Evaluation of pixel sensors produced with a commercial 150nm CMOS process for the CMS Phase-2 Upgrade

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Introduction

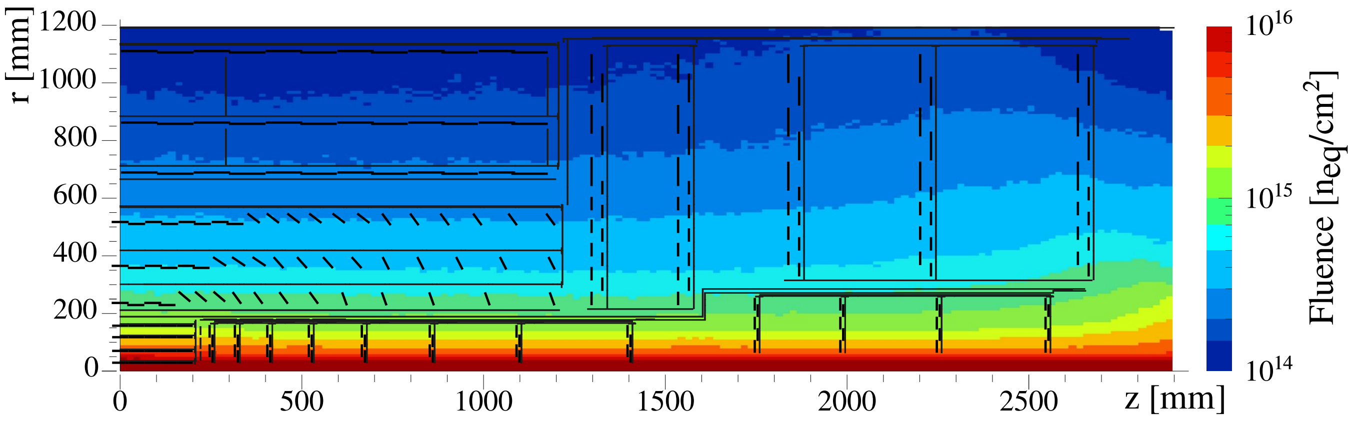
CMS Inner Tracker Phase-2 Upgrade

- Experiment at CERN LHC
- Upgrade to High Luminosity LHC
  - Nominal Luminosity increased x7.5
  - ~10x higher data collection rate than previous 10 years of LHC

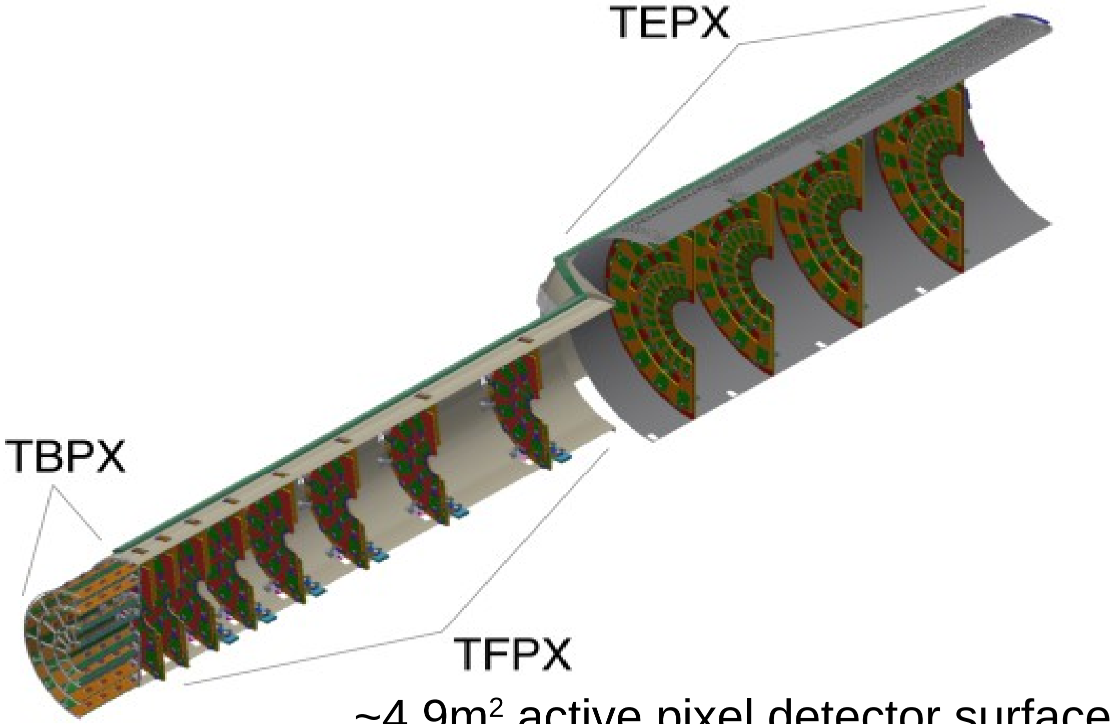
Challenges for Inner Tracker

- High radiation
  (order 10^{16} 1 MeV n_{eq}/cm^2 over lifespan)
- «pile-up» of up to 200
- Required latency of 12.5 μs for Trigger

Needs replacement of the full Inner Tracker



The Phase-2 Upgrade of the CMS Tracker TDR



~4.9m² active pixel detector surface

The Phase-2 Upgrade of the CMS Tracker TDR

Introduction

CMS Phase-2 Hybrid pixels

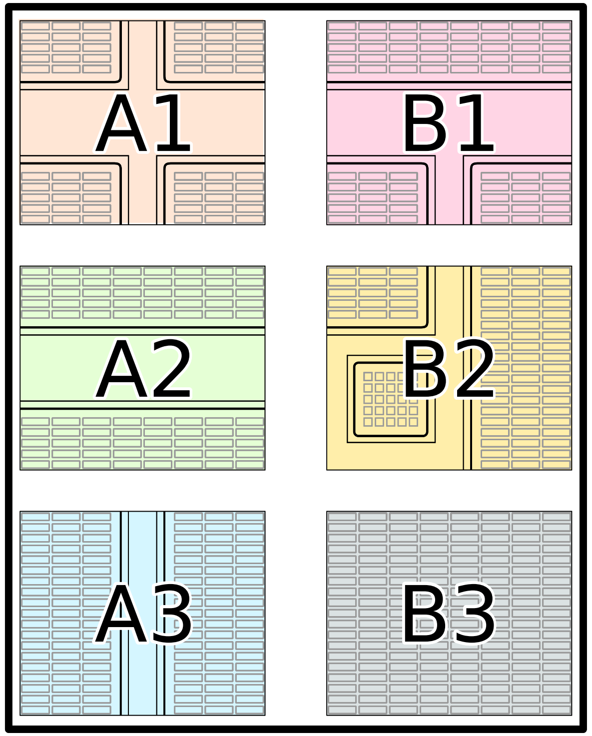
- CMS RD53B (CROC) read-out chip
- 25x100μm^2 pixel pitch, ~150μm thick
- Different sensor designs evaluated

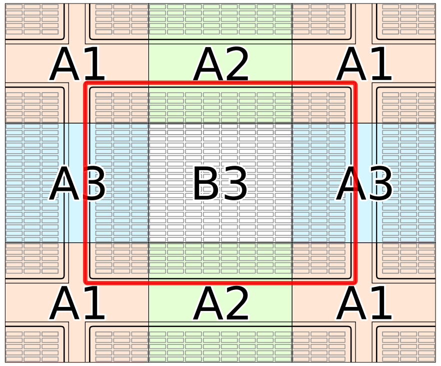
LFoundry CMOS process

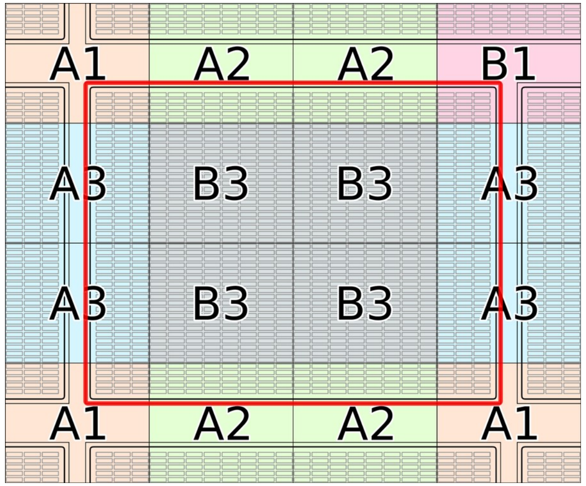
- «Sub-reticles» as building blocks for wafer (~1cm^2)
- Stitching within sensitive area of sensor
  - Allows for large sensors (here up to ~16cm^2)

