Radiation-tolerant silicon detectors for the LHC Phase-II upgrade and beyond:

An overview of RD50 activities

Jennifer Ott
Helsinki Institute of Physics & Aalto University

on behalf of the RD50 Collaboration

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

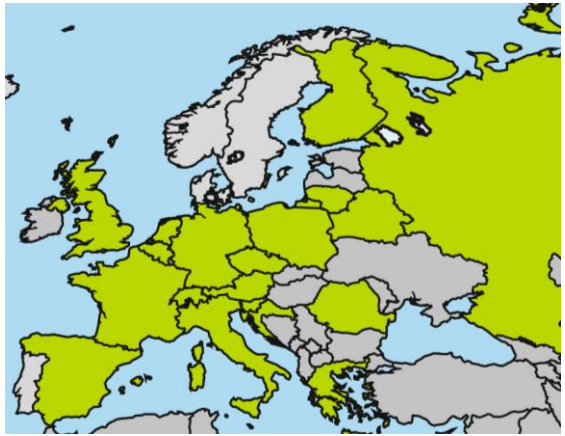
28th International Workshop on Vertex Detectors, 13.-18.10.2019

The RD50 Collaboration

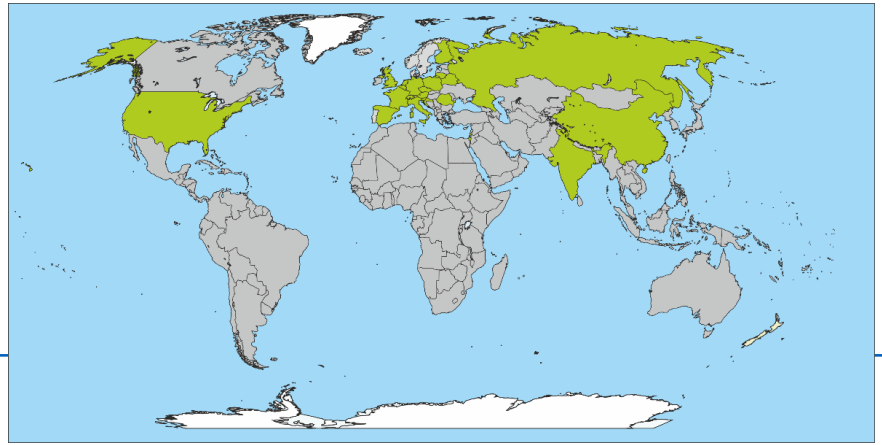
60 institutes and 360 members

50 European institutes

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



M. Moll, June 2019



7 North-American institutes

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

1 Middle East institute

Israel (Tel Aviv)

2 Asian institutes

China (Beijing-IHEP), India (Delhi)

RD50 Organizational Structure

Co-Spokespersons

Gianluigi Casse and *Michael Moll*

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

M. Moll, June 2019

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 modeling (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 P2, 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)

RD50 activities so far

- Development of detector technologies
  - Extensive research and development of silicon strip and pixel technology
  - Demonstration of the performance of planar segmented sensors to the maximum fluences anticipated for the HL-LHC
  - Pioneering design and production of Low Gain Avalanche Detectors, double-column 3D detectors
- Development of several unique characterization methods and systems for sensor and material analyses
- Aiming to form standards for measurement and analyses procedures
- Collecting large datasets for evolution of IV, CV, CC for varying parameters: radiation type, annealing, material, ...
- Defect characterization:
  - Identification of defects responsible for the degradation of various detectors
  - Extensive evaluation of defect-engineered silicon and other semiconductor materials
- Development of damage parameters and models essential for sensor design AND for planning the running scenarios of LHC experiments and their upgrades (evolution of leakage current, CCE, power consumption, noise,….)

Close links to the LHC experiments and upgrades!

RD50

RD50 work plan

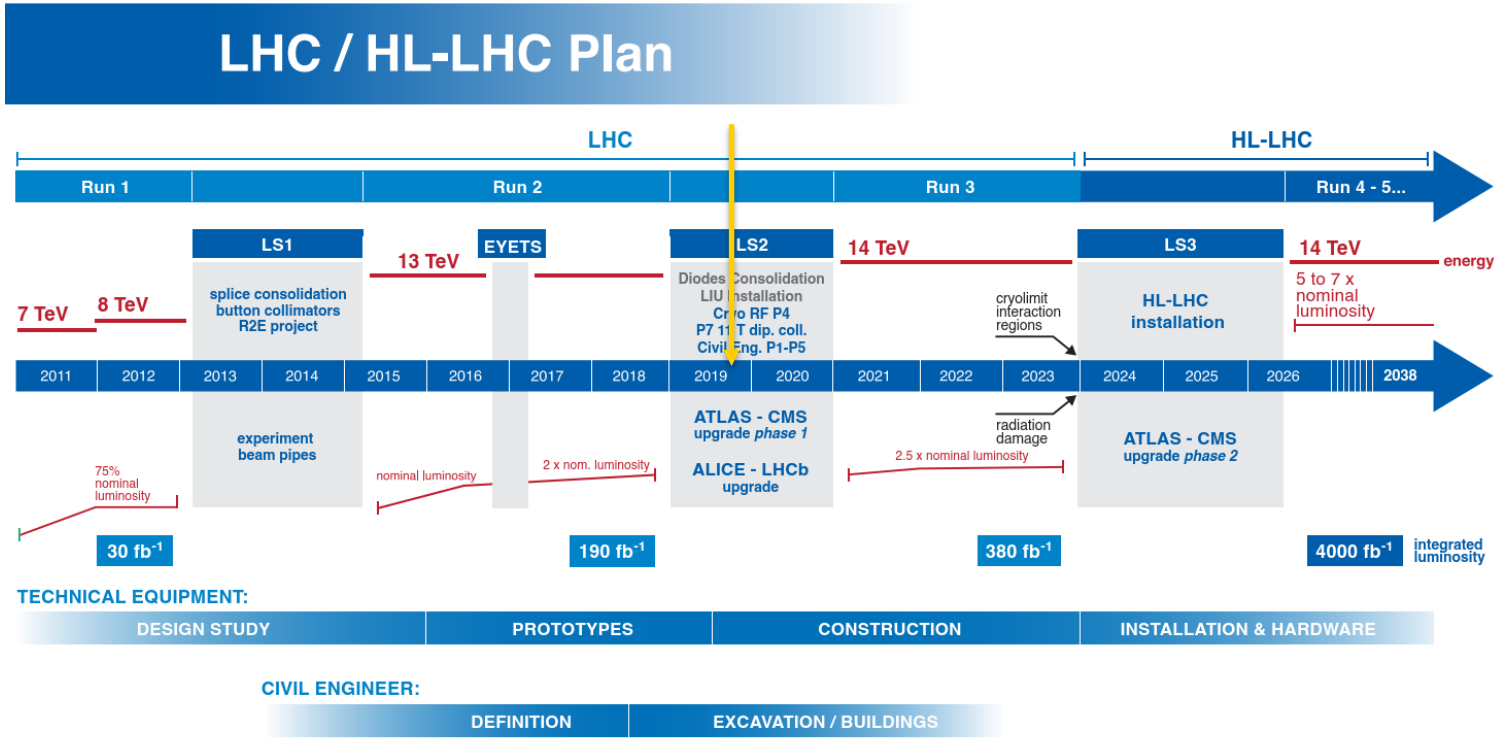
Prolongation request & 5-year work program submitted, **and approved** by CERN Research Board, in 2018: https://cds.cern.ch/record/2320882/files/LHCC-SR-007.pdf

