DEVELOPMENT OF RADIATION HARD SENSORS

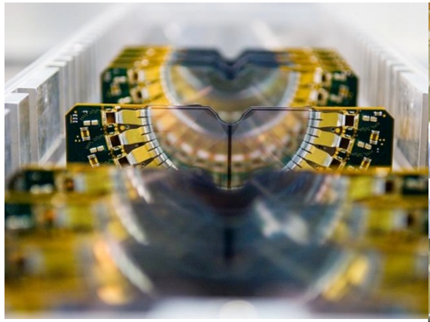
P. Riedler
CERN

Present LHC Tracking Sensors

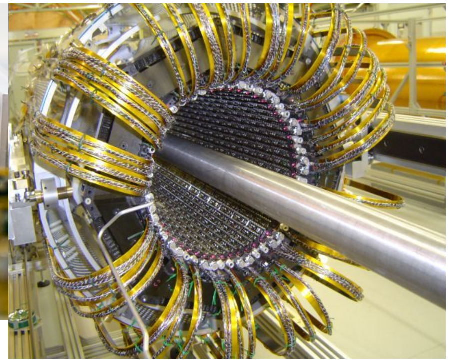
Silicon tracking detectors are used in all LHC experiments:

Different sensor technologies, designs, operating conditions,….

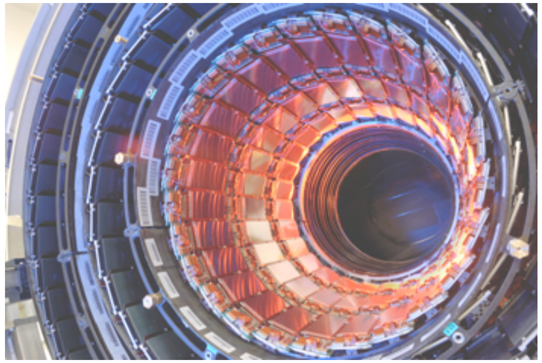
ALICE Pixel Detector



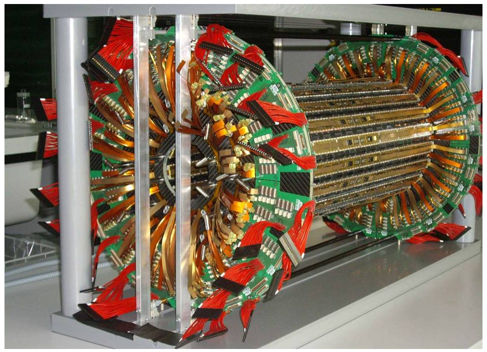
LHCb VELO



ATLAS Pixel Detector

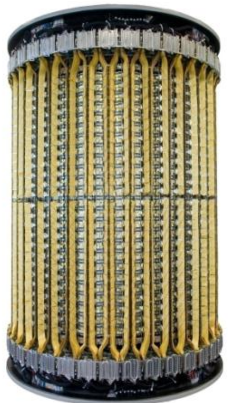


CMS Strip Tracker IB

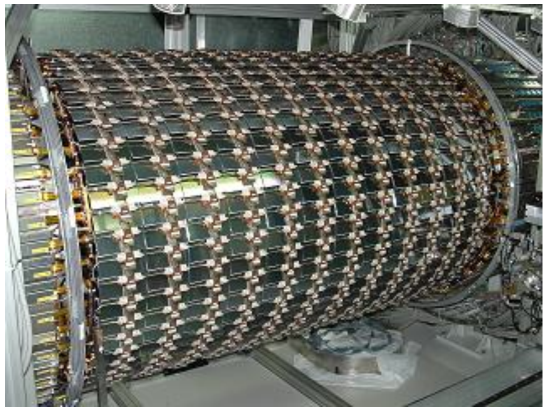


CMS Pixel Detector

ALICE Drift Detector



ALICE Strip Detector

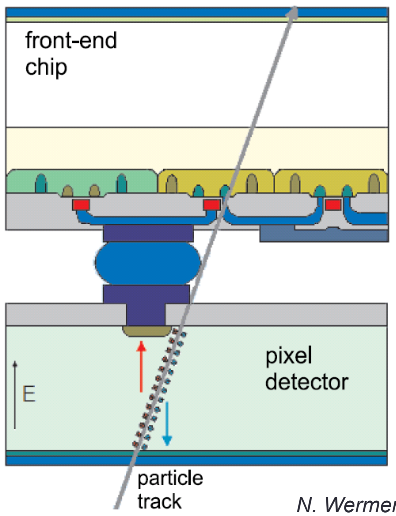


ATLAS SCT Barrel

Silicon-Sensors

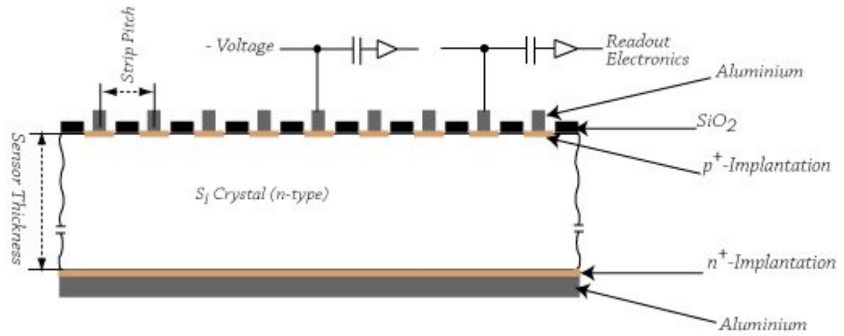
All present sensors produced in a **planar process:**

