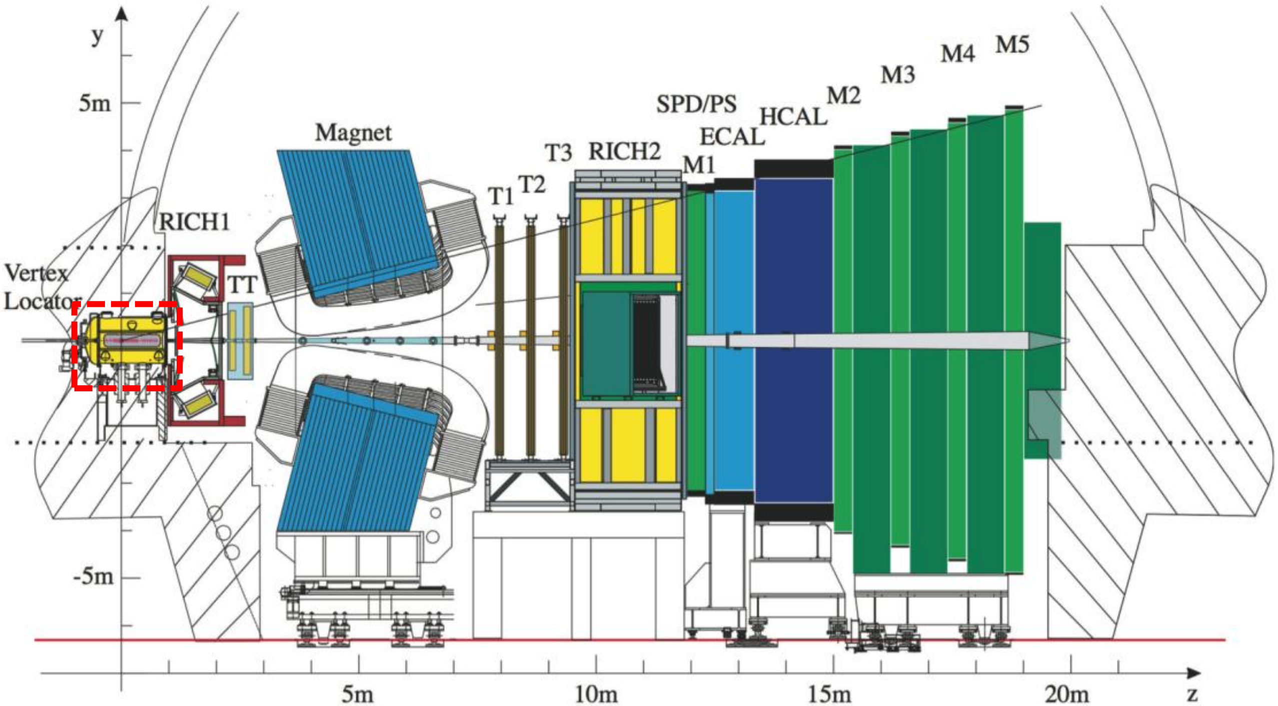
Radiation damage effects in the LHCb Vertex Locator

Zhou Xing
Syracuse University
on behalf of the LHCb VELO group

22nd RD50 Workshop, Albuquerque, NM, USA

The LHCb detector

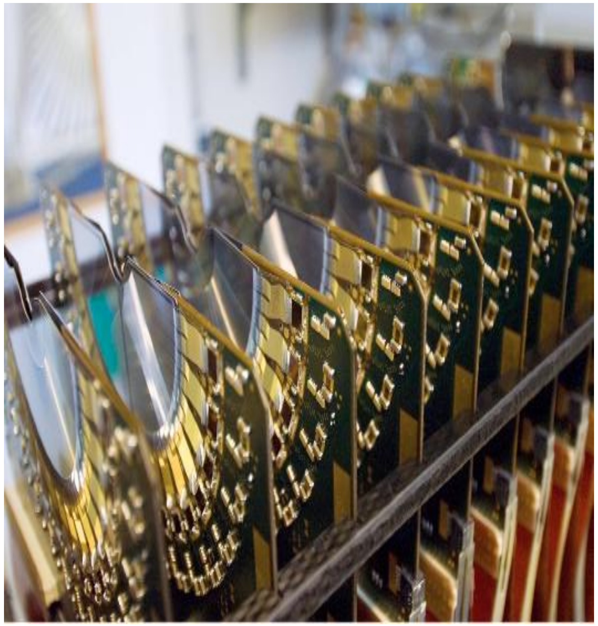
➢The LHCb experiment is dedicated to searching for New Physics in the heavy flavor sector including measurements of CP violation and rare decays

