Performance of Capacitively Coupled Active Pixel Sensors in 180nm HV-CMOS Technology after Irradiation to HL-LHC Fluences

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Simon Feigl[1] **– CERN, University of Oslo** (PhD student)

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on behalf of the ATLAS upgrade HV-CMOS collaboration:

Bonn University, CERN, CPPM Marseille, Geneva University, Göttingen University, Glasgow University, Heidelberg University, LBNL

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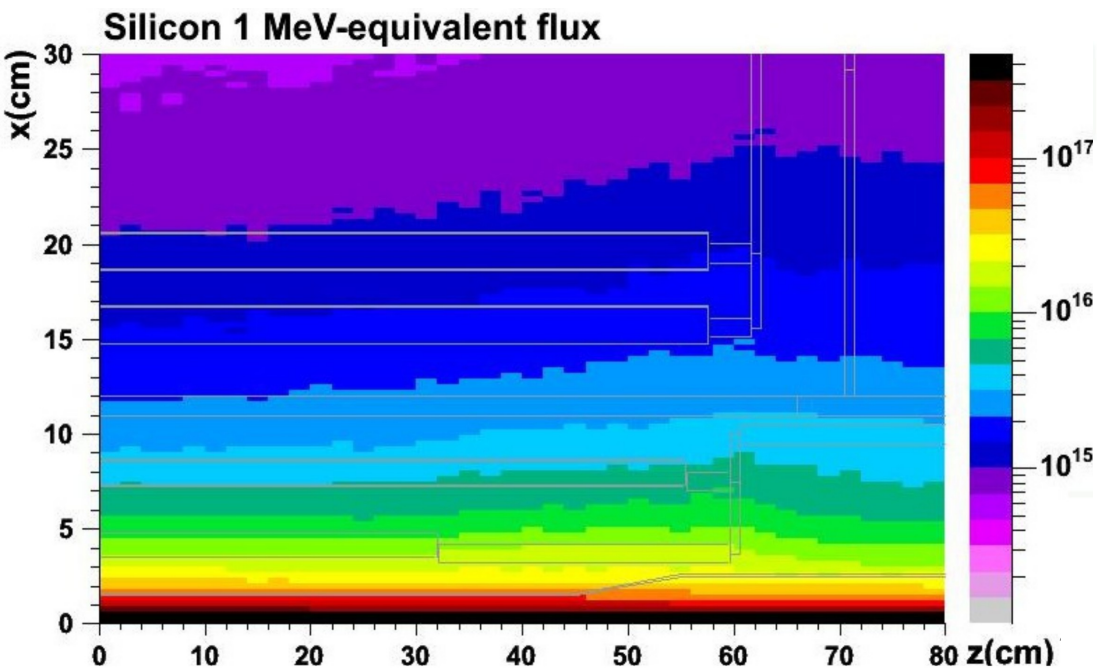
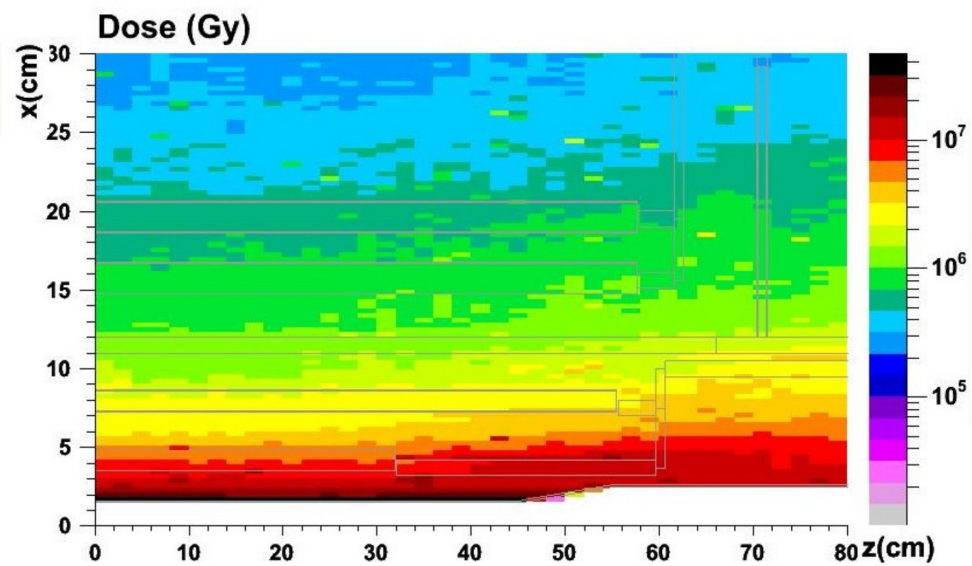
(FP7 – Marie Curie Actions – ITN TALENT)

HEP detector challenges

- requirements on silicon detectors for future colliders are challenging
- environment/specs for HL-LHC tracker detectors:
  - high radiation levels: ≈ 2e16 neq/cm^2, ≈ 1 GRad (pixel layers)
  - large surface at reasonable cost (strip layers: ≈ 200m^2)
  - fast (40MHz readout)
  - high spatial granularity (≈ 50-100 μm)

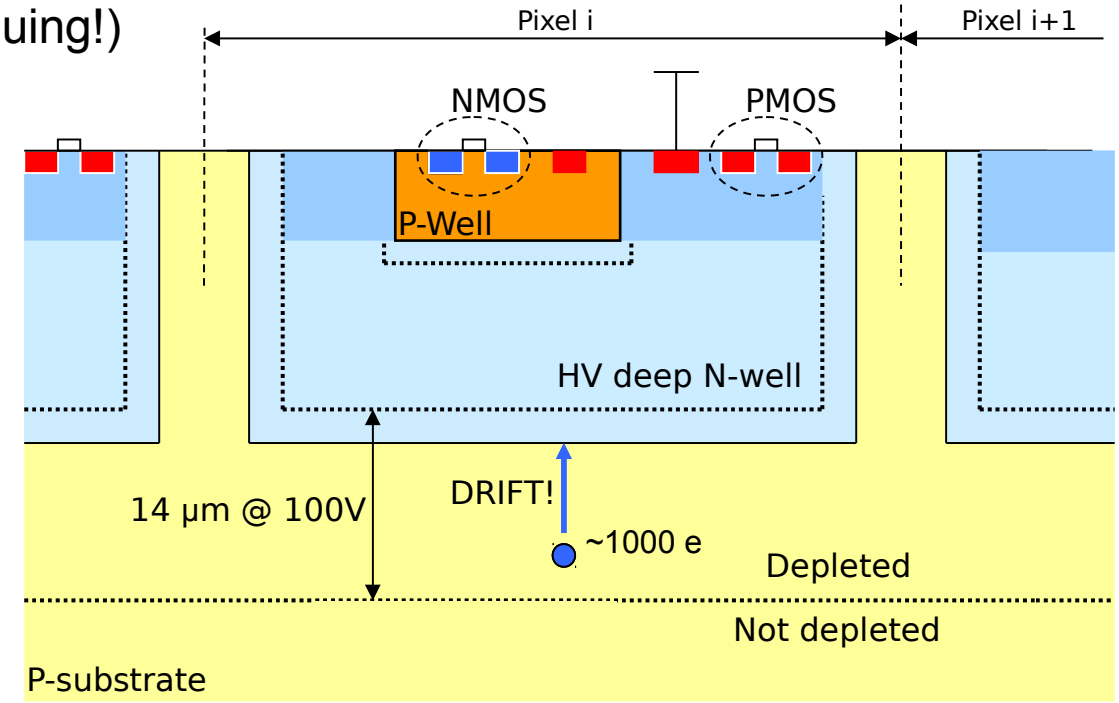




HV-CMOS process[2] properties and sensor ideas

- CMOS electronics inside deep n-well (NMOS inside additional p-well): "Smart Diode Array" (SDA)
- low substrate resistivity, high N_{eff}
- negative biasing creates depletion zone around n-wells
- charge collection by drift
- signal amplification on sensor chip
- capacitive coupling to readout chip (gluing!)
- small pixel size

Technology	Austria Microsystems (AMS) + IBM 350 nm / 180 nm
Substrate Resistivity	> 10 Ωcm
Pixel Size	down to 20 µm
Depletion Depth	≈ 10 – 20 µm
Reverse Bias Voltage	down to ≈ -100V
MIP Signal Charge	≈ 1000 e



[2] AMS H18 / IBM CMOS 7HV Process

Suitability for future tracker detectors

demand for future tracker detectors	realized by	key sensor/process property
radiation hard (electronics)	deep sub-micron technology	feature size in deep sub-micron range
radiation hard (bulk)	radiation induced augmentation of doping concentration is insignificant	N_{eff} > 1e14 /cm3, low substrate resistivity
radiation hard (bulk)	short drift time (= little trapping)	small depletion depth at maximum bias voltage
large area at low cost	cheap production	industrialized process
exceptional spatial resolution	pixel size down to 20 µm	
low material budget	thinning of sensor possible	
fast	use as monolithic detector	electronics on sensor
fast	use as hybrid detector with existing fast ROC	designed to be compatible with ATLAS FE-I4 ROC
little cooling	indications that it can operate at “high” temperatures also after irradiation	

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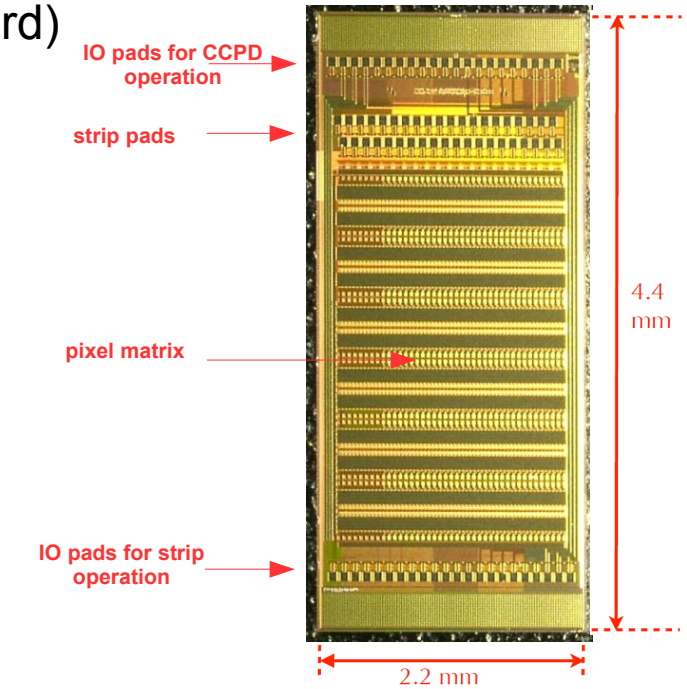
Prototype Sensors

- First prototypes in 350nm technology yielded promising results (see backup slides)
- 180nm Prototype sensors: HV2FEI4v1 (1st generation, rad-soft electronics design)
  HV2FEI4v2 (2nd gen, rad-hard)
  - designed by Ivan Perić (University of Heidelberg)
  - 60 columns x 24 rows
  - pixel size 33x125 μm^2
  - ASIC designed to fit FEI4 readout chip
    → use of highly optimized readout electronics
  - on-pixel electronics: amplifier, discriminator, TuneDACs etc.
  - IO bond pads for different operation modes