Advantages

- Use of commercial production lines
  - Higher throughput
- Smaller feature sizes than conventional methods







Introduction

LFoundry CMOS sensors

3 prototype sizes:

Label	Size [mm²]	Sensors [#]
Small	330.92	18
Large	805.97	56
Quad	1550.82	96

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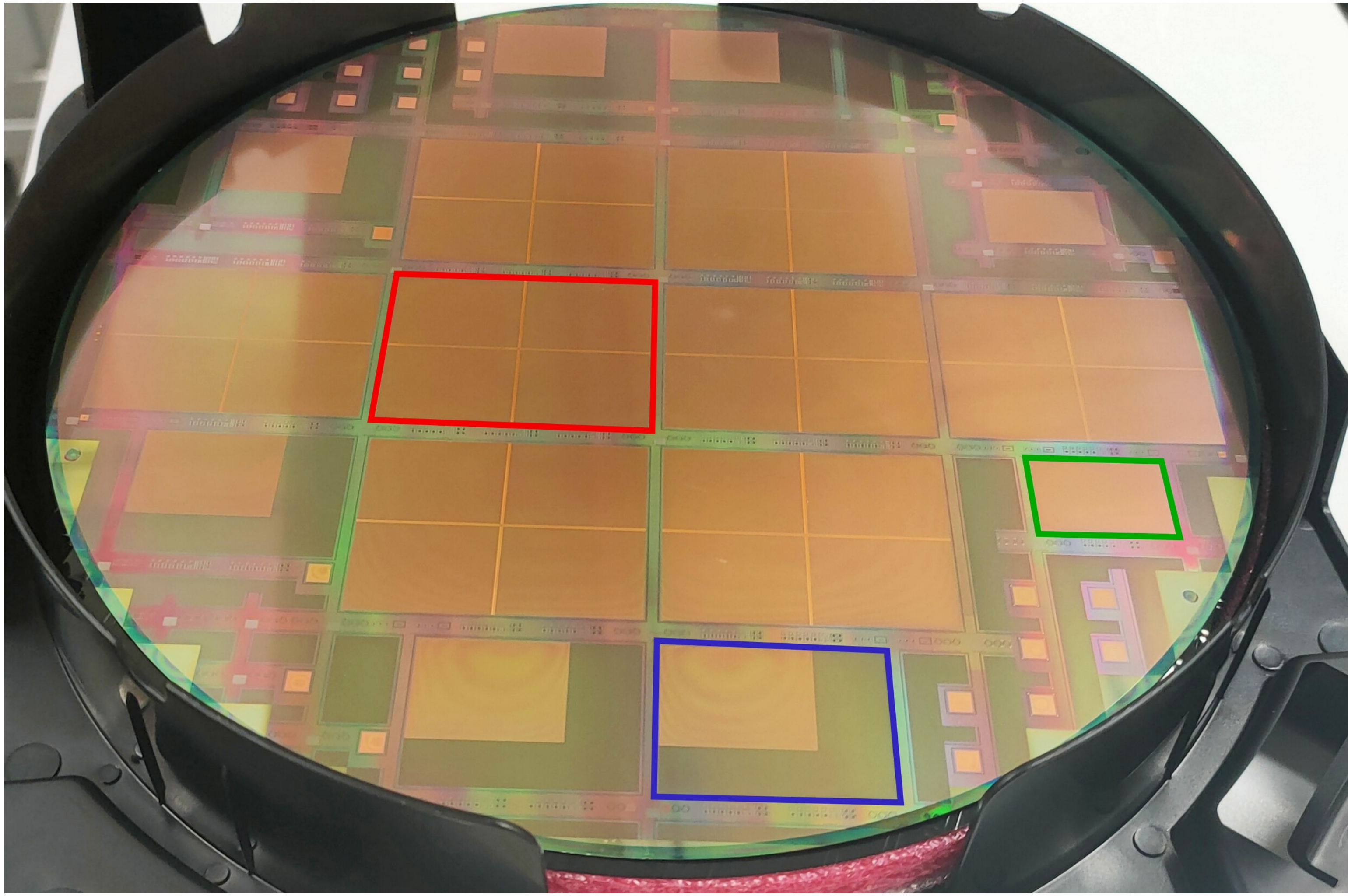


Small and Large sensor to be used with single CROC read-out chip

Quad sensor to be used with 4 CROC read-out chips per sensor

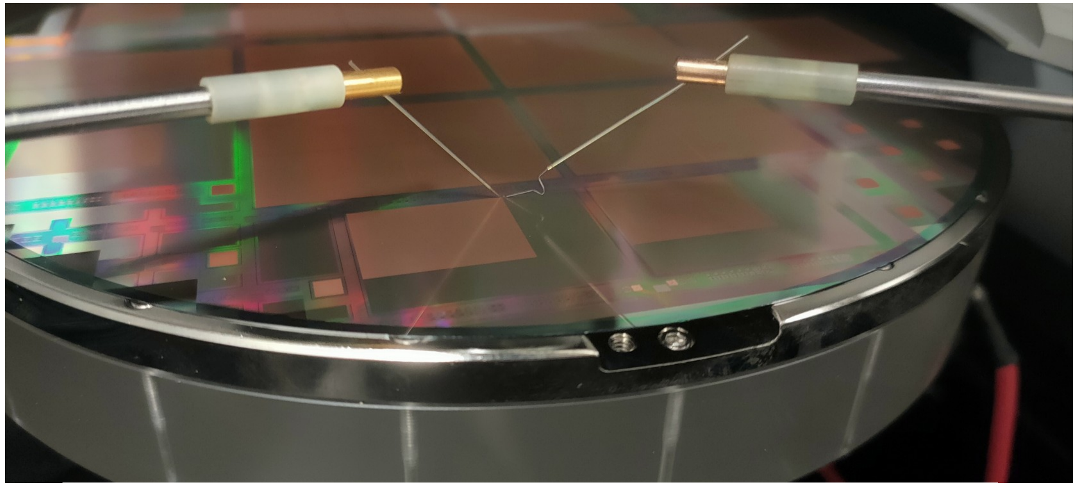
Wafer level testing

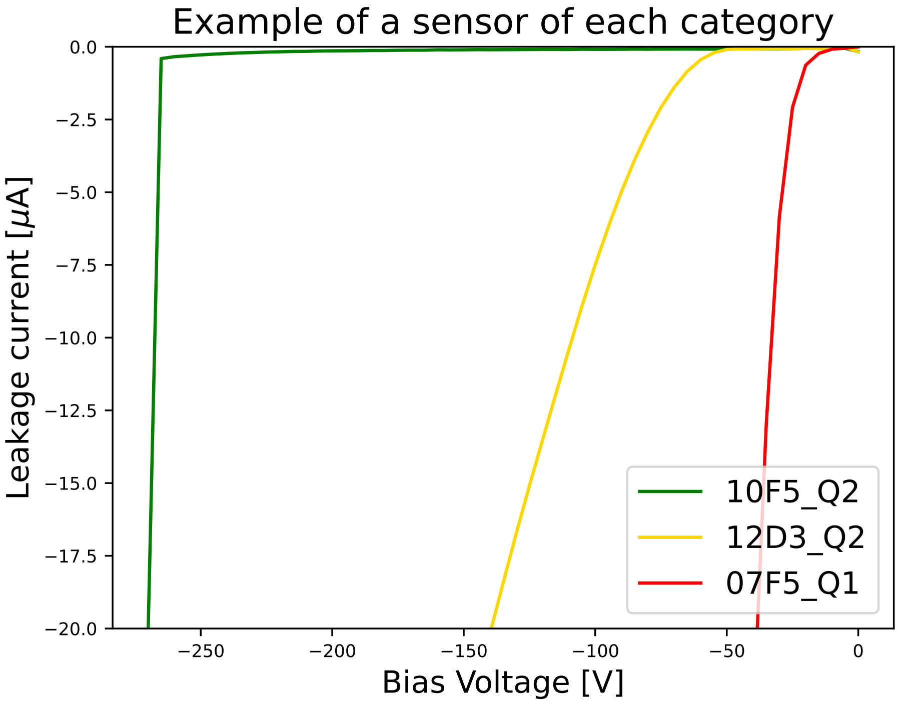
IV-curves

- Testing yield of sensors using IV-curves
  - Negative Bias from back side
  - Ground through «bias grid»
    All pixels connected through in-pixel resistors

