Radiation Damage in Silicon Particle Detectors in High Luminosity Experiments

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within the framework of
RD50 Collaboration
&
LHCb VELO Group

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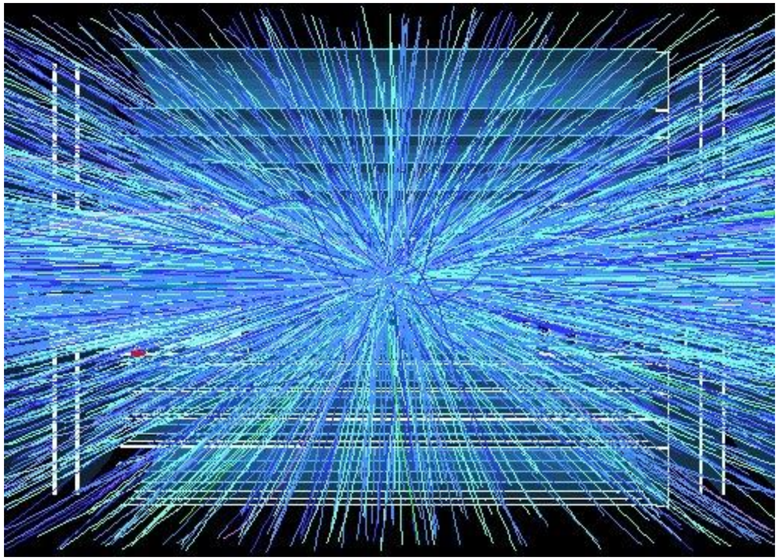
Outline

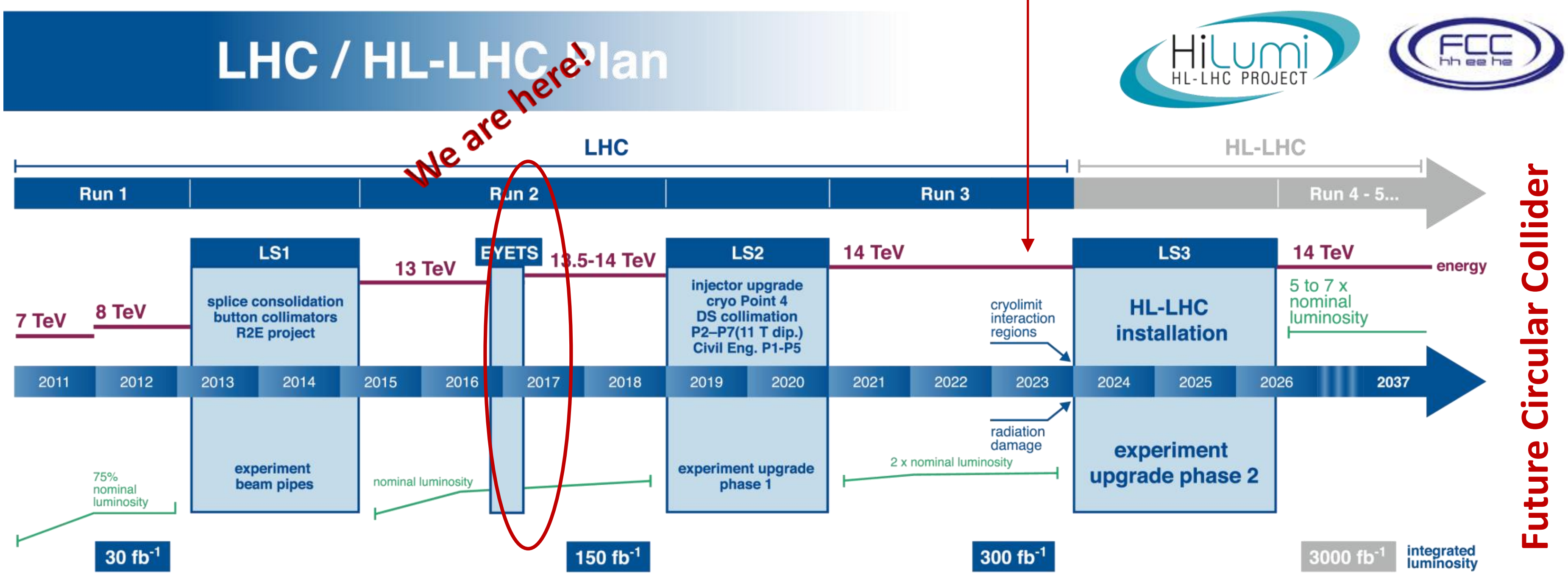
1. Introduction.
2. The timeline of LHC and experiments.
3. Radiation induced changes in properties of the silicon tracking detectors.
4. Radiation damage in the LHCb VELO.
5. Development of new structures:
   - 3D Pixels,
   - HVCMOS,
   - LGAD.
6. Measurement technique: TCT.



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

HL-LHC Timeline

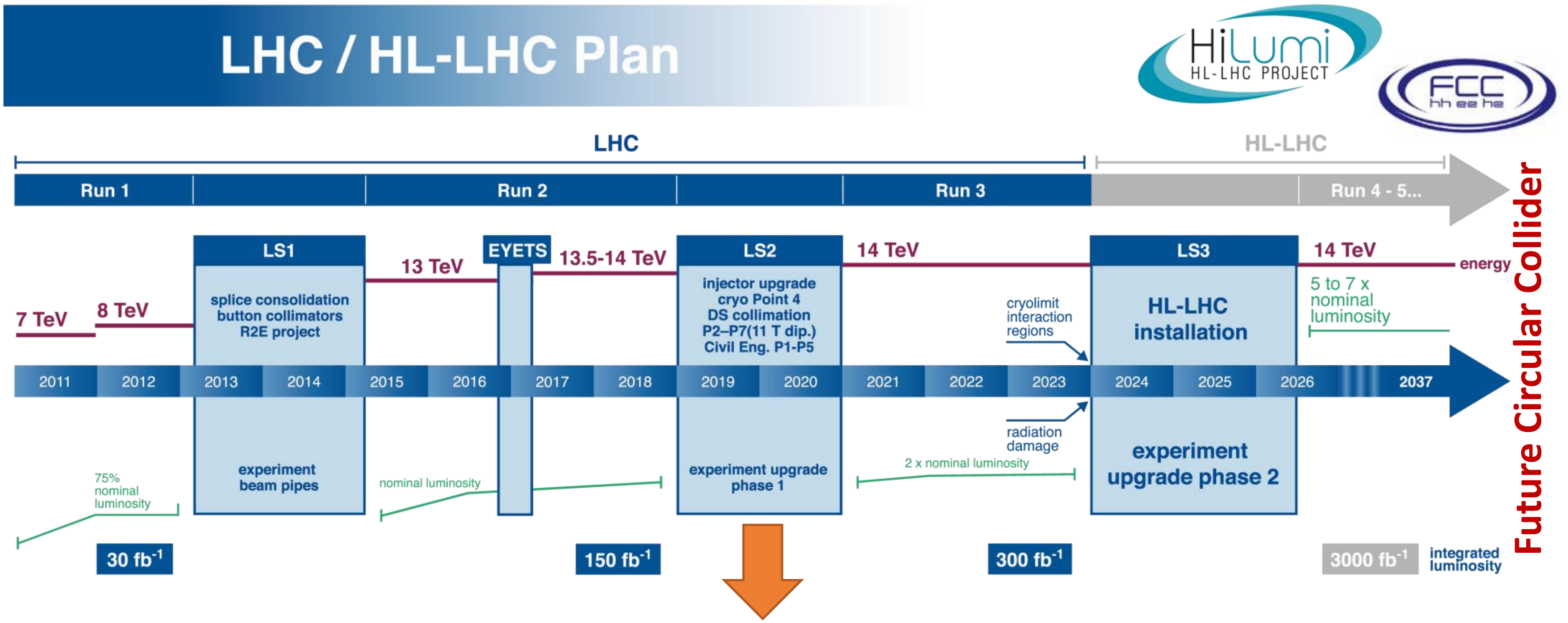
1. LHC was planed for 10 years of operation ($\mathcal{L} = 300\ fb^{-1}$), i.e. till the end of Run 3 (**2023**).
2. It was assumed that tracking detectors will have to be replaced due to radiation damage and ageing (or new physics program).
3. Based on experience from Run I, with new technologies in mind, it's the right time to design them **NOW**!



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

Experiments - Phase 1 Upgrade

5.1. Upgrade of the silicon tracking detector.

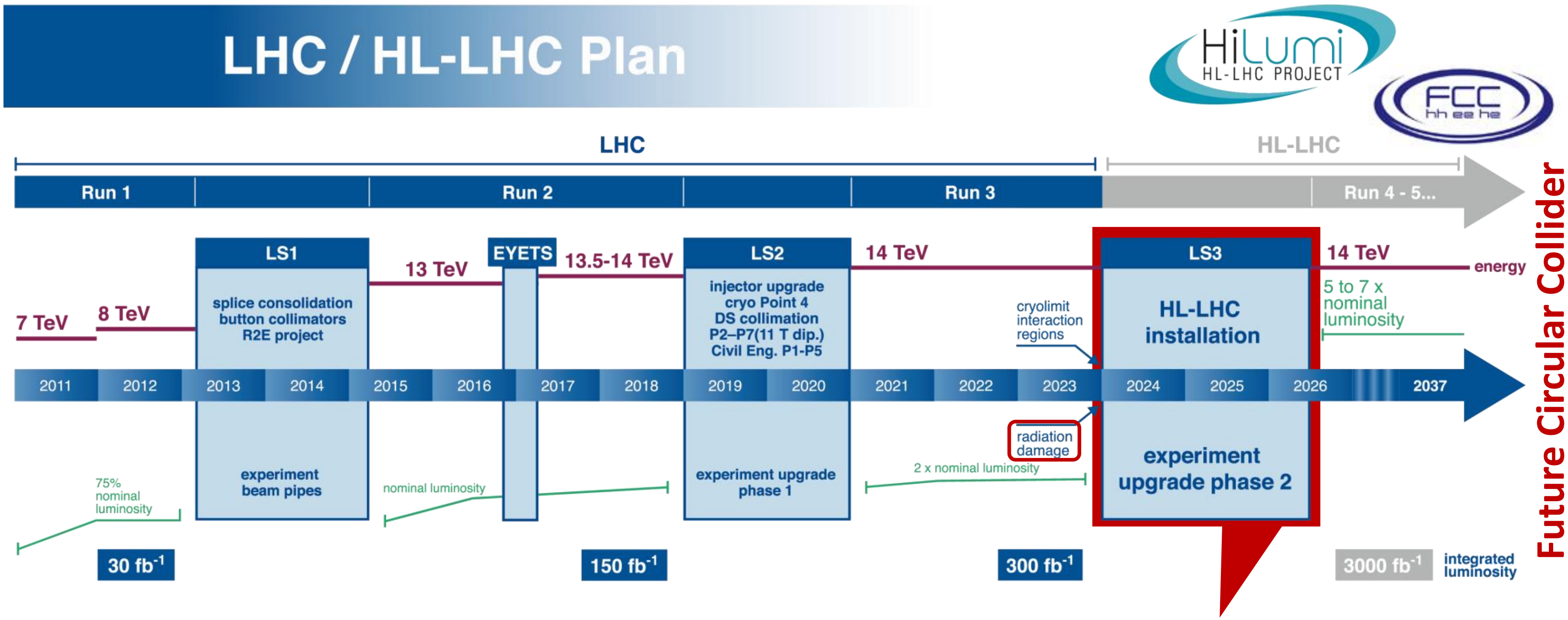


Phase 1 Upgrade (24 months):

- CMS - Pixel detector replacement,
- **LHCb - VELO strip detector replacement by pixels, new strip UT.**

Experiments - Phase 2 Upgrade

5.2. Upgrade of the silicon tracking detector.

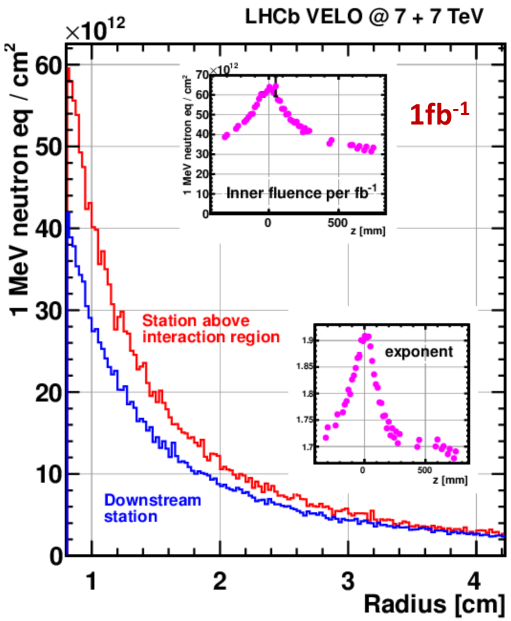


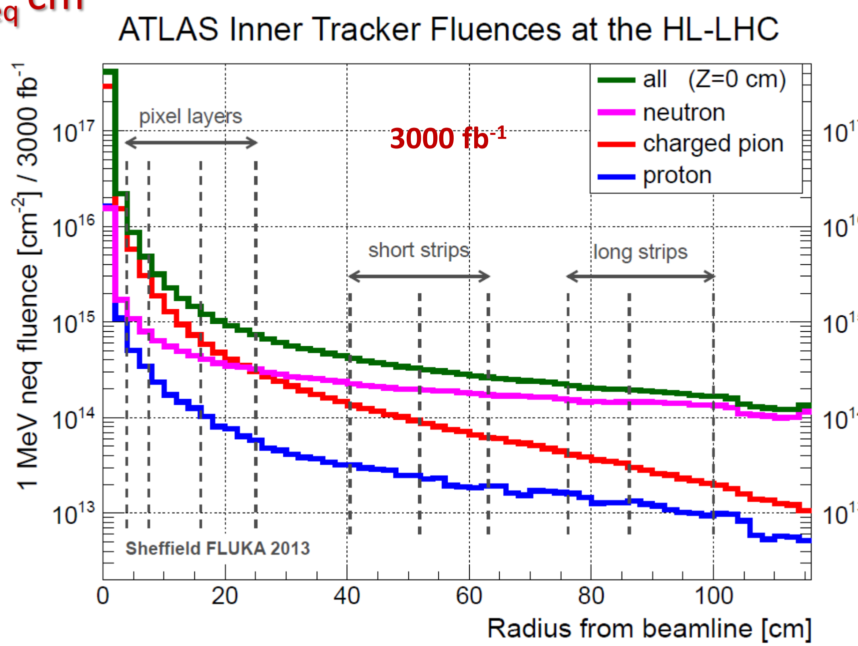
Phase 2 Upgrade (30 months):

