# Radiation hardness of a CMOS sensor process for a novel Depleted Monolithic Active Pixel Sensor

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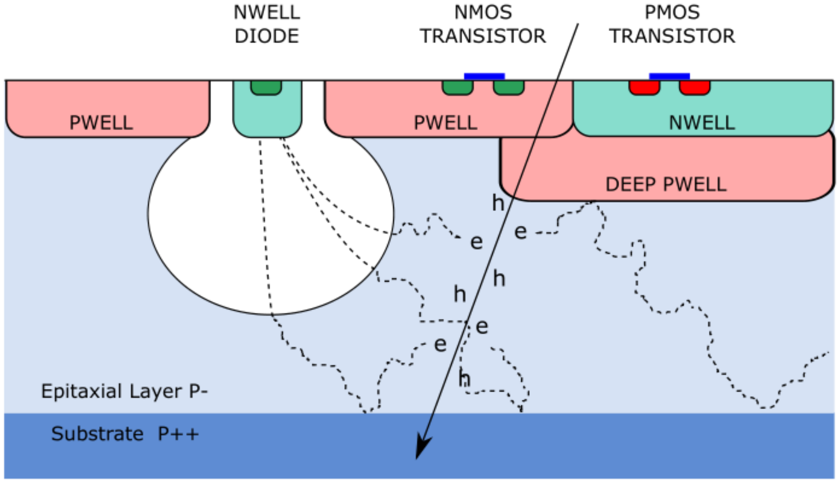
# HV-CMOS at HL-LHC

- Active sensors an interesting option for ATLAS Phase II pixel upgrade
- Challenging radiation environment

| | ATLAS - LHC | ATLAS HL-LHC | |
|---|---|---|---|
| | | Outer (r > 10 cm) | Inner (r = 3.3 cm) |
| NIEL ($n_{eq}$ /$cm^2$) | 2 x $10^{15}$ | $10^{15}$ | 2 x $10^{16}$ |
| Ionizing dose (Mrad) | 80 | 50 | > 500 |

- Requirements:
  - Charge collection by drift
  - Radiation hard electronics design
  - Compatibility with the rest of ATLAS ITk
- "Drop-in" CMOS detector planned for outermost ATLAS pixel layer

# TowerJazz 180 nm Investigator

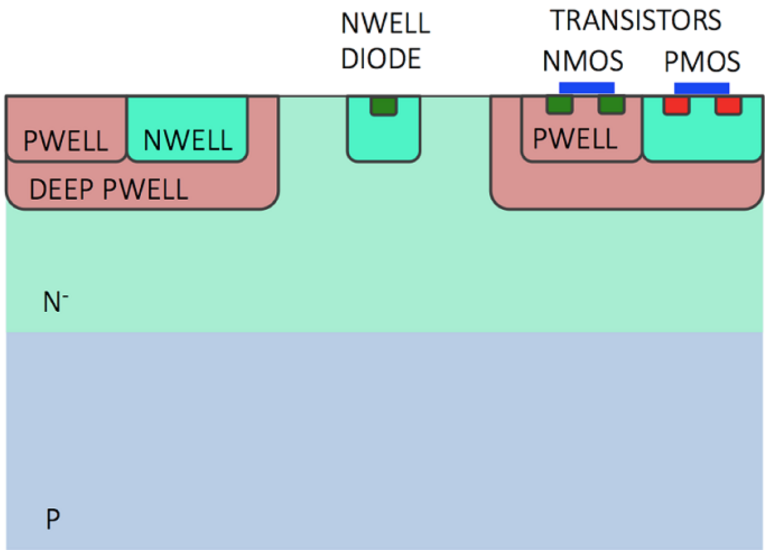



*ALICE ITS Upgrade TDR*

- DMAPS evolved from ALPIDE chip for ALICE ITS upgrade
- Small fill factor, low capacitance design (5 fF)
  - Higher gain, faster response, higher *Q/C*
  - Potentially lower power consumption
  - Important to ensure efficient charge collection, especially on pixel edges

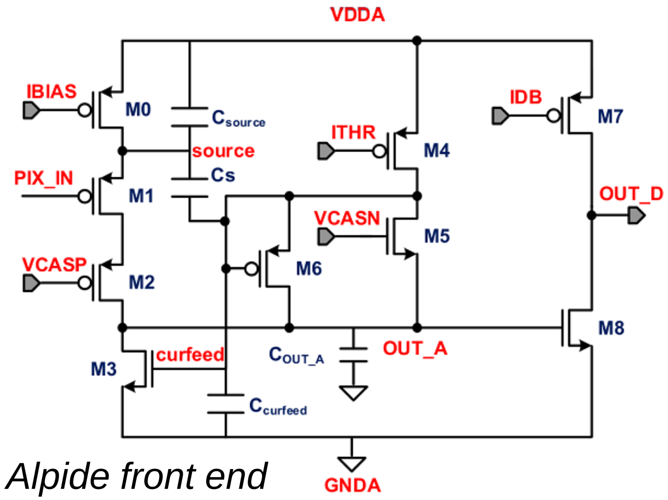
*C. Gao et al., NIM A (2016) 831*
*http://www.sciencedirect.com/science/article/pii/S0168900216300985*

- Modified process
- Additional n-layer to generate a deep junction, maintaining low *C*
- Significantly improved charge collection after irradiation
- No significant circuit or layout changes required

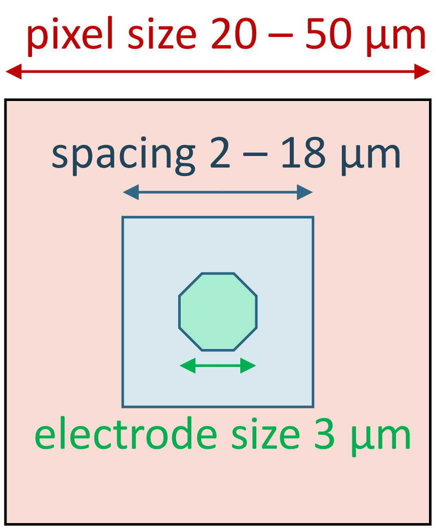


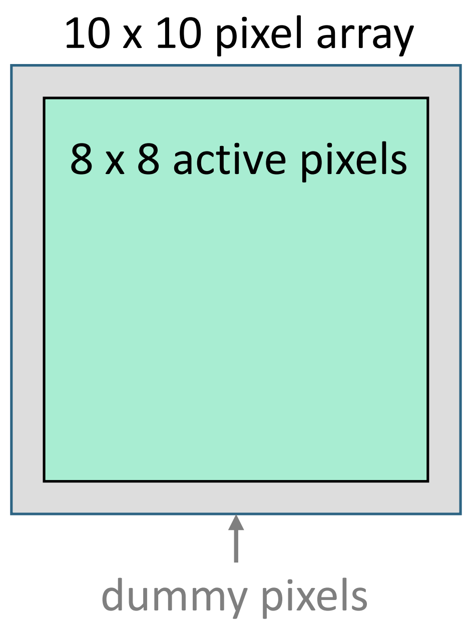
# TowerJazz 180 nm Investigator

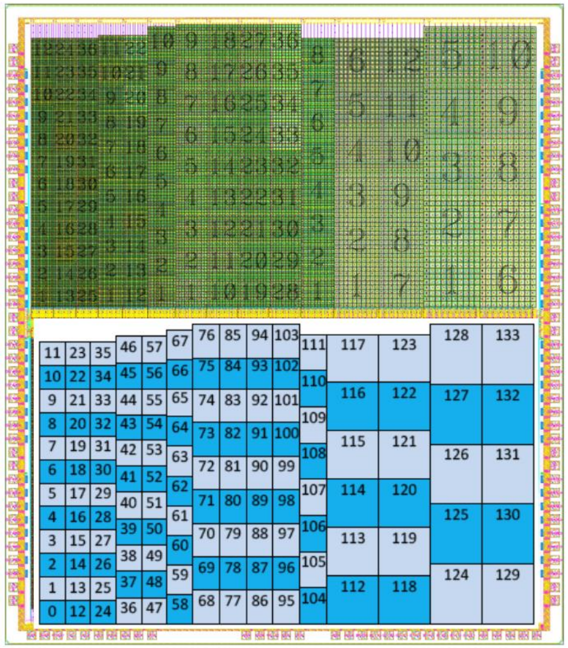
- Charge collection in a thin 25 µm epi-layer (high resistivity)
- Maximal bias voltage 6 V
- Internal charge sensitive amplifier (CSA) in pixel cells
- Investigator chip consists of > 250 test matrices with different pixel flavours
- Charge collection tests with E-TCT, source measurements and test beam