- High resistivity wafers (few kΩcm), 4”- 6” diam. O(200-300 μm) thick
- Specialized producers (~10 world wide) no industrial scale production like in CMOS processing
- Sensor prices scale roughly with the number of mask layers (single sided and double sided processing)
- **Inner tracker regions: pixel sensors** (areas ~ 2 m^2, fluences ~ 10^{15} n_{eq} cm^{-2})
- **Outer tracker regions: strip sensors** (areas up to 200 m^2, fluences ~ 10^{14} n_{eq} cm^{-2})



N. Wermers/Univ. of Bonn

*ALICE uses also silicon drift detectors (2 layers)

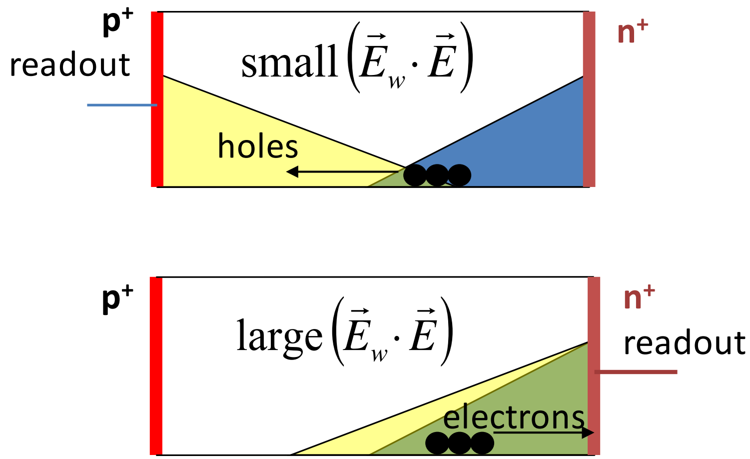


Thomas Ferbel. Experimental Techniques in High Energy Physics. Addison-Wesley Publishing Company, Inc.,1987

Sensor Technology in Present Experiments

- p-in-n, n-in-p (**single sided process**)
- n-in-n (**double sided process**)
- Choice of sensor technology mainly driven by the **radiation environment**

	Fluence 1MeV n_{eq} [cm^{-2}]	**Sensor type**
ATLAS Pixel*	1 x 10^{15}	n-in-n
ATLAS Strips	2 x 10^{14}	p-in-n
CMS Pixels	3 x 10^{15}	n-in-n
CMS Strips	1.6 x 10^{14}	p-in-n
LHCb VELO	1.3 x 10^{14}**	n-in-n, n-in-p
ALICE Pixel	1 x 10^{13}	p-in-n
ALICE Drift	1.5 x 10^{12}	p-in-n
ALICE Strips	1.5 x 10^{12}	p-in-n



G. Kramberger, Vertex 2012

n-side readout (n-in-n, n-in-p):
- Depletion from segmented side (under-depleted operation possible)
- Electron collection
- Favorable combination of weighting field and
- Natural for p-type material

** per year

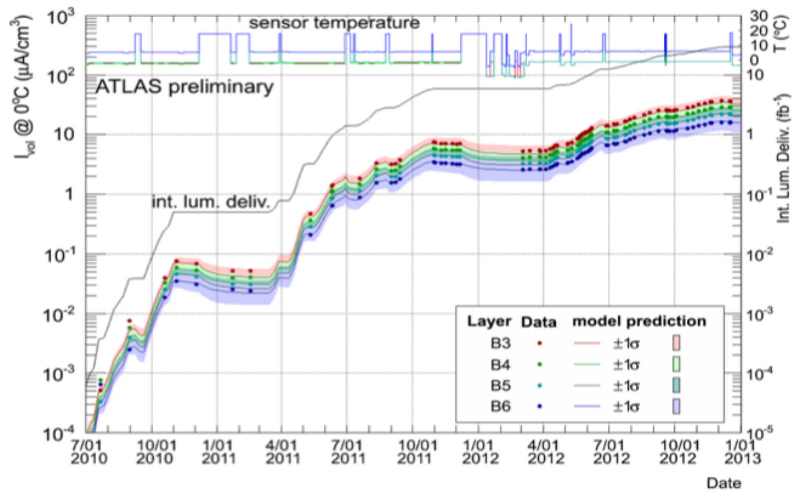
Radiation Damage Effects in Sensors

- Effects observed in ATLAS, CMS and LHCb (lower luminosity in ALICE)
- **Main challenge for the sensors is an increase in leakage current:**
  - Risk of thermal runaway -detector becomes inoperable
    - Operate sensors at low temperatures (see talk by B. Verlaat)
  - Increase in shot noise - degraded performance
- Leakage current increases with integrated luminosity in agreement with the predictions

- **Further effects:**
  - Sensor depletion voltage changes with radiation damage
  - Loss of signal due to radiation induced damage

