Characterization of passive CMOS sensors for the HL-LHC upgrade

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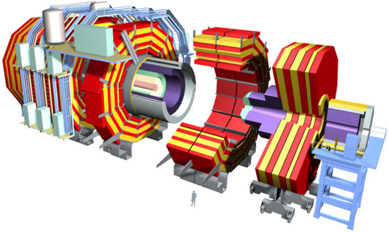
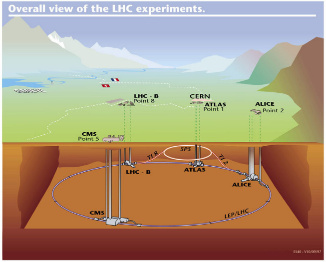
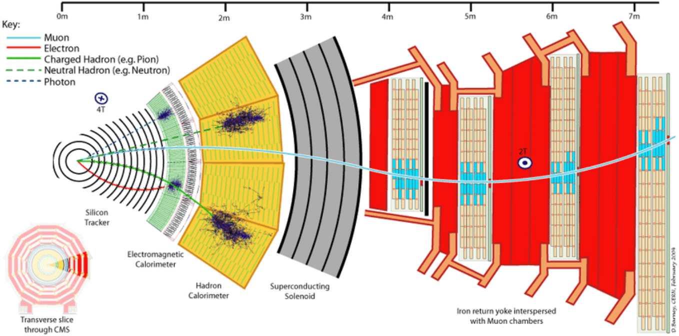
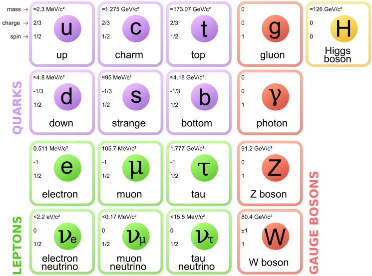
The LHC and the CMS detector







New physics around the corner ?



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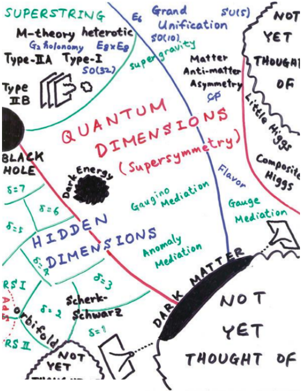
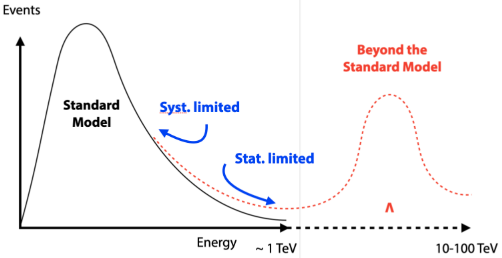
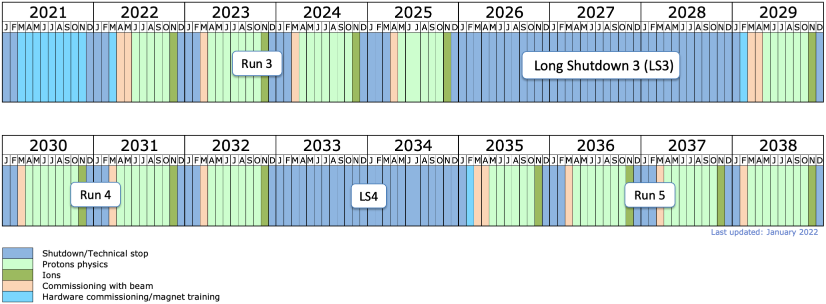




The HL-LHC upgrade



- New challenges between Run3 and HL-LHC:
  - Pileup $\times 8$ $(25 \to 200)$
  - Hit rate $\times 8$ ($\to 3.2$ GHz.cm^{-2})
  - Latency $\times 4$ $(3.2 \to 12.8\mu s)$
  - Trigger rate $\times 8$ ($100 \to 750$ kHz)
  - Radiation $\times 10$ ($\to 2 \times 10^{16}$ neq.cm^{16})

The Inner Tracker (IT) needs to be made more performant to be able to cope with this environment

