CMS Tracker

HEPHY group report

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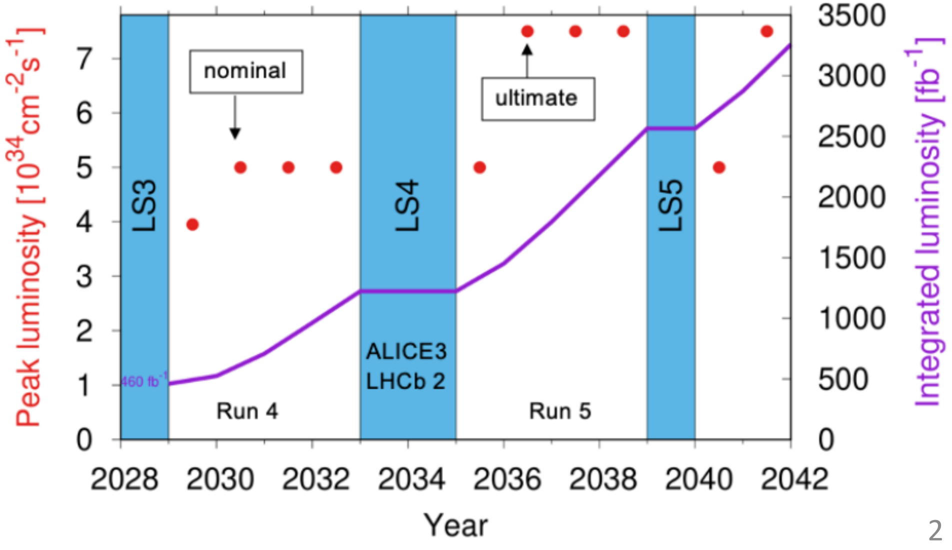
17/2/2023

High Luminosity LHC

High luminosity upgrade of LHC

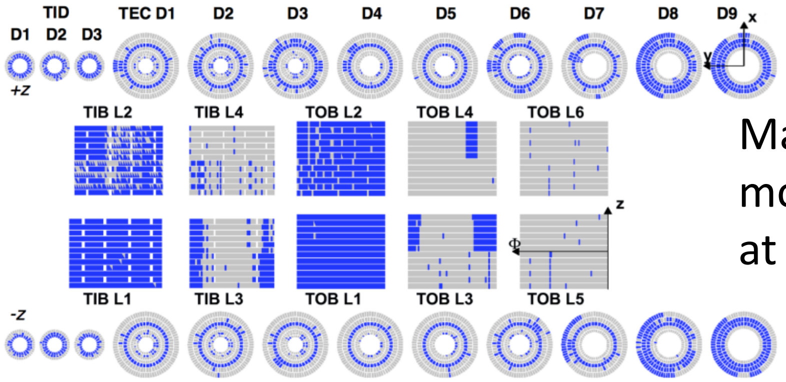
- 5-fold increase of peak luminosity (5×10^{34} $cm^{-2}s^{-1}$)
- 10-fold increase of integrated luminosity (3000 fb^{-1})
- Pile up 140-200 p-p collisions

Long Shutdown 3 (LS3) scheduled for 2026-2028

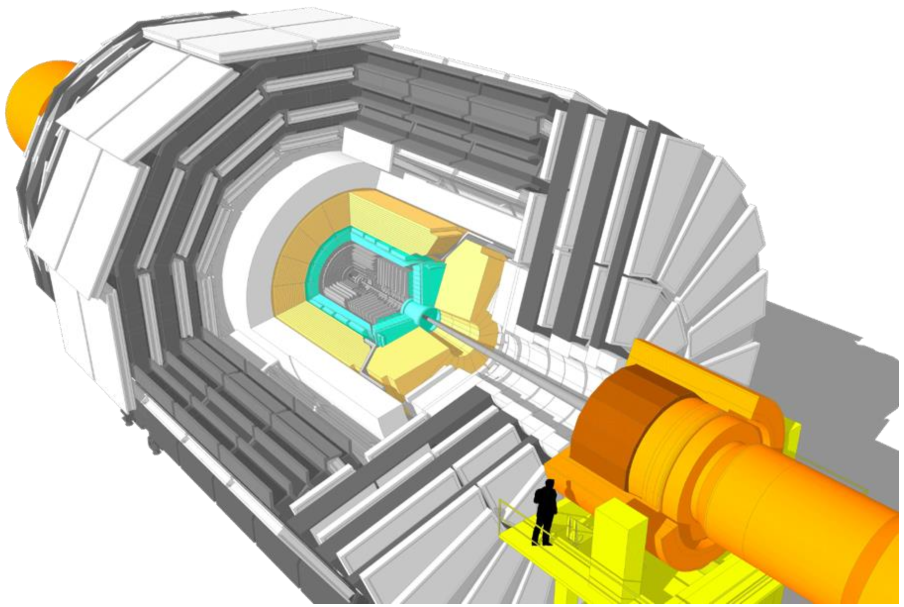


Tracker Phase-2 Upgrade

- **Current** tracking system **not expected** to tolerate the increased radiation levels of HL-LHC



Map of non-functional modules of current system at 1000 fb^{-1}



Tracker will need a **full replacement**!!

Phase-2 upgrade → 200 m^2 silicon sensors required!

HEPHY plays a key role in Tracker *Phase-2 upgrade project*

- Simulations and design of sensors and test structures
- Electrical characterization of sensors and test structures
- Preparation, negotiations and QA of series production
- Co-Conveners of sensor development working group

Tracker Phase-2 Upgrade

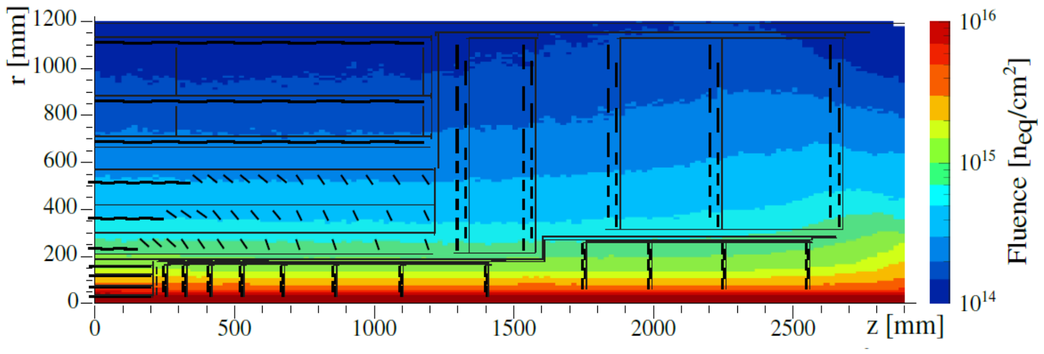
Tracker must maintain the excellent performance of the current system on tracking efficiency and background rejection in the harsh environment of HL-LHC!

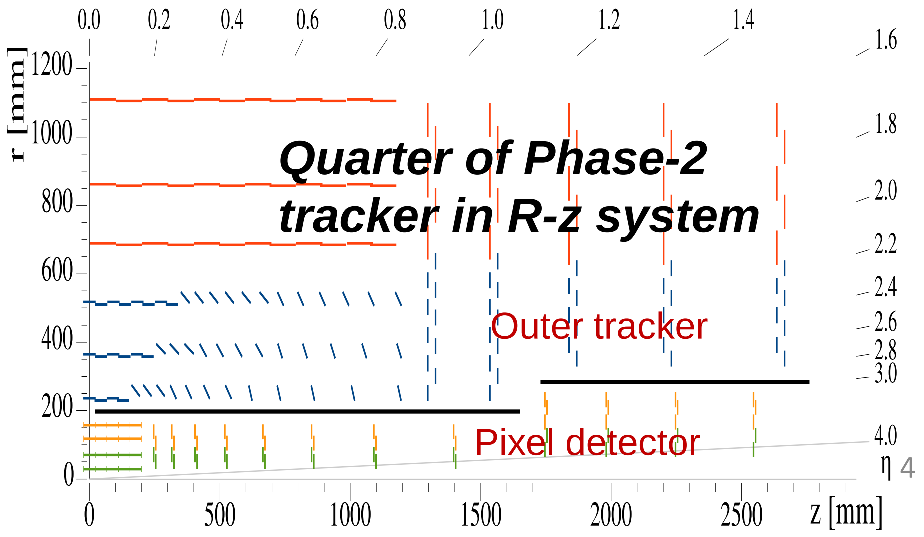
- **Increased radiation levels** and **pile-up** main challenges
  - radiation hard sensors
  - higher granularity for sufficient two track separation

- Level1 Trigger needs **tracking information**
  - currently only calorimeter and muon system send data to L1
  - with increased pile-up, trigger rate can not keep up with full event rate
    → data **reduction** is required!

L1 contribution concept plays a major role on outer tracker **module** and **layout design!**

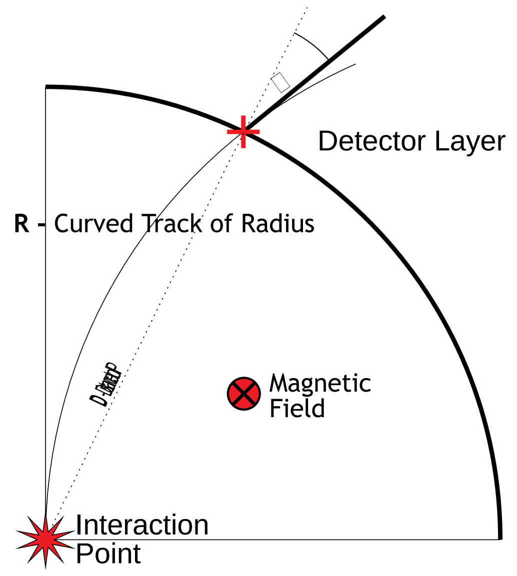
FLUKA simulation of expected delivered fluence on Ph-2 tracker after 3000 fb^{-1}





Outer Tracker p_T modules

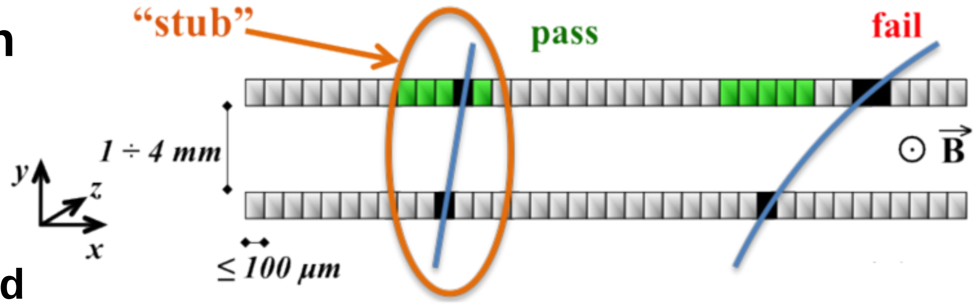
- tracker forwards data to L1 only from **high transverse momentum tracks!**



- high p_T events (above ~ 2 GeV/c^2) transmitted to L1 trigger → **stubs**
  - one order of magnitude data reduction without sacrifice of interesting physics events

- outer tracker modules (**p_T modules**) will be performing the event filtering

- each **p_T module comprises 2 sensors and performs hit correlation**
  - sensors parallel and narrowly arranged form a *track selection window* (tunable)
  - bending angle of track at a magnetic field **depends on** p_T
  - high p_T particles feature **smaller bending angle** and 'hit' **a narrower band** of strips/pixels
    → succeed to fall within the acceptance window



Outer Tracker p_T modules

The 2S Module

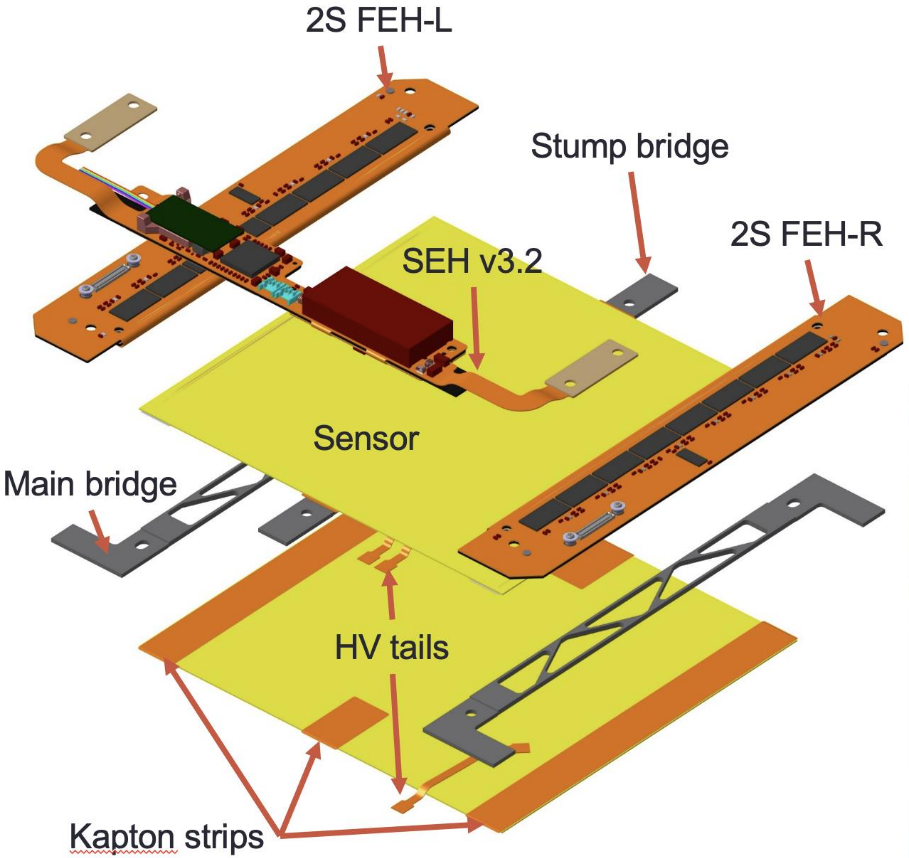
- **2** x **S**trip sensors: **2S sensor**
  - Size: 10 x 10 cm^2
  - Pitch: 90 µm
  - Length: 5 cm
  - strips per sensor: 2x1016