- Breakdown voltage
  - Sharp increase of leakage current by voltage

Category	Breakdown
Red	<45 V
Yellow	>=45V <100V
Green	>=100V





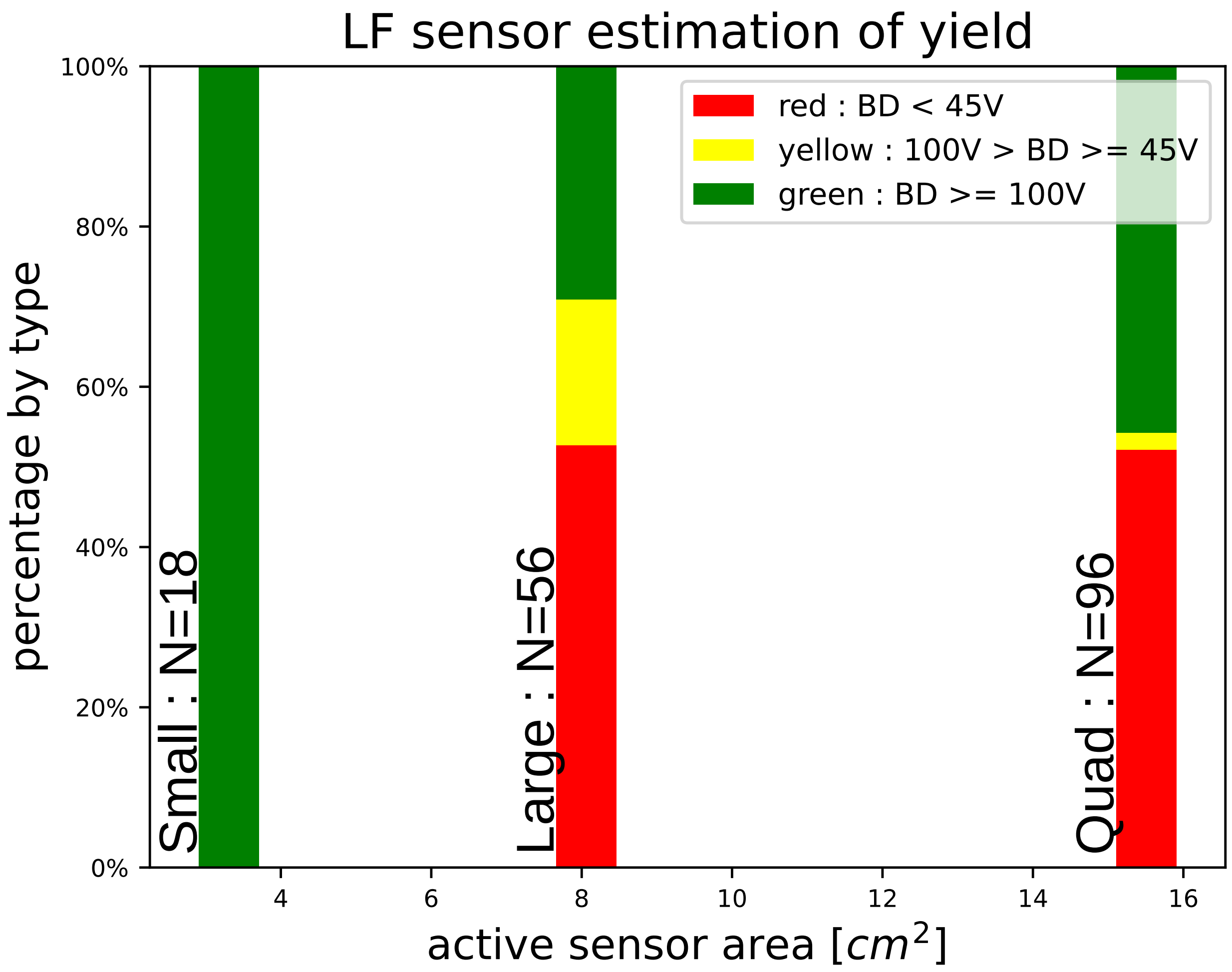
Wafer level testing

IV-curves

- 3 conditions chosen for breakdown definition
- All have to be fulfilled to decide breakdown

Metric	**Condition**
Abs Voltage	>20V
Abs Current	>0.75 µA/cm²
Slope	>20% increase over 5V

Category	**Breakdown**
Red	**<45 V**
Yellow	**>=45V <100V**
Green	**>=100V**



- High yield for small sensors
- Low yield for the larger sensors
    - Not fully understood why

Wafer level testing

CV-curves

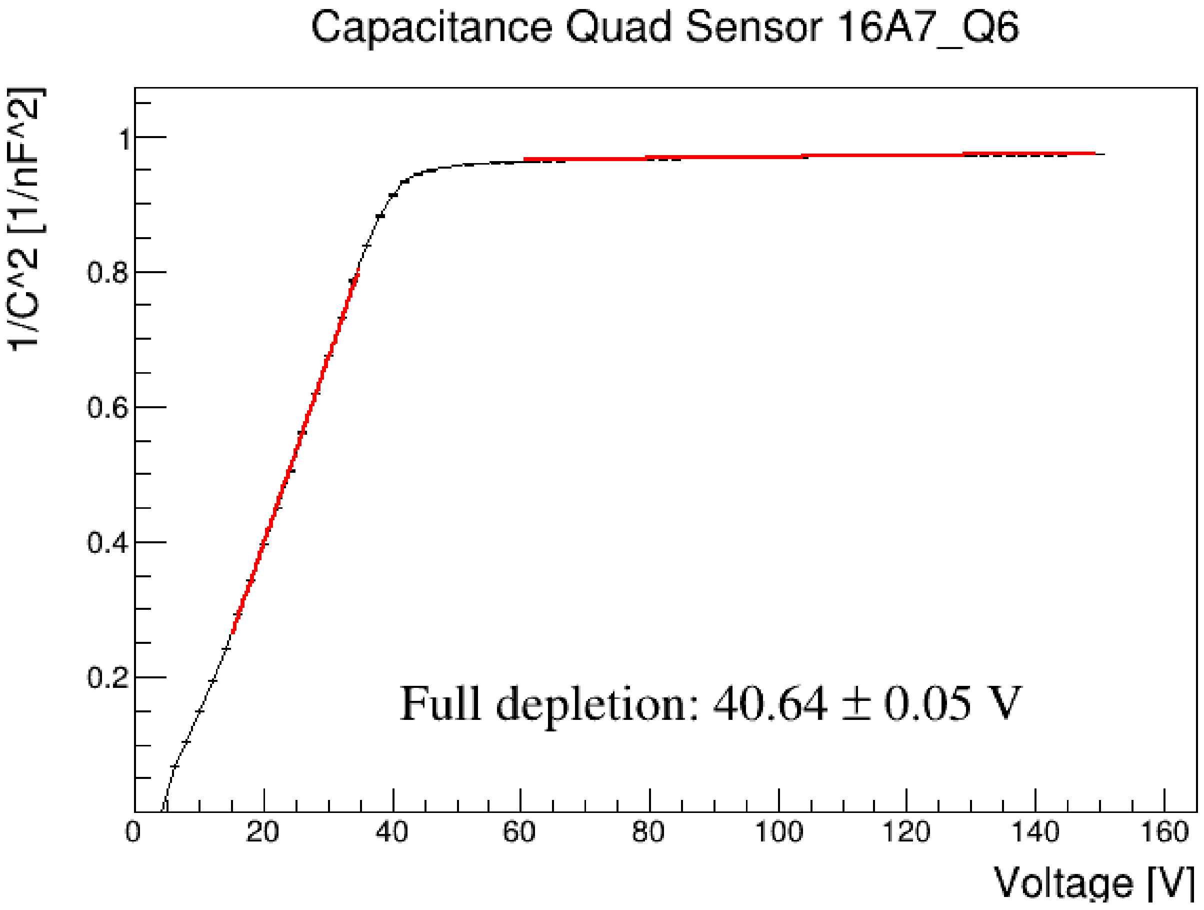
Measure capacitance with CV-measurement

Performed with LCR-meter (10 kHz)

