Depleted monolithic CMOS pixel detectors in 150 nm LFoundry technology for the ATLAS Inner Tracker Upgrade

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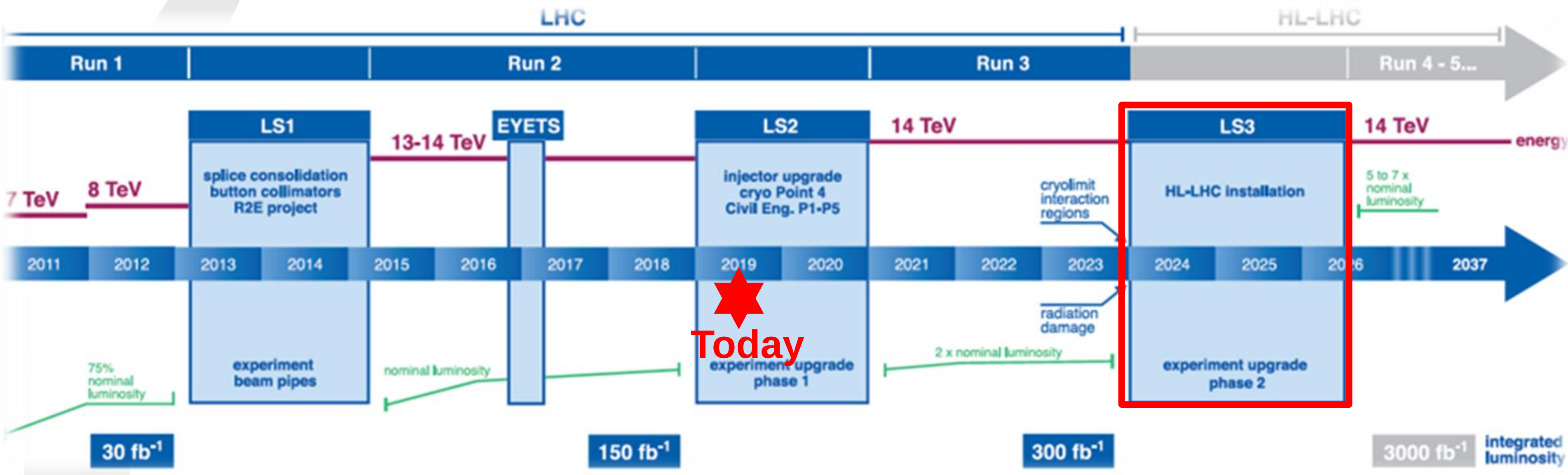
STREAM Final Conference
Geneva, 17th Sep 2019

Outline

- ATLAS Inner Tracker (ITk) upgrade
- CMOS sensor option for pixels
- LF-CPIX characterization and beam measurement
- LF-Monopix1 characterization and beam measurement
- Conclusion

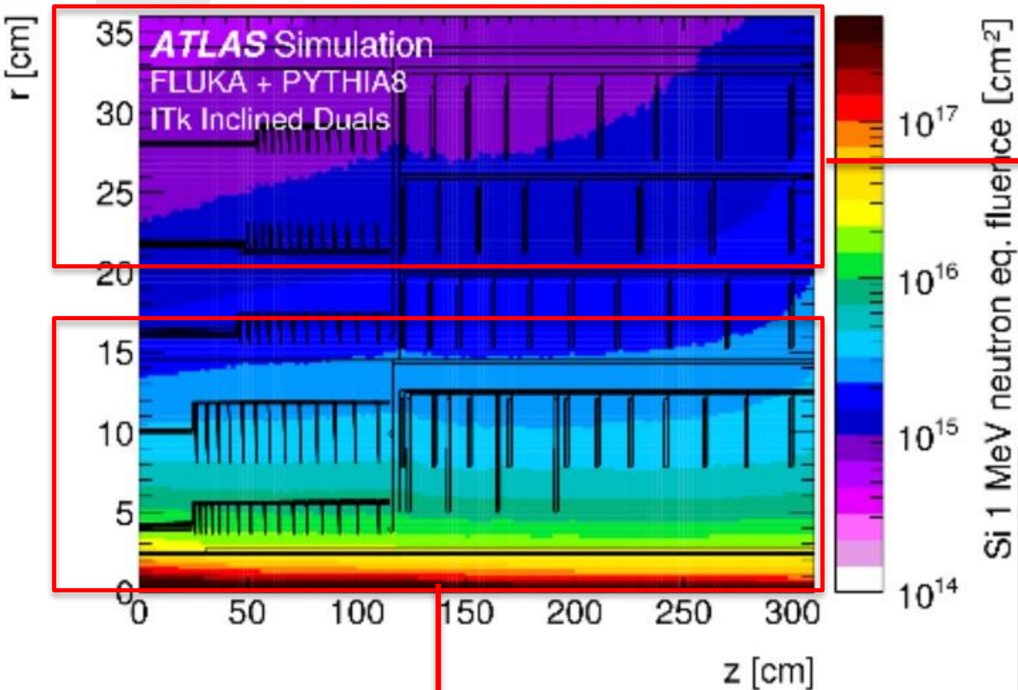
LHC / HL-LHC Plan



- The High Luminosity Large Hadron Collider (HL-LHC) is foreseen to switch on by 2026 with a center of mass energy of 14 TeV and a peak instantaneous luminosity of 7.5×10^{34} $cm^{-2}s^{-1}$, five times higher than at present.
- The increased luminosity will result in ~ ten times higher radiation levels and ten times higher data rates.

ATLAS ITk upgrade for HL-LHC

- To match the requirements in terms of radiation hardness, readout speed and granularity at the HL-LHC, the replacement of the present Inner Tracker (ITk) is needed.



Outer layers
- Occupancy 1-2 MHz/mm^2
- NIEL ~ 10^{15} n_{eq}/cm2
- TID ~ 80 Mrad
- Larger area (10 m^2)

Inner layers
- Occupancy 10-30 MHz/mm^2
- NIEL ~ 10^{16} n_{eq}/cm^2
- TID ~ 50 Mrad
- Larger area (10 m^2)

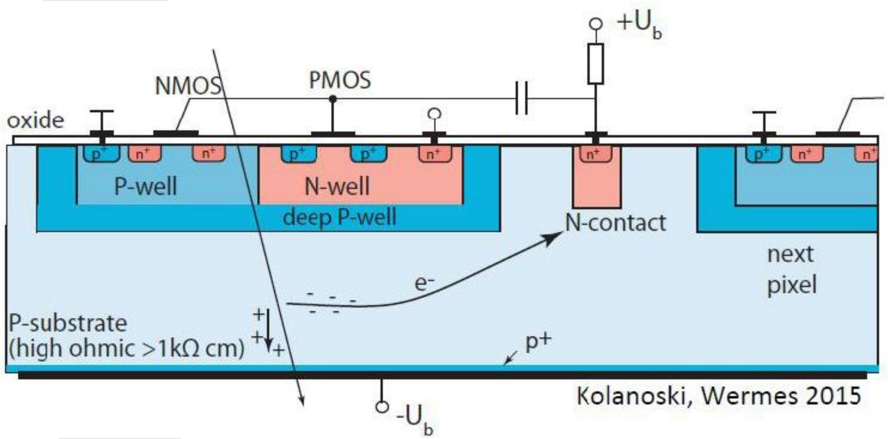
Outer pixel layers (two possibilities):
- Classical hybrid pixel as the baseline. (Planar sensor + RD53 readout IC).
- Full monolithic CMOS chip with integrated readout .

Monolithic CMOS Sensor

- Commercial process (mass production technology).
- No hybridization (reduced material budget and costs, easier procurement).
- Considerable depleted regions in high resistive substrates, fast charge collection by drift.

Two design approaches

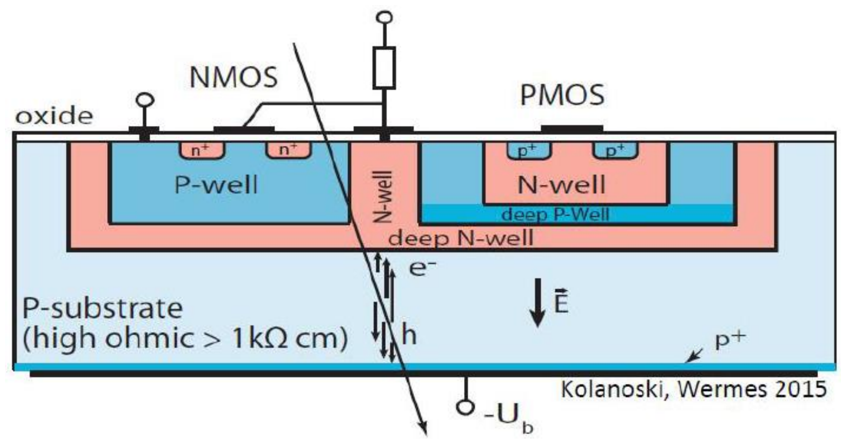
"Small Collection Diode"



PROS: Small sensor capacitance → low power consumption

CONS: Long drift distances → Less radiation hard

"Large Collection Diode"



PROS: Short drift distances→ radiation tolerant

CONS: Large sensor capacitance →noise & speed (power) penalties

$$ENC^2_{thermal} \propto \frac{4}{3}\frac{kT}{g_m}\frac{C_d^2}{\tau} \qquad \tau_{CSA} \propto \frac{1}{g_m}\frac{C_d}{C_f}$$

LFoundry technology

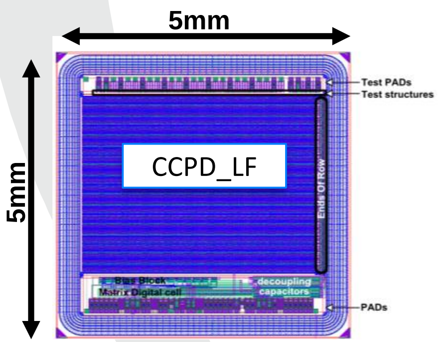
LF technology development line

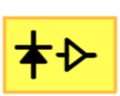
- The process:
  - DeepNW/DeepPW 150nm LF process
  - 7 metal layers
  - High resistivity (> 2kΩ.cm)

Characterization results (today !)

