Radiation hardness of present pixel modules

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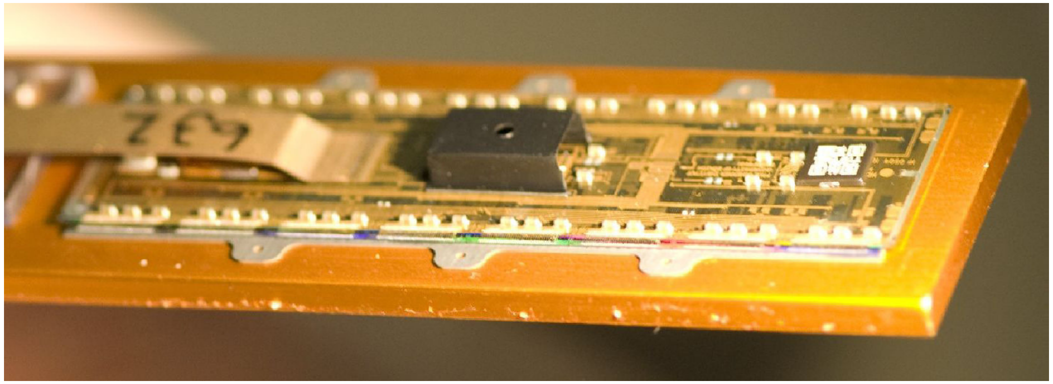
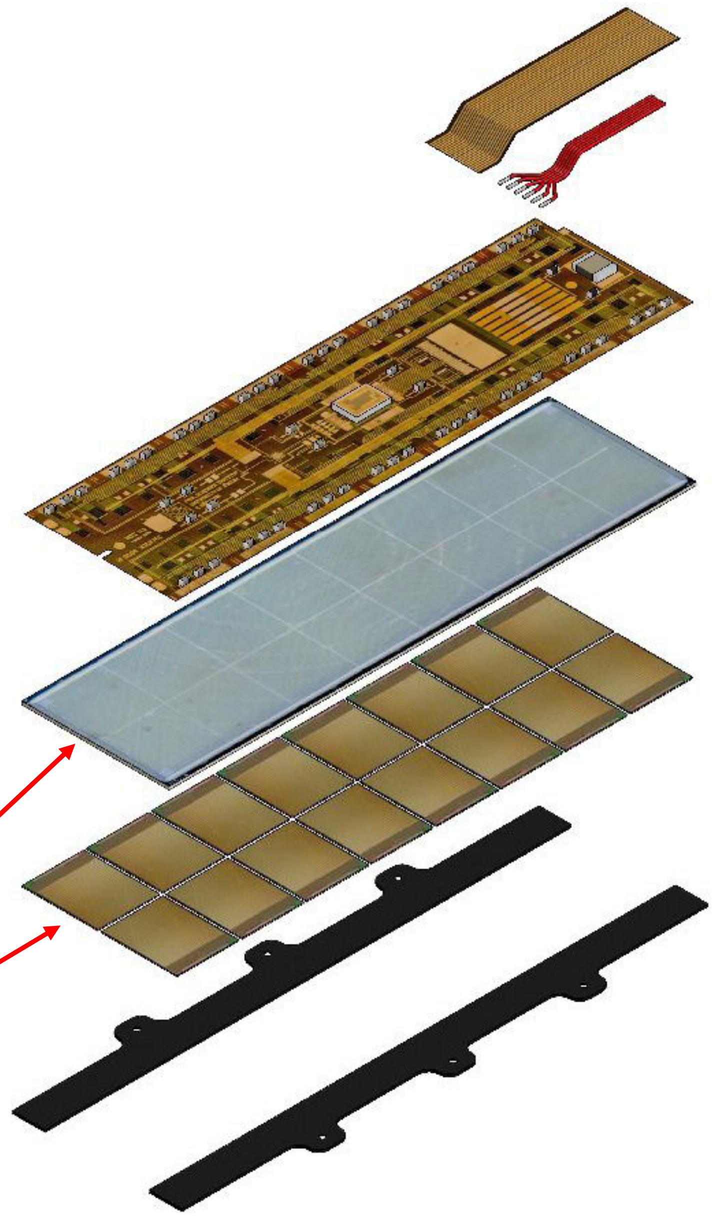


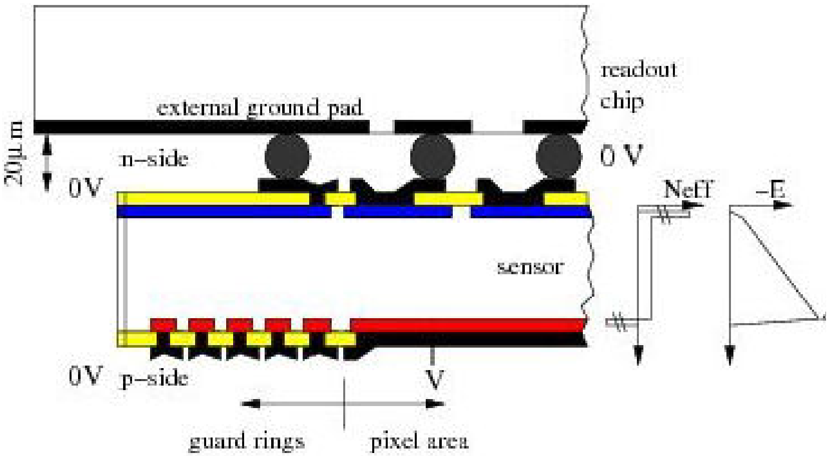
Introduction

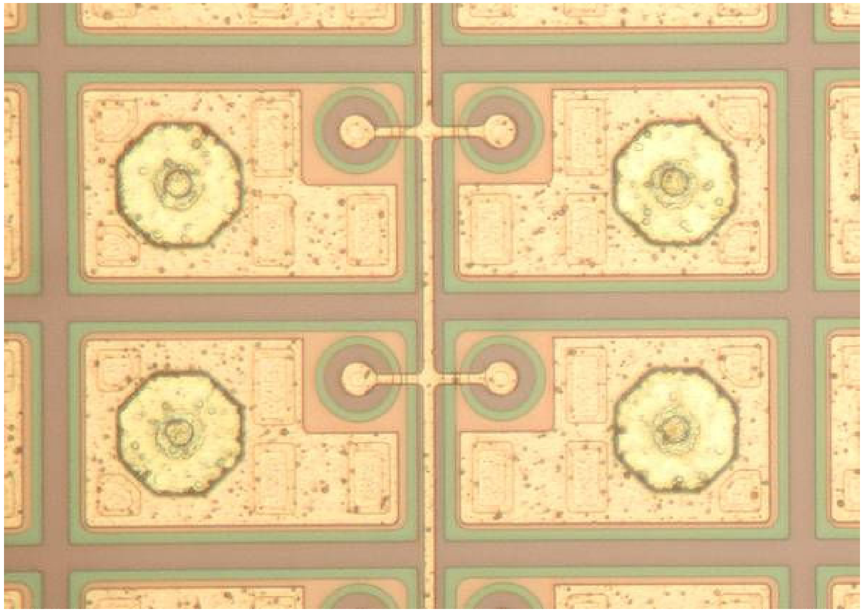
- LHC upgrade phase I planned after pixel replacement
  - Pixel detector has to cope with such an environment
  - Modules have only be tested to hardron fluences up to ~$10^{15} n_{eq}/cm^2$
    - ~ 3 yrs in the 4cm layer at $L=10^{34}\ s^{-1}cm^{-2}$
    - ~1.5 times the specification
  - Module have potential to perform well at higher fluences
  - Parts most sensitive to radiation
    - Sensor (charge collection, operation voltage, leakage current)
    - Readout chip (not much known on performance degradation at high hadron fluences)



Sensor concept (Bpix)

- Collect electrons (n-side readout)
  - Less prone to trapping
  - Larger Lorentz angle
  - n-side isolation required (moderated p-spray BPix)
- Avoid problems in module design
  - N-Substrate
  - Guard rings (and junction) on back side
  - All sensor edges on ground potential
- Pixel call layout
  - Punch through biasing grid
    - Testability (prior to bump bonding)
    - Protect unconnected pixels
    - Loss of effective area
  - Small gaps between implants
    - Homogenous drift field
    - Rather high interpixel capacitance (~80fF)





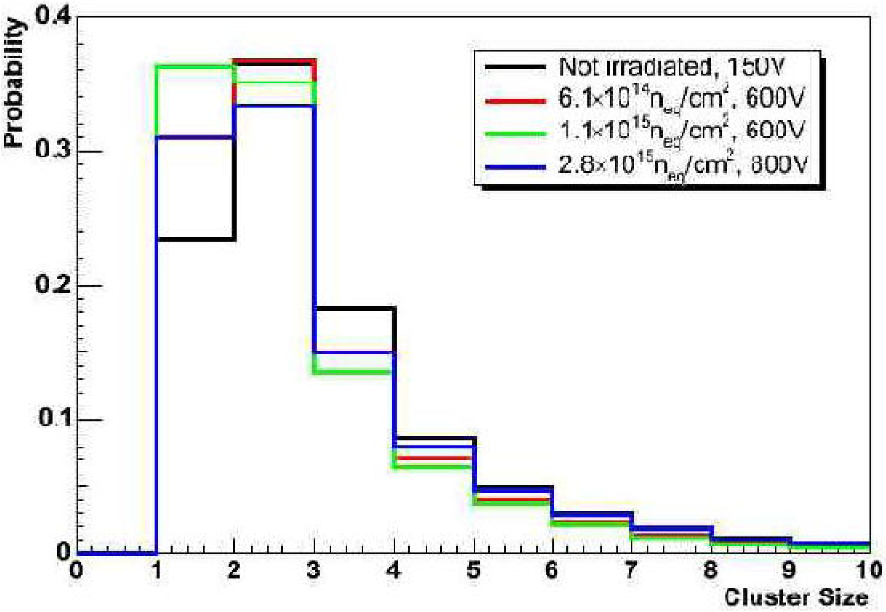
Radiation hardness study

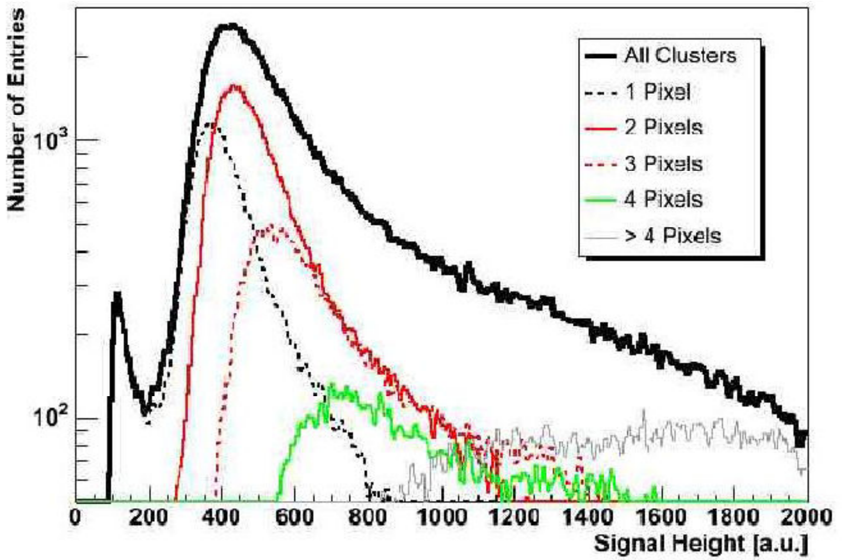
- Irradiated numerous samples consisting of a small sensor and 1 ROC
  - PSI Pi-E1 up to ~ $6\times10^{14} n_{eq}/cm^2$
  - CERN-PS up to ~ $5\times10^{15} n_{eq}/cm^2$

