TWEPP 2015, Lisbon
September 29

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

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on behalf of the CMS collaboration

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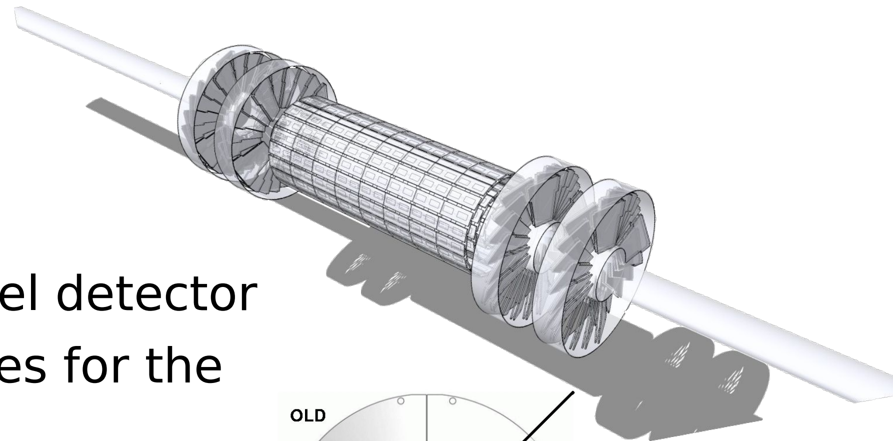
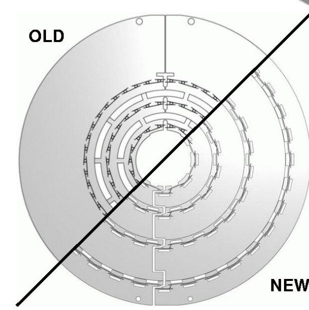
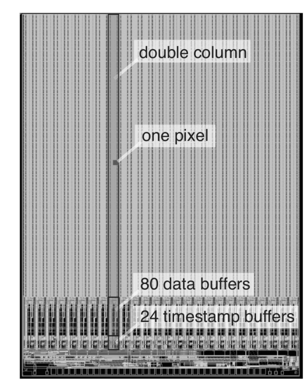
PSI

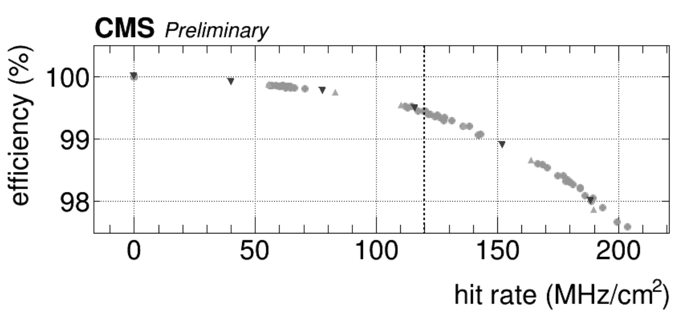
Outline

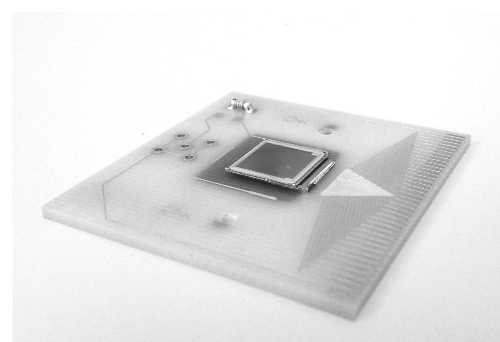
- The CMS pixel detector
- The Phase I upgrade of the pixel detector
- The readout chip and challenges for the upgraded chip
- Irradiation study: motivation and doses
- Test setups
- Selected results
- Summary and conclusion