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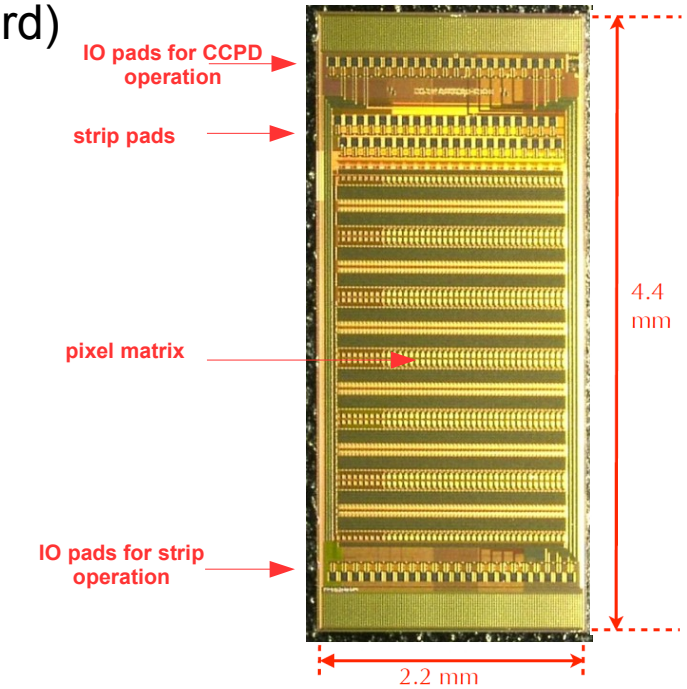
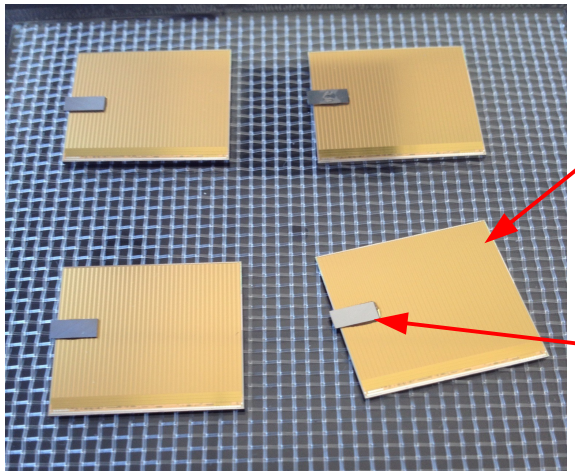
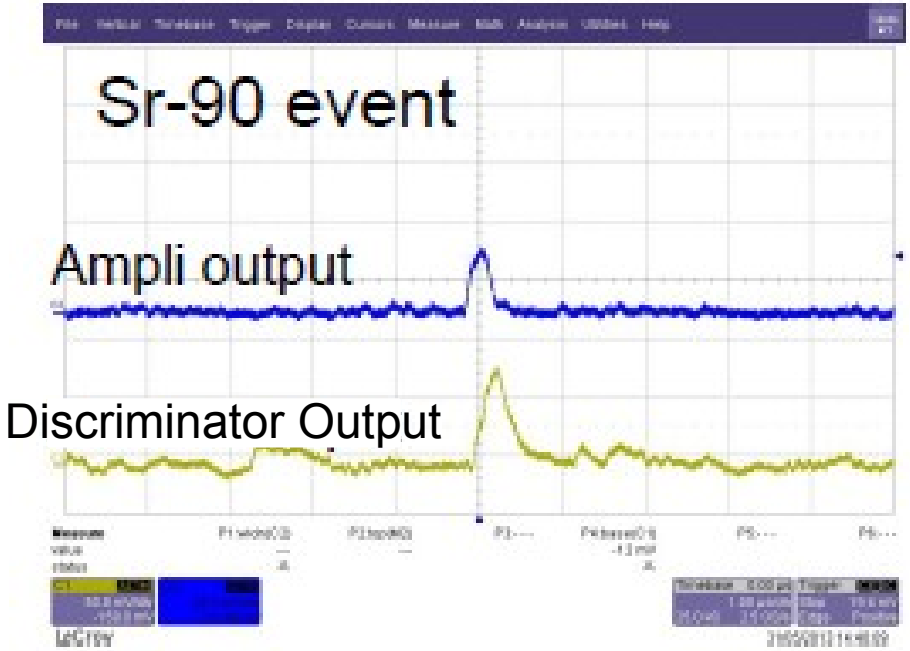
- Standalone measurements
  - investigation of performance of sensor electronics
  - irradiation effects
- CCPD: Capacitively Coupled Pixel Detector
  - HV2FEI4 glued onto ATLAS pixel front-end chip (FE-I4)
  - proof of principle
  - irradiation effects
- Strip-Readout

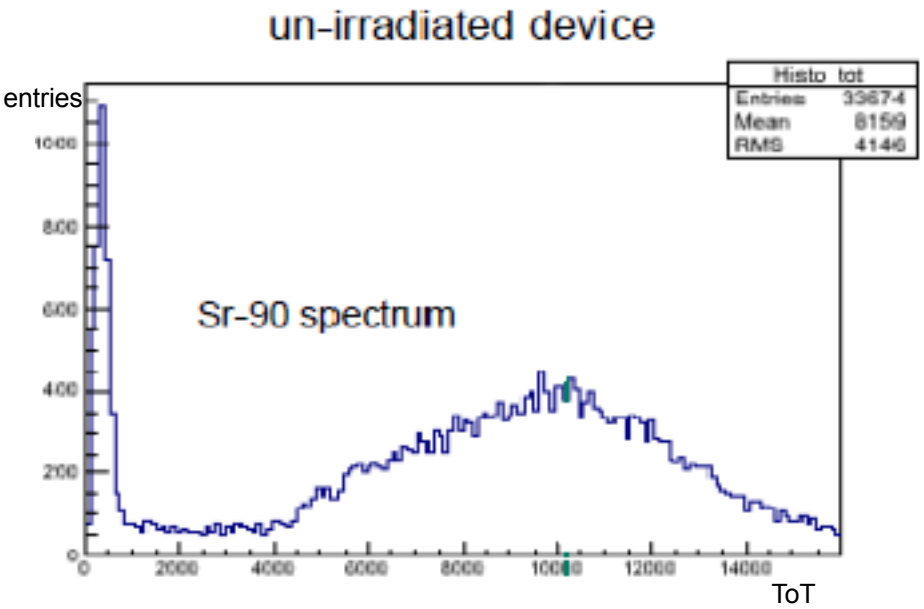


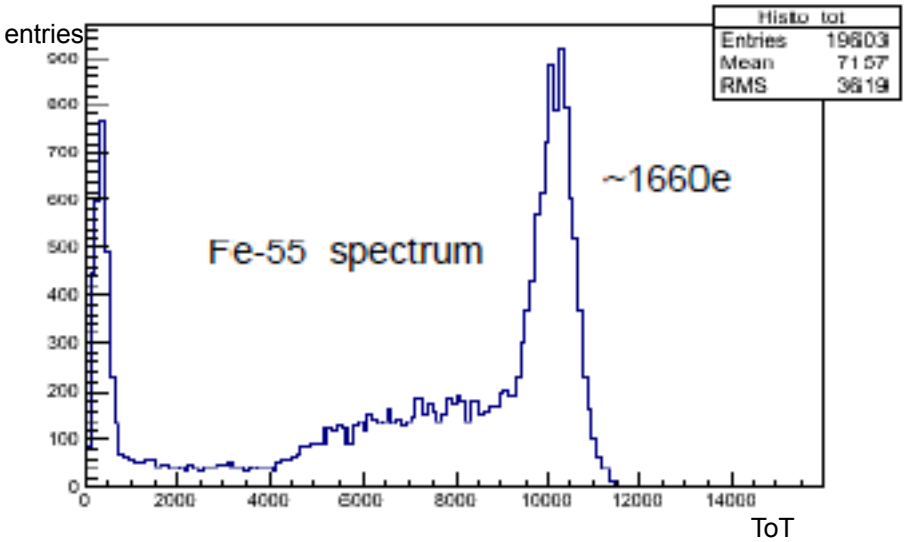


HV2FEI4v1 (1st Generation)

- electronic elements from standard library (not radiation hard)
- physics events clearly visible
- ^{90}Sr and ^{55}Fe-spectra recorded

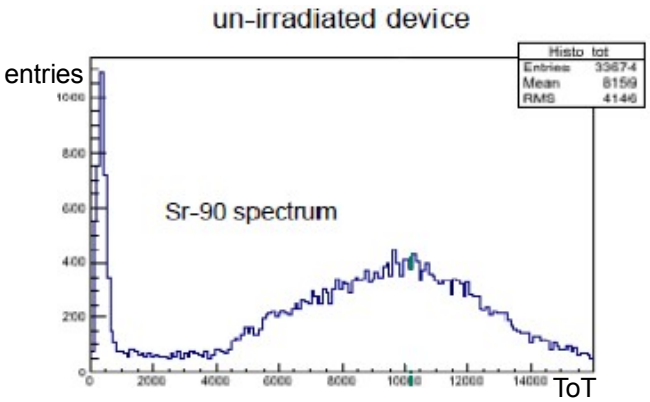


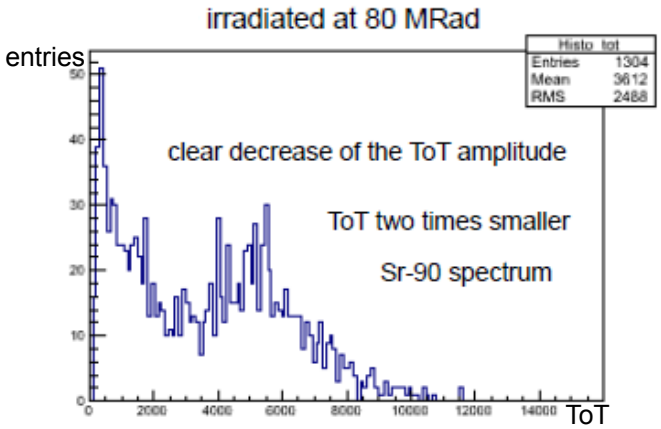


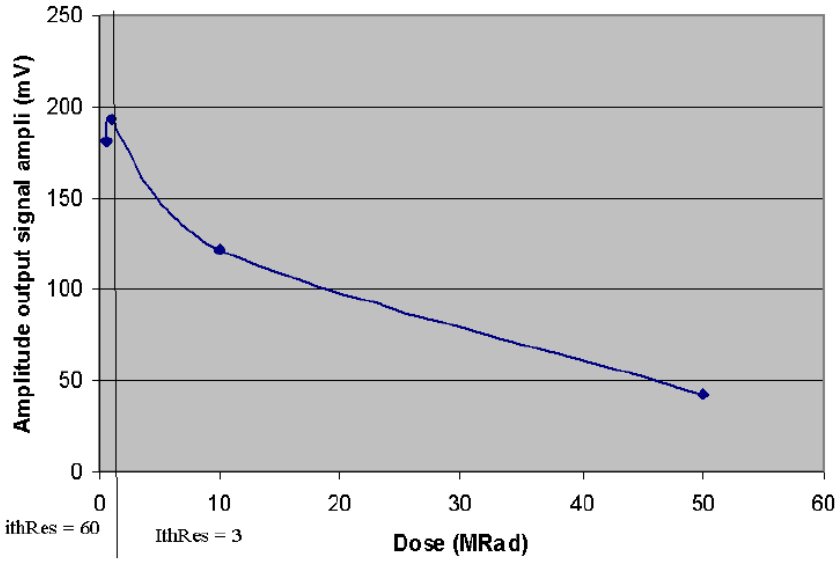


HV2FEI4v1 – Ionizing Radiation Effects

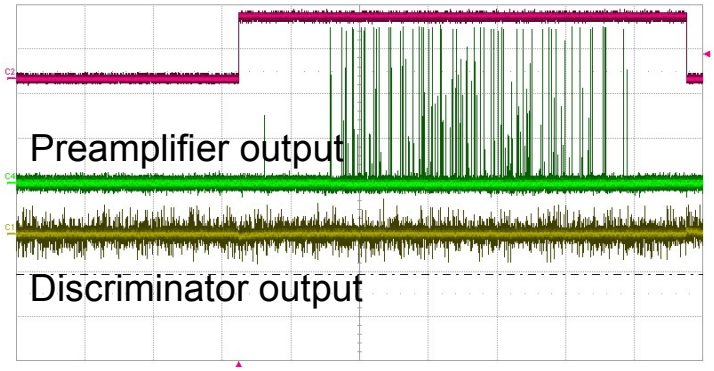
- ^{90}Sr-spectrum still visible after 80 Mrad proton irradiation (but visible effects)
- particle signals observed up to 200 Mrad
- preamp worked after 200Mrad, discriminator died
- reasons for signal loss:
  - large amplifier gain drop
  - large leakage current