*Alpide front end*
*D. Kim et al. TWEPP 2015*

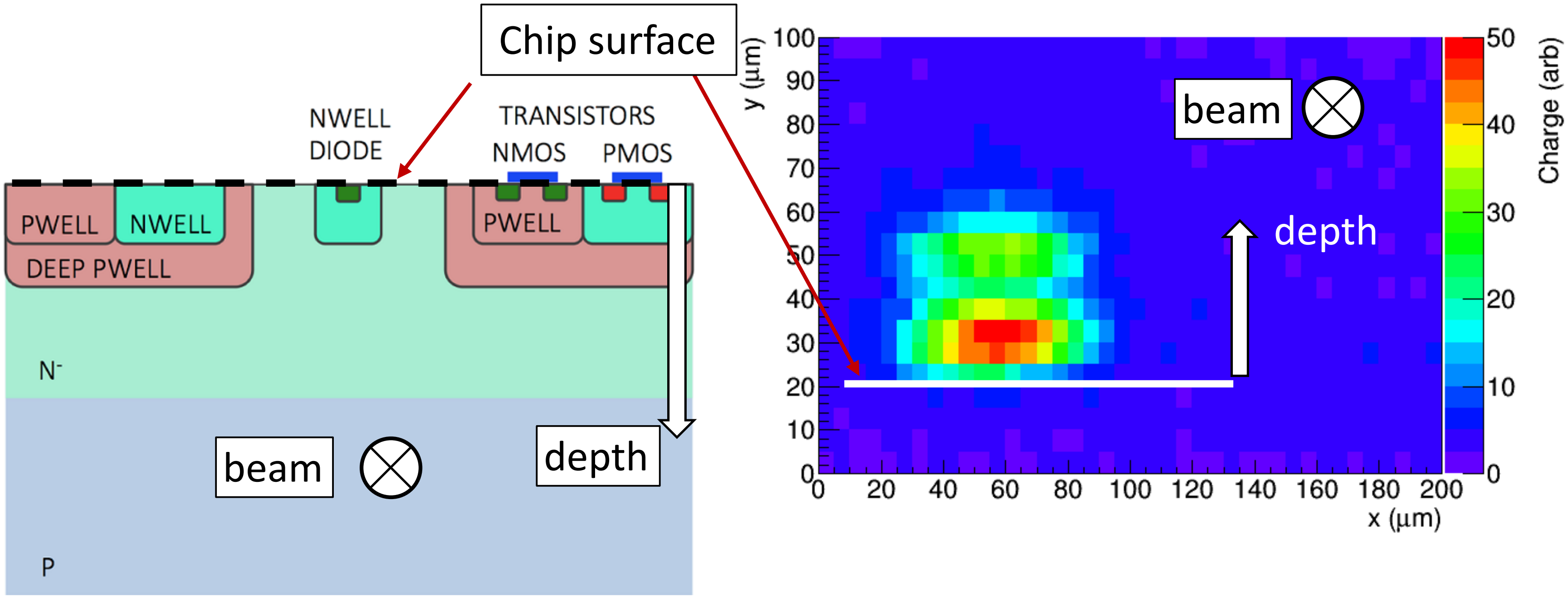


# E-TCT

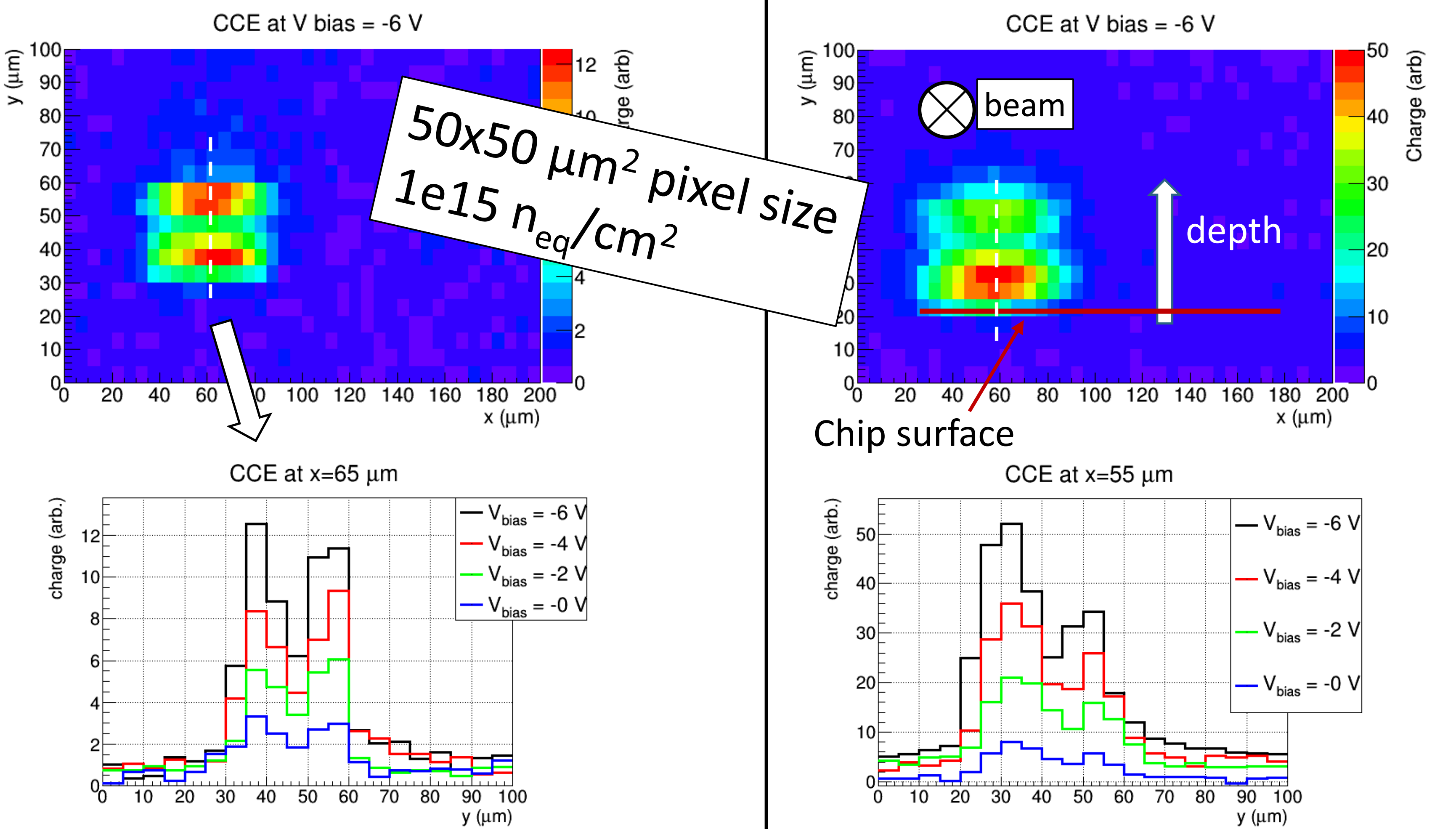
# E-TCT principle




- Inject charge carriers into the sample with laser light from sample edge
- Readout individual pixels
- Can study response uniformity within the pixel
- TCT measurements made with chips from two wafers with different n-layer doping
  - W11 weakly doped, W16 strongly doped n-layer
- Neutron irradiated chips (Ljubljana):
  - 1e15, 2e15, 5e15, 1e16 $n_{eq}/cm^2$

# Results 1e15 – single pixel 50 x 50 µm²

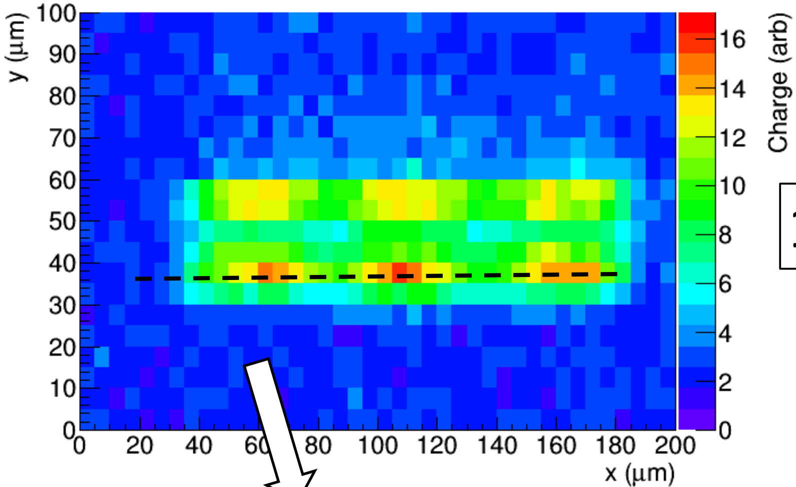
Wafer 11 (weaker n-layer doping) | Wafer 16 (stronger n-layer doping)

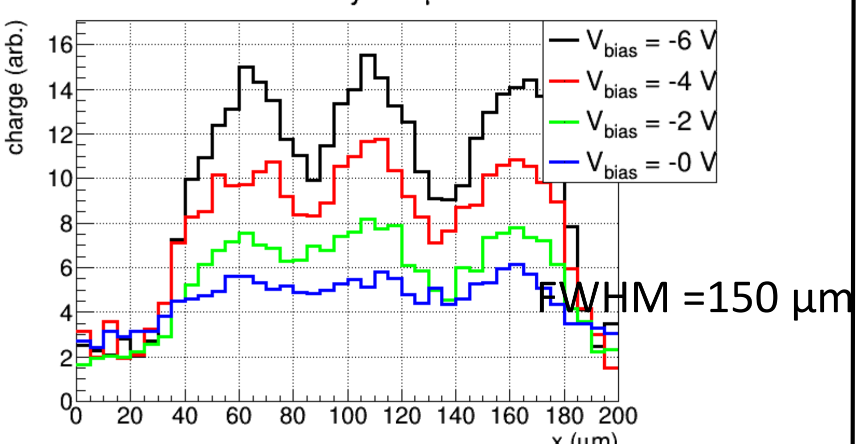



Both wafers have two peaks of charge collection along the depth (double junction)

# Results 1e15 – 3 neighbours 50 x 50 μm²

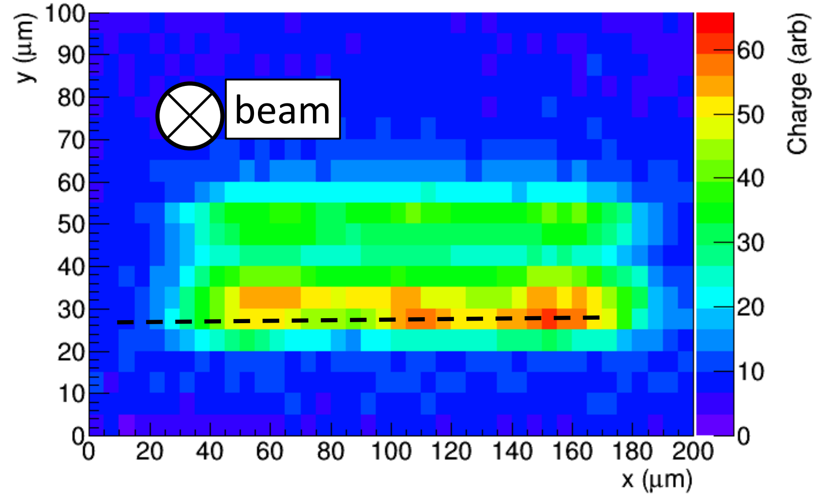
## Wafer 11 (weaker n-layer doping)

