Study of prototypes of LFoundry active and monolithic CMOS pixels sensors for the ATLAS detector

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PSD11, Milton Keynes
07/09/2017

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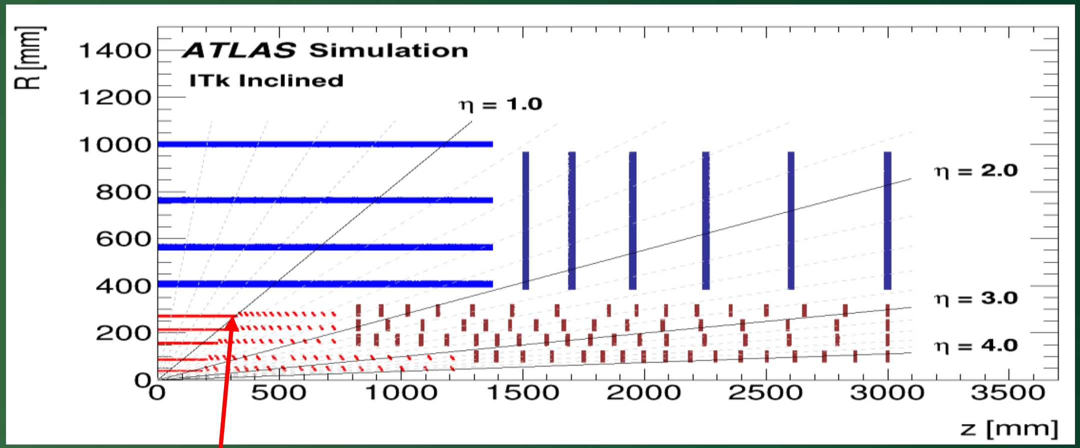
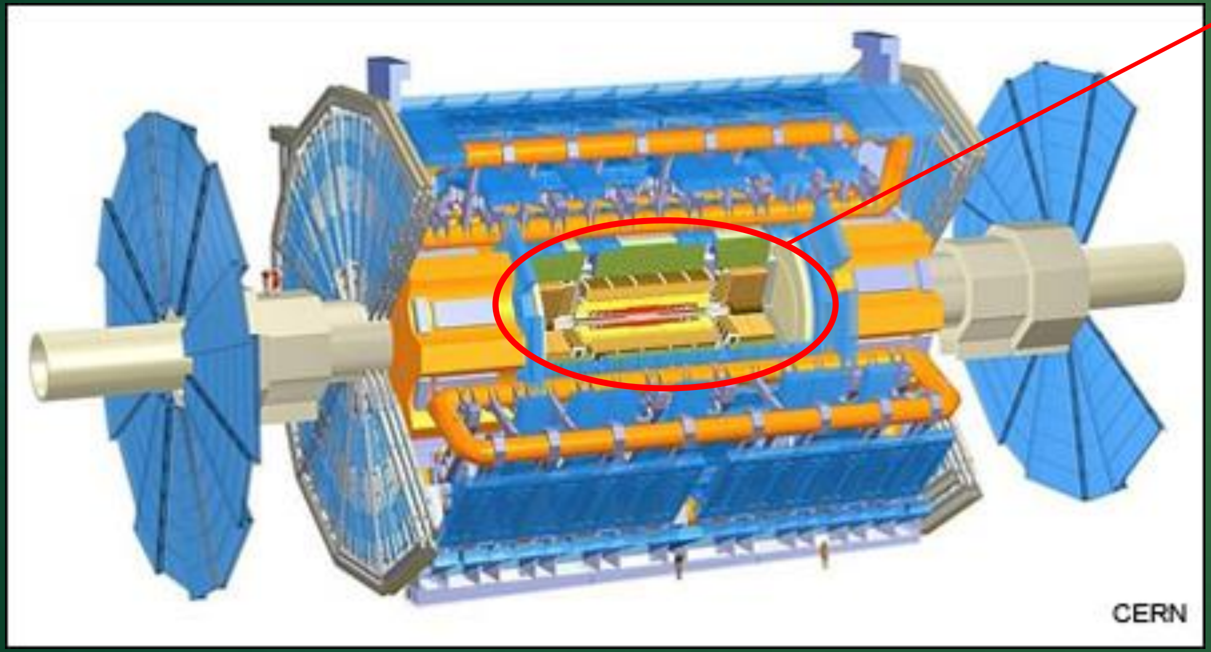
UNIVERSITY OF OXFORD

The ATLAS experiment

- Large multi-purpose HEP experiment
- At LHC, CERN
- Upgraded for HL-LHC (2025+)

ITK: the upgraded tracking system





Inner tracker: Silicon pixel detectors

Outer tracker: Silicon strip detectors

At the last pixel layer (~30 cm from vertex) expected:

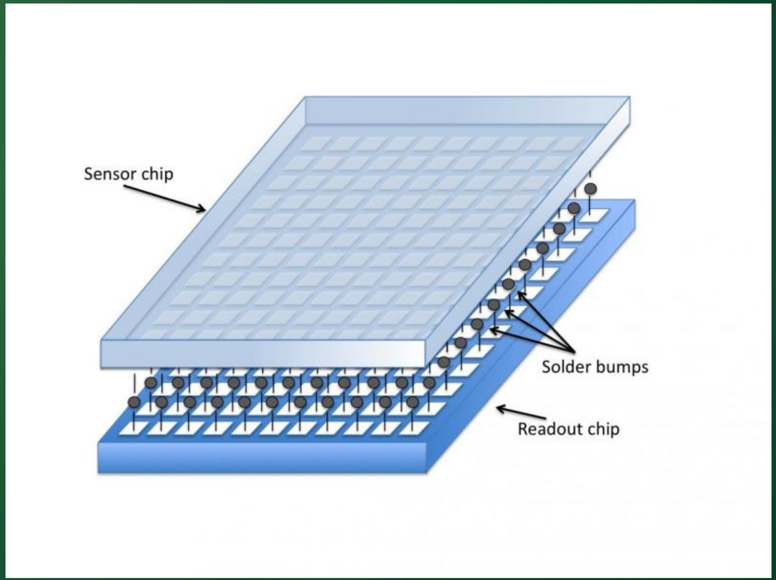
- 80 Mrad Total Ionization Dose
- $1.5 \cdot 10^{15}$ n_{eq}/cm^2 fluence

Bunch crossing: 25 ns

Hybrid Silicon pixel detectors in HEP

- One of the standard technologies for tracking systems in HEP experiments
  - High resistivity Silicon substrate
  - High reverse bias voltage applied

  (the two points above:) High and fast signal (charge $\sim\sqrt{\rho \cdot V}$)
  - Good tolerance to radiation ($\sim 5 \cdot 10^{15}\ n_{eq}/cm^2$)
- Some limitations:
  - Read-out chip bump-bonded to the substrate
  - Expensive and time-consuming process



CMOS detectors

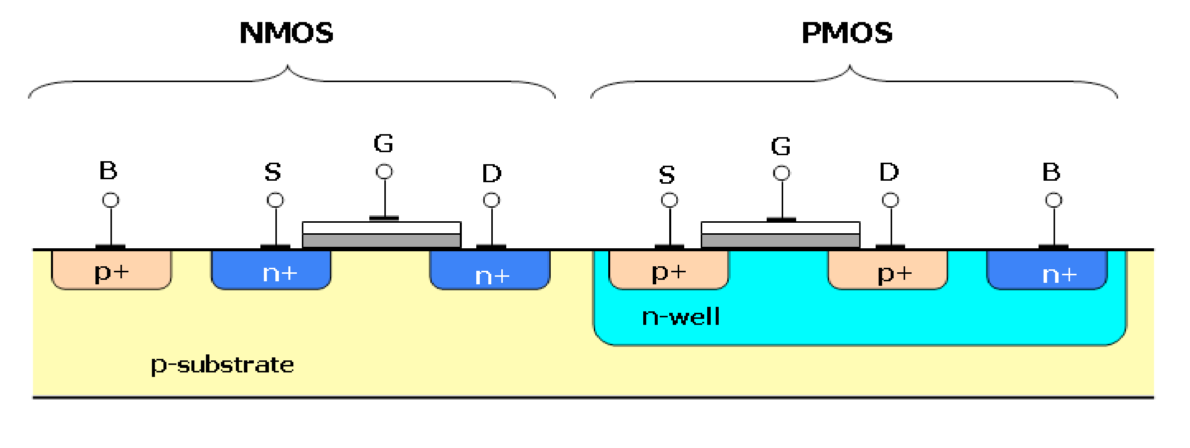
- Read-out integrated with sensor
- Process used in many applications
  - Robust
  - Cheap

But:

- Charge collected via diffusion
  - Slow
  - Low signal
- Radiation tolerant…?

Can we use them in the harsh HEP environment (HL-LHC)?

- Necessity of depleting the substrate
- Some modifications to the standard fabrication process:
  - High resistivity substrate
  - High reverse bias add-ons



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- Read-out integrated with sensor
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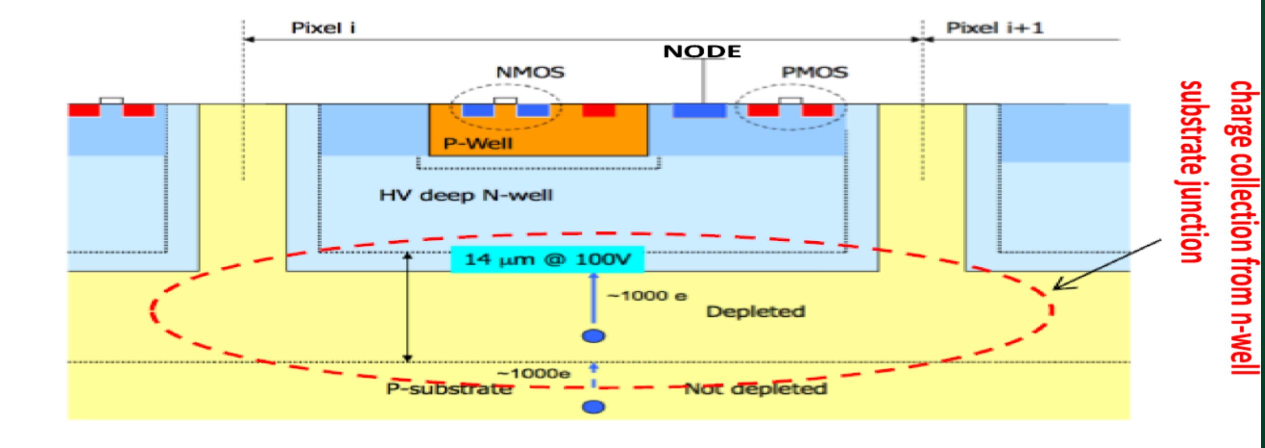
But:

- Charge collected via diffusion
  - Slow (>> 25ns)
  - Low signal
- Radiation tolerant…?

Can we use them in the harsh HEP environment (HL-LHC)?

