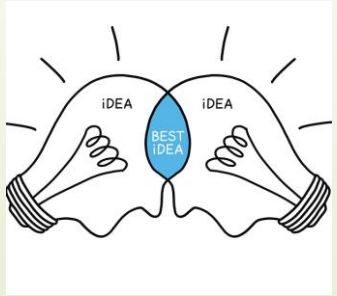
Silicon Detectors for the LHC Phase-II Upgrade and Beyond – RD50 Status Report

Tomasz Szumlak on behalf of **RD 50 Collaboration**

- The R&D Collaboration: „Radiation hard semiconductor devices for high luminosity colliders” was proposed in 2001 and approved in 2002 as **RD 50**
- RD50: 59 institutes (49 Europe, 1 Middle-East, 7 North America, 2 Asian)
- 354 members
- **Diverse expertise** within the **RD 50 Collaboration**
  - Solid state physics
  - Interaction of radiation with matter
  - Experimental high energy physics
  - Electronics and ASIC design
  - Sensor design



- New semiconductor materials (studying and recommendation), relating microscopic radiation damage processes (provide deep understanding respective macroscopic effects), modelling the damage mechanisms

RD50 Organizational Structure

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 devices**
- **EPI, MCZ and other materials**
- **NIEL (experimental)**
- **Device modeling**
- **Operational conditions**
- **Common irradiations**

- Wafer procurement (M.Moll)
- Acceptor removal (Kramberger)
- TCAD simulations (J.Schwandt)

New Structures

Giulio Pellegrini
(CNM Barcelona)

- **3D detectors**
- **Thin detectors**
- **Cost effective solutions**
- **Other new structures**
- **Detectors with internal gain**
- **LGAD: Low Gain Avalanche Det.**
- **Deep depleted Avalanche Det.**
- **Slim Edges**
- **HVCMOS**

- LGAD (S.Hidalgo)
- HVCMOS (E. Vilella)
- 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**
- **Timing 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), Budget holder & GLIMOS: M.Moll & M.Glaser (EP-DT)

- **RD 50 accomplishments (so far!)**

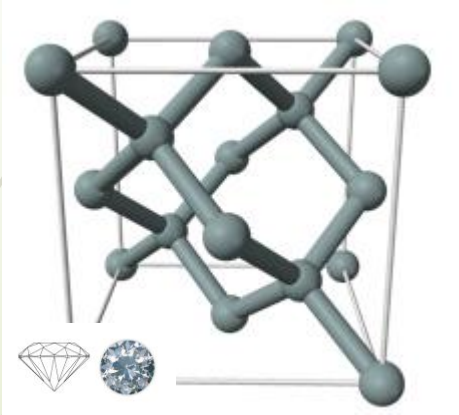
- New structures
  - p-type micro-strip and pixel technology
  - 3D detectors (double column)
  - LGAD (Low Gain Avalanche Detector) detectors for 4D tracking
- Understanding materials properties
  - Modelling – provide models and their tunings (parameters) for the designers, also essential for upgrade planning (leakage current increase, charge collection efficiency, etc…)
  - Using this knowledge to improve radiation hardness via defect engineering (not only in silicon but also in other semiconducting materials)
  - Identification of defects that are responsible for degradation of detector properties

- **RD 50 accomplishments (so far!)**
- Sensor and material characterisation methods originated by RD 50
  - TCT (Transient Current Technique)
  - E-TCT (Edge TCT)
  - TPA-TCT (Two Photon Absorption TCT)
  - Alibava DAQ system
  - Developed a number of „design-patterns” for performing sets of measurements and data analyses
  - Commercial spin-offs
- All this hard work and effort proved that planar semiconductor detectors can cope with the particle fluences expected during HL-LHC operation period ($\sim 2-3\times 10^{16}\,\frac{n_{eq}}{cm^2}$)

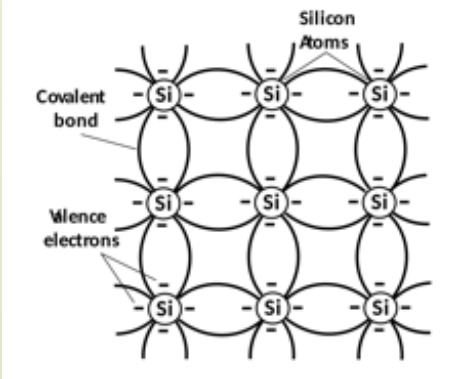
- Mentoring and guidance
  - Large data sets for IV, CV and CCE profiles after irradiation and annealing
  - Evolution of the vital parameters
  - Variations related on a particular material type, thickness, strip/pixel topologies, radiation type and energy spectra
  - Help with setting-up simulations

- **RD 50 is your must-have-friend if you are serious about planning upgrades and building next generation of tracking detectors**

Micro to Macro – macroscopic parametrisation of radiation damage

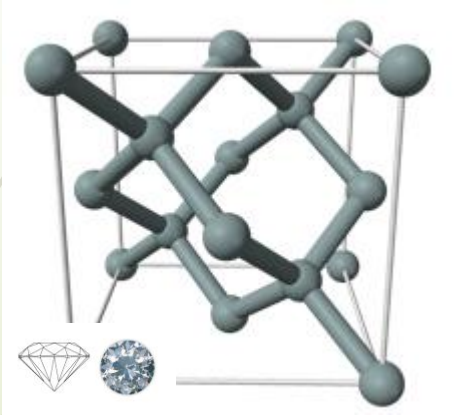


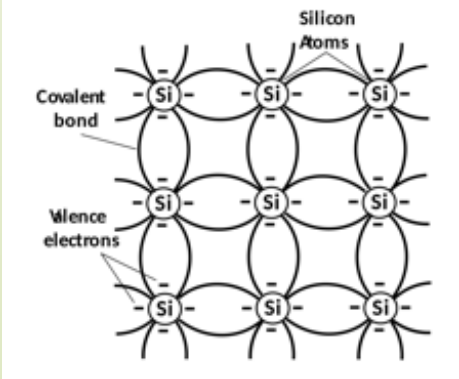
- Silicon atoms in a monocrystalline substrate are arranged in a structure identical to a diamond cubic



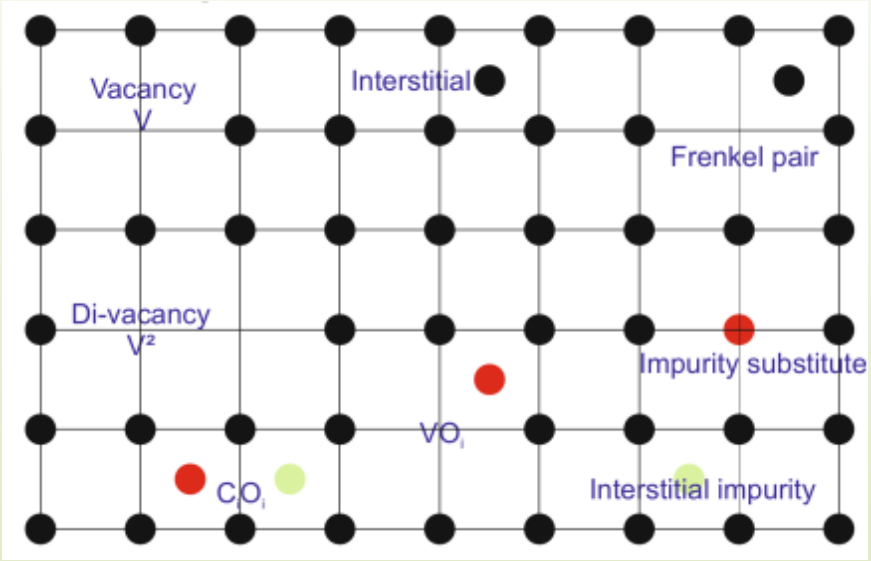
- Strong covalent bonds form very strong structure
- However, there are defects that make this nice picture not so perfect anymore…

Micro to Macro – macroscopic parametrisation of radiation damage





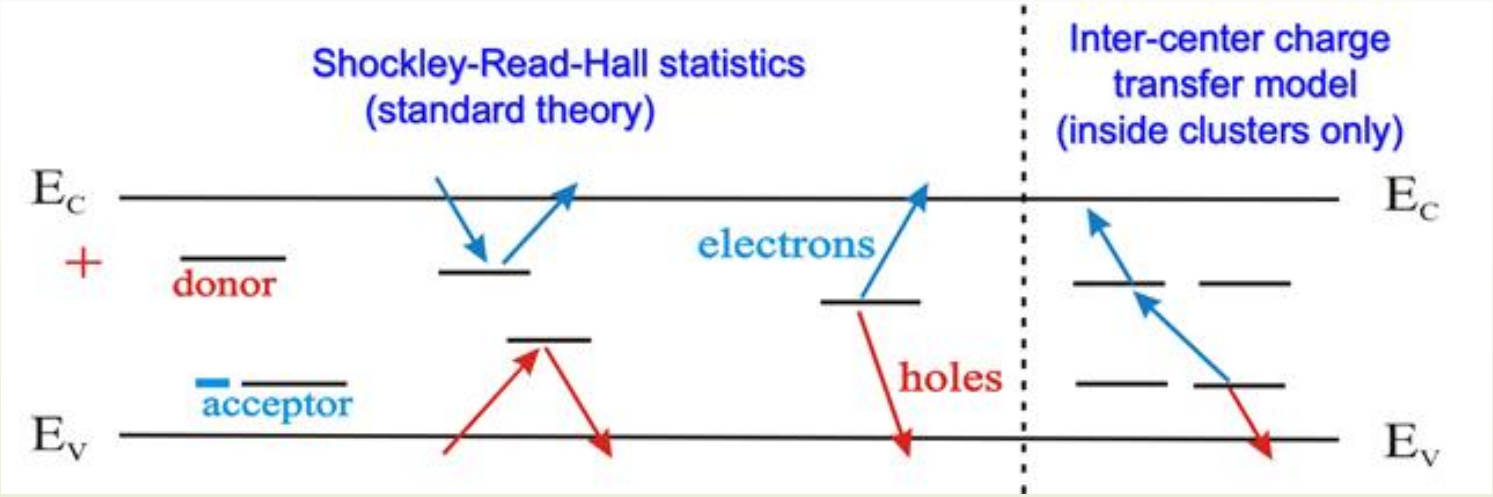
- The silicon nice lattice may be „spoiled” in a number of ways
- Not wanted **contamination** of the crystal
- **Deliberately introduced defects** being a part of the property engineering through diffusion and ion implantation
- Devices build of silicon may be **exposed to hadronic radiation** that alters the material properties (large energy transfers)



Micro to Macro – macroscopic parametrisation of radiation damage

We can successfully explain evolution of semiconductor devices assuming that the **radiation introduces defects into the lattice**

- **Increase in leakage current** due to additional paths for generation
- **Change in depletion voltage** due to introduction of charged defects
- **Reduction of the collected charge** due to shallow trap stopping carriers for times comparable with integration times of read-out electronics



- Charged defects N_{eff}, V_{FD} - donors in upper and acceptors in lower half of band gap
- Electrons and holes trapping CCE – both shallow and deep defects; in room temperature fast de-trapping
- **Leakage current generation** – most effective defects located close to the mid-gap region
- **Enhanced generation** of leakage current and space charge

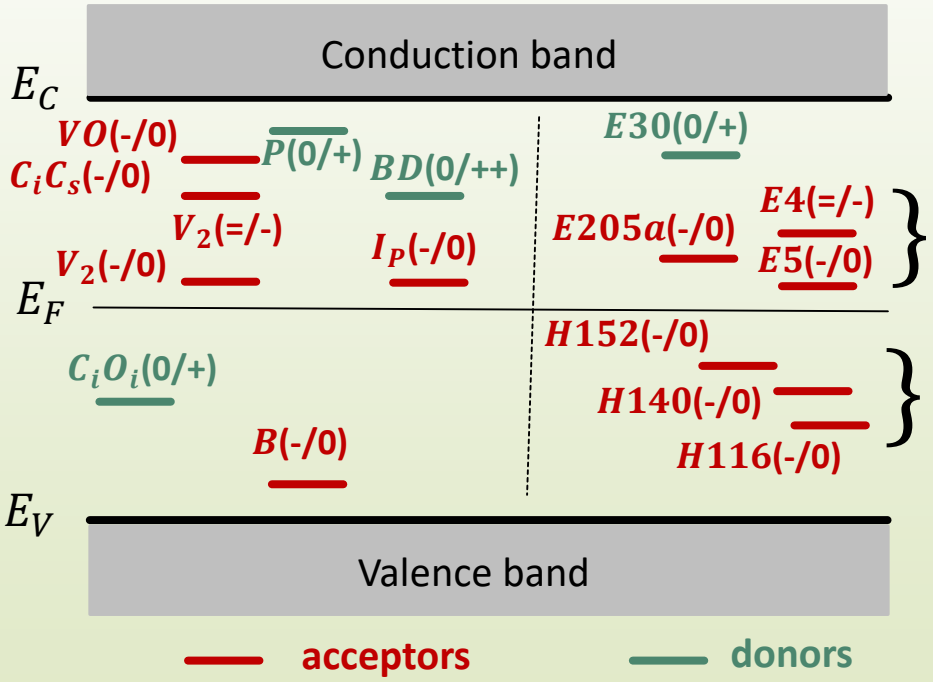
F. Hartmann, Evolution of Silicon Sensor Technology in Particle Physics, Springer Tracts in Modern Physics 275

