CMOS Strip Sensor Characterization for the ATLAS Phase-II Strip Tracker Upgrade

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With inputs from ATLAS CMOS Strip Calibrators
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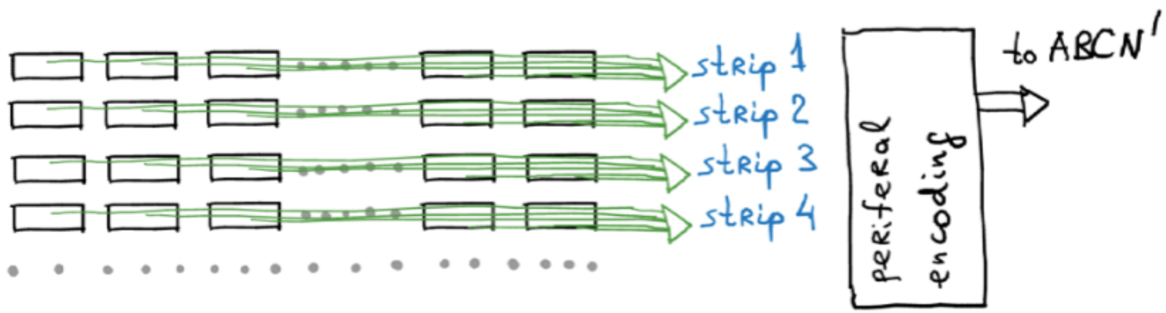
Outline

- **CMOS for the ATLAS ITk-Strip**
- **Preliminary results of OVERMOS**
- **Testing CHESS 2 in-pixel electronics**
- **Summary and Outlook**

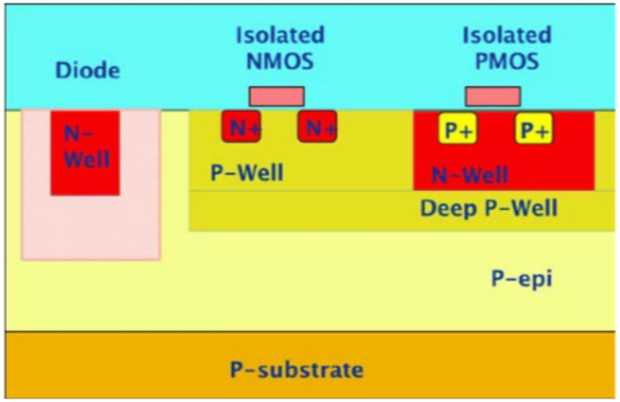
CMOS for the ATLAS ITk-Strip

- Evaluate CMOS technologies for ITk-Strip
  - "Strip" composed from pixels with individual readout
  - Similar readout chain: sensor (Analog FE + comparators)->ABCN'->HCC'
- Possible improvements compared to conventional strip detector:
  - Lower costs
    - Standard commercial technologies
    - much less wire-boding
  - Lower material budget
    - Integrated front-end electronics and sensitive volume on the same silicon substrate
    - Possible to be thinned to less than 100um
  - Higher position resolution
    - Flexible to implement pixelated structure

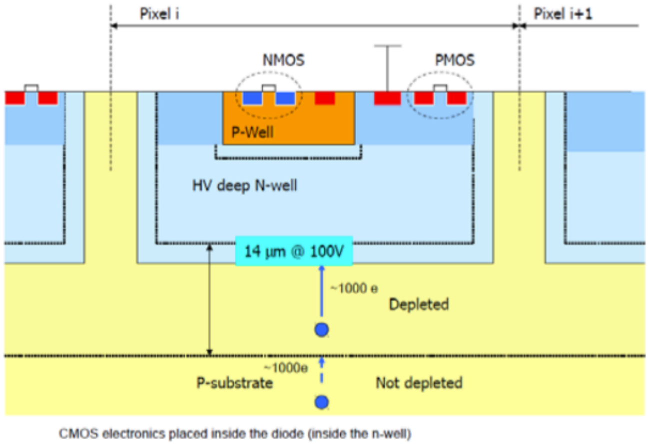


HV/HR-CMOS Technology

- Depleted CMOS benefits from HV/HR technology -> radiation hardness
    - $d \propto \sqrt{\rho \times V}$
- High-Resistivity CMOS technology
    - Depletion zone ~10-20 μm
    - High resistivity: > kOhm*cm
    - Small collection well
    - Small capacitance = low noise/power
    - Longer drift distance
    - TowerJazz-OVERMOS 1.0/ 1.1
- High-Voltage CMOS technology
    - Depletion zone: ~100 μm
    - High bias voltage: ~100 V
    - Large collection well
    - Larger capacitance = higher noise/ power
    - Short drift distances, high field
    - AMS-CHESS 1/2