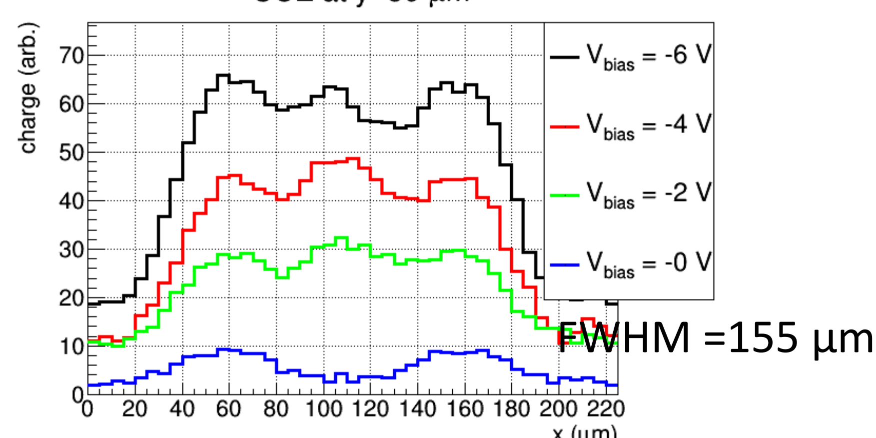



1e15

## Wafer 16 (stronger n-layer doping)

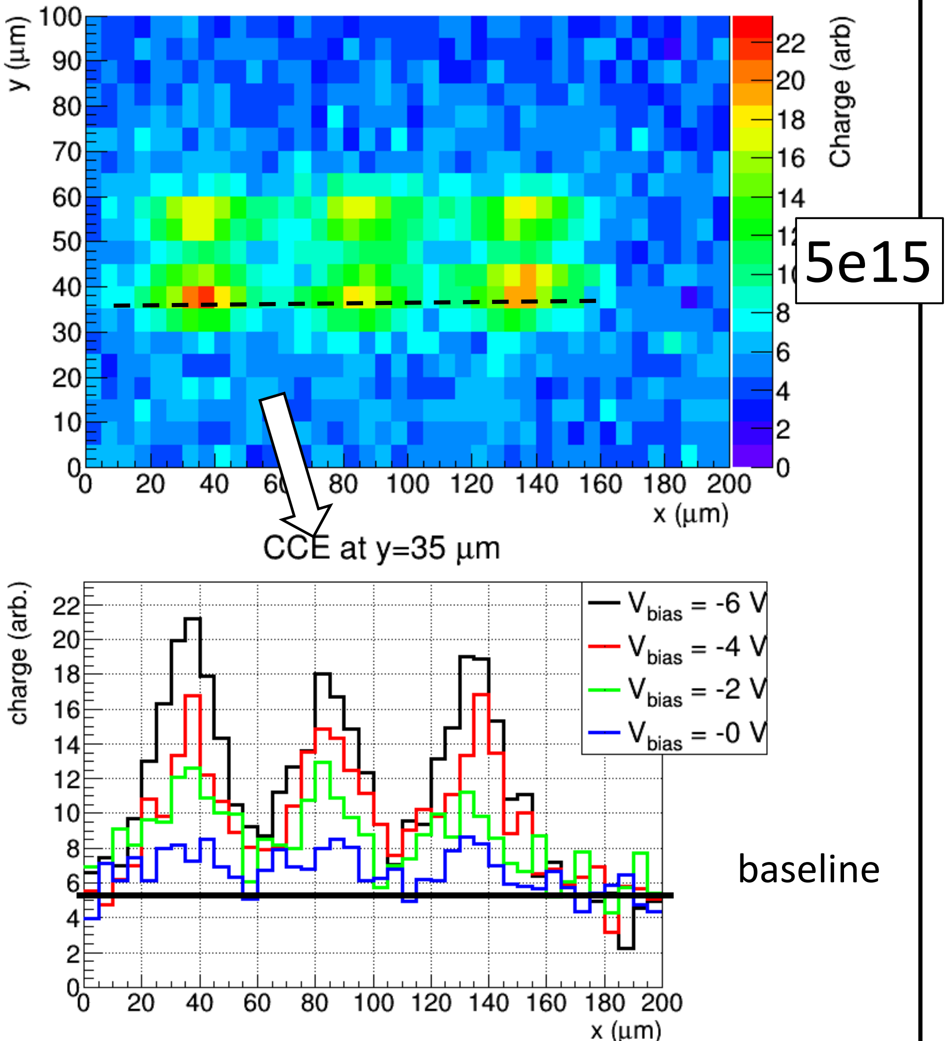


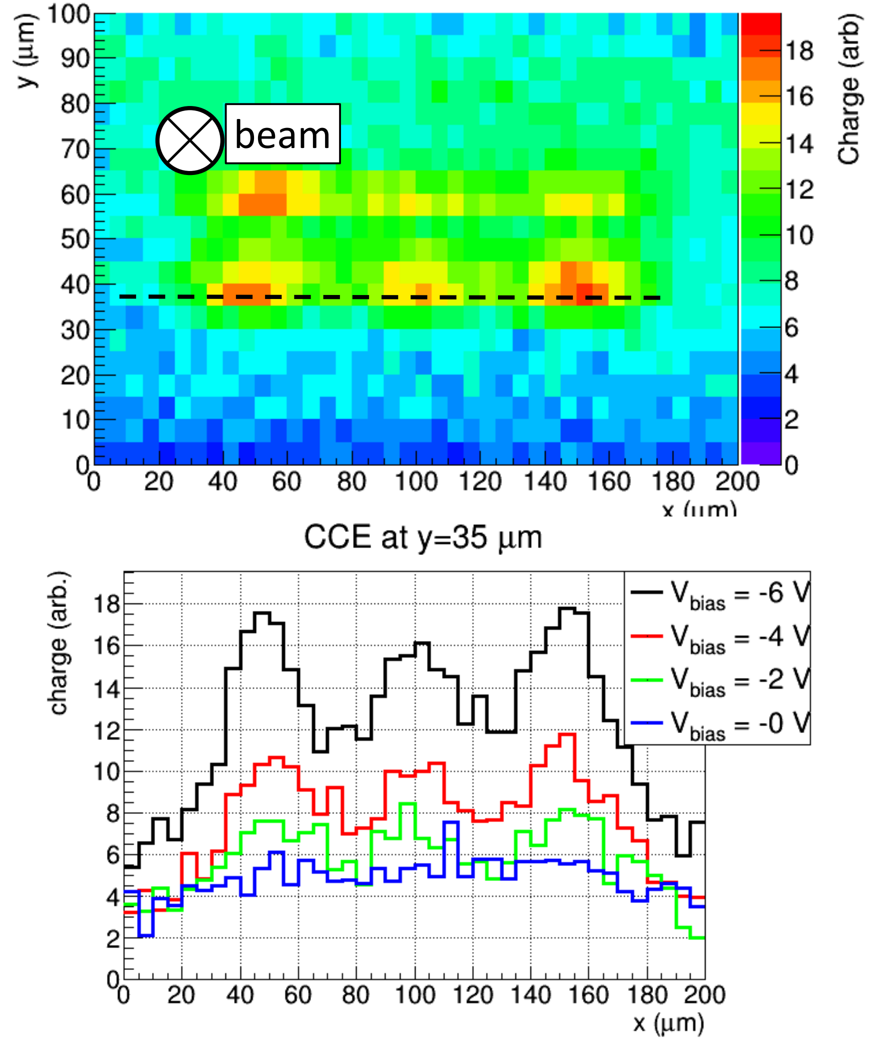

Pixels read out individually, signals summed offline
Charge uniformity between pixels is slightly better on W16

# Results 5e15 – 3 neighbours 50 x 50 μm²

Wafer 11 (weaker n-layer doping)