Micro to Macro – hunt for defects

P(0/+) – Phosphorus shallow dopant (positive charge)

BD(0/++) – positive charge, depends on type of radiation and oxygen concentration

E30(0/+) – positive charge, depends on type of radiation



Leakage current generation

Reverse annealing effects

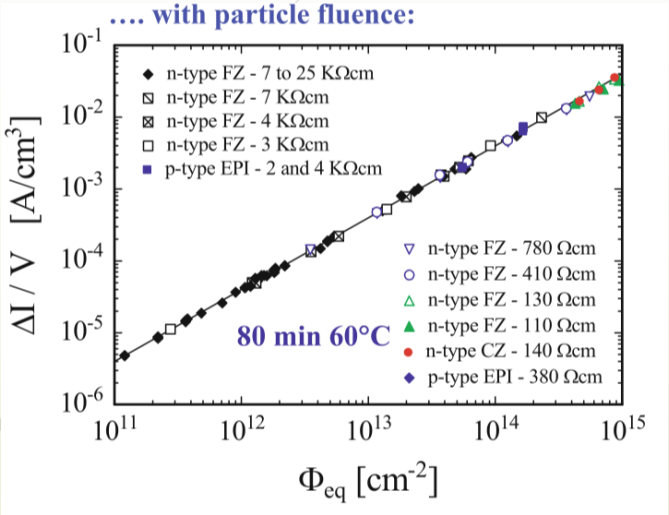
$I_P(-/0)$ – leakage current and negative charge

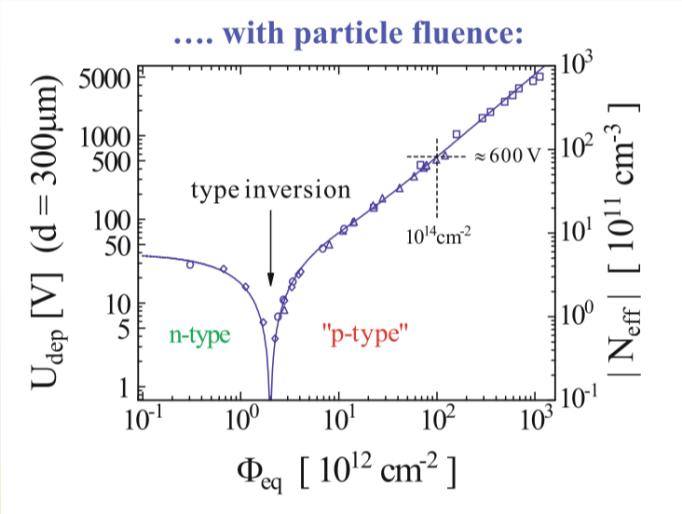
B(-/0) – boron shallow dopant (negative chargé)

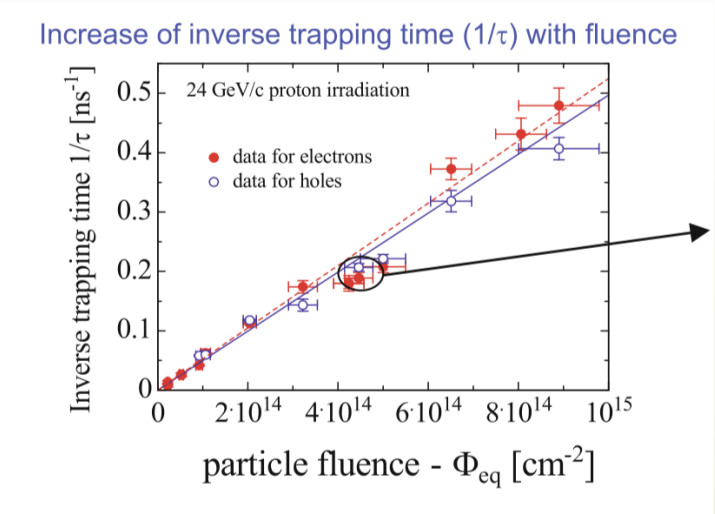
For more extensive list and description see: **M. Moll „Displacement Damage in Silicon Detectors for High Energy Physics", IEEE Transactions on Nuclear Science 65, vol. 8**

- Build a consistent list of defects introduced by different types of radiation (e, γ, n, p, π)
- The defect formation rates strongly depend on the radiation type, its energy spectrum and also material

Micro to Macro – Hamburg Model







- **Leakage Current**

$$\frac{\Delta I}{V_{det}} = \alpha(t,T) \cdot \phi_{eq}$$

- **Depletion voltage**

$$N_{eff} = N_{D,0} \cdot e^{-c_D \phi_{eq}} - N_{A,0} e^{-c_A \phi_{eq}} - b\phi_{eq}$$

- **Decrease of CCE**

$$N_i = g_i \phi_{eq} f_i(t) \rightarrow \frac{1}{\tau_{eff}} = \gamma \phi_{eq}$$

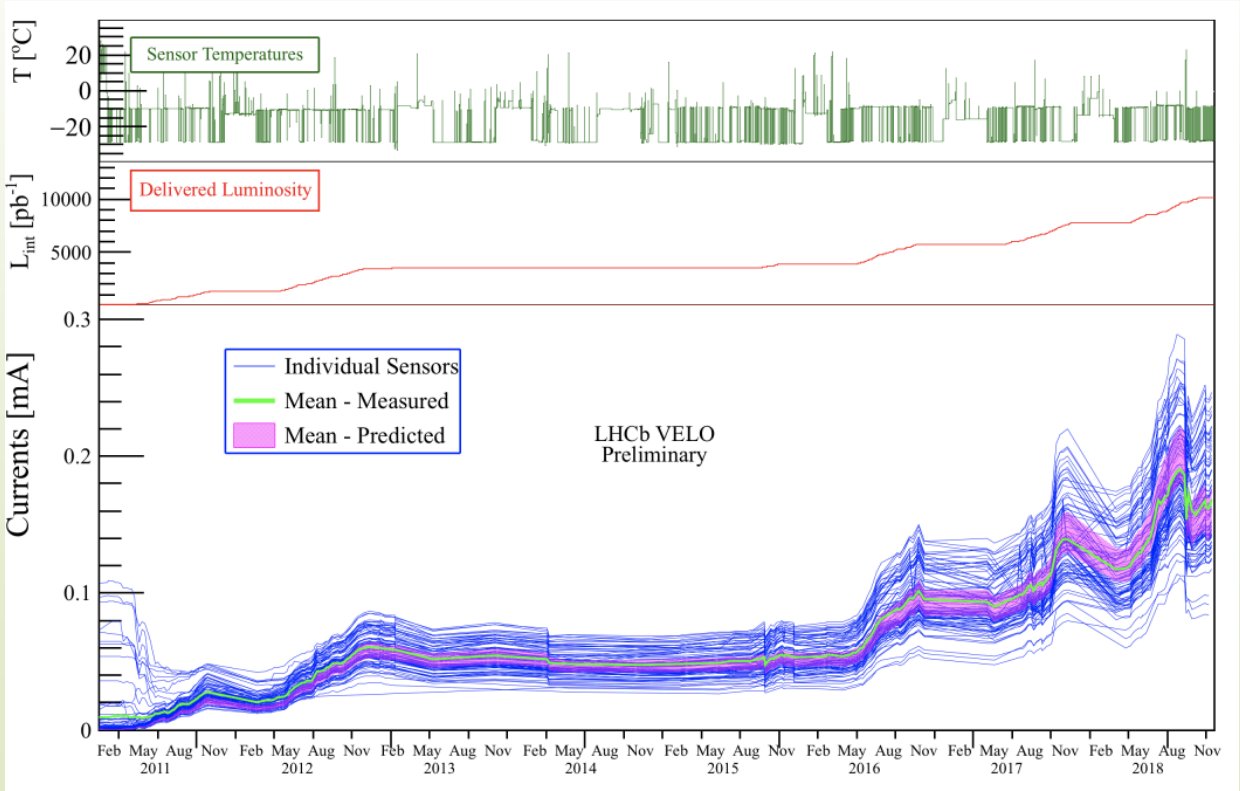
$$Q_{(e,h)} = Q_{0(e,h)} e^{-\frac{1}{\tau_{eff(e,h)}}}$$

$$\tau_{eff(e,h)} \propto N_{defects}$$

Wunstorf, R.: Radiation hardness of silicon detectors: current status. IEEE Trans. Nucl. Sci. 44(3), 806–814 (1997)

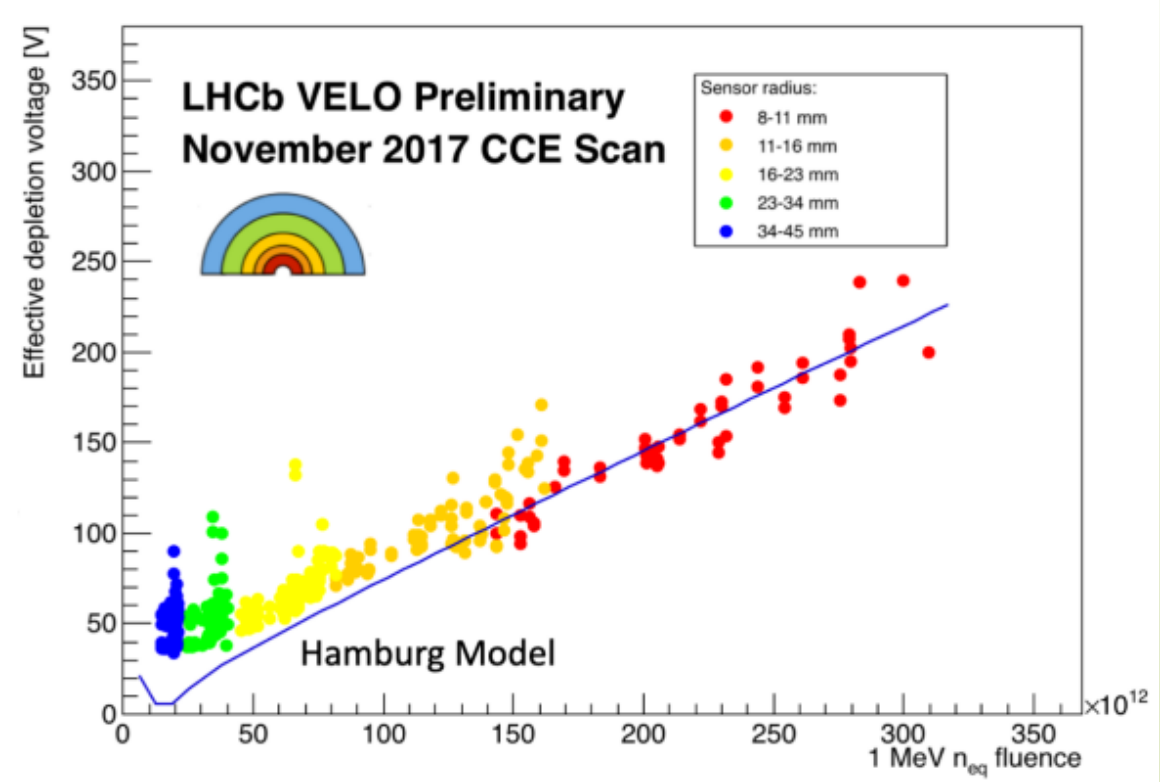
Hamburg Model – How are you doing? (A word from experiments…)

- LHCb (Large Hadron Collider beauty) was among the most irradiated detectors at LHC
- Very detailed studies and measurements during data taking periods
- The evolution of the leakage current and depletion voltage was done using the Hamburg model
- Detailed simulations using two models: DPMJET-III with FLUKA and Pythia 8 with GEANT4