2014~2015
Small size demonstrator

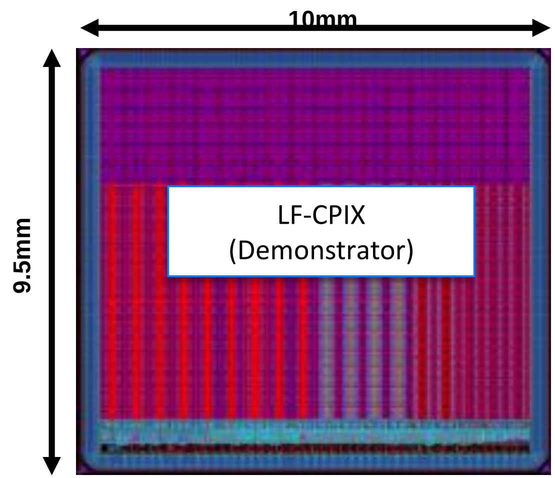
CCPD_LF:
$33 \times 125 \mu m^2$ pix ; 6pix → 2 FEI4 pix
5×5 mm^2 IC, **bondable to FE-I4**
Bonn / CPPM / KIT




Diode + preamp

2016~2017
Large size demonstrator

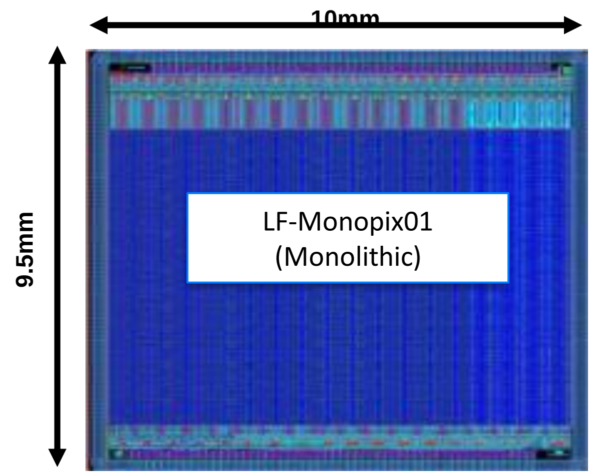
LF-CPIX:
$50 \times 250 \mu m^2$ pix ; diff. pix flavors
10×10 mm^2; 2 versions -Guard-Ring-
Bonn / CPPM / IRFU

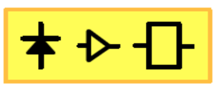



Diode + preamp

2017~Present
Large Monolithic demonstrator

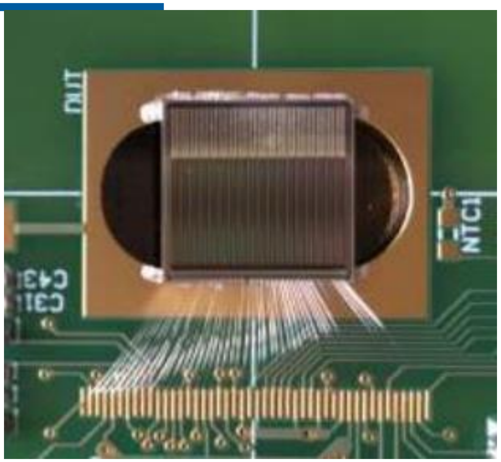
LF-Monopix1:
$50 \times 250 \mu m^2$ pix
10×10 mm^2 IC
1st full monolithic demonstrator!
Bonn / CPPM / IRFU



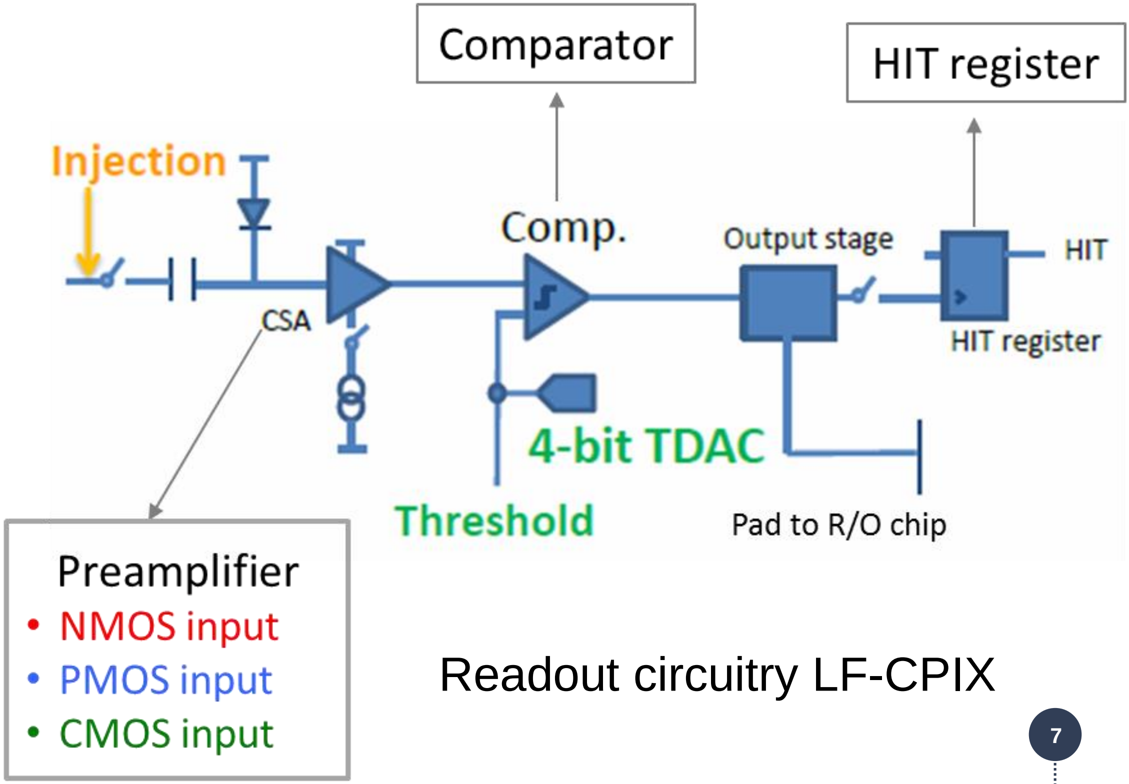

Diode + Amp + Digital

LF-CPIX pixel and matrix architecture

- <u>LF-CPIX:</u>
  - Testing of **sensor diode collection** part.
  - Testing of **analog part** of pixels.

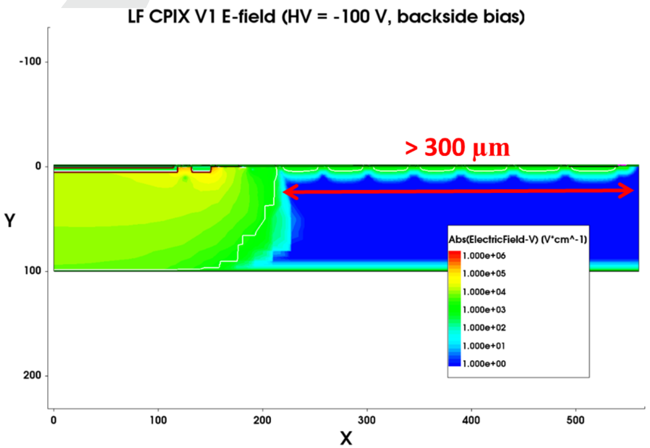


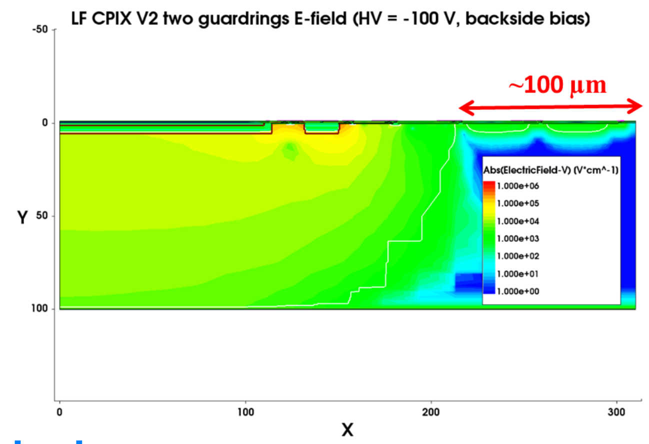
- Process: LFoundry 150 nm CMOS process.
- Wafer resistivity: >2kΩ cm.
- Pixel size: 250 µm x 50 µm (can be bump bonded to FE-I4 readout chip).
- Matrix: 23 x 106.
- Flavor: 3 types of CSA



