The CMS Phase-2 Outer Tracker sensor production, status and first results

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on behalf of the CMS collaboration

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High Luminosity LHC

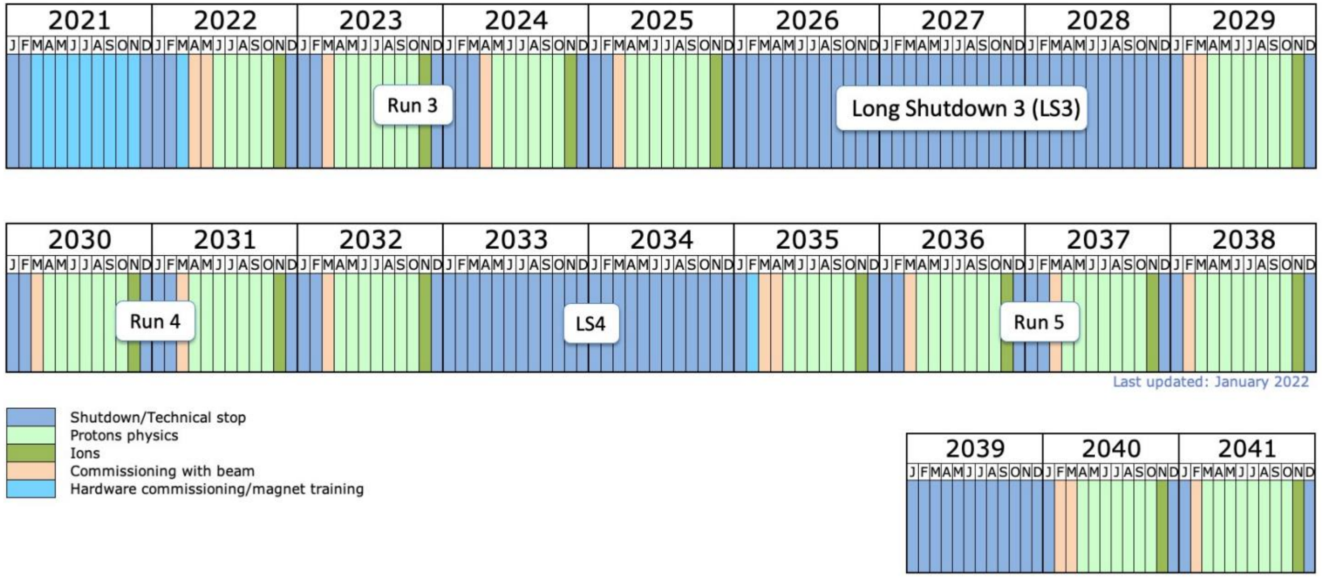
Transition to HL-LHC at Long Shutdown 3 *(2026-2028)*

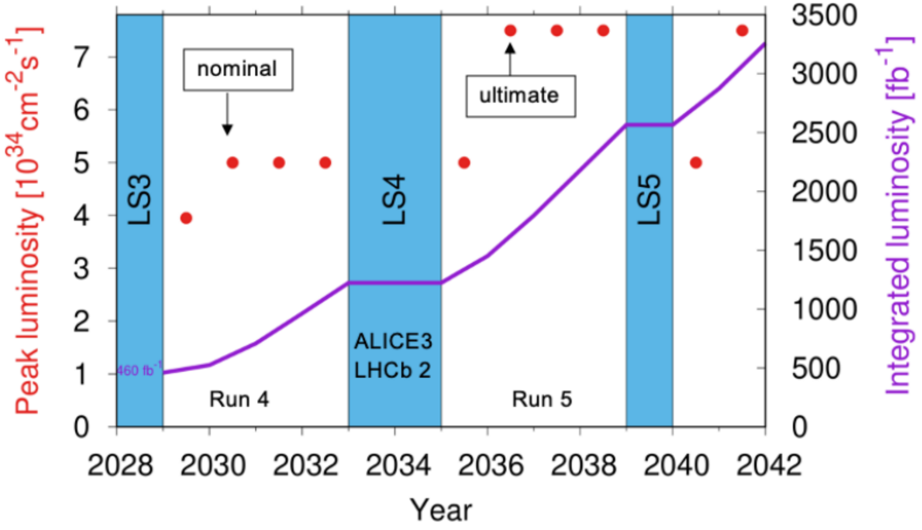
	LHC	HL-LHC
Peak Luminosity	1.5×10^{34} $cm^{-1}s^{-1}$	$5\text{-}7.5\times10^{34}$ $cm^{-1}s^{-1}$
Integrated Luminosity	500 fb^{-1}	3000-4000 fb^{-1}
Pile-up	20-30	140-200

Motivation

- Explore new channels of Higgs boson events
- New Physics (SUSY, Dark matter, Rare decays..)

Provisional long-term schedule





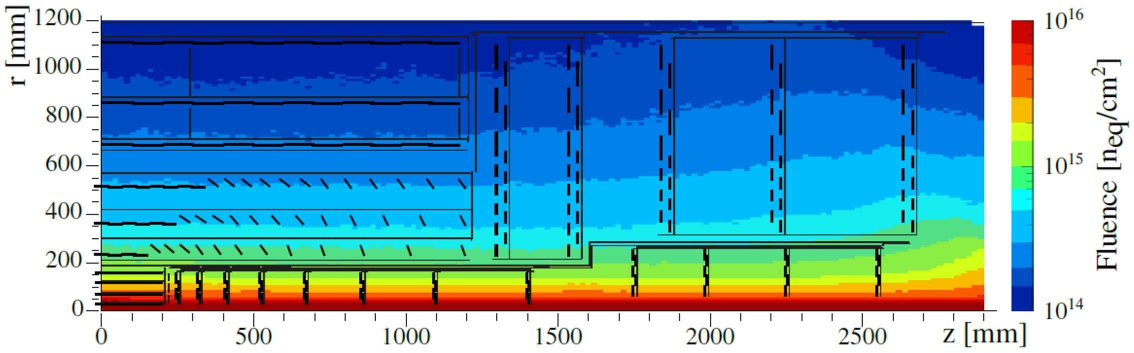
Tracker Phase-2 Upgrade

CMS tracking system will need a full replacement!!!

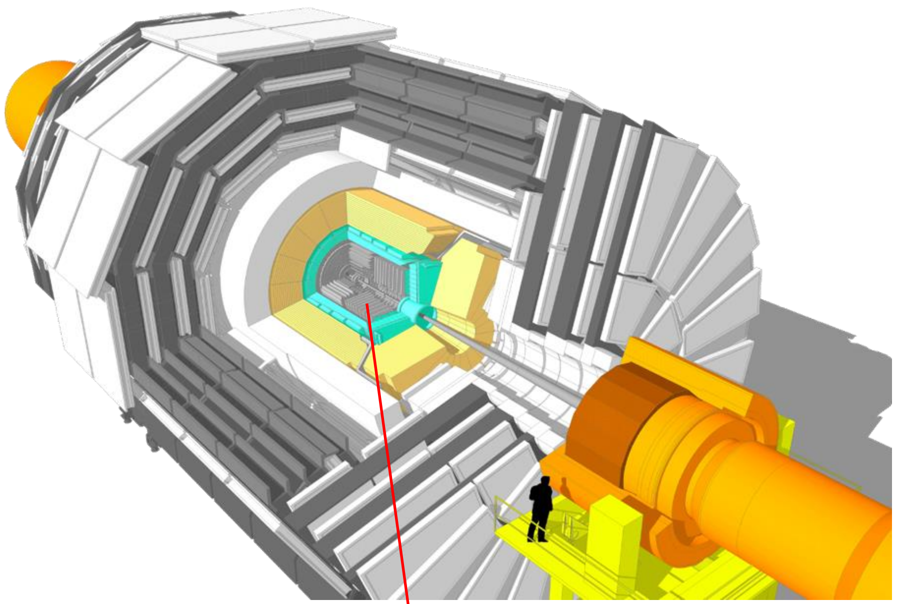
- Current system will reach **the end of its lifetime** after Run3!

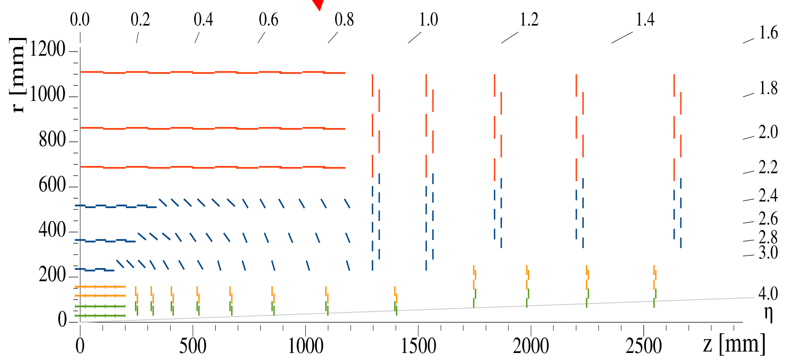
  Not expected to tolerate the increased radiation levels of HL-LHC!

  - Innermost layers :
    - Fluences up to 2.3x10^{16} n_{eq}/cm^2 (Inner) / 1x10^{15} n_{eq}/cm^2 (Outer)
    - Total Ionizing Dose: 12MGy



- Increased particle density requires **higher detector granularity**

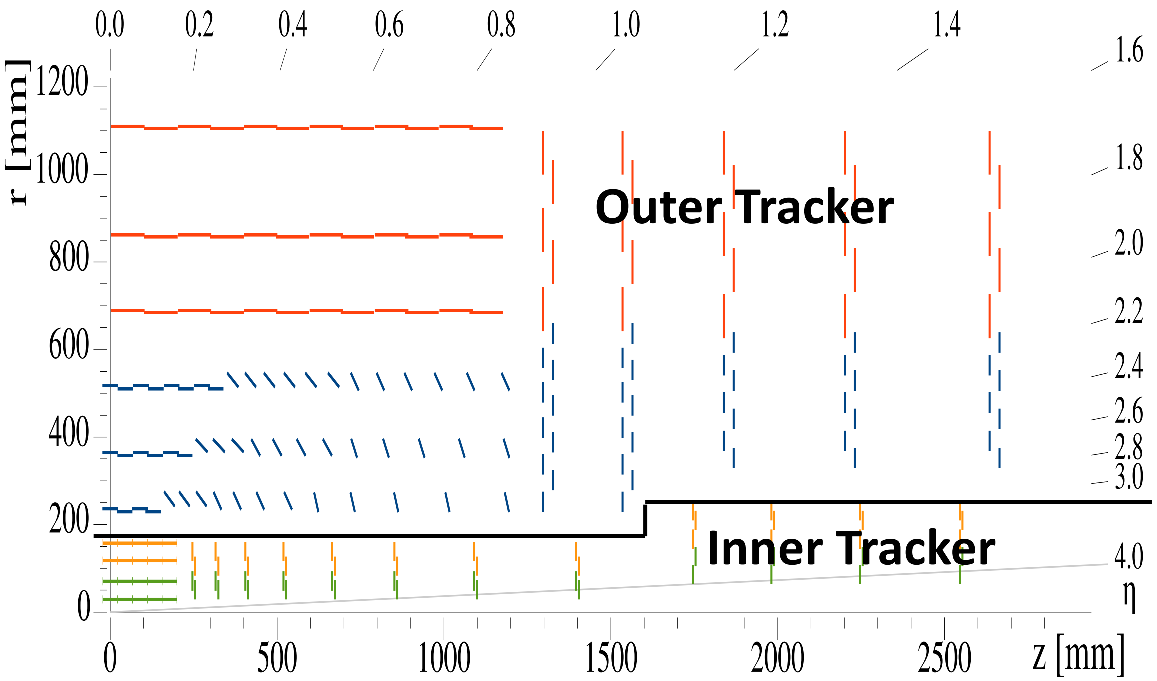


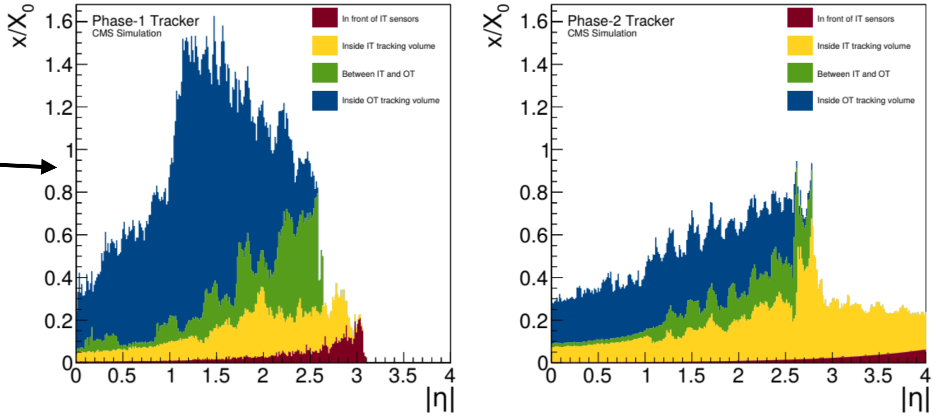


Layout of Phase II Tracker

Tracker Phase-2 Upgrade

- **More radiation hard sensors and electronics**
- **Coverage up to |η| = 4 (Inner tracker)**
- **Higher granularity (increase by ~4)**
  - ~ x20 more channels
- **Tracking information to Level-1 Trigger**
  - New module design
- **Reduced material budget**
  - New geometry
  - Fewer layers/light material
  - CO_2 cooling

