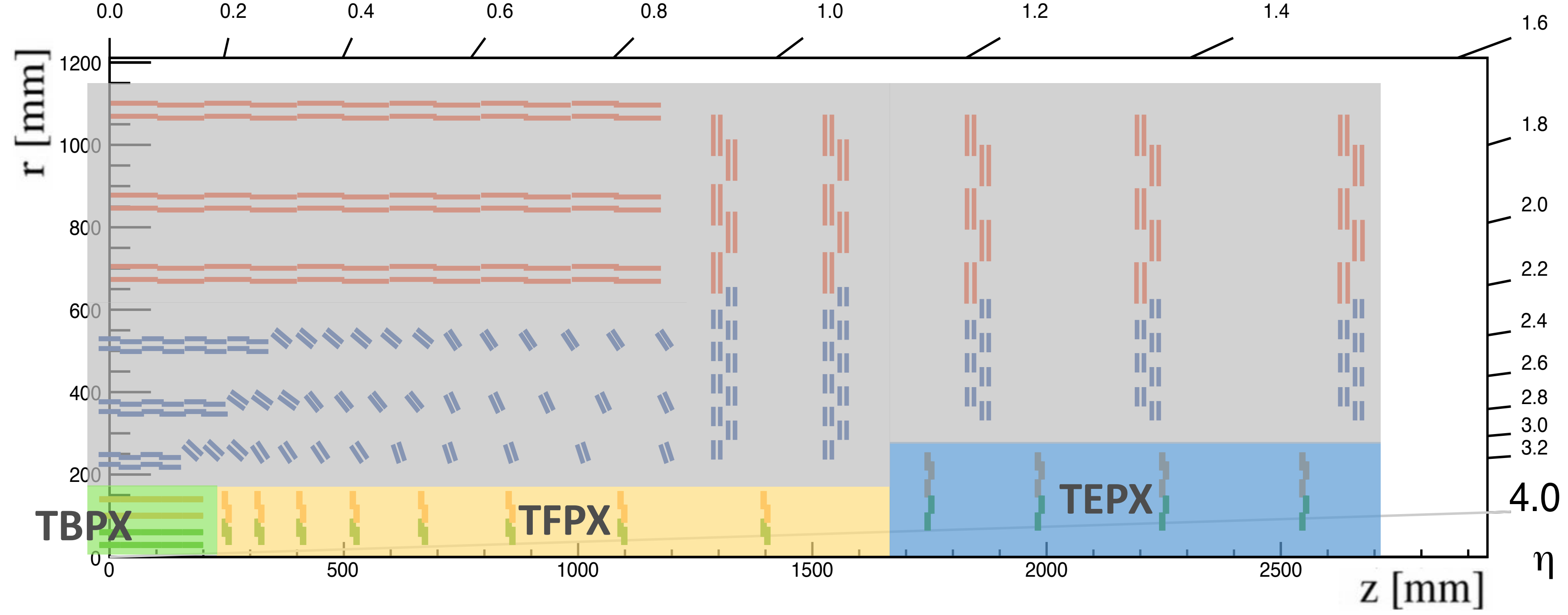




INNER TRACKER

Also a dedicated poster: ***The CMS Pixel Detector for the High Luminosity LHC*** *- Antonio Cassese*

Phase-2 CMS Inner Tracker

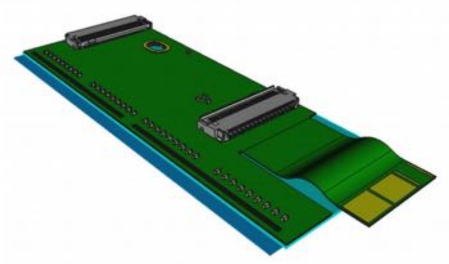


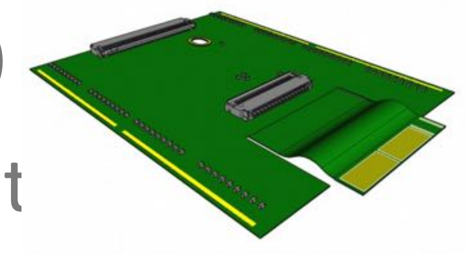
- **TBPX** : **T**racker **B**arrel **P**i**X**el
  - 4 Layers, no crack at z=0
- **TFPX** : **T**racker **F**orward **P**i**X**el
  - 8 small disks on each side
- **TEPX** : **T**racker **E**ndcap **P**i**X**el
  - 4 large disks on each side

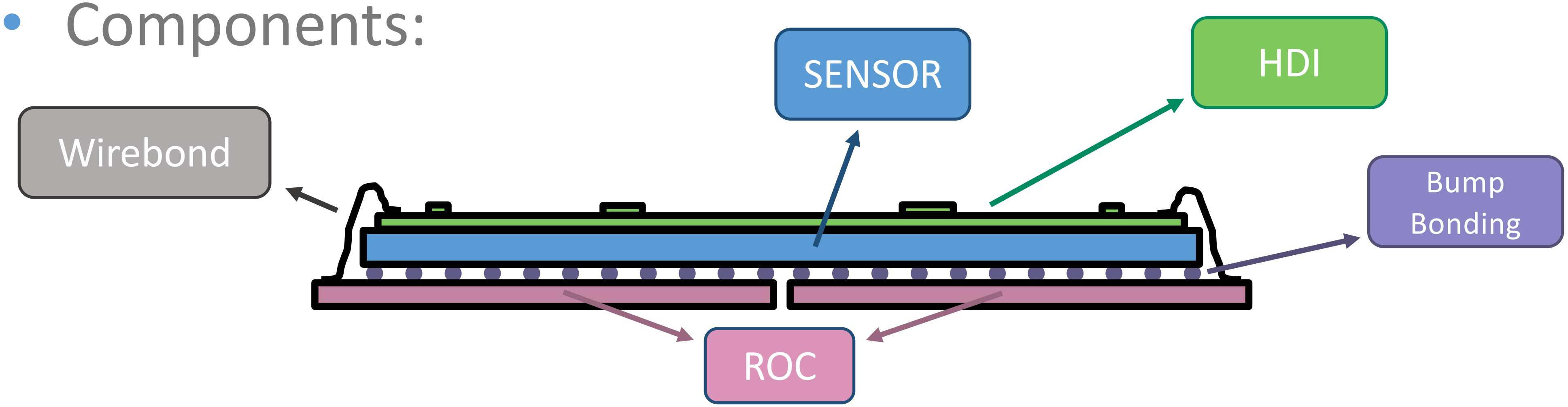
Extended coverage up to |η|= 4
Innermost modules located at r=2.75cm form the beamline

Modules

- Two types of Pixel Modules
  - 1x2 and 2x2 readout chip
- 3892 module plus spares (1156 1x2, 2736 2x2)
  - 2 Billon pixel (124 million in current detector)
- Read Out Chip (ROC) only active element on module
- Components:

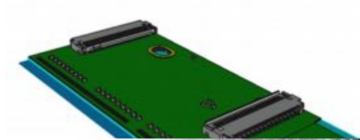


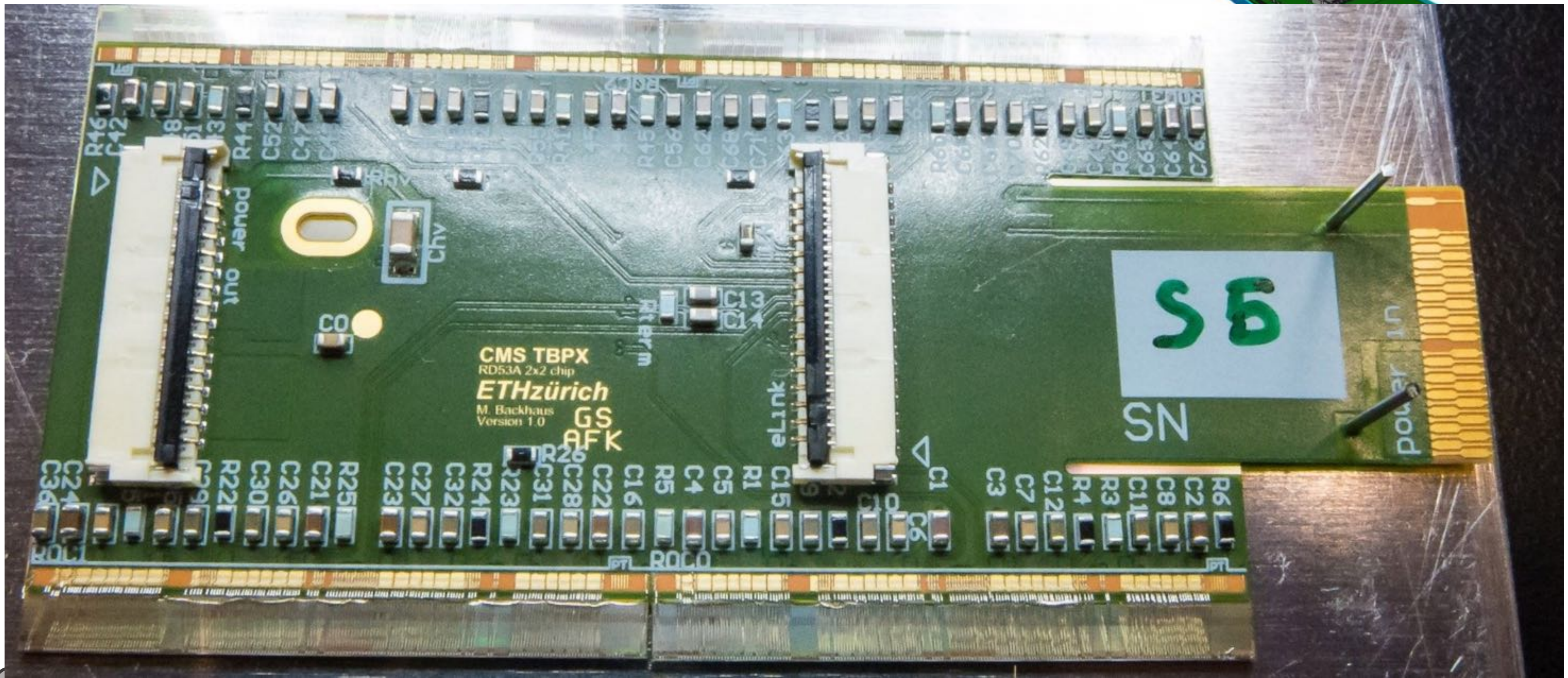


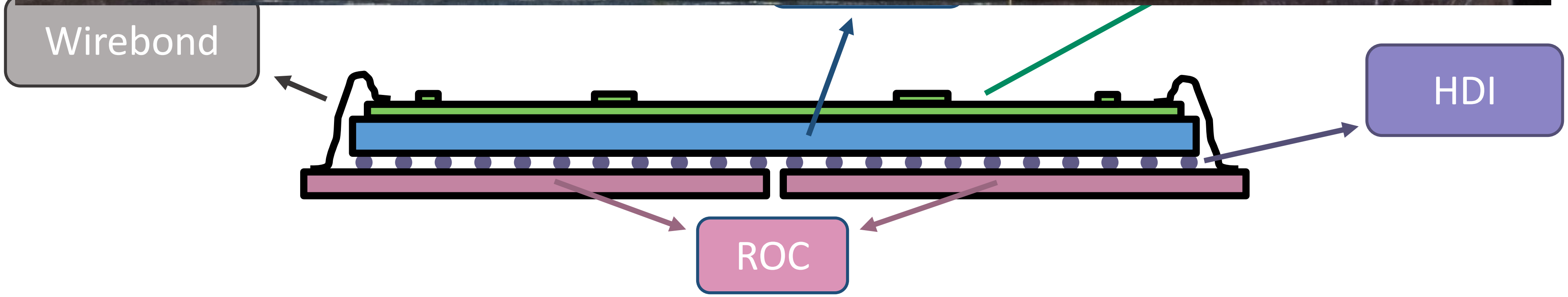


Modules

- Two types of Pixel Modules

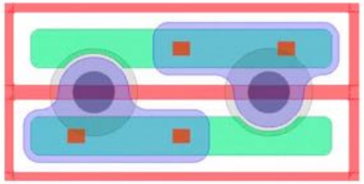




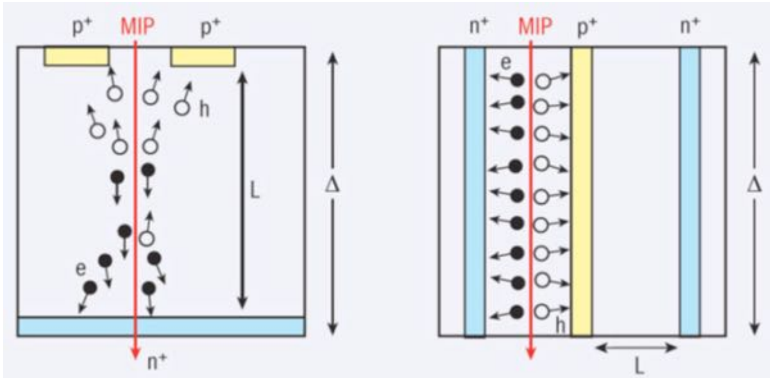


Sensors

- Intese R&D program carried out
  - Several report on posters:
    - ***Characterization of irradiated passive CMOS sensors for tracking in HEP experiments*** - Franz Glessgen
    - ***Performance of highly irradiated FBK 3D and planar pixel detectors*** - Rudy Ceccarelli
    - ***Study of irradiated 3D pixel sensors from CNM*** - Clara Lasaosa Garcia
- 25x100cm^2 pixel cells with 150µm active thickness
- 2 different technology will be adopted
  - n-in-p planar sensors
    - Bitten implant, no punch-through bias dot
    - Hit efficency >99% after 2x10^{16} n_{eq}/cm^2
  - 3D pixel sensors on Barrel layer1
    - Better power consumption
    - Stable hit resolution performances up to 10^{16} n_{eq}/cm^2

