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Radiation Hard Pixel Sensors for the Phase 2 Upgrade of the CMS Inner Tracker

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on behalf of the Tracker Group of the CMS Collaboration

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The CMS Inner Tracker (IT) for Phase 2

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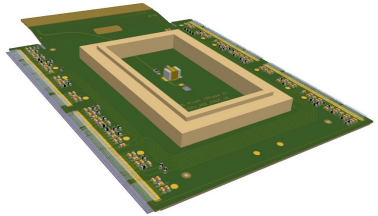
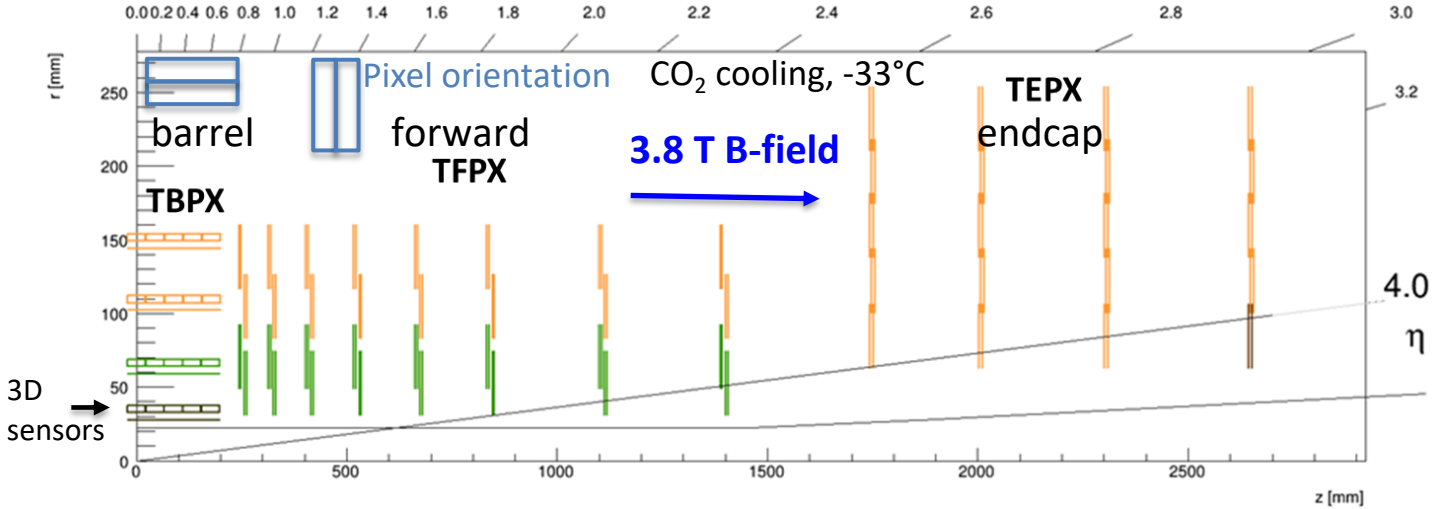
HL-LHC [1] upgrade to greatly expand the physics reach of the experiments

- **Instantaneous luminosity** increased up to 7.5E34 $cm^{-2}s^{-1}$
  - Reduced pixel size by x6 to 25x100 μm^2 to maintain occupancy $<10^{-4}$ at L1
- **Integrated luminosity increased** by x10 to 3000-4000 fb^{-1}
  - Radiation hard planar sensors, 3D sensors in innermost barrel layer

TEPX module



CMS Inner Tracker (IT) with extended coverage to $|\eta| \simeq 4.0$ for HL-LHC discovery and precision physics[2]



3892 modules with 1x2 and 2x2 readout chips

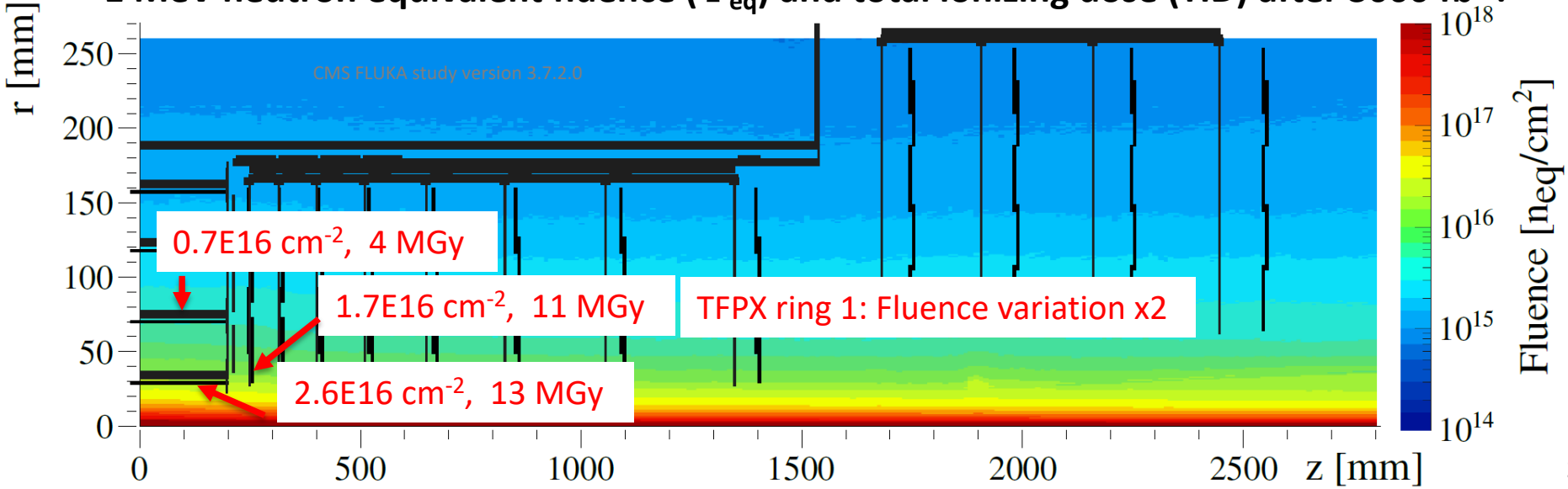
[1] The HL-LHC project.
[2] The Phase 2 Upgrade of the CMS Tracker (TDR).

Radiation Effects

Severe radiation effects during HL-LHC running

- Sensors: Higher operation voltages, smaller signal, large leakage currents →cooling critical
- Total Ionizing Dose (TID) effects readout chip performance
- TBPX layer 1 and TFPX ring 1 foreseen to be replaced during HL-LHC

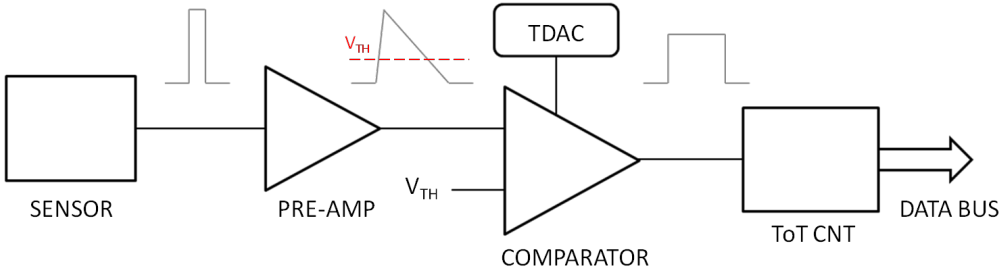
1 MeV neutron equivalent fluence (Φ_{eq}) and total ionizing dose (TID) after 3000 fb^{-1}:



CMS IT Readout Chip

CROC frontend chip in 65 nm CMOS developped by RD53 [1]

- Radiation hard to 1 Grad
- Power < 1 W/cm²
- Serial powering via shunt-LDO regulators
- CMS: Linear analog front-end [2,3] with Krummenacher feedback
  - Can cope with large detector leakage currents
- Low, adjustable threshold: 1000 e vs. 2000 e of current chip
  - Sensor thickness 285 µm (current detector) → 150 µm (upgrade)
- 4 bit digital readout with time-over-threshold counter (ToT)



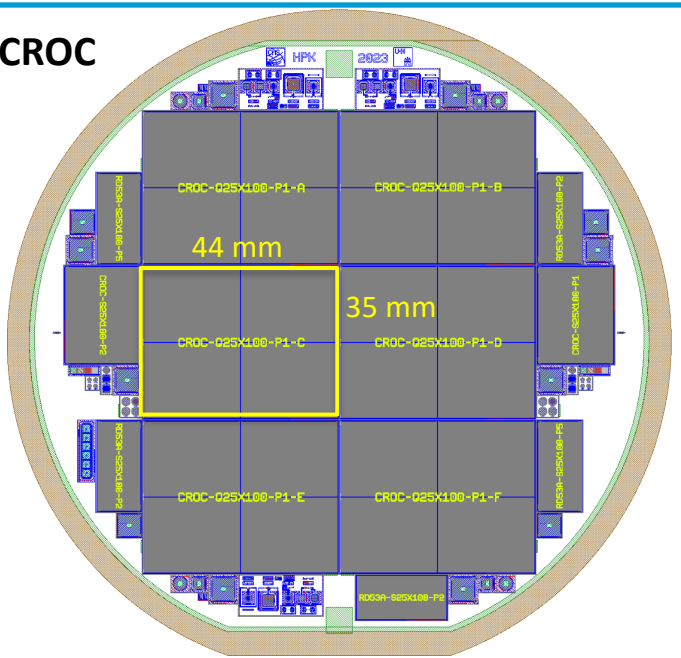
Single chip PCB for testing

[1] RD53B user guide.
[2] 2021 JINST 16 P12014.
[3] CERN-RD53-PUB-20-002.