- Measured charge value obtained from a Sr-90 beta particle
- Leakage current stayed within “limits”
- Spatial resolution decreases to “binary” value (not measured)
- Presently no independent trigger (no efficiency measurement possible)

Data processing

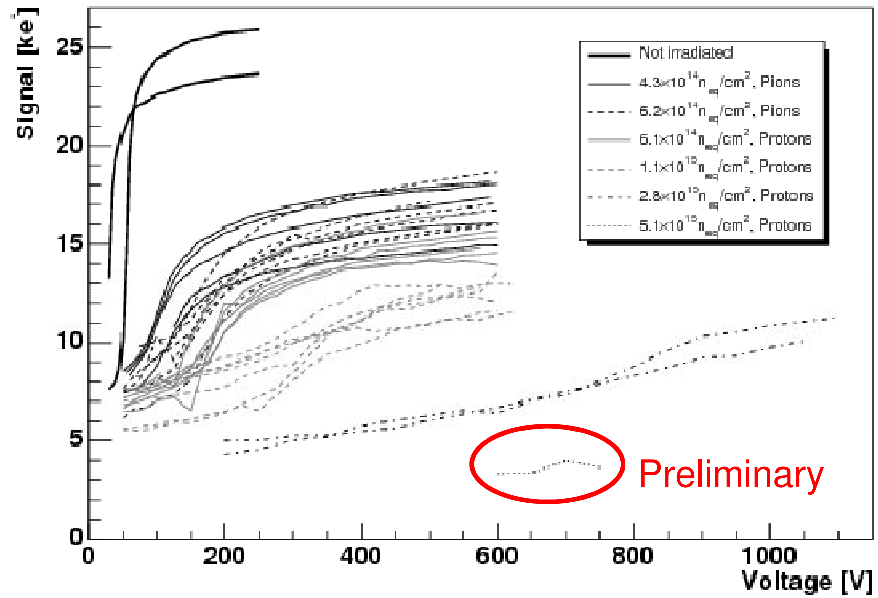
- Beta-spectrum of Sr-90 contains many low energetic particles
- No scintillator to filter out “high” energy particles
  - Tail with large clusters
  - For clusters > 3 pixels spectrum in not described by Landau
  - For clusters of size 1-3 the MPV depends on cluster size
- Only single pixel clusters are used

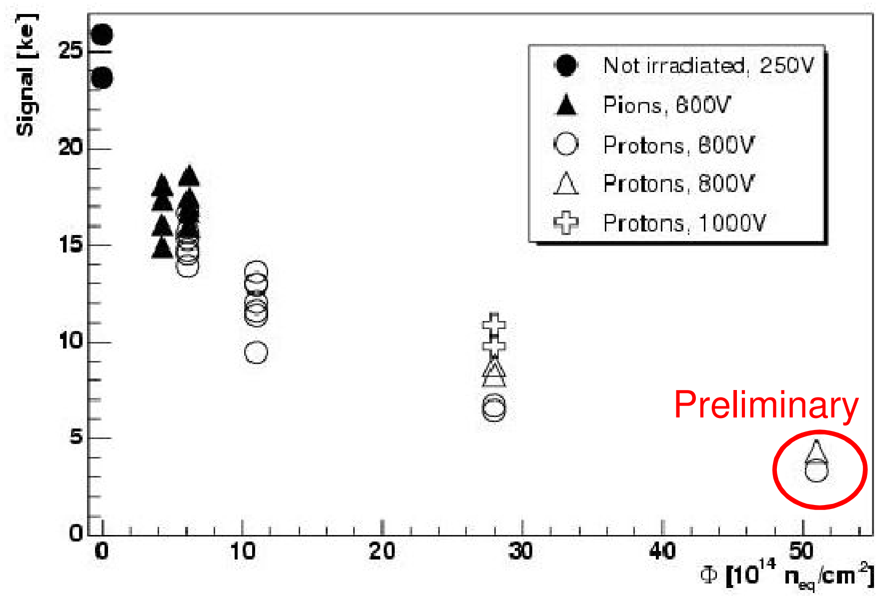




Results

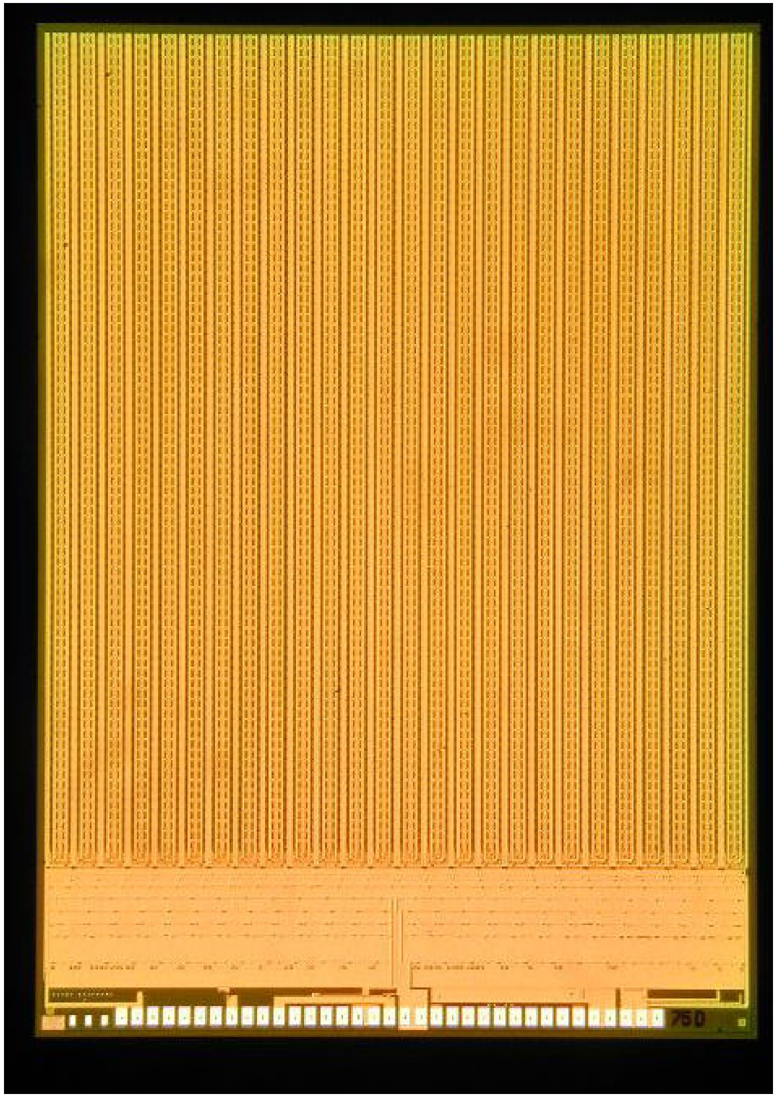
- Highly irradiated sensors operative up to 1kV
  - Presently problems with high voltage capability of the setup (connectors, PCBs etc.
- No signal saturation with bias for $\Phi > 2 \times 10^{15} n_{eq}/cm^2$
- Sensor with $\Phi = 2.8 \times 10^{15} n_{eq}/cm^2$ deliver > 5ke (at 800V)
  - No sign for charge multiplication
- Sensors seems suitable for upgraded LHC





