139th LHCC Meeting – OPEN Session - 11 September, 2019

RD50 Status Report
- September 2019 –

Radiation hard semiconductor devices for very high luminosity colliders

Outline:

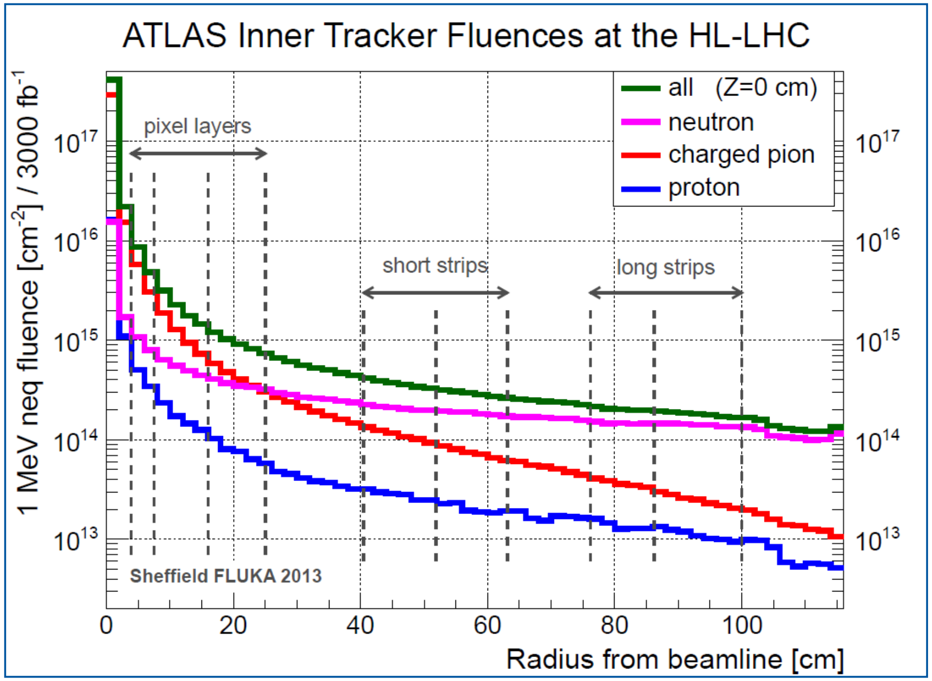
- RD50 Collaboration
- Scientific results 2018/19 (some highlights)
    - Defect and Material Characterization
    - Detector Characterization
    - New Detector Structures
    - Full Detector Systems
- RD50 - 5 Year Work Plan (Status of Milestones)
- Outlook and request to the LHCC

RD50 Motivation and Challenge

Silicon detectors upgrades and operation

- Radiation Hardness -

- **LHC operation**
- **HL-LHC (High Luminosity LHC)**
  - detector developments for HL-LHC
    - starting after LS3 (~2024-26);
    - expect 4000 fb^{-1} (nominal LHC was 300 fb^{-1})
- **HL-LHC operation & upgrades**
  - operation of HL-LHC
    - damage modelling, evaluation, mitigation
  - ATLAS Pixel replacement, LHCb upgrade, …
- **FCC – Future Circular Collider**



[I. Dawson, P. S. Miyagawa, Sheffield University, Atlas]

- **Increasing radiation levels**
  - Semiconductor detectors will face $>10^{16}$ n_{eq}/cm^2 (HL-LHC) and $>7\text{x}10^{17}$ n_{eq}/cm^2 (FCC-hh)
    → detectors used at LHC cannot be operated after such irradiation
- **New requirement and new detector technologies**
  - New requirements or opportunities lead to new technologies (e.g. HV-CMOS, LGAD,…) which need to be evaluated and optimized in terms of radiation hardness

The RD50 Collaboration

- RD50: 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), **Croatia** (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)

New members since last LHCC marked red

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)

Full member list: www.cern.ch/rd50

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
- SiC based detectors

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)