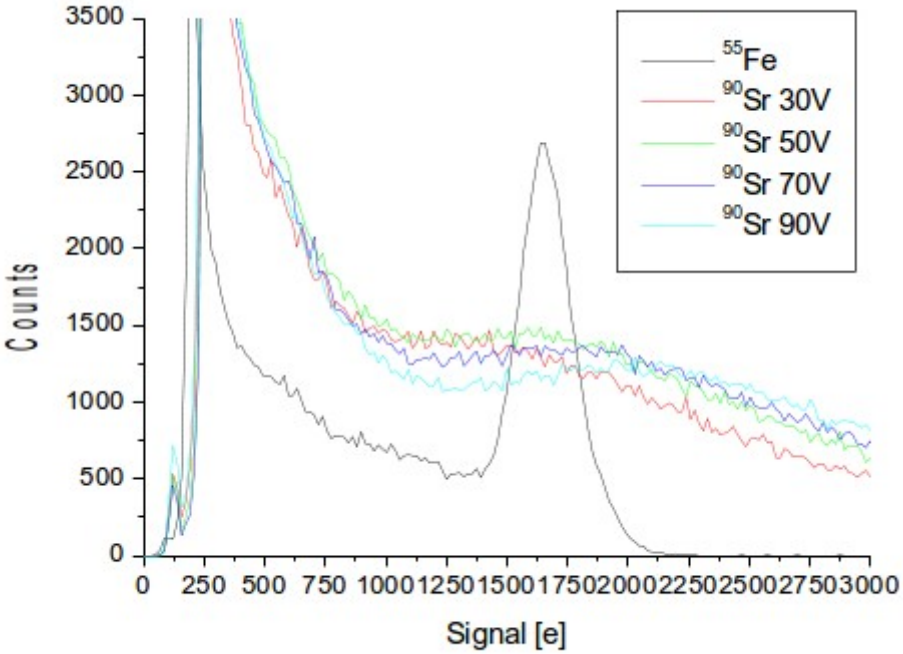


after 200Mrad



HV2FEI4v2 (2nd Generation)

- rad-hard design
- different pixel types:
  - “normal”: guard rings implemented
  - “rad-hard”: circular transistors (→ larger capacitance → lower gain)
- ^{55}Fe- and ^{90}Sr-spectra measured



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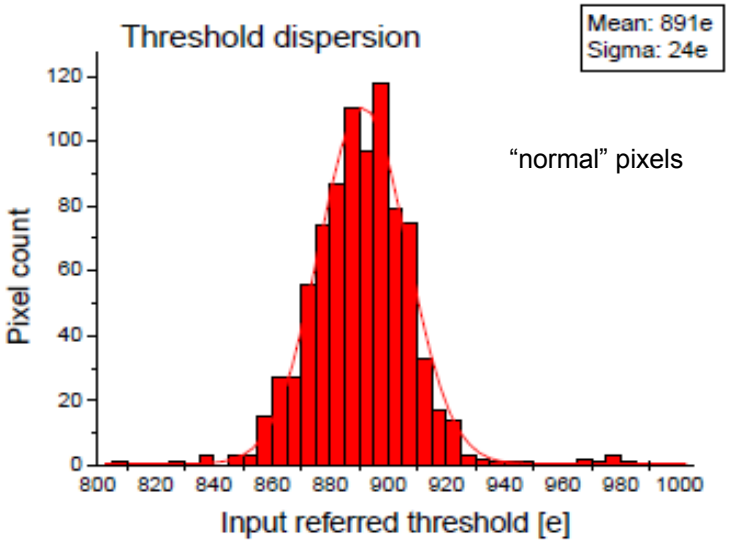
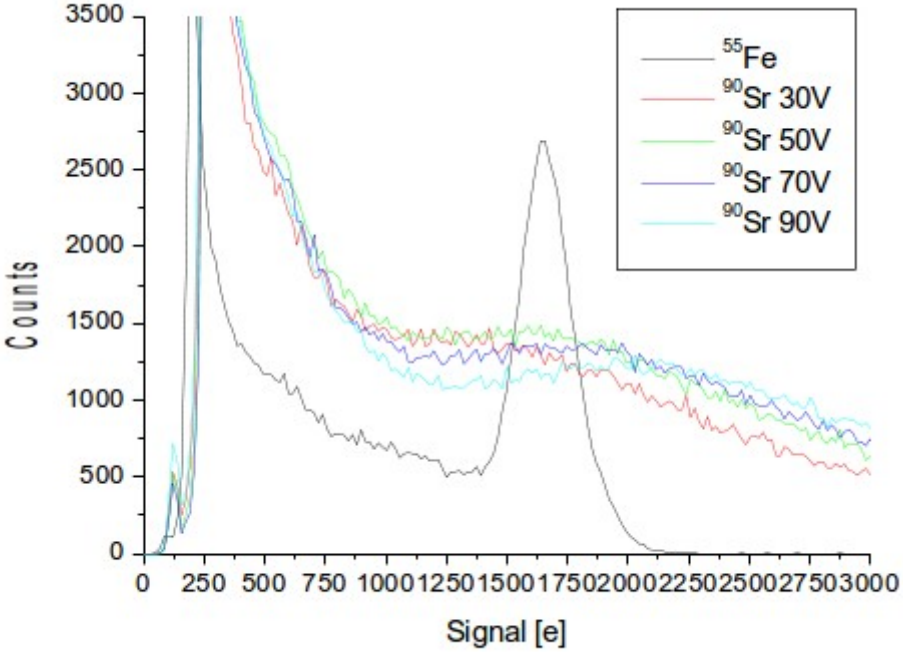


- threshold tuning implemented



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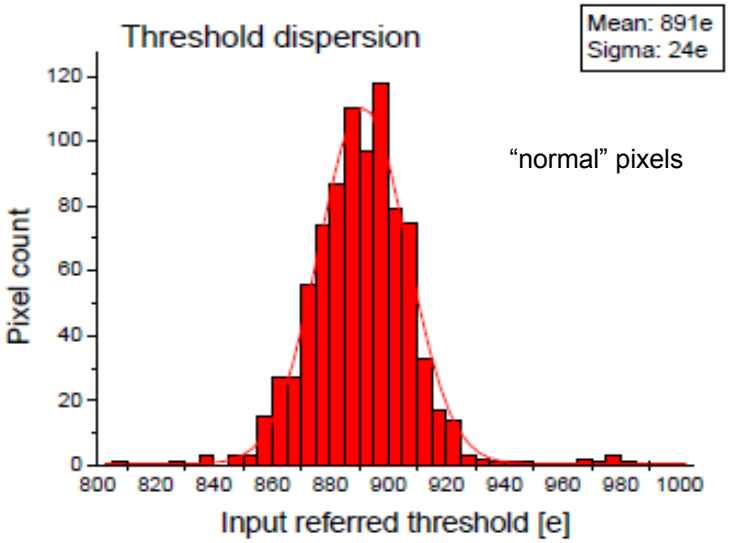

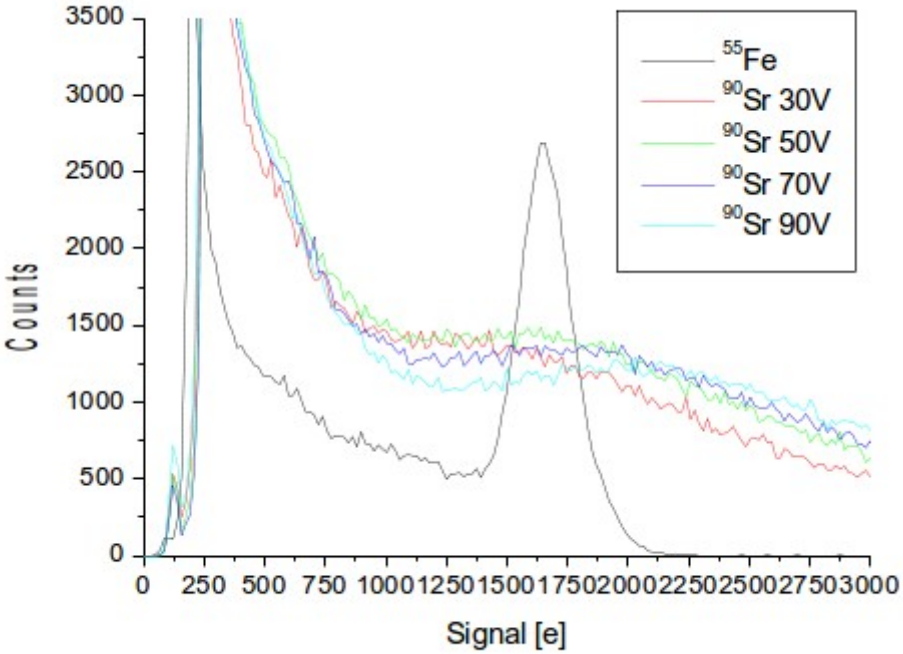

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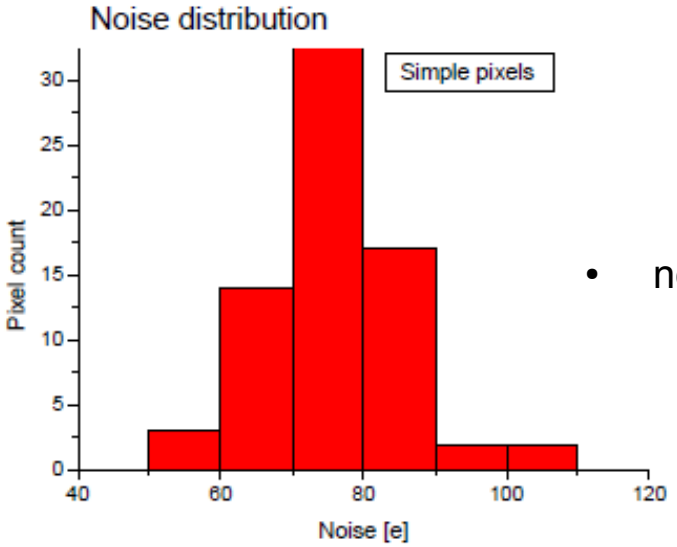


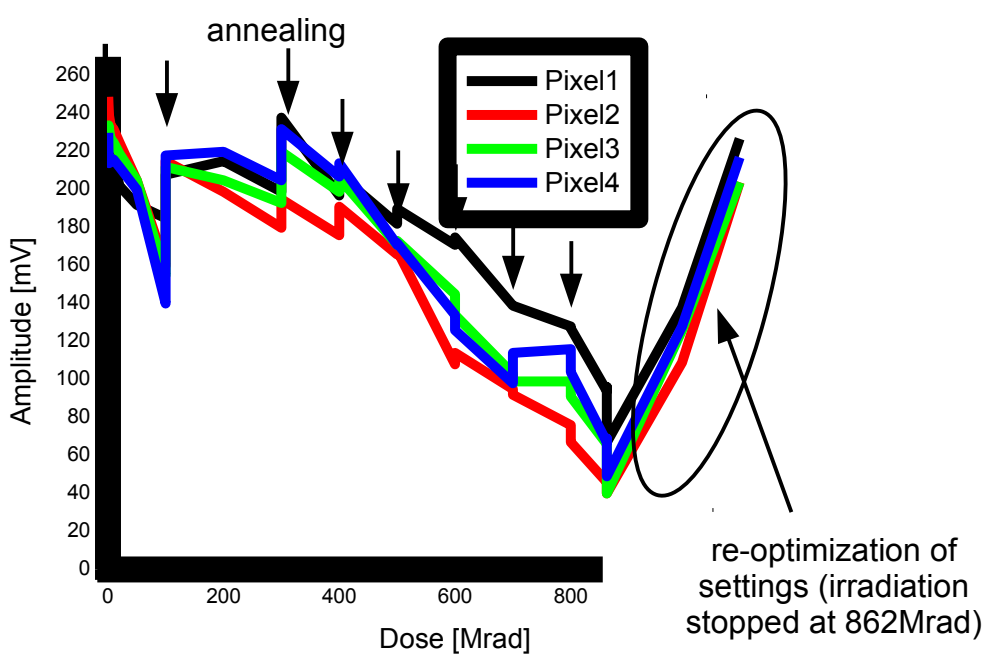
- noise ≈ 75e

HV2FEI4v2 – Ionizing Radiation Effects

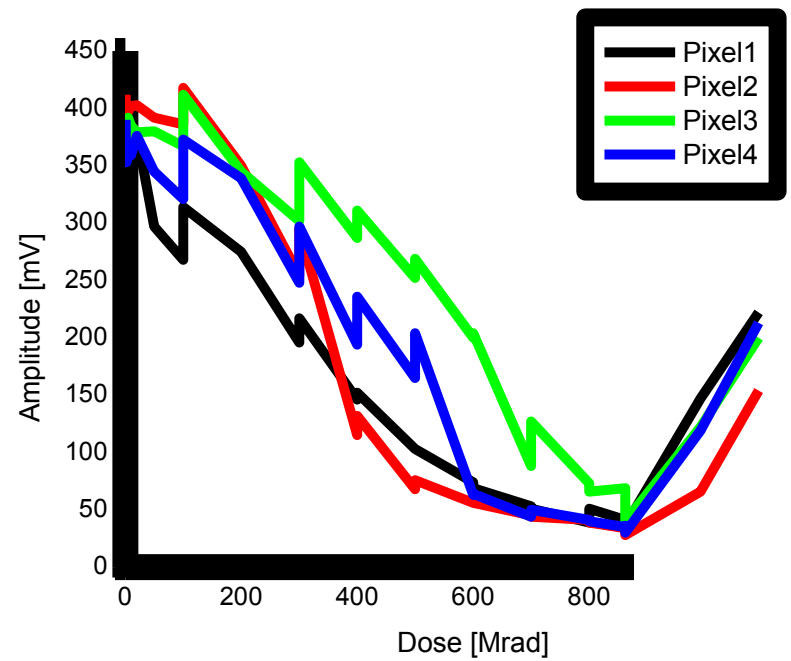
- X-ray irradiation to 862 Mrad, 2 hours of annealing at 70°C after each 100Mrad, powered on during irradiation
- amplifier gain loss in rad-hard pixels fully recovered after optimizing chip settings

