

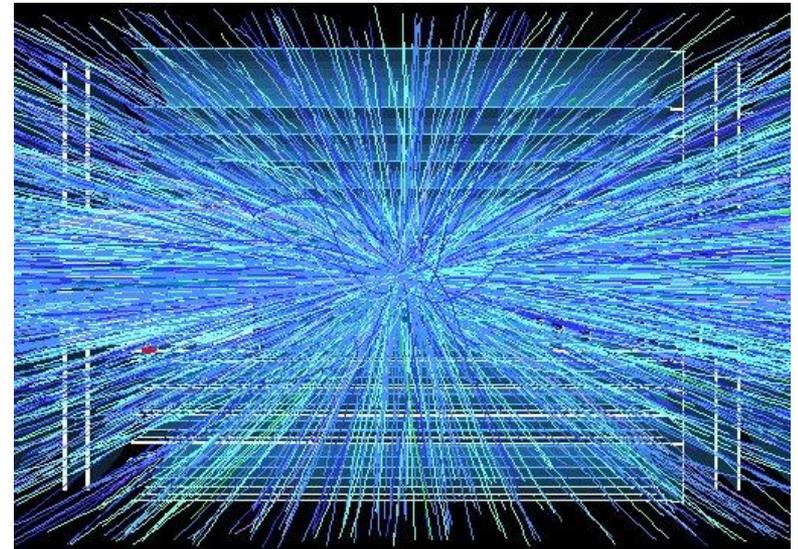
Radiation Damage monitoring in LHCb Vertex Locator



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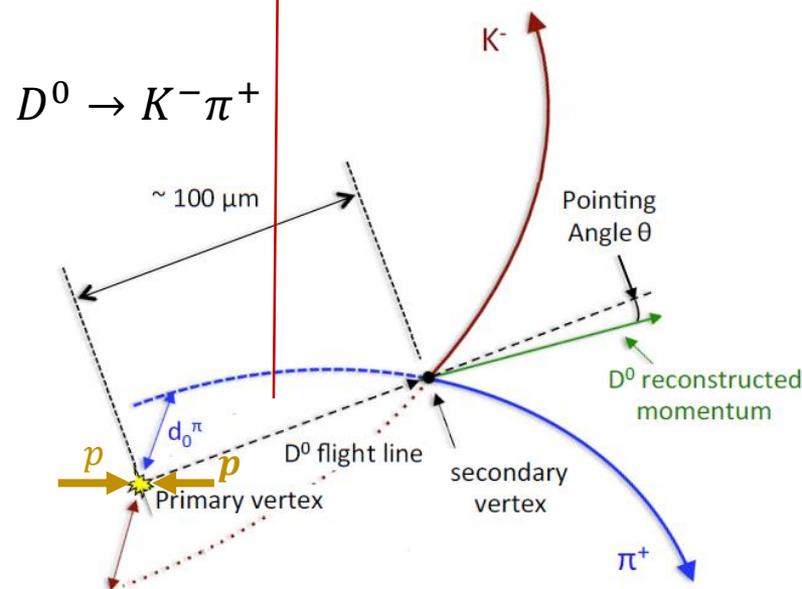
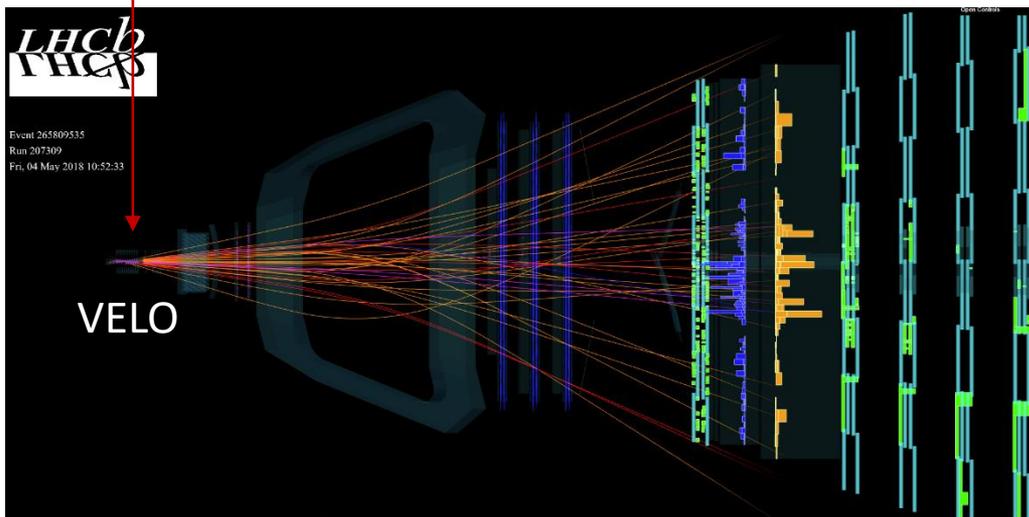
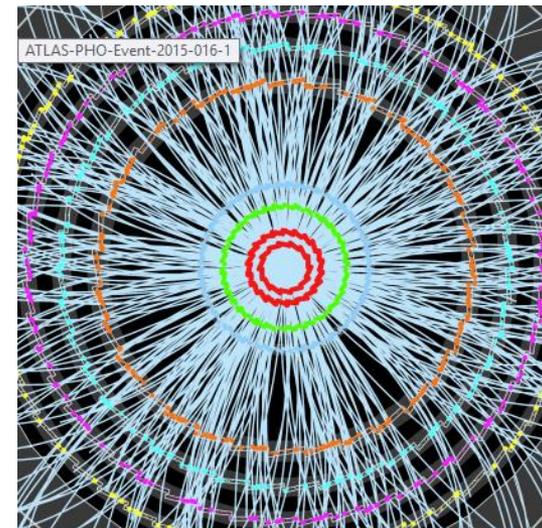


1. Why silicon trackers?
2. LHCb and VELO detector.
3. Radiation induced changes in properties of the silicon tracking detectors.
4. Radiation damage monitoring in the LHCb VELO.
5. Development of new structures:
 - 3D Pixels,
 - HVCMOS,
 - LGAD.
6. Measurement technique: TCT.



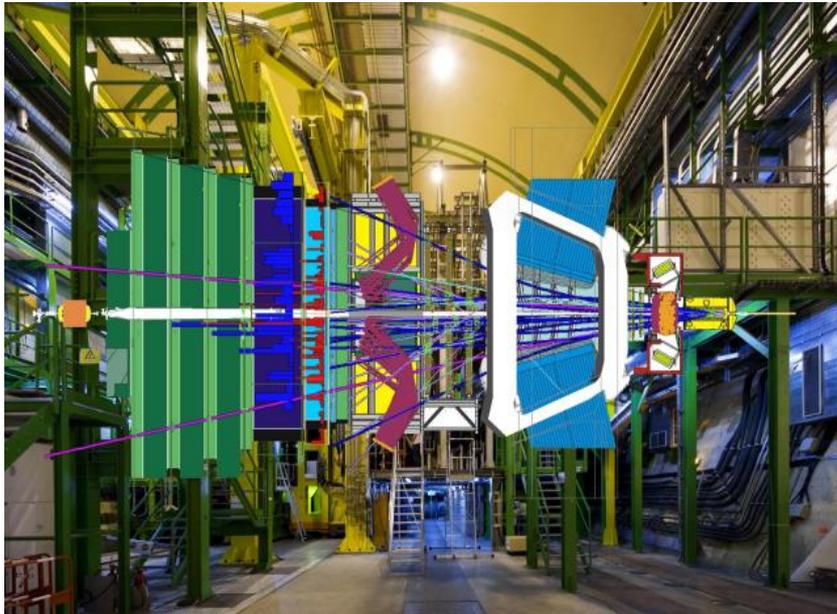
Simulation of 400 proton-proton collisions in just one 25 ns bunch crossing at the HL-LHC

- LHC parameters:
 - proton-proton energy: $E_b = 3.5 - 6.5$ TeV,
 - pp total cross-section: above 101 mb,
 - Luminosity: about $2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
 - bunch-crossing: 50 ns, 25 ns,
 - 200-2000 particles produced in one X-ing,
- ➔ hostile radiation environment



The detector dedicated for studying flavour physics at LHC.

Especially **CP violation and rare decays of beauty and charm mesons.**

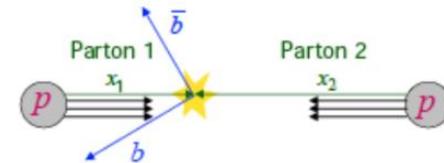


Physics program:

- **CP Violation**,
- **Rare B decays**,
- B decays to charmonium and open charm,
- Charmless B decays,
- Semileptonic B decays,
- Charm physics,
- B hadron and quarkonia,
- QCD, electroweak, exotica ...

$$\sigma_{b\bar{b}} = (75.3 \pm 14.1) \mu\text{b}$$

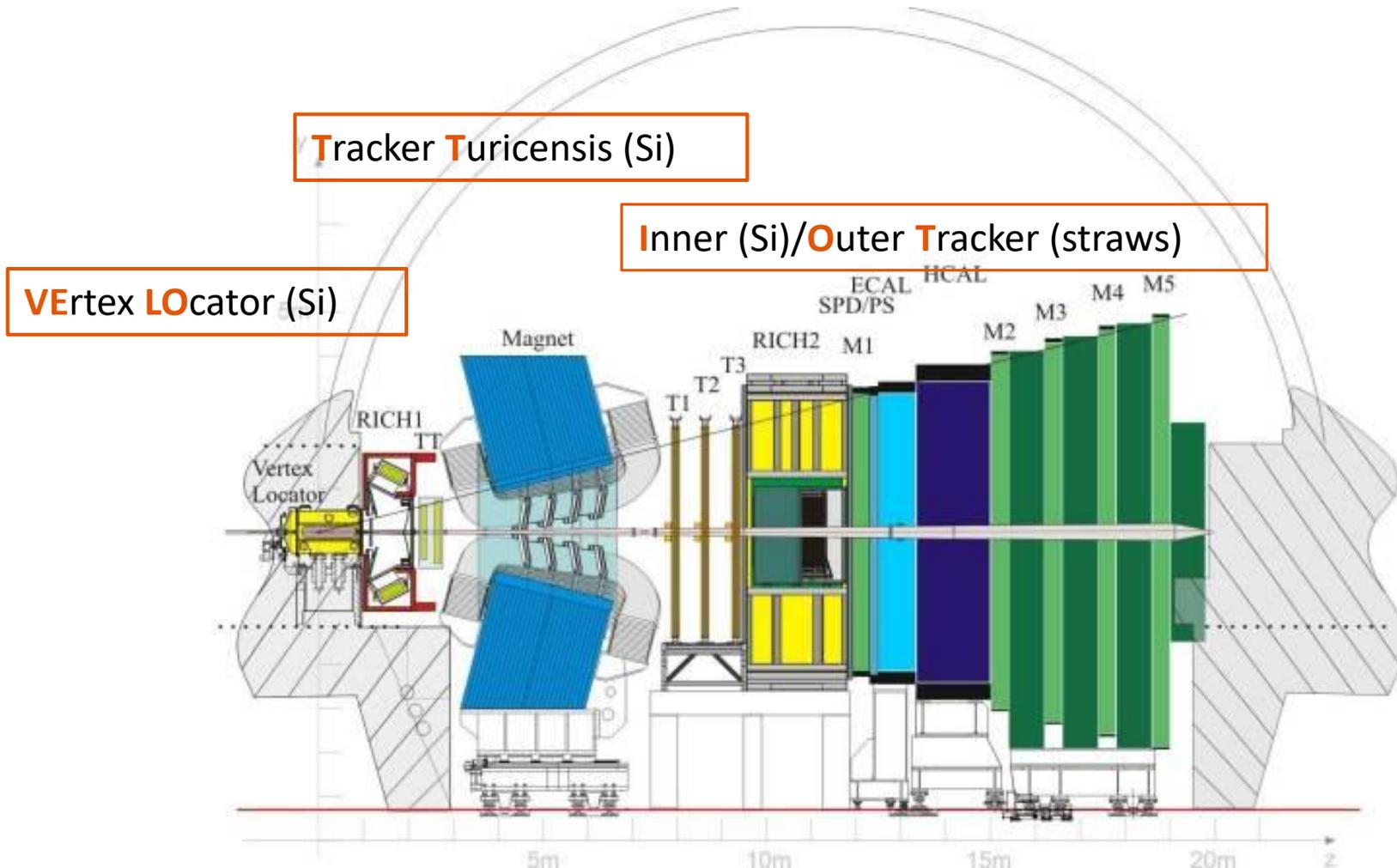
$$\sigma_{c\bar{c}} = (1419 \pm 133) \mu\text{b}$$



Excellent performance:

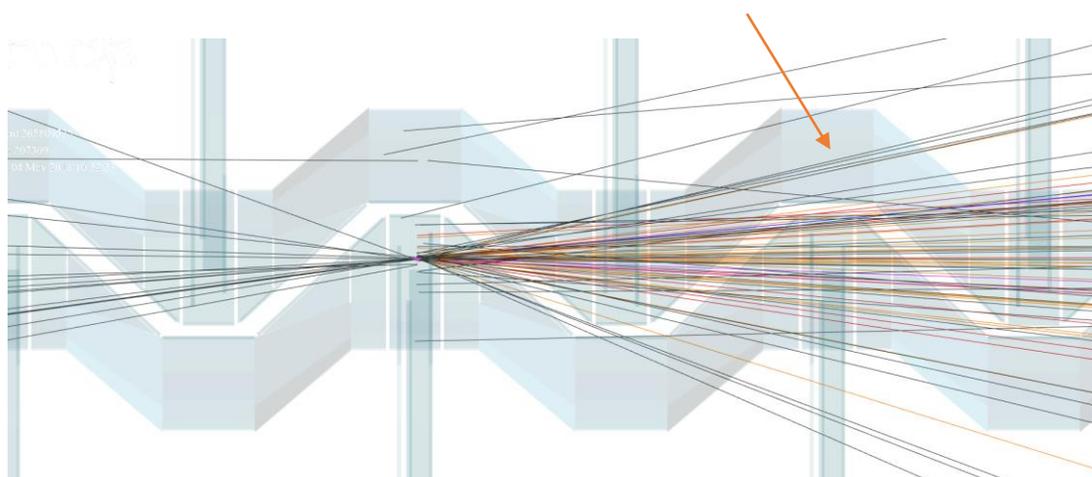
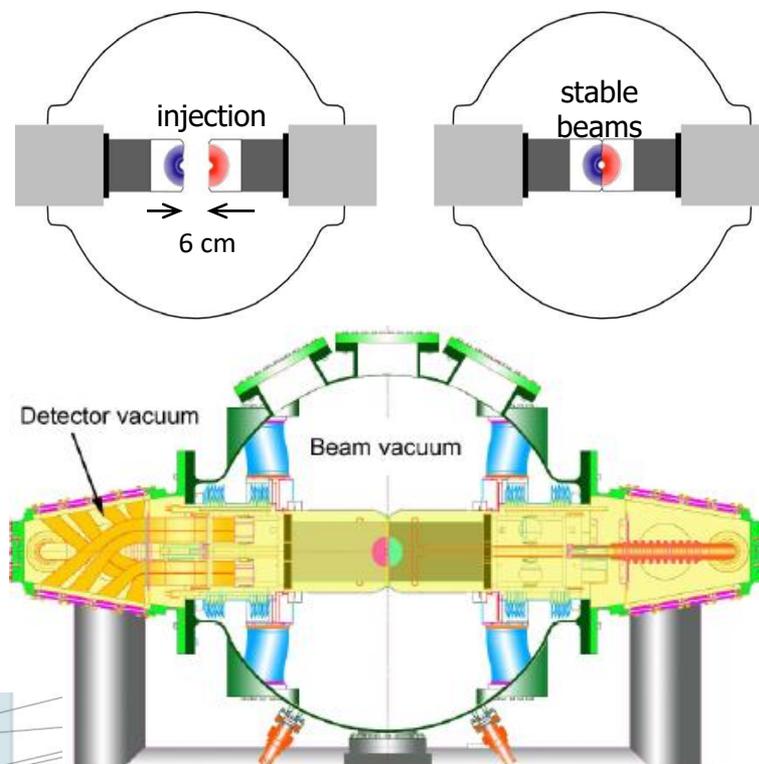
- 3 fb⁻¹ accumulated in RUN I
- 3.26 fb⁻¹ in Run II
- **Excellent Time and Vertex Resolution**
- Precise tracking: $\delta p/p \sim 0.4 - 0.6\%$
- Hadronic identification 2-100 GeV/c