Planar Sensor Modules for CMS IT

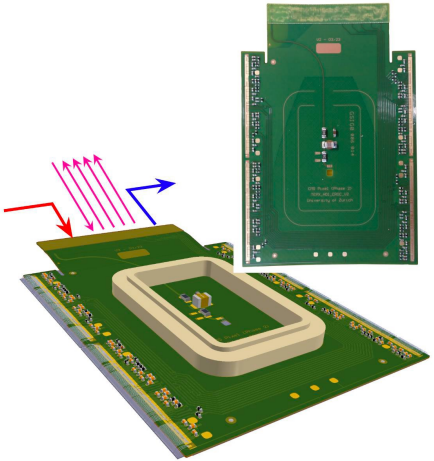
Only two types of hybrid planar bare sensor modules: 2x2 and 1x2 CROC

- Logistics and management of spares easier
- However, full modules (flex prints) in TBPX, TFPX, TEPX differ
- 150 µm thick n^+p sensors, signal (MPV) 11 ke for a MIP

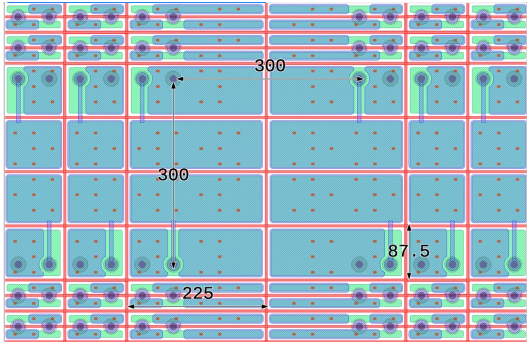


6 2x2 sensors per 150 mm wafer or
12 1x2 sensors (not shown)

TEPX module



Large pixels in inter-chip regions:
no dead regions



[1] Evaluation of Planar Silicon Pixel Sensors with the RD53A Readout Chip for the Phase-2 Upgrade of the CMS Inner Tracker (arXiv:2307.01580).

Selected Sensor Specifications

	Planar	3D
active thickness, polarity	150 µm, n^+p, pstop	150 µm, n^+p, pspray
depletion voltage, V_{fd}	< 100 V	< 10 V
breakdown voltage	> 350 V	> V_{fd} +35 V
leakage current (before irradiation)	< 0.75 µA cm^{-2} at V_{fd} +50 V, 20 °C	< 2.5 µA cm^{-2} at V_{fd} + 25 V, 20 °C
leakage current after Φ_{eq} = 5E15 cm^{-2} *	< 45 µA cm^{-2} at 600 V, -25°C	
leakage current after Φ_{eq} = 1.5E16 cm^{-2}		< 100 µA/cm^2 at V_{op} (<200 V), -25°C
hit efficiency (before irradiation)	99 %	96 (97) % at 0°(10°) angle
hit efficiency for Φ_{eq} = 5E15 cm^{-2} hit efficiency for Φ_{eq} = 1E16 cm^{-2} hit efficiency for Φ_{eq} = 1.5E16 cm^{-2}	99 % 98 %	 96 (97) % at 0°(10°) angle

*Annealing at 60°C for 1 hr

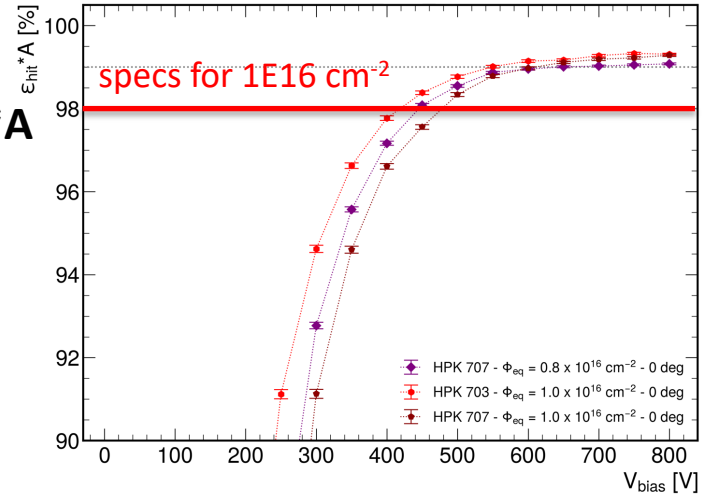
V_{op}: operation voltage

Performance: Hit Efficiency

Planar Sensors + CROC

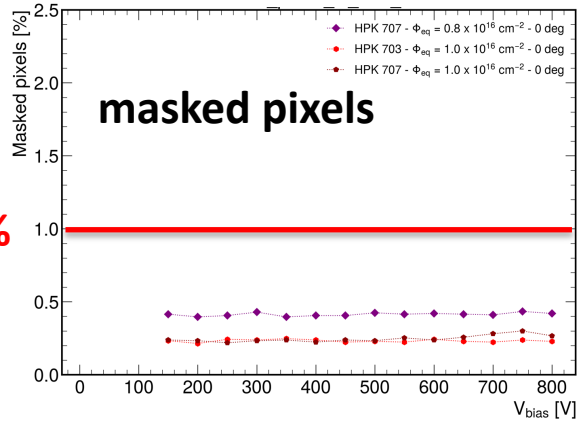
- HPK-CROC single chip assemblies irradiated up to Φ_{eq} = 1E16 cm^{-2} at CERN PS (23 GeV p)
- Excellent performance:
  - **ε > 98%, taking noisy pixels into account**
  - **Noisy pixel < 1 %**

ε*A

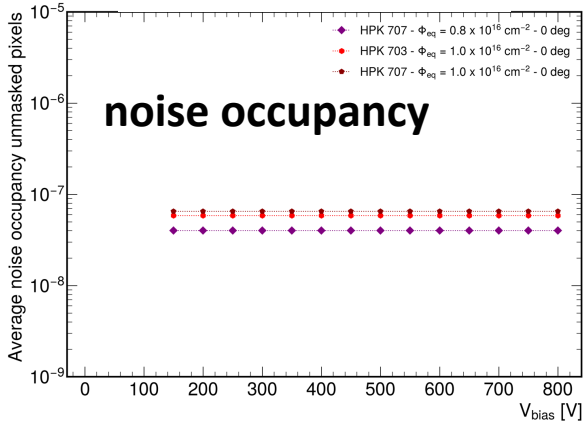


fluence gradient:
Selected ROIs with different fluences on the same module

1 %



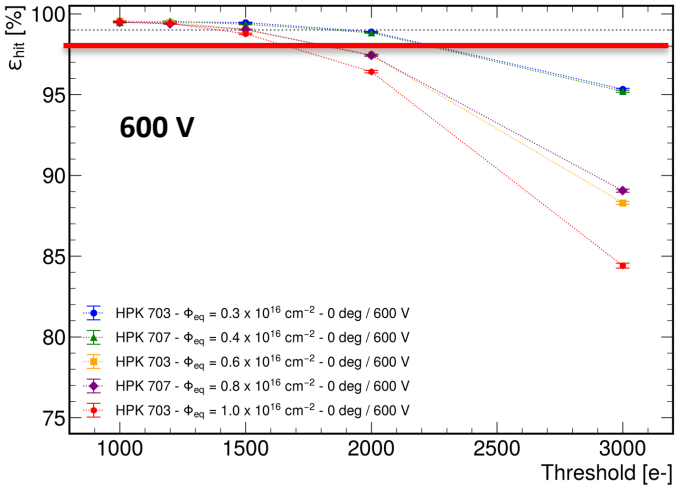
10^{-7}



Performance: Hit Efficiency vs. Thresh.

