Review of radiation hardness of CMOS MAPS sensors

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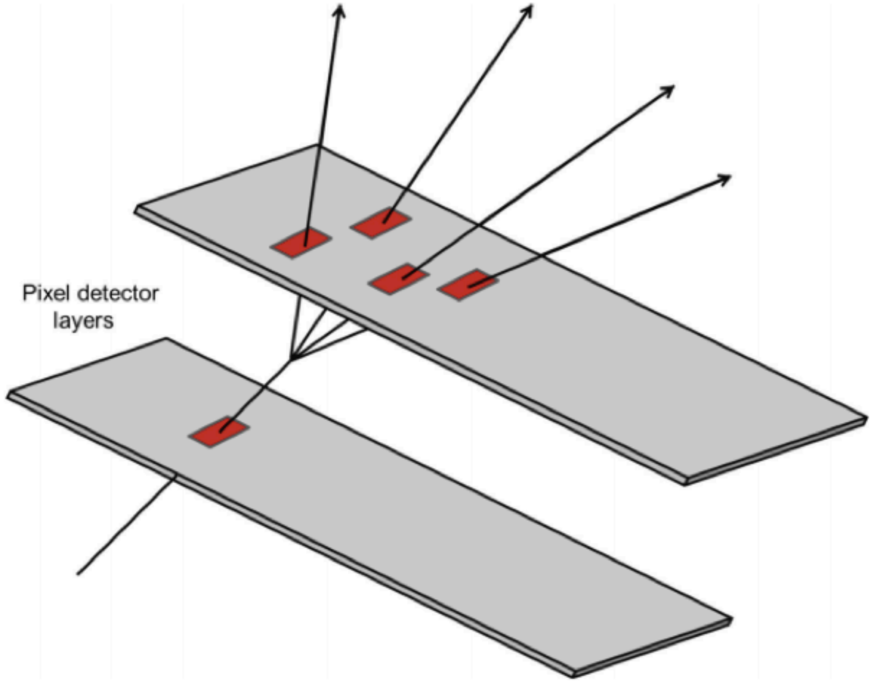
RADIATION HARDNESS REQUIREMENT ON VERTEX DETECTOR

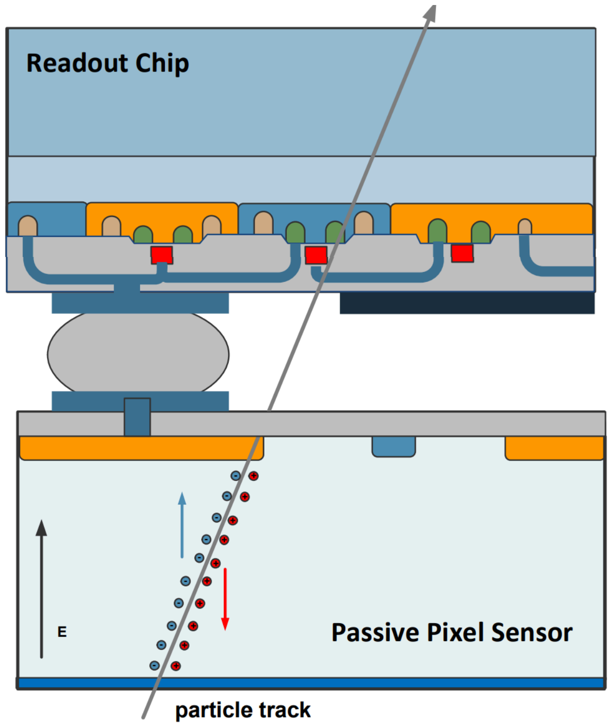
- Radiation tolerance **(per year):** 1 MRad &2×10^{12} 1 MeV n_{eq}/cm^2
- Need to re-visit the radiation hardness requirement
  - For smaller beam pipe design
  - May need to deal with higher dose (need input)



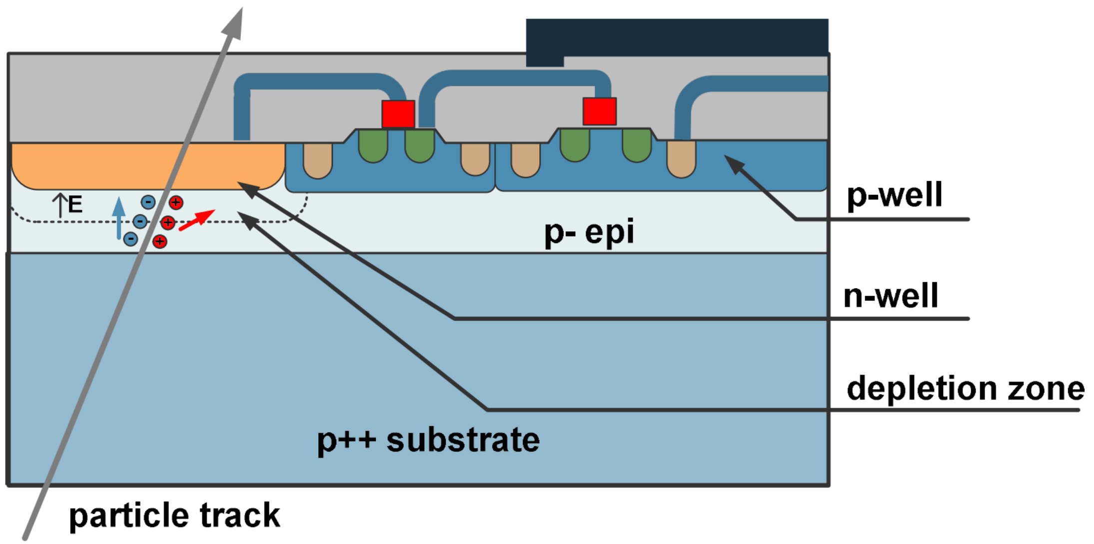
CMOS PIXEL SENSOR

- Monolithic pixel (CMOS imaging CIS process or SOI process) is ideal for CEPC application
  - low material budget (can be thin down to 50µm)
  - Material budget is about 5-10 times smaller than Hybrid pixel technology
  - Lots of development on going:
    - CEPC Jadepix and Taichu chip…
    - ATLAS CMOS pixel development

Hybrid pixel



Monolithic Pixels



Two type of CMOS sensor

2 types of design proposed for implementing DMAPS in HEP:

Large Fill-factor

- Electronics in collection n-well
- High resistivity substrate
- Large signal
- Larger fill factor
- **High capacitance (~100 fF)**