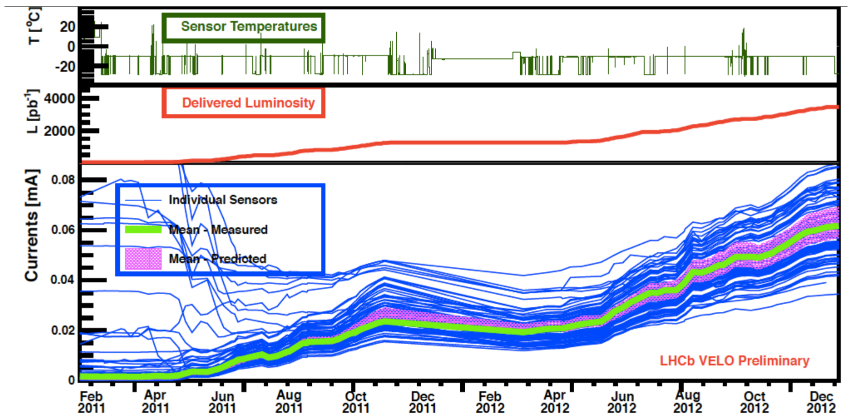
Effects will increase for HL-LHC

Leakage current vs. integrated luminosity (examples)



ATLAS SCT Barrel
H. Pernegger, LHCP 2013

Excellent agreement over 4 orders of magnitude, need a good knowledge of inputs (L,flux,T).



LHCb VELO
H. Snoek, Hiroshima 2013

Key Sensor Issues for the Upgrades

- **Radiation damage** will increase to several 10^{16} n_{eq} cm^{-2} for the inner regions in ATLAS and CMS
  - Example of common activities to develop radiation harder sensors within the RD50 collaboration
  - Operational requirements more demanding (low temperature and all related system aspects)
- **Increased performance:**
  - Higher granularity
  - Lower material budget
- **Control and minimize cost**
  - Large areas
  - Stable and timely production

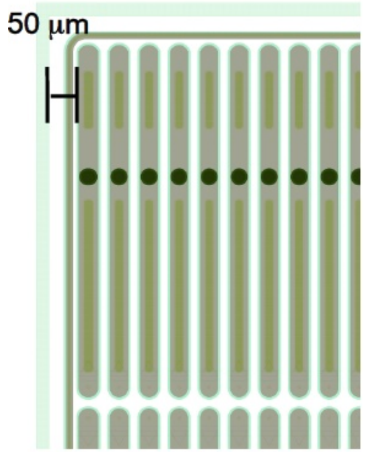
Upgrades	Area	Baseline sensor type
ALICE ITS	10.3 m^2	CMOS
ATLAS Pixel	8.2 m^2	*tbd*
ATLAS Strips	193 m^2	n-in-p
CMS Pixel	4.6 m^2	*tbd*
CMS Strips	218 m^2	n-in-p
LHCb VELO	0.15 m^2	*tbd*
LHCb UT	5 m^2	n-in-p

Sensor R&D – Main Areas (selection)

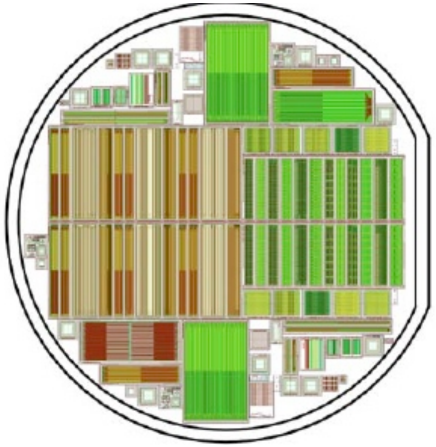
- **Planar sensors** (pixels and strips):
  - n-in-p sensors
  - Optimized designs
  - Reduced edge regions
  - Thinner sensors

- **"Novel" concepts:**
  - 3D detectors
  - CMOS sensors
  - Work on diamond continues

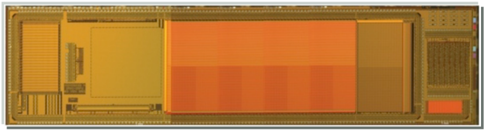
- **Simulation and study of radiation induced macroscopic changes**
  - Better understanding and prediction of the effects, improved designs



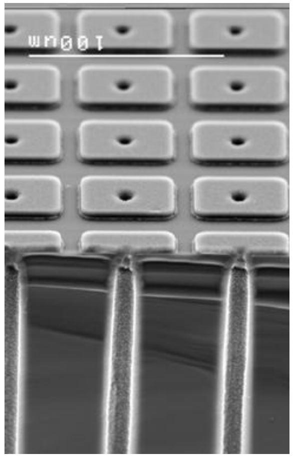
Slim active edge sensor for ATLAS
A. Macchiolo, Hiroshima 2013