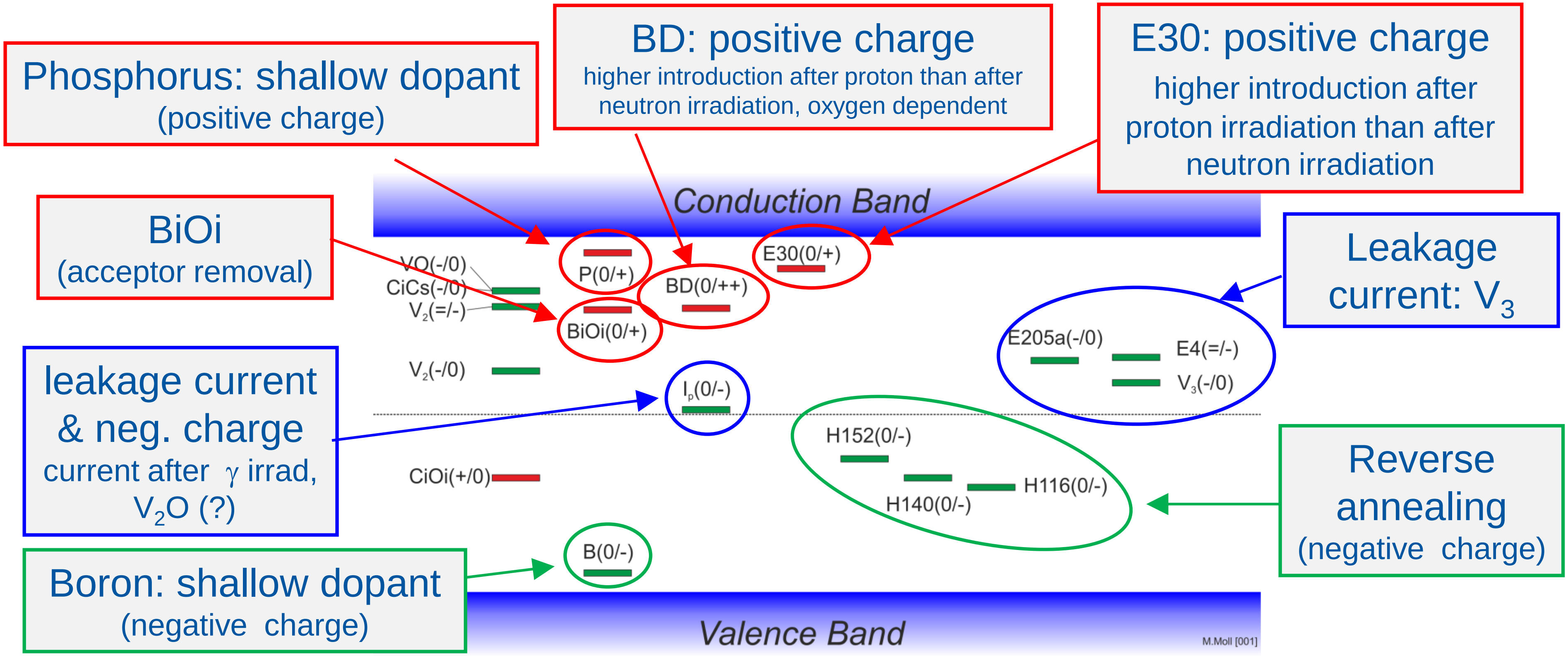
Collaboration Board Chair & Deputy: G.Kramberger (Ljubljana) & J.Vaitkus (Vilnius), Conference committee: U.Parzefall (Freiburg)
CERN contact: M.Moll (EP-DT), Secretary: V.Wedlake (EP-DT), Budget holder: M.Moll & M.Glaser (EP-DT) , EXSO: R.Costanzi (EP-DT)

Defect & Material Characterization

Recent results 2018/19

Radiation induced defects with impact on device performance

RD50 map of most relevant defects for device performance near room temperature:



Phosphorus: shallow dopant
(positive charge)

BD: positive charge
higher introduction after proton than after neutron irradiation, oxygen dependent

E30: positive charge
higher introduction after proton irradiation than after neutron irradiation

BiOi
(acceptor removal)

Leakage current: V_3

leakage current & neg. charge
current after γ irrad, V_2O (?)