SI TRACKING DETECTORS:



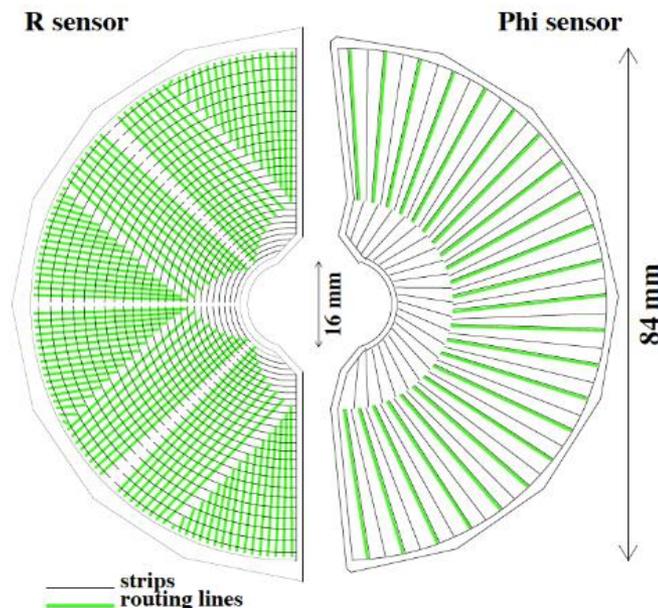
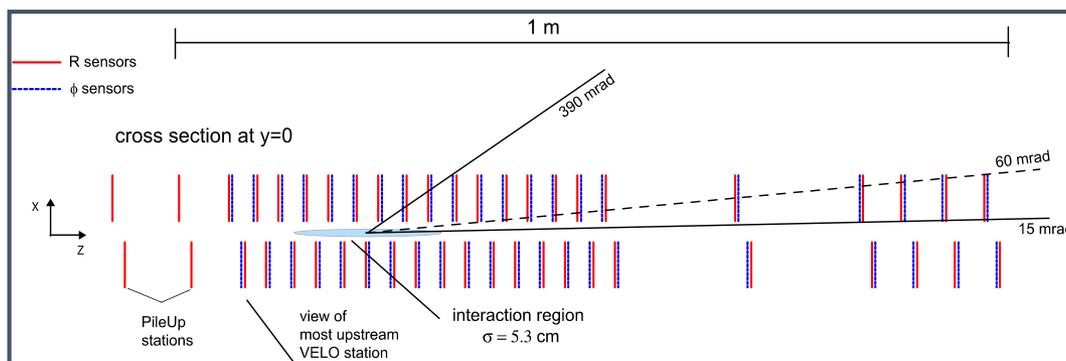
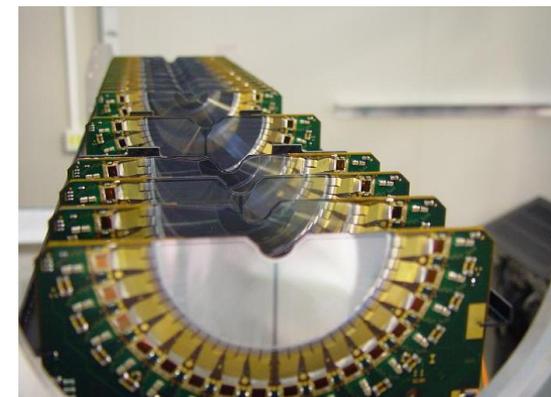
VERtex LOcator

- Close proximity of the beam-pipe.
- VELO halves are movable- the movement is steered by a precise system (accuracy of $10\ \mu\text{m}$),
- When stable beams, the silicon edge is only 8 mm from the proton beam – **sensors are in harsh particle fluence** .
- Designed to tolerate 5 years running at LHC (!).
- Operated in a secondary vacuum, separated from the LHC vacuum by 300 μm thick aluminium foil.

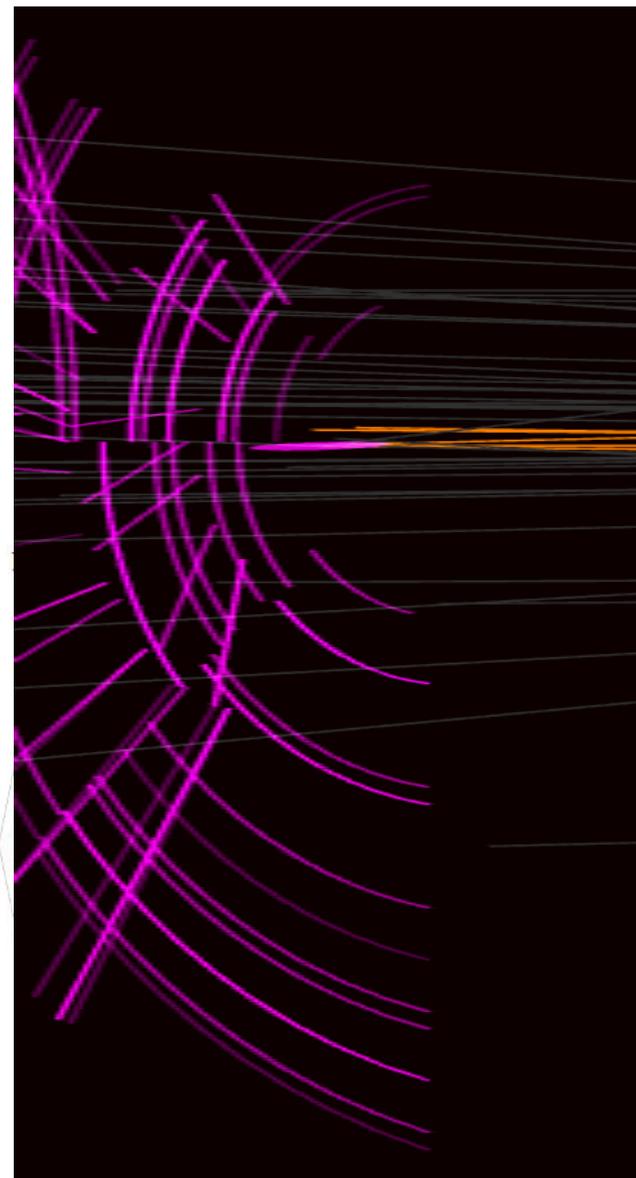
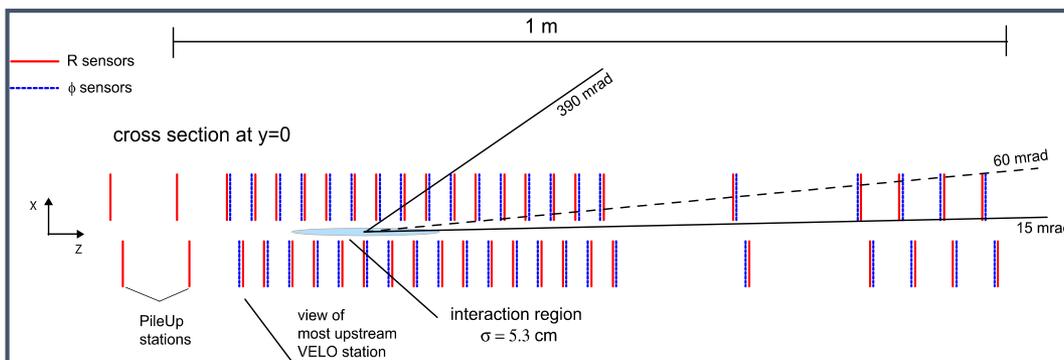


[Performance of the LHCb Vertex Locator, J. Instrum. 9 \(2014\) P09007](#)

- VELO consist of 42 modules (two halves).
- Modules have two (R and Phi) microstrip silicon oxygenated n^+ -on-n sensors (two sensors are n^+ -on-p).
- Evaporative CO₂ cooling system keeps sensors at -7°C.
- The geometrical acceptance of the VELO is 15-390 mrad – defines the acceptance for whole LHCb

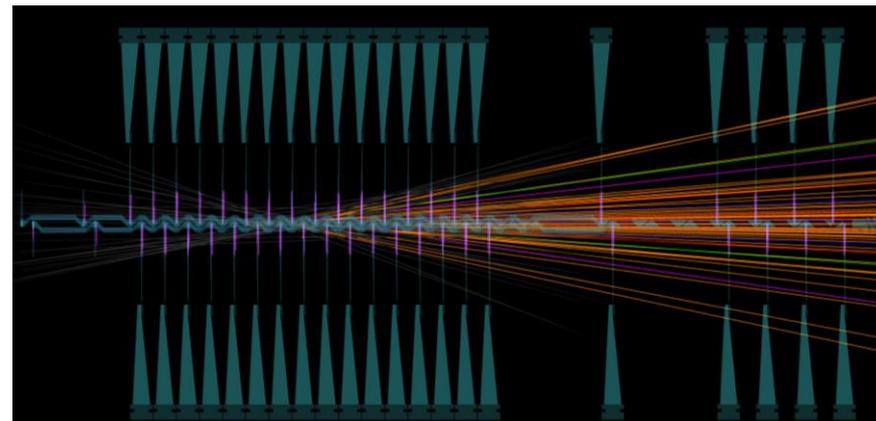


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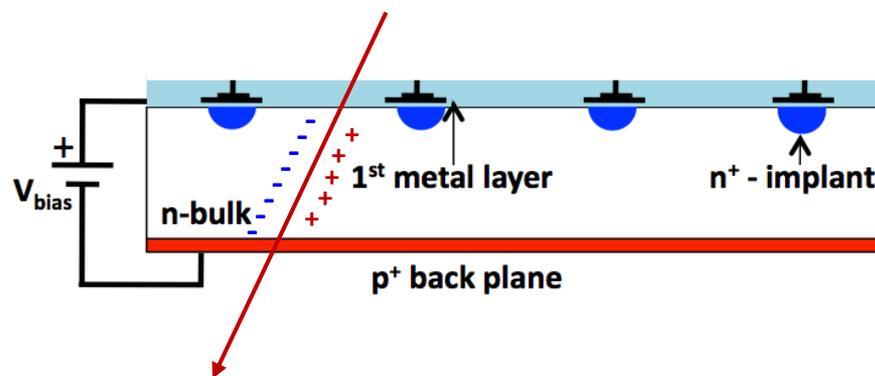
Physics motivation for the use of silicon trackers:

- position resolution of few micrometers,
- very good separation of close tracks,
- low ionization energy (3.6 eV) enables a high signal-to-noise ratio even for thickness 250-300 μm ($\rho=2.33 \text{ g/cm}^3$),
- high carrier mobility: $\mu_e=1450 \text{ cm}^2/\text{Vs}$ and short charge collection time (10 ns).
- large-scale availability and relatively low cost due industrial mass production



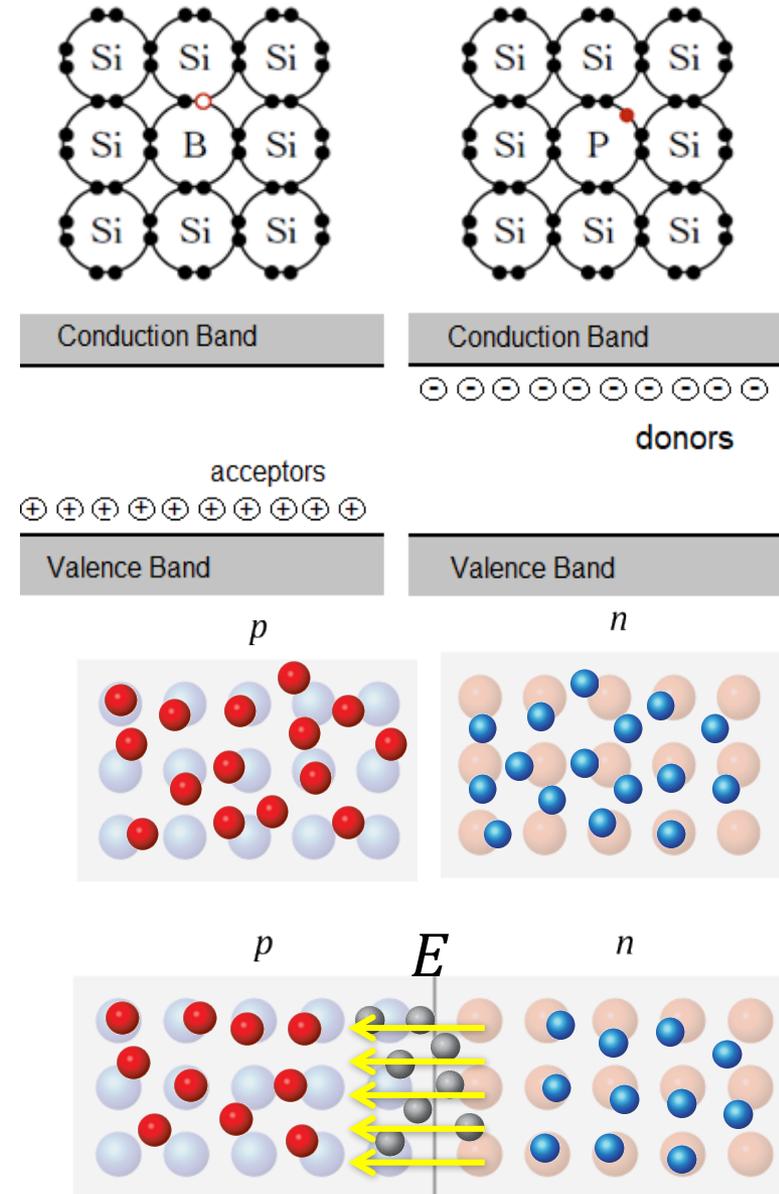
Semiconductor detectors are basically solid state ionization chambers.