- LHC: new quadrupoles in the collision region, crab cavities,
- CMS: new tracker, HGCAL,
- ATLAS: replacement of the Inner Detector,
- LHCb major detector upgrade during LS4

High Level of fluence @ LHC and HL-LHC

1. LHC will produce collisions at a rate of about $5\cdot10^{9}\ s^{-1}$.
2. The annual dose at HL-LHC will be similar to the total dose until LS3:
   - end of Run III (300 fb^{-1}) $\Phi\sim2\cdot10^{15}\ n_{eq}\ cm^{-2}$
   - HL-LHC (3000 fb^{-1}) $\Phi\sim2\cdot10^{16}\ n_{eq}\ cm^{-2}$



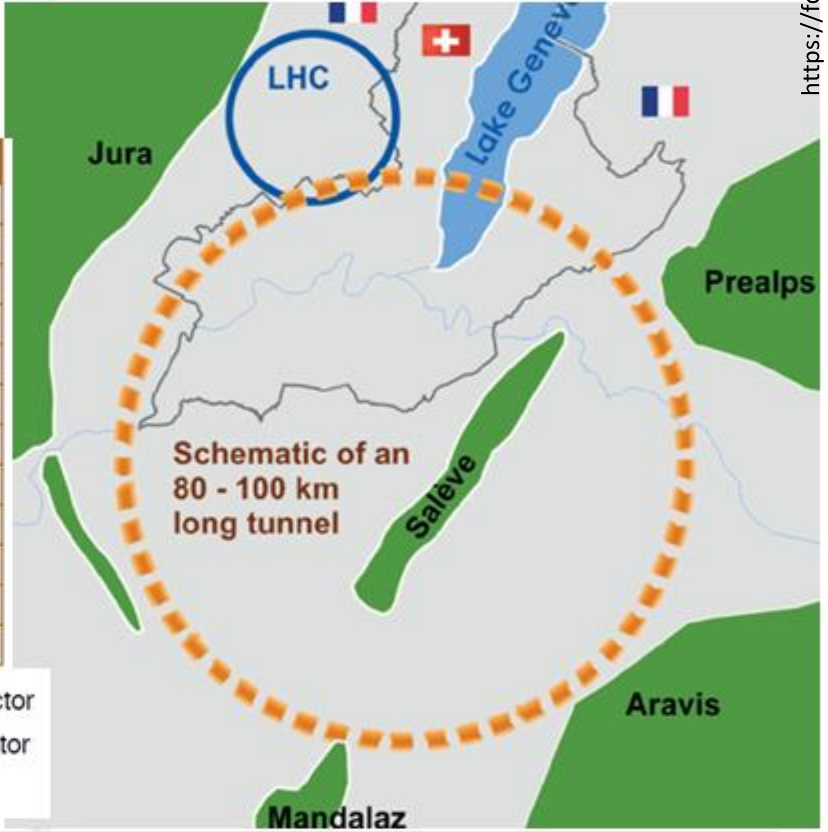


4. **The main objective for RD50 is development of radiation hard semiconductor detectors for HL-LHC.**
5. The radiation hardness above $10^{16}\ n_{eq}\ cm^{-2}$ (while maintaining the S/N ratio > 10) is required with fast signal collection and affordable cost. Current LHC detector can operate up to fluence $10^{15}\ n_{eq}\ cm^{-2}$
6. Defect induced by particle radiation and their influence on detector performance are of major interest to RD50.

Future Circular Collider

- **FCC machine:**
  - FCC-hh (pp collider): final goal defining the whole infrastructure
    → ~ 16T magnets → 100TeV pp collider in 97.75km tunnel
  - FCC-ee: as a potential first step
  - FCC-eh: as an option

Parameter	FCC-hh		HE-LHC	(HL) LHC
Collision cms energy [TeV]	100		27	14
Dipole field [T]	16		16	8.33
Circumference [km]	97.75		26.7	26.7
# IP	2 main & 2		2 & 2	2 & 2
Beam current [A]	0.5		1.12	(1.12) 0.58
Bunch intensity [10^{11}]	1	1 (0.2)	2.2 (0.44)	(2.2) 1.15
Bunch spacing [ns]	25	25 (5)	25 (5)	25
beta* [m]	1.1	0.3	0.25	(0.20) 0.55
Luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	5	30	25	(5) 1
# Events/bunch crossing	170	<1020 (204)	~800 (160)	(135) 27
Stored energy/beam [GJ]	8.4		1.3	(0.7) 0.36
Synchrotron rad. [W/m/ap.]	28.4		4.6	(0.33) 0.17



- **Baseline** (phase 1): 10 yrs of operation @ $L_{peak} = 5\times10^{34}cm^{-2}s^{-1}$ → **2.5 ab^{-1}** per detector
- **Ultimate** (phase 2): 15 yrs of operation @ $L_{peak} \leq 30\times10^{34}cm^{-2}s^{-1}$ → **15 ab^{-1}** per detector

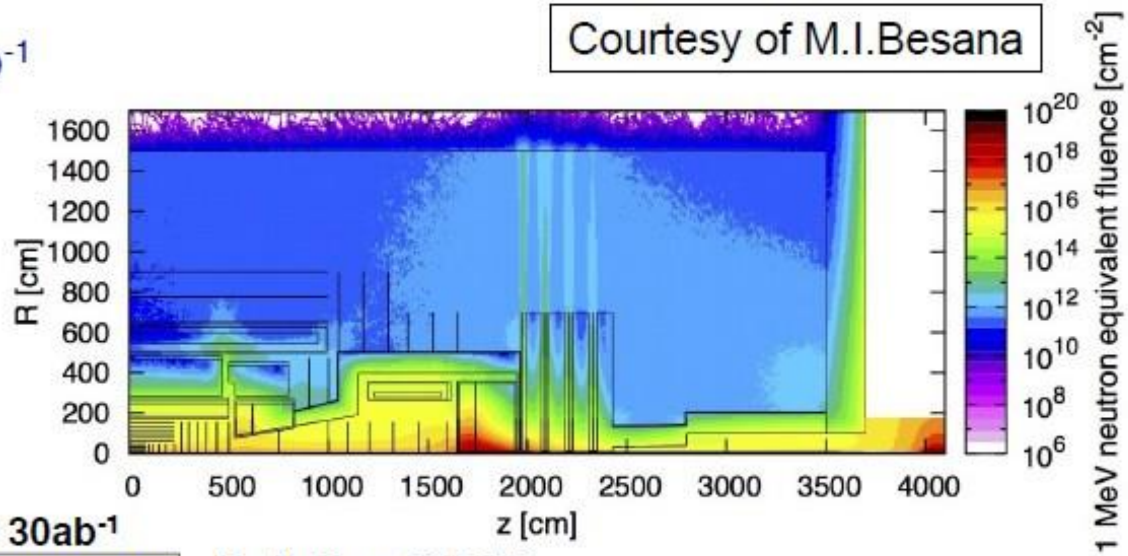
→ **Total: O(20)ab^{-1} per experiment**

https://fcc.web.cern.ch/Pages/default.aspx

Tracker & Long-term Damage after 30ab^{-1}

- 1 MeV neq fluence after 30ab^{-1}

Courtesy of M.I.Besana



Long-term damage for Tracker after 30ab^{-1}

R [mm]	z[m]	Dose [MGy]	1 MeV equivalent Fluence [cm^{-2}]
25	0	320	5.5 10^{17}
60	0	88	1.25 10^{17}
100	0	40	6 10^{16}
150	0	23	3.3 10^{16}
270	0	8.8	1.51 10^{16}
900	0	0.65	3.2 10^{15}
25	5	410	3.7 10^{17}
50	16	250	2 10^{17}

Radiation @ FCC:

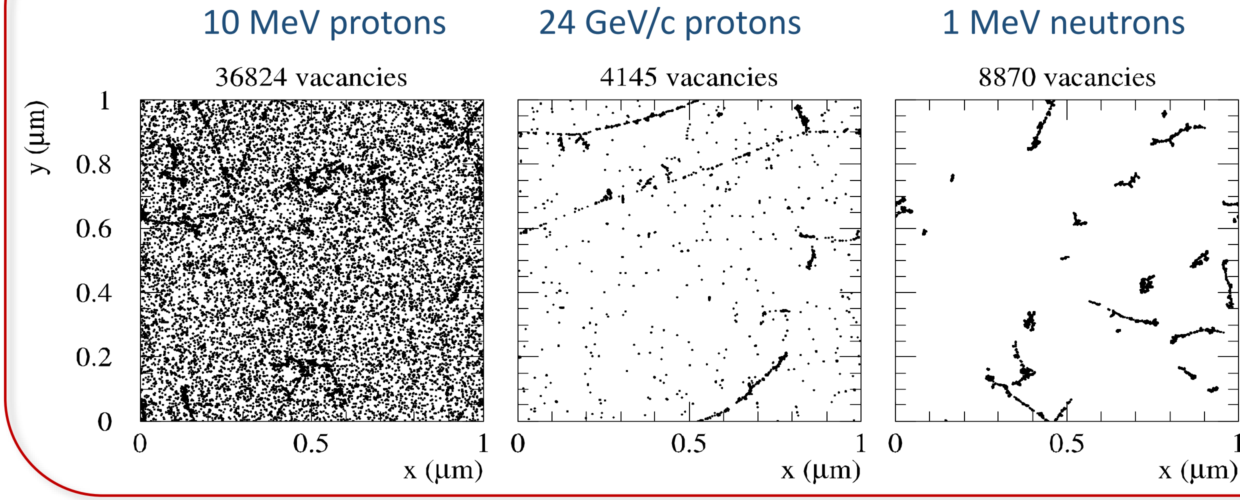
→ @R=25mm: ~6x10^{17} neq cm^{-2} ,TID~0.4GGy

- LHC = 1
- HL-LHC → 20x LHC
- FCC → 600x LHC

The source of radiation damage

1. The main source of radiation is from particles produced in soft p-p interactions (neutrons, pions, protons) and secondary interactions with the detector material.
2. Non-Ionizing Energy Loss (E_k > 15 eV) of impinging particle may displace a silicon atom from the lattice.
3. Creation of defects depends on the kind of particle and its energy.
4. Displacements of silicon atoms produce vacancies and interstitials.

Simulation of radiation 10^{14} particles/cm^2



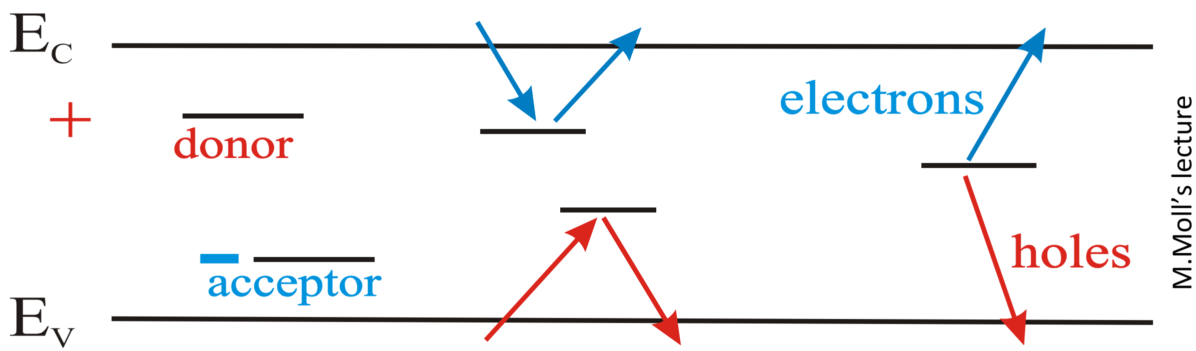
[Mika Huhtinen NIMA 491(2002) 194]

5. Crystal impurities interact with defects causing the change in electrical properties of detector.

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

Radiation Damage - effects

Radiation induced changes in properties and structures of the silicon tracking detectors are observed as **macroscopic effects** caused by **microscopic defects:**



charged defects ⇒ effective doping concentration N_{eff}, depletion voltage V_{dep}

Trapping (e and h) ⇒ Charge Collection Efficiency CCE

generation/recombination ⇒ leakage current I

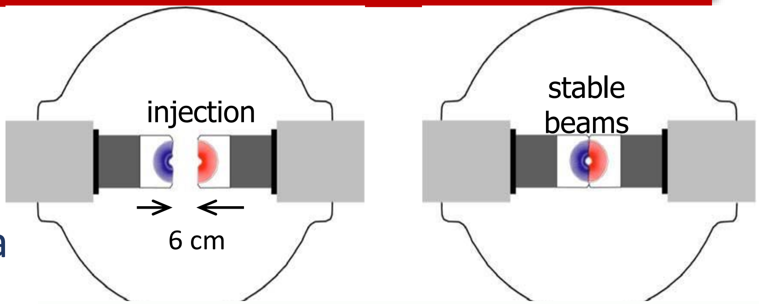
The microscopic defects accumulate over time and have a damaging impact on the sensor performance.