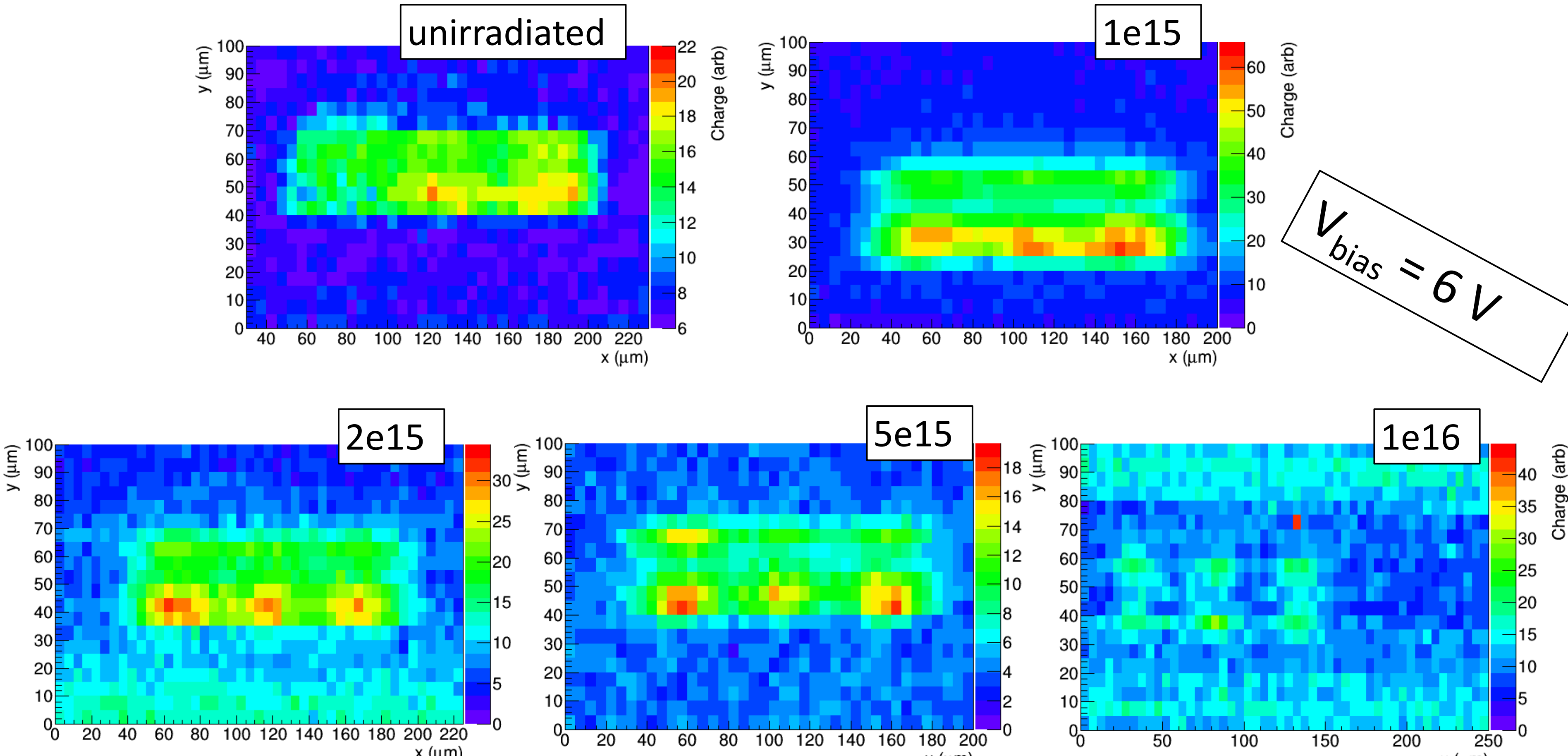

Wafer 16 (stronger n-layer doping)



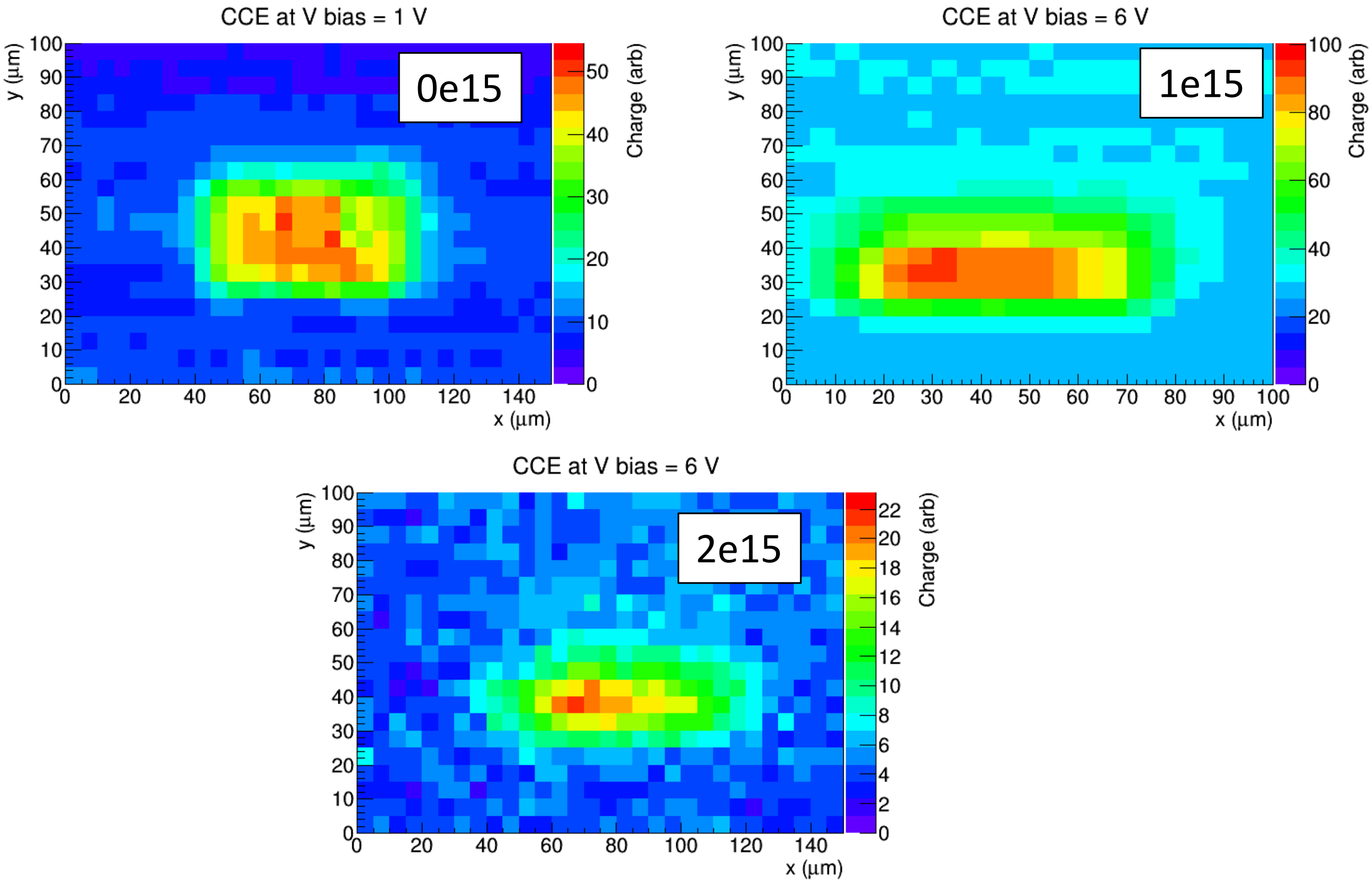

Charge uniformity between pixels is better on W16 (eff. ≈ 50 %) than on W11 (eff. ≈ 20 %)

# Summary for all fluences

- Signals from three neighbour pixels (50 x 50 $\mu m^2$ pixel size) summed together
- Neutron irradiated chips 0 – 1e16 $n_{eq}/cm^2$
- Up to 5e15 $n_{eq}/cm^2$ good response uniformity
- Higher charge collection at the front and at the back side of epi-layer seen (double peak)



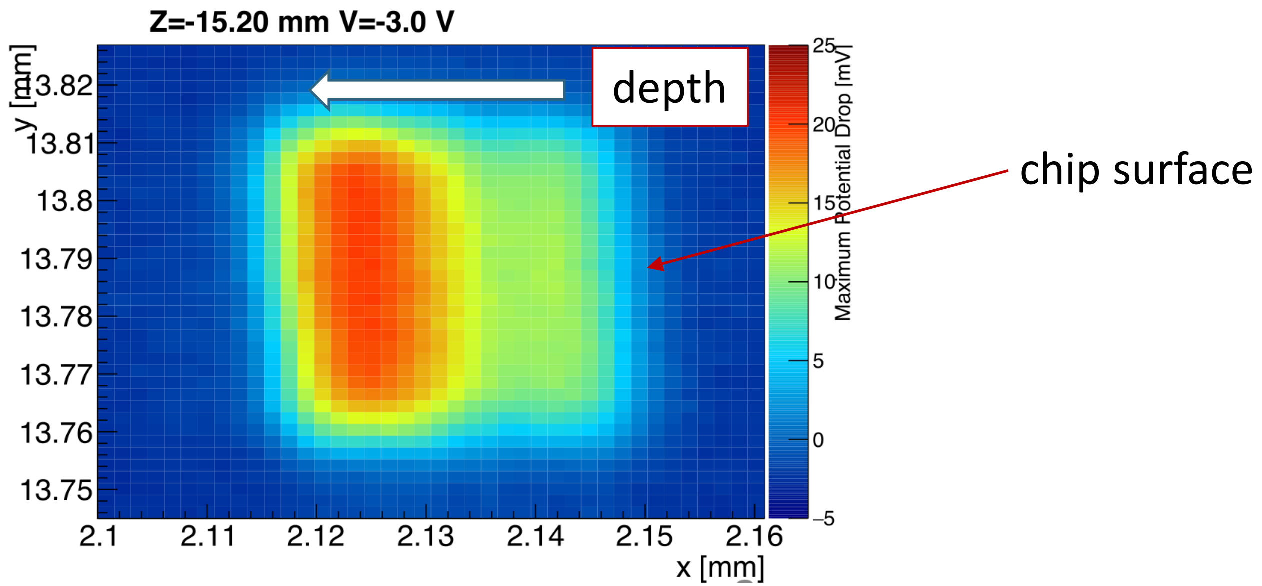
# 20 x 20 μm² pixel size, 3 neighbours



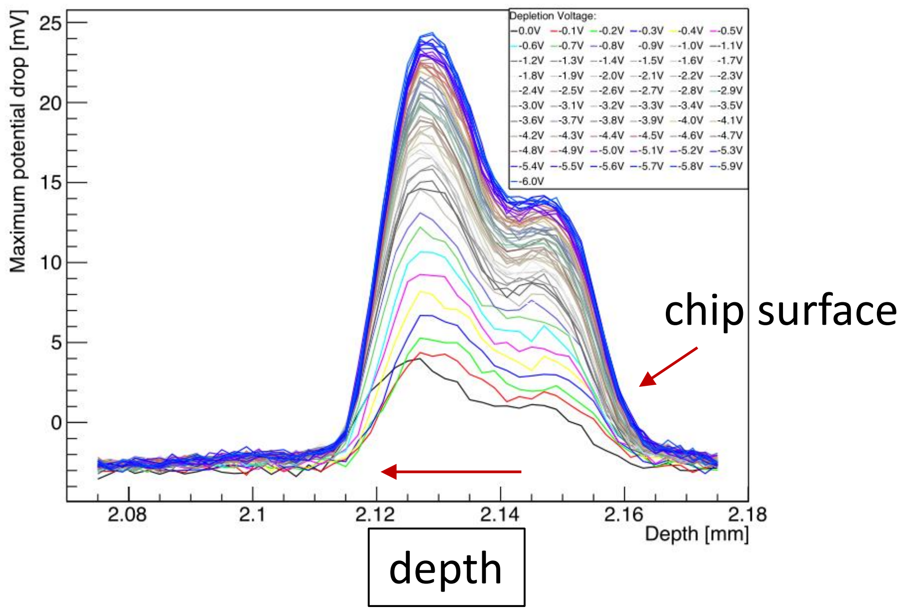

- 20 x 20 μm² pixels challenging to measure with E-TCT (small!)
- Measurements up to 2e15 show relatively good charge uniformity in the matrix