Reverse annealing
(negative charge)

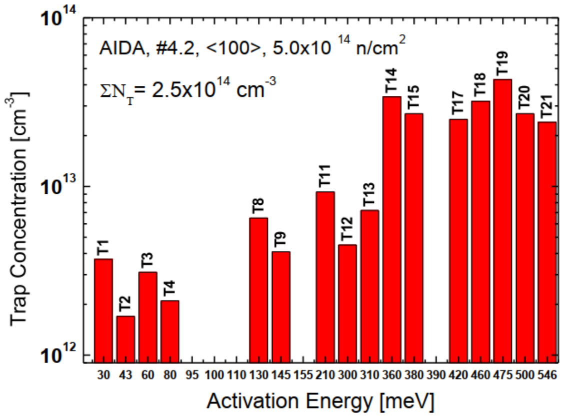
Boron: shallow dopant
(negative charge)

- Trapping: Indications that E205a and H152K are important (further work needed)
- Converging on consistent set of defects observed after p, π, n, γ and e irradiation.
- Defect introduction rates are depending on particle type and energy, and some on material!

Material Characterization

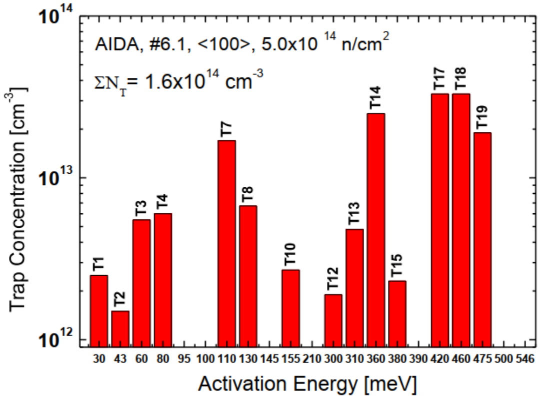
- Nitrogen-enriched FZ silicon wafers (NitroSil project)
  - N-enriched wafers [Topsil] showed after irradiation a lower trap density
  - Defect Characterization by HRPITS (wafer level technique):

[N] = 1.4 · 10^{15} cm^{-3}



[traps] = 2.5 · 10^{14} cm^{-3}

[N] = 2.0 · 10^{15} cm^{-3}



[traps] = 1.6 · 10^{14} cm^{-3}

Kaminski, RD50 workshop, Nov 2014

Radiation Hardening with Nitrogen ??

Vacancy Suppression

$$N_2 + V \rightleftharpoons N_2V$$

Interstitial Suppression

$$N_2V + I \rightleftharpoons N_2$$

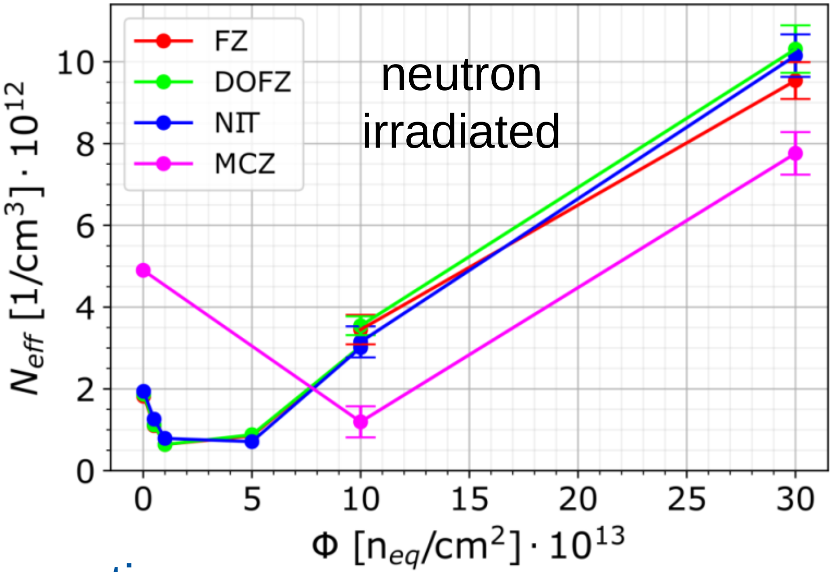
Assuming effect similar to “Watkins kick-out mechanism” for Carbon and Boron

