Silicon Detectors for the LHC Upgrade and Beyond

RD50 Status Report

Albert-Ludwigs-Universität Freiburg

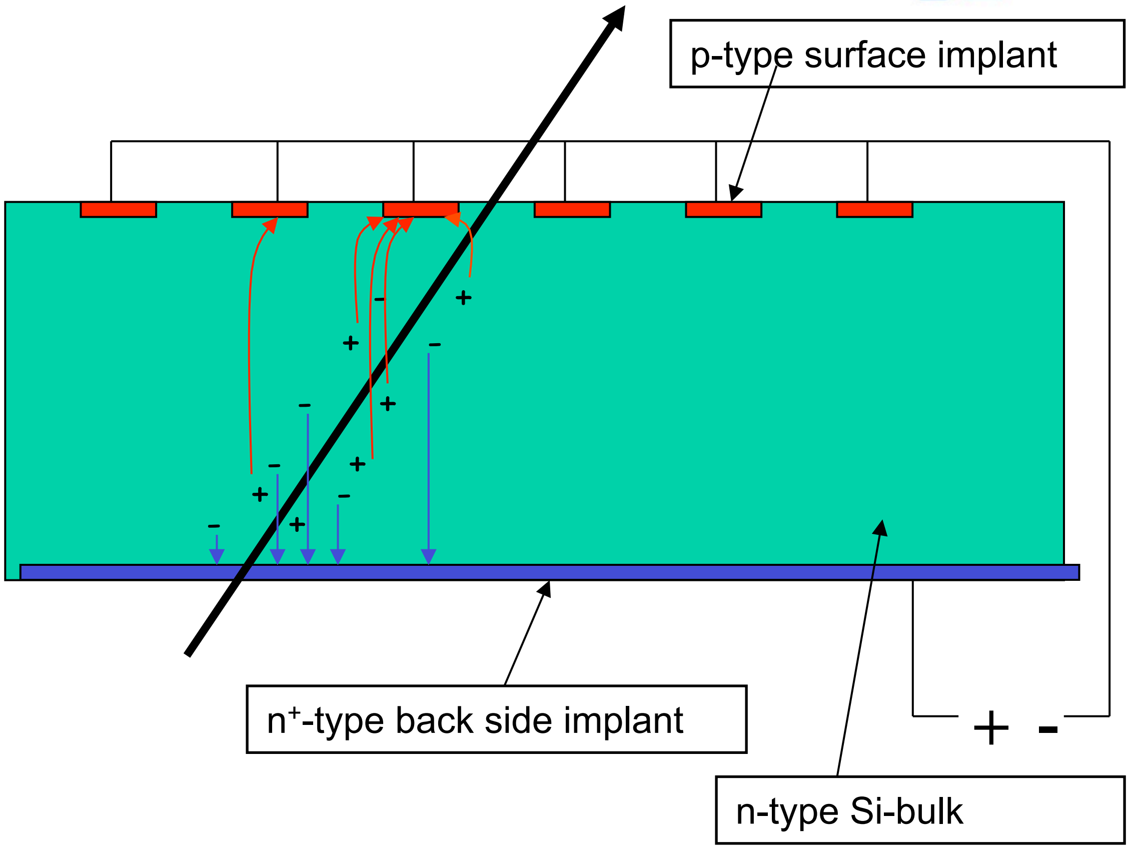
Ulrich Parzefall

on behalf of the RD50 Collaboration

with input and results from many many RD50 colleagues

RD50

- RD50 is a CERN-Collaboration connecting 300+ members, from all LHC experiments plus many others
- RD50 mandate to develop and characterize radiation-hard silicon sensors for future colliders
- Original RD50 target: radiation hard silicon for Phase-2 LHC upgrades (HL-LHC)
  - Radiation dose $3 \cdot 10^{16}$ n_{eq} /cm^2
- New: collider experiments beyond LHC: e.g. FCC
  - Radiation dose > $7 \cdot 10^{17}$ n_{eq} /cm^2, 200 MGy, in FCC