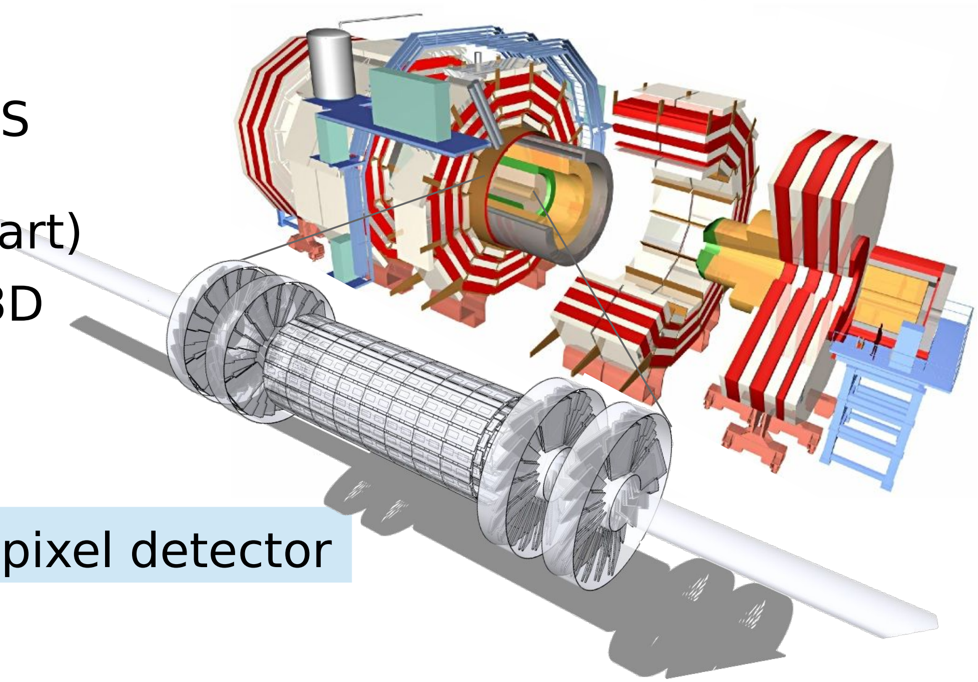




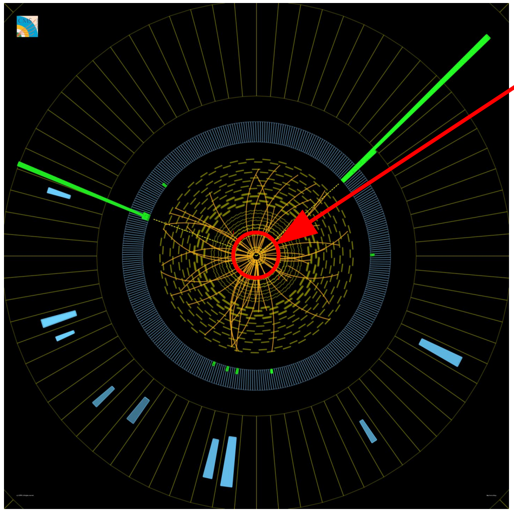


The CMS pixel detector

- 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



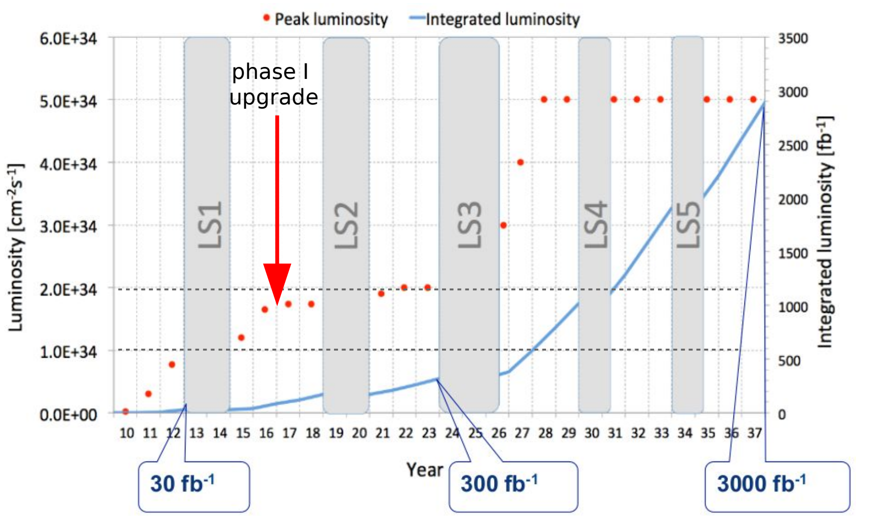
CMS event display

- 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

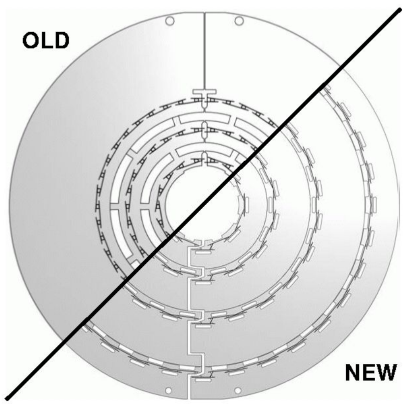
- Design luminosity of present detector: $L=1\cdot10^{34}\ cm^{-2}s^{-1}$
- LHC: increase of luminosity to $L=2\cdot10^{34}\ cm^{-2}s^{-1}$

→ upgrade pixel detector to avoid performance loss



LHC schedule as of June 2015 [F. Bordry]

- new features include:
  - Additional layer in barrel and endcap → more hit points for improved tracking and vertex reconstruction
  - Layer 1 closer to interaction point (r = 3.0 cm)
  - Reduction of material budget, new CO_2 cooling
  - New readout chip with digital data transmission for increased readout speed
  - New powering scheme with DC-DC converters

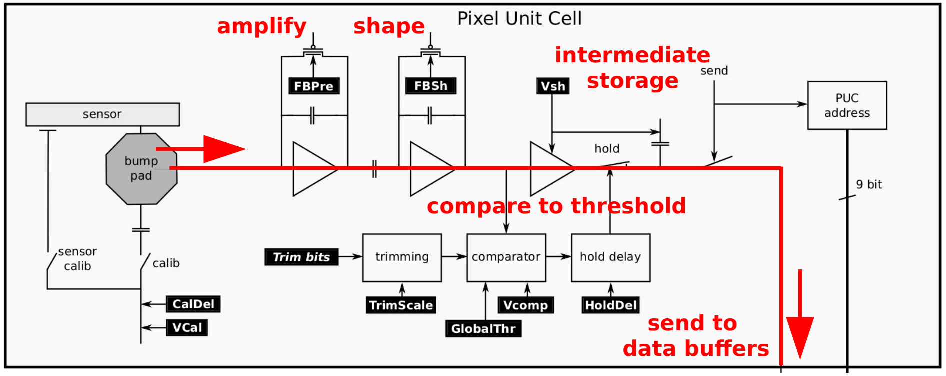


Barrel pixel layout old/new [S. Streuli]

Goal: guarantee high detector performance under tightened conditions

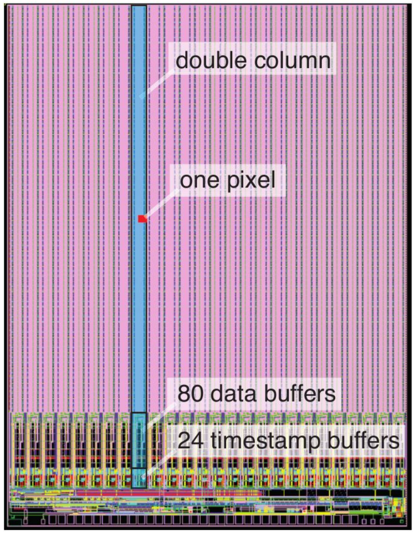
The readout chip (ROC)

- 250 nm CMOS technology
- 4160 pixel unit cells arranged in 26 double columns with periphery, buffers and 8-bit ADC



Pixel unit cell of the ROC [F. Meier]

- Tasks of the ROC:
  - collect and process ionization charge produced by charged particles in silicon sensor
  - compare charge to threshold → zero suppression
  - notify ROC periphery to read out charge from pixel
  - store hit information until L1 trigger validation
- Controlling of the ROC: 18 DACs and registers
- This study: ROC for layers 2 – 4 and endcaps, dedicated ROC for layer 1 (higher occupancy)



ROC components [F. Meier]

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Challenges for the new digital ROC

- Efficient hit finding for up to factor 5 higher occupancy
    - Factor 5: 2x lumi., innermost layer radius 4.4 → 3.0 cm, contingency
  - → increase buffers for hit and time stamp information to prevent buffer overflow
  - → add additional readout buffer to avoid data loss during trigger latency

- Increase bandwidth: read out larger number of channels with only slightly increased number of readout links
  - → change from analog readout to 160 Mbit/s digital readout

- Better charge sensitivity to increase lifetime of detector
  - → lower comparator threshold, reduced cross-talk and timewalk

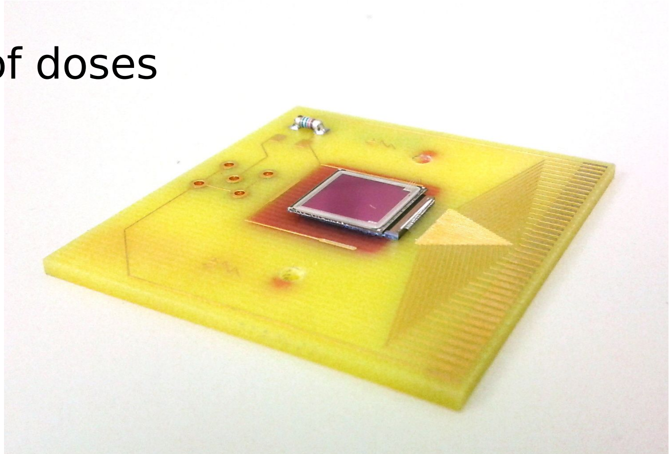
New ROC design needs to be validated by
lab measurements, beam tests, and **irradiation studies**

Why irradiation studies?

