PhD Seminar
August 26, 2015

ETH zürich

Radiation tolerance of the readout chip for the Phase I upgrade of the CMS pixel detector

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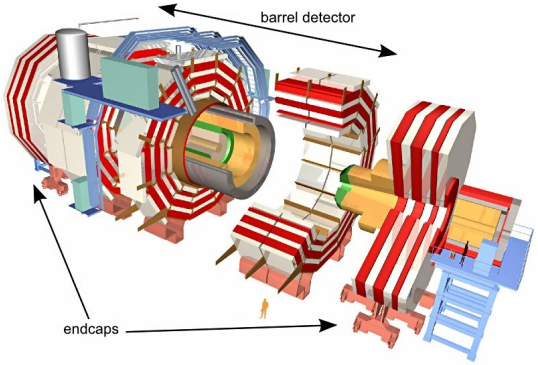
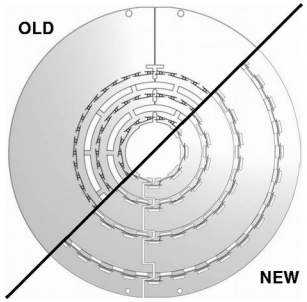
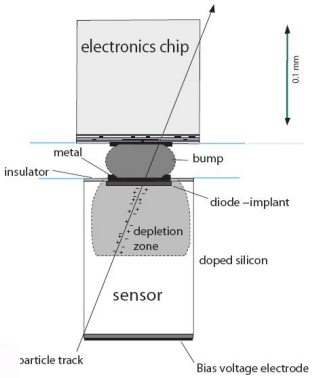
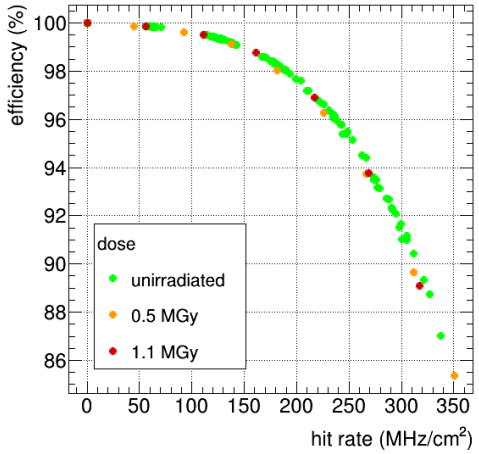
Outline

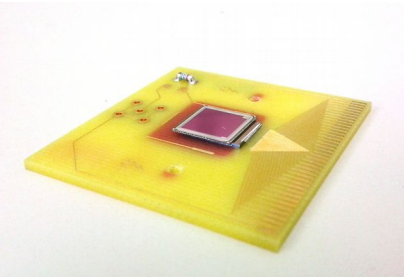
- The CMS pixel detector
- The Phase I upgrade of the pixel detector
- The readout chip and challenges for the upgraded chip
- Irradiation study: motivation and doses
- Test setups
- Selected results
- Summary and conclusion





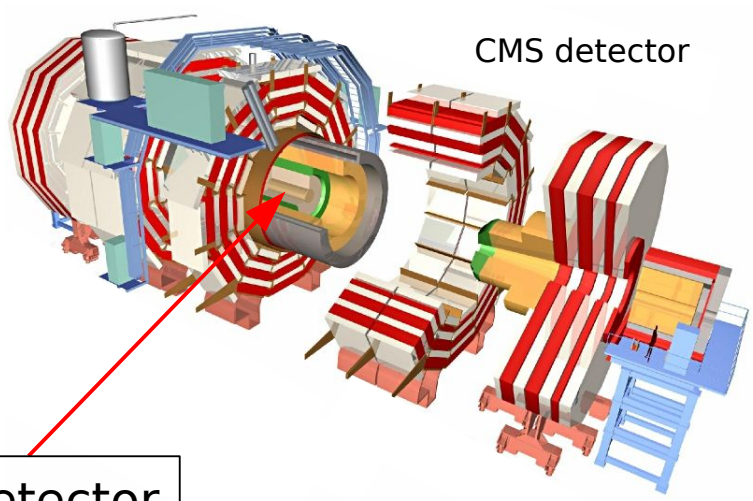




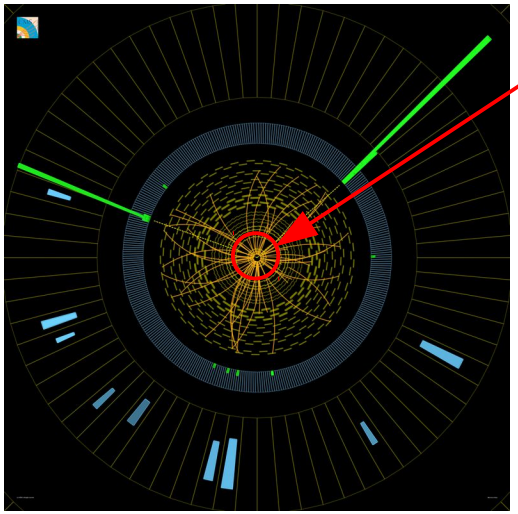


The CMS pixel detector

- Located in the center of CMS close to interaction point
  r = 4.4 to 10.2 cm (barrel part)
- Layer structure to provide 3D track of charged particles



CMS pixel detector



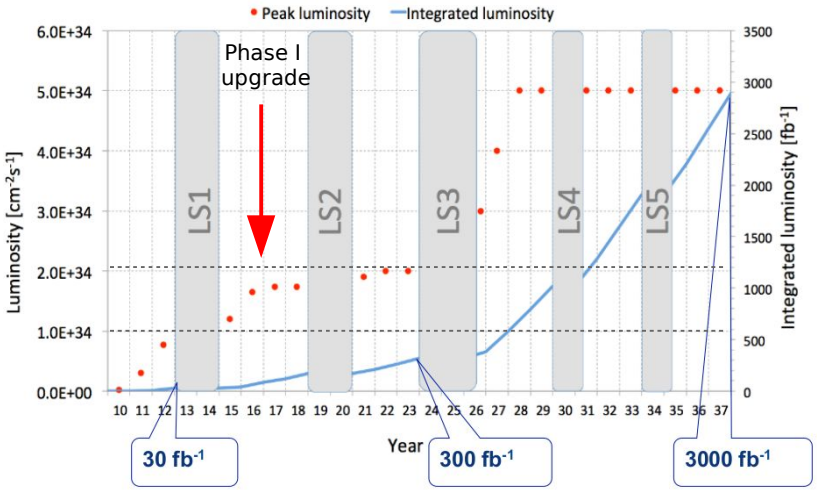
CMS event display

- 3 barrel layers, 2 layers per endcap
  → each layer provides 2D hit information
- 66 M readout channels
- Pixel size 100 x 150 μm
  → resolution: ≈10 μm in rφ , 24 μm in z
- 40 MHz operation, trigger latency 3.2 μs

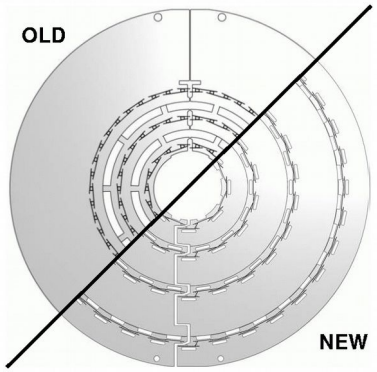
The Phase I upgrade of the pixel detector

- Design luminosity of present detector: $L=1\cdot10^{34}\,cm^{-2}s^{-1}$
- LHC: increase of center of mass energy $\sqrt{s}=13$ TeV and lumi. to $L=2\cdot10^{34}\,cm^{-2}s^{-1}$

  → upgrade of pixel detector required to avoid performance loss
- new features include:
  - Additional barrel layer and endcap
    → more hit points for improved vertex reconstruction
  - Innermost layer closer to interaction point (r = 3.0 cm)
  - Reduction of material budget, new CO_2 cooling
  - New readout chip with digital data trans-mission for increased readout speed



LHC schedule as of June 2015 [F. Bordry]

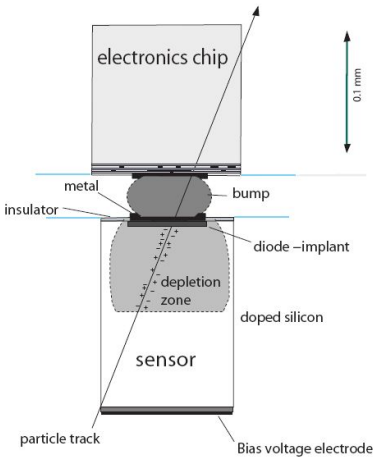


Barrel pixel layout old/new [H.-C. Kaestli]

Goal: guarantee high detector performance under tightened conditions

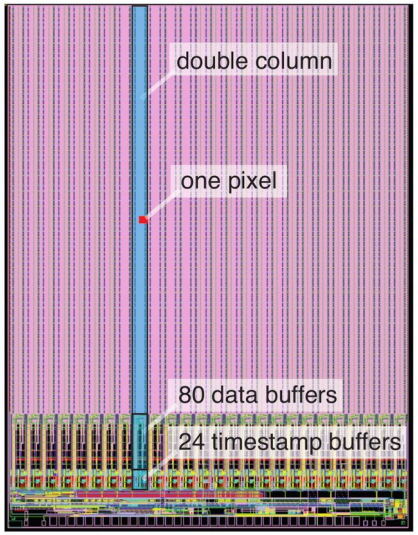
The readout chip (ROC)