The RD50 Collaboration

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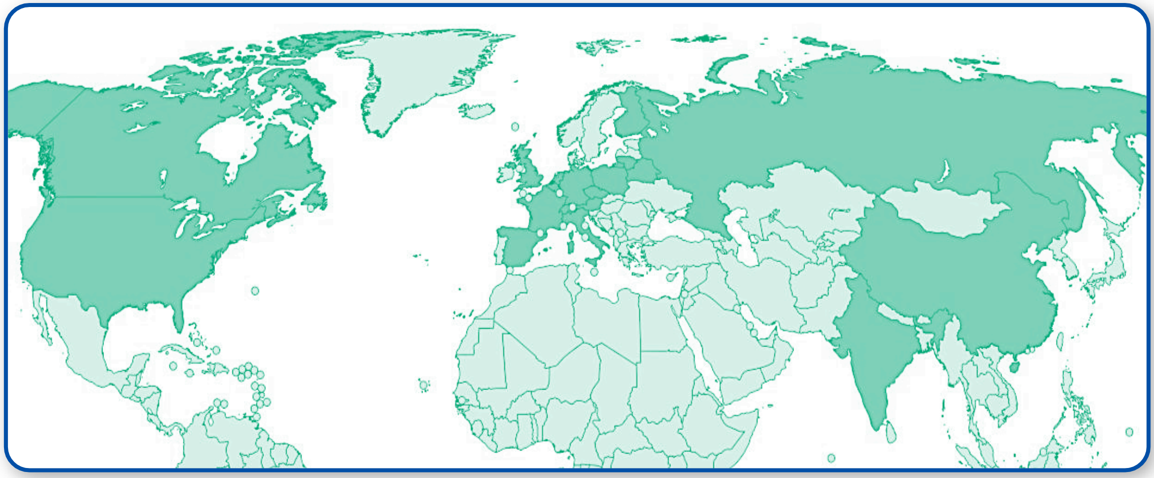
Worldwide Collaboration: 59 institutes, more than 300 members

(see http://cern.ch/rd50)



50 European institutes

Austria (Wien), Belarus (Minsk), Belgium (Louvain), Czech Republic (Prague (3x)), Finland (Helsinki, Lappeenranta), France (Paris, Orsay), Germany (Bonn, Göttingen, Dortmund, Erfurt, Freiburg, Hamburg (2x), Karlsruhe, Munich (2x)), Italy (Bari, Perugia, Pisa, Trento, Torino), Kroatia (Zagreb), Lithuania (Vilnius), Netherlands (NIKHEF), Poland (Krakow, Warsaw (2x)), Romania (Bucharest (2x)), Russia (Moscow, St. Petersburg), Slovenia (Ljubljana), Spain (Barcelona (3x), Santander, **València**), Switzerland (CERN, PSI), United Kingdom (Birmingham, Glasgow, Lancaster, Liverpool, Manchester, Oxford, RAL)

7 North-American institutes

USA (BNL, Brown Uni, Fermilab, New Mexico, Santa Cruz, Syracuse), Canada (Montreal)

1 Middle-Eastern institute

Israel (Tel Aviv)

2 Asian institute

India (Delhi), China (Beijing)

RD50 Structure

- Today examples from four main research lines

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

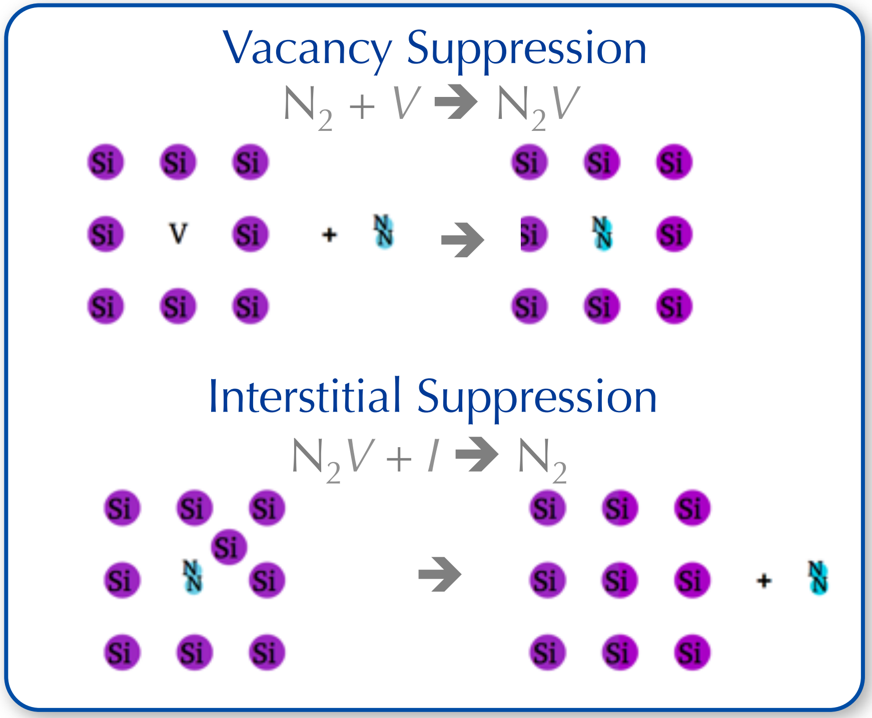
Gregor Kramberger
(Ljubljana University)