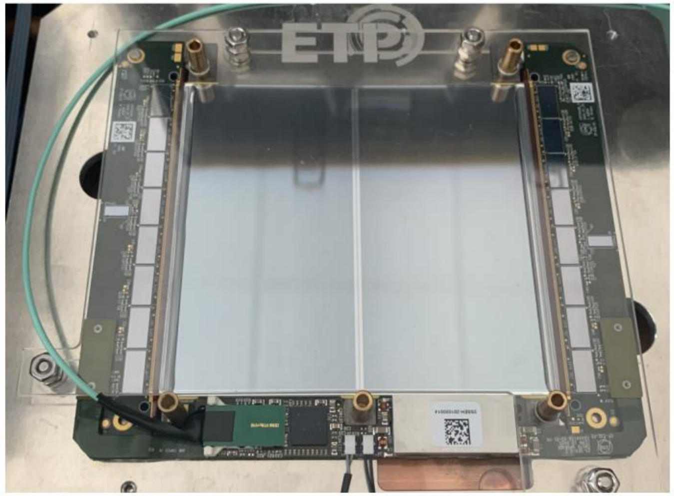
- 2 x 8 **C**MS **B**inary **C**hips: **CBC**
  - 2x127 channels per chip
  - Bump bonded to flexible hybrid
  - Connects to top and bottom sensors
  - Inter-chip communication via hybrid

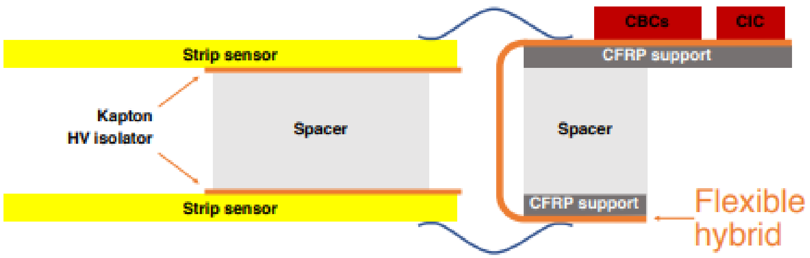
- **C**oncentrator AS**IC**: **CIC**
  - collects data from 8 CBCs (half module)

- Low Power GigaBit Transceiver ***lpGBT* + *VTRx+***
  - Bandwidth: 5 Gb/s

- 2-stage DCDC powering
  - 12 V to
    - 2.5 V (opto)
    - 1.25 V (ASICS)



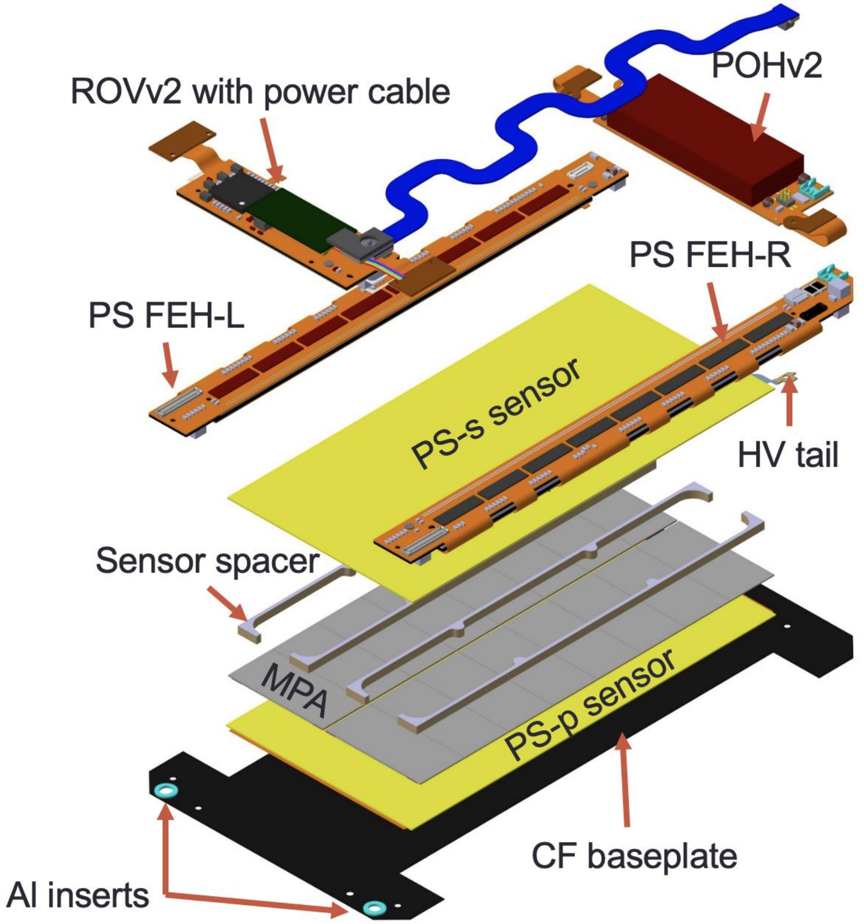


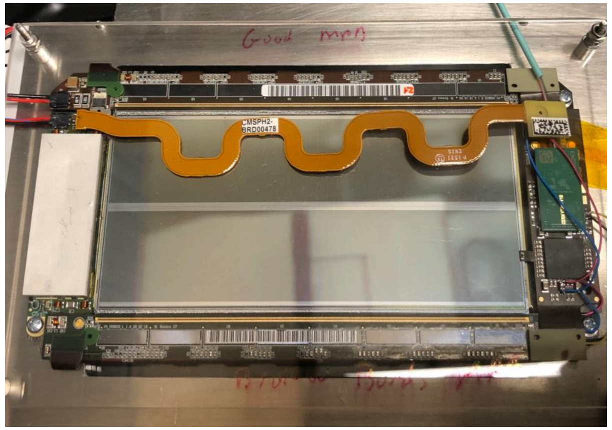


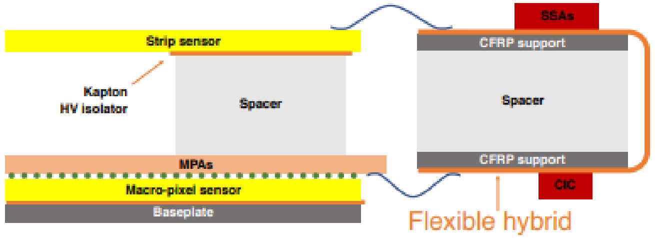
Outer Tracker p_T modules

The PS Module

- MacroPixel sensor: **PS-p sensor**
  - Size: 5 x 10 cm^2
  - Pitch: 100 µm
  - Length: 1.5 mm
  - No. of pixels: 32x960
- Strip sensors: **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 MacroPixel sensor
  - Includes correlation logic
- Concentrator ASIC: **CIC**
  - collects data from 8 MPAs
- Low Power GigaBit Transceiver ***lpGBT + VTRx+***
  - Bandwidth: 5 or 10 Gb/s
- 2 stage DCDC powering
  - 12 V to
    - 2.5 V (opto)
    - 1.25 V (ASICS)
    - 1.05 V (MPA digital)



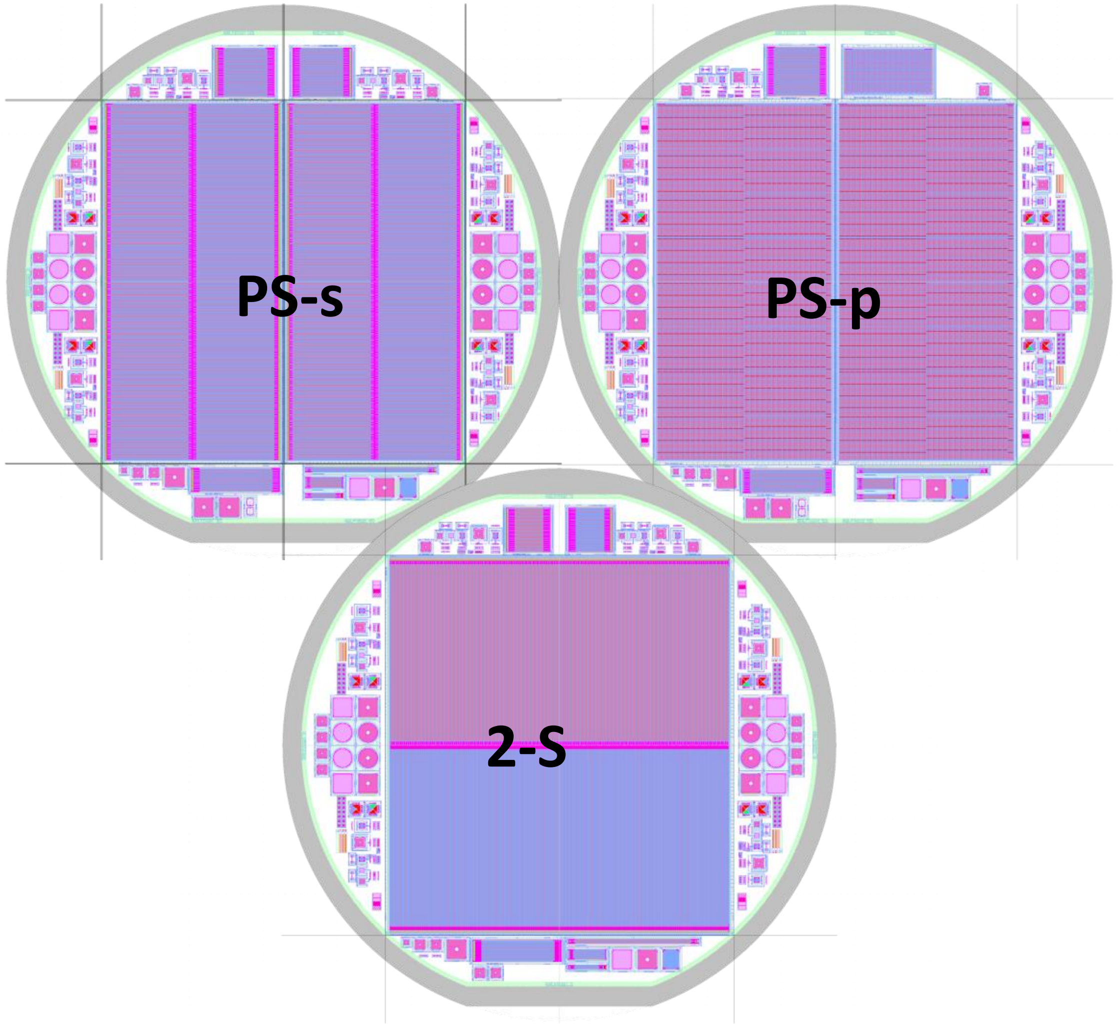




Outer Tracker sensors

Baseline selection of the Phase-2 Outer Tracker Sensors

- **n–on–p** type sensors
- **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 for strip/pixel isolation
- Produced on 6'' wafers (150mm thickness)
  - host several test structures and mini-sensors



HEPHY in CMS Phase II

Note: In 2015 the decision was that HEPHY contributes to sensors only!