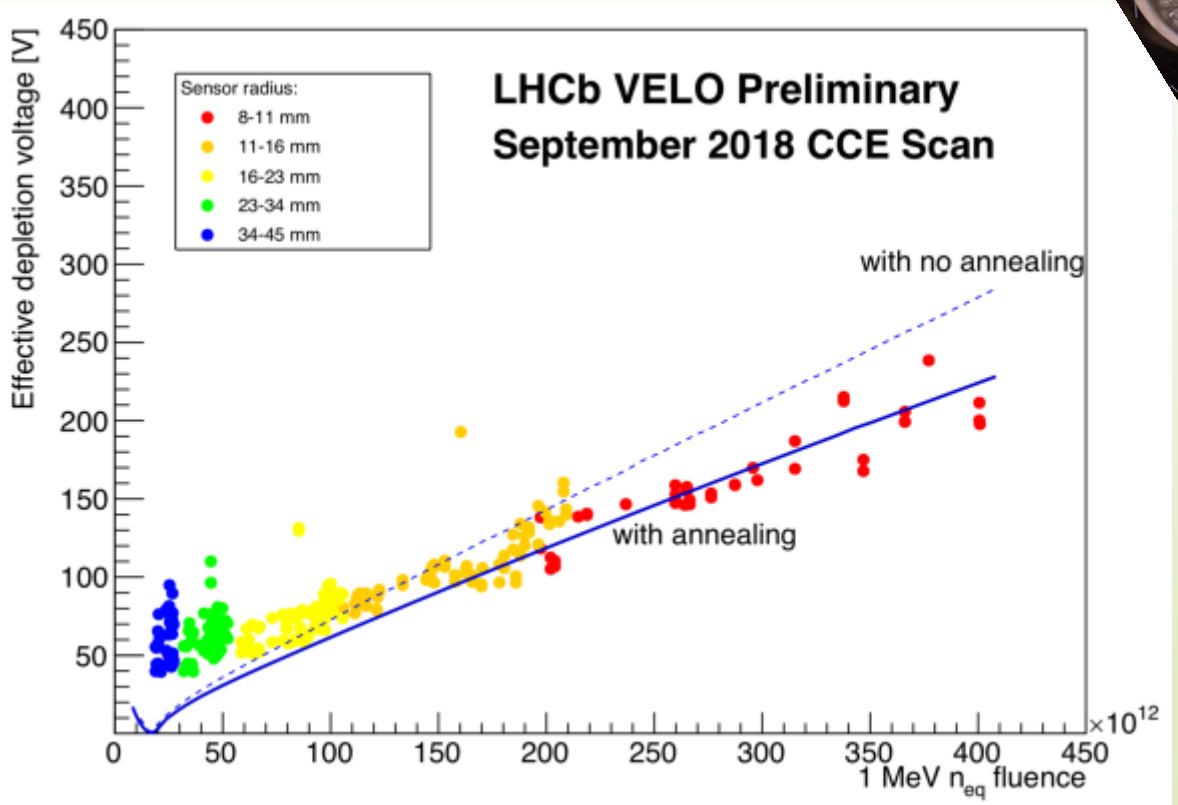
Hamburg Model – How are you doing? (A word from experiments…)

- LHCb VELO (vertex locator) was among the most irradiated detectors at LHC
- Very detailed studies and measurements during data taking periods
- The evolution of the leakage current and depletion voltage was done using the Hamburg model
- Detailed simulations using two models: DPMJET-III with FLUKA and Pythia 8 with GEANT4



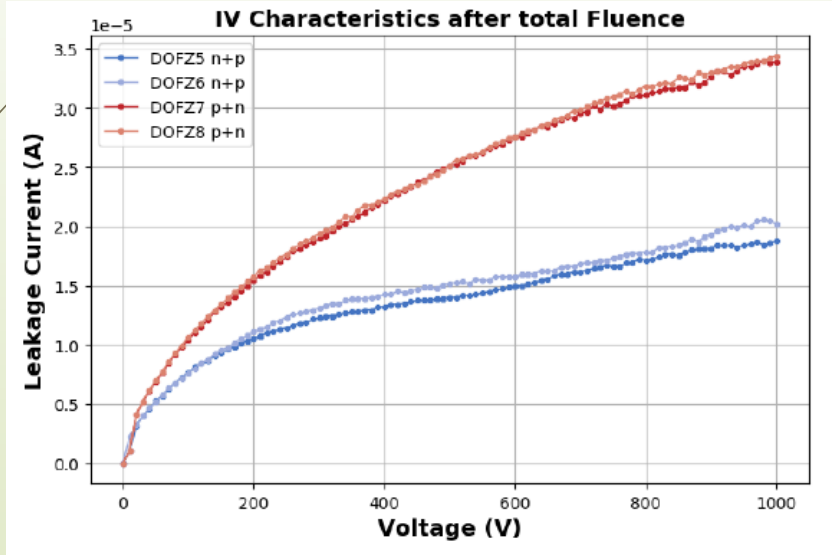
Hamburg Model – How are you doing? Cooking the VELO…

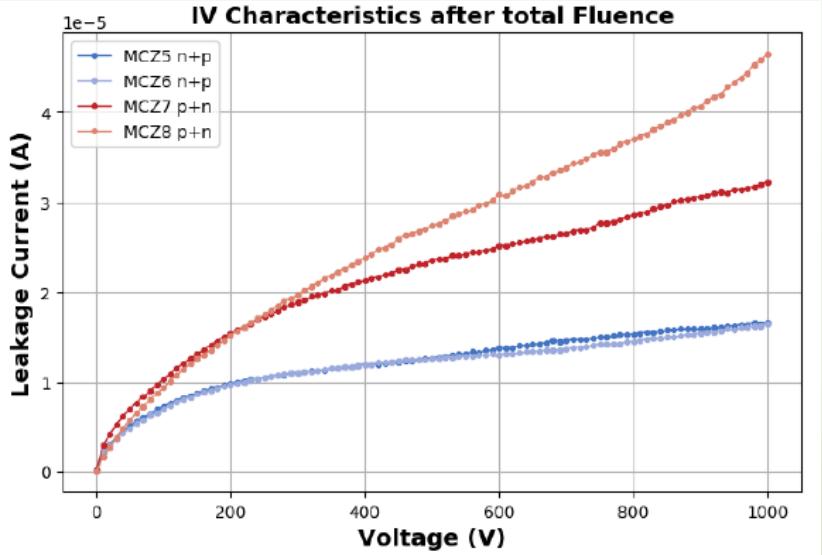
- Past the summer 2018 the monitoring suggested that VELO can have troubles coping with radiation
- Since it was kept at low temperatures all the time and based on the Hamburg Model a decision has been made to **deliberately rise the temperature and anneal the detector**!
- **Measurements in excellent agreement with the model**!



Something unexpected – mixed irradiation, order matters…

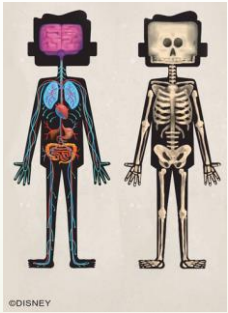
- Two n-type bulk samples were irradiated with proton and neutrons in different order (**p+n**) and (**n+p**) – total irradiation fluences were $\phi_{max} = \mathbf{6 \times 10^{14}}$ n_{eq}/cm^2



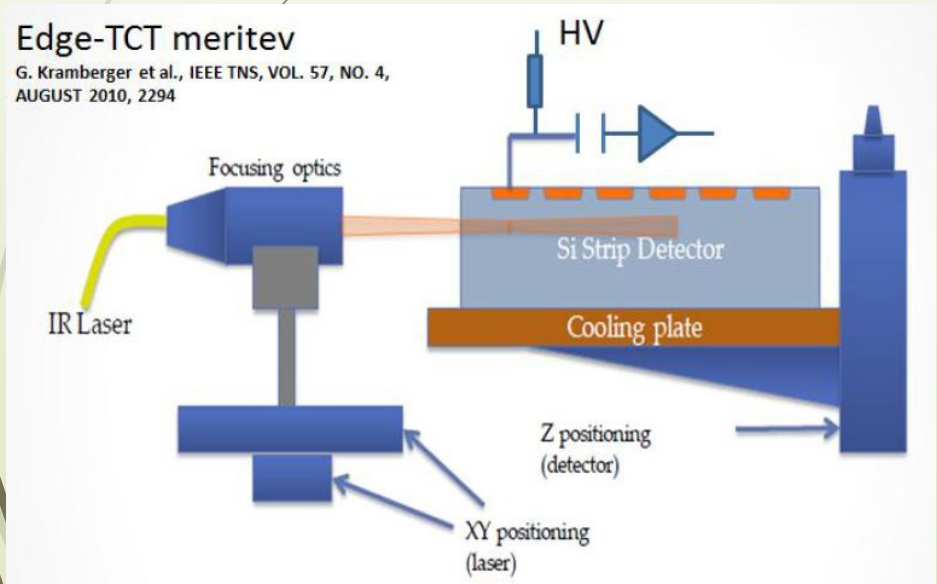


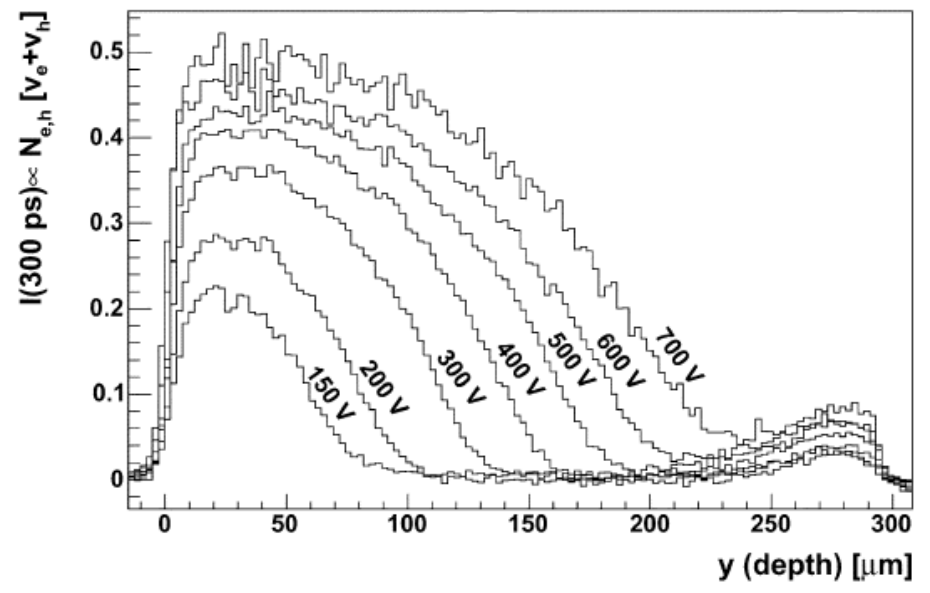
- Observed charge after annealing depends on irradiation order
- Quite puzzling - analysis ongoing (need to repeat the experiment)

Material characterisation – understanding electric field



- Well established and mature TCT/E-TCT technique
- (Fairly) New one – two photon absorbtion TPA-TCT
- Can measure charge generation, charge velocity and e-field profile





Kramberger, G. et al.: Investigation of Irradiated Silicon Detecotrs by Edge-TCT, IEEE Trans. Nucl. Sci. 57(4), (2010)