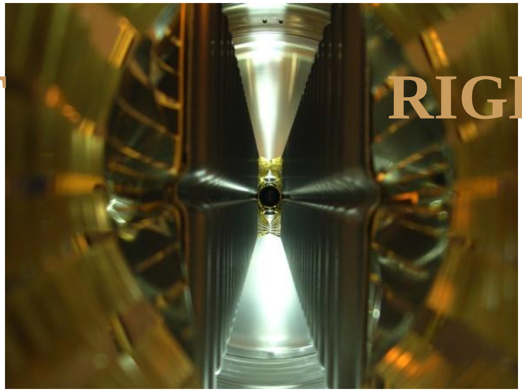


➢Single-arm spectrometer covering the forward $b\bar{b}$ production

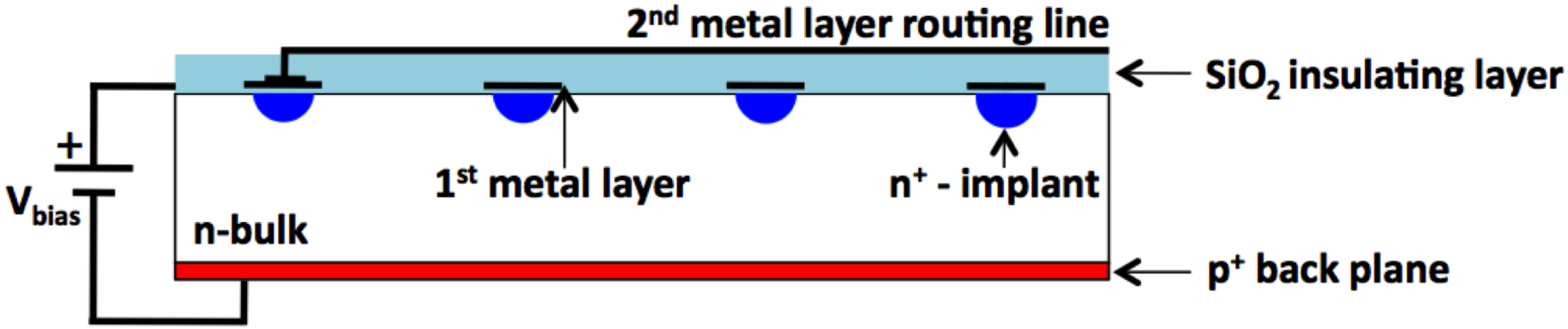
The LHCb Vertex Locator

- VELO (VErtex LOcator) silicon micro-strip detector is the highest precision vertex detector at the LHC with its inner radius only ~8 mm from the proton beams (first active strip)
- It consists of mostly n^+-on-n silicon sensors (only 1 n^+-on-p module).
- R-φ measuring strips: pitches 40-120 μm, thickness 300 μm
- Evaporative CO_2 cooling system
- Silicon operating temperature ~ -8 °C
- Two halves retracted to 30 mm during beam injection

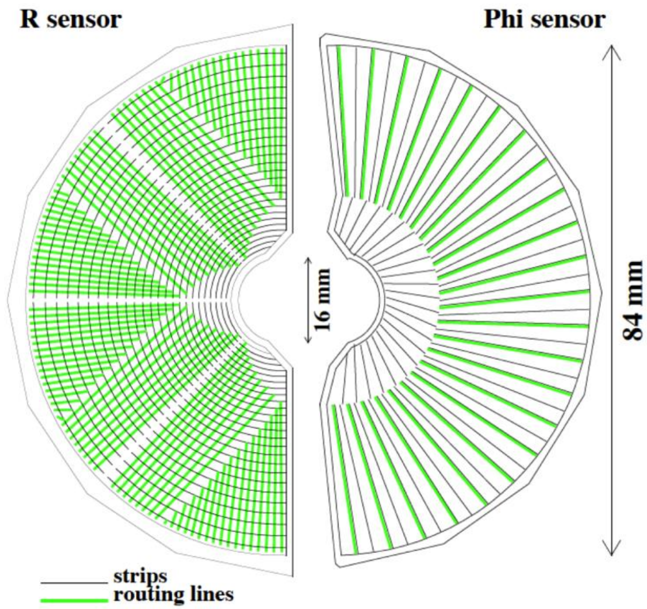




Double metal readout lines



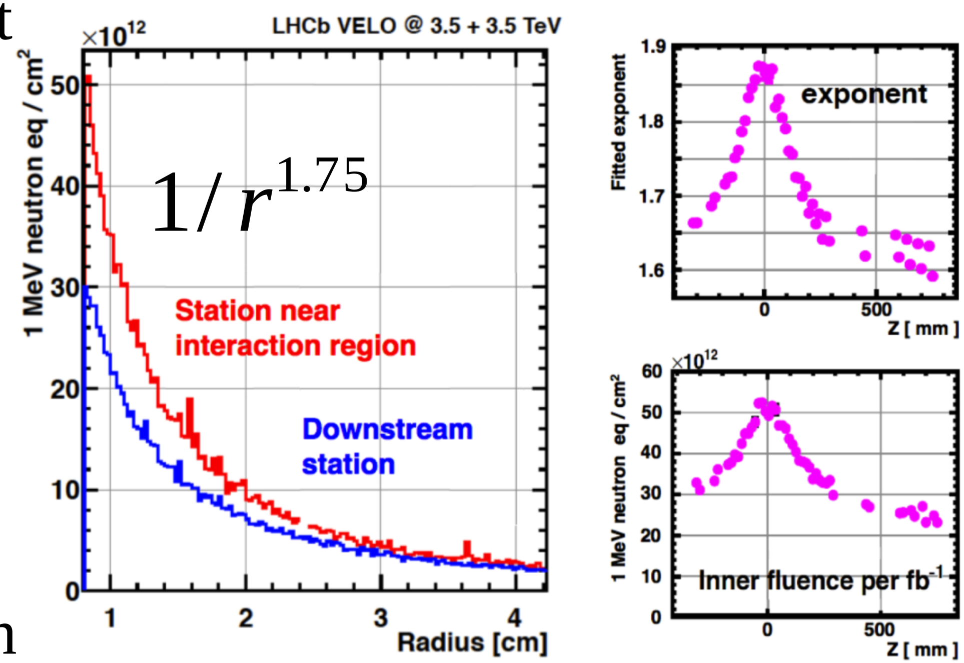
- Each n$^+$ implant is read out via a capacitively coupled first metal layer
- Strips connected via a second metal layer routing line to the edge of the sensor where the readout electronics are located
- Routing lines perpendicular to R sensors strips and parallel to φ-sensors strips



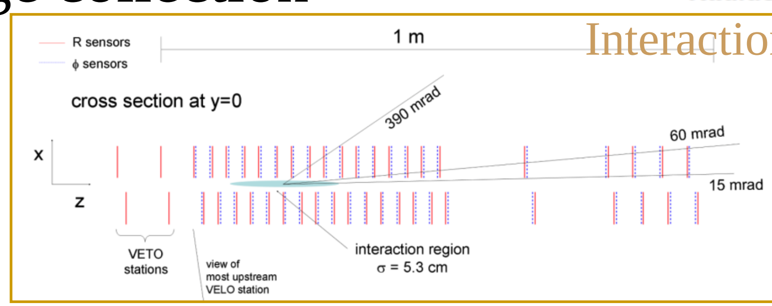
VELO radiation environment

- ➢VELO operates in a harsh and non uniform radiation environment
- ➢At the nominal LHC energy, VELO accumulates ~ 0.5×10^{14} n_{eq} /cm^2 in the inner most region per fb^{-1}
- ➢Bulk damages caused by defects
  - ➢Change of V_{dep}
  - ➢Increase of I_{leak}
  - ➢Decrease of charge collection efficiency

Fluence profile per fb^{-1} (Simulation)



Interaction point z~0 mm



Current in irradiated silicon sensors (simple view)

Current = bulk current + surface current

- ❑Increases with fluence
- ❑Exponential dependence on temperature
- ❑Should saturate with HV