RD50 work plan [70 milestones]

- **Defect and Material Characterization**
  - *p-type silicon [7 MS]*
  - *Cluster defects [4 MS]*
  - *Theory of defects [5 MS]*
- **Device Characterization and Device Simulation**
  - *Silicon materials [5 MS]*
  - *Extreme fluences [5 MS]*
  - *Experimental techniques [3 MS]*
  - *Surface damage [1 MS]*
  - *TCAD simulations [7 MS]*
- **New structures**
  - *3D sensors [6 MS]*
  - *LGAD [4 MS]*
  - *CMOS [6 MS]*
  - *New Materials [5 MS]*
- **Full Detector Systems**
  - *LHC [7 MS];*
  - *HL-LHC [3 MS]*
  - *FCC [2 MS]*

M. Moll, June 2019

Upgrades towards the HL-LHC

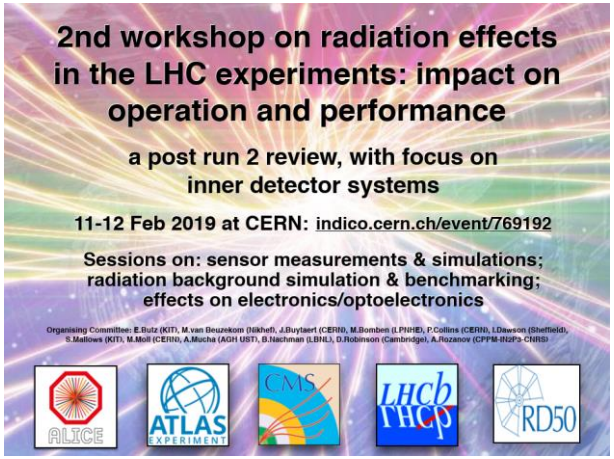


L. Rossi, 8th HL-LHC Collaboration Meeting, 2018

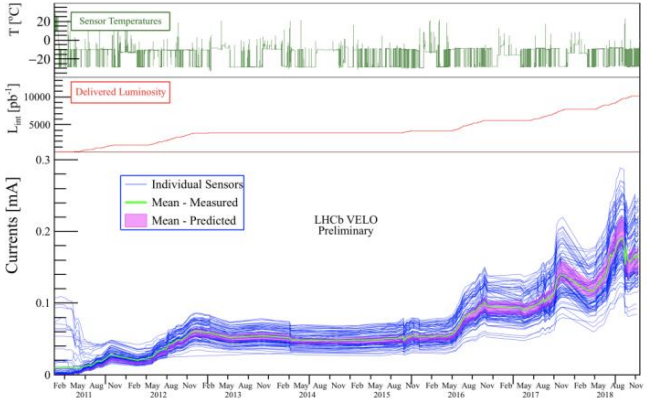
Full detector systems

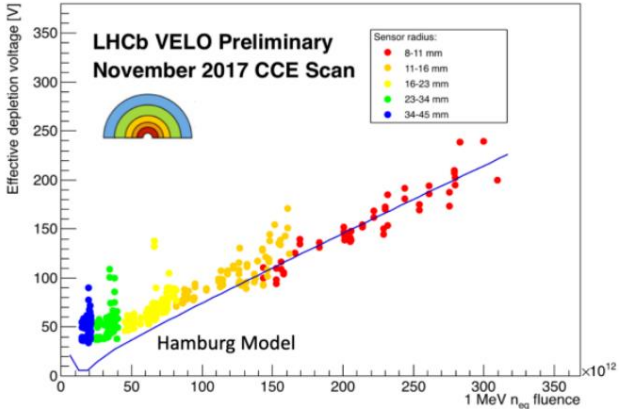
- Detailed monitoring of running detector systems