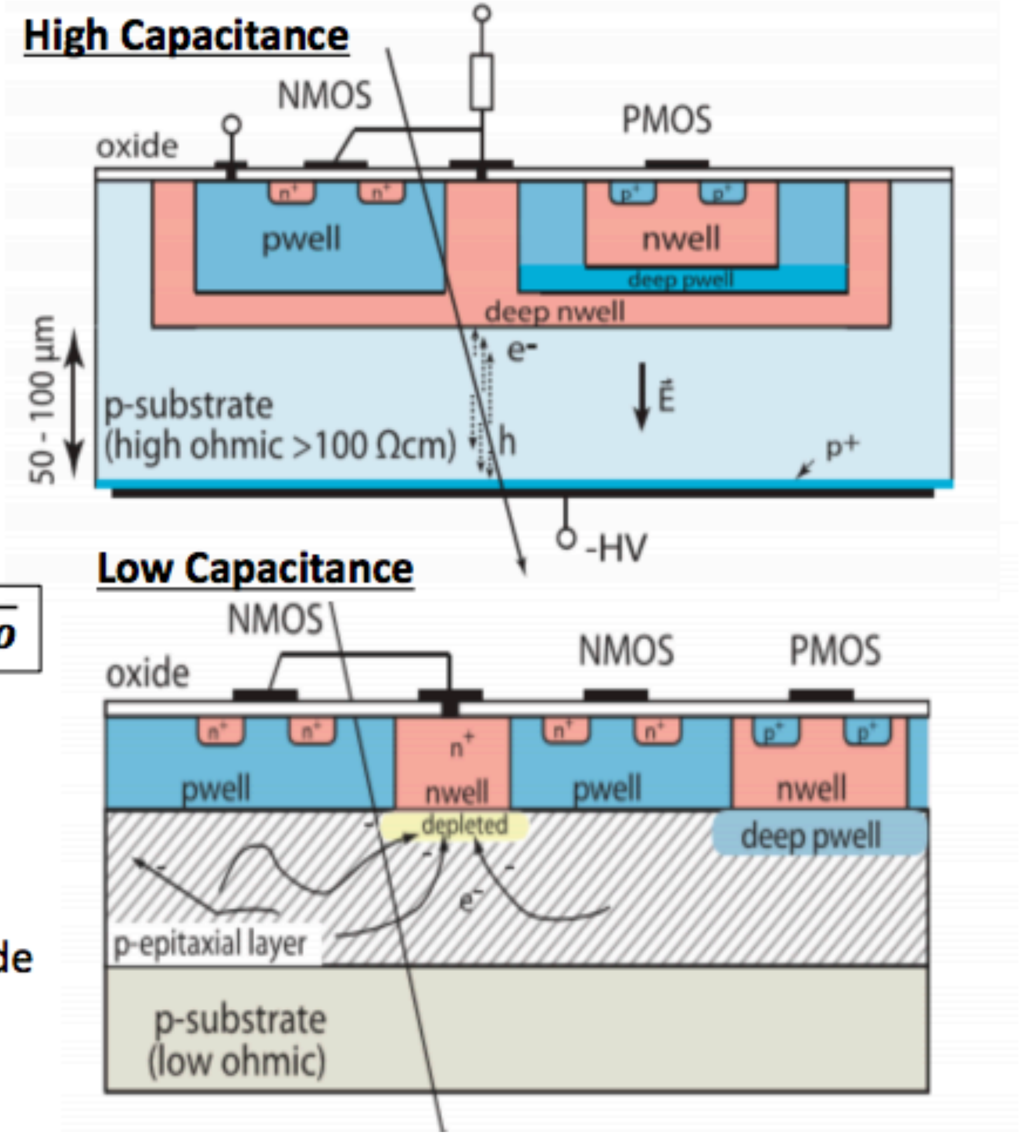
AMS and Lfoundry (CCPD for ATLAS)

Depletion depth ~ $\sqrt{V\rho}$

Small Fill-factor

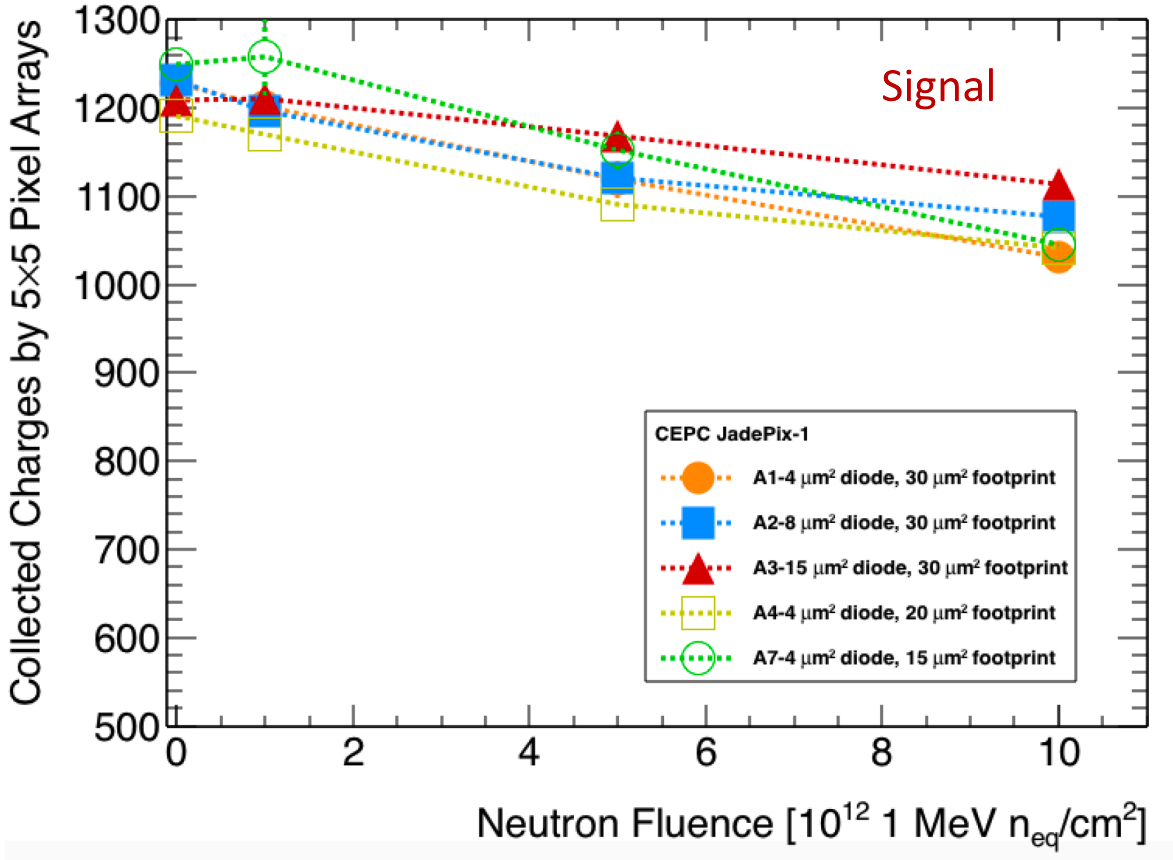
- Electronics next to electrodes
- Low resistivity substrate
- Epitaxial layer for collection
- Smaller fill factor
- Weak field long collection times away from the electrode
- **Low capacitance (~5 fF)**
- Design of ALPIDE, MALTA