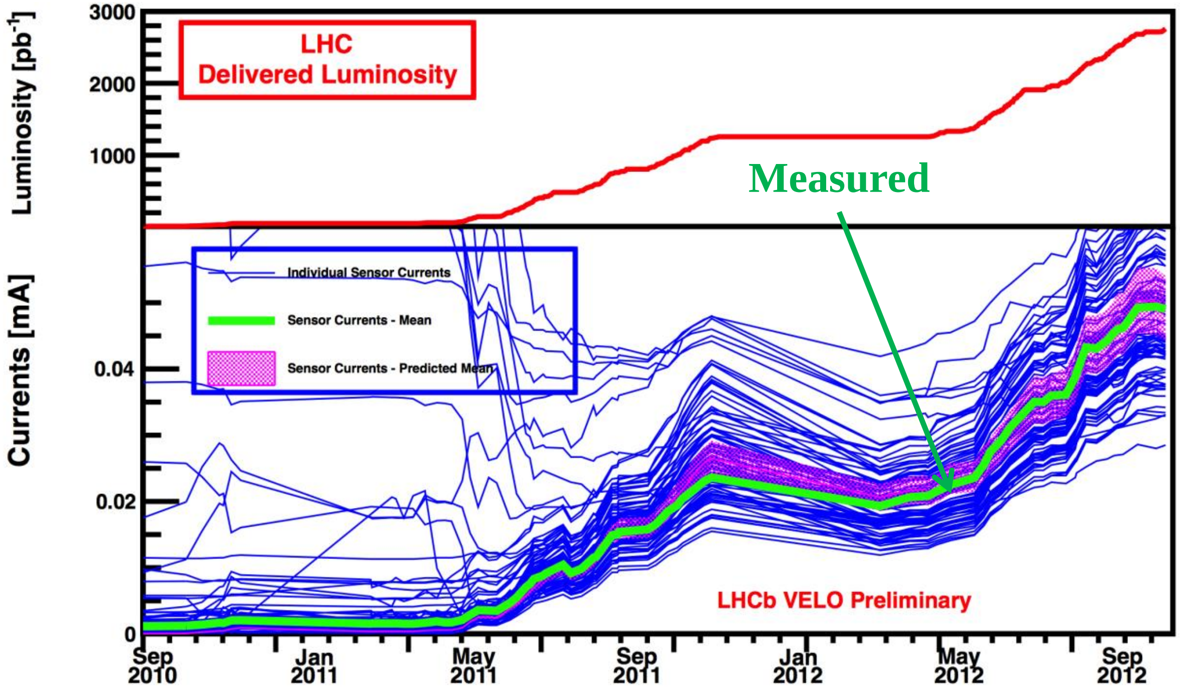
- ❑Decreases with fluence (usually)
- ❑Flat or weak temperature dependence
- ❑HV dependence

➢In order to follow the evolution of the bulk current we should disentangle the two

Bulk current measurements

3 fb^{-1} delivered luminosity

- Bulk current in silicon well predicted and provides an important probe of accumulated fluence
- Currents measured in operational conditions without beam

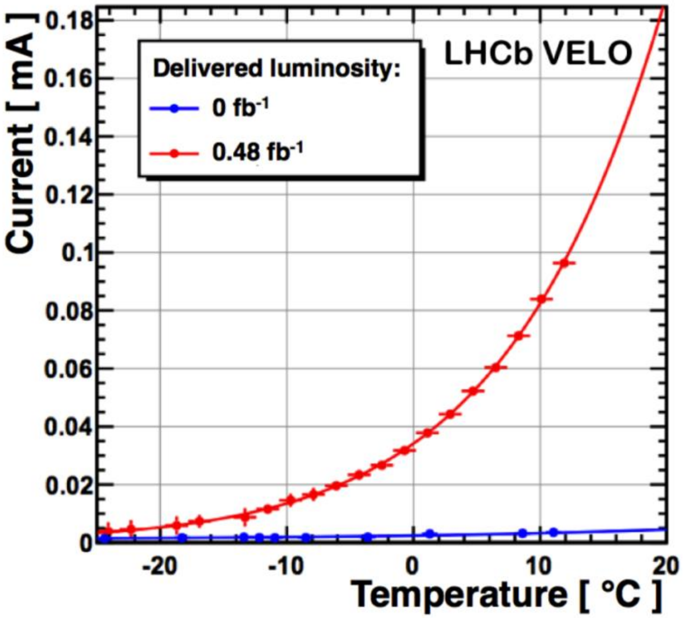


- The majority of the sensors show a sharp increase in bulk current as the sensors get more irradiated
- Consistent with MC predictions

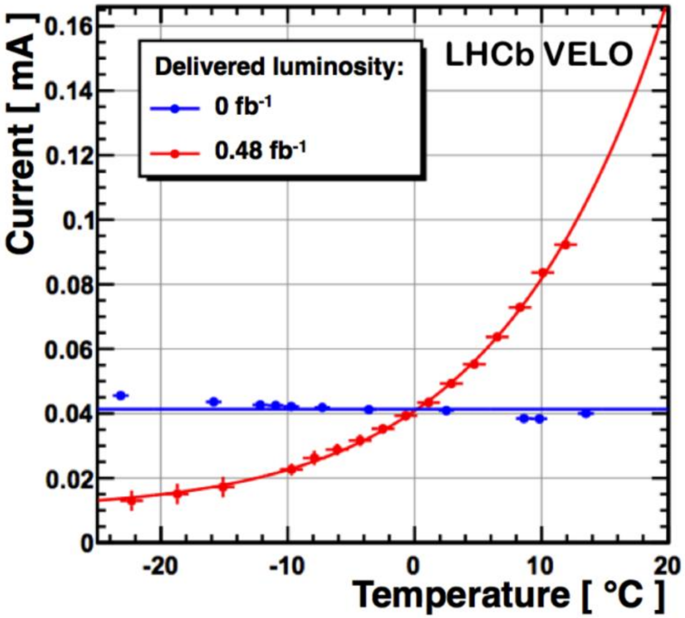
LHCb-PUB-2011-020
LHCb-PUB-2011-021

Current vs. temperature

- The Current vs. temperature (IT) scan have been used to precisely extract the leakage current and monitor its evolution with accumulated radiation.
- It can also disentangle bulk current from surface current