Planar Sensors + CROC

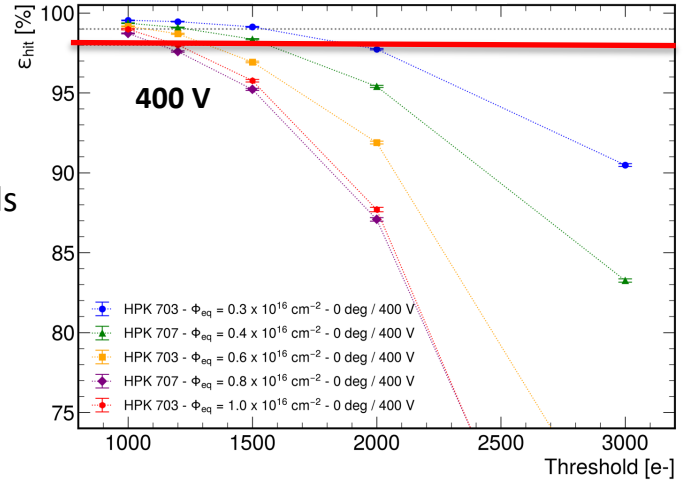
- HPK-CROC single chip assemblies irradiated up to Φ_{eq} = 1E16 cm^{-2} at CERN PS (23 GeV p)
- Threshold < 1500 e required at 600 V for ε > 98% for Φ_{eq} > 5E15 cm^{-2}
- Stronger degradation at 9.5° angle due to charge sharing (backup)



ε for non-masked pixels

fluence gradient:
Selected ROIs with different fluences on the same module

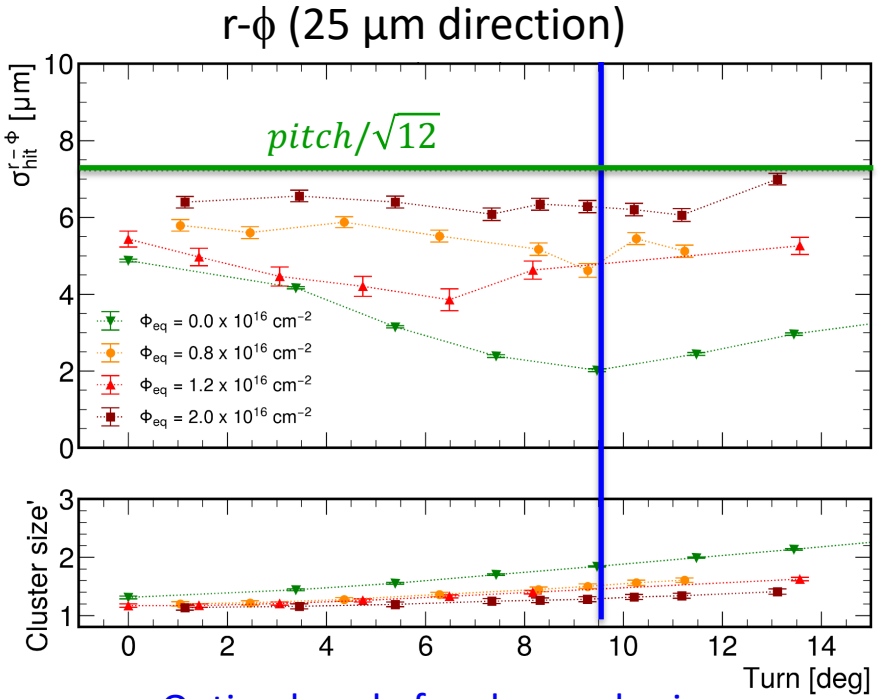
stronger degradation at 400 V:



Performance: Spatial Resolution

Spatial resolution determined in DESY II testbeam [1]

- Electron energies 1-6 GeV, here: 5.2 GeV
- Prototype sensor-**RD53A** modules, final pixel cell
- Measured width of residual distribution corrected for track resolution
- Resolution 2 µm at optimal angle
- Degradation with irradiation, but always better than the „binary“ resolution $pitch/\sqrt{12}$



Optimal angle for charge sharing

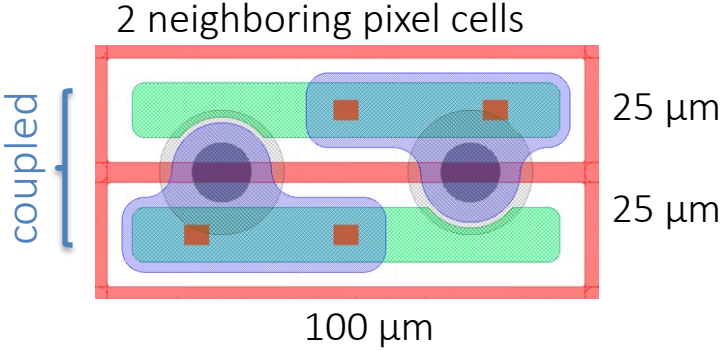
$$\theta_{opt} = \text{atan}\frac{pitch}{thickness}$$

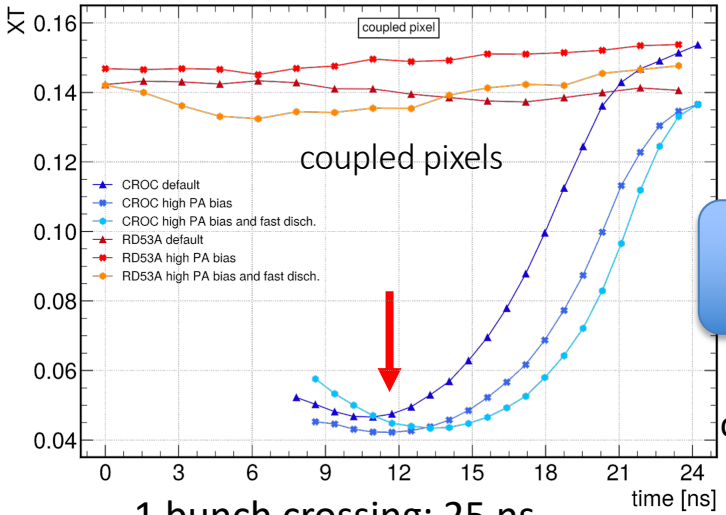
[1] The DESY II test beam facility (NIMA, Vol. 922, 2019, P 265-286).

Cross Talk in Planar Sensors

25 x 100 µm² sensor pixels matched to 50 x 50 µm² in FE chip

- Overlap of metal and neighbor implant →**cross talk, XT**
- Depends on fine tuning of readout timing vs. signal injection
- 4% to 6% for coupled, 2.4% to 2.8% for uncoupled pixels
- Independent of timing and much larger in assemblies with first prototype chip RD53A

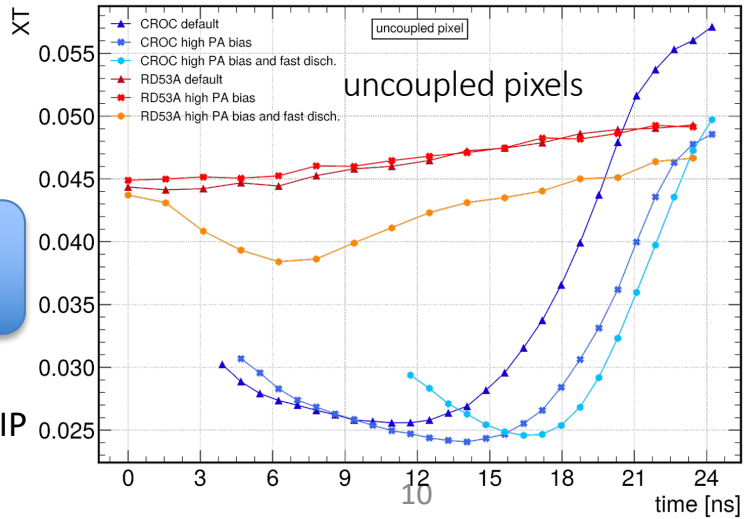




1 bunch crossing: 25 ns

Well within 10 % requirement

Threshold
ca. 10 % of MPV for MIP



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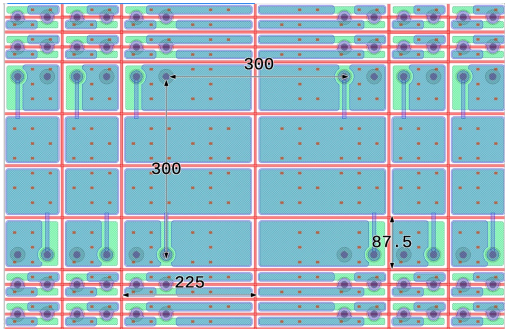
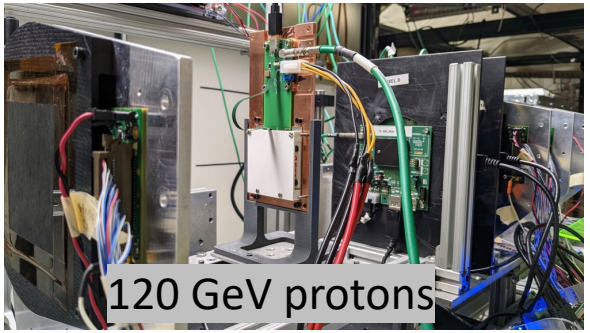
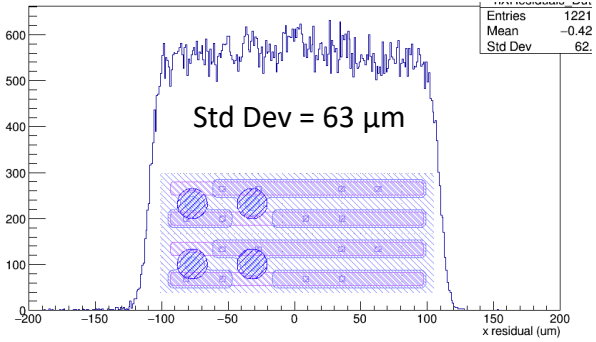
Validation of a Full Module

