# Study of the readout chip and silicon sensor degradation for the CMS pixel upgrade

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# Pixel detector building blocks

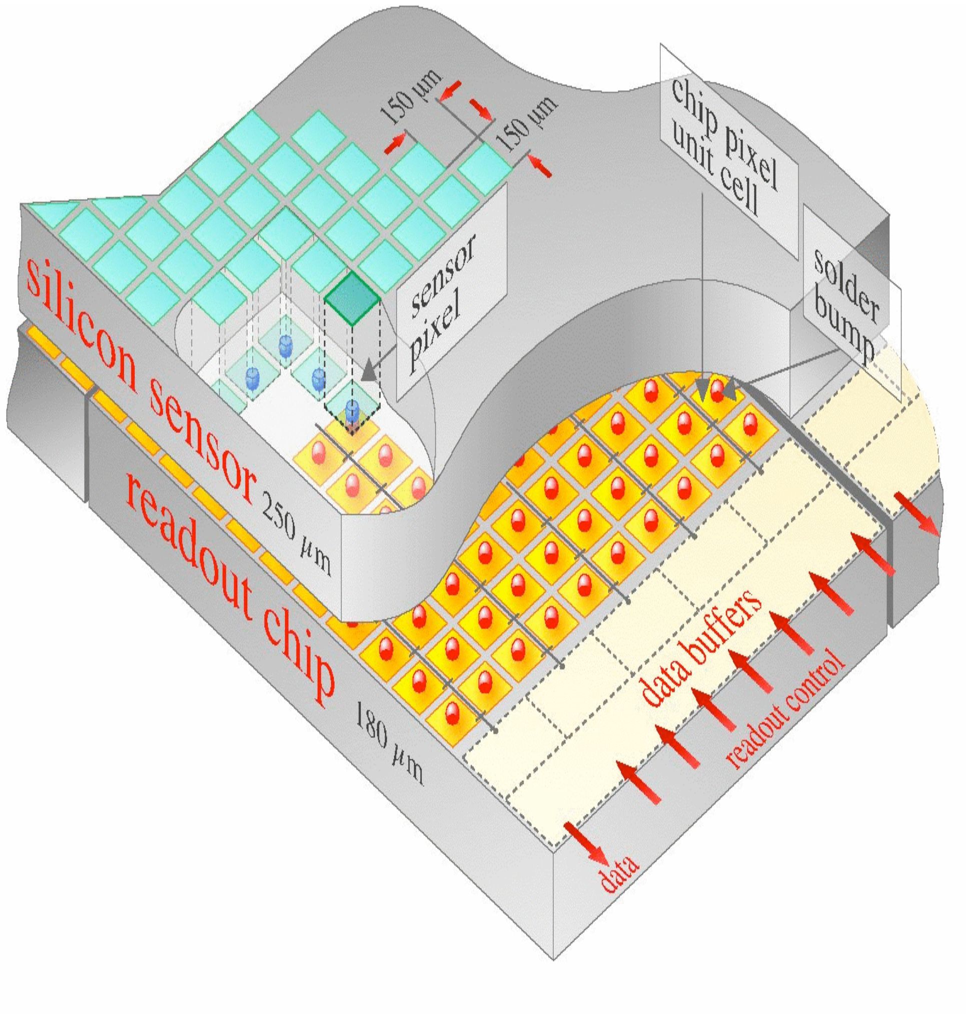
**Hybrid detector**

**Sensor:**
Silicon → see next slide

**Readout chips:**
0.25 micron CMOS IBM technology

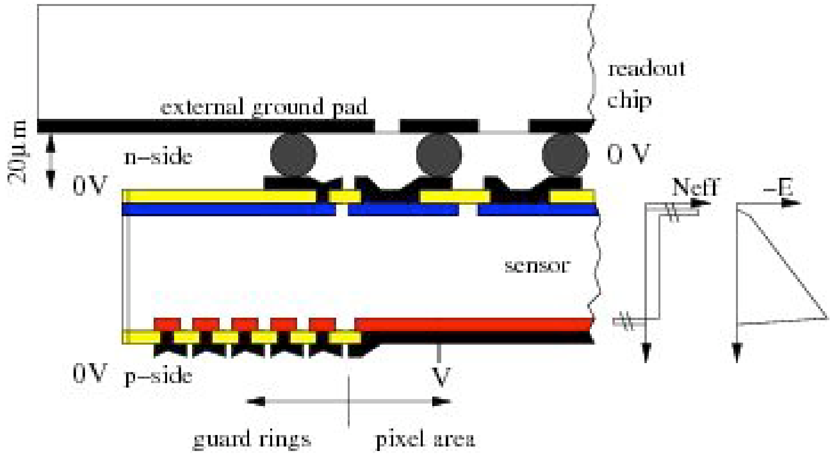
**Bump bonding needed to connect the sensor to the Readout chip (ROC)**