- Necessity of depleting the substrate
- Some modifications to the standard fabrication process:
  - High resistivity substrate
  - High reverse bias add-ons
    - Deep N-well

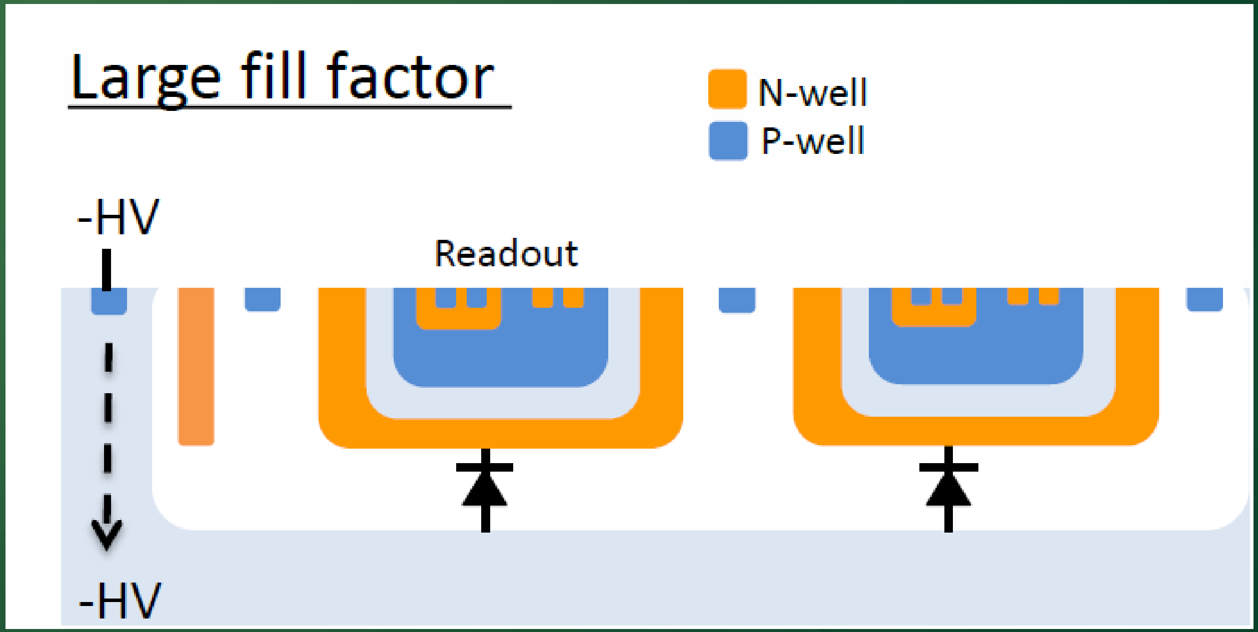


CMOS sensor development in ATLAS

- Large collaboration with many institutions involved
- Sensors produced by 3 foundries currently under investigation:
  - TowerJazz (https://indico.cern.ch/event/615961/contributions/2659613/)
  - ams (https://indico.cern.ch/event/615961/contributions/2659636/)
  - LFoundry → Subject of my talk
- **Goal**: fabricate and test a fully monolithic CMOS module for ATLAS high luminosity upgrade (2025+)

LFoundry process

- High resistivity wafer
- High bias voltage provided by multiple (4) nested wells
- 150 nm technology
  - Radiation tolerant
- Large fill factor approach
  - Read-out inside N-Well
- Back-side process
  - Back biased



LFoundry sensors

CCPD_LF

- Small prototype
  - 5x5 mm^2

LF-CPIX

- Large prototype
  - $9.5x10mm^2$

- CSA and comparator implemented in the sensor
- Can be capacitative coupled to standard R/O chip or single pixel standalone read-out

Active CMOS

- Submitted Sep. 2014
- Submitted Mar. 2016

Design by SiLab Bonn, CPPM Marseille, KIT Karlsruhe and Irfu

SI LAB Silizium Labor Bonn

KIT Karlsruher Institut für Technologie

Centre de Physique des Particules de Marseille CPPM

Irfu - CEA Saclay Institut de recherche sur les lois fondamentales de l'Univers

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Active CMOS

LF-MONOPIX

- Large prototype
  - 9.5x10mm^2
- Full in-pixel read-out (FE-I3)

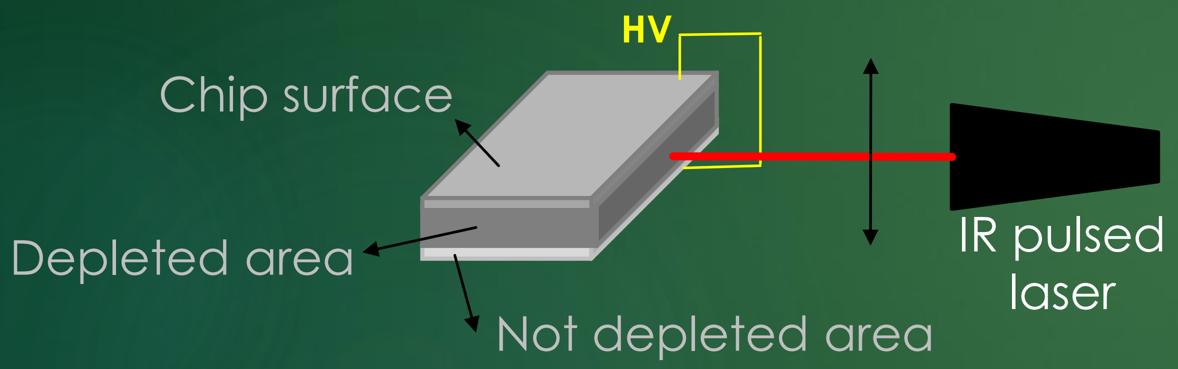
Fully Monolithic

- Submitted Sep. 2014
- Submitted Mar. 2016
- Submitted Aug. 2016

Design by SiLab Bonn, CPPM Marseille, KIT Karlsruhe and Irfu

Tests

- Signal in substrate and depletion with
  - Edge-TCT (Transient Current Technique)

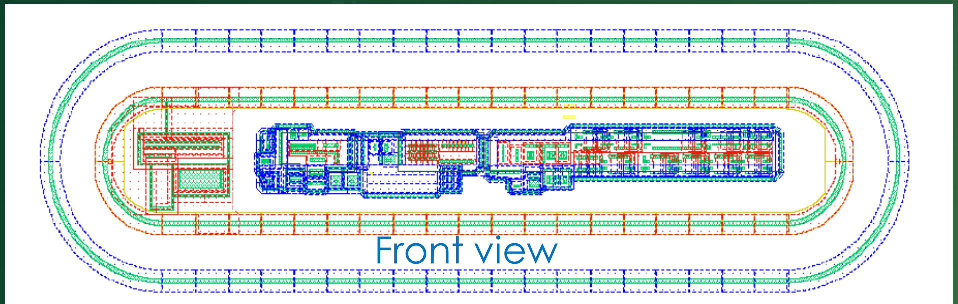


- Test beam
  - ELSA facility (Bonn)
  - 3.2 GeV electrons
  - Telescopes available (MIMOSA or FE-I4)

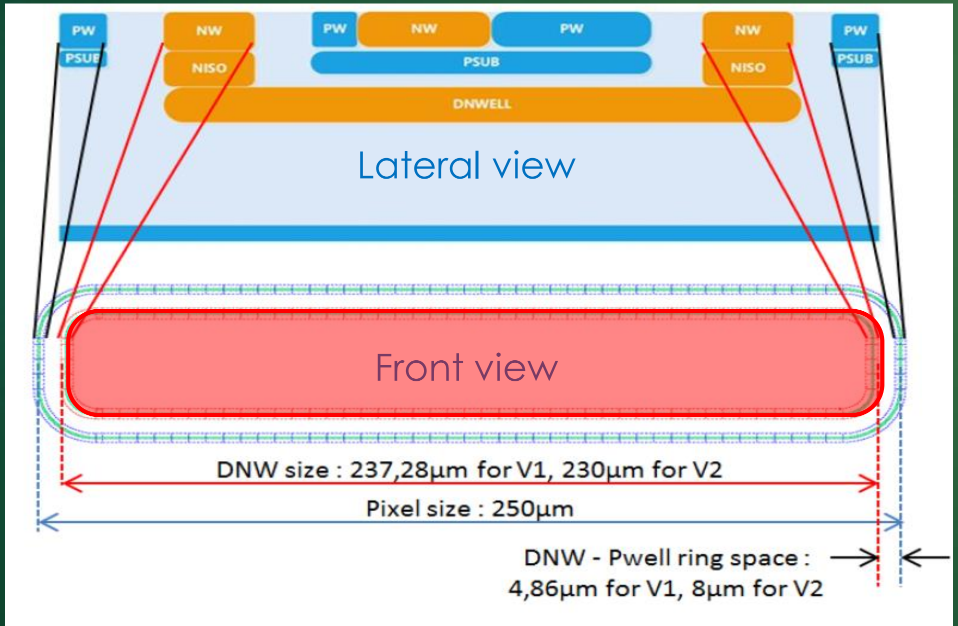
- Gain and noise on active structures
- X-ray characterization
- Different irradiations

Neutrons Protons X-rays

CCPD_LF and LF-CPIX: overview

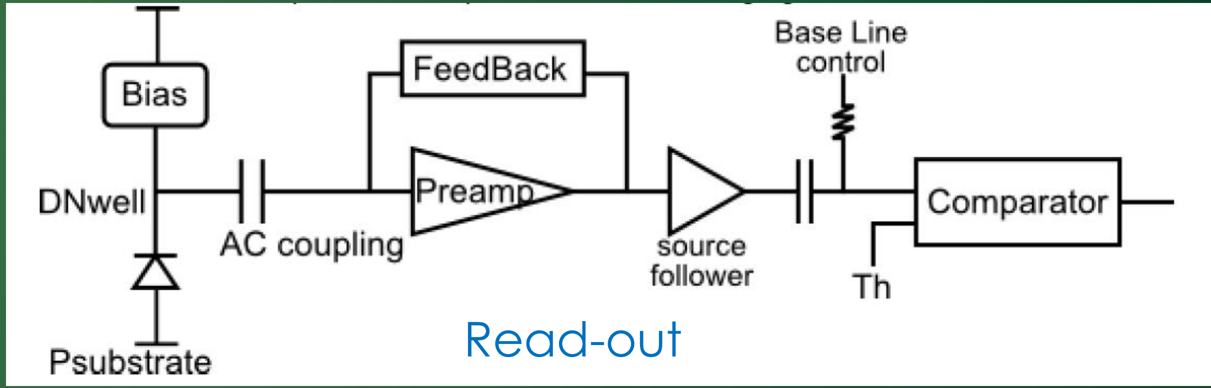


CCPD_LF, size: 125x33 μm²



LF-CPIX, size: 250x50 μm²

Large (>60%) fill factor
Larger signal and collection area
Larger capacitance (noise)