In contrast to energy spectroscopy, in high energy tracking experiment, a particle deposits only a small fraction of its total energy, created charge carriers are collected by segmented detector (strips or pixels).

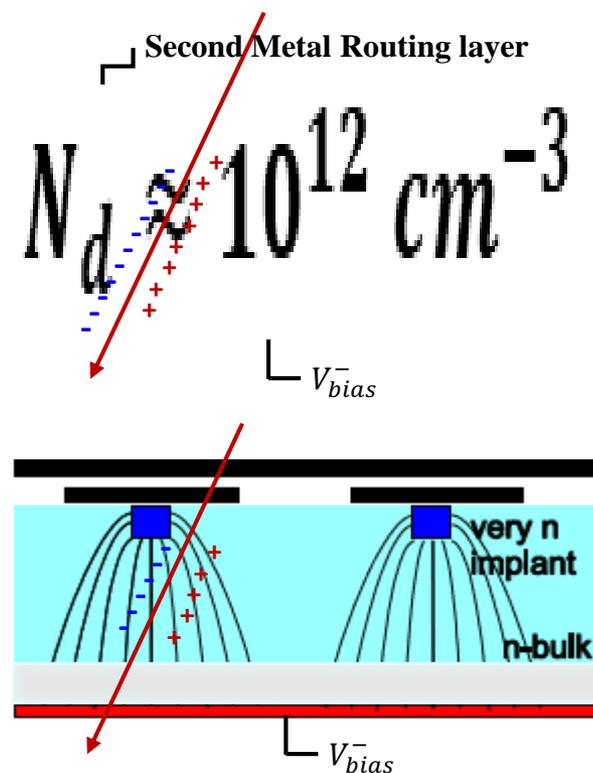
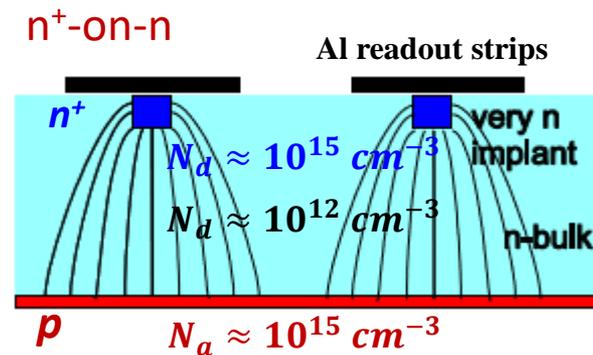


Multiple layers of detectors make a track reconstruction possible.

- Silicon belongs to IV group with four valence electrons which form a covariant bonding with the neighbour atoms.
- Si atom substituted by atom from V (P) or III (B) or group form an additional energy slightly below the conduction band (**donors, n-type**) and a bit above the valence level (**acceptors, p-type**).
- **At room temperature 99.6% of the donors electrons are ionized**, and therefore contribute to conduction. The same happens for holes.
- Once an n-type silicon is put into physical contact with a p-type silicon, the donors diffuse to the p-side and recombine with acceptors on p-side.
- The diffusion of electrons (majority carriers) leaves positive ions on the n-side and causes the excess of negative charge on the p-side. An electrical field builds up what prevents further diffusion.
- Region around the junction is free of charge and is called the **depletion zone**.
- The reverse bias is applied to broaden the depleted region



- VELO modules have two types (R and Φ) of microstrip silicon oxygenated n^+ -on-n sensors (two sensors are n^+ -on-p).
- Sensors are 300 μm thick, strip pitches: 40-100 μm .
- In case of abrupt junction: one side is heavily doped, (n^+ or p^+), the depleted region thickness extends much further into the low doped side of the junction. In case of n^+ -n junction, the n^+ region plays a role similar to p doped side.
- Sensors should operate when the whole active area is fully depleted; otherwise part of the created charge carriers cannot be collected by electrodes.
- The main danger to this fabulous properties of the silicon detector is the physical devastation of its fragile crystal and distortion of the electrical levels.



IONIZATION

- Ultimately associated with transfer of kinetic energy from incident particle to the bound electrons of the material substance.
- X-rays, gamma rays: ionization is mainly the result of the transfer of photon energy to a bound electron providing sufficient kinetic energy to detach the electron from the atom. If the electron is energetic enough, it too can further ionize.
- All charge particles that create free charge in materials, DIRECTLY through the coulombic interaction with the electrons of the substance.

Electronics tend to be most sensitive to ionization effects (SEU).

Detectors and sensors are sensitive to both effects, with the most important damage often coming from bulk effects.

ATOMIC DISPLACED EFFECTS

- Caused by particles (neutrons, pions, ions, even electrons) that can displace atoms from their position in lattice and produce damage in bulk of material; mainly **elastic interaction**.

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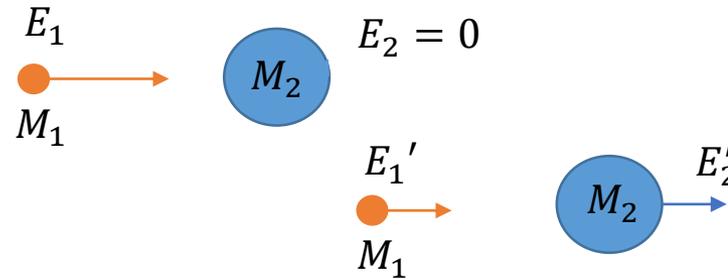
Electronics, because of the thin sensitive layer, tend to be most sensitive to ionization and the associated accumulation of charge in the material.

Detectors and sensors are sensitive to both effects, with the most important damage often coming from bulk effects.

ATOMIC DISPLACED EFFECTS

- Caused by particles (neutrons, pions, ions, even electrons) that can displace atoms from their position in lattice and produce damage in bulk of material; mainly **elastic interaction**.

- In elastic collisions kinetic energy is conserved.



- The maximum transferable energy for a given incident particle M_1, E_1 is:

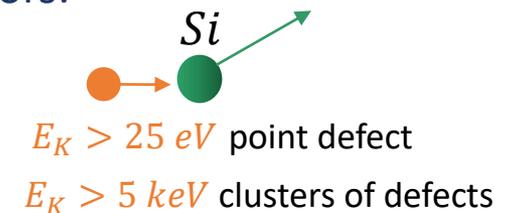
$$E_2' = E_1 \frac{4M_1M_2}{(M_1 + M_2)^2} \quad (\text{non-relativistic})$$

- The minimum energy of the incident particle to transfer to the target particle energy above a threshold:

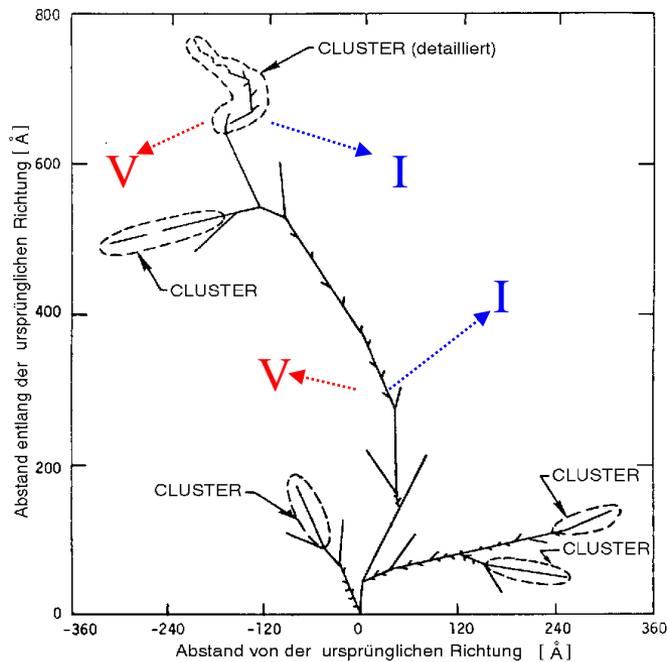
$$E_{min} = E_{th} \frac{(M_1 + M_2)^2}{4M_1M_2}$$

- Displaced damage threshold energies for a typical semiconductors:

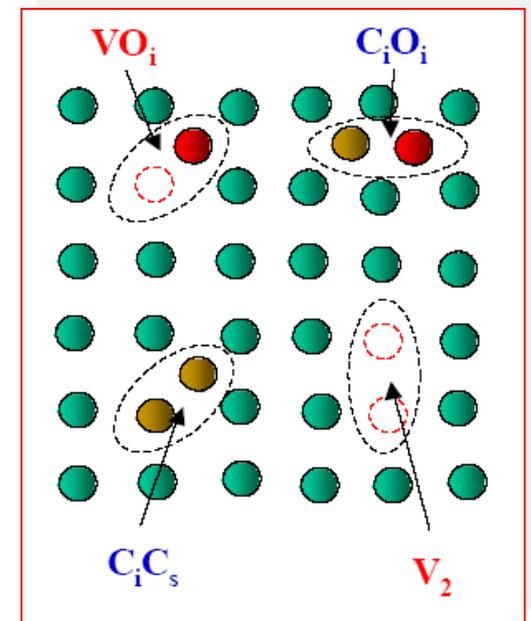
Diamond	Germanium	Silicon	GaAs
35±5 eV	27.5 eV	25 eV	7-11 eV



- Result: structural damage to lattice (defects).
- Mechanism:
 - particle transfers energy to the lattice nucleus, called Primary Knock-on Atom (PKA),
 - vacancies and interstitials are created,
 - they can move and interact with the lattice atoms.



I = interstitial
 V = vacancy
 S = substitutive
 O = Oxygen
 C = Carbon
 P = Phosphorus



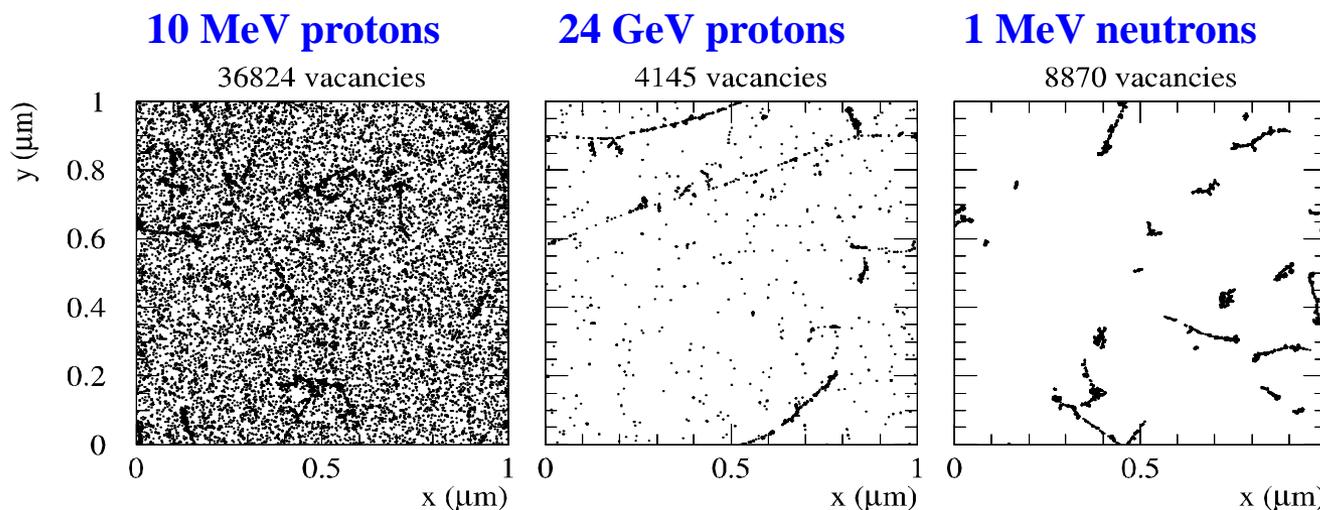
- Displacement damage depends on the primary energy transferred by the incident particle (thus the type of particle):

$Co^{60} \gamma$	Electrons	Protons/Neutrons
$E \approx 1 MeV$ Only point defects	$E > 255 keV$ for displacement $E > 8 MeV$ for cluster	$E > 185 eV$ for displacement $E > 35 keV$ for cluster

Simulation:

Initial distribution of vacancies in $(1\mu m)^3$ after 10^{14} particles/cm²

[Mika Huhtinen NIMA 491(2002) 194]

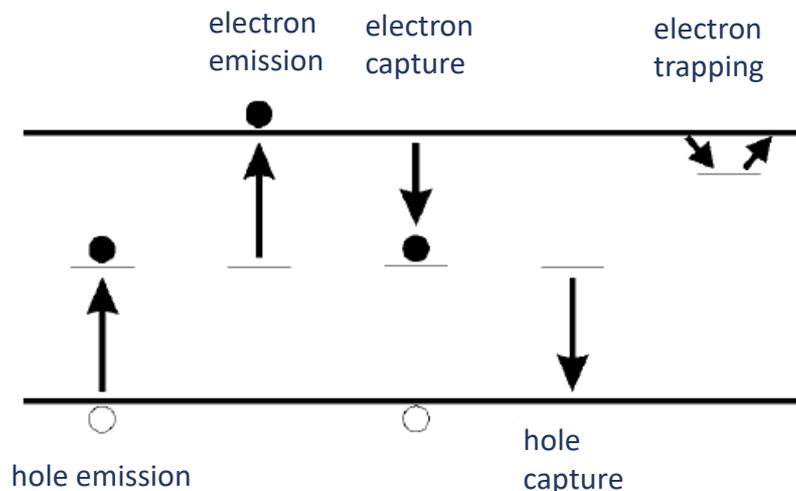
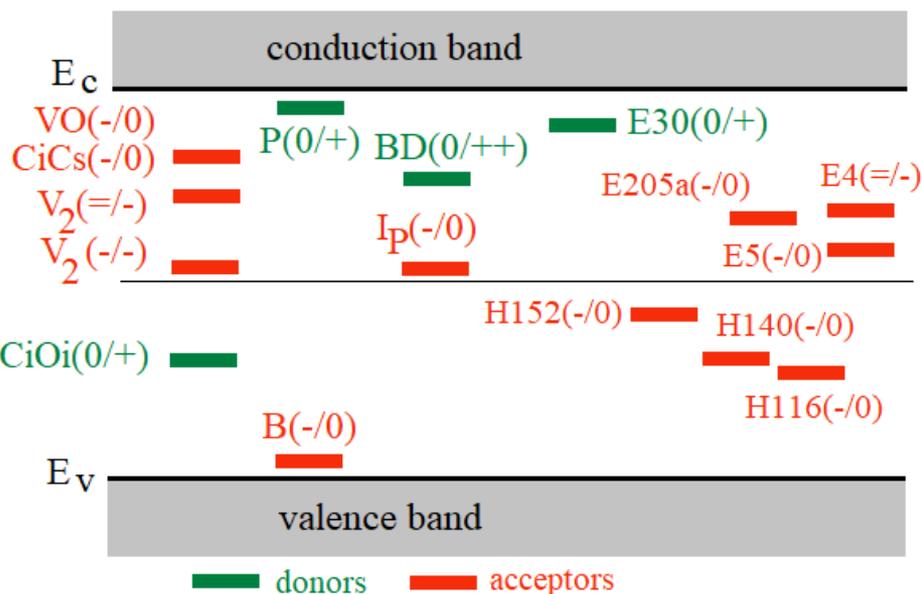