Readout circuitry LF-CPIX

Improved guarding-ring strategy for LF-CPIX

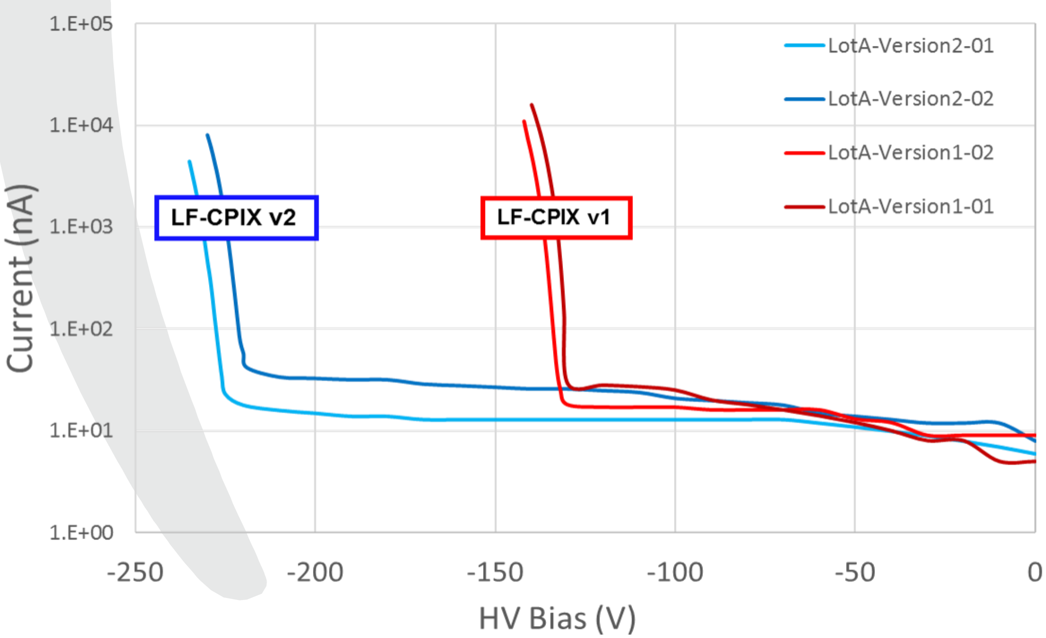




LF-CPIX (V1) → **LF-CPIX (V2)**

guard-ring numbers reducing

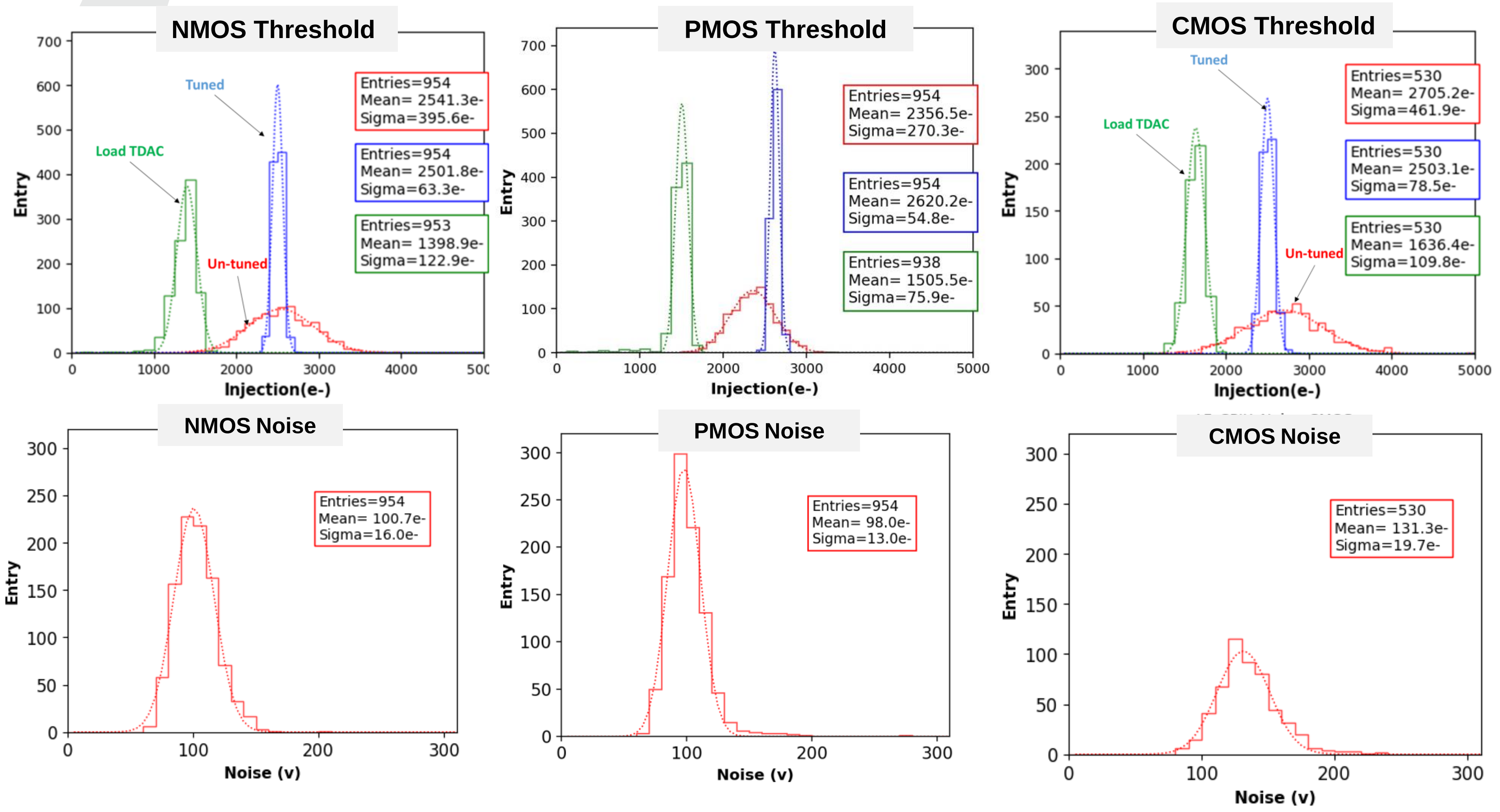
guard-ring gap reducing



- Breakdown voltage of V2 is higher than V1, agree with the TCAD simulations!
- The high BV achieved → enhanced radiation hardness.

LF-CPIX: Laboratory results before irradiation

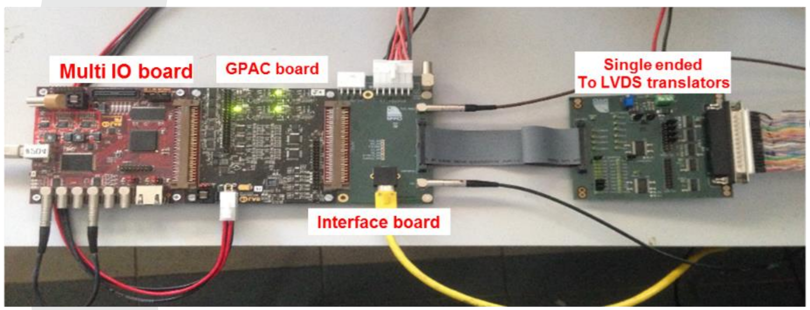
- All 3 flavors are working well and the threshold can be tuned, the threshold mean value less than 1500e- can be achieved.
- Typical noise mean value less than 130e-.



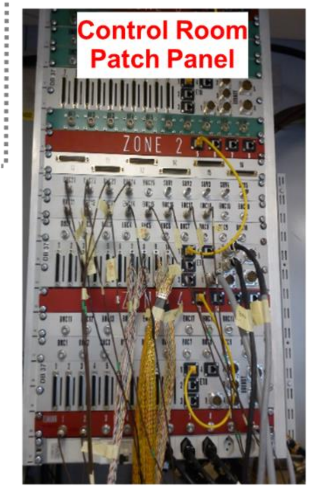
Setup under proton beam @ CERN PS

- Aug → Sep 2017 :
- 24 GeV protons irrad.
- ~150 MRad reached (roughly 2 times the dose expected for the ITk 4th layer).
- Fluence: 2.6×10^{15} n_{eq}/cm^2.