Constant monitoring of radiation influence on silicon sensors:

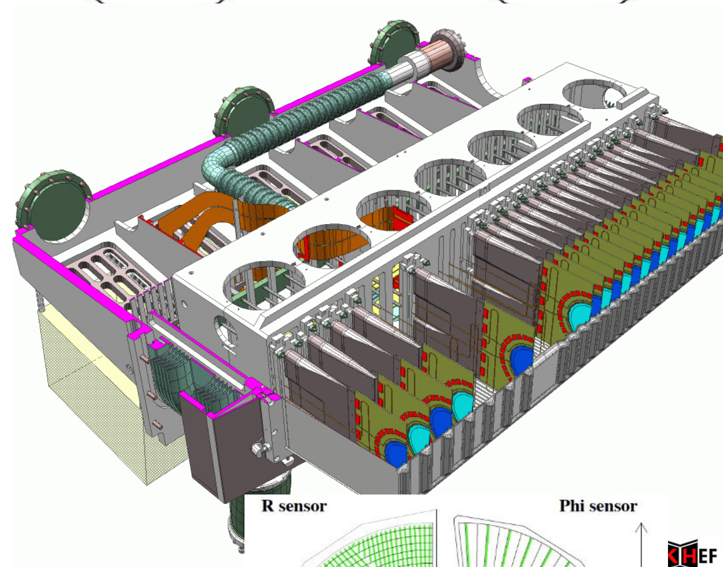
- Current - Voltage scans (**IV**),
- Current - Temperature scans (**IT**),
- Charge Collection Efficiency scan (**CCE**),
- Change of effective depletion voltage (**V_{ED}**)

The LHCb VELO

VErtex LOcator

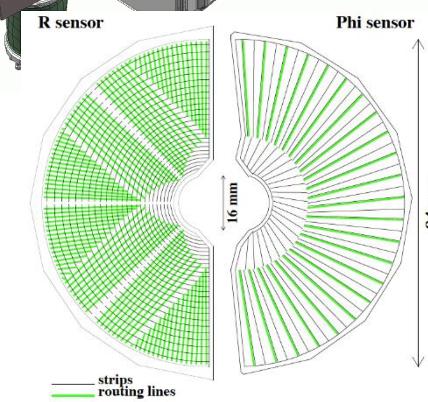


- Close proximity of the beam-pipe.
- VELO halves are movable- the movement is steered by a precise system (accuracy of 10 μm),
- When stable beams, the silicon edge is only 8 mm from the proton beam – sensors are in harsh particle fluence .
- Operated in a secondary vacuum, separated from the LHC vacuum by 300 μm thick aluminium foil.



Sensors

- VELO consist of 42 modules (two halves).
- Modules have two (R and Phi) microstrip silicon oxygenated n^+-on-n sensors (two sensons are n^+-on-p).
- Sensors are 300 μm thick, strip pitches: 40-100 μm.
- Evaporative CO_2 cooling system keeps sensors at -7^{o}C.

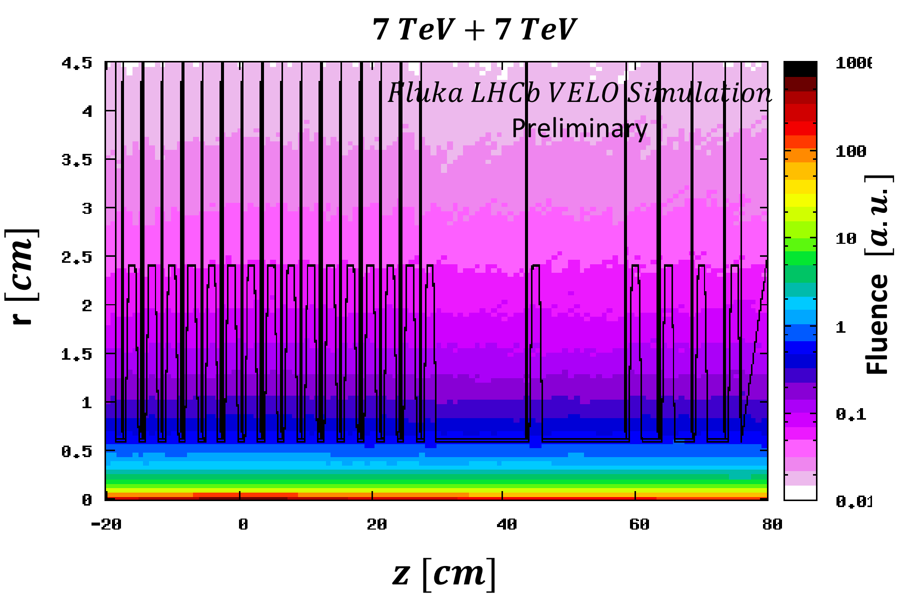


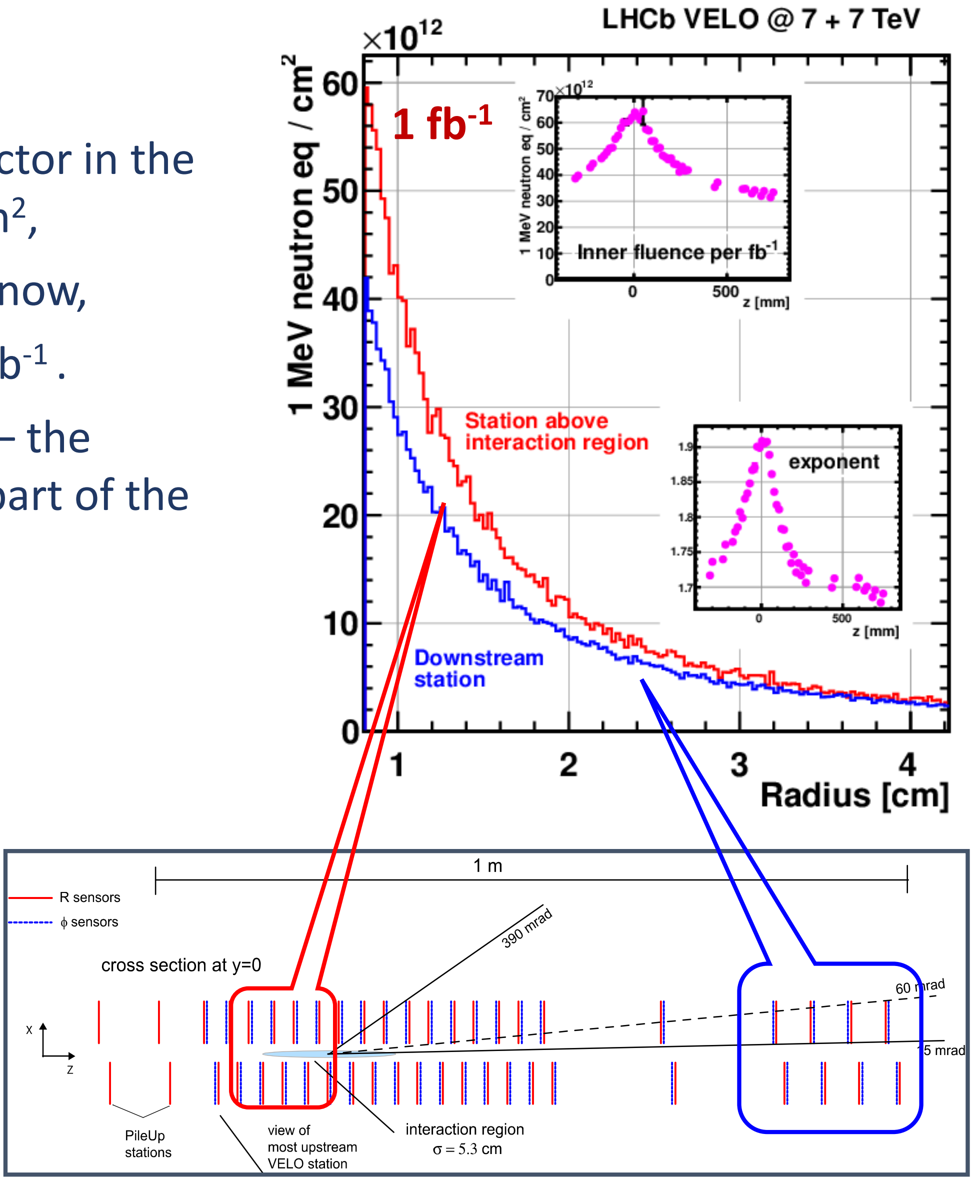
Performance of the LHCb Vertex Locator, *J. Instrum.* 9 (2014) P09007

Particle Fluence

Radiation environment

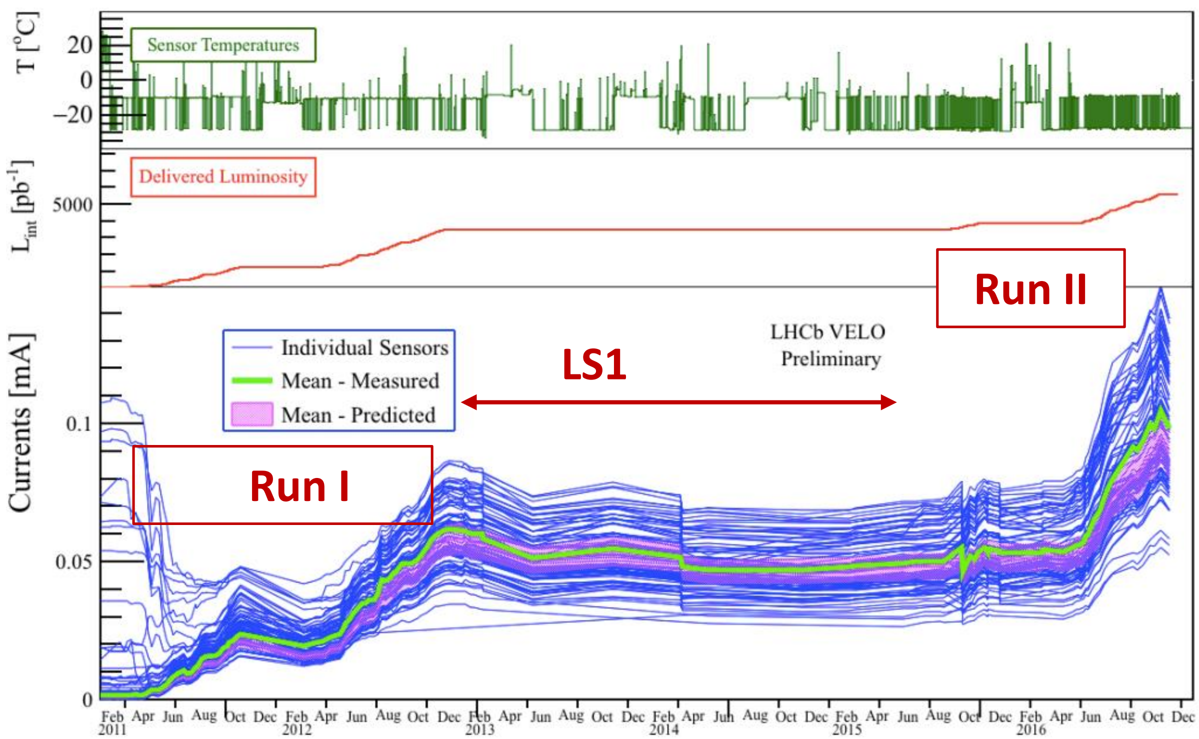
1. VELO is currently the **most exposed** detector in the LHC- fluence up to $1.8 \cdot 10^{14}$ 1MeV n_{eq}/cm^2,
   - LHCb has collected almost 5 fb^{-1} until now,
   - VELO is designed to cope with 10-11 fb^{-1} .
2. The radiation field is highly non uniform – the fluence accumulated in inner and outer part of the sensor differs by a factor of ten.





Leakage Current

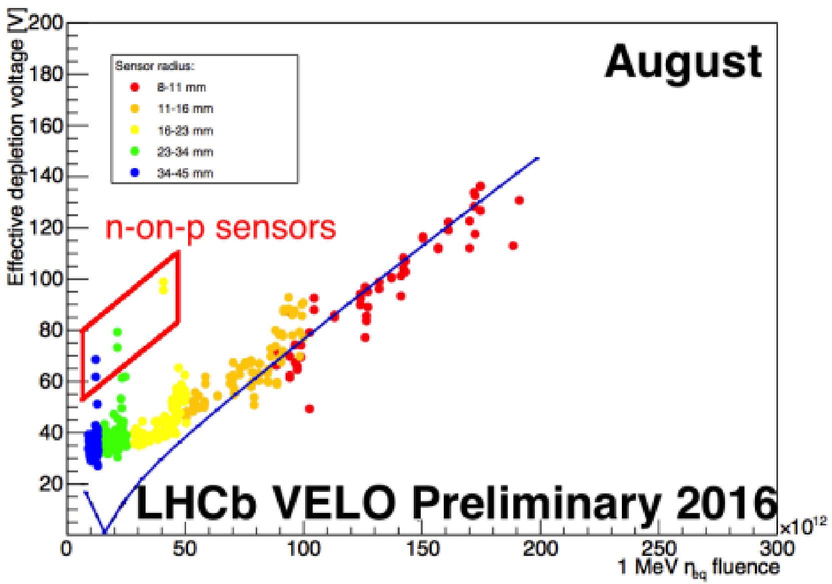
1. The level of leakage current reveals the amount of the radiation damage contained in a detector volume.
2. The increase in leakage current is proportional to the accumulated fluence (time, delivered luminosity) : $\Delta I = \alpha \cdot \phi_{eq} \cdot V$, typically 2 μA per 100 pb^{-1}
   annealing constant $\alpha(20°\mathrm{C}) = (3.99 \pm 0.03) \cdot 10^{-17}$ A/cm
3. The currents of the sensors are measured as a function of time while operating at nominal conditions (depletion voltage, temperature)

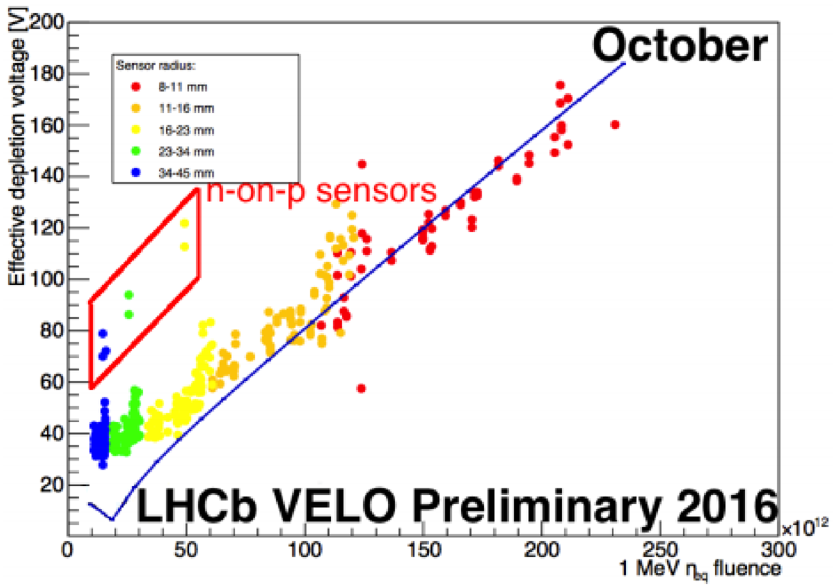


- Bulk currents increases with fluence es expected, with occasional drops due to annealing.