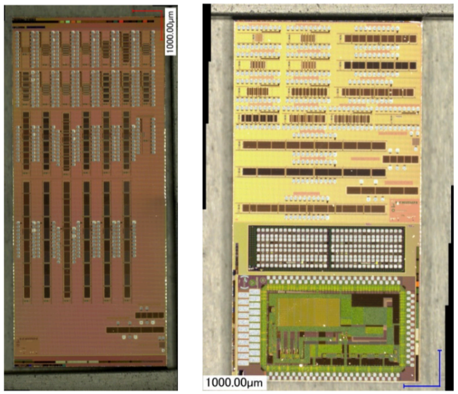


HR-CMOS Layout

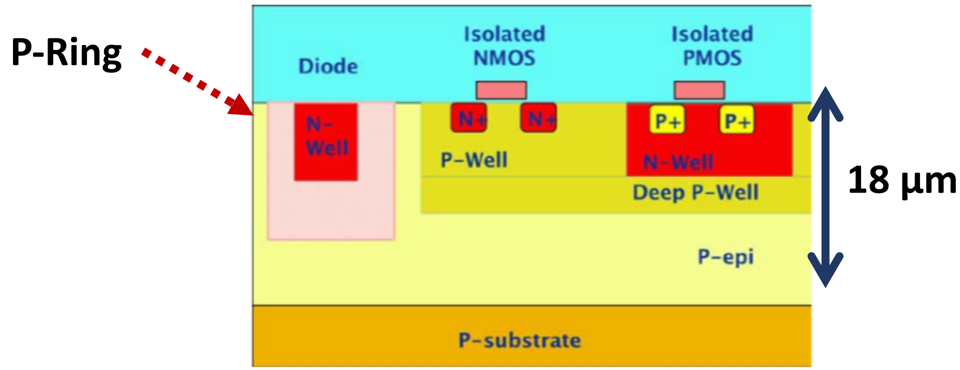


HV-CMOS Layout

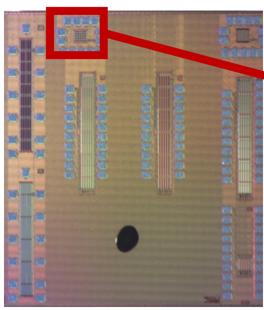
OVERMOS Description

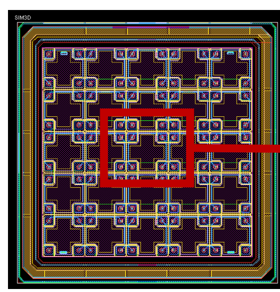


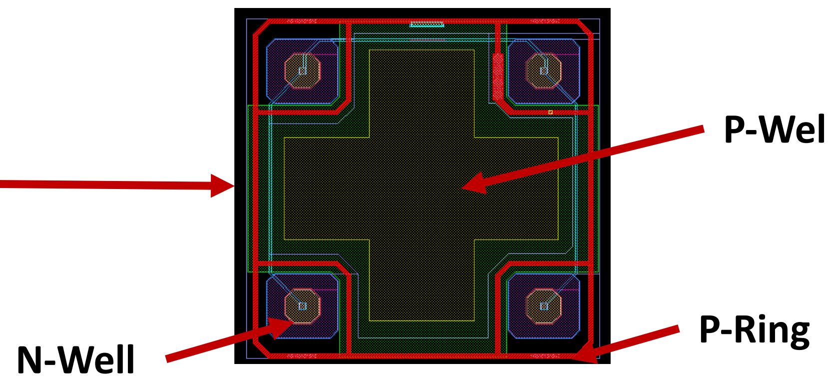
OVERMOS 1.0 with p/n type sub



OVERMOS 1.0 Layout: cross view





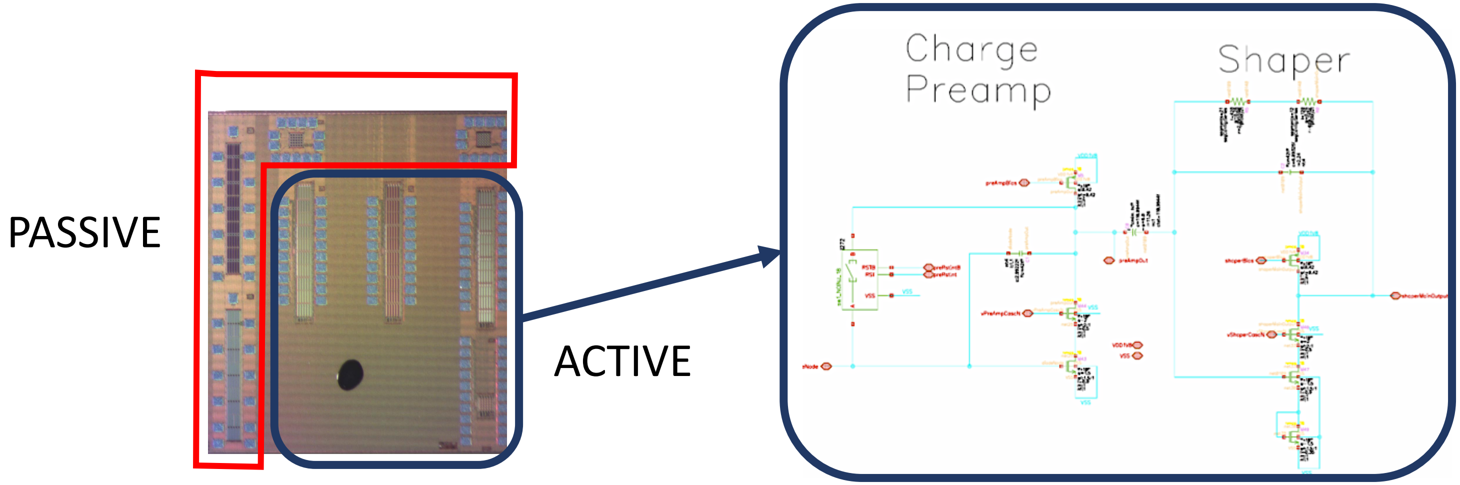


OVERMOS 1.1 with p type sub

OVERMOS 1.1 Layout: top view

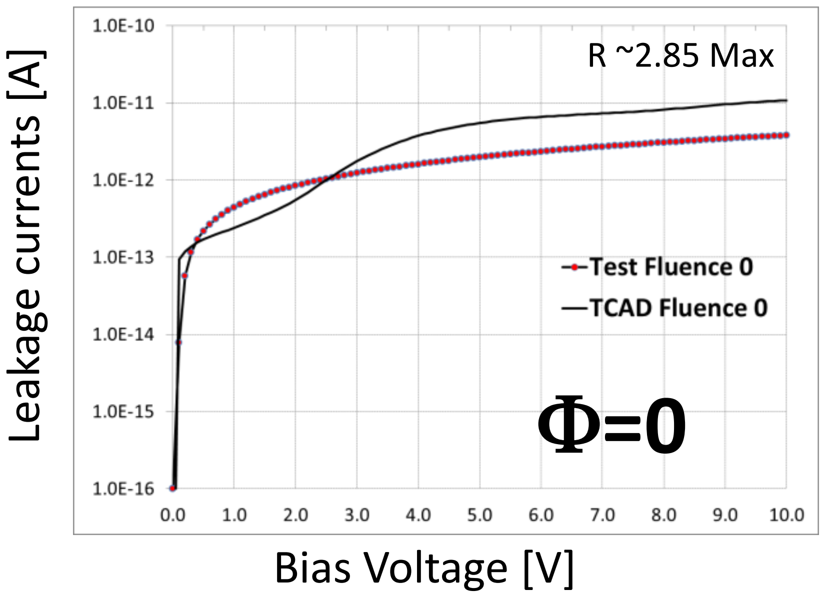
- Collaborated between RAL and IHEP
- Fabricated with TJ 180 nm Hi-res;18 µm thick epitaxial layer 1kOhm*cm
- Small (4 x 4 µm^2) 4 collecting nodes each pixel
- P-Rings implanted in OVERMOS 1.1 to improve short problem in 1.0

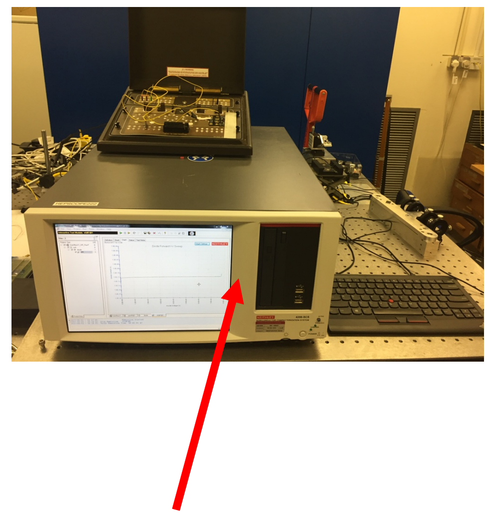
OVERMOS 1.1 Test

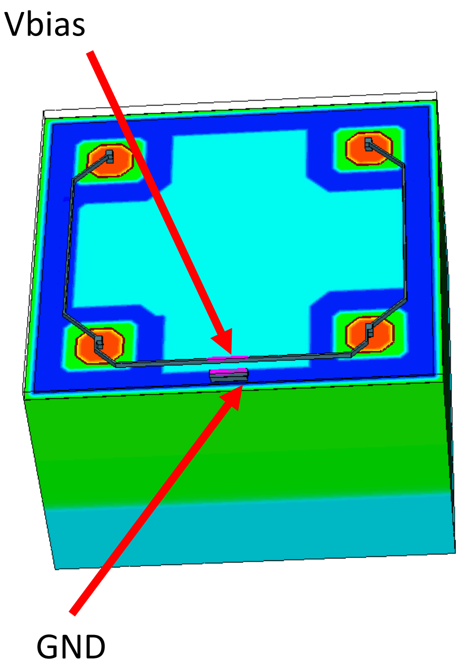


Passive pixel without in-pixel electronics • “Diode”: sensor characteristics	Active pixel, with in-pixel electronics • Charge amplifier + Shaper
Test • IV/CV: depletion voltage • Laser injection: charge collection • Irradiation: radiation hardness	Test • TCT: depletion depth • ^{55}Fe: MIP response