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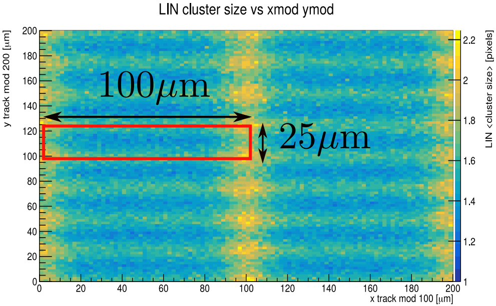
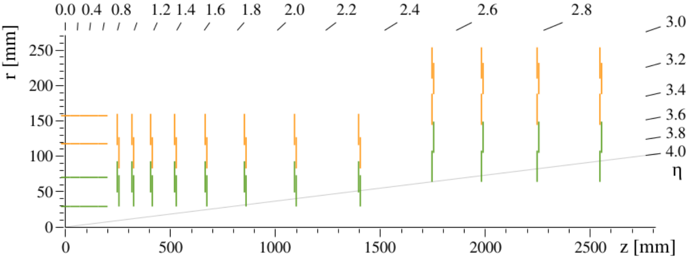
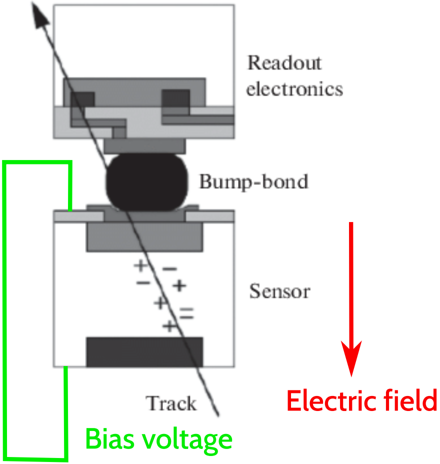
The CMS Inner Tracker



- Split in barrel and endcaps.
- Around 2 billion pixels for the whole IT.
- Around 5 m^2 of active silicon area.
- Crucial importance in triggering and track reconstruction.

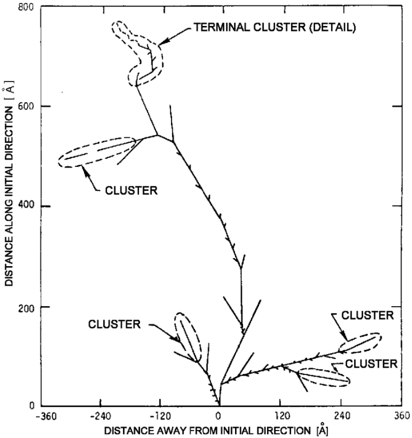


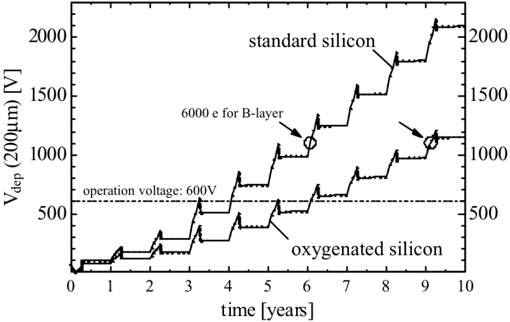
Hybrid pixel detectors



Radiation damage in silicon

- ➜ Incoming particles can displace the silicon nuclei which produces deffects and charge traps.
- ➜ The bias voltage needs to be increased with increased radiation levels to collect enough charges.





CMOS for HEP

- CMOS device: combination of 2 MOSFET transistors for low-power operation.
- Exclusive technology for modern integrated circuits.
- Modern way of building them (on high resistivity substrate) allows for their use in HEP.

Current situation in HEP

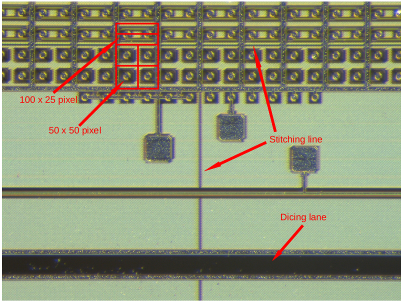
- Full wafer litography for passive sensors
- Increasing demand for large-scale sensor wafer production
- Few large scale suppliers available
- Risk: single vendor scenario, possibility of not achieving the production levels needed for increasing silicon areas in tracking detectors.