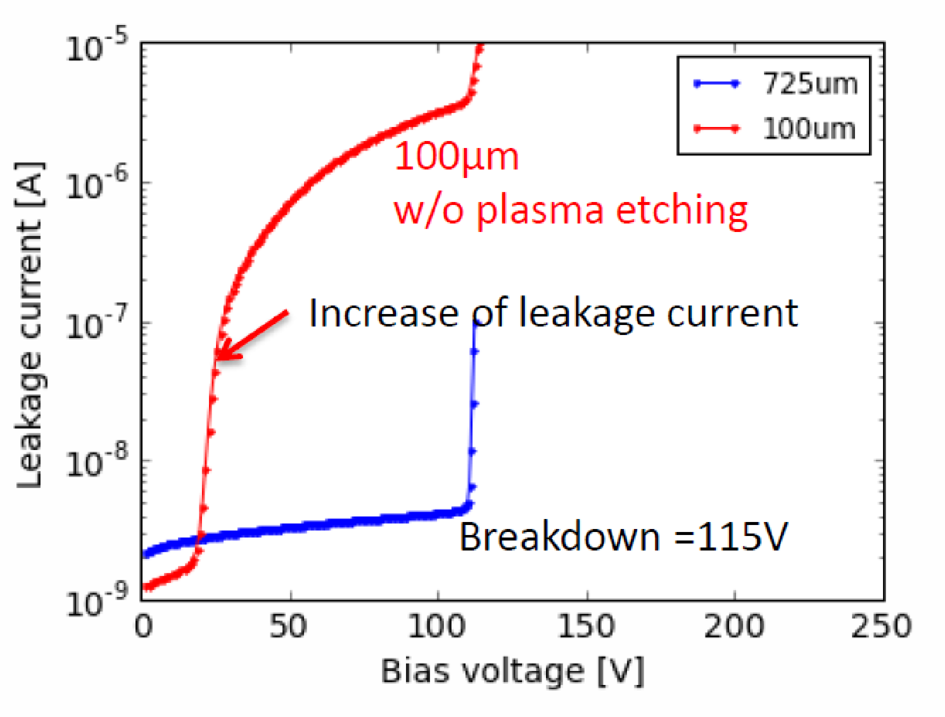
3 "flavours" of Preamp implemented:

NMOS PMOS CMOS

T. Hirono et al, "Characterization of Fully Depleted CMOS Active Pixel Sensors on High Resistivity Substrates for Use in a High Radiation Environment", arXiv:1612.03154

CCPD_LF: pre-irradiation performances

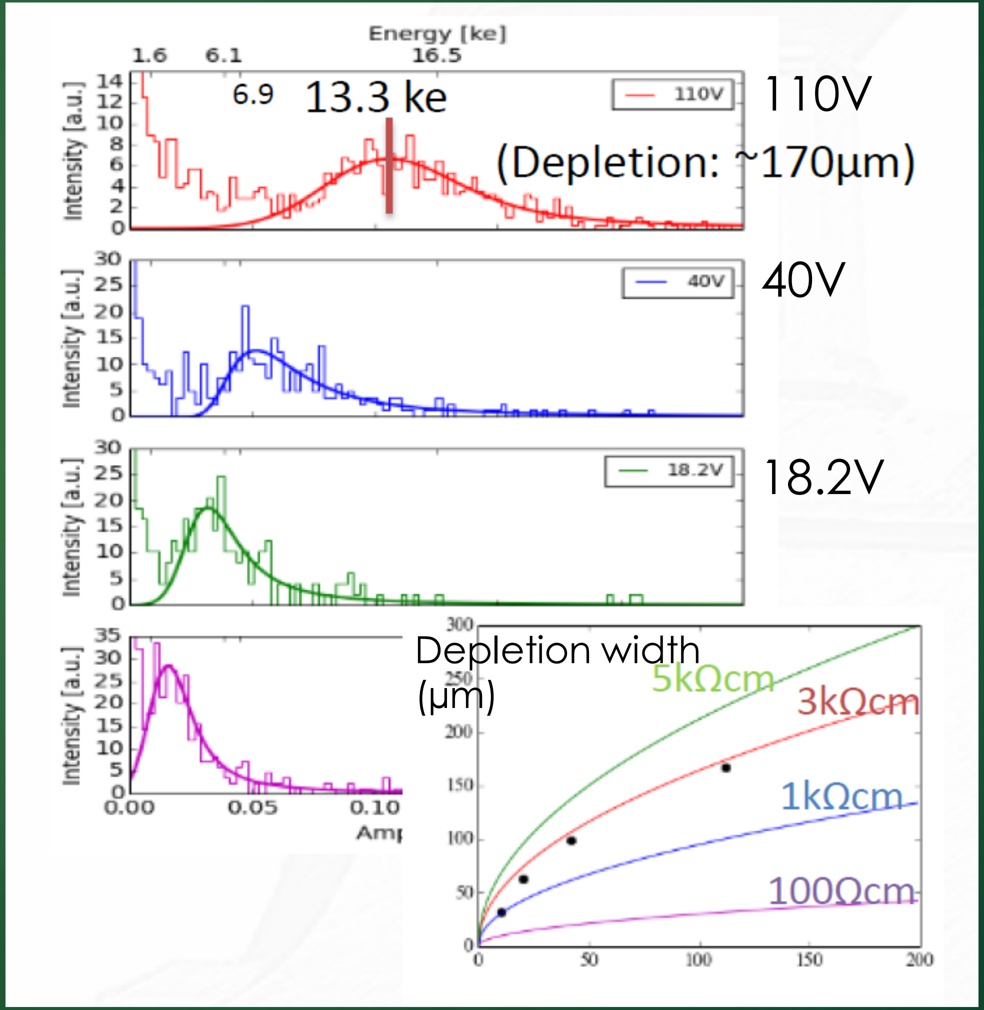
IV curve



100 µm thin sensor thinned with old back-side process

T. Hirono

Charge spectra (3.2 GeV electron beam)

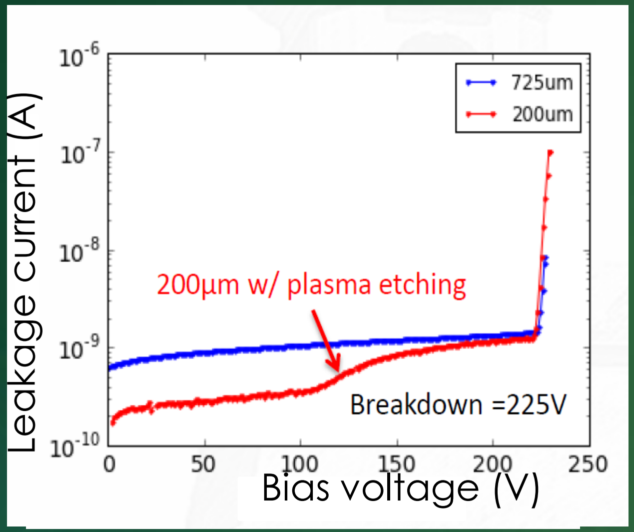


Peak of MIP distribution proportional to depletion depth

Resistivity compatible with ~3kΩ·cm

LF-CPIX: pre-irradiation performances

IV curve

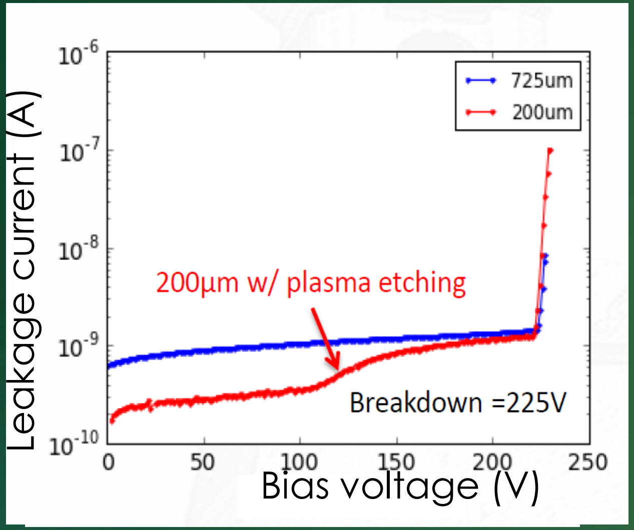


200 µm thin sensor thinned with improved back-side process

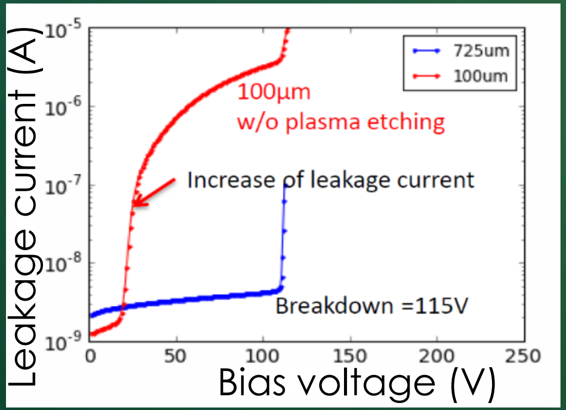
T. Hirono

LF-CPIX: pre-irradiation performances

IV curve



Compare with CCPD_LF



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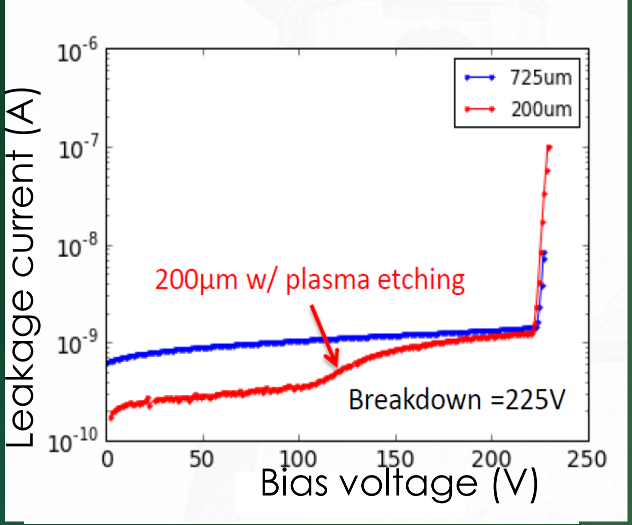
LF-CPIX: pre-irradiation performances

IV curve



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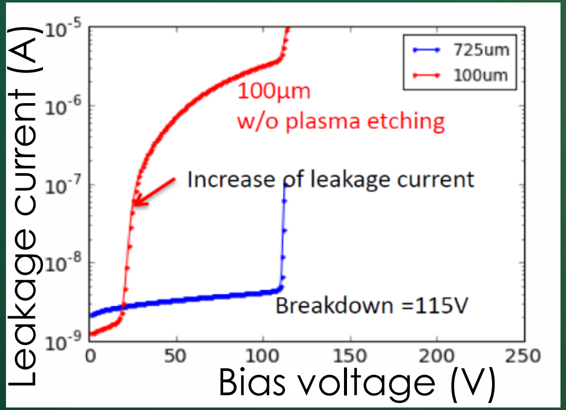