- 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)

Material R&D: NitroStrip

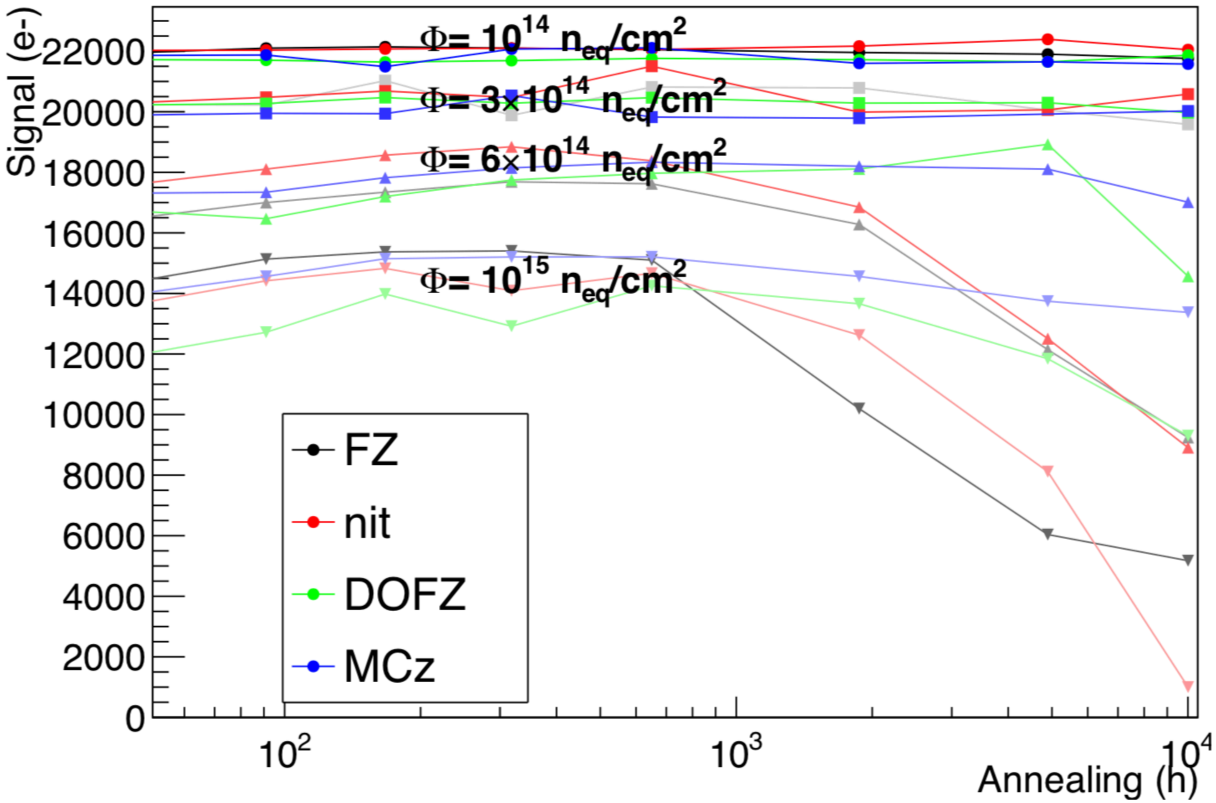
- Current RD50 Project: Nitrogen-enriched Silicon sensors
- Simulation indicates that N_2 can mitigate effects of radiation damage
- Wafer-level measurements show N_2-enriched wafers have lower trap density with increasing N_2 concentration after irradiation to $5 \cdot 10^{14}\ n_{eq}/cm^2$
- 24 wafers in 1+3 types
- NitroStrips (NIT) plus standards:
  - Float-Zone (FZ), diffusion-oxygenated FZ (DOFZ), Magnetic Czochralski (MCz)