Bulk current dominated sensor both before and after irradiation



Surface current dominated sensor before irradiation, Bulk dominated after

Effective band gap energy

- I-T curves can give a measure of effective band gap

$$I(T) \propto T^2 \exp(\frac{-E_g}{2kT})$$

- $E_g = 1.16 \pm 0.06$ eV (weighted average)

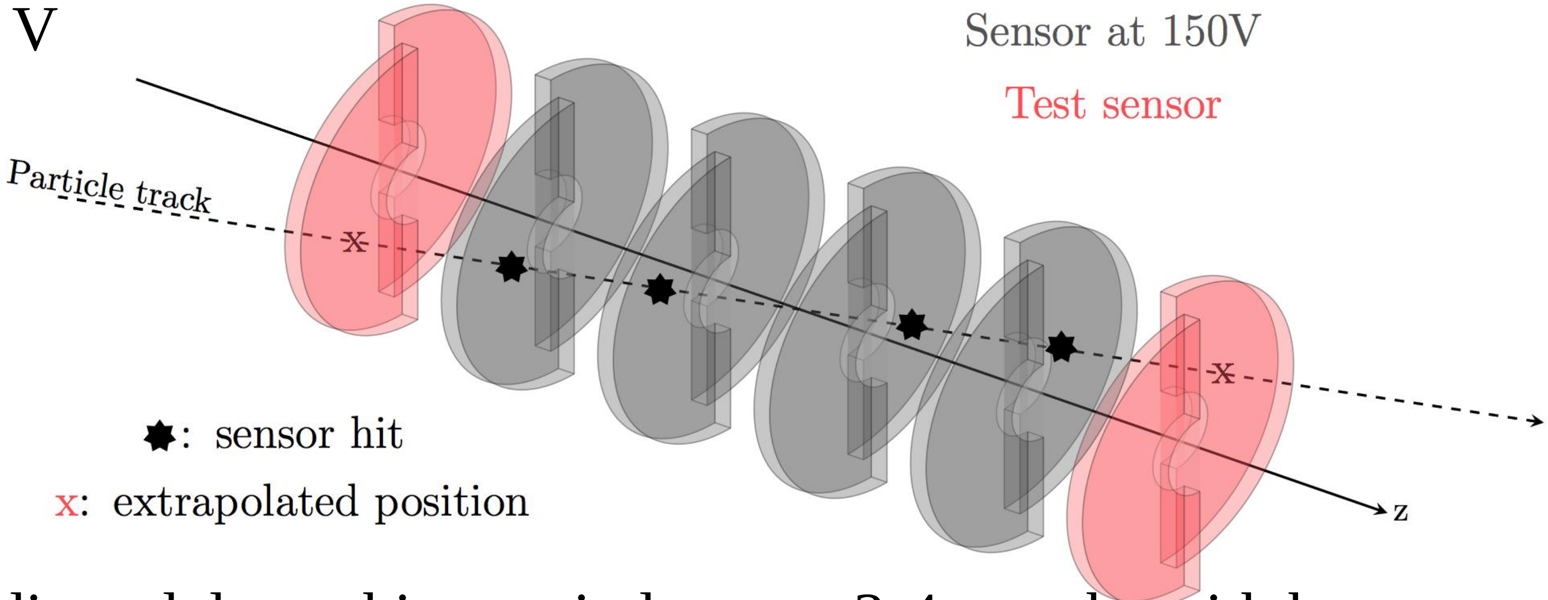
Delivered luminosity [fb^{-1}]	Bias voltage [V]	E_g [eV]
0.48	100	$1.17 \pm 0.07 \pm 0.04$
0.48	150	$1.18 \pm 0.05 \pm 0.04$
0.82	150	$1.14 \pm 0.06 \pm 0.04$
1.20	150	$1.15 \pm 0.04 \pm 0.04$

compared to 1.21 eV from A. Chilingarov, Tech. Rep. PH-EP-Tech-Note-2013-001

LHCb-PUB-2011-020
LHCb-PUB-2011-021
CERN-LHCb-DP-2012-005 **arXiv:1302.5259**

Charge Collection Efficiency Scan

➢Method of Charge Collection Efficiency (CCE) measurements, with tracking sensors biased at 150 V and test sensors biased from 0 to150 V

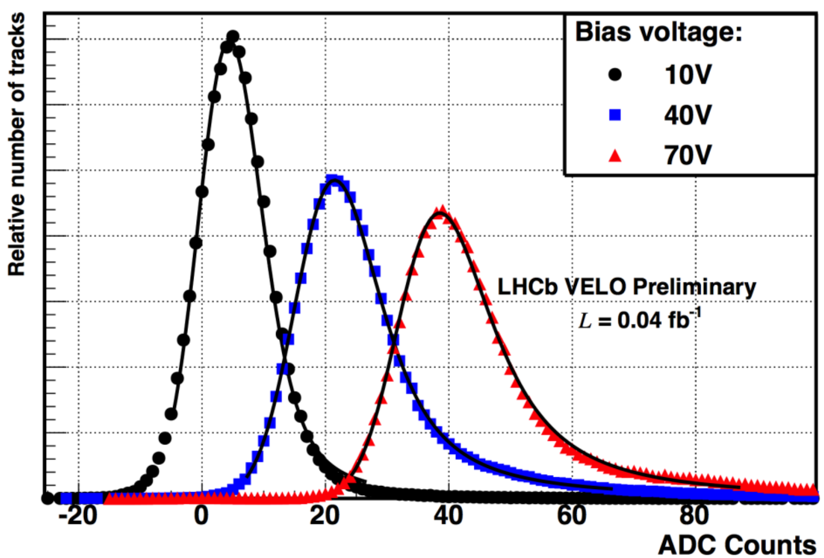


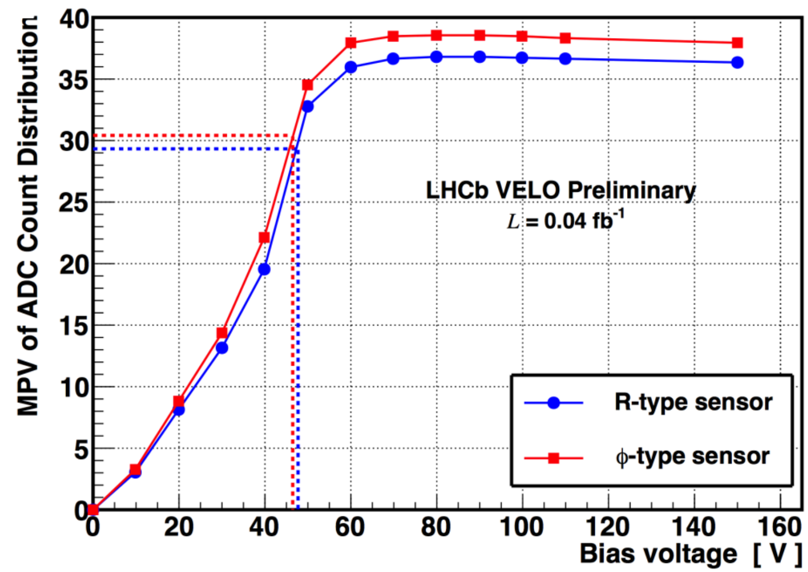
➢Dedicated data taking periods every 3-4 months with beam collisions