Point defects + cluster defects + impurities = degradation of the detector

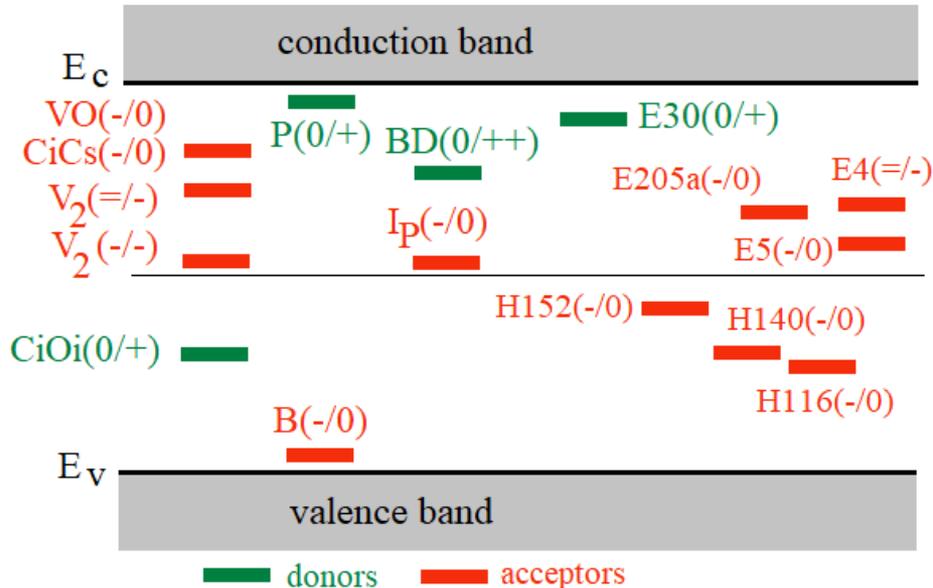
- Created defects influence the energy levels of the initial semiconductor.
- Point defect states can act as:
 - donors,
 - acceptors (the dominant defect charge states),
 - electrically neutral,
 - filled with electrons or not.

Energy levels created by particle radiation serve as intermediate steps promoting electrons into the conduction band, creating holes in the valence band.

The net effect on the detector performance is always negative.



- Experimental analysis of the radiation-induced lattice disorder:
 - Thermally Stimulated Current (TCT).
 - High Resolution Transmission Electron Spectroscopy (HR-TEM),
 - Electron Paramagnetic Resonance

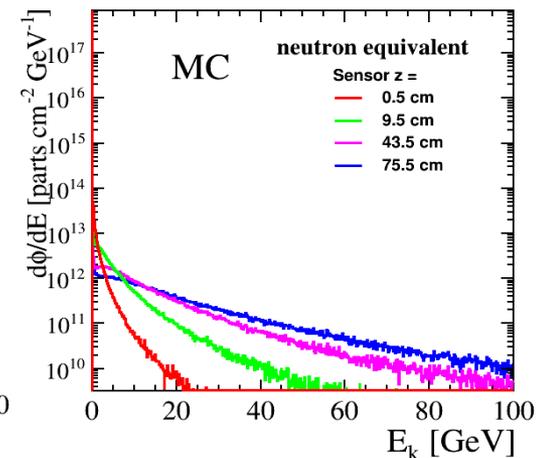
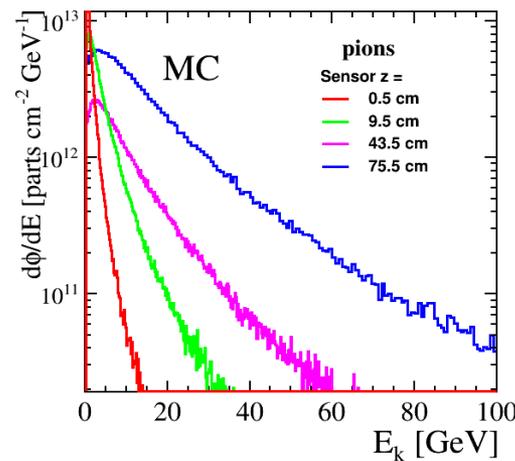
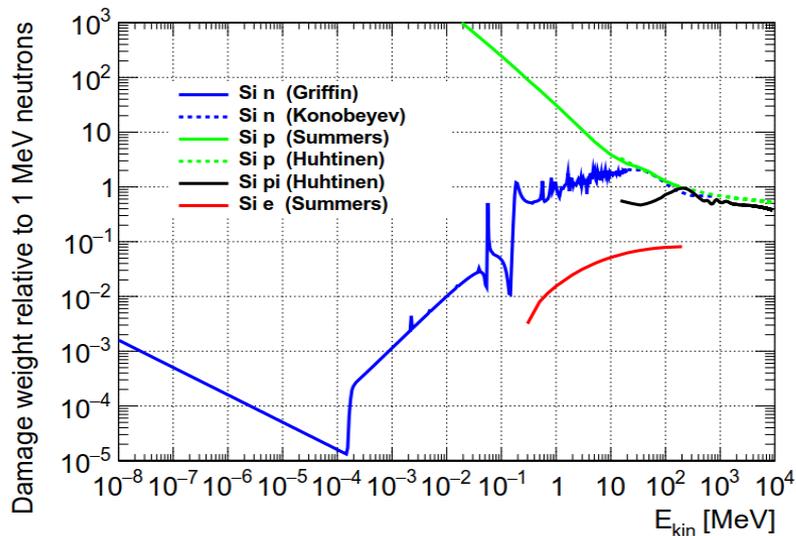


- VP : vacancy-phosphorus complex VP , (**E-centres**) form an energy level right below CB ($E_C - 0.456$ eV) what results that phosphorus does not fulfil the role of a donor. This process is responsible for so-called *donor removal*,
- Combination of a vacancy and oxygen VO_i (**A-centres**) forms a neutral acceptor state in the upper half of the band gap, with energy ($E_C - 0.18$ eV) and act as a **trapping centre**.
- H defects**, which introduce space charges and are responsible for so-called *reverse annealing*

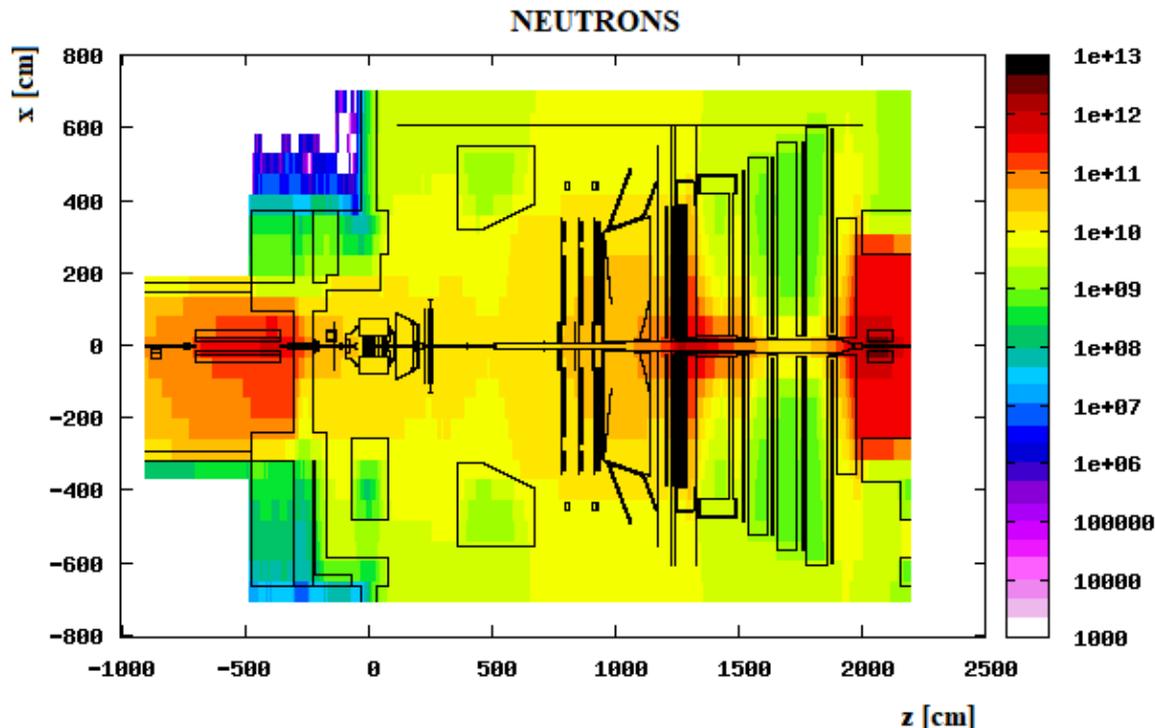
- **Fluence** ϕ is the number of particles dN incident on a sphere divided by its cross-sectional area da : $\phi = \frac{dN}{da}$.
- Observation: degradation of silicon devices is approximately proportional to amount of displacement damage (DD), i.e. to the kinetic energy imparted to the silicon atoms – NIEL scaling.
- DD can be expressed in terms of the damage caused by a certain flux of mono-energetic neutrons, for example neutrons with energy 1 MeV.
- A particle fluence ϕ can be reduced to an **equivalent 1MeV** ϕ_{neq}
- The damage efficiency of any flux of particle with a given kinetic energy E can be expressed by a **hardness factor** κ :

$$\phi_{eq} = \kappa \int \phi(E) dE$$

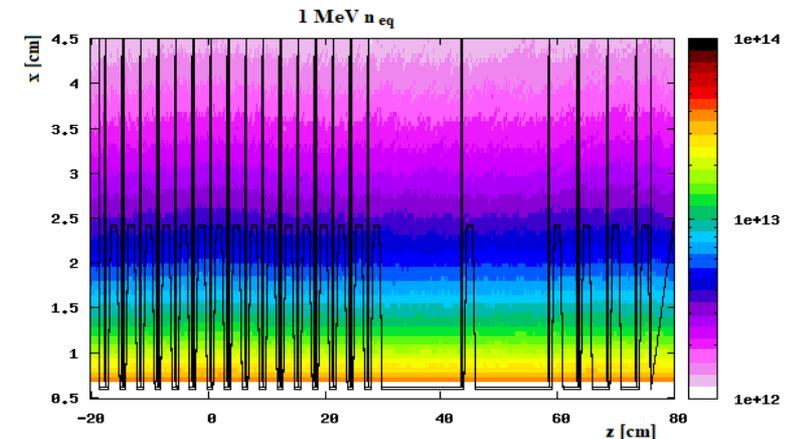
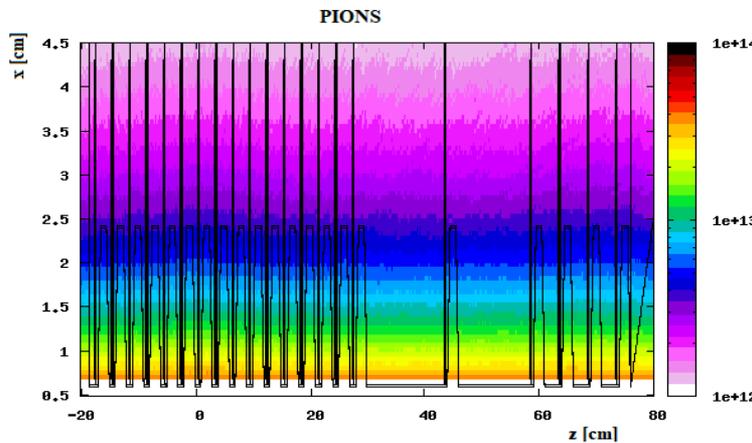
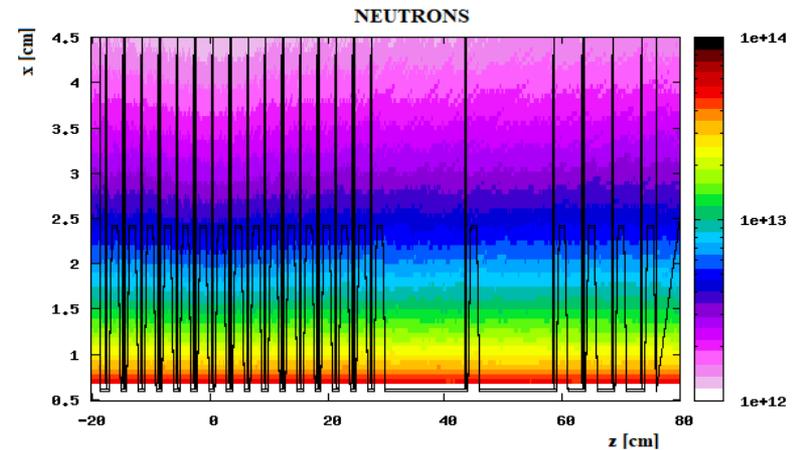
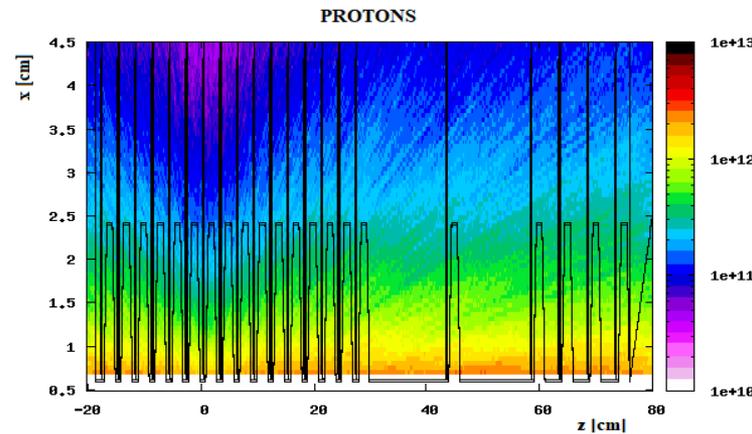
$$\kappa = \frac{D_{part}}{D_{1\text{ MeV } n}}$$