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

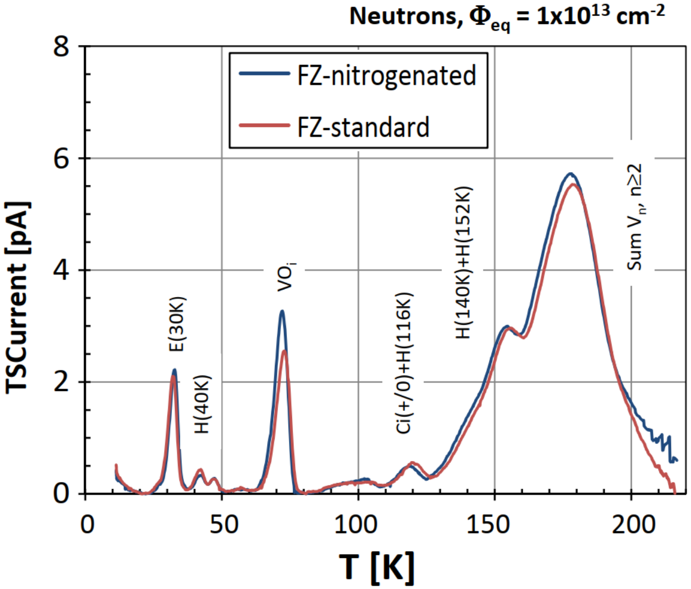
- RD50 NitroStrip project (2016-2019)
  - N-enriched wafers processed to Silicon Sensors (pad and segmented)
  - Irradiation (proton/neutron) and measurement (sensor/defects) campaigns

Nitrogen-enriched Silicon

- 24 wafers processed with strip and pad sensors
  - FZ, FZ+Nitrogen [NIT], FZ+Oxygen [DOFZ], Magnetic Czochralski [MCZ]
- Irradiations: Neutrons, Protons(23 MeV,23 GeV); Characterization: CV, IV, e-TCT, TCT, TSC



[J.C.Hönig et al. – RD50 Nov.2018]



[E.Fretwurst et al. – RD50 Nov.2018]

- Observation:
  - No difference between standard and Nitrogen-enriched sensors in effective doping, electric field structure, leakage current, charge collection and defect concentration!
- Repetition of material analyses:
  - SIMS measurements: [N] <10^{15}cm^{-3} while before processing it was [N]=2.4x10^{15}cm^{-3}
  - **Nitrogen is seemingly out-diffusing during the wafer processing!**

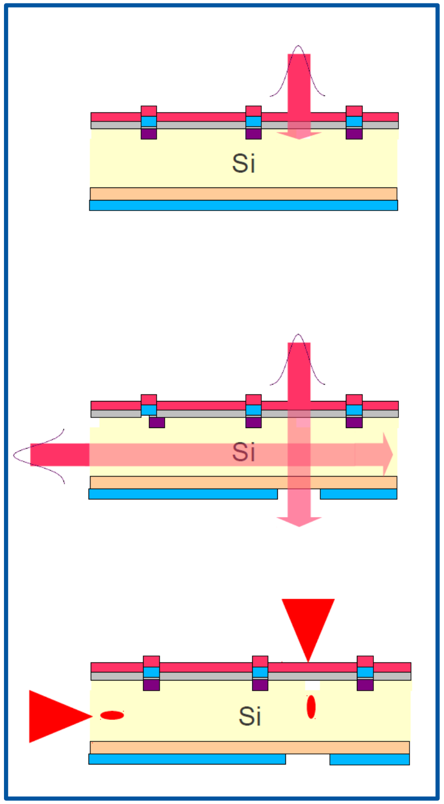
Detector Characterization

Recent results 2018/19

Transient Current Technique (TCT)

- Pulsed laser induced generation of charge carriers inside detector
  - Study of: electric field in sensor, charge collection efficiency, homogeneity,..
  - Benchmark simulation tools, measure physics parameters from mobility to impact ionization

- New TCT technology: TPA-TCT – Two Photon Absorption TCT



- **TCT (red laser)**
  - short penetration length (650nm = 1.9eV)
  - carriers deposited in a few μm from surface
  - front and back TCT: study electron and hole drift separately
  - 2D spatial resolution (5-10μm)