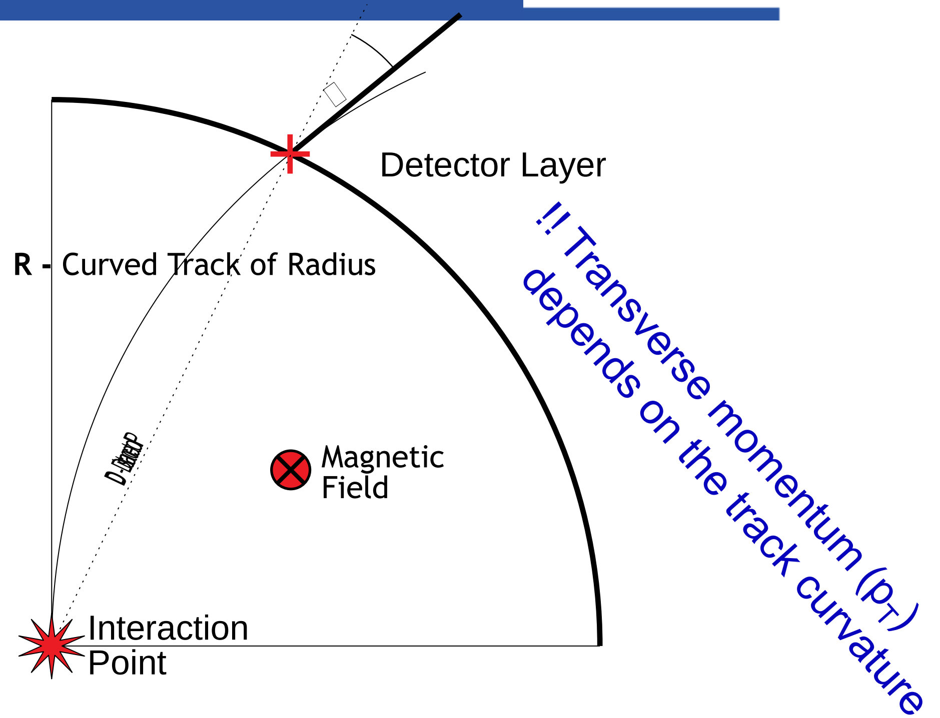




Tracking information to L1-Trigger

- L1-trigger receives data only by muon system and calorimeter. **Not sufficient** in HL-LHC due to high rates and PU!

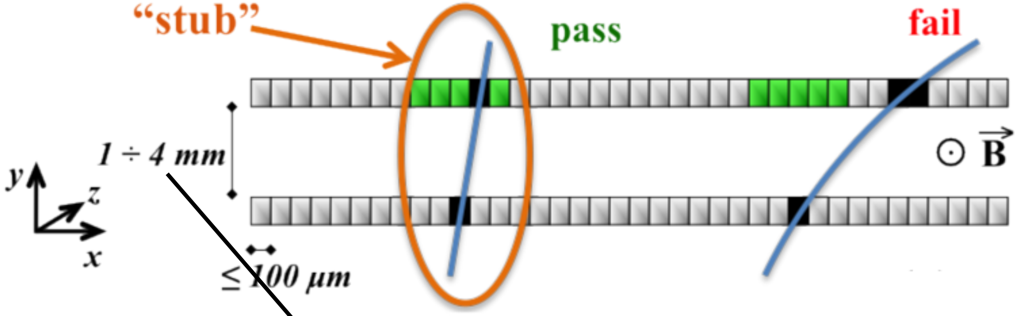
- **Phase-2**: Trigger rates up to **750kHz**
  - Adding tracking information will enhance its performance
  - Amount of track-information should be reduced at the front-end
  - **Fact**: Majority of tracks come from **low** momentum particles



- Outer Tracker modules will be doing the **self-selection** of events (**p_T modules**)
  - Only events which correspond to high p_T tracks (**stubs**) will be sent out

↓

- **p_T module**: Two parallel - closely spaced sensors which accept track patterns with p_T **beyond a set threshold** (p_T > ~ 2GeV)
  - The signals are correlated by the read-out ASICs
  - The acceptance window is tunable



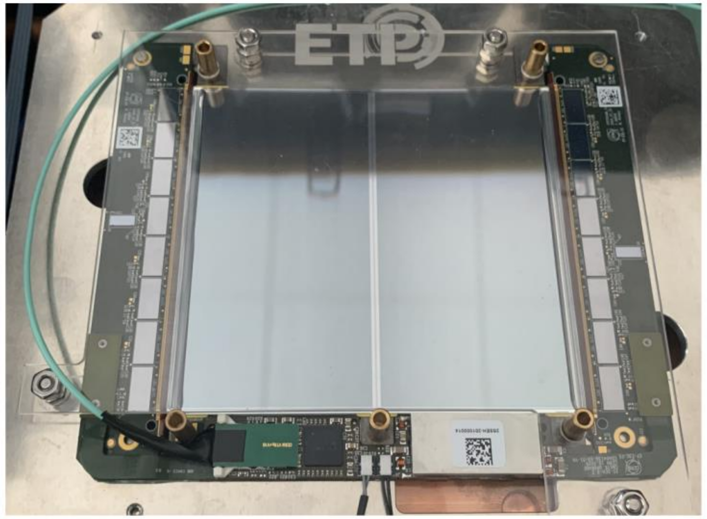
The sensor-spacing is determined by the module location

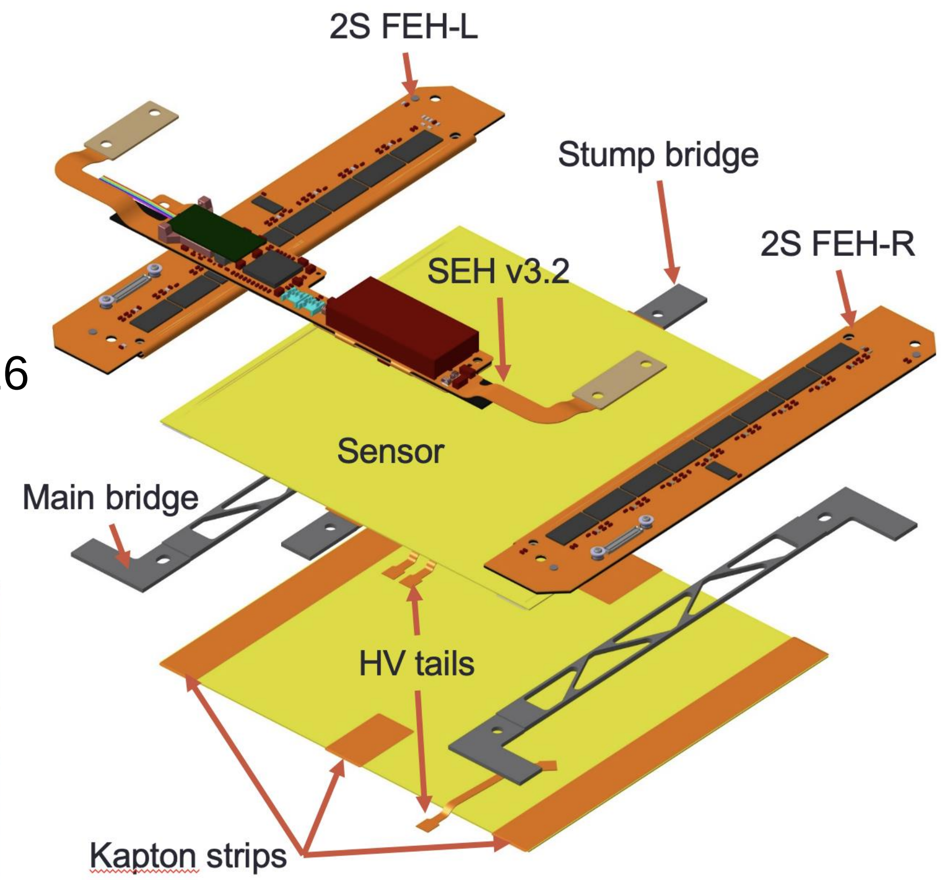
The 2S Module

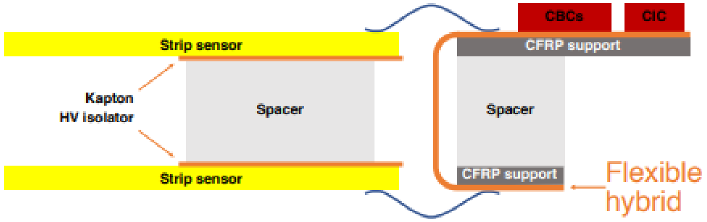
- **2** x **S**trip sensors

2S sensor

- Size : 10 x 10 cm^2
- Pitch : 90 µm
- Length : 5 cm
- No. of strips/sensor : 2x1016







- **2 x 8 CMS Binary Chip (CBC)**
  - 2x127 channels per chip
  - Bump bonded to flexible hybrid
  - Connects to top and bottom sensors
  - Inter-chip communication via hybrid
- **Concentrator ASIC: CIC**
  - collects data from 8 CBCs (half module)
- **Low Power GigaBit Transceiver**
  - *lpGBT + VTRx+*
- **2-stage DCDC powering**
  - 12 V to 2.5 V (opto)
    1.25 V (ASICS)

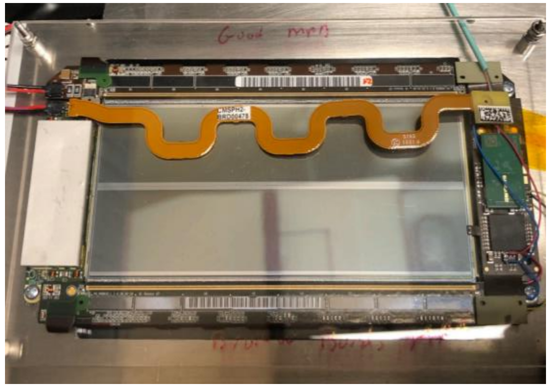
The PSS Module

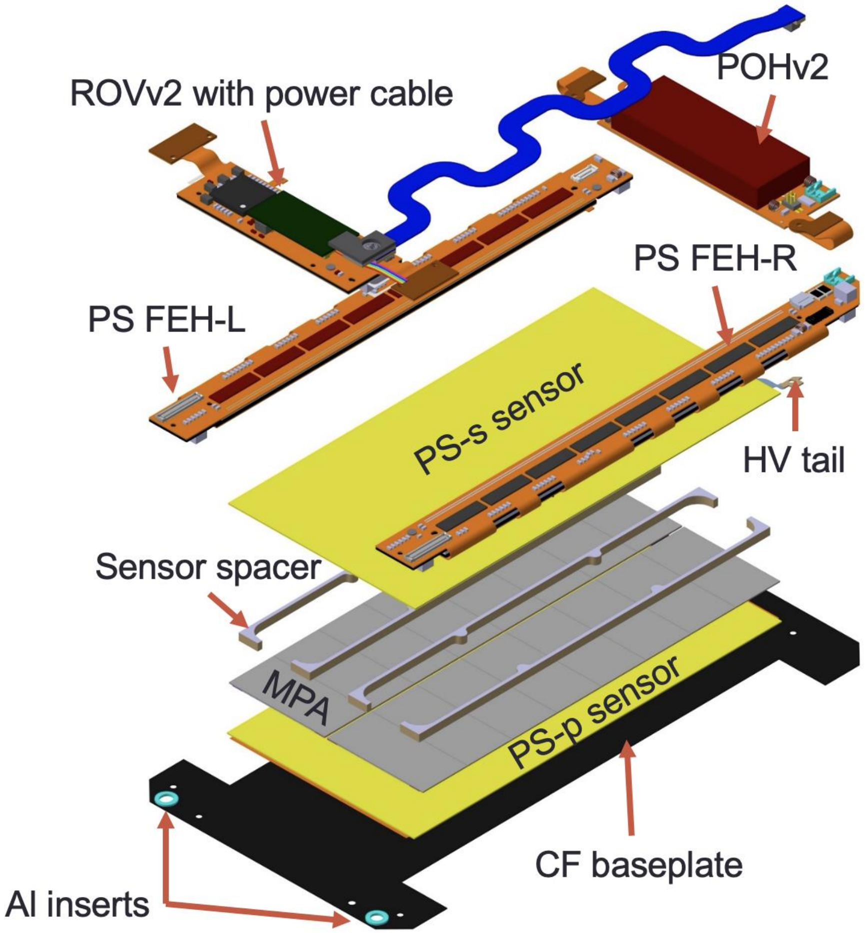
Macro-pixel sensor:

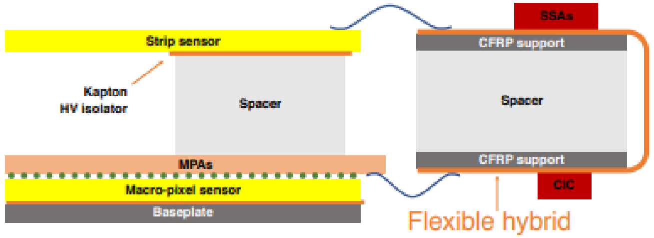
- **PS-p sensor**
  - Size : 5 x 10 cm^2
  - Pitch : 100 µm
  - Length : 1.5 mm
  - No. of strips : 32x960