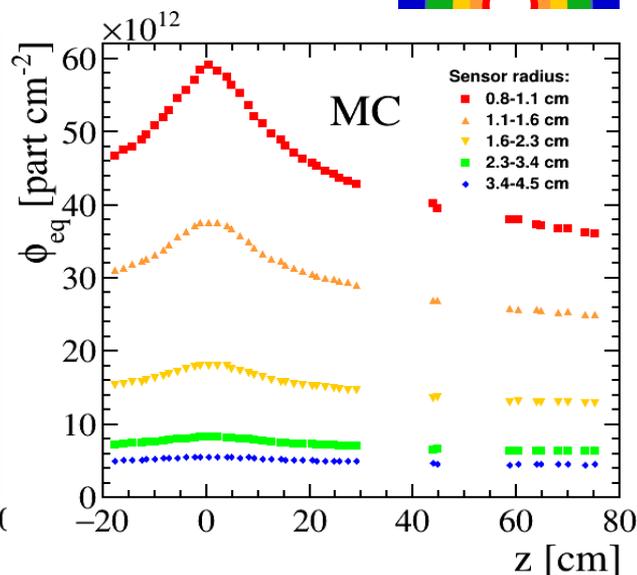
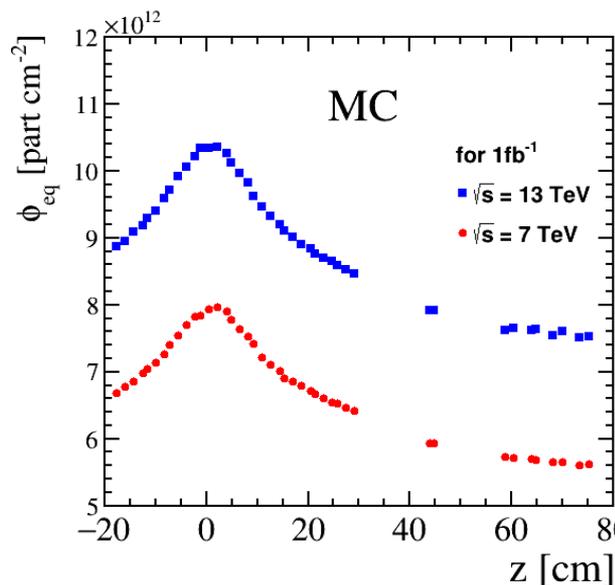
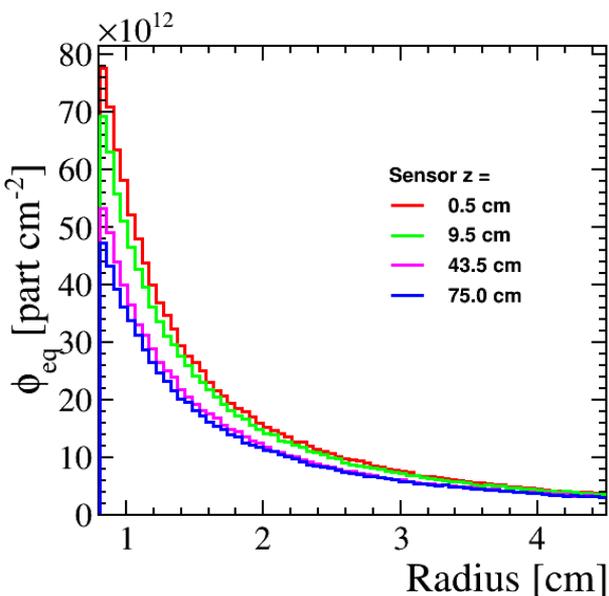
- In the LHC environment, the main source of particle radiation:
 - prompt production of particles (pions, protons, neutrons, kaons, electrons, muons, and photons),
 - production of secondary particles in interactions with the detectors and the decay of radionuclides.
- It not practical/possible to measure directly the particle fluence inside the detector (material budget, too high doses).
- Fluence and other dosimetry parameters need to be simulated (FLUKA and Geant 4).



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 - production of secondary particles in interactions with the detectors and the decay of radionuclides.



- The detailed simulation for the VELO region showed that the fluence is strongly depended on radius and z position of the sensor.
- Until the end of Run II, the maximum fluence that inner part of the sensor will obtain is above $5.5 \times 10^{14} n_{eq}$.



The net effect of particle radiation on the detector performance is always negative.

The main macroscopic effects caused by the radiation:

Increase in leakage current, caused by creation of generation and recombination centres.

Change of the effective doping concentration with significant influence on operating **voltage** needed for total **depletion**.

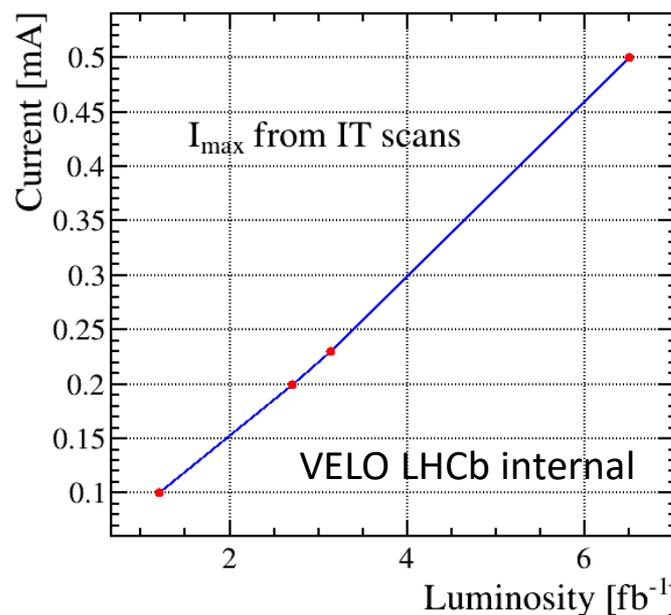
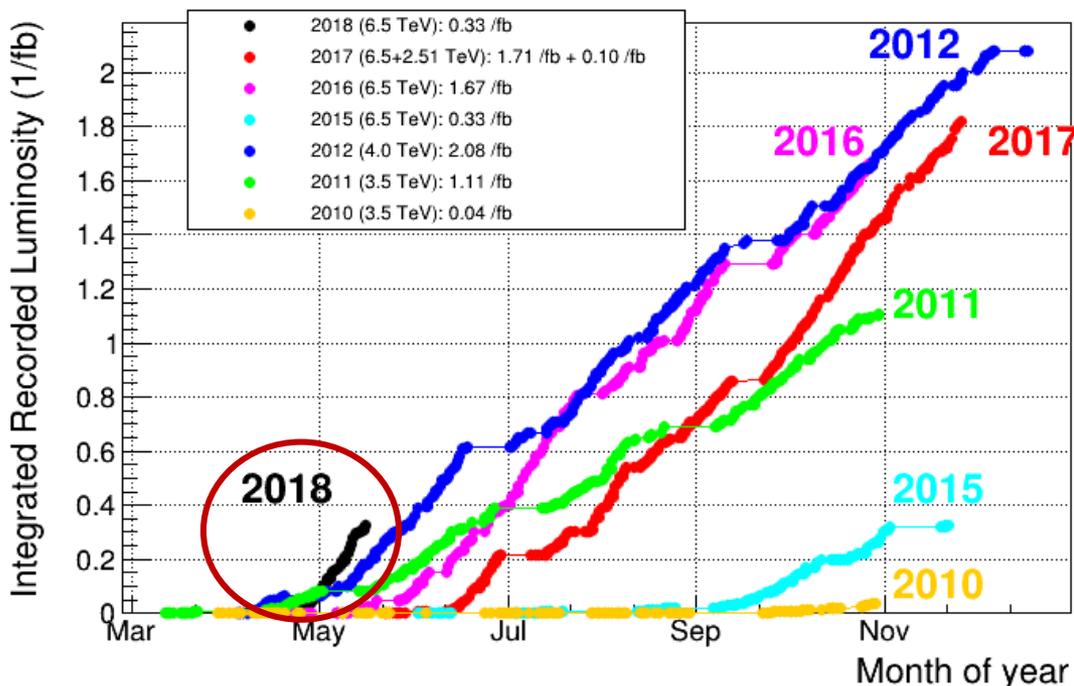
Loss of charge collection efficiency due to charge carrier trapping.

Selected methods to monitor radiation influence on VELO:

- Current-Temperature scans (IT)
- Charge Collection Efficiency scan (CCE)

- Defects close to the mid-gap, are the most responsible for generation of electron-hole pairs and the leakage current.
- Leakage current depends on defect density. The level of leakage current reveals the amount of the radiation damage contained in a detector volume.
- The increase in leakage current is proportional to the accumulated fluence (time, delivered luminosity): $\Delta I = \alpha V_{ol} \phi_{eq}$

LHCb Integrated Recorded Luminosity in pp, 2010-2018



- The increase of leakage current due to irradiation is proportional to the number of defects created in volume V_{ol} .

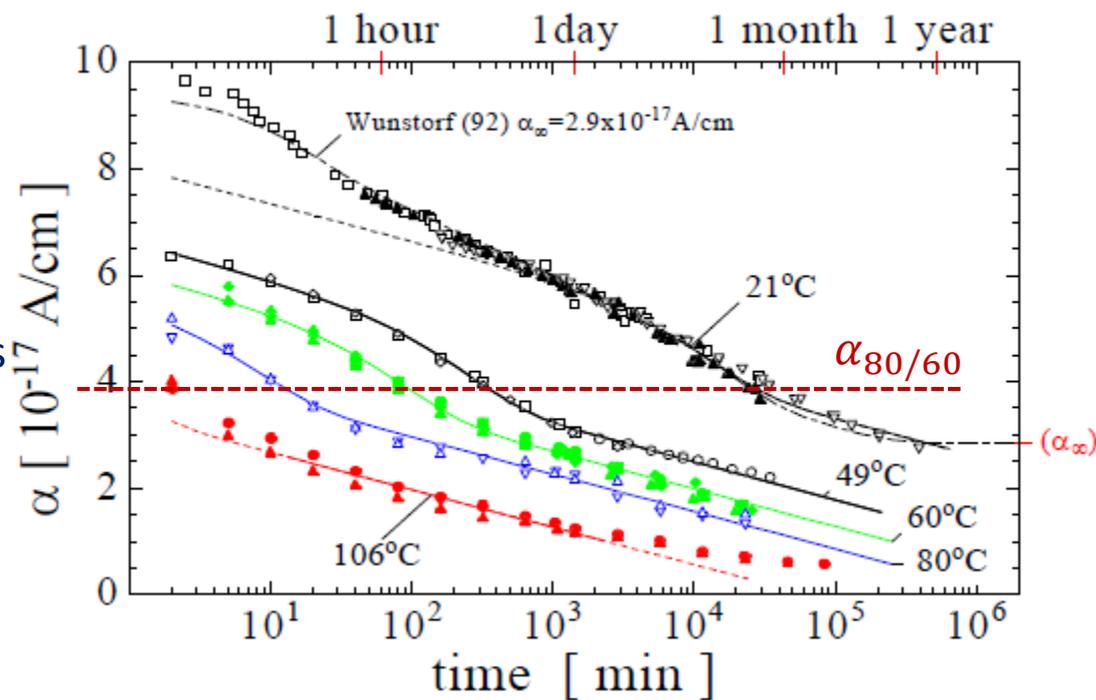
$$\Delta I = \alpha V_{ol} \phi_{eq}$$

α is called the *current related damage rate* or *damage constant*

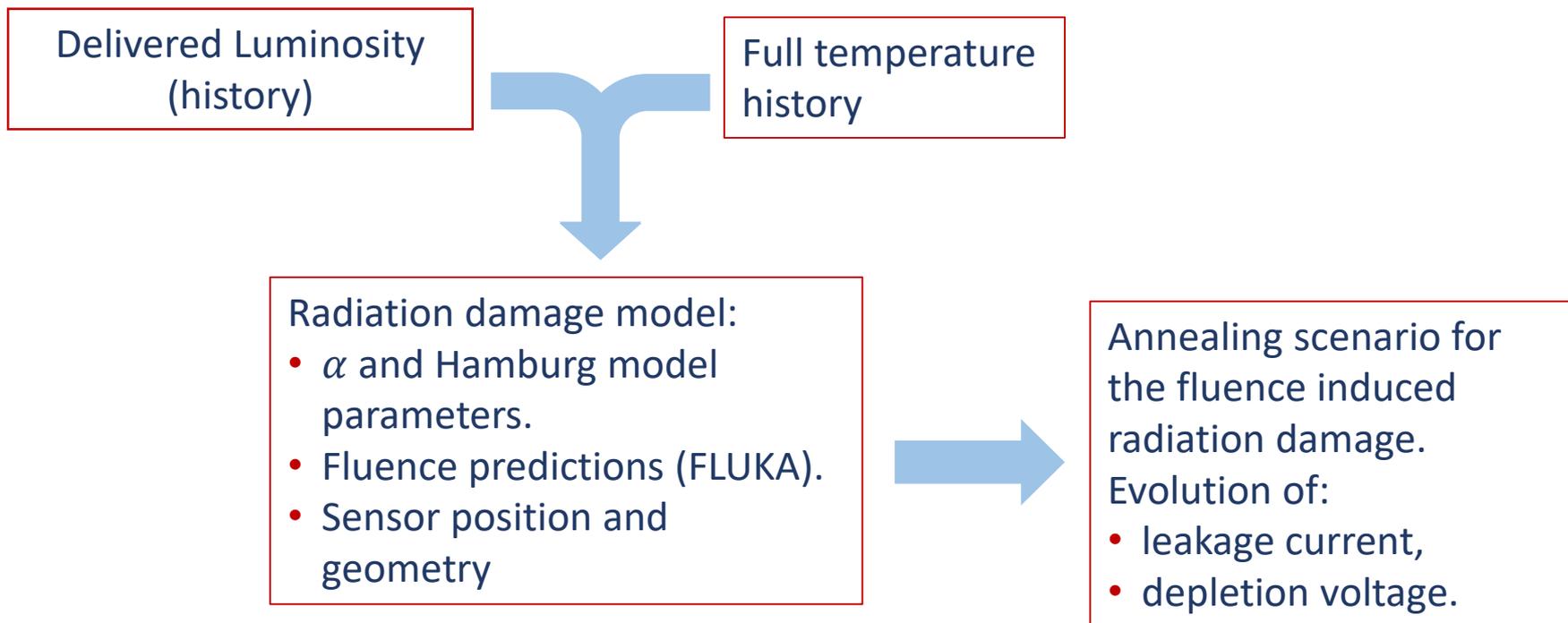
value after 80 minutes of annealing at 60 °C (~10 years of LHC operational conditions):