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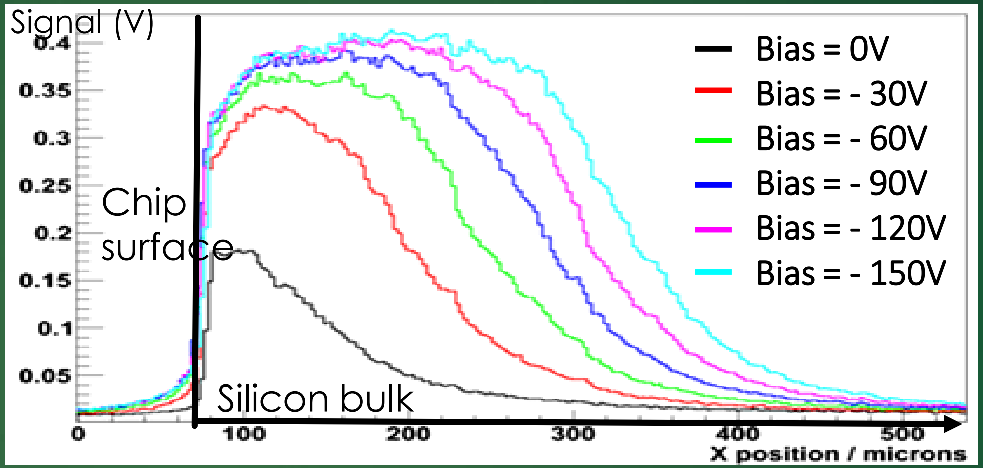
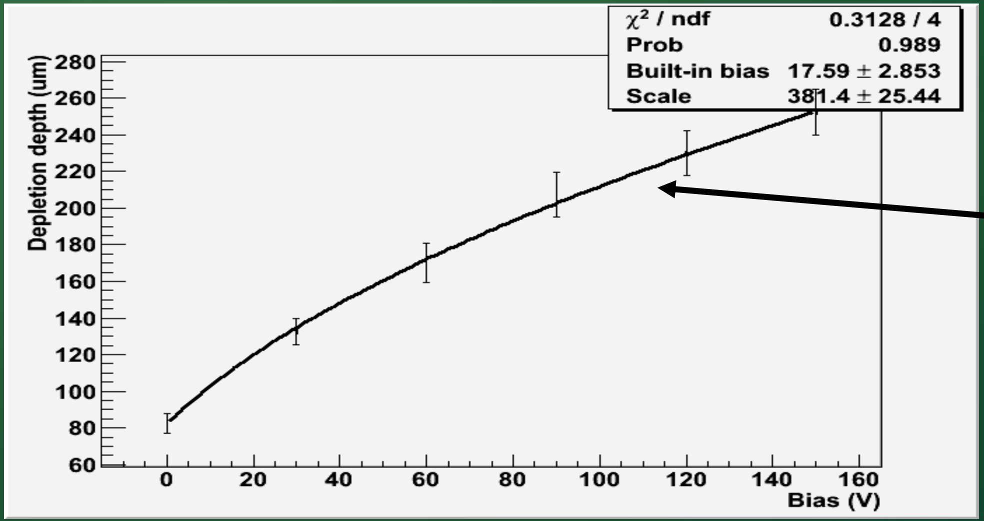
Edge-TCT on active pixels





L. Vigani, L. Ambroz

Charge collected as a function of depth in Silicon bulk (different biases)

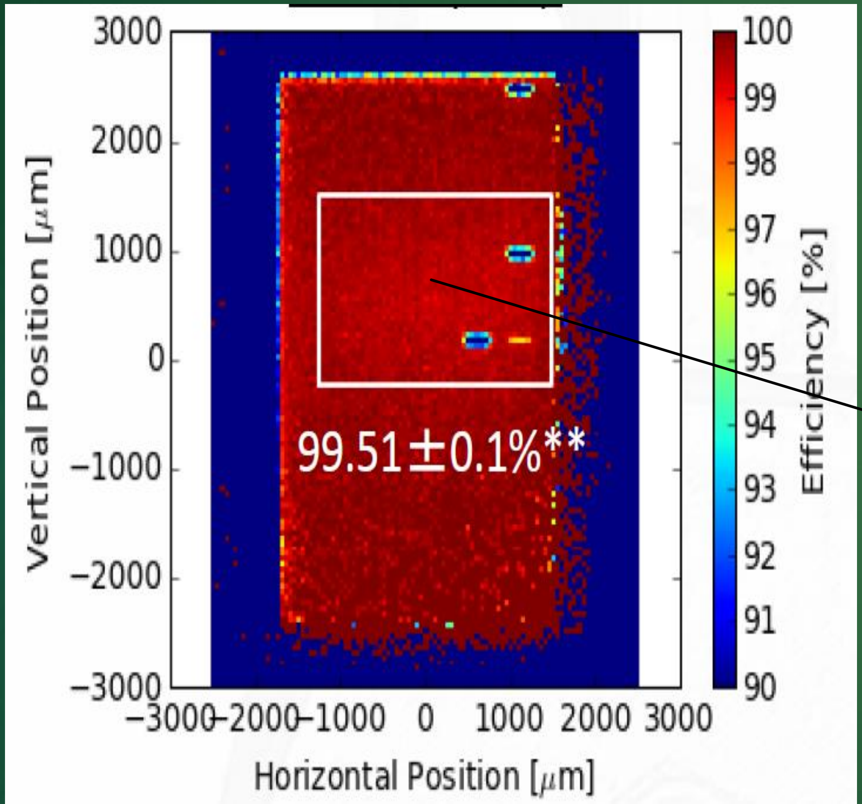
FWHM vs bias

Depletion depth Vs Bias voltage

Fit parameters compatible with 4.2 kΩ ·cm resistivity

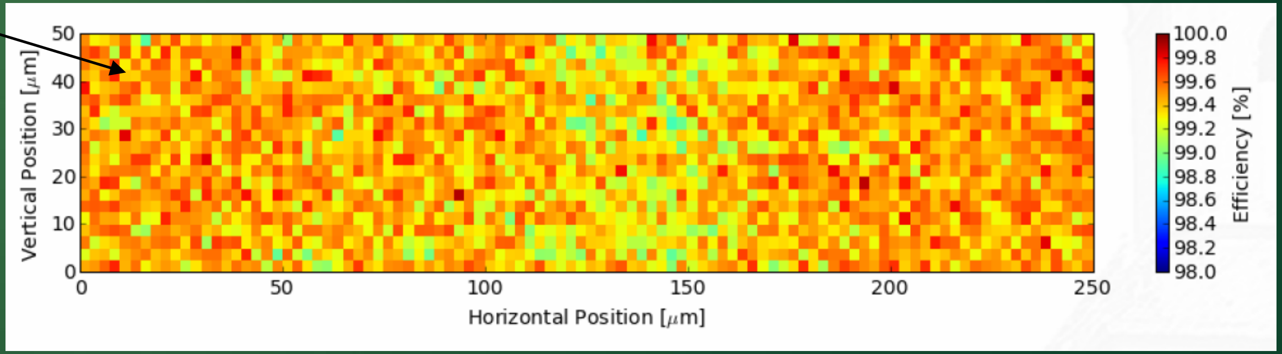
LF-CPIX: pre-irradiation performances

Efficiency (3.2 GeV electron beam + MIMOSA telescope)



(Threshold: 2750e)

In pixel: homogeneous



** excluding masked pixels

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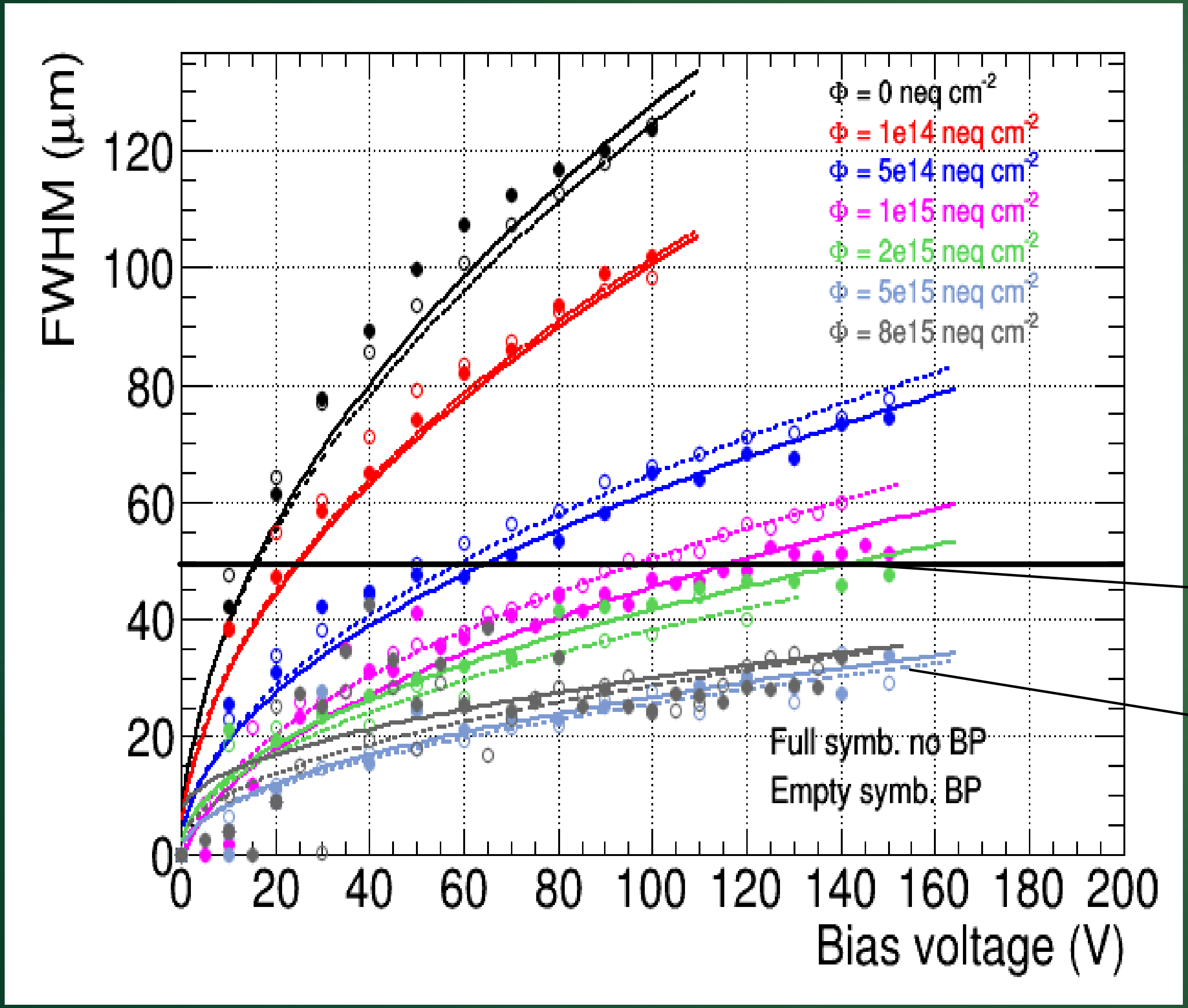
Very promising!