- TBPX 2x2 module in FNAL testbeam
- Excellent performance confirmed
- Larger cells in inter-CROC regions
- Below: Two columns of 225 x 25 µm^2
  - Residuals as expected
- Efficiency of special cells > 99 %
- Analysis of irrad. 2x2 module under way

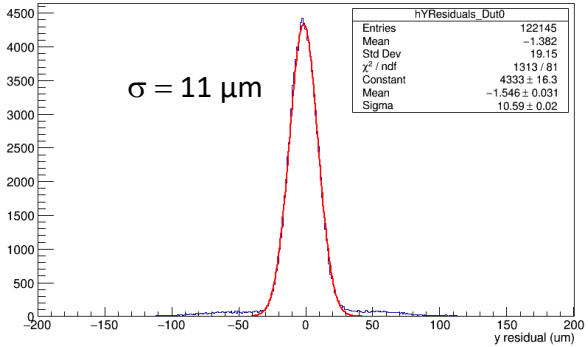


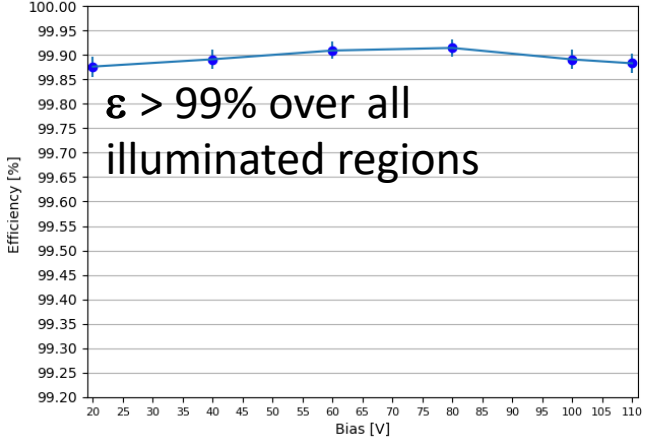


x residuals (225 µm side)



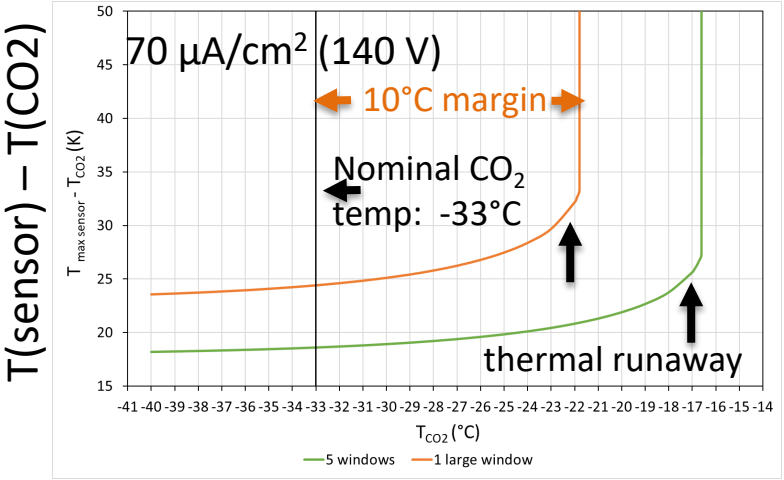
y residuals (25 µm side)



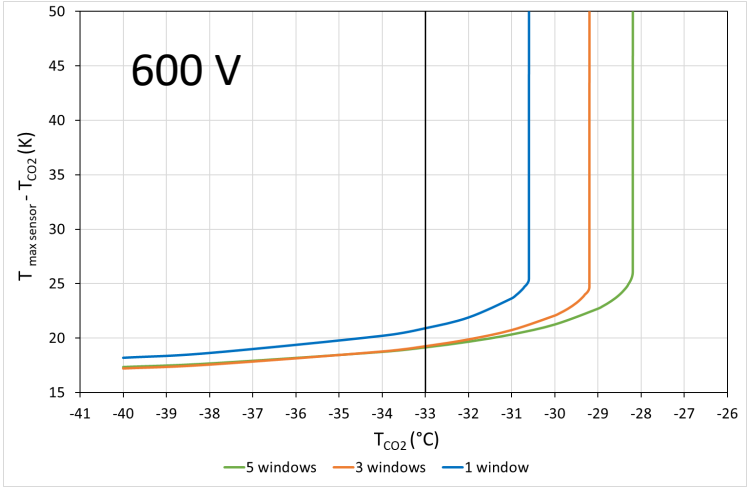


Why 3D: Thermal Simulations

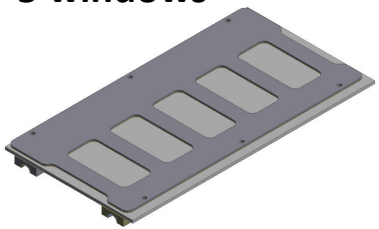
3D sensors in layer 1, Φ_{eq} = 1.5E16 cm^{-2}



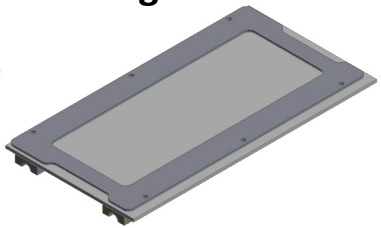
planar sensors in layer 2, Φ_{eq} = 1E16^{-2} cm^{-2}



5 windows



1 large window



- 3D sensors only solution for layer 1 for Φ_{eq} = 1.5E16 cm^{-2}
- Thermal performance of 3D sensors good enough to select lighter design for cooling plate and mechanics
- Planar sensors have sufficient margin in all other layers for fluences Φ_{eq} < 1E16 cm^{-2}

CMS 3D Sensors

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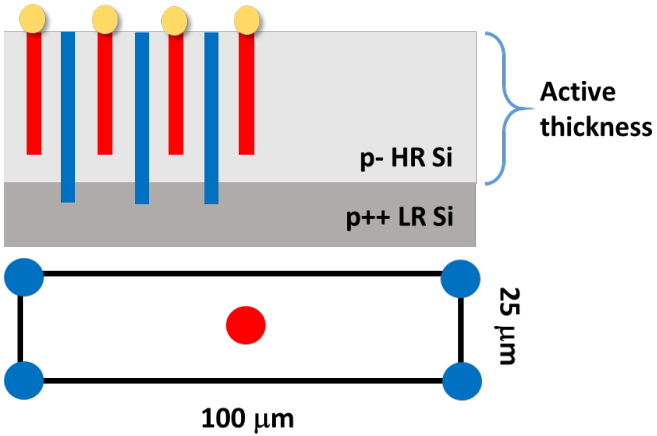
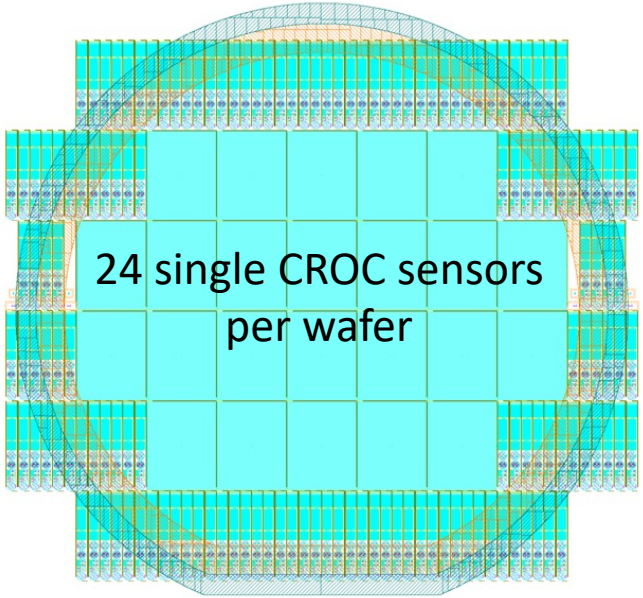
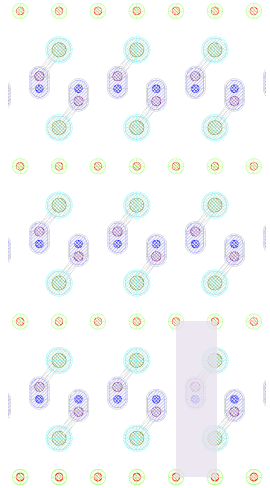
Basic geometry