Strip sensor:

- **PS-s sensor**
  - Size: 5 x 10 cm^2
  - Pitch: 100 µm
  - Length: 2.5 cm
  - No. of strips: 2x960





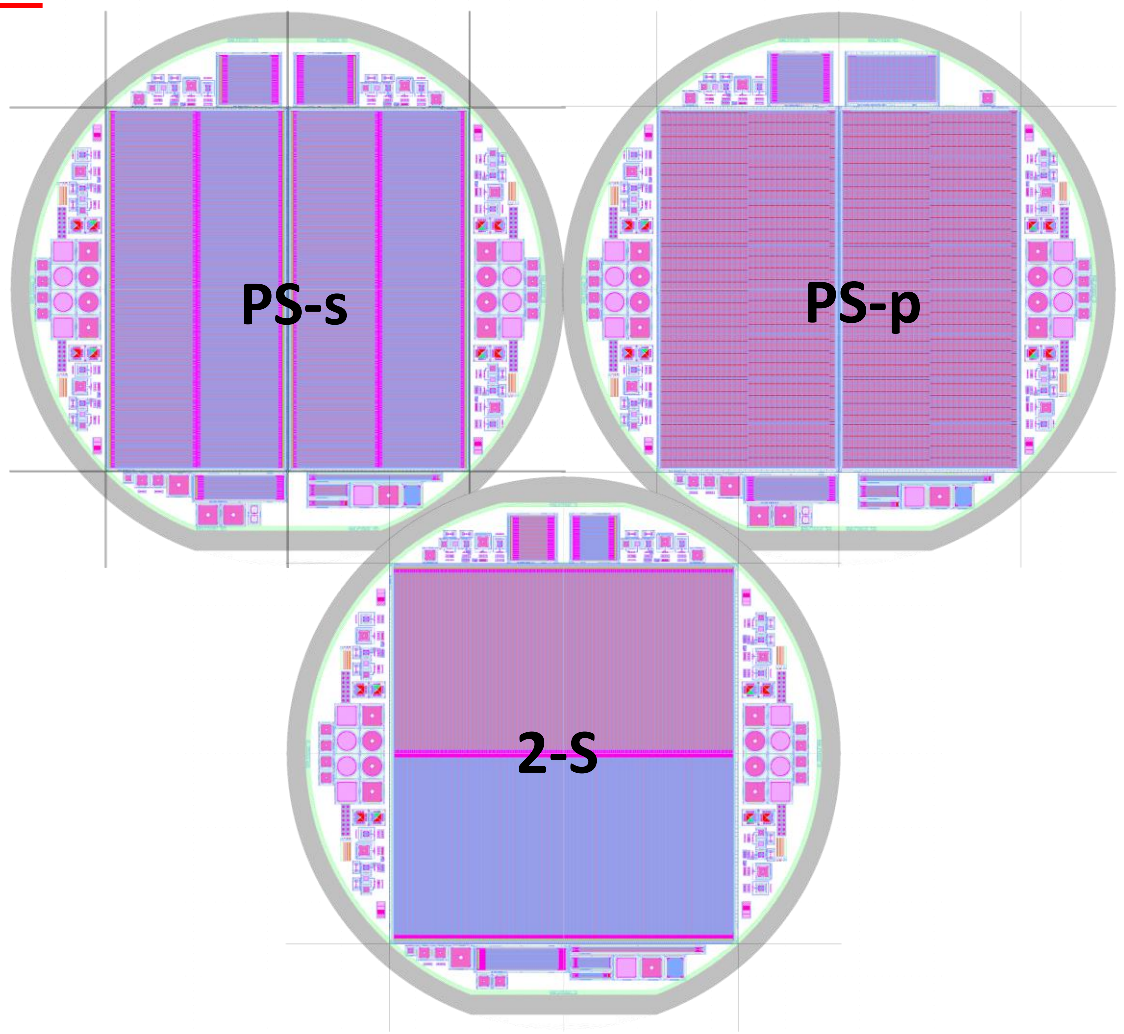


- **2 x 8 Short Strip ASIC (SSA)**
  - 120 channels per chip
  - Sends hits to MPA
  - Bump bonded to flexible hybrid
- **16 MacroPixel ASIC: MPA**
  - 120 x 16 pixels per chip
  - Bump bonded to Macro-Pixel sensor
  - Includes correlation logic
- **Concentrator ASIC: CIC**
  - collects data from 8 MPAs
- **Low Power GigaBit Transceiver**
  - *lpGBT + VTRx+*
- **2 stage DCDC powering**
  - 12 V to
    - 2.5 V (opto)
    - 1.25 V (ASICS)
    - 1.05 V (MPA digital)

Phase-2 Sensors Baseline

Baseline selection of the Phase-2 Outer Tracker Sensors

- **n–on–p** type sensors (n^+ implants on p-type substrate)
- **290 µm** active thickness
  - with an extra **30 µm** thick backplane
- high resistivity **Float-Zone process**
  - Bulk resistivity **3.5-8 kΩ·cm**
- Biasing via:
  - **Polysilicon resistors** (strip sensors)
  - **Punch-through structures** (Macro-pixel sensors)
- P-stop technique to achieve sufficient strip isolation
- Produced on 6'' wafers (150mm thickness)
  - host several test structures and mini-sensors



Wafer Layouts

Irradiation Results

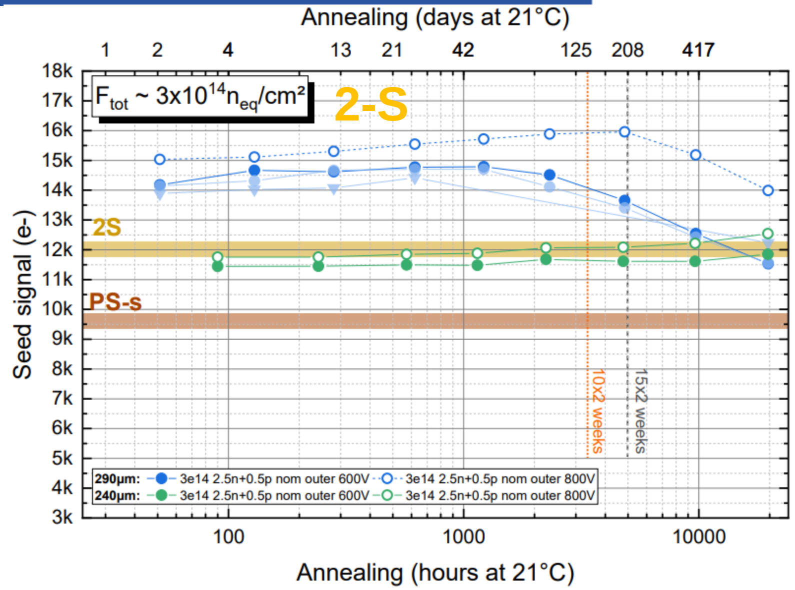
- Seed signal over annealing time (expected HL-LHC scenario)
  - **-600V:** maximum operation voltage after irradiation
  - **-800V:** foreseen boost only for regions receiving higher fluences

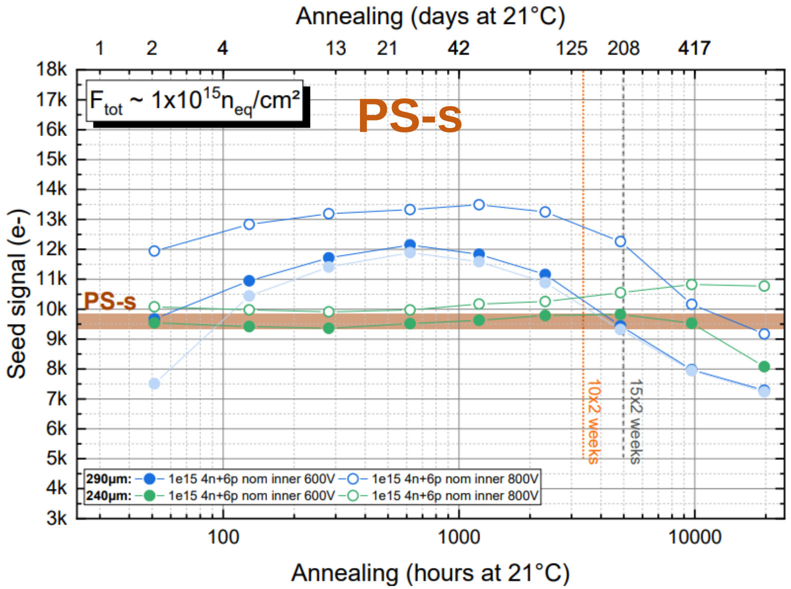
- 2-S and PS-s prototypes were irradiated at the **maximum expected fluences** (p + n)

- In the 2S region, **FZ290** (baseline sensor) **well above the limit**

- In the PS region, **FZ290** with a boost up to -**800V** collects sufficiently high charge**!**