**Pixel size:** 100 μm x 150 μm



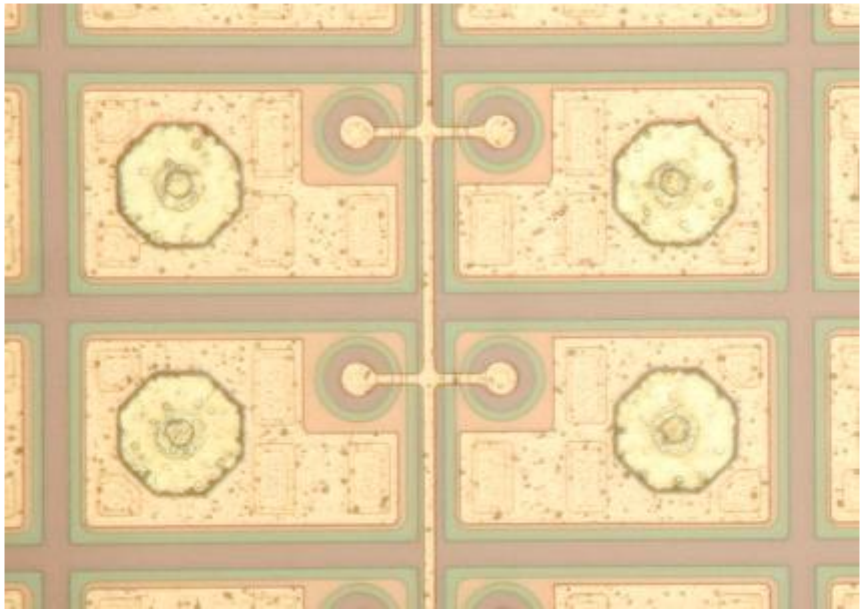
# Sensor choice ($n^+$-in-n)

- **$n^+$ implants on n substrate**
- **p junction on the back side** (double sided processing)
  - Collects electrons: higher mobility and larger Lorentz angle
  - Charge trapping is reduced