Setup in Control Room



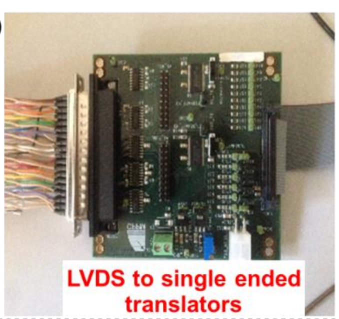
Power Supplies with sense (Vdda, Vddd, VddaPRE)
Polarization (BL, TH, VcascP, VcascN, Vcasc2) →
LVDS signals (LdDAC, CLConf, SR_EN, Sin, LdPIX Reset) →
(Inj & HV) →
← (Amp, Monitor)
← LVDS signals (Sout)

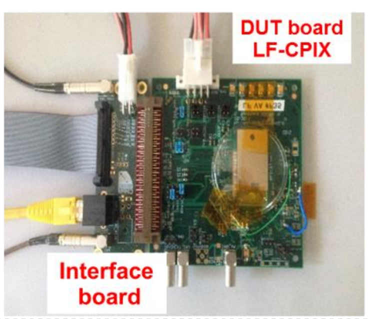


distance of 20m

Setup in Irrad Zone2

Power Supplies with sense (Vdda, Vddd, VddaPRE)
Polarization (BL, TH, VcascP, VcascN, Vcasc2) →
LVDS signals (LdDAC, CLConf, SR_EN, Sin, LdPIX Reset) →
(Inj & HV) →
← (Amp, Monitor)
← LVDS signals (Sout)

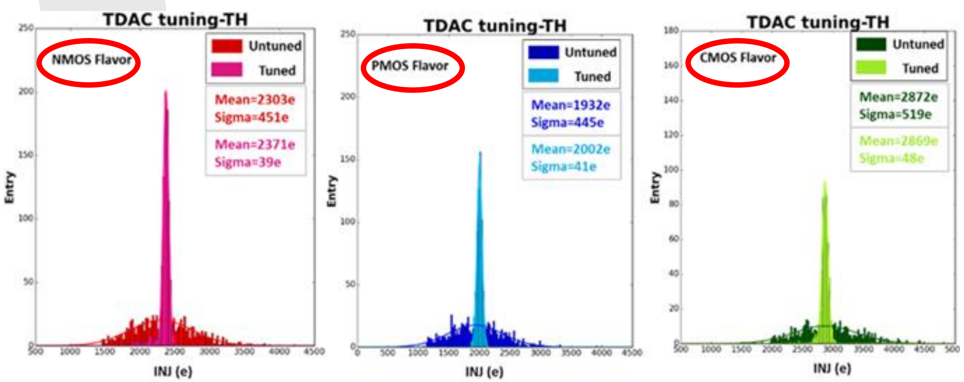




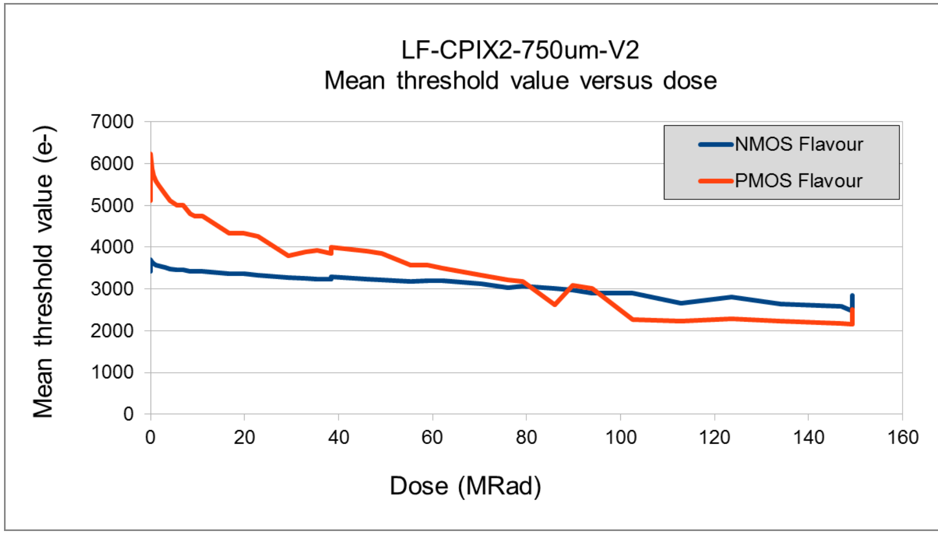
LF-CPIX testing after irradiation

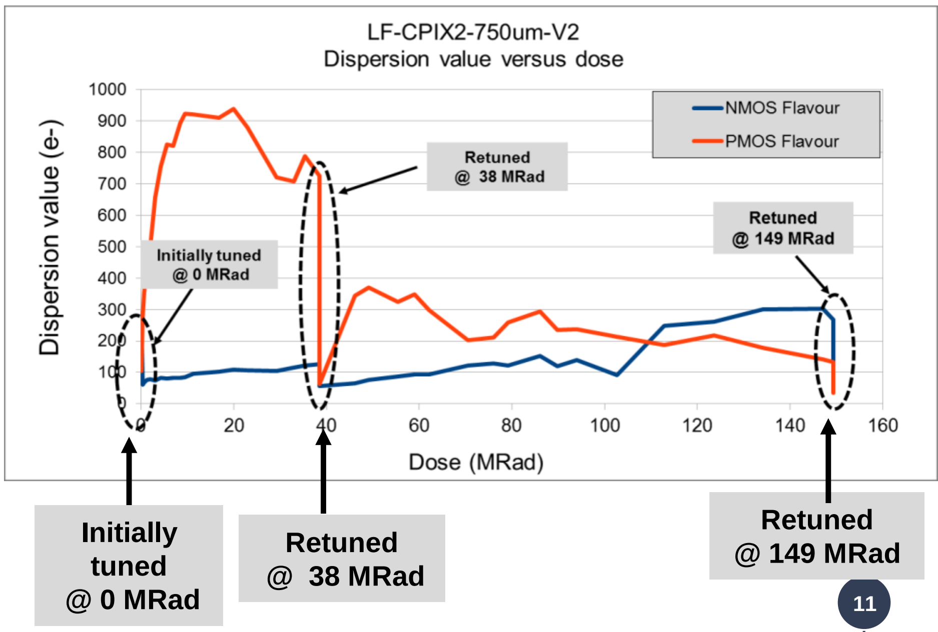
PS irradiation → 150 MRad

- The threshold mean value for both NMOS and PMOS flavors are 2000e- after proton beam irradiation up to 150Mrad.
- The threshold dispersion for the 3 flavors can be tuned to less than 50e- after proton beam irradiation up to 150Mrad.



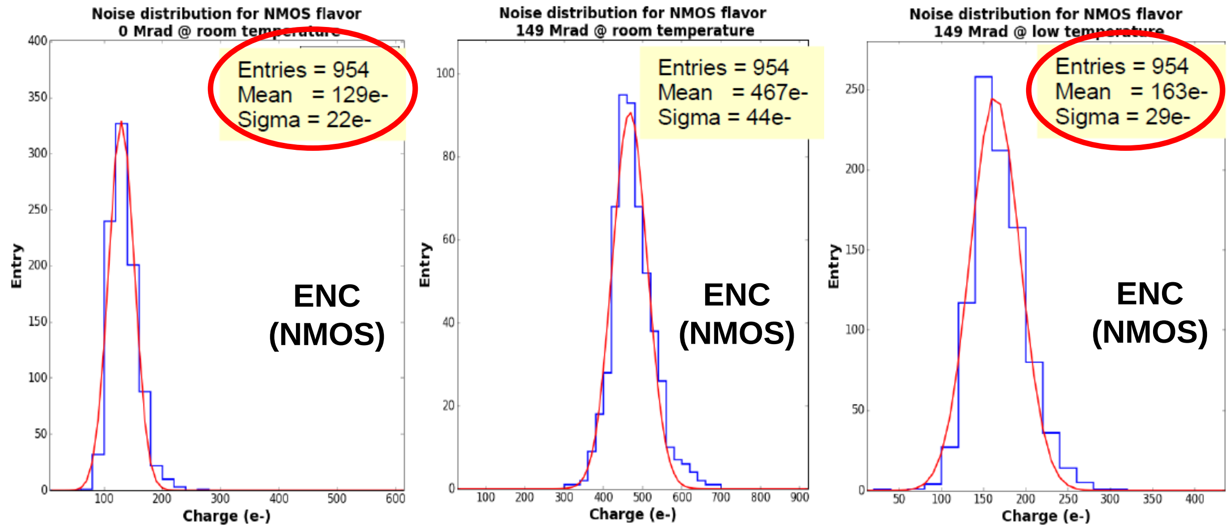
Threshold scan and tuning after radiation





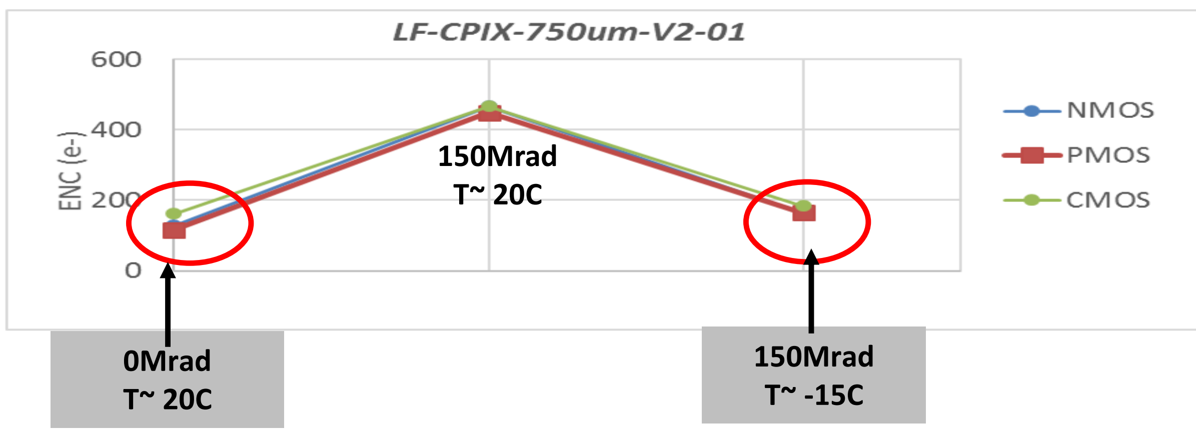
LF-CPIX: Noise after 150 Mrad proton beam irradiation