W. von Ammon *et al.*, J. Cryst. Growth 226, 19 (2001)



Material R&D: NitroStrip

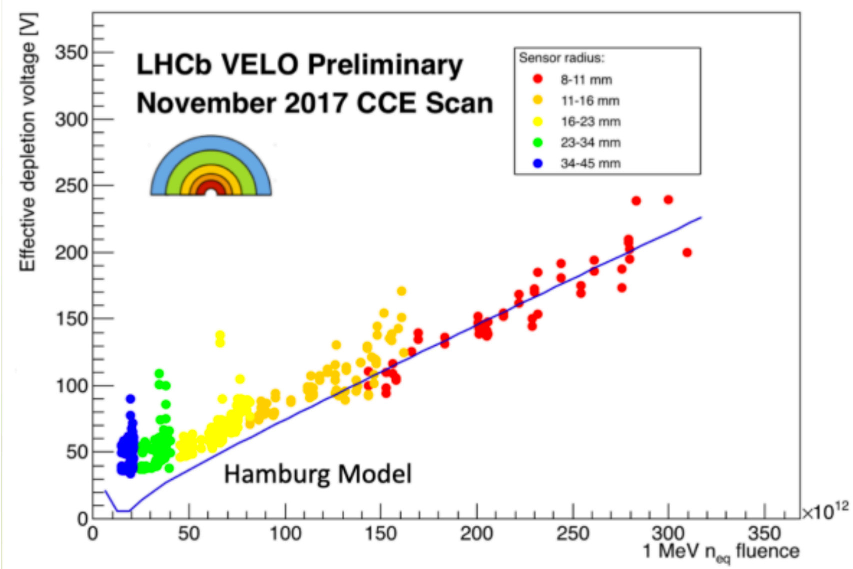
- Preliminary NitroStrip results, summarising a wealth of individual measurements:
- **N$_2$-enriched sensors** do not show a significant advantage. They suffer as the other types ☹
- Annealing was expected to be beneficial, but does not help either ☹
- Suspected reasons:
  - N$_2$ content too low to be effective
  - N$_2$ might be reduced during high T processing steps, or too low from the start
  - SIMS measurements in Progress
  - N$_2$ does not help, simulations are incorrect

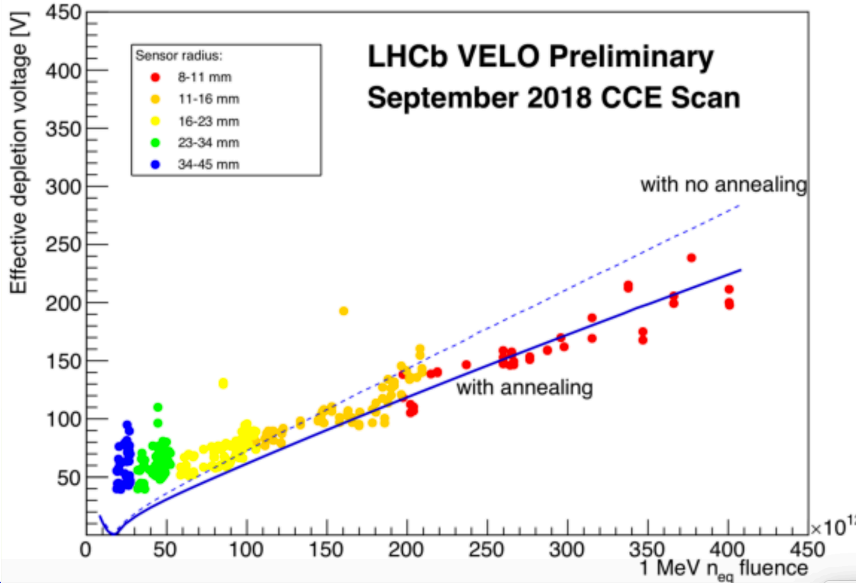


- Future prospects: depending on SIMS results, next run with higher N$_2$ concentration, or conclude N$_2$ is not working