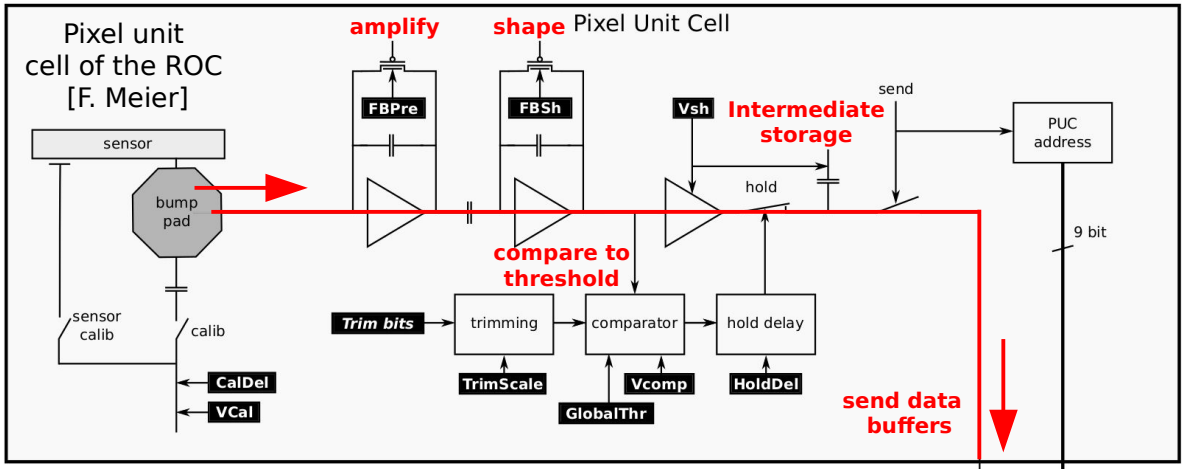
- 4160 pixel unit cells arranged in 26 double columns with periphery, buffers and digitizer
- Tasks of the ROC:
  - collect and process charge deposited in silicon sensor by charged particles
  - compare charge to adjustable threshold → zero suppression of data
  - notify ROC periphery to read out charge from pixel
  - Store hit information until L1 trigger validation
- Controlling of the ROC: 18 digital-analog-converters (DAC) and registers



Hybrid pixel concept
[L. Rossi et al.]

ROC components [F. Meier]





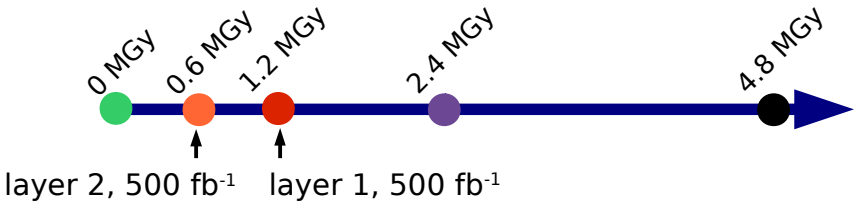
Challenges for the new digital ROC (Selection)

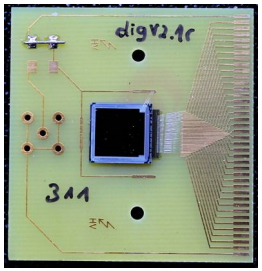
- Hit rate increases up to factor 5
  - → increase buffers for hit and time stamp information
  - → add additional readout buffer to avoid data loss during trigger latency
- Read out larger number of channels with only slightly increased number of readout links
  - → change from analog readout to 160 MHz digital readout
- Better charge sensitivity to increase lifetime of detector
  - → lower comparator threshold, reduced cross-talk and timewalk

New ROC design changes need to be validated by lab measurements, beam tests, and **irradiation studies**

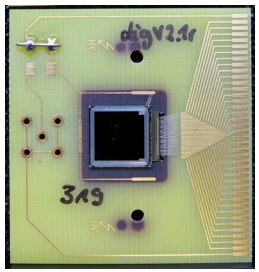
Irradiation overview

- Irradiation of final CMS pixel readout chip for layers 2 – 4
- Test longevity and ensure good performance of the ROC throughout its foreseen lifetime in highly radiative environment in CMS
- Target doses:
  - **0.6 MGy** (max. expected life-time dose for layer 2 – 4 ROC)
  - **1.2 MGy** (layer 1 after 500 fb^{-1})
  - 2.4 MGy and 4.8 MGy
- 23 MeV proton beam at Zyklotron AG Karlsruhe
  - Stopping power 18.1 (MeV cm^2)/g
  - Hardness factor ≈ 2
- Energy dose units:
  1 rad = 0.01 Gy = 0.01 J/kg





non-irradiated



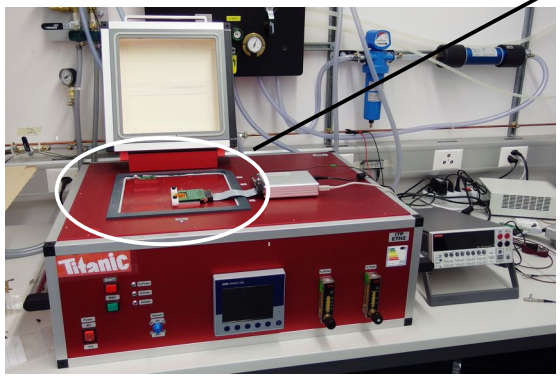
irradiated (4.2 MGy)

target dose (Mrad)	target dose (MGy)	Measured dose (MGy)	fluence (1MeV N_{eq}/cm^2)	fluence (protons/ cm^2)
60	0.6	0.5/0.6*	0.4e15	0.2e15
120	1.2	1.1/1.5*	0.8e15	0.4e15
240	2.4	2.2	1.6e15	0.8e15
480	4.8	4.2	3.2e15	1.6e15

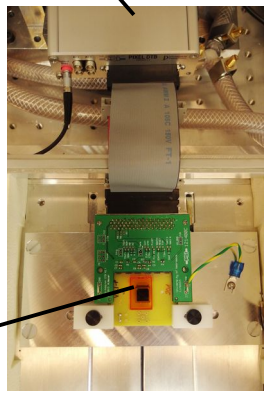
* single chip module and bare ROCs respectively

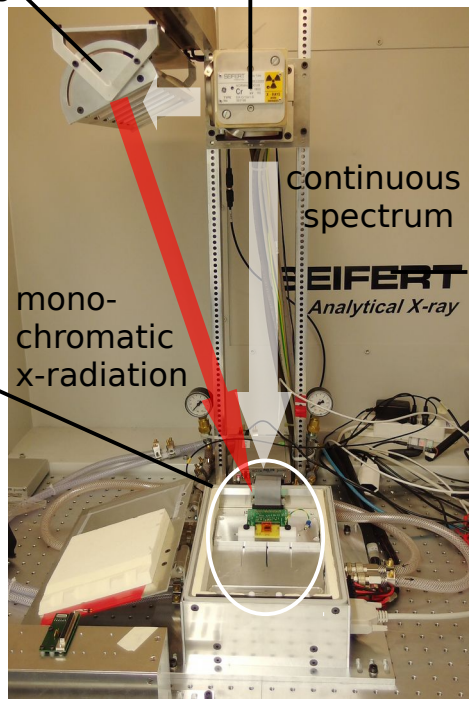
Test setups

- Two setups to test irradiated samples at controlled temperature and humidity
  - Climatic chamber for electrical test
  - x-ray setup to generate charge in Si sensor with x-rays
- Read out samples with digital test board and dedicated readout software



climatic chamber setup





X-ray setup

cooling plate

test board

USB to PC

sensor bias

sample

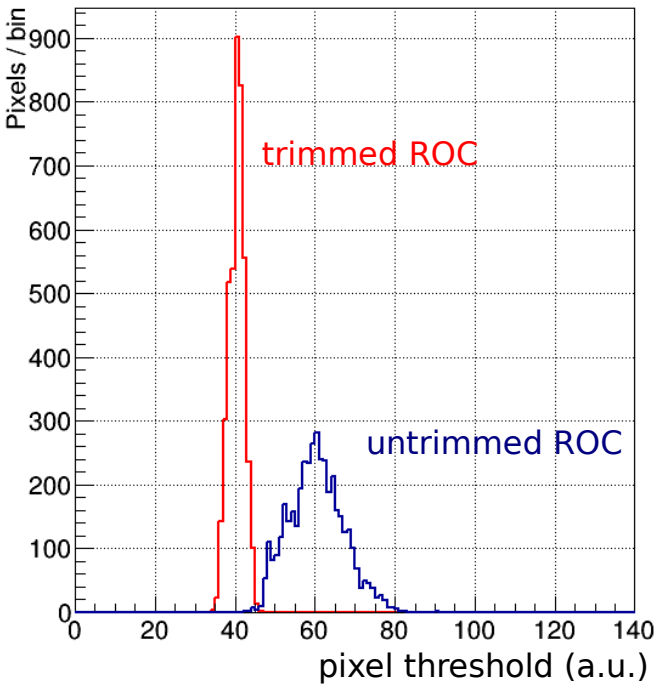
ROC properties to be tested after irradiation

- Prerequisite for operating ROC after irradiation:
  - sufficient current supply and feeding voltages
  - DACs programmable
  - DAC ranges sufficient to find working point

- Important properties and performance parameters to test:
  - Band gap reference voltage shift
  - reading out test pulses and particle hits
  - low preamplifier noise
  - **setting a low and uniform threshold and operating the ROC at this threshold**
  - small timewalk for low in-time threshold
  - reading out analog pulse height information
  - **high single pixel hit finding efficiency**

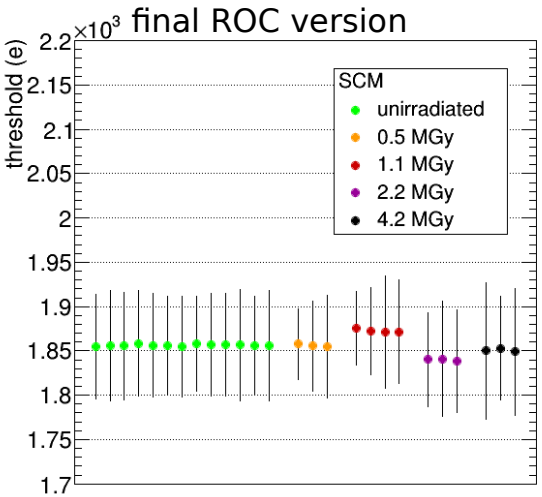
Threshold

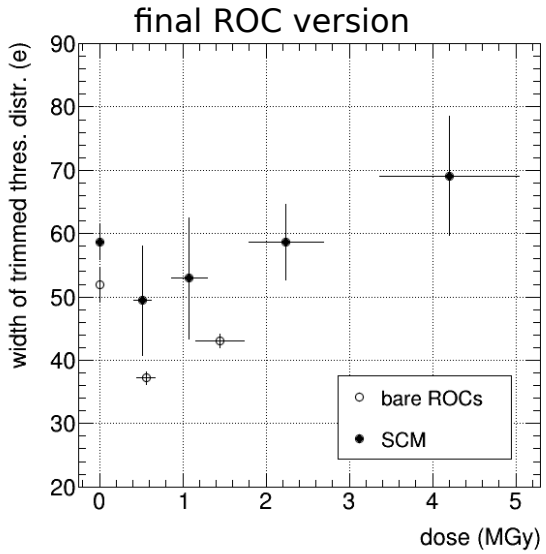
- Pixel detector: 66 million readout channels (increase by factor ≈2 with upgrade)
  → requires zero suppressed readout to keep data volume manageable
- Only charges exceeding the threshold of the pixel's comparator are read out
  → setting a low and uniform threshold is an important feature of the ROC
- Threshold can be adjusted (“trimmed”) by:
  - setting global threshold DAC
  - setting “trim bits” for individual pixels