Radiation effects on preamplifier gain

rad-hard pixels



simple pixels



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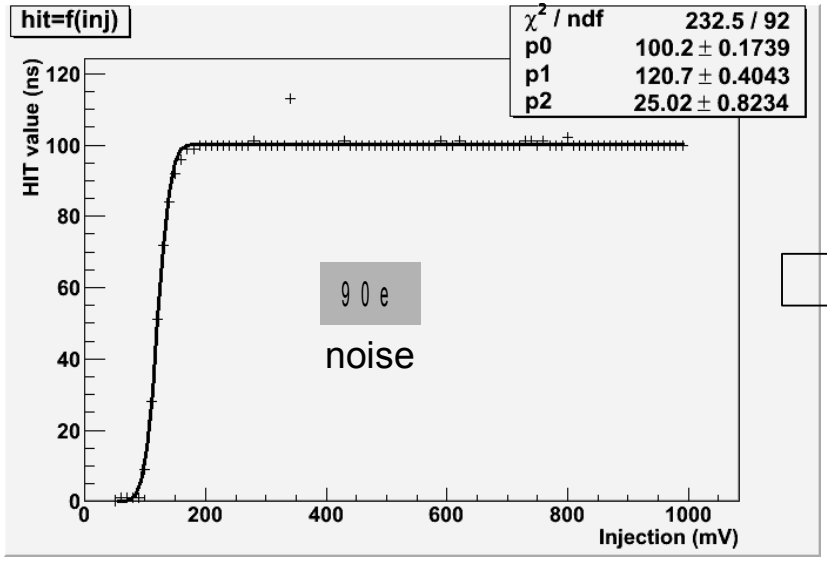
- amplifier gain loss in rad-hard pixels fully recovered after optimizing chip settings
- noise increase on partially rad-hard pixel: 90e → 150e (at room temperature)
- amplifiers work with reduced bias current (2μA instead of 5μA)

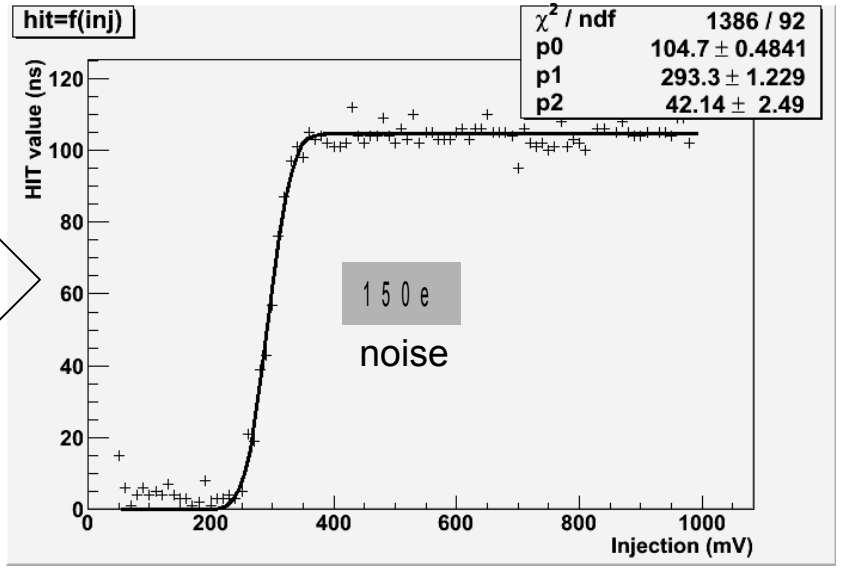
Radiation effect on noise level

before irradiation

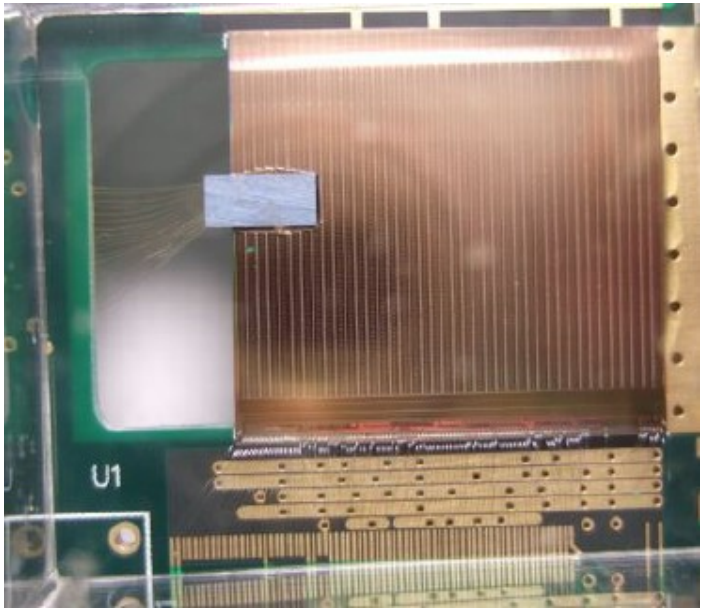


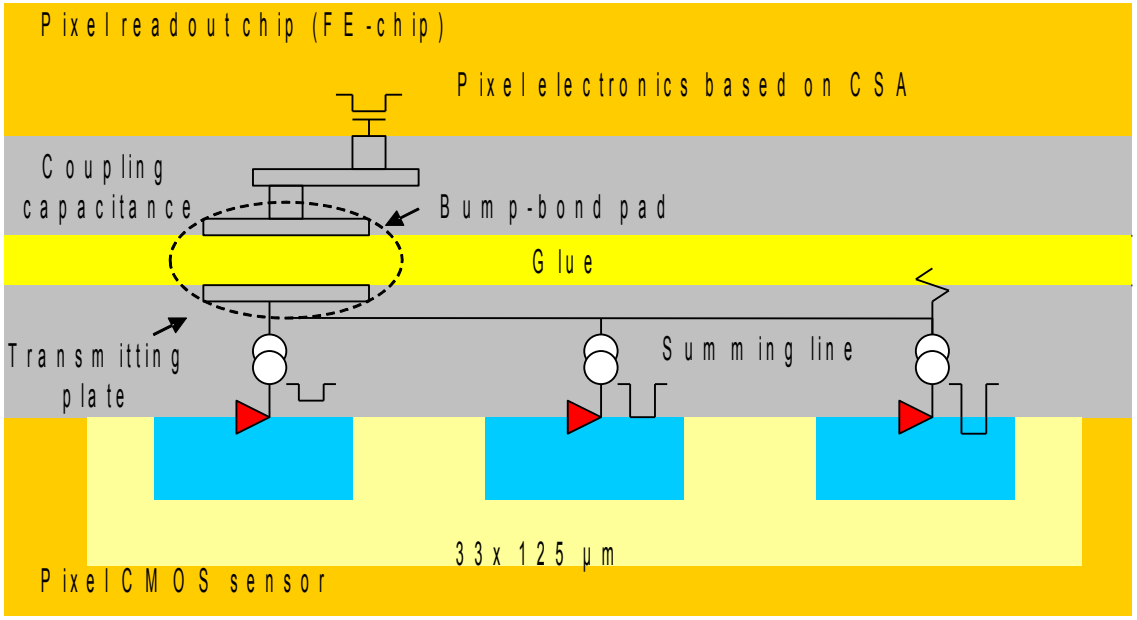
862 Mrad

after irradiation



CCPD – Capacitively Coupled Pixel Detector





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  - capacitive coupling possible
  - gluing instead of bump-bonding
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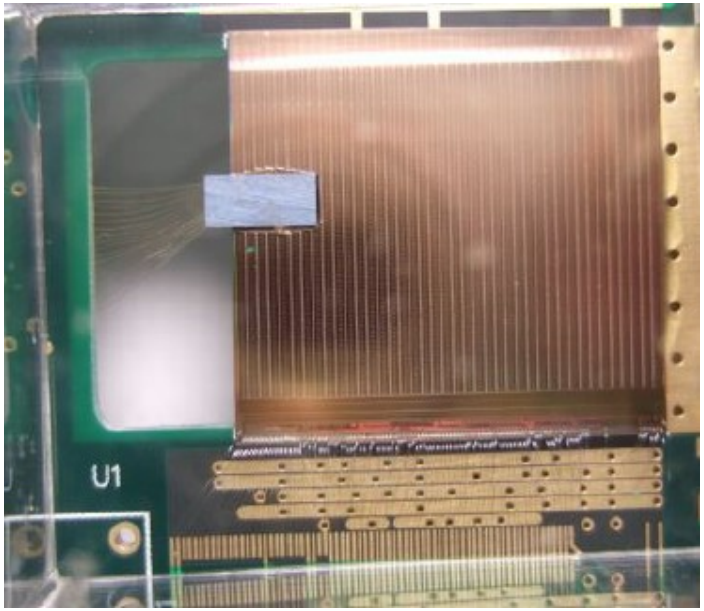