  → comparison of data with models developed within RD50

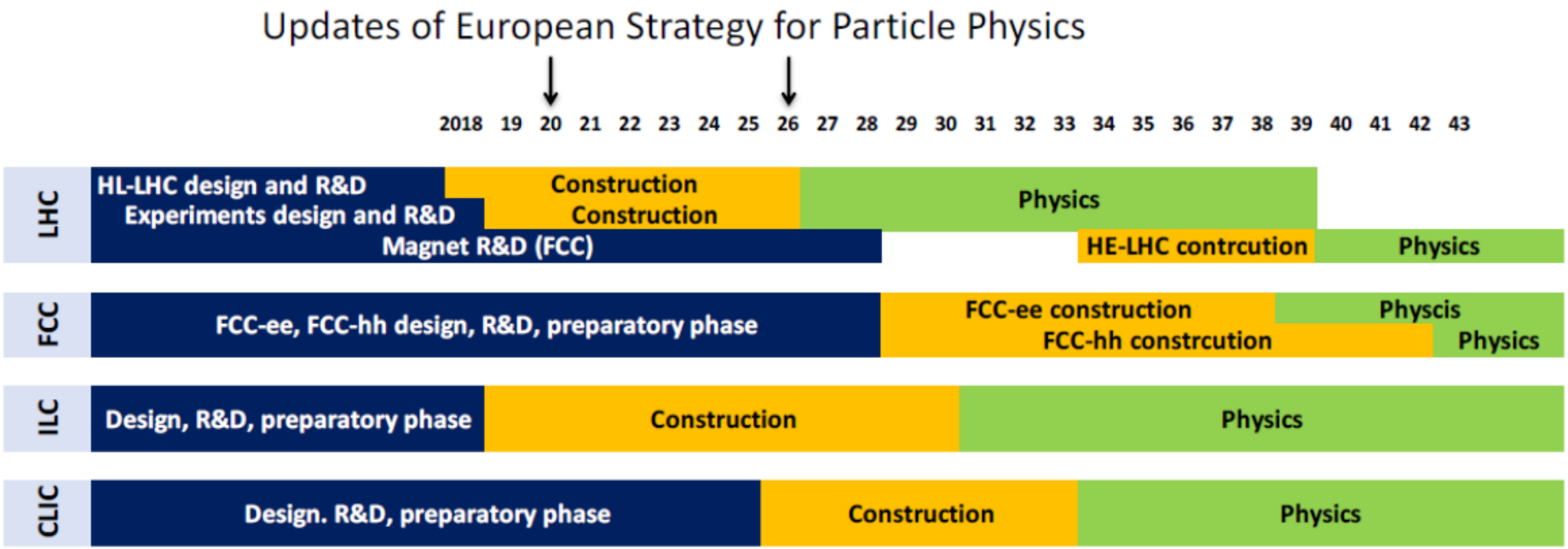


Example: LHCb VELO detector





Beyond the HL-LHC



D. Contardo, LHC Days 2018

Extreme conditions in future colliders

HL-LHC

- Max. fluence on silicon detectors ~$3x10^{16}$ n_{eq}/cm^2
- Pileup ~200, for mitigation: timing resolution < 50 ps

Future colliders

- Fluence on inner layers up to $7x10^{17}$ n_{eq}/cm^2 (FCC)
- Similar pileup conditions to HL-LHC
- Desired resolution: 1-3 µm (lepton colliders)
- Material budget: down to 1% X_0

Requests for ...

Efficient tracking (in 4D)

- **Timing resolution**
  - Silicon sensors with gain
  - 3D detectors
- **Improved spatial resolution**
  - Small pixels
  - 3D detectors
- **Operation at extreme fluences**
  - Radiation tolerance of material
  - Sensor design (incl. thickness)

”New” technologies

- **Detectors with gain: large signal with very fast rise time**
  - Low Gain Avalanche Diode (LGAD)
  - Deep-diffused avalanche photodiodes

Talk by Sofia Otero Ugobono

- **3D detectors: short drift distances for charge carriers:**
  - Attractive both for 2D/3D tracking AND timing applications
- **(HV-)CMOS**
  - Access to large-scale industrial production
  - Reduction of costly hybridization

Talk by Eva Vilella

- **Improvement of planar pixel sensors**
  - Trench insulation, insulation with ALD-Al_2O_3 instead of p-implants, slim edges ...

Characterization methods

A wide variety of methods used within RD50:

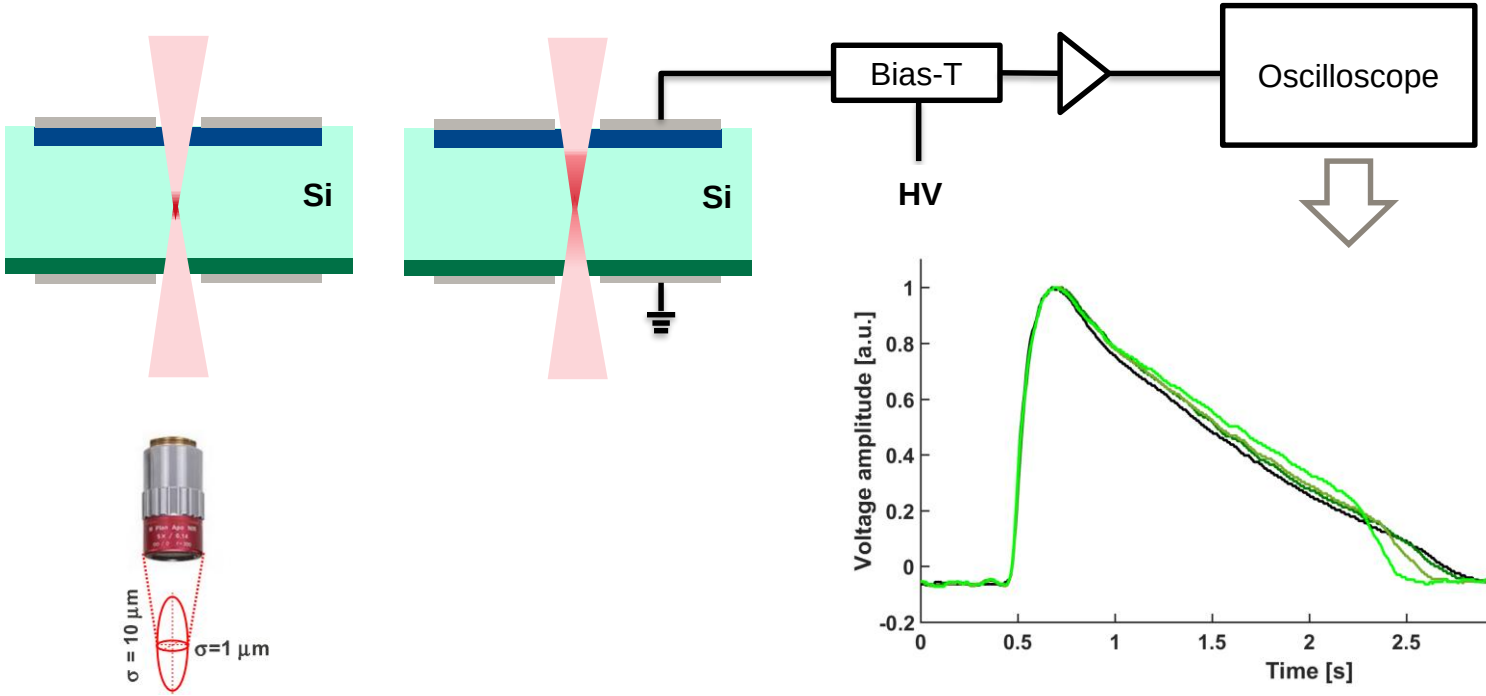
- CV/IV (Capacitance/Current-Voltage Measurement)
- TCT (Transient Current Technique)
- Probing with radioactive sources and test beams

- SIMS (Secondary Ion Mass Spectrometry)
- SEM & TEM (Scanning Electron Microscopy & Transmission Electron Micr.)
- FTIR (Fourier Transform Infrared Spectroscopy)
- C-DLTS (Capacitance Deep Level Transient Spectroscopy)
- TSC (Thermally Stimulated Currents)
- µPC / µPCD (Microwave-probed photoconductance (decay))

Detector characterization

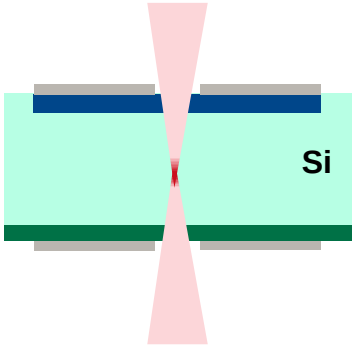
Particulars d.o.o.