- **TCT (infrared laser)**
  - long penetration (1064nm = 1.17 eV)
  - similar to MIPs (though different dE/dx)
  - top and edge-TCT
  - 2D spatial resolution (5-10μm)

- **TPA-TCT (far infrared)**
  - No single photon absorption in silicon
  - 2 photons produce one electron-hole pair
  - Point-like energy deposition in focal point
  - **3D** spatial resolution (1 x 1 x 10 μm^3)

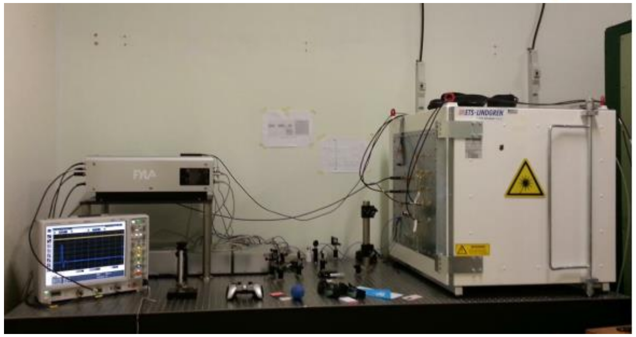
edge-TCT: 2010

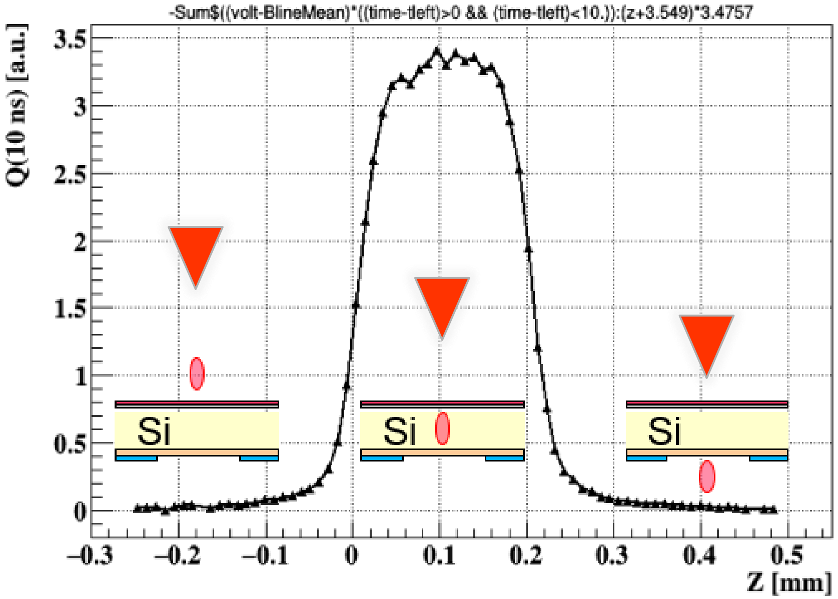
TCT commercialized: 2013

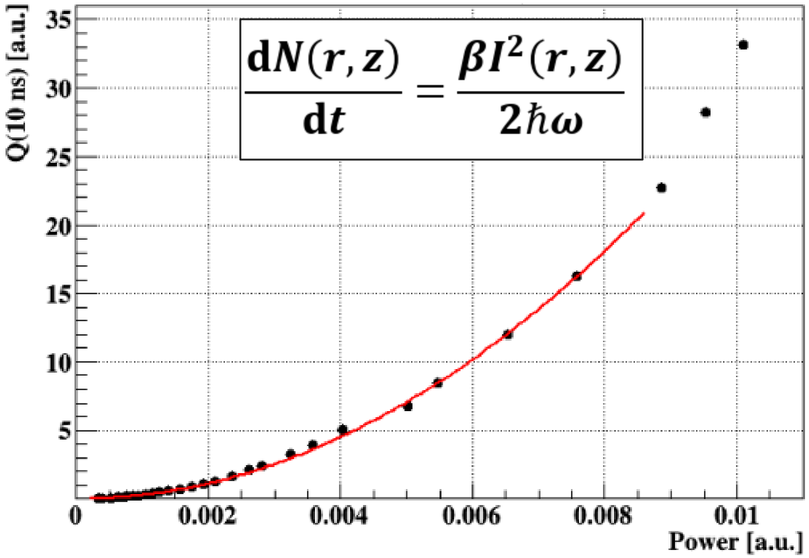
TPA-TCT: Proof of concept presented by RD50 in 2015