Radiation Hardness of ROC

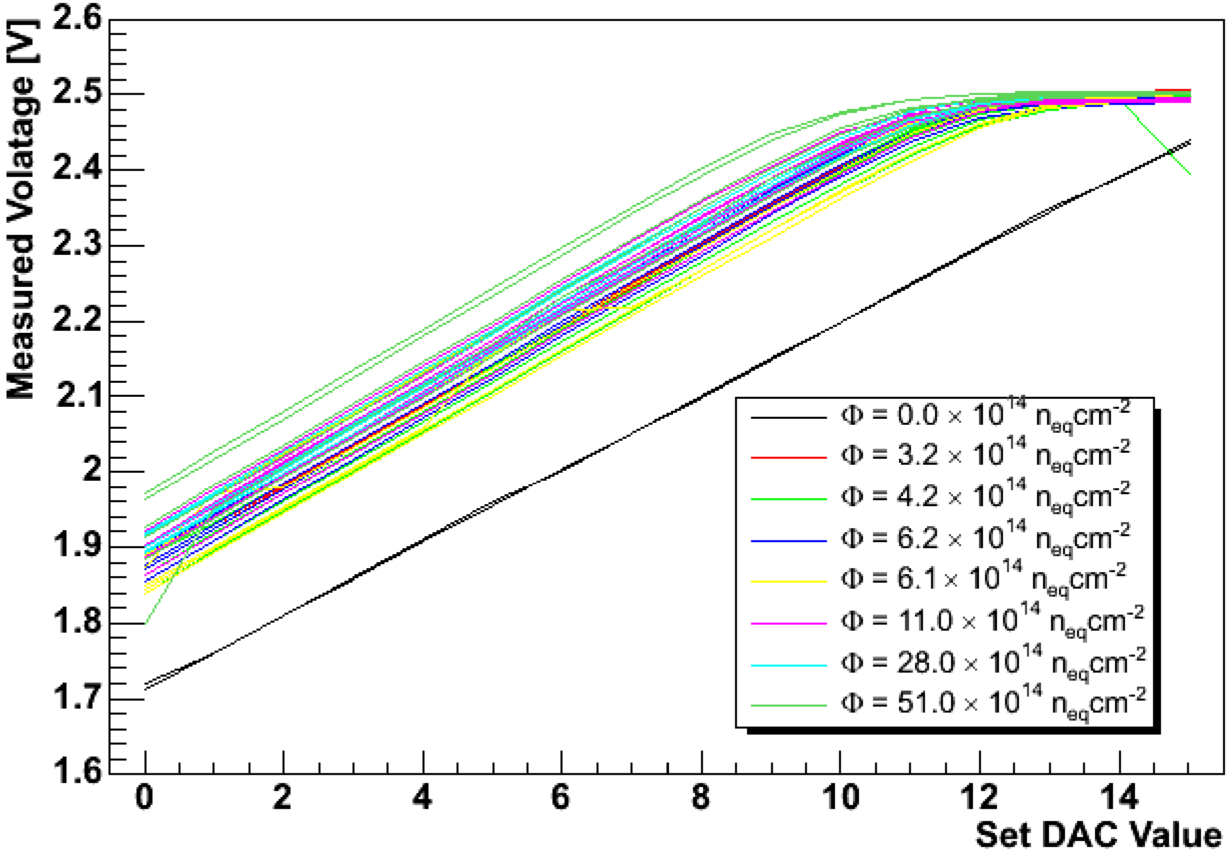
- At high Luminosities 2 problems
  - Instantaneous rate of particles
    - Potential data loss (talk of H.-C. Kästli)
  - Integrated dose (“radiation damage”)
    - Change of transistor parameters
- Present ROC (PSI-46v2.1)
  - Process: 0.25 μm with special design rules, 5 metal layers + mim Cap.
  - Number of transistors: 1.3M (~250 per pixel cell)
  - Power consumption: 120 mW (28 mW/pixel)
  - Power supplies: 2.5 V (digital), 1.7V (analogue)
  - plus voltage regulators on chip.
  - Data- and timestamp buffer: 32 resp. 12 per double column.



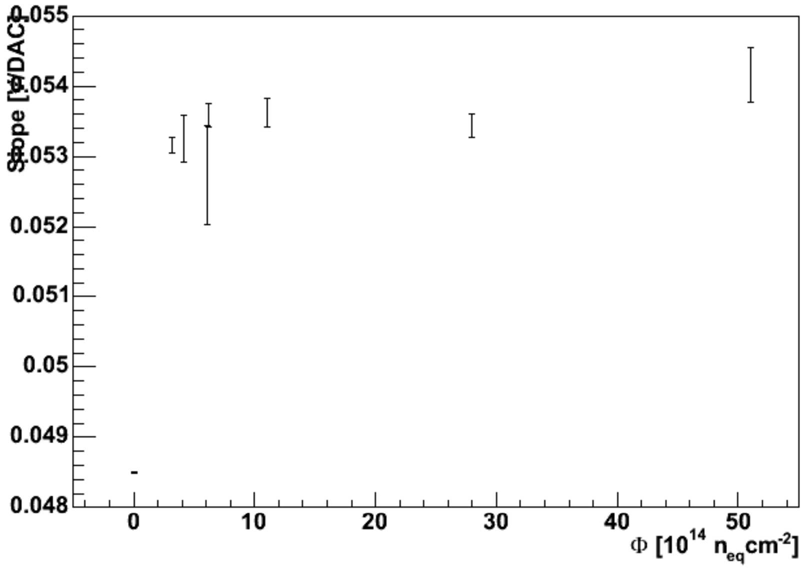
Radiation effects on the ROC

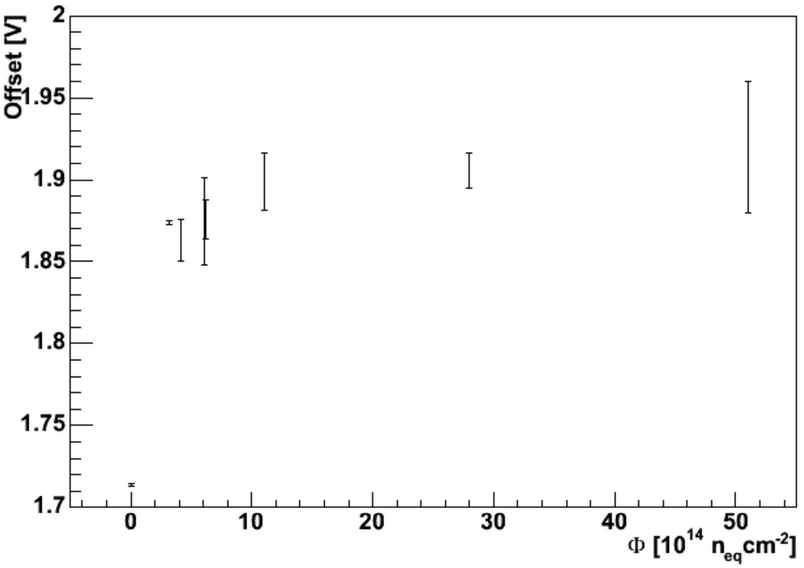
- **ROC stays fully operational within the full fluence range tested (up to $\Phi=5\times10^{15}N_{eq}/cm^2$).** All sensor data were taken with irradiated ROCs
- Apart from few settings (preamplifier and shaper feedback, source follower) the standard calibration procedure was followed
- Try to characterize the degradation
  - voltage of band gap reference (done)
  - peaking time of preamplifier as function of I_a (in progress)
  - Skipping speed of column drain (to be done)
  - High frequency limit of the ROC (to be done)

Band gap reference



- Saturation of Voltage is due to the limitation of the input Voltage (2.5 V) and not a radiation effect





- Shift of offset and slope by ~10%
- Saturates after the lowest dose
- All internal voltages are derived from the band gap reference
- All important calibrations (threshold, pulse height, etc.) use the injection of calibration pulses (Vcal)
  - All values have to be scaled by ~10%

Rise time of preamplifier

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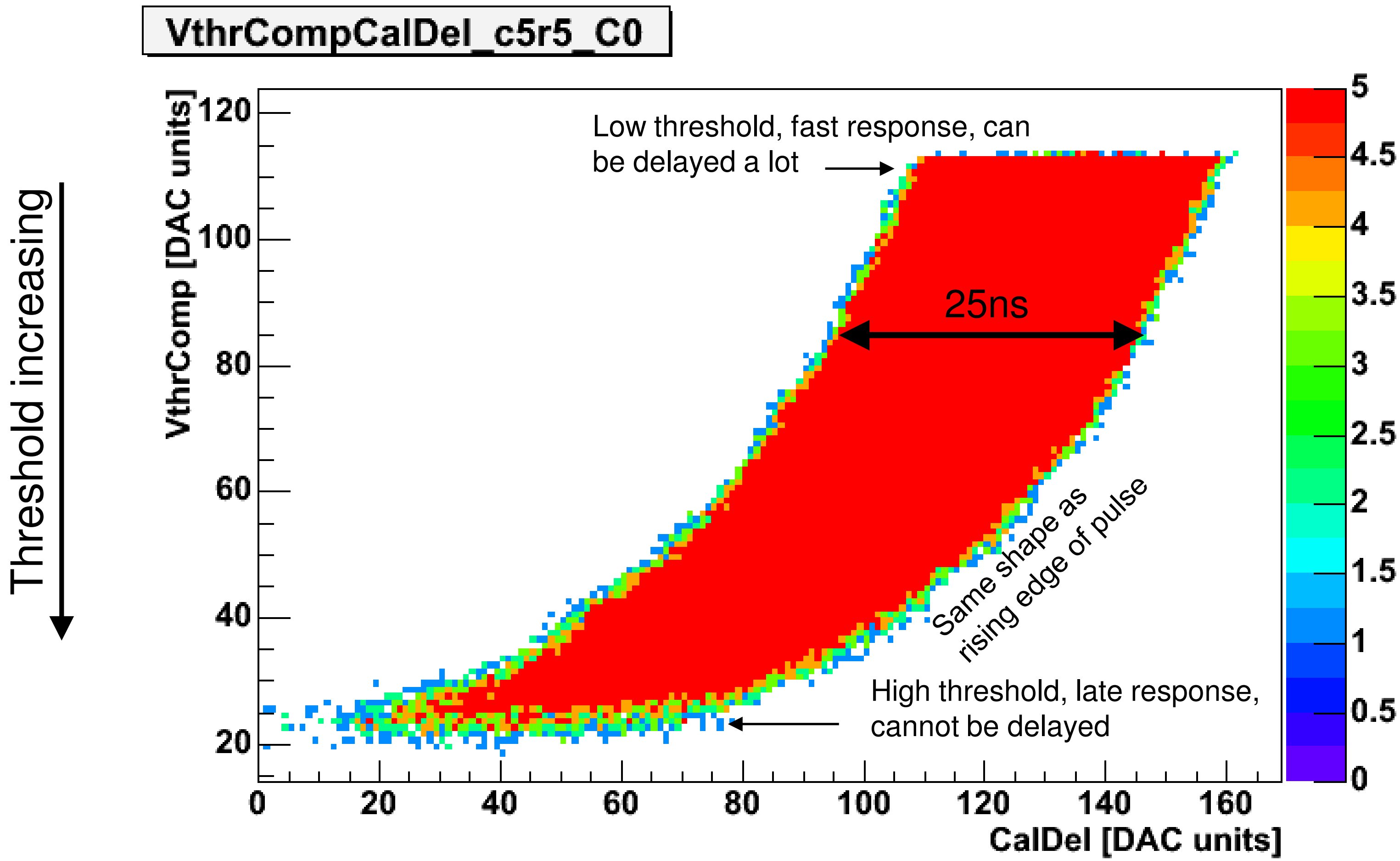
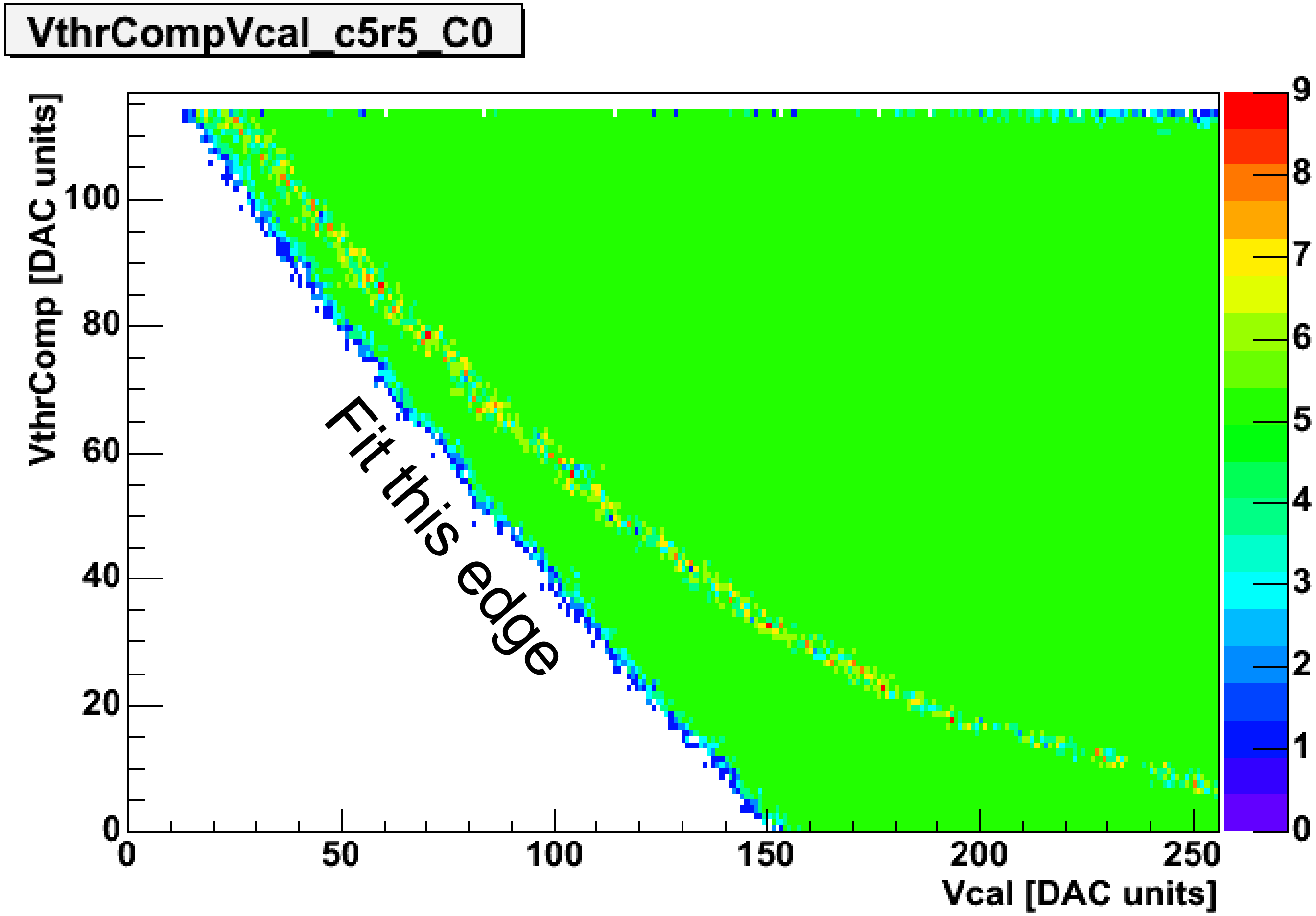