Transient Current Techniques: TCT

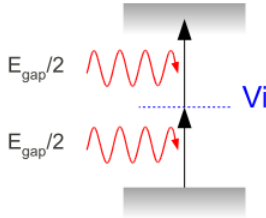


Detector characterization

Transient Current Techniques: TPA-TCT



TPA: Conventionally, no excitation if $E_{photon}<E_{gap}$~1 eV.
But, if **TWO** photons arrive in ~100 attoseconds:



$$\tau_{virtual} \approx \frac{\hbar}{E_{gap}/2} \approx 0.1\ fs$$

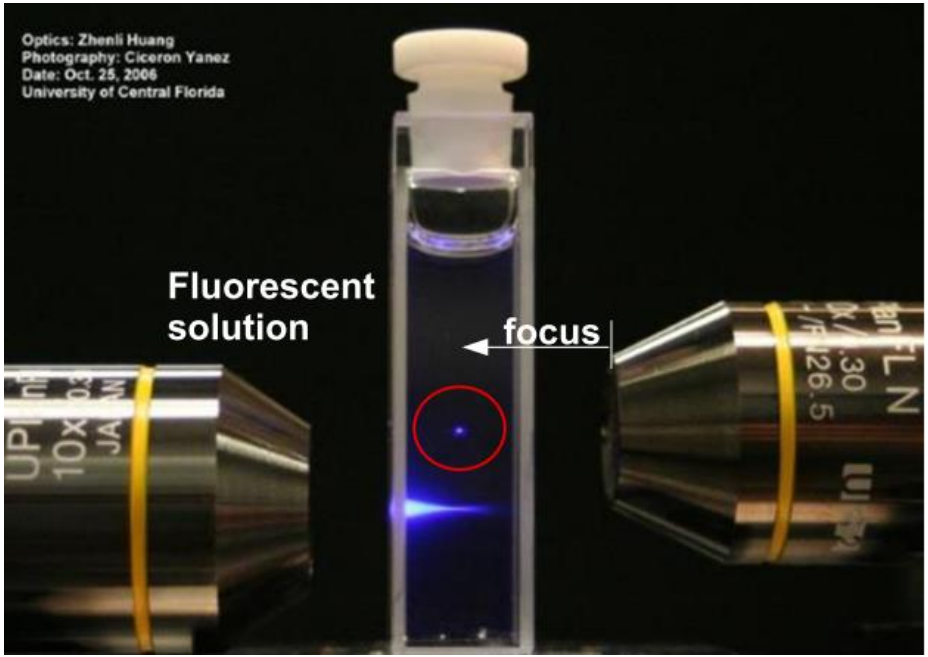
Two Photons ($E>E_{gap}/2$) must be:

1) **coincident in time** (pulsed **mode-locked fs-lasers**)
2) and in **space** (**microfocusing**)

Two-photon absorption (TPA)

Detector characterization

Transient Current Techniques: TPA-TCT



M. Fernandez Garcia et al, VCI 2019

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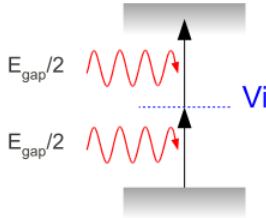

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Two Photons ($E>E_{gap}/2$) must be:

1) **coincident in time** (pulsed **mode-locked fs-lasers**)
2) and in **space** (**microfocusing**)

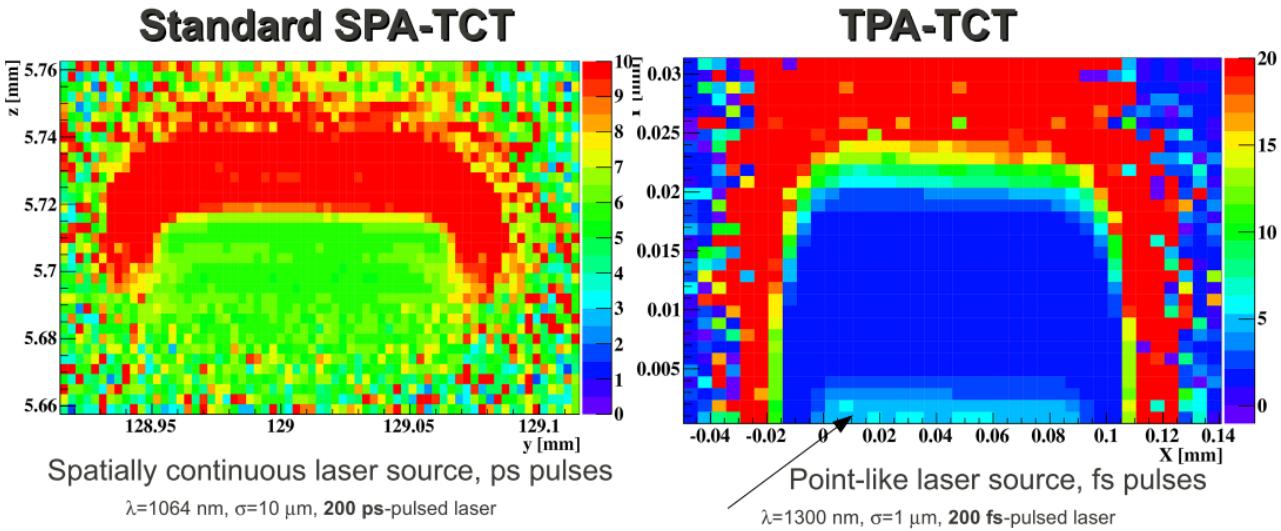
Laser: low energy, but high intensity!