CCPD_LF: neutron irradiation



Charge collection depth measured with edge-TCT

- Passive test structures
- Charge collected in 25ns
- FWHM of signal region

Measurements and irradiation performed at Ljubljana

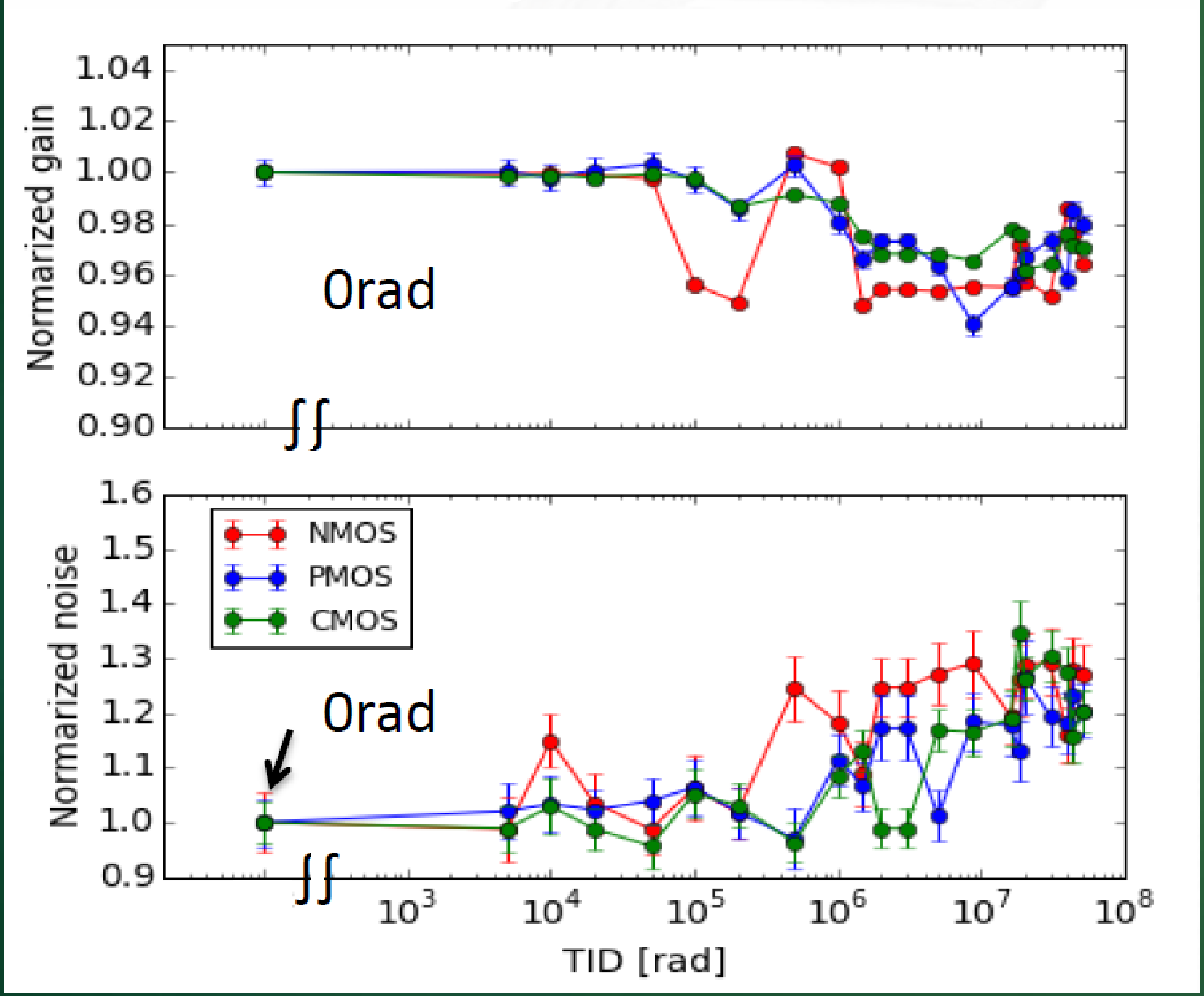
~50 µm depletion after 10^{15} n_{eq}/cm^2

Small depletion after considerable irradiation dose (~$5 \cdot 10^{15}$ n_{eq}/cm^2)

I. Mandić et al., "Neutron irradiation test of depleted CMOS pixel detector prototypes", 2017 JINST 12 P02021

LF-CPIX: X-ray irradiation

Normalized gain and noise vs TID



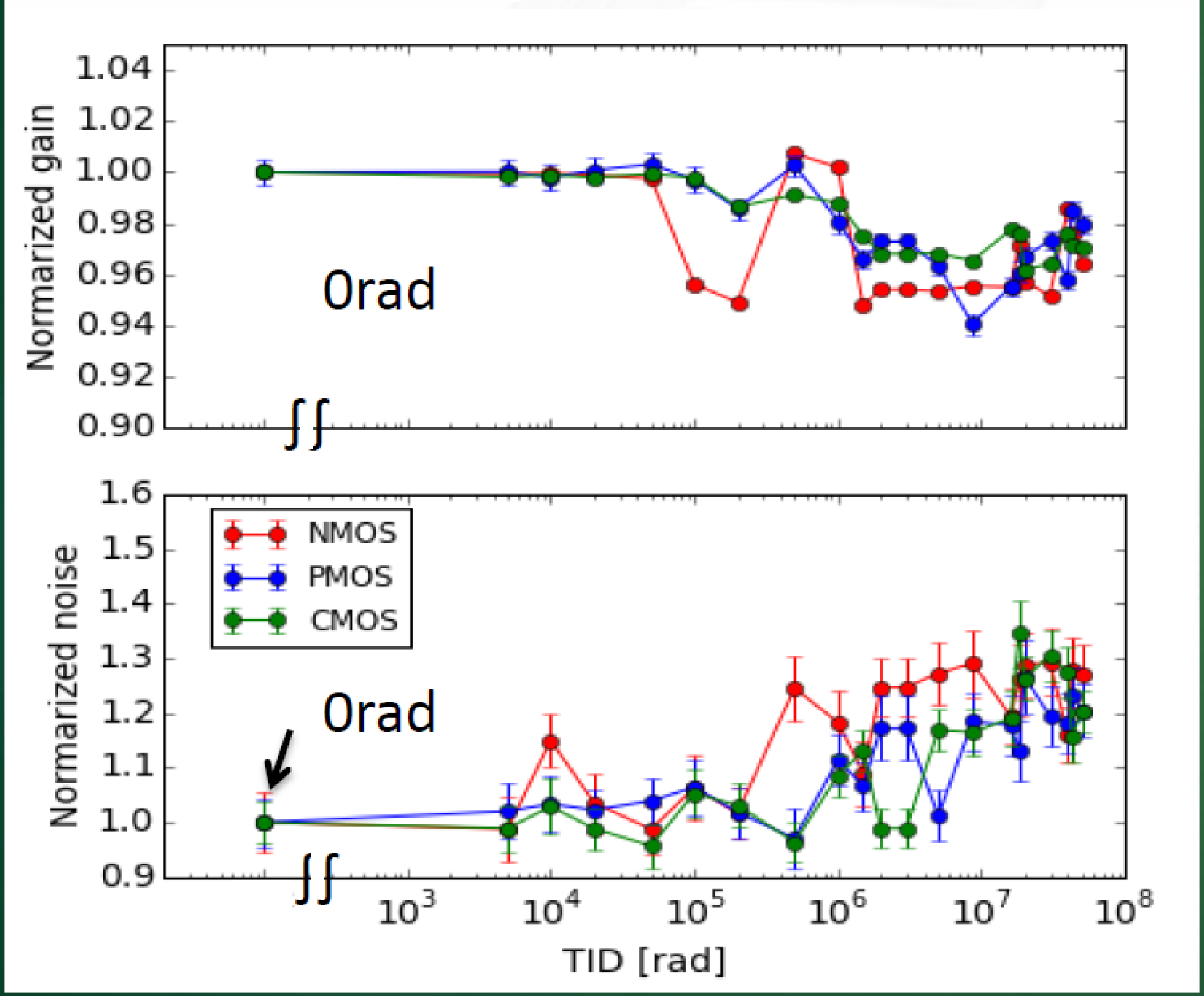
Until 100 Mrad:

- Gain loss < 7%
- Noise increase < 30%
- No significant differences among the 3 flavours

T. Hirono

LF-CPIX: X-ray irradiation

Normalized gain and noise vs TID



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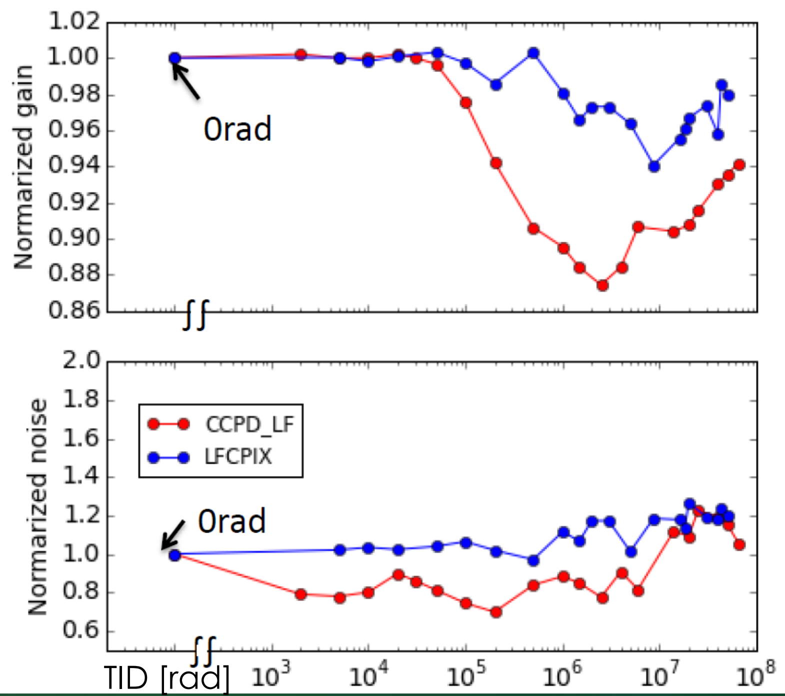
Comparison with CCPD_LF:



Gain:
LF-CPIX > CCPD_LF

Noise:
LF-CPIX ≈ CCPD_LF

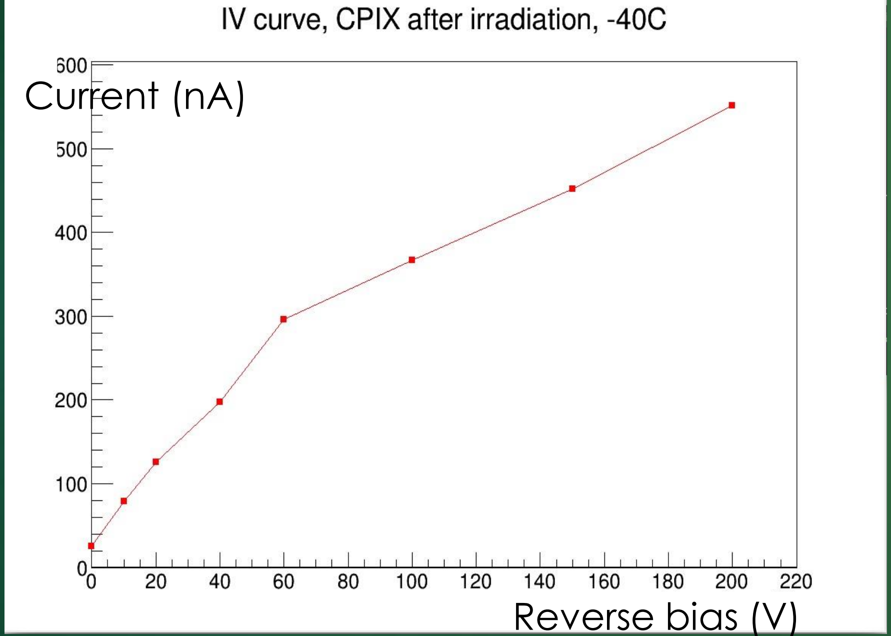
Reason:
larger pixel size…?
Not clear.