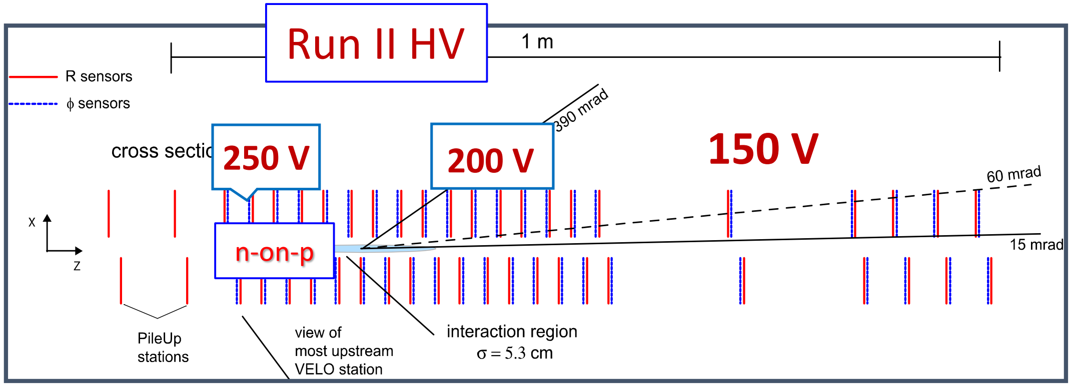
CCE – Effective Depleted Voltage V_{ED}

1. At the production, initial depletion voltage was 25-70 V.
2. Sensors in 2011-12 were biased at 150 V, currently 150-200 V (250 V for n-on-p).



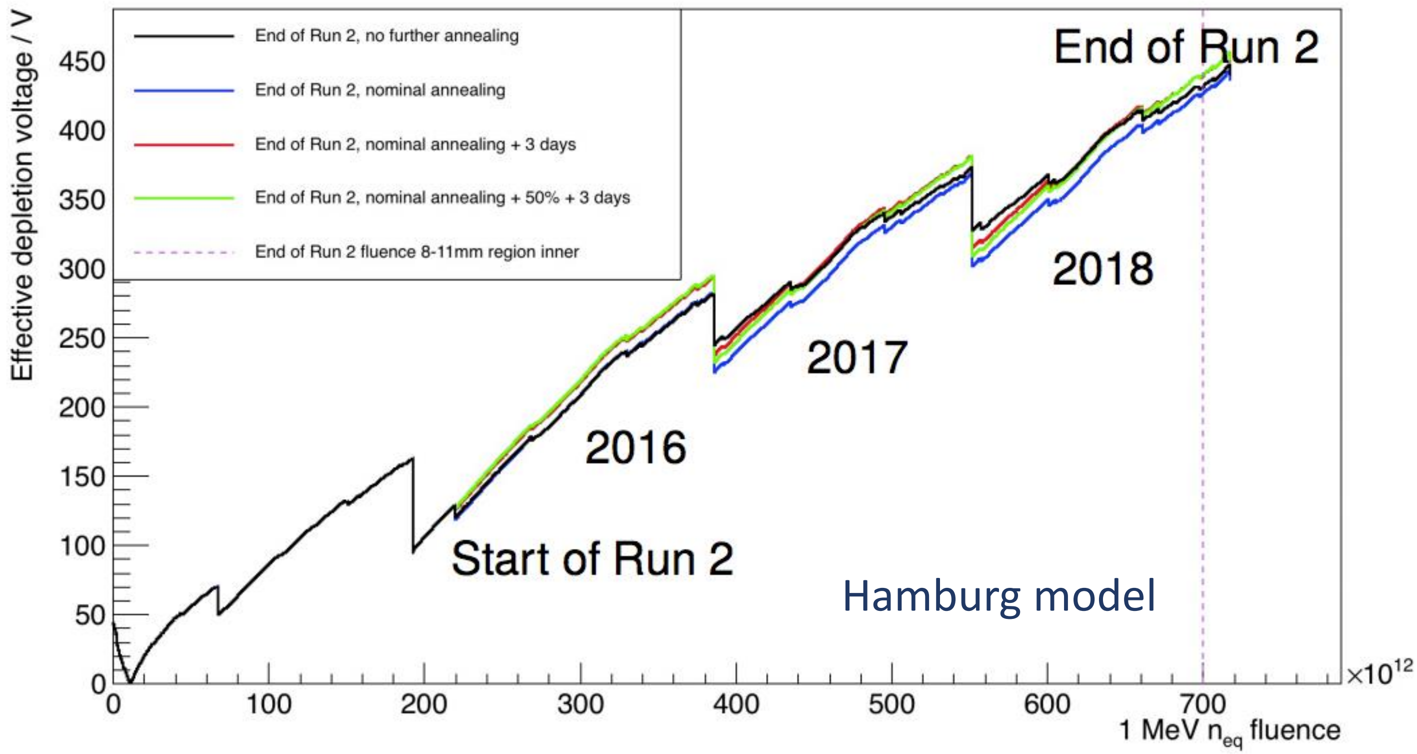


4. Good agreement with **Hamburg model**
5. We need to increase the bias voltage to 300 V, first in the most irradiated sensors.



V_{ED} – expectations for Run II

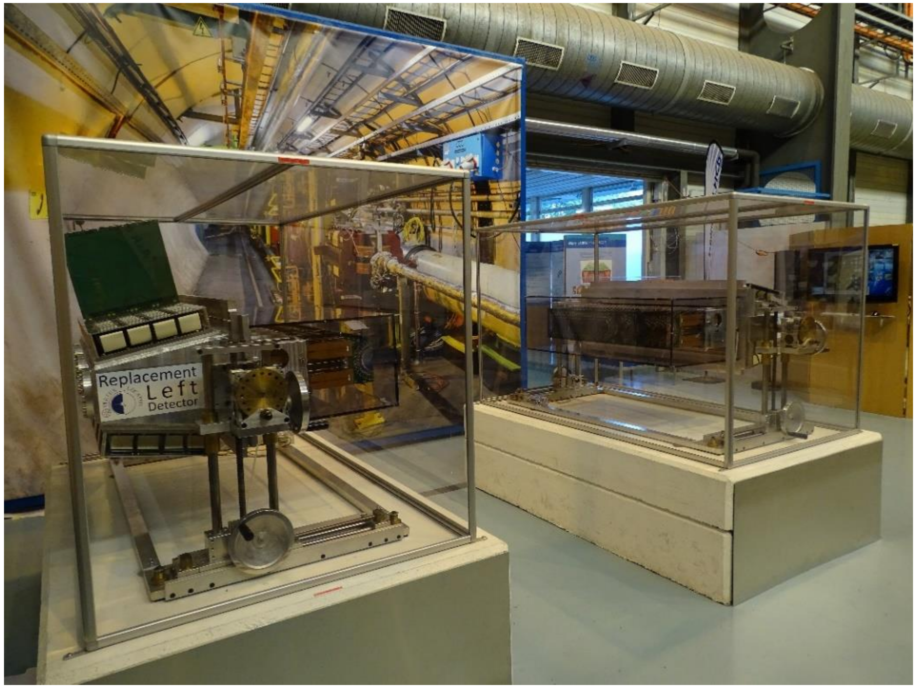
1. LHCb is supposed to collect 8 fb^{-1} by the end of Run II, what means that the VELO sensors will accumulate maximum of $7 \cdot 10^{14}$ 1MeV n_{eq}/cm^2 (most irradiated tips of the sensor).



3. VELO sensors can be operated up to 500V.
4. During LS2 (2018-19) VELO microstrip sensors will be replaced by pixels.

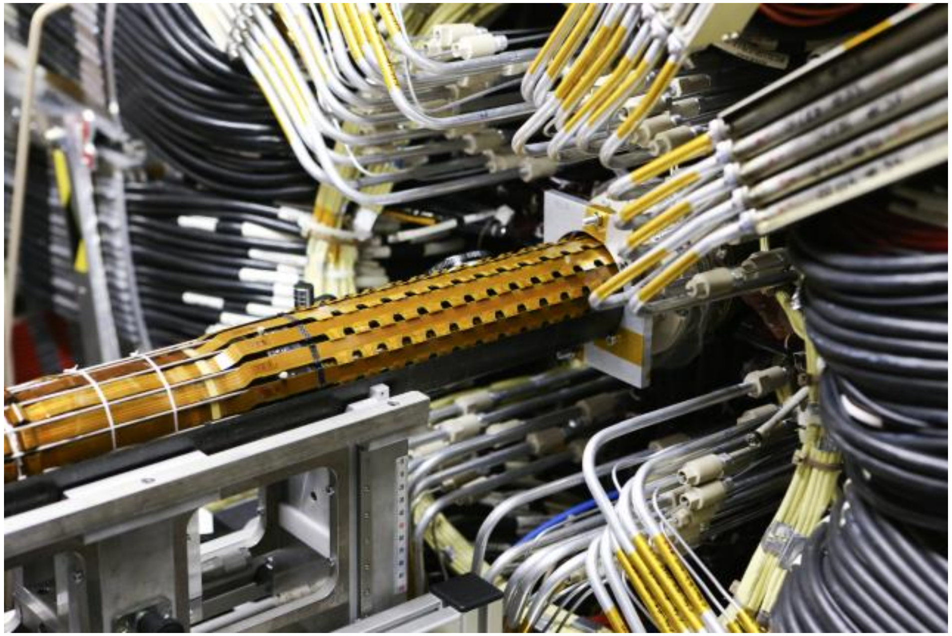
The first radiation concern

The LHCb silicon vertex detector will not be replaced.
The main VELO upgrade (pixels) is planned for LS2 (2018).



VELO replacement is currently on display at LHCb Pit.

The new innermost layer of ATLAS Inner Tracker was installed (IBL) inside the Pixel Detector during LS1.



Call RD50 in case of radiation damage problem…

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 the LHC to $7.5 \cdot 10^{34}$ $cm^{-2}s^{-1}$.

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.
4. The current activities od RD50 include:

a) identifying the defects through dedicated measurement techniques (DLTS, TSC, TCT) or monitoring the macroscopic changes in HEP experiments.

b) work out how to get rid of damage (or avoid it) – new technologies, new structures (3D sensors, HV CMOS, LGAD, simulation (FLUKA, GEANT4, TCAD…).

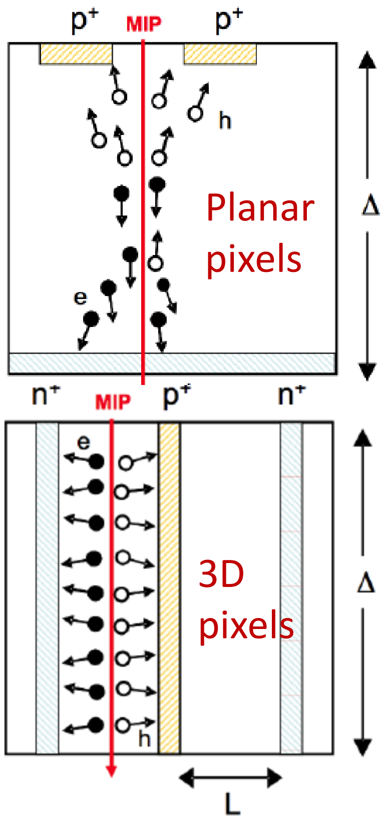
c) test the solution:
   - neutron exposition in nuclear reactor,
   - proton irradiation at cyclotrons and synchrotrons,
   - new dedicated irradiation center @ CERN.

d) incorporate the feedback from experiments.

Advanced detector design – 3D pixel sensors

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 μm, distance L: 50 – 100 μm (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 (bump-bonding, time, cost, yield).

3D pixel sensors for LHC

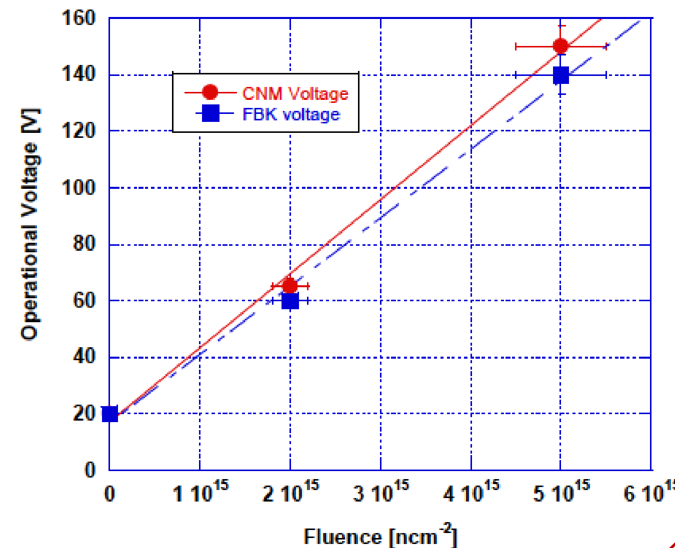
For LHC a few devices were projected and tested for radiation hardness:

- 230 µm thick sensors by CNM and FBK
- FEI4s: 50x250 µm 2E, 67 µm inter-el. distance

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

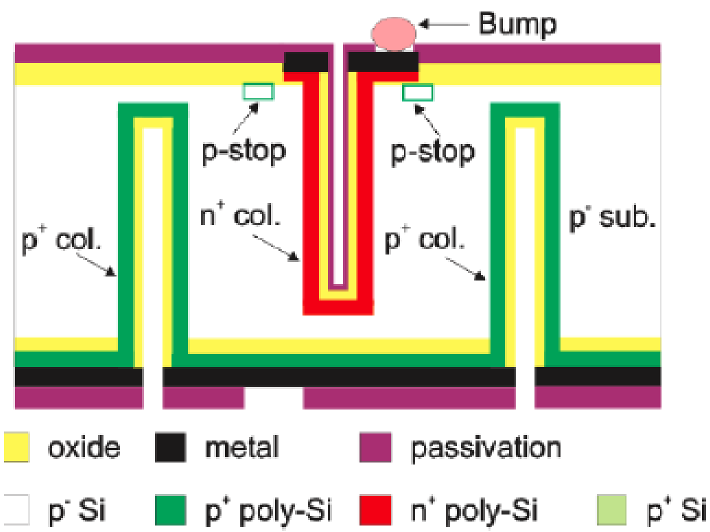
Double sided (DDTC) technique:

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



ATLAS IBL Coll, JINST 7 (2012)P11010

CNM 3D pixels for IBL



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

Promising for HL-LHC!