Possible improvements

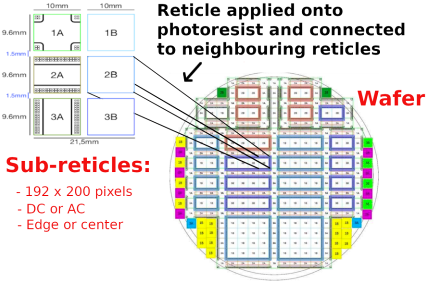
- Use a CMOS processing line on large, high resistivity wafers.
- Access to more (industrial) vendors for large-scale silicon production
- Additional features from CMOS processes
  - Poly-silicon resistors, MIM capacitors for AC-coupling
  - Additional metal layers for redistribution layers

Design

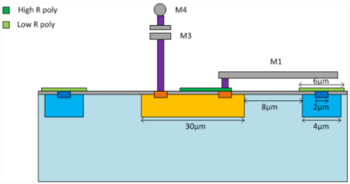
- LFoundry sensor submission:
  - n^+ in p implants
  - 150 μm thickness
  - 50×50 and $25 \times 100 \mu m^2$ pixel sizes investigated
  - AC and DC-coupled pixels tested

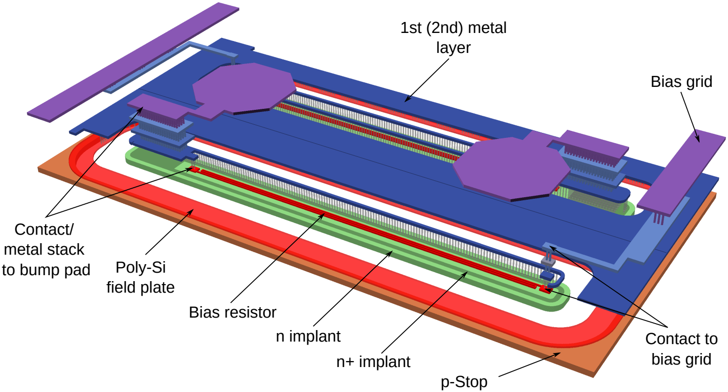


- Wafer built using stitching technology
  - Sub-reticles (building blocks) define specific areas of the sensor (edge, center, ...)
  - A few of these subreticles are enough to build the whole sensor, without limiting its size.



- CMOS processes allows for the deposition of additional metal layers over each pixel and leads to nice new features:
  - AC coupling for noise reduction (capacitor M3)
  - Redistribution of signal from the sensor to the bump bonds, great to cover gaps between chips in a detector
  - Shielding between the implant and the bump pad to avoid cross-talk (measured cross-talk under 3 %, more than double for other producers).
  - 2 MΩ polysilicon resistor for pixel biasing, allows on-sensor testing before flip-chipping (yield increase).





Requirements

- ➜ Participation to the CMS market survey for the Inner Tracker sensors with the LFoundry submission
- ➜ List of requirements to meet in order to reach the Invitation to Tender and be able to include LFoundry sensors in the production

Parameter	Requirement	Additional condition
Breakdown voltage	> 300 V	Before irradiation
Breakdown voltage	> 600 V	At 5×10^{15} $n_{eq}.cm^{-2}$
Leakage current	< 0.75 $\mu A.cm^{-2}$	Before irradiation, at $V_{dep} + 50V$
Leakage current	< 45 $\mu A.cm^{-2}$	At 5×10^{15} $n_{eq}.cm^{-2}$, at $600V$
Hit efficiency	99%	Before irradiation, at $V_{dep} + 50V$
Hit efficiency	99 %	At 5×10^{15} $n_{eq}.cm^{-2}$, under $V_{BD} - 100$ V and at -25^oC
Hit efficiency	98 %	At 1×10^{16} $n_{eq}.cm^{-2}$, under $V_{BD} - 100$ V and at -25^oC