HEPHY responsibilities in CMS Outer Tracker

2010 – 2019: *Participation in all development studies of the sensors*
(Materials, thickness, radiation hardness, simulations, production process, design choices, etc.)
2008 – 2018: *Establishing alternative European sensor producer (Infineon)*
Stopped by Infineon in 2018 due to commercial reasons
2019: *Final design and wafer layout for all three sensor types*
(PS-p pixel design from KIT)
2014 – 2019: *Conduction of the procurement process* (~18 MCHF)
2019 – 2024: *Definition and supervision of the Quality Assurance Campaign to produce ~ 29.000 sensors*
Process Quality Control (PQC) as major contribution from HEPHY
(Viktoria Hingers PhD Thesis) – **CMS PhD thesis award winner 2021**

Managerial responsibilities

Thomas Bergauer
2016-2021: Co-Convener of the HGCal Sensor WG
Marko Dragicevic
Since 2014: Co-Convener of the Tracker Sensor WG
Since 2017: Tracker Resource Manager

Staff

Active contributors today

Staff Scientists

- **Marko Dragicevic**
  - Convener: Outer Tracker Sensors WG
  - Tracker Resource Manager
- **Thomas Bergauer**
  - Ex-convener: HGCal Sensors WG
  - Also: Group Leader Detector Development (non-CMS)

PhDs

- **Konstantinos Damanakis:** Tracker sensor QA (since Oct. 2020)

PostDocs

- **Moritz Wiehe:** HGCal (until August 2022) – currently fellow position at CERN
- **Ioannis Kopsalis**: HGCAL+Tracker (since February 2023)
- **Suman Chatterjee**: part-time contribution to HGCAL measurements

Sensor QA team

- **Margit Oberegger**
- **Andreas Bauer**
- **Stefan Schultschik**

Additional support

- **Wolfgang Brandner**
- **Florian Buchsteiner**

Quality assurance

- Outer tracker requires about 28.000 silicon sensors
  - 16200 x **2S** + 5960 x **PS-s** + 6400 x **PS-p**

- The large-scale production was contracted to Hamamatsu Photonics

- Sensor **production** (deliveries) started **summer 2020**
  - Campaign started within COVID-19
  - Lockdowns had significant effects on all centres
  - All institutes managed to keep up
  - A few problems identified during pre-production and now corrected

Quality Assurance plan

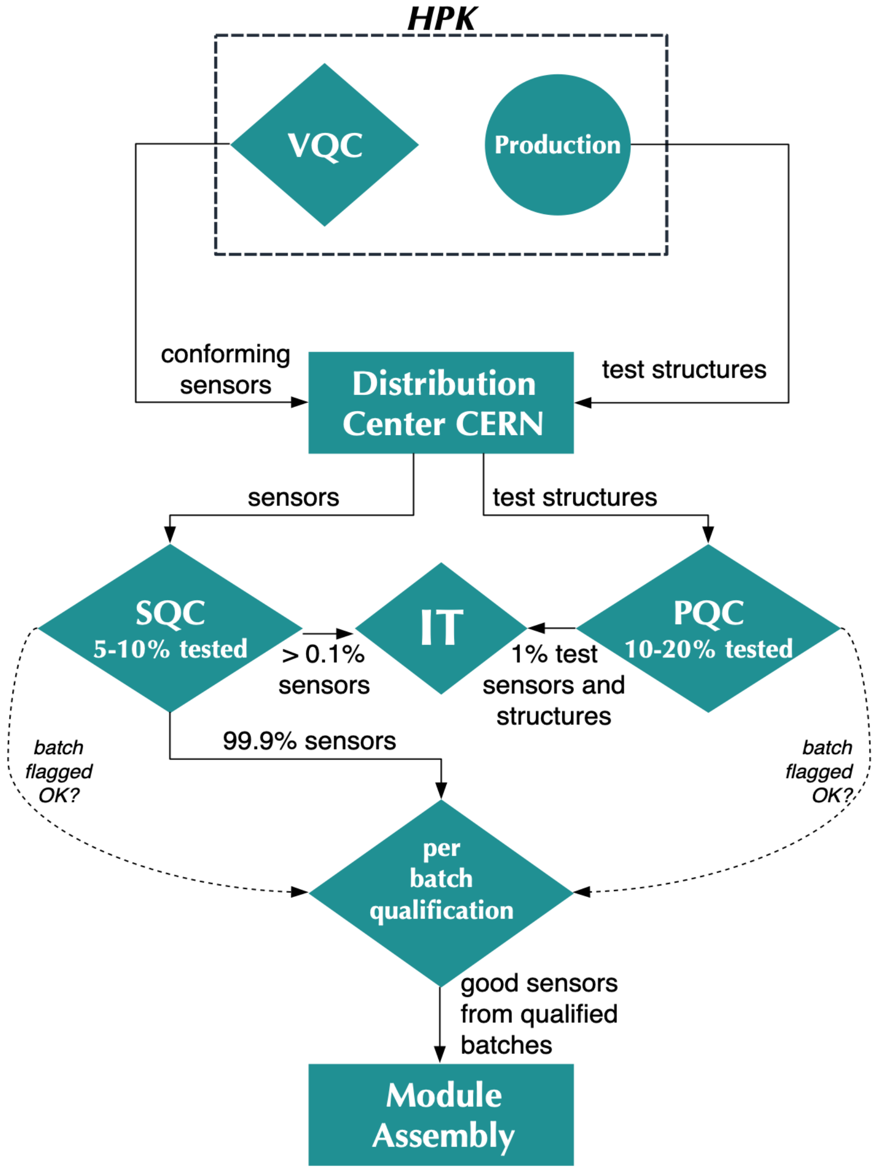
- Quality control comprises four parts
  VQC - *Vendor Quality Control*
  SQC - *Sensor Quality Control*
  PQC - *Process Quality Control*
  IT - *Irradiation Tests*

- **All sensors** characterized by **vendor**
  Only sensors complying with the specs are sent to CERN
  Results recorded in DB for each sensor

- Acceptance using **sample measurements** at SQC, PQC and IT

- Production and QA monitored by **expert panel**

- Effort lead by HEPHY and KIT
  Participants
  Europe: Demokritos(Athens), Perugia,
  US: Brown, Rochester
  Asia: Delhi, NCP Pakistan



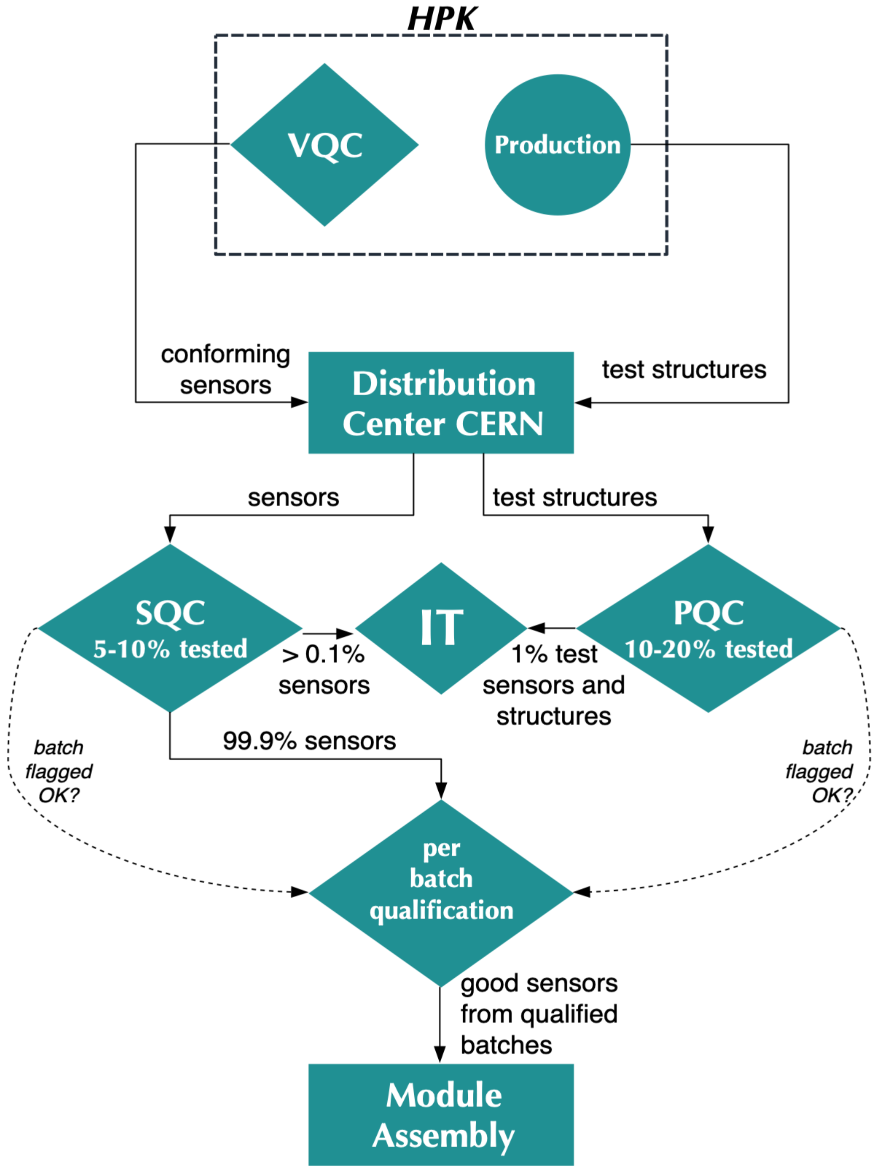
Quality Assurance plan

HEPHY responsibilities

- **Managerial tasks**
  - Overall planning
  - Co-convener of weekly acceptance meetings (OTSEPP)
  - Contact to Tracker and CMS
  - Contact to Vendor (HPK)

- **Sensor Quality Control (SQC)**
  - Responsible for testing 25% of the production

- **Process Quality Control (PQC)**
  - Test structures, characterisation methods and setups developed at HEPHY
  - Responsible for testing 25% of the production

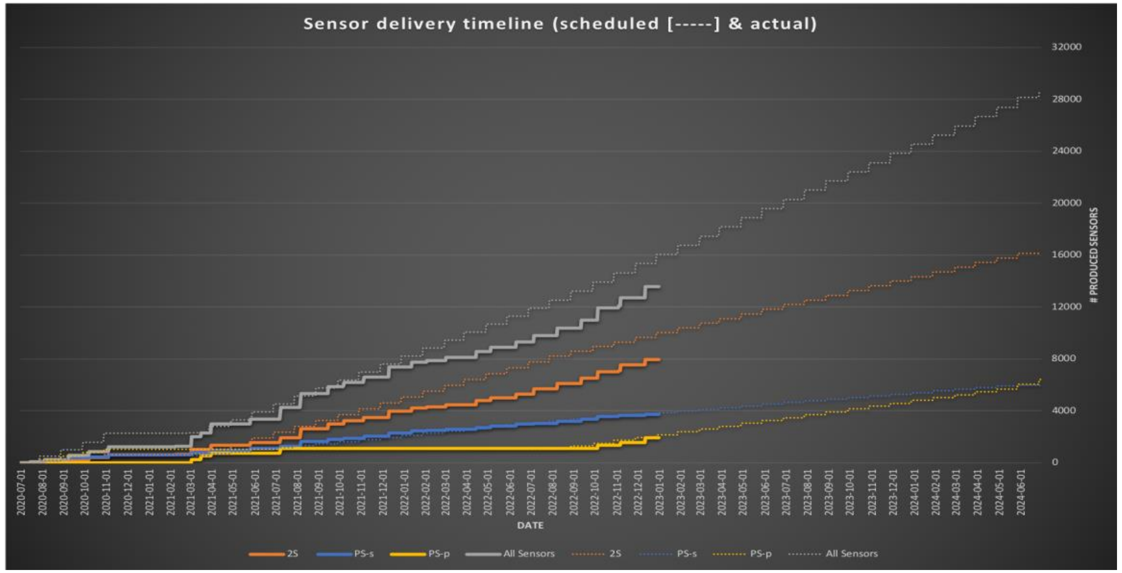


Sensor production status

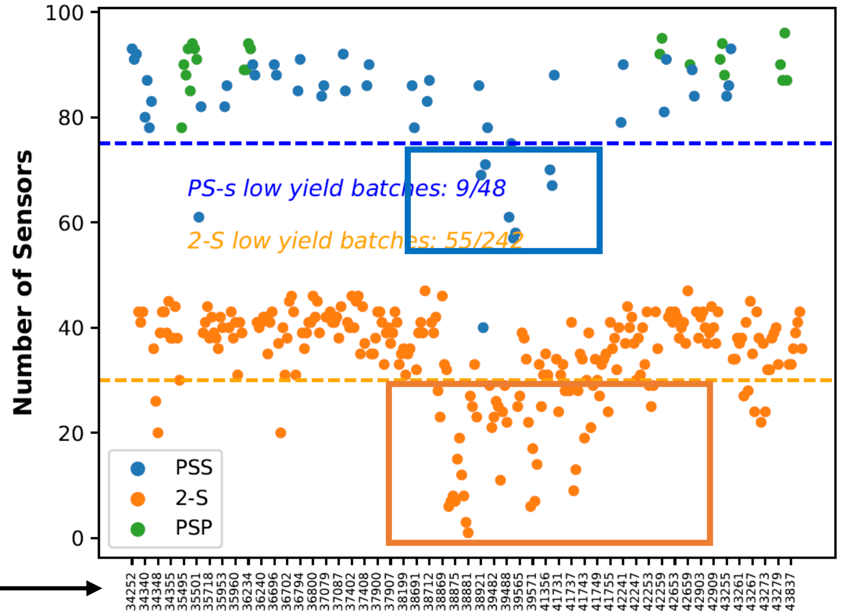
Current status

- **Today**:
  > 13000 wafers (~ 50%) delivered
  > 3000 sensors IV tested
  > 1000 sensors fully tested
  > 3000 halfmoons tested (check it again)

  } by CMS



- **Low yield** batches at first 3 quarters of 2022
  - HPK managed to recover since summer and stabilize the yield to the agreed numbers
  - No impact on module production