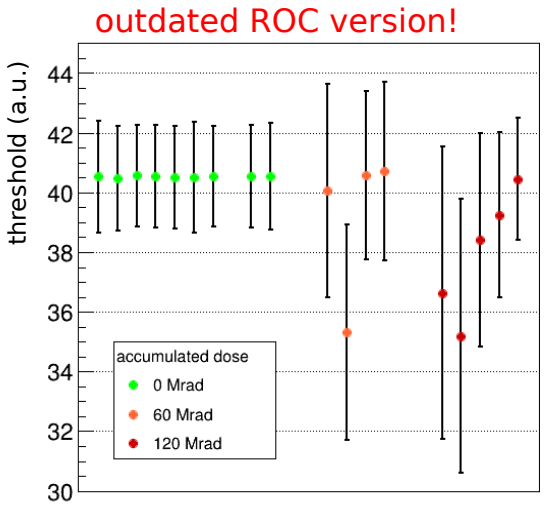


Threshold

- Set same physical threshold before and after irradiation
- Threshold ≈ 1850 e (c.f. analog ROC 3500 e in-time threshold)
- data: mean of trimmed thres. distribution, error: width of distr.



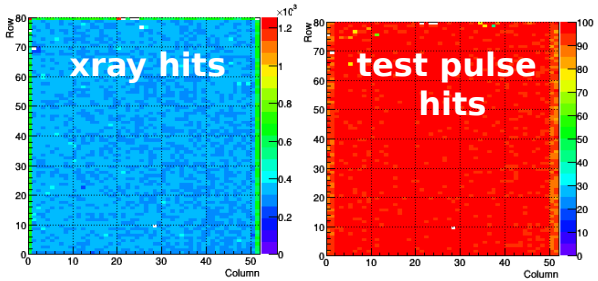




- Low and uniform threshold can be set for all samples up to 4.2 MGy
- Width of trimmed threshold distribution about 70 electrons after 4.2 MGy
- Not for granted! Inhomogeneous threshold after irradiation due to insufficient dynamic range of global threshold DAC for intermediate ROC version

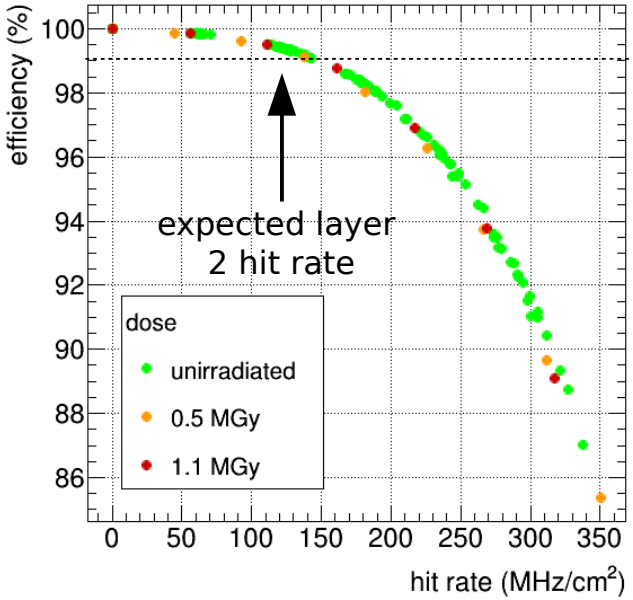
Hit finding efficiency

- Measure hit finding efficiency while sample is exposed to high rate X-radiation to create additional readout traffic
- Analysis: split hits from xrays and hits from test pulses
  - xrays: overall ROC hit rate calculation
  - test pulses: calculate test pulse detection efficiency



- No significant change in efficiency observed up to 1.1 MGy
- Efficiency better than 99% at expected layer 2 hit rate of 120 MHz/cm^2
- Samples trimmed to low thresholds
  - ≈ 1850 electrons up to 0.5 MGy
  - ≈ 2100 electrons at 1.1 MGy

  → high efficiency at low threshold up to expected layer 1 dose



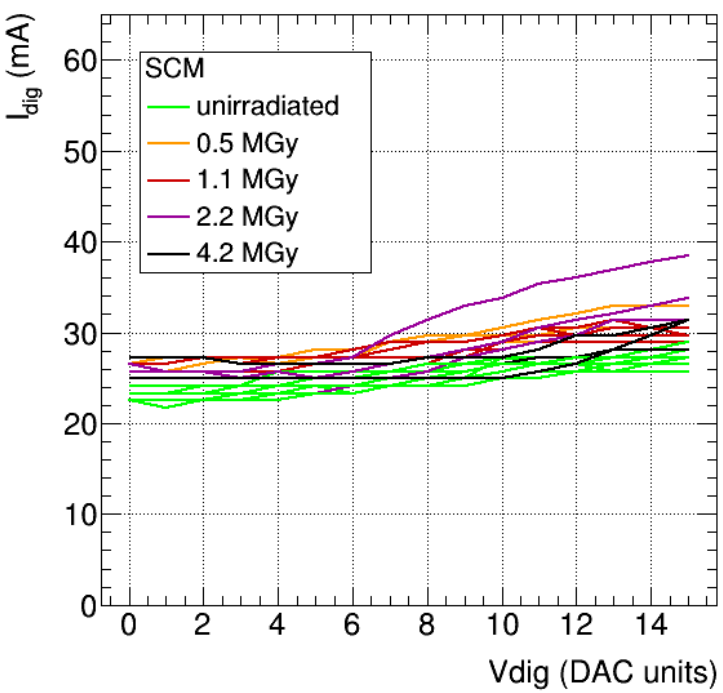
Summary

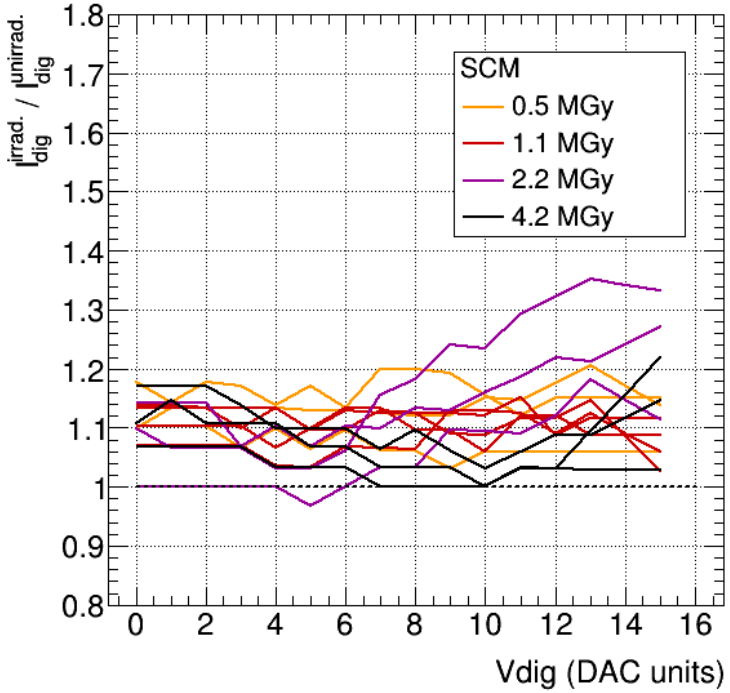
- The CMS pixel detector will be replaced in winter 2016/2017
- The new digital ROC for layers 2 – 4 shows excellent radiation tolerance, no problems observed up to expected lifetime dose of 0.6 MGy
- Results of several irrad. campaigns contributed to the design of the ROC and triggered further modifications for the layer 1 ROC
- Results contributed to the decision process to define the detector's supply voltages
- Results show that it is feasible to operate the ROC efficiently after receiving the expected layer 1 dose

Back up

Digital current

- Digital current vs Vdig

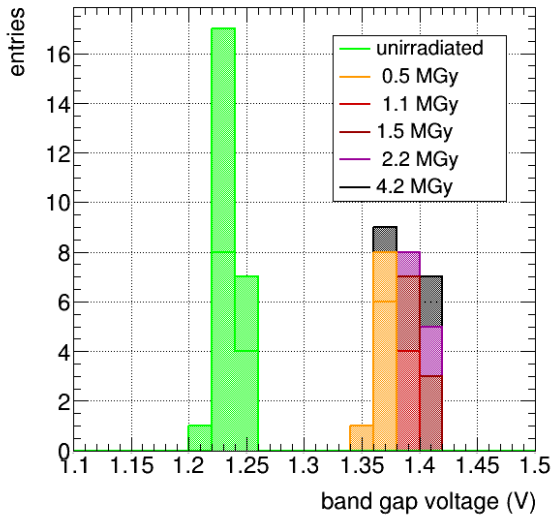


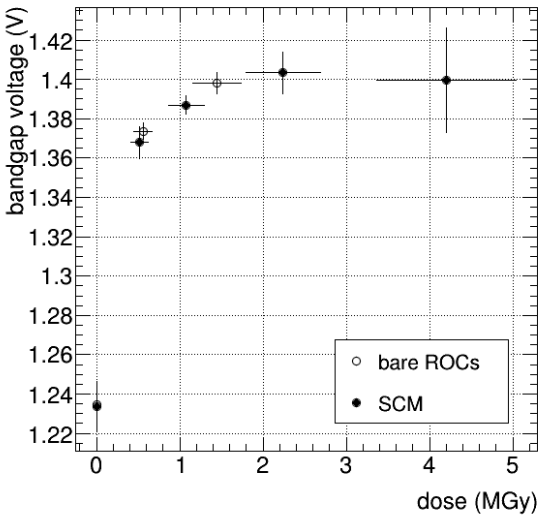


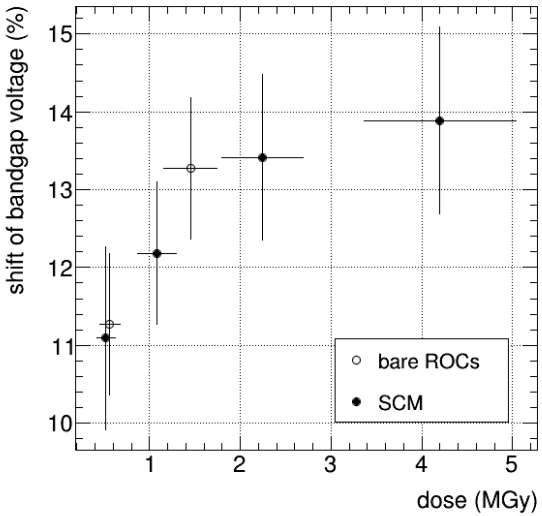
- Idig increase for low Vdig around ≈ 10% (vbg shift)
- Additional increase for high Vdig at high dose