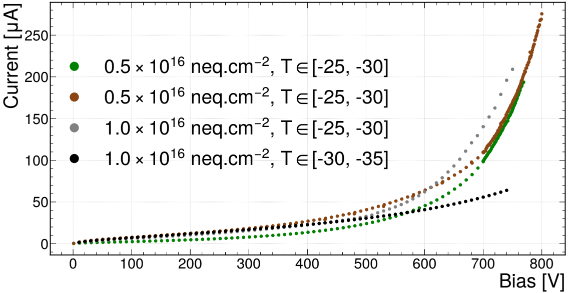
	RUN 4		RUN 5		RUN 6		Run 4+5		Run 4+5+6	
	1E16 1 MeV n_eq	Grad	1E16 1 MeV n_eq	Grad	1E16 1 MeV n_eq	Grad	1E16 1 MeV n_eq	Grad	1E16 1 MeV n_eq	Grad
BPIX L1	0.73	0.40	1.16	0.63	1.63	0.89	1.88	1.03	3.51	1.91
BPIX L2	0.20	0.11	0.31	0.18	0.44	0.25	0.51	0.29	0.94	0.55
FPIX R1	0.48	0.31	0.77	0.50	1.08	0.70	1.25	0.81	2.34	1.50
FPIX R2	0.23	0.17	0.36	0.27	0.51	0.38	0.59	0.44	1.11	0.82

Sensors

Size	Type	Serial Number	Irradiation dose (neq.cm^{-2}) and TB location
25×100	DC	14C4S12	0.17×10^{16}, DESY
50×50	AC	12D6S4	0.44×10^{16}, DESY
25×100	DC	14C4S11	0.73×10^{16}, DESY
25×100	DC	12D6S12	0.82×10^{16}, DESY
25×100	DC	14C4S12	0.95×10^{16}, SPS
25×100	DC	12D6S12	1.65×10^{16}, SPS

- ➜ Intensive testing of the sensors in testbeam needed to compare to the requirements and to the performance of the other producers.
- ➜ Total of 6 sensors tested in beam (DESY and SPS), two reirradiated and retested.
- ➜ 7 different irradiation levels tested, 3 close to 1×10^{16} neq.cm^{-2}

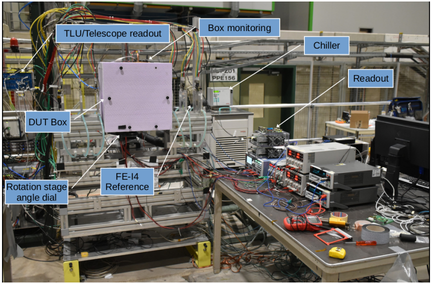
IV measurements

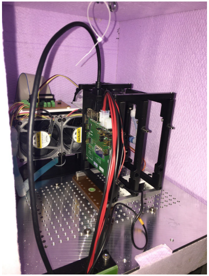


➜ Breakdown voltage higher than 600 V tested on 4 different sensors and for fluences up to 1×10^{16} neq.cm^{-2}

Testbeam setup

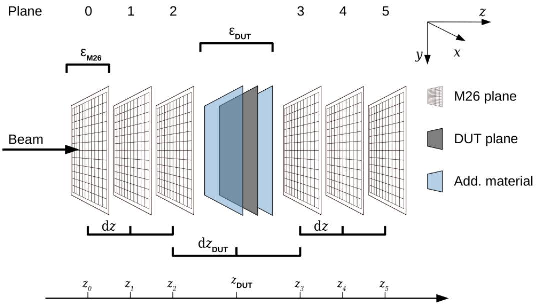
- Two different testbeam locations: DESY (Hamburg), 5 GeV electrons and SPS (CERN), 120 GeV pions.
- The DAQ revolves around three elements:
  - MIMOSA telescope for precise measurement of the tracks (but bad timing measurement $\approx 115\mu s$)
  - FEI4 chip with sensor (used in ATLAS tracker) to reach a timing precision of 25 ns
  - The Device Under Test (DUT) itself.
- Events are defined using a Trigger Logic Unit (TLU) that distributes the triggers and the readout systems of the different hardware components are combined using the EUDAQ software.