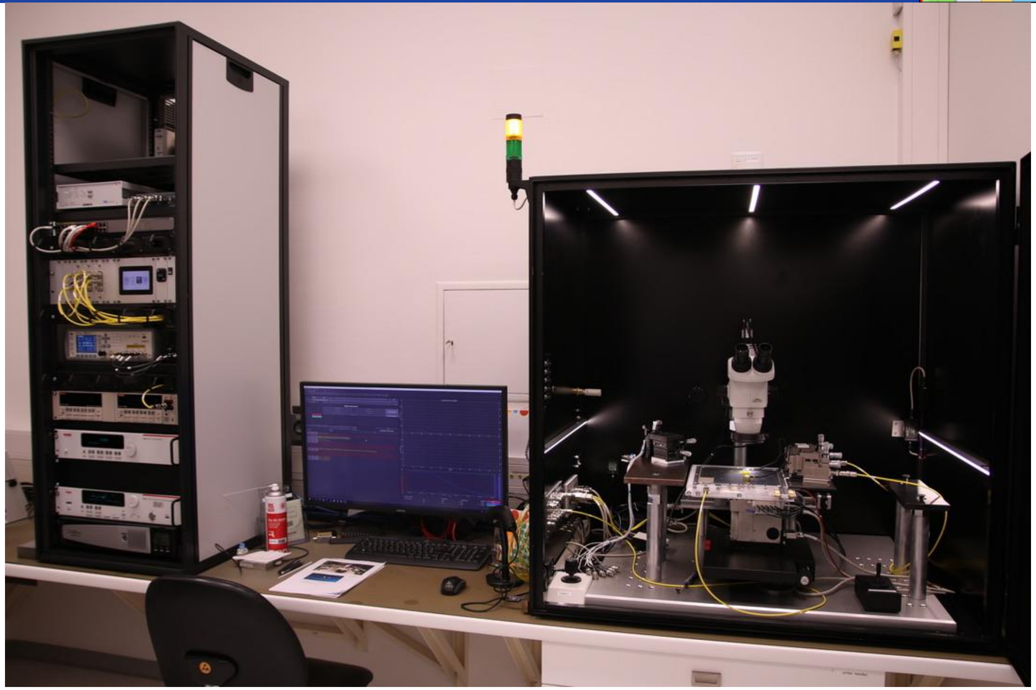


Batch ID →

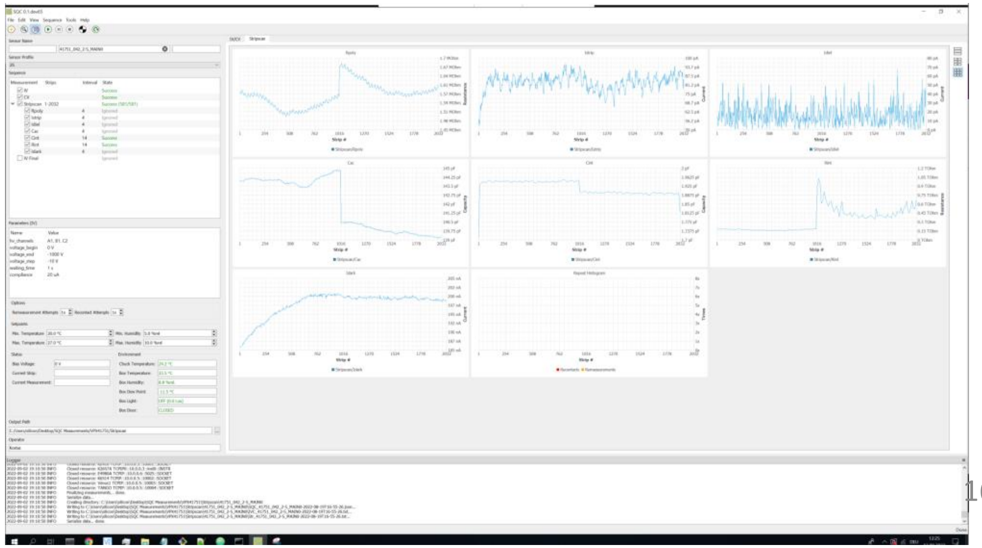
Sensor Quality Control at HEPHY

Sensor Quality Control

- Custom-made semi-automated setup developed at HEPHY
  - Can automatically characterize ~2000 strips in 6-8 hours
- **Custom software** to control setup implemented in **Python**
  - Developed/maintained by B.Arnold
  - Replaced the old python-made SW developed by D. Blöch
- Setup in operation **every day** to test 1-2 sensors
  - Mainly operated and maintained by Stefan and Kostas
  - Fully characterize at least 3 sensors per batch of ~40, one batch per week
- In addition, **long-term tests** are performed in the **climate chamber**
  - Include more detailed studies on humidity and temperature sensor response



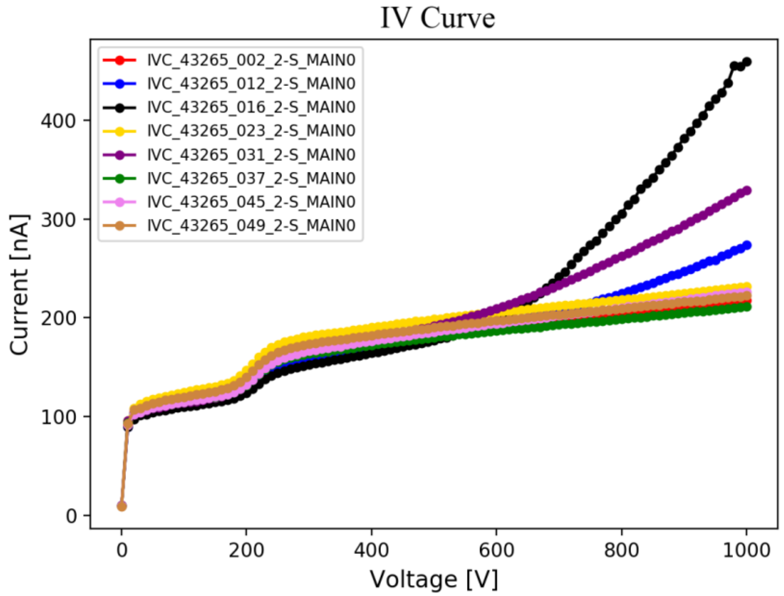
Global parameters	(inter-)strip parameters
Total leakage current Total capacitance	strip current, strip polysilicon resistance Coupling capacitance, dielectric current Inter-strip capacitance, inter-strip resistance

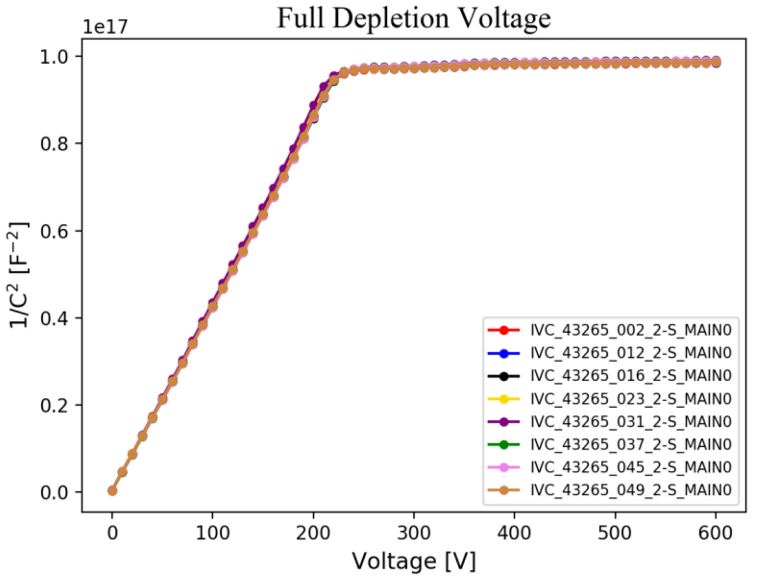


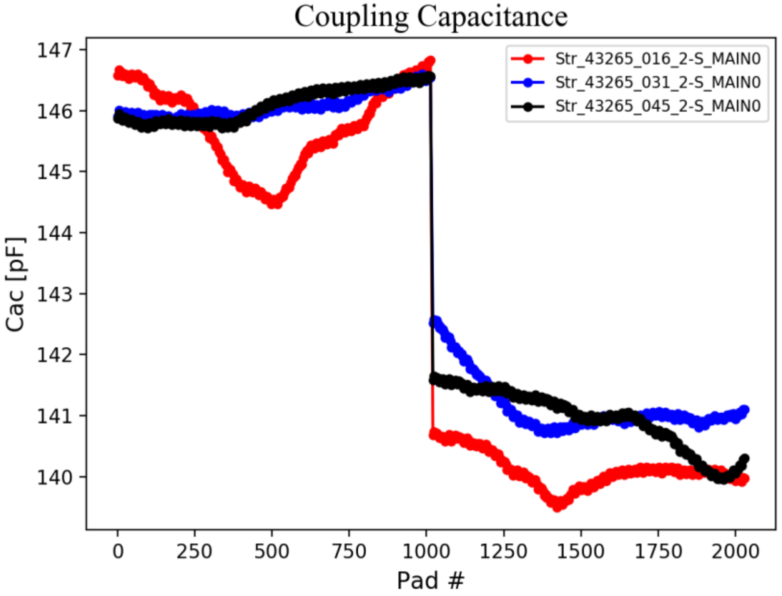
Sensor Quality Control

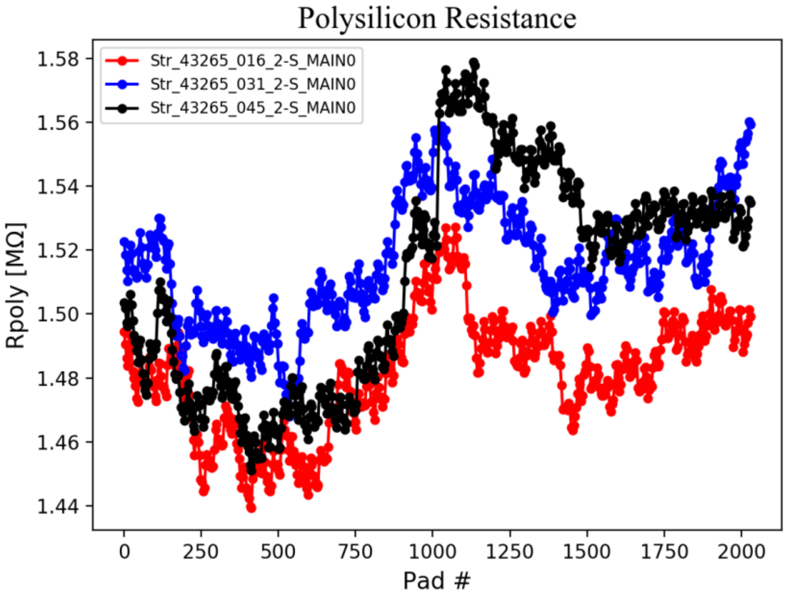
A typical batch

- Measurements performed at T = 20-23 ^{o}C and RH<10%
- 20% of batch is IV-CV tested
- 3-5 of the “worst” sensors of the batch fully characterized
- All SQC data evaluated by Outer Tracker silicon sensor experts
  - data stored on the CMS database









Process Quality Control at HEPHY

Process Quality Control

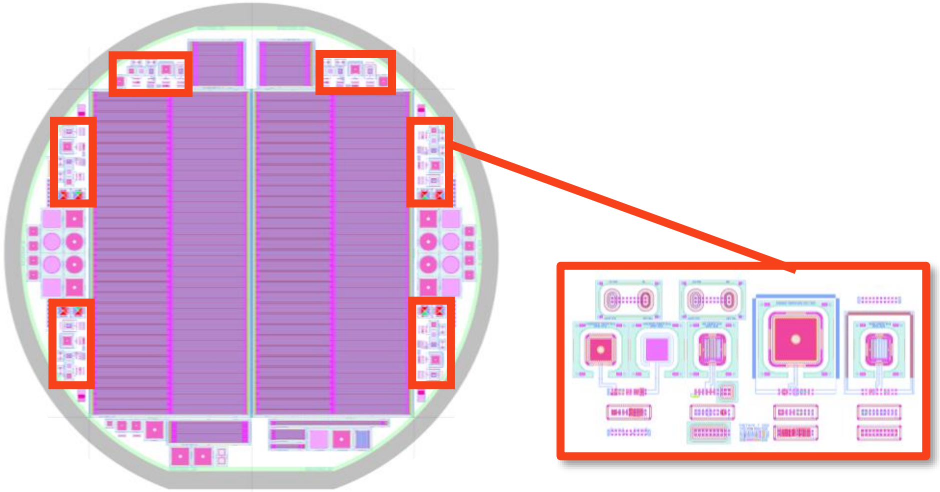
- **Measurements on test structures** to evaluate the **quality and stability** of the production process
  6” AC coupled (Tracker 2S and PS-s)
  6” DC coupled (Tracker PS-p)
  8” DC coupled (HGCal)