Band gap reference voltage

- Band gap voltage serves as reference for all DACs on the ROC → shift leads to changes in all DAC settings
- Measurement of vbg on all samples before and after irradiation

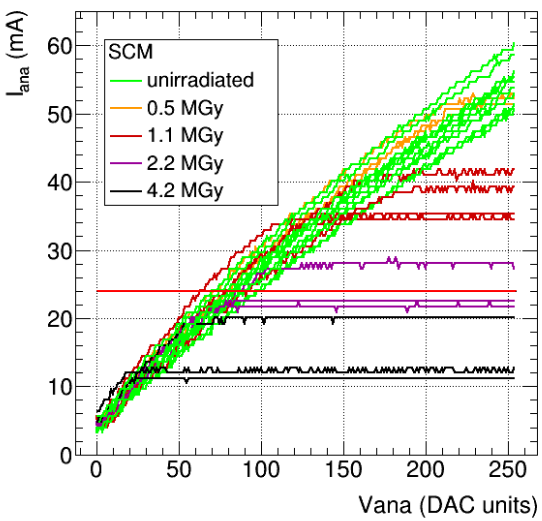


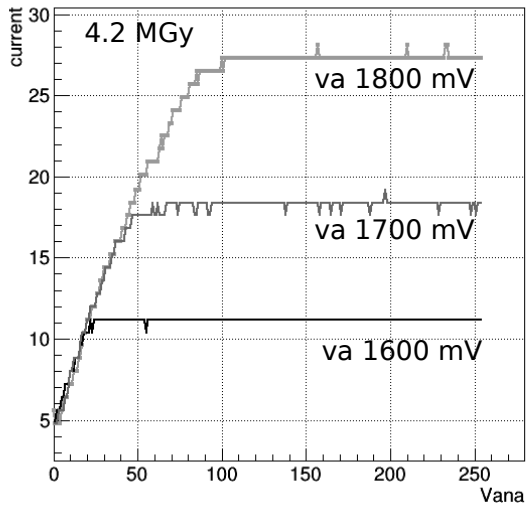


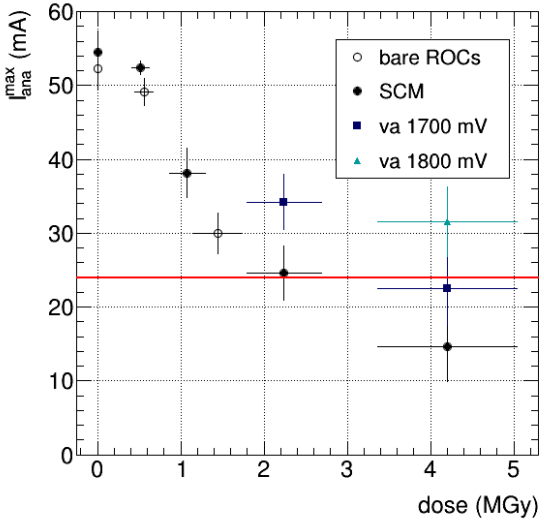


- Saturation above 2 MGy observed
- Vbg shift used to correct test pulse strengths and threshold settings after irradiation

Analog current





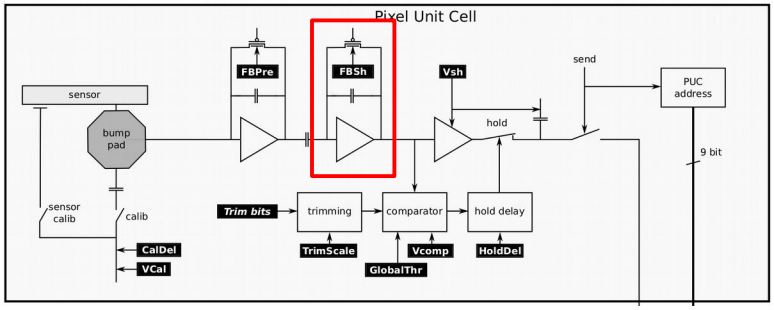


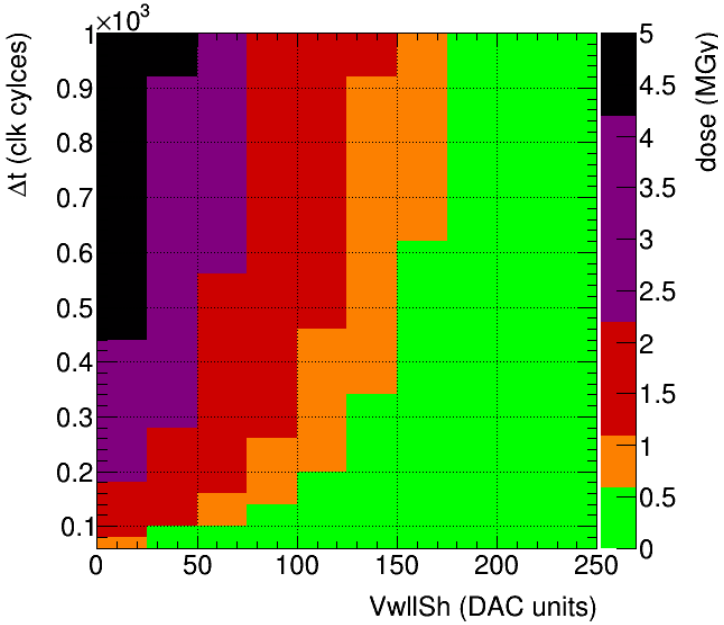
- ROC working point at I_{ana} = 24 mA (can be set with Vana DAC)
- I_{ana} saturates at dose dependent level
- Maximum I_{ana} close or below 24 mA working point for dose >= 2.2 MGy for unreg. analog voltage 1.6 V
- Saturation level depends on unregulated analog voltage va
- max I_{ana} sufficient for:
  - va = 1.7 (1.8) V for 2.2 MGy (4.2 MGy)

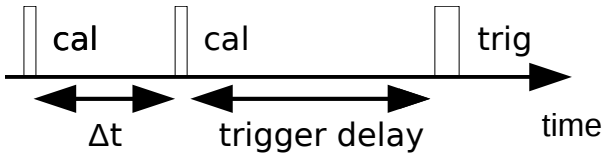
  → operate highly irradiated samples at elevated analog voltage

Shaper recovery time

- Shaper gets slower after irradiation
- Need to adjust shaper feedback to read out test pulses
- Quantify effect of irradiation:
  - Send two test pulses with time Δt in between
  - Trigger on 2nd pulse
  - Measure for which Δt and which shaper feedback setting 2nd pulse can be read-out
- Enough dynamic range to adjust feedback after 0.6 MGy
- For higher doses: dose-dependent minimum Δt between pixel hits



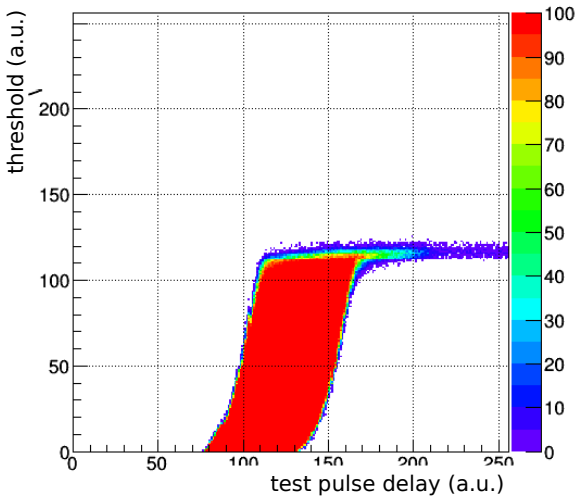




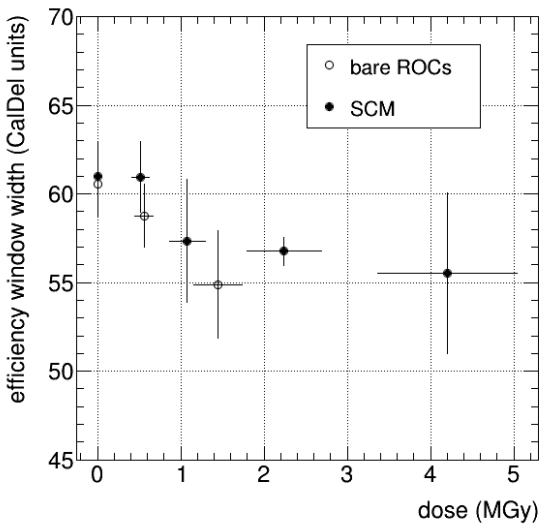
Basic test pulse readout

- Most simple test: try to read out test pulse injected to pixel

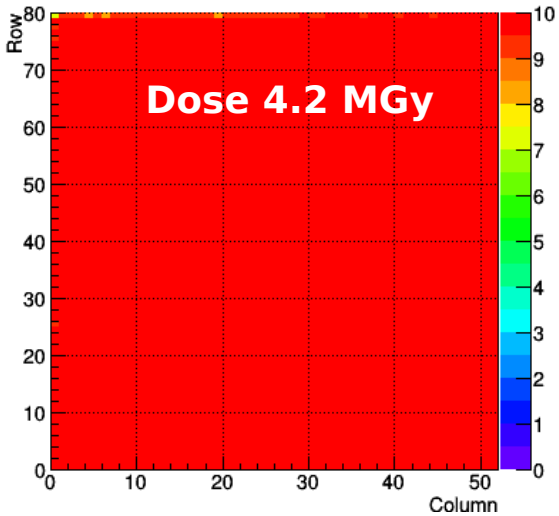
Single pixel: working point in threshold – test pulse delay space