Detector characterization

Transient Current Techniques: TPA-TCT

Example: HVCMOS sensor scanned from the side (edge-TCT)

- TPA provides better contrast, and can resolve even very small structures at the surface

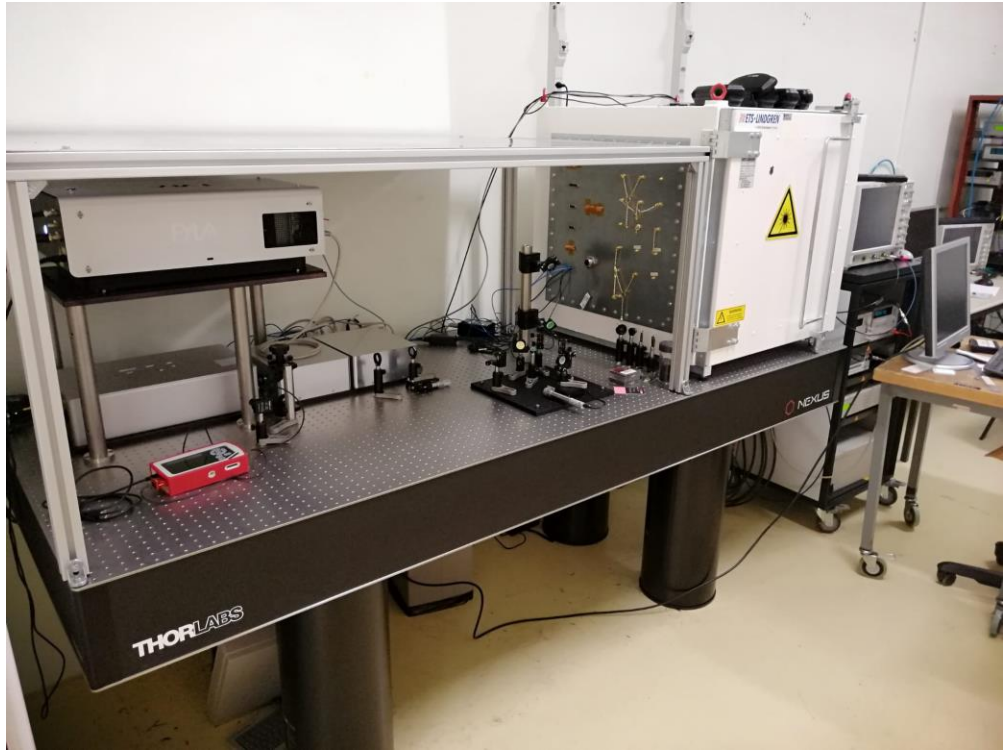


M. Fernandez Garcia et al, VCI 2019

Detector characterization

Transient Current Techniques: TPA-TCT

Setup at CERN SSD lab



M. Fernandez Garcia et al, 2019

Experimental work and simulations

Continuous interaction and iteration: experimental input to simulations; prediction of properties or trying to identify a defect or structural cause behind empirically observed behavior

- **Experiment level**: event generator & simulation → predicting fluence distribution
  - DPMJET+FLUKA, Pythia8 + GEANT4

Talk by Rogelio Palomo

- **Sensor level:** TCAD for structure simulation, defect modelling, ...
  - Commercial packages: Synopsys Sentaurus, Silvaco Atlas
  - O.S. Software: KDetSim, TRACS, Weighfield2

Defect and material characterization

Defect and Material Characterization

- p-type silicon [7 MS]
- Cluster defects [4 MS]
- Theory of defects [5 MS]

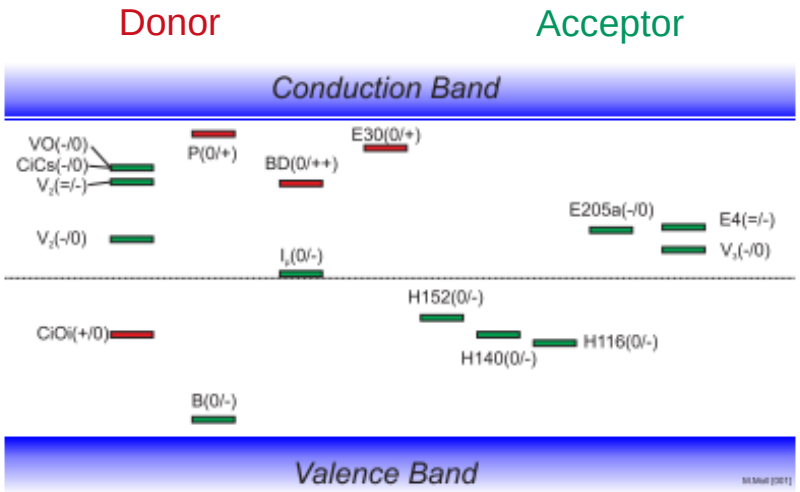
Device Characterization and Device Simulation

- Silicon materials [5 MS]
- Extreme fluences [5 MS]
- Experimental techniques [3 MS]
- Surface damage [1 MS]
- TCAD simulations [7 MS]

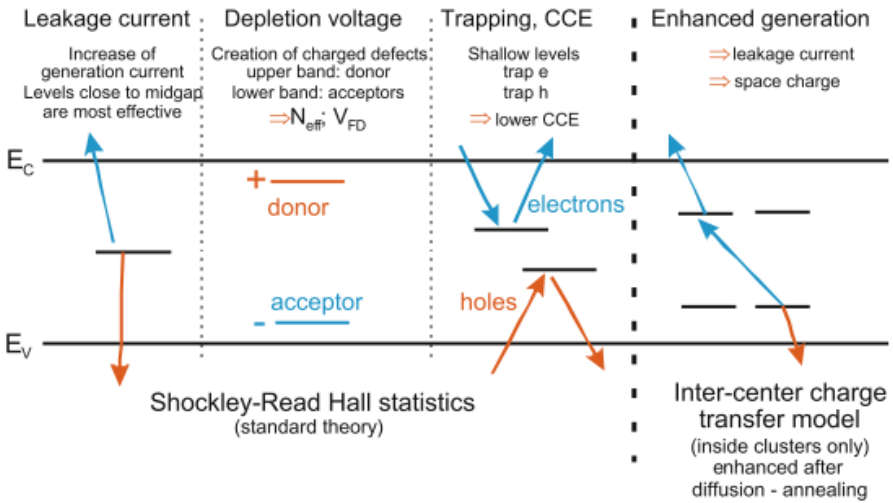
From microscopic properties to macroscopic effects

- a key topic for RD50 from the start!