Passive Pixel Leakage Currents







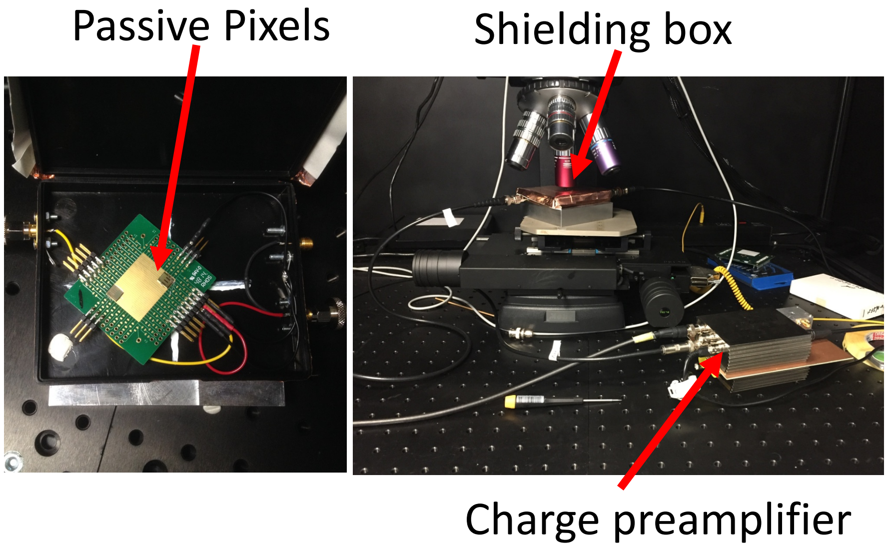
Keithley 4200 Semiconductor Characteristic System

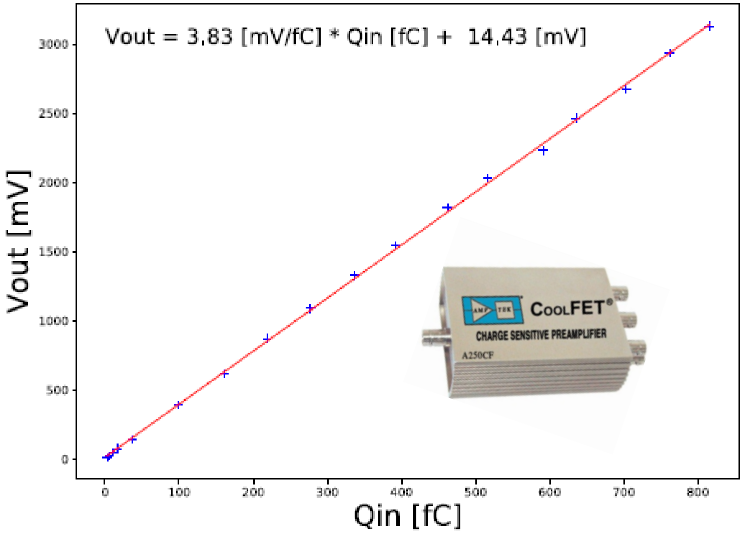
- Probing pixel (40X40 μm^2) with Keithley 4200 SCS
- HV bias voltage applied to n-well and p-well grounded
- Leakage current for tested and TCAD results differ by ~ 3 max

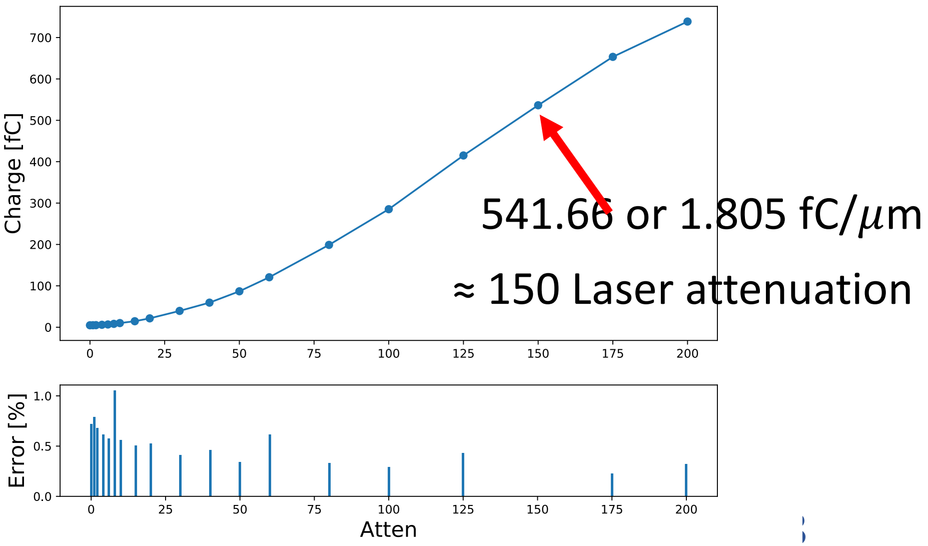
Passive Pixels Laser Response

- Sensor signal amplified with an external preamplifier (A250CF coolFET), bias voltage up to 10 V

- Laser information:
  - Adjustable intense (calibrated)
  - Wavelength: 1064 nm
  - Beam spot: ~5x5 μm^2



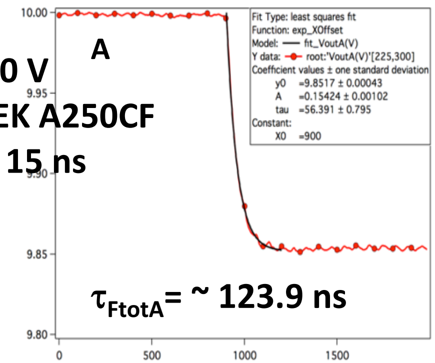


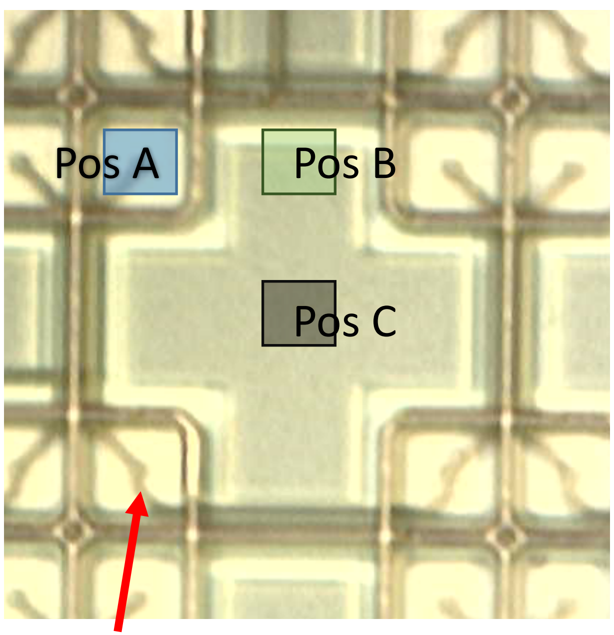


Laser Response Results

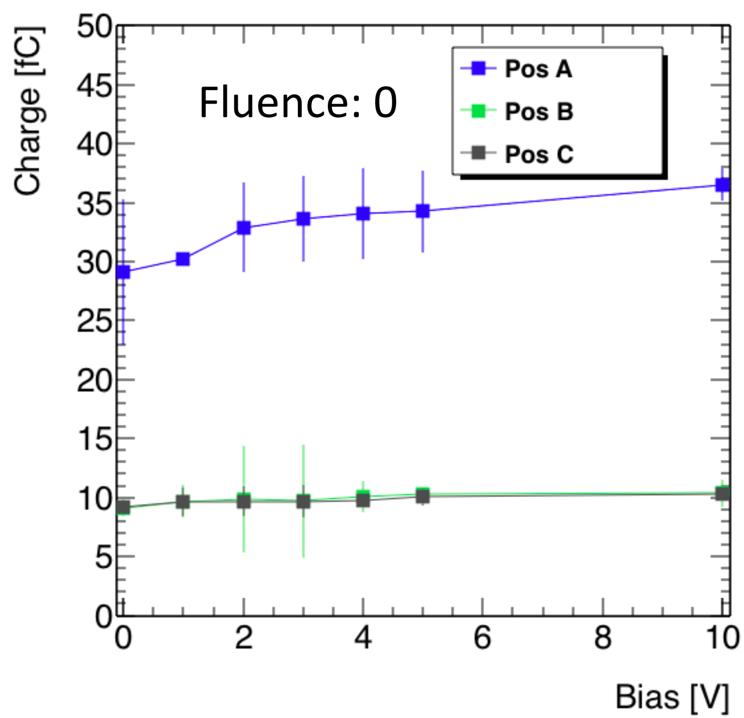
- <Q injected> = 1.805 fC/μm
- Total collected charge vs. Bias , points A,B,C.
  - Diode, between two diodes, center
- Charge increased with Bias; largest near collection diode
- Collection time: A < B < C