dose dependent width of efficiency window in DAC units: effect of band-gap drift



Number of read out test pulse hits in pixel array

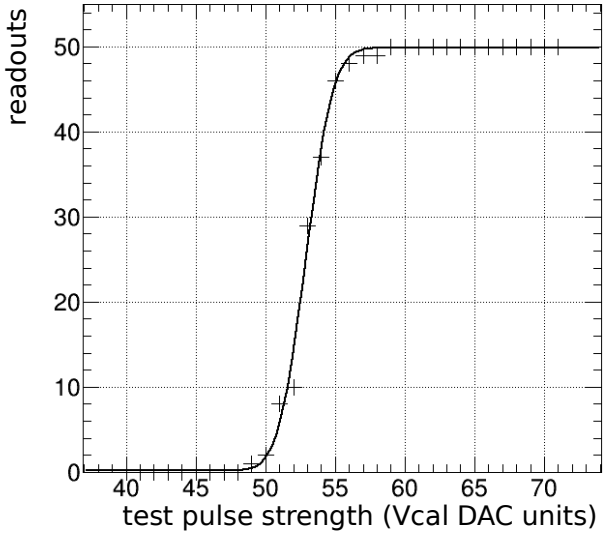


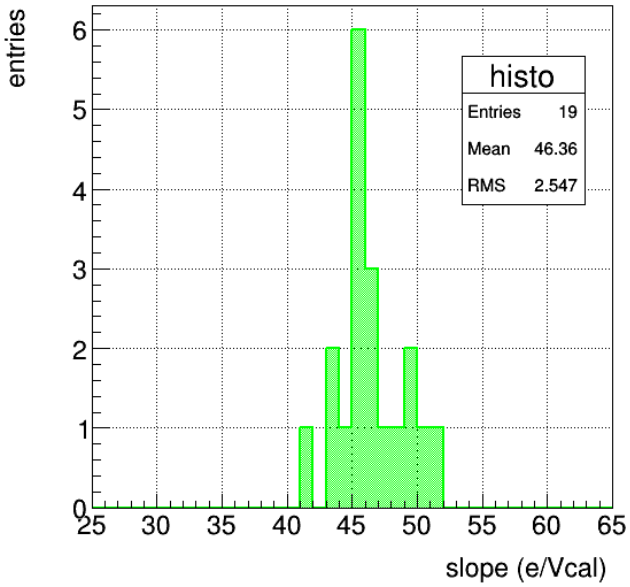
- Efficient readout of test pulse for all samples up to dose of 4.2 MGy
- No significant problems with pixel defects observed

Amplifier noise

- Measure turn-on of #read-out pulses vs test pulse strength → smeared out step function around threshold
- Smearing due to preamp noise → quantify noise using width of fitted error function

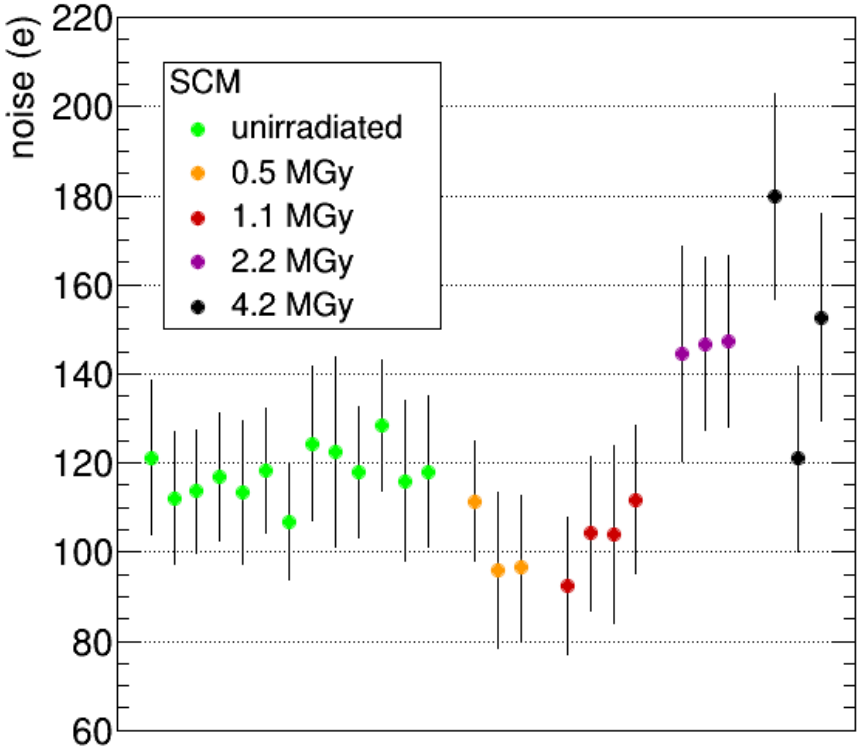
- Convert test pulse strength unit (Vcal Dac setting) into number of electrons using an energy calibration with mono-chromatic x-radiation as reference energies
  - 1 Vcal unit = 46.4 electrons





Amplifier noise

- data: mean noise per ROC, error: width of noise distribution
- Conversion based on 46.4 e/Vcal and corrected with band gap voltage shift
- No problems observed for relevant doses in spite of possibly under-depleted sensor
- Noise well below 200 electrons even after 4.2 MGy
- Decrease of noise for 0.5 and 1.1 MGy understood (due to changed preamp and shaper feedback ratio)

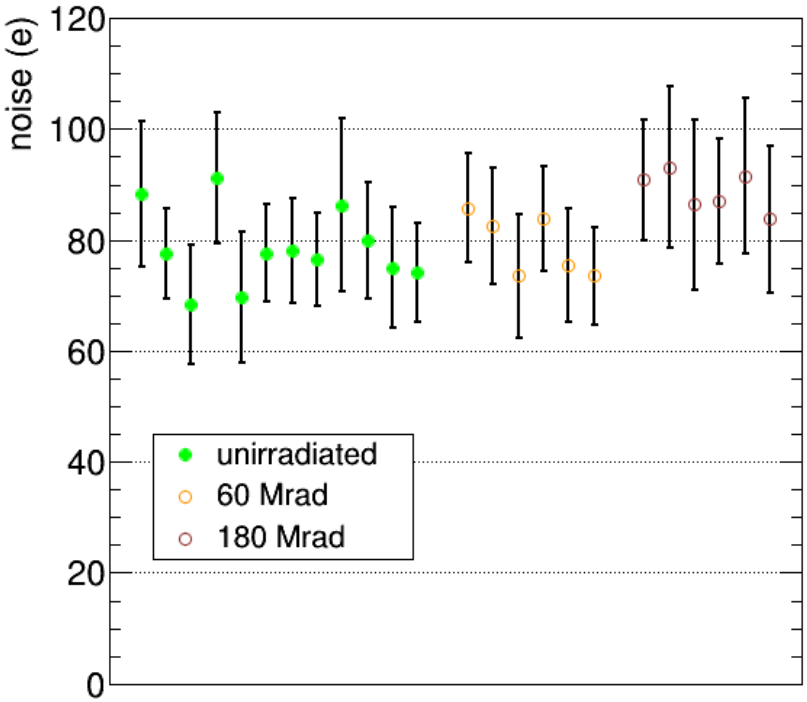


Noise – bare ROCs

- No influence of possibly under-depleted sensor and leakage current
- Measure Vcal scurve width
- Conversion based on 46.4 e/Vcal and band gap voltage shift

Dose (MGy)	Noise (e)
0	78.55
0.6	79.10
1.5	88.76

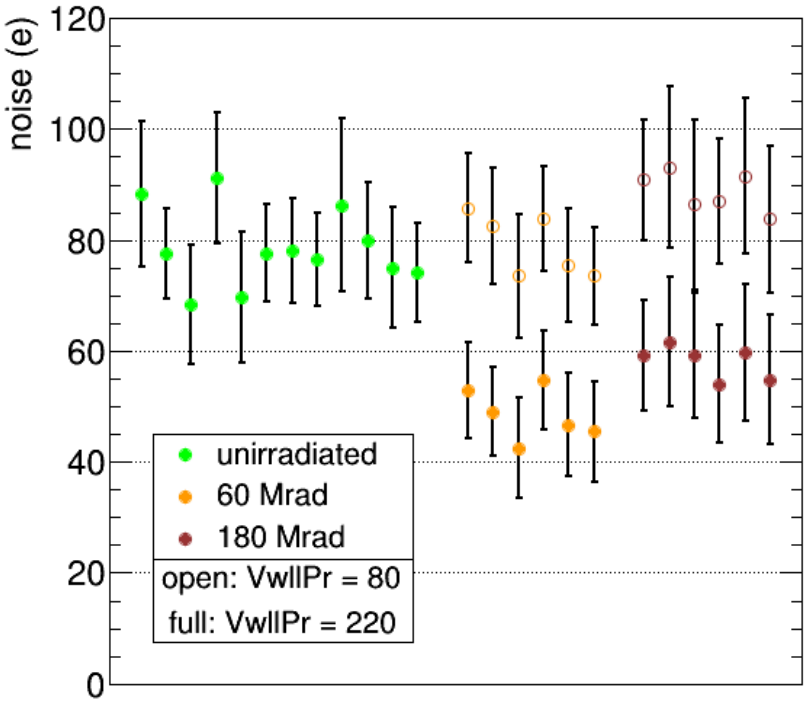
- Noise unchanged after 0.6 Mrad, 13% increase after 1.5 MGy