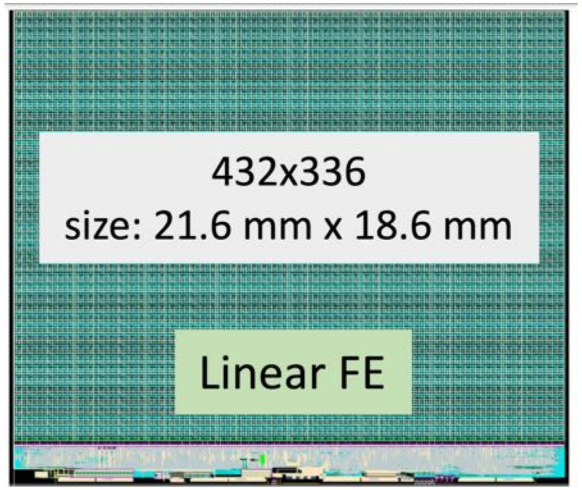


Bitten implant design



C-ROC

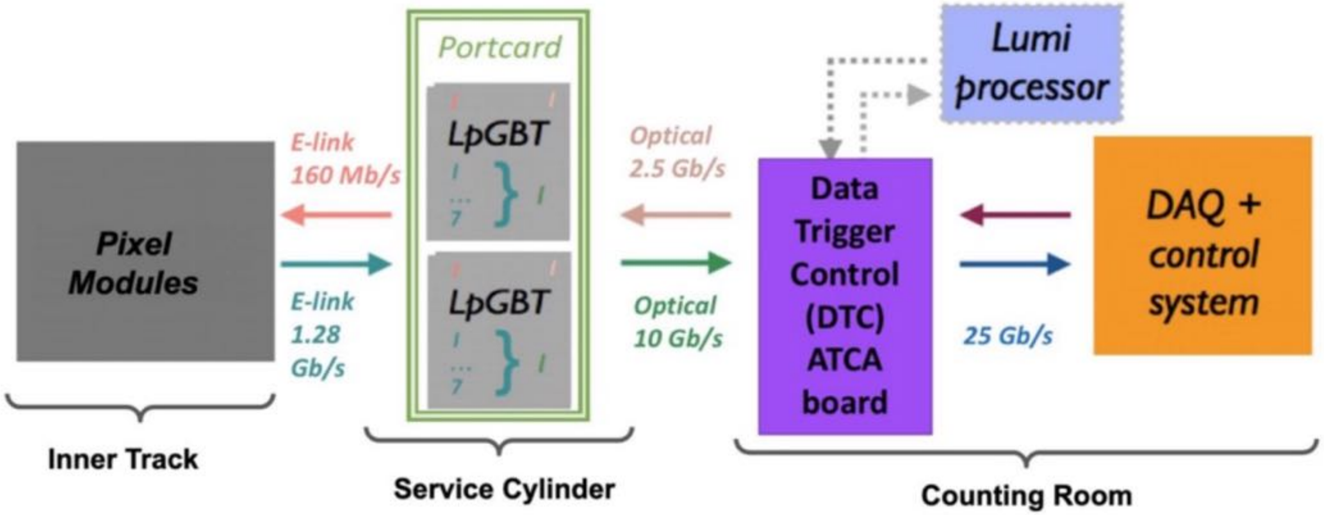
- ASIC based on CMOS 65nm technology (CERN RD53 project)
  - Radiation tolerant up to 1 Grad
  - Strongly protected against SEU effects
  - Low power consumption < 1 W/cm2
    - At CMS Level1 trigger rate of 750 kHz
  - Serial powering via on-chip shunt-LDO regulators (1 for analog, 1 for digital sections)



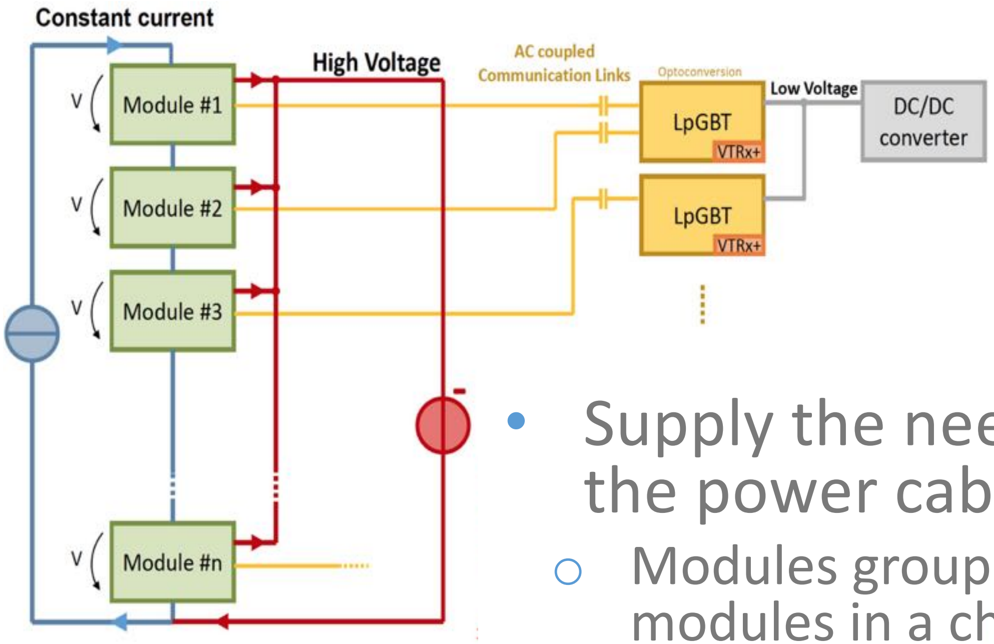
- CMS flavor of RD53 ROC : C-ROC
  - First wafer level test performed
    - All details on poster: ***Wafer level test of the readout chip of the CMS Inner Tracker for HL-LHC*** - *Michael Grippo*
  - Full size ASIC: 432x336 channels
  - Analog FE linear architecture
  - 4 bit digital readout with selectable 6-to-4-bit dual slope ToT mapping for charge compression (elongated clusters, heavy ionizing particles)

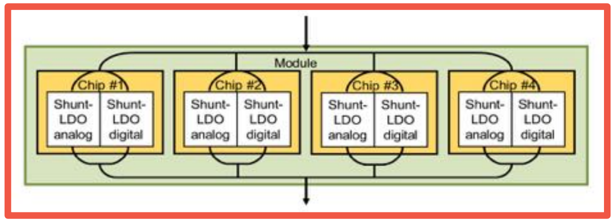
Read out architecture

- Comunication electronics hosted on dedicated board:
  - Portcards optoelectronic service card
- Portcard houses 3x lpGBTs and VTRx+ links, powered via cascaded DC-DC converters
- Up to 6 electrical up-links at 1.28 Gb/s → module to lpGBT
  - Rates reduction achived with data formatting
- One electrical down-link at 160 Mb/s → lpGBT to module
  - clock, trigger, commands, configuration data to modules
- 28 Data Trigger Control boards required for inner tracker



Powering scheme

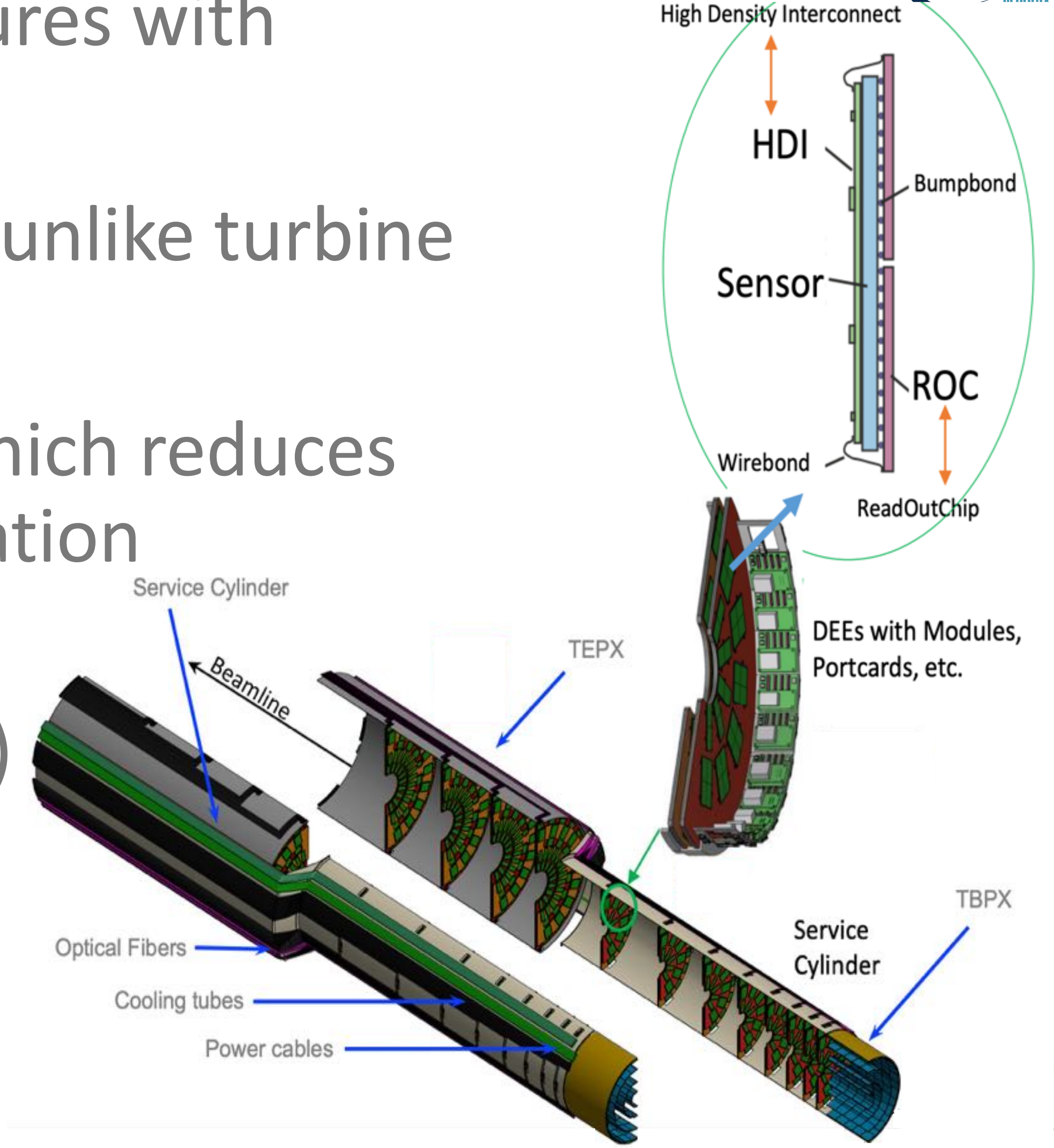


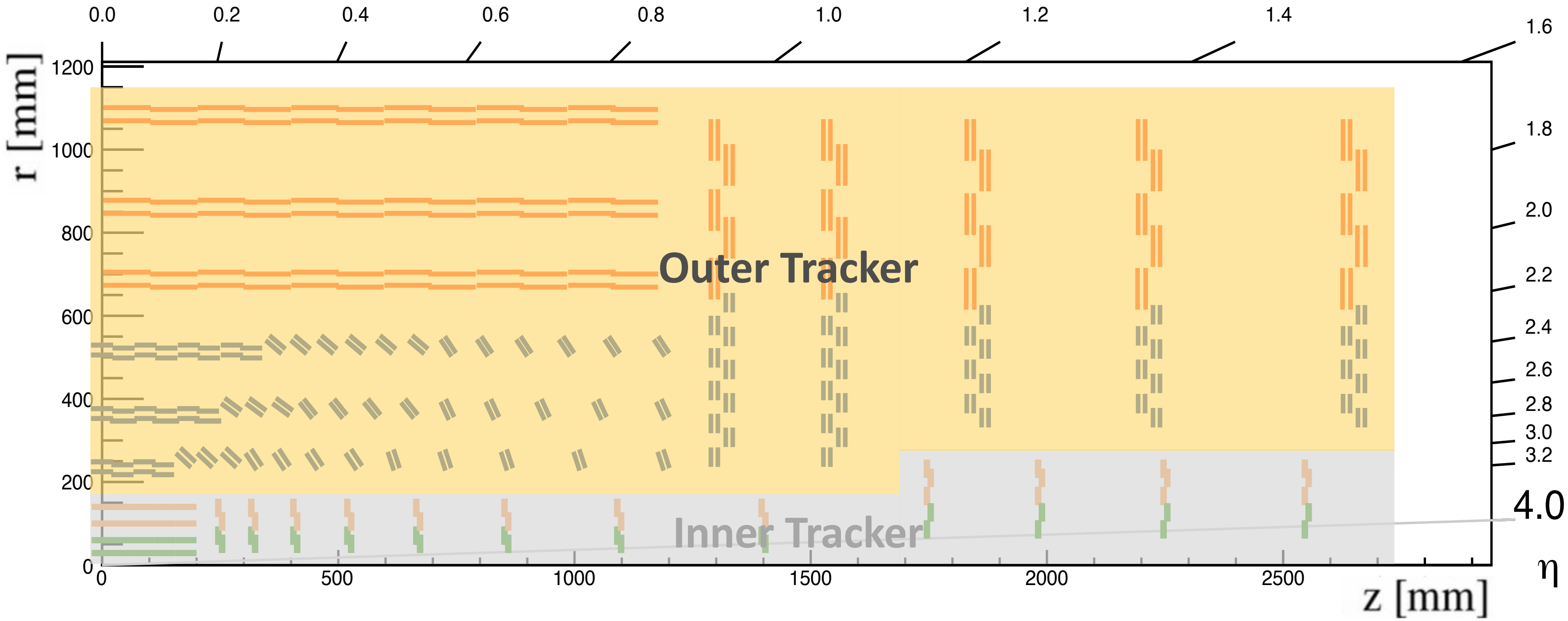


- Supply the needed 50 kW with a limited mass of the power cables → SERIAL POWERING
  - Modules grouped in 500 serial power chains, up to 12 modules in a chain
    - Modules powered in series, chips within each module powered in parallel
    - A shunt-LDO (SLDO) on each chip provides voltage regulation for each chip while maintaining a constant current
  - Chips in a module in parallel (4A for 1x2 modules, 8A for 2x2 modules)
  - Sensor bias following the serial power chains with single return line
  - Single power supply module: current source (SP), HV for sensor (0-800V), LV for portcards and pre-heaters required by CO_2 cooling