$$\alpha_{80/60} = (3.99 \pm 0.03) \times 10^{-17} \text{ Acm}^{-1}$$

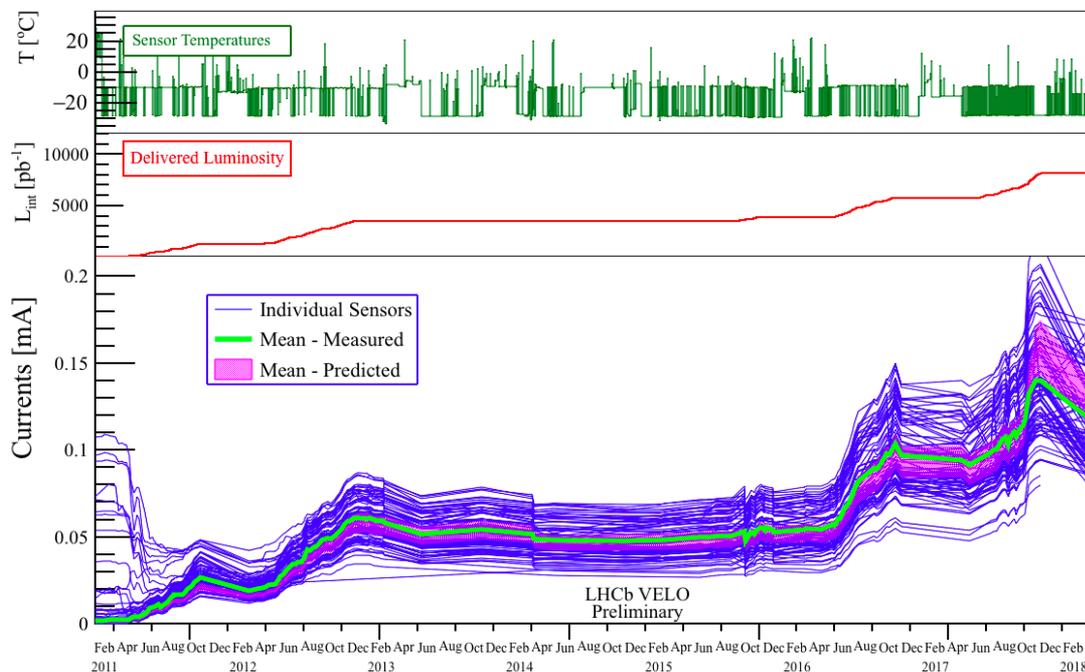
- The damage rate depends on the annealing condition, i.e. time and temperature after the irradiation.
- LHC silicon trackers are simultaneously irradiated and annealed at temperatures $[-30, +10]^\circ\text{C}$.
- Parametrisation of damage rate α is obtained basing on experimental data (Hamburg model - M.Moll thesis 95).



- Two main signs of radiation damage: increase of **leakage current and depletion voltage** are constantly monitored during detector operation to predict whether the detector will perform successfully until the end of data taking.
- Evolution of the current and effective depletion voltage is based on the Hamburg model.
- In realistic condition, sensors are irradiated on a real time scale with long- term annealing (10 years).
- The procedure for obtaining a unique evolution of radiation damage, for each sensor:



- The currents of the sensors are measured as a function of time while operating at nominal conditions (depletion voltage, temperature).



- Bulk currents increases with fluence as expected, with occasional drops due to annealing.
- The average increase is **2 μA per 100 pb⁻¹**.

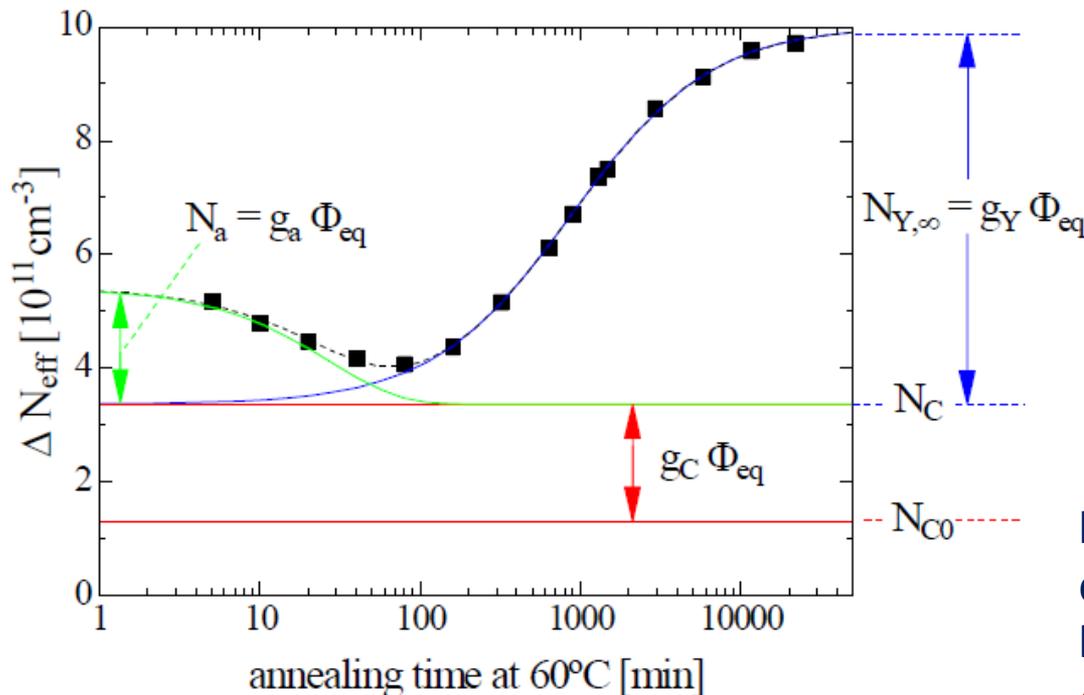
- The depletion voltage is proportional to the absolute value of the effective doping concentration N_{eff} .
- Change of N_{eff} as a function of fluence ϕ , time t after the irradiation and the temperature T can be parametrised as:

$$V_{dep} = \frac{e}{2\epsilon} |N_{eff}| d^2$$

$$N_{eff} = N_d - N_a$$

$$\Delta N_{eff}(\phi, t(T)) = |N_{eff,0}| - N_{eff}(\phi_{eq}, t(T))$$

$$N_{eff}(\phi_{eq}, t(T)) = N_a(\phi, t(T)) + N_C(\phi) + N_Y(\phi, t(T))$$



$$N_a(\phi, t(T))$$

short-term beneficial annealing:
decay of acceptors

$$N_C(\phi)$$

stable damage:
incomplete donor removal +
introduction of stable acceptors

$$N_Y(\phi, t(T))$$

long-term reverse annealing:
damage continues even when radiation
has stopped, **sensors need to be cooled!**

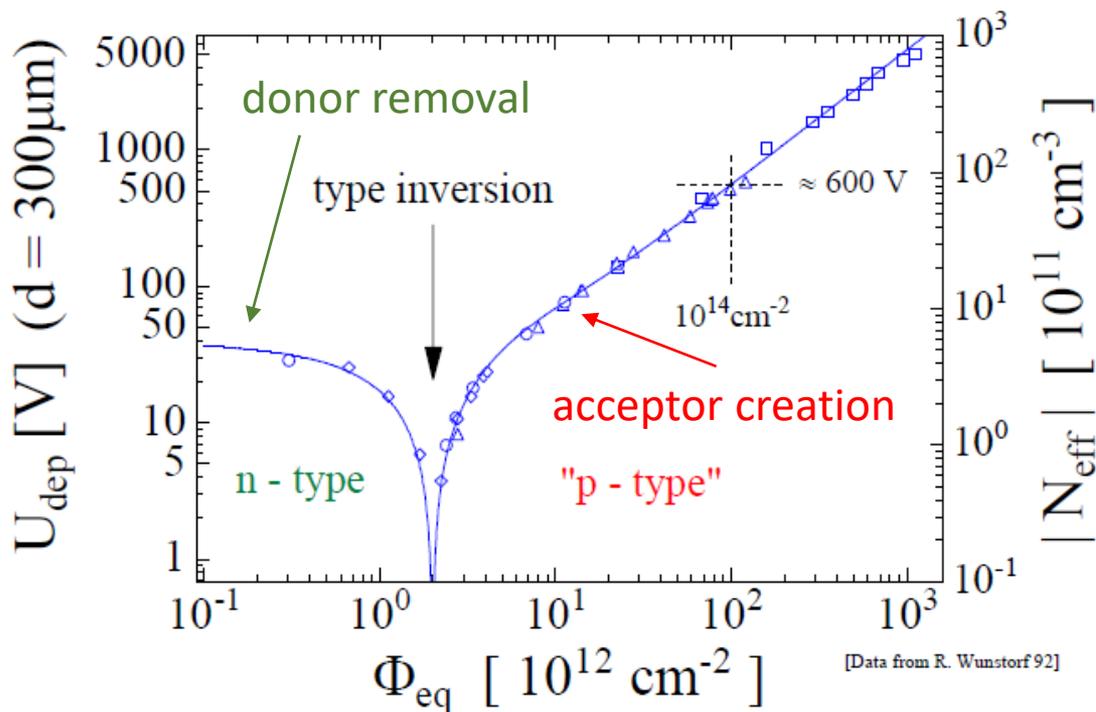
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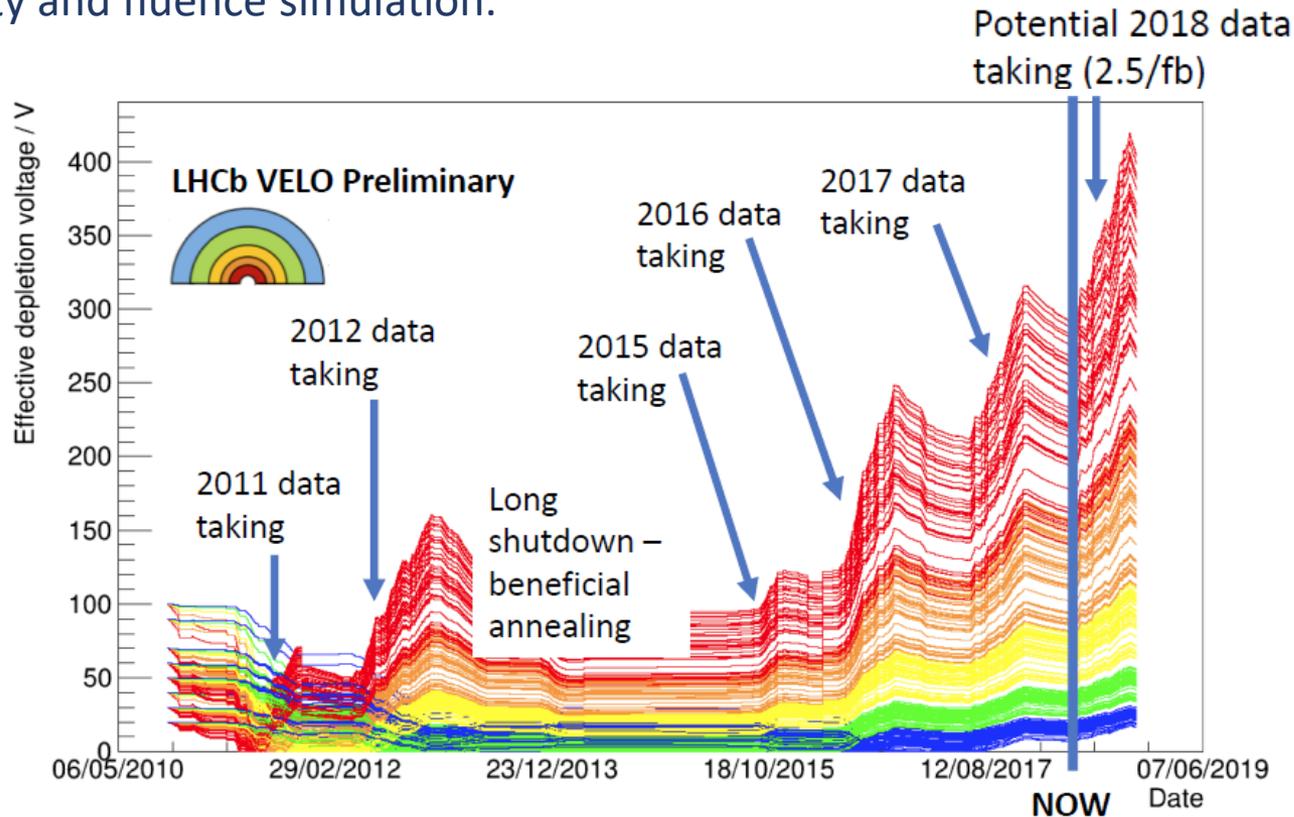
$$\Delta N_{eff}(\phi, t(T)) = |N_{eff,0}| - N_{eff}(\phi_{eq}, t(T))$$

$$N_{eff}(\phi_{eq}, t(T)) = N_a(\phi, t(T)) + N_c(\phi) + N_Y(\phi, t(T))$$



the electrical properties of the silicon have been changed from n-type to p-type.....