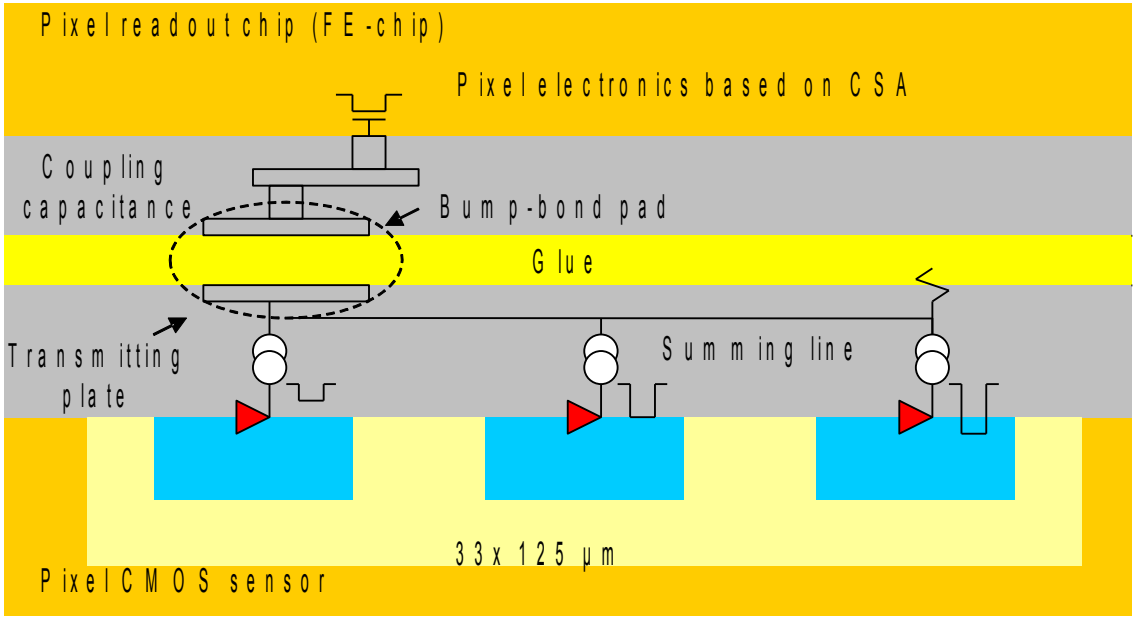

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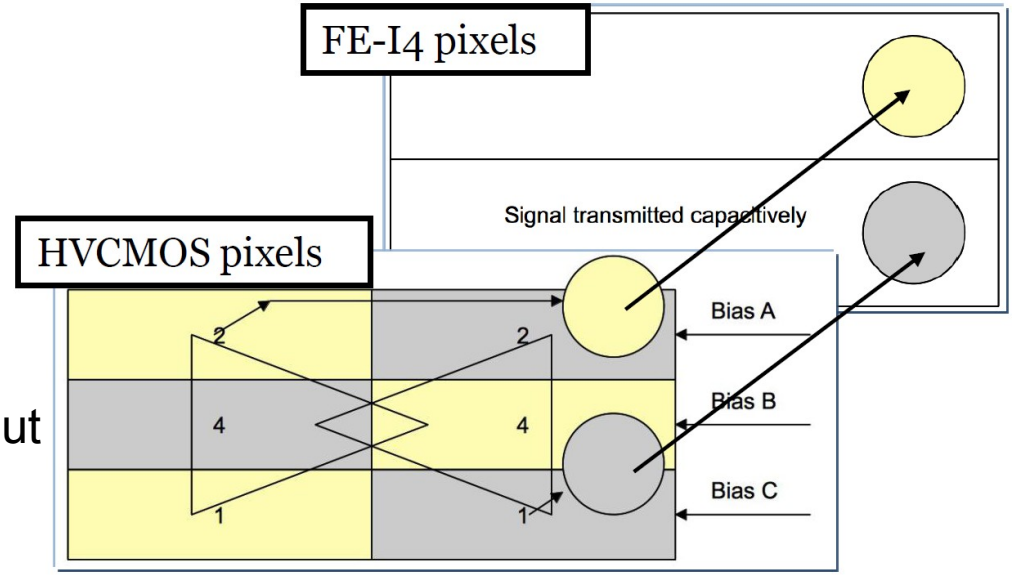
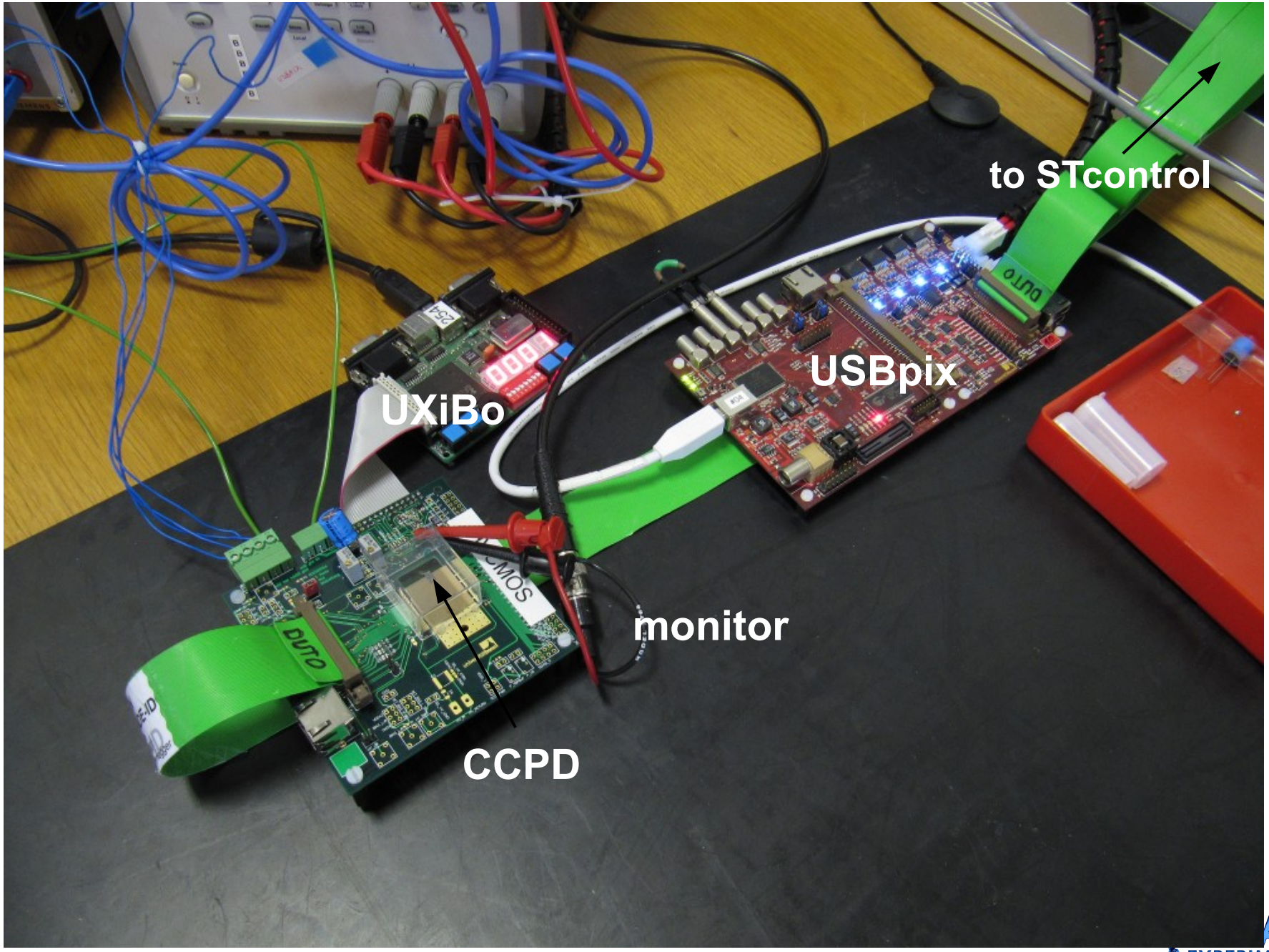
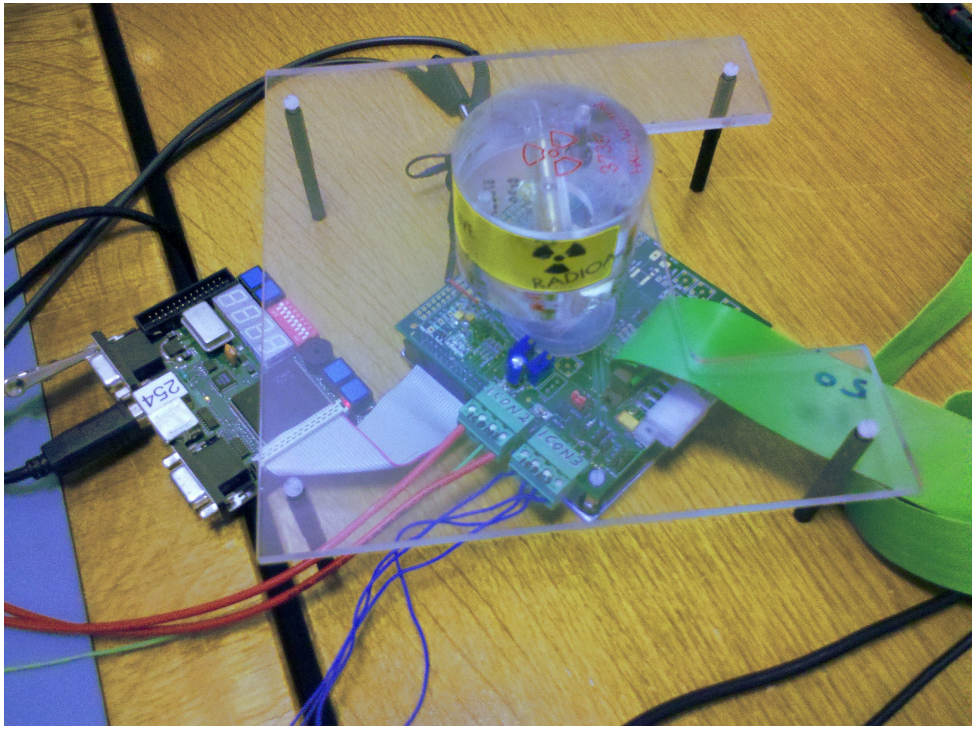
- readout with FE-I4 / sub-pixel structure
  - three sub-pixels connected to one readout pad
  - position encoding in signal height
    → <u>improves spatial resolution</u> with respect to standard FE-I4 cell

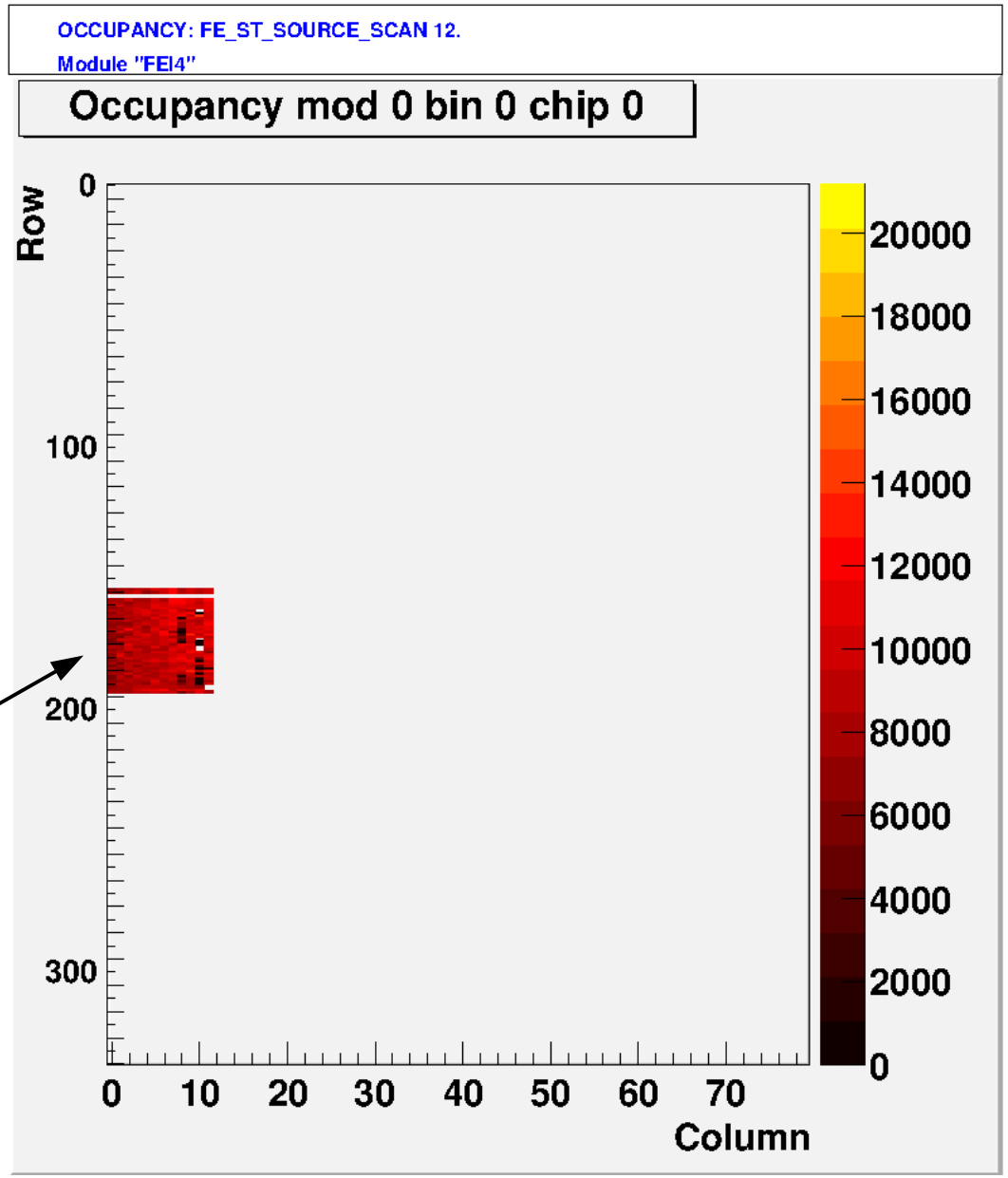


CCPD Setup

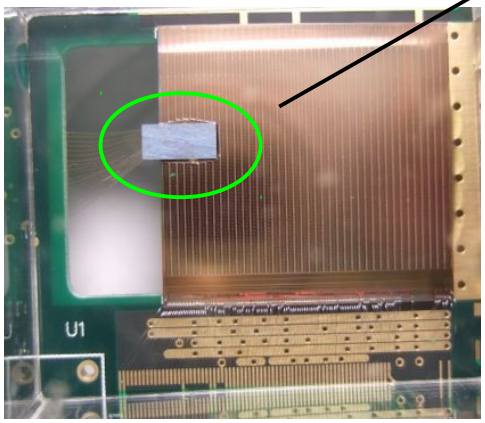


CCPD (HV2FEI4v1 on FEI4) – It Works





- ^{90}Sr-source
- Readout by FEI4 (STcontrol)
- w/o source: 0 rate
- w/ source: kHz rate