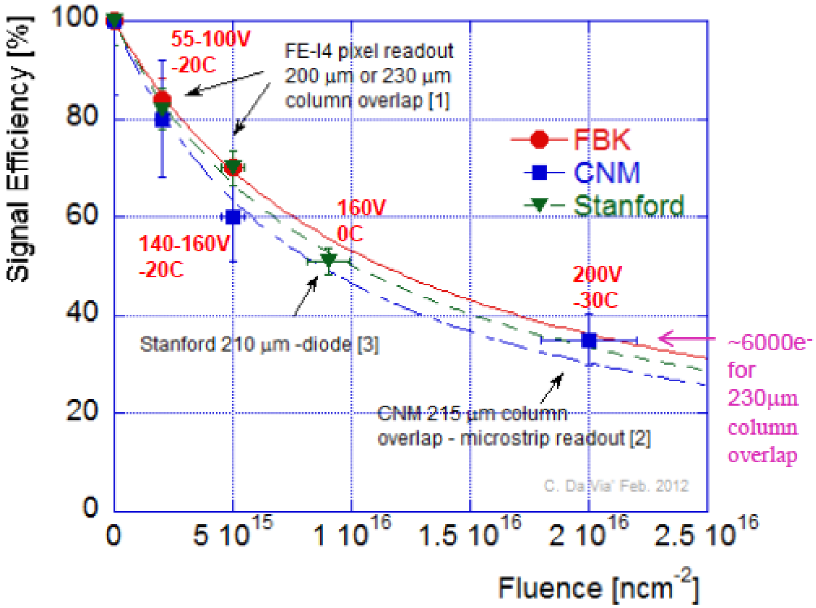
time, cost?

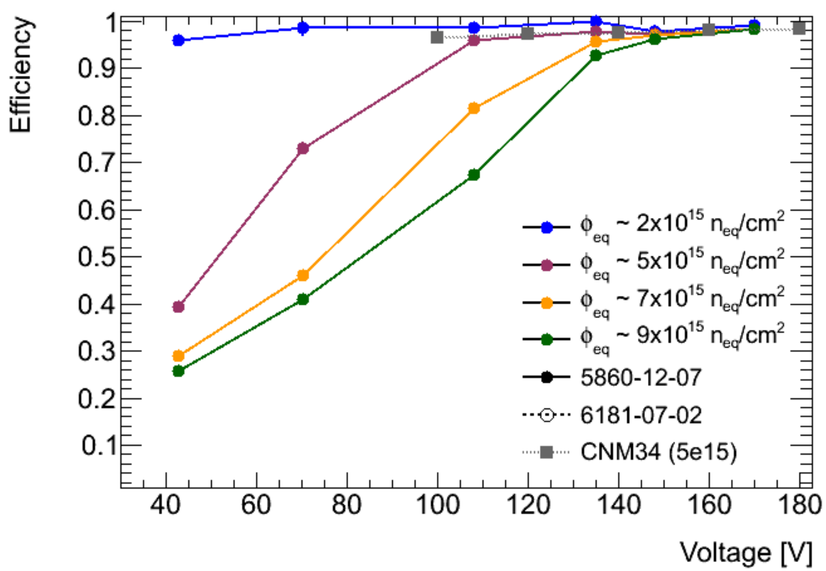
G. Pellegrini et. al. NIMA 592(2008), 38
G. Pellegrini et. al. NIMA 699(2013), 27

3D pixel sensors for HL-LHC - prospects

The signal efficiency is about 60-70% at $5\cdot10^{15}$ $n_{eq}cm^{-2}$ and 30% at almost 10^{16} $n_{eq}cm^{-2}$ with not much increase of V_{bias}.

Signal efficiency was improved with decreasing electrode distance.





Lopez Paz et al..
RD50 workshop 2015, CERN

[1] ATLAS IBL Collaboration, submitted to JINST (2012)
[2] M. Koehler et al. NIMA 659 (2011) 272
[3] C. Da Via, et al., NIMA 604 (2009) 505

Compilation by C. Da Via

RD 50 project:

Joint MPW pixel run for ATLAS, CMS, LHCb.

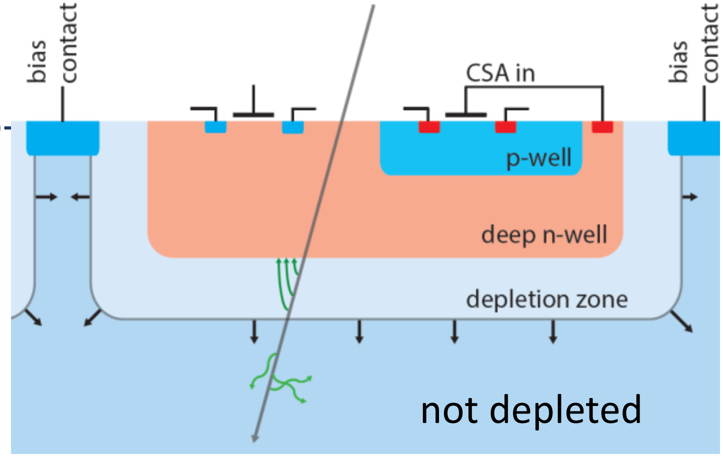
Motivations:

1. Manufacture smaller area pixels on thin sensors.
2. Study of radiation hardness.

New technology – HV CMOS

High Voltage CMOS

- n-wells are implanted in low resistivity (~10 Ωcm) p-type substrate and play role of electrode implant,
- biased with 60 V but allows only shallow ($10 - 20\ \mu m$) depletion zone, signal 1-2 kel.
- thin active layer,
- low drift distance, small drift time (fast collection),
- radiation hard (less trapping),



From: S. Fenandez-Perez, TWEPP 2015

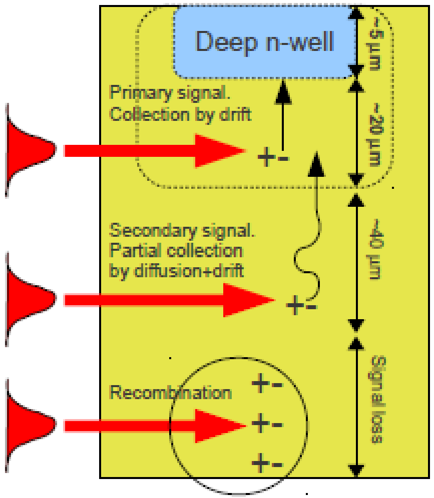
- possible to use capacitive coupling through glue instead of bump-bonding,
- industrial process enables large volume production in relatively short time,
- both pixel and strip detector possible,
- fully monolithic devices don't require a bump-bonded read-out.

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

HV CMOS – signal collection

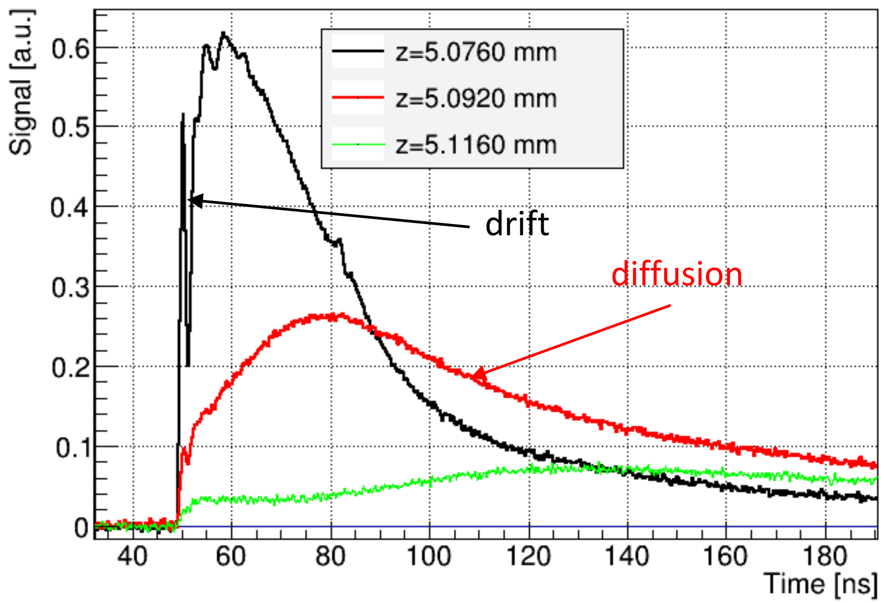
High voltage is used to deplete a part of the substrate:

- The main charge collection mechanism is drift,
- Part of the signal originates from the undepleted region and is collected by diffusion,
- Edge-TCT measurements showed drift and diffusion component



Side view of HVCMOS

M.Fernández García RD50 Workshop Nov 2014



The charge collection profiles of irradiated samples show quick disappearance of drift constituent.

HV CMOS – irradiation tests

Charge collection properties studied after irradiation to high neutron fluences with Edge-TCT techniques.

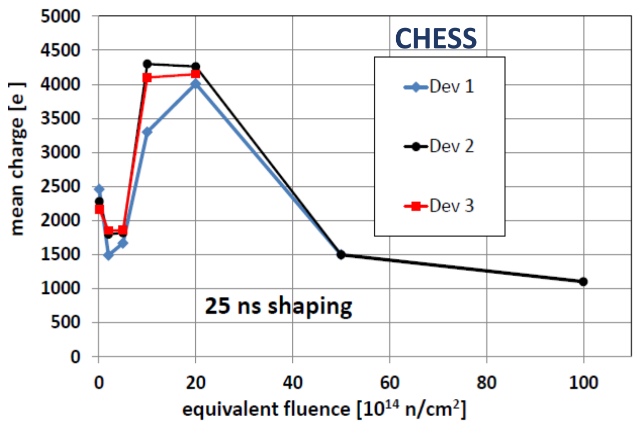
AMS $350nm$ production, CHESS-1 sensors

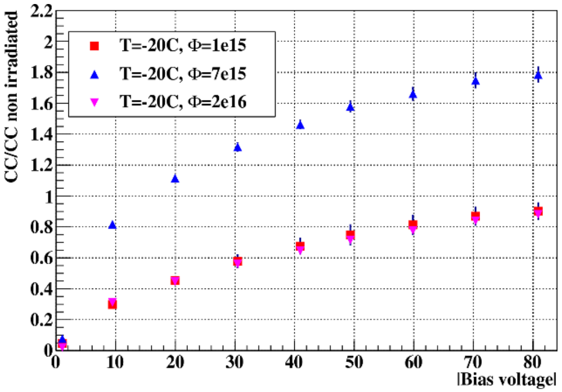
- 2 mm x 2 mm passive sensor (400 pixel)
- Sr90 electrons for CCE, 25 ns shaping, 120 V, TCT

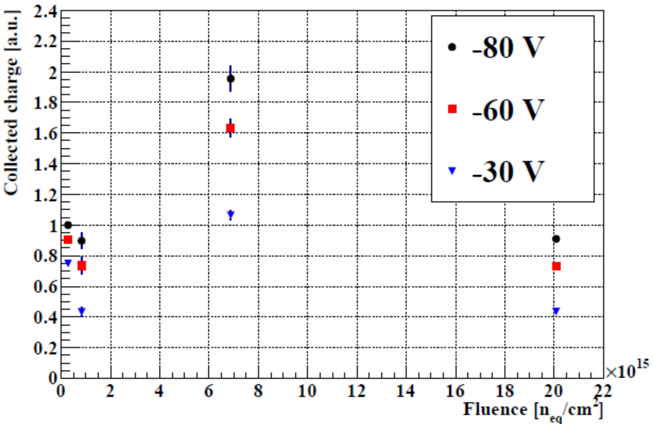
AMS $180nm$ production, HV2FEI4

- 100 µm x 100 µm passive pixel,
- IR-laser, 5ns integration

A.Affolder et al., 2016 JINST 11 P04007







M. Fernández García 2016 JINST 11 P02016

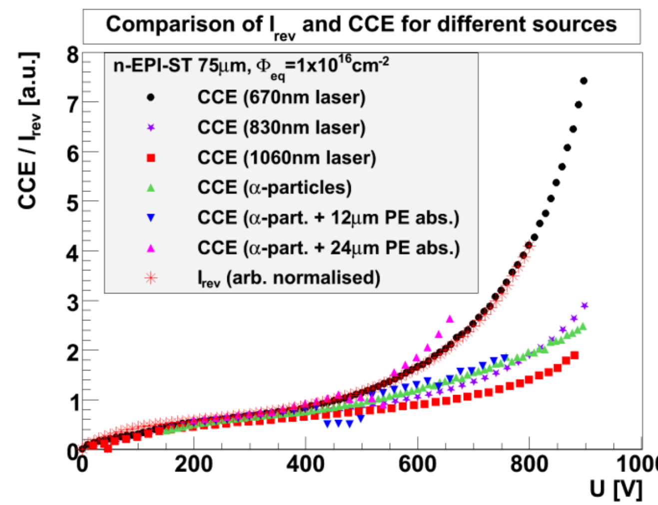
- CCE decreases for fluence up to $2\text{-}5 \cdot 10^{14}$ $n_{eq}cm^{-2}$ due to diffusion decrease.
- For higher fluence the signal is rising due to increase of active volume (acceptor removal).
- Finally CCE degrades due to more intense trapping caused by space charge.
- For fluence $2 \cdot 10^{16}$ $n_{eq}cm^{-2}$ @ 80V charge collection is 90% of signal before irradiation!

Very promising for high radiation environment!