MPV_{seed} > 3 x threshold(e^-) → **12000 (2S)** / **9600 (PSS)**

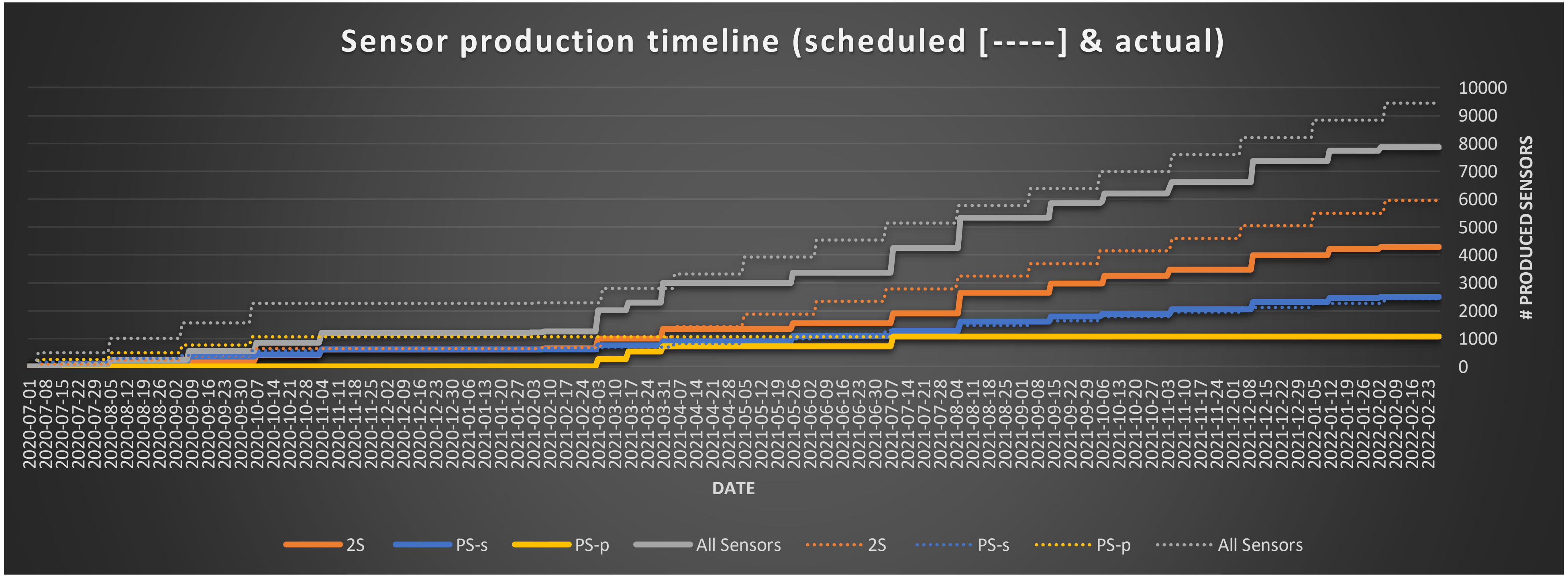




Sensor production status and Quality Assurance plan

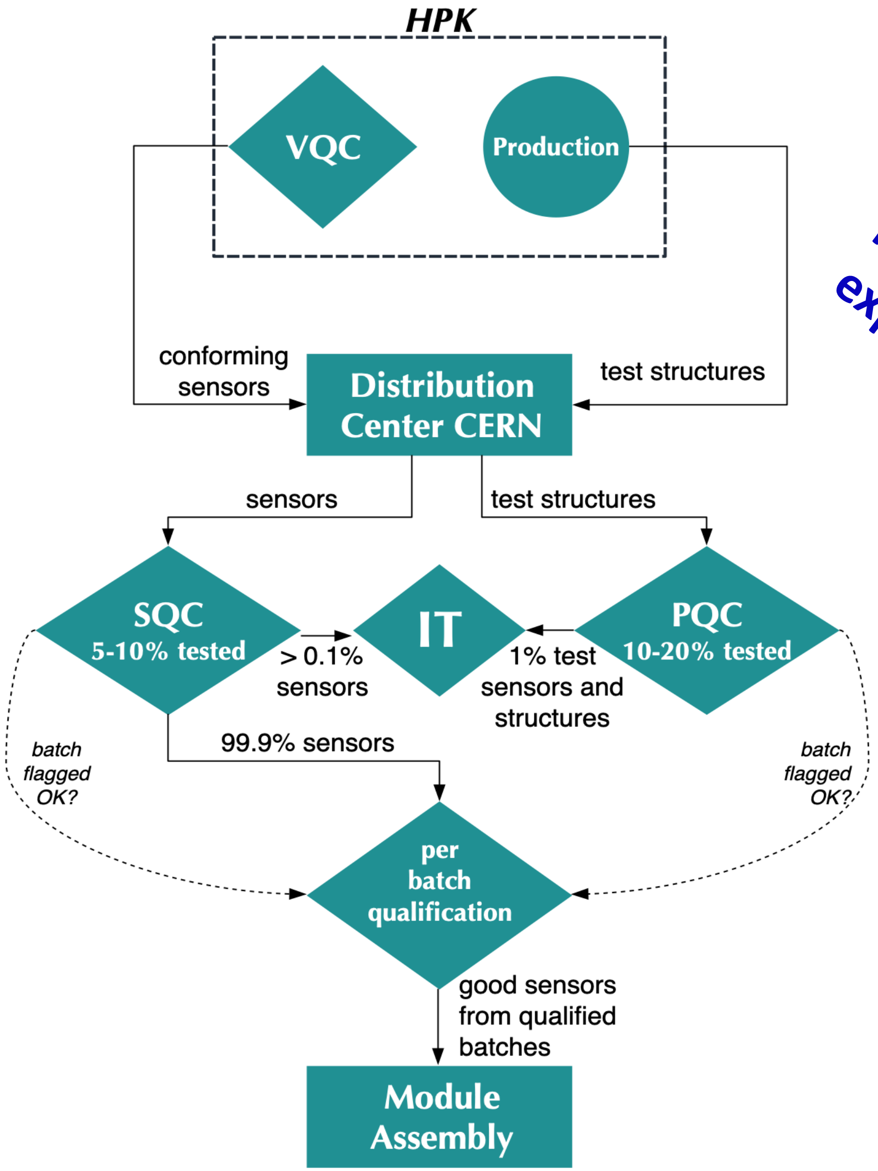
Production Status

- ❑ The OT sensor production was contracted to **HPK Photonics**
- ❑ Sensor **production** (deliveries) started since **summer 2020**
- ❑ Sensor production phase running until ~ **mid 2024**
  - Almost 24.000 sensors in total
- ❑ So far:
  - More than 5000 wafers (~8000 sensors or > 20%) delivered and qualified



Quality Assurance

- Quality control comprises four parts
  - **VQC** - *Vendor Quality Control*
  - **SQC** - *Sensor Quality Control*
  - **PQC** - *Process Quality Control*
  - **IT** - *Irradiation Tests*
- **All sensors** characterized by **vendor**
  - Only sensors complying with the specs are sent to CERN
- Acceptance using **sample measurements** at SQC, PQC and IT

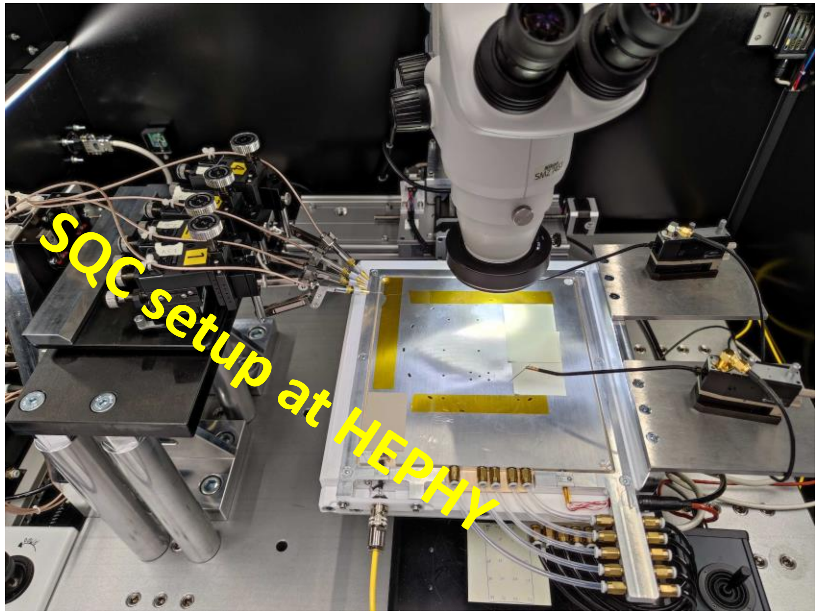


Production and QA monitored by CMS expert panel

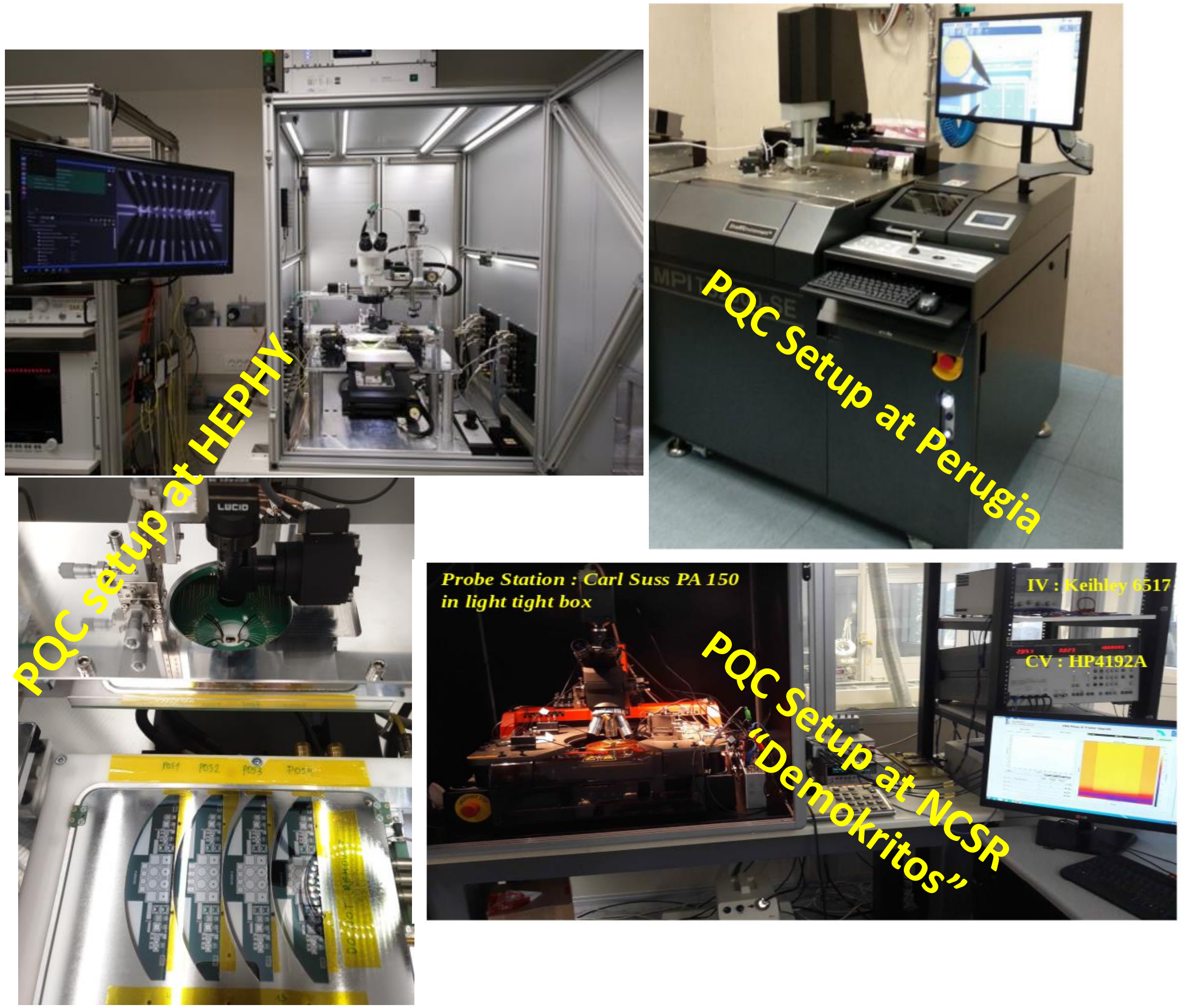
Sensor Quality Control

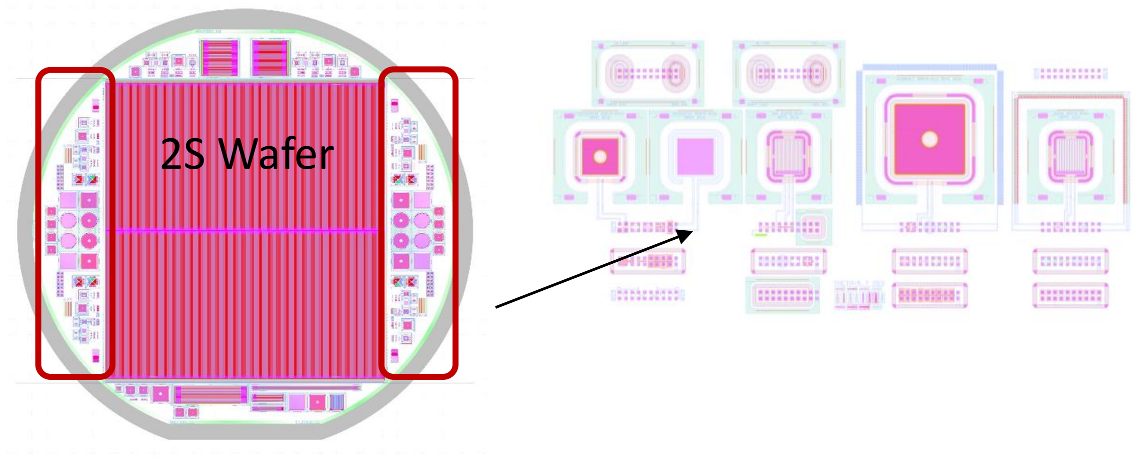
- **Comprises tests on real production sensors on a sample basis (5-10% of a batch)**:
  - **Global parameters**
    - Total leakage current
    - Capacitance
  - **Strip/inter-strip parameters**
    - Strip current
    - Polysilicon resistance
    - Coupling capacitance (AC-coupled)
    - Dielectric current (AC-coupled)
    - Inter-strip capacitance
    - Inter-strip resistance

- **Sensor long-term behavior at nominal voltage**
  - sensor operation inside a Climate Chamber at fixed humidity (less than 10%) and temperature (20 ^{o}C)



Process Quality Control





- ❑ **Monitors the quality and stability of the production process**
- ❑ **Tests on sets of dedicated test structures**
  - **Characterization** of production process
  - Parameters **not measured** on sensors (oxide quality, surface generation current, flat-band voltage etc)
  - High level of automatization
  - **Similar structures** for strip and macro-pixel wafers
- ❑ **Important tool also for HGCAL sensors**

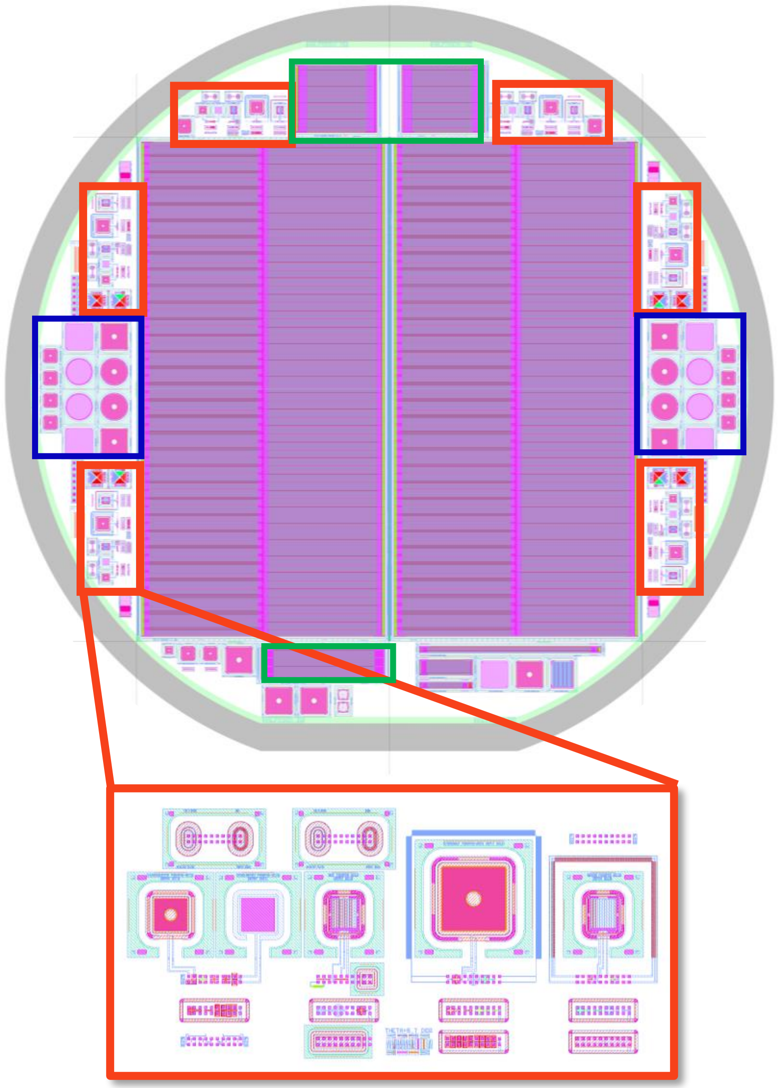
Process Quality control

PQC test structures

- **15 sets each hosting different structures**:
  - Larger structures (diodes, MOS and GCD)
  - Smaller structures (Van-der-Pauw, FET, Cap etc) contained within the flute