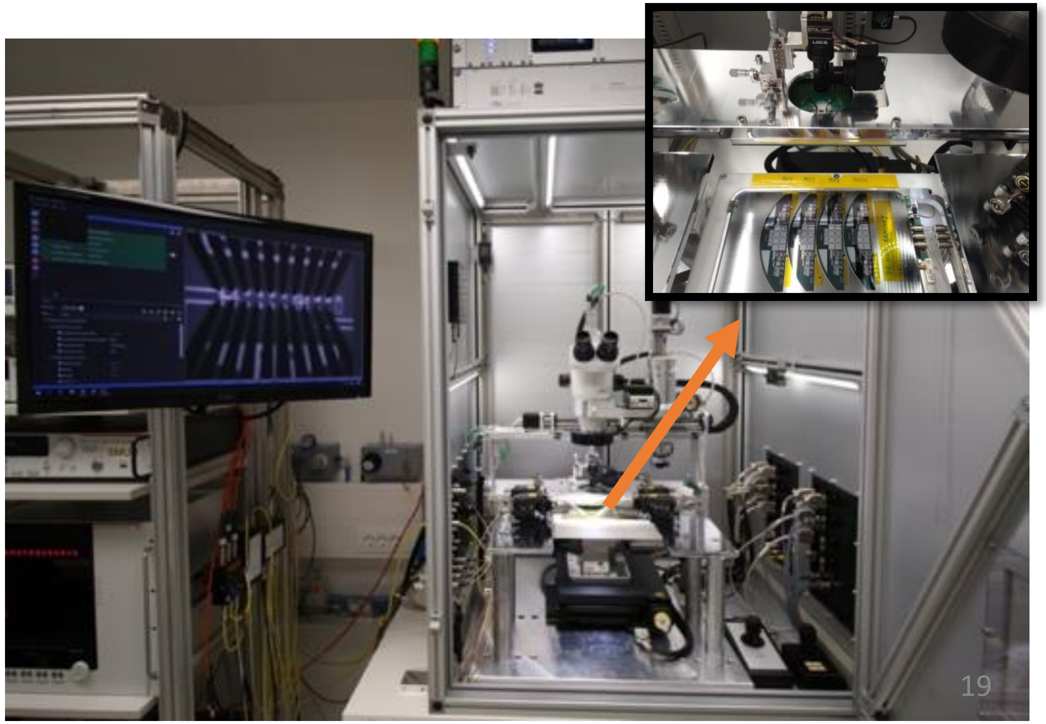
- **Identical** set of test structures on **all wafers**

- Use **standardised pattern** of 20 connection pads: **flute**
  - Connect using standardised probe cards
  - Use switching to access all structures on one flute
  - Automatic movement to next flute

- New **custom-made semi-automated probe station** build from scratch in 2019
  - Custom-made Python SW to control the setup
    - Developed/maintained by B. Arnold

- HGCAL uses almost identical to TK test structures





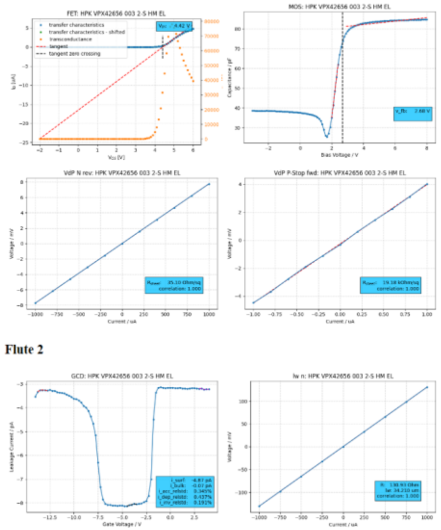
Process Quality Control

- For each batch of ~40 wafers we perform **multiple tests and several parameters are extracted**
  - Data analysed by dedicated scripts → tables/plots with the parameters of interest are generated

- All Tracker PQC centers produce **consistent** results, **reliably** and **quickly**

- Also used to **understand** and **qualify** the **process** used for the future **HGCal production**

Test structure	parameters
Diode	Full-depletion voltage, bulk resistivity
MOS	Flat-band voltage, oxide concentration, oxide thickness
MOSFET	Threshold voltage
GCD	Surface generation current, recombination velocity
Coupling capacitor	Coupling oxide thickness
Van der Pauw	Polysilicon/ p-stop/ strip sheet resistance
Dielectric breakdown structure	Oxide breakdown voltage



Flute 1:

#	fet	v_fb	c_acc	t_ox	n_ox	vdpPoly	vdpPoly_r	vdpN	vdpN_r	vdpPstp	vdpPstp_r	cap_l	cap_r
#	V	V	pF	nm	1E10cm^-2	kOhm/sq	kOhm/sq	Ohm/sq	Ohm/sq	kOhm/sq	kOhm/sq	pF	pF
HPK_VPX42900_001_PSS_HM_EL	3.74	2.44	81.1	708.3	9.5	2.12	2.14	34.9	34.7	18.9	19.1	2.41	2.30
HPK_VPX42900_001_PSS_HM_ER	4.61	---	---	---	---	2.13	2.14	35.1	34.8	19.4	19.4	---	---
HPK_VPX42900_001_PSS_HM_WL	4.44	2.47	79.6	721.5	9.4	2.17	2.17	35.0	35.0	19.6	19.6	2.36	2.25
HPK_VPX42900_001_PSS_HM_WR	4.77	---	---	---	---	2.15	2.16	34.7	35.0	19.2	19.3	---	---
HPK_VPX42900_005_PSS_HM_EL	4.57	2.53	80.5	713.6	9.7	2.07	2.07	35.0	34.7	19.1	19.1	2.39	2.28
HPK_VPX42900_005_PSS_HM_ER	4.58	---	---	---	---	2.07	2.08	34.6	34.8	19.5	19.5	---	---
HPK_VPX42900_005_PSS_HM_WL	4.44	2.54	79.2	725.5	9.6	2.11	2.12	34.9	34.9	19.6	19.5	2.35	2.24
HPK_VPX42900_005_PSS_HM_WR	4.66	---	---	---	---	2.11	2.12	34.7	35.2	19.1	19.1	---	---
HPK_VPX42900_008_PSS_HM_EL	4.53	2.51	80.4	714.6	9.7	2.10	2.08	34.9	34.8	19.2	19.2	2.33	2.24
HPK_VPX42900_008_PSS_HM_ER	4.58	---	---	---	---	2.08	2.08	34.8	34.7	19.4	19.4	---	---
HPK_VPX42900_008_PSS_HM_WL	4.41	2.55	79.4	723.8	9.6	2.11	2.12	34.9	34.8	19.5	19.5	2.34	2.24
HPK_VPX42900_008_PSS_HM_WR	4.61	---	---	---	---	2.12	2.12	35.0	35.0	19.0	19.0	---	---
HPK_VPX42900_015_PSS_HM_EL	4.41	2.57	80.5	713.3	9.9	2.05	2.06	34.7	34.5	19.4	19.4	2.40	2.29
HPK_VPX42900_015_PSS_HM_ER	4.54	---	---	---	---	2.06	2.05	34.5	34.9	19.3	19.3	---	---
HPK_VPX42900_015_PSS_HM_WL	4.62	2.61	79.4	723.8	9.8	2.09	2.08	34.9	34.7	19.3	19.3	2.34	2.23
HPK_VPX42900_015_PSS_HM_WR	4.55	---	---	---	---	2.09	2.09	37.5	36.7	19.1	19.0	---	---
HPK_VPX42900_018_PSS_HM_EL	4.31	2.58	80.5	713.7	9.9	2.04	2.05	35.4	34.6	19.5	19.5	2.38	2.27
HPK_VPX42900_018_PSS_HM_ER	4.49	---	---	---	---	2.04	2.05	34.6	34.8	19.5	19.6	---	---
HPK_VPX42900_018_PSS_HM_WL	4.65	2.63	79.1	726.3	9.8	2.04	2.06	34.8	34.9	19.4	19.4	2.33	2.22
HPK_VPX42900_018_PSS_HM_WR	4.50	---	---	---	---	2.08	2.09	34.6	35.0	19.5	19.3	---	---
HPK_VPX42900_023_PSS_HM_EL	3.93	2.60	80.7	711.8	10.0	2.03	2.04	34.8	34.5	20.6	20.6	2.38	2.27
HPK_VPX42900_023_PSS_HM_ER	4.47	---	---	---	---	2.02	2.00	34.5	34.8	19.6	19.6	---	---
HPK_VPX42900_023_PSS_HM_WL	4.40	2.63	79.4	723.7	9.9	2.05	2.07	34.9	34.9	19.6	19.7	2.35	2.24
HPK_VPX42900_023_PSS_HM_WR	4.37	---	---	---	---	2.07	2.08	44.3	34.9	24.3	21.3	---	---
HPK_VPX42900_029_PSS_HM_EL	4.57	2.42	80.8	711.3	9.4	2.03	2.04	34.7	34.7	18.8	18.8	2.33	2.25
HPK_VPX42900_029_PSS_HM_ER	3.92	---	---	---	---	2.04	2.05	34.4	34.8	20.6	20.7	---	---
HPK_VPX42900_029_PSS_HM_WL	3.83	2.45	80.0	717.7	9.4	2.07	2.08	35.6	34.5	20.7	20.7	2.36	2.26
HPK_VPX42900_029_PSS_HM_WR	4.69	---	---	---	---	2.08	2.09	34.7	35.0	19.0	19.0	---	---
HPK_VPX42900_034_PSS_HM_EL	4.42	2.44	80.7	711.5	9.5	2.04	2.04	34.8	34.6	18.9	19.0	2.38	2.27
HPK_VPX42900_034_PSS_HM_ER	4.16	---	---	---	---	2.04	2.05	34.4	34.8	20.4	20.4	---	---
HPK_VPX42900_034_PSS_HM_WL	4.05	2.45	80.1	716.8	9.4	2.07	2.07	34.7	34.5	23.4	23.3	2.37	2.25
HPK_VPX42900_034_PSS_HM_WR	4.72	---	---	---	---	2.09	2.09	34.9	34.9	19.1	19.1	---	---
HPK_VPX42900_043_PSS_HM_EL	4.54	2.45	81.0	708.8	9.5	2.04	2.04	34.6	34.7	19.4	19.6	2.34	2.25
HPK_VPX42900_043_PSS_HM_ER	4.43	---	---	---	---	2.04	2.05	34.7	34.7	19.8	20.1	---	---
HPK_VPX42900_043_PSS_HM_WL	4.41	2.49	80.3	715.6	9.6	2.06	2.07	34.9	34.9	19.7	19.7	2.34	2.25
HPK_VPX42900_043_PSS_HM_WR	4.64	---	---	---	---	2.07	2.09	34.7	35.0	19.2	19.2	---	---
HPK_VPX42900_049_PSS_HM_EL	4.55	2.49	81.2	707.7	9.7	2.05	2.06	34.7	34.9	19.8	19.1	2.32	2.24
HPK_VPX42900_049_PSS_HM_ER	4.51	---	---	---	---	2.04	2.06	34.6	34.6	20.3	19.6	---	---
HPK_VPX42900_049_PSS_HM_WL	4.36	2.51	80.2	716.5	9.6	2.07	2.09	34.9	34.9	20.4	19.3	2.31	2.22
HPK_VPX42900_049_PSS_HM_WR	4.62	---	---	---	---	2.09	2.10	34.8	34.9	19.1	19.3	---	---

A few exemplary results from production period

Sensor quality

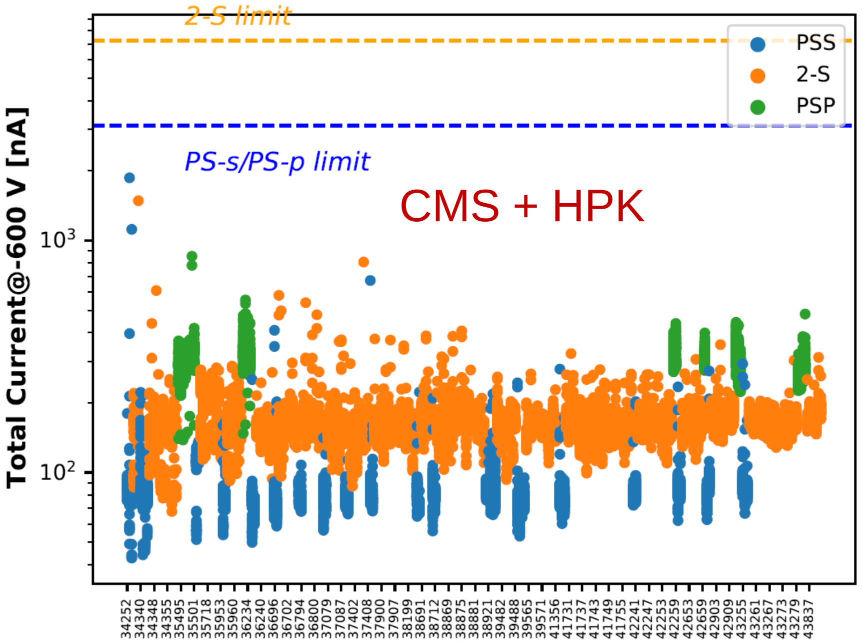
- Sensors are specified to exhibit low leakage current up to **-800V**
  - All tested up to **-1000V**
  - **V_{bias}= -600V** is the maximum operation bias voltage

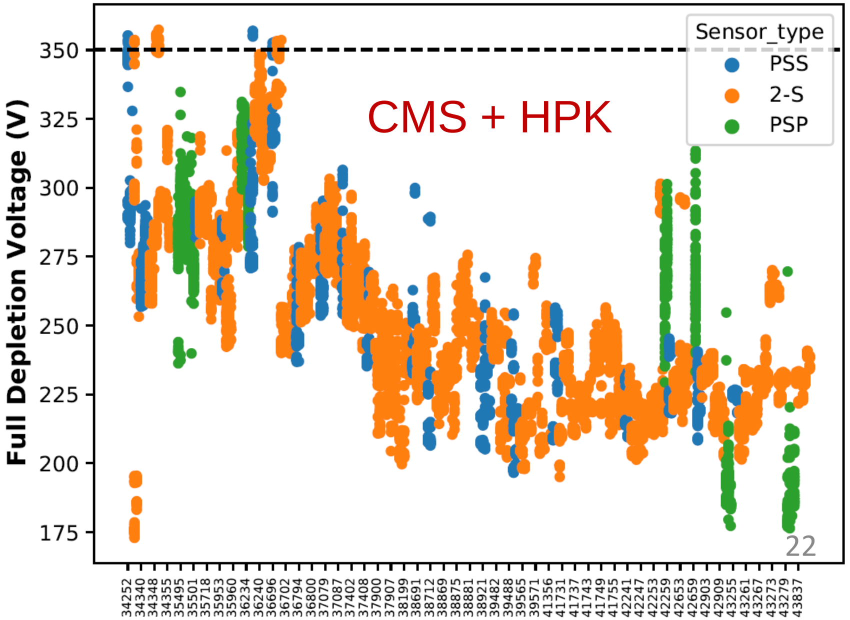
- Increasing batch number on x axis indicates **time evolution**