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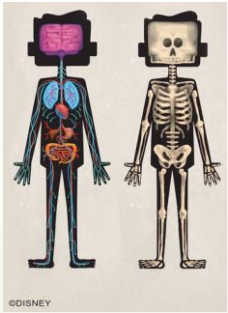
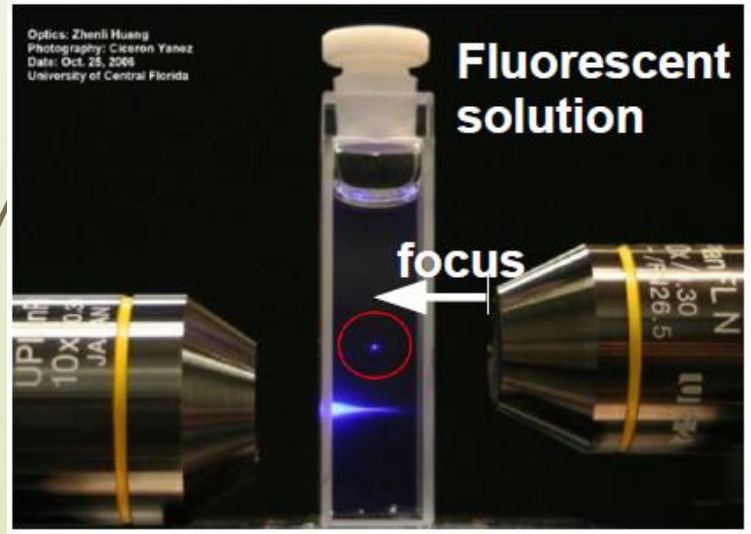
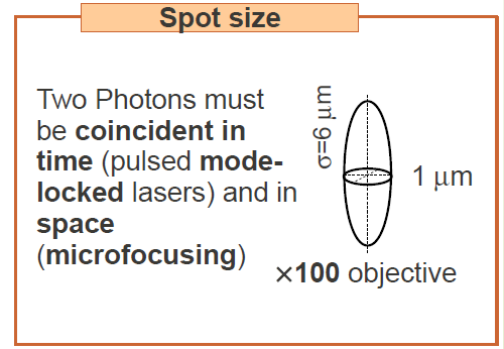
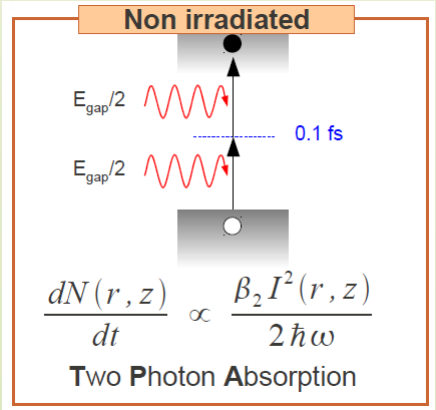
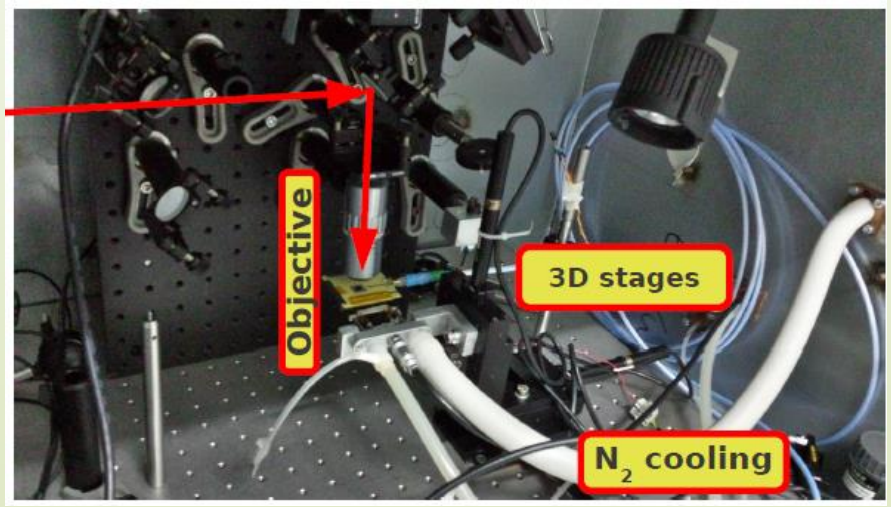


- TPA-TCT offers interesting advantages – confined energy pulses and very high resolution
- Much more challenging experimentally
- RD 50 takes part in building table-top device









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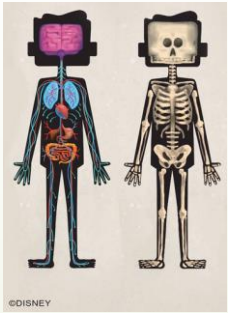

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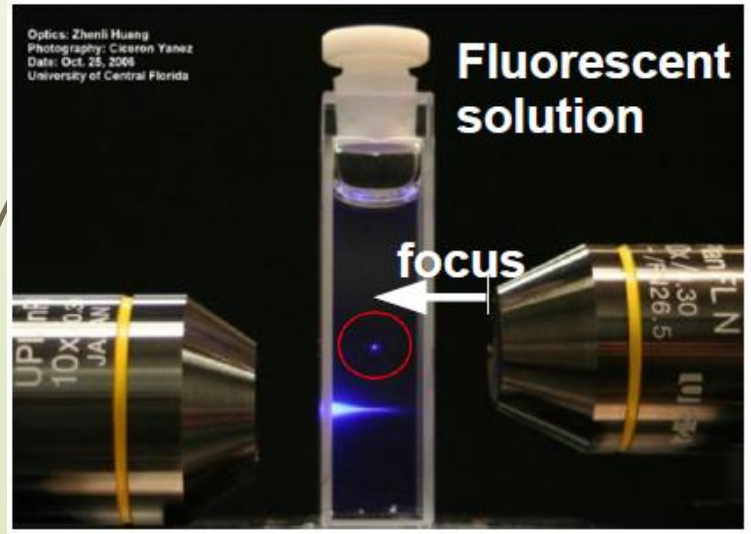
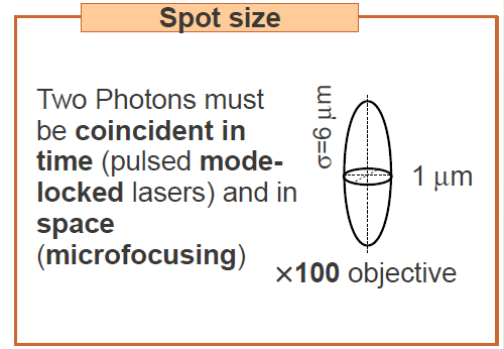
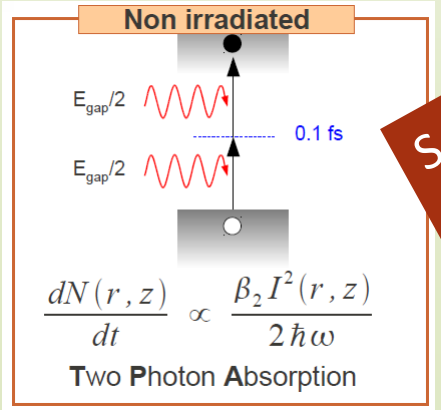
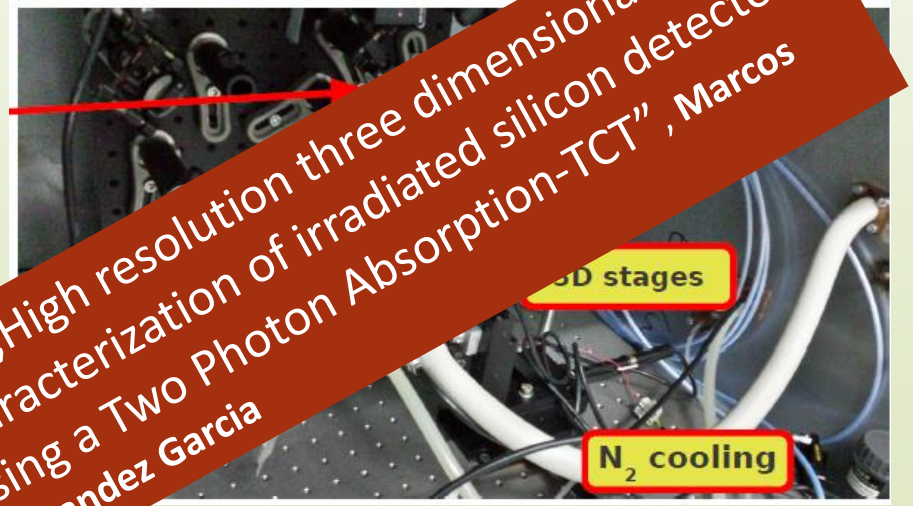






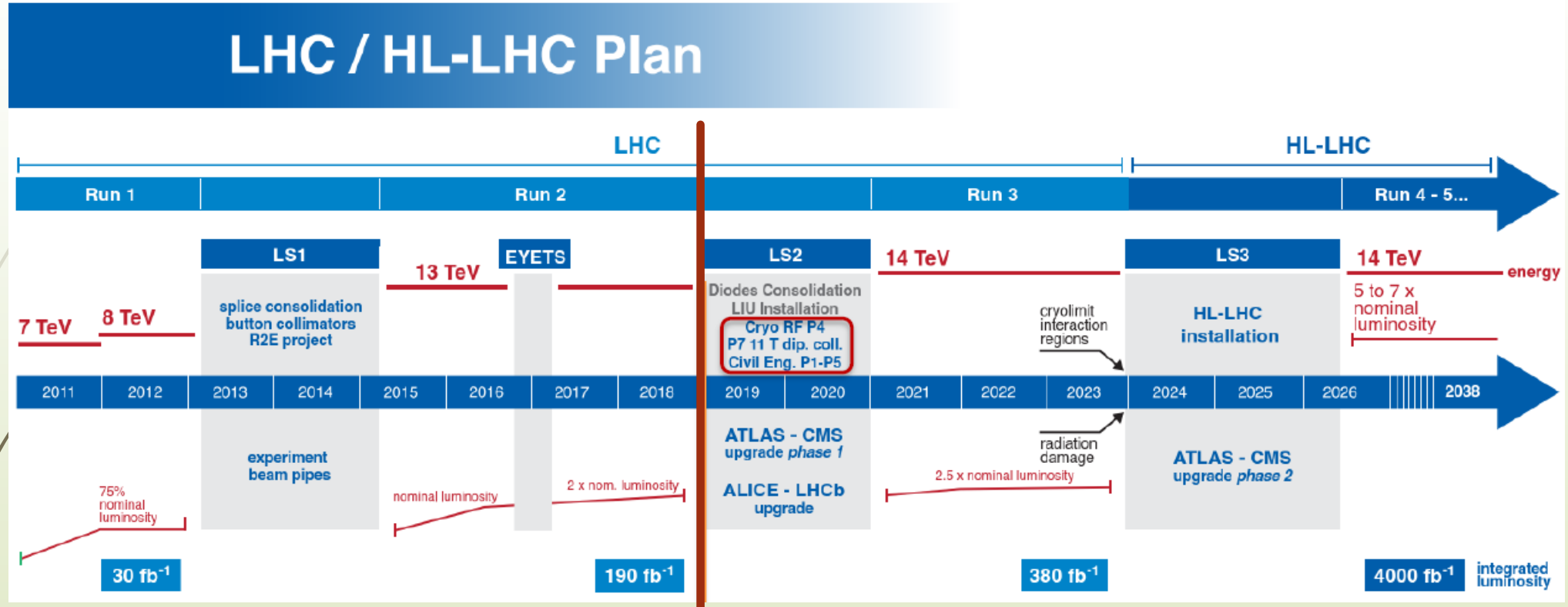


See „High resolution three dimensional characterization of irradiated silicon detectors using a Two Photon Absorption-TCT", **Marcos Fernandez Garcia**

Silicon Simulation

- Two separate domains
  - Silicon simulation – detector characterisation
    - Commercial s/w **TCAD Synopsys Sentaurus**, **Silvaco**
    - RD 50 s/w packages: **KDetSim**, **TRACS**, **Weighfield2**
    - Very detailed studies of sensor performance in harsh radiation environment
  - Physics event generators + transport code + digitisation
    - DPMJET-III + FLUKA and Pythia 8 + GEANT4 most popular @LHC
    - This is the only feasible way to predict particle fluence maps
    - Significant updates (new tunings and better understanding of the specific LHC conditions and beam shape dependency)

Let's switch gears – High Lumi LHC (HL-LHC)



It is history now…

- HL-LHC = LHC on steroids (well not only that): new service tunnels, new superconducting links near ATLAS and CMS, „CRAB" cavities for ATLAS and CMS, new focusing magnets, collimators and bending magnets