Time Evolution of Silicon Doping Concentration: The Hamburg Model

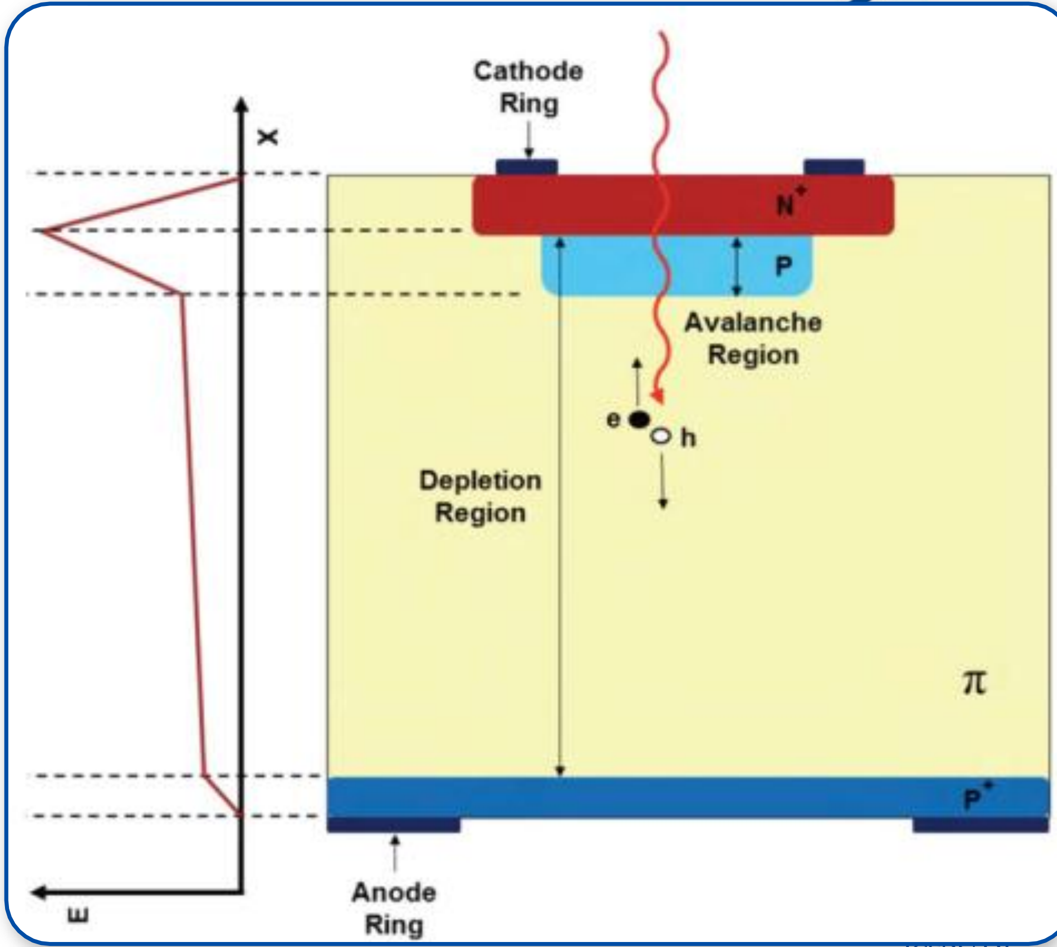
- Radiation damage effect on leakage current described by **RD50 Hamburg model**, including annealing
- **LHCb** vertex locator among the most irradiated detectors at LHC
- LHCb performs evolution of leakage current and depletion voltage with Hamburg Model
- In July 2018 monitoring suggested that VELO can have troubles coping with radiation
- VELO warmed up to accelerate beneficial annealing, based on Hamburg Model
- Depletion voltage successfully reduced