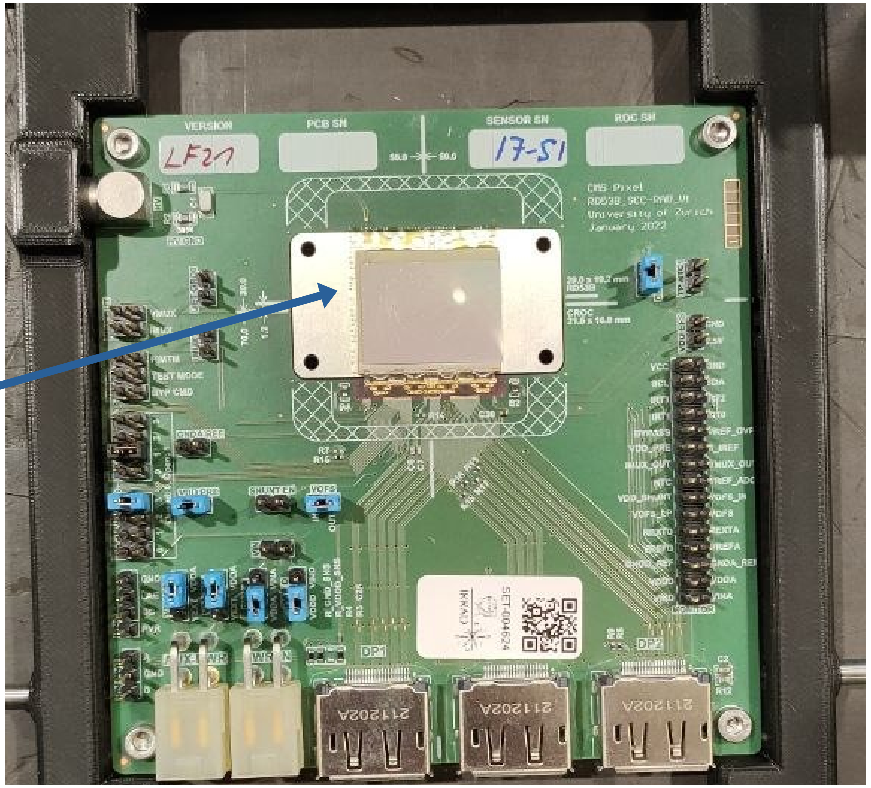
- Calculation of depletion voltage
  - Below depletion: $\frac{1}{C^2} \propto U_{ext}$
  - Above depletion: $\frac{1}{C^2} \approx const$
- Wafer resistivity estimation

$$\rho(\Omega \cdot \mathrm{cm}) = \frac{d^2}{0.3^2 \cdot U_{depl}} \left(\frac{\mu \mathrm{m}^2}{\mathrm{V}} \right)$$

  - Measured: 6‘145 Ωcm
  - Expected from wafer: 4‘000-8‘000 Ωcm



Testbeam studies



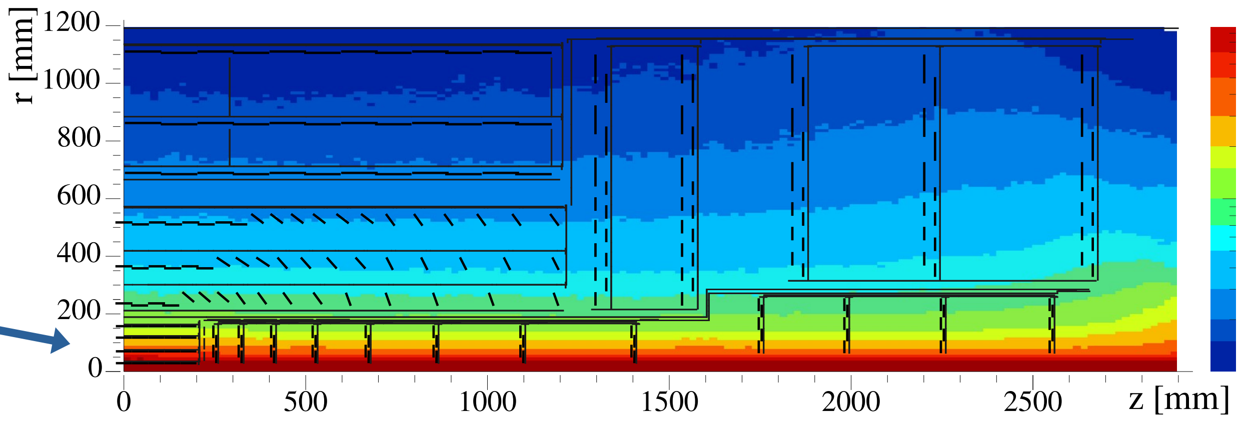
Modules

Testbeam studies performed with multiple sensors on Single-chip modules:

Module name	Sensor Type	Irradiation [1MeV n_{eq}/cm^2]
LF-17_S1	Small	ca. 6-8 10^{15}
LF-12_S1	Small	ca. 6-8 10^{15}
LF-12_L1	Large	-
LF-17_L1	Large	-

Irradiation

- After initial testbeam with fresh sensors
  - 2 sensors irradiated with 24 GeV proton beam at IRRAD @CERN
  - Expected fluences in Barrel around Layer 2 and 3