PS irradiation → 150 MRad

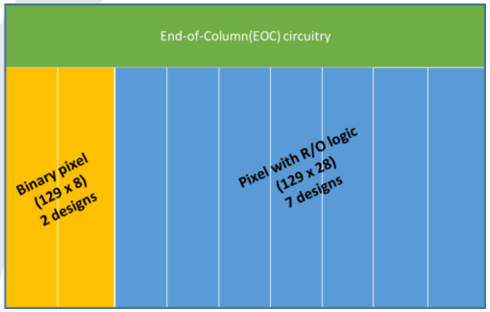


Pre-rad T~ 20C **150 Mrad T~ 20C** **150 Mrad T~ -15C**

- The noise mean values for all flavors are less than 200e- at low temperature after proton beam irradiation up to 150Mrad.

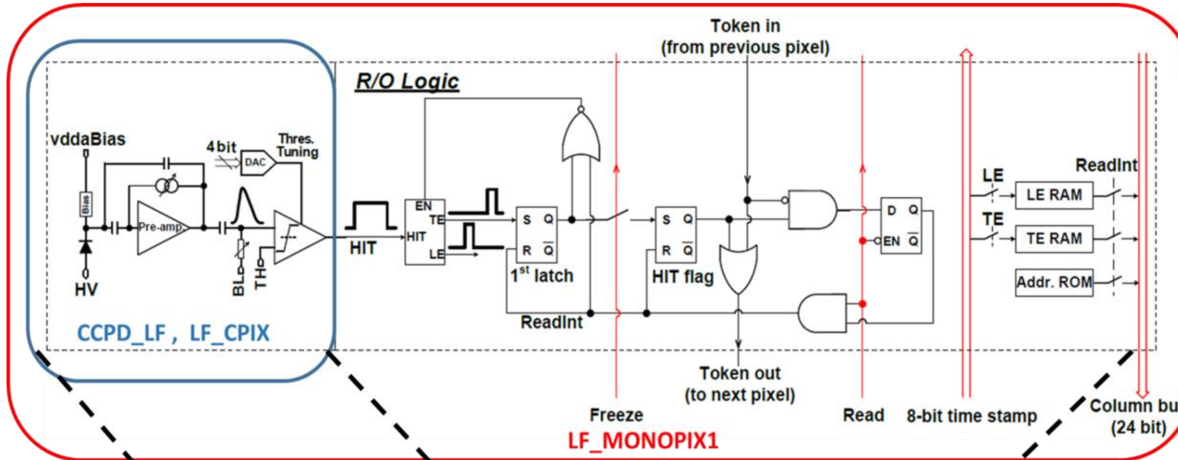


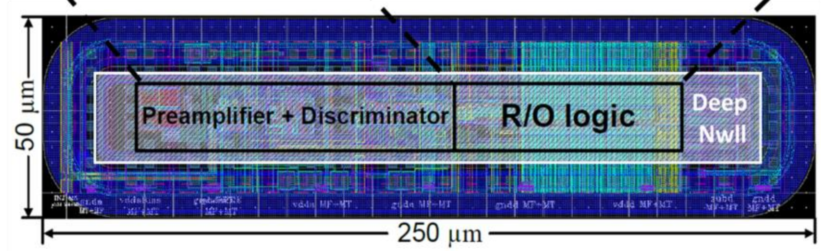
LF-Monopix1: Pixel design



Flavor No	1	2	3	4	5	6	7	8	9
R/O logic	Out		In-Pixel						
Amplifier	CMOS							NMOS	
Discriminator	V2		V1	V2	V1	V2	V1	V2	V1
Discriminator Domain	Dig		A+D	Dig		A+D			
Token	CMOS			Current Steering					
Source Follower	P	N							

- 150nm CMOS process, LFoundry (Resistivity >2kΩ.cm).
- Similar diode and analog front end circuitry design as in LF-CPIX.
- 129 x 36 pixel array (9 sub matrices with different pre-amplifiers, discriminators, R/O concepts …).
- Column-drain R/O logic (FE-I3 like).
- 40 MHz (up to 160MHz by design) LVDS serial output.

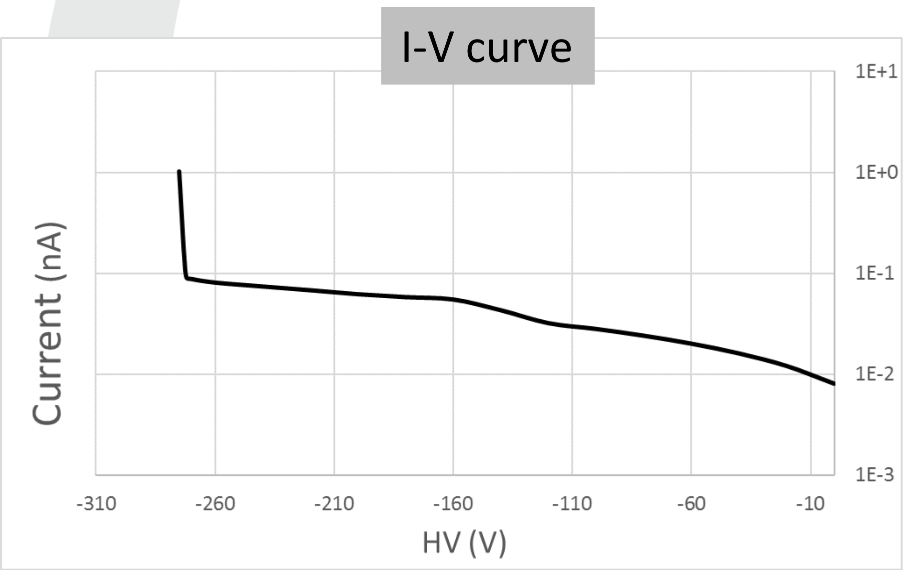


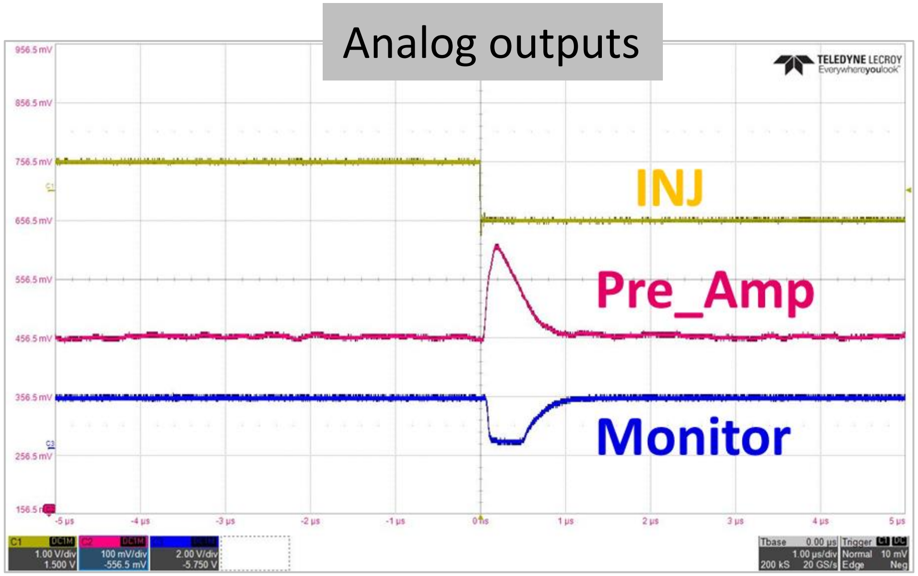


The schematic of LF-MONOPIX1 in-pixel electronics

LF-Monopix1: Laboratory results before irradiation

- The breakdown voltage is around -280V at room temperature, which is an improved value with respect to previous prototype in this technology and matches simulation results.
- Both the preamplifier and discriminator have good response with external test injection