CMS Tracker Sensor Campaign



ALICE ITS prototype CMOS sensor MIMOSA32

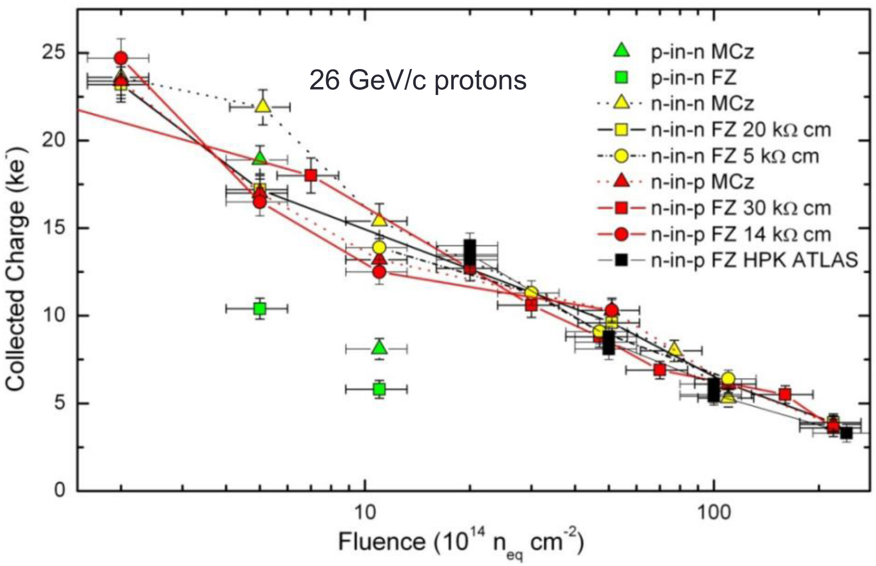


3D sensor
S. Kuehn, NSS 2012

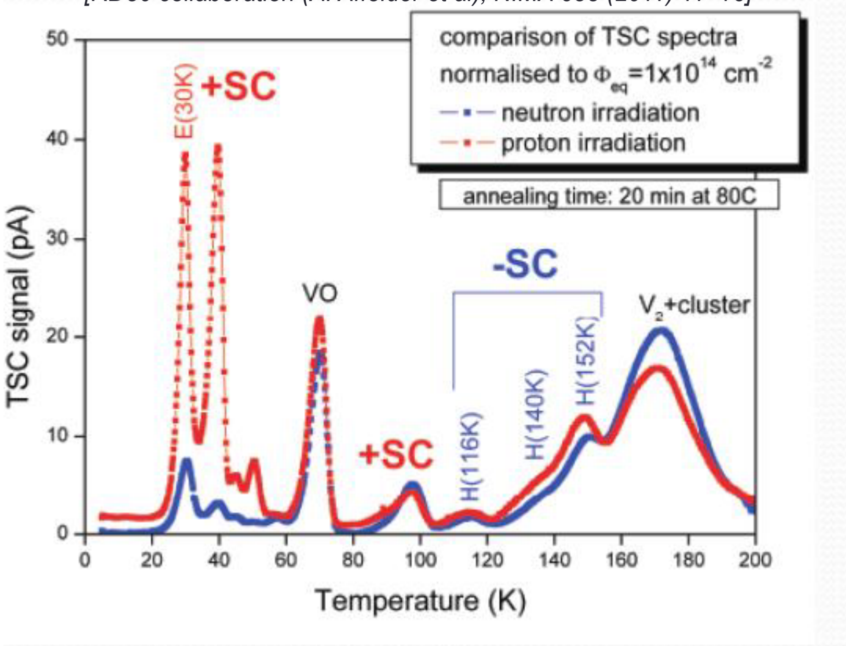
Radiation Defect Study and Simulation

- In depth **understanding of the defects – allows prediction of effects and improvements in design and material**
- Effort led by RD50 collaboration
- Systematic measurement and simulation (TCAD and custom)

[A. Affolder et. al., Nucl. Instr. Meth. A, Vol.623 (2010), 177 – 179]

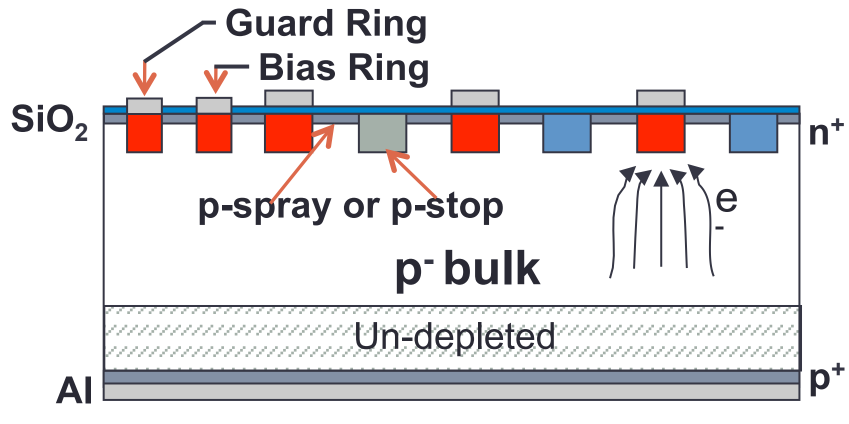


[RD50 collaboration (A. Affolder et al), NIMA 658 (2011) 11–16]