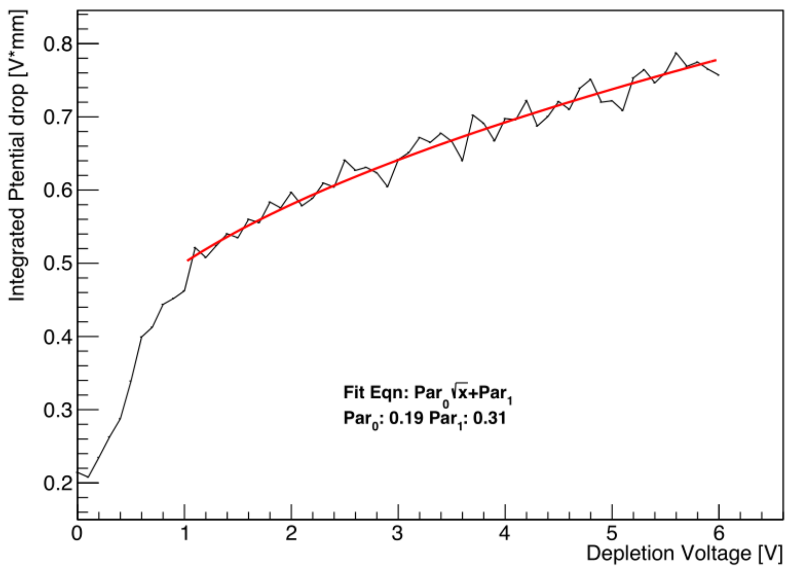
# E-TCT at CERN

- unirradiated chip
- 50 x 50 μm$^2$ pixels
- double peak structure visible




*A. Sharma, C. Solans, CERN*

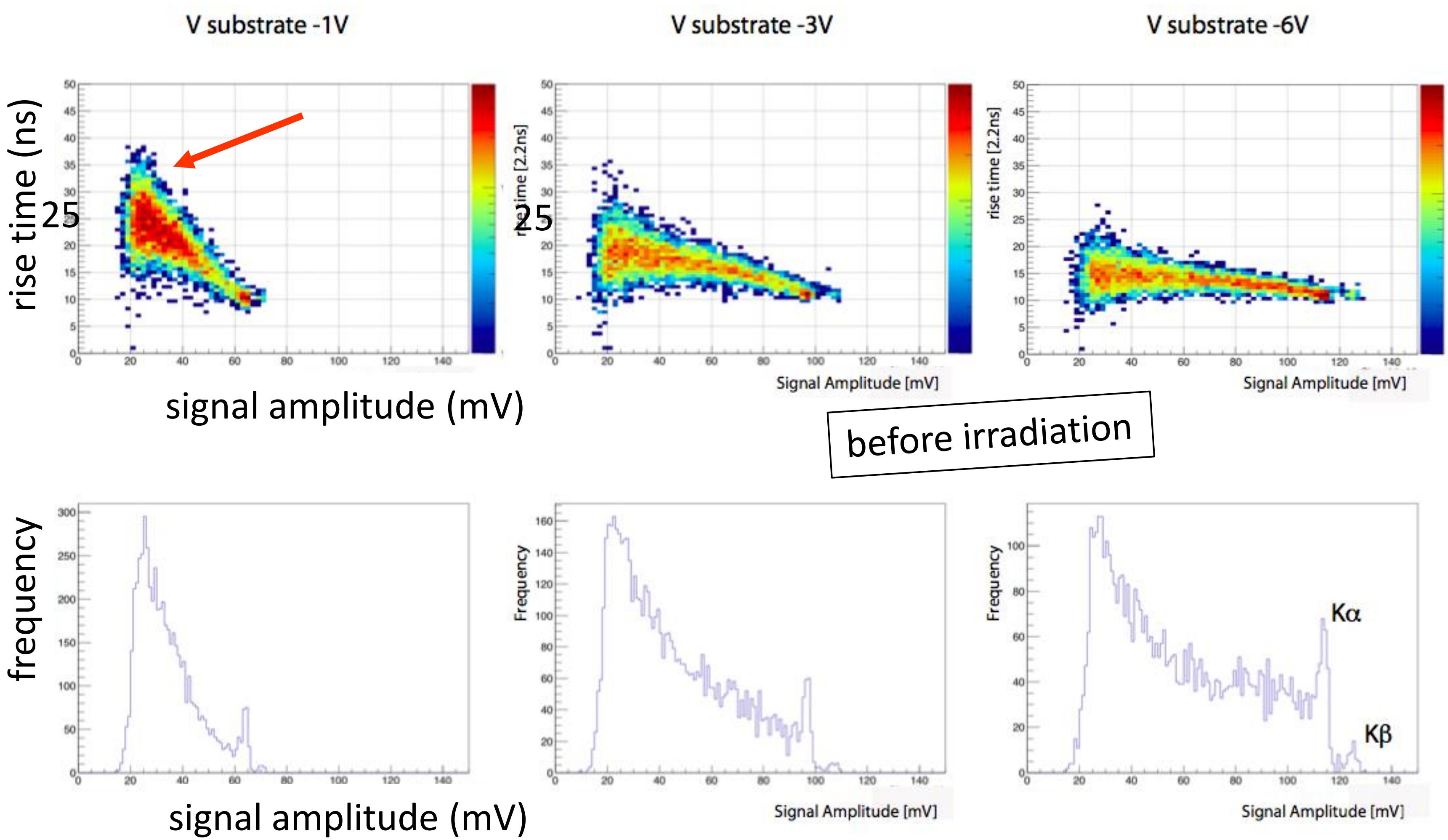


# Source measurements

# $^{55}$Fe standard process

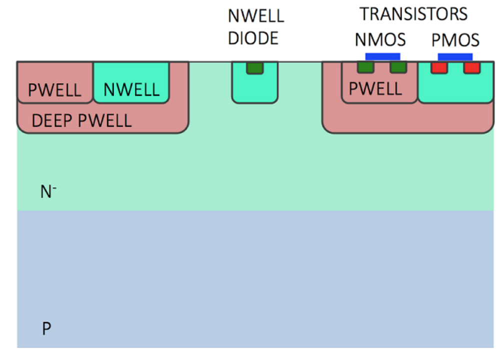
- Standard process chips, calibration with $^{55}$Fe ($K_\alpha$ 5.9 keV)
- Rise time vs. amplitude: significant fraction of slow ("diffusion") signals
- Faster charge collection for shared hits at higher $V_{bias}$