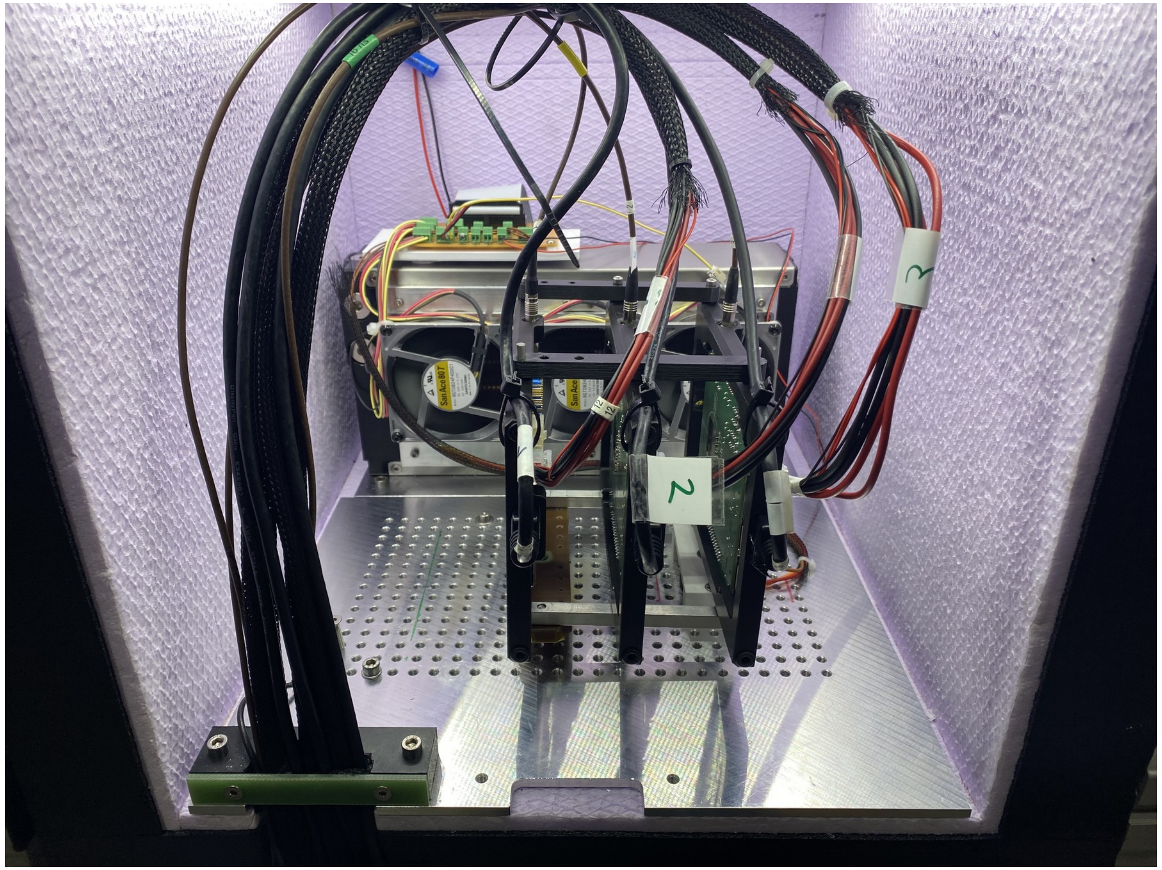


The Phase-2 Upgrade of the CMS Tracker TDR

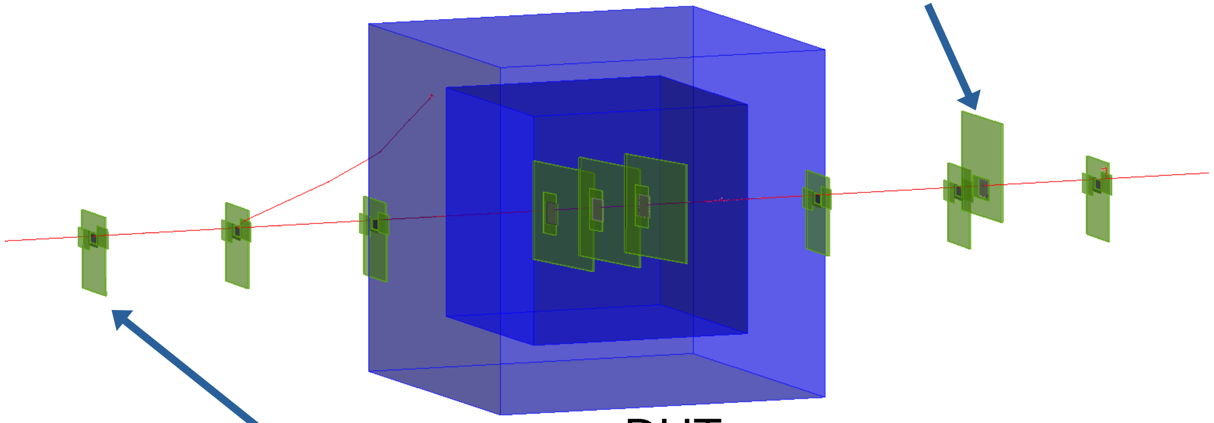
Testbeam studies

Testbeam setup

- SPS @CERN 120 GeV pion beam
- CMOS modules in climate controlled box
  - T_{box} ~-35°C



EUDET telescope



1 plane with CROC module
(for time resolution)

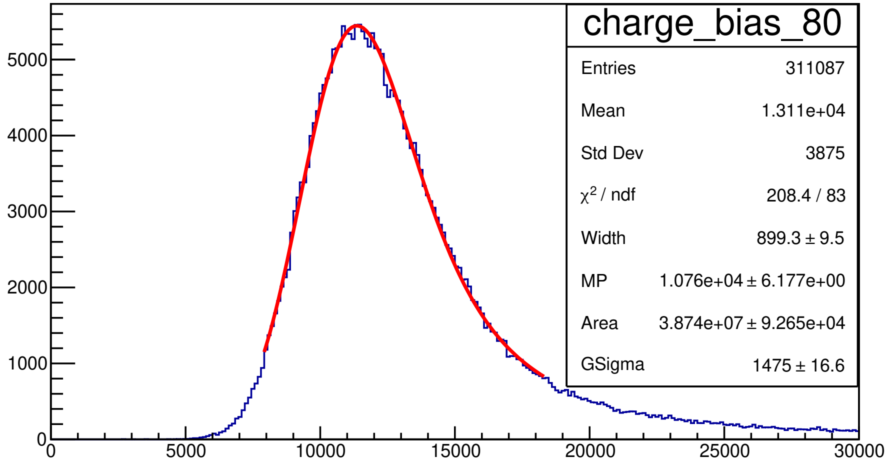
DUTs

6 planes with mimosa26 modules
(for spatial resolution)

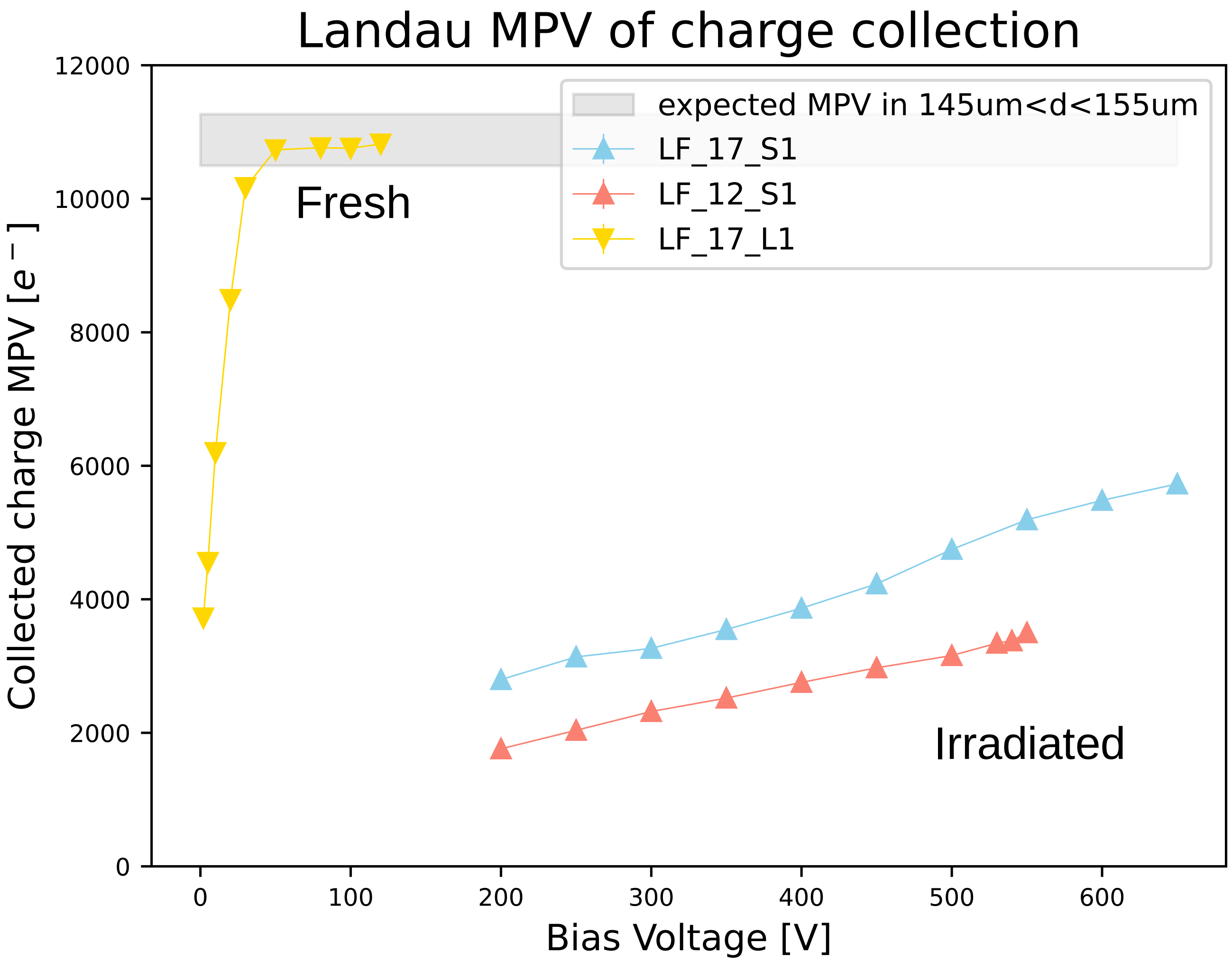
Testbeam studies

Charge collection studies

- CROC charge measurement in ToT with 4bit resolution
- Fit of Landau convoluted with Gauss
  - Landau: charge deposition
  - Gauss: different noise effects



charge_bias_80	
Entries	311087
Mean	1.311e+04
Std Dev	3875
χ^2 / ndf	208.4 / 83
Width	899.3 ± 9.5
MP	1.076e+04 ± 6.177e+00
Area	3.874e+07 ± 9.265e+04
GSigma	1475 ± 16.6



Approximation of expected **Most Probable Value**

$$\Delta_p(keV) = 12.325 + ln(\xi/I) = x(um)(0.1791 + 0.01782 \cdot ln(x(um)))$$

$$\xi = 0.1535 \cdot \frac{z^2 \cdot Z}{A\beta^2}\rho = 1.78 \cdot 10^{-2}/\beta = 0.0178$$

- Charge collection for fresh sensor as expected
- Lower charge collection for irradiated sensors
  - Charge trapping effects from irradiation

Testbeam studies

Efficiency studies

Measurement of efficiency of LFoundry sensors, Hits on sensor compared with tracks reconstructed in telescope