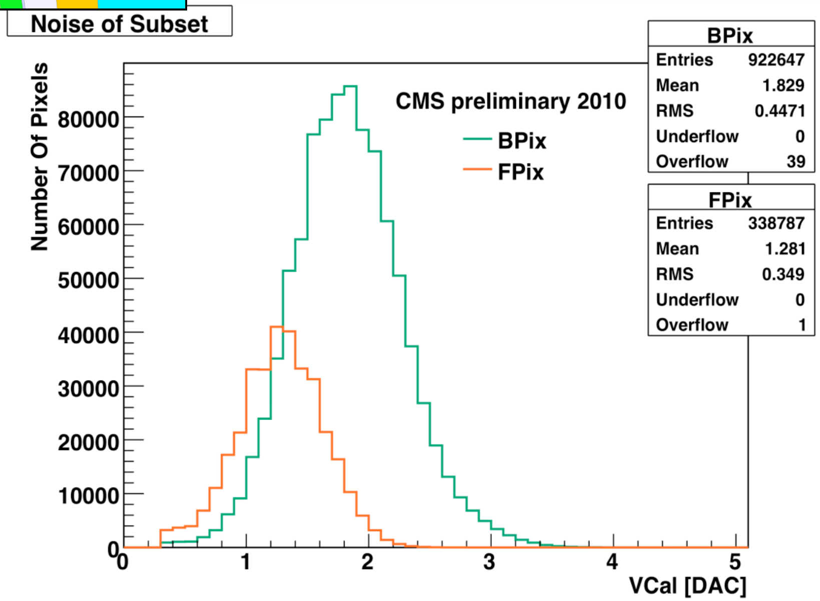


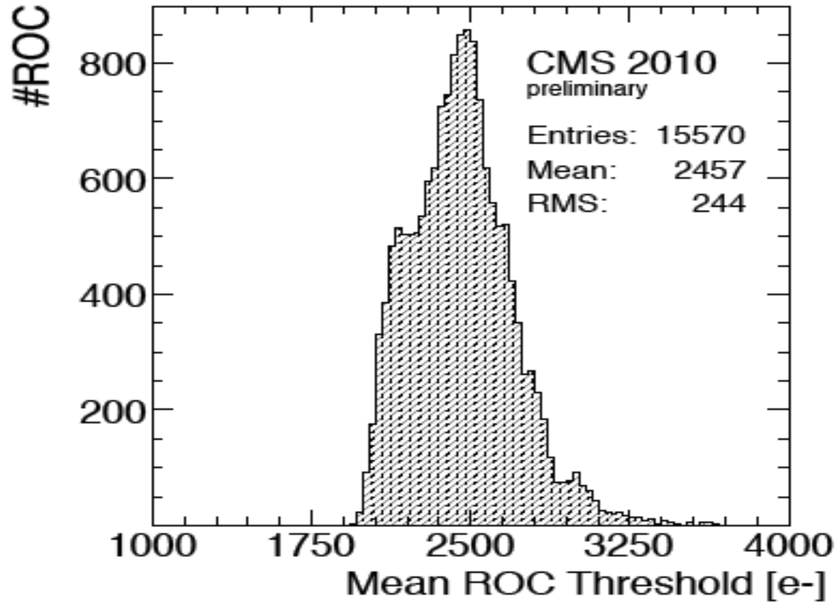

- **Radiation hardness motivates:**
  - O enriched (FPIX: 100-FZ, BPIX: 111-DOFZ)
  - Guard rings on back side
  - All sensor edges at ground potential

- **Pixel cell layout**
  - Moderated p-spray with bias grid
  - Small gaps (20 μm)



# Performance



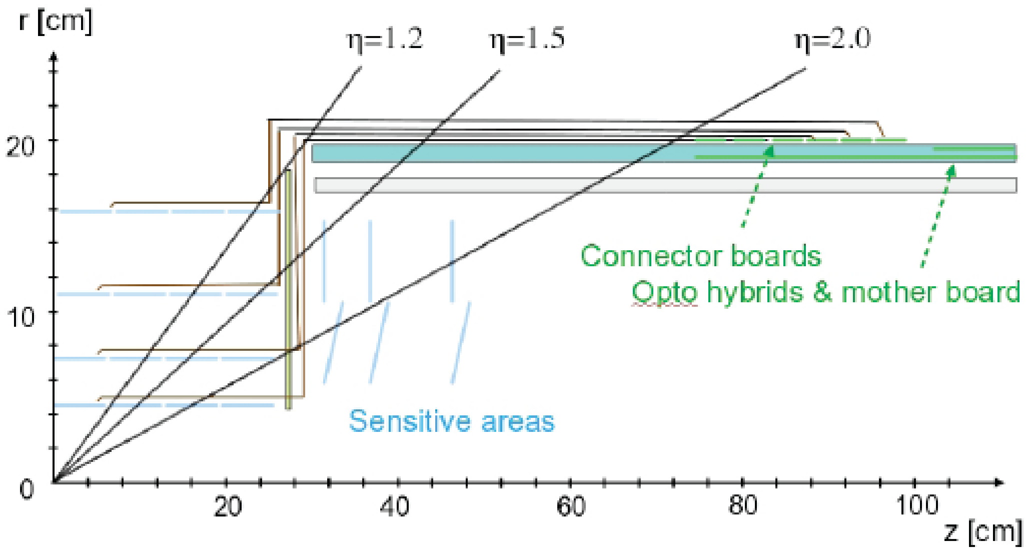




- The expected signal for a MIP is 22000 electrons
- Noise = 1.8 * 65 = 120 electrons
- The pixel detectors are almost noiseless

- Threshold: 2500 electrons
- Thresholds are much above the pixel noise
- Thresholds are determined by the readout chip internal cross-talk

# Pixel upgrade

- **Current** luminosity is more than **1 $fb^{-1}$.** Fluence is about **$1.2 \times 10^{12}$ $n_{eq}/cm^2$**
- **Upgrade phase I (2016)**: predicted luminosity **70 $fb^{-1}$.** Fluence **$5 \times 10^{14}$ $n_{eq}/cm^2$**
- **Extreme scenario**: luminosity **250 $fb^{-1}$**. Fluence **$1.3 \times 10^{15}$ $n_{eq}/cm^2$**




4 barrel layers + 3 endcap disks

- From the sensor point of view, major impact comes from:
  - New cooling system down to -20 °C (now running at +7 °C)
  - Peak luminosity increase up to $2 \times 10^{34}$ $cm^{-2}$ $s^{-1}$
  - Possibility of reducing the inner radius currently discussed

# Radiation effects

1) **Sensor damage** – increased leakage currents
Seen from the beginning in CMS: 1 $fb^{-1}$ → 0.75 nA/pixel
Potential limits on power supplies → 70 $fb^{-1}$

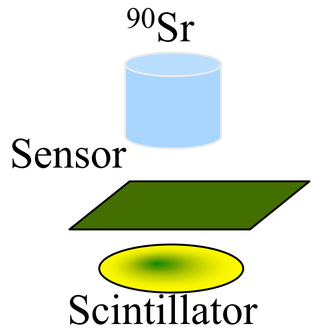
2) **Sensor damage** – partial depletion, charge trapping,
need to increase the bias voltage.
Not yet observed in CMS.