➢Extrapolate tracks to the test sensor and determine amount of charge collected

Effective depletion voltage

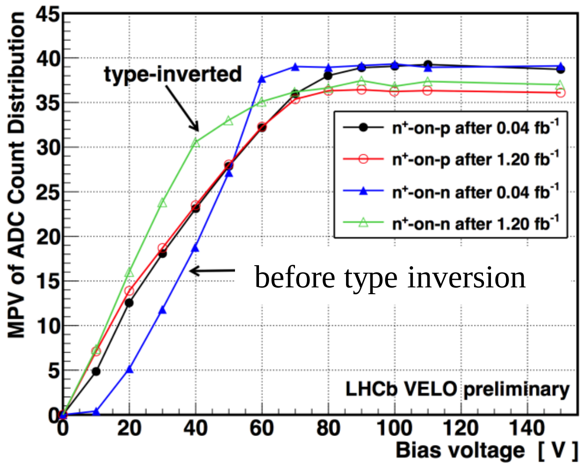
- A single module, using 2010 CCE scan data
- Effective Depletion Voltage (EDV) is defined as the biasing point where MPV is 80% of the maximum

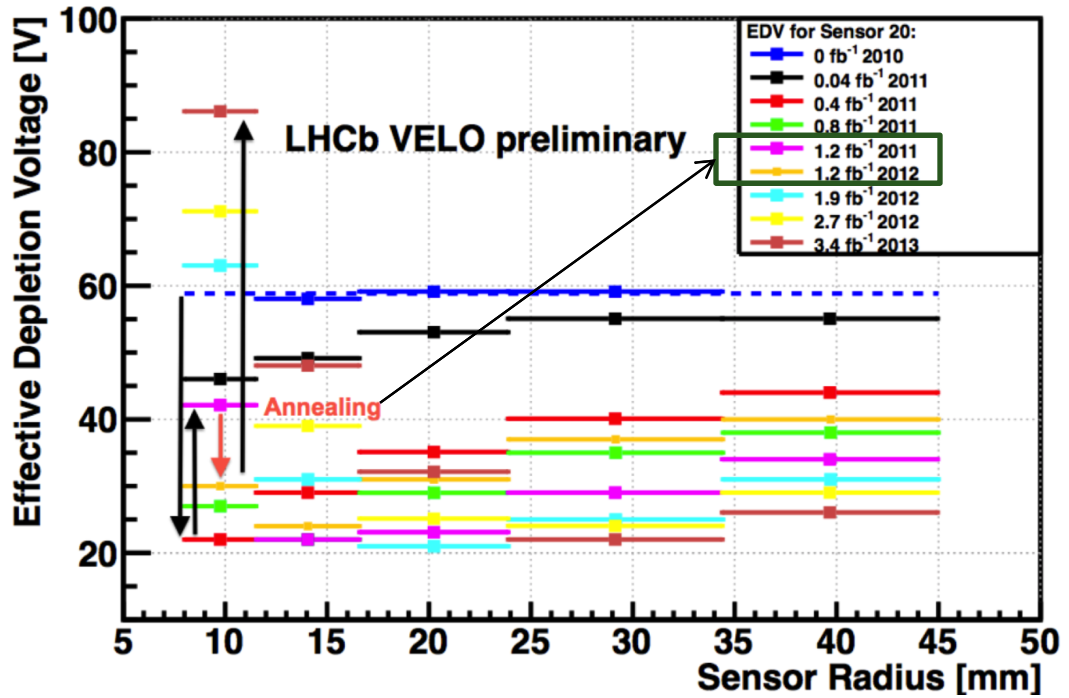




Fluence dependence I

- ➢EDV decreases with fluence before type-inversion
- ➢EDV increases with fluence after type-inversion
- ➢Type-inversion starts in inner radial regions