Defect and material characterization



M. Moll 2018



F. Hartmann, 2017

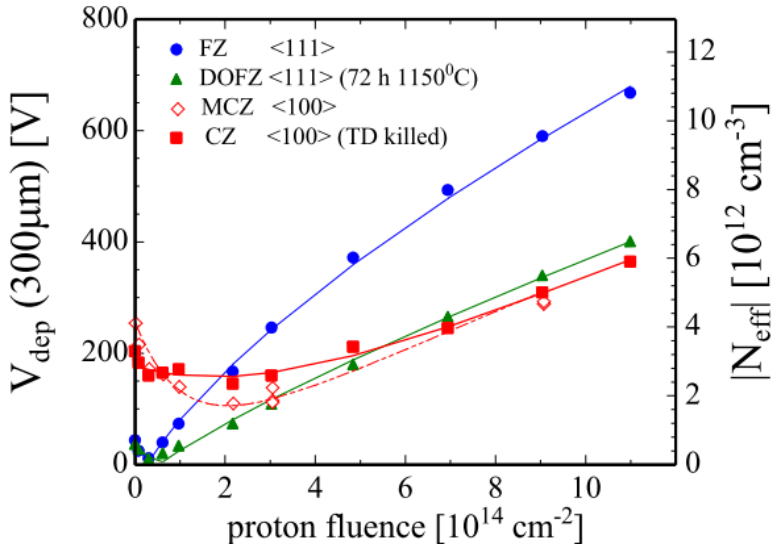
Defect engineering approaches

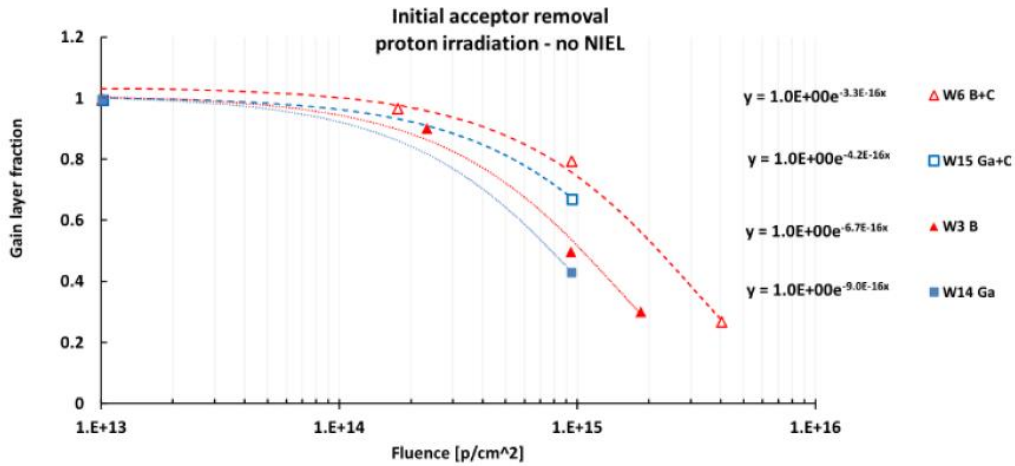
- **Use of p-type instead of n-type Si**
  - No ”type inversion”, less pronounced increase in V_{fd}
  - Most scenarios for future detectors are now based on p-type sensors! (or are at least strongly considering them)

- **Oxygen-containing material: DOFZ or MCz**
  - Somewhat limited by practical concerns / availability of suitable starting material – FZ remains dominating

- **Co-doping with carbon**
  - Promising for LGAD gain layer retention!

Defect engineering approaches

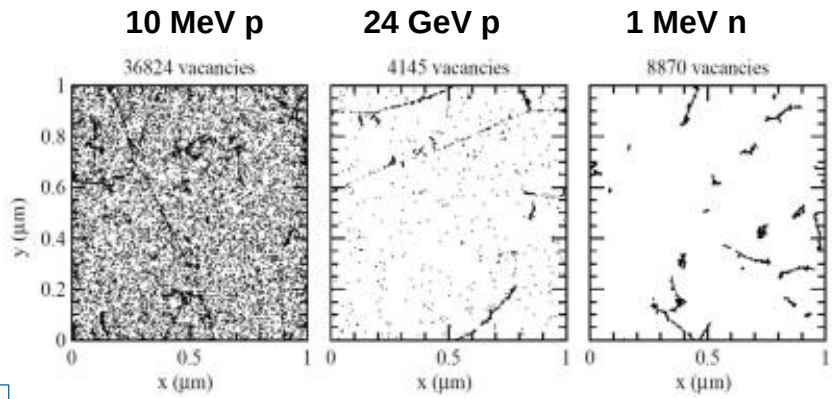




Evaluation and comparison of radiation damage

Target: compare and scale damage in silicon caused by different types and energies of radiation

- Introduction of different defect species; point defects vs defect clusters

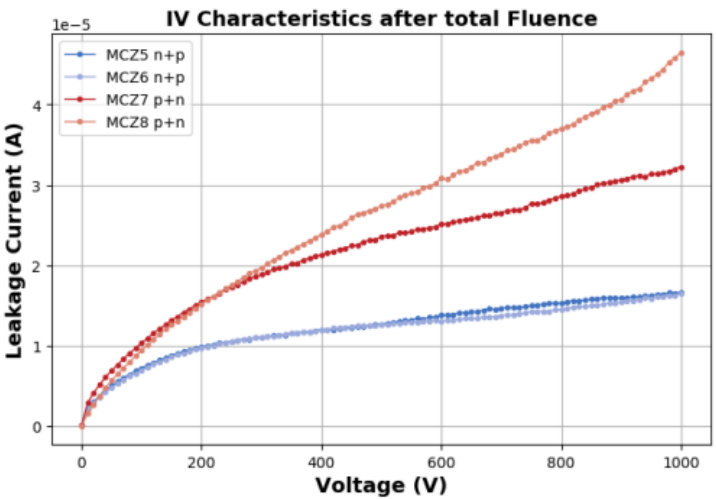


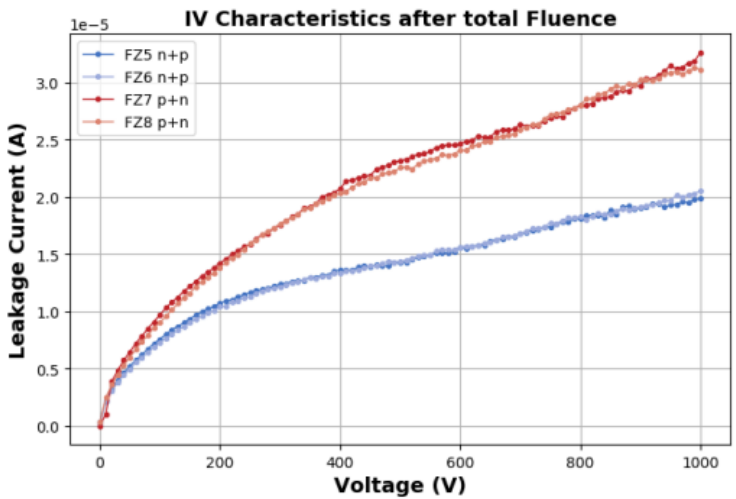
M. Huhtinen 2002

Mixed irradiation

Order of irradiation can make a significant difference – not fully explained by thermal history between/before irradiations!