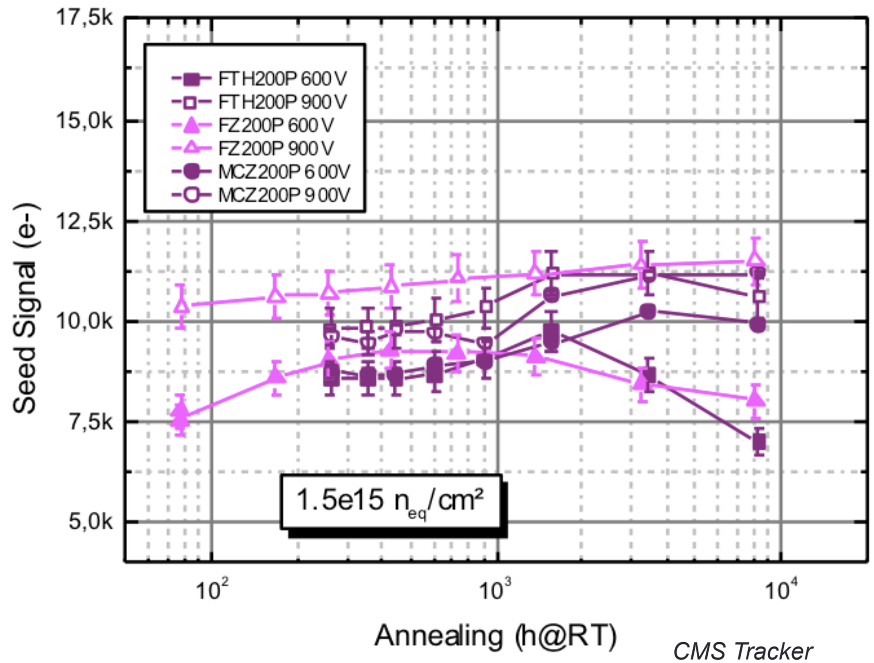


n-in-p Sensors

- **n-side readout**
  - Collection of electrons
  - Fast signal, less trapping
- **As n-in-n sensors depletes from the segmented side**
  - Under-depleted operation possible
- Flat annealing behaviour after high radiation
- **Single sided process**
  - Electrode isolation needed (p-spray, p-stop), no back side patterning
  - Cheaper than n-in-n (~30-40 % less)
  - More foundries available
- **E.g. adopted as baseline for ATLAS and CMS outer tracker upgrade**



N. Unno, Trento 2012

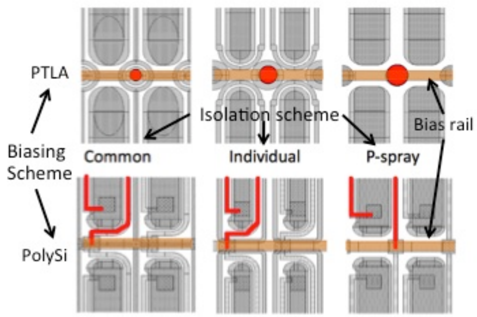


CMS Tracker From D. Eckstein

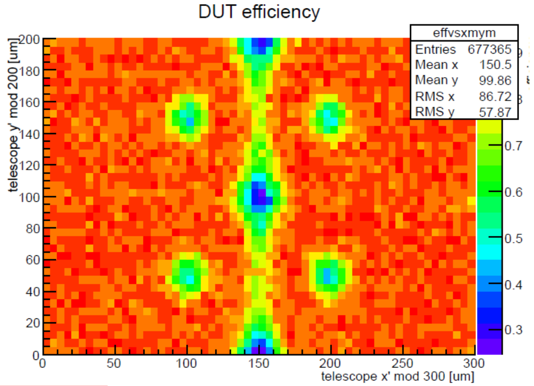
Planar Sensors at few 10^{15}-10^{16} 1MeV n_{eq}

Further improve planar sensors for high fluence operation:

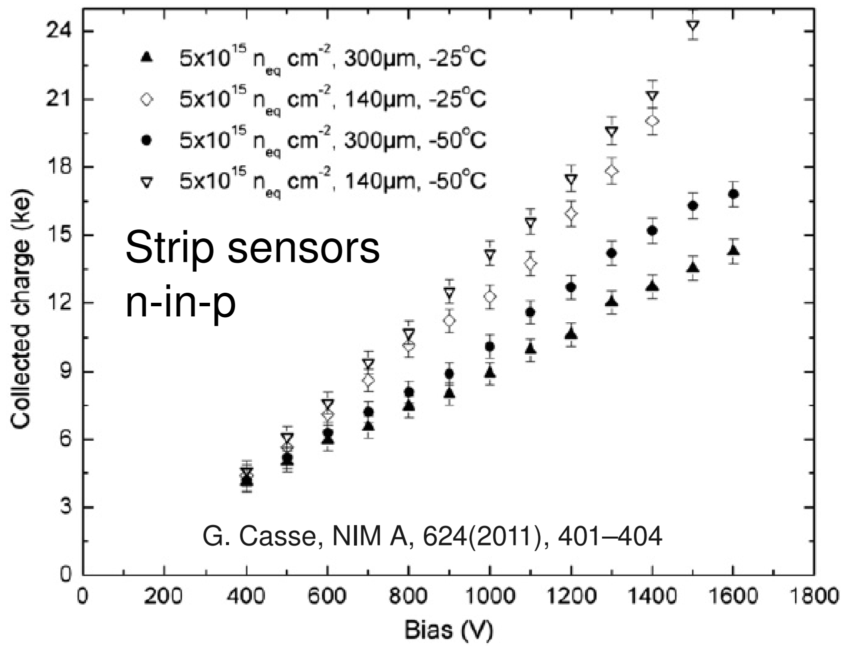
- **Optimize design**
  - e.g. bias structures, isolation
- **Thin sensors**
  - Reduced material budget
  - Reduced leakage current
  - At high bias voltage charge multiplication effects in n-in-p sensors observed
  - Long term behaviour under study
  - Increased leakage current and noise
  - Efforts to exploit effect by design engineering (e.g. trenches or modified implants)