3) **ROC (Readout chip) damage** – change of the internal voltages .
Not yet observed in CMS.

• Studies presented here intend to determine at which fluence the effects become a problem.

# Testing setup

Measurements by
<u>Joaquin Siado</u> (UPRM)




- Test sensor + readout chip
- Measured charge value obtained from MIP beta particles emitted by $^{90}$Sr (products endpoint 2.28 MeV)
- Trigger provided by a scintillator detector
- Samples were cooled through a Peltier to -20°C or -25°C depending on fluence
- Temperature and humidity sensors

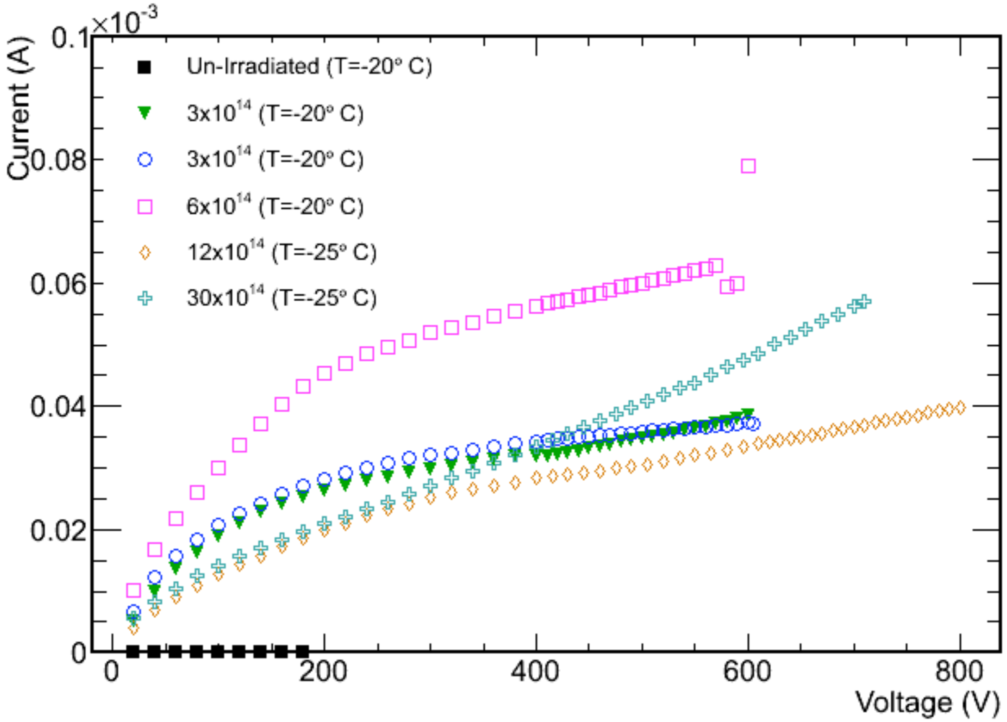
# Samples tested

- Samples consisting of sensor + readout chip

- Irradiated with protons (24 MeV) at Karlsruhe in 2010
- Fluences tested:
  - Unirradiated
  - 3 x$10^{14}$ $n_{eq}/cm^2$
  - 6 x$10^{14}$ $n_{eq}/cm^2$ → 70 $fb^{-1}$
  - 12 x$10^{14}$ $n_{eq}/cm^2$ → 250 $fb^{-1}$
  - 30 x$10^{14}$ $n_{eq}/cm^2$ (only partially tested)