Mechanical Structure

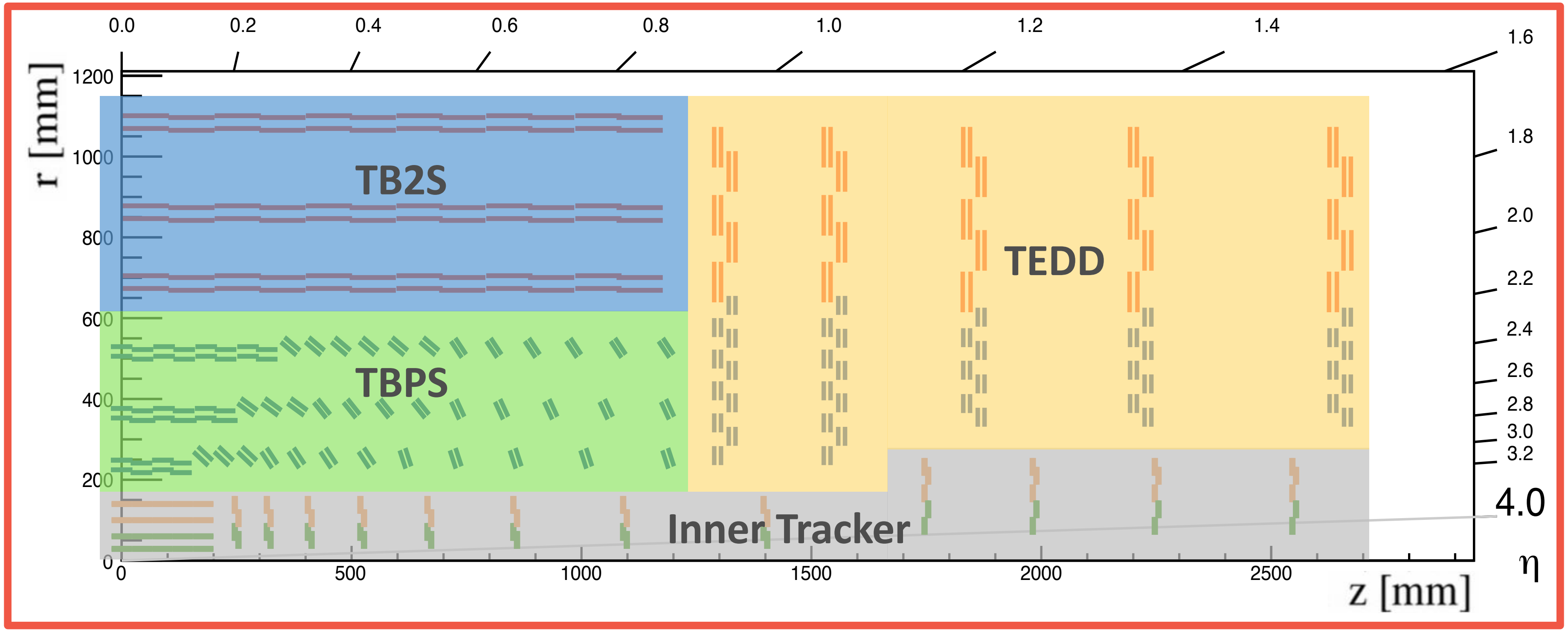
- Light Carbon Fiber structures with embedded cooling pipes
- Disks with flat geometry (unlike turbine in current detector)
- Improved fiber routing which reduces radiation induced attenuation
- Cooling based on evaporative CO_2 (T=-35°C) distributed in 1.8 mm outer diameter stainless steel pipes (168 cooling loops)





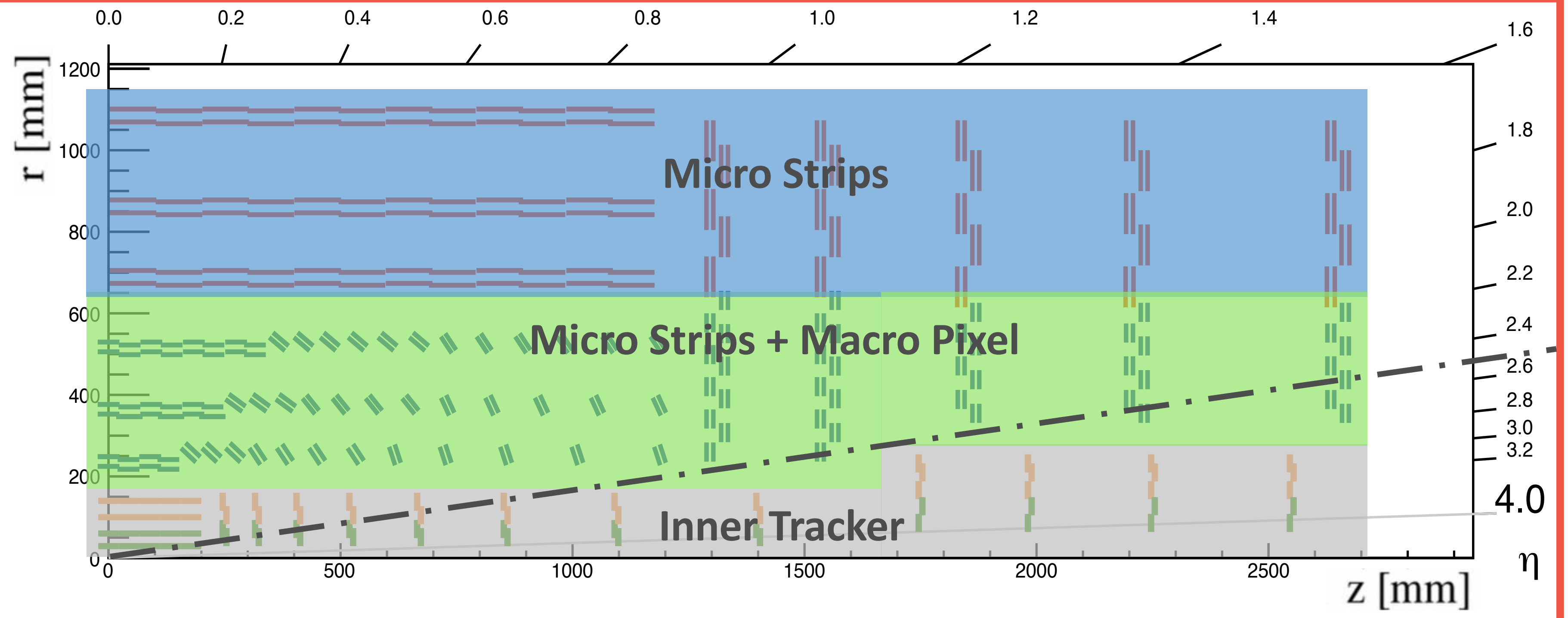
OUTER TRACKER

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



- 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

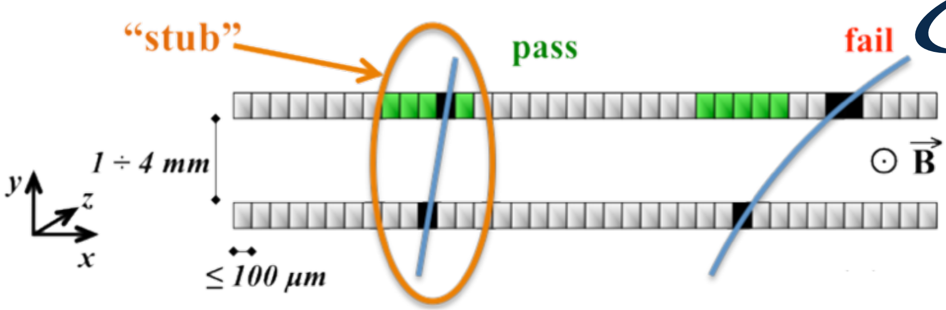
- HL-LHC will deliver an high instantaneus luminosity with a high PileUp
  - It's fundamental to be more selective at L1 trigger in order to keep data rate under control