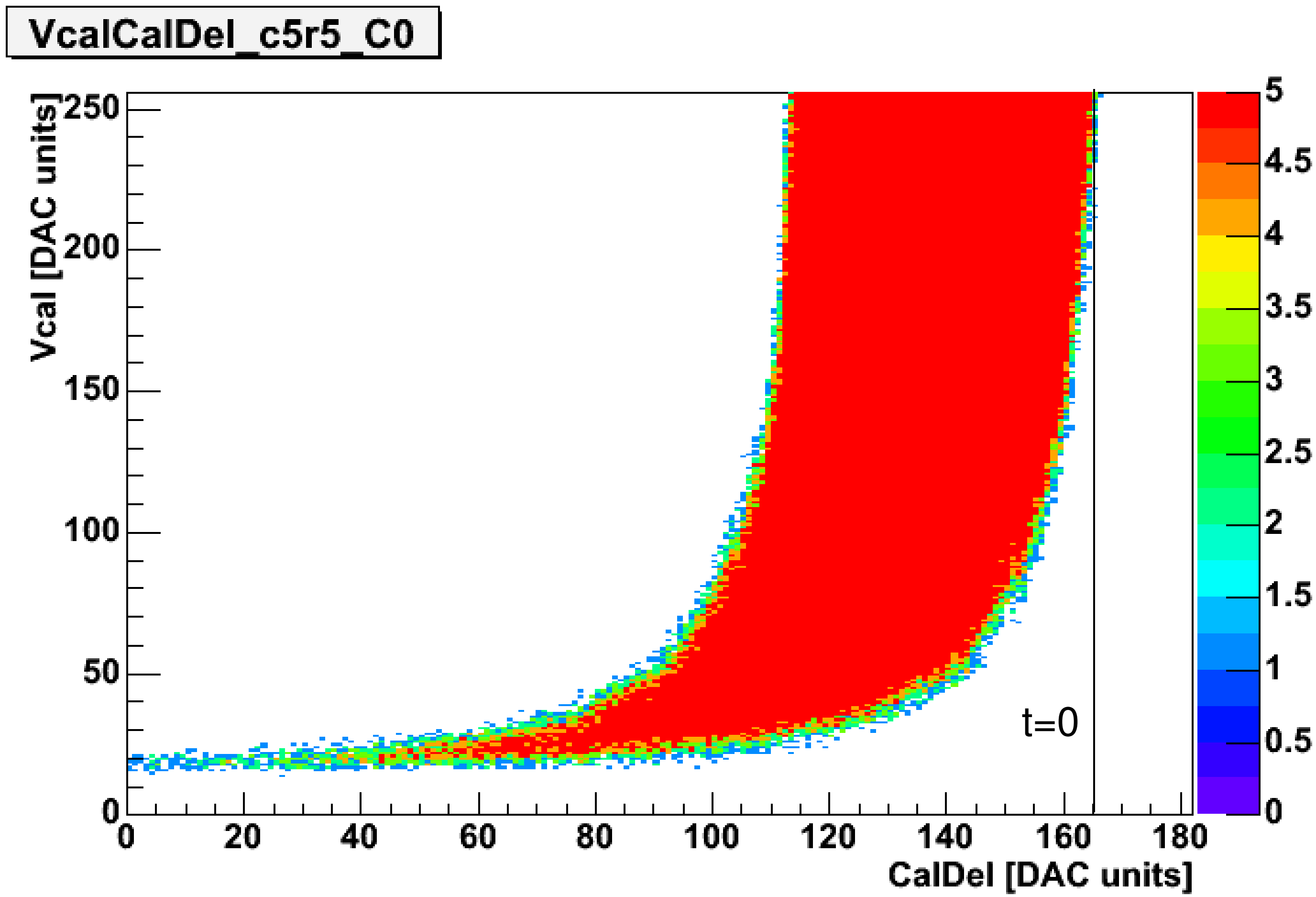
- Cannot directly be measured (no “transparent” mode)
- Presented method is very indirect and time consuming
- Use feature to delay injection of calibration signal
- Now have to calibrate both axis

Calibration of pulse height



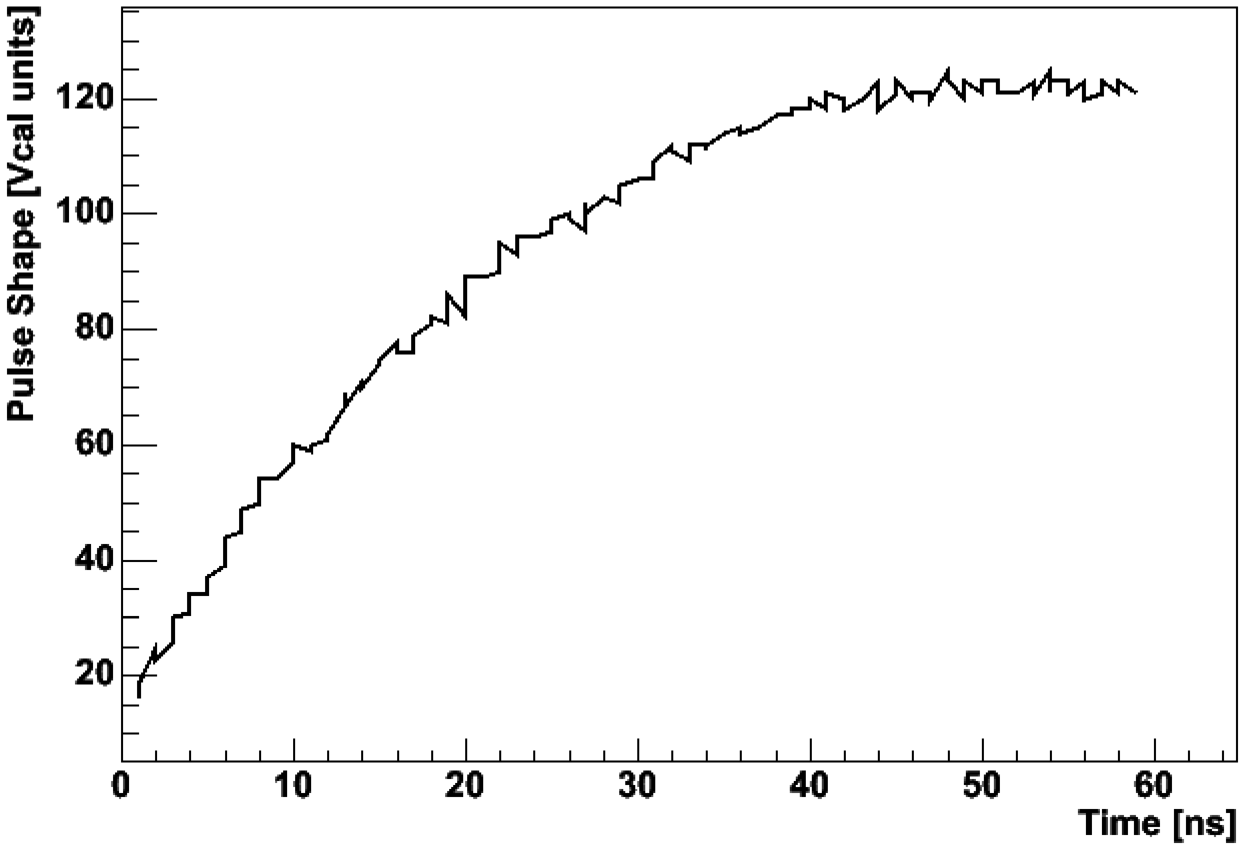
- Use 2 settings for the trigger latency to also get low amplitude pulses from the next bunch crossing to get the “real” threshold