New Structures: Fast Silicon - LGAD

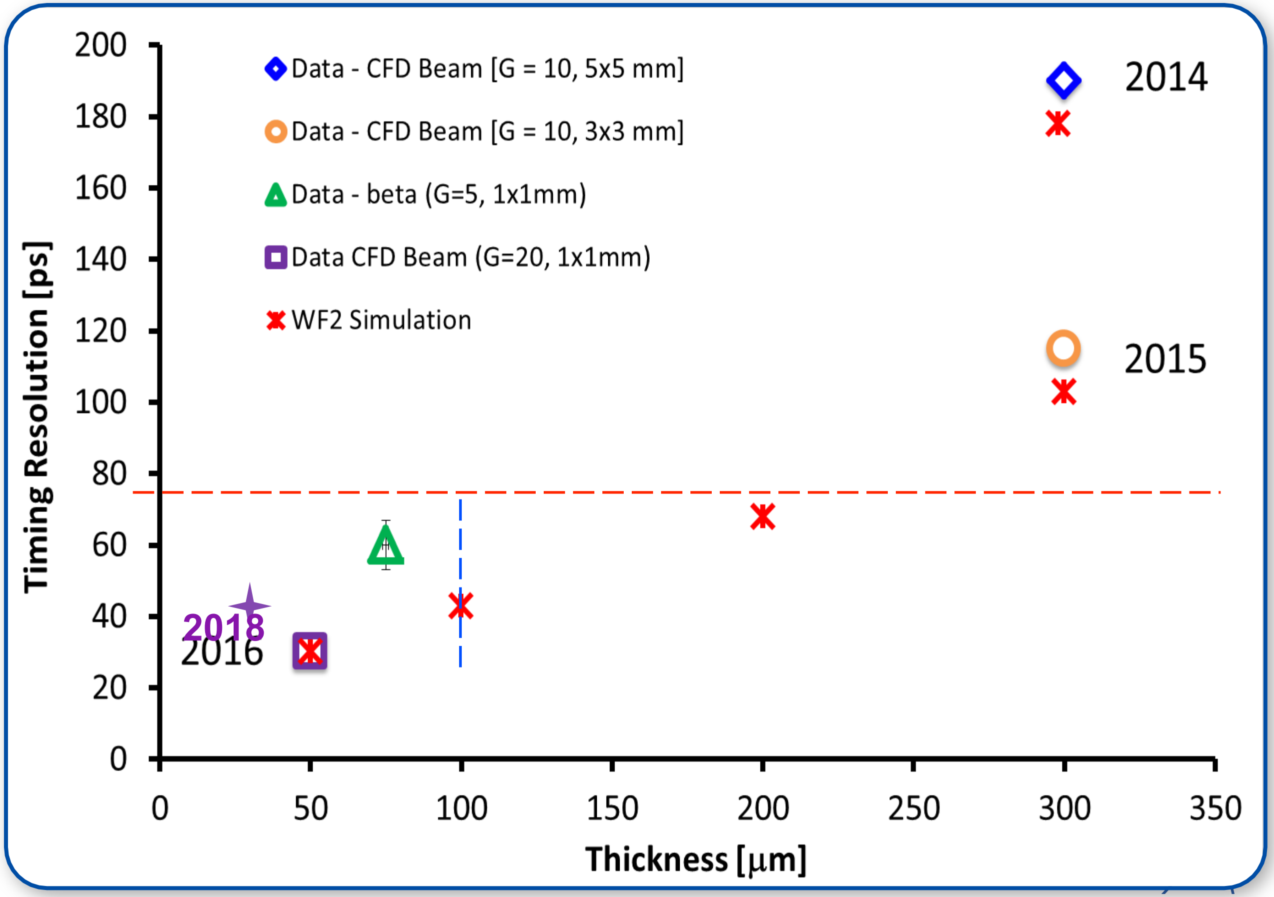
- HL-LHC: need to separate 300 simultaneous collisions every 25ns
- Idea: use time as 4th dimension.
  - Traditional detectors far too slow
  - Add a thin p-layer to conventional Si-detectors
- **Low Gain Avalanche Detectors (LGAD)**
  - Multiplication layer with very high E-field -> thin avalanche region with moderate gain (10-50) at the readout electrode
  - Manufactured by CNM, FBK, HPK
  - To be implemented in fast timing layers of
  - CMS Endcap Timing Layer (ETL)
  - ATLAS High Granularity Timing Detector (HGTD)