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

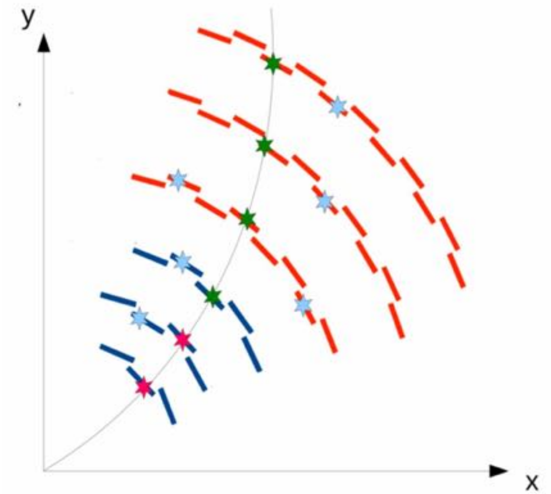
pT Modules

- 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

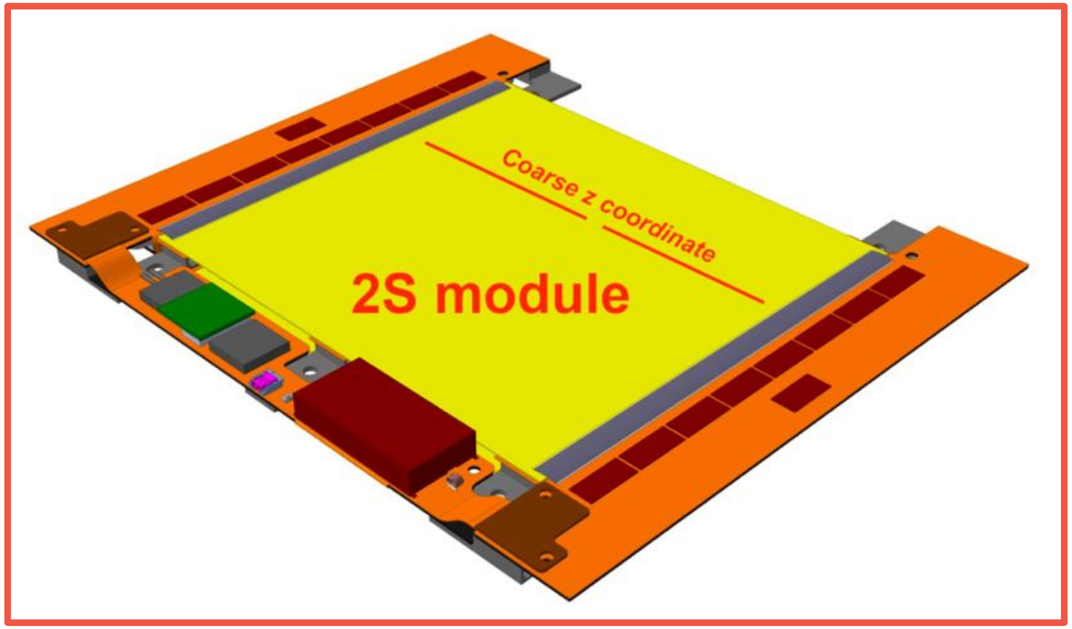


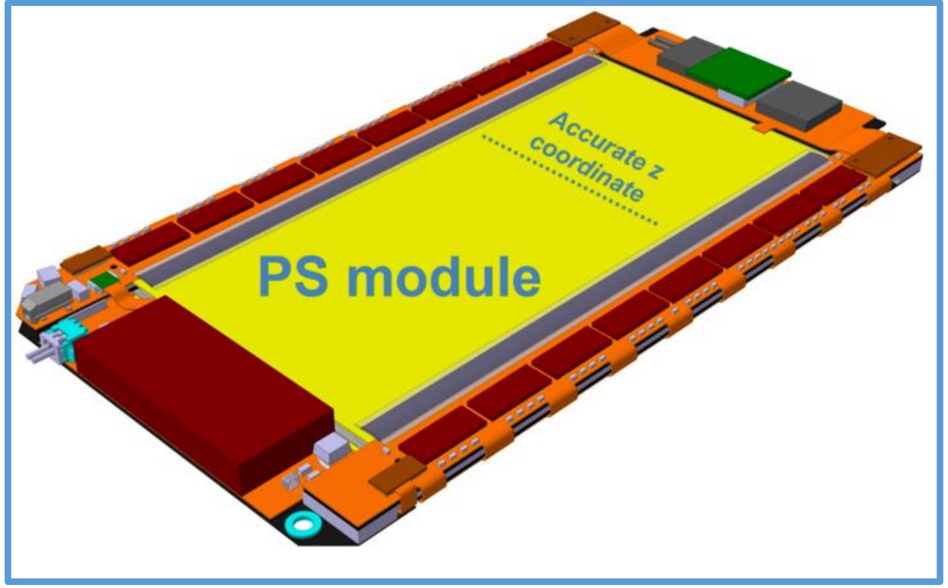
Track Trigger

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



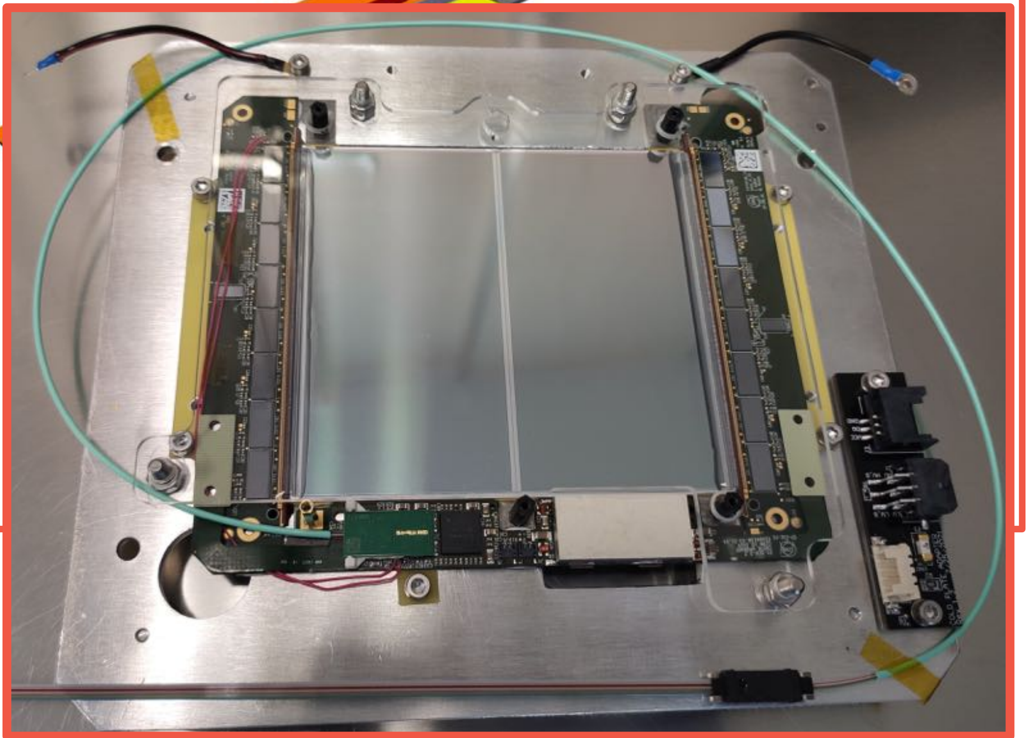
Phase-2 Tracker Modules

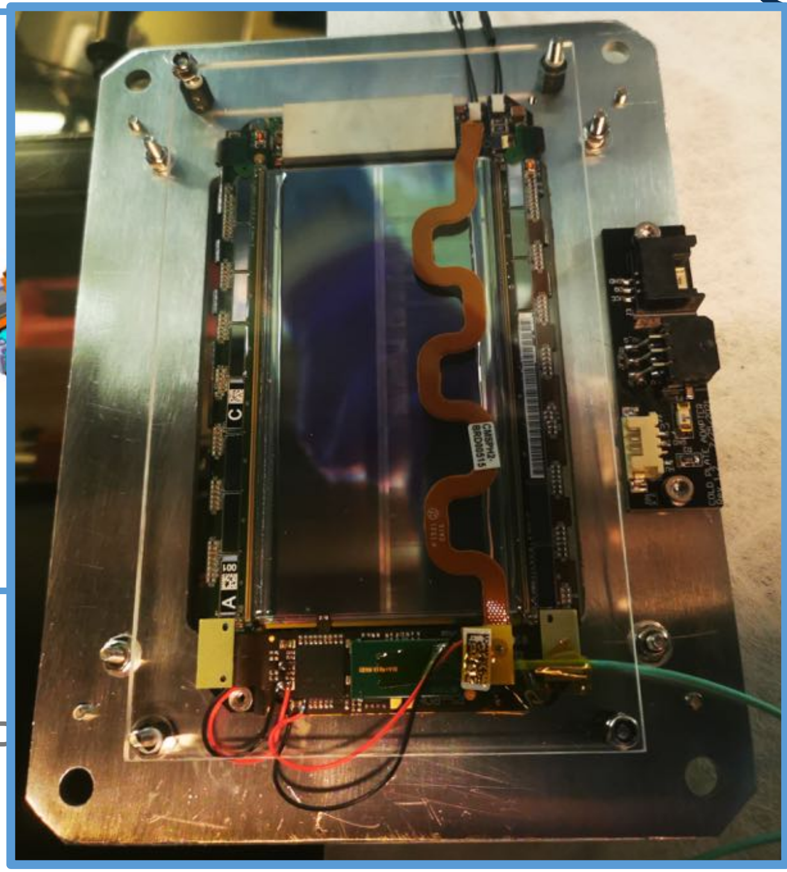




- Two type of modules:
  - 2S Modules
    - 2 different spacing : 1.8mm & 4mm
    - 2 micro strip sensors with 5cm x 90µm strips
    - Sensor dimension are 10cm x 10cm
      - two column of 1016 strips
  - PS Modules
    - 3 different spacing : 1.6mm & 2.6mm & 4mm
    - One strip sensor: 2.5cm x 100µm 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
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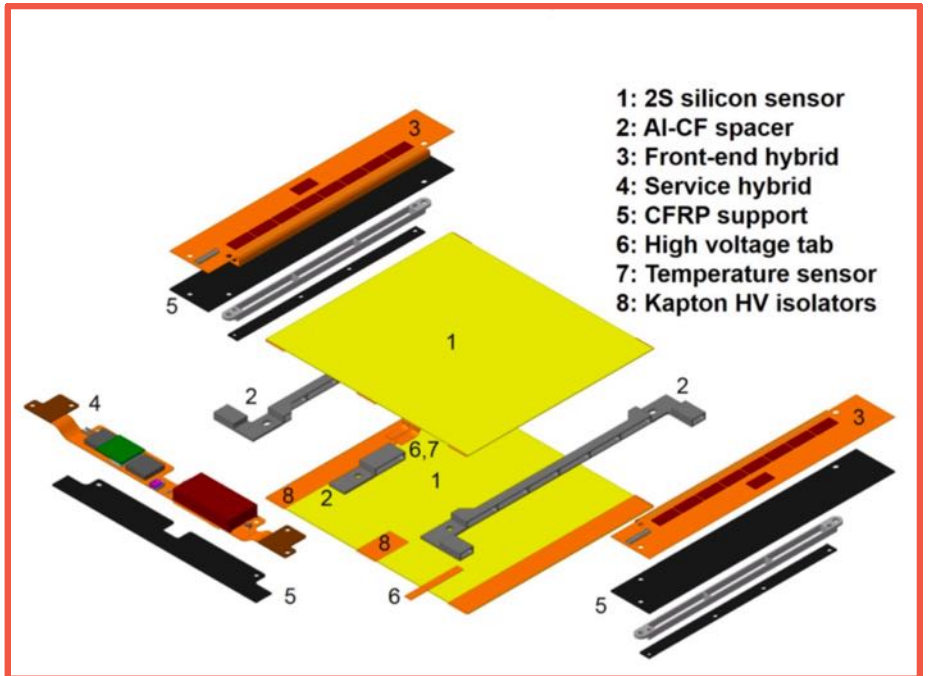
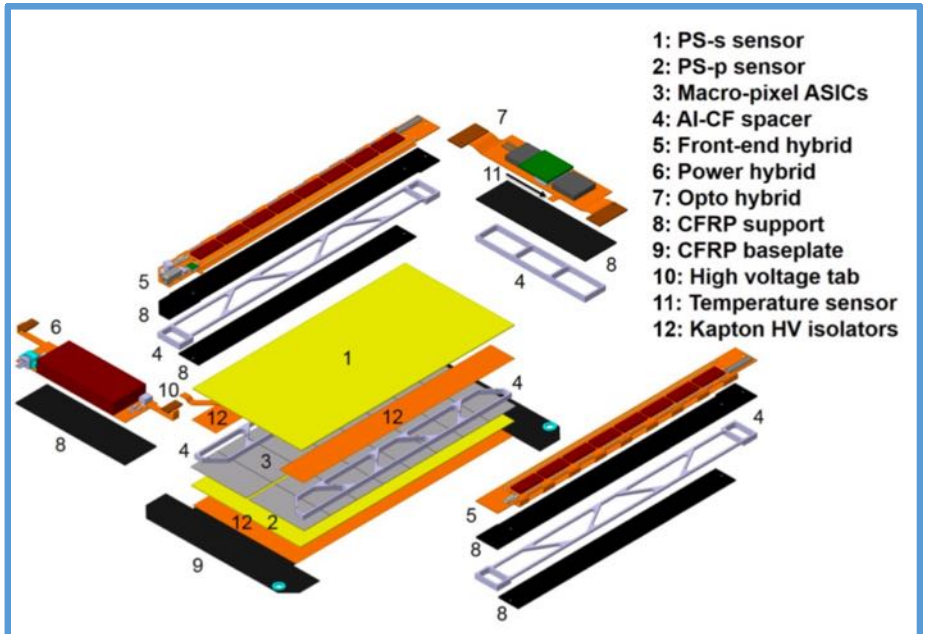
  - One strip sensor: 2.5cm x 100µm strips
  - m x 100µm
  - m
    - two column of 960 strips
    - ~30k pixels

First prototypes (with almost final chips and hybrids) assembled this year → now it's time to test and test and test…

Modules Service Systems



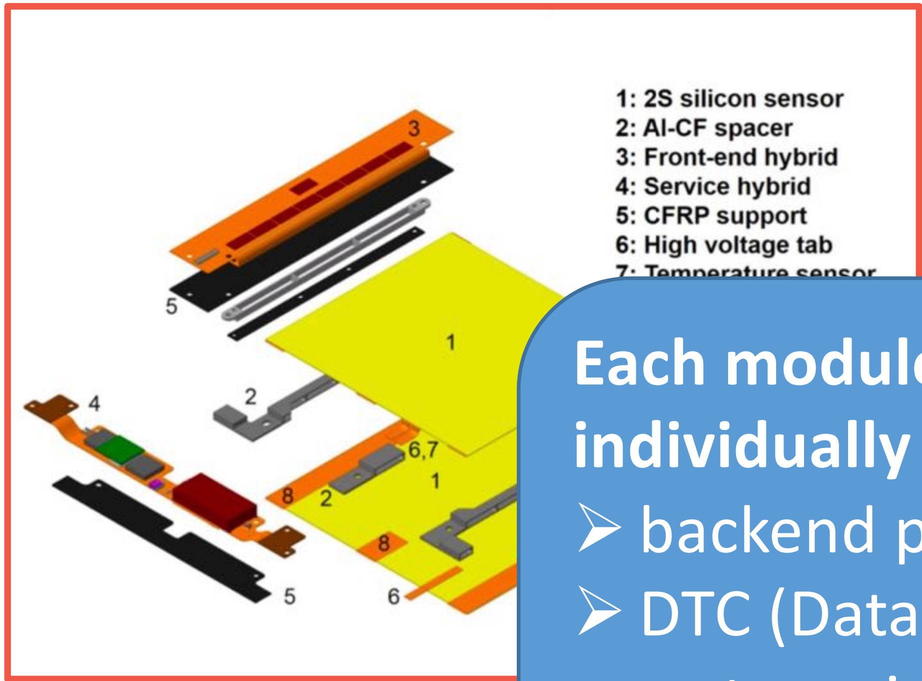


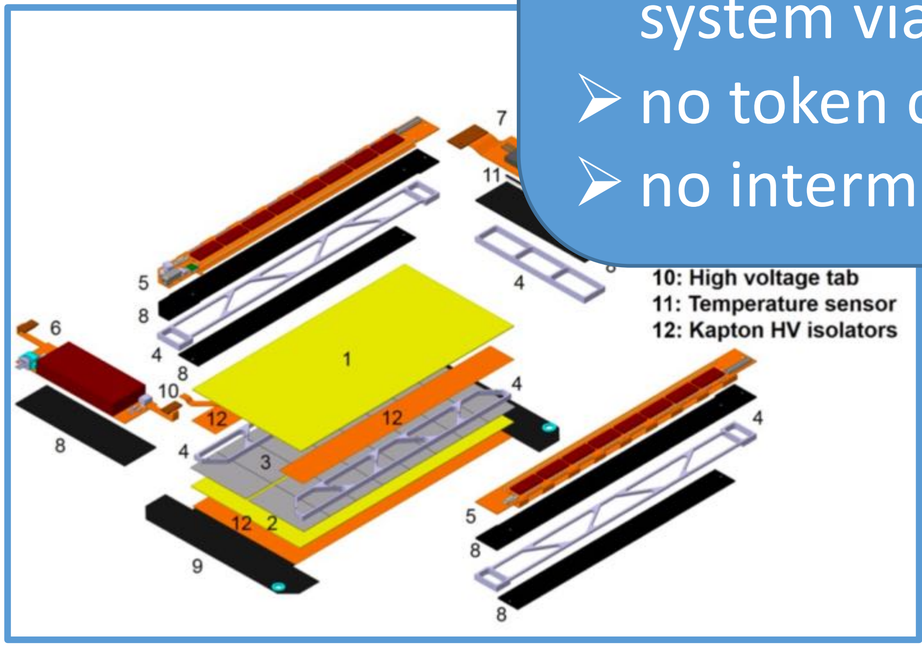
- Module houses both frontend and service hybrids
- Service hybrid(s) has:
  - lpGBT
    - Low Power Gigabit Transceiver
  - VTRx+
    - Versatile Link Plus Transceiver
  - DCDC converters

HL-LHC common development

- Frontend hybrids have readout chip and data concentrator

Modules Service Systems





- Module houses both frontend and service hybrids

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Each module is a functional unit individually connected to:

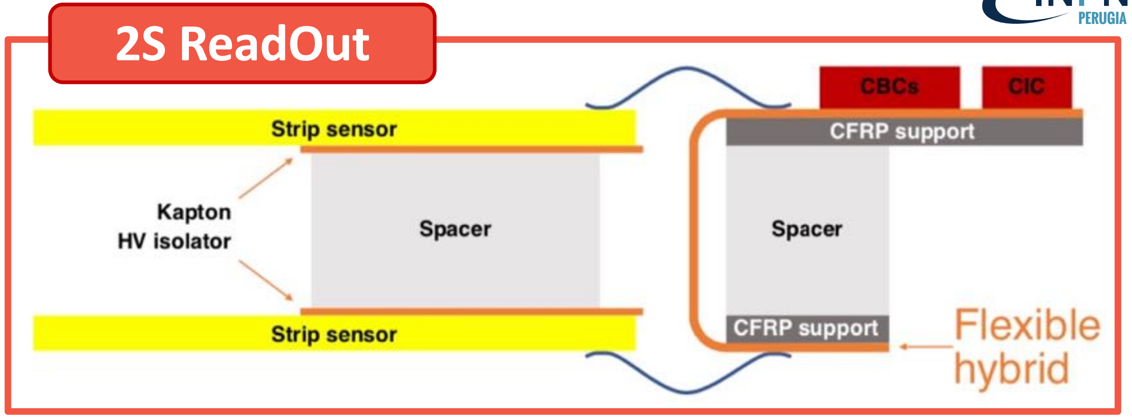
- backend power system
- DTC (Data, Trigger and Control) system via Optical link
- no token control rings
- no intermediate power grouping