- p + n or n + p irradiation, each approximately $3x10^{14}$ n_{eq}/cm^2





J. Gosewisch et al, November 2018

Scaling of radiation damage

Non-Ionizing Energy Loss (NIEL) scaling

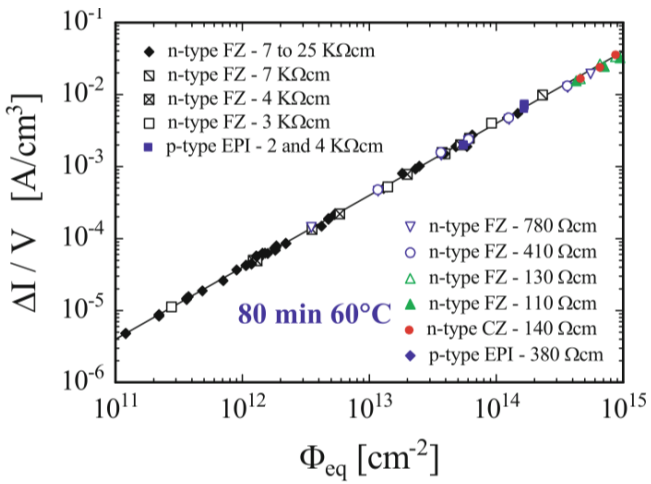
- Point of reference: particles with largest fraction of non-ionizing, i.e. nuclear interaction energy losses → **neutrons**
- Simulations from 1990s-2000s indicated that pion irradiation damage would be the most significant contribution in the LHC tracking detectors, and noted that pions compared well with 1 MeV neutrons

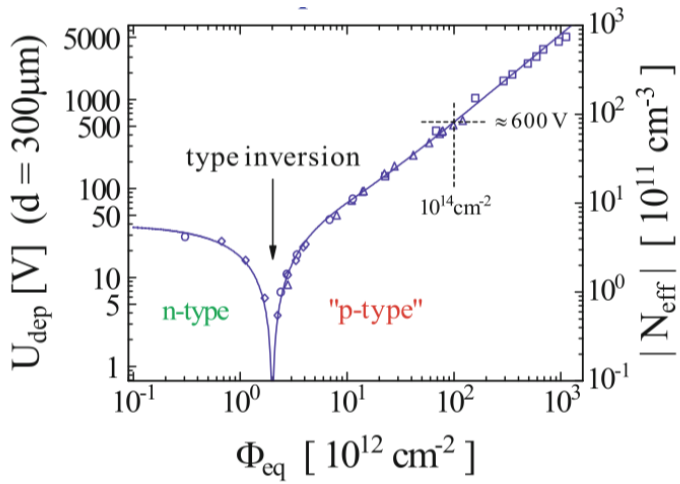
...

"1 MeV n_{eq}"

NIEL scaling & the Hamburg model

- Utilizing **hardness factors** to scale irradiation with other particle species (mostly protons of different energies) to 1 MeV neutrons
- Radiation damage evaluated as changes of **full depletion voltage** (V_{fd}) and **leakage current** over a detector volume





M. Moll 1992, R. Wunstorf 1999

NIEL scaling & the Hamburg model: limitations

- Significant uncertainties associated with 1 MeV n definition through neutron spectra, cross sections, and dislocation energy estimations

M. Huhtinen et al, LHC Experiments Radiation Damage workshop 2019

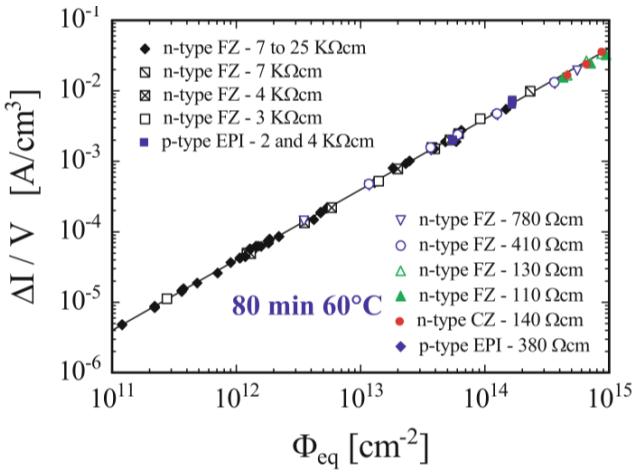
- Especially in future detectors: leakage current is **not necessarily the most relevant parameter**, or at least **not the only relevant parameter**, in the quantification of radiation damage

Charge collection length?

Charge collection efficiency?

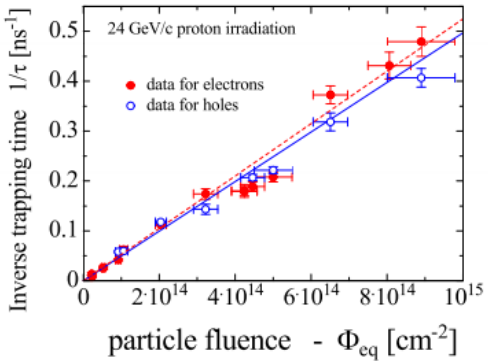
Acceptor removal rate?