- Harsh radiative environment in CMS close to interaction point
  - Expected hadron fluence layer 1 after 500 fb^{-1}: $\Phi \approx 3 \cdot 10^{15}\ n_{eq}/cm^2$
- Transistor thresholds shift after irradiation due to energy deposit in gate oxide layers of field effect transistors → absorbed energy dose is quantity of interest (c.f. for sensor it is the particle fluence)

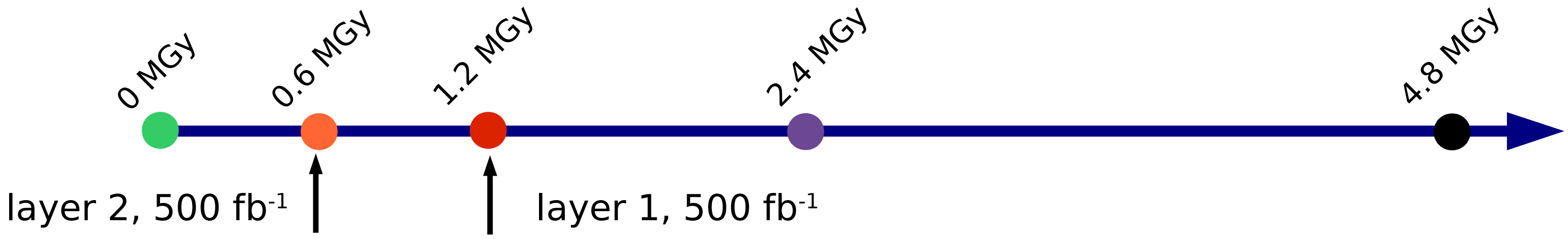
- Purpose of irradiation study:
  - test longevity and ensure good performance of the ROC throughout its foreseen lifetime in CMS
  - explore the limits of the ROCs in terms of doses

- Test chip functionality and performance after irradiation
  - Are available ranges for adjusting operation parameters sufficient?
  - Which chip properties change with irradiation and by how much?



Irradiated ROC with PCB staining after absorbing a dose of 1.1 MGy

Overview



- Irradiation of final CMS pixel readout chip for layers 2 – 4
- 23 MeV proton beam at Zyklotron AG Karlsruhe[1)]
  - Stopping power 18.1 (MeV cm^2)/g
  - Hardness factor ≈ 2
  - Dose rate ≈ 130 kGy/min
- Target doses:
  - **0.6** MGy (max. expected lifetime dose for layer 2 – 4 ROC)
  - **1.2** MGy (layer 1 after 500 fb^{-1})
  - **2.4** and **4.8** MGy
- 20% error on the measured dose according to irradiation facility

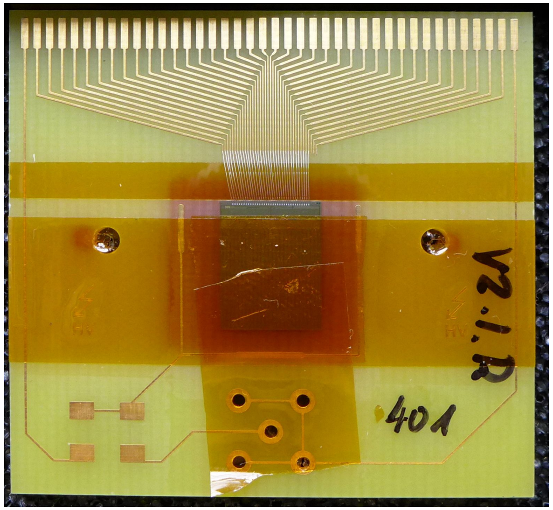
target dose (Mrad)	target dose (MGy)	Meas. dose (MGy)	fluence (1MeV n_{eq}/cm^2)	fluence (protons/ cm^2)
60	0.6	0.5/0.6*	0.4e15	0.2e15
120	1.2	1.1/1.5*	0.8e15	0.4e15
240	2.4	2.2	1.6e15	0.8e15
480	4.8	4.2	3.2e15	1.6e15

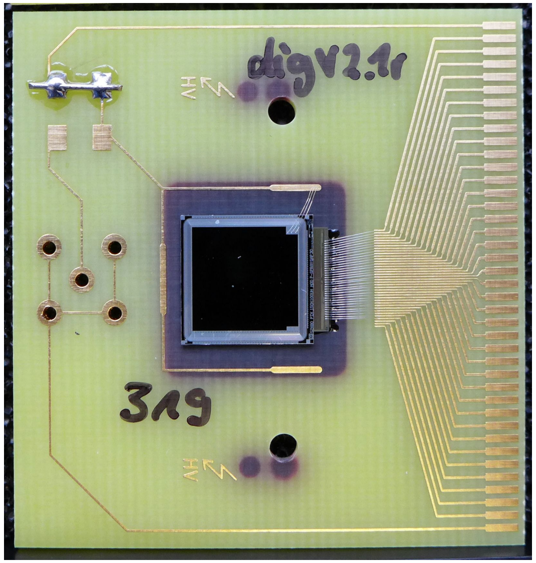
* single chip module and bare ROCs respectively

1) thanks to the CMS pixel group at KIT for the support!

Irradiated samples

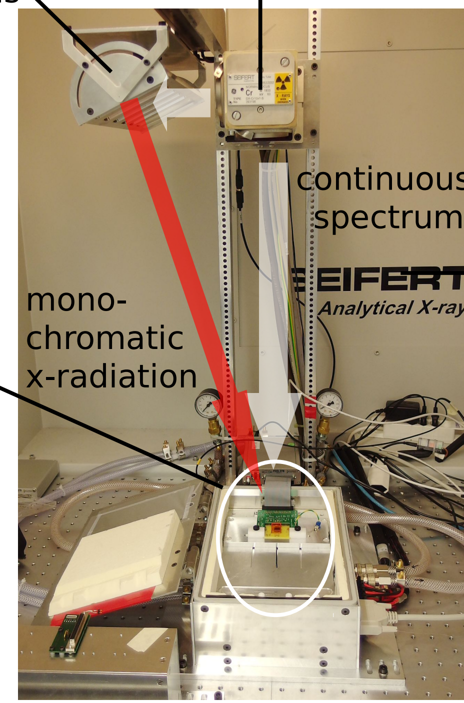
- Irradiated bare ROCs and ROCs bump-bonded to silicon sensor
- Samples and target doses:
  - Bare ROCs (without sensor)
    - 0.6 MGy (6 samples)
    - 1.2 MGy (6 samples)
  - Single chip modules, SCM (with sensor)
    - 0.6 MGy (3 samples)
    - 1.2 MGy (4 samples)
    - 2.4 MGy (3 samples)
    - 4.8 MGy (3 samples)
- Indicated “bare ROCs” or “SCM” in the plots to distinguish the two groups of samples