T. Hirono

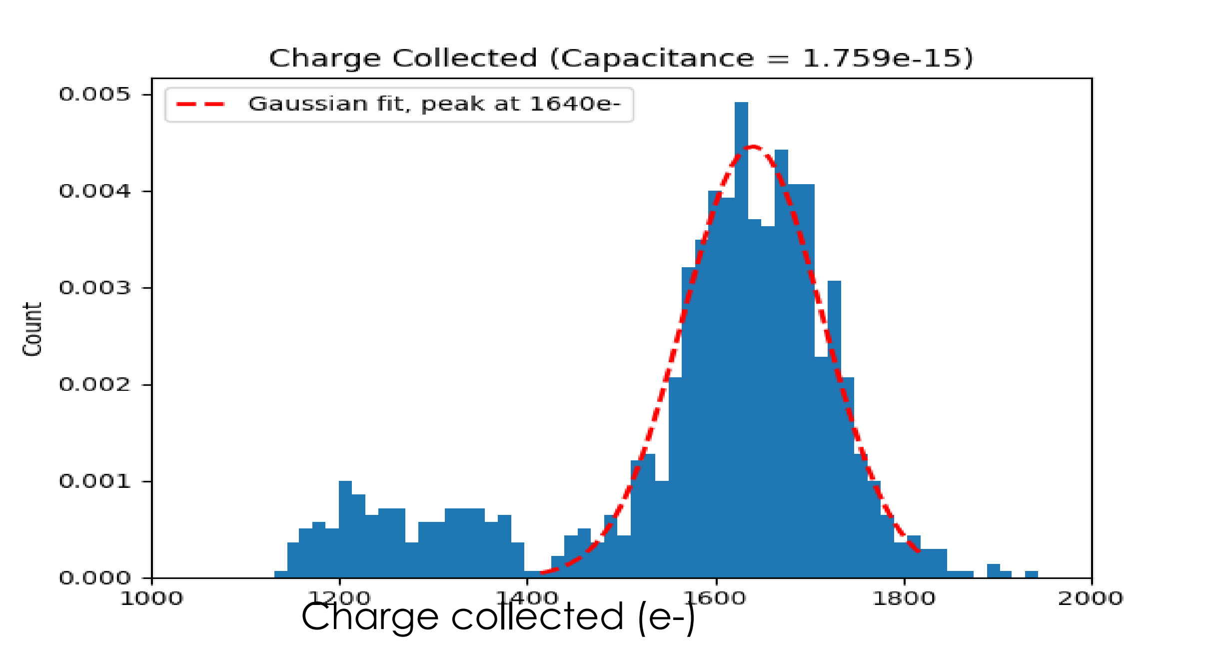
LF-CPIX: proton irradiation

- At Birmingham Cyclotron
- 27 MeV protons
- Fluence: 10^{15} n_{eq}/cm^2
- TID: 133 Mrad

I-V curve



X-ray (Fe^{55})



Good behaviour even after 10^{15} n_{eq}/cm^2

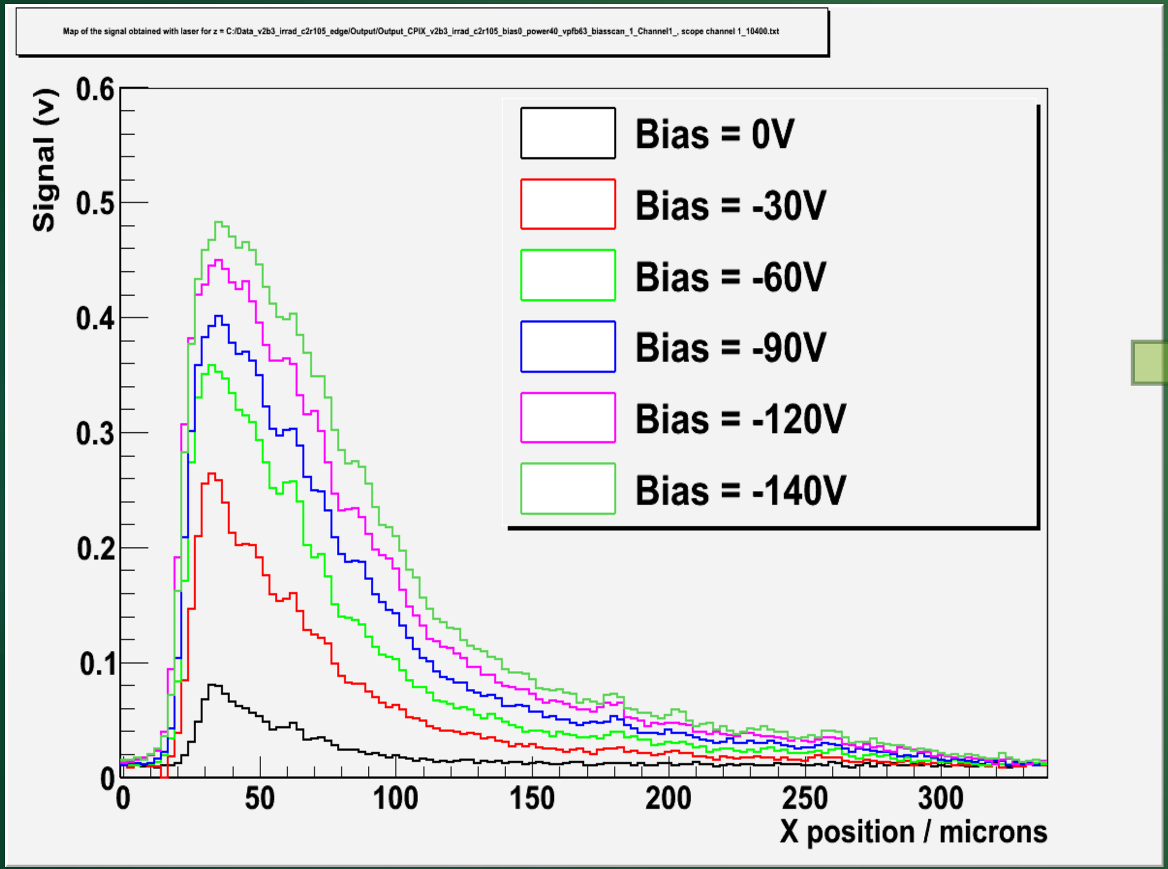
L. Vigani
D. Huang

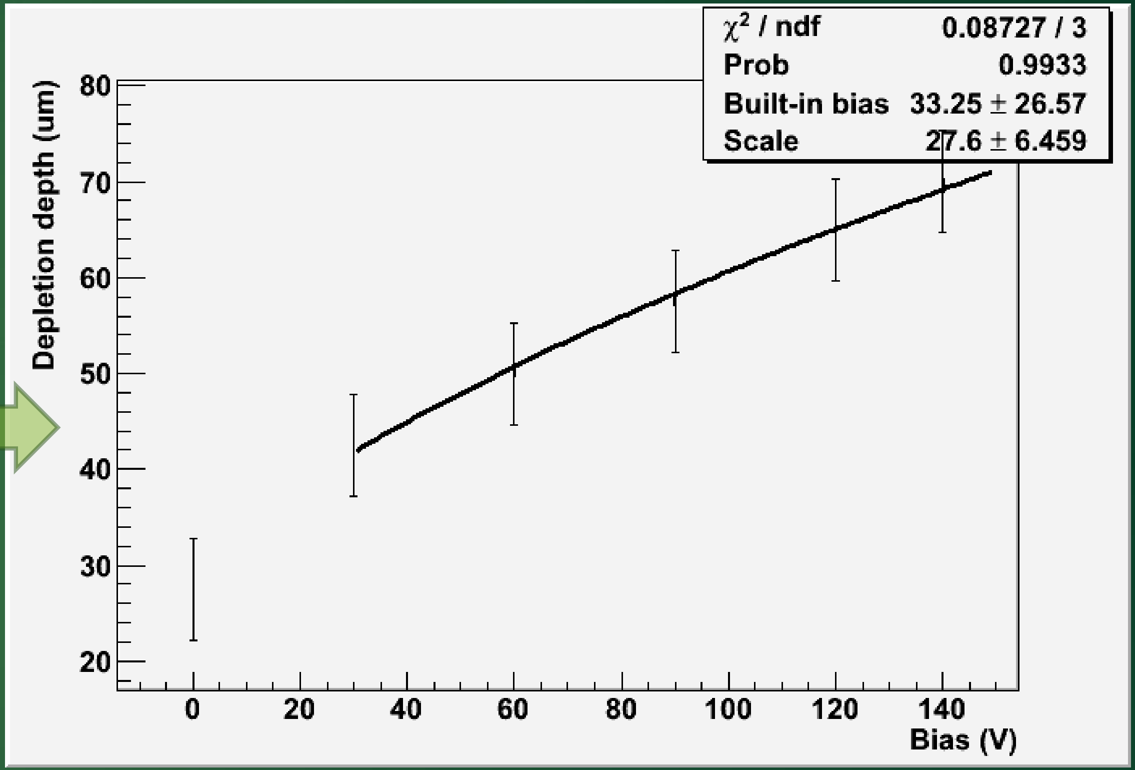
This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement no. 654168.
AIDA 2020

LF-CPIX: proton irradiation

- Edge-TCT

Signal vs depth, bias scan (T = -2C)