L. Rossi, Project status, 8th HL-LHC collaboration meeting

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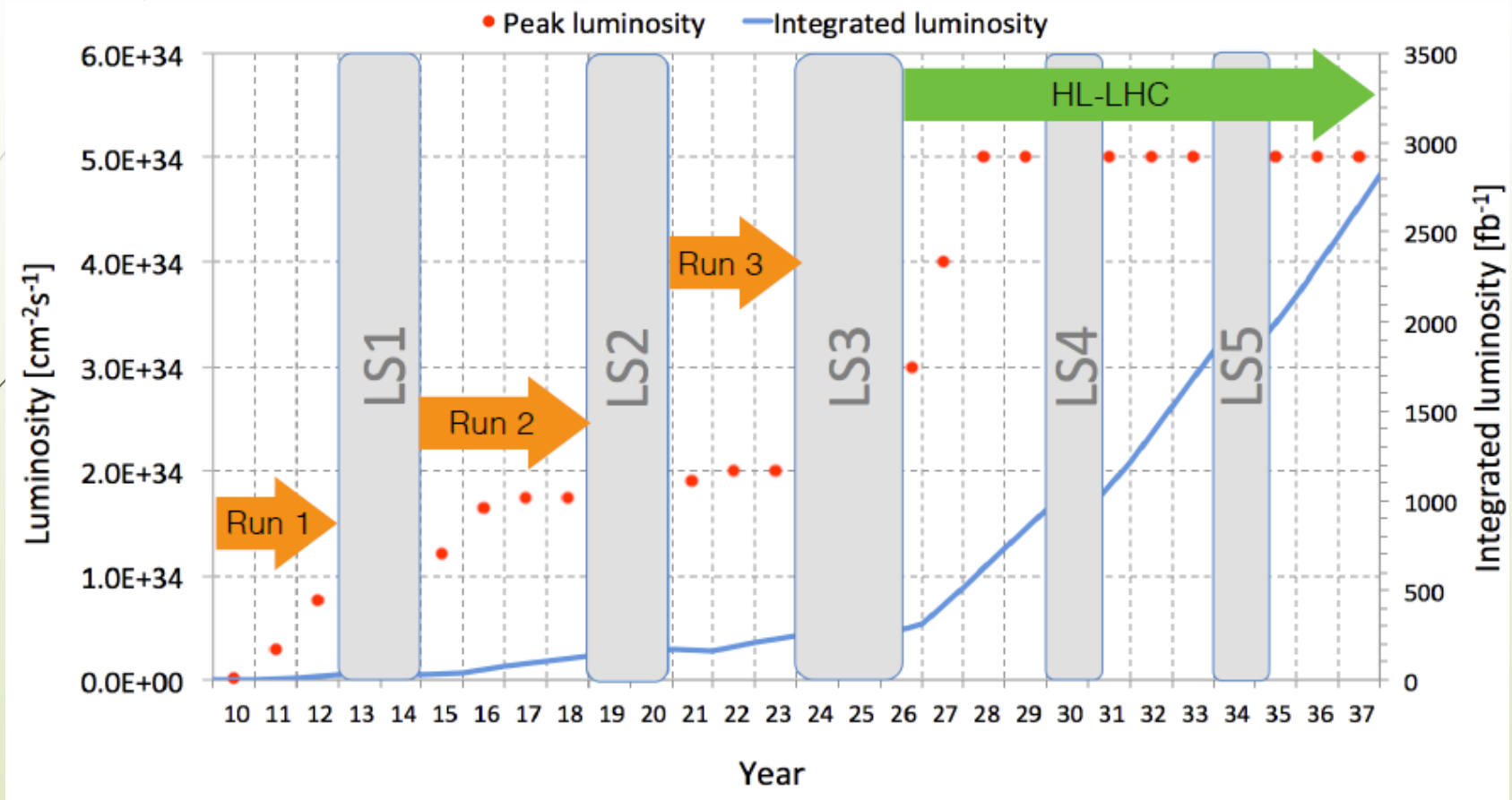
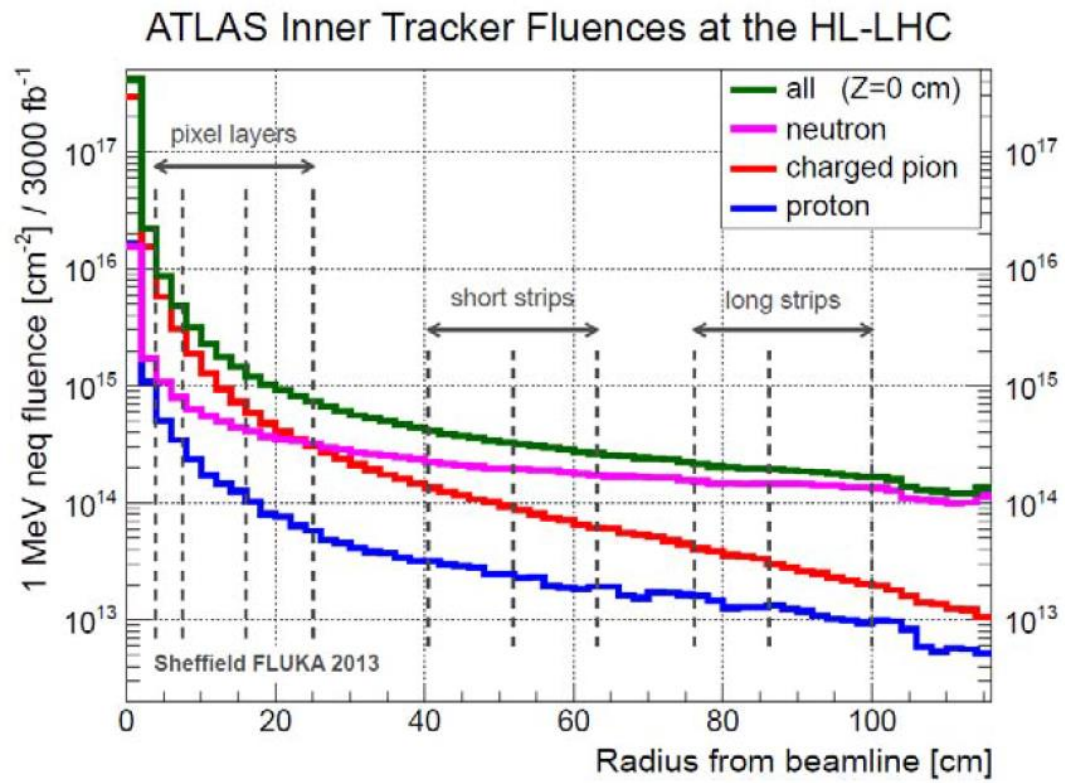


- Two luminosity scenarios
  - Nominal: $\mathbf{5 \times 10^{34}} Hz/cm^2$ - 140 proton – proton interactions per one crossing (in the picture)
  - Ultimate: $\mathbf{7.5 \times 10^{34}} Hz/cm^2$ - up to 200 interactions per one crossing

HL-LHC: new limits of extreme fluences

- Silicon detectors to be exposed to particle fluences up to $\sim 2 \cdot 10^{16} \frac{n_{eq}}{cm^2}$
- Critical role of RD50 Collaboration: mandate to develop semiconductor sensor and characterisation techniques for extreme fluences (here we mean HL-LHC)



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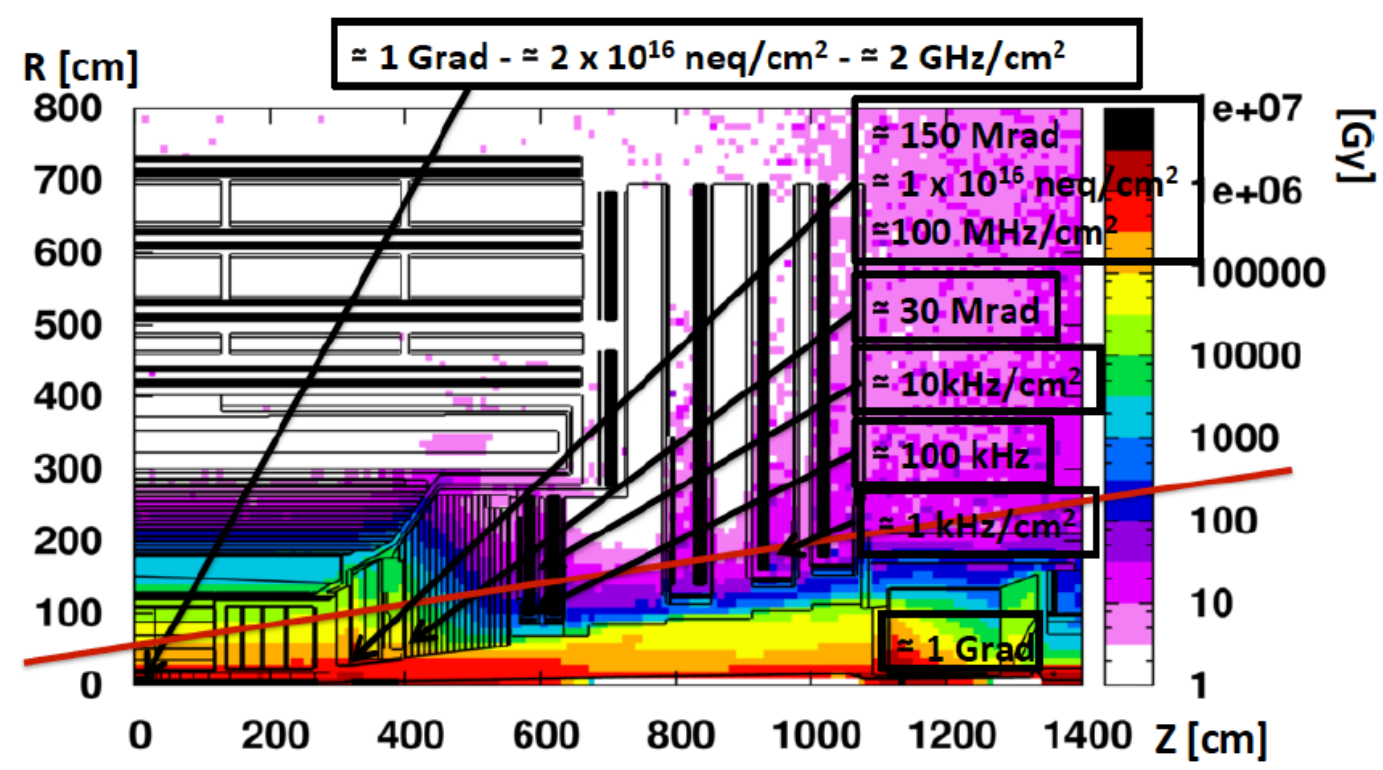

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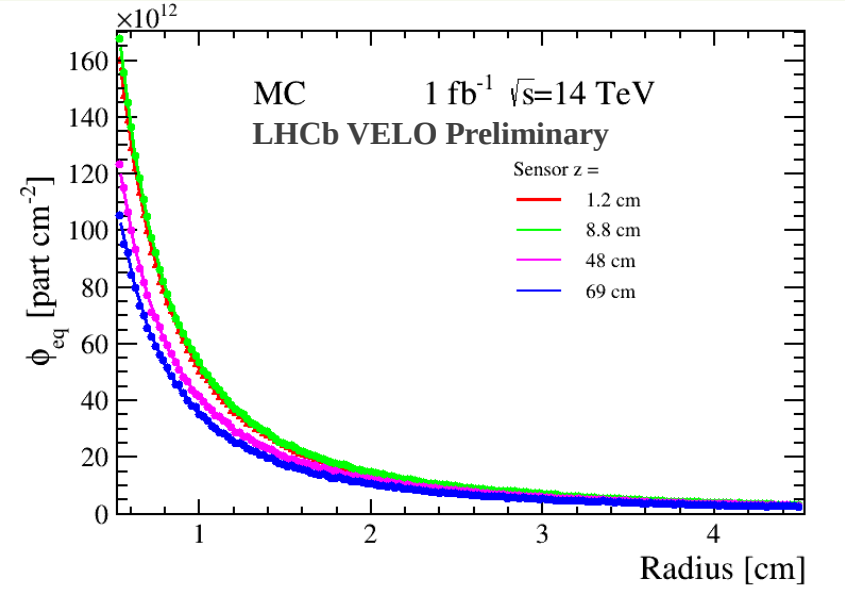
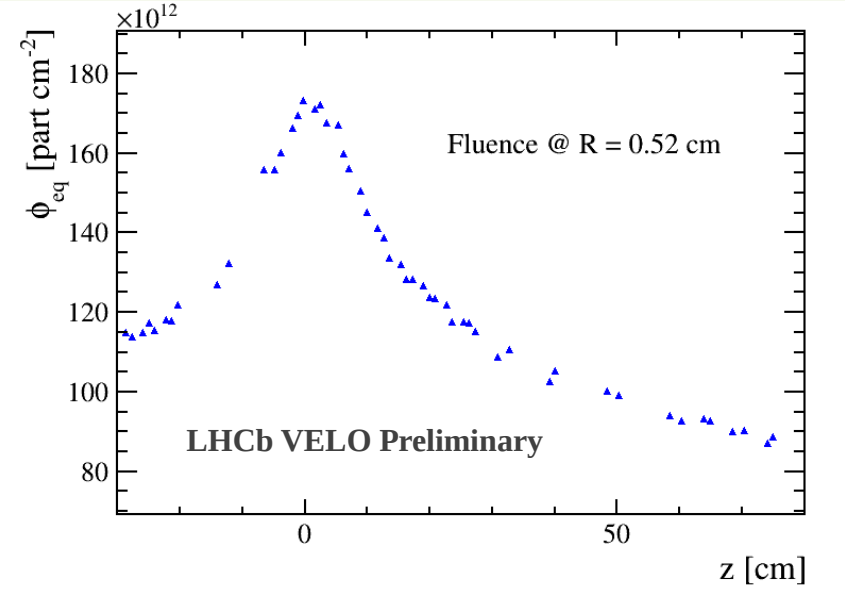