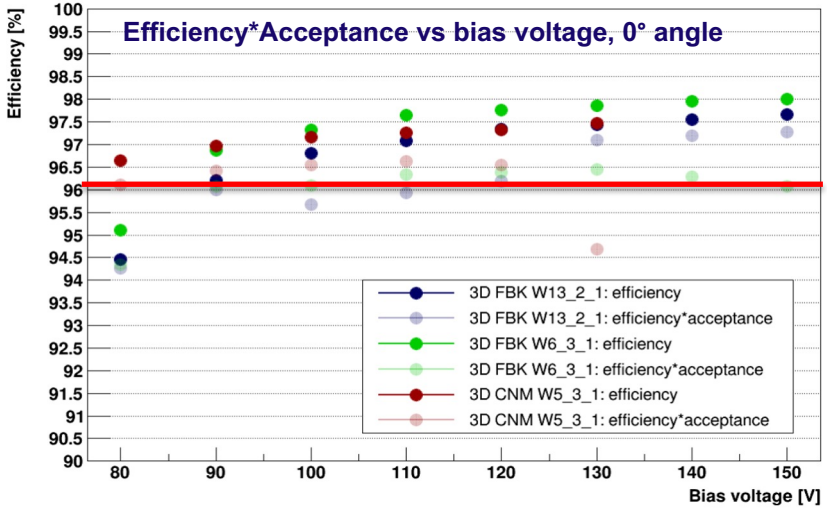
- 150 mm Si-Si wafers
- 150 µm active thickness, p-spray isolation
- Support wafer thinned to 100 µm at hybridization vendor
- 25x100 μm^2 pixel cell with 1 electrode at the center
- Single-CROC size for higher production yield
  - Module contain two sensors

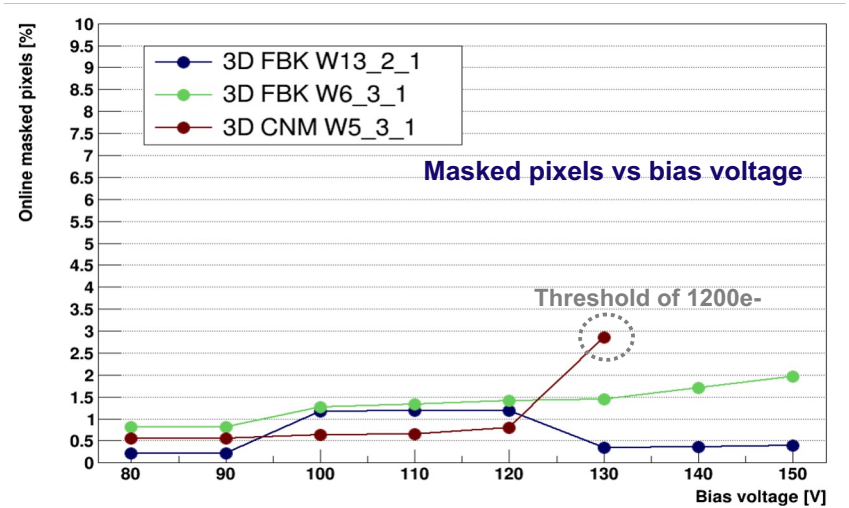
[1] Results on proton-irradiated 3D pixel sensors interconnected to RD53A readout ASIC (NIMA, Vol. 944, 2019, 162625).

Validation of 3D Assemblies

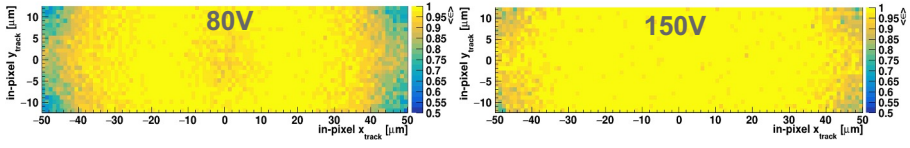
- Modules tuned to 1000 e threshold at -30°C
- Operation range from full ε to onset of noise: 90 V → 130 V (CNM) and →150 V (FBK)

- Noisy and ”stuck” pixels masked
  Noisy = occupancy >2x10^{-5}





Efficiency map in the pixel cell

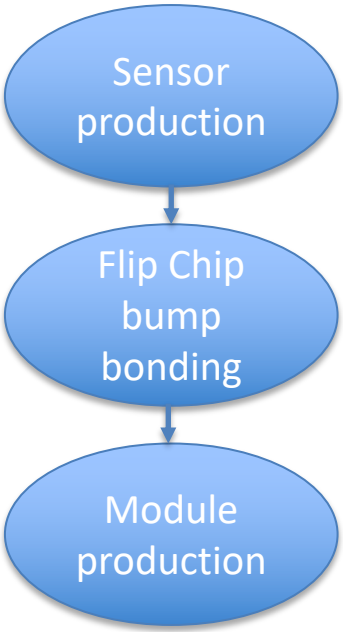


24 GeV protons
Φ_{eq} ~ 1E16 cm^{-2}

Production

Module production

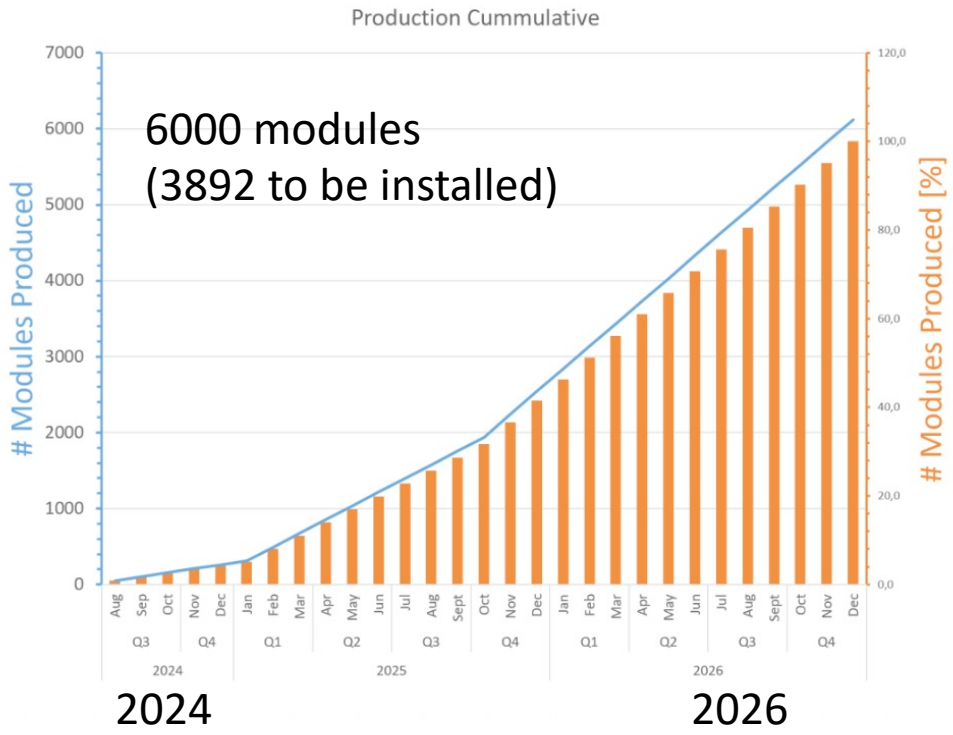
- Follows CROC and sensor production, flip chip
- 12 production and test centers: Europe/US
- Max throughput 300 modules per month



optical inspection
IV curves (*)

optical inspection
bare module tests
only on demand

extensive QC incl.
cold cycle tests



(*) no bias grid for planar sensor , only guard ring IV plus IV on test sensors

Summary and Outlook

- Entirely new CMS Tracker for HL-LHC for optimal physics reach in challenging condition
- Inner Tracker: Hybrid pixel detector modules with pixel sizes of 25 µm x 100 µm
- Planar sensors with 150 µm active thickness, innermost TBPX layer: 3D sensors
- Excellent performance of prototype modules: hit efficiency, spatial resolution, radiation hardness
- Planar sensor modules qualified to $\Phi_{eq} > 1 \times 10^{16}$ cm^{-2}
- 3D sensors modules qualified to $\Phi_{eq} > 1.5 \times 10^{16}$ cm^{-2}