HV2FEI4v1 – Non-Ionizing Radiation Effects (Bulk Damage)

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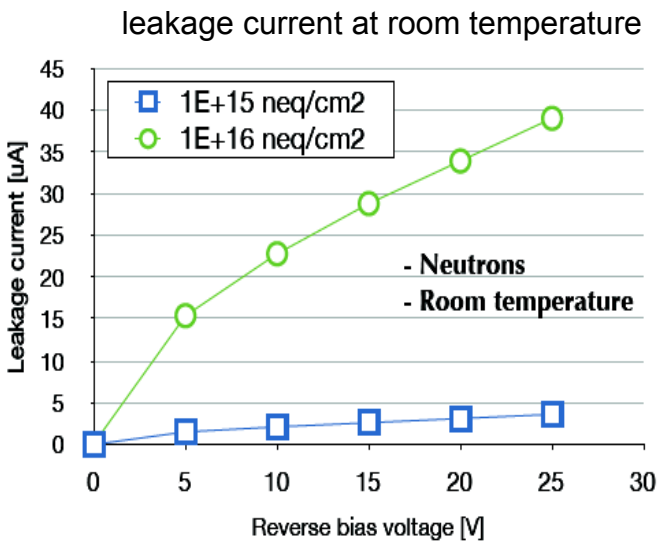
- irradiation of HV2FEI4v1 to 1e15 and 1e16 neq/cm^2 in Ljubljana
- leakage current behaves as expected



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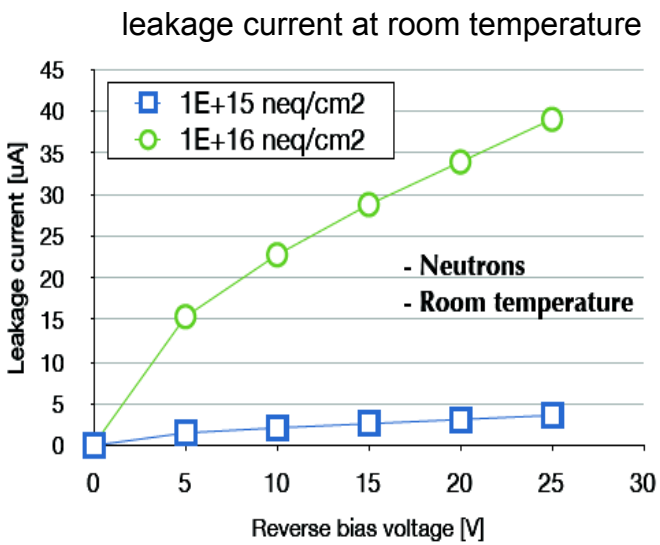
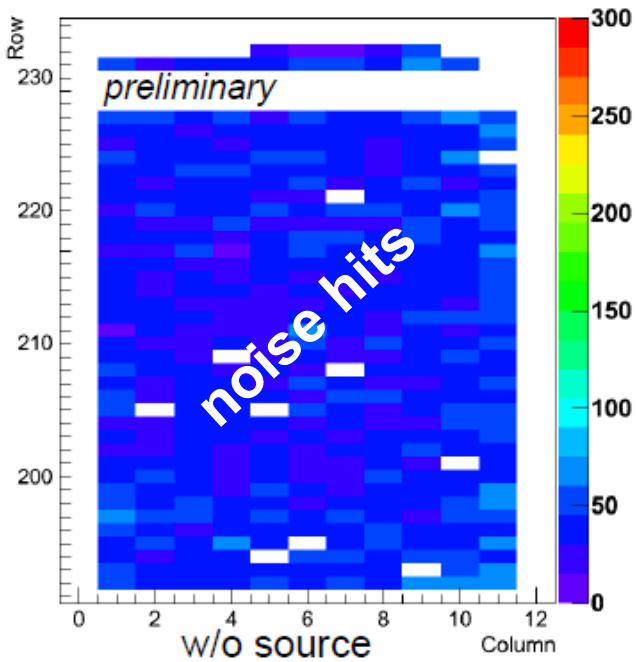
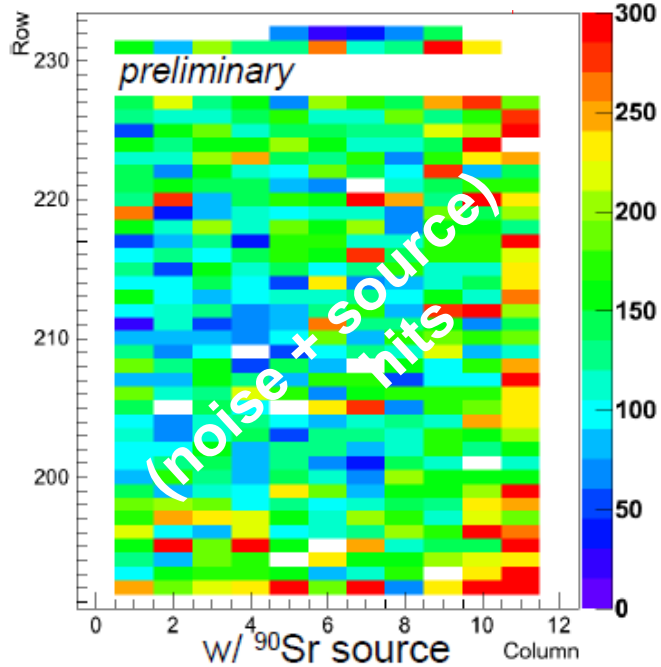
- leakage current behaves as expected
- sensor works even at room temperature!





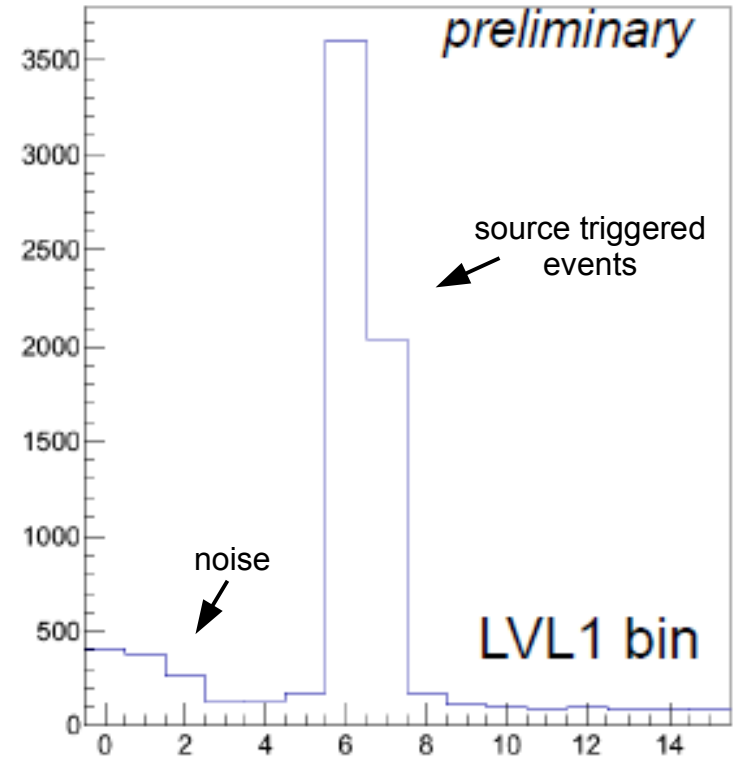


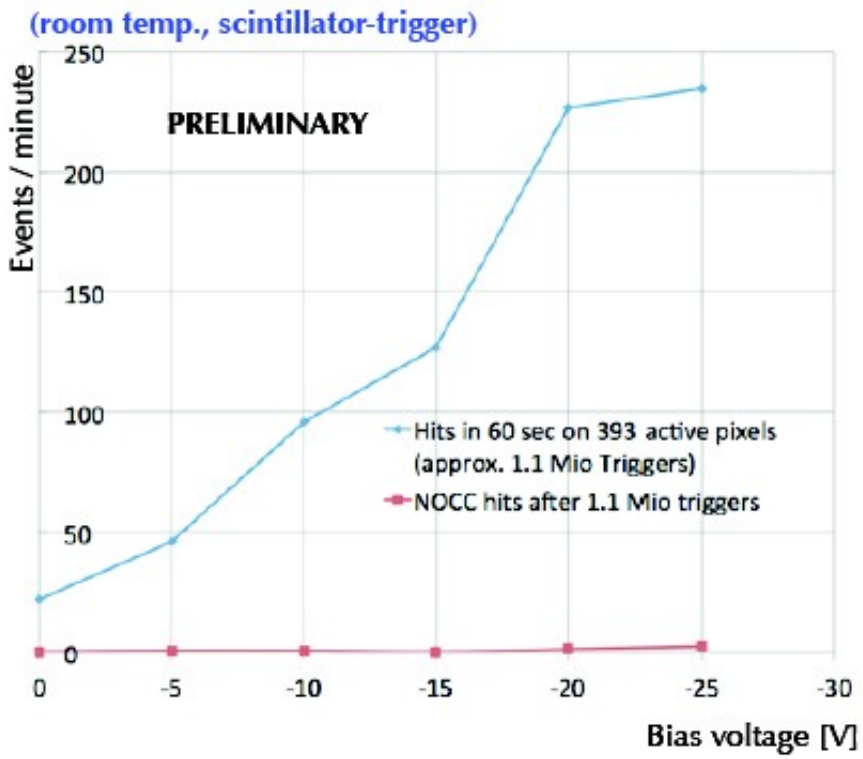
settings:

- 30 days of annealing at room temperature
- occupancy after 10 minutes
- self-trigger
- bias: -10V

CCPD – Particle Detection

- first measurements with scintillator trigger
- LVL1-distribution clearly show that we really see physics
- rate goes up with -HV, saturation still to be seen
- further measurements will include higher bias voltage

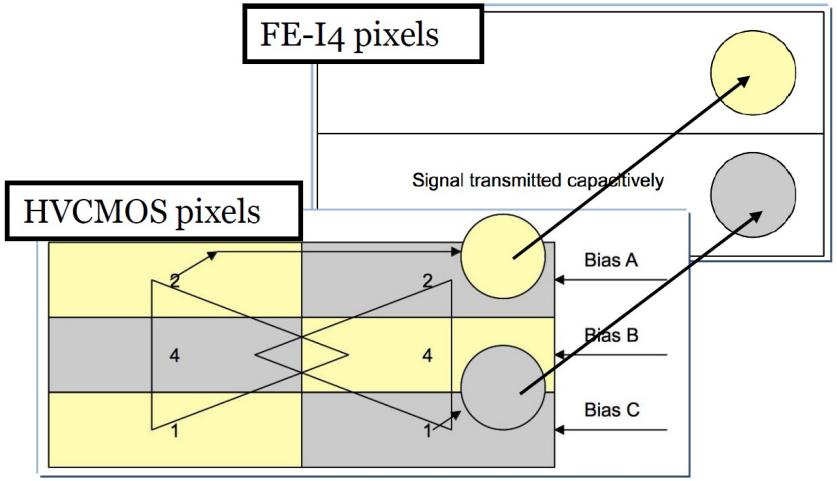




after 1e16 neq/cm^2 !