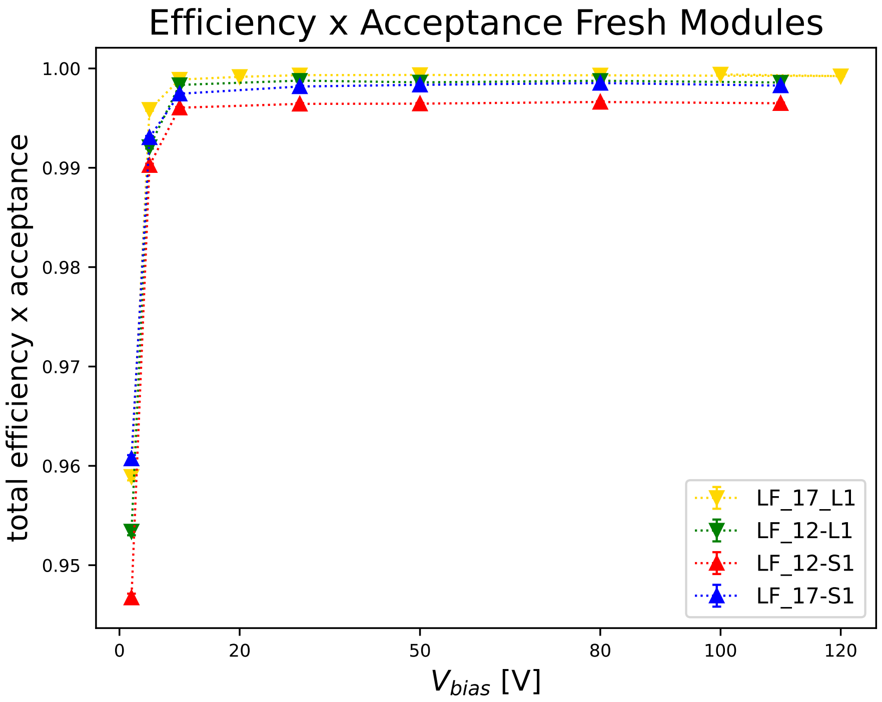
- **Efficiency x Acceptance**
  - Acceptance:
    relative amount of active pixels in region of interest

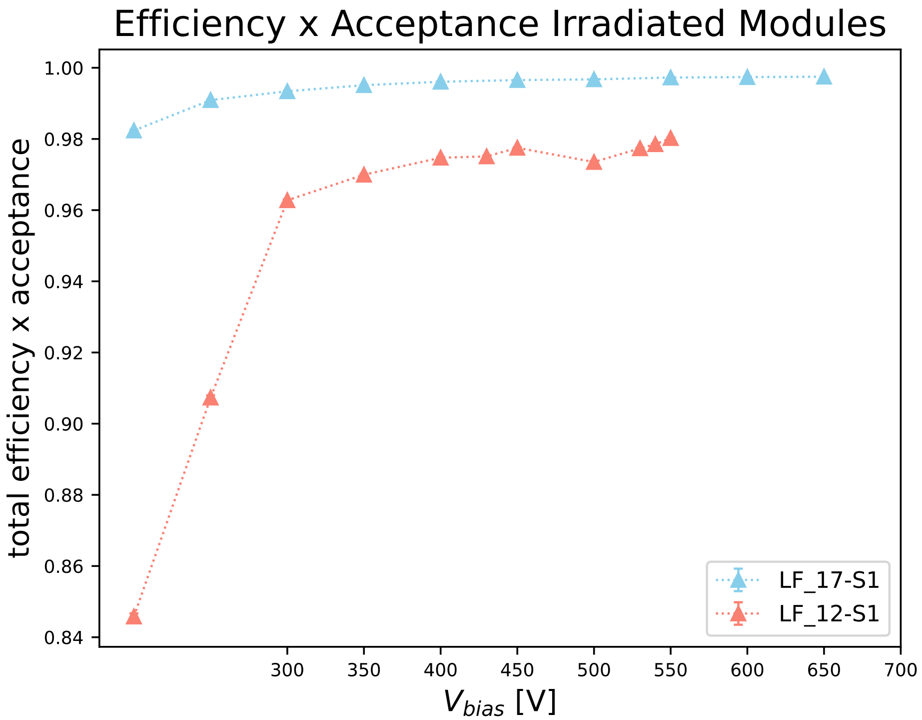
Fresh

Module	Sensor	Irradiated	Peak Efficiency
LF_17_S1	small	-	99.82%
LF_12_S1	small	-	99.65%
LF_12_L1	large	-	99.85%
LF_12_L1	large	-	99.95%

Irradiated

Module	Sensor	Irrad [1MeV n_{eq}/cm^2]	Peak Efficiency
LF_17_S1	small	ca. 6-8 10^{15}	99.75%
LF_12_S1	small	ca. 6-8 10^{15}	98.02%





Testbeam studies

Efficiency studies

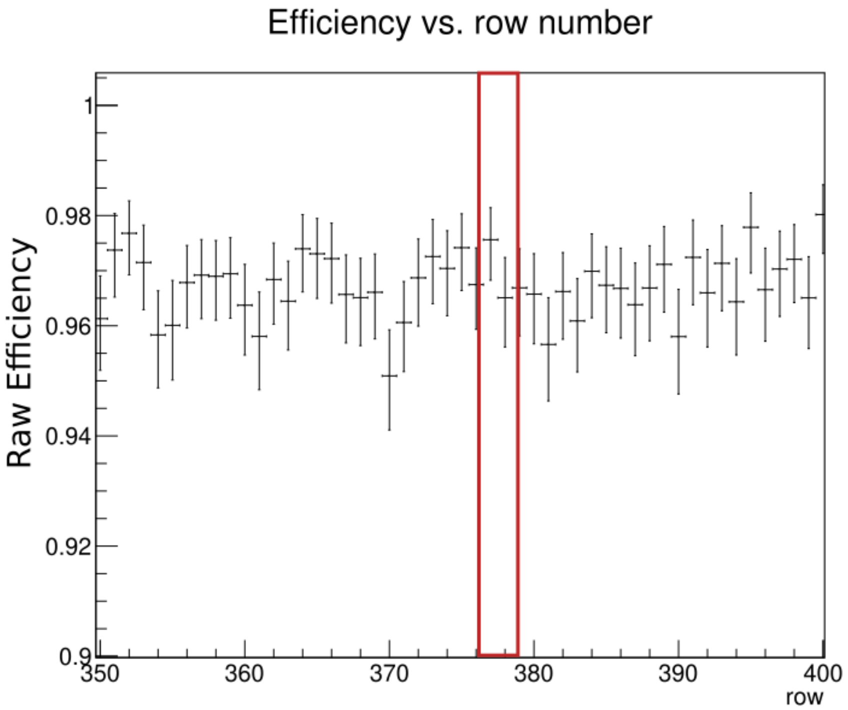
Measurement of efficiency of LFoundry sensors, Hits on sensor compared with hits in Telescope planes

Stitching lines

- Regions where two sub-reticles are «stitched» together on the wafer
- No observable differences found at subreticle edges
- Efficiency similar to surrounding for low and high V_{bias}

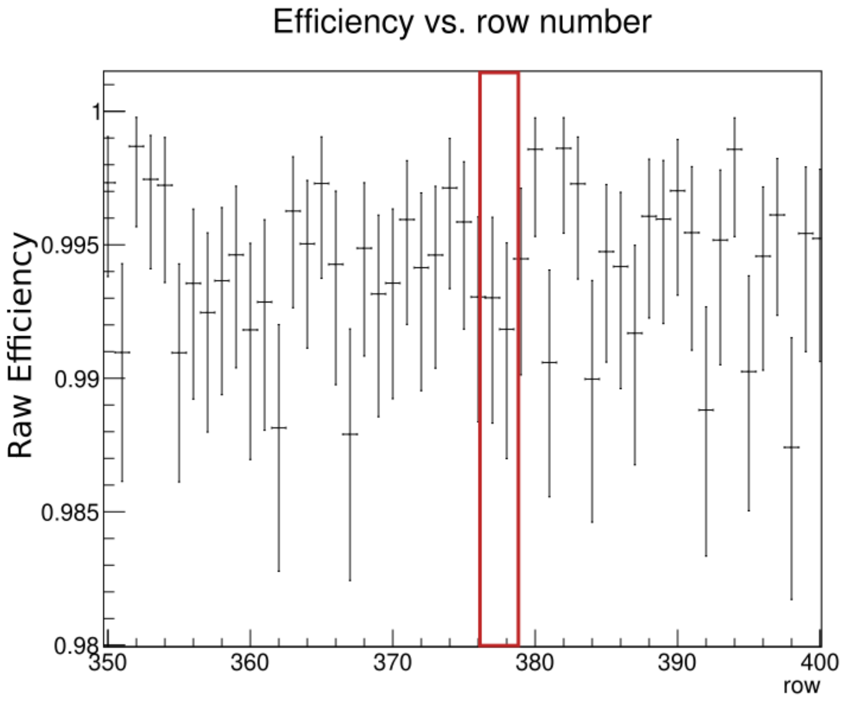
LF_17_S1:

Bias: 300V



LF_12_S1:

Bias: 300V



Summary

Sensors produced with commercial CMOS process

- For hybrid detectors
- Evaluated on wafer level and as single-chip modules in testbeams

Wafer level testing

- High yield for smaller sensors
- Low yield for larger sensors → Not fully understood
- Full depletion at ~40V, in line with approximated wafer resistivity

Testbeam

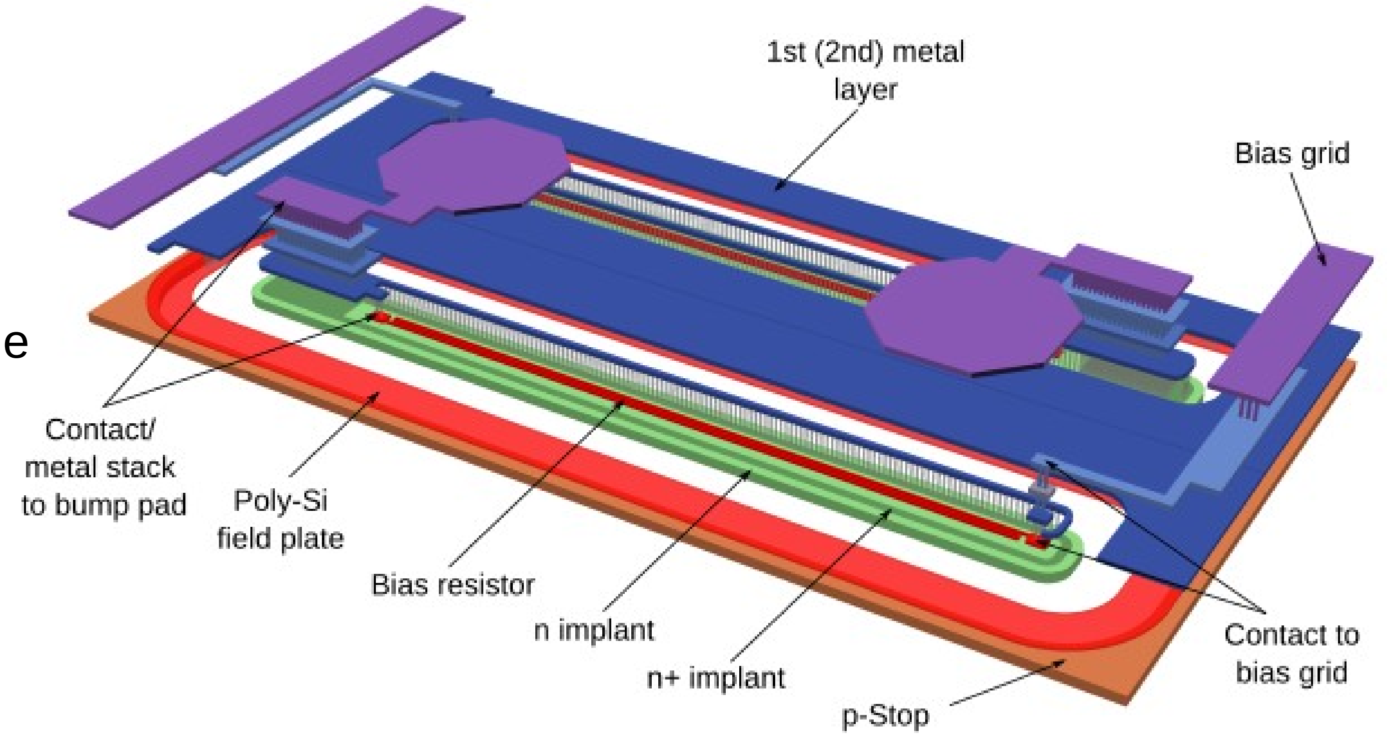
- Charge collection following expected pattern
- High efficiencies for both fresh and irradiated (ca. 6-8 10^{15} 1MeV n_{eq}/cm^2) sensors
  - Fresh: Around 99.9%
  - Irradiated: 98.0% - 99.7%
- No differences observed along stitching lines

Backup

LFoundry sensor

Bias Grid

- Every pixel has two contacts
  - One to ROC pixel
  - One to «bias grid»
- Bias grid connects all pixels through large in-pixel resistor
- Possibility to bias all pixels at the same time without ROC (Resistors in parallel)
- High-ohmic connection between pixels (Resistors in series)



Wafer level testing

CV-curves

Determination of the full depletion voltage with CV-measurement

Performed with LCR-meter

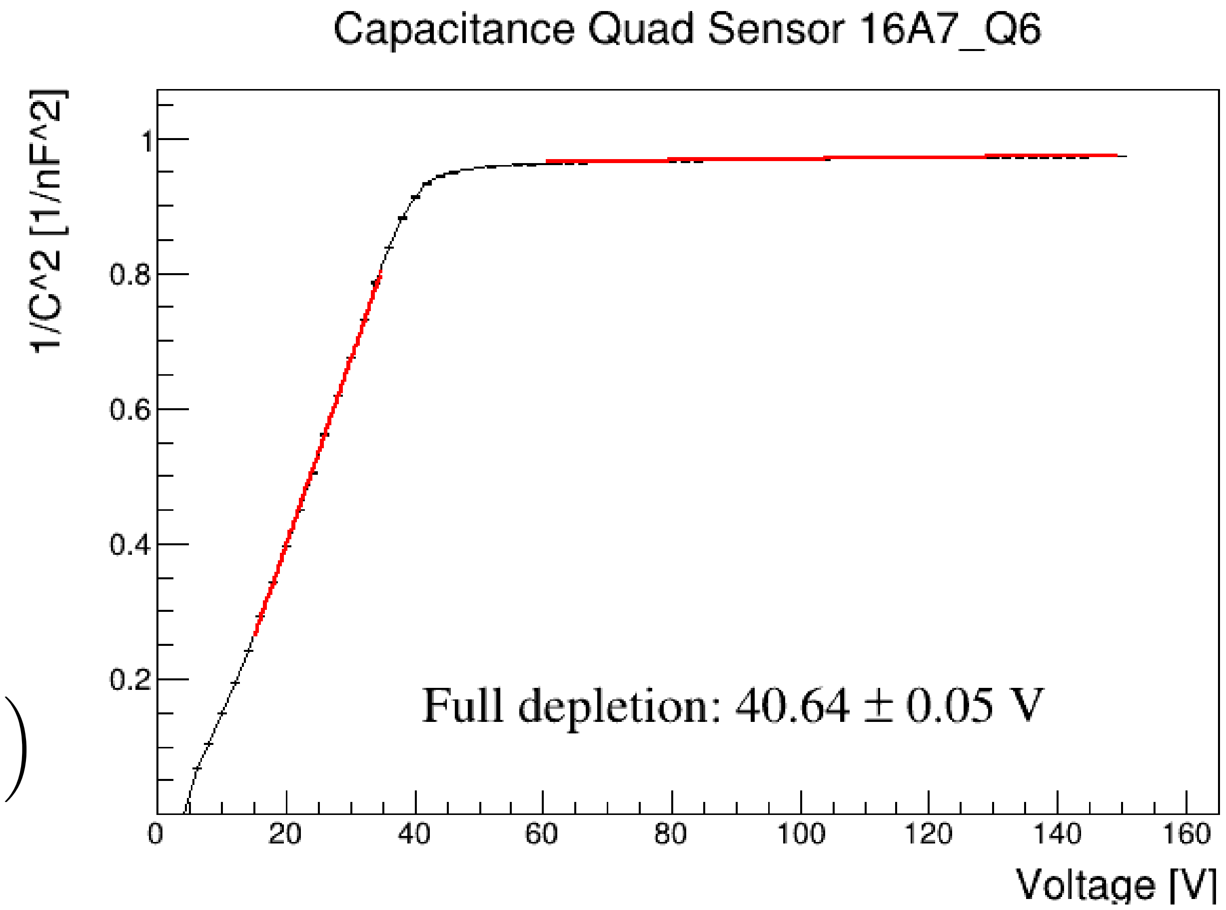
Calculation of Capacitance by Voltage

$$\frac{1}{C^2} = \frac{1}{A\epsilon_0\epsilon_{Si}}\frac{2}{e}(\frac{1}{N_A} + \frac{1}{N_D})U_{ext}$$