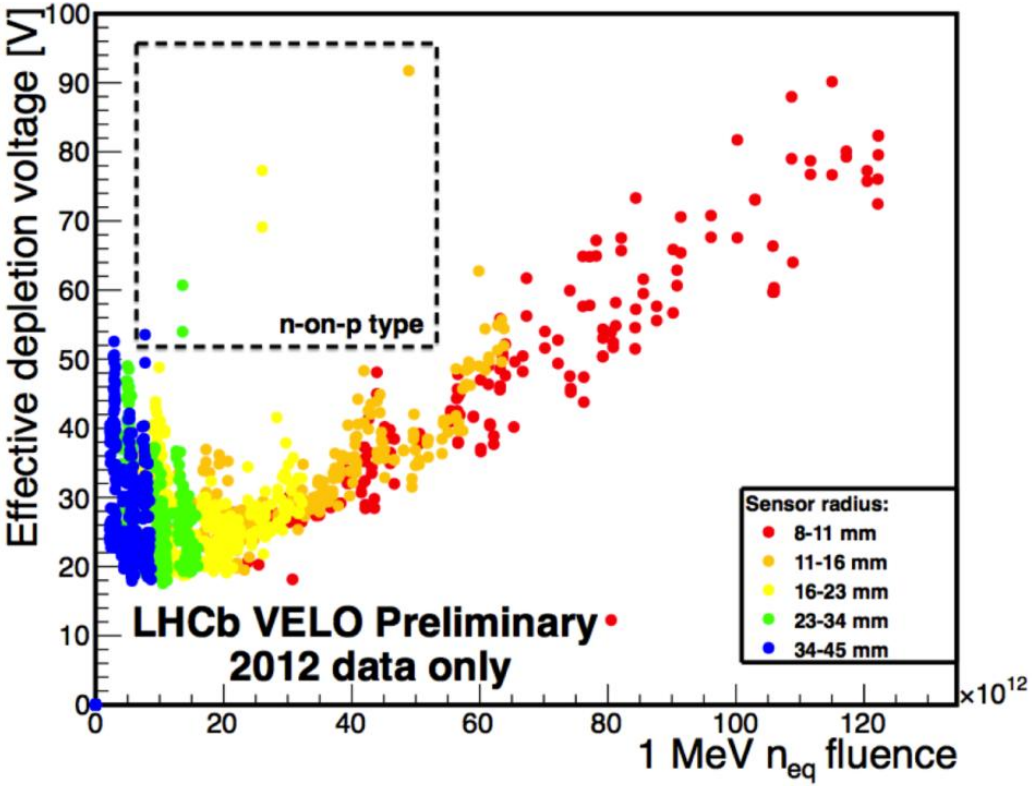




a single sensor, n type sensor

Fluence dependence II

- Observed EDV has a minimum of ~18 V before type-inversion
- Type-inversion occurs at 15×10^{12} n_{eq}/cm^2
- EDV of the p sensors begin to increase having received significantly less fluence than n type sensors

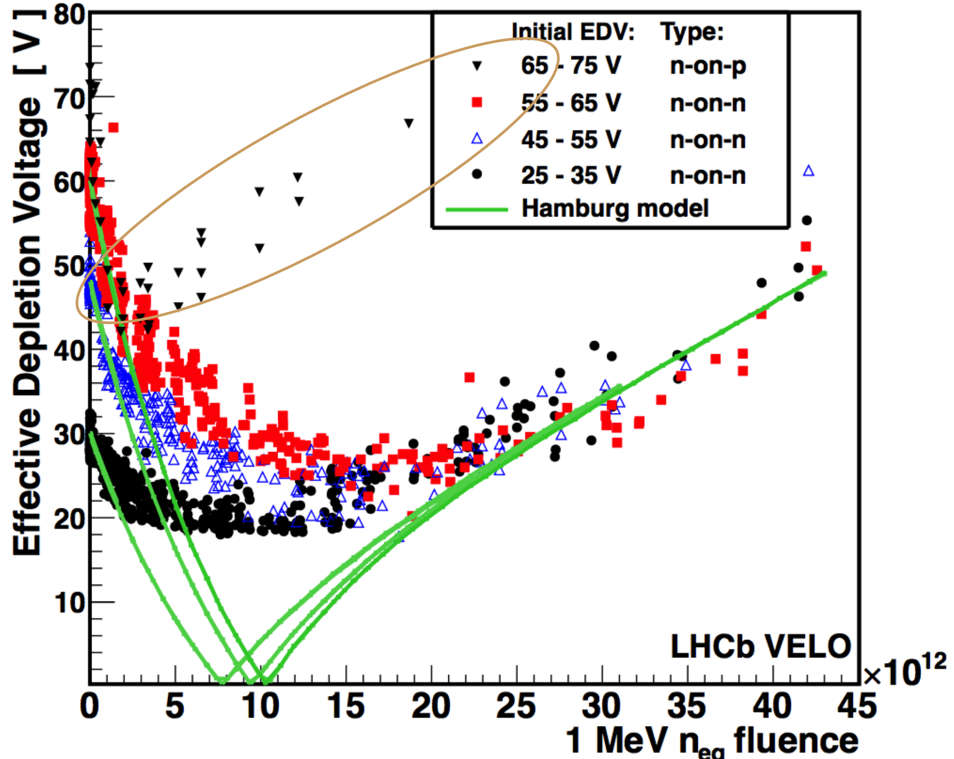


All sensors included

p sensors have no tracks in the inner most regions

Hamburg Model Comparison

- ➢The irradiation-induced change in the depletion voltage is modeled as a function of time, temperature and fluence by Hamburg Model

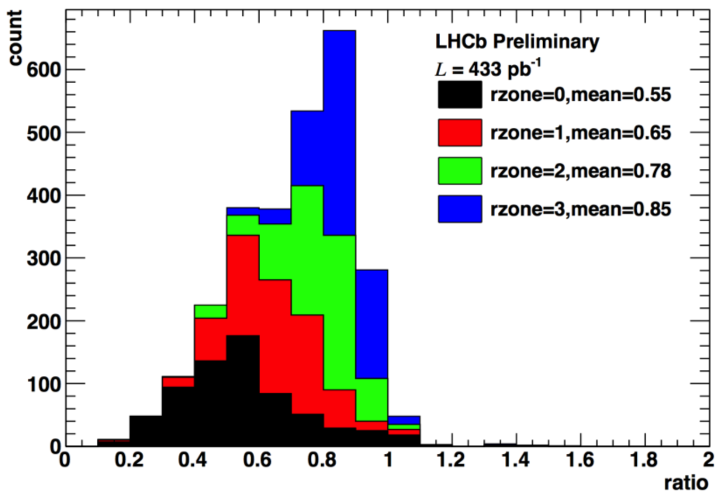


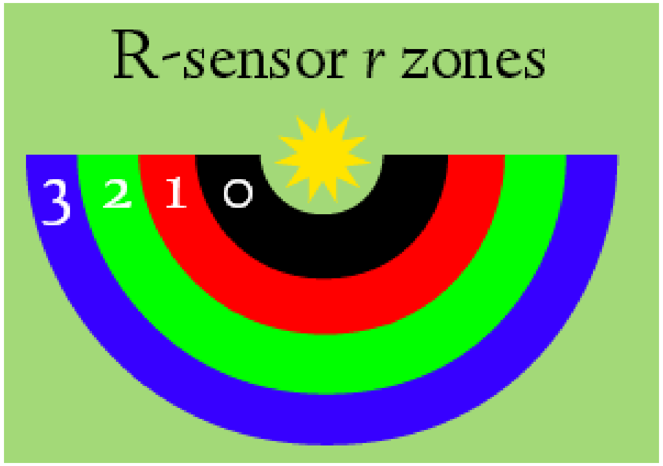
- ➢Good agreement at low and high fluences
- ➢Discrepancy around type-inversion point due to finite charge collection time

R. Wunstorf *et al.*, *Results on radiation hardness of silicon detectors up to neutron fluences of* 10^{15} n/cm^2, Nucl. Instrum. Meth. **A315** (1992), no. 13 149 .