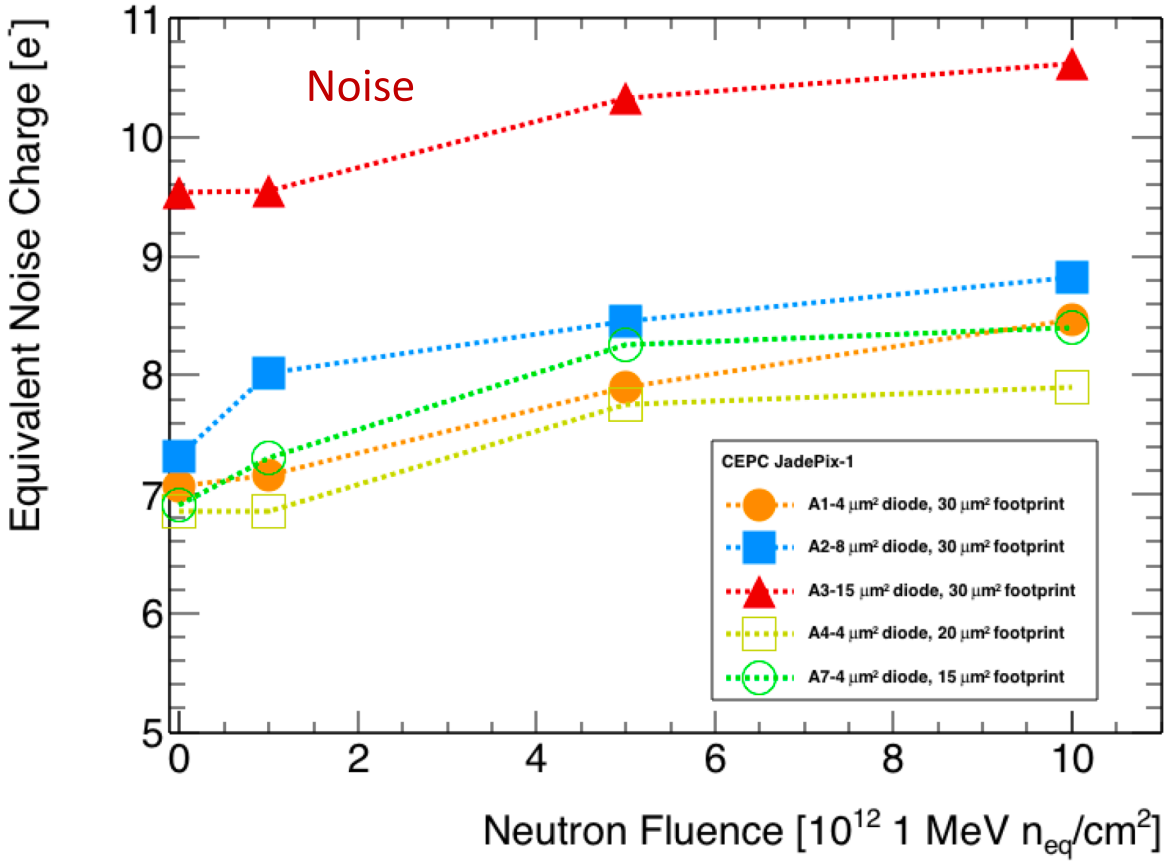
CEPC Jadepix and Taichu



CEPC JadePix-1 radiation hardness

- TJ180 CIS technology
- Neutron Irradiation up to 10^{13} Neq/cm^2
  - Signal to Noise ratio above 50 after irradiation
  - Jadepix-1 met CEPC requirement





LFOUNDRY HV-CMOS SENSOR

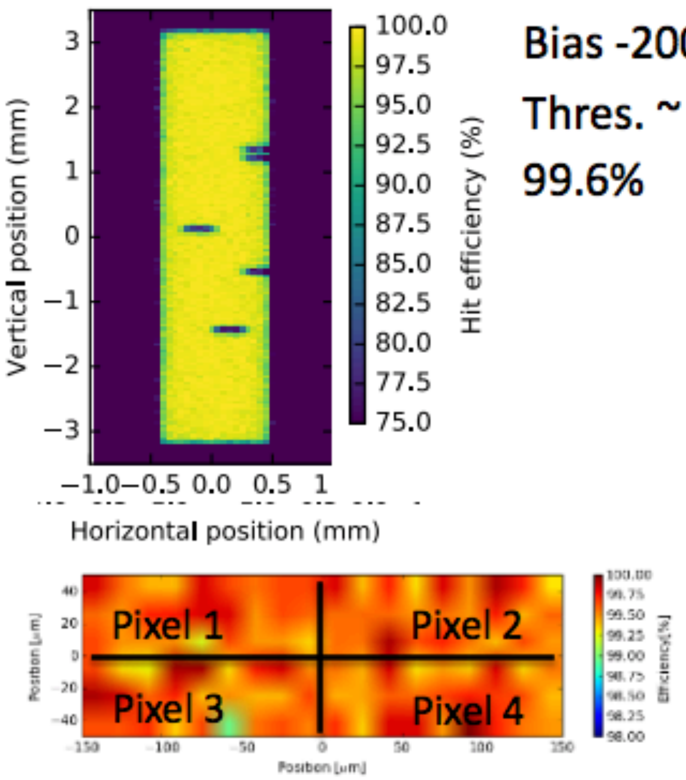
- ➢ Lfoundry HV CMOS technology
- ➢ Proton Irradiation up to 10^{15} N_{eq}/cm^2 : efficiency ~99% after irradiation

T. Hirono, et. al, DOI: 10.1016/j.nima.2018.10.059

- High and uniform efficiency even after irradiation

Before irrad.