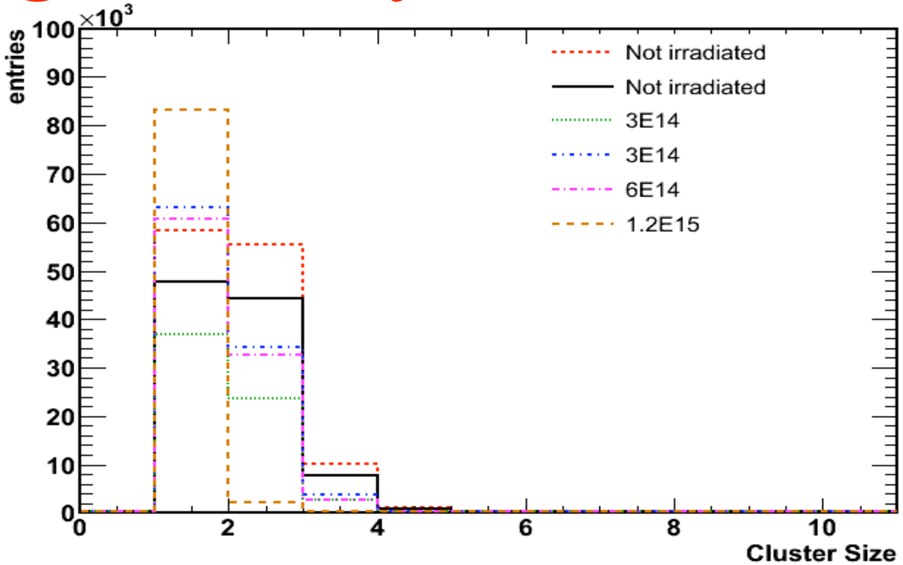
- To avoid annealing, samples kept in freezer at -18°C

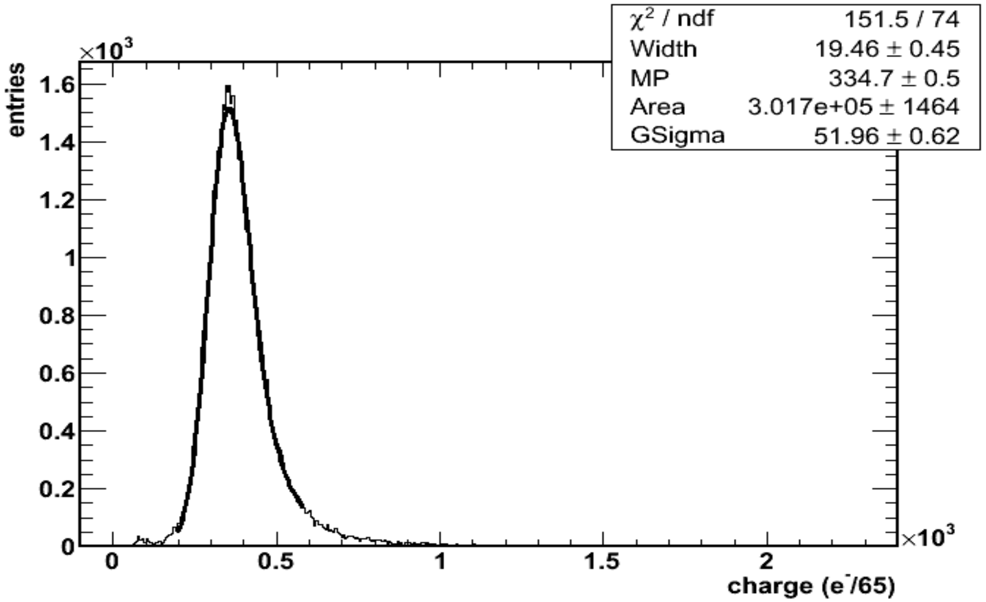
- Current – voltage curves confirm the goodness of the samples



# Signal Height analysis

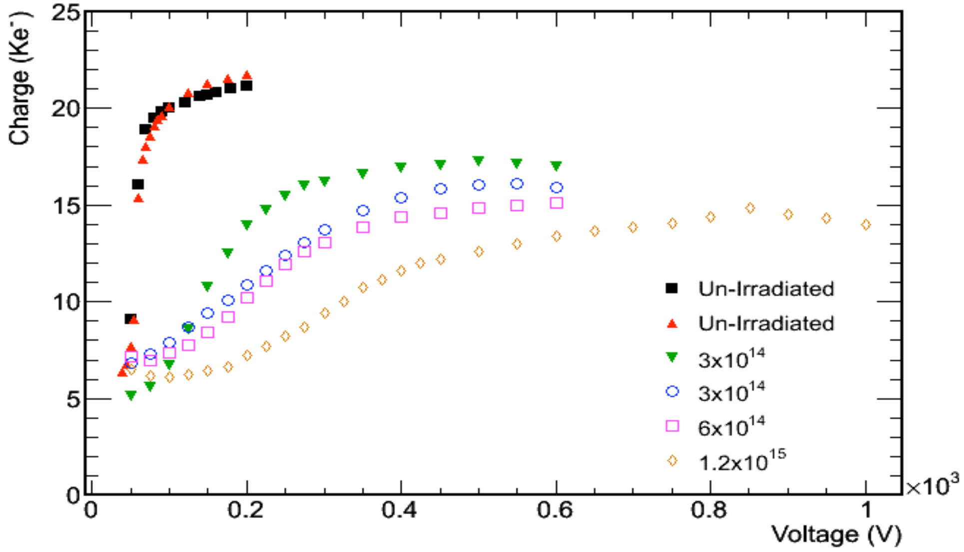
- Beta-spectrum of $^{90}Sr$ contains many low energetic particles + multiple scattering
- **Only single pixel clusters are used → selects particles going perpendicular to the pixels**
- Cluster size distribution already shows change in efficiency. Absolute efficiency measurement not possible due to multiple scattering
- Fit to the deposited charge distribution as a Landau convoluted with a Gaussian