Definition of t_0



- Use the lowest possible threshold and a very high signal to define time = 0

Reconstructed rise time



- Plot shows rise time **for one pixel** only
- Need a few 100 pixel per chip
- Measure dozens of chips
- Proof of principle done
- Automate procedure (next week)
- Then measure the other quantities

Conclusions

- **ROC stays fully operational within the full fluence range tested (up to $\Phi > 5\times10^{15} n_{eq}/cm^2$).**
- Studies on the exact changes of the analogue ROC behavior are under way
  - Band gap reference shifts by ~10%
  - Rise time is being measured (changes seem moderate)
  - Other quantities to be measured
- Sensor delivers sufficient charge up to $\Phi \sim 2.8\times10^{15} n_{eq}/cm^2$ (10 yrs at 4cm at $L=10^{34}$ $cm^{-2}s^{-1}$)
- High bias voltages bring considerable benefit
- Present module seems a suitable option for replacement of the pixel detector

Reserve

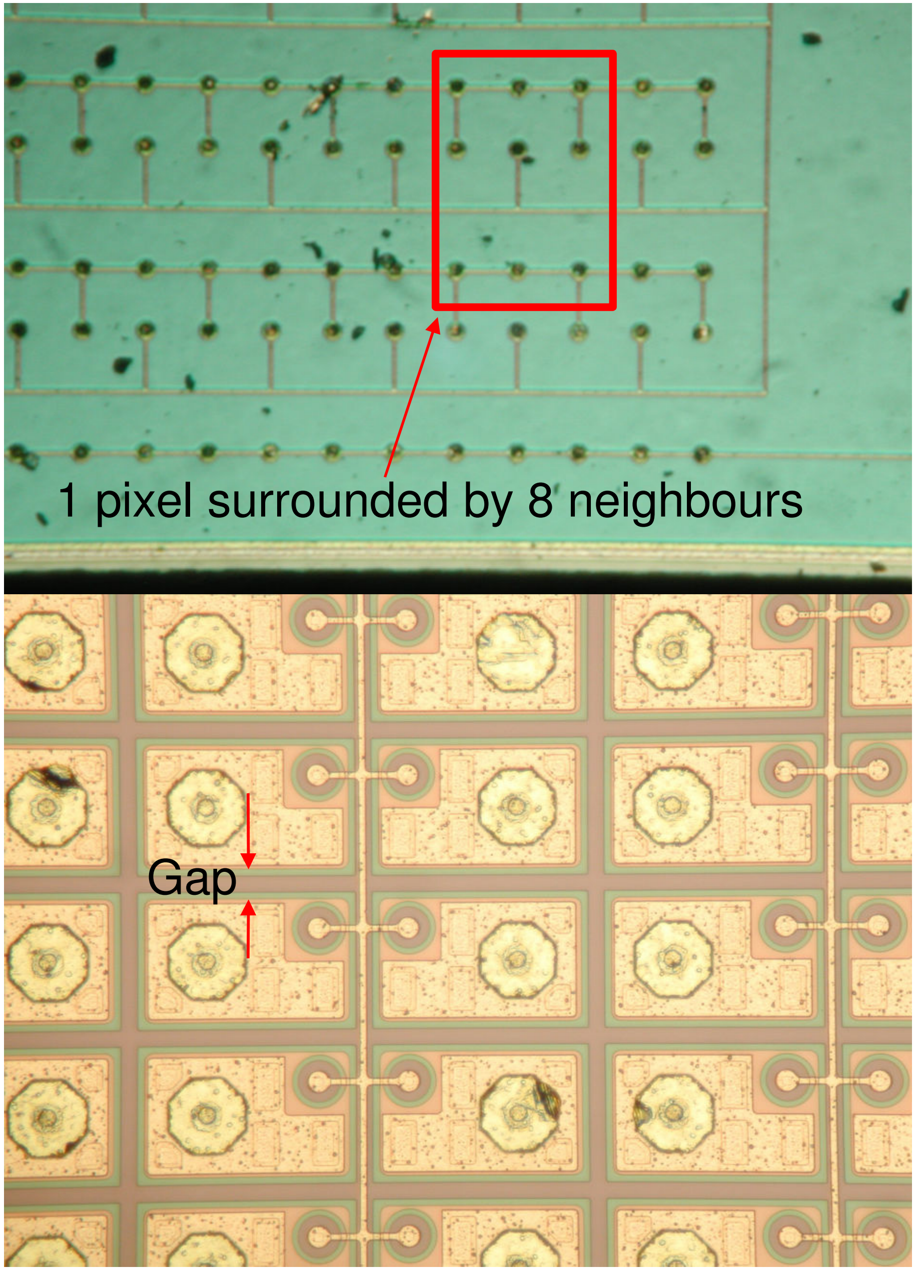
Sensor R&D

- Increase gap between implants
  - Reduce pixel capacitance
  - Might affect charge collection and breakdown behavior
  - Have sensors in hand (also irradiated), can decide in “last minute”
  - Presently done:
    - Systematic measurement of inter pixel capacitance
    - Compare other properties of “large” gap sensors
- Single sided sensors (n-in-p)
  - Possible financial benefit
  - Destructive sparking at sensor edge (at ~600V)
  - Try different materials (glues, silicone, Kapton, etc.)

Reserve 2

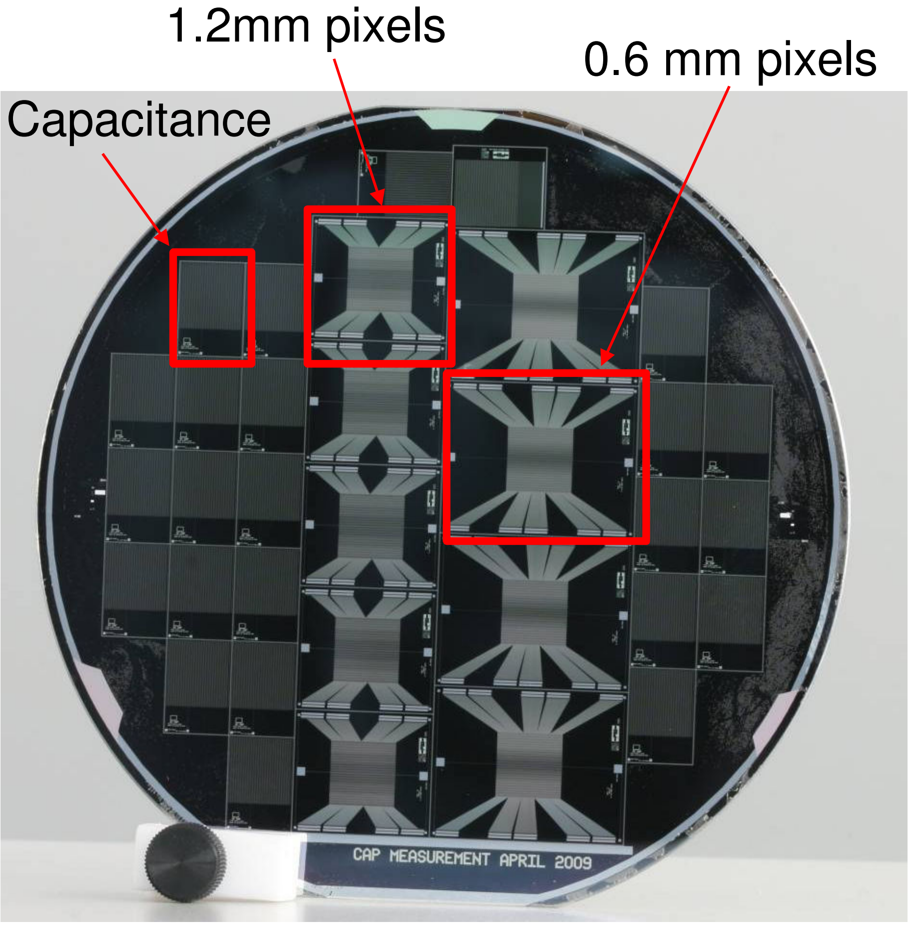
Measurement technique

- Bump bond a fan-out to a sensor (instead of a ROC)
  - connects 1 out of 6 pixels to wire bond pad (in total 975)
  - connects all other pixels to another wire bond pad
- Measure the capacitance of the sample
- Remove the fan-out and measure its stray capacitance
- Divide the (small) difference by the number of pixels (975 in our case)
- History
  - Started in 2004 (4 samples with pitch 125×125 μm²)
  - Continued 2006 (with Uni-HH) using ~100 small samples (22×40) with correct pitch(150×100 μm²)
  - 2009 Use original “single chips sensors” (52×80) pixels