HL-LHC common development

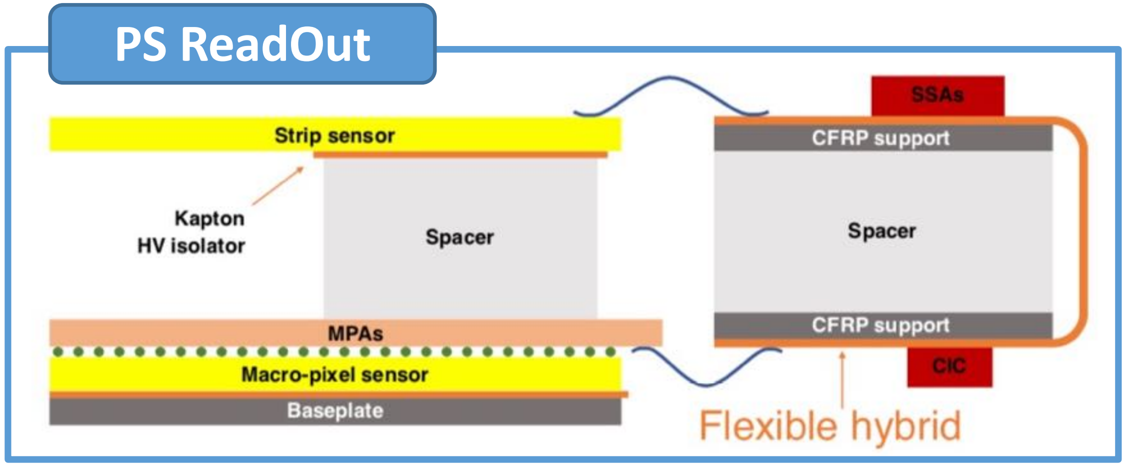
- Frontend hybrids have readout chip and data concentartor

Modules ReadOut

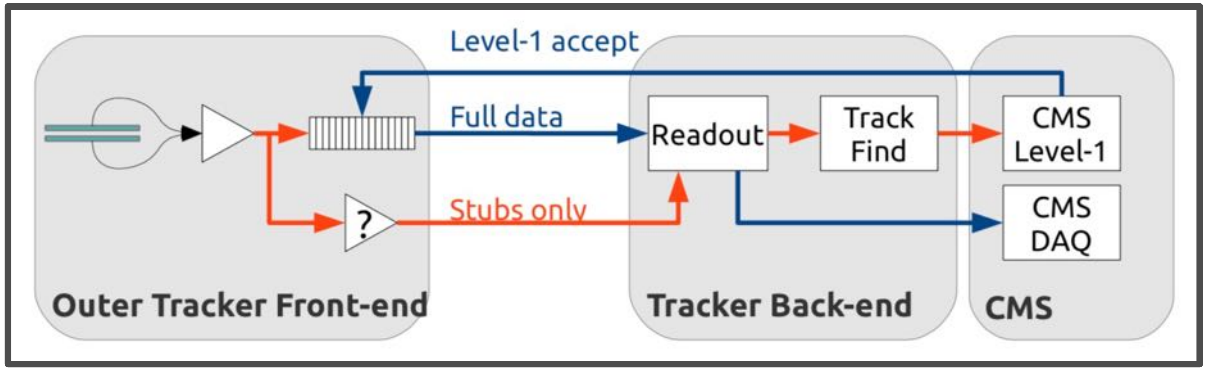
- 2S Module ASICs
  - CMS Binary Chip (CBC) for readout and stub finding for L1
    - both sensors read out by same chip
    - Datailed description on poster: ***Studies of the CBC3.1 readout ASIC for CMS 2S-modules*** – *Kirika Uchida – Geoff Hall*
  - 254 channels per chip
    - 127 from each sensor
  - 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



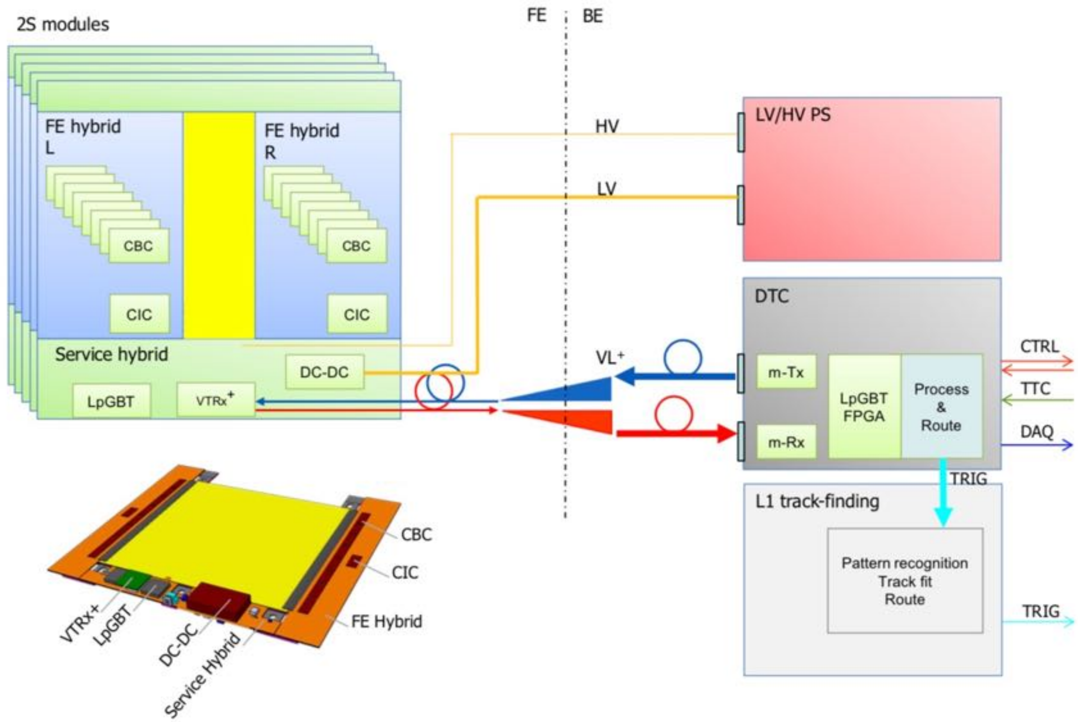
- Common ASIC:
  - CIC concentrator chip Receives L1 information and readout data
  - "Data hub" to service hybrid
  - Done in 65 nm technology



Backend

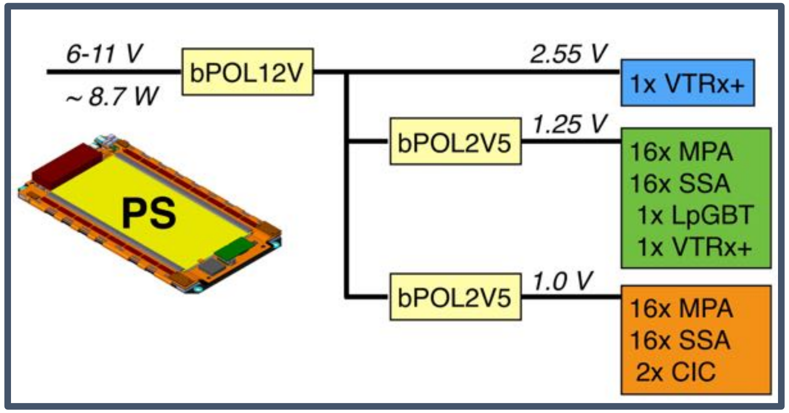
- DTC (**D**ata, **T**rigger and **C**ontrol) boards readout and control module
  - ACTA standard
  - Details on poster: ***The DAQPATH readout system of the Serenity boards for the CMS Phase-II Upgrade –*** *Paolo Prosperi*

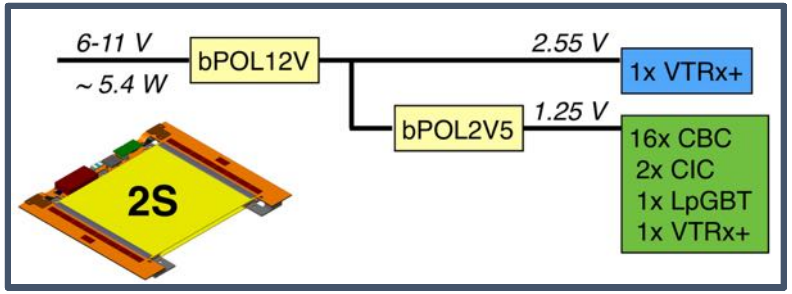
- Bi-directional optical links
  - **2.56 Gb/s DTC → Module**
    - clock, trigger, fast-commands and programming
  - **5.12 or 10.24 Gb/s Module → DTC**
    - L1 and DAQ data
- L1 data at 40 MHz
- DAQ data (after L1) at 750 kHz



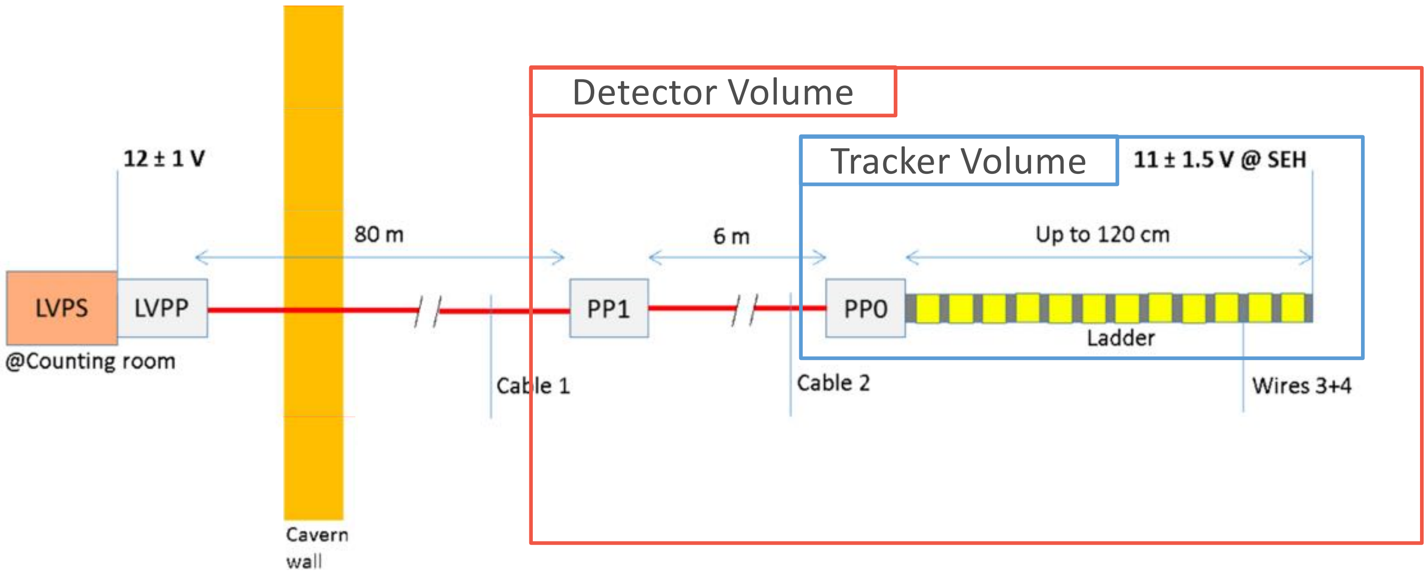
Powering & Cooling

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

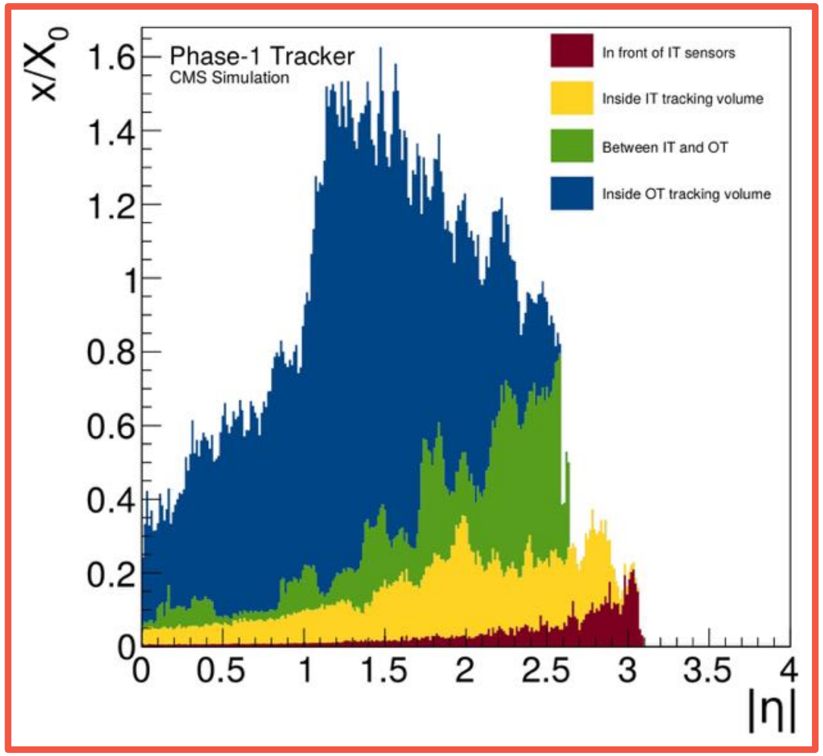


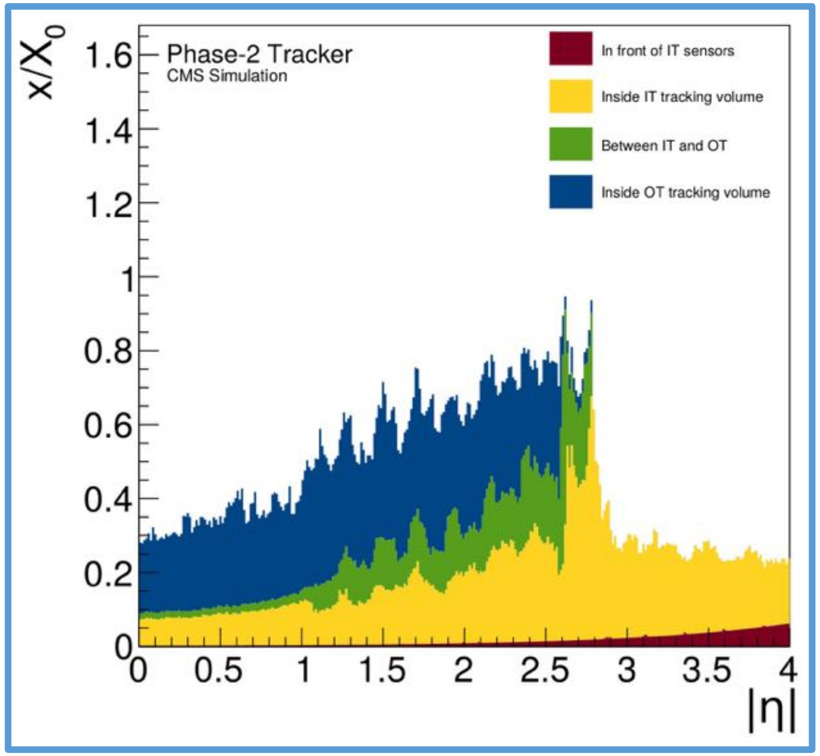


Powerful cooling system:
- (4+1) x 50W cooling plants
- based on two-phase CO_2 cooling system (-35°C set point)
- small pipes