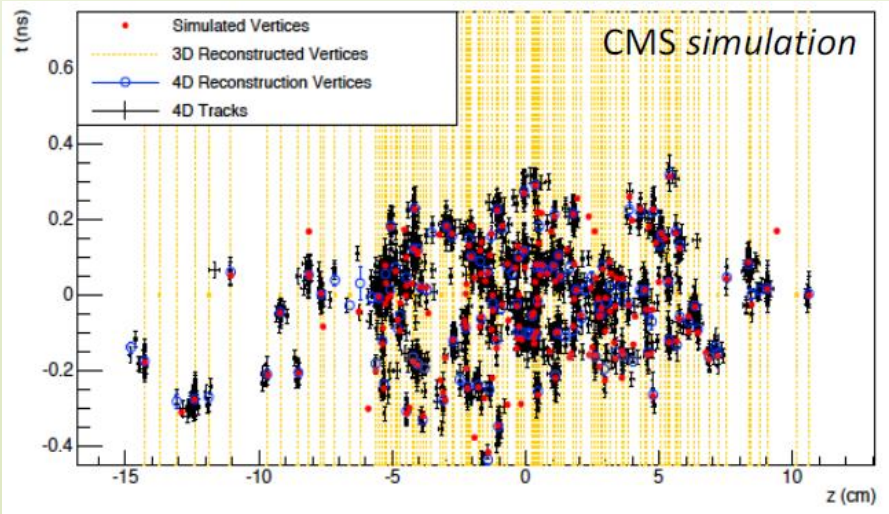


N_{eq} fluence reaches $\phi_{max} = 1.72 \times 10^{14}$ n_{eq}/cm^2 at $R = 0.5\ cm$ (for 1fb^{-1}, $\sigma_{pp} = 80\ mb$)

$\phi_{\max(50fb^{-1})} = 0.86 \times 10^{16}$ n_{eq}/cm^2

„New Machine” – new challenges

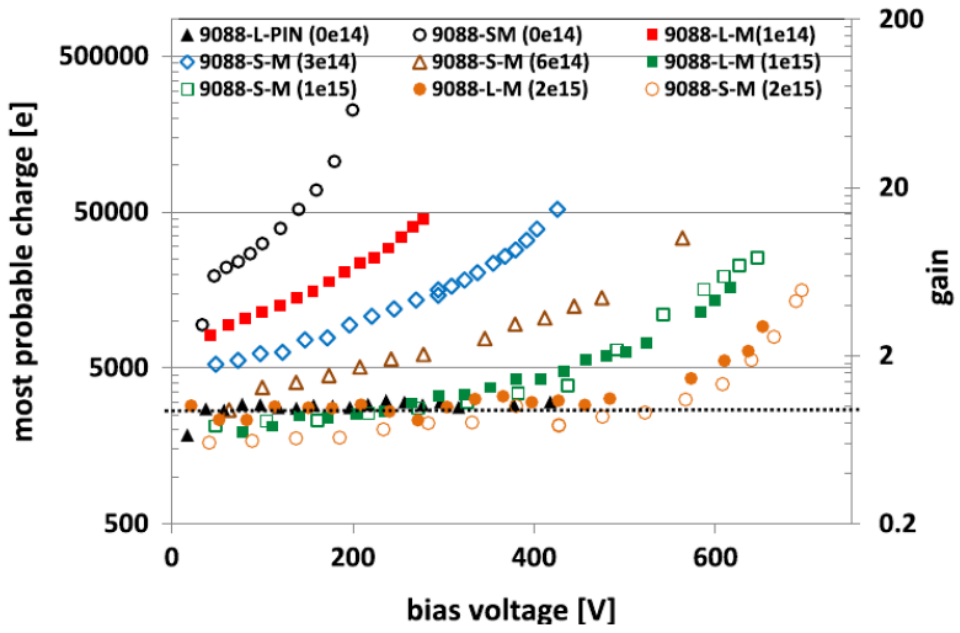
- In order to be able to use the physics potential @HL-LHC it is necessary to increase granularity, lower the material budget and go even more forward (especially for ATLAS and CMS)
- Precise timing essential for coping with large pile-up (up to 200 interactions)
  - Both ATLAS and CMS considering high granularity LGAD detectors
- Thinning essential for radiation hardness (200 μm or 150 μm options considered)
- Alternative technologies for expensive bump bonding

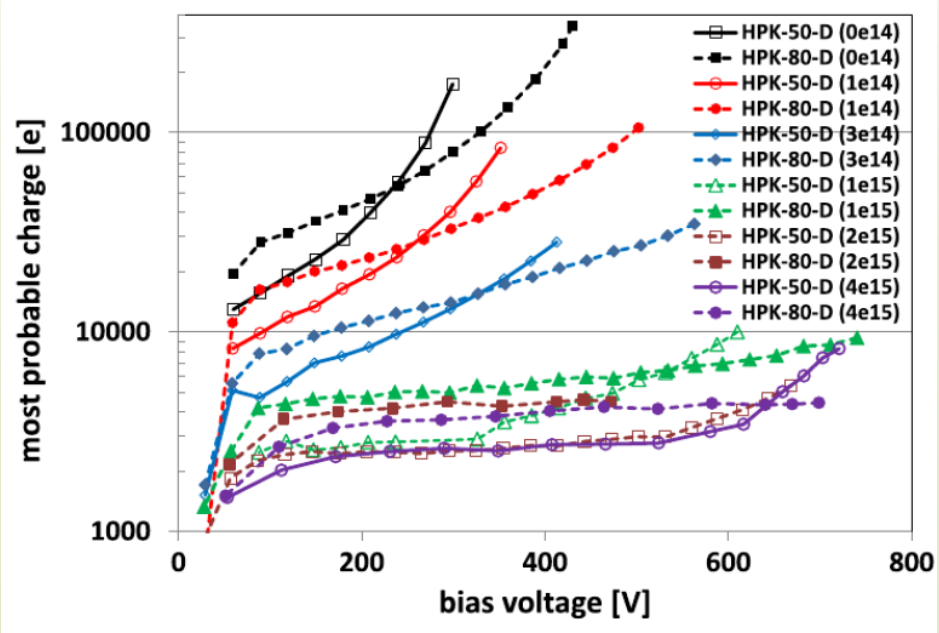


Timing information (aka 4D tracking) with precision better than 50 ps is essential for high efficiency of primary vertices reconstruction and track association

Have you ordered a new structure? Recent RD50 activities

- Thin (50 μm) LGAD detectors
  - CME Endcap Timing Layer
  - ATLAS High Granularity Timing Detector
  - Need to understand strong acceptor removal (drop in gain with particle fluence)
    - p-doping layer with Gallium instead of Boron or carbon co-implantation?

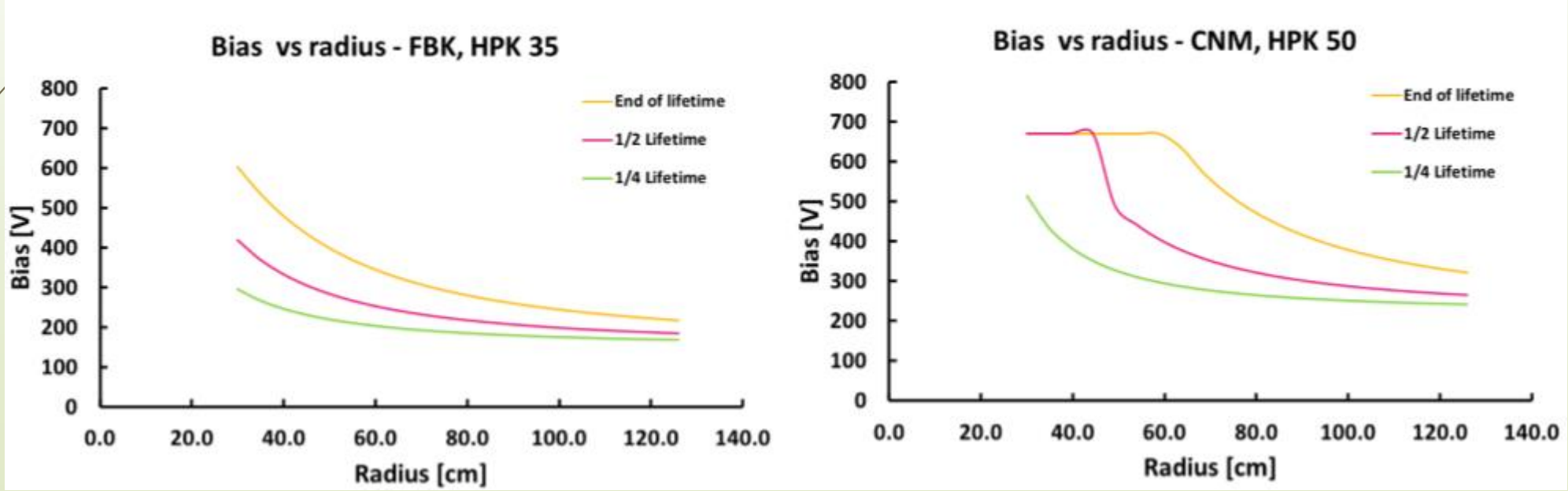




NIMA 891 (2018) 68 – 77; M. Ferrero, 33rd RD50 workshop

Have you ordered a new structure? Recent RD50 activities

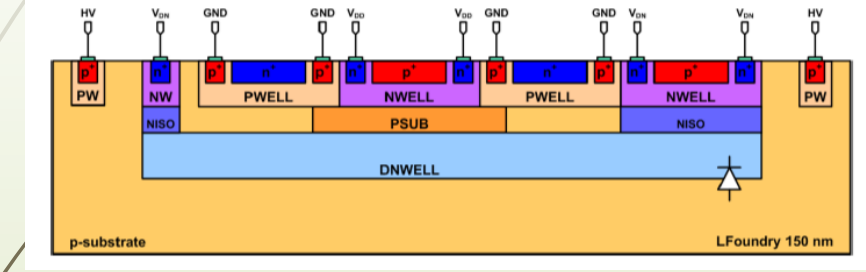
- Vital to be able to „hold” voltage without breakdown at the end of the lifetime of the detector providing good enough timing resolution (better than 45 ps) and good hit reconstruction efficiency (decent S/N ratio)