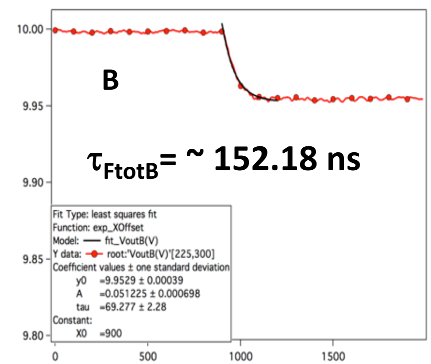
Bias: 10 V
AMPTEK A250CF
τ_{RAMP}= 15 ns

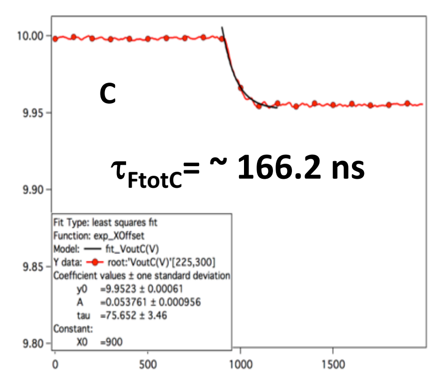




Diode

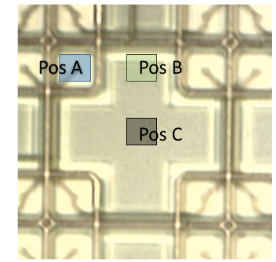


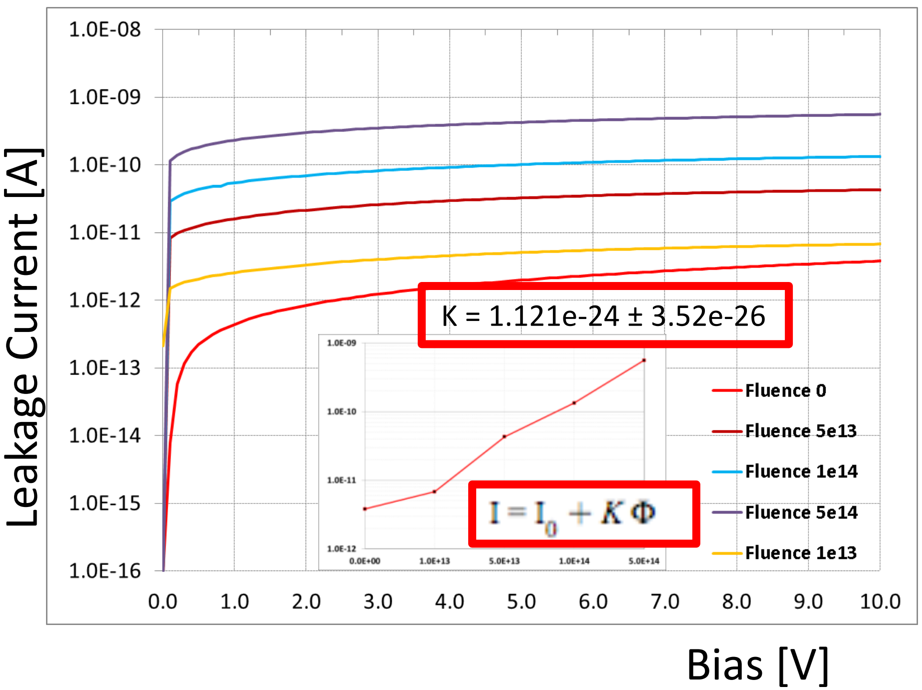


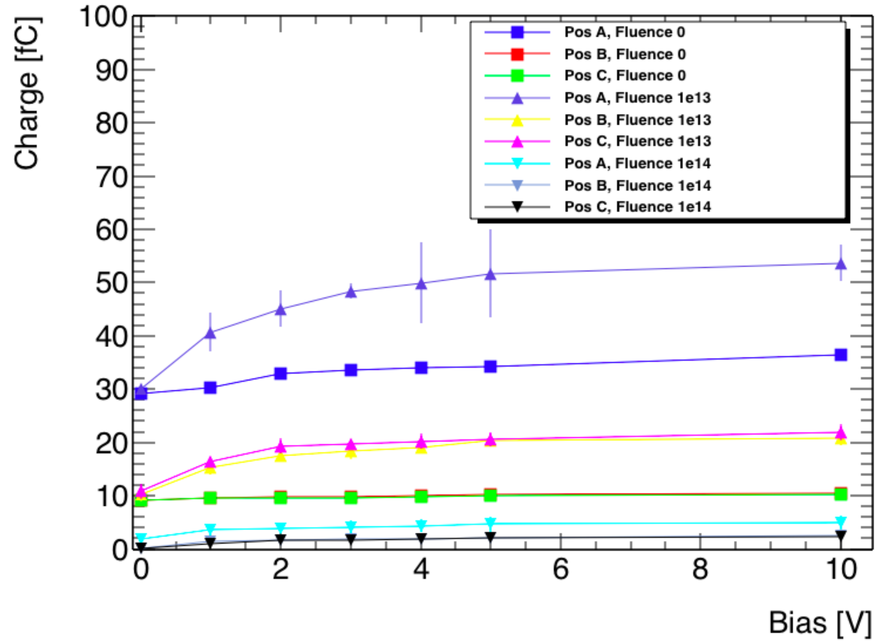


Passive Pixel Irradiation Test

- Irradiated at Ljubljana (Reactor) in October 2017
  - 1E13, 5E13,1E14 and 5E14 n_{eq}/cm^2
- Leakage current linear increase with fluencies, as expected
- Charge collection initial increase for irradiated; drops by tenfold at Φ = 1e14 w.r.t Φ = 0





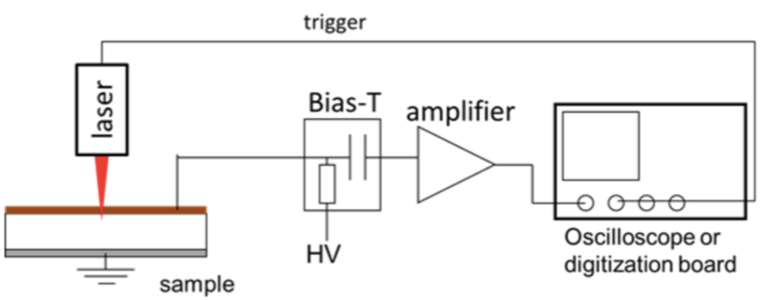


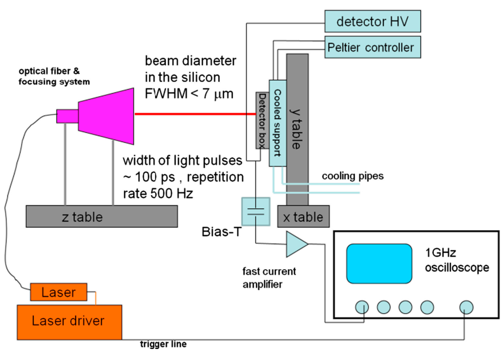
Active Pixel TCT

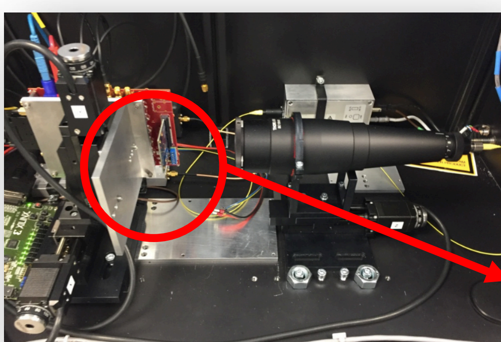
- Active pixel (400X40 μm^2) scanned with Top-TCT and Edge-TCT