Material Budget



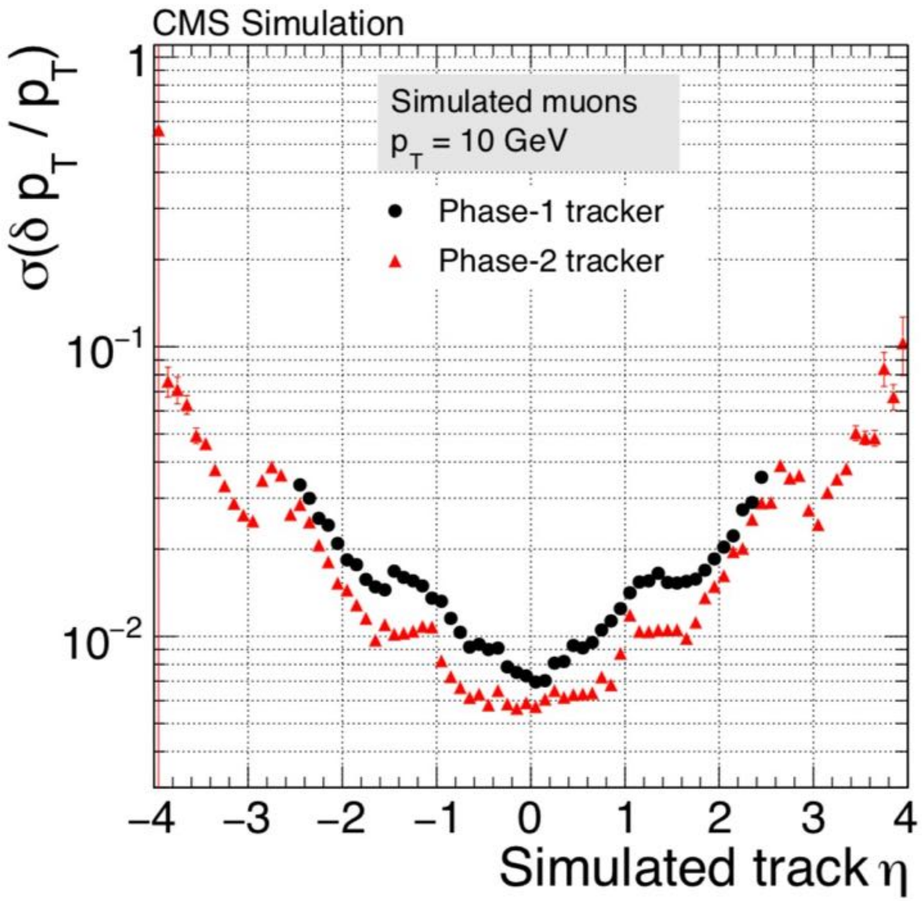


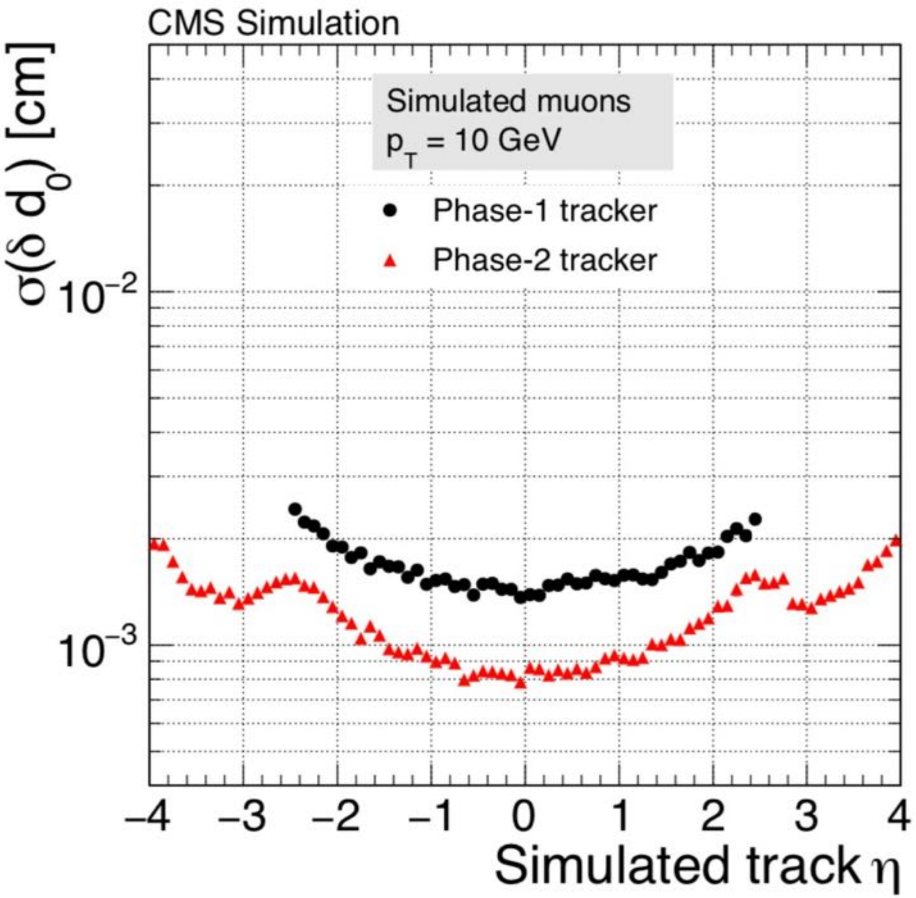
- Material budget much reduced wrt Phase0/1 detector despite an increase in the number of channels

  - *DCDC converters*
  - *Fewer layers*
  - *Lighter materials*
  - *Optimized service routing*
  - *CO_2 cooling*
  - *Inclined geometry*

Performances: Phase-1 vs Phase-2

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

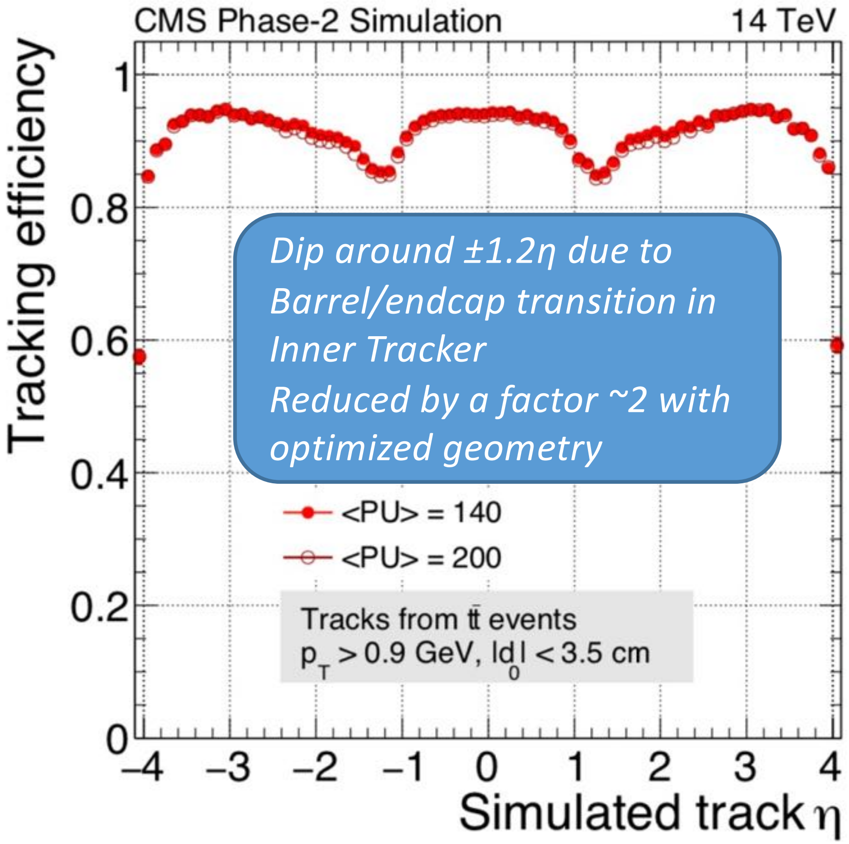


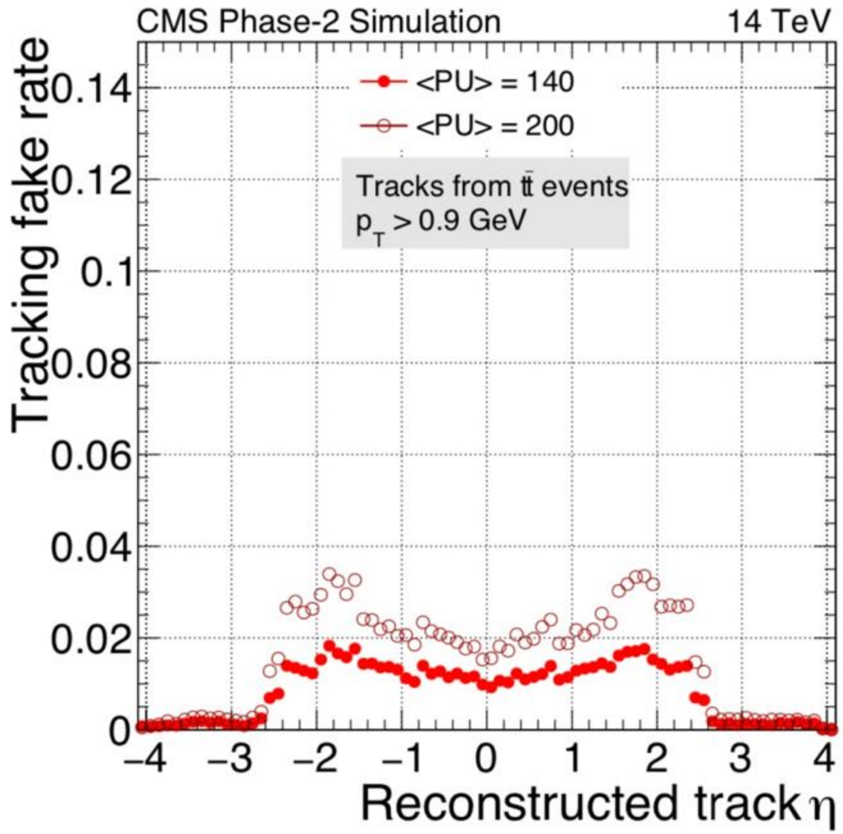


Performances: High PileUp

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

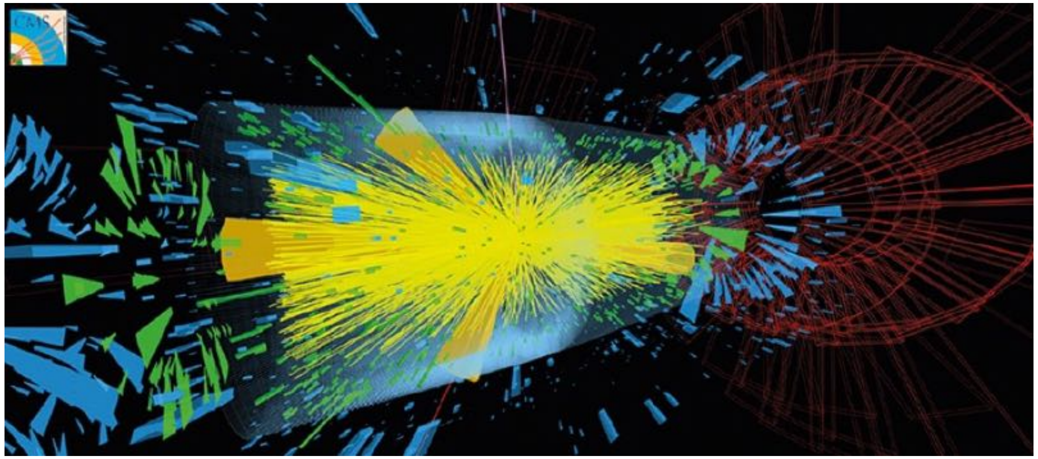
- *Dip around ±1.2η due to Barrel/endcap transition in Inner Tracker*
  - *Due to TDR geometry, reduced by a factor ~2 with optimized geometry*





Conclusions

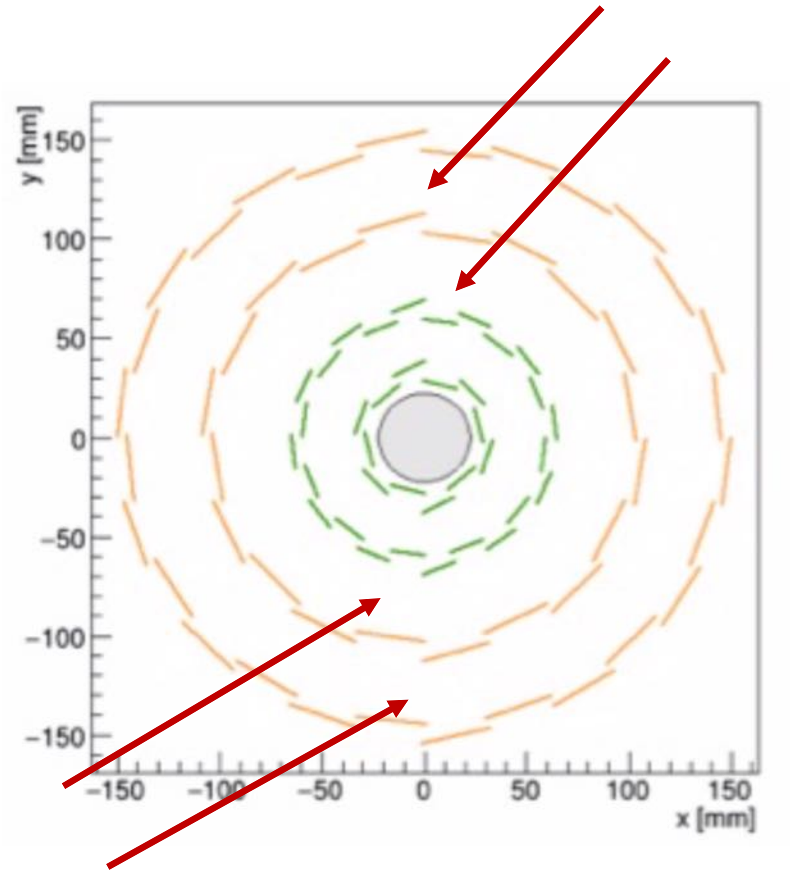
- Ambitious upgrade project underway for the CMS Outer Tracker for the HL-LHC running
  - Designed to maintained or improve tracking performance compared to current system even in the presence of up to 200 pile-up events
  - Tracks above 2 GeV as L1 primitives at 40MHz
- Improvements result in the tracker being more performant and yet more light-weight compared to its predecessor
- Advanced layout and integration studies
- First fully equipped modules prototype in 2022
- …a long way toward HL-LHC!