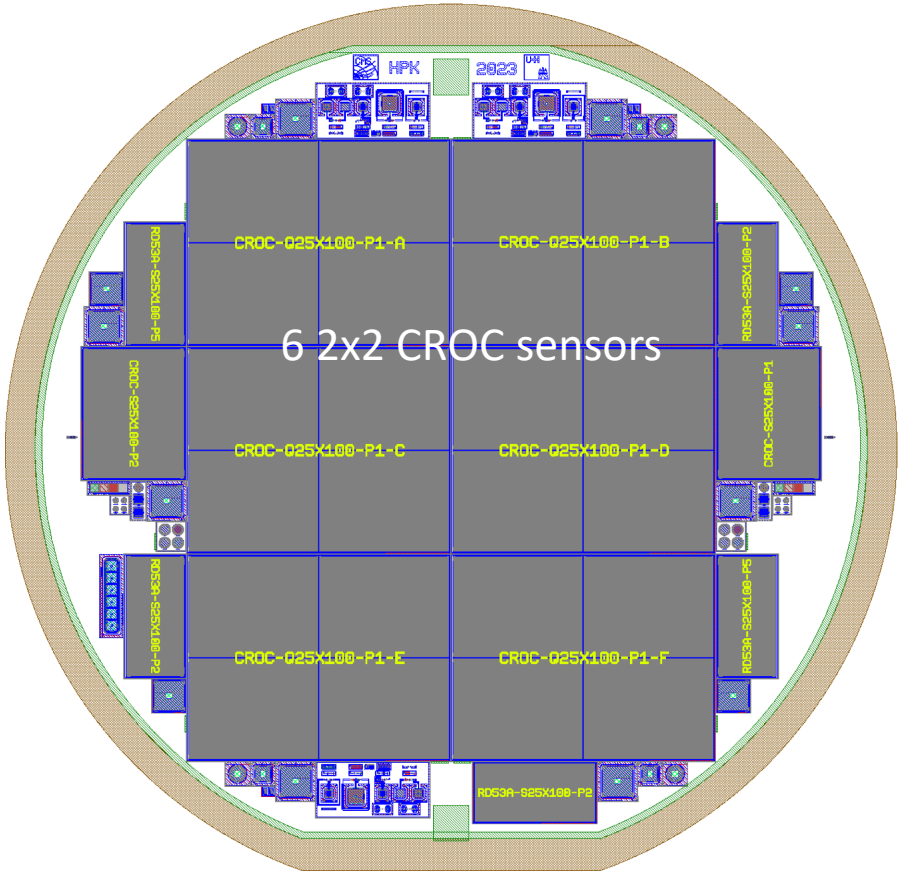
Towards production

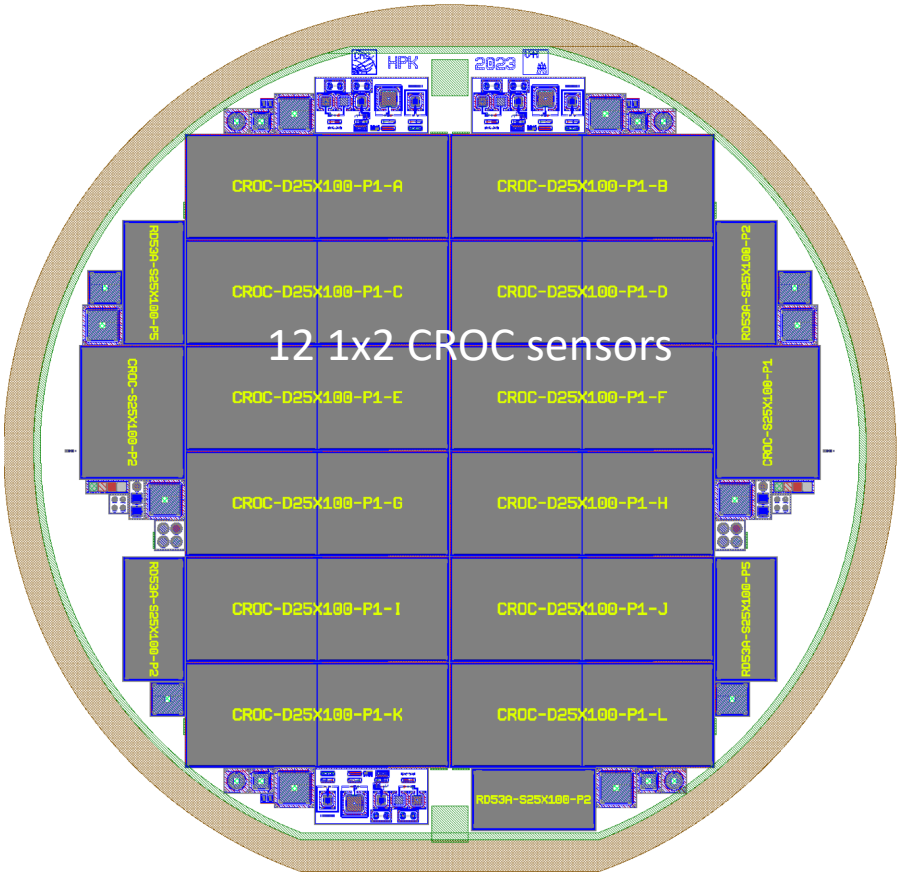
- First orders for (pre)production planar and 3D sensors have been placed
- Module production driven by CROC_v2 FE chip will start Q3/2024 and last 2.5 years

See also talks on "TID effects study on the monitoring system of the RD53 chip" by Mohsine Menouni
and "Prototype validation for the CMS Inner Tracker Phase-2 upgrade" by Nazar Bartosik

Backup

Planar Sensor Wafer Layouts





Modules

Installed	TBPX	TFPX	TEPX	Total
1x2	324	832	0	1156
2x2	432	896	1408	2736
Total	756	1728	1408	3892

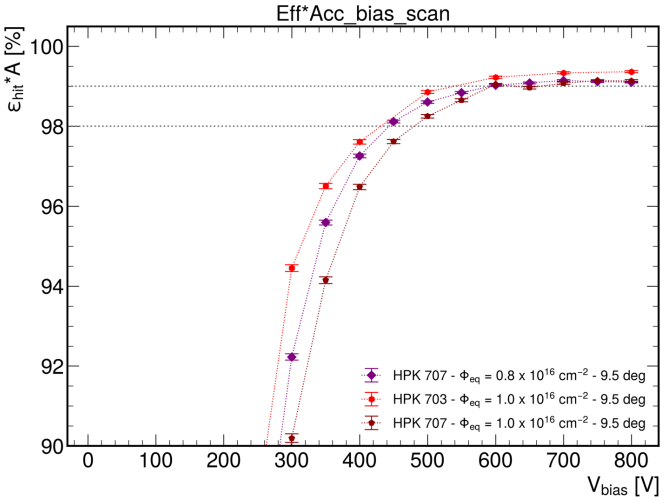
	RUN 4 (800 fb^{-1})		RUN 5 (1300 fb^{-1})		RUN 4+5 (2100 fb^{-1})		RUN 4+5+6 (3000 fb^{-1})		Not in Chamonix 2022 (4000 fb^{-1}) For reference only	
	1E16 1 MeV neq	Grad	1E16 1 MeV neq	Grad	1E16 1 MeV neq	Grad	1E16 1 MeV neq	Grad	1E16 1 MeV neq	Grad
TBPX L1	0.69	0.36	1.12	0.58	1.81	0.93	2.58	1.34	3.44	1.78
TBPX L2	0.18	0.11	0.29	0.17	0.48	0.28	0.68	0.40	0.98	0.54
TFPX R1	0.46	0.31	0.75	0.49	1.22	0.79	1.74	1.13	2.32	1.5
TFPX R2	0.21	0.14	0.35	0.23	0.57	0.37	0.82	0.53	1.09	0.71

- tkLayout
  https://cms-tklayout.web.cern.ch/cms-tklayout/layouts/recent-layouts/OT801_IT701/irradiation_Pixels.html
- Chamonix 2002 luminosity profile

Performance: Hit Efficiency @9.5°

Planar Sensors + CROC

- HPK-CROC single chip assemblies irradiated up to Φ_{eq} = 1E16 cm^{-2} at CERN PS (23 GeV p)
- Excellent performance:
  - **ε > 98%, taking noisy pixels into account**
  - **Noisy pixel < 1 %**



fluence gradient:
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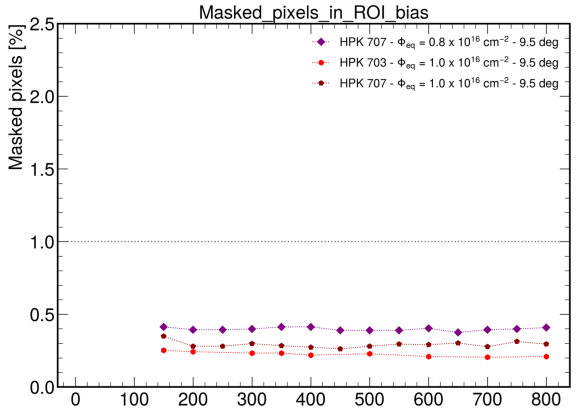
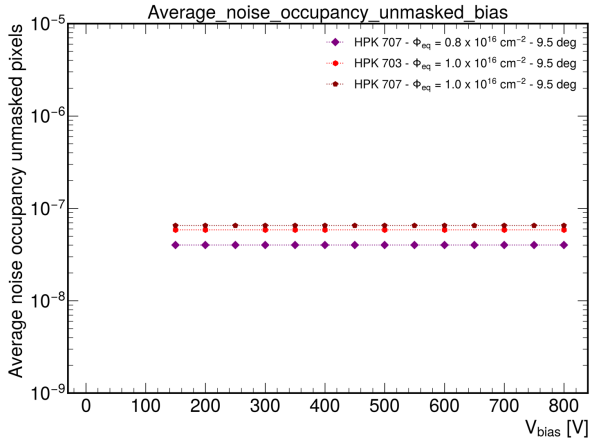
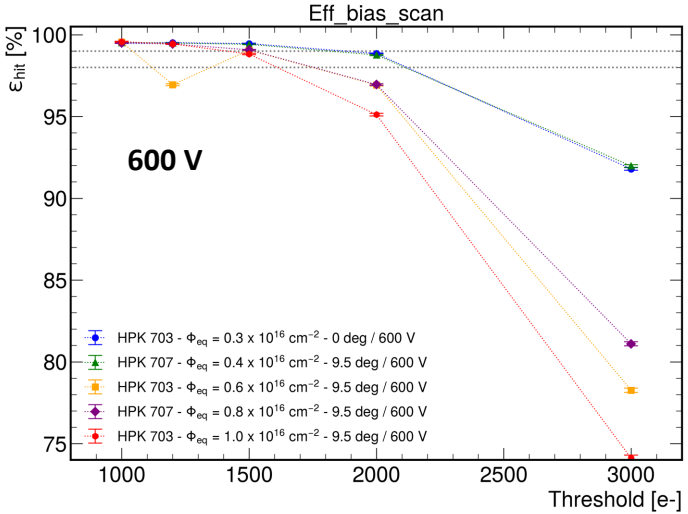