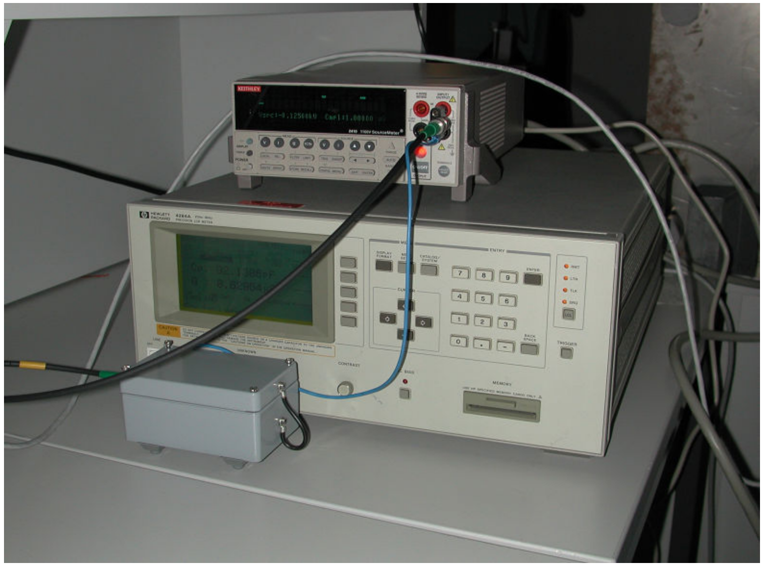


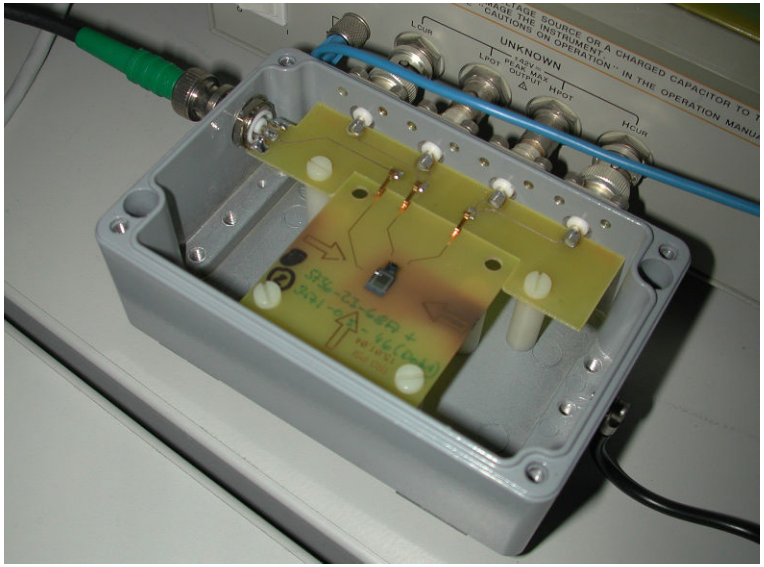
Fan outs

- Used sensor manufacturer (CiS) to process fan outs on standard silicon with a simple 3 mask process
  - metal/passivation/bumps
- 19 capacitance measurement structures
- 9 structures "macro-pixels"
  - 4 or 8 pixels are connected together and routed to a wire bond pad
  - bond pattern fits to APV hybrids (kindly provided by Alan Honma)
  - Also "bricked" pattern

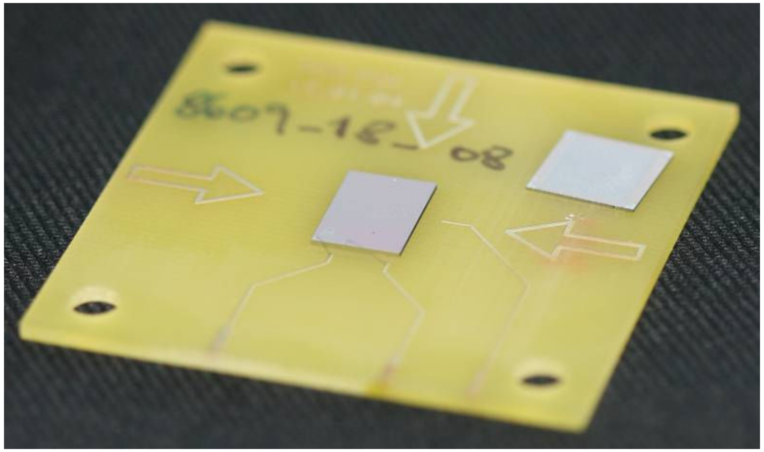


Equipment

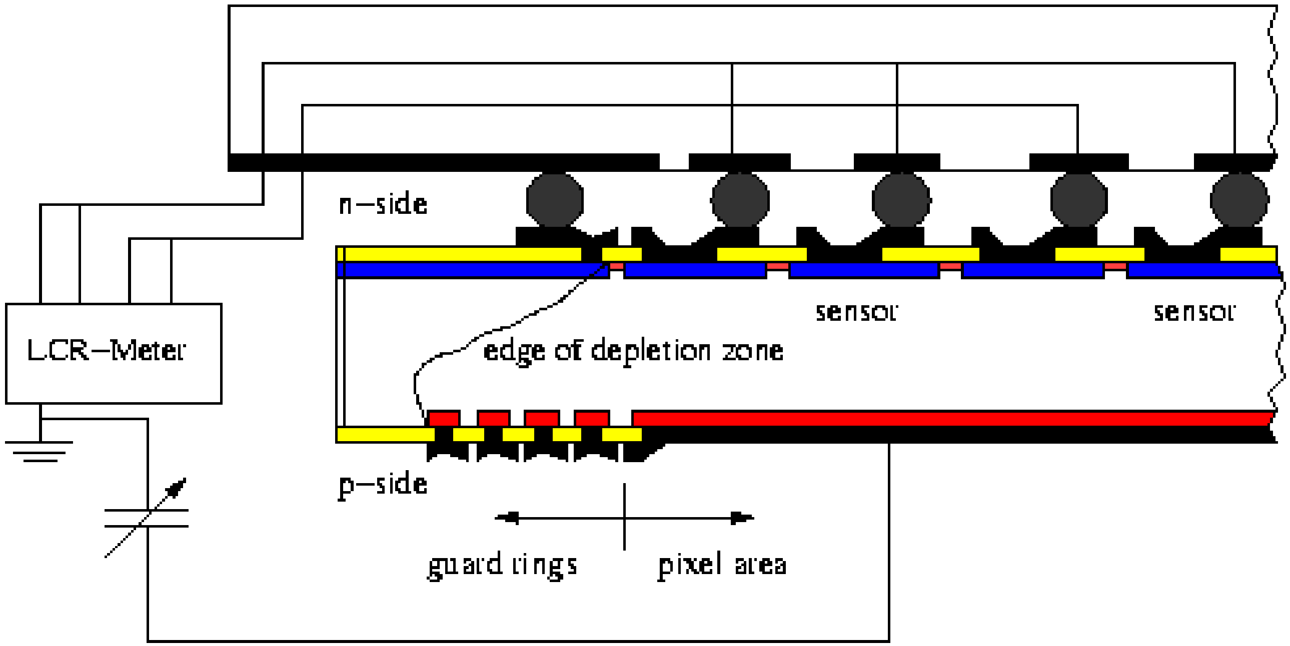




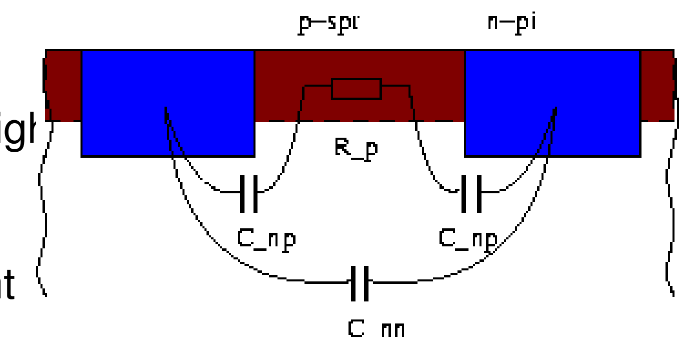
- LCR-meter HP 4284A
  - Signal level 100mV
  - Frequency 100kHz
  - Mode: C_p-G
- Bias voltage 0-500V



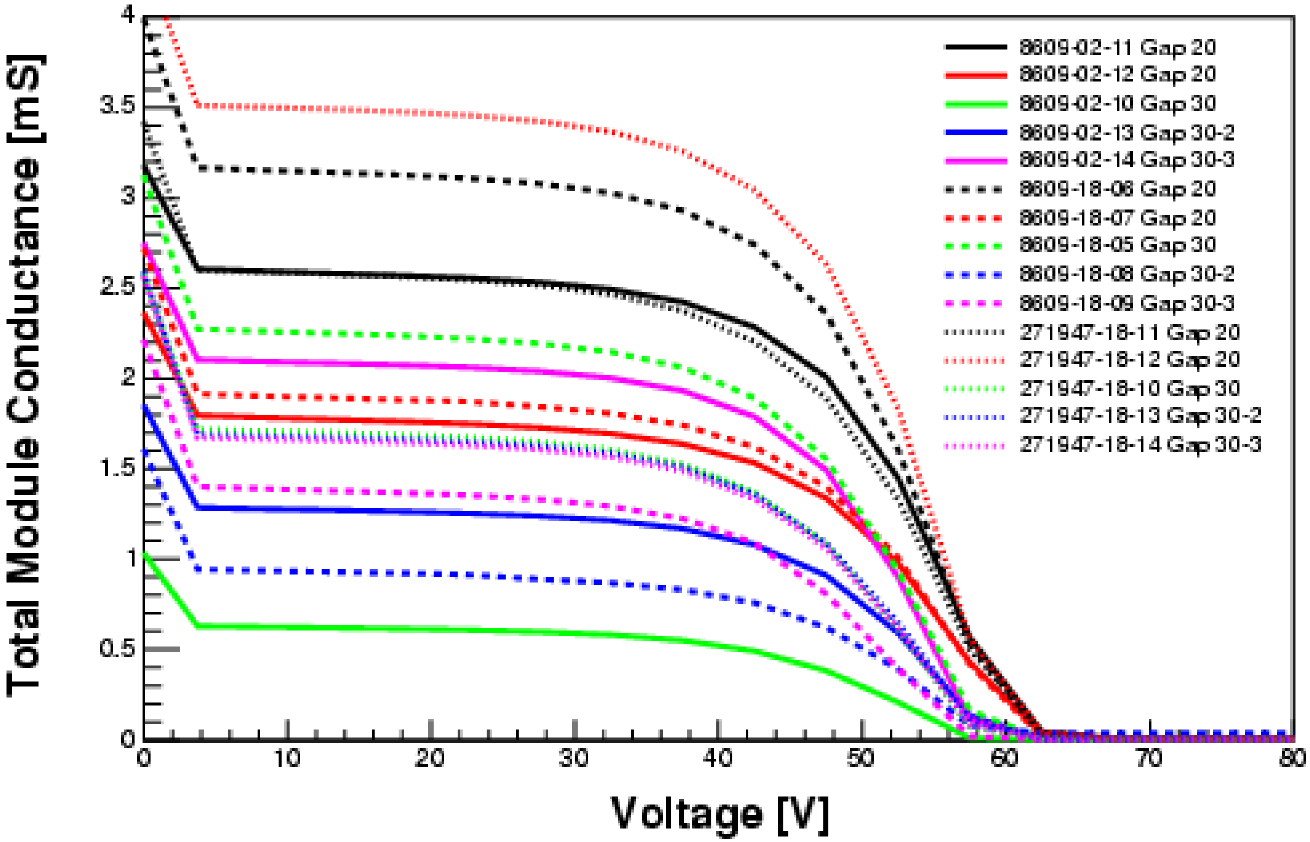
Measurement



- For V < V_{depl}: all pixels are connected
  - capacitance value does not make sense
  - transconductance (G in parallel mode)reflects is higl
- For V > V_{depl}:
  - transconductance drops rapidly and stays constant
  - capacitance steadily decreases