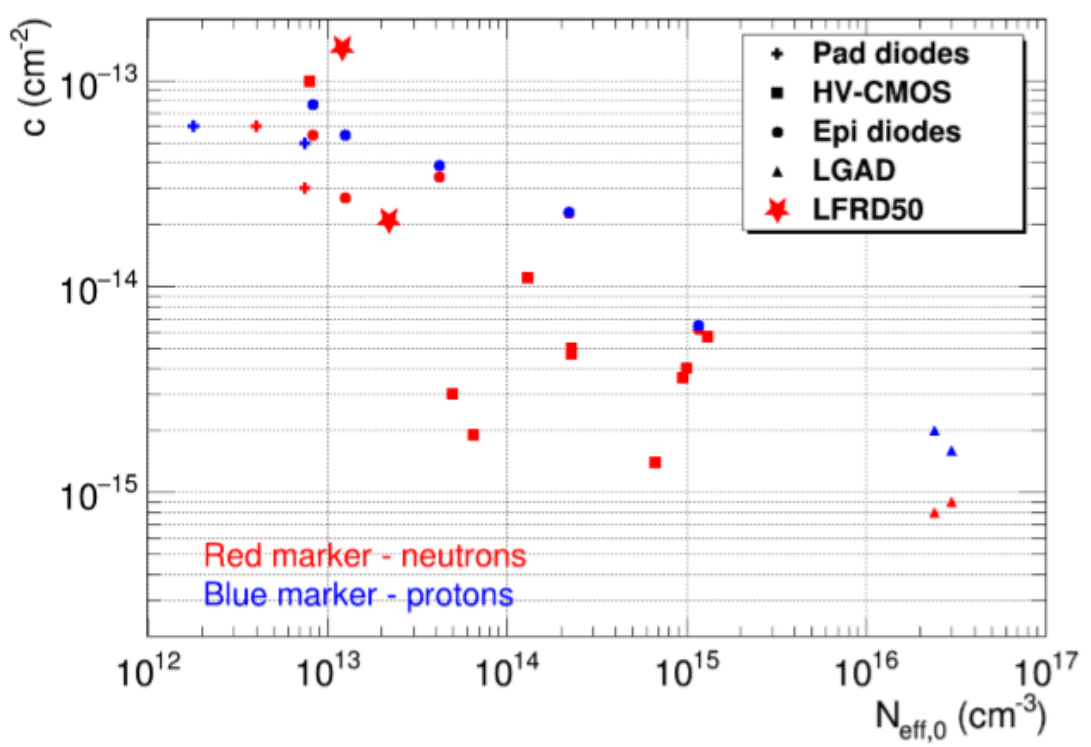


- Collected charge at least 5 fC at the end of lifetime (ASIC)

Have you ordered a new structure? Recent RD50 activities

- HV-CMOS – common fabrication of RD50 – MPW1 (150 nm LFoundry proces)





- Analysed irradiated pixel detectors
- Used E-TCT to measure N_{eff} as a function of particle fluence
- Acceptor removal parameter c has been estimated
- Acceptor removal constant higher for substrates with lower initial resistivity

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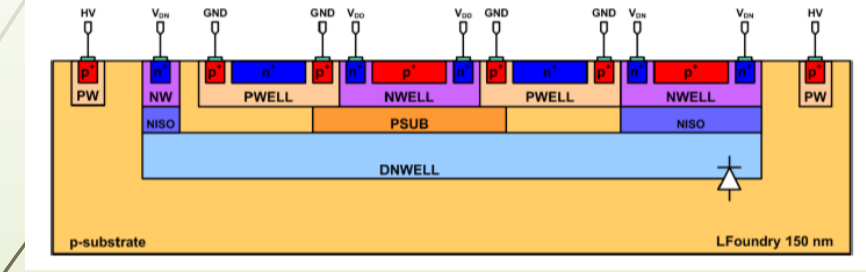

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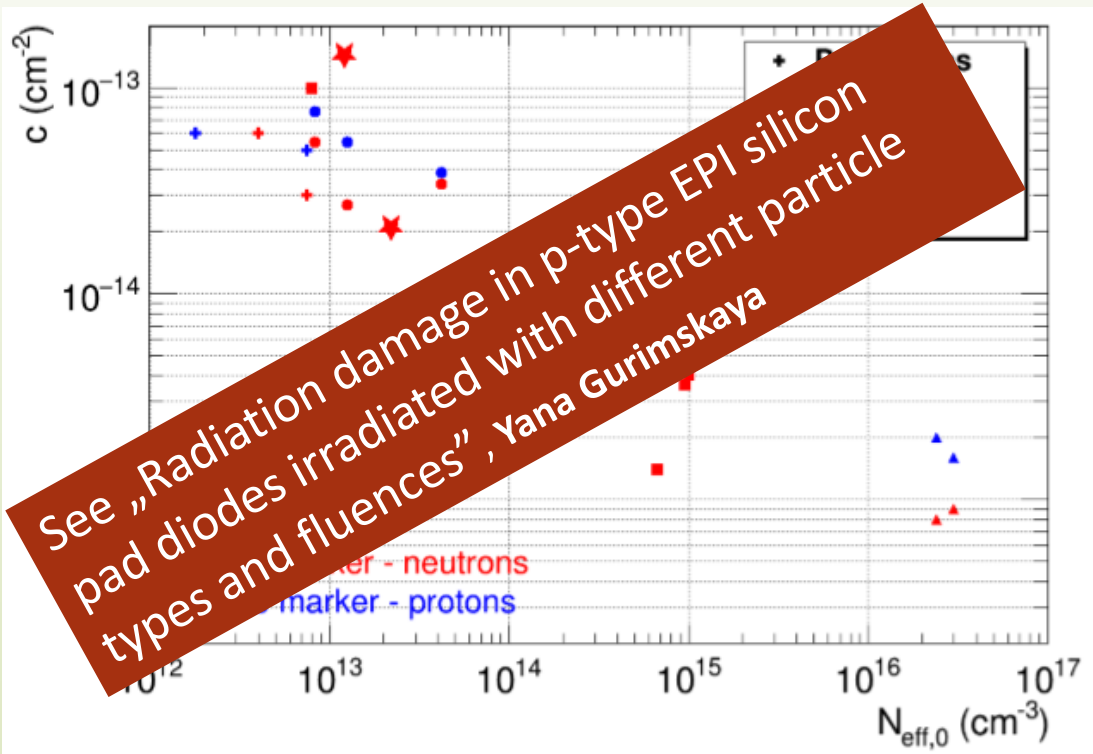
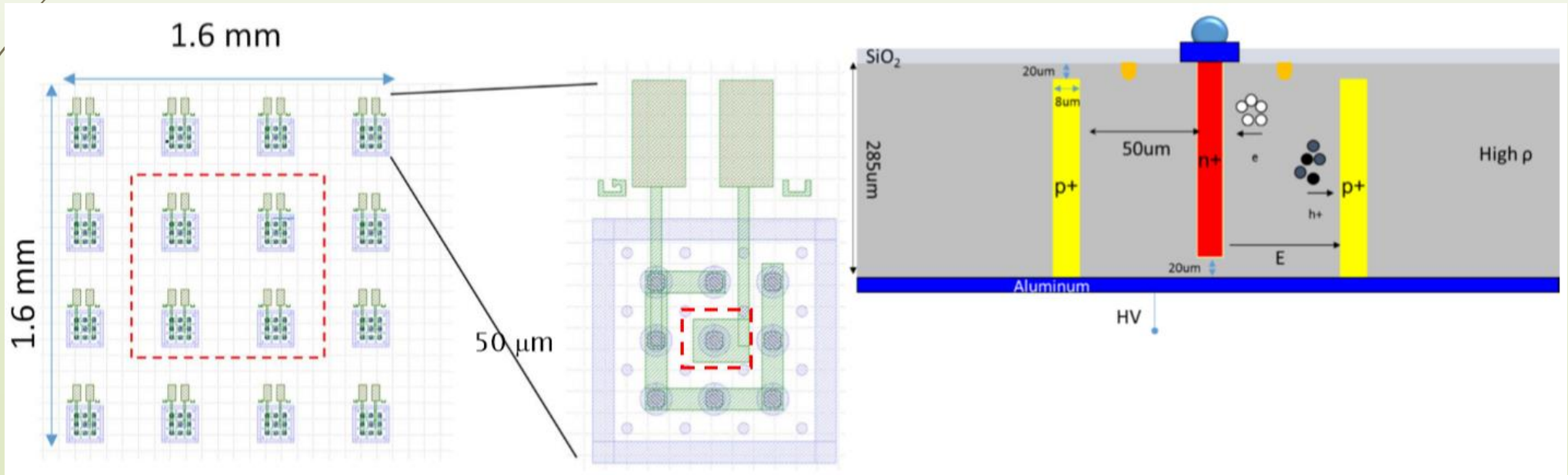


See „Radiation damage in p-type EPI silicon pad diodes irradiated with different particle types and fluences", Yana Gurimskaya

Have you ordered a new structure? Recent RD50 activities

- LGAD are the favourite timing detectors for HL-LHC, but this come at a cost – radiation hardness and fill factor may be a problem
- What about using 3D well established technology?
- Tested small cel 3D silicon detectors



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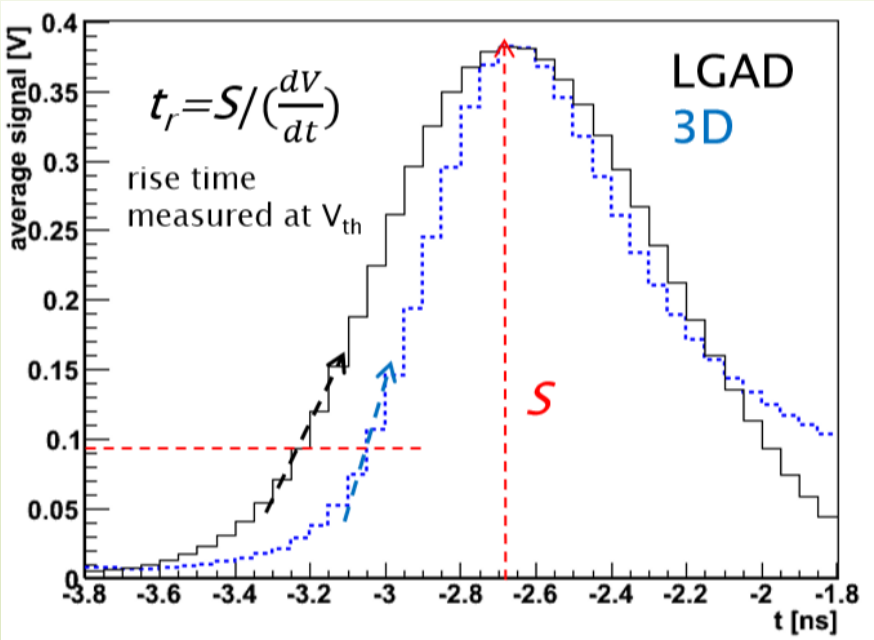
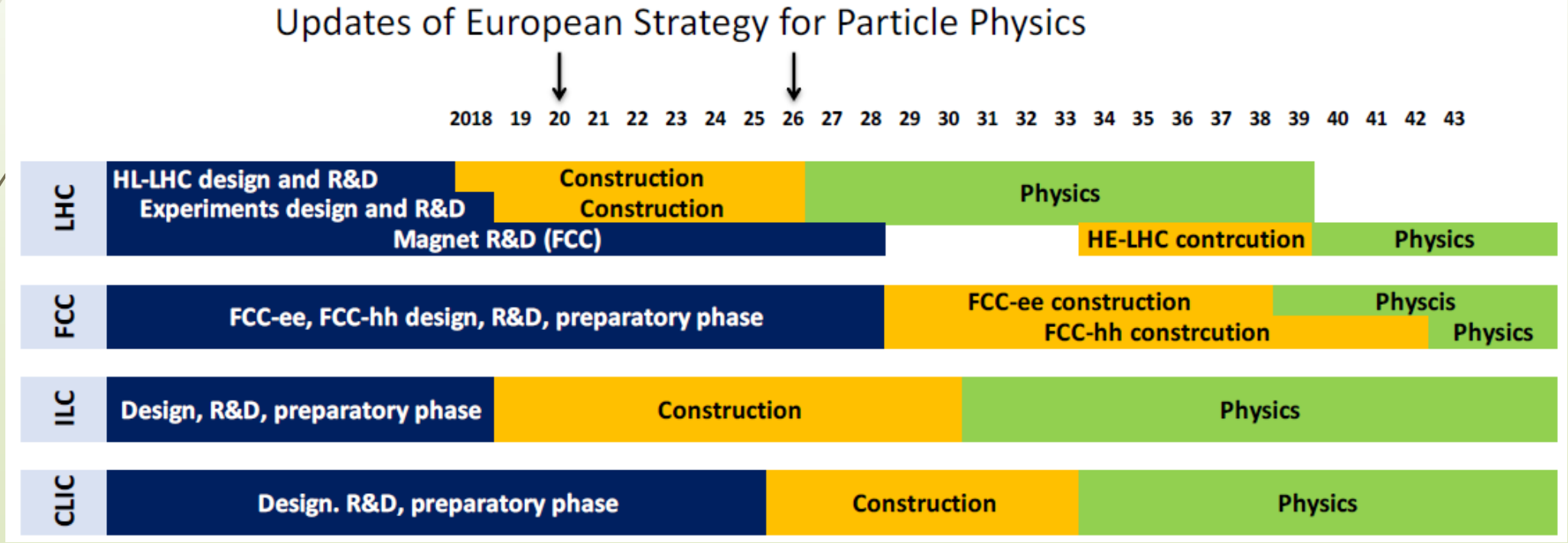