ATLAS-HPK (N. Unno, Trento 2012)



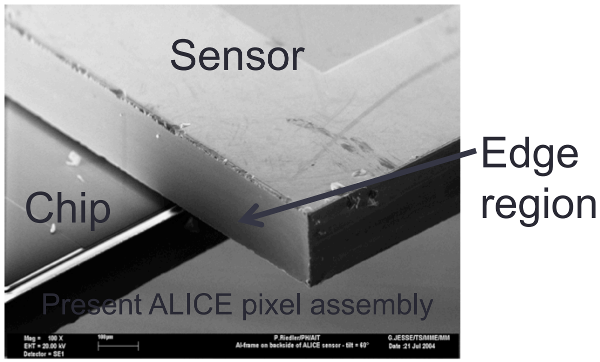
CMS preliminary

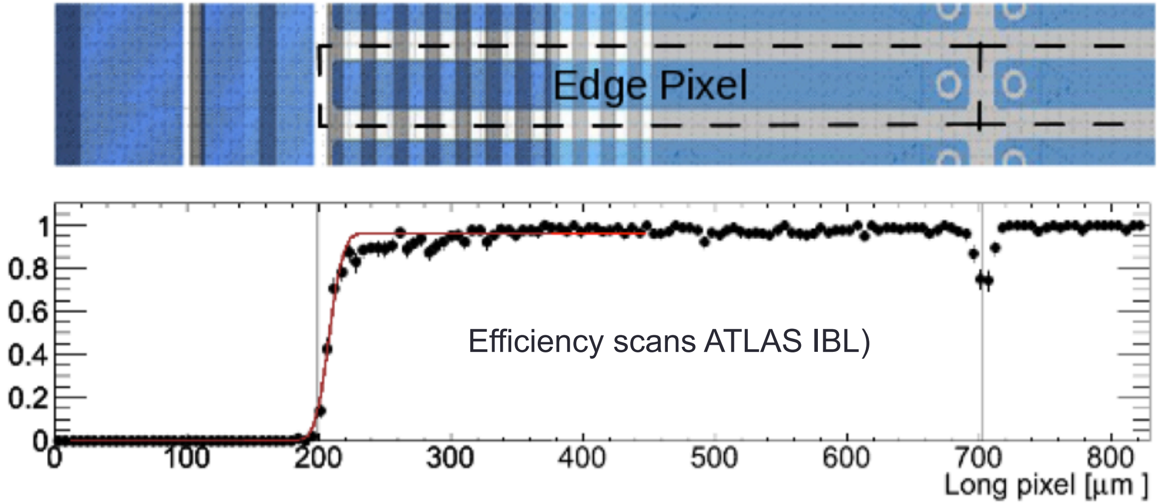


Slim-Edge and Edgeless Sensors

- **Guard rings are located in the edge region of the sensor to degrade the potential to the edge – insensitive region**
- **Reduce the edge** of the silicon sensors to allow for better overlap with less material

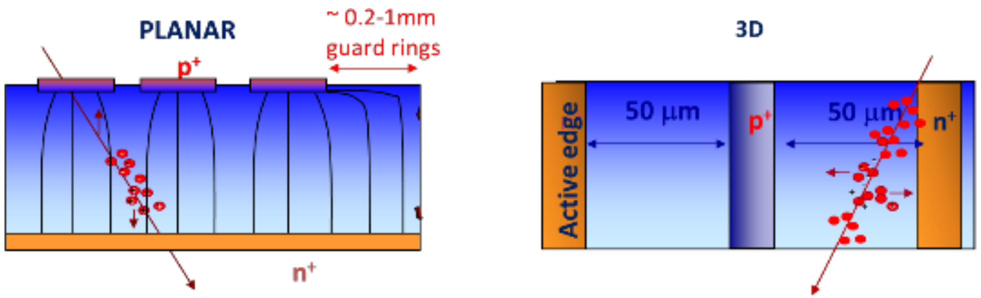
- **Several techniques under study:**
  - Shifted guard rings (used for ATLAS IBL n-in-n planar sensors)
  - 3D electrodes in the edge region (used for ATLAS IBL 3D sensors)
  - SCP (Scribing, Cleaving, edge Passivation)
  - Active edge sensors with sideways implantation