CCPD – Sub-Pixel Encoding

- sub-pixel encoding works on single pixel cells
- individual sub-pixels well separated in ToT-spectrum



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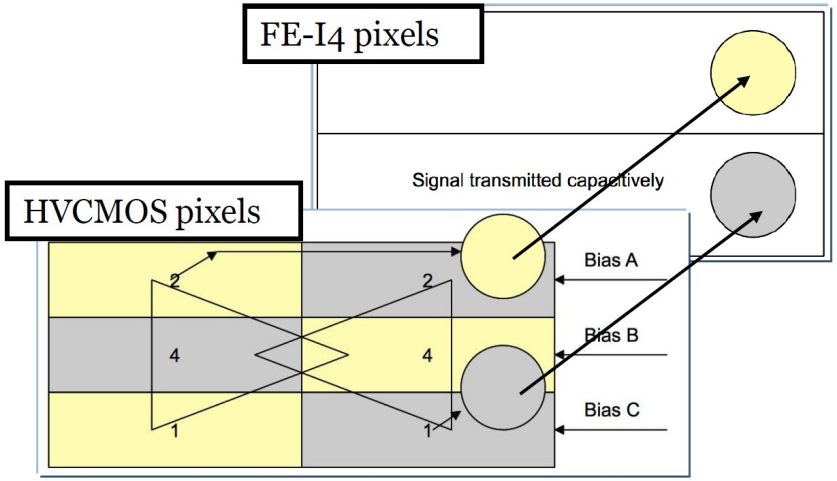

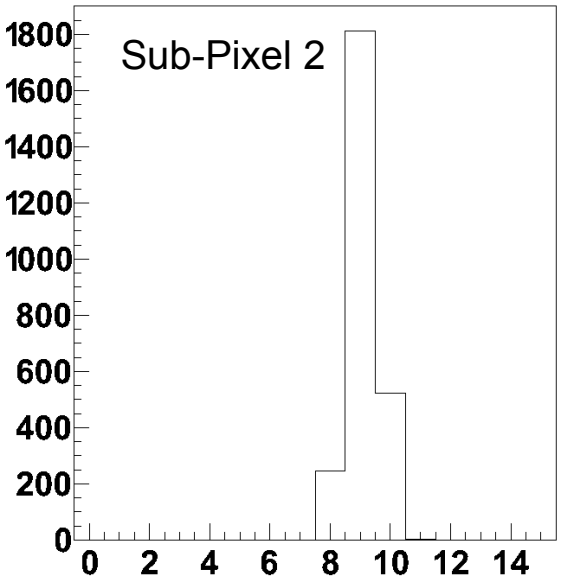

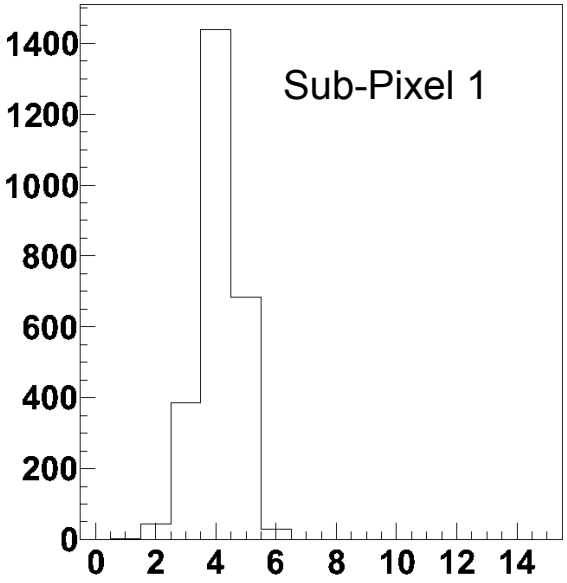

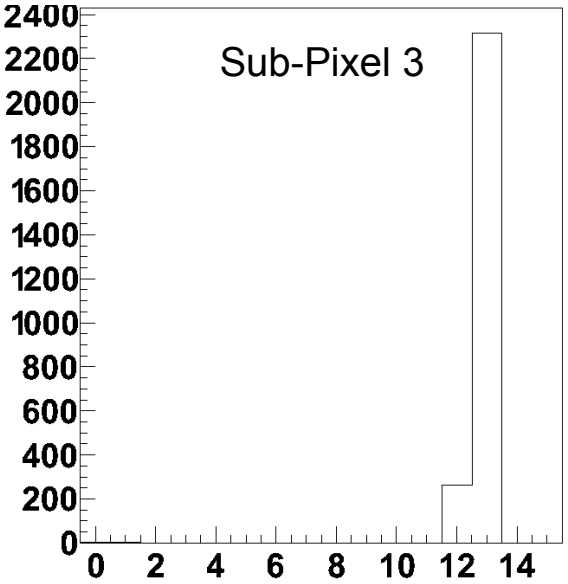

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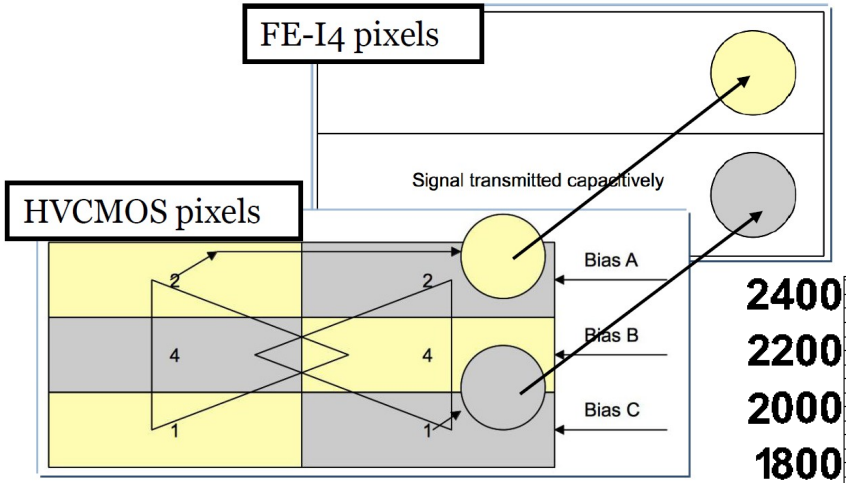
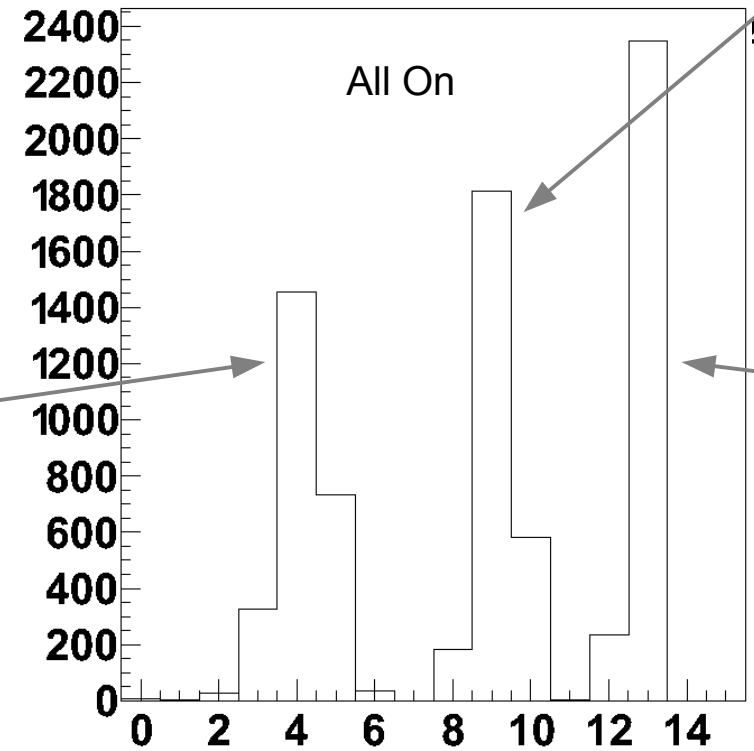
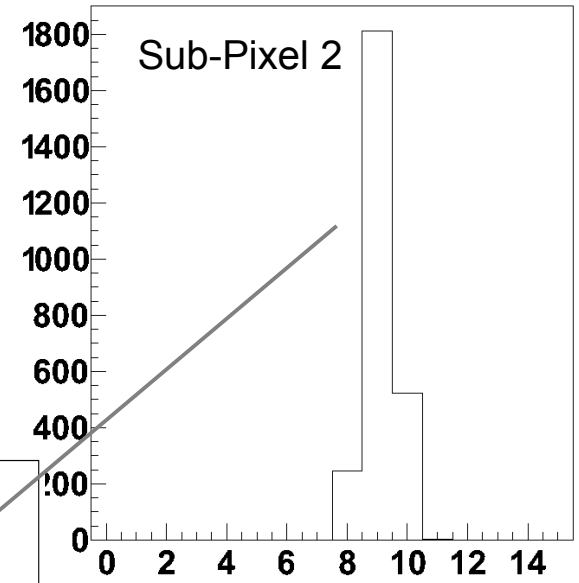
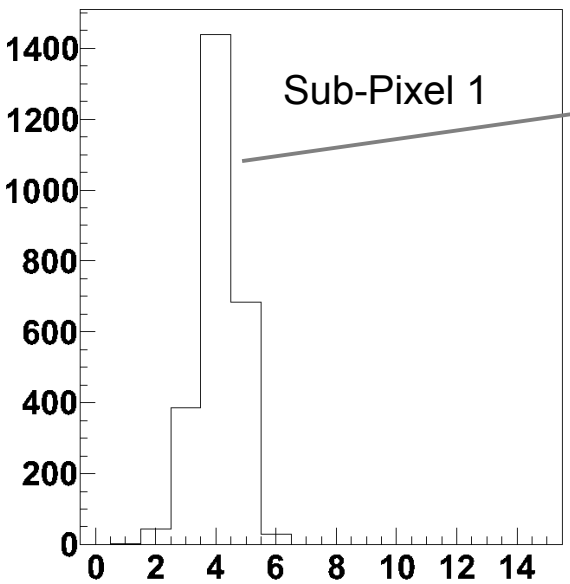
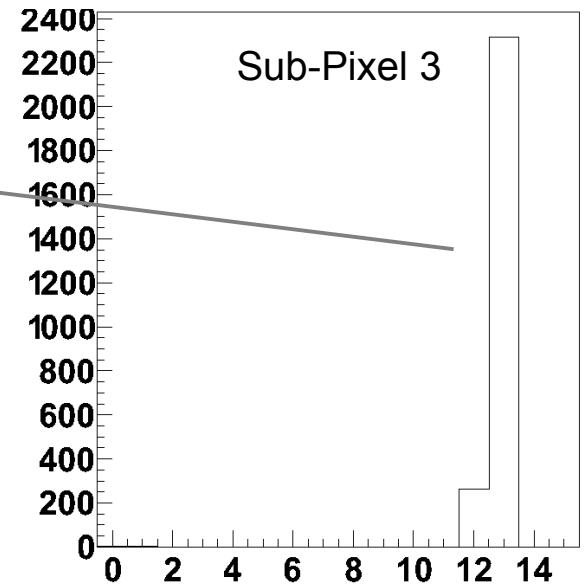


unirradiated sensor!