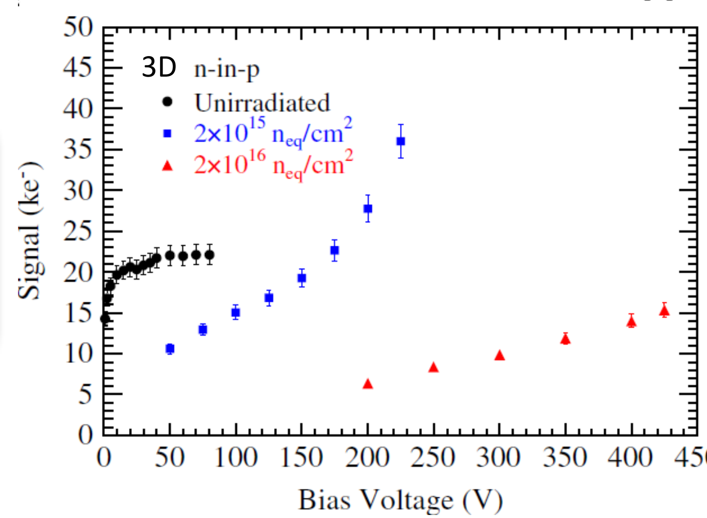
Charge multiplication in Si detectors

Charge multiplication:

- signal larger than expected from conventional silicon devices observed after irradiation $2\text{-}5 \cdot 10^{15}\ n_{eq}cm^{-2}$,
- irradiation causes negative space charge in detector bulk that increases the electric filed (>15 V/µm), impact the ionisation which manifests through charge multiplication,
- observed in different types of devices (diode, strip, 3D), at very high bias voltages, heavy irradiated,
- could be beneficial for sensors and give extra signal – usable for HL-LHC.



J.Langeet al, 16thRD50 Workshop, Barcelona



M. Kohler, NIM A, 659 (2011), 272–281

RD50 project: exploit charge multiplication detectors:

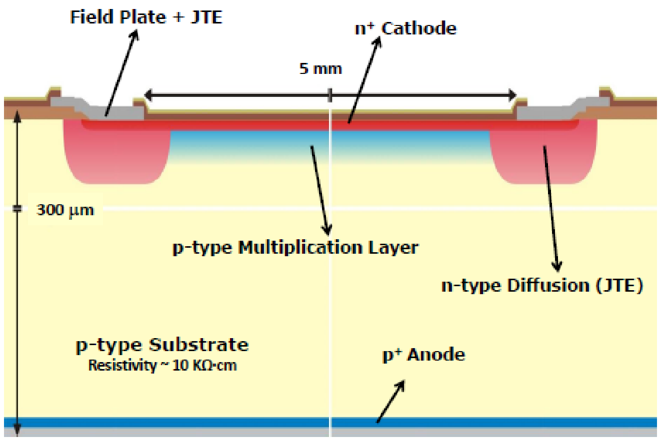
- 1 cm x 1 cm, n-in-p FZ strip detectors,
- LGAD sensors (first segmental sensors on thin substrates).

Aims:

- exploit the charge multiplication effect,
- fabricate, test and irradiate sensors,
- simulate and predict (TCAD),
- measure with TCT setup.

LGAD

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



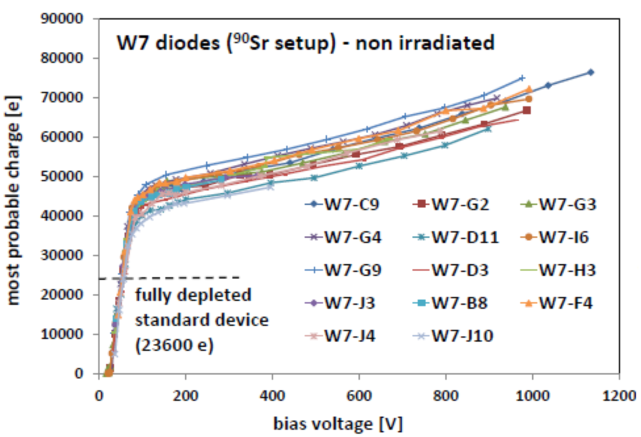
Advantages:

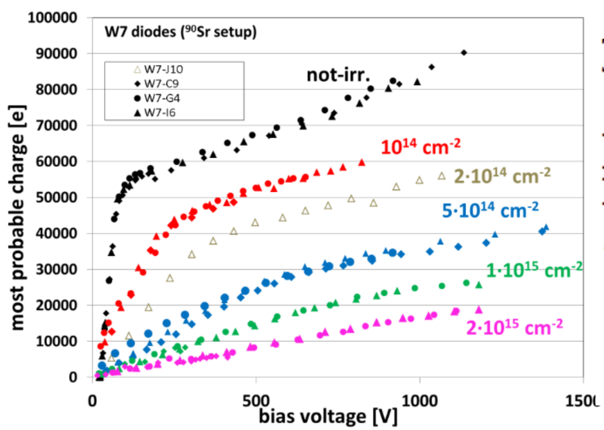
- higher charge collection efficiency,
- short drift time,
- signal shorter and steeper while retaining a large amplitude due to the multiplication mechanism.

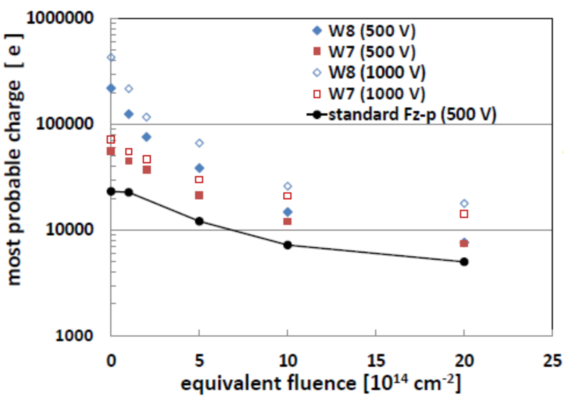
After irradiation (reactor neutrons and 800 MeV protons):

- decrease of charge collection,
- decrease of multiplication (before irradiation it was 3 times higher than standard diode), after irradiation with fluence $2\cdot10^{15}$ $n_{eq}cm^{-2}$ the gain was lost.

G.Kramberger RD50 Workshop June 2014







G.Kramberger et al. 2015 JINST 10 P07006

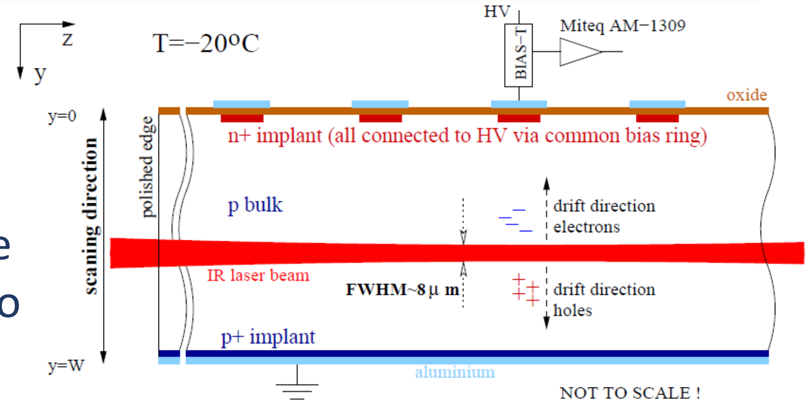
New technology – Gallium instead of Boron or add Carbon to prevent Boron removal

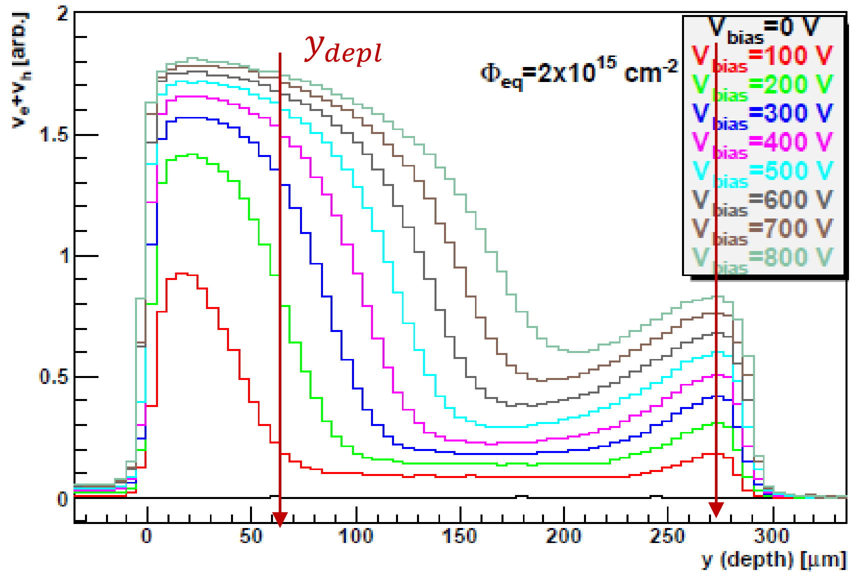
Measurement techniques - TCT

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.





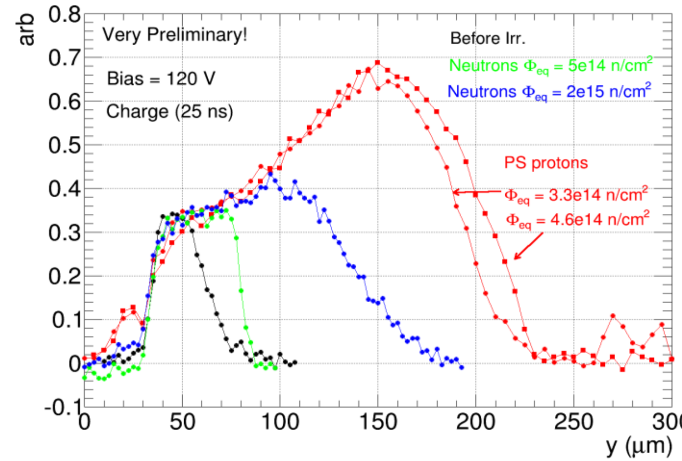
G. Kamberger et al. 2014 JINST 9 P10016

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

TCT- flash of results

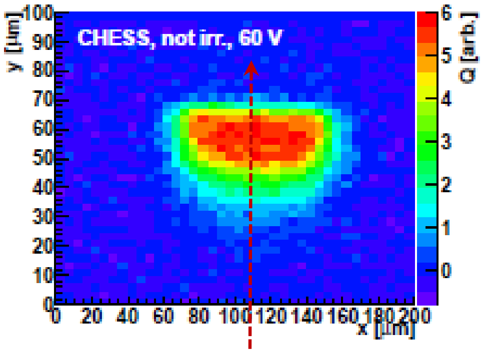
HV-CMOS – different structures:

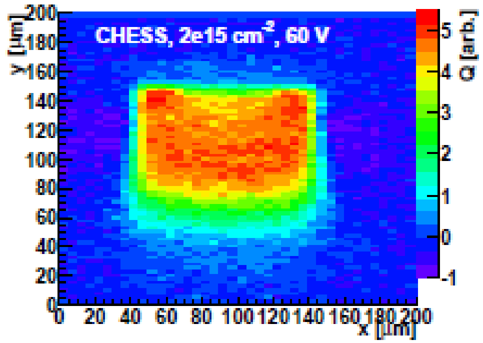
- irradiated by reactor neutrons and PS protons,
- charge profiles at different depth and vs. bias voltage,
- width of charge collection,
- determination of N_{eff}



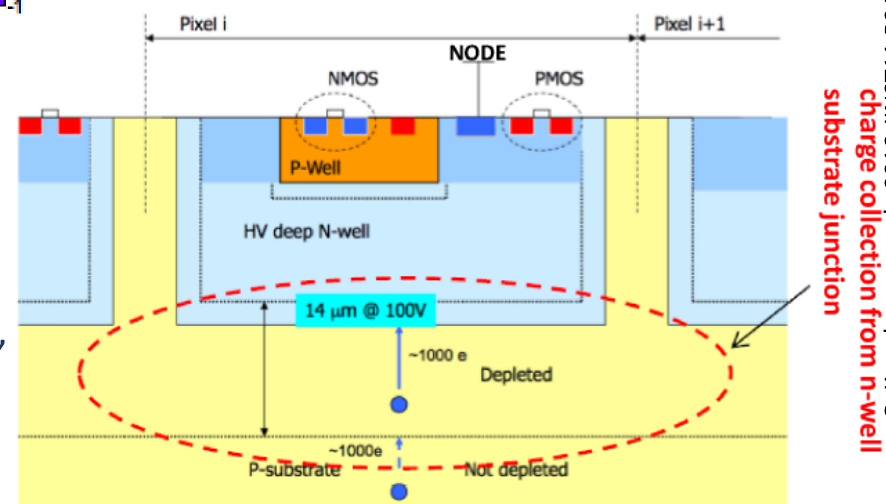
Igor Mandić, RD50 Workshop, June 2016, Torino

AMS CHESS1 chips (20 Ωcm)





Scan direction



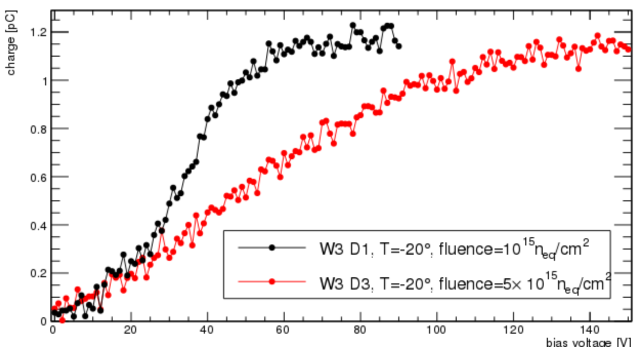
G. Kramberger et al., 2016 *JINST11 P04007*

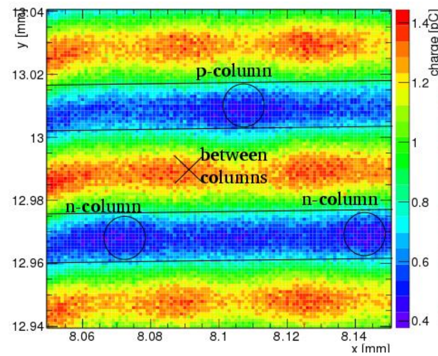
Results:

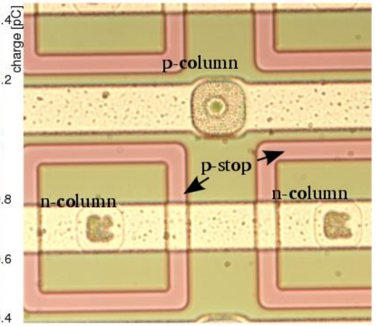
- neutron irradiation up to $2 \times 10^{15}\, n_{eq}\, cm^{-2}$ - increase of depletion region (initial acceptor removal), increase of space charge and charge collection
- these effects are degrading with fluence

TCT- 3D and LGAD example

3D pixels (CNM) –
irradiated by reactor neutrons with $5 \times 10^{15}\, n_{eq}\, cm^{-2}$

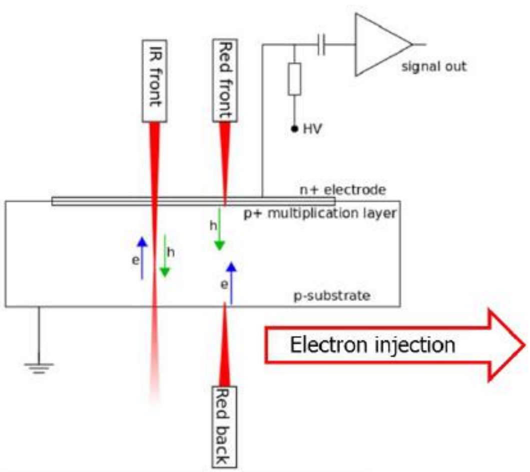


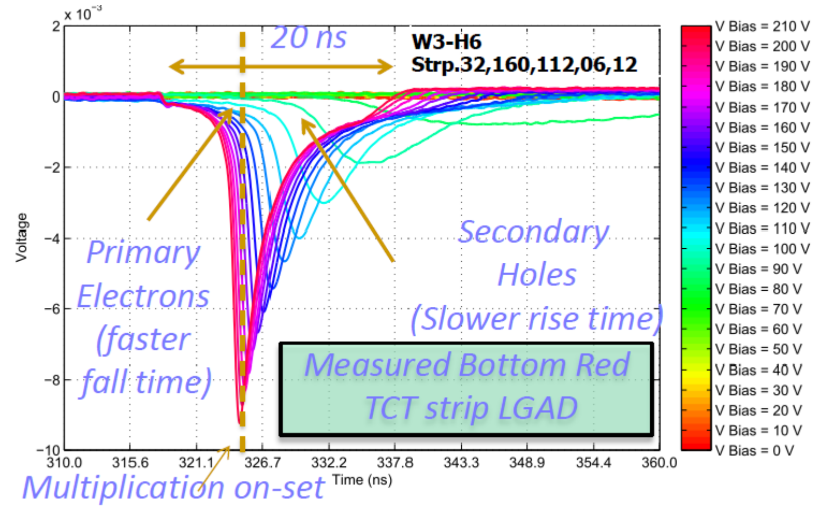




G.Pellegrini RD50 Workshop Dec 2015

Signal amplification in strip-LGAD





Iván Vila, RD50 Workshop, June 2016

SUMMARY

1. Silicon detectors currently installed in LHC experiments need to be replaced by 2023 at the latest.
2. Current technologies are not sufficient to withstand fluence at the level of $10^{16}\, n_{eq}\, cm^{-2}$.
3. The new region of interest for FCC – fluence up to $10^{18}\, n_{eq}\, cm^{-2}$.
4. RD50 Collaboration has been working on:
   - new technologies and new structures: 3D sensons, LGAD, HV-CMOS description of defects and material characterization,
   - simulation of the structures and radiation effects,
   - methods of measurements and test of irradiated devices.
5. The monitoring of radiation damage in Vertex Locator @ LHCb showed symptoms of degradation at the level as expected.
6. Vertex Locator is performing successfully in Run II obtaining the resolutions similar to Run I.

Thank you for your attention!

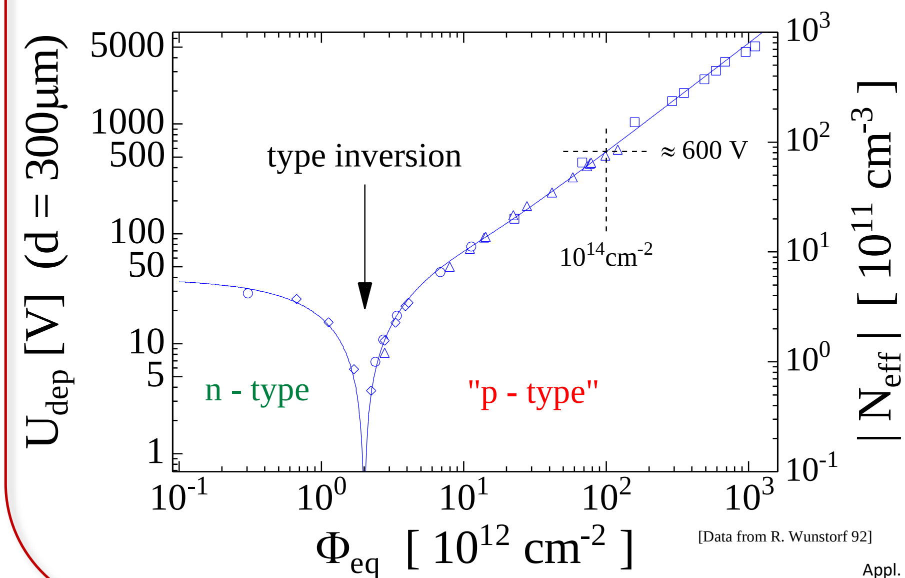
SPARES

Radiation damage effects (1)

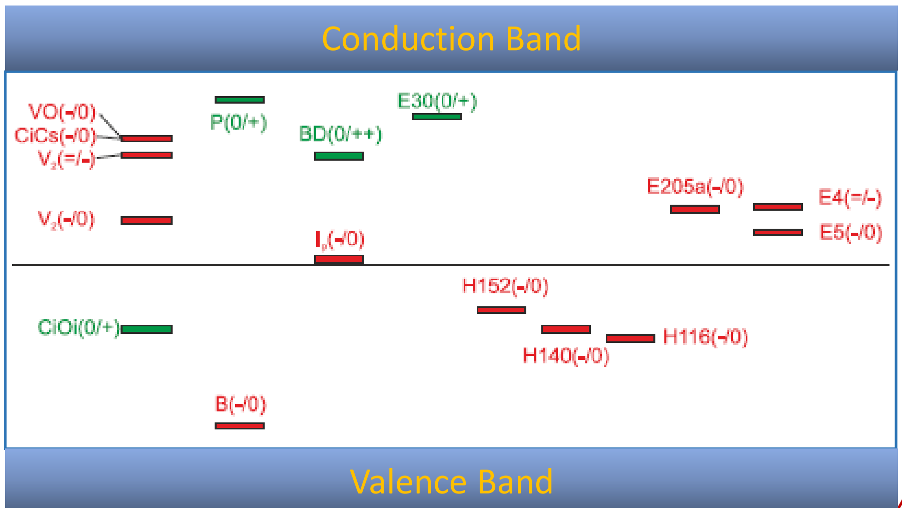
Radiation induced changes in properties and structures of the silicon tracking detectors are observed as ...

macroscopic effects … caused by … **microscopic defects**

1. Change of depletion voltage:



- due to charged energy levels in the depleted region.



Appl. Phys. Lett. 82, 2169 (2003), Nucl. Instr. and Meth. in Phys. Res. A 611 (2009) 52, Appl. Phys. Lett. 92 (2008) 024101;) J.Appl.Phys. 117 (2015) 164503; Nucl. Instr. and Meth. in Phys. Res. A 612 ,525-529, 2010.

Defects change the effective doping concentration and has impact on bias voltage used to fully deplete the sensor. Significant progress on identifying defects was performed within RD50 group.

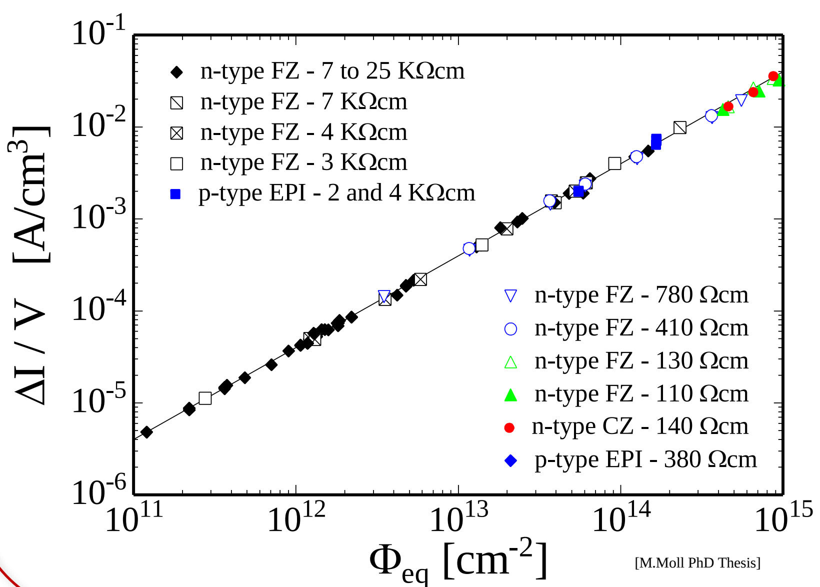
Due to excess of acceptor-like defects and donor removal, initially n-type sensor changes into p-type sensor (at LHC first observed in LHCb VELO).

Radiation damage effects (2)

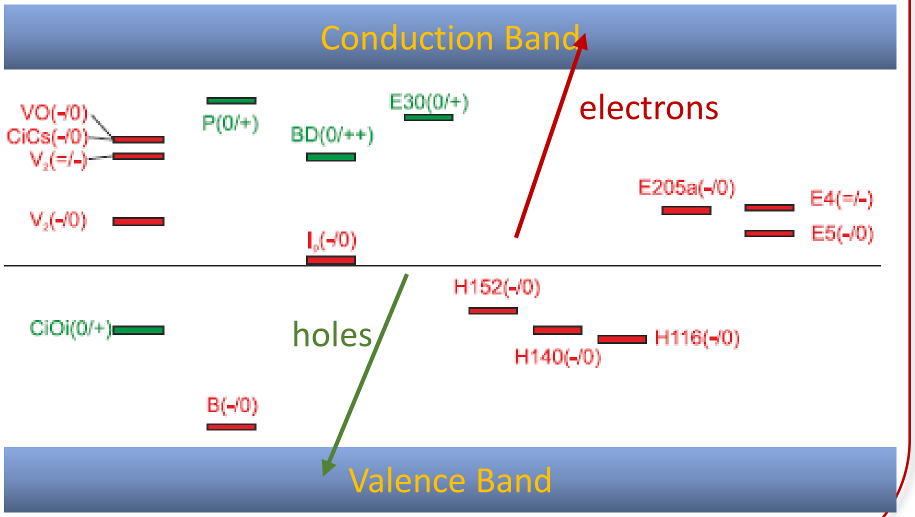
Radiation induced changes in properties and structures of the silicon tracking detectors are observed as ...

macroscopic effects ... caused by ... **microscopic defects**

2. Increase of leakage current:



- bulk current due to generation/recombination centers in the mid-gap.



Defects are able to capture and emit electrons and holes – source of the reverse-bias current.

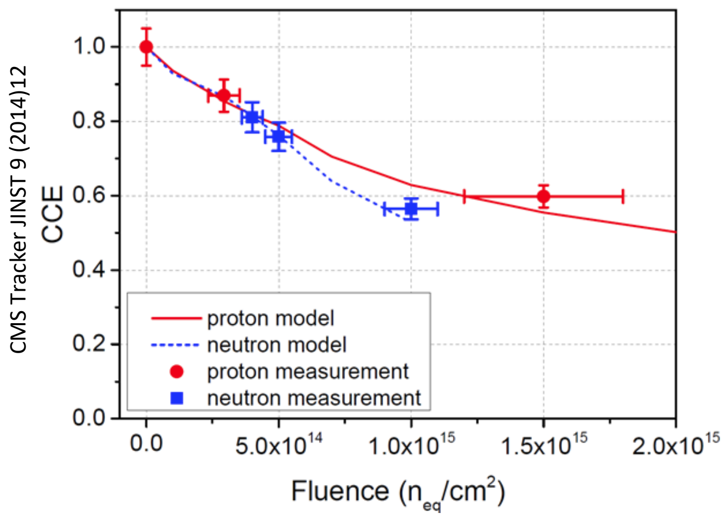
Higher noise and power consumption.

Radiation damage effects (3)

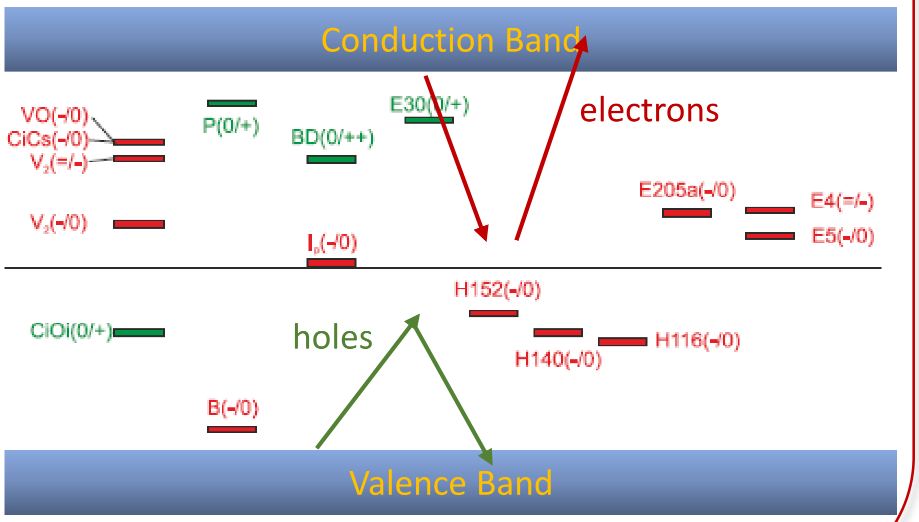
Radiation induced changes in properties and structures of the silicon tracking detectors are observed as ...

macroscopic effects ... caused by ... **microscopic defects**

3. Decrease of charge collection efficiency:



❑ due to damage induced trapping centers.