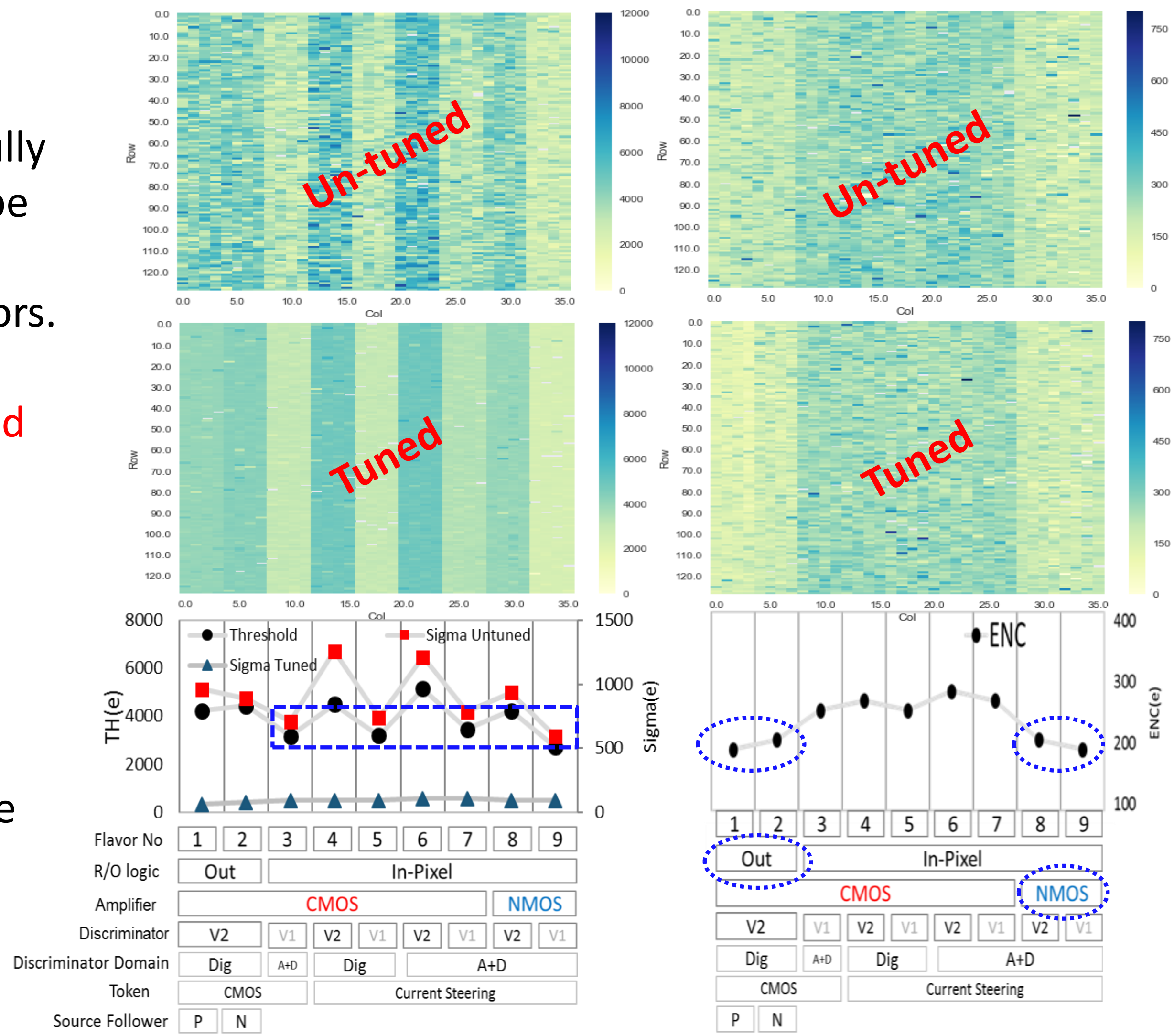


Breakdown ~ -280 V

Responses of the preamplifier and discriminator

LF-Monopix1: Laboratory results before irradiation

- All the flavors of pixels with fully integrated read-out logic can be tuned with a dispersion within 110e~148e depending on flavors. The noise value for different flavors falls between 190 e- and 280 e-.
- V1 discriminator shows better performance on dispersion;
- the NMOS input transistor preamplifiers show lower noise than CMOS flavors.



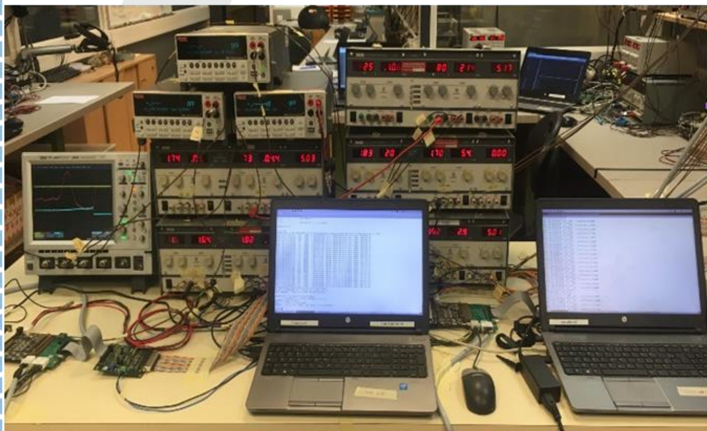
Threshold mapping

Noise mapping

LF-Monopix1: Setup under proton beam @ CERN PS

- Oct → Nov 2018 :
- 24 GeV protons irrad

Setup in Control Room



Control Room Setup

Power Supplies →

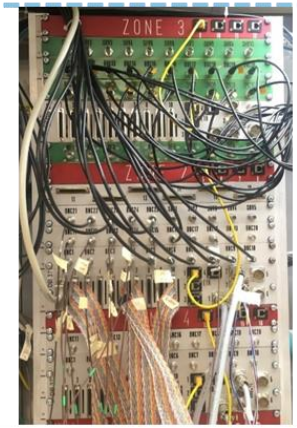
LF_MONOPIX LVDS signals ↔

Inj →

HV →

Disc_out ←

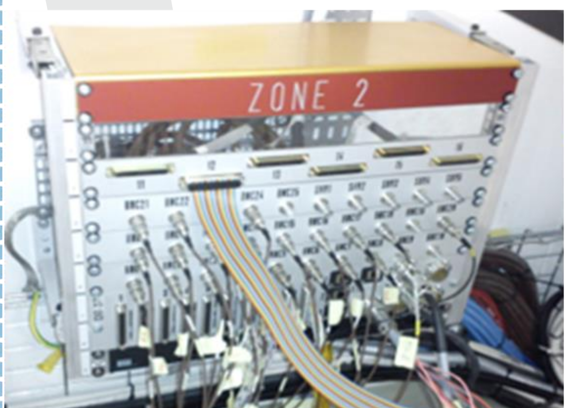
Amp_out ←



Control room Patch panel

↕ distance of 20m

Setup in Irrad Zone2



IRRAD Zone Patch panel

Power Supplies →

LF_MONOPIX LVDS signals ↔

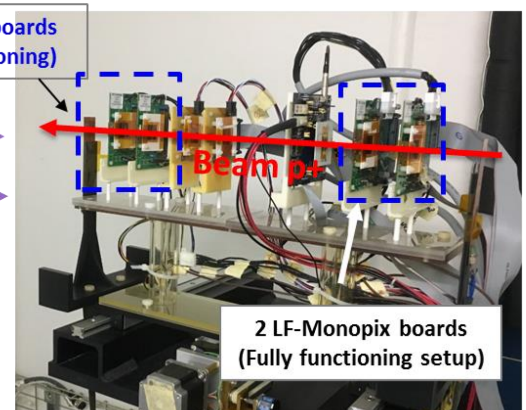
Inj →

HV →

Disc_out ←

Amp_out ←

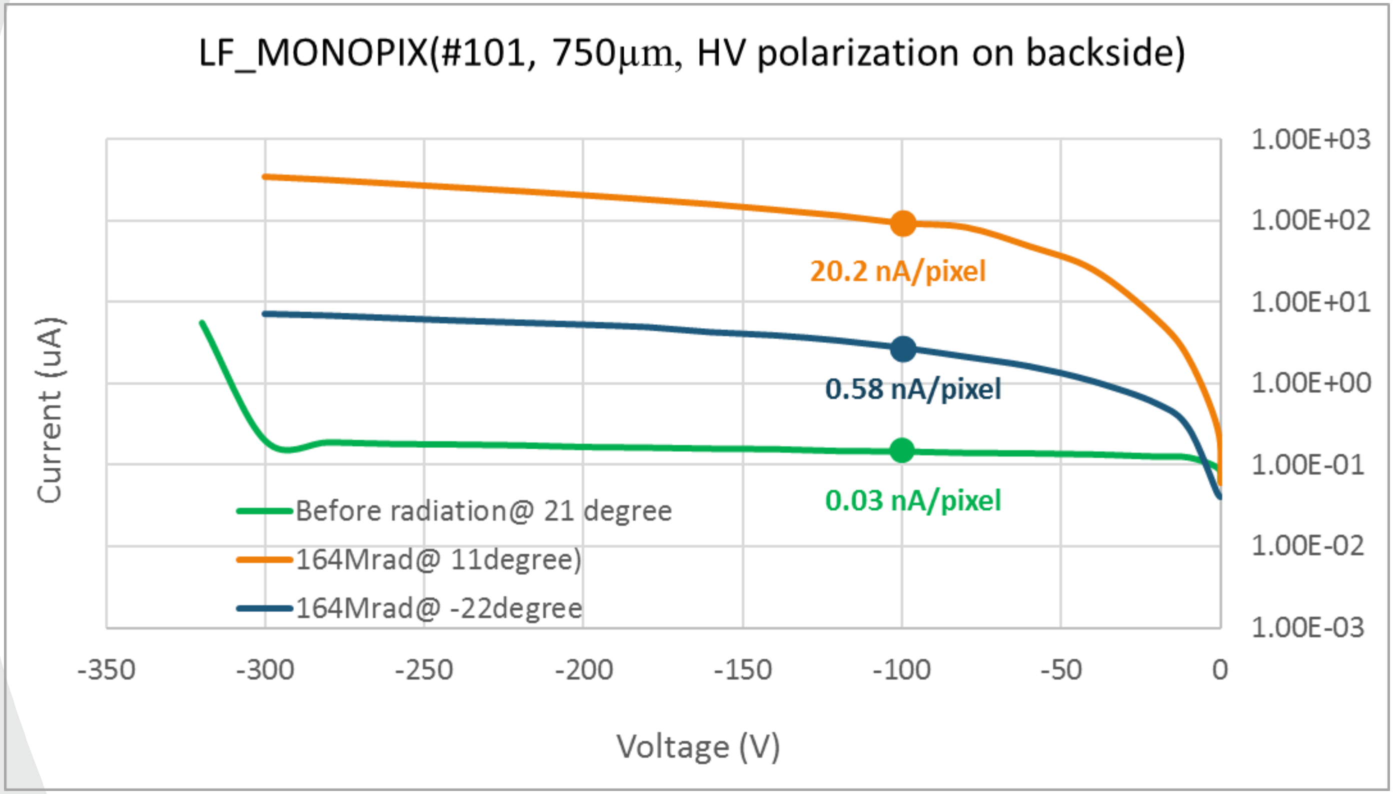
2 LF-MONOPIX boards (non-fully functioning)