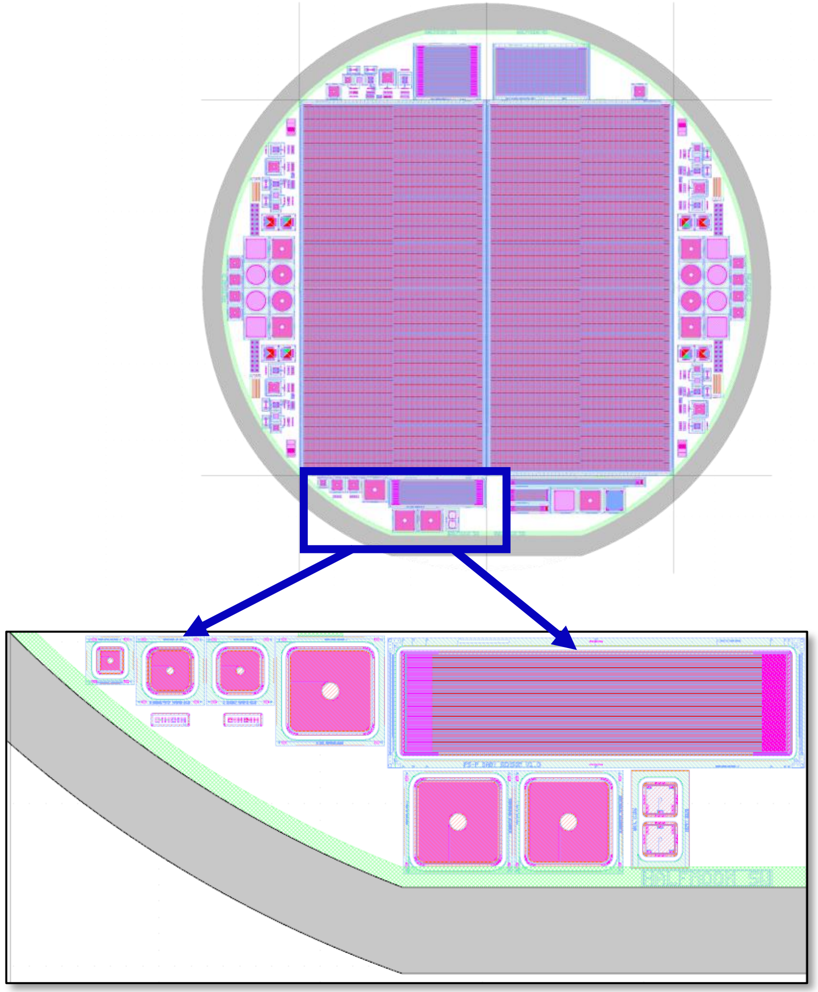
- **Each set replicated 6 times on each wafer**

- **Wafer also hosts**:
  - Diodes and MOS structures in several configurations
  - Additional mini sensors



Irradiation Tests

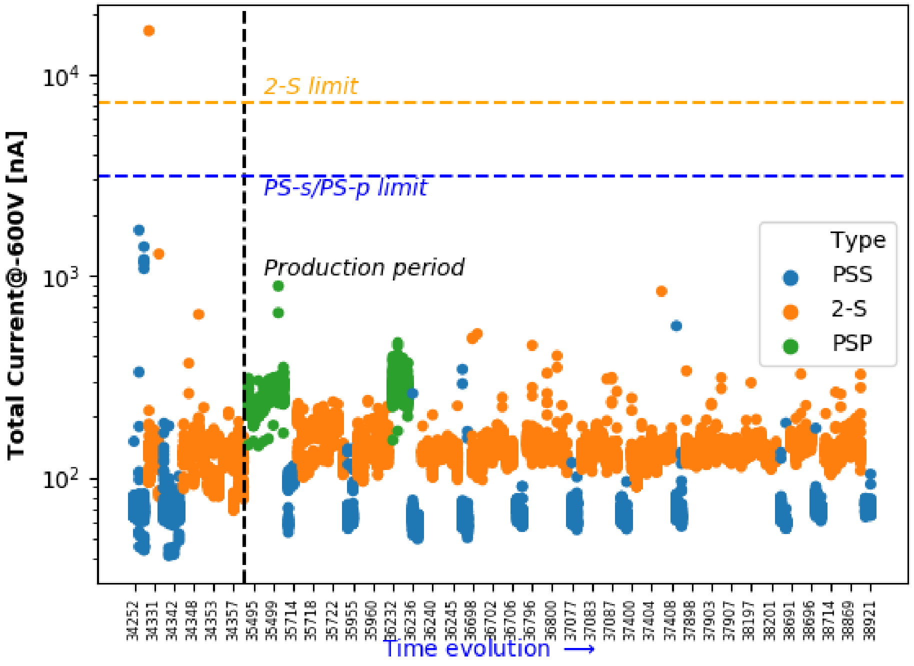
- Irradiate **mini sensors and test structures**
  - Only a tiny fraction of sensors as well
- Irradiate up to max. expected fluence
  - **Proton** and **neutron** irradiation
- Perform **electrical characterisation** and study **Charge Collection Efficiency** after irradiation
- Characterisation done by using an Alibava setup
- Check consistency with irradiation campaign from **R&D** phase

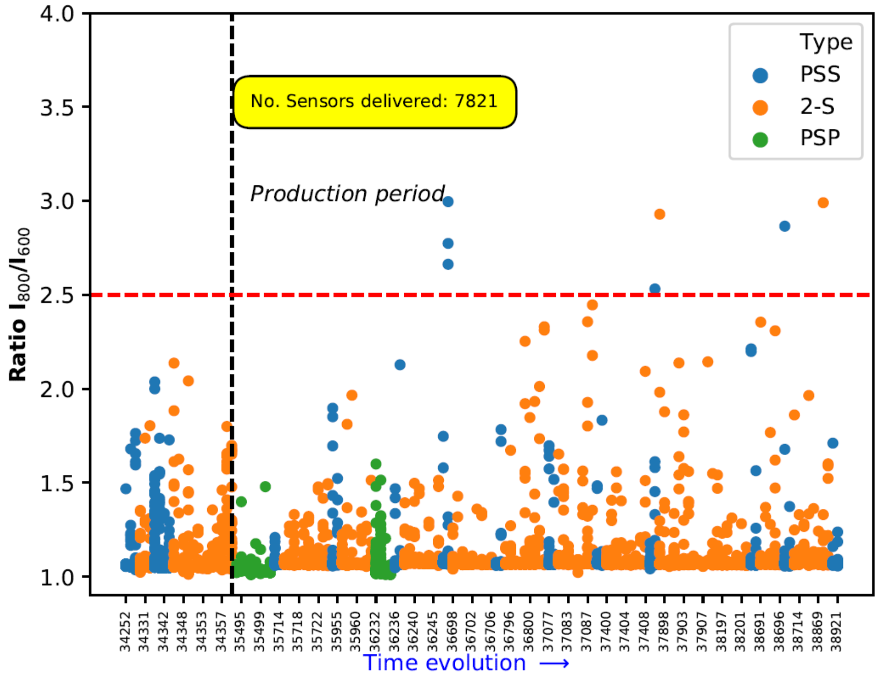


First results from the quality assurance process

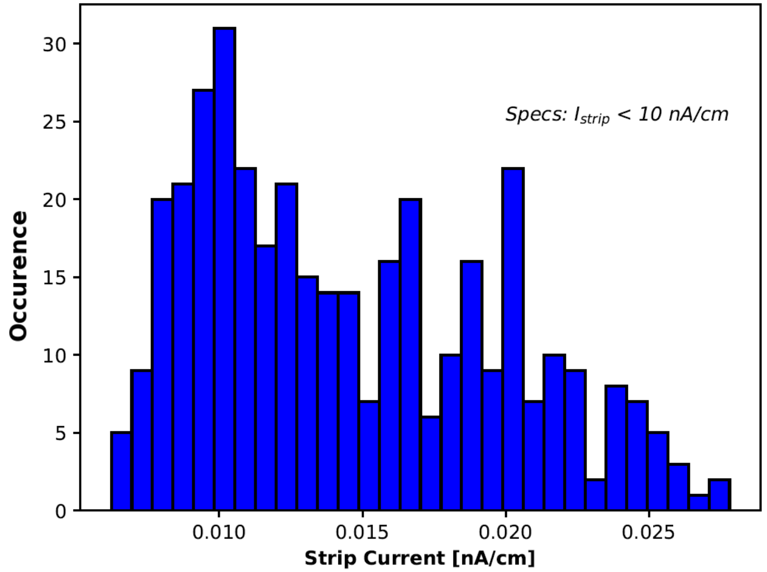
Total leakage current

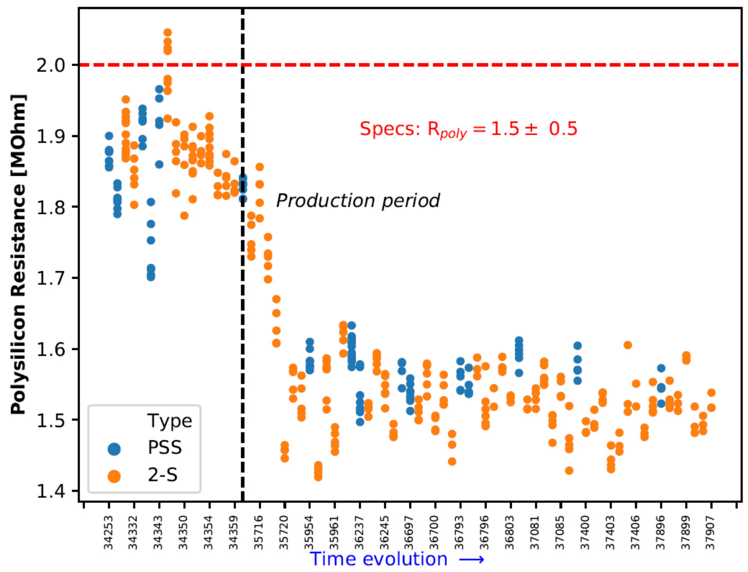
- Maximum operation voltage after irradiation at **-600V**
  - Boost up to **-800V** only for sensors, highly affected by irradiation
- **Acceptance limit**:
  - I_{600} < 7.25 µA (**2-S**)
  - I_{600} < 3.125 µA (**PS-s**/**PS-p**)
  - I_{800}/I_{600} < 2.5
- Sensors produced by HPK show a remarkably low total current
  - Low leakage current up/beyond -800V
  - Small increase in currents between -600 and -800V