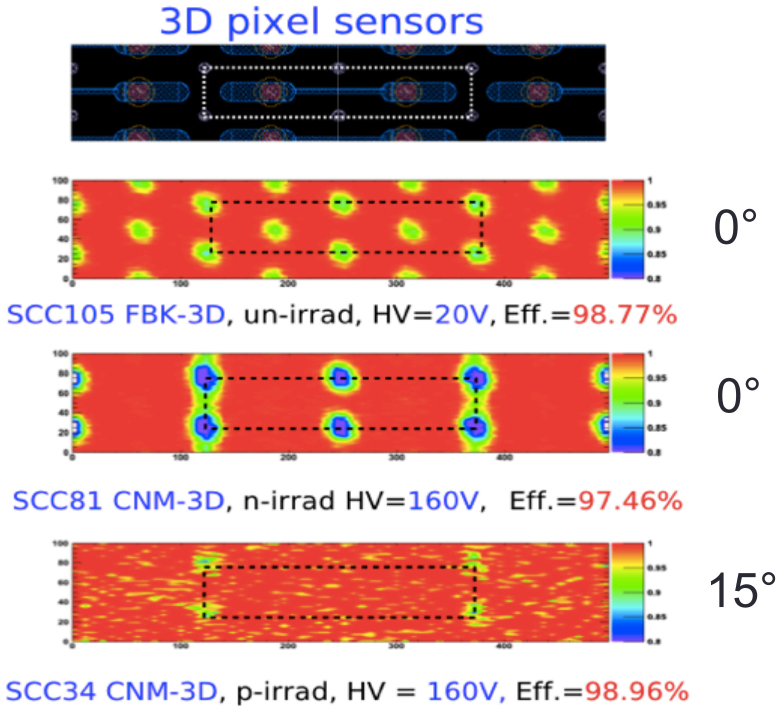


From: "Prototype ATLAS IBL Modules using the FE-I4A Front-End Readout Chip" (JINST 7 (2012) P11010)

3D Sensors



- **Both electrode types are processed inside the detector bulk**
- Max. drift and depletion distance set by electrode spacing **- reduced collection time and depletion voltage**
- **Very good performance at high fluences**
- Production time and complexity to be investigated for larger scale production
- Used in ATLAS IBL



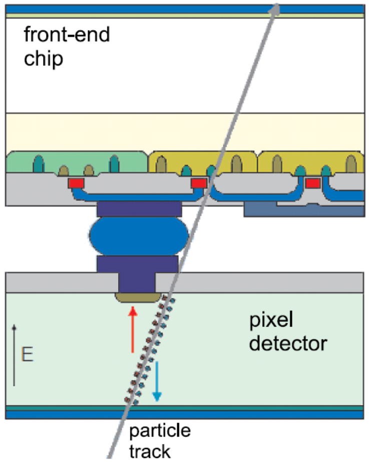
ATLAS IBL Sensor (Threshold: 1600 e
p-irrad: 5×10^{15} n_{eq}/cm^2 with 24 MeV protons
n-irrad: 5×10^{15} n_{eq}/cm^2 by nuclear reactor)

From: *Prototype ATLAS IBL General Meeting*, S. Tsiskaridze (IFAE-Barcelona)

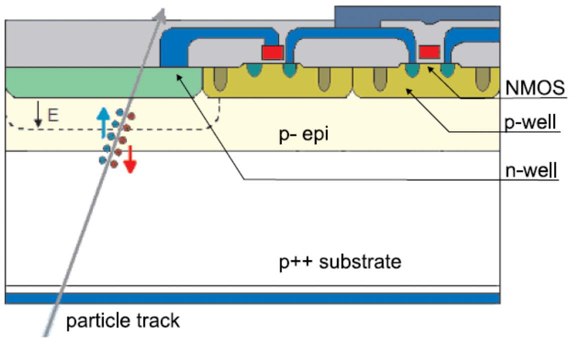
CMOS Sensors

- CMOS sensors **contain sensor and electronics combined in one chip**
  - No interconnection between sensor and chip needed
- Standard CMOS processing
  - Wafer diameter (8")
  - Many foundries available
  - Lower cost per area
  - Small cell size – high granularity
  - Possibility of stitching (combining reticles to larger areas)
- Very low material budget
- CMOS sensors installed in STAR experiment
- Baseline for ALICE ITS upgrade (and MFT, LOI submitted to LHCC)