LGAD: Performance Evolution

- LGADs under study for ≈ 5 years
- Time resolution σ_t < 50ps required
- Reduced thickness improves σ_t
- Detectors get thinner and improve time resolution with each generation

σ_t versus LGAD thickness (pre-irradiation)

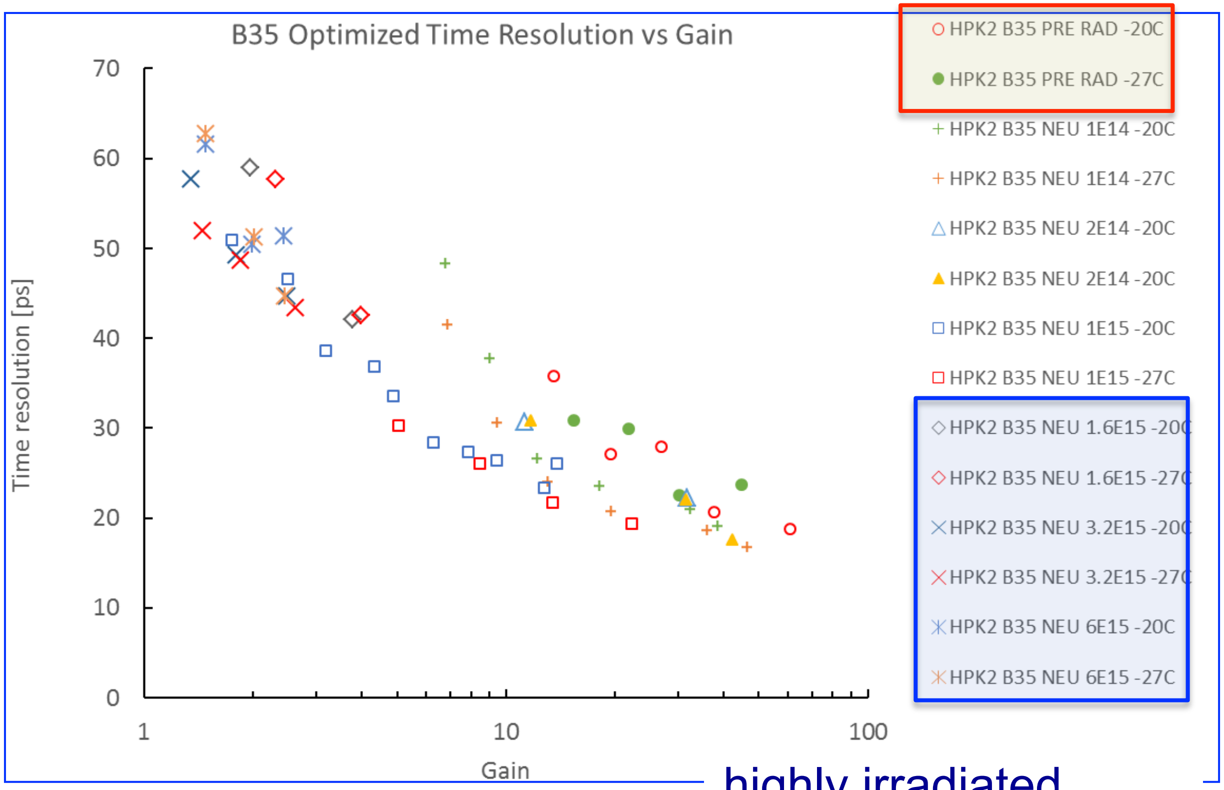


H. F.-W. Sadrozinski, RD50 workshop, Jun 2018

LGAD: Time Resolution, Gain and Radiation Hardness

- LGAD σ_t improves with gain
- Need to have sufficient gain (≈ 8-10) to reach goal of 50ps timing
  - Gain limited to ≈ 20 by onset of HV breakdown
- Problem: gain decreases as function of radiation
- Gain of 30-50 and σ_t < 40ps achieved before irradiation
- Gain drops to 2-3 and σ_t ≈ 50ps after few $10^{15} n_{eq}$