Noise – bare ROCs (2)

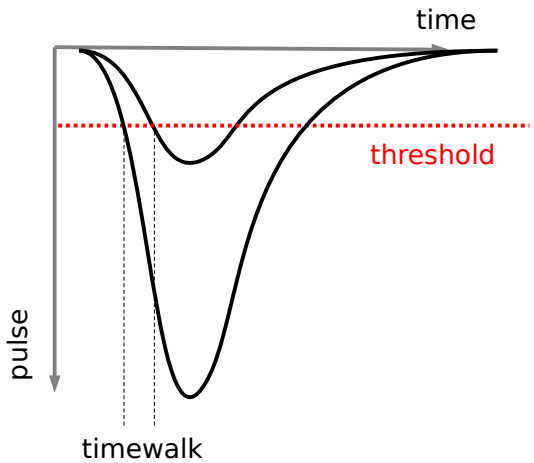
- First qualification done with VwllPr = 80 (changed in sync with VwllSh)
- Later: found that only VwllSh has to be lowered → qualification with VwllPr = 220

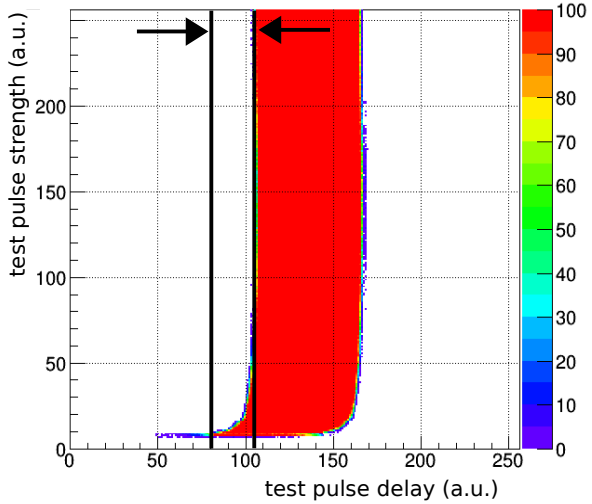
- Noise about 35% lower for weaker preamp feedback!
- Can noise be lowered for unirradiated ROCs by changing preamp and shaper feedback ratio?

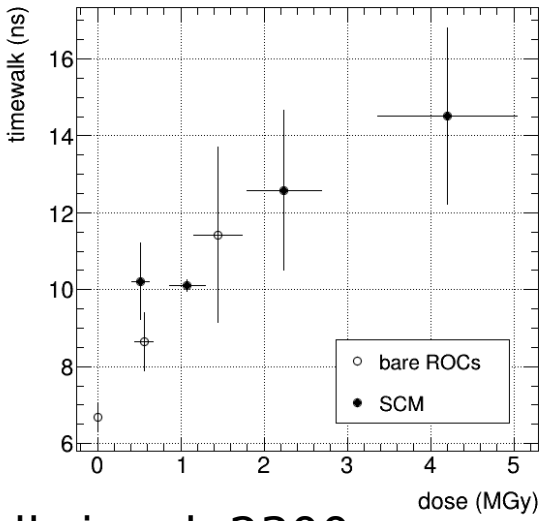


Comparator timing (timewalk)

- Timing difference between small and large signal in comparator
- Important: timewalk < 25 ns → prevent hit migration to wrong bunch crossing





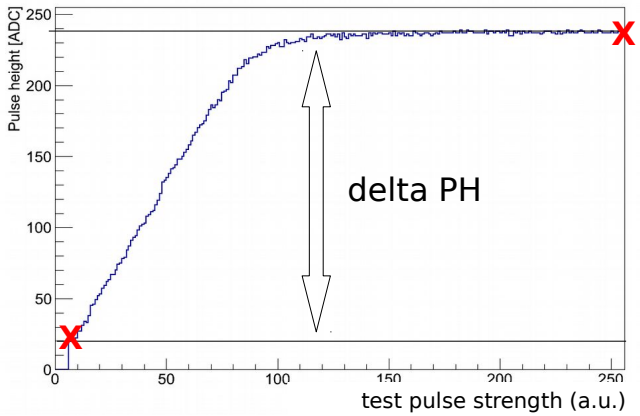


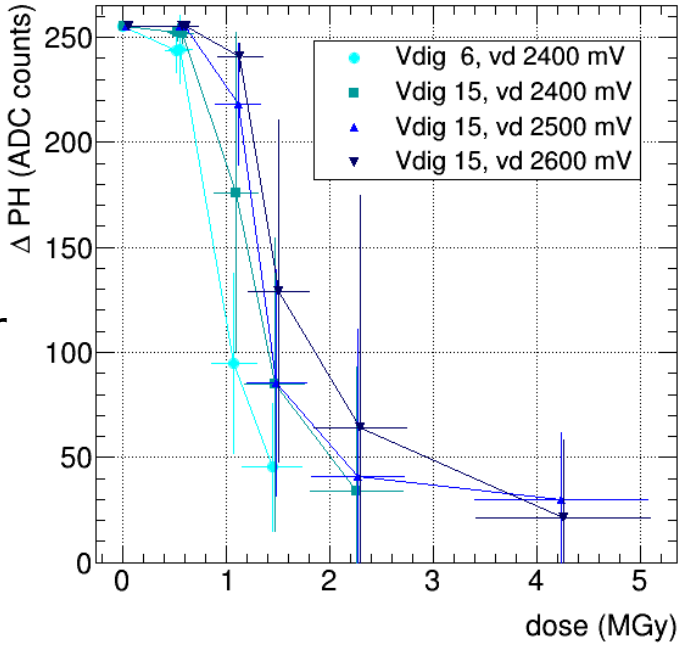
- threshold 1850 e, large signal: 83000 e, small signal: 2300 e
- Threshold, and signal strengths corrected for band gap drift after irradiation
- Timewalk well below 25 ns for signals between 2300 and 83000 electrons up to 4.2 MGy

  → no need to artificially increase threshold to limit timewalk

Pulse height

- Not a binary detector: analog pulse height (PH) information for each hit used to improve spacial resolution by weighting charges within hit clusters
- PH should be linear function of deposited charge (up to preamp saturation)
- Measure maximum delta PH
- Delta PH optimal after 0.6 MGy for default unreg. digital voltage
- For higher doses: Delta PH limited because of increased voltage regulator drop-out
- Can be partly recovered with higher supply voltage
- Design change implemented in layer 1 ROC to stabilize delta PH vs dose

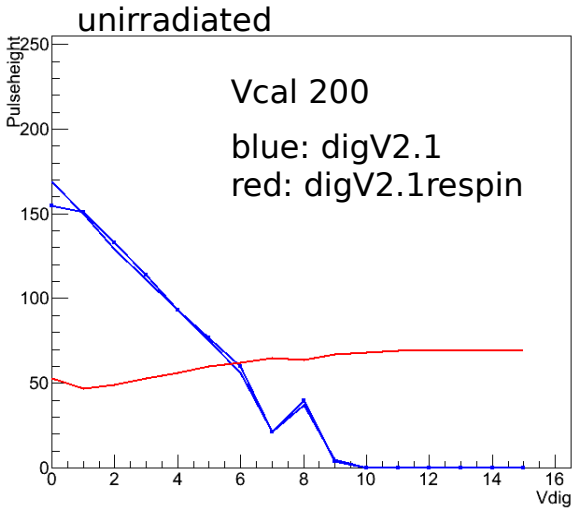


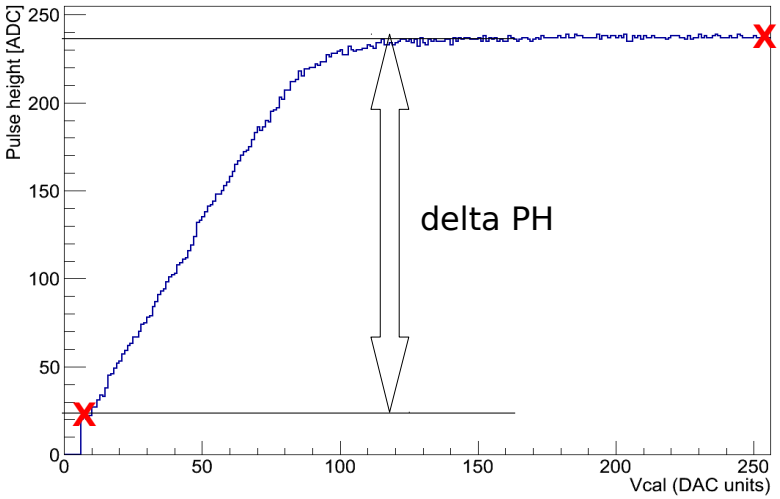


Pulse height

- Analog pulse height (PH) used to improve spatial resolution by weighting charges in pixel clusters
- Different signal charges should lead to different PH outputs (ADC counts)
- Bug fix in digV2.1respin: disentangled Vdig and pulse height
- Irradiation digV2.1: limited PH ADC coverage after 1.2 MGy
  → had to increase Vdig to recover

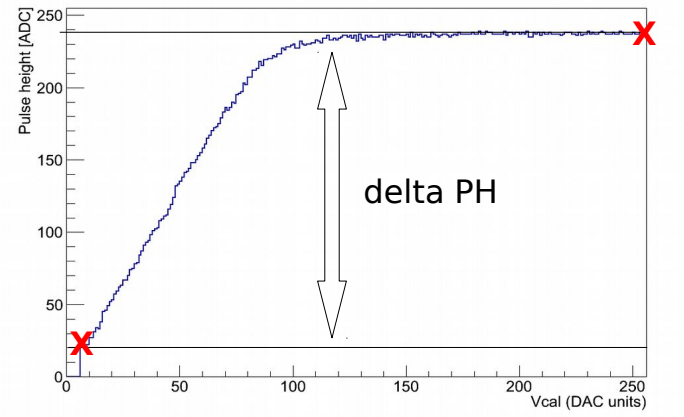
- What is the maximum PH difference of Vcal 50 low range and Vcal 255 high range after irradiation?