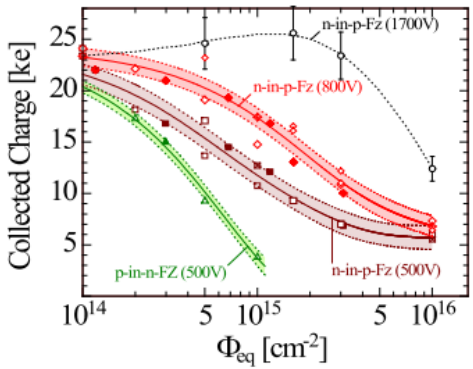
Quantification of radiation damage: some alternatives



- Various deep and shallow level defects → **leakage current** → higher noise, breakdown, higher power consumption
  - Introduced in the Hamburg model, still valid
  - Further studies and larger datasets needed for **p-type** Si substrates

Quantification of radiation damage: some alternatives



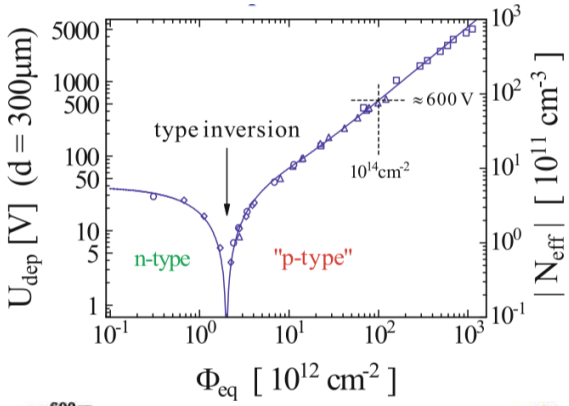


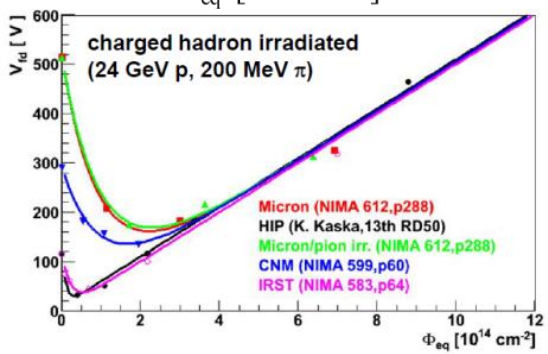
- Deep-level defects, clusters → charge trapping → reduced **charge collection length** & **charge collection efficiency** → decreased spatial resolution, smaller signal, slower signal
  - Introduced in Hamburg model, additional data collected over the years
  - Evolution and amount of collected charge becomes more relevant than the concept of full depletion at high fluences

O. Krasel et al, 2004

G. Casse et al, 2010

Quantification of radiation damage: some alternatives

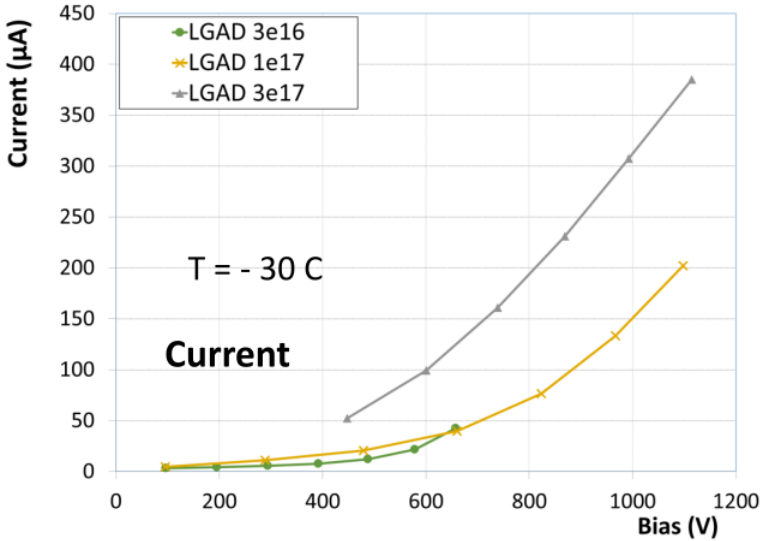


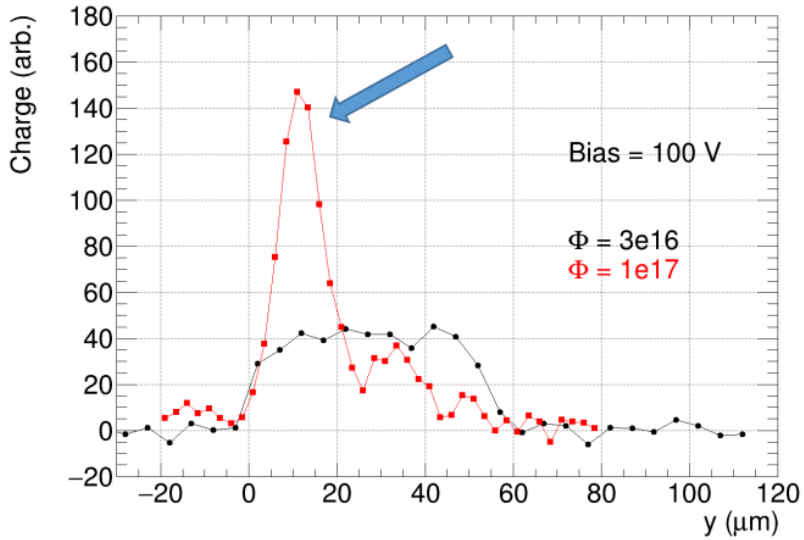


- Change in states of of dopant atoms, creation of charged defects → change in N_{eff}
- n-type: space charge sign inversion → higher V_{bias} required
  - Introduced in the Hamburg model
- p-type: **acceptor removal** → (space charge sign inversion), reduced gain → (higher V_{bias} required), worse timing resolution
  - Has risen to attention in recent years due to the increase of interest in p-type substrates and LGADs with a p-type gain layer

Talk by Michael Moll

Studies at ultra-high fluences: $3x10^{17}$





I. Mandić et al, June 2019

- Charge multiplication at low voltages even in pad detectors
- Behavior changes with time or repeated measurements
- Limited prediction of models for lower fluences – more experimental data with high fluences required!

Summary

- The RD50 Collaboration has been very successful in the understanding of radiation effects, and the development of radiation-hard silicon detectors for LHC experiments
  - Combining a variety of disciplines, and providing a forum for uniting experts in different fields and developing new ideas

- Continuing the mandate to develop radiation-hard semiconductor detectors towards upgrades for the HL-LHC and future collider experiments with even higher luminosities
  - At the same time continued validation of models and understanding of radiation damage with feedback from **ongoing** experiments!

- Successful development and implementation of cutting-edge silicon detectors for extreme-luminosity environments requires a deep understanding of radiation-induced defects and their macroscopic effects specifically for the detector technology or application in question

Thank you!

RD50 Workshop Krakow, June 2017

Backup