- Noise occup. < 1.2 Hz/pix
- 1% masked pixels
- Dry ice cooling



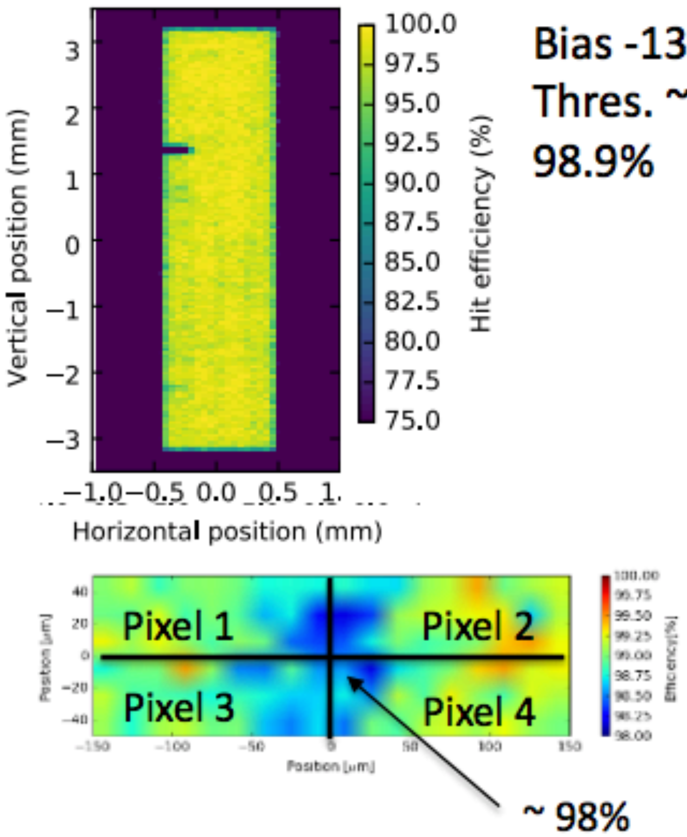
Bias -200V

Thres. ~ 1800 e^-

99.6%

After $10^{15} n_{eq}/cm^2$ (neutron)

- Noise occup. < 0.1Hz/pix
- 0.2% masked pixels
- Dry ice cooling



Bias -130 V

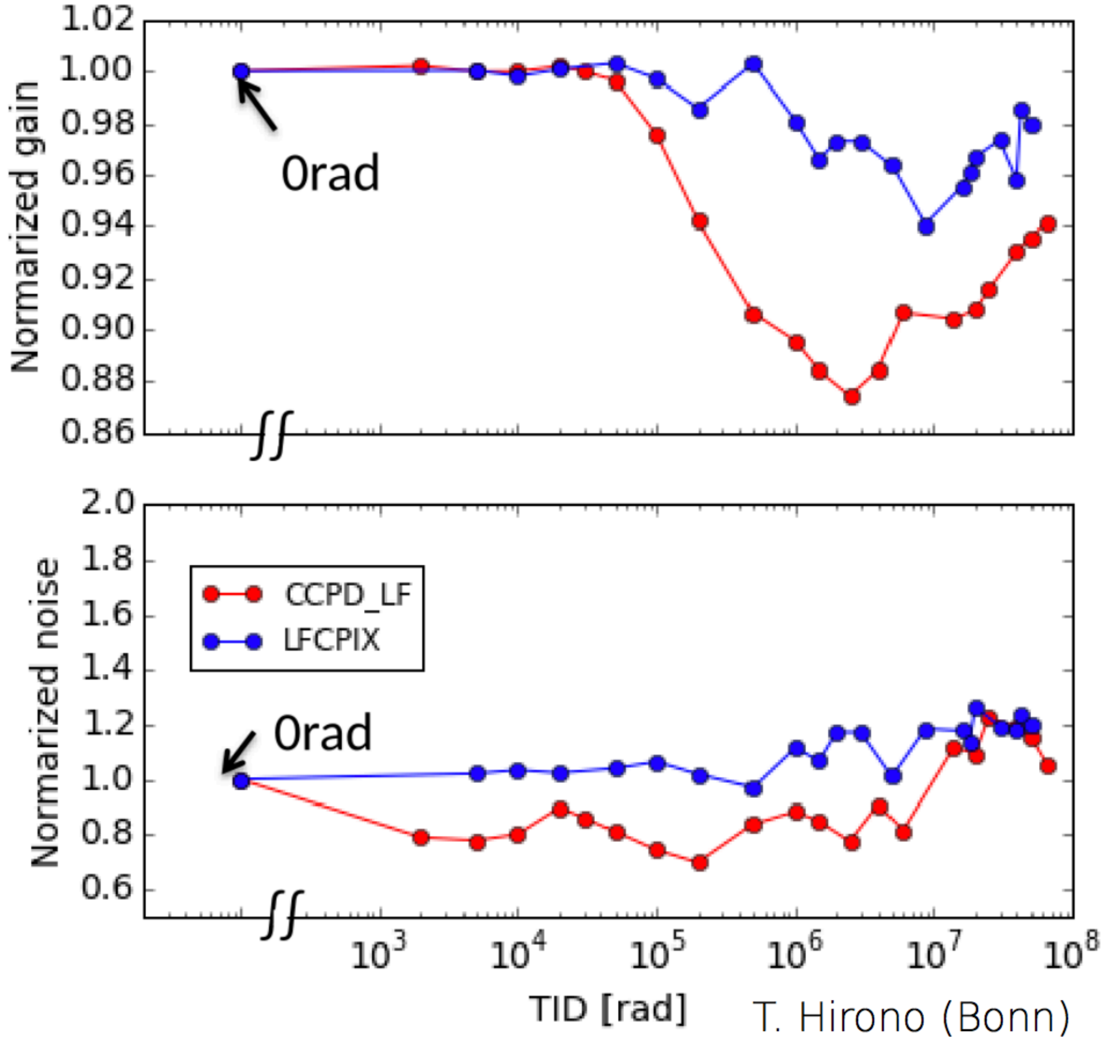
Thres. ~ 1700 e^-

98.9%

LFOUNDRY HV-CMOS SENSOR

- ➢ X ray irradiation up to 50Mrad
- ➢ Tiny impact to overall efficiency
- ➢ 20% higher noise