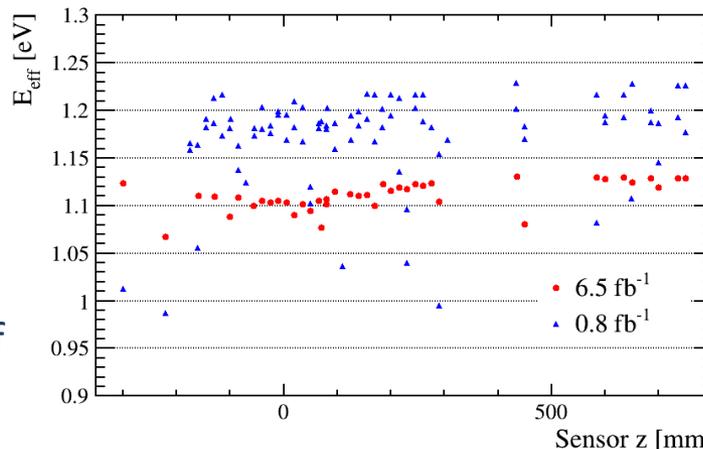
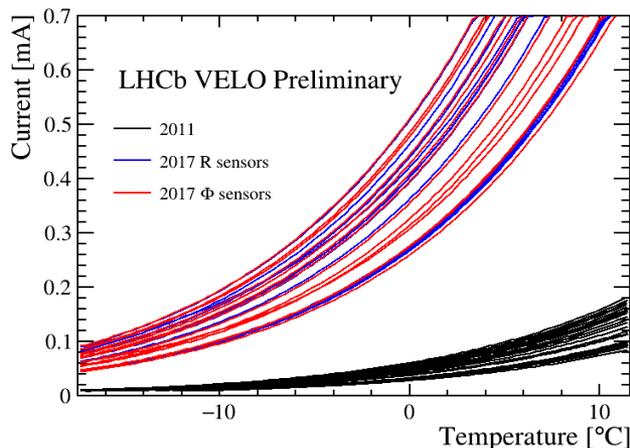
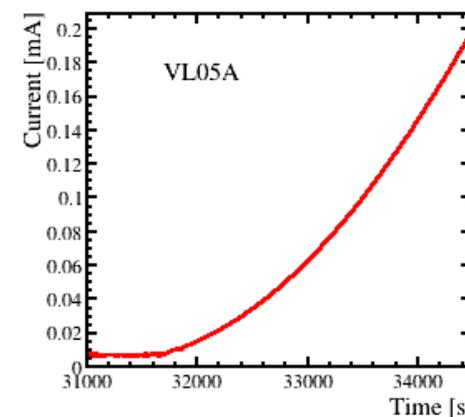
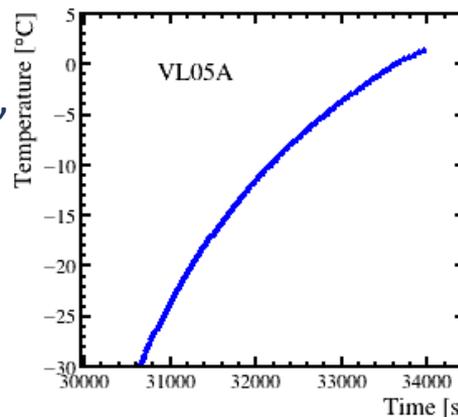
- Depletion voltage is predicted basing on temperature history, LHCb delivered luminosity and fluence simulation.



- The Hamburg model prediction and simulation of fluence expected for the actual LHC parameters, shows that the operational bias voltage will have to be increased to 450 V, which still is below the hardware limit.

- The bulk generation current is mainly the result of thermal excitation, it varies exponentially with temperature.
- We can perform measurements of the current as a function of the sensor temperature (IT scans).
- A lot of technical problems (current and temperature are recorded by two systems, problem with cooling).
- Clear increase of currents is visible.

$$I(T) \propto T^2 e^{-\frac{E_{eff}}{2k}T}$$

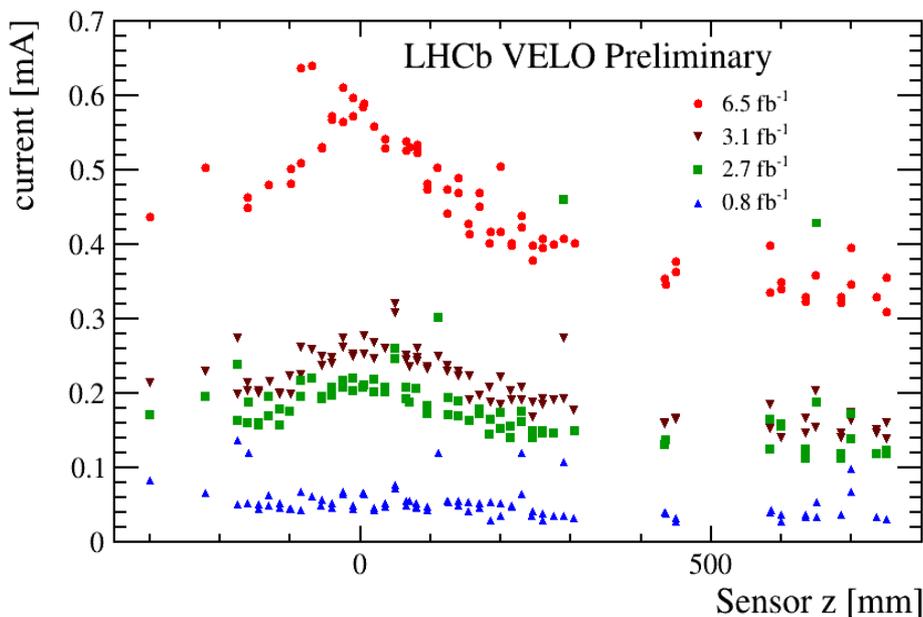


- The first observation of decrease of the effective energy gap after irradiation of $4.5 \times 10^{14} n_{eq}$ fluence

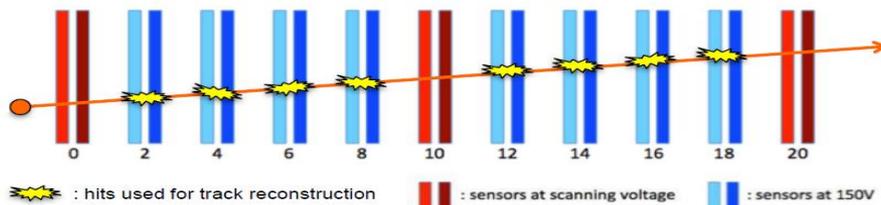
IEEE TNS (Volume: 65, Issue: 5, May 2018)

- Currents measured at different temperatures may be scaled to 0°C.
- The largest increase of currents occurs in sensors close to the interaction point.

$$\frac{I(T_R)}{I(T)} = \left(\frac{T_R}{T}\right)^2 \exp\left[-\frac{E_g}{2k}\left(\frac{1}{T_R} - \frac{1}{T}\right)\right]$$



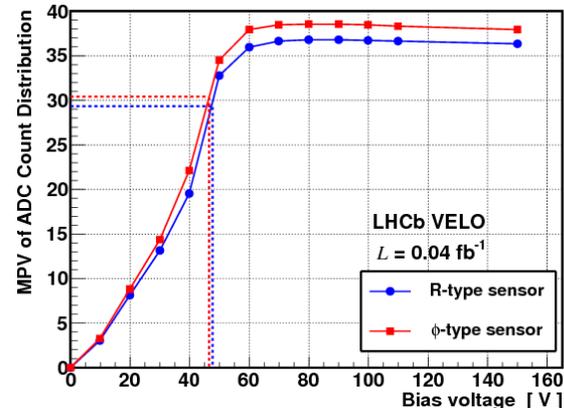
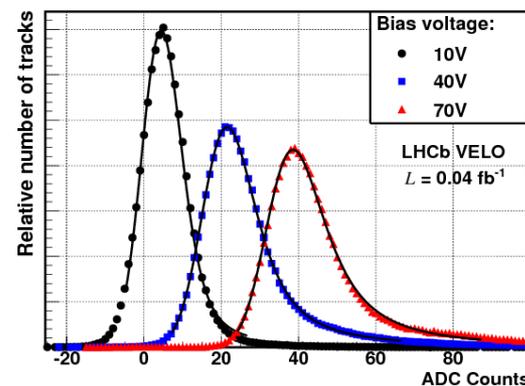
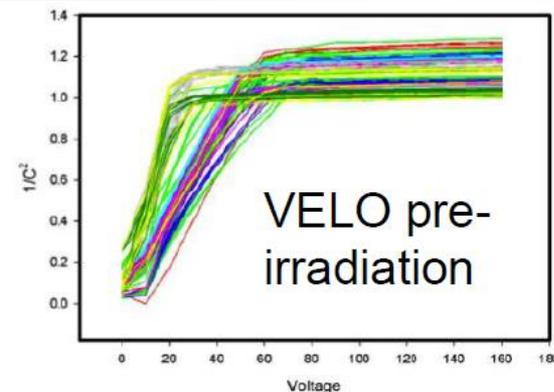
- Standard method for U_{dep} measurement uses C-V scans – possible at the lab before the detector commissioning.
- After installation sensors are not accessible any more and another method is applied:
 - During data taking a tested sensor is excluded from the track fit.



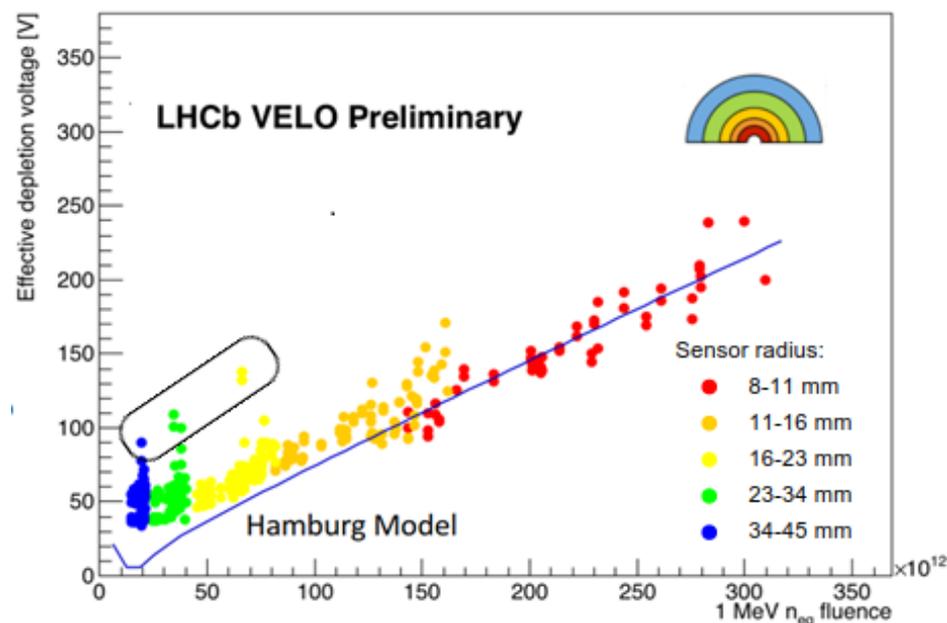
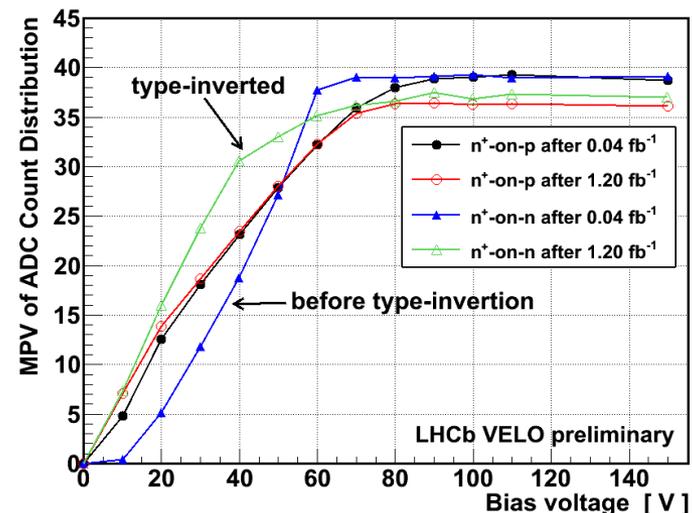
- A voltage bias scan is performed on it and the charge deposited in sensor around the track intercept is measured.

- The effective depletion voltage (V_{ED}) is the voltage where MPV is 80% of maximum.

- This method effectively determines **Charge Collection Efficiency** and is used to measure:
 - Effective Depletion Voltage (V_{ED})
 - Cluster Finding Efficiency (**CFE**)



- Such tests are performed often (every two months), currently almost automatically (steered by the Shift Leader).
- About an hour of data taking period is lost, but CCE scans are done in both Si trackers at the same time.
- Results:
 - **Type inversion** occurred at $(10-15) \times 10^{12}$ $1\text{MeV } n_{eq}/\text{cm}^2$, inversion started at inner radius.
 - Very clean pattern of the most damaged regions of sensors.
 - Prediction for VED evolution until the end of Run II (2018).
 - Study of Second Metal Layer Effect.



1. The first period of LHC operation was planned for 10 years ($\mathcal{L} = 300 \text{ fb}^{-1}$), i.e. till the end of Run 3 (**2023**).
2. It was assumed that tracking detectors will have to be replaced due to radiation damage and ageing (or new physics program).
3. HL-LHC will produce collisions at a rate of about $5 \cdot 10^9 \text{ s}^{-1}$.
4. The annual dose at HL-LHC will be similar to the total dose until LS3:

- end of Run III (300 fb^{-1}) $\Phi \sim 2 \cdot 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$
- HL-LHC (3000 fb^{-1}) $\Phi \sim 2 \cdot 10^{16} \text{ n}_{\text{eq}} \text{ cm}^{-2}$



4. Two major shutdowns (**LS2 & LS3**) – main accelerator and detector upgrades.

Future Circular Collider

RD50 - Radiation hard semiconductor devices for very high luminosity colliders.

1. Formed in 2001, approved by CERN in 2002.
2. The main objective is:

Development of radiation hard semiconductor detectors for the luminosity upgrade of LHC to $7.5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$.

3. Challenges:

- radiation hardness up to 10^{16} cm^{-2} required,
- fast signal collection – plan for 10 ns bunch crossing,
- low mass to reduce multiple scattering close to interaction point,
- affordable cost.

AGH joined RD50 in 2012



3D Pixels /Strips

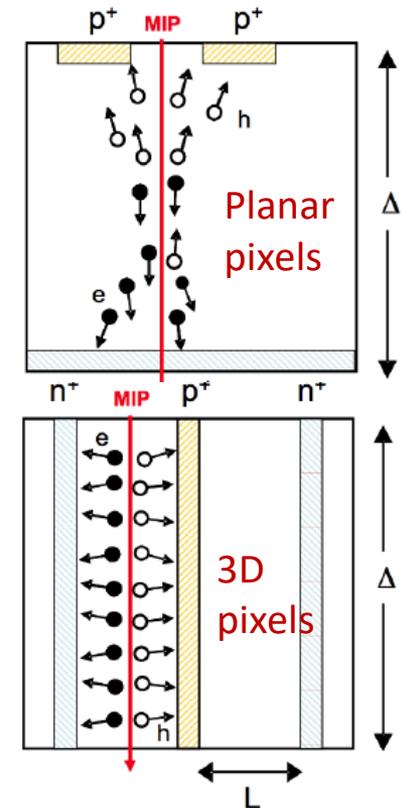
1. Currently a well known technology (S.I. Parker et al., NIMA 395(1997)328).
2. 3D pixel sensors are installed in ATLAS IBL, AFP, CMS Totem.
3. They are designed as **vertical narrow columnar p and n electrodes** penetrating the silicon substrate.