Defects act as a trapping centers - electrons and holes are re-emitted with some time delay.

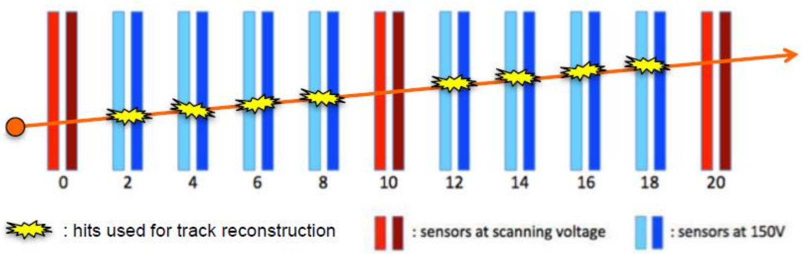
The signal charge is trapped and may be released too late for 25 ns read-out.

This is the most serious problem for detector irradiated with fluence above 10^{15} $n_{eq}cm^{-2}$.

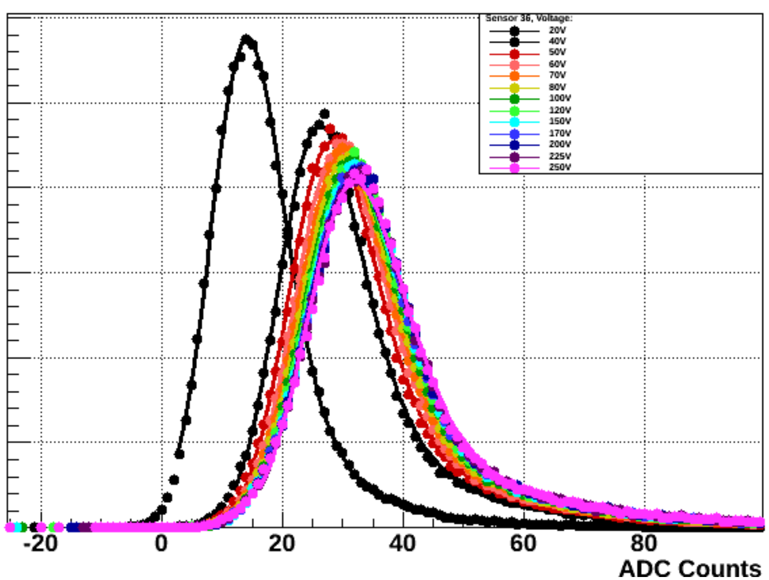
Charge Collection Efficiency - V_{ED}

Charge Collection Efficency (CCE)

1. During data taking a tested sensor is excluded from the track fit.

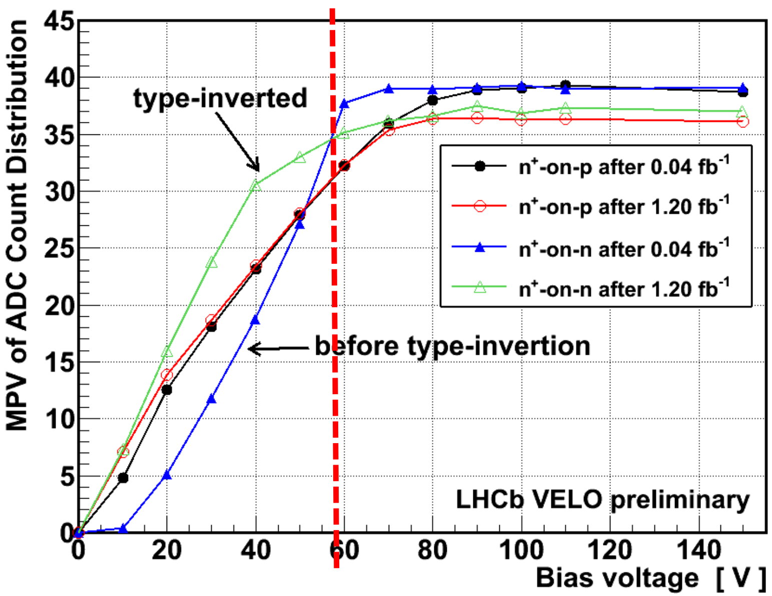


2. A voltage bias scan is performed on it and the charge deposited in sensor around the track intercept is measured.



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

4. **Type inversion** occurred at $(10\text{-}15)\times 10^{12}$ 1MeV n_{eq}/cm^2, inversion started at inner radius.



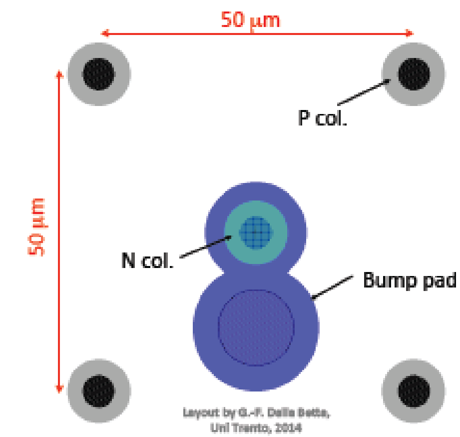
CCE scan is used to measure:

- Effective Depletion Voltage (**V_{ED}**)
- Cluster Finding Efficiency (**CFE**)

3D pixel sensors for HL-LHC

Development of new generation 3D pixel sensors for HL-LHC:

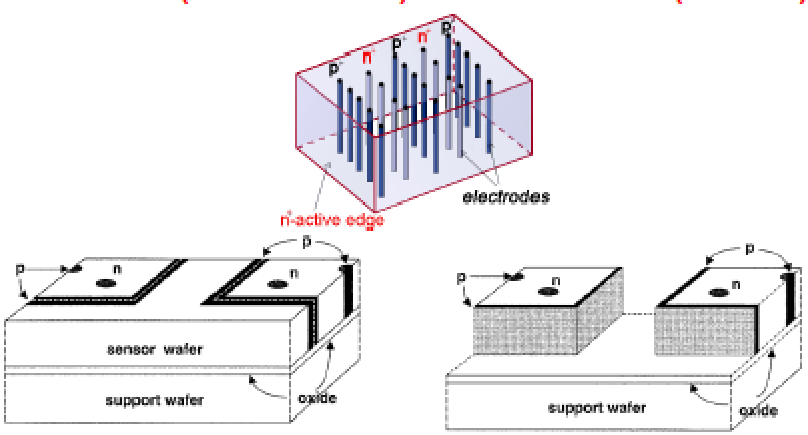
- radiation hardness up to $2 \cdot 10^{16}\ n_{eq}cm^{-2}$.
- reduced pixel size: $50 \times 50\ \mu m^2$ or $25 \times 100\ \mu m^2$.
- small inter-electrode distance (less trapping).
- reduced thickness $100 - 150\ \mu m$ (small leakage current).



First prototype of new generation 3D pixels finished (January 2016).

Three different technologies tested:

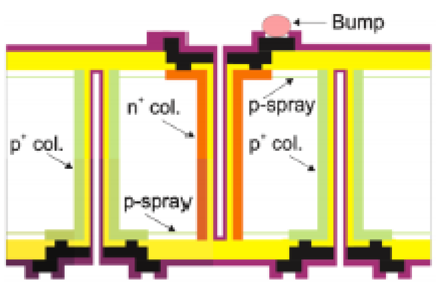
SNF (Stanford) / SINTEF (Oslo)



C. Kenney et al., IEEE TNS 48 (2001) 2405

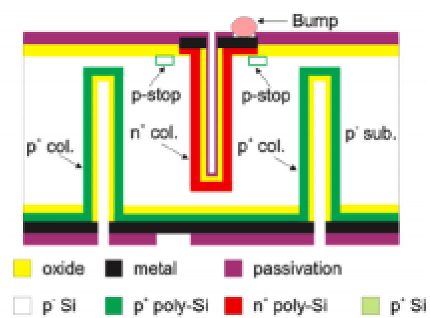
single sided, active edge

FBK (Trento)



A. Zoboli et al., IEEE TNS 55(5) (2008) 2775
G. Giacomini, et al., IEEE TNS 60(3) (2013) 2357

CNM (Barcelona)



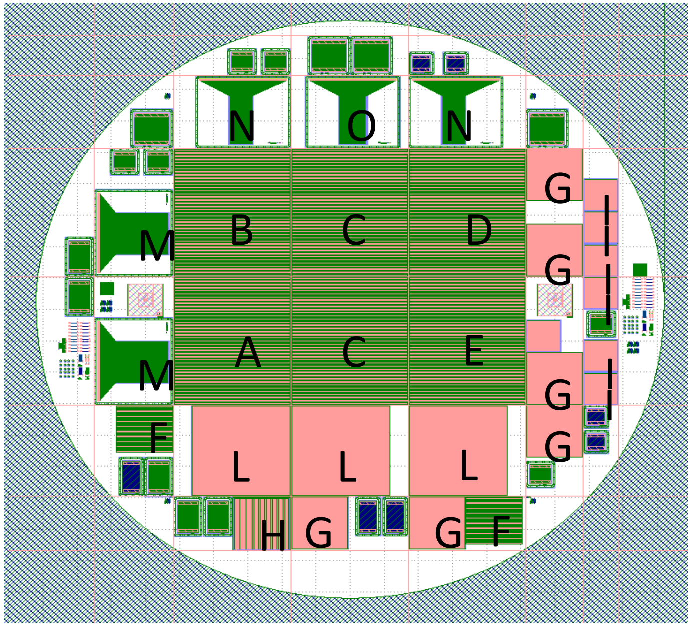
G. Pellegrini et al. NIMA 592(2008) 38
G. Pellegrini et al. NIMA 699(2013), 27

double sided

Joint 3D MPW pixel run

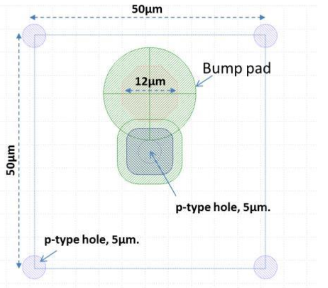
Joint Multi Project Wafer pixel run for ATLAS, CMS, LHCb.

G.Pellegrini RD50 Workshop Dec 2015



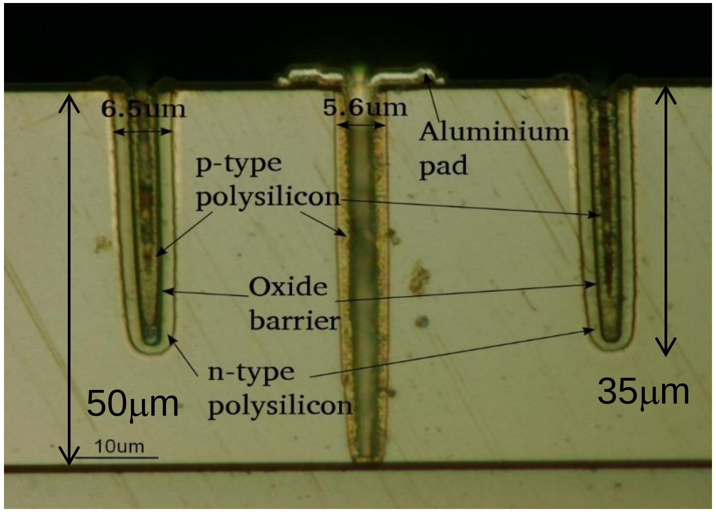
Test of different configurations for various read out chips and pitch size:

- A: standard Fe-I4
- B:25x100um2 ("25x500" 1E, with 3DGR - a la GP).
- C:50x50um2 with the rest connected to GND with 3DGR
- D:25x100um2 (2E - version 4x100+grid to GND - a la GF)
- E:50x50um2 with the rest connected to GND without 3DGR
- F:FEI3 device: x 50x50um2 with rest to GND with 3D GR
- G: ROC4sens 50x50um2
- H: PSI46dig
- I FERMILAB RD ROC 30x100um2
- L: Velopix 55x55um2
- M: Strip 50x50um2
- M Strip 25x100um2
- O Strip 30x100um2f



Also single sided technology:

- $50\mu m$ thick detectors with SOI support wafer ($350\ \mu m$),
- Possible to thin down the detectors.
- $5\mu m$ hole diameter.
- Detector tested, good I-V,
- more complicated technology



RD50 Organisation

RD50 - Radiation hard semiconductor devices for very high luminosity colliders

Co-Spokespersons

Gianluigi Casse and ***Michael Moll***

(Liverpool University, UK & FBK-CMM, Trento, Italy) (CERN EP-DT)

Defect / Material Characterization
Ioana Pintilie
(NIMP Bucharest)

- Characterization of microscopic properties of standard-, defect engineered and new materials pre- and post-irradiation
- DLTS, TSC, ….
- SIMS, SR, …
- NIEL (calculations)
- Cluster and Point defects
- Boron related defects

Detector Characterization
Eckhart Fretwurst
(Hamburg University)

- Characterization of test structures (IV, CV, CCE, TCT,.)
- Development and testing of defect engineered silicon devices
- EPI, MCZ and other materials
- NIEL (experimental)
- Device modeling
- Operational conditions
- Common irradiations
- Wafer procurement (M.Moll)
- Acceptor removal (Kramberger)

New Structures
Giulio Pellegrini
(CNM Barcelona)

- 3D detectors
- Thin detectors
- Cost effective solutions
- Other new structures
- Detectors with internal gain (avalanche detectors)
- LGAD:Low Gain Avalanche Det.
- Deep depleted Avalanche Det.
- Slim Edges
- HVCMOS
- 3D (R.Bates)
- LGAD (S.Hidalgo)
- Slim Edges (V.Fadeyev)

Full Detector Systems
Gregor Kramberger
(Ljubljana University)

- LHC-like tests
- Links to HEP(LHC upgrade, FCC)
- Links electronics R&D
- Low rho strips
- Sensor readout (Alibava)
- Comparison:
  - pad-mini-full detectors
  - different producers
- Radiation Damage in HEP detectors
- Test beams (M.Bomben & G.Casse)

Collaboration Board Chair & Deputy: G.Kramberger (Ljubljana) & J.Vaitkus (Vilnius), Conference committee: U.Parzefall (Freiburg)
CERN contact: M.Moll (EP-DT), Secretary: V.Wedlake (EP-DT), Interim budget holder & GLIMOS: M.Moll (EP-DT)

M.Moll September 2016