Backup

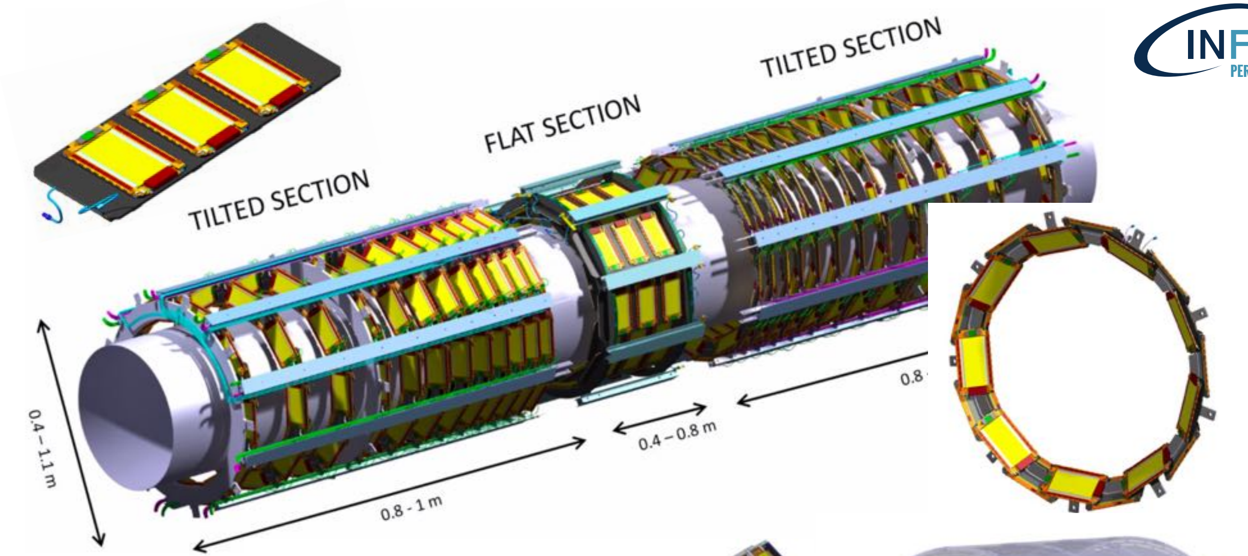
Inner Tracker insertion

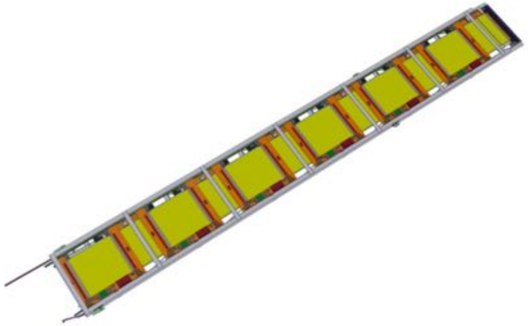
- Two ladder of each Barrel Pixel layer skewed in rϕ
  - This will allow the detector insertion and removal without any action on the beam pipe

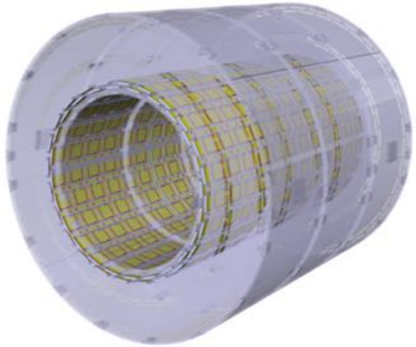


Mechanics

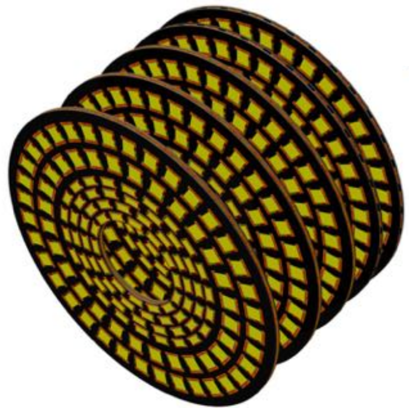
- **TBPS**
  - Flat Part: planks
  - Tilted Part: rings
- **TB2S**
  - Ladder support structure
- **TEDD**
  - Building block: DEE (half disk)
  - Double-Disk to be hermetic also with rectangular modules

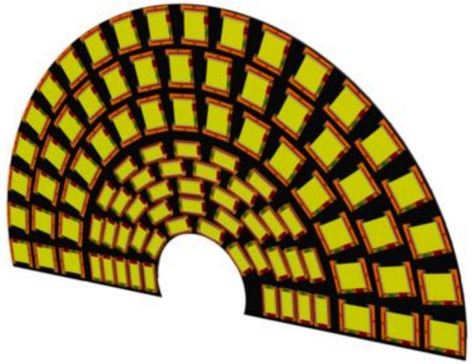






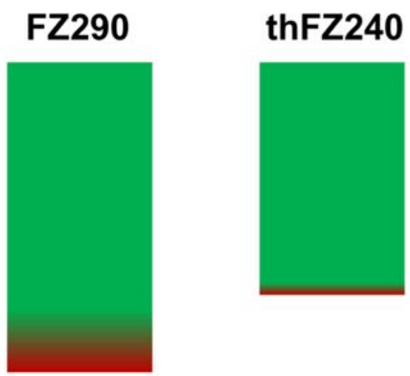
Module type and variant		TBPS	TB2S	TEDD	Total per variant	Total per type
2S	1.8 mm	0	4464	2792	7256	**7680**
	4.0 mm	0	0	424	424	
PS	1.6 mm	826	0	0	826	**5616**
	2.6 mm	1462	0	0	1462	
	4.0 mm	584	0	2744	3328	
Total		**2872**	**4464**	**5960**	**13296**	





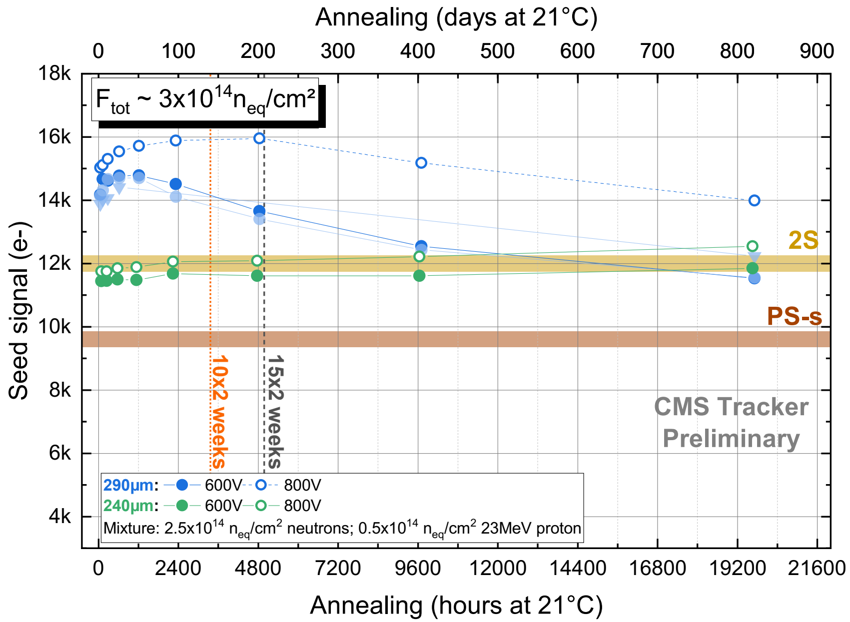
Sensors

- 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

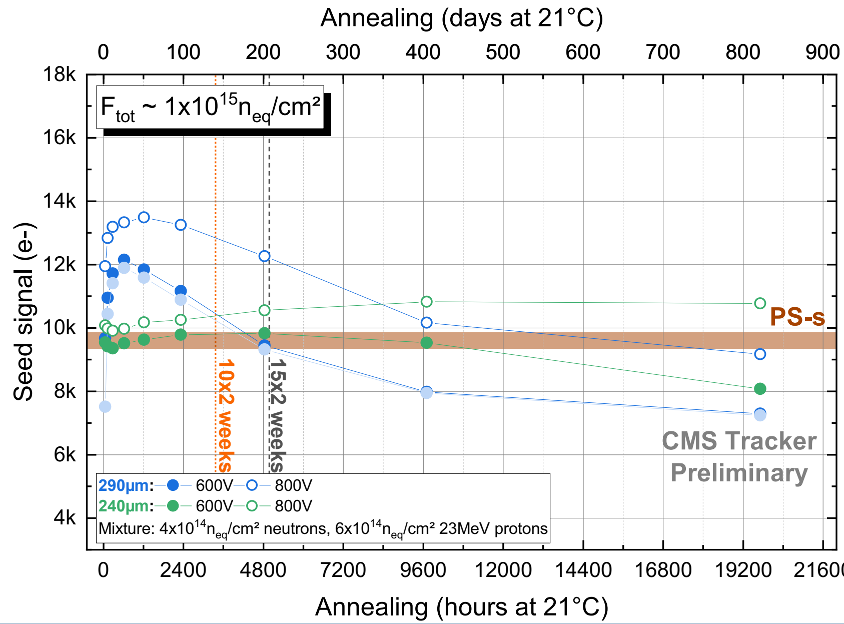


Sensors

- 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**



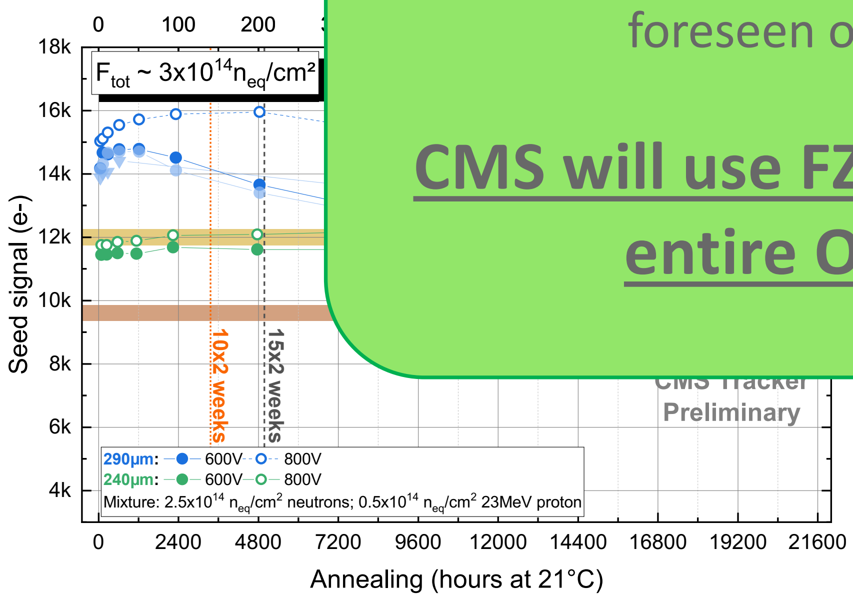
- Expected max. PS fluence after 3000fb^{-1}
- Signal measurements:
  - **thFZ240 only just above PS-s limit**
  - **FZ290 comfortably above with 800V**

Sensors

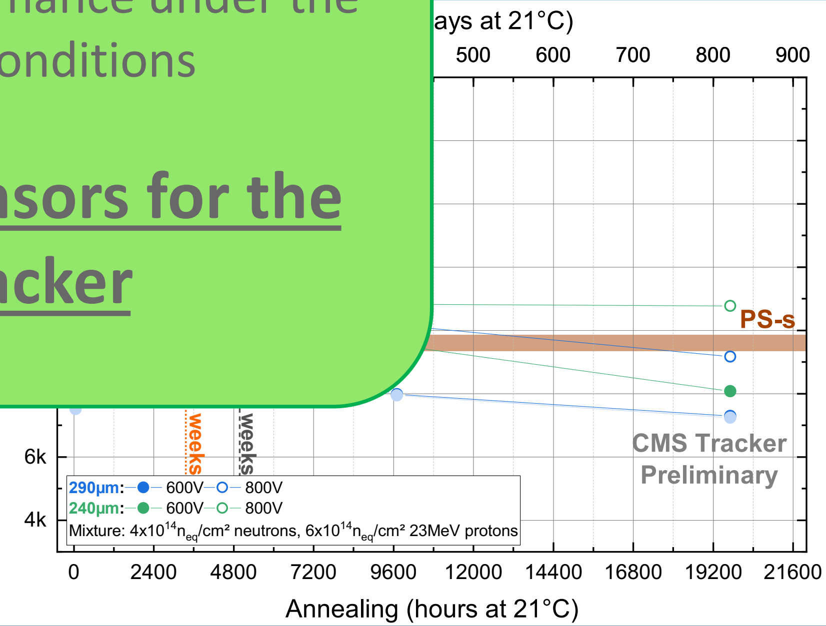
- Irradiation campaign to study the sensors behavior and perform a technology choice:
  - Take nominal expected max. fluences for outer (2S) and inner (PS) regions after 3000fb^{-1}
  - Consider the ... hadrons