Top-TCT is useful for:
- Charge collection
- Spatial resolution

Edge-TCT can be used for the following:
- Depletion depth

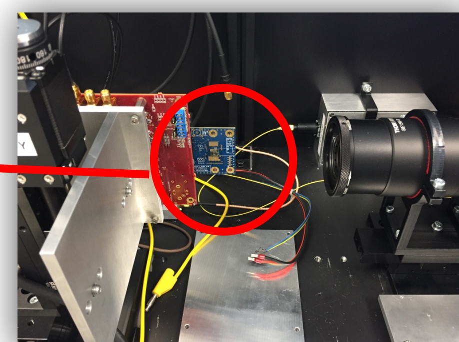






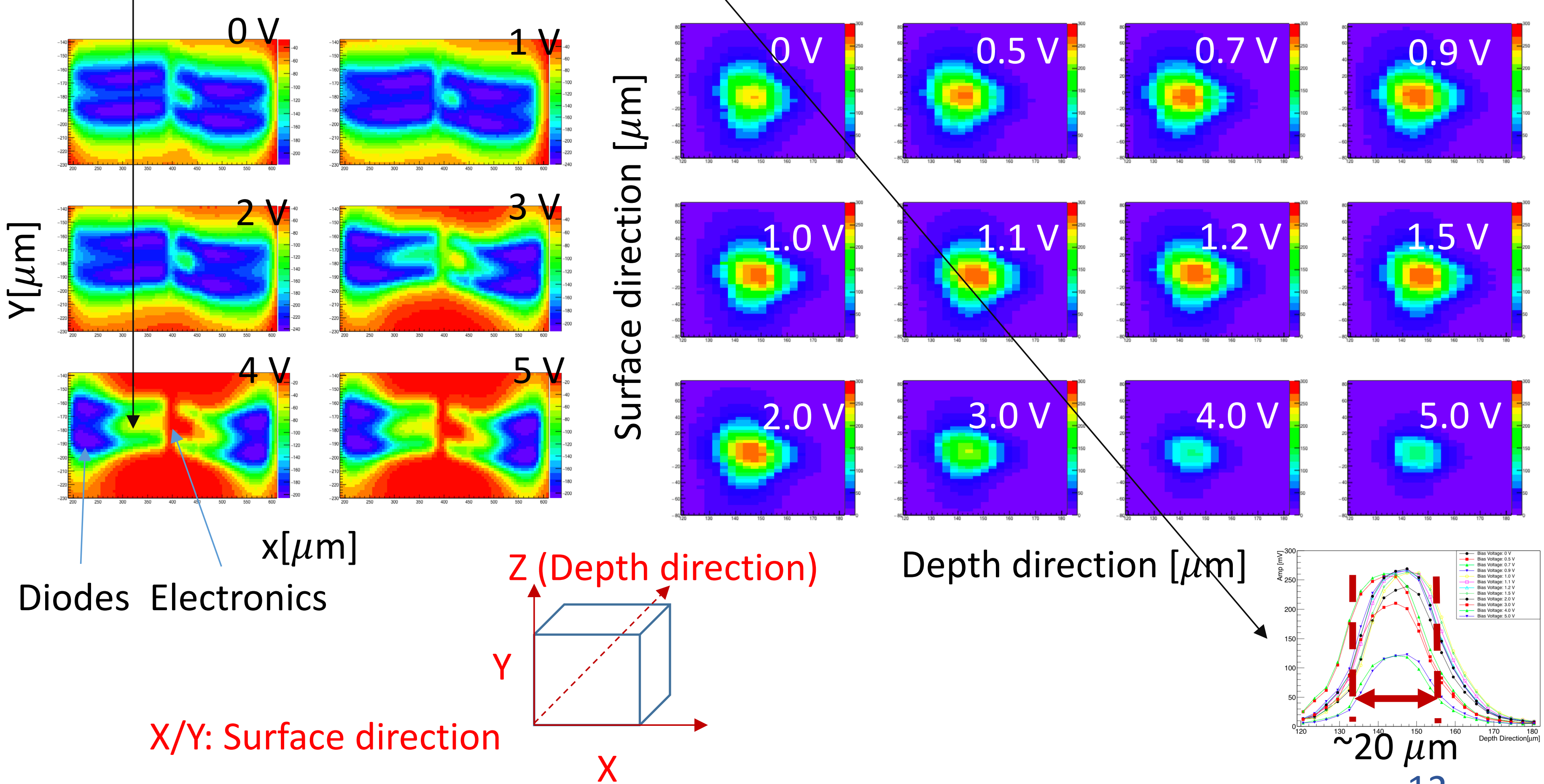
Perpendicular

Parallel



Top-TCT/Edge-TCT Results

- Clear structure/ Depletion region ~20μm(Consistent with Wafer epi 18μm)
- The bias strange behavior need to be further understood

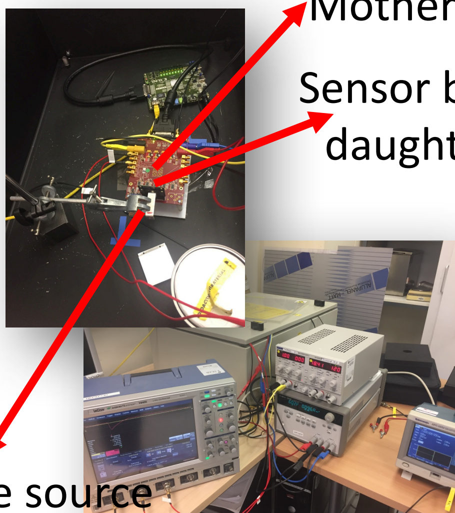


^{55}Fe MIP Test

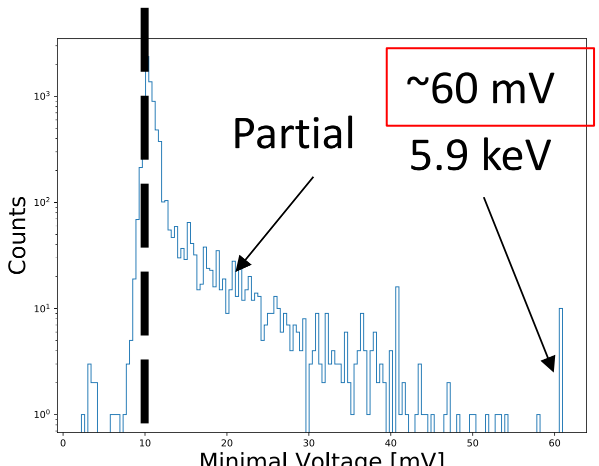
- ^{55}Fe Kα x-ray = 5.9 keV/3.6 eV ≈ 1640 e$^-$
- Kα peak visible even with low statistics; reasonable compared to simulation