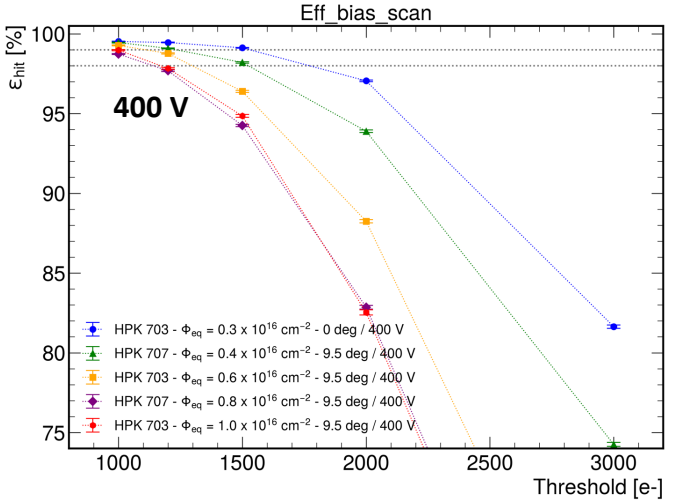
Performance: Hit Efficiency vs. Thresh.

Planar Sensors + CROC @ 9.5°

- HPK-CROC single chip assemblies irradiated up to Φ_{eq} = 1E16 cm^{-2} at CERN PS (23 GeV p)
- Threshold < 1500 e required at 600 V for ε > 98% for Φ_{eq} > 5E15 cm^{-2}, much stronger degradation at 9.5° due to charge sharing

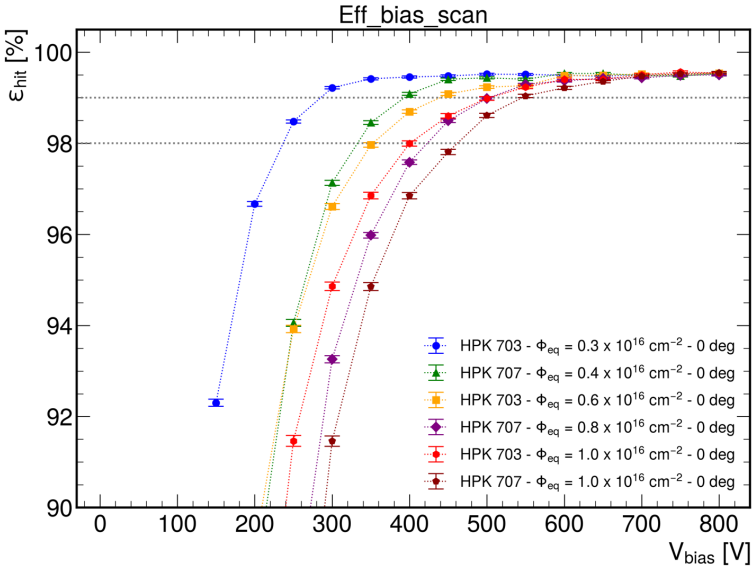


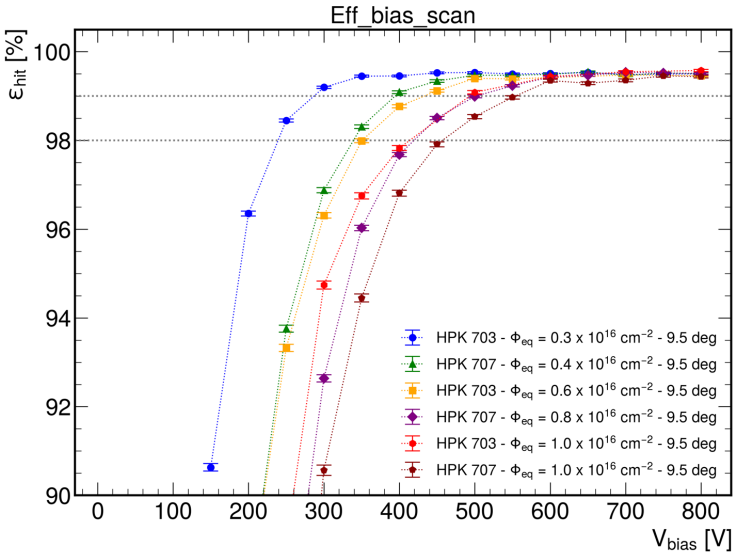
fluence gradient:
Selected ROIs with different fluences on the same module



Performance: Hit Efficiency

hit efficiency,
not corrected for acceptance

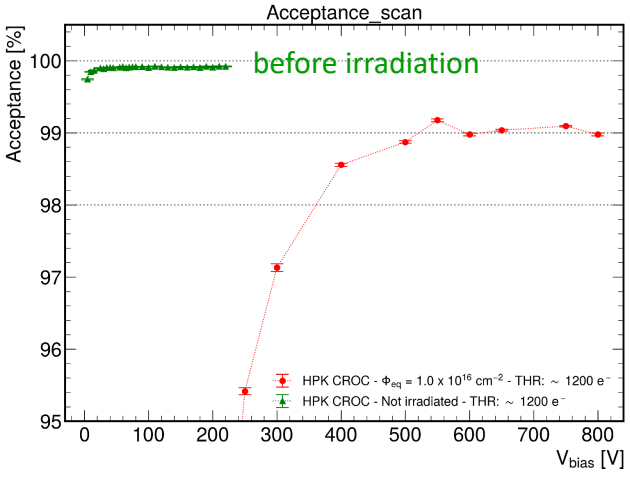


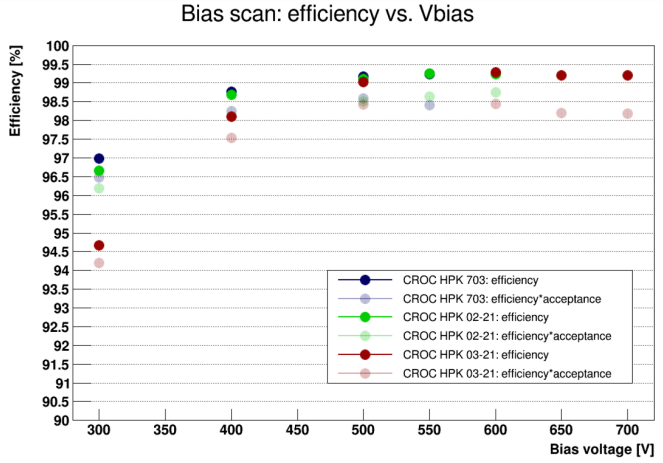


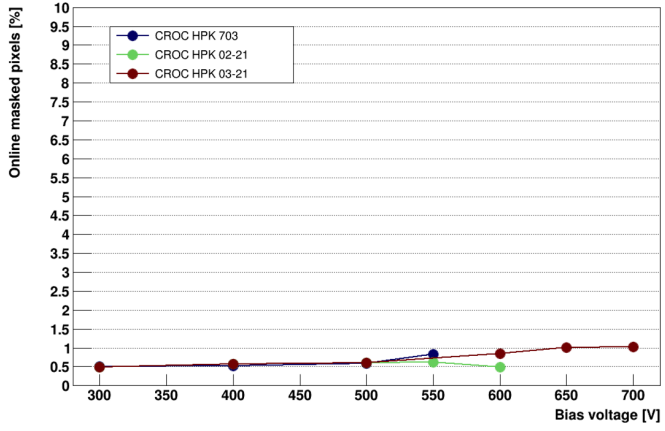
Performance: Hit Efficiency

Planar Sensors + CROC

- HPK-CROC single chip assemblies irradiated to Φ_{eq} = 1E16 cm^{-2} at CERN PS (23 GeV p)
- Excellent performance:
  - **ε > 98%, taking noisy pixels into account**
  - **Noisy pixel < 1 %**