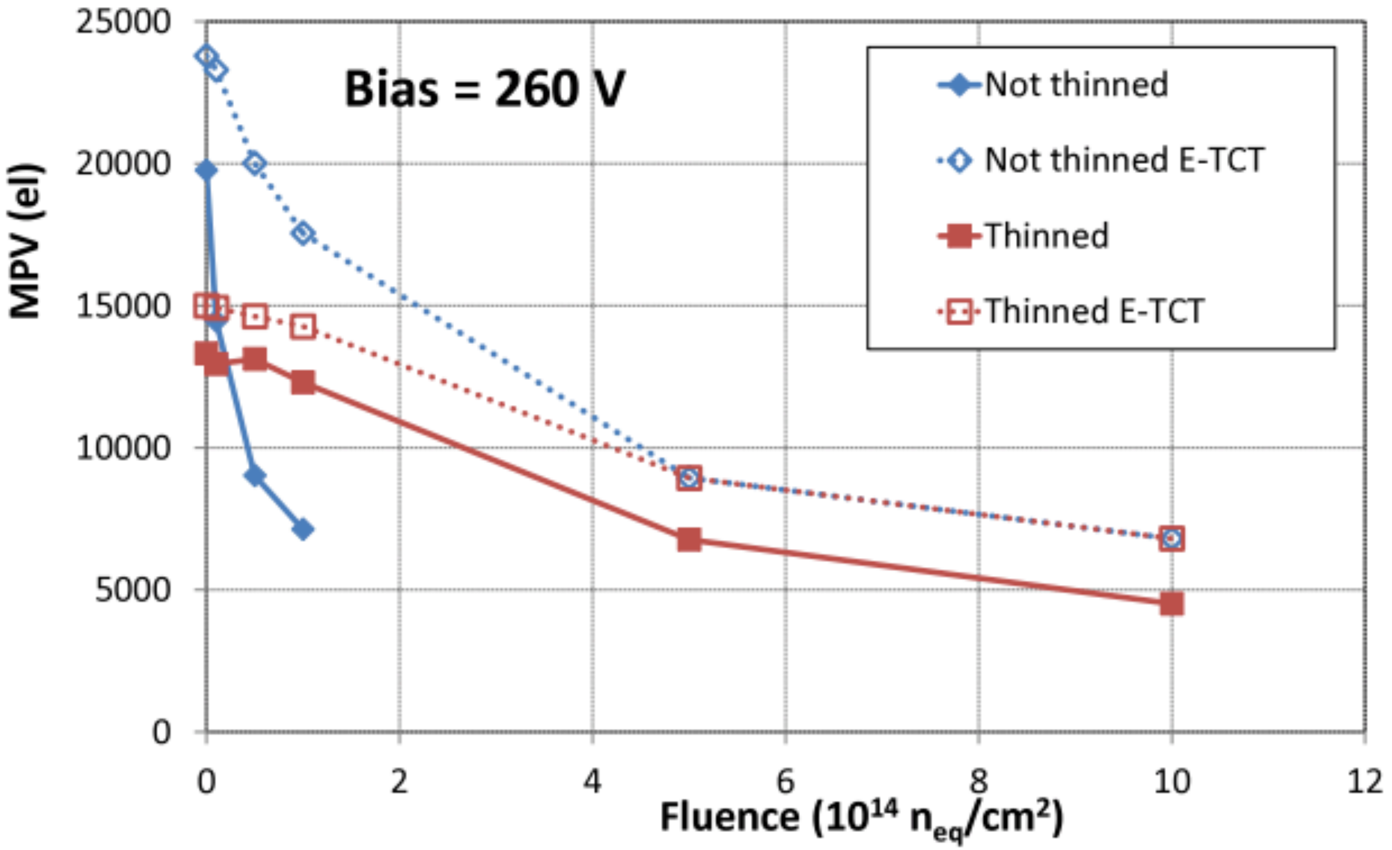
- X-Ray irradiation and test pulse injection up to 50Mrad



T. Hirono (Bonn)

AMS HV-CMOS SENSOR

- AMS 180nm CMOS technology (for ATLAS pixel) , HV-CMOS
- Proton Irradiation up to 10^{15} N_{eq}/cm^2
  - Collected charge decreased to 30% after irradiation
  - Still much higher than noise level (100~200e), still have high efficiency



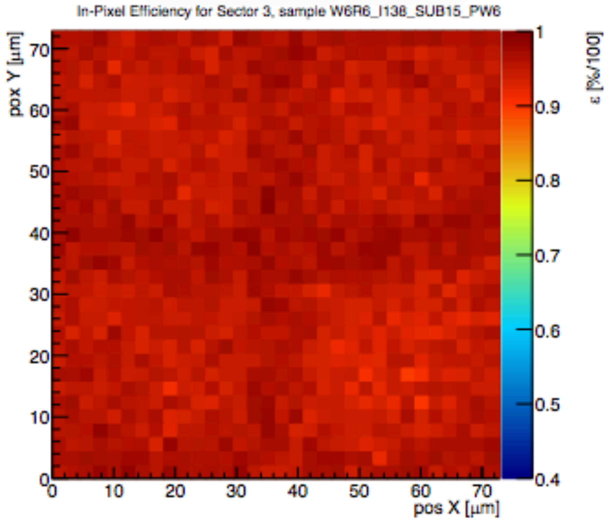
MALTA CHIP DEVELOPMENT FOR ATLAS PIXEL

- TJ-180 CIS technology
- Proton Irradiation up to $5*10^{14}$ N_{eq}/cm^2

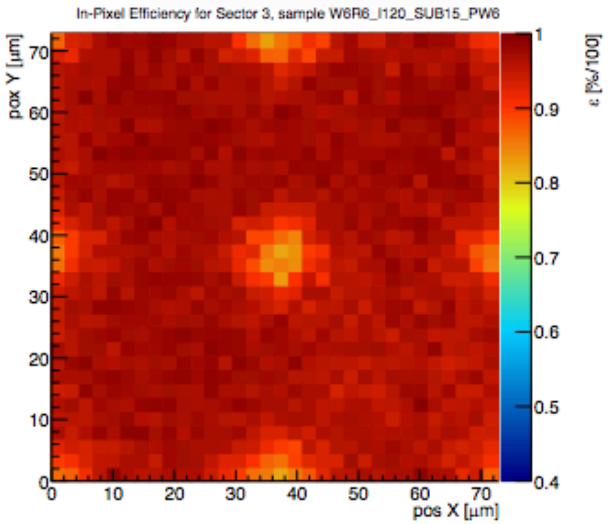
- 180 GeV pions at SPS at CERN, Summer 2018
- Results show decrease in efficiency after irradiation to 5e14 n_{eq}/cm^2
- Inefficiency in pixel periphery
- Too noisy to operate at low threshold after irradiation
- 4 pixels per plot