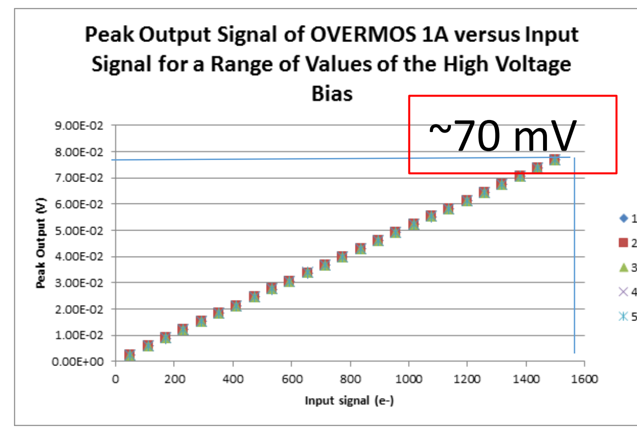
Mother board

Sensor bonded on daughter board



^{55}Fe source



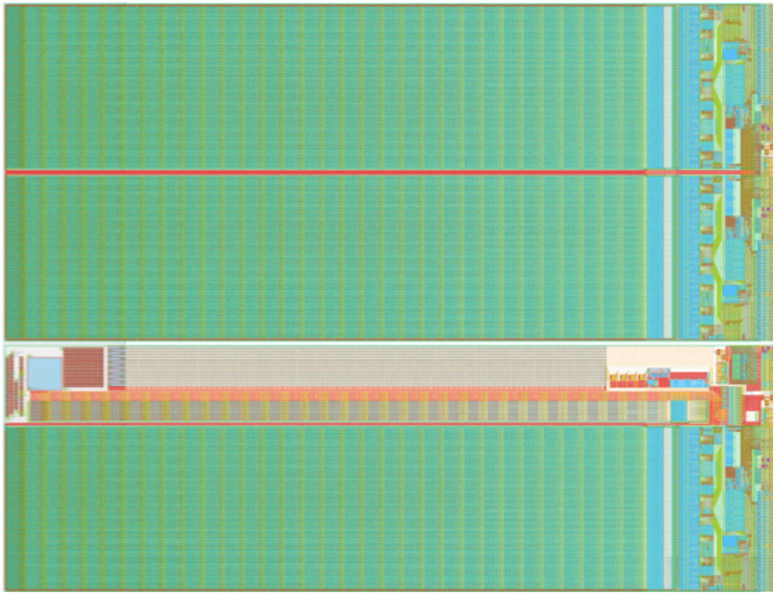


Summary:

Both passive and active pixels functional; performance to be understood with more measurements

AMS-CHESS 2

- CHESS-2 : second generation of CHESS sensors. *(developed to evaluate operation of CMOS strip in arrays with digital outputs)*
  - Designed at UCSC and SLAC.
  - Manufactured in the AMS-H35 high voltage process.
  - Full reticle monolithic demonstrator chip.
  - Produced using 4 different wafer resistances.
    (20, 50-100,200-300,600-2000[Ohm*cm])

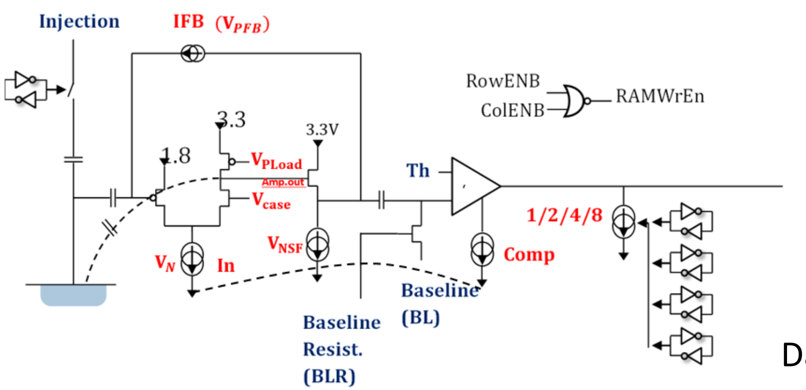


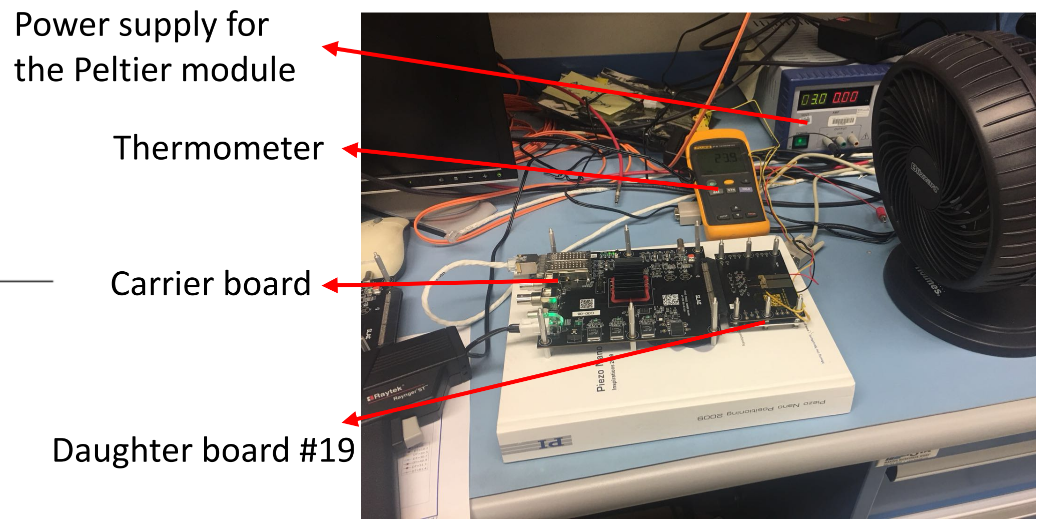
Layout of CHESS-2 chip

3 arrays of 128 X 32 strip-lets with full digital encoding and readout.

In-pixel Electronics

- Charge preamplifier, comparator and encoding are implanted in pixels
- Continuous attempts to make the in-pixel electronics work:
  - added Cooling (Peltier) module into the test system;
  - enabled using an external pulse as Charge Injection signal
  - enabled reading 8 hits from each matrix at a time.

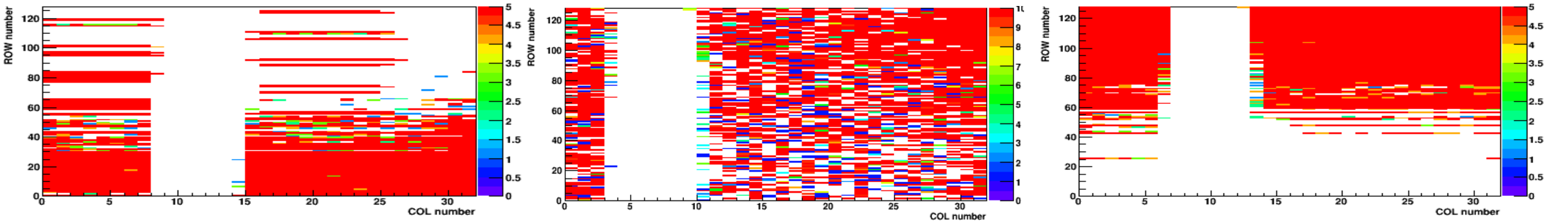




Test Results of CHESS2

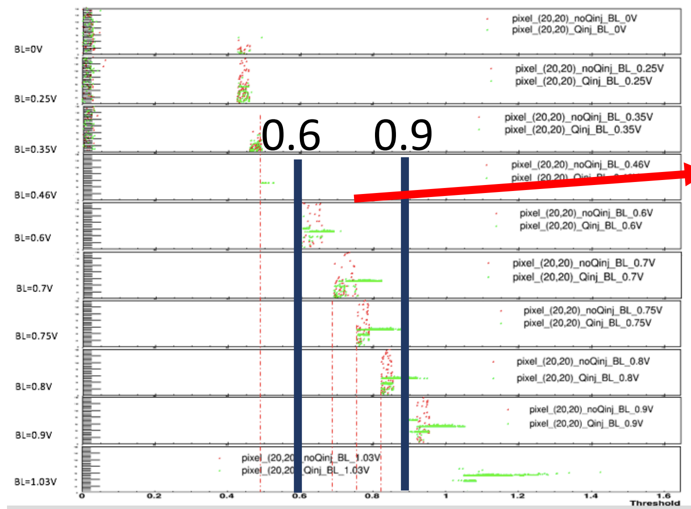
Hit map of the 2nd matrix of the 3 chips

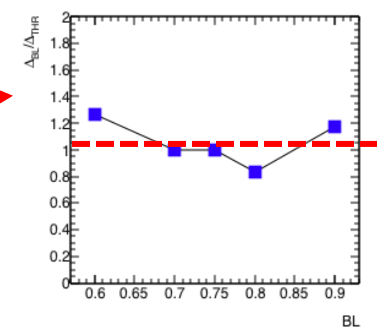
- Different Dead band on each array.
- Pixels beyond the “dead band” are “alive”.