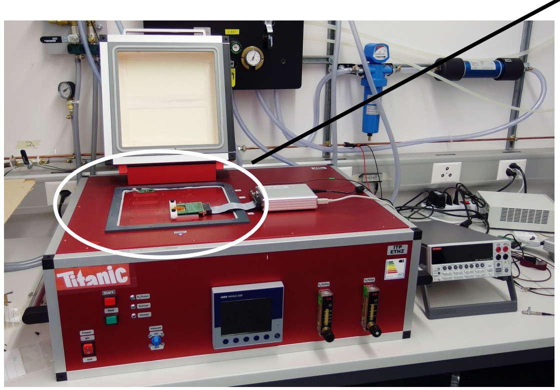


Test setups

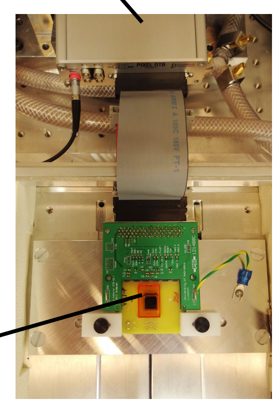
- Two setups to test samples before and after irradiation at controlled temperature and humidity
  - Climatic chamber for electrical test
  - x-ray setup to generate charge in Si sensor with x-rays
- Read out samples with customized test board and dedicated readout software