IRRAD Zone table

Leakage Current: Radiation under PS@CERN

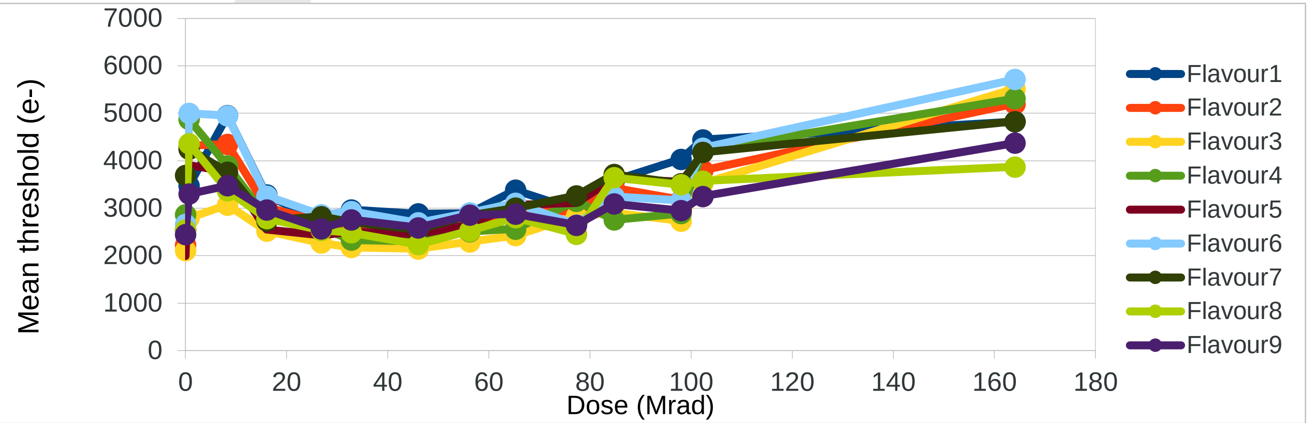
- Oct → Nov 2018 :
- 24 GeV protons irrad
- TID~164 MRad reached (roughly 2 times the dose expected for the 4th layer)
- NIEL=2.7× 10^{15} $n_{eq}\cdot cm^{-2}$



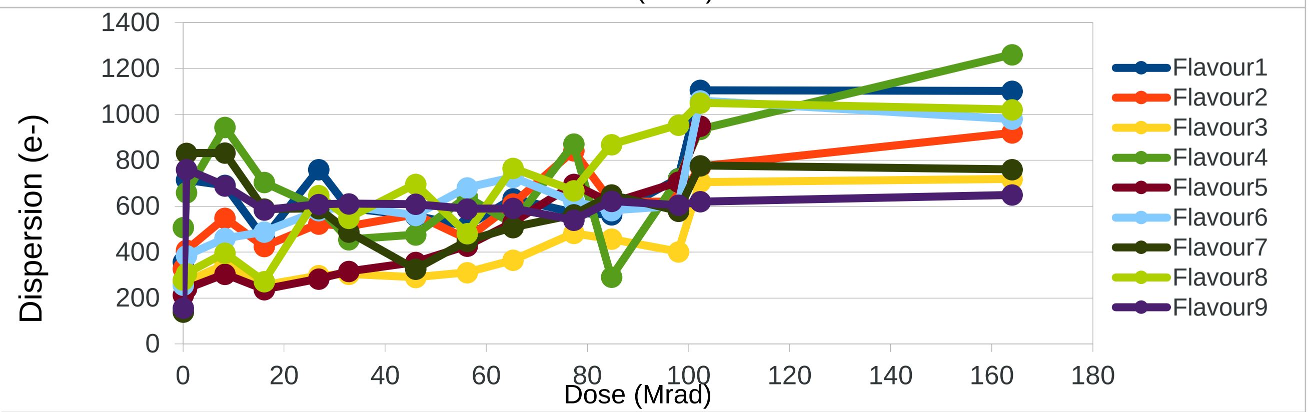
The leakage current increases after irradiations, when the sensor was cooled down to -22 ° C and the per-pixel leakage appears to be less than 0.58 nA, well below the HL-LHC design requirement (10 nA/pixel).

Mean th, dispersion and noise VS Dose (temp=21° C)

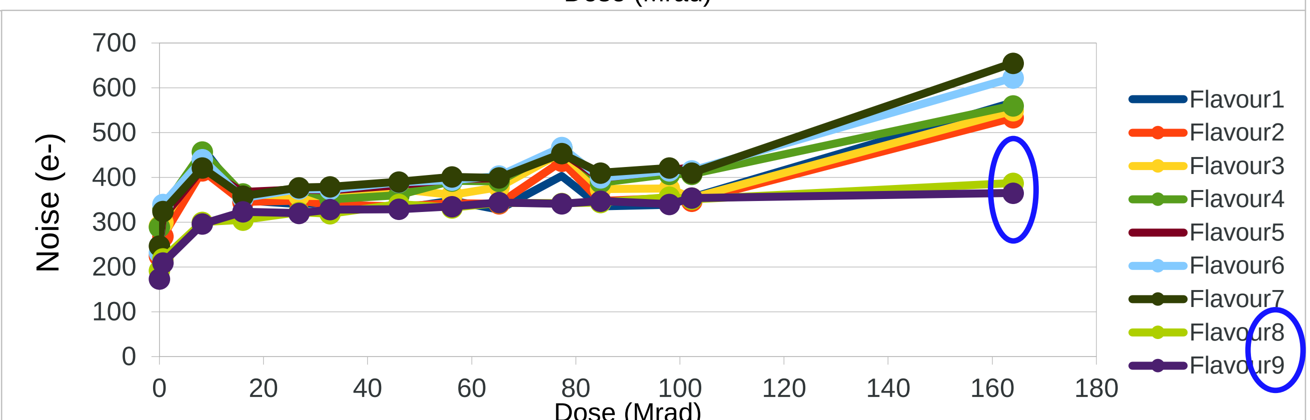
LF_MONOPIX #101 (750um)



Mean threshold versus dose
(Load the tuned TDAC
One column each flavor)



Dispersion versus dose
(Load the tuned TDAC
One column each flavor)



Noise versus dose
(Load the tuned TDAC
One column each flavor)

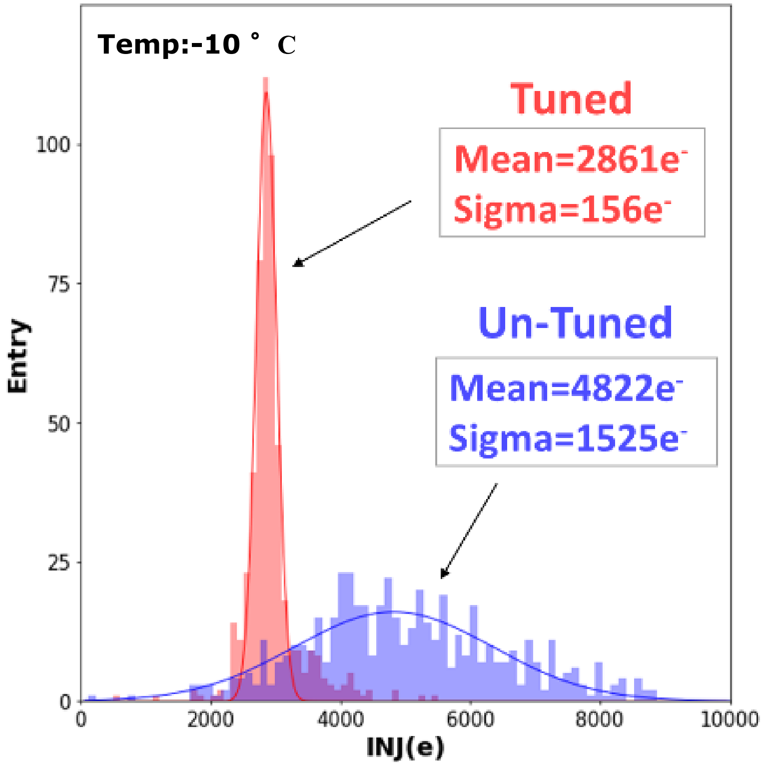
LF_MONOPIX1: threshold tuning (TID=164Mrad)