pre-irradiation

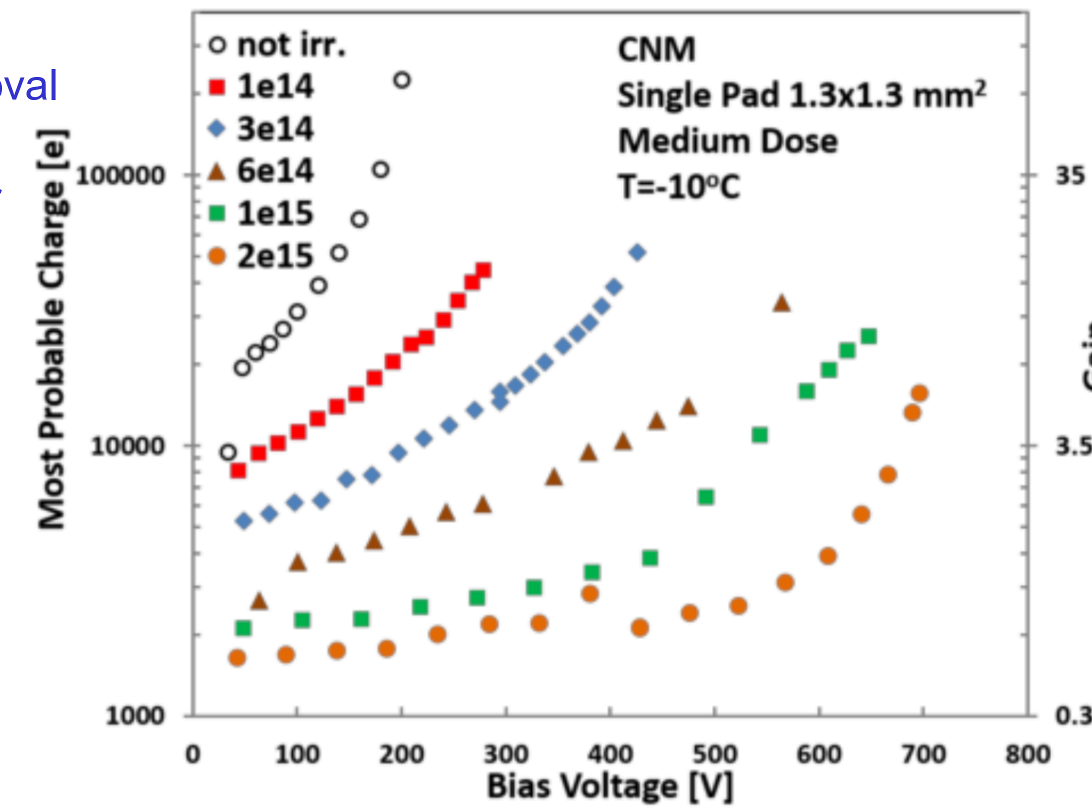


H. F.-W. Sadrozinski, RD50 workshop, Jun 2018

highly irradiated
$\Phi < 1.5 \cdot 10^{15}\ n_{eq}\ /cm^2$

LGAD: Irradiation

- LGAD gain increases with bias voltage
- Gain decreases with radiation (limited mitigation with higher bias)
- Reason: radiation dose changes doping
  - Multiplication layer diminishes
  - Significant Boron acceptor removal (not fully understood)
  - Radiation deactivates gain layer
- Timing resolution also decreases
- LGAD radiation hardness not yet sufficient for HL-LHC applications major R&D topic
- Currently testing other forms of high gain sensor (e.g. 3D)



NIMA 891 (2018) 68 - 77

Main RD50 Achievements & Summary

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This talk is biased and covers only very few highlights. Other key achievements:

- Sensor material: ***p*-type Silicon replacing n-type** (no type inversion, collection of electrons instead of holes)
- Sensor technologies: CMOS processed silicon, ⋯
- Development of unique characterization methods and systems for sensor and material analyses: **Transient Current Technique** (TCT), **edge-TCT**, Two-Photon Absorption-TCT (TPA-TCT), **ALiBaVa** readout system
- Original mission (HL-LHC) about to be completed successfully, R&D in final steps. Construction of detectors starting in 1-2 years
- Now focusing on new generation of colliders (FCC), pushing the radiation boundary by an order of magnitude. Will be rather difficult. We need new thinking, and younger people
- RD50 is still your must-have friend if you are serious about installing silicon in a harsh radiation experiment!

RD50 Members at Torino Meeting