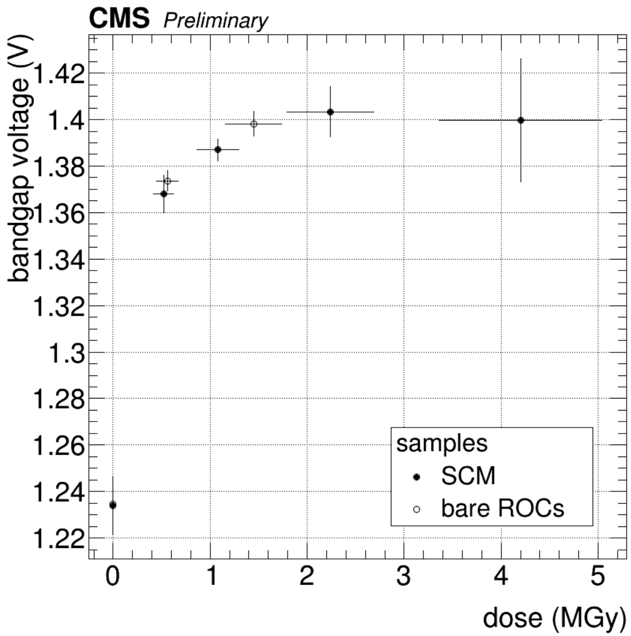
X-ray setup

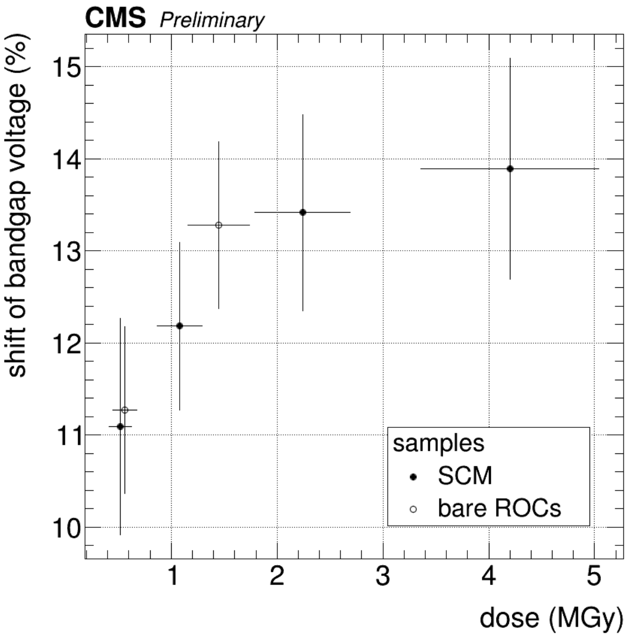


climatic chamber setup



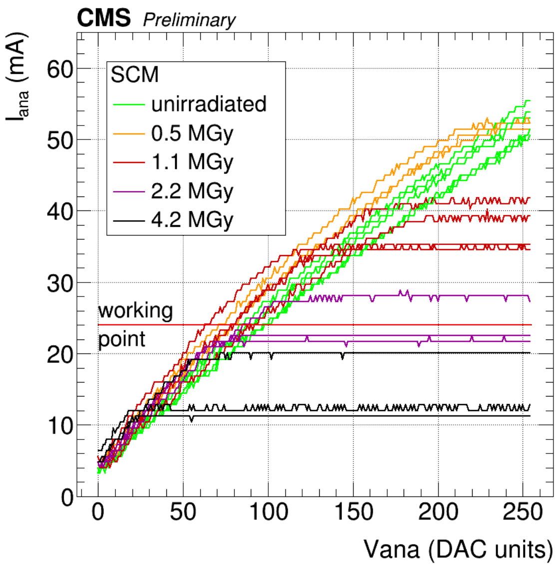
Band gap reference voltage

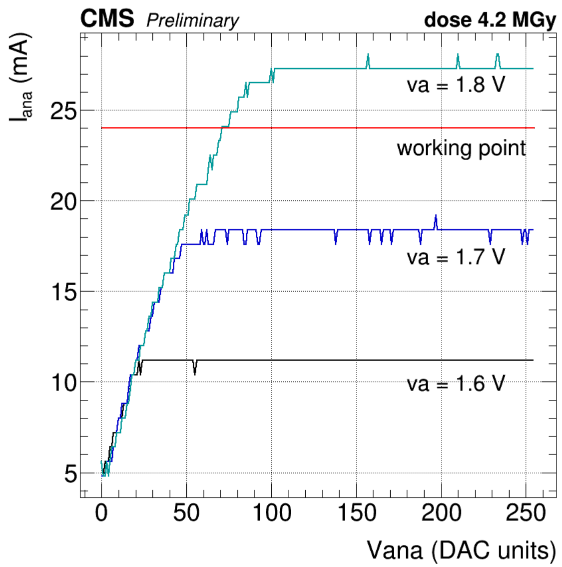


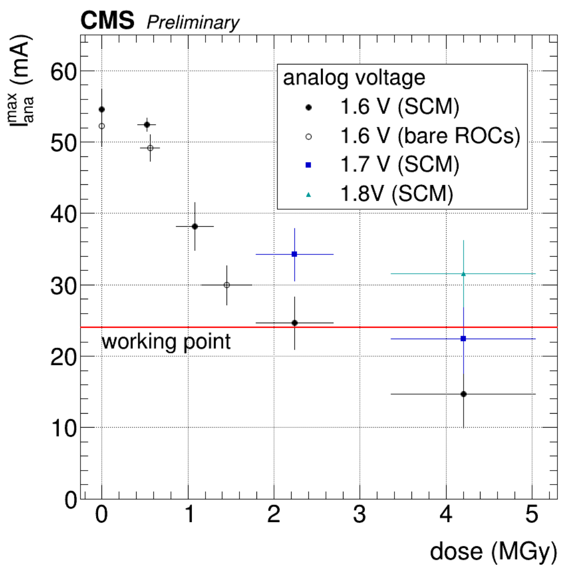


- Band gap voltage (vbg) serves as reference level for all DACs on the ROC
- Measurement of vbg on all samples before and after irradiation on dedicated test pad
- Shift of 11% after 0.6 MGy, saturation above 2 MGy
- Vbg shift used to correct DAC settings after irradiation
  - e.g. test pulse strengths and threshold settings

Analog current

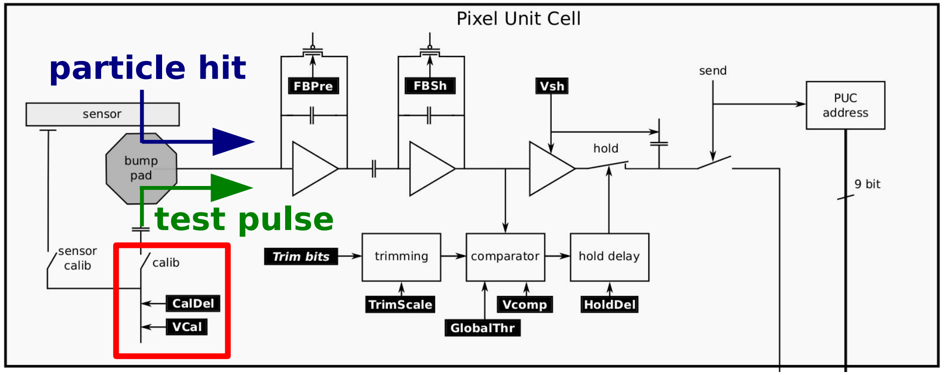




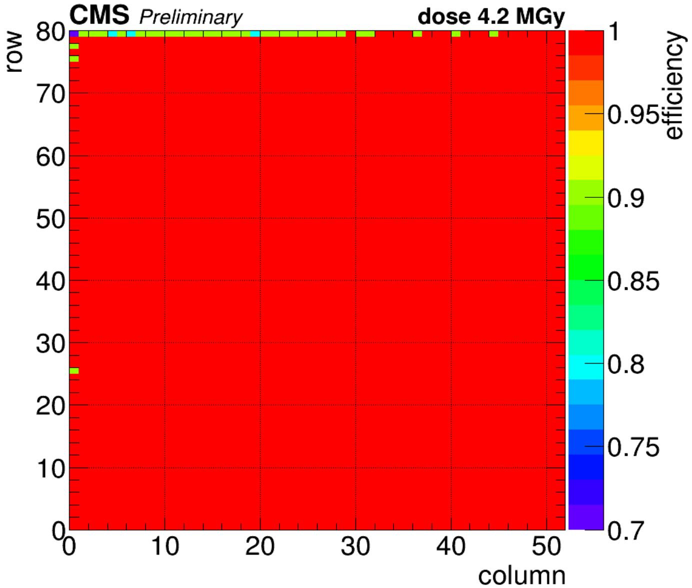


- Analog current as measured with test board as function of regulator setting Vana
- Target working point of 24 mA
- Dose dependent saturation level due to increased regulator drop-out
- Sufficient analog current for relevant doses up to 1.1 MGy
- Operate highly irradiated samples at elevated analog voltage

Test pulse readout



test pulse generator



- Test pixel functionality and basic readout by measuring response efficiency of individual pixels with internal test pulses
- Test pulses:
  - same readout chain as pulses from sensor
  - strength adjustable with DAC
- Test pulses can be read out from all samples up to 4.2 MGy
- No significant pixel defects observed

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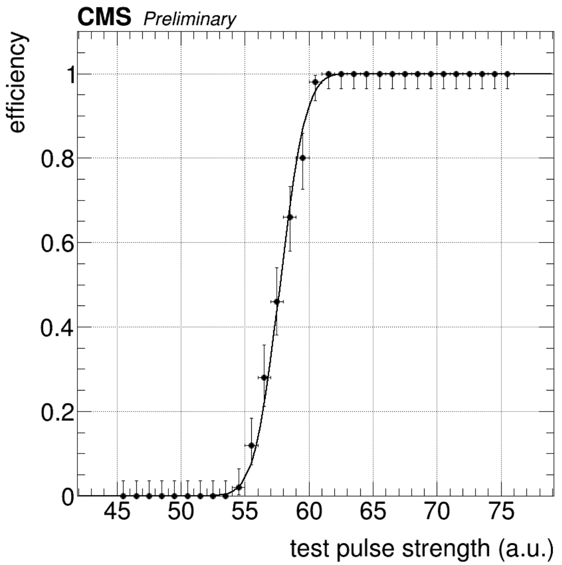
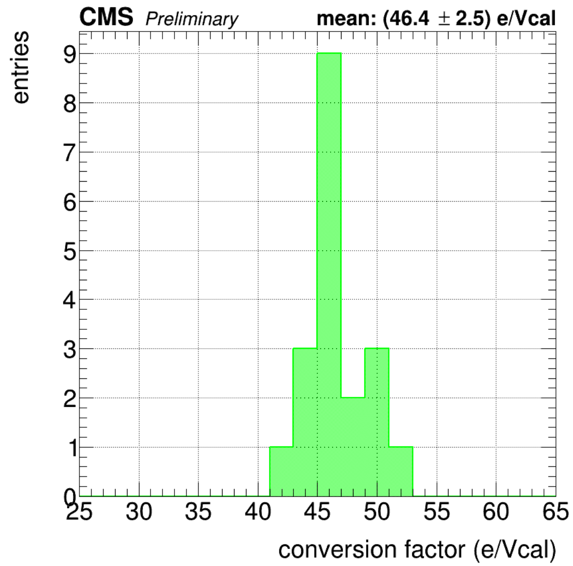
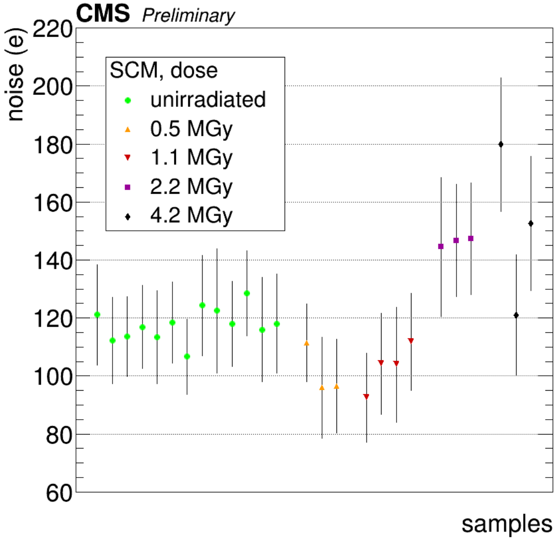
Amplifier Noise