- Limits set by dashed lines
  - I_{600} < 7.25 µA (**2-S**) / 3.125 µA (**PS-s**/**PS-p**)

- Majority stay below **1 µA**, while most of them even below 200nA!
  - only a handful of outliers measured during pre-production phase

- Full depletion voltage below **350V**
  - A few wafers with **ρ <** 3.5 kΩcm on pre-production period
    → results in V_{FD} near the limit
  - HPK selected material of higher resistivity from wafer supplier and now is well within the specifications



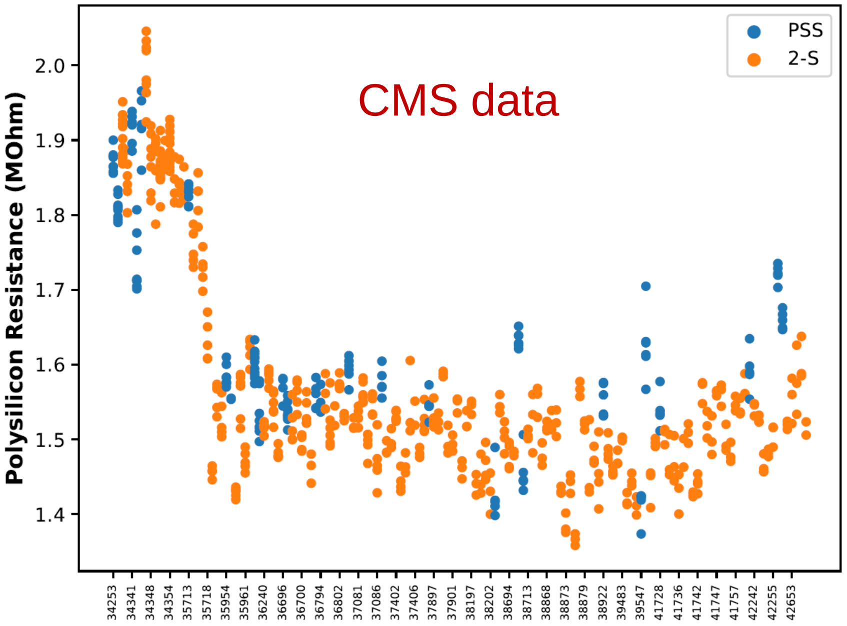


Sensor quality

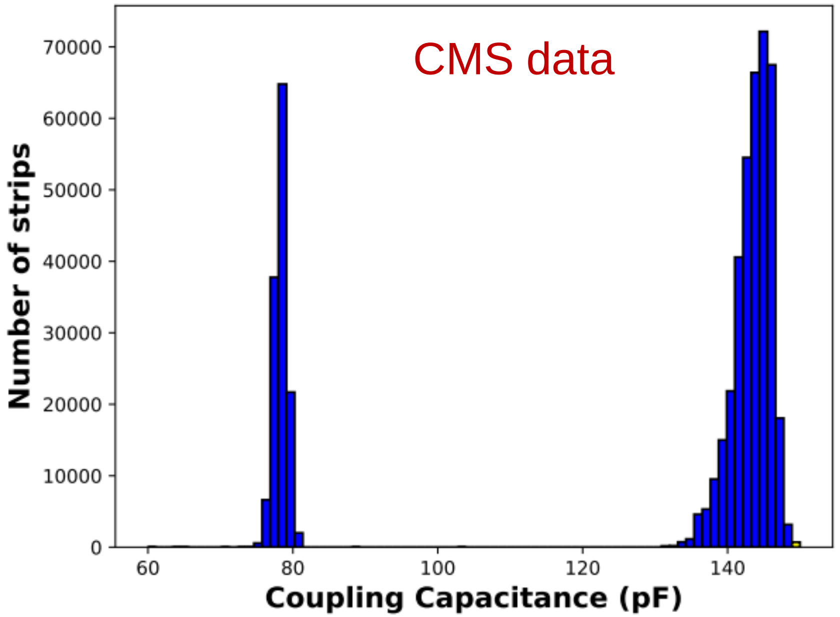
A few examples from strip quality results

- strip parameters are measured at **-600V**

- parameters uniform over each sensor



- The resistance of the poly-silicon resistor was **adapted** to 1.5 MΩ after the pre-production (target 1.5 ± 0.5 MΩ)



- Coupling capacitance very homogeneous over production time
  - Two distributions due to two different strip sensors

From QC to module integration

- After qualification, sensors are stored at SQC centers until they are forward to module assembly centers

- Module integration will begin/ramp up mid 2023

- IV characterization performed at all modules
  - QC centers should provide the information:
    - history of each sensor
    - problems that may came up at SQC concerning the sensor behavior
    - impact of environmental conditions on sensors (e.g humidity)
    - recovery counter-actions in case a sensor shows unstable behavior

- QC centers need to transmit all the gained experience/knowledge/observations from testing process and based on that develop a recommended procedure about sensor handling

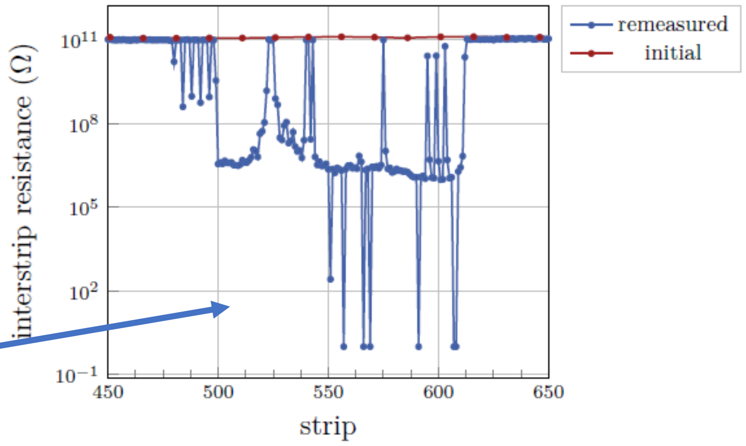
Charge-up issues

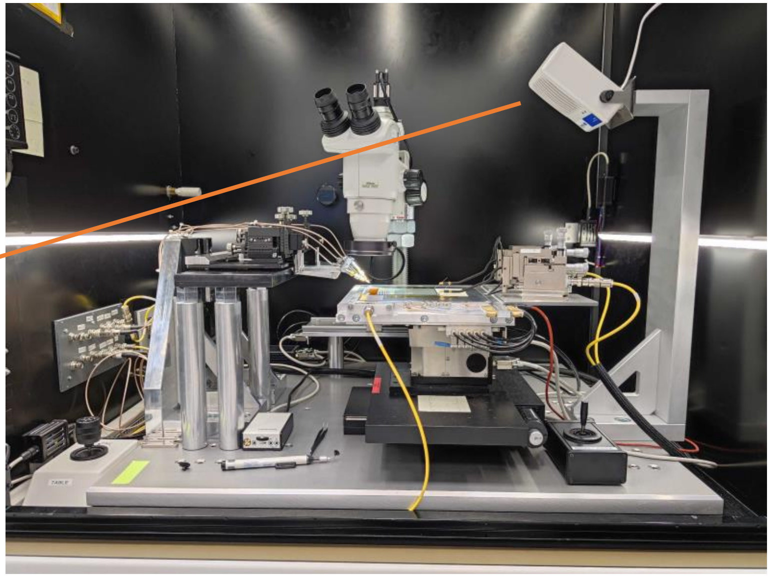
- Sensors **charged up** from packaging
  - charges introduced by plastic cards used by HPK
  - observed also by ATLAS, confirmed by HPK

- Charges on sensor's surface **deteriorates** its electrical properties
  - e.g impact on inter-strip isolation or IV behaviour

- **No permanent** damage on sensors but creates severe problems on qualification process

- Issue not solved yet by vendor, however CMS found a solution to mitigate this problem
  - Blowing ionized air for a short time **dissipates** the charges
  - Ion blowers installed now **at every** SQC center
    - recommended to module assembly groups





Impact of humidity on sensor behavior

At module centers

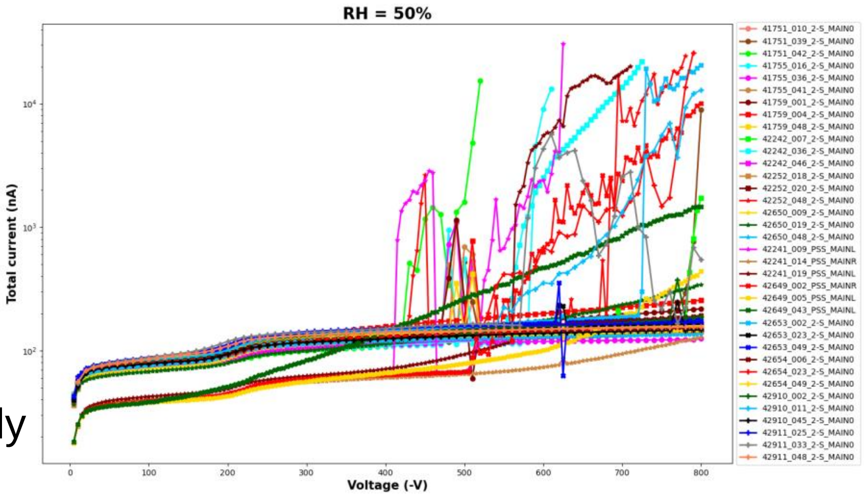
- IV performed at RH = 20% based on the module assembly instructions
  - low humidity to minimize its impact on sensor IV
- However sensors will stay at ESD-safe lab conditions (~ 50%) for several hours during the assembly process
- Even at 20%, a number of sensors might show unstable IV behavior due to their long exposal at high RH
- Studies conducted at HEPHY to investigate the **impact of humidity** on sensor behavior and **build up a strategy of sensor recovery**
  - Emulate an extreme scenario → a sensor stays at lab humidity over a **full weekend**
  - Perform IV at RH = 50% and at RH = 20%
  - Apply different recovery steps according to sensor response

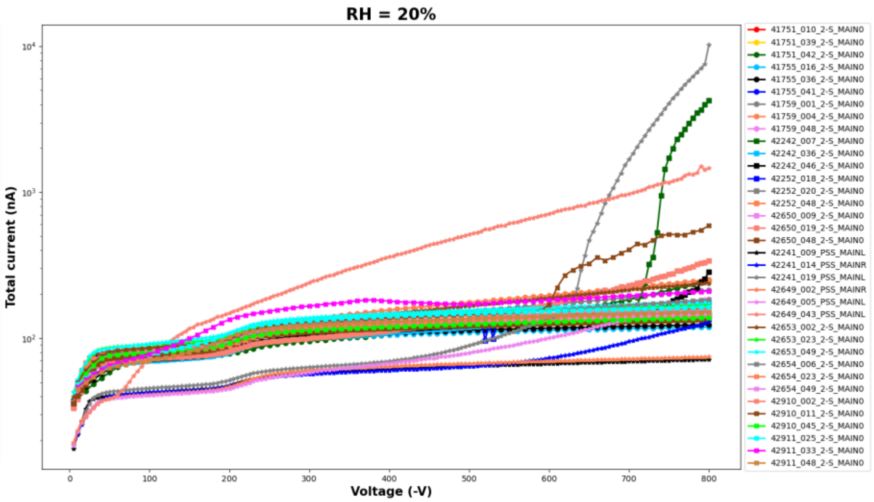
Impact of humidity on sensor behavior

- 36 good sensors included on the top plots
    - had an initial good IV behavior
    - tested below RH=10%

IV@50% : almost 50% unstable

IV@20% : **5/36** did not recover immediately

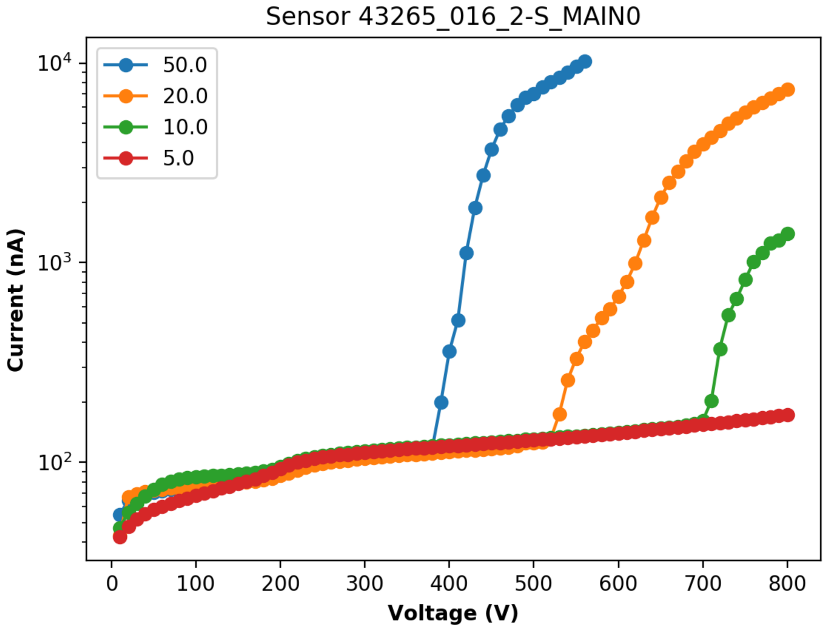




Recovery

- Example from one sensor
- Early breakdown at **50%** as well as at **20%**
- Combination of **ramping down** humidity and operating the sensor at the **breakdown voltage** is a successful strategy
- Sensor returns into its initial good behavior!