- Timing in small cell 50x50 μm^2 3D detectors was measured and simulated
- Timing resolution comparable with LGAD type sensor performance
- Can be considered as a backup solution for LGAD detectors (especially in the places with the harshest radiation)

G. Kramberger, 33rd RD50 Workshop, CERN 2018

Into the future

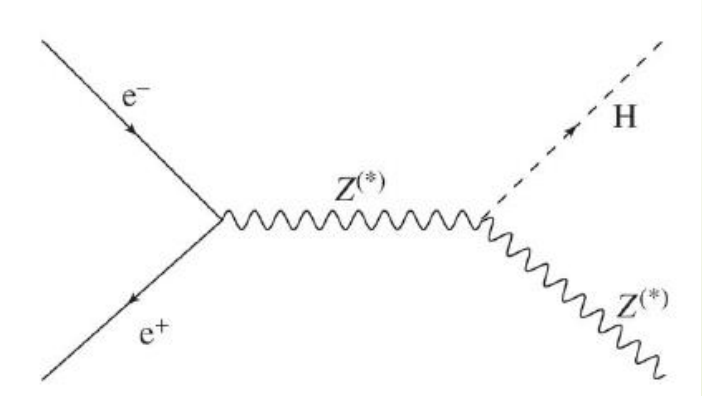
- We are at the precipice of the future of HEP – need to provide soon an update of European Strategy for Particle Physics
- Large collaborations have been formed around ideas of linear and circular accelerators have been formed and presented in recent years some excellent ideas

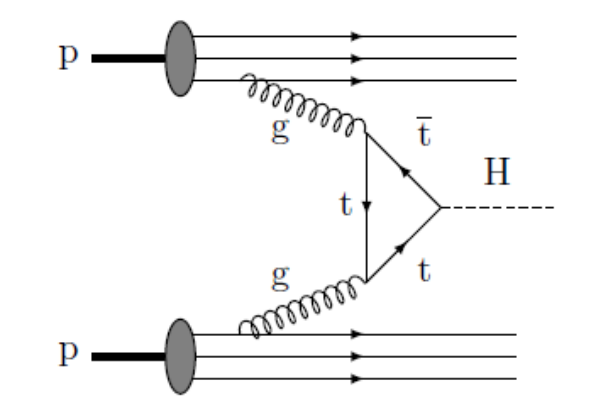


D. Contardo, 2018 LHC Days in Split

Into the future

- Both linear (e^+e^-) and circular (e^+e^-, hh, eh) would primarily act as Higgs factories

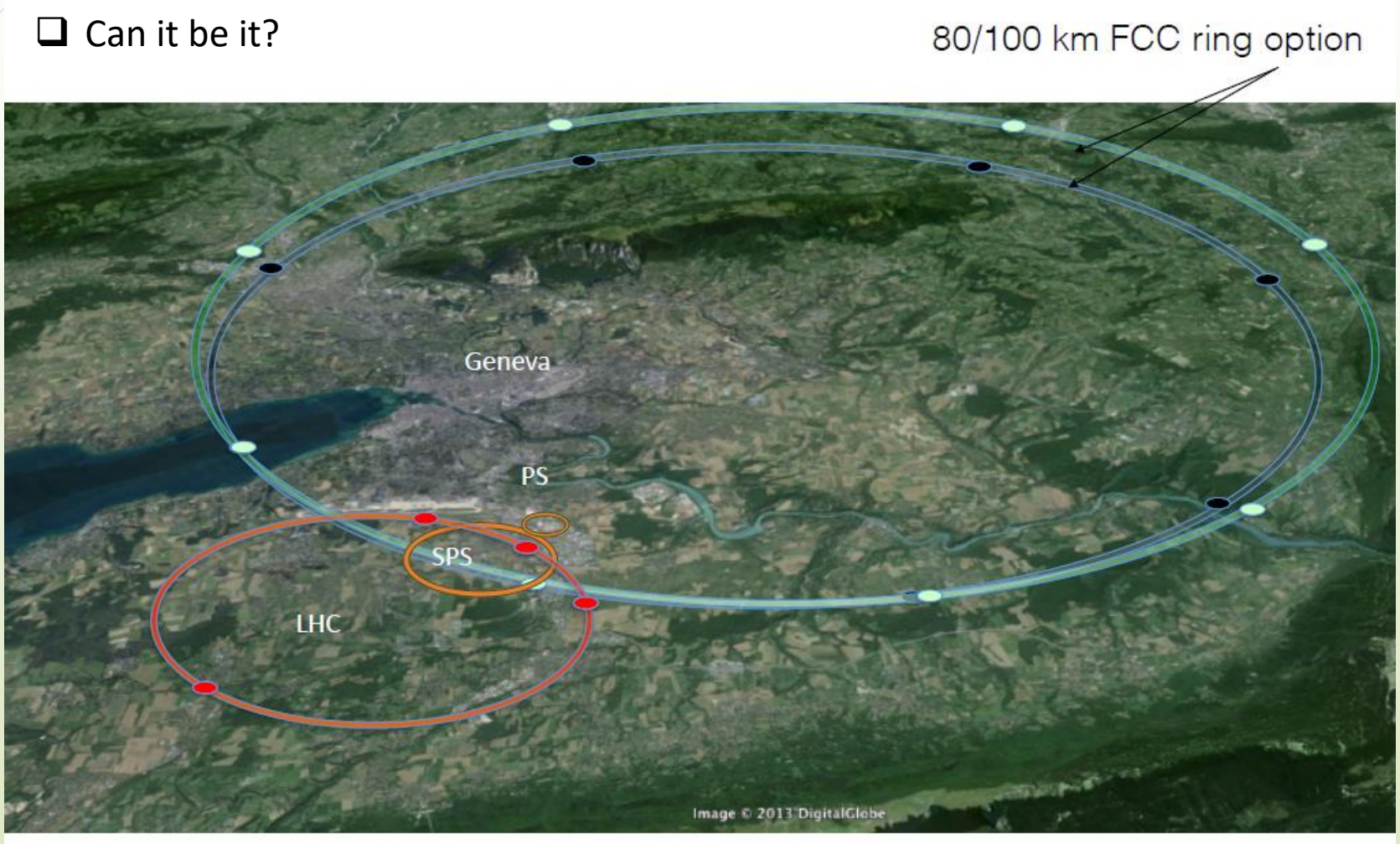




- Circular options seems to offer more…
  - FCC (Future Circular Collider) can be build in steps, we can start with electron machine ($\sqrt{s} = 90 - 350$ GeV) for ultra precise electro-weak tests and production of new heavy particles
  - Energy can be scaled down to create Z and W factories (potentially huge samples)
  - Conditions (pile-up) similar to HL-LHC – up to 180 interactions per crossing

Into the future – FCC?

- Can it be it?

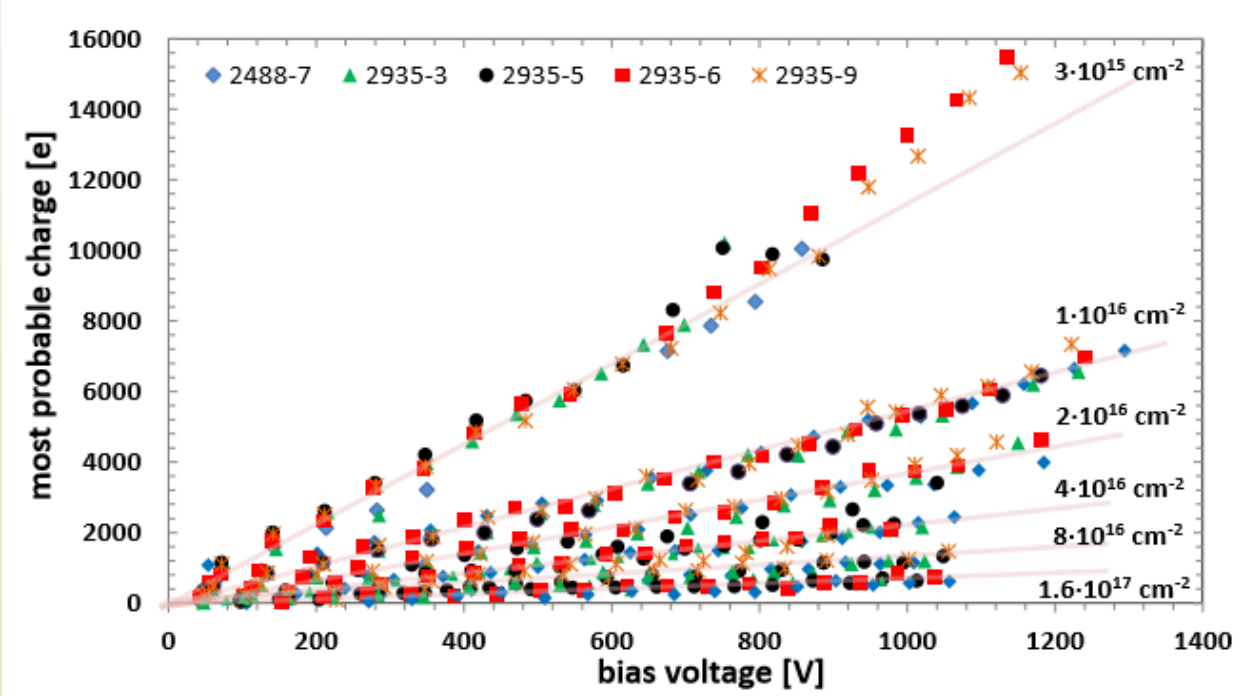


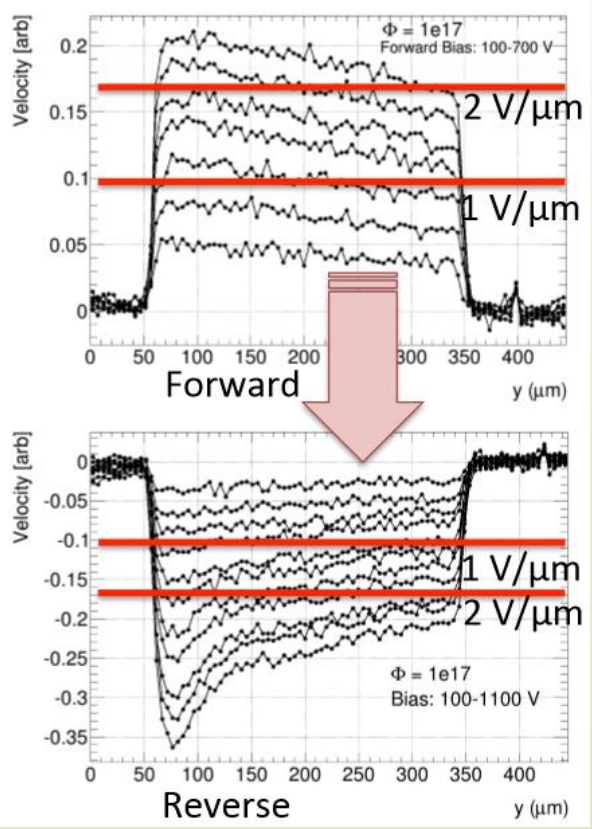
Into the future – FCC?

- A lot of hope with new silicon sensors that could cope with new extreme conditions
- Fluences up to $\mathbf{7 \times 10^{17} \frac{n_{eq}}{cm^2}}$
- High spatial resolution ($\sim 1\mu m$), light and low power consumption, timing capabilities
- **RD50 is an ideal environment for ironing out new ideas and leading the research programme**
  - Characterization – leakage current, annealing effects, signal at the end of the lifetime of detector, temperature dependence
  - Microscopic defects analysis related with new extreme fluence limits
  - New/Extended models for describing sensor performance
    - TCAD with extreme damage effects
    - Parameterisation of operation characteristics (CCE, trapping, current)
  - Searching of new structures (LGAD, 3D, HV-CMOS, …)

Final frontier?

- Stressing silicon structures with fluence $10^{17}\ \frac{n_{eq}}{cm^2}$
- Tests with specially designed sensors (n^+implants in p-type bulk), irradiated up to $1.6 \times 10^{17}\ \frac{n_{eq}}{cm^2}$
- Is it still alive…





M. Mikuž, 28th RD50 Meeting Torino 2016, G. Kramberger et al., JINST 8, P08004 2013

Summary

- A number of R&D project ongoing to prepare new silicon sensors to target HL-LHC and new future machines and their detectors
- RD50 Collaboration is very active and still growing!
- It is ideal environments to develop new ideas and tackle hard new fluence frontiers for future experiments