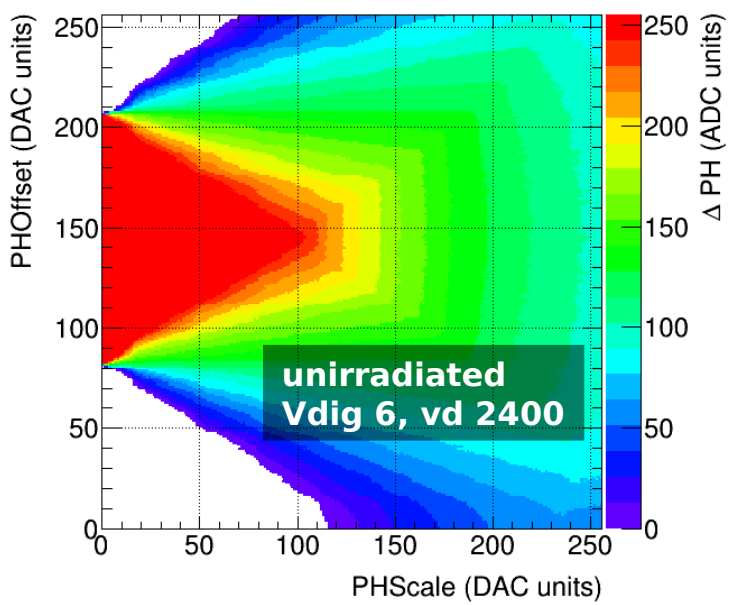


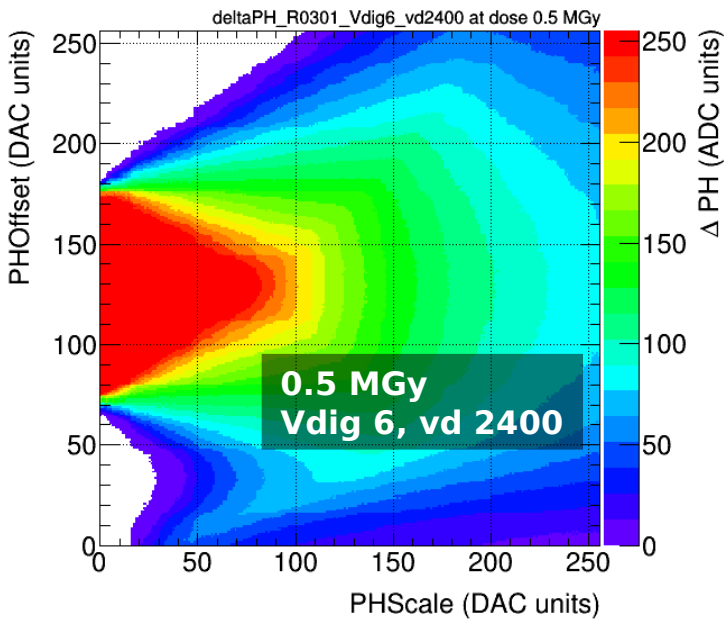


Pulse height – layer 2 dose

- Maximum delta PH depends on PHScale and PHOffset
- Sample trimmed as in slide 9
- Full coverage up to 0.5 MGy, standard settings Vdig 6, vd 2400 mV

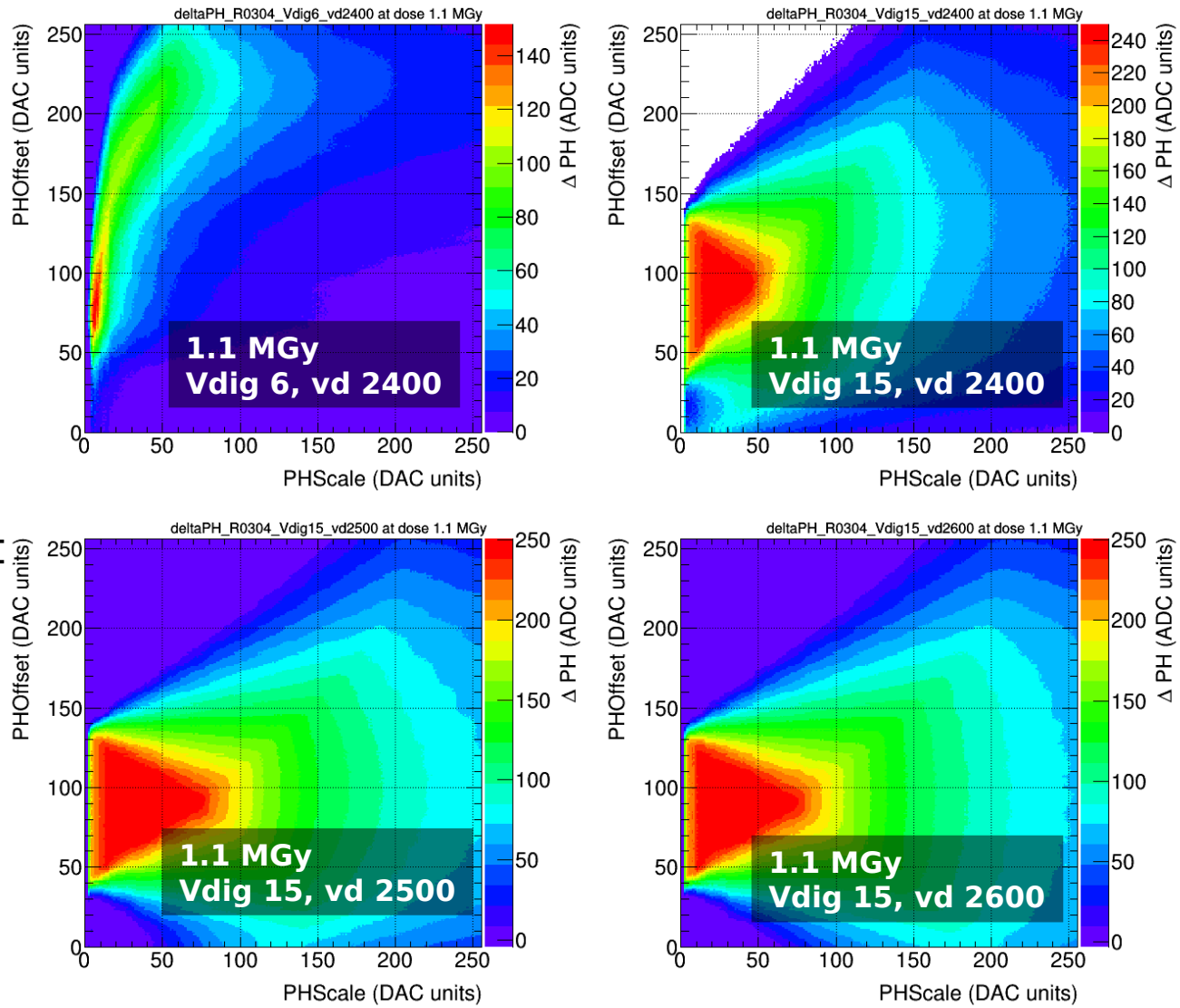




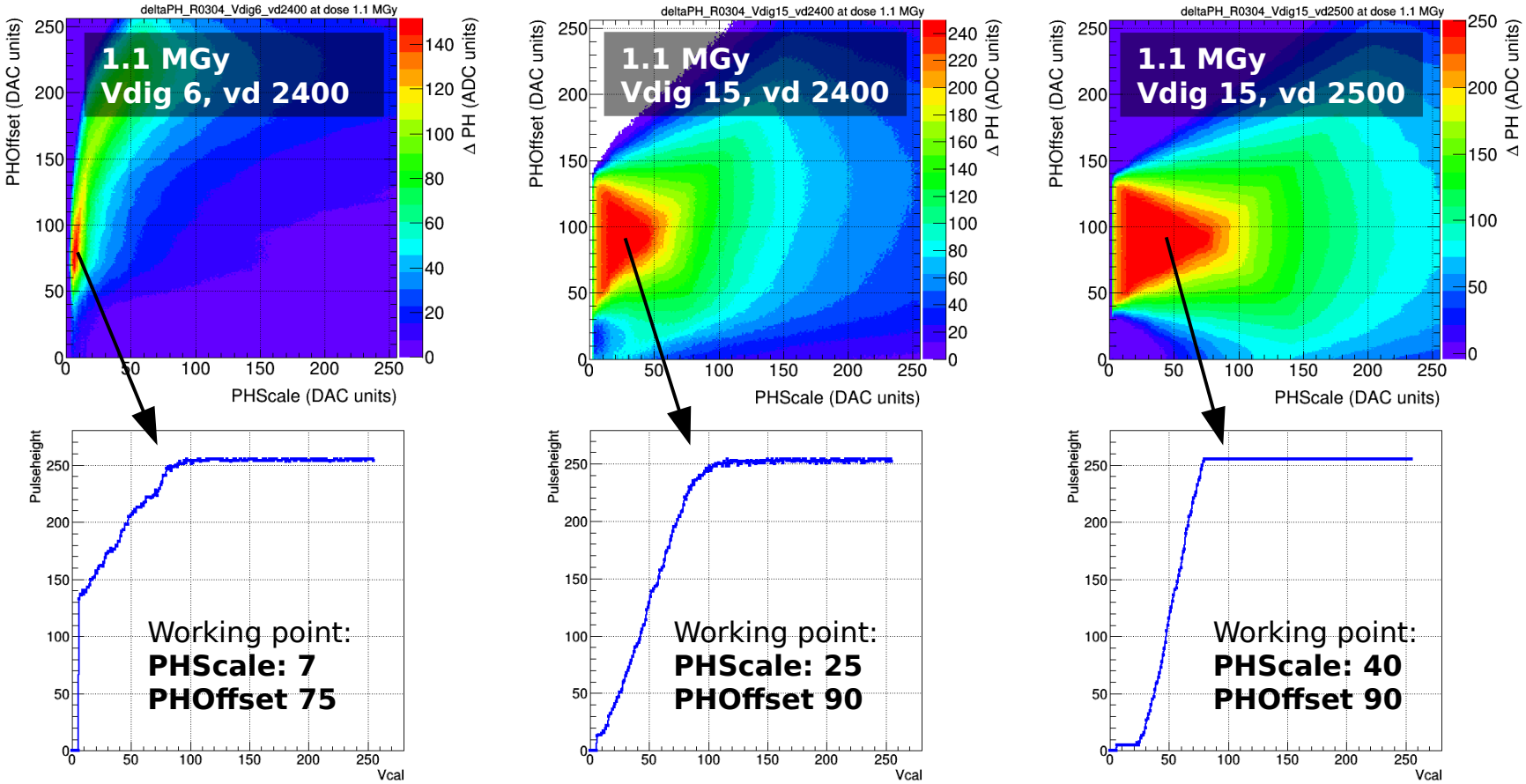


Pulse height – vd dependence

- 1.1 MGy: limited PH coverage
- PH spread improved for Vdig 6 → 15
- Further improvement if vd is increased