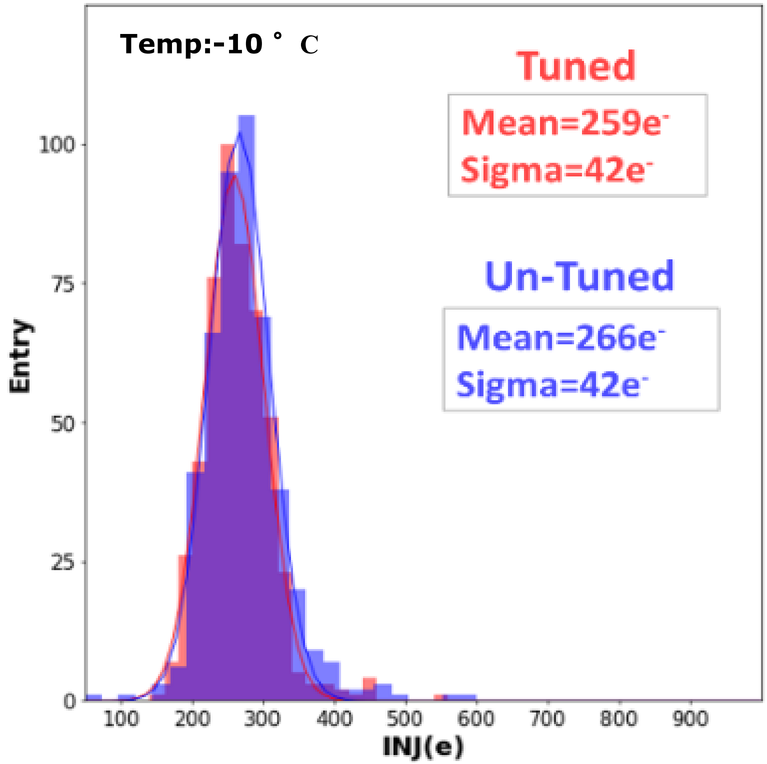
- Tested at the end of radiation campaign (Total dose=164Mrad)
- **Flavor9: NMOS CSA + V1 Disc**

1. Simple threshold scan with global TH	→	2. TDAC tuning with same global TH	→	3. Load the TDAC values with lower global TH

Un-tune
Pixel masked (0.0%)

Load TDAC
Pixel masked (1.9%)

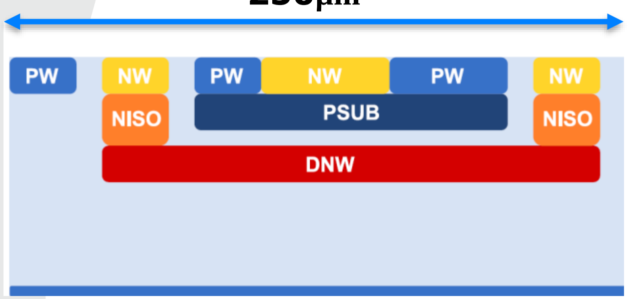




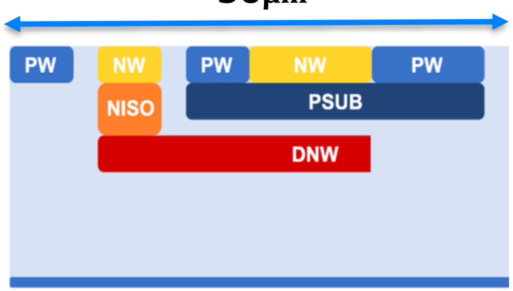
Small pixel approach for LF-MONOPIX2

Motivation :

- Increase the granularity → Better track parameter resolution, avoid in-pixel pileup at high particle rates.
- Decrease the sensor capacitance → Resulting in low noise.



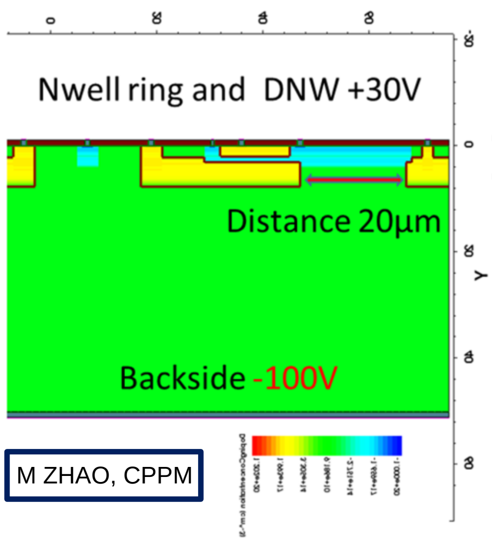
Current Pixel cross-section (250µm× 50µm)

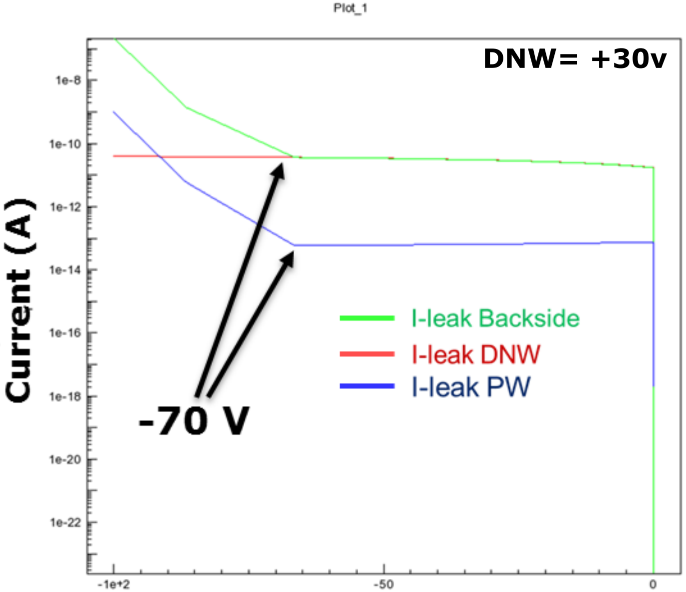


reduce the size of the pixel (50µm× 50µm)

- When the voltage of top Dnwell and Nwell ring is 30V, the BreakDown Voltage is -70V from the substrate, and the current is 50fA from PW and 80pA from DNW.

- The total Voltage potential at 100 V is achieved.





Conclusion & outlook

- Promising results of LF-CPIX were shown in terms of:
  - Good breakdown voltage characteristics (BV below -200V).
  - Radiation hardness of the technology:
    - Tuning of all the 3 flavors possible (threshold dispersion<50e).
    - Limited noise increase after 150 Mrad (noise<200e).
- LF-Monopix1: fully functional demonstrator chip with column drain readout.
  - Good breakdown voltage characteristics (BV below -28 0V).
  - Limited threshold dispersion (can be tuned within 110e~148e depending on flavor).
  - ENC for different flavors is between 190e- to 280 e-.
  - Good irradiation performances:
    - TID=164 MRad and NIEL=$2.7 \times 10^{15}\ n_{eq} \cdot cm^{-2}$ reached
    - Limited leakage current increase after 164 MRad.
    - Limited ENC increase.
    - The threshold can be tuned down to 2861 e- with a dispersion 156 e-.
- Next step and Outlook.
  - Need to understand the radiation effect on different parts of the chip.
  - Need to reduce the pixel size and leakage current (layout optimization).
  - Based on the results of the LF-MONOPIX1, find best strategy for the next demonstrator.

The collaboration works on an improved full size LF_MONOPIX2 and small pixel ICs that could be used in ATLAS ITk outer layer or in other contexts. → target: end of 2019

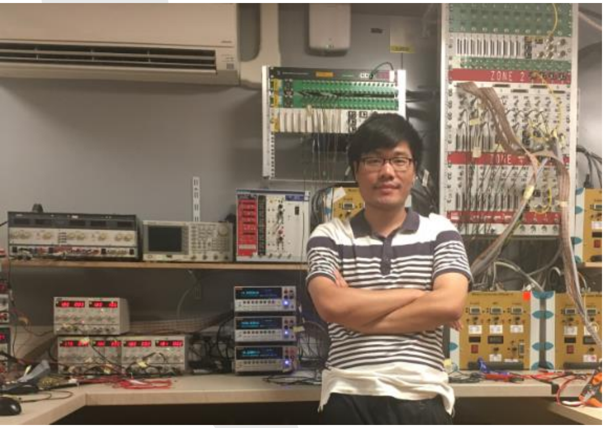
My PhD activities

Simdet 2016

Annual meeting 2017

Vienna Business School

Secondment at CERN



TWEPP 2018

CV Writing & Job Interview Workshop 2019

My PhD

Thanks for your attention !