Noise behavior

No beam crossing





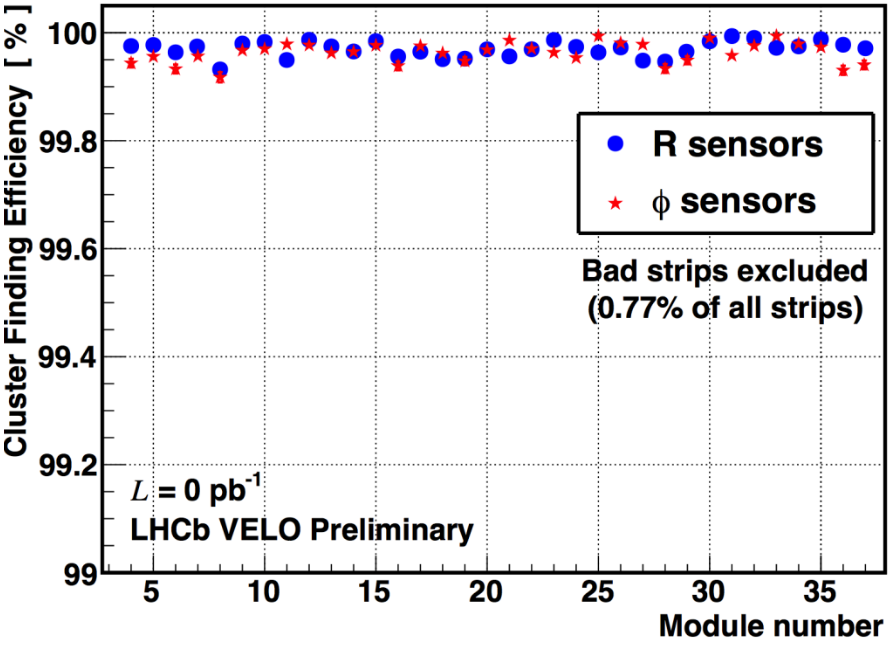
- ➢Noise vs bias voltage can be used to extract the EDV of the sensor
- ➢Ratio of irradiated EDV to unirradiated EDV (final/initial) plotted as a function of radius (before type inversion)

Cluster finding efficiency

➢A high cluster finding efficiency is important to elements of tracking and vertexing

➢Cluster Finding Efficiency (CFE) measured by comparing the track extrapolation to locally reconstructed cluster

Before irradiation

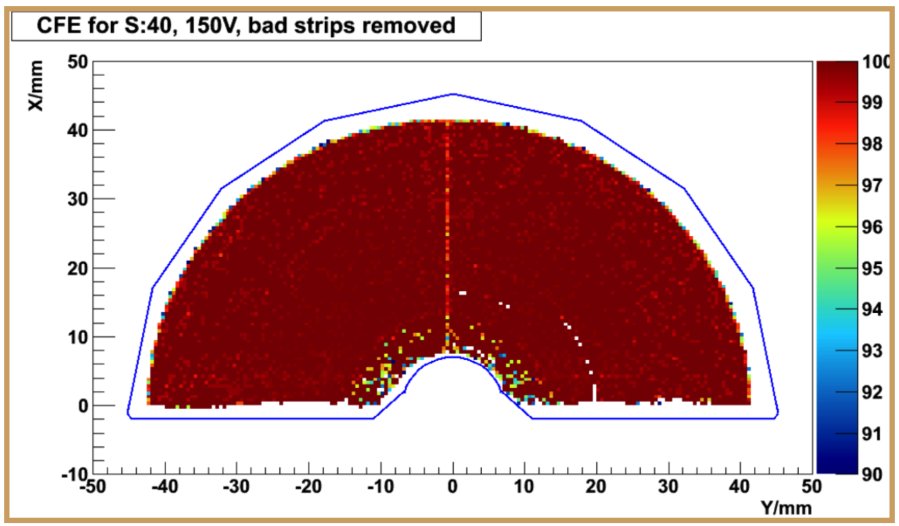


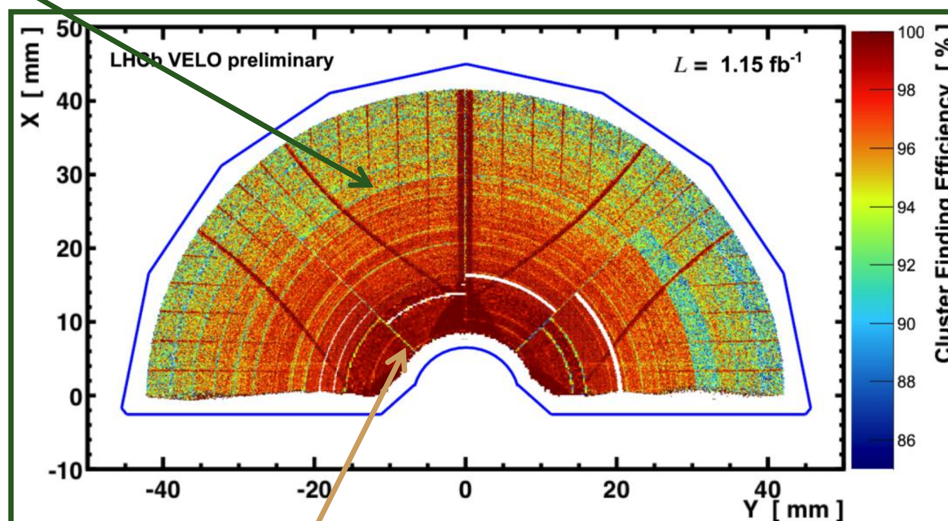
Charge loss due to double metal effect

- March 2011, after 40 pb^{-1}
- CFE is ~ 100% across the whole sensor

- Oct. 2011, after 1.15 fb^{-1}
- Outer region sensors have reduced efficiencies
- High efficiency regions in absence of routing lines