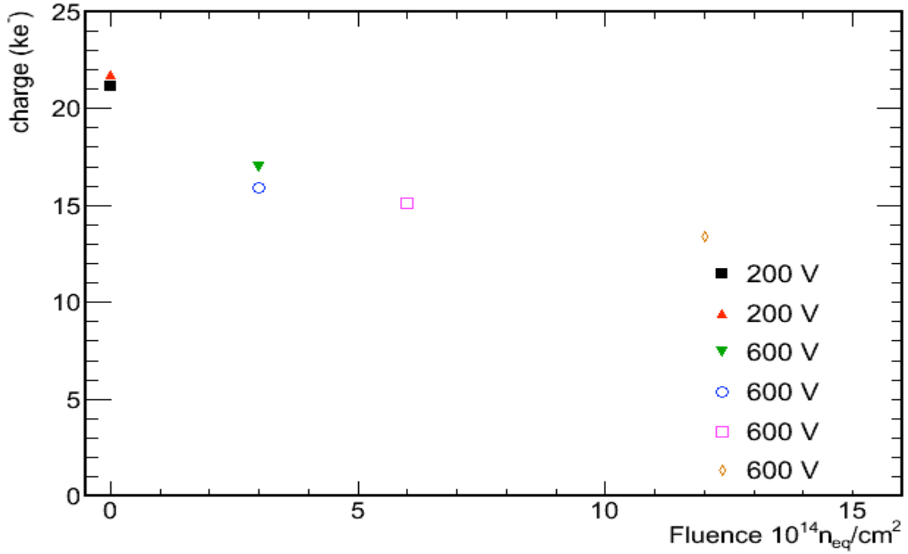


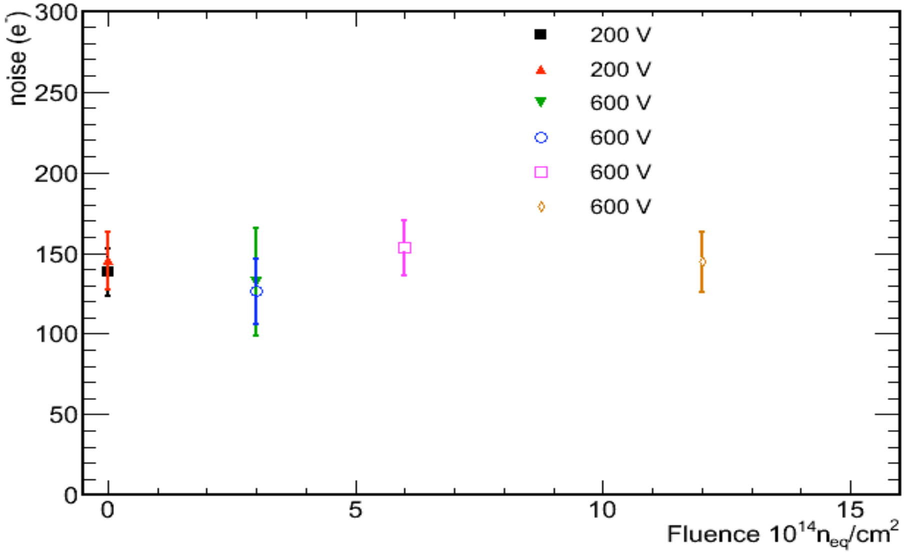
# Signal Height Results

- Results presented here are compatible with T.Rohe et al, NIM A (2010) 624:414-418
- Charge collected is 13000 electrons for $\phi$=1.2x10$^{15}$ $n_{eq}/cm^2$ above 600 V
- Highly irradiated sensors operative up to 1000 V
- Such high voltages are currently limited in CMS by connectors, cables and power supplies
- Lorentz angle diminishes at high voltage: effect not addressed here