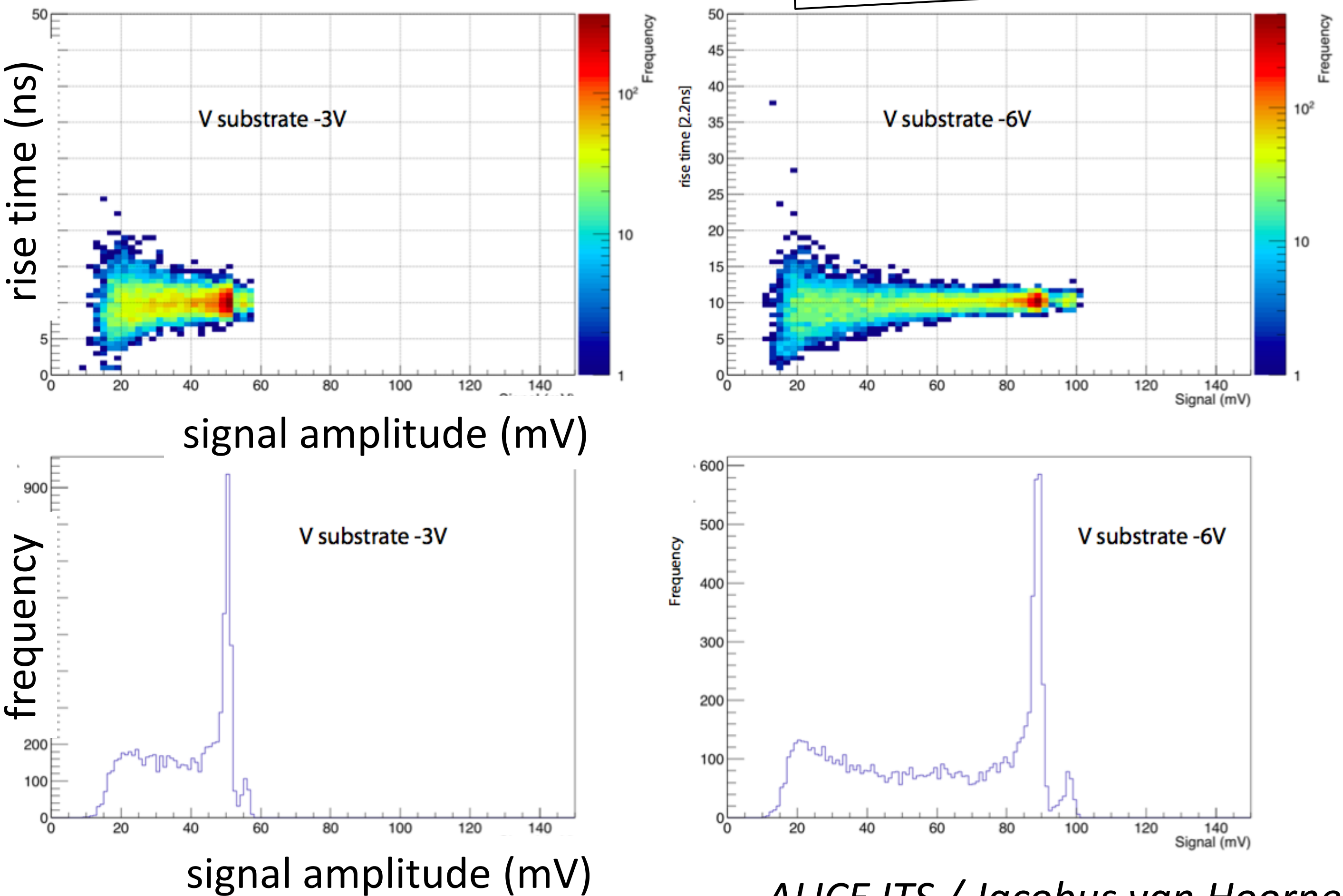

*ALICE ITS / Jacobus van Hoorne IEEE NSSMIC2016*

# $^{55}Fe$ modified process

- Chips produced in modified process
- Lesser spread in charge collection time
- Better energy resolution

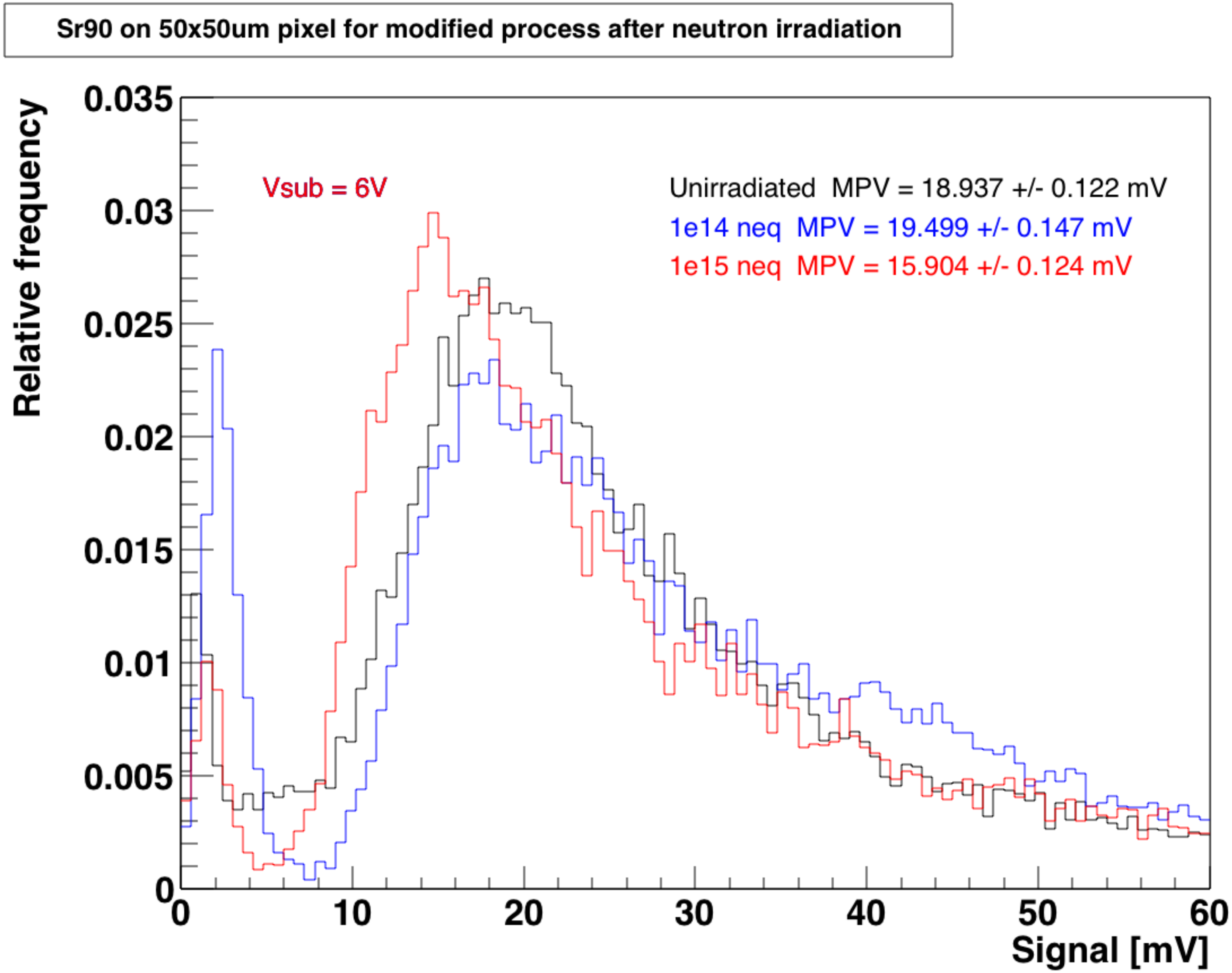



before irradiation




*ALICE ITS / Jacobus van Hoorne IEEE NSSMIC2016*

# $^{90}Sr$ spectra – modified process



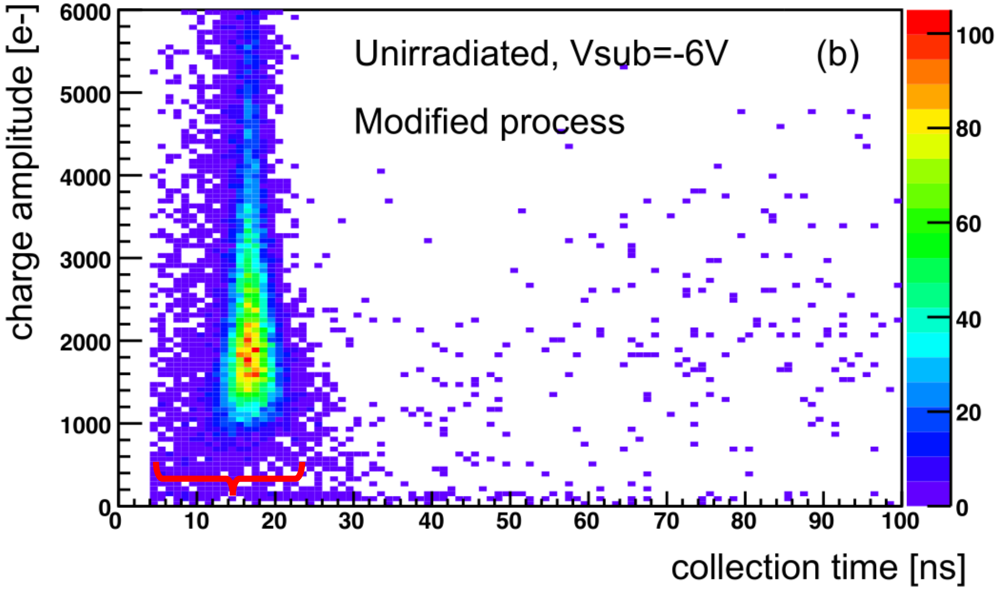

Neutron irradiation
1e14, 1e15 $n_{eq}/cm^2$
(Ljubljana)

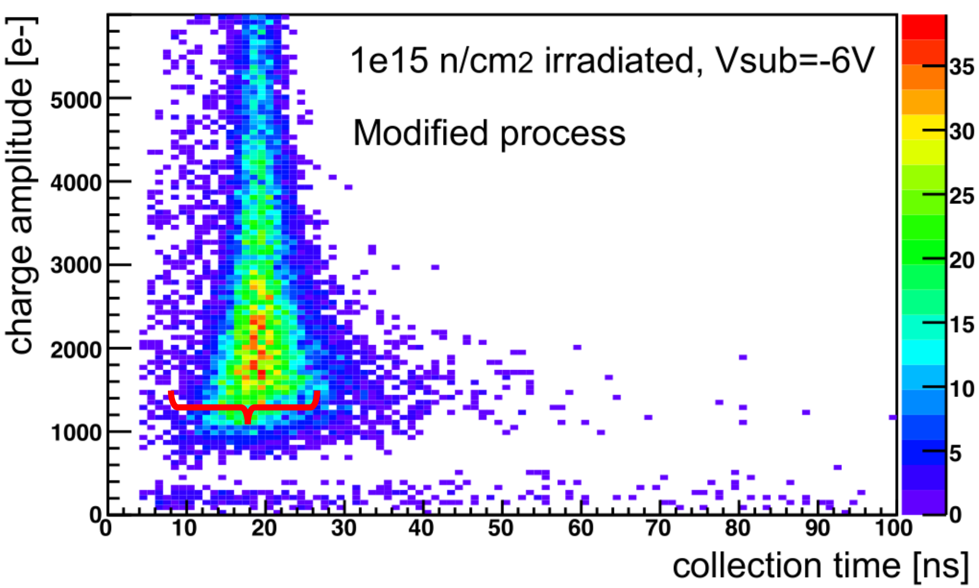
MPV around 2000 $e^-$

*C. Riegel, CERN*

Little change in signal spectrum after neutron irradiation up to 1e15 $n_{eq}/cm^2$
Clear separation of signal and noise