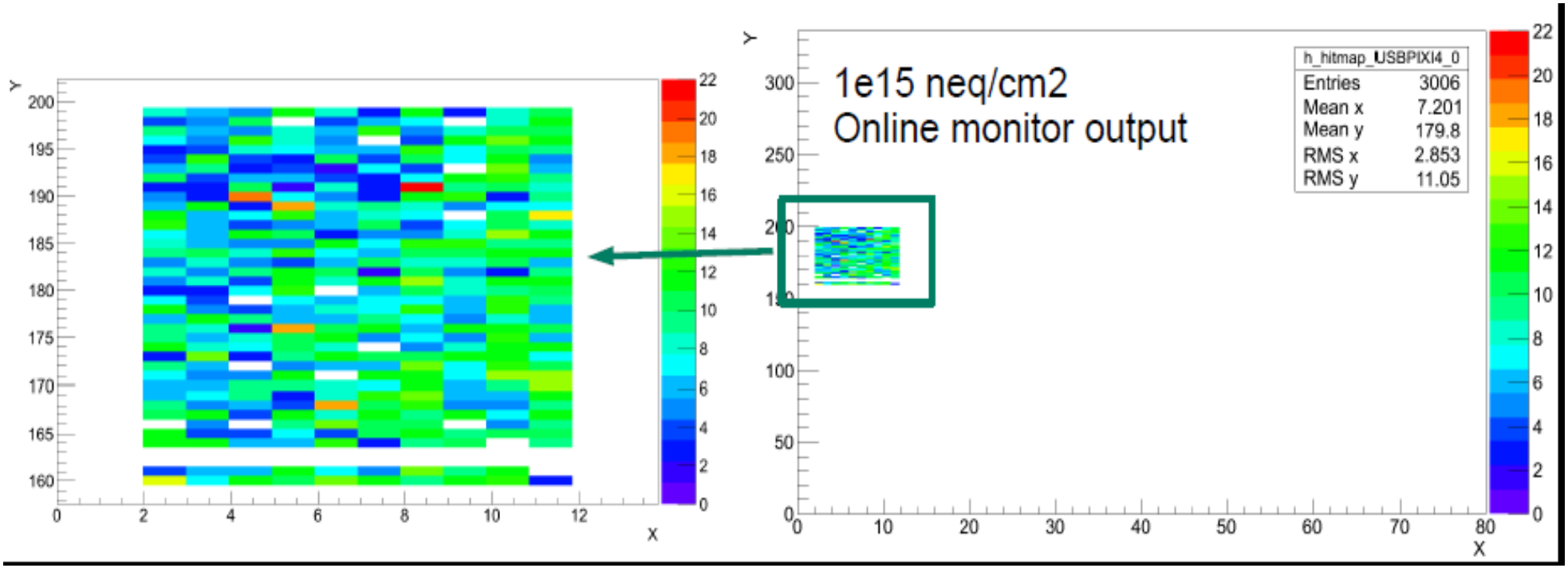






CCPD – Test Beam

- data taken, but problems with reconstruction (DUT data stream sync problems during data taking)
- HV-CMOS worked in test beam!
- no cooling!
- next studies: efficiency comparison unirrad./irrad, spatial resolution



stay tuned!

CCPD - Outlook

- performance of sensors has to be measured systematically:
  - cooled sensors
  - rate and leakage current vs. bias voltage
  - efficiency
  - spatial resolution

- 2nd generation sensors ready → CCPDs to be tested

- neutron irradiation of 2nd generation sensors

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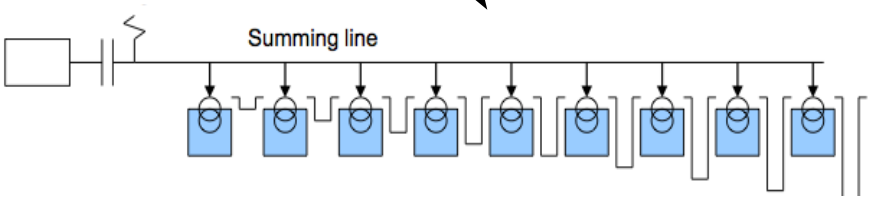
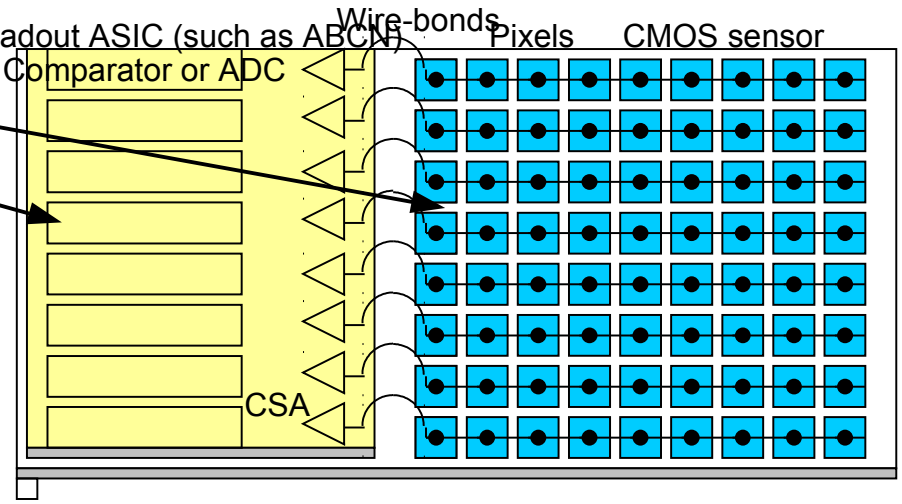
- *optimization of pixel electronics and geometry*

- *engineering run (full size sensors suitable for large scale HEP detectors)*

Strip Readout

- Pixels are summed to “virtual strips”
- Readout with analogue or digital readout chips
- Hit position encoded again in pulse height





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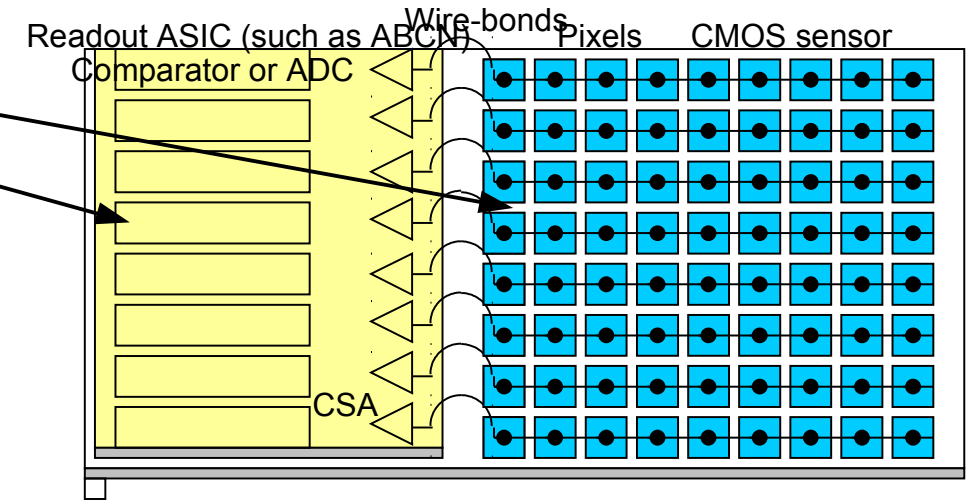
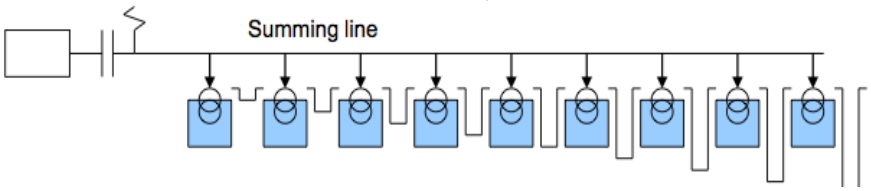
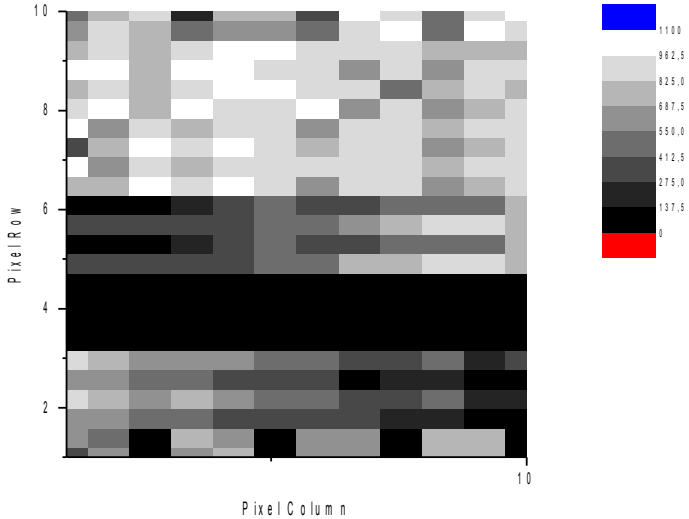




- pixel hitmap reconstructed from strip information (here: shadow of a wire)



cheap pixel sensor used as strip detector → 200m^2 affordable!

Outlook on HV-CMOS technology for sensors

- HV-CMOS processes enable the fabrication of active sensors with many advantageous properties needed for HL-LHC application and beyond:
  - cheap & fast production
  - rad-hard
  - high spatial resolution
  - fast
  - thin
  - low bias voltage
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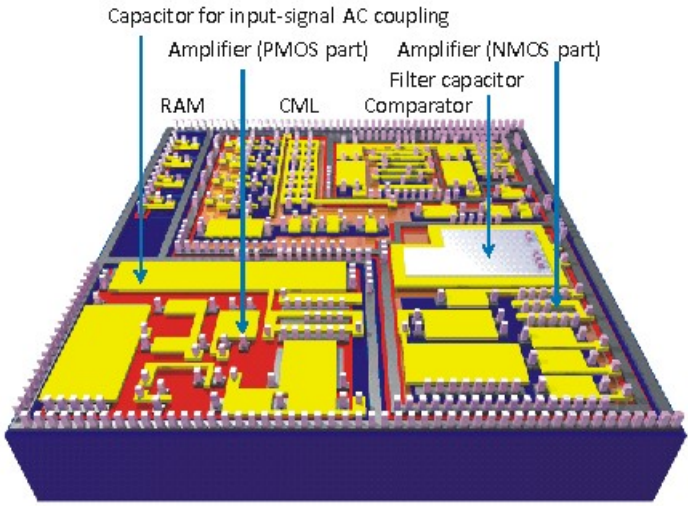
  - ideas to use 65 and 130nm
- final goal: full-size detector for large scale HEP tracking detectors

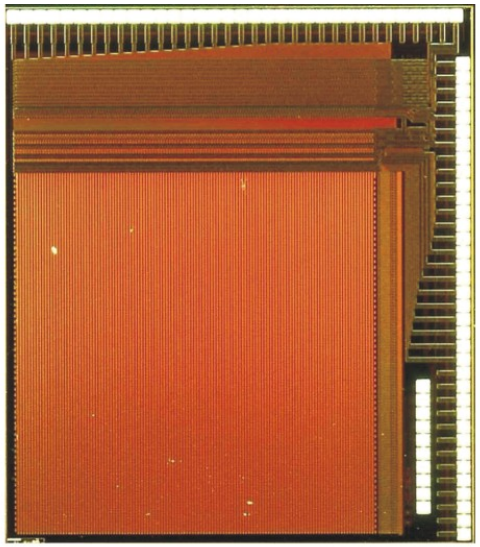
Thank you!

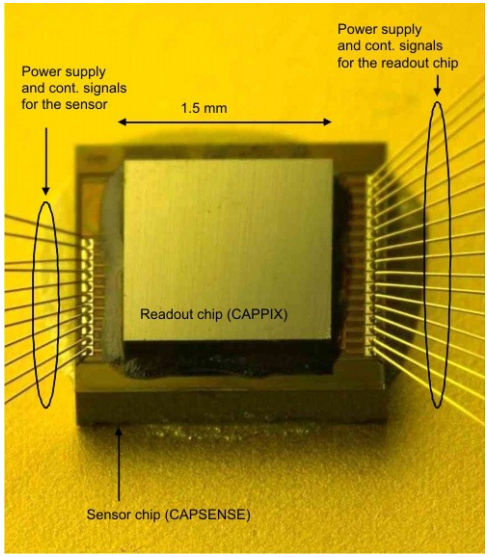
Backup Slides

Development in 350nm Technology

- used AMS 0.35µm technology
- Several prototypes have been designed
- Three detector types:
- A) Monolithic detector with intelligent CMOS pixels
- Pixel electronic is rather complex – CMOS based charge sensitive amplifier, usually discriminator, threshold tune…
- B) Monolithic detector with 4-PMOS-transistor pixel and rolling shutter RO
- C) Capacitively coupled hybrid detectors
- Good results, >98% efficiency in test-beam, high radiation tolerance







Pixel Schematics

normal pixel