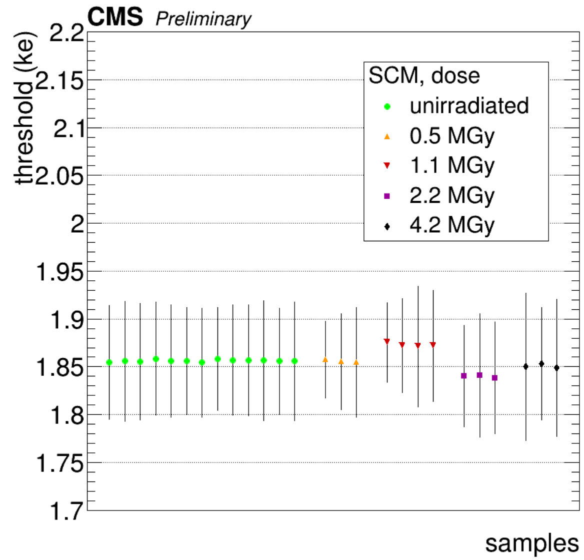
- Pre-amplifier noise proportional to width of turn-on of pixel response efficiency as function of test pulse strength
- Conversion from test pulse strength to electrons using energy calibration with mono-chromatic X-rays as reference energy → mean ≈ 46 electrons/test pulse unit
- No increase of noise for relevant doses
- Noise < 200 electrons even after highest dose of 4.2 MGy
  - (c.f threshold ≈ 1500 – 2000 e)

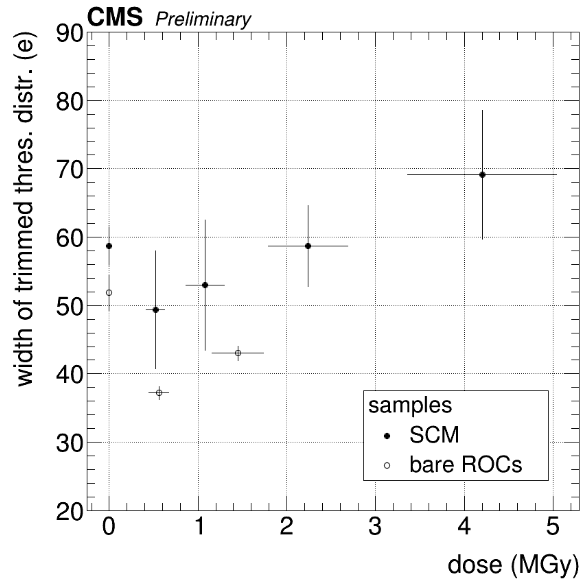
Threshold

- Set pixel threshold to same physical value before and after irradiation (≈ 1850 e)
- Plot: mean and width of threshold distribution of all pixels for several samples

- Low and uniform threshold can be set up to highest doses:
  - Global threshold range sufficient
  - Pixel-individual threshold bits working

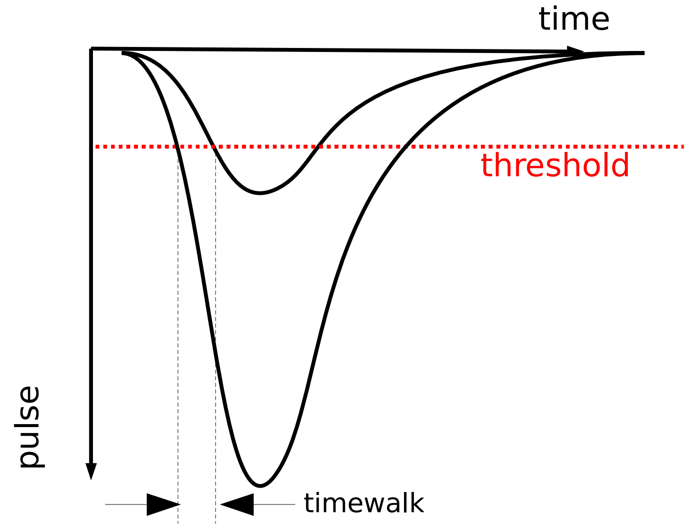
- Threshold width < 80 electrons
- Bare ROCs: smaller width due to lower noise (no sensor → lower input capacity)