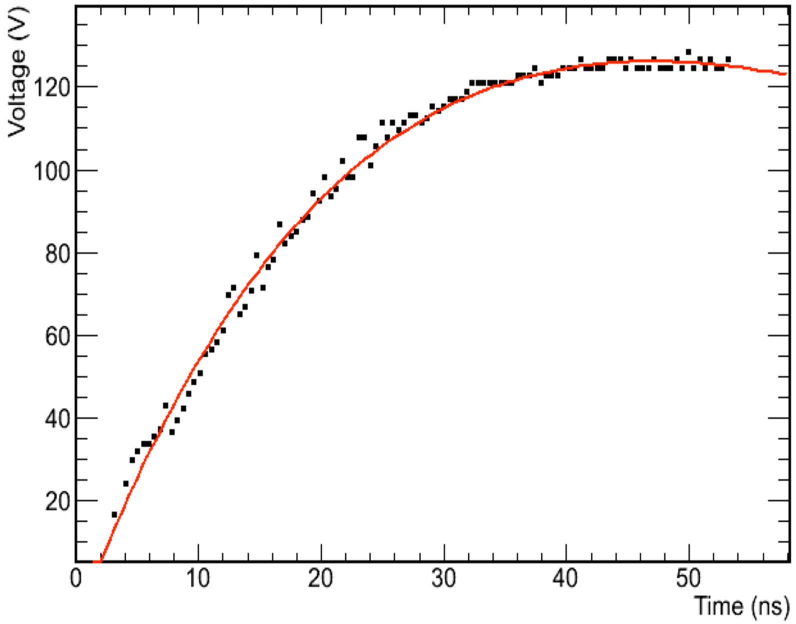



# Readout chips at high fluences




- Readout chip functioning with minimal changes to the nominal settings
- Small changes to the preamplifier and shapers feedback circuits applied
- Noise stable even at high irradiation (shown for full depletion or high bias voltage)
- Thresholds set to 3900 electrons in all measurements (low enough compared to charge collected)

# Characteristic time measurement

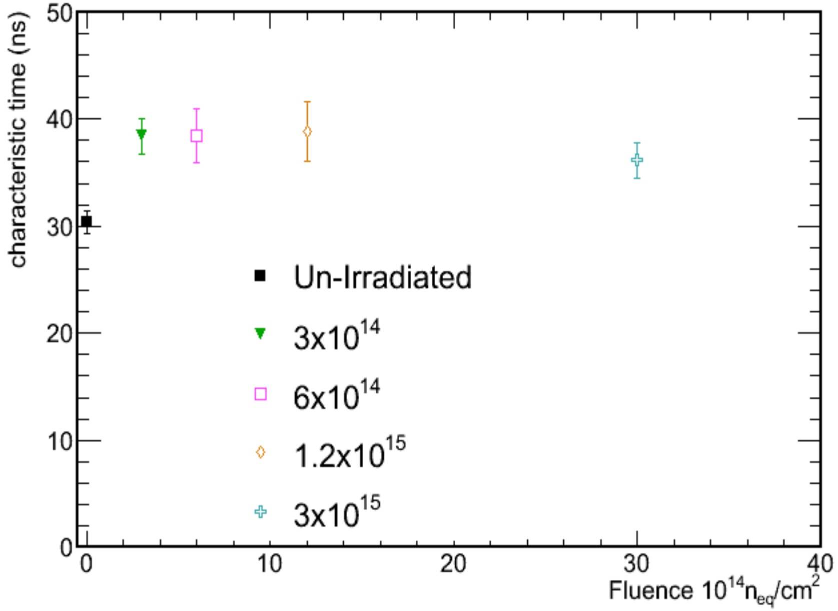



- Leading edge of the preamplifier output is sampled indirectly through a delay scan
- Characteristic time:
  - extracted using a fit :

$$PH(t) = p_0 + p_1 \cdot t \cdot e^{-\frac{t}{p_2}}$$

  - for unirradiated readout chips **without** sensor is ≈ (27 ± 1) ns
  - for unirradiated readout chips **with** sensor is ≈ (30 ± 1) ns
- Sensor adds an extra capacitance in series to the readout chip capacitance