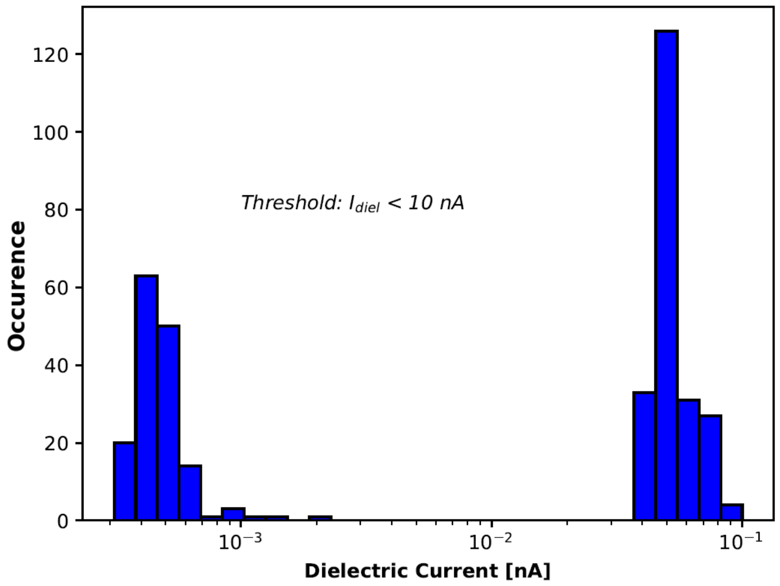


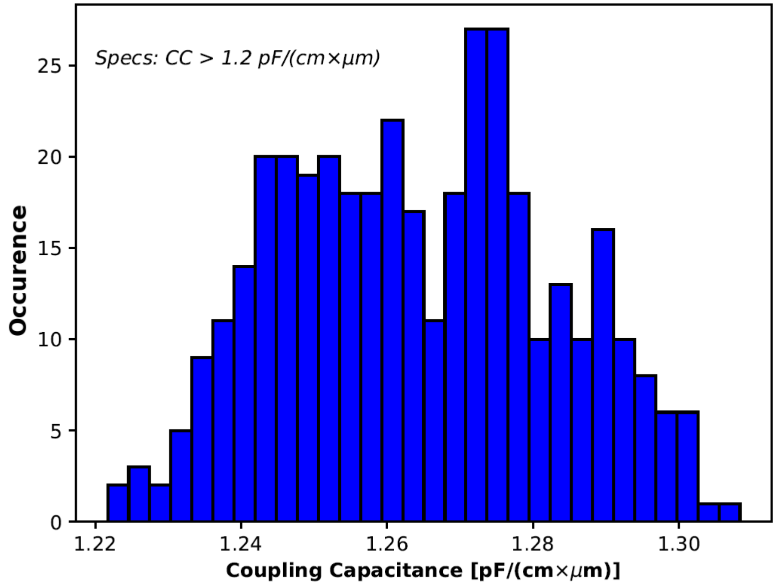


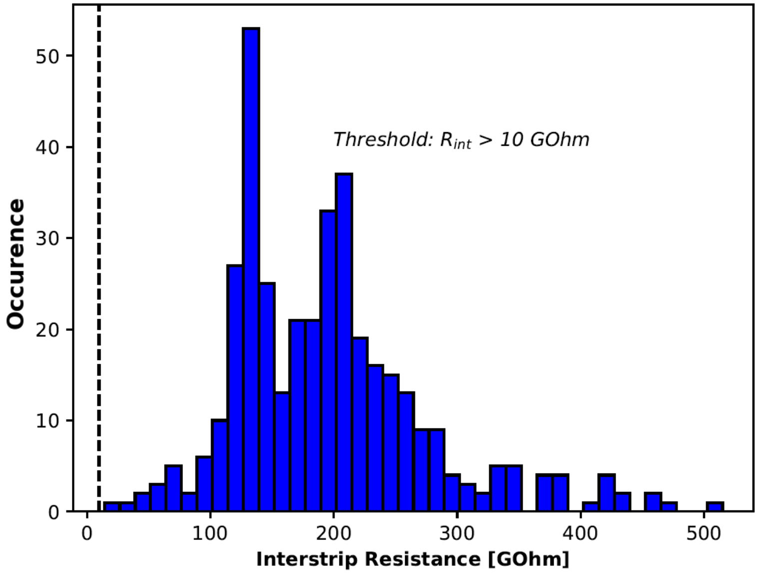
Strip parameters Summary

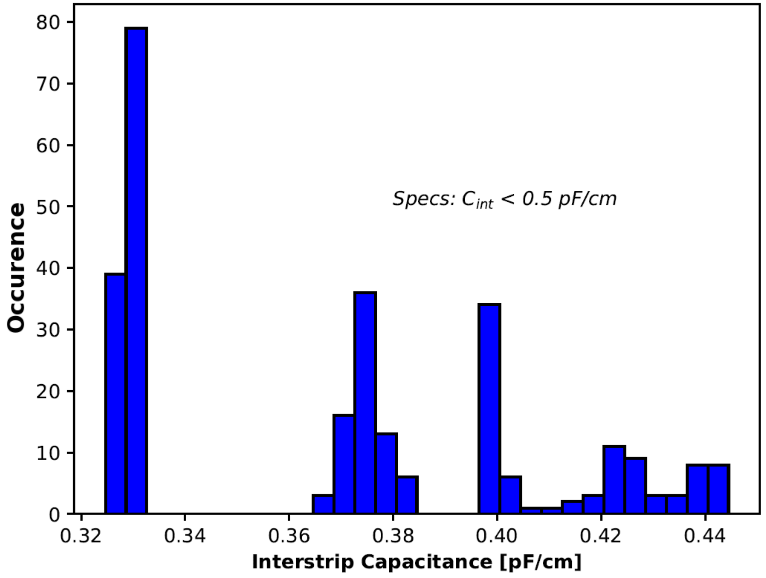






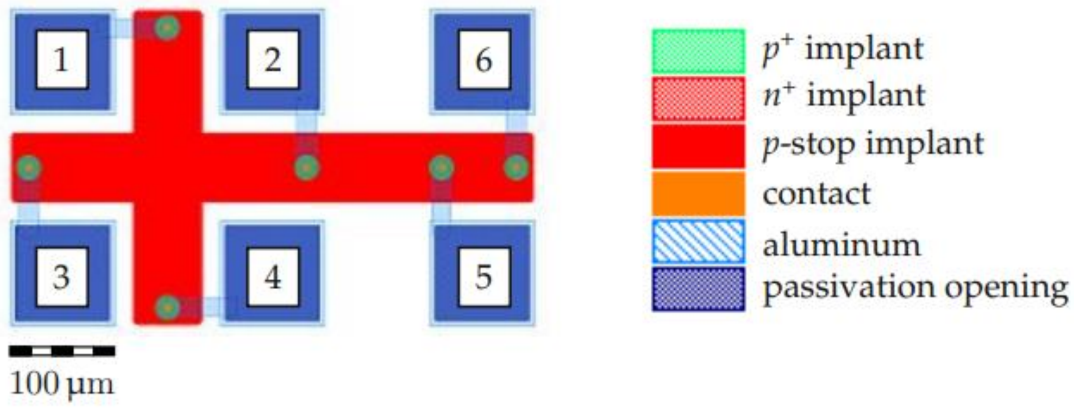




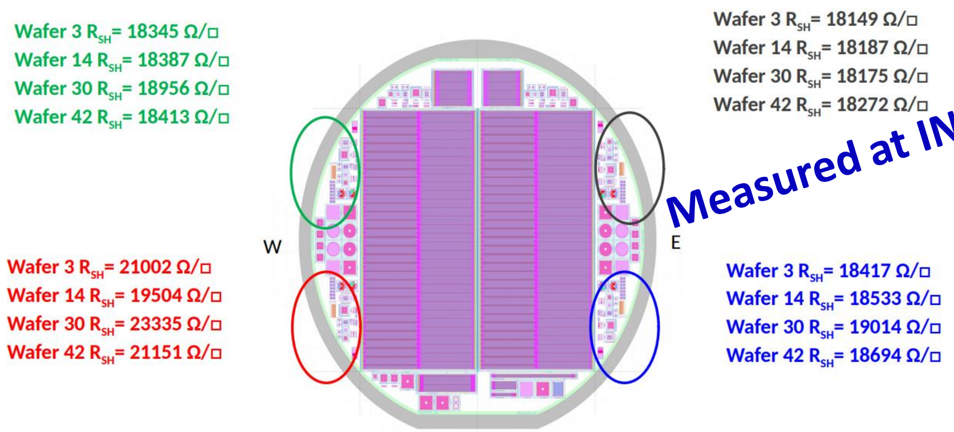


P-stop resistivity

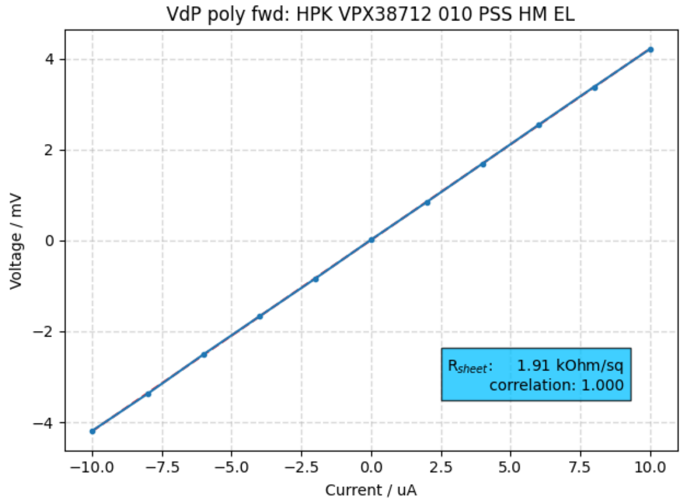
- **Van der Pauw structure** : resistivity measurement of thin films e.g.**, ion implantation layers**
- Dedicated p-stop Van-der-Pauw test structures are hosted on the wafers
- P_{stop} resistivity is usually **quite uniform** over a wafer
- Sometimes **significant inhomogeneity** (non uniform p-stop doping concentration) over the wafer has been observed



$$R_{sheet} = \frac{\pi}{ln2}\frac{V_{34}}{I_{12}}$$



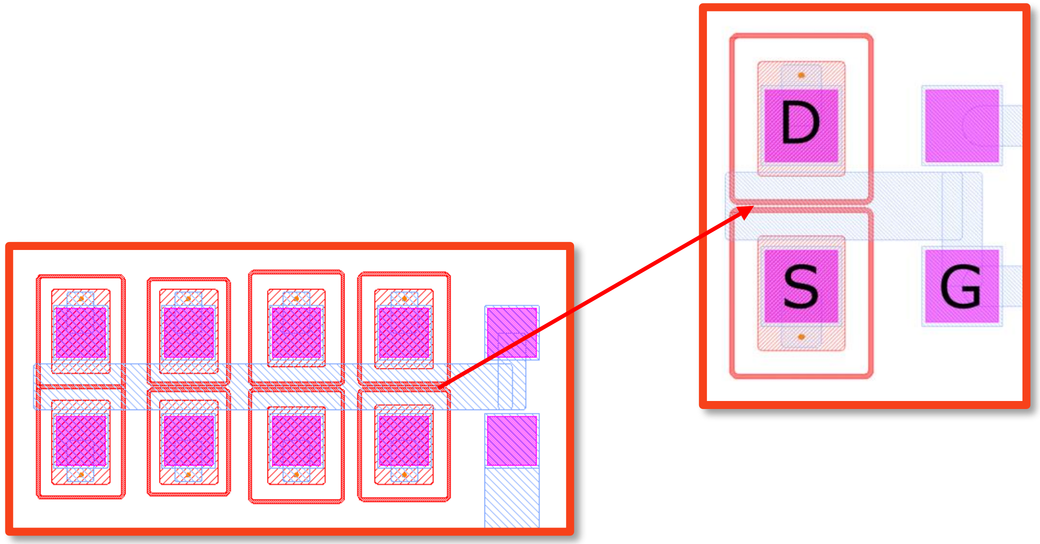
Measured at INFN Perugia

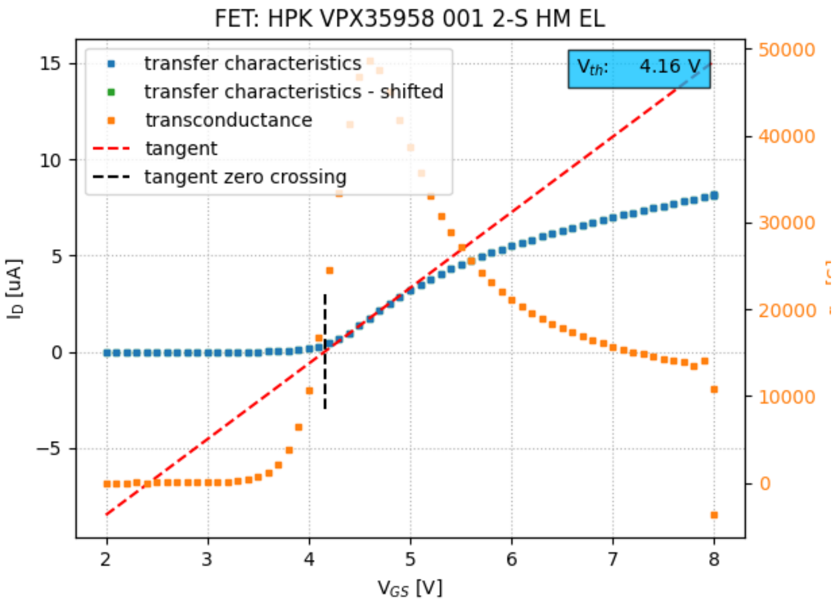


Typical IV ramp of p-stop VdP

Field Effect Transistor

- **FET (Field-Effect Transistor)** useful for assessing inter-channel properties
- It contains a **p-stop** implantation encircling the S-D
- The **threshold voltage** (=voltage at which the D-S channel becomes conductive) is a direct indication of the p-stop quality
  → Sensitive to p-stop variations
- V_{th} is extracted from the I_D – V_{GS} plot
- Low threshold voltage indicates lower p-stop implantation dose → Not desired!