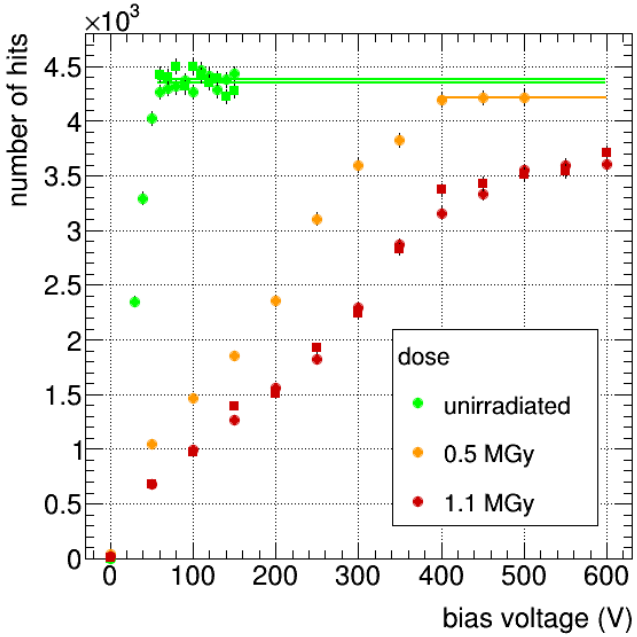
Pulse height – layer 1 dose



- PH cannot be stretched below a certain ADC minimum after ROC received 1.1 MGy if digital voltage is too low → regulator drop-out too large

Depletion voltage

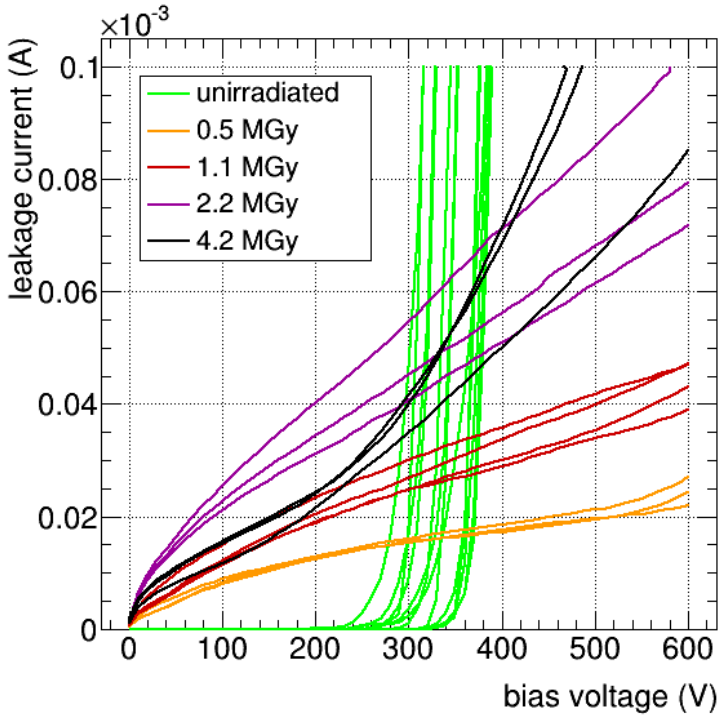
- For SCM: need to find bias voltage setting after irradiation
- Measure depletion voltage:
  - Trim sample to low threshold
  - Expose sample to high energetic mono-chromatic X-radiation (Ba 32 keV → 8900 electrons)
  - Measure number of hits vs bias → should saturate at depletion voltage

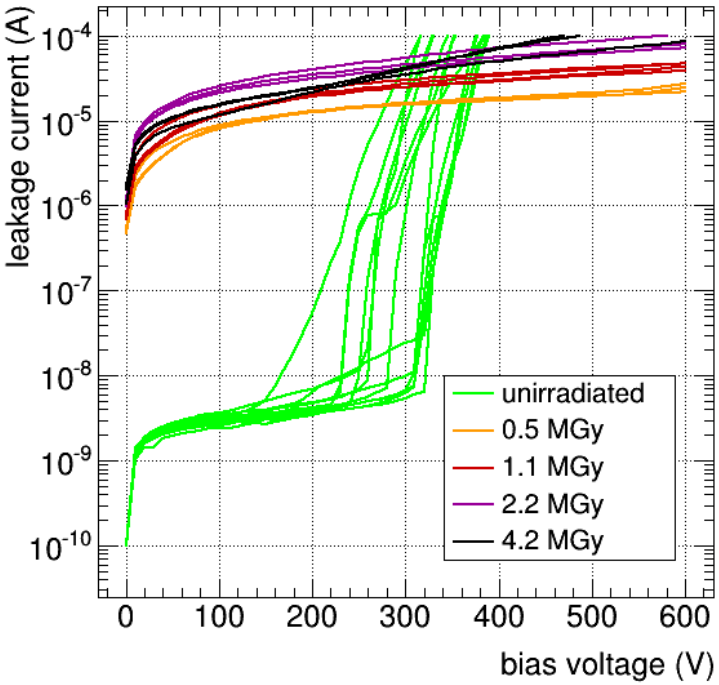


- Depletion before irrad. at -60 V
- Depletion after 0.5 MGy at -400 V
- Unclear behavior for 1.1 MGy samples
- Samples with dose > 0.5 MGy probably under-depleted at bias -400V

Leakage current

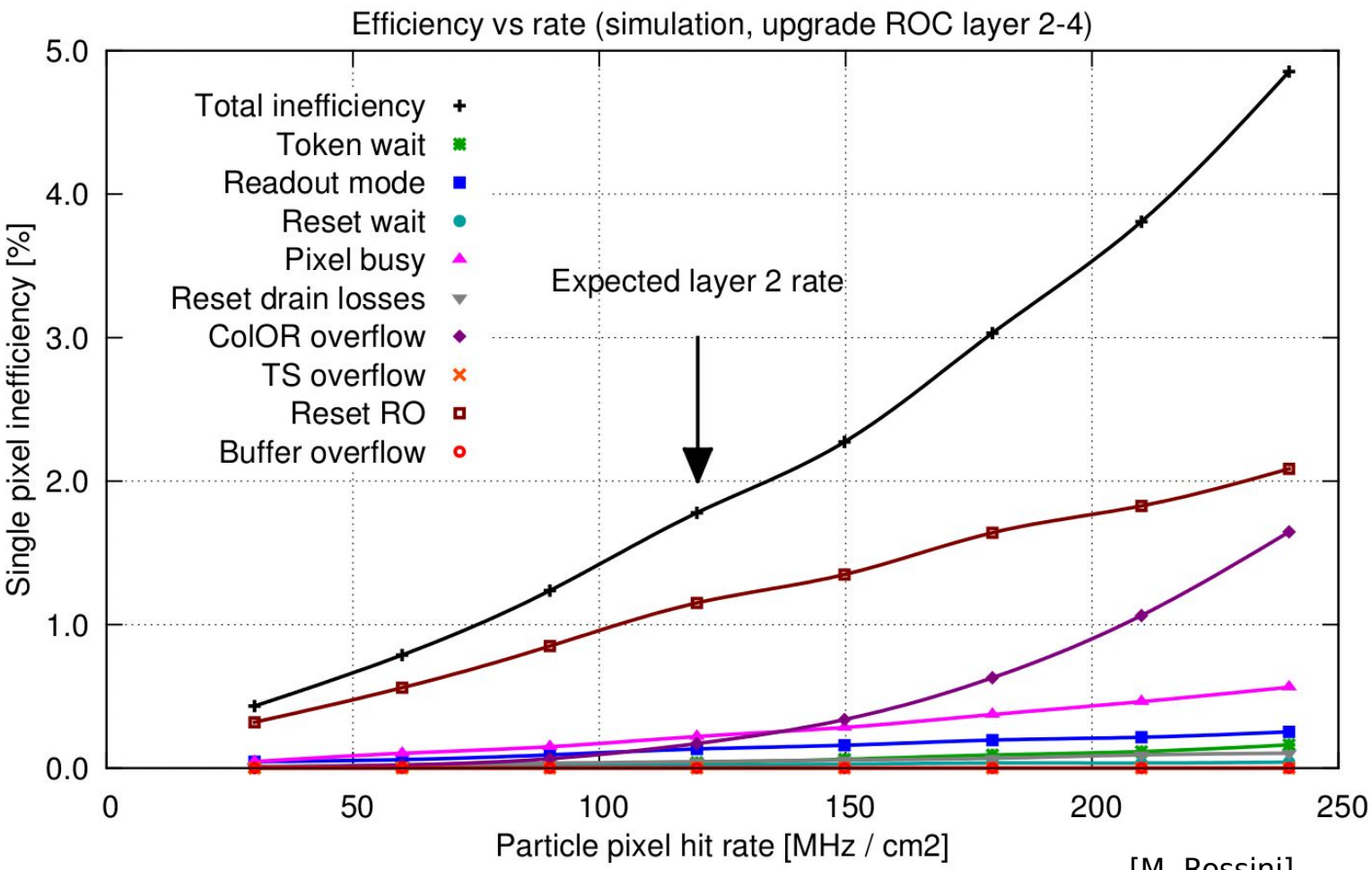
- Leakage current at -20C





- Leakage current increases approx. linearly with dose after type inversion
- Exception: dose 4.2 MGy leakage current smaller than at 2.2 MGy below 300 V. Why?

High rate efficiency loss mechanisms



[M. Rossini]