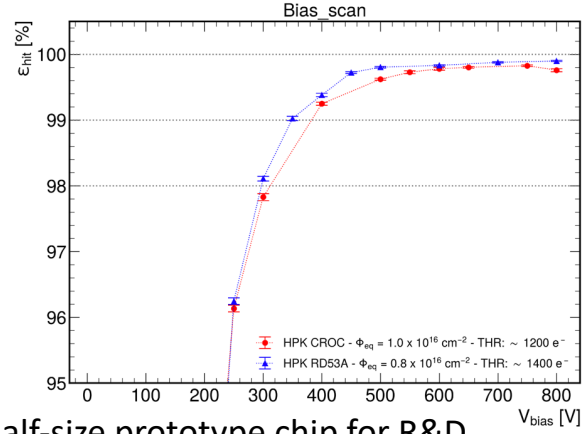


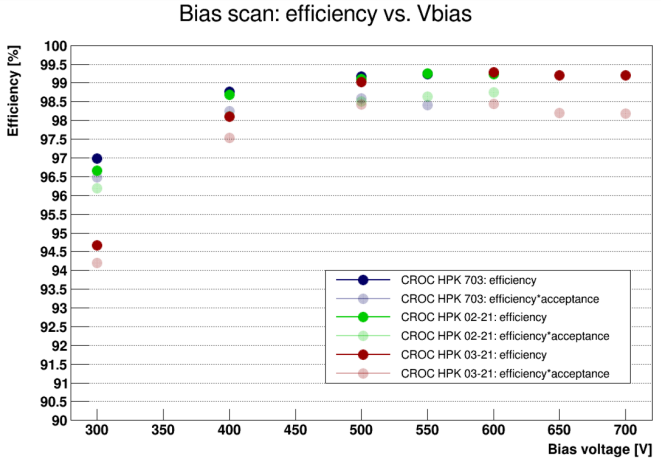


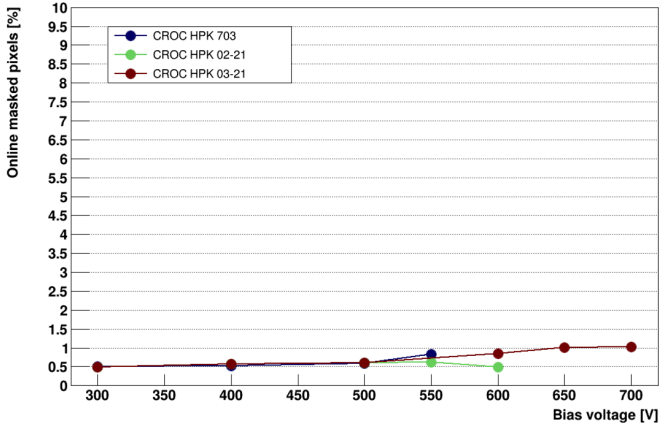
Performance: Hit Efficiency

Planar Sensors + CROC

- HPK-CROC single chip assemblies irradiated to Φ_{eq} = 1E16 cm^{-2} at CERN PS (23 GeV p)
- Excellent performance:
  - ε > 98%, taking noisy pixels into account
  - Noisy pixel < 1 %
- Consistent results for CROC and RD53A* modules:



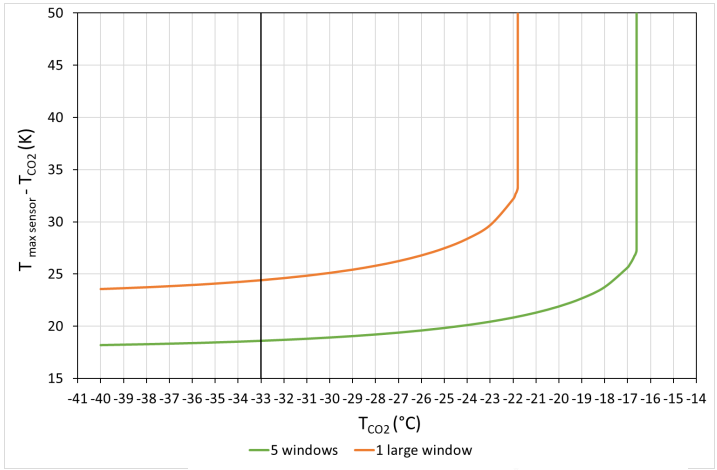


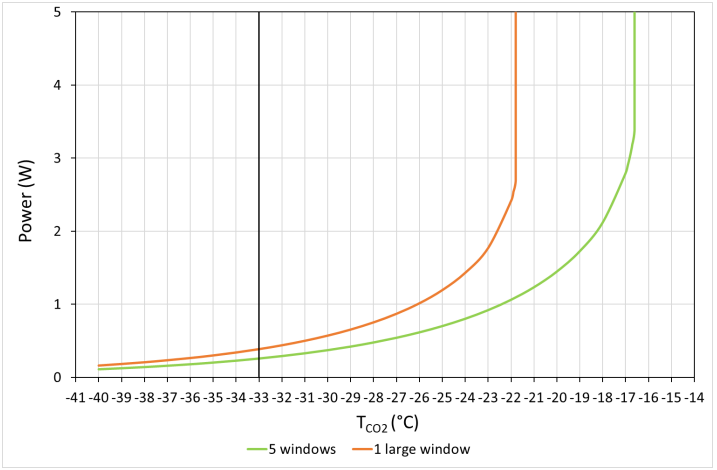


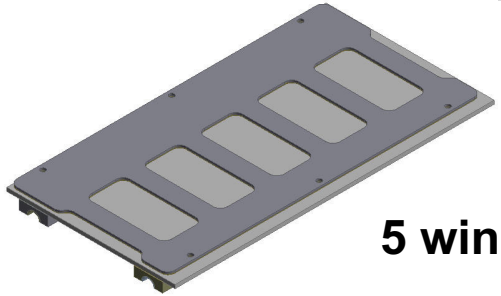
* RD53A: Half-size prototype chip for R&D

Thermal simulations: 3D

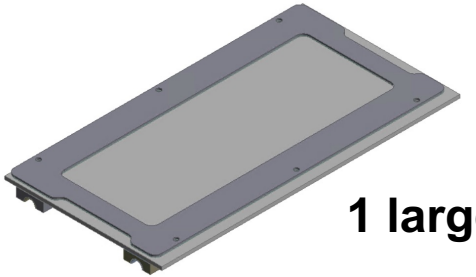
Last simulations – Plot with 70 uA/cm2 (140 V) for two different conditions of the cooling plate





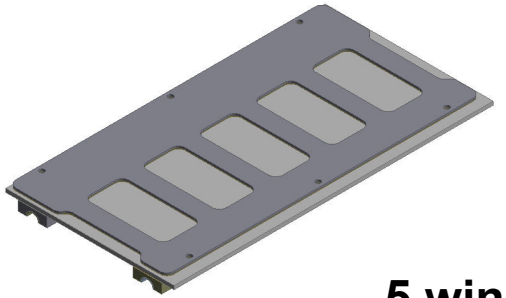


5 windows

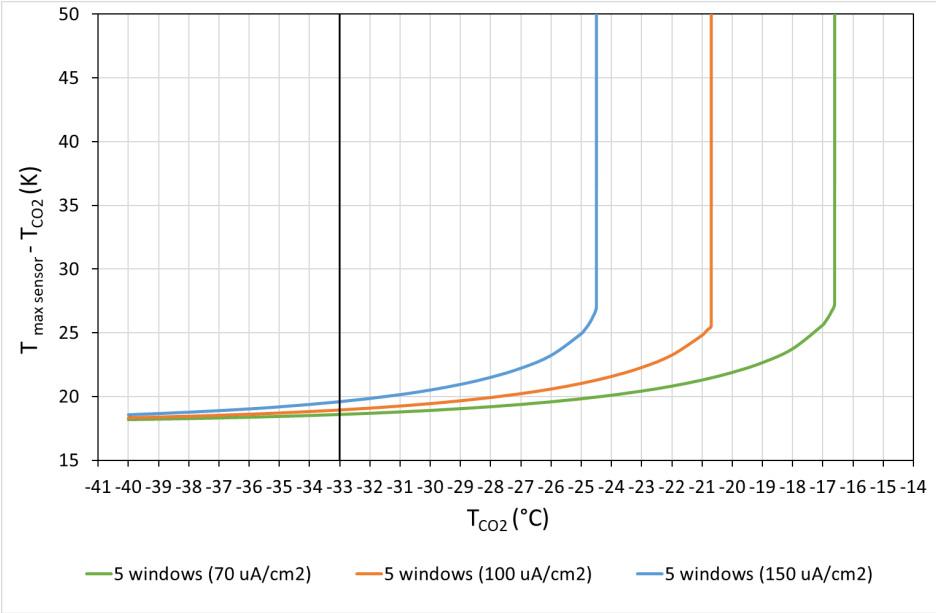


1 large window

Thermal simulations: 3D



5 windows



Cooling plate with 5 windows – From 70 uA/cm^2 to 150 uA/cm^2 (140 V) the margin for thermal runaway is reduced by around 8°C.
We can expect the same reduction for 1 window configuration (simulations are running).

L1 sensor technology: 3D Sensor Qualification

Universität Hamburg
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Recent results beyond 1E16

- **FBK** 100x25 3D sensors irrad. at KIT
- 23 MeV: High dose: 2-2.5 Grad
- Measured at CERN and DESY testbeam
- 1.4E16
  - ε: 99% at 130V
  - Noise(*) <1% up to 140 V
- 1.8E16
  - ε: 98% at 170V
  - Large increase of noisy pixels for V_{bias}> 140 V

* Noisy pixels defined with a cut at $2x10^{-5}$ on occupancy, corresponding to 1% of the L1 occupancy