Threshold sweeping:

- ~0.25mV Signal observed;
- Good linearity with BL within(0.6-0.9V)





Summary and next:

- **Stable and repeatable results could be got with optimized firmware, cooling module and external pulzer;**
- **Go for beam tests after remaining issues fixed**

Summary and Outlook

- Evaluate depleted CMOS pixels (HV/HR) for ATLAS ITk Strip
- We actively participate in characterization of OVERMOS 1.0/1.1 and Chess 2 prototype chips
- Next: deeper understanding of HR-CMOS sensor before/after irradiation and HV-CMOS -> evaluation reports

Thank You

Backup

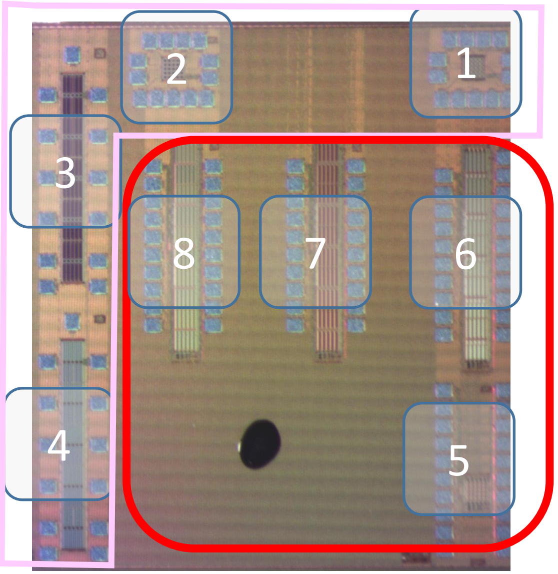
OVERMOS Structures

2: Basic Passive: 5x5 of 40 x 40 um

3: Basic Passive Large: 5x5 of 40 x 400 um merged

4: Basic Passive Large: 5x5 of 40 x 400 um

PASSIVE



1: Symmetric Passive: 5x5 of 40 x 40 um

8: Basic Active Large 5x5 of 40 x 400 um

7: Basic Active Large Merged 5x5 of 40 x 400 um

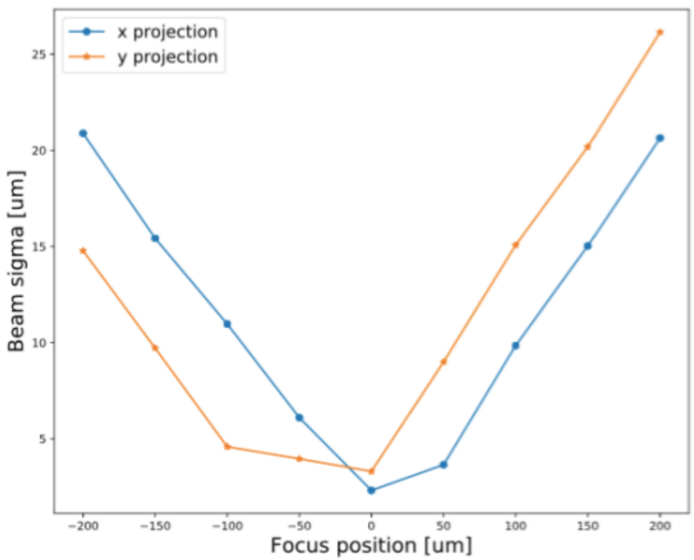
6: Basic Active AC Large 5x5 of 40 x 400 um independent diode biasing AC coupled

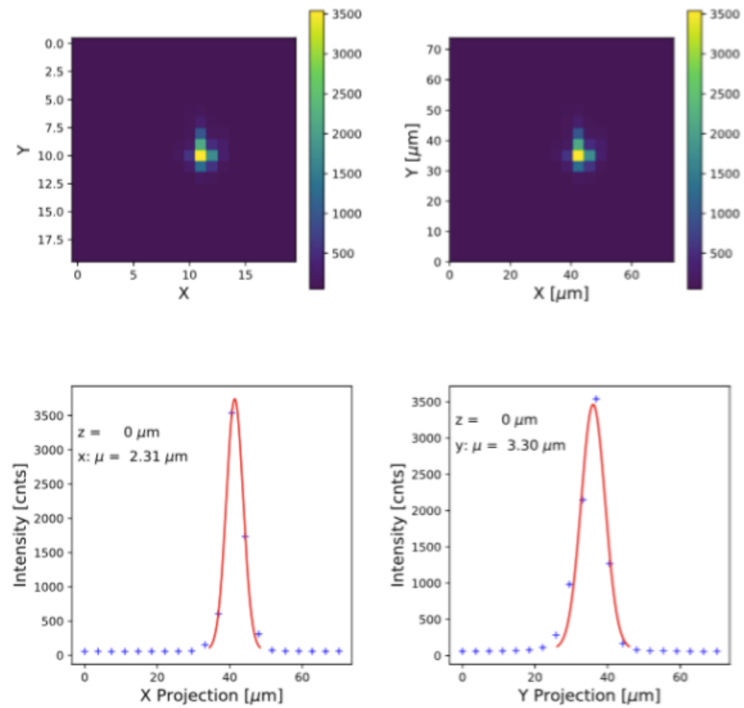
5: Basic Active: 5x5 of 40 x 40 um

ACTIVE

- The PASSIVE pixels consist of arrays of pixels with different arrangements of the 4 collecting nodes (of the same size) within each pixel
- The ACTIVE pixels, i.e. with in-pixel electronics, all allow analogue readout of the pixels