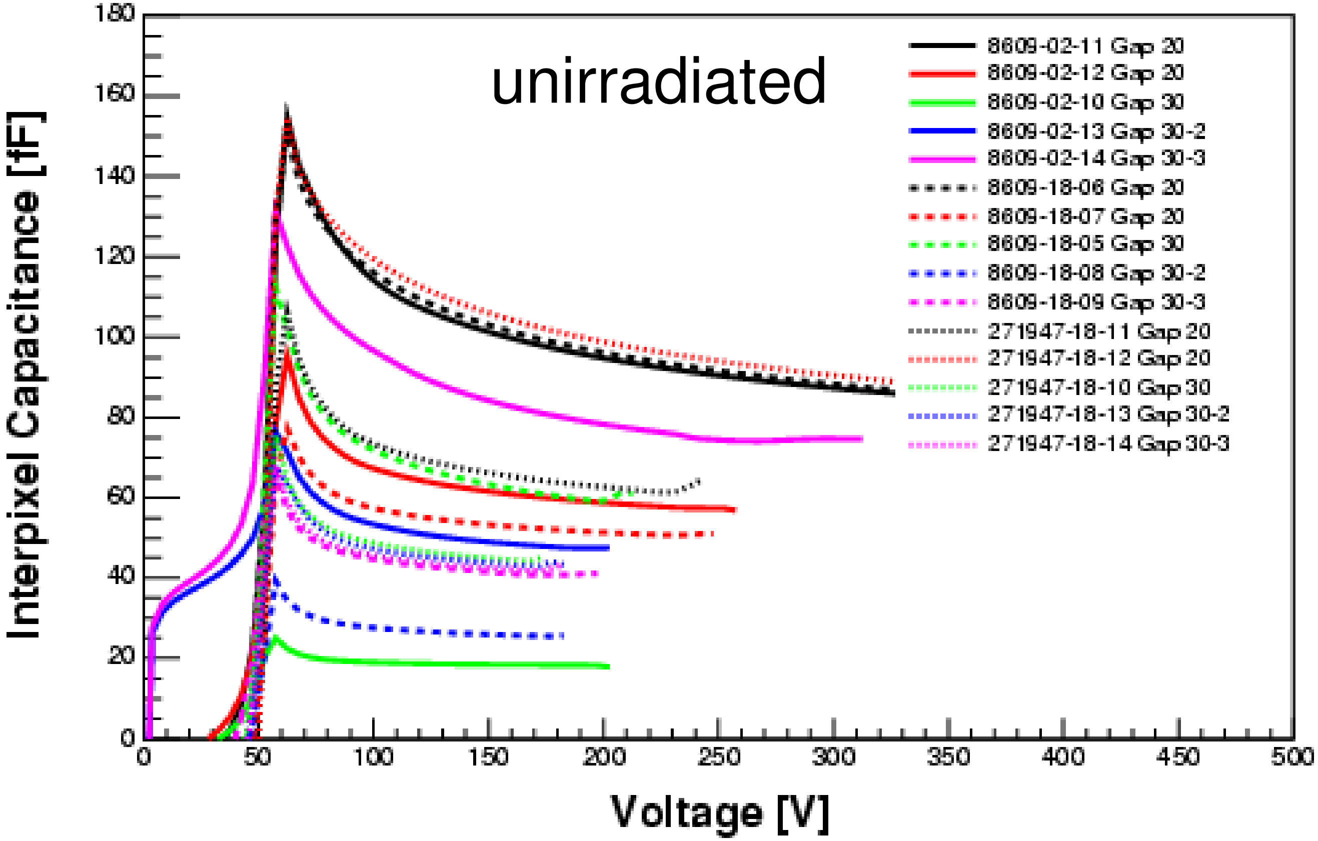


First results conductance



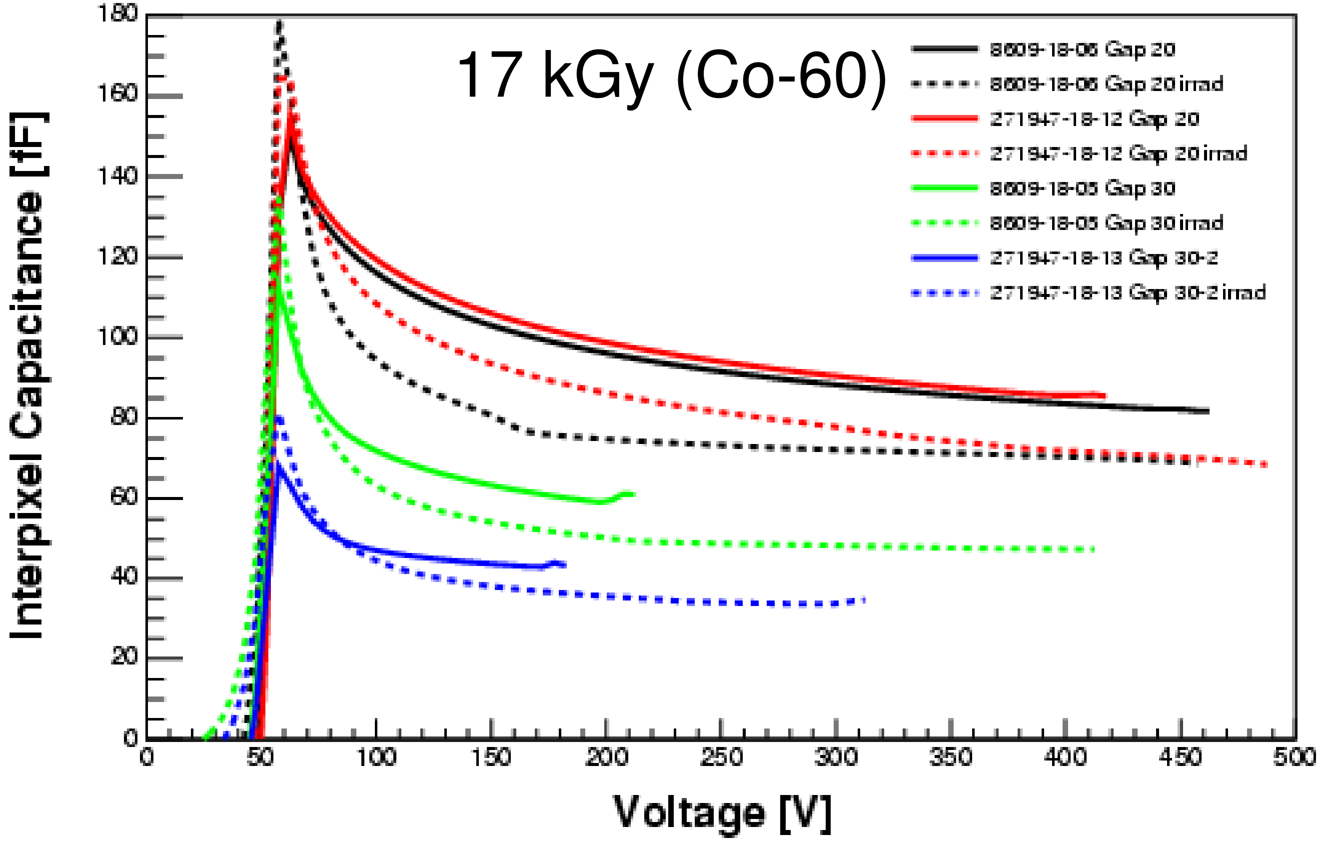
- Nice visualisation of V_{depl}
- Smaller gaps tend to have higher conductance

First results capacitance



- Inter pixel capacitance in bias dependent and saturates about 300-350V
- Increasing the gap from 20 to 30 μm results in a drop of C(150V) ~100 to 70 fF
- **Large fluctuations** and some outliers
  - more statistics
  - check dependence on technology parameters (mainly p-spray dose)

Irradiation with Co-60 source



- Gamma irradiation generates surface damage relevant for possible changes of the capacitance.
- Dose 17 kGy: fixed charge is saturated
- **Capacitance saturates faster** (p-spray layer depletes earlier due to fixed charge)