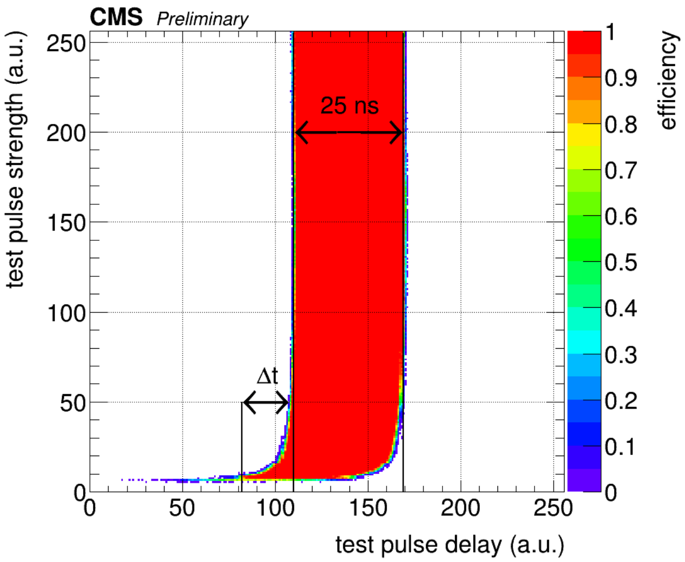




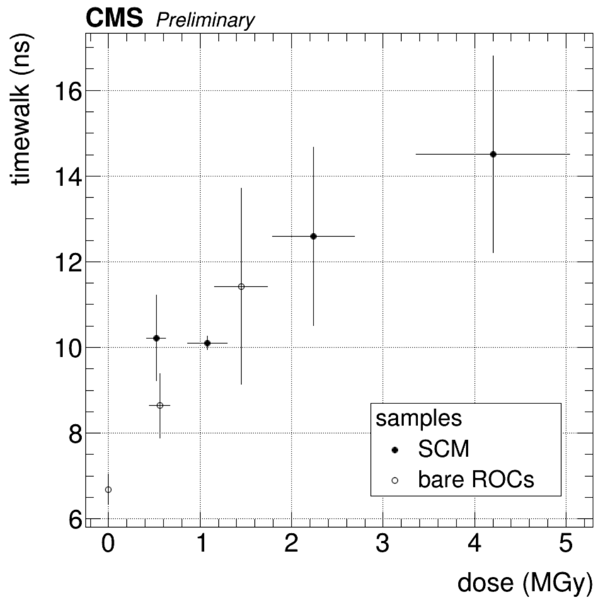
Comparator timing (timewalk)

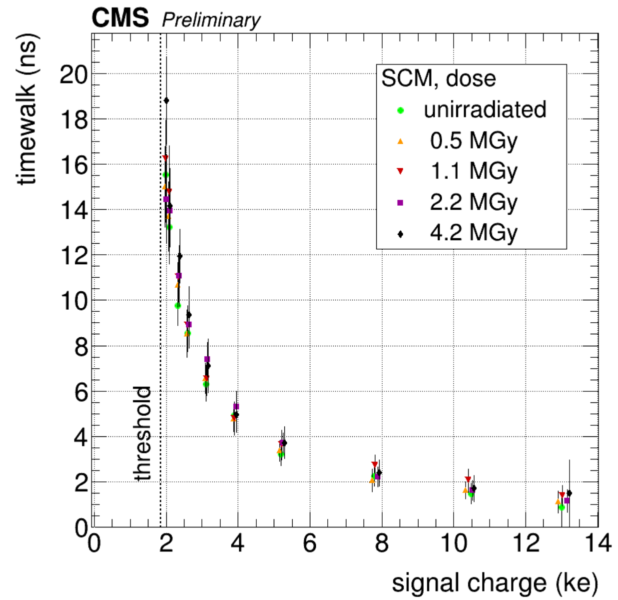
- Timing difference between small and large signal in comparator
- Requirement: timewalk < 25 ns
  → prevent hit migration to wrong bunch crossing
- Measurement with test pulses:
  - Test pulse read-out if in triggered bunch crossing
  - Measure test pulse delay for different signals
  - Calibrate delay with efficiency window width (=25ns)
- Settings
  - threshold 1850 e
  - large signal ≈ 83000 e
  - small signal ≈ 2300 e





Comparator timing (timewalk) cont.

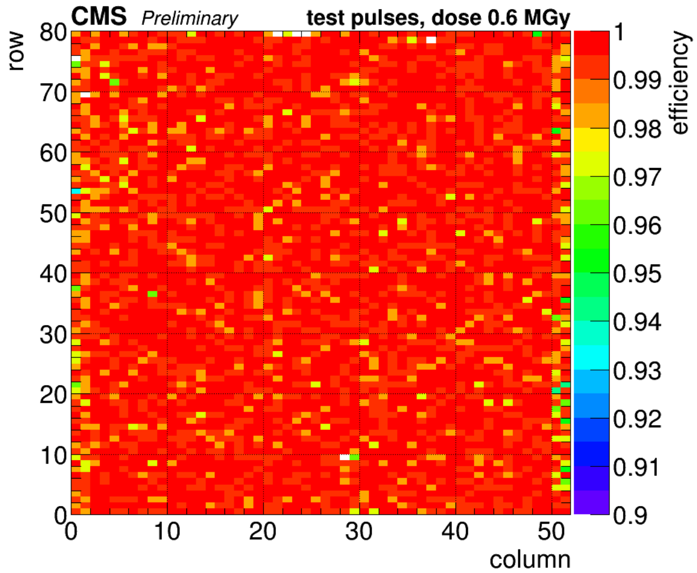


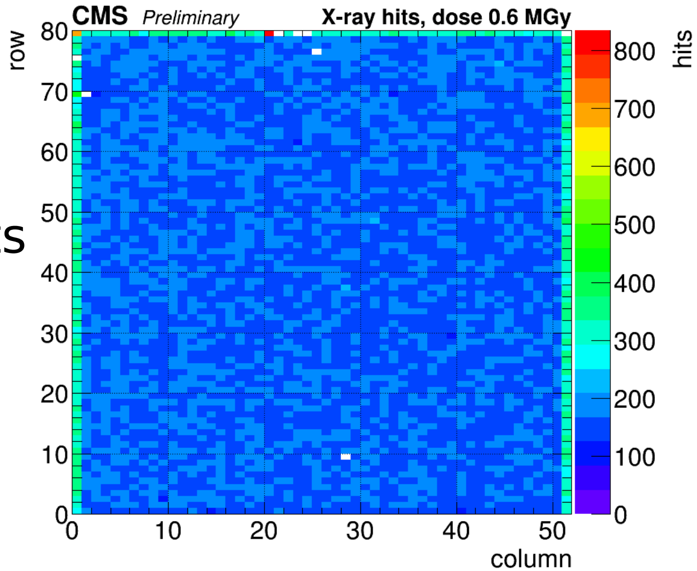


- Timewalk for fixed signal (≈ 2300 e) as function of dose (left) and as function of signal strength of small signal (right)
- Slightly increases from 7ns to 10 ns after 0.6 MGy
- Stays well below 25 ns even for very low signals and up to doses of 4.2 MGy
- No need to increase threshold to prevent hit migration
  - c.f. present detector: 2.5 ke minimal threshold → 3.2 ke in-time threshold due to timewalk