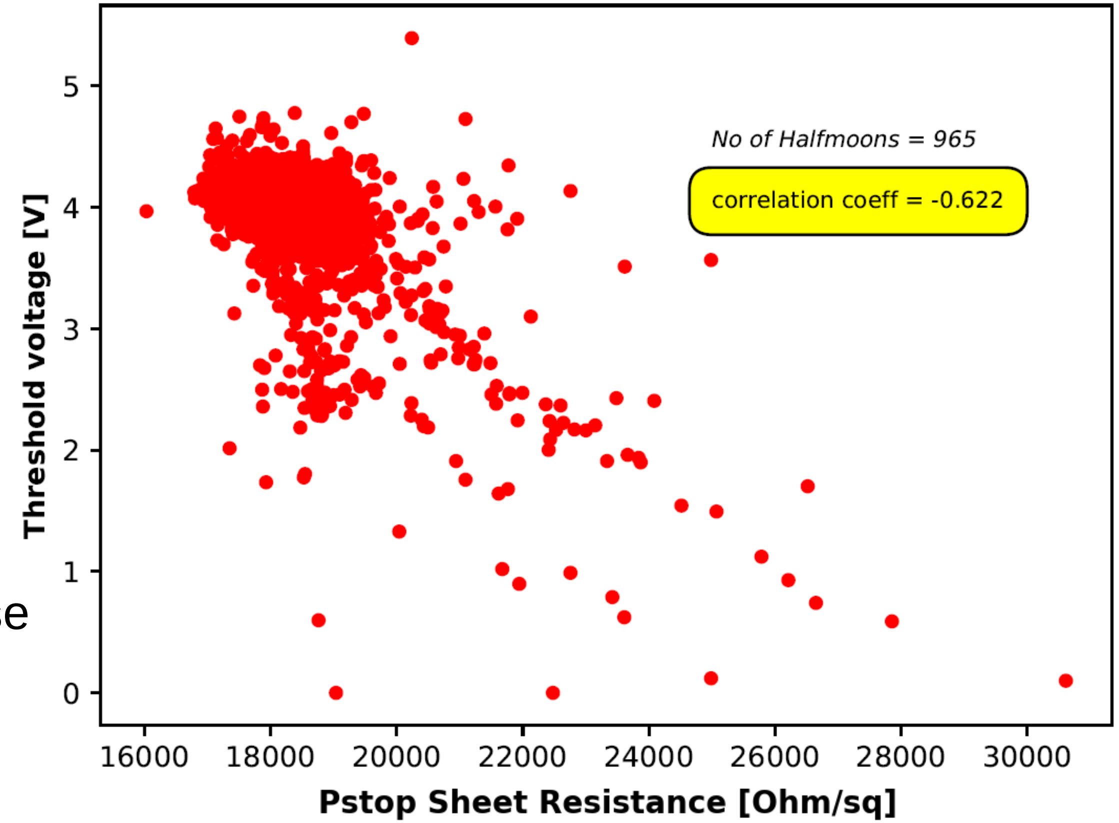


Usual values: 3V < V_{th} < 5V

Inter-strip isolation

- V_{th} and p-stop resistivity give an indirect indication (qualitatively) of the inter-strip isolation
  - The two parameters are **(weakly) anti-correlated**

- Lower p-stop implantation dose could result to a poor interstrip isolation of the adjacent strips
  - **No interstrip resistance issues observed** on the wafers with lower threshold voltages
    - R_{int} uniform and well above the threshold
  - Studies of **interstrip resistance after irradiation** on these samples is on-going



- This proves how PQC can spot, **in time**, small inconsistencies in the production process

Summary

- Delivered sensors by HPK show an excellent quality, respect the CMS specifications and are consistent to the results from the prototyping phase!

- Production phase is ongoing and proceeds smoothly, without any problems

- **Promising news**: Outer Tracker will receive high quality sensors!

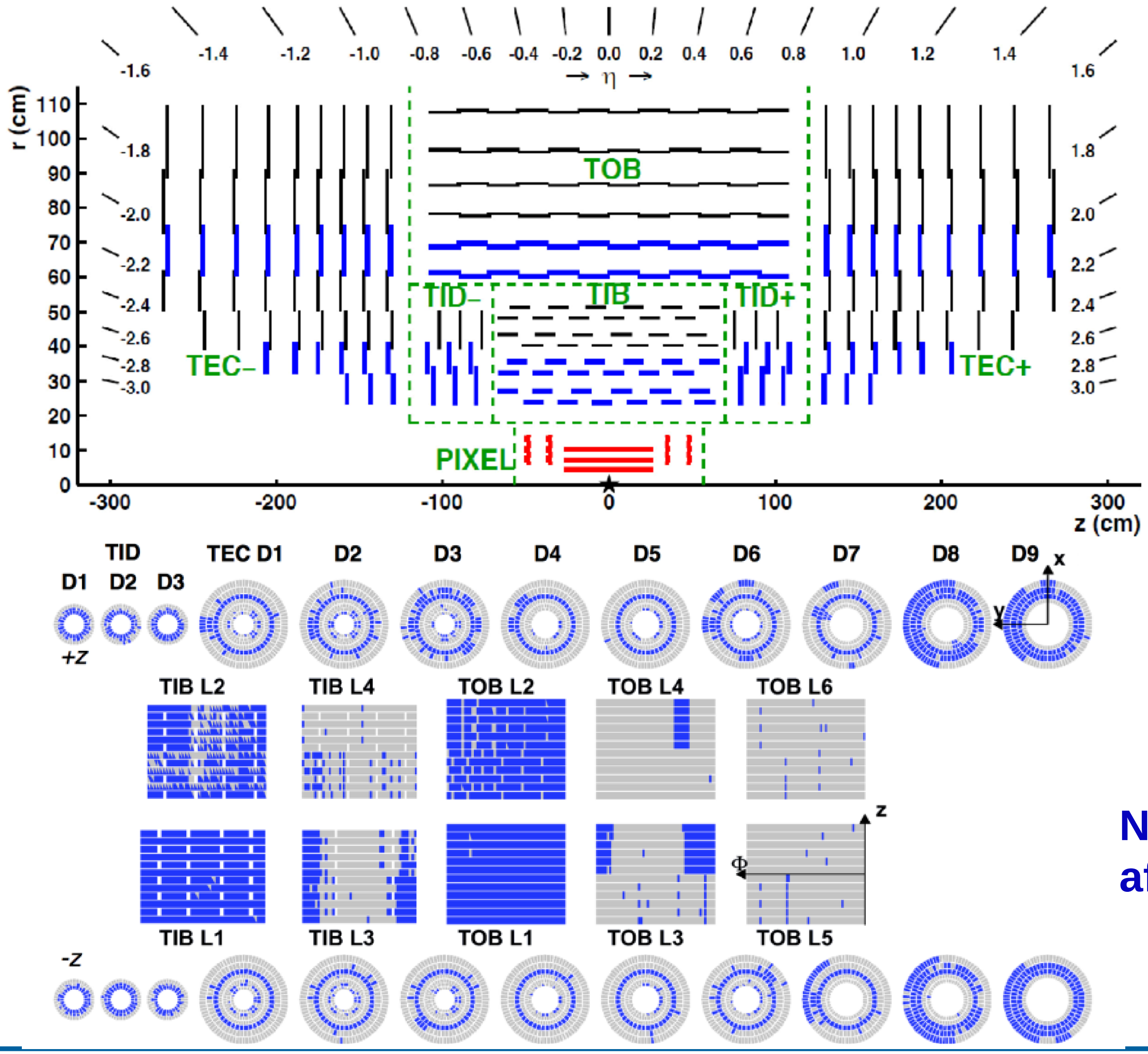
Thank you for your attention!

References

- CMS collaboration, **“The Phase-2 Upgrade of the CMS Tracker, Technical Design Report”**, July 2017
- The Tracker group of the CMS collaboration, **“Selection of the silicon sensor thickness for the Phase-2 Upgrade of the CMS Outer Tracker”** , *December 2020 (v8 September 2021)*
- The Tracker group of the CMS collaboration, **“P-Type Silicon Strip Sensors for the new CMS Tracker at HL-LHC”** , *June 2017*
- Viktoria Hinger PhD Thesis, **“Silicon Sensor Process Quality Control for the CMS Phase-2 Upgrade”**, *February 2021*

Back up slides

Ph-1 Outer Tracker Limitations



Phase-1 CMS Tracker Layout

Number of non-functional modules of Outer tracker after receiving 1000 fb^{-1} (colored with blue)

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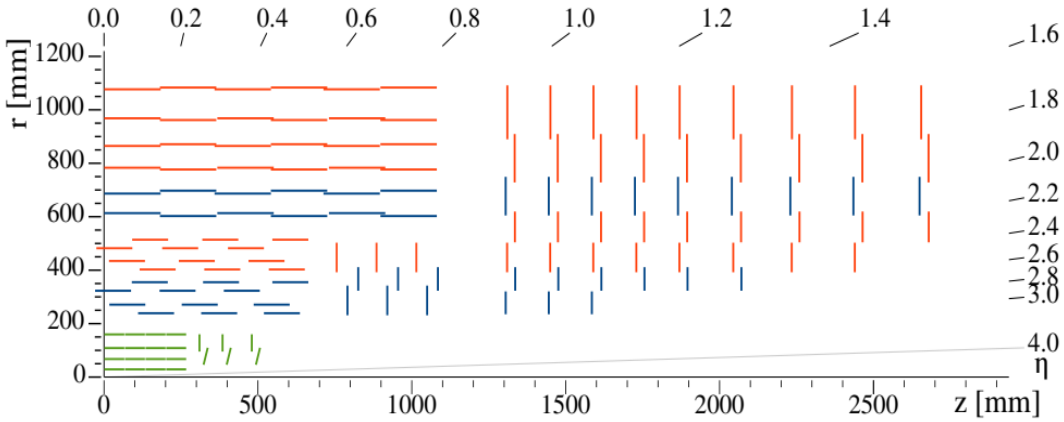
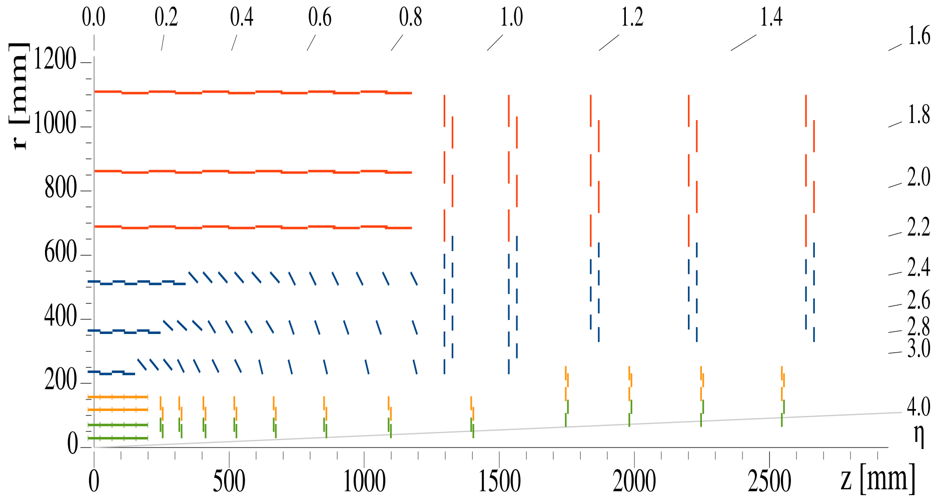
Comparison of Phase-1 to Phase-2 outer tracking system

	CMS Outer Tracker Phase 1	CMS Outer Tracker Phase 2
Total surface	~ 206 m2	~ 191 m2
# Modules	15148	13296
# Strips	9.3 M	42 M
# Macro-pixels	0	172.5 M
L1 trigger rate	100 kHz	750 kHz
Latency	3.2 μs	12.5 μs
Powering	direct	DC –DC converters
Cooling	C_6F_{14}	CO_2

Phase 1

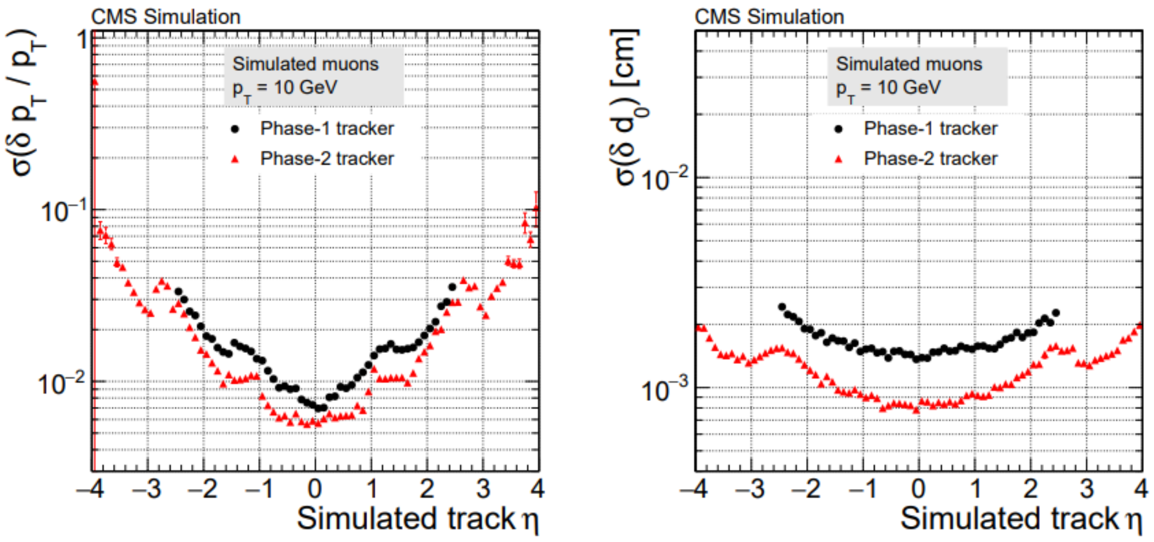


Phase 2



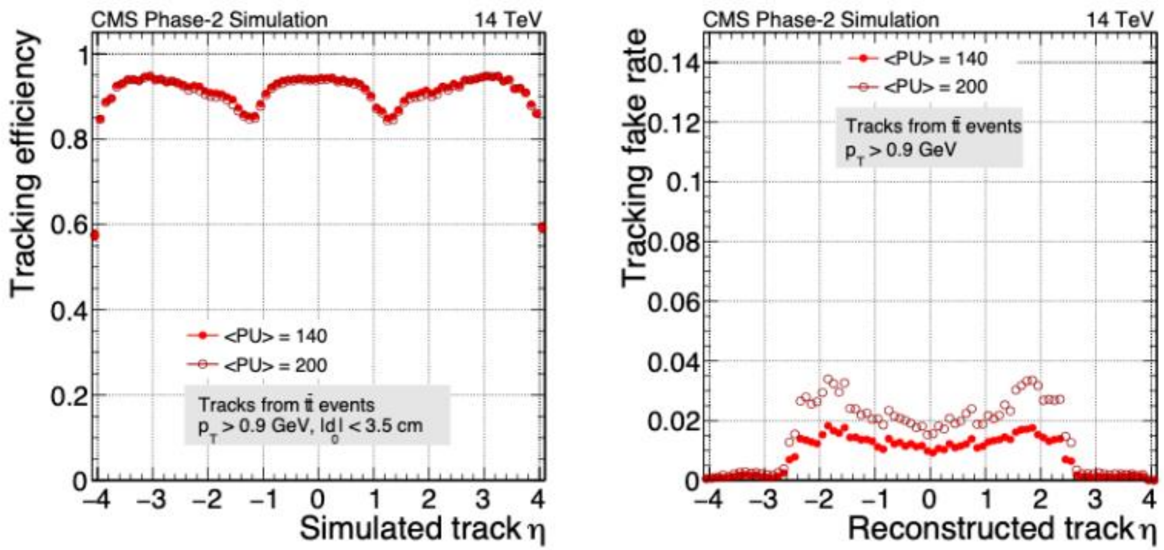
Ph-2 Tracker Performance

p_T resolution



- Relative resolution of the p_T and resolution of the transverse impact parameter as a function of η
- Single isolated muons with a **p_T = 10 GeV**

Tracking efficiency



- Tracking efficiency and fake rate as a function of the η for tt-bar events for 140 PU and 200 PU
- Tracks with p_T > 0.9 GeV produced within a radius of 3.5 cm from the centre.