~70 µm depletion depth

L. Vigani
D. Huang

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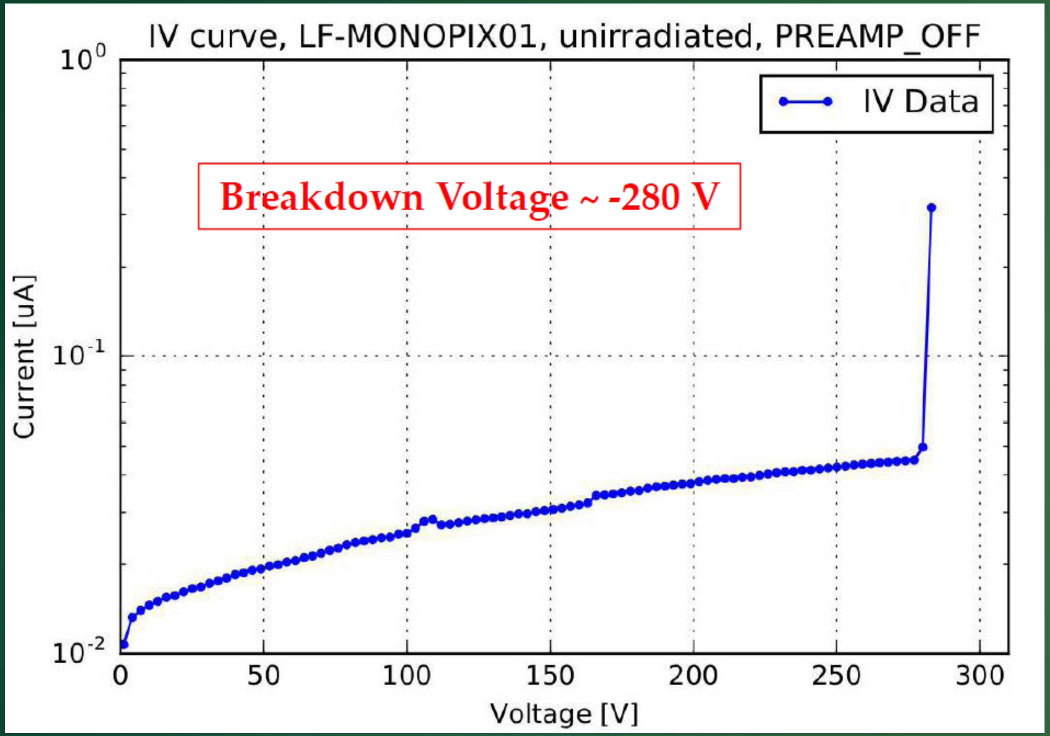
LF-MONOPIX

Layout: Read-Out electronics added to the LF-CPIX design

- 150nm CMOS
- Resistivity >2 kΩ ·cm
- 129 x 36 pixel array @ 40MHz clock (25 ns resolution)
- 40 MHz LVDS serial output
- 8-bit leading edge/trailing edge time stamps (ToT)
- 7 flavours of in-pixel read-out (depending on preamp and discriminator)
- 2 flavours of “external” read-out