Unirradiated

Threshold ~250 e-

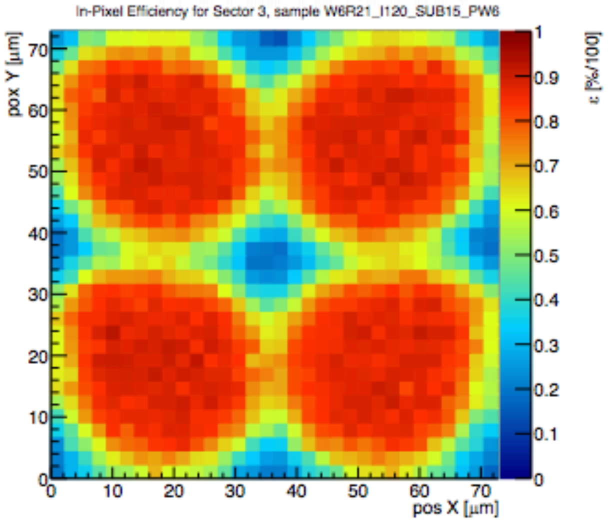


Threshold ~400 e-



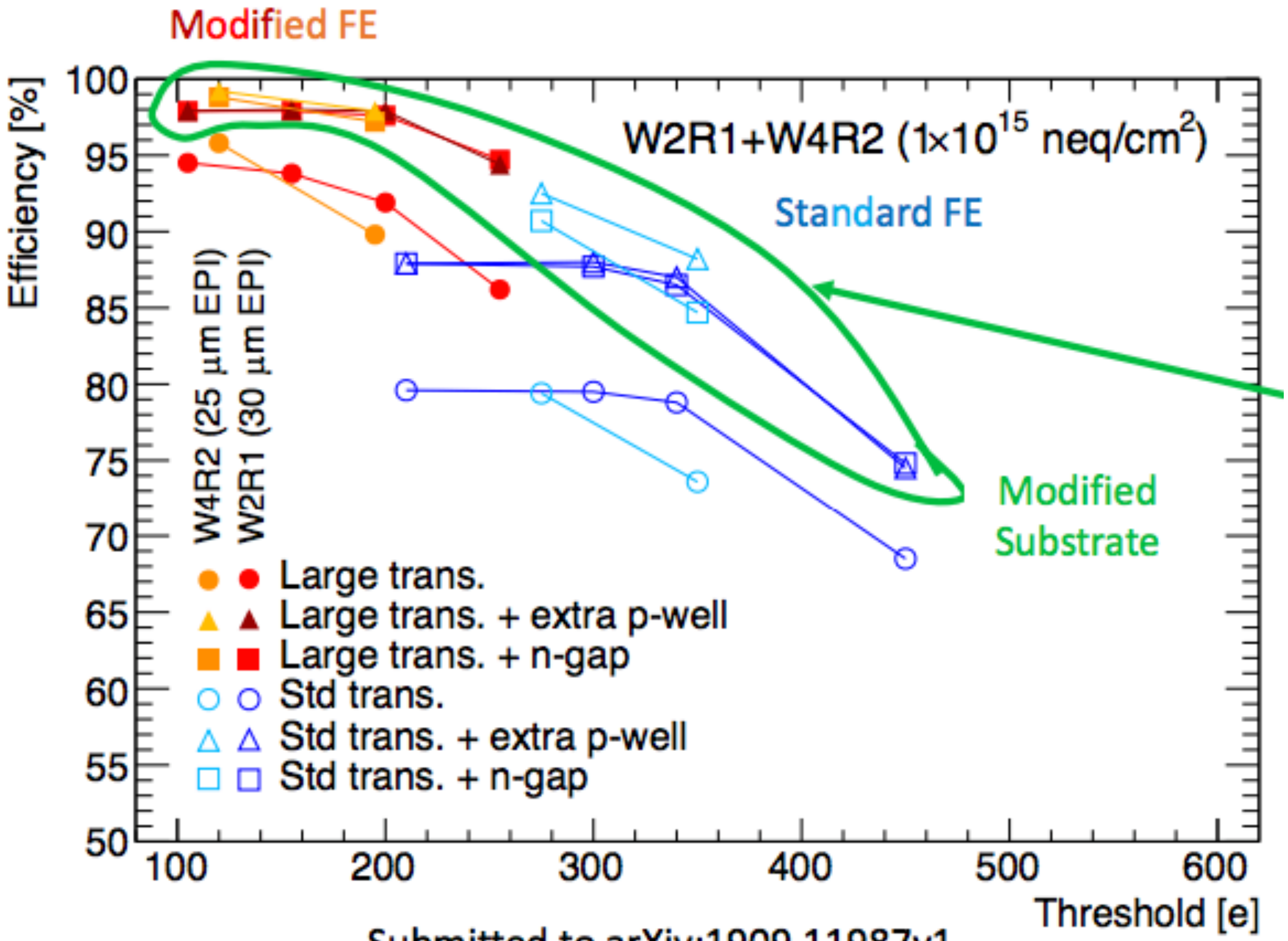
5e14 n_{eq}/cm^2

Threshold ~400e-



MALTA CHIP DEVELOPMENT FOR ATLAS PIXEL

- TJ-180 CIS technology
- Need to modify lots of process to reach $10^{15}\ N_{eq}/cm^2$: efficiency ~97%