# $^{90}Sr$ - Collection time after irradiation



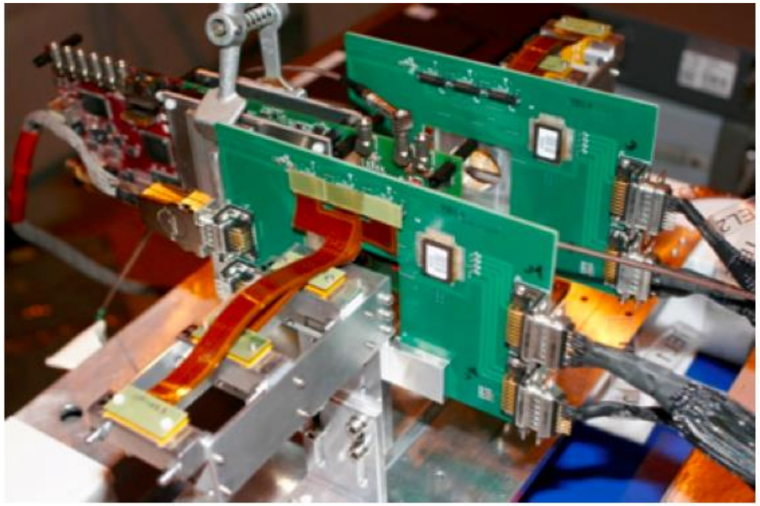




- Charge vs. collection time on 50 x 50 μm² pixels
- Little change in the signal shape after irradiation
- Charge collection times within 25 ns can be achieved
- Chips produced in standard process do not give a measurable signal after 1e15 n/cm²

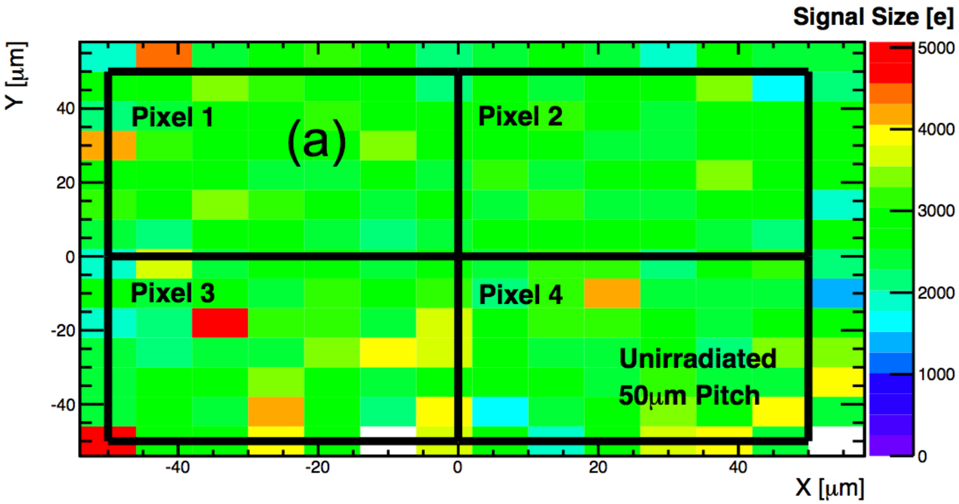
*C. Riegel, CERN*

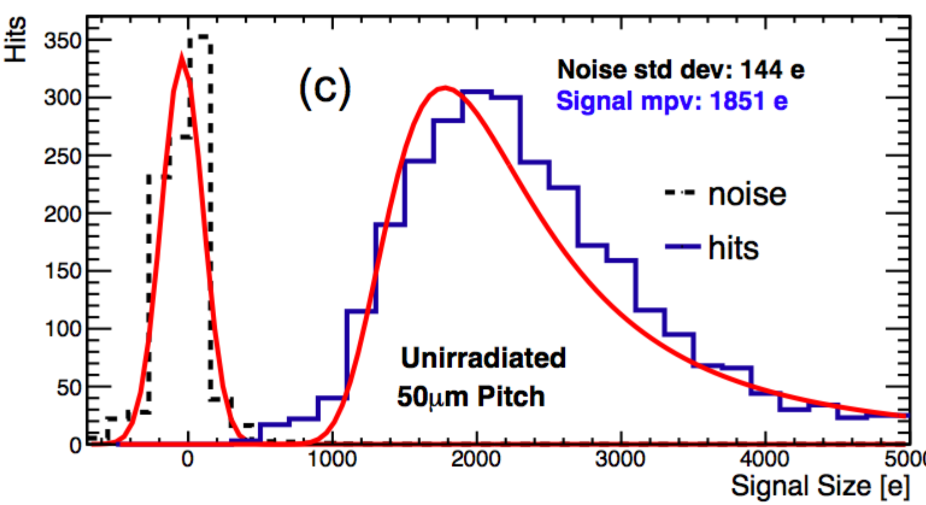
# Test beam

- SPS 180 GeV pions
- Unirradiated 50 x 50 µm$^2$ pixel size
- 1e15 n/cm$^2$ irradiated 25 x 25 and 30 x 30 µm$^2$



Signal size on four neighbour pixels (unirrad.)

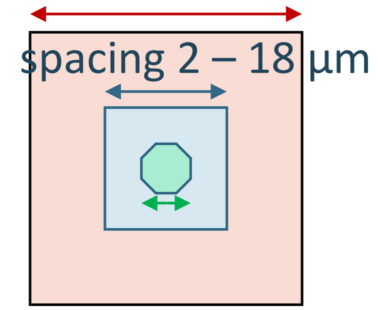


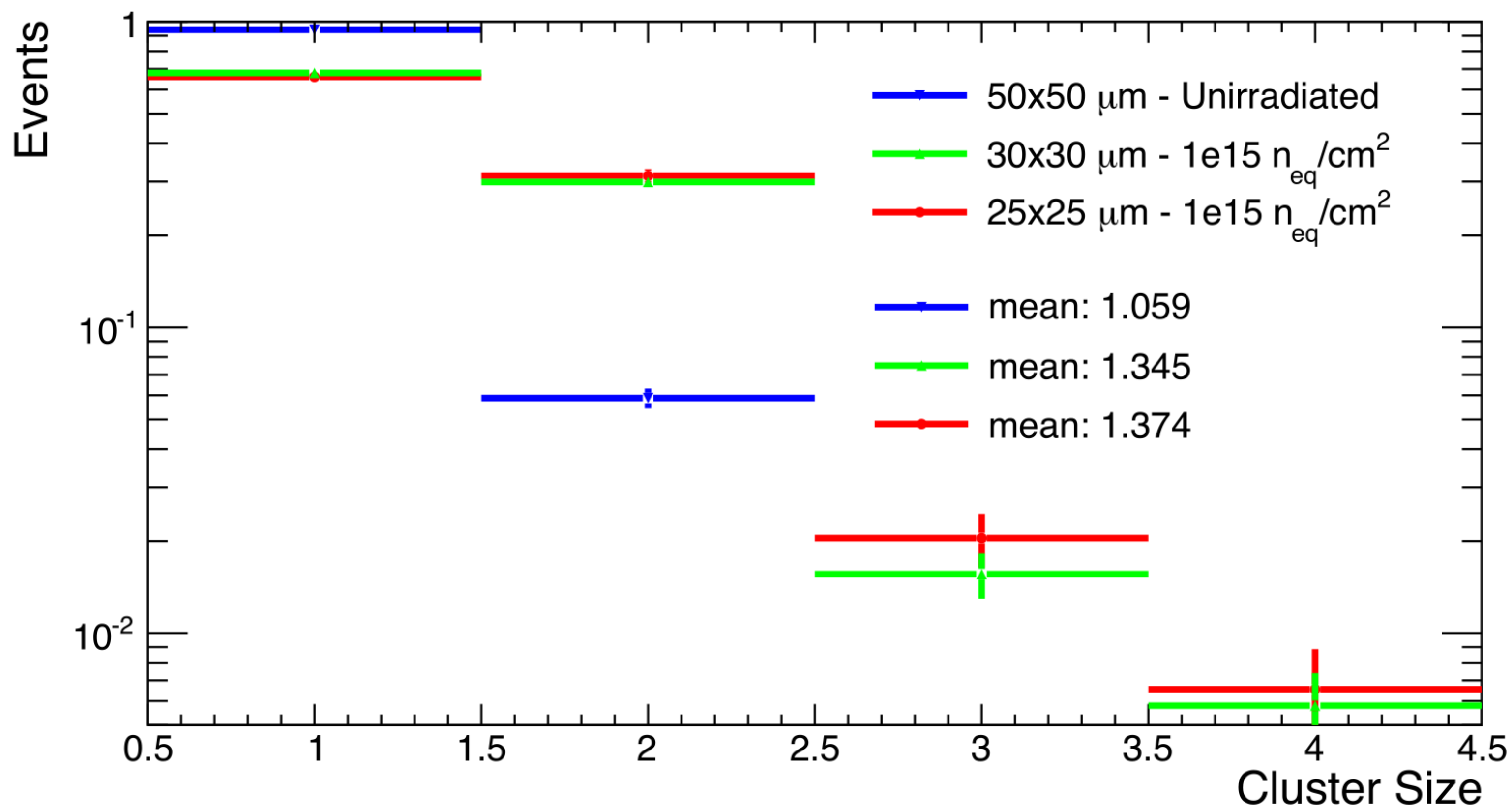




*H. Pernegger, Trento 2017*

# Cluster size

- Cluster size in dependence of pixel pitch
- Larger pixels → smaller cluster size
- Also influenced by spacing between DNW and DPW
  - 25x25 and 30x30 µm$^2$ pixels have 3 µm spacing
  - 50x50 µm$^2$ pixels have 18 µm spacing