Leakage current

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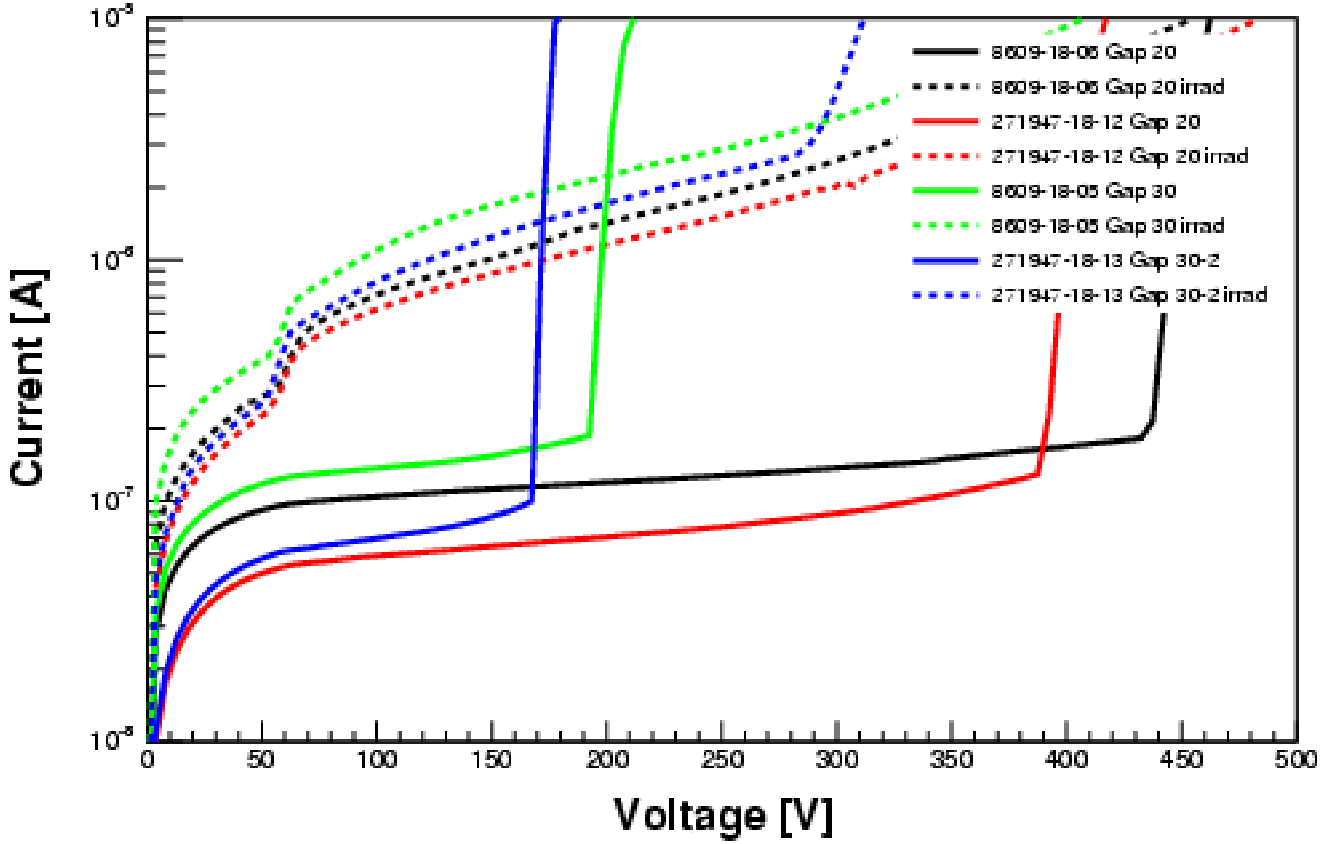


- Surface current rises due to irradiation
- Sensors with small gap have higher breakdown voltage
- After irradiation breakdown **disappears**

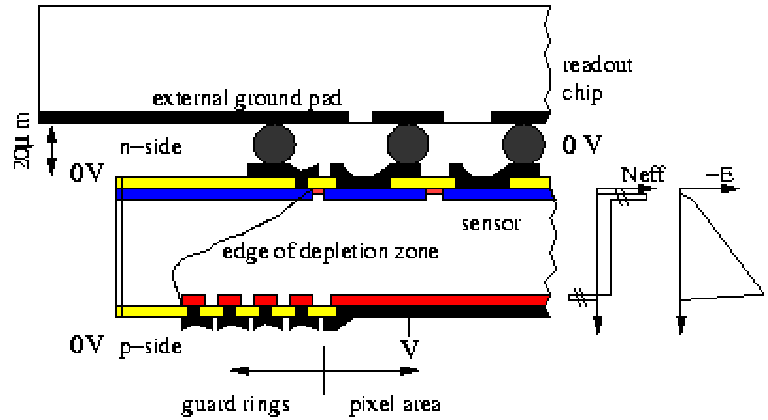
Plans

- Continuation of measurements
  - More samples, better statistics
  - Other samples. Try to get
    - **forward sensors**
    - p-stop sensors from barrel pixel prototyping (available in small quantities)
    - 3d sensors
      - **IRST (promised)**
      - Sintef (via Purdue ??)
- Try to understand dependence on technology parameters (mainly p-spray dose)
  - measure directly (difficult)
  - simulation (just started)
- Use measurements to calibrate simulation

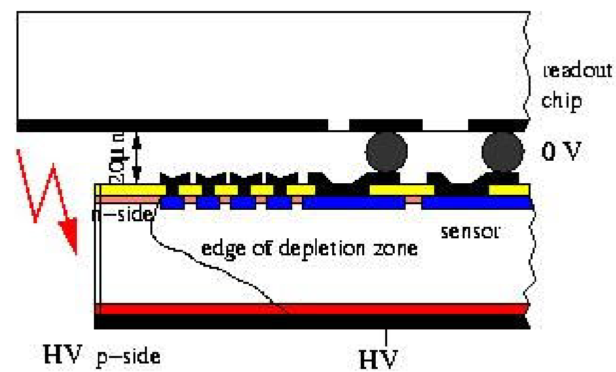
Single Sided Sensors

- Present CMS pixel detector uses n-in-n-sensors
  - double sided processing (back side is structured)
  - all sensor edges on ground
  - most expensive part of the module (only bump boning is more expensive)
- Exploring n-in-p sensors as alternative
  - recent studies show radiation hardness
  - single sided process promise prize benefit of factor 2-3
  - Absence of guard rings on back side lead to the risk of (destructive)sparking to the ROC

n-in-n

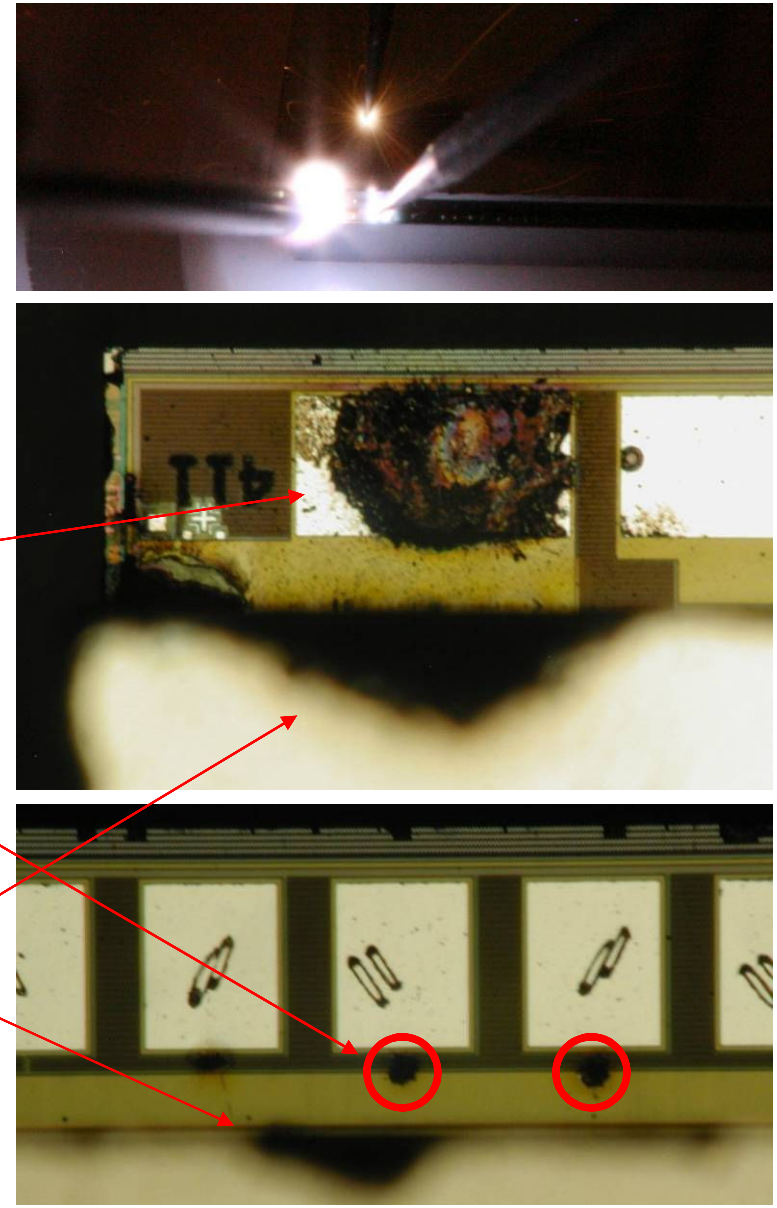


n-in-p



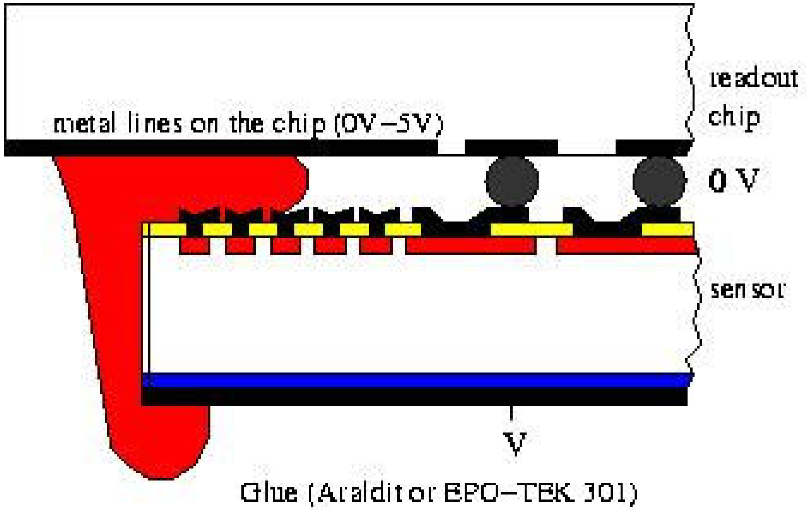
Sparking at Sensor Edge

- Bump bonded rejected material from PSI-PILATUS project (p-in-n sensors and defective ROCs)
- Applied bias voltage to the sensor while ROC was grounded
- Breakdown occurs at ~500V
  - Grounded pad on ROC completely destroyed
  - Other pads also damaged
  - Voltage surprisingly high
    - spark comes from sensor back side?
    - 500V →500μm air?
    - Aluminium also evaporated on sensor backside



Edge Protection

- Tried to passivate edges with glue
  - Araldit (standard)
    - used as underfill and glue in CMS module production
    - no change of break down voltage
  - EPO-TEK 301
    - very liquid, fills part of the gap
    - break down at ~700V



- Investigate further possibilities (Kapton?)