Telescope alignment

- 6 telescope planes with a pixel size of $18.4 \times 18.4 \mu m^2$ are used for tracking reaching a resolution of $3 \mu m$ on the DUT plane.
- Telescope is roughly aligned by hand and the 6 positioning parameters of each plane are then computed by minimizing the residues on each plane.

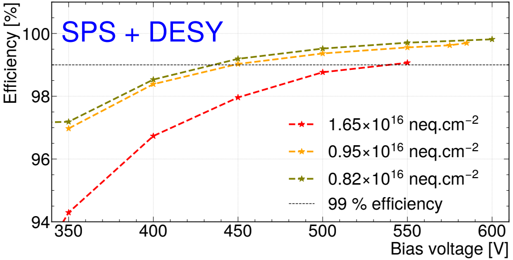


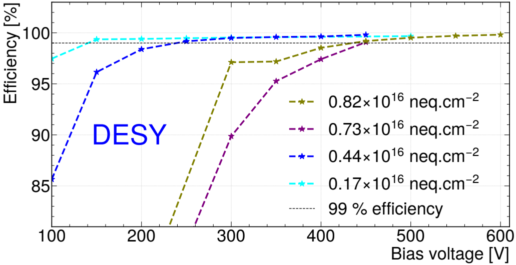
- Efficiency ε defined as

$$\varepsilon = \frac{\text{Number of detected tracks}}{\text{Total number of tracks}}$$

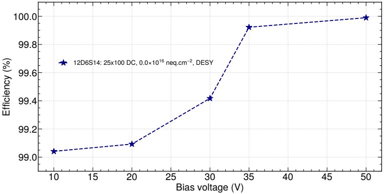
- 99 % efficiency reached consistently for sensors irradiated up to fluences of 2×10^{16} neq.cm^{-2} within the required bias interval.
- Different sensors tested in different environments (SPS and DESY) at similar irradiation levels have very similar efficiency curves.

Irradiated sensors





Fresh sensor



Charge collection

- Energy deposition by charged particles crossing a medium can be described by the following equation

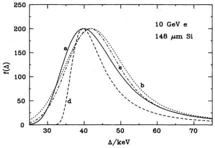
$$\frac{\partial f}{\partial x} = \int_0^\infty W(E)\,(f(x,\Delta - E) - f(x,\Delta))\,\mathrm{dE}$$

where $f(x,\Delta)$ is the probability of depositing the energy Δ when crossing a material of thickness x and $W(E)$ is the probability per unit path length of transferring an energy E to the medium.

- $W(E)$ is computed using the Bethe-Bloch formula and the distribution of charge deposition is then a Landau function with MPV

$$\Delta_p = \zeta\left(\ln\frac{2mc^2\beta^2\gamma^2}{I} + \ln\frac{\zeta}{I} + j - \beta^2 - \delta(\beta\gamma)\right)$$

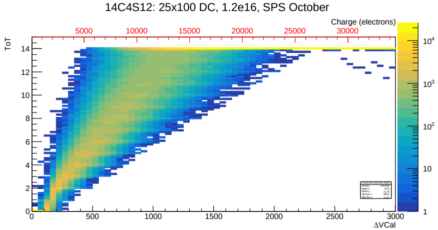
- If the incoming particles are electrons, the computations are much tougher (low mass, interchangeability of incoming and target particles, ...) $\rightarrow$ detailed papers (Bichsel):

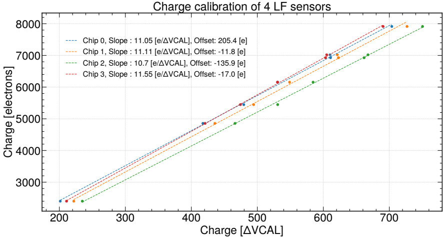


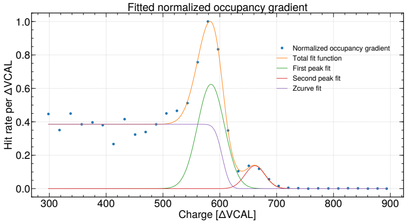
$\rightarrow$ 10 GeV incoming electrons deposit around 41 keV in 148 μm thick silicon, a charge of 11400 e

Charge calibration

- Measuring the in-pixel charge deposition is a 3-step process.
- Step 1: Measure the relation between ToT and the charge measured by the chip (VCAL).
- Step 2: Measure the relation between VCAL and the physical charge using Xray transitions of known energy. The hit rate as a function of the pixel threshold is the integral of the Xray spectrum.
- Step 3: Measure the ToT in testbeam and convert it pixel by pixel to a charge in electrons.