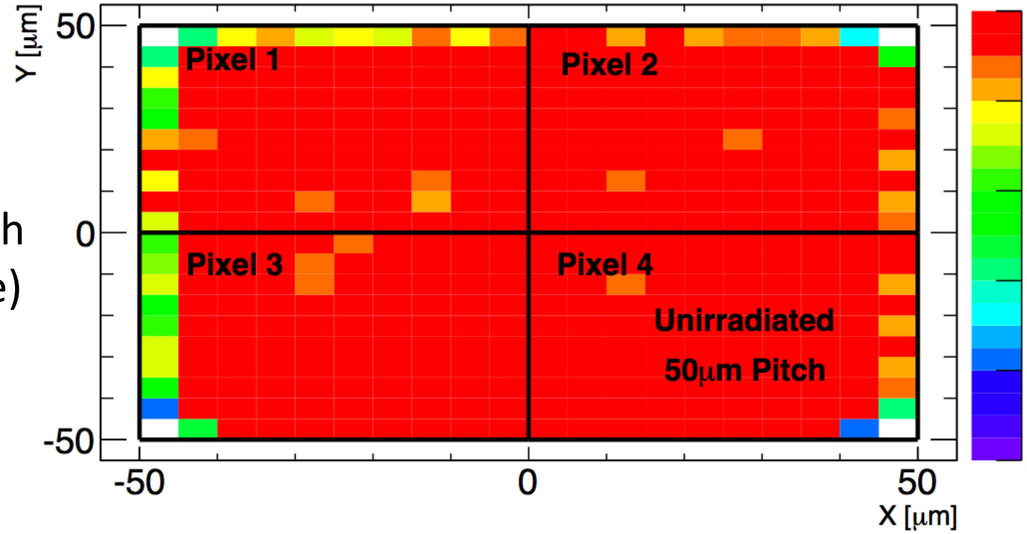


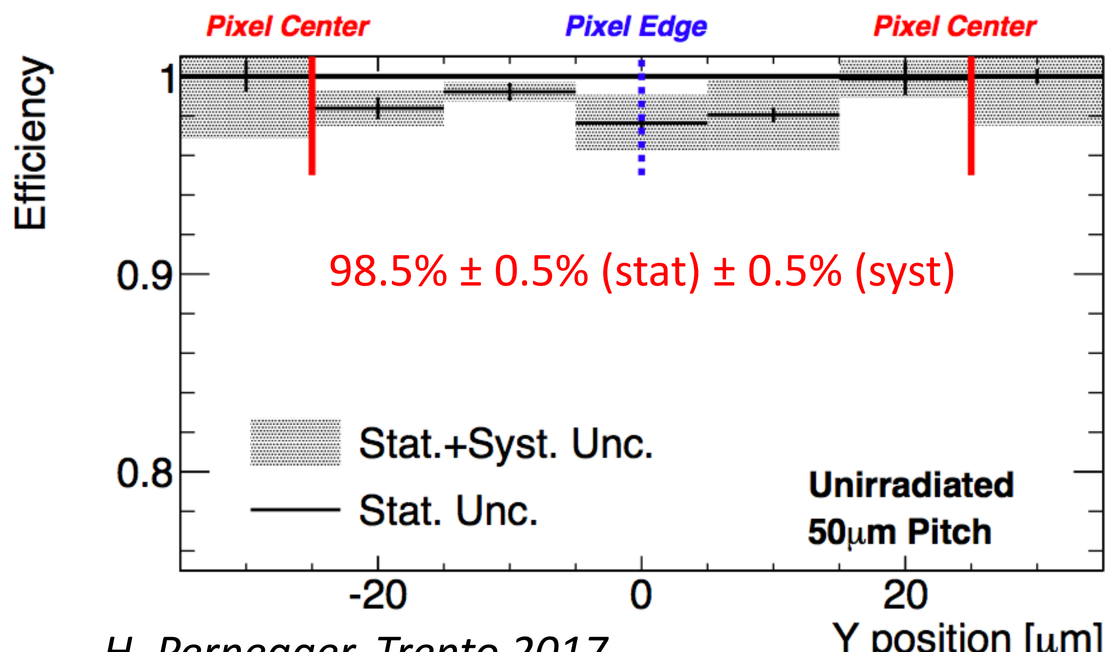

*H. Pernegger, Trento 2017*

# Unirradiated sample efficiency

- Unirradiated sample
- Efficiency 98.5 % a bit low due to a high threshold 640 $e^-$ (common mode noise)




efficiency across pixel:



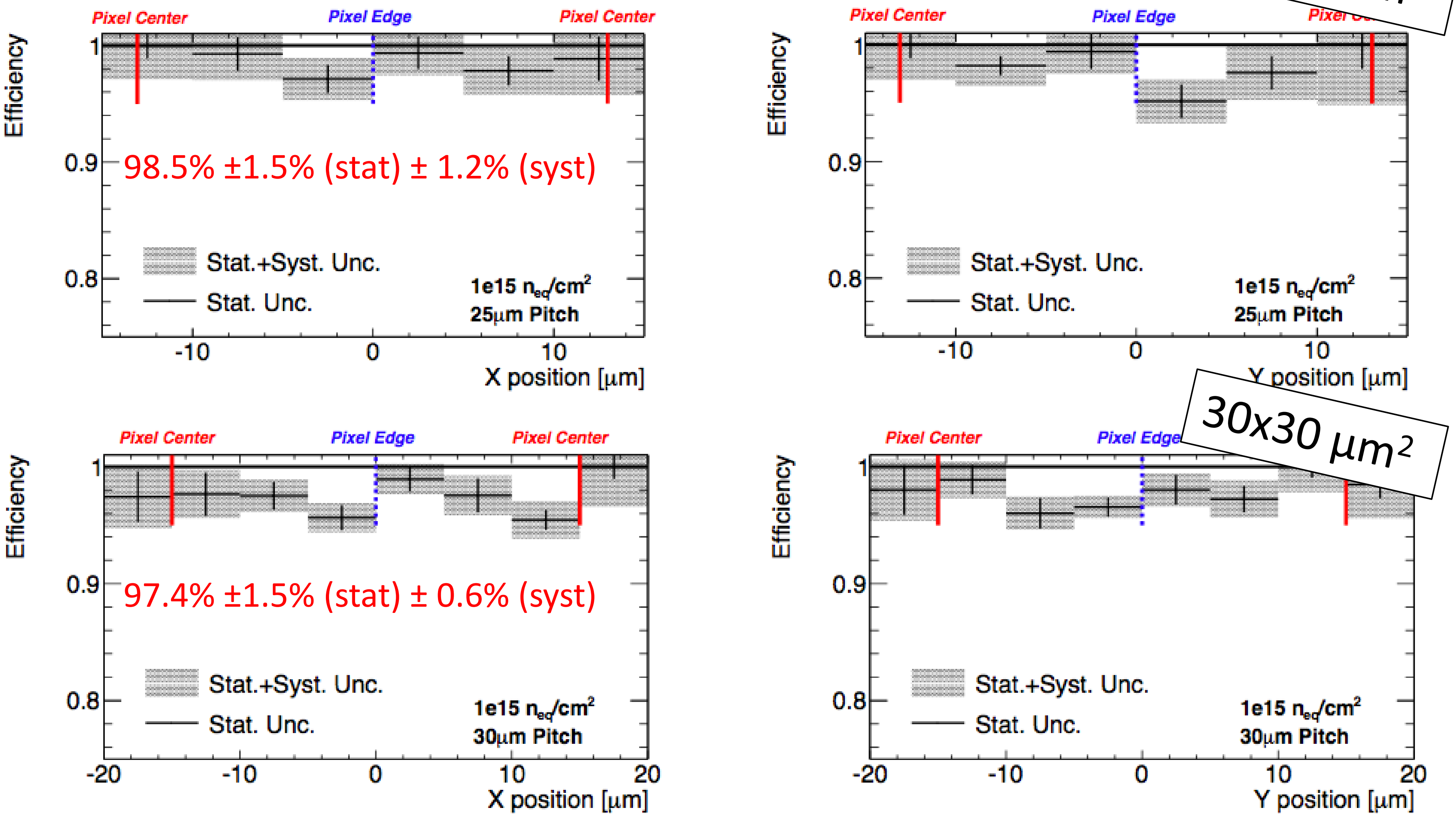

*H. Pernegger, Trento 2017*

# Irradiated sample efficiency

- 1e15 irradiated 25x25 and 30x30 µm$^2$
- Good uniformity across pixel

*H. Pernegger, Trento 2017*

25x25 µm$^2$




30x30 µm$^2$

# Summary

- Low capacitance sensor technology promising for use in DMAPS
- Characterisation of irradiated chips with complementary methods
  - E-TCT:
    - Good charge collection efficiency and uniformity up to 5e15 $n_{eq}/cm^2$
    - Response more uniform in chips with highly doped n-layer
  - Radioactive source scan:
    - Obtained good charge spectra also after irradiation to 1e15 $n_{eq}/cm^2$
    - Collection time within 25 ns
  - Test beam:
    - Good efficiency > 97 % before and after irradiation to 1e15 $n_{eq}/cm^2$
- Sensors can be made radiation hard – sufficient for ATLAS outer pixel layers

# Outlook

- New submission of an FEI4 sized demonstrator chip (2 designs):

- TJ MALTA
  - Full matrix = 512x512 pixels
  - Design/CERN
  - Active area 18 x 18 mm$^2$
  - Hit memory in active matrix
  - All hits are asynchronously transmitted over high-speed bus to EoC logic
  - No clock distribution over active matrix to minimize power and digital-analog cross-talk

- TJ MonoPix
  - 512x256 pixels (36.4 x 36.4 µm$^2$ pixel size)
  - Design/Bonn
  - Active area 18 x 10 mm$^2$
  - Hit memory in active matrix (2 flip-flop per pixel)
  - Synchronous column drain architecture
  - Hit address asserted to bus with 40 MHz token
  - 6 bit ToT coding at end of column

Design Team: W. Snoeys, T. Kugathansan, C. Marin Tobon, I. Berdalovic, R. Cardella, N. Egidos (CERN) J. Rousset, B. Blochet (MIND), K. Moustakas, T. Wang (Bonn)

- Characterisation of proton irradiated samples
- TID measurements
- Design of a quad module for implementation in ATLAS