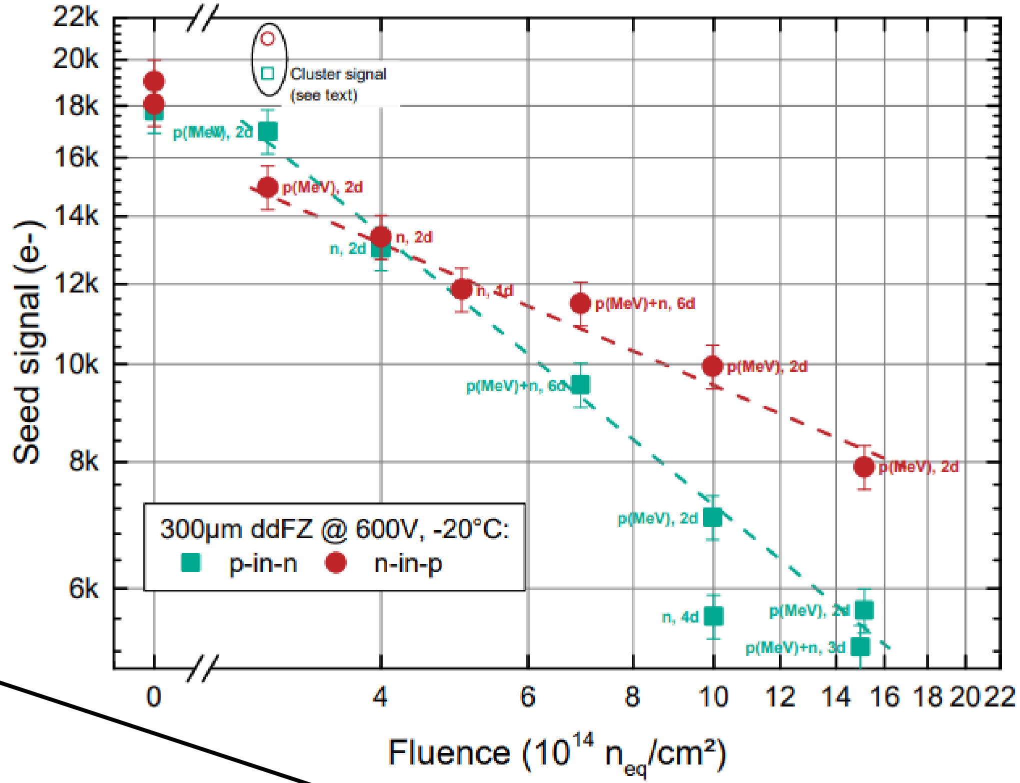
Irradiation Campaign

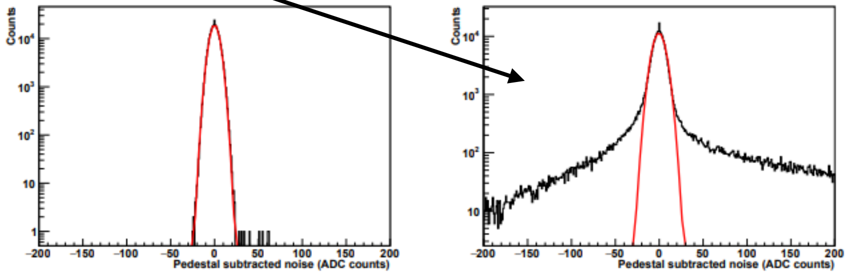
Sensor type selection

- ❑ p-on-n (hole collection) show faster decrease of collected charge with fluence
  - **Trapping effect** becomes dominant at higher fluences, holes have **lower mobility** than electrons

- ❑ High fluences: N**on-Gaussian noise** observed in p-on-n sensors which could act as fake hits

- ❑ n–on–p was selected as **the baseline type** for the OT tracker sensors



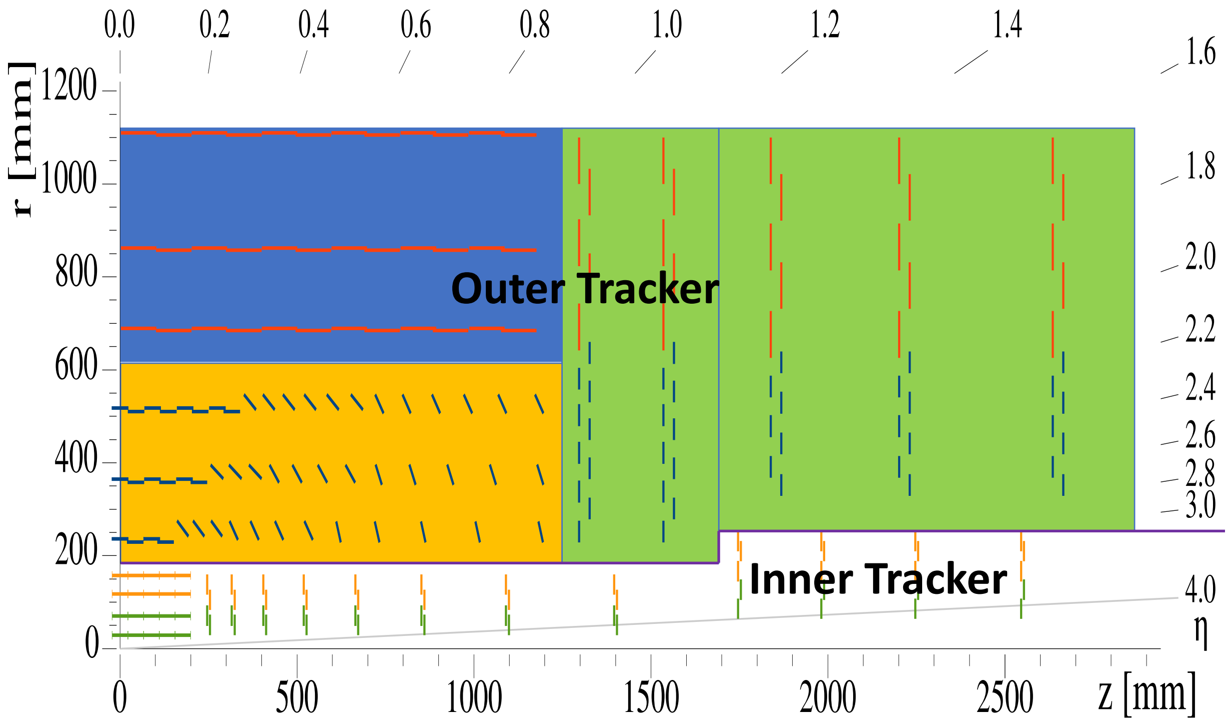


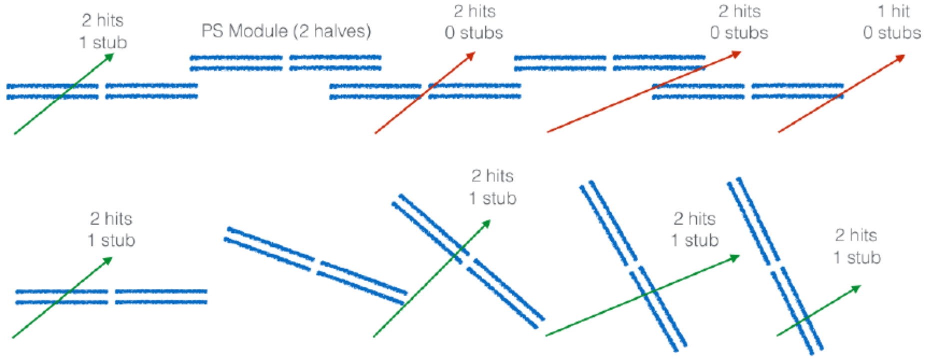
OT Tilted geometry

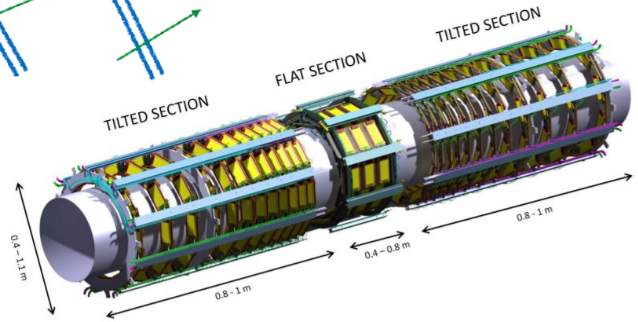
Tracker Phase-2 Upgrade

TBPS tilted geometry

- Reduced number of modules
- Smooth transition from barrel to Endcap
  - Better trigger performance than **flat** geometry
  - Inefficiencies due to large incidence angles of particles







TBPS = Tracker Barrel innermost (PSS modules)

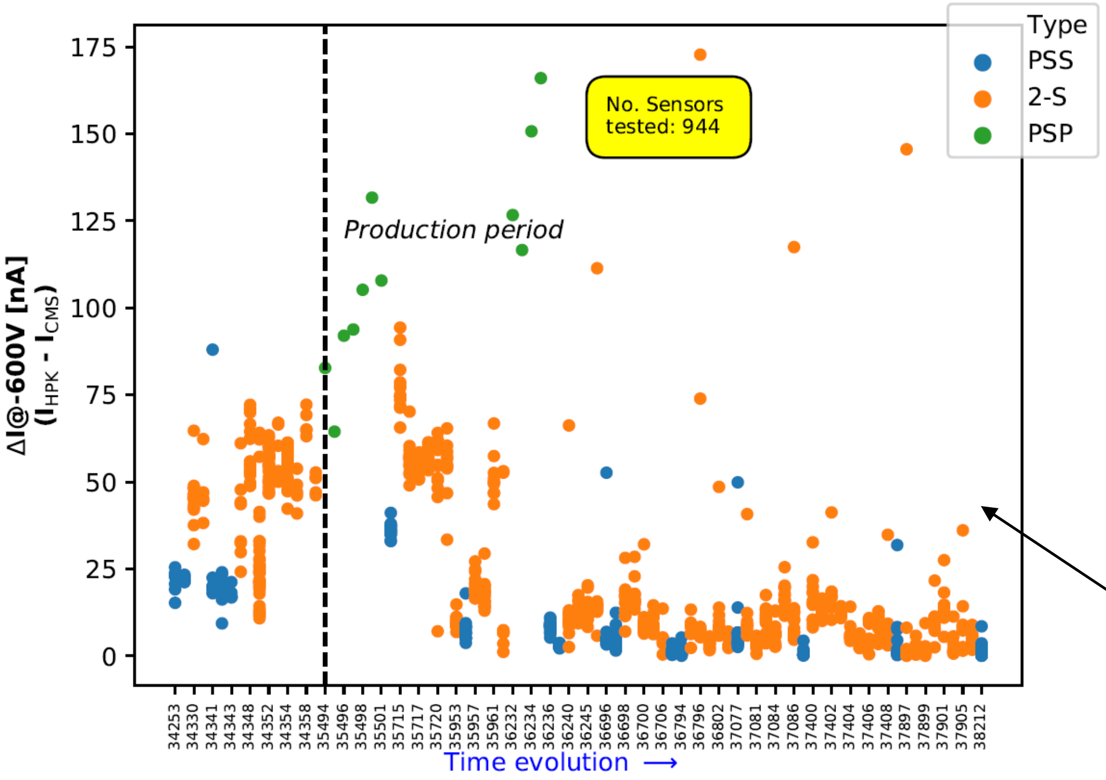
TB2S = Tracker Barrel outermost (2S modules)

TEDD = Tracker Endcap Double Disk

Total leakage current

- Consistency check between IV performed by HPK and QC centers

- ΔI (abs values) corresponds to the difference of the measured currents on each sensor respectively



Contains sensors tested **both** by HPK and QC centers