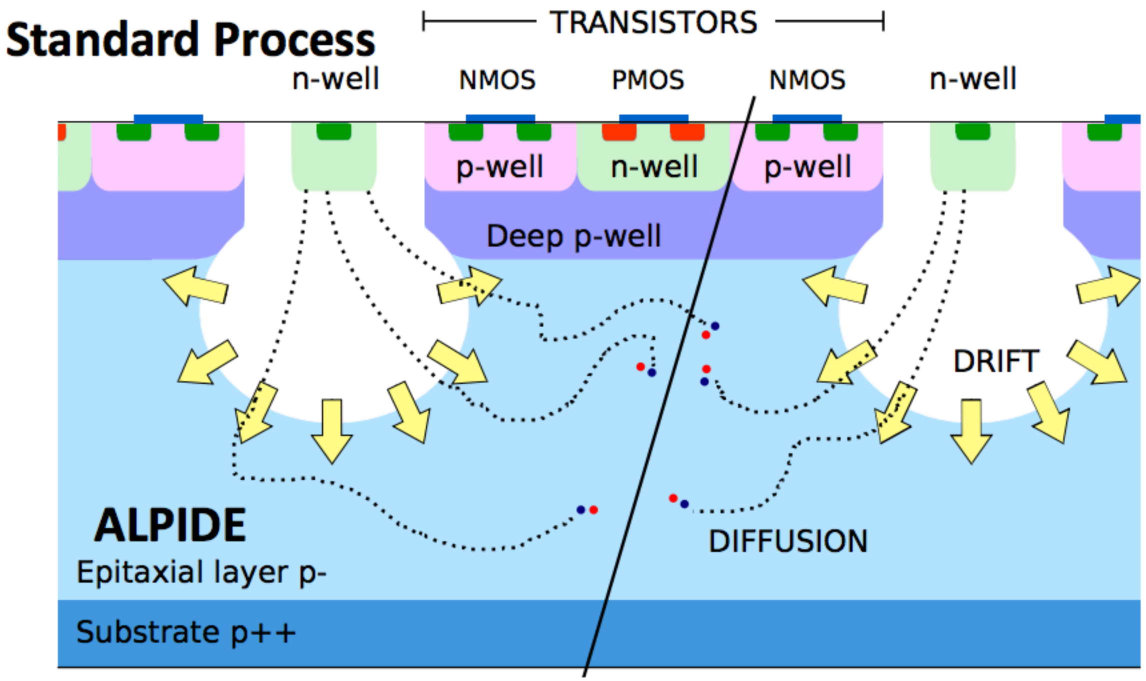
Submitted to arXiv:1909.11987v1

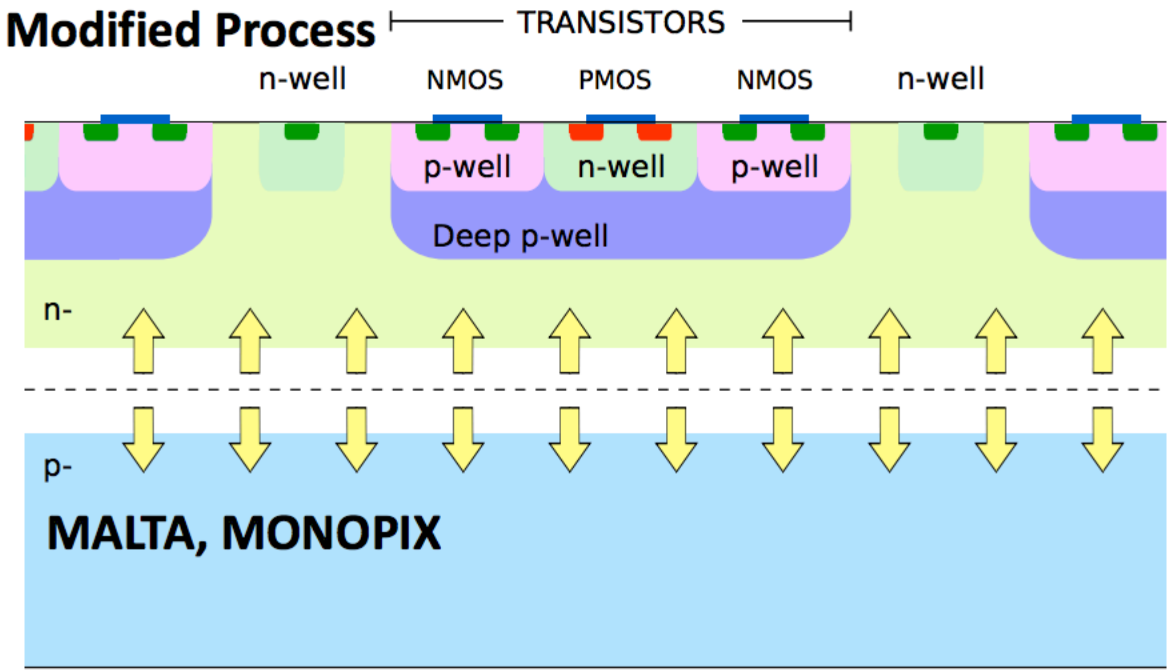
SUMMARY

- Need to re-visit the radiation hardness of vertex detector for small beam pipe
- CEPC vertex detector requirement in CDR
  - Radiation tolerance **(per year):** 1 MRad &2×10^{12} 1 MeV n_{eq}/cm^2
- CEPC Jadepix study showed TJ180 technology works after 1×10^{13} 1 MeV n_{eq}/cm^2
- ATLAS CMOS sensor R & D showed
  - CMOS sensor can work at fluence 1×10^{14} 1 MeV n_{eq}/cm^2 , 50MRad
  - Lfoundry HV-CMOS technology performed better in high does
  - Need modifications for TJ-180 technology to reach 1×10^{15} 1 MeV n_{eq}/cm^2
    - Inefficiency start to show up after 1×10^{14} 1 MeV n_{eq}/cm^2
- For CEPC design:
  - Vertex detector better to operate below the fluence 1×10^{14} 1 MeV n_{eq}/cm^2
  - Otherwise, we need to re-visit the pixel technology