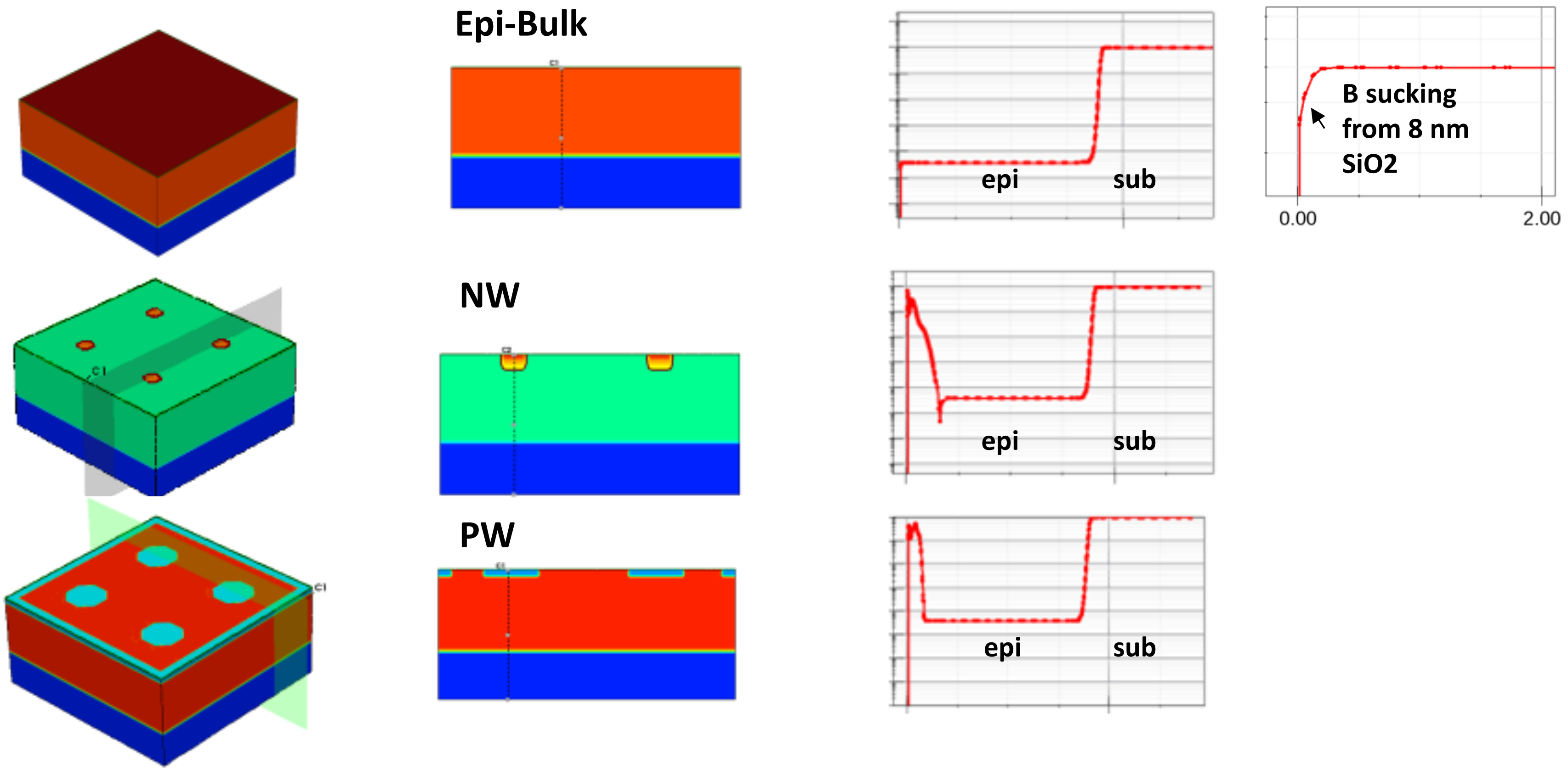
Beam Profile





Laser beam size vs. focusing – Measured beam size with beam profiler

TCAD Simulation



- Individual doping profiles for OVERMOS were obtained using **SPROCESS**, to simulate a (simplified) CMOS fabrication by using TJ foundry process information
- These (1D) doping profiles were then implemented in **SDE**
- Huge reduction in mesh size (O(3e5) points) and computation time

Irradiation

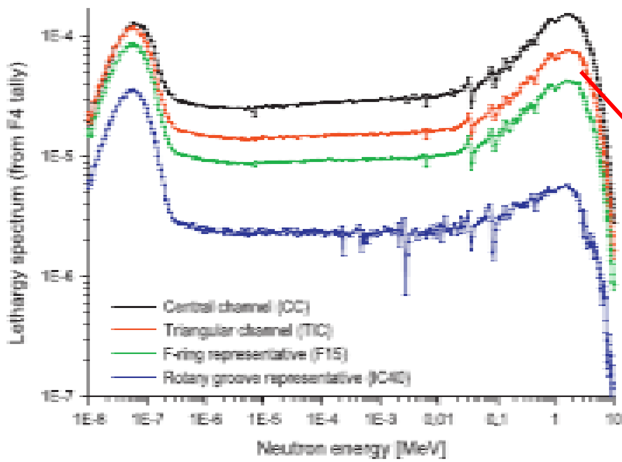


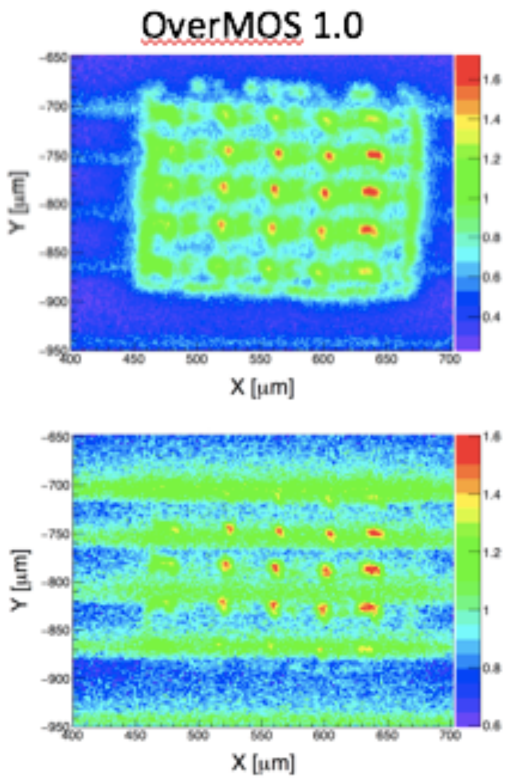
Fig. 4. Lethargy neutron spectrum in representative irradiation channels in core 189 of the TRIGA reactor. Normalization per source neutron.

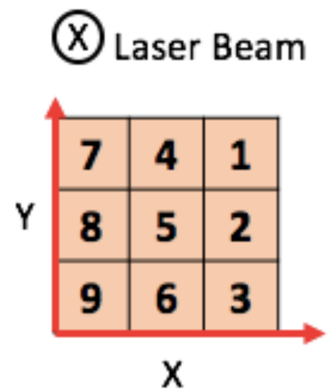
Fractions of thermal (<0.625 eV), epithermal (0.625 eV–0.1 MeV), and fast (>0.1 MeV) neutron fluxes in TRIGA (core 189) irradiation channels.

Irradiation channel	**Thermal** (%)	**Epithermal** (%)	**Fast** (%)
CC	26.6	33.9	39.5
ThCol	79.0	14.4	6.6
RPP	57.2	23.9	18.9
RBP	83.3	12.2	4.5
TangCh	57.8	24.9	17.3
F15	42.6	28.5	28.8
F19	50.0	25.3	24.6
F22	47.8	26.2	26.0
F24	47.4	26.5	26.1
F26	48.4	25.9	25.7
IC40	60.4	25.1	14.5
TIC	37.9	29.4	32.7

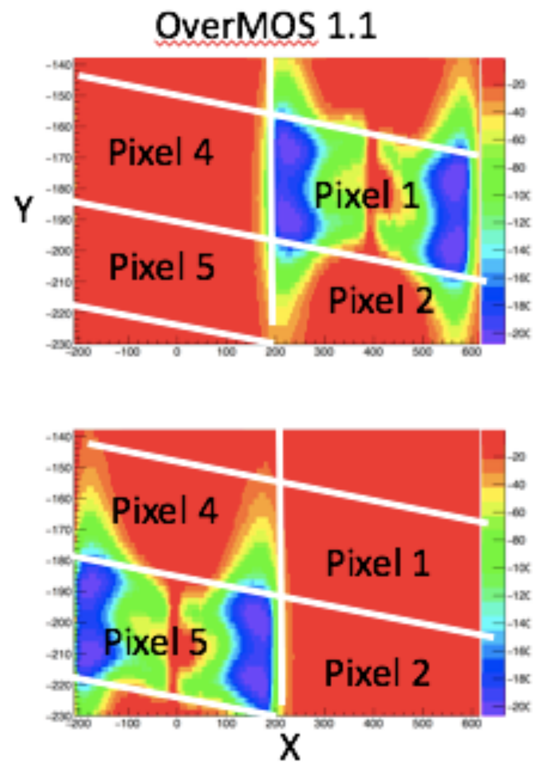
- OVERMOS devices have been irradiated at Ljubljana in October 2017 to 1E13, 5E13,1E14 and 5E14 n fluence
- Estimated around 30% of fluence consisting of high energy neutrons (> 100keV)

Short Problem





Select one pixel to output (per picture) and move the laser to scan



- All channels will show response regardless of which channel the laser hits
- The diodes are isolated by P-rings, so only the hit channel does show a significant response with negligible crosstalk