- 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**



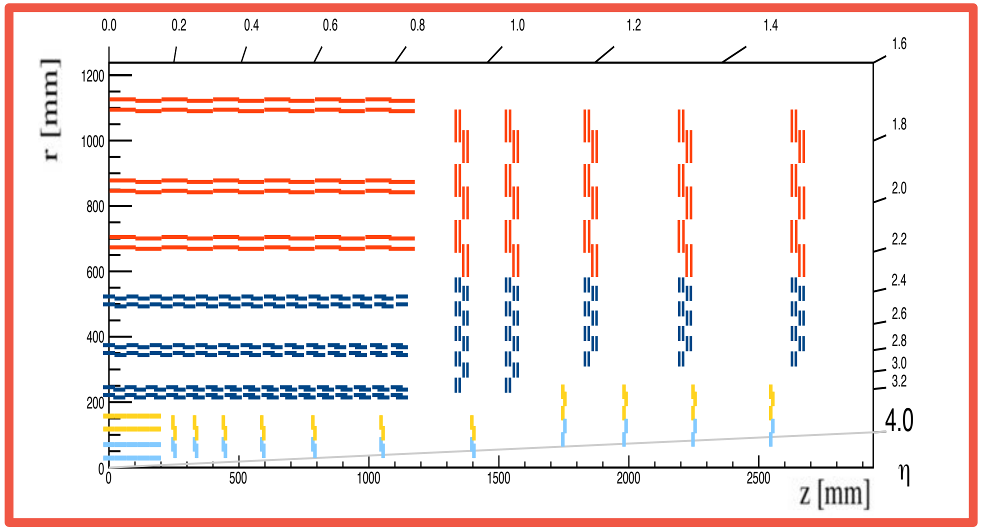
- Expected max. PS fluence after 3000fb^{-1}
- Signal measurements:
  - **thFZ240 only just above PS-s limit**
  - **FZ290 comfortably above with 800V**

Tilted Barrel Geometry

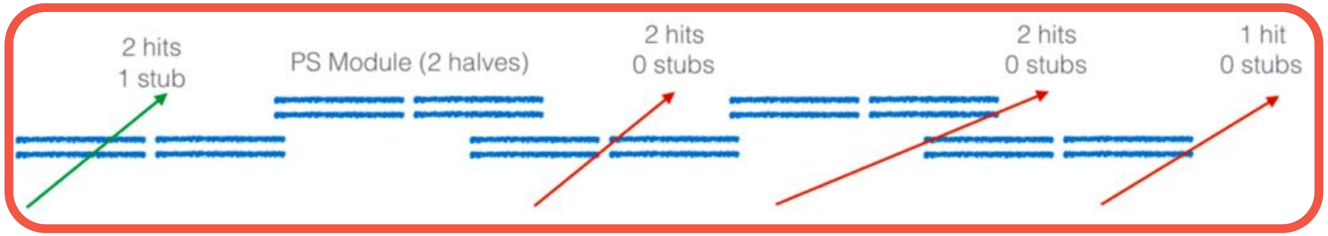
- Stubs generation works only if the charged particle cross the two sensors on the same halve of the same module
- This is not true for (flat) barrel peripherical modules

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

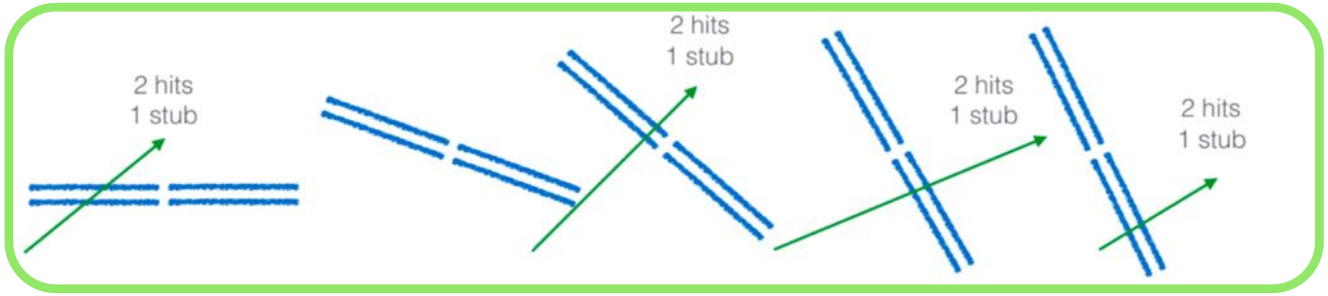
Technical Proposal Geometry



Flat Geometry



Tilted Geometry



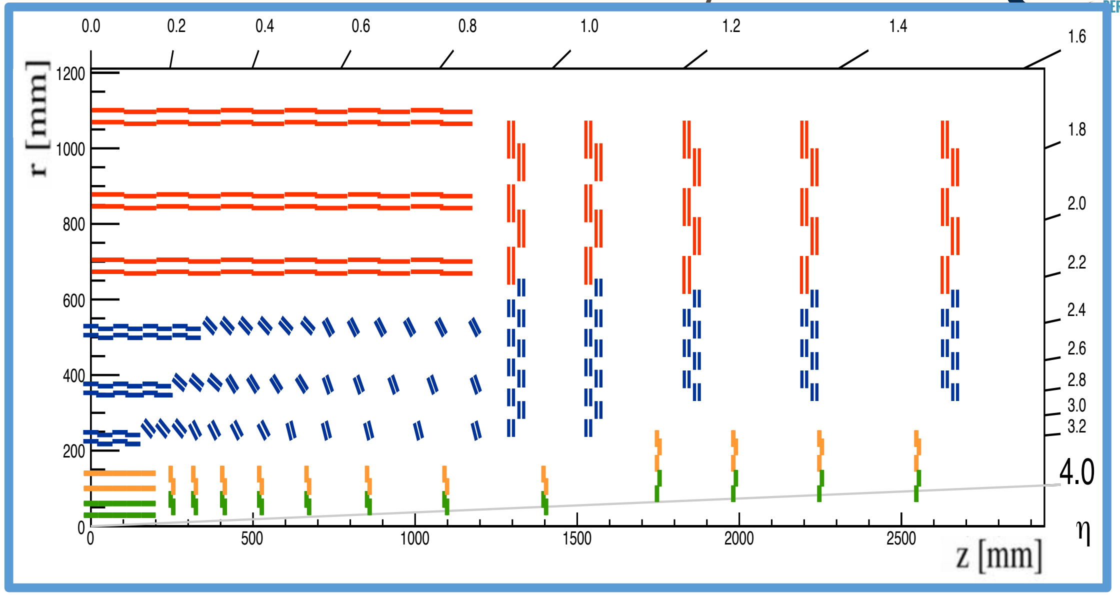
Tilted Barrel Geometry

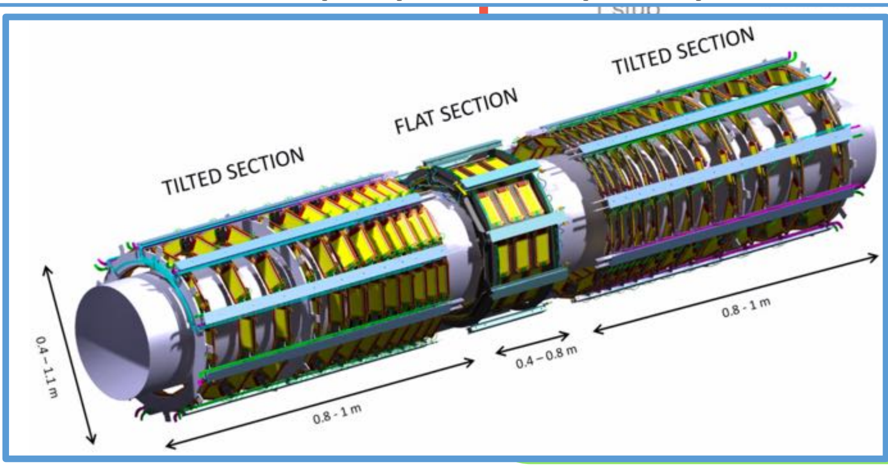
- Stubs generation works only if the charged particle cross the two sensors on the same halve of the same module
- This is not true for (flat) barrel peripheral modules

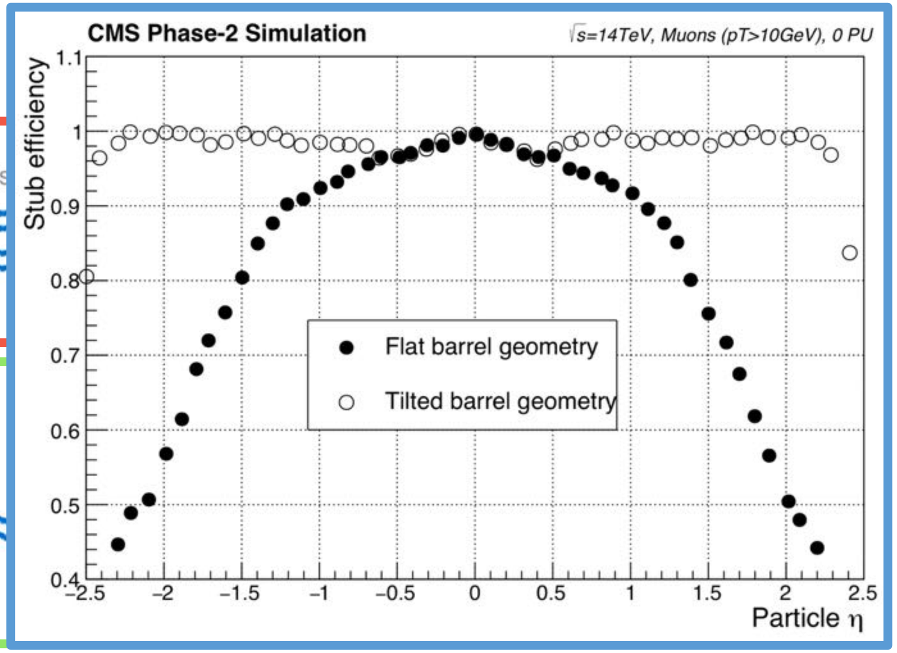
→ **(increasingly) Tilt peripherical barrel modules**

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

Tilted Barrel Geometry

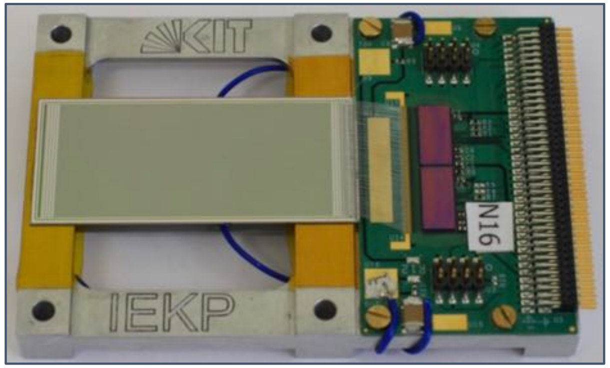


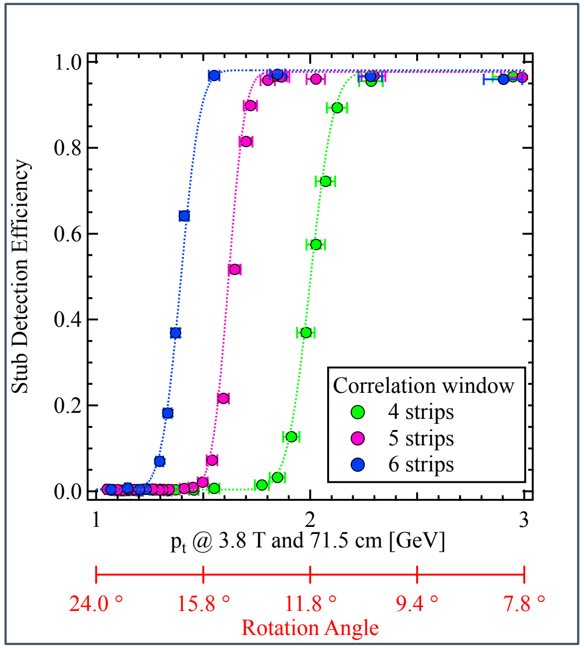




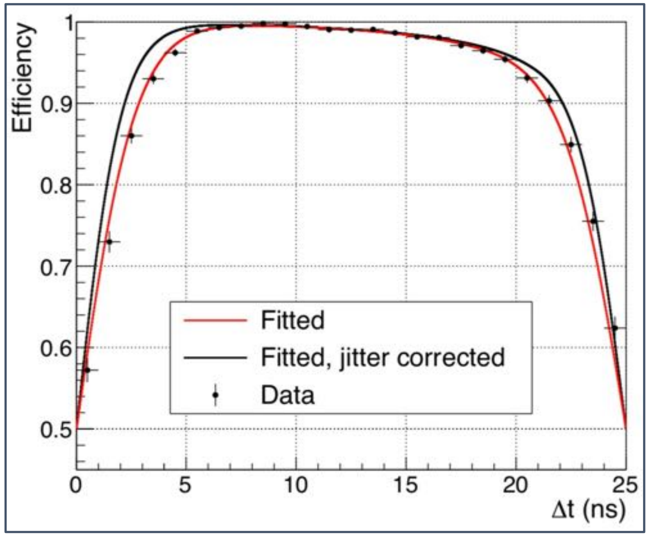
Some highlights from beam tests

- Different module prototypes tested in particle beam





- ○ **2S**
  - Full size module and mini-module has been tested
  - No services and no data Concentrator
  - Stubs finding capabilities tested
    - ○ Magnetic bending «simulated» with module rotation



- ○ **PS**
  - Single sensor (pixel) with MPA readout
    - ○ <u>No stub info</u>
  - MPA+SSA intercommunication was tested on bench

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/cm² both materials are comparable
- dark noise occupancy was measured:
  - lower than 10^{-5} while expected hit occupancy is ~10^{-2}
  - Scale with annealing (current) and not with thickness