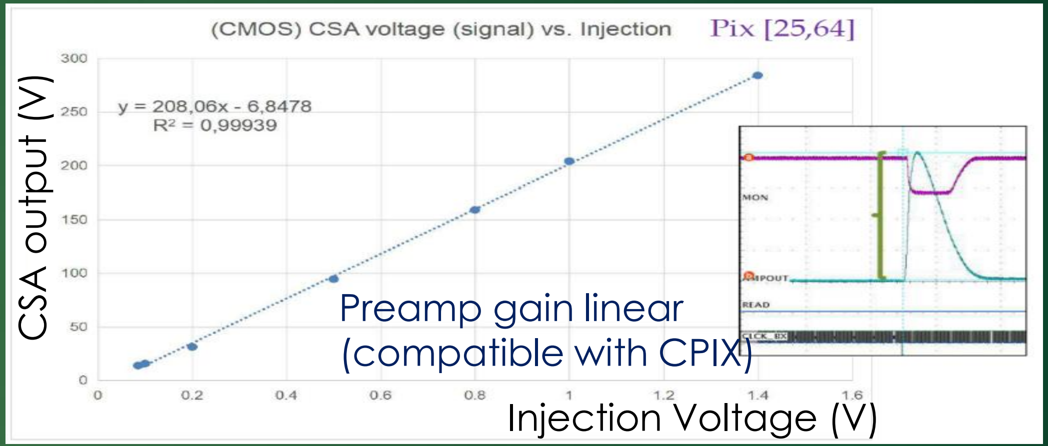
LF-MONOPIX: pre-irradiation studies

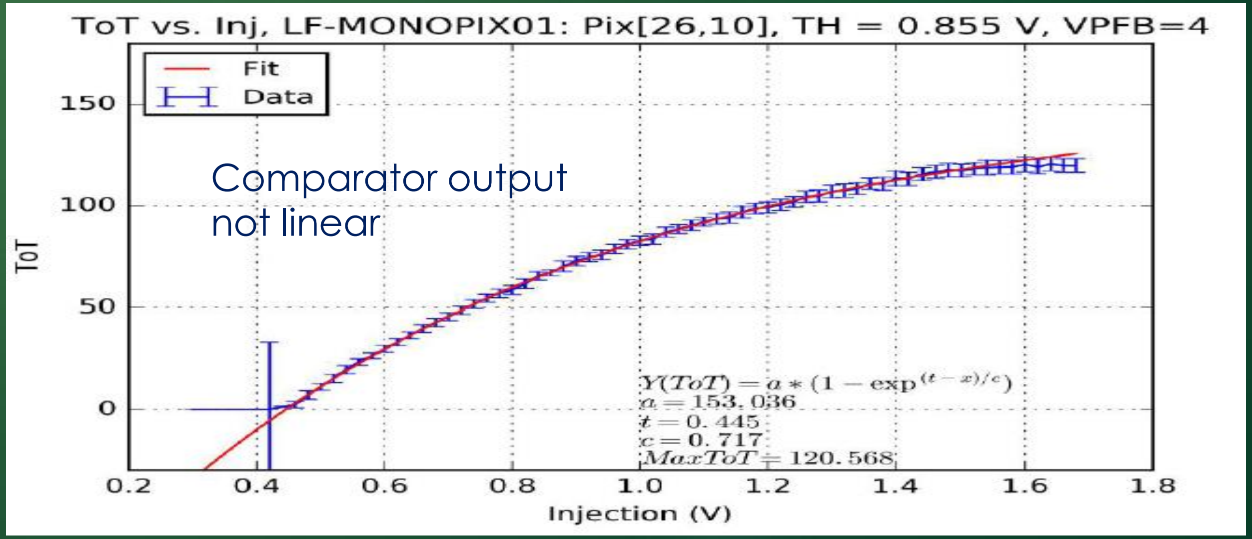
IV curve



Breakdown voltage higher than LF-CPIX

Gain

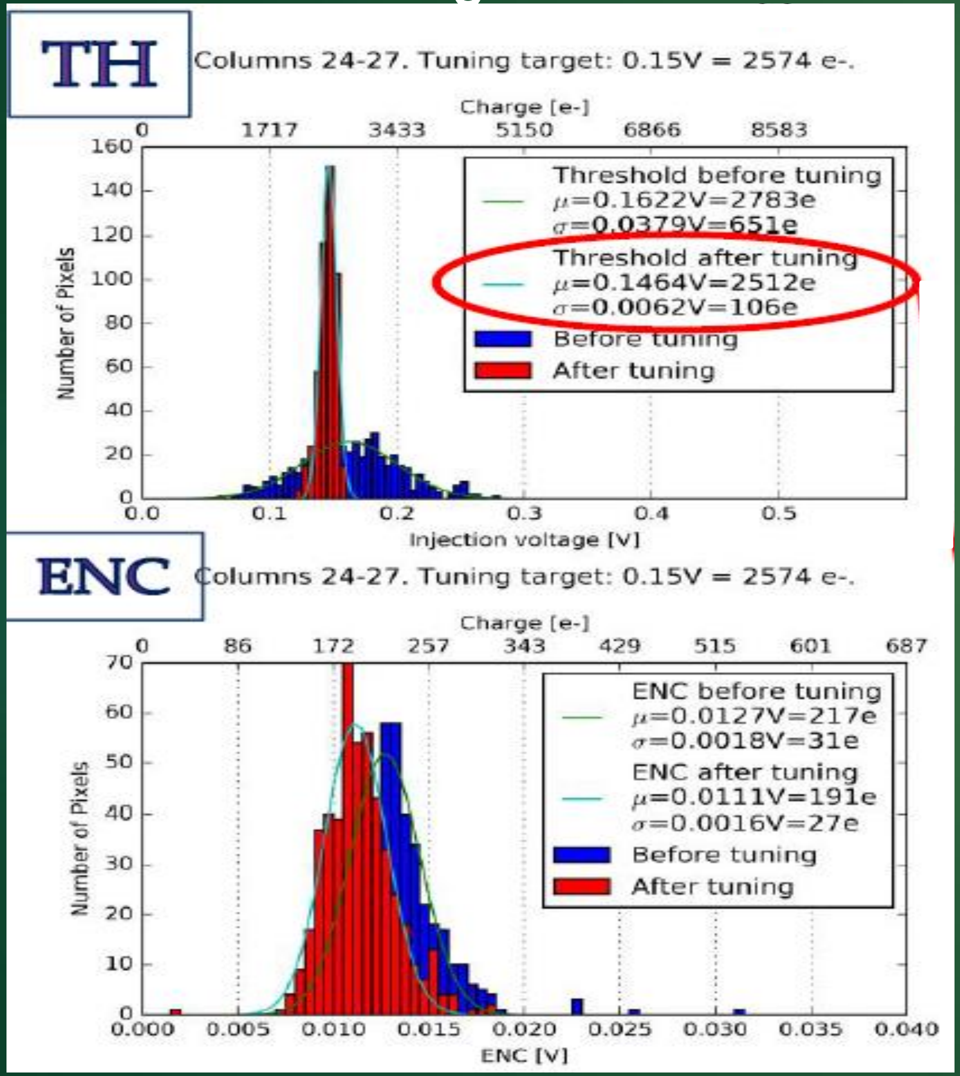




I. Caicedo

LF-MONOPIX: pre-irradiation studies

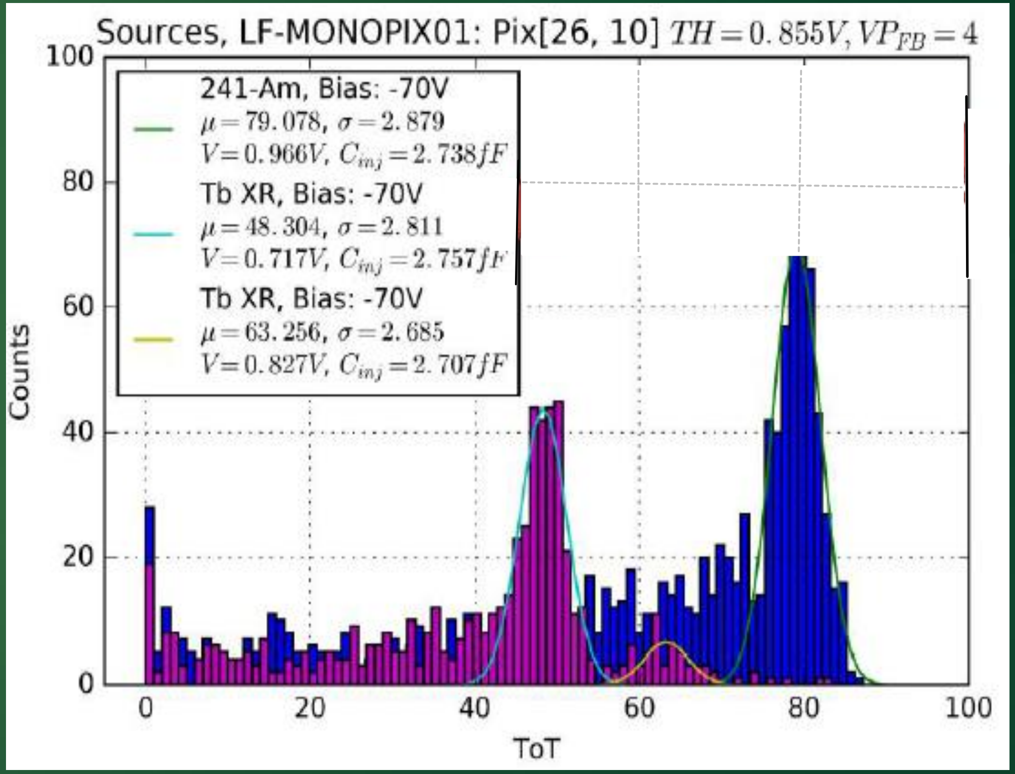
Threshold tuning and noise



Threshold tunable with ~100e dispersion
Noise ~ 180÷200e

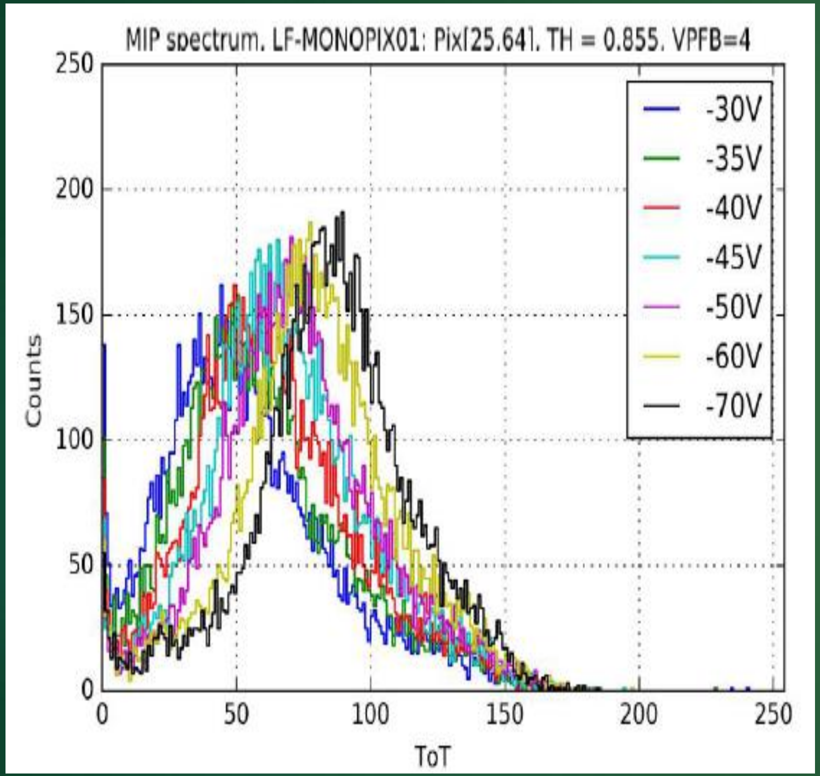
I. Caicedo

X-ray spectra

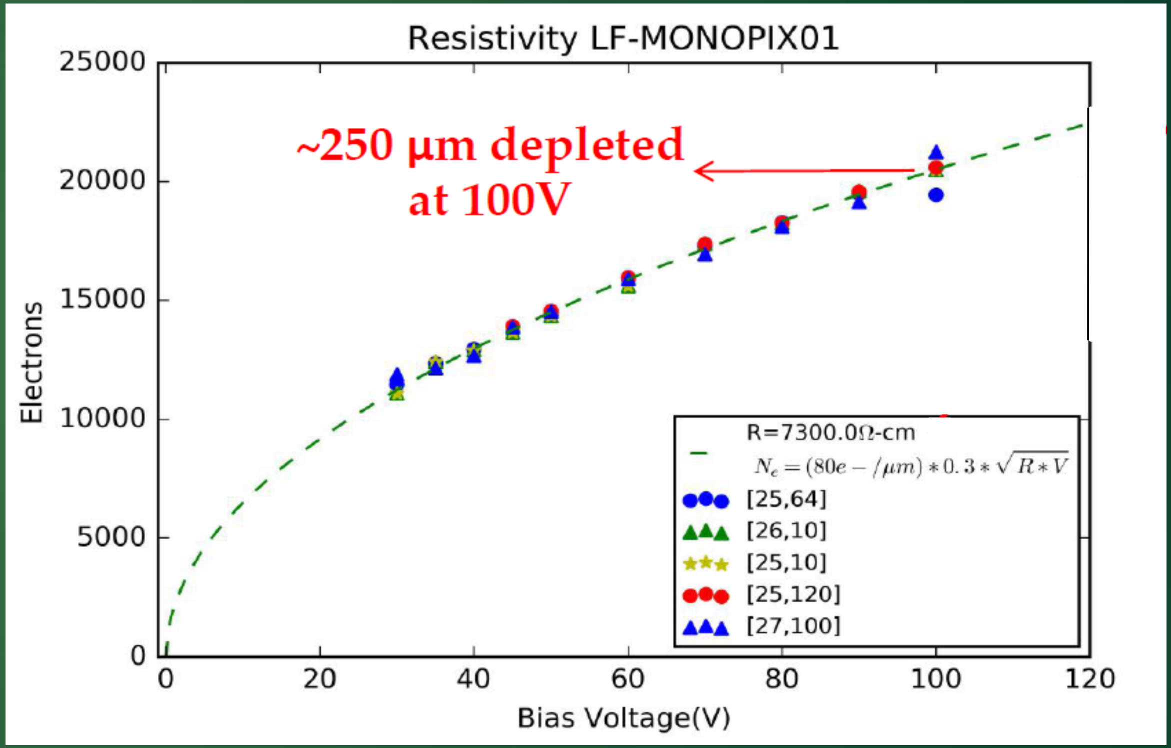


LF-MONOPIX: pre-irradiation studies

MIP spectra (from 3.2 GeV electron beam)



Bias scan



Spectra at different biases: MPV (peak) proportional to depletion depth

Resistivity of 7.3 kΩ·cm: higher than usual (3÷5.5 kΩ·cm)

I. Caicedo

LF-MONOPIX: irradiation plans

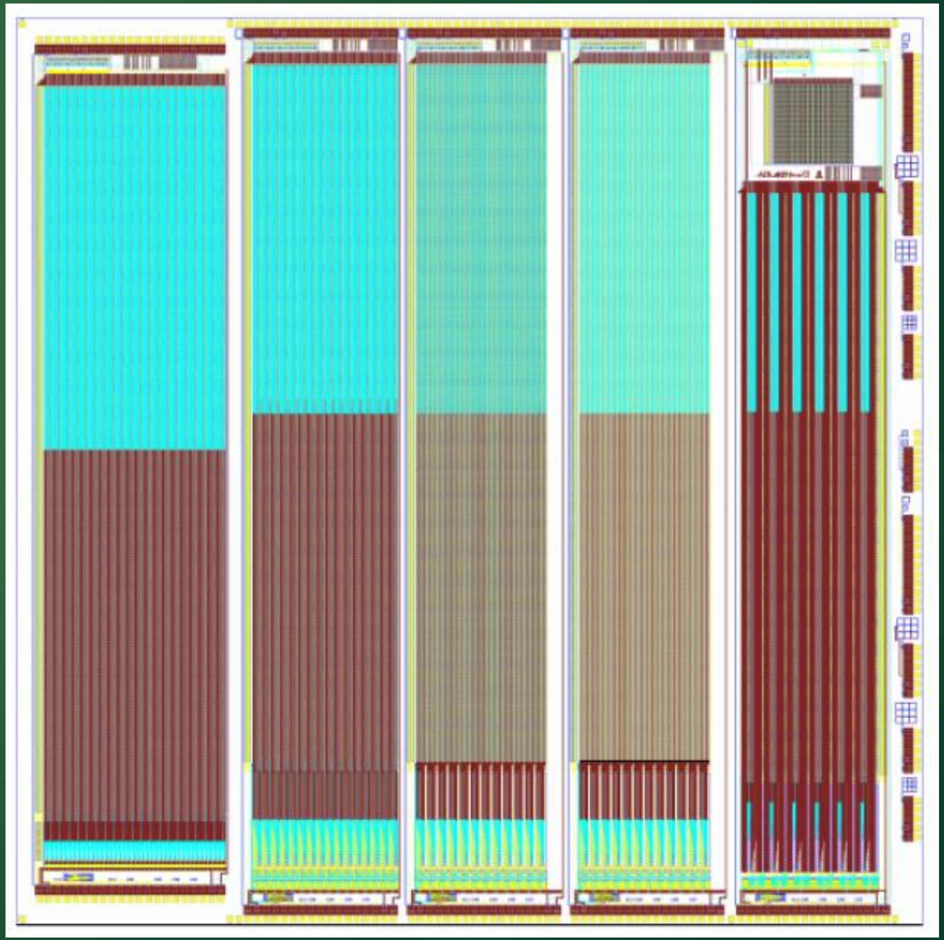
- Neutron: $1 \cdot 10^{14}$, $5 \cdot 10^{14}$, $1 \cdot 10^{15}$, $2 \cdot 10^{15}$ n_{eq}/cm^2 (done in JSI, testing started at Bonn)
- Proton: 100 Mrad-200 Mrad (Jul 2017 by CPPM)
- X-ray: 0 - 80Mrad (To be defined)

LF ALPHA sensor (ATLASPix)

- ATLAS-LFoundry-Pixel-Heap-Access (ALPHA) Sensor
- LFoundry LFA 150 nm process
- 6 independent sensors
- 10 x 10 mm² die
- 1 column drain sensor
- 3 parallel-pixel-to-buffer (PPtB) sensors
- 1 waveform sampling sensor
- 1 CCPD test sensor

Karlsruher Institut für Technologie

R. Blanco et al., "HVCMOS Monolithic Sensors for the High Luminosity Upgrade of ATLAS Experiment", Journal of Instrumentation, Volume 12, April 2017



Conclusions

- CMOS sensor development for ATLAS upgrade in good shape
- Three main foundries (strategies) under investigation
- LFoundry sensors are promising candidates
  - Large fill factor
  - Good performances have been observed on 2 active prototypes before and after irradiation
  - First fully monolithic device tested successfully before irradiation
  - More post-irradiation studies to come

Next

- Build a fully monolithic CMOS demonstrator module

Backup: MONOPIX details