# Characteristic time measurement



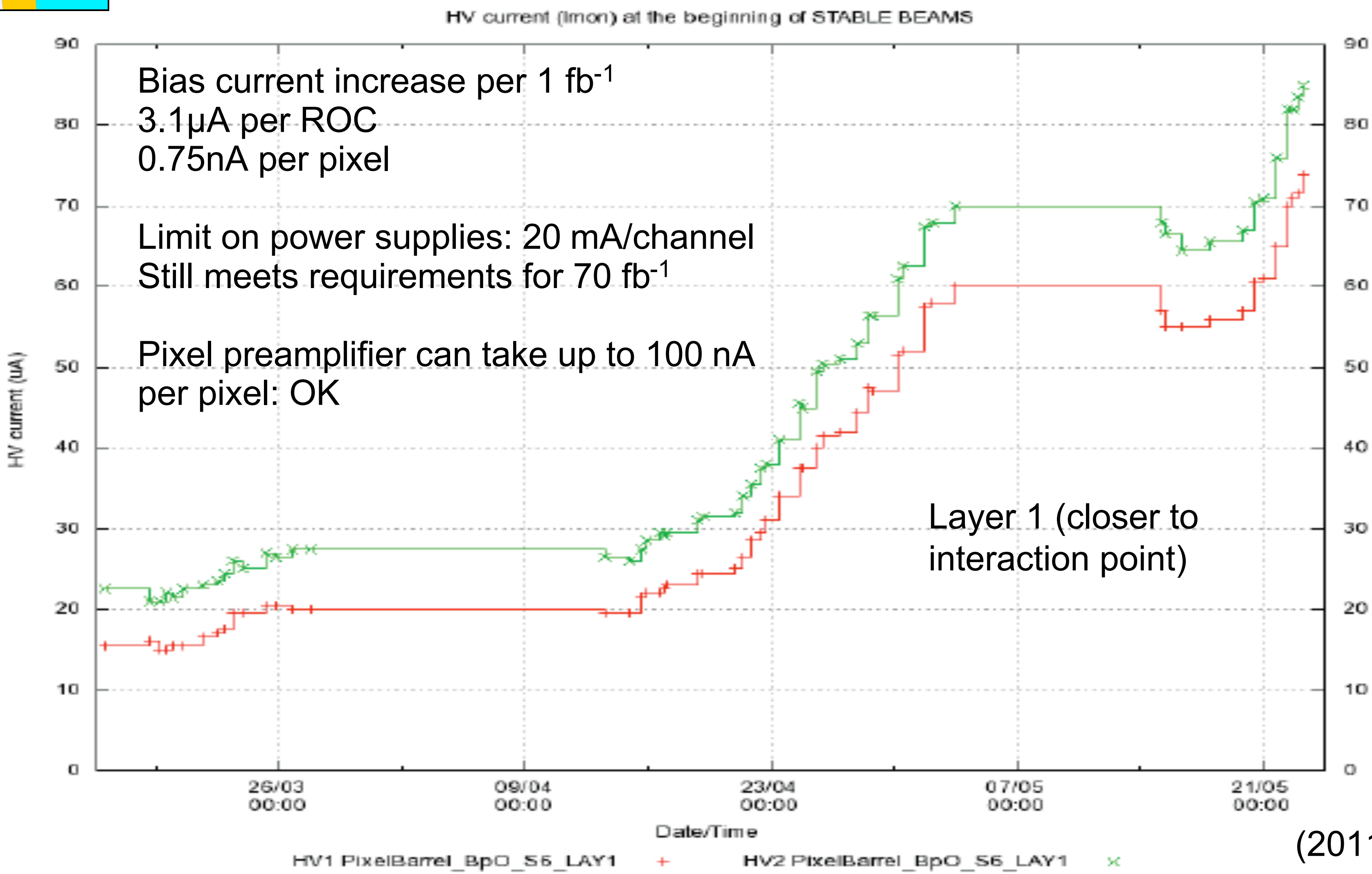

| Radiation ($10^{14}$ $n_{eq}/cm^2$ ) | time (ns) |
|---|---|
| 0 | 30±1 |
| 3 | 38±2 |
| 6 | 39±3 |
| 12 | 39±3 |
| 30 | 36±2 |

- Characteristic time increases with fluence. Quite flat for irradiated samples
- Specific tests still need to be performed to:
  - Determine if the main effect comes from a saturation given by the capacitance of the sensor
  - Detangle the effect of the radiation damage on the readout chip
  - Recover the characteristic time by changing the analog current

# Conclusions

- Present CMS sensor and readout chips have been tested up to fluences of $1.2 \times 10^{15}$ $n_{eq}/cm^2$ → 250 $fb^{-1}$
- Charge collected is >13000 electrons when bias voltage >600 V even for fluences of $10^{15}$ $n_{eq}/cm^2$
- Readout chip does not manifest major changes up to the tested fluences
- Leakage current may limit current CMS inner pixel layer lifetime to 70/fb: still enough up to upgrade phase I
- Pixel upgrade will not suffer from leakage current so much as operating temperature will change +7°C → -20°C (exponential effect)

# Leakage current – CMS pixels (Layer 1)




(2011)