Hybrid Pixel Detector



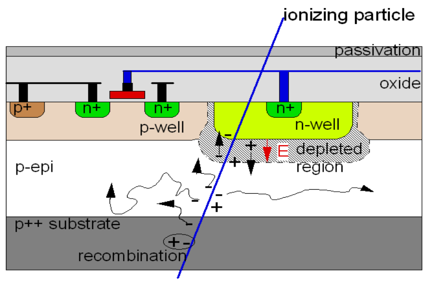
CMOS (Pixel) Detector

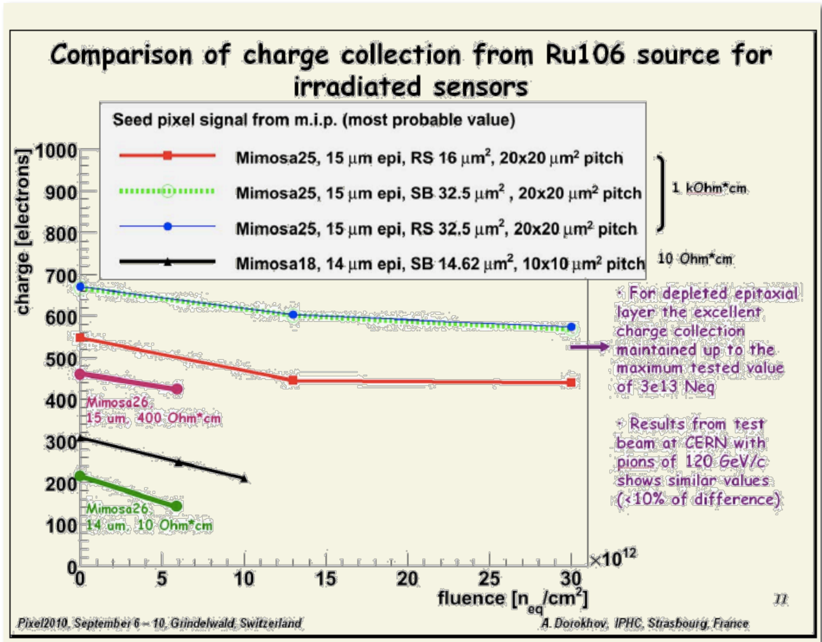


CMOS Sensors

Traditional sensor, examples: MIMOSA, MIMOSTAR,..

- Only few transistors per cell (size ~ 20 um x 20 um)
- Rolling shutter architecture (**readout time O(100 μs)**)
- **0.35 μm CMOS technology** with only one type of transistor
- Charge collection by diffusion
- **Limited radiation tolerance for "traditional sensors"** < 10^{13} n_{eq} cm^{-2}





A. Dorokhov et al. (IPHC Stassbourg)
Taken from W. Snoeys, Hiroshima 2013

Achieving better radiation tolerance

- Moving to deeper sub-micron CMOS
- Changing to collection by drift (higher resistive material and bias)

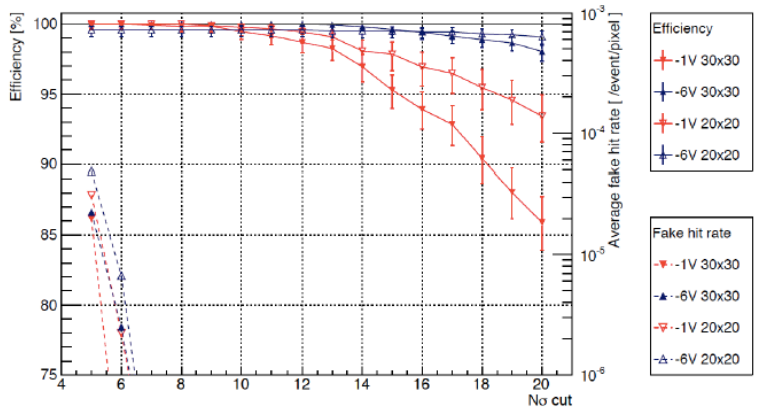
Other improvements:

- Investigate different architectures
- Optimize power management

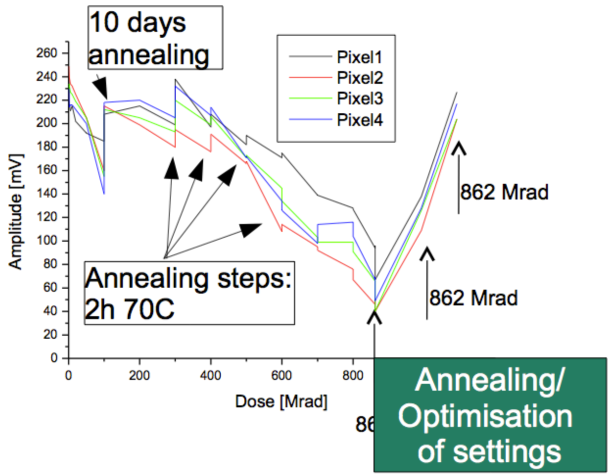
CMOS Sensor Developments

- **Many different variations under study (examples):**
  - CMOS process with deep p-well (for ALICE ITS upgrade)
  - HV-CMOS process
  - CMOS process with back side junction
  - Silicon on Insulator technology
- **Encouraging new results also for radiation tolerance,** but further work needs to be done

Examples:



ALICE Explorer 1 irradiated to 10^{13} n_{eq} cm^{-2}
(C. Cavicchioli, Hiroshima 2013)



CCPD2 chip irradiated with X-rays to 862 Mrad
(I. Peric, Hiroshima 2013)

Summary

R&D activities on sensors in different areas

- **Planar sensors and novel structures:**
  - Common developments on material and simulation within RD50
  - Many interesting developments for high fluence environment: thin sensors, n-in-p, n-in-n, 3D, ...
  - Large scale production for some techniques to be shown
  - Cost and throughput for large areas to be investigated (producers)
- **CMOS sensors**
  - Several techniques under study in parallel (Workshop?)
  - First encouraging results concerning radiation hardness
  - Low cost technology for large area coverage in wafer production
  - Outer layer coverage interesting, but to be shown how to realize this in a power effective design

Common efforts in BOTH areas required to prepare for the next generation of sensors

List of references

Many thanks for providing material:

D. Abbaneo, P. Collins, D. Eckstein, Ingrid M. Gregor, V. Manzari, S. Mersi, M. Moll, D. Münstermann, N. Wermes, H. Pernegger, W. Snoeys...

Material taken from recent conferences and workshops:

- Trento Workshop 2012
- Hiroshima Workshop 2013
- NSS 2012
- VCI Conference 2013
- LHCP 2013
- IAP VII/37 Fundamental Interactions, Gent, 2013