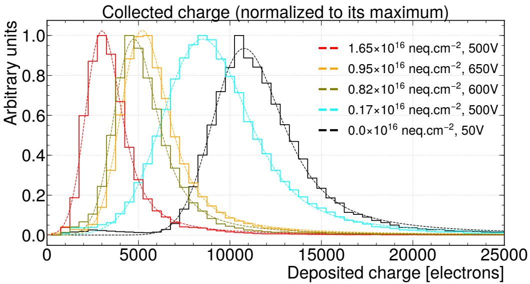




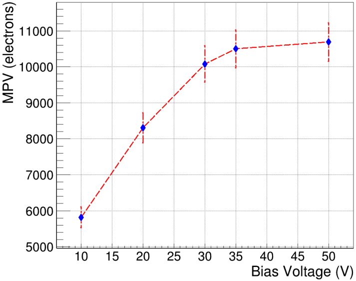


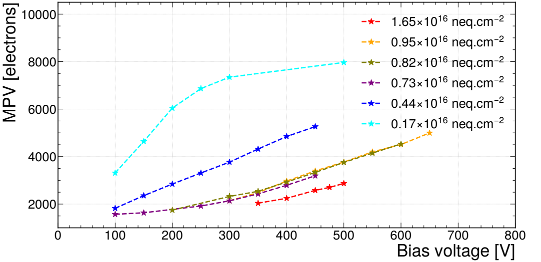
- The total charge deposition per cluster is measured and fitted with a convolution of a Landau and a Gaussian distribution to account for detector noise.
- The charge collection for a fresh sensor is compatible with the theoretical value.
- Reduction of charge collection with increasing fluence.

Irradiated sensors



Fresh sensor





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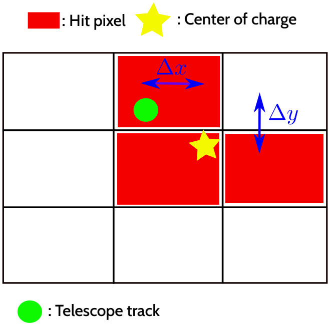
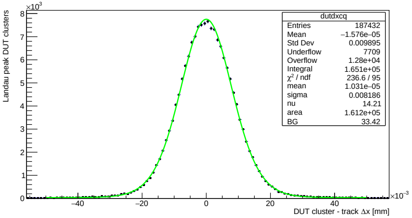
Resolution measurements

- The resolution of a sensor is extracted from the distribution of the residues r defined for each track as: $r = x_{\text{DUT}} - x_{\text{telescope}}$
- The resolution of a hit depends on the DUT and the telescope resolution

$$\sigma_{\text{hit}} = \sqrt{\sigma_{\text{DUT}}^2 + \left(\frac{\sigma_{\text{telescope}}}{\cos(\theta)}\right)^2}$$

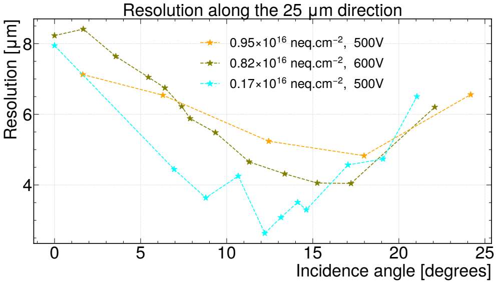
- The standard deviation σ_{hit} is extracted from a fit to the distribution of the residues and $\sigma_{\text{telescope}}$ is obtained from simulation yielding σ_{DUT}.