3. Advantages:

- diameter: $10\ \mu\text{m}$, distance L : $50 - 100\ \mu\text{m}$ (**small drift distance, less trapping**),
- **lower depletion voltage: 10-200V** (lower power), thinner detectors possible,
- fast signal formation,
- radiation hard,
- active or slim edges technology.

4. Problems:

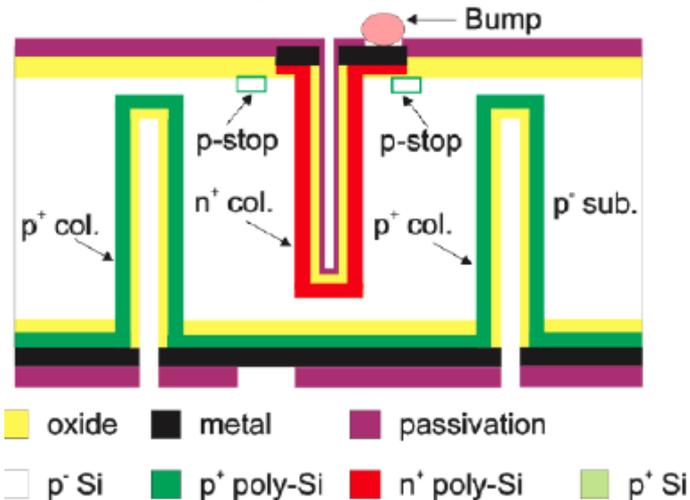
- Non uniform spatial response (electrodes are inefficient regions).
- Higher capacitance, higher noise.
- **Complicated fabrication technology** (time, cost, yield).



Double sided (DDTC) technique:

- n+ and p+ columns are etched from the two sides of the sensor wafer.
- Slim edges (200 μm)

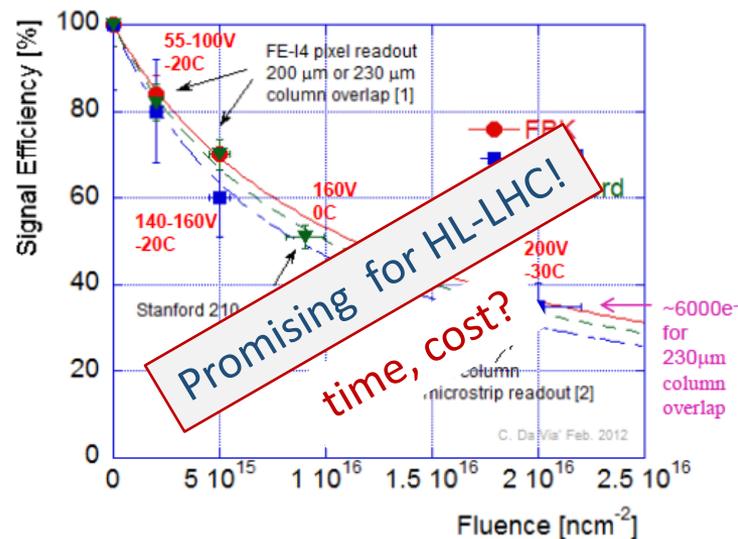
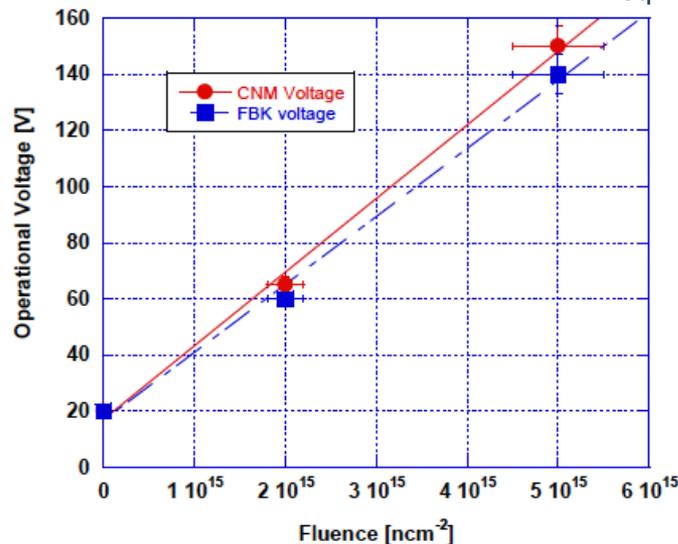
CNM 3D pixels for IBL



G. Pellegrini et. al. NIMA 592(2008), 38
 G. Pellegrini et. al. NIMA 699(2013), 27

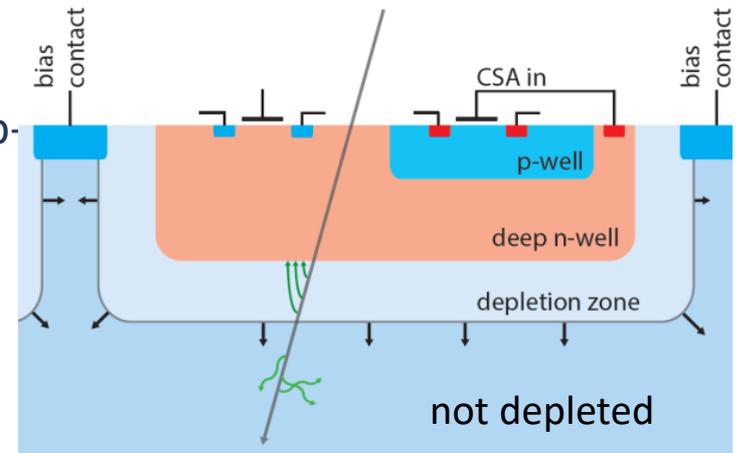
Radiation hardness up to $5 \cdot 10^{15} n_{eq} cm^{-2}$
 established:
 Efficiency for CNM sensors reached 99%.

3D sensors irradiated (protons, neutrons, pions, electrons) up to IBL fluence $5 \cdot 10^{15} n_{eq} cm^{-2}$



High Voltage CMOS

- n-wells are implanted in low resistivity ($\sim 10 \Omega\text{cm}$) p-type substrate and play role of electrode implant,
- biased with 60 V but allows only shallow (10 – 20 μm) depletion zone, signal 1-2 kel.
- thin active layer,
- low drift distance, small drift time (fast collection),
- radiation hard (less trapping),
- possible to use capacitive coupling through glue instead of bump-bonding,
- industrial process enables large volume production in relatively short time,
- both pixel and strip detector possible,
- fully monolithic devices don't require a bump-bonded read-out.



RD50 started to work on HV-CMOS devices in 2014 with a focus on characterizing the radiation damage

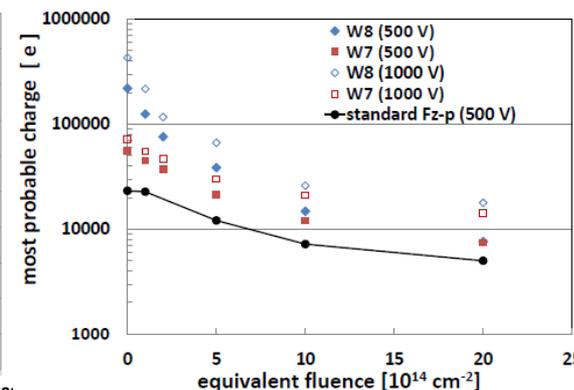
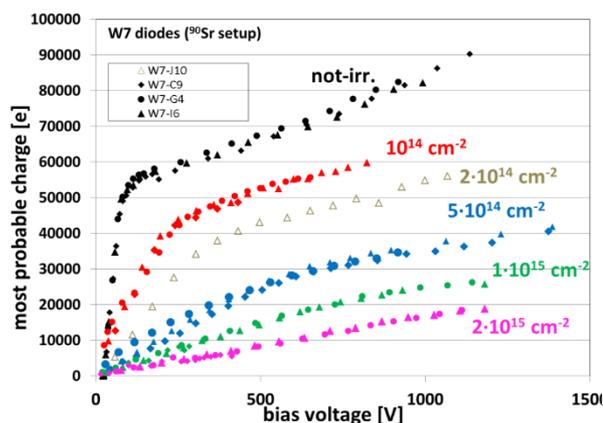
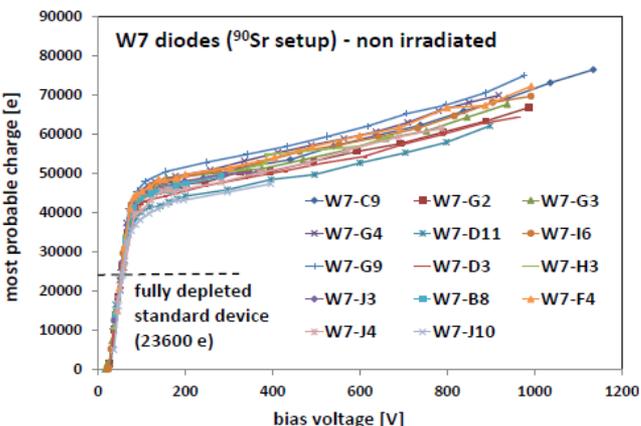
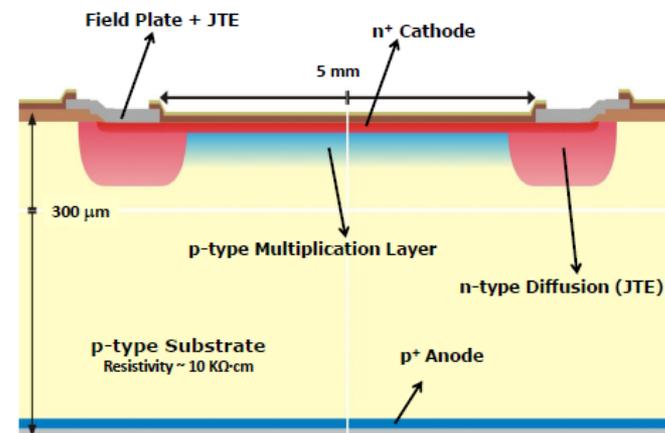
The Low Gain Avalanche Detector (LGAD): a new concept of silicon radiation detector with intrinsic multiplication of the charge.

Advantages:

- higher charge collection efficiency,
- short drift time,
- signal shorter and steeper while retaining a large amplitude due to the multiplication mechanism.

After irradiation (reactor neutrons and 800 MeV protons):

- decrease of charge collection,
- decrease of multiplication (before irradiation it was 3 times higher than standard diode), after irradiation with fluence $2 \cdot 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ the gain was lost.

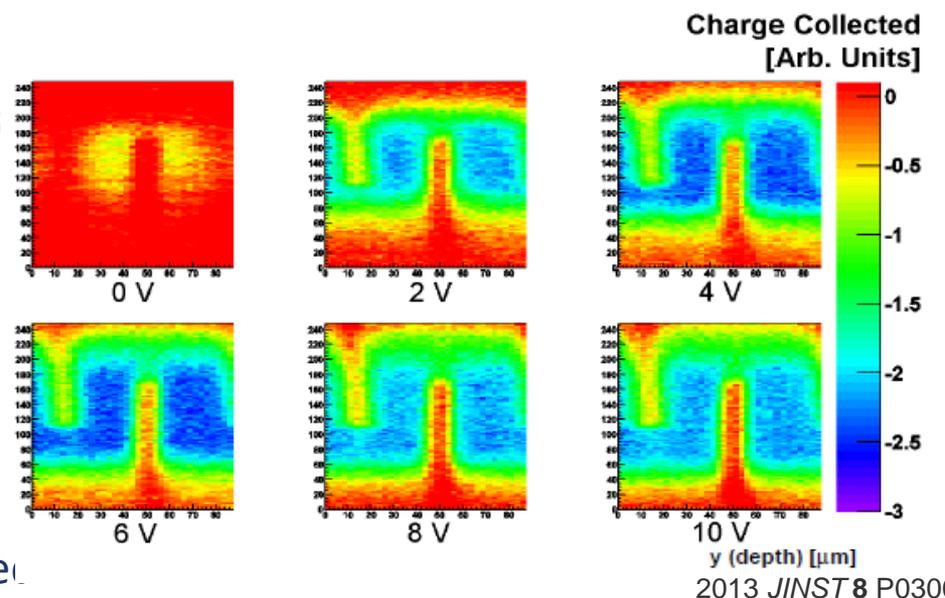
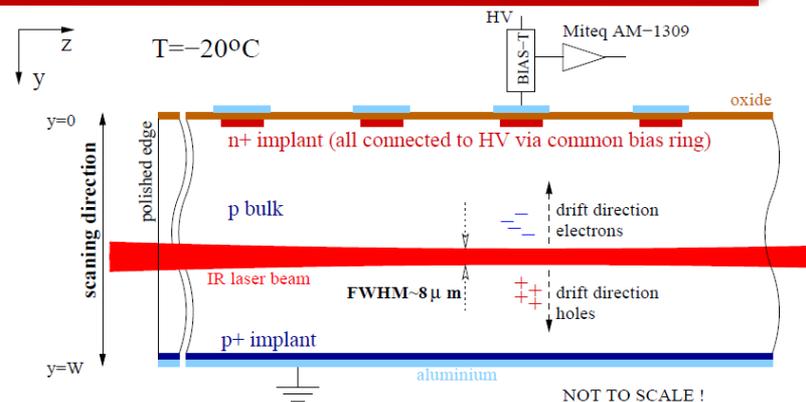


New technology – Gallium instead of Boron or add Carbon to prevent Boron removal

Edge Transient Charge Technique:

Method of reconstruction of electric field pioneered by Ljubljana group and promoted by RD50.

- photon pulses (below 1Hz) from an infrared laser are directed towards the detector edge, perpendicular to the strips and focused to the region below the readout strip, electron-hole pairs are produced,
- scans across the detector thickness enables relative measurement of the induced current **at given depth**, extrapolate rise time, drift velocity and charge collection profiles $Q(V_{bias})$,
- mobility of electrons and holes can be extracted from the drift time,
- finally, **the electric field** can be reconstructed by determination of drift velocity.



Edge-TCT is widely used ideal tool to study substrate properties!

- There is no heavy flavour physics without precise vertex reconstruction.
- The best choice for tracking detector is semiconductor technology.
- These devices are under influence of very severe particle radiation.
- Macroscopic changes are observed due to microscopic damage of crystal lattice.
- It requires constant monitoring of the VELO sensors.
- A few interesting results: leakage current and effective depletion voltage evolution, decrease of silicon effective energy gap.

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Paweł Kopciewicz
Wojciech Krupa

Dziękuję bardzo za uwagę!