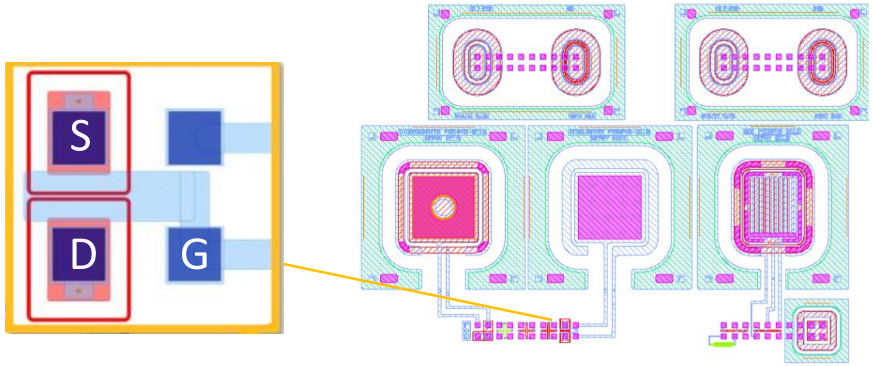
More statistics collected



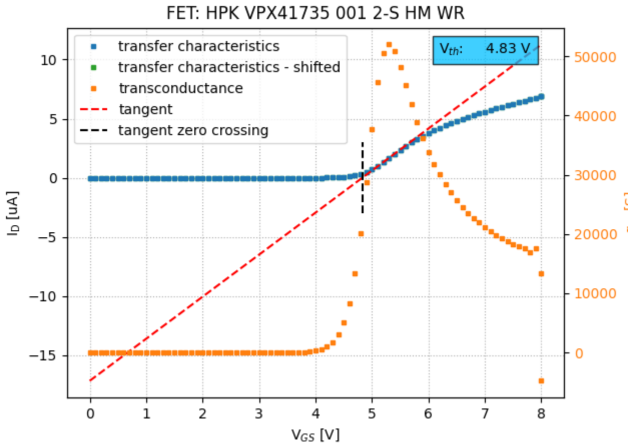
PQC results

- To characterize **the quality of p-stop**, CMS uses dedicated test structures

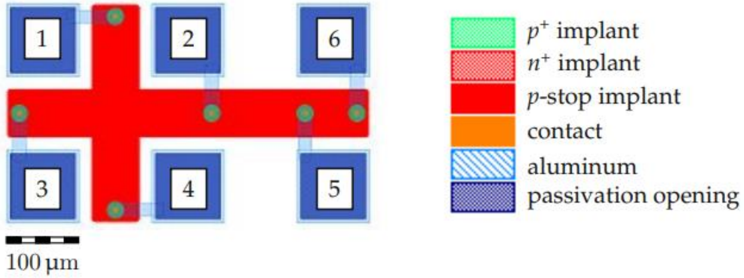
- MOS Field Effect Transistor (MOSFET) with p-stop implantation encircling Source and Drain
  - S-D geometry mimics **inter-channel** region of sensor
  - new structure in Phase-2 CMS Process Quality Control

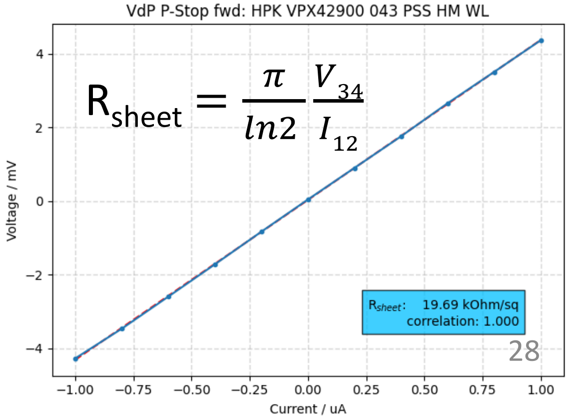


- **Threshold voltage** (V_{th}) parameter of interest
  - voltage at which S-D channel becomes conductive
  - indicator of p-stop implantation dose
    - low effective dose can lead to poor inter-strip isolation before and especially after irradiation



- P-stop implantation dose can be also characterized by a dedicated **Van-der-Pauw structure**
  - p-stop sheet resistance (R_{sheet}) extracted
  - high R_{sheet} indicates lower p-stop dose





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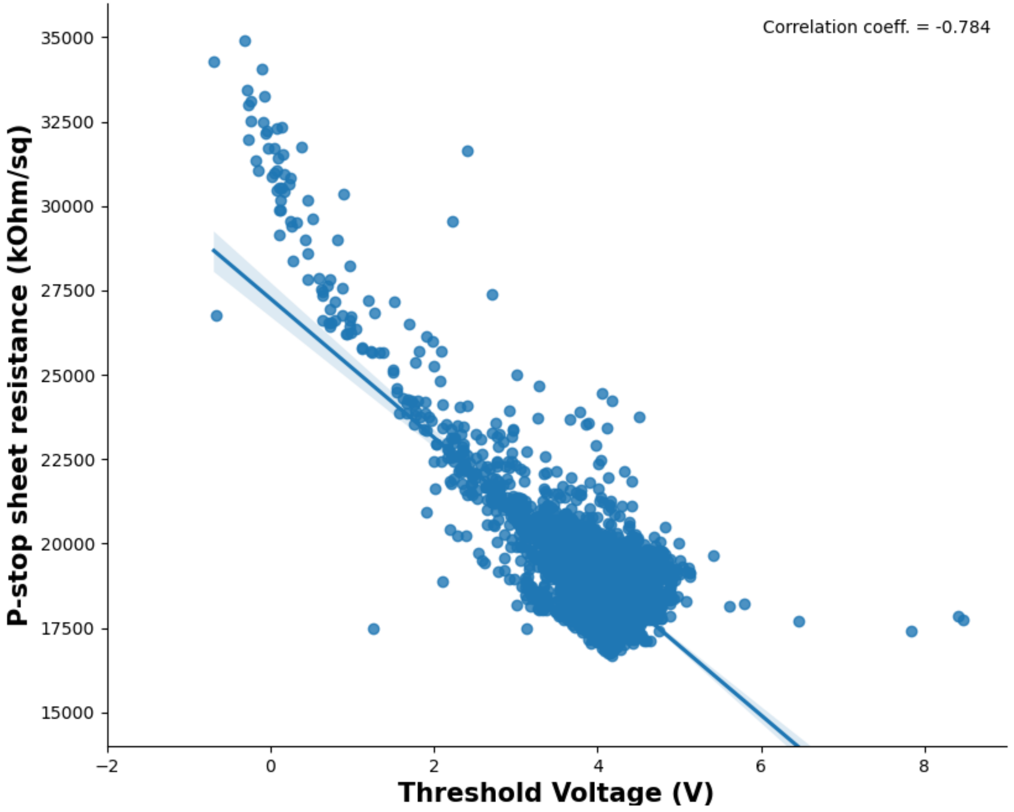
- **Threshold voltage and p-stop sheet resistance show an anti-correlation!**



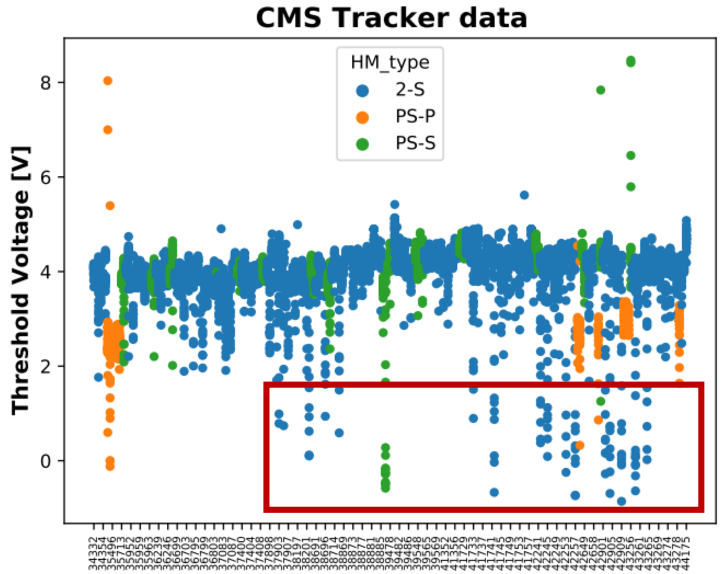
PQC results

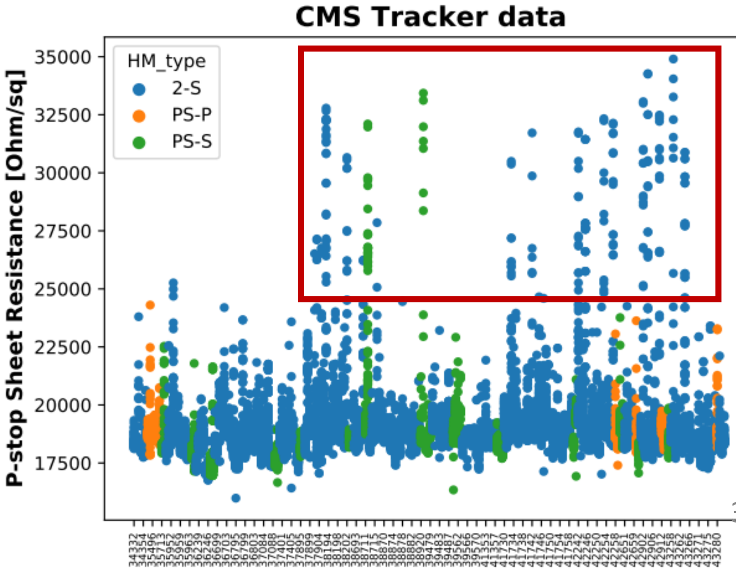
- Expected values (90% within this range)
  - V_{th} : **3 – 5 V**
  - p-stop R_{sheet}: **18 – 22 kΩ/sq**

- In principle **uniform** over a wafer but occasionally inhomogeneity is observed

- Low V_{th} (<1 V) or high R_{sheet} values measured more frequently on the latest batches
  - indicator that the **p-stop effective implantation dose is lower** on these wafers
  - issue also **acknowledged by HPK** but still under investigation

- However, sensors from the respective wafers show **no deterioration** of inter-strip resistance **before nor after** irradiation!
  - Good strip separation shown on all IT performed so far

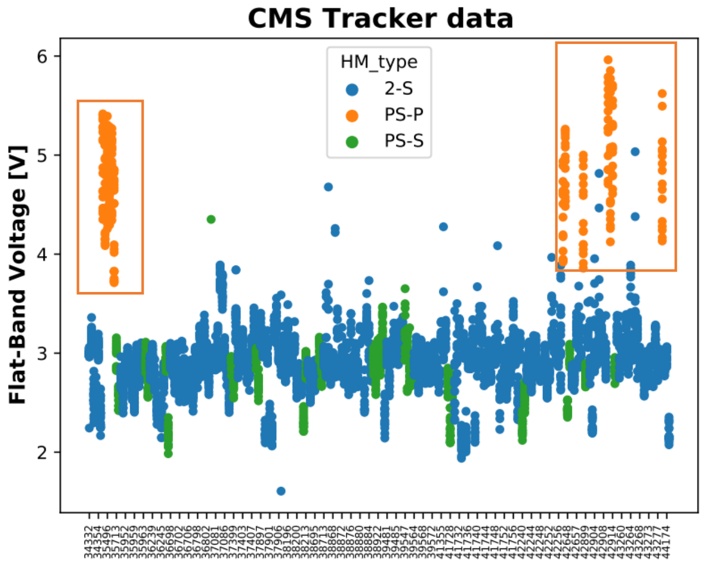


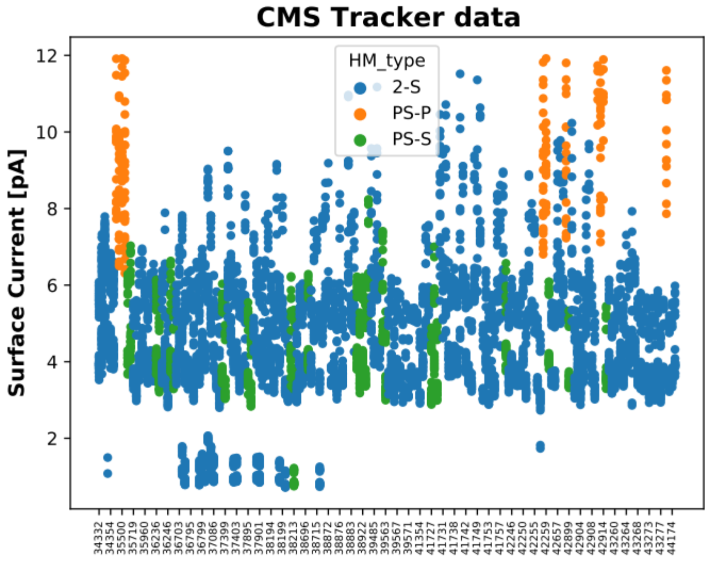


PQC results

Si-Si0$_2$ interface properties

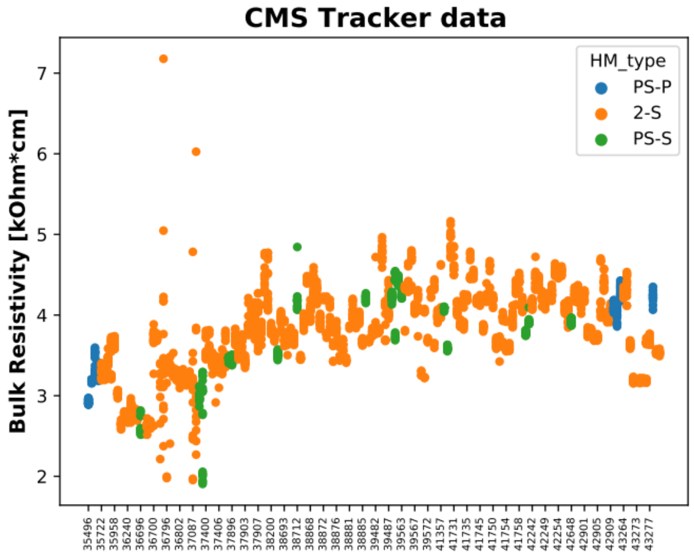
- examined through **MOS capacitor** and **Gate Controlled Diode (GCD)**
- flat-band voltage increases with positive oxide charges
- surface current indicates the number of interface traps
- stability over production timeline is observed for both parameters
- Macro-pixel (**PS-p**) sensors feature higher positive oxide charge concentration at interface → Attributed to processing