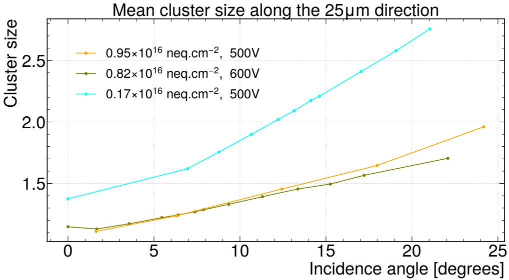




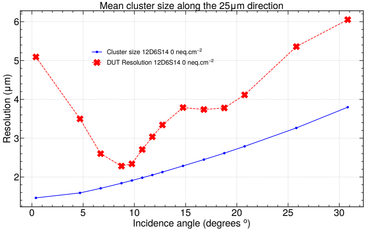
Irradiated sensors

- ➜ Resolution improves with increasing 2-pixel charge sharing.
- ➜ Resolution is worsened by 3-pixel (and larger) clusters because of threshold effects and non-linear charge sharing.
- ➜ Resolution at optimal angle goes from 2μm for an unirradiated sensor to around 5μm for a fluence of 1.2×10^{16} neq.cm^{-2}.



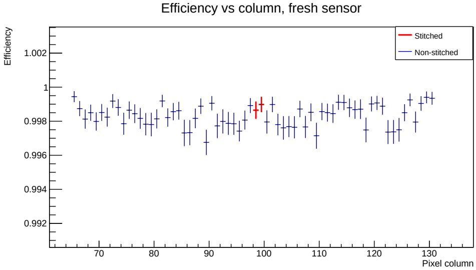


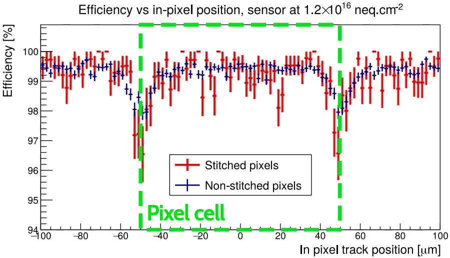
Fresh sensor

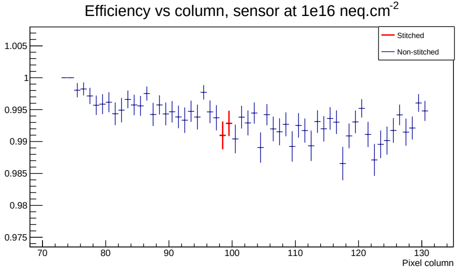


Stitching

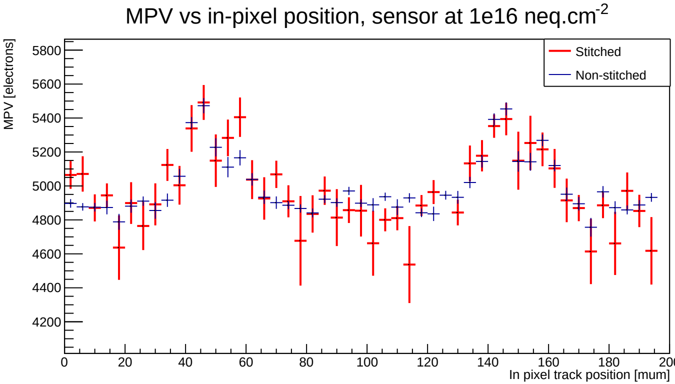
- Important aspect to test: does stitching locally degrade the performance of the sensor ?
- Per column efficiency shows no difference to other columns for fresh of irradiated sensors.







- ➜ In-pixel measurement of charge collection for the columns adjacent to the stitching line is not lower than the other columns
- ➜ In-pixel charge collection modulation because of the increased maximal charge range when it is divided into 2 pixels (no ToT saturation).



Summary

- ➜ The passive CMOS technology is promising in terms of cost and throughput.
- ➜ The performances of the sensors match the requirements for the HL-LHC Inner Tracker Upgrade.
- ➜ The LFoundry sensor submission has been nominated in the PRR together with 2 other producers for its inclusion in the Invitation to Tender.