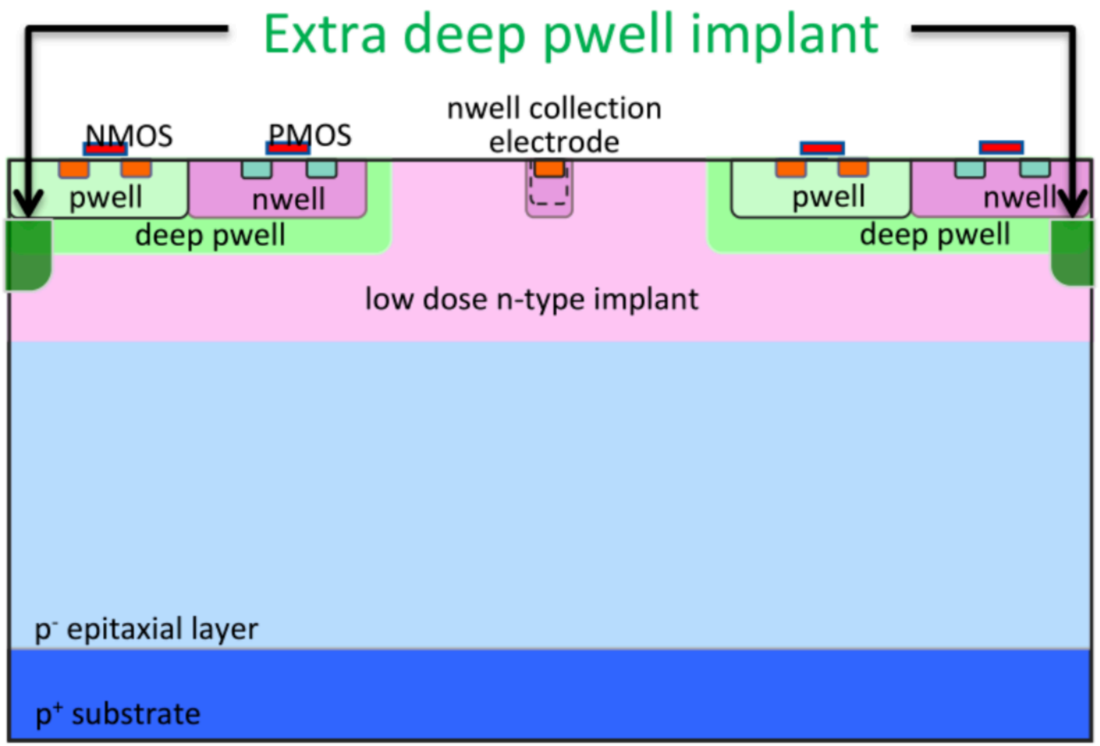
Modification of TJ180 technology

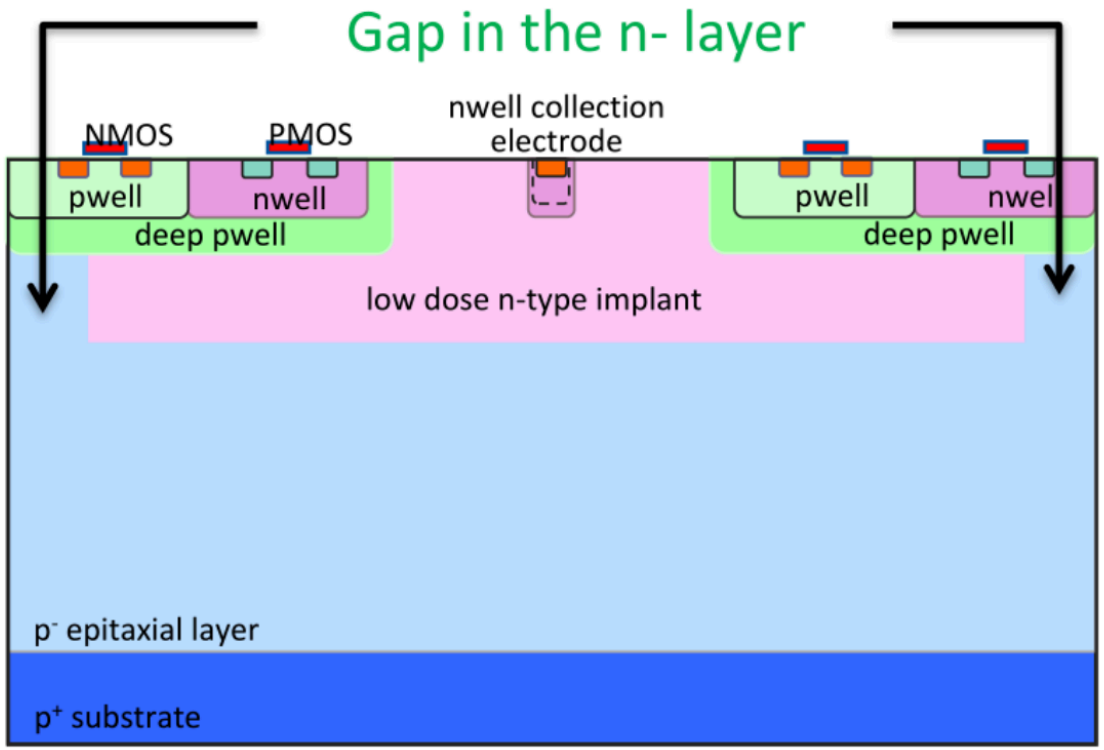
Modification of TJ-180 CIS technology to increase its radiation hardness





MODIFICATION OF TJ180 TECHNOLOGY



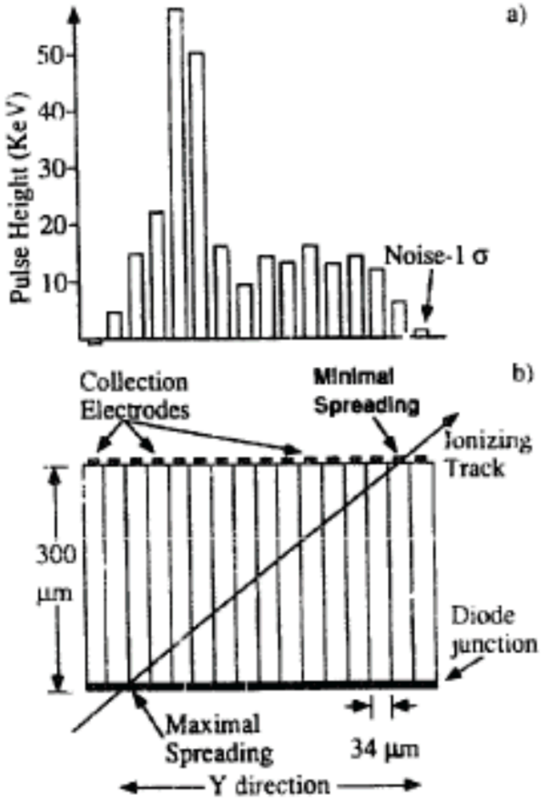


- Additional deep p-type implant
- Requires additional mask, but can use 'known' process step

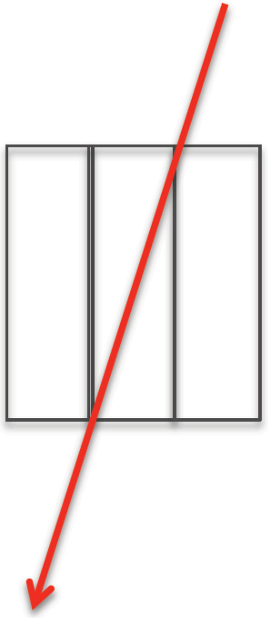
- Creating a gap in the deep n-type implant
- Mask change, no additional mask required

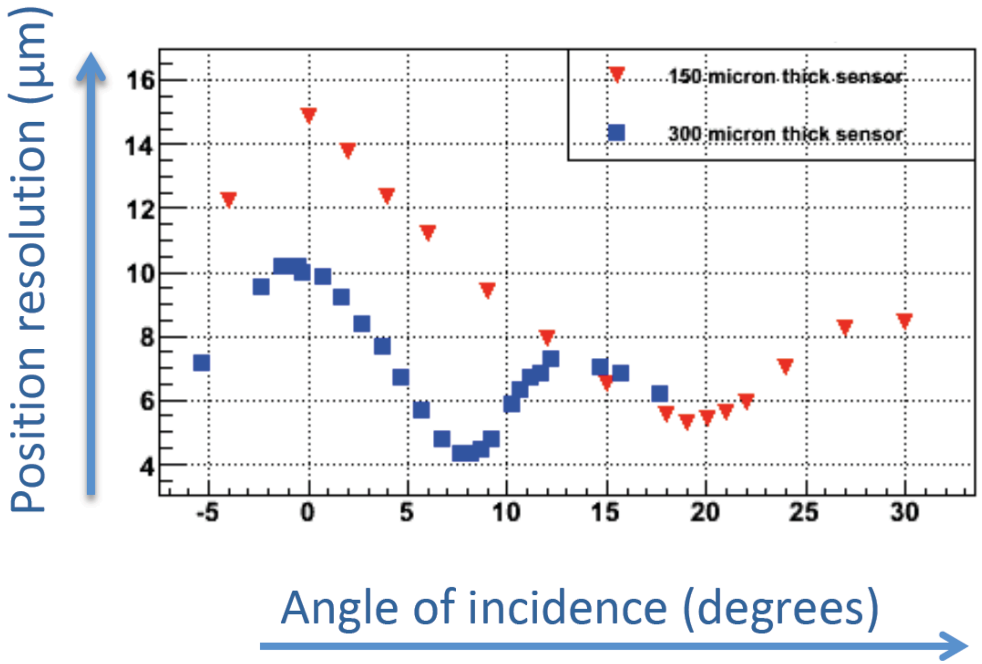
VERTEX DETECTOR WITHOUT ENDCAP ?

- Long barrel was not ideal in the past, with hybrid thick pixel sensor (300µm)
  - Charge sharing in small incident angle track help to improve resolution
  - Large incident angle track cause large charge sharing → low S/N



C. Kenney et al. NIM A 654 (2011) 258-265





Timepix3: X. Llopart, J. Buytaert, M. Campbell, P. Collins et al.

Average of extreme pixels in the cluster gives better results
In this case the signal (and the S/N) for a single channel reduces with track inclination

Can optimize resolution using track inclination to enhance charge sharing, can also be done using a magnetic field

VERTEX DETECTOR WITHOUT ENDCAP ? (LONG BARREL)

- Using thin CMOS pixel sensor, charge sharing effect is small
  - Cluster size and charge sharing can be control using thin active layer silicon
  - In-pixel amplifier in electronics improved S/N
  - No major technical issue of long barrel design