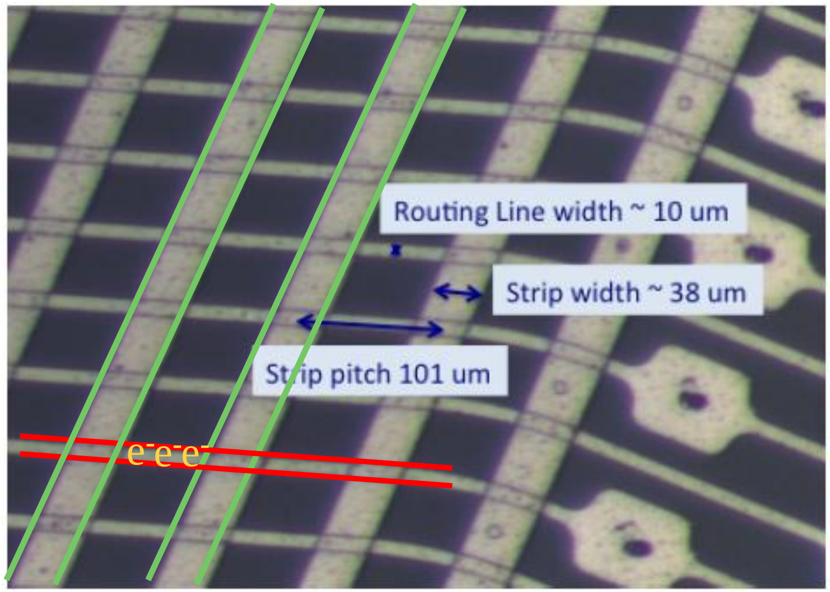
double metal coverage

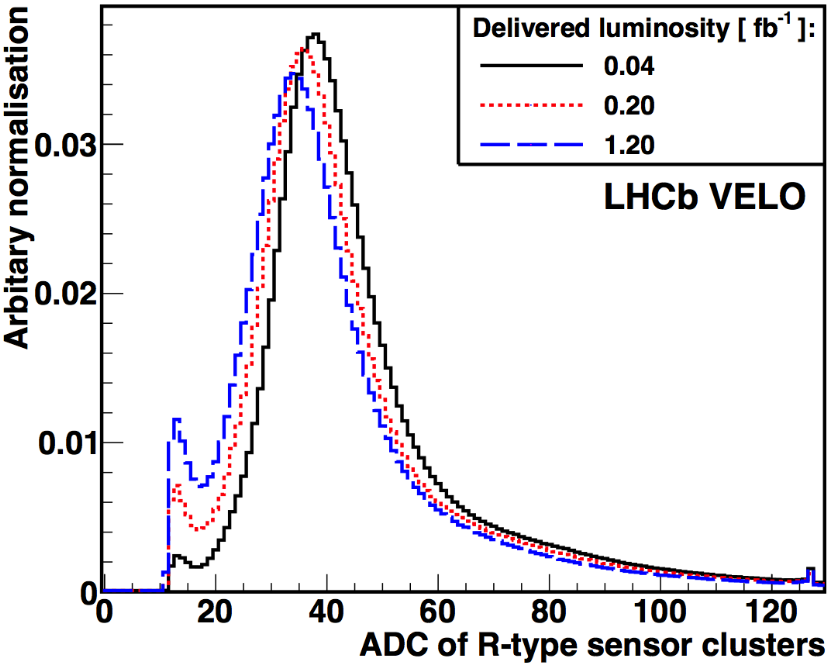




No double metal coverage

Charge coupling on 2nd metal layer



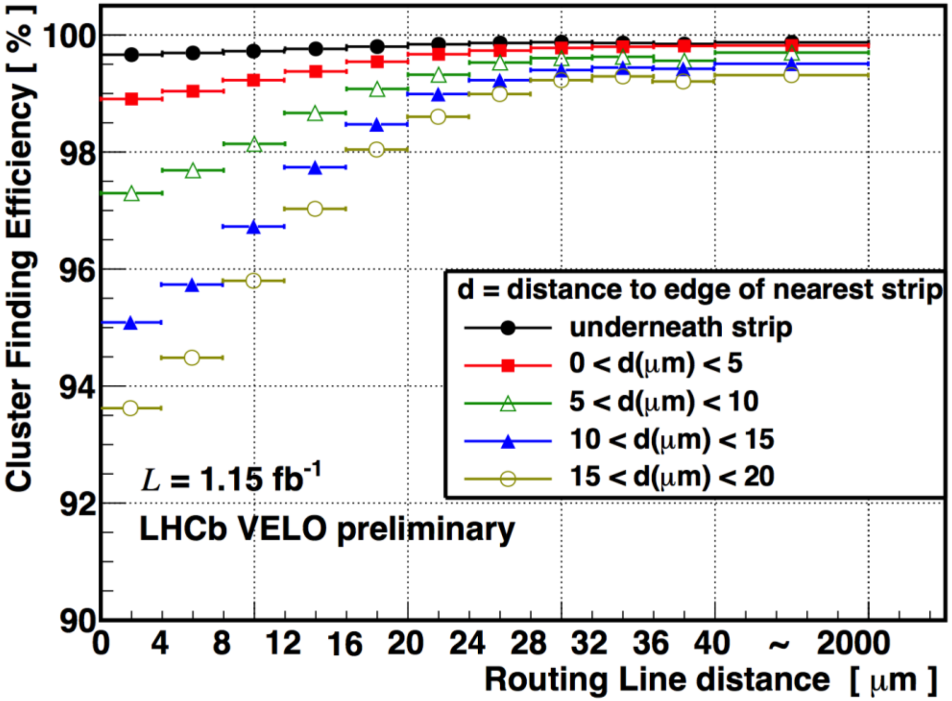


- ➢Radiations can change the field profile across the inner sensor which induces a capacitive coupling of charges to routing lines for R-sensors
- ➢This coupling through routing lines reduces cluster finding efficiency
- ➢Charge induced on a routing line can introduce a noise cluster for the inner R sensors

Dependence of the coupling

- Coupling is shielded when the track is close to the strip

- Coupling causes larger inefficiencies when the track is close to the routing line



Conclusions

- Radiation damage effects are studied with several monitoring methods
  - Current measurements (vs time, temperature) gain insights on measuring fluence and aging
  - Change of depletion voltage with fluence agrees well with expectations
  - Noise measurements can also monitor the radiation
  - Other effects: cluster finding efficiency decrease observed in some regions of R-sensors due to second metal layer effect
- Currently no significant effect on physics performance

A. Affolder et al.
Radiation Damage in the LHCb Vertex Locator
Submitted to JINST(e-print arXiv:1302.5259 [hep-ex], CERN-LHCb-DP-2012-005)