Bulk resistivity

- measured either via a dedicated Van der Pauw structure or via a diode
- data from VdP structure
- trend nicely correlated with sensor V_{FD} evolution



Other activities

- Group is mainly occupied by production task for Tracker and HGCAL
- Some small R&D projects are starting in parallel

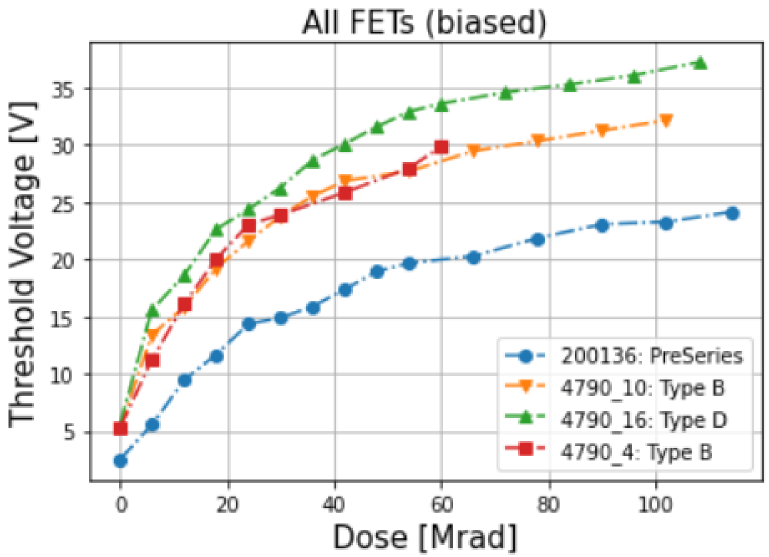
X-ray irradiation tests on MOSFET

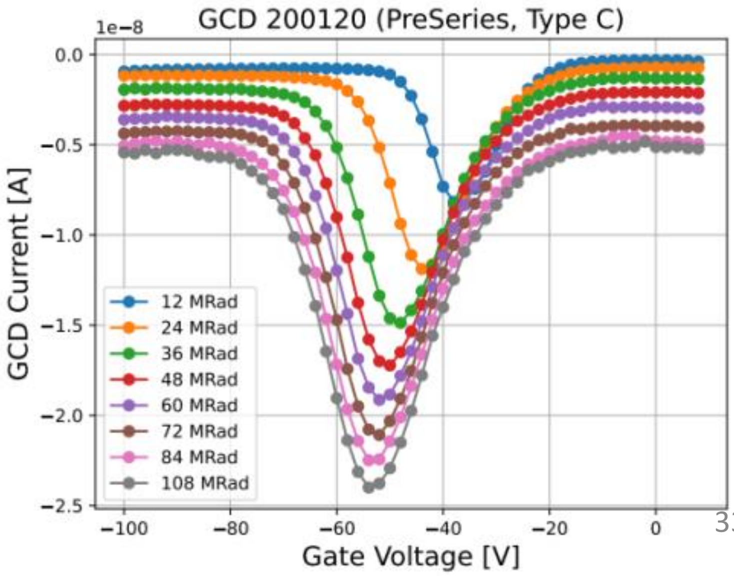
- X-ray irradiation studies at CERN
  - master thesis project of **Veronika Kraus**
  - irradiate samples of different thickness up to maximum expected fluence

- **MOSFET**:
  - threshold voltage increases with X-ray dose
  - inter-play of different oxide trap types
  - **Future plans**: with a smaller irradiation step size investigate the behavior of inter-channel isolation at low doses

- **Gate Controlled Diode (GCD):**
  - surface current increases with irradiation
    → Interface trap density
  - results in agreement with previous TK-HGCAL studies

- Not yet conclusive studies, evaluation of results and future plans still under progress





Diode structure:

- suffers from non optimal design
  → Guard- and Edgering need to be opened to connect to flute
    - Limits HV stability

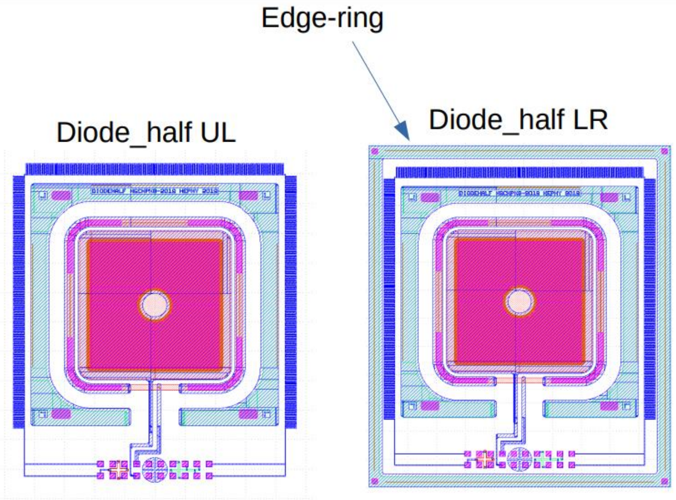
- **assumption**: parastic currents from dicing edge which is near (a few mm)

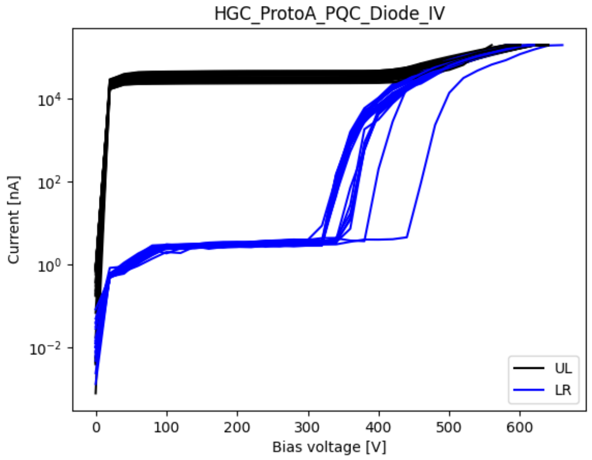
- wafers host the standard structure with the opened edge ring and one with an optimized design

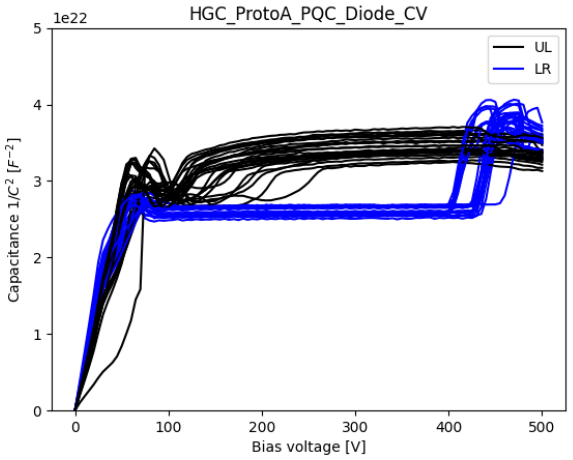
- Comparing the two structures we see **a clear improvement** on IV of the one with the optimized design

- Current at expected level of a few nA up to 300 - 400 V

- Results from a particular thickness (120 µm epi)
  - collecting more statistics now also with other thickness (300 µm and 200 µm FZ)

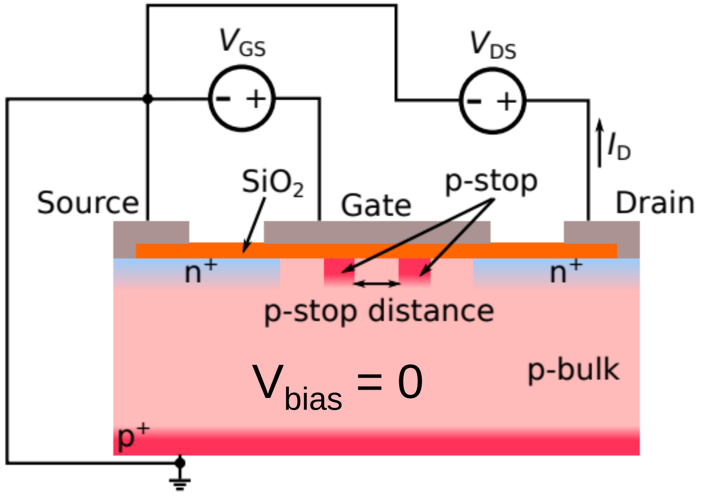




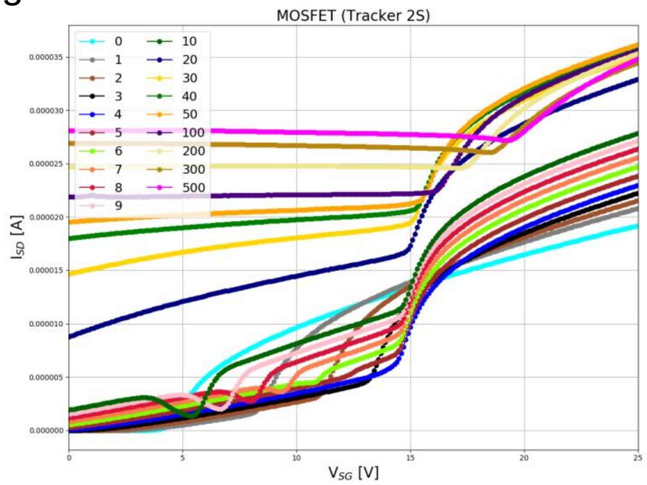


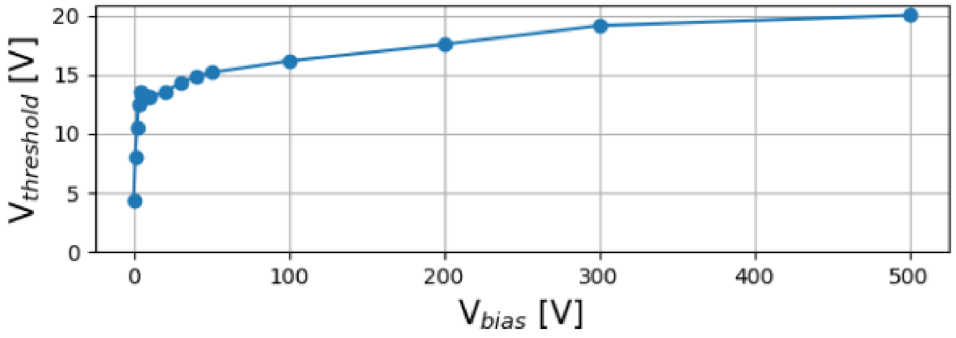
Optimization of test structures

MOSFET measurement:



- performed on PQC with the Si bulk unbiased
- depleting the region around the implants should lead to different electric field distribution when the G-S voltage is applied
  - might impact the formation of the conductive path between the channels
- We are investigating how the threshold voltage varies wrt different applied V_{bias}
  → **on going studies by Suman S.**
- First results show a clear positive shift of V_{th} with increasing V_{bias}
  - Saturation observed around 300V when full bulk is depleted
  - Explanation of observed kink at subthreshold regime (obvious at low V_{bias}) still under investigation





Summary

- Phase-2 outer tracker construction fully under way!
    - Sensor production is half-way
    - Module assembly ramps up mid of 2023

- Quality of delivered sensors by Hamamatsu is very good as shown by collected/analysed data

- HEPHY is one of the leading institutes of CMS sensor Quality Assurance project

- Group is busy with carrying out the construction task for Phase-2, will continue well into 2024
    - small R&D projects only carried out on the side,
    - next larger target would be Phase 3 (future upgrade of the inner tracker with timing layers)

Thank you for your attention!