- Below depletion: $\frac{1}{C^2} \propto U_{ext}$
- Above depletion: $\frac{1}{C^2} \approx const$

Resistivity estimation $\rho(\Omega \cdot \mathrm{cm}) = \frac{d^2}{0.3^2 \cdot U_{depl}}\left(\frac{\mu\mathrm{m}^2}{\mathrm{V}}\right)$

- Measured: 6‘145 $\Omega\mathrm{cm}^2$
- Expected from wafer: 4‘000-8‘000 $\Omega\mathrm{cm}^2$

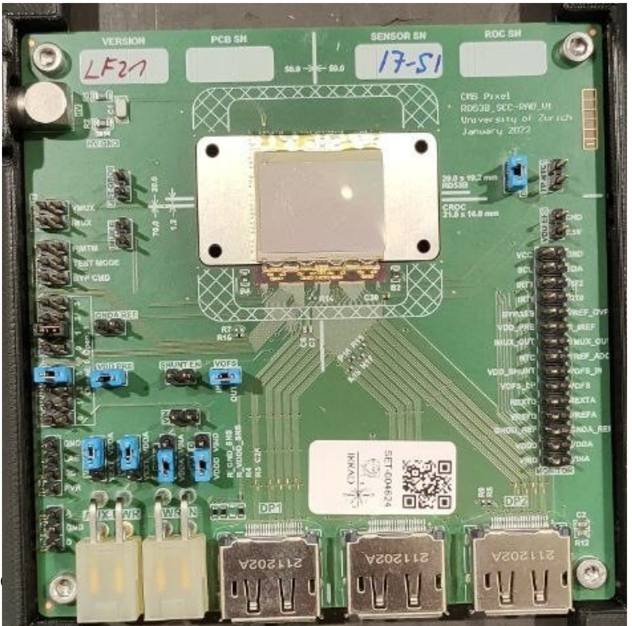


September 2022: Module tuning

Tuning of DUTs:

Module	Sensor	Bias [V]	Threshold [e$^-$]	Masked pixels	Irradiated [1MeV neq/cm^2]
LF_17_S1	small	80	1325	641 / 0.5%	-
LF_17_S1	small	300	1200	222 / 0.1%	ca. 6-8 10^{15}
LF_12_S1	small	80	1200	201 / 0.5%	-
LF_12_S1	small	300	1200	498 / 1.1%	ca. 6-8 10^{15}
LF_12_L1	large	110	1500	10	-
LF_12_L1	large	80	1200	22	-

LF_17_S1



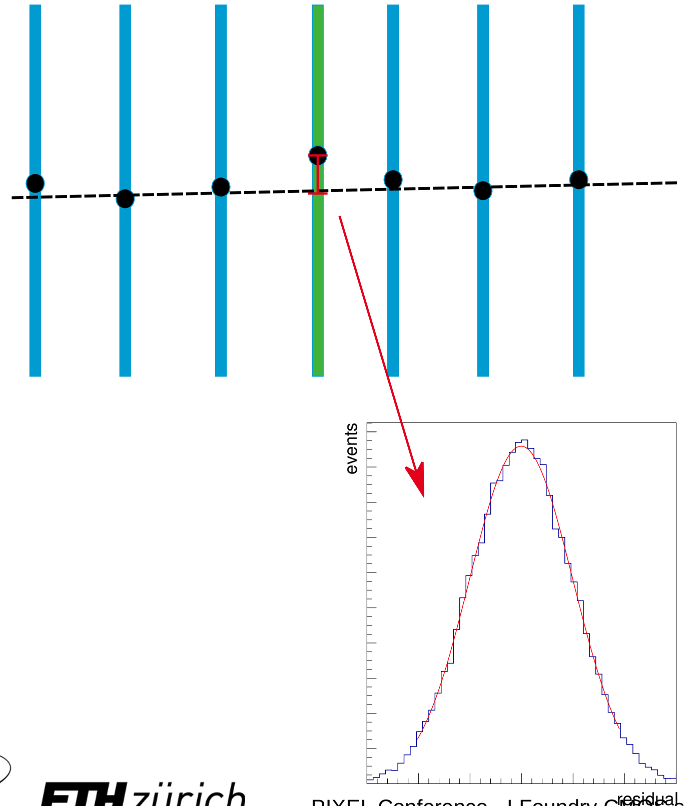
LF_12_L1

Testbeam studies

Resolution studies

Determining the spatial resolution of sensors

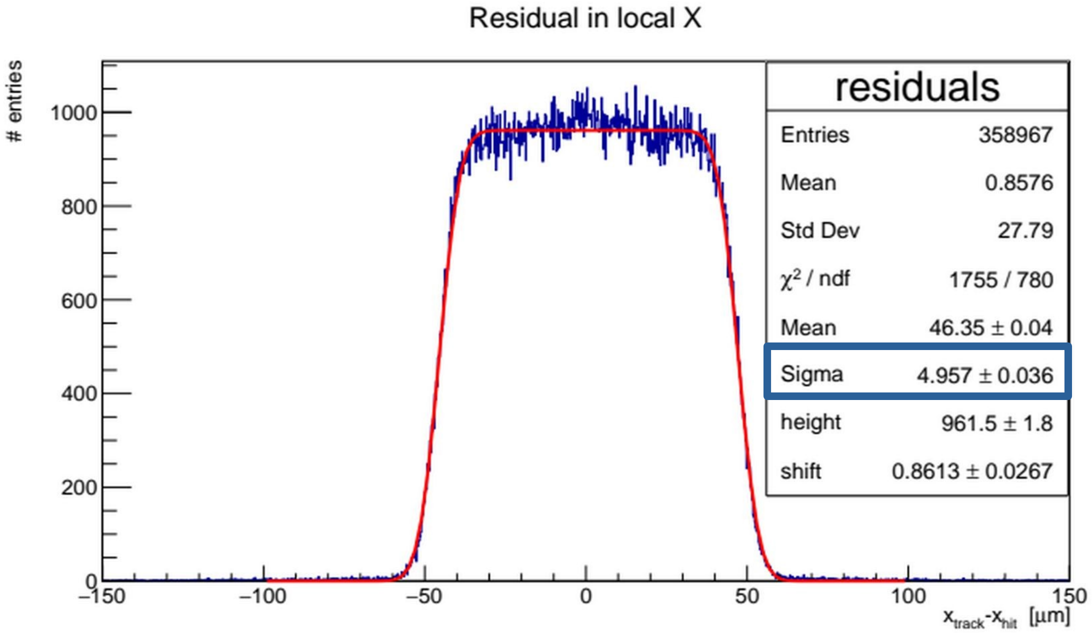
$$\sigma_{dut} = \sqrt{(\sigma_{reco}^2 - \sigma_{telescope}^2)}$$



Different effects observed worsening reconstruction (e.g. bending effects support plate)

Therefore data-driven approach for $\sigma_{telescope}$.

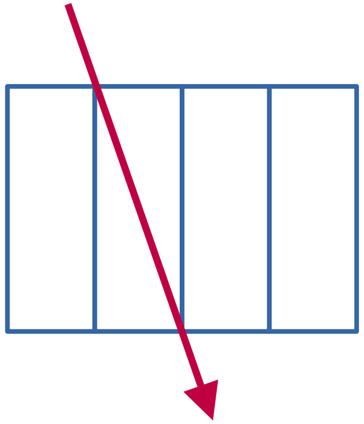
- Measure spread of rising slope along long axis of pixels
- Effect from sensor resolution very small
- Results in combined resolution of telescope and background effects



Testbeam studies

Resolution studies

- Resolution depends on the incident angle due to charge sharing information
- Perpendicular incidence: 0°



Expected resolution minima:

pitch = 25µm
depth = 155µm

$\tan^{-1}(p/d)$ = 9.2°
$\tan^{-1}(2p/d)$ = 17.8°