Hit finding efficiency

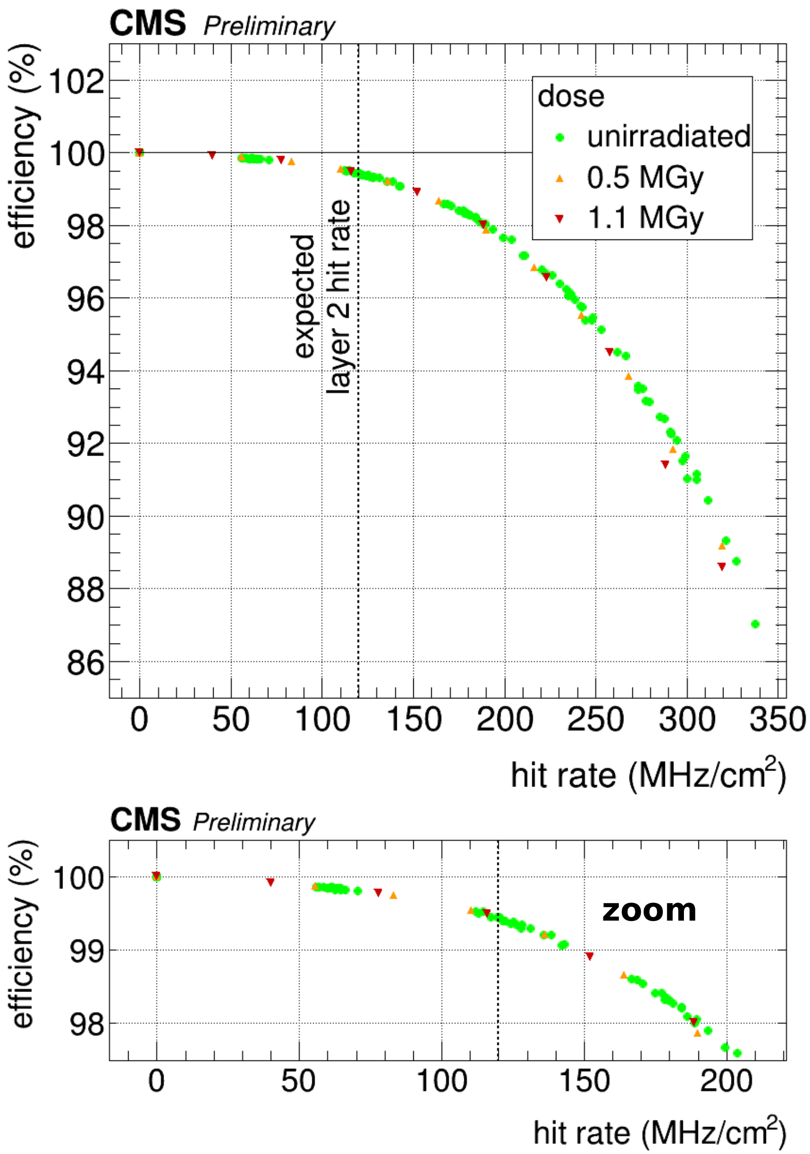
- Operate sample under more realistic conditions:
  - High occupancy O(100 MHz/cm^2)
  - Low threshold ≈ 2000 e
  - All pixels sensitive (unmasked)
- Create readout traffic with X-rays and inject test pulses
  → check if pulse can be read-out from the correct pixel in the correct bunch crossing
- Analysis: split hits from X-rays and hits from test pulses
  - xrays: overall ROC hit rate calculation
  - test pulses: calculate test pulse detection efficiency





Hit finding efficiency cont.

- Layer 2: expected single pixel hit rate ≈ 120 MHz/cm²
- No degradation of hit finding efficiency for relevant hit rates up to expected layer 1 dose (1.1 MGy)
- Excellent efficiency > 99% at expected layer 2 hit rate



Conclusions

- The CMS pixel detector will be replaced during the extended year end technical stop in winter 2016/2017

- The new digital ROC for layers 2 – 4 shows good radiation tolerance, no significant problems observed up to the lifetime dose expected for 500 fb^{-1} of 0.6 MGy
- Promising results up to dose of 4.2 MGy

- Results of several irradiation campaigns contributed to the design of the Layer 2 – 4 ROC and helped to finalize the design of the layer 1 ROC (about to be submitted)

- Experience with irradiated ROCs helped to define the detector's supply voltages (DC-DC converter)
  - See K. Klein's poster on DC-DC converters for the CMS pixel detector upgrade

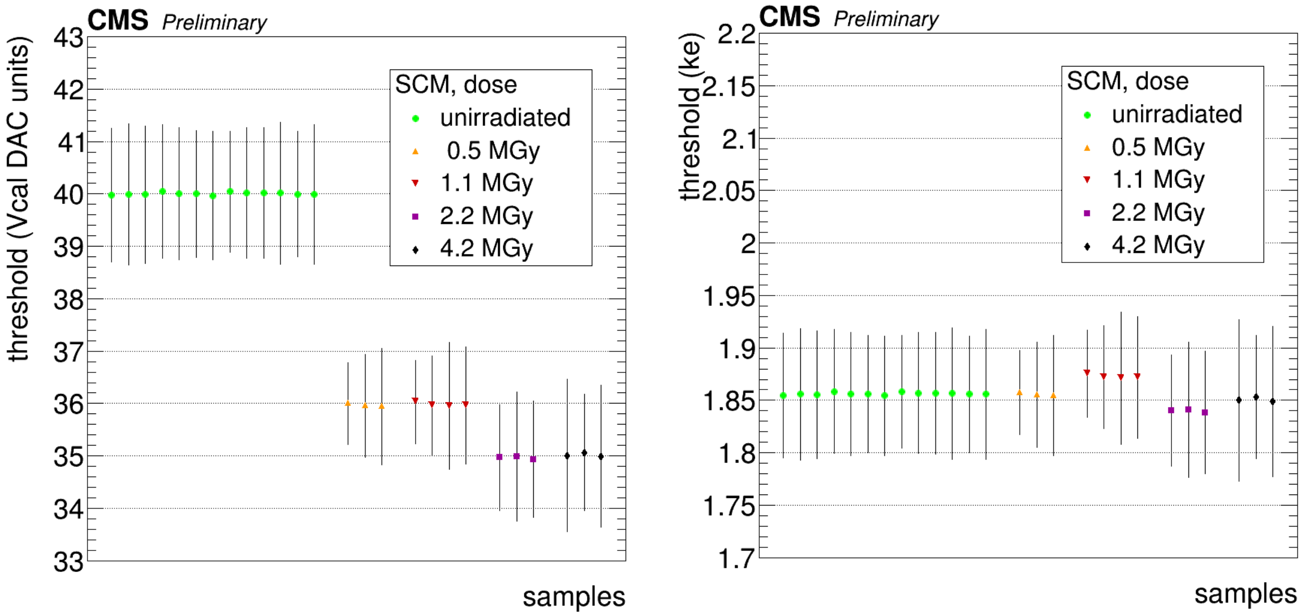
Back up

Qualification after irradiation

- Prerequisite for operating ROC after irradiation:
  - sufficient current supply and feeding voltages
  - DACs programmable
  - DAC ranges sufficient to set desired operation parameters (e.g. threshold)

- 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 efficiency

Threshold



- Set pixel threshold to same physical value before and after irradiation
- Correct dependence of internal test pulses (Vcal) on band gap reference voltage → different Vcal thresholds correspond to same physical threshold

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