Table-top TPA-TCT system

- Seed funding: CERN KT-Fund grant
  - Development of a customized fiber-laser (1550nm, 60fs) with external company
  - Laser operational at CERN since August 2019
  - Proof of concept achieved:







$$\frac{dN(r,z)}{dt} = \frac{\beta I^2(r,z)}{2\hbar\omega}$$

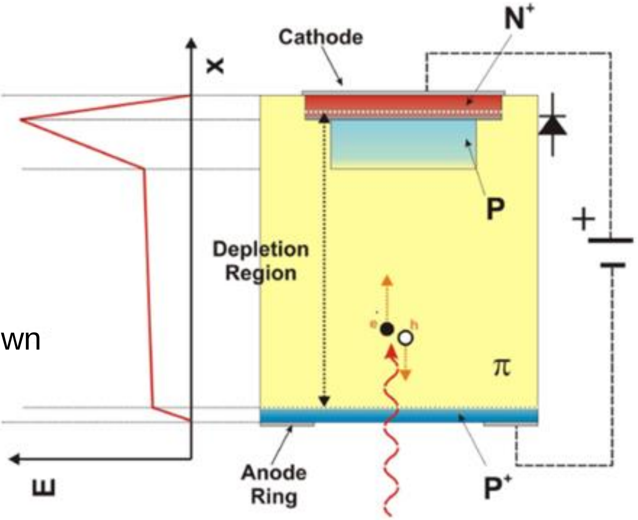
- Control and DAQ software under development
- System development ongoing (mechanics, automation, cooling, …)

New Structures

Recent results 2018/19

LGAD: Low Gain Avalanche Detectors

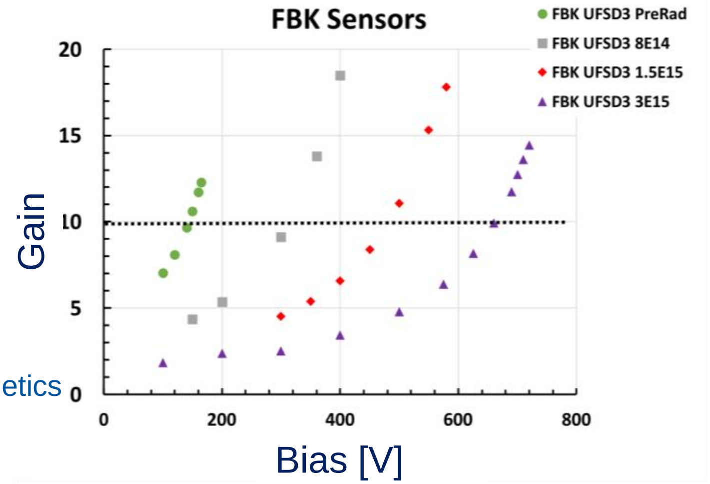
- **Origin:** Pioneered by RD50 with CNM,Barcelona (and later also FBK,Trento)
  - RD50 working on LGADs since ≈2010 (≈ 50 production runs)
- **Application:** LGAD for timing detectors
  - Intrinsic gain of devices allows for excellent timing performance (<50ps)
  - Time-tagging of particle tracks in order to mitigate pile-up effects
  - To be implemented in ETL(CMS) and HGTD(ATLAS)
- **Concept:** similar to APD but lower gain O(10)
  - Impact ionization in p^+-implant (multiplication layer) produces gain
  - Tailored multiplication layer ([B]~10^{17}cm^{-3}); challenge: optimize gain vs. breakdown
- **Foundries:**
  - CNM (Barcelona, ES), FBK(Trento,IT), HPK (Japan), IHEP(Bijing, China), Micron(UK), BNL(USA) and soon CIS(Erfurt, Germany)



- **Areas of LGAD developments within RD50**

$$\sigma_{\text{jitter}}{}^{2} = \frac{Noise}{\mathrm{d}V/\mathrm{d}t} \approx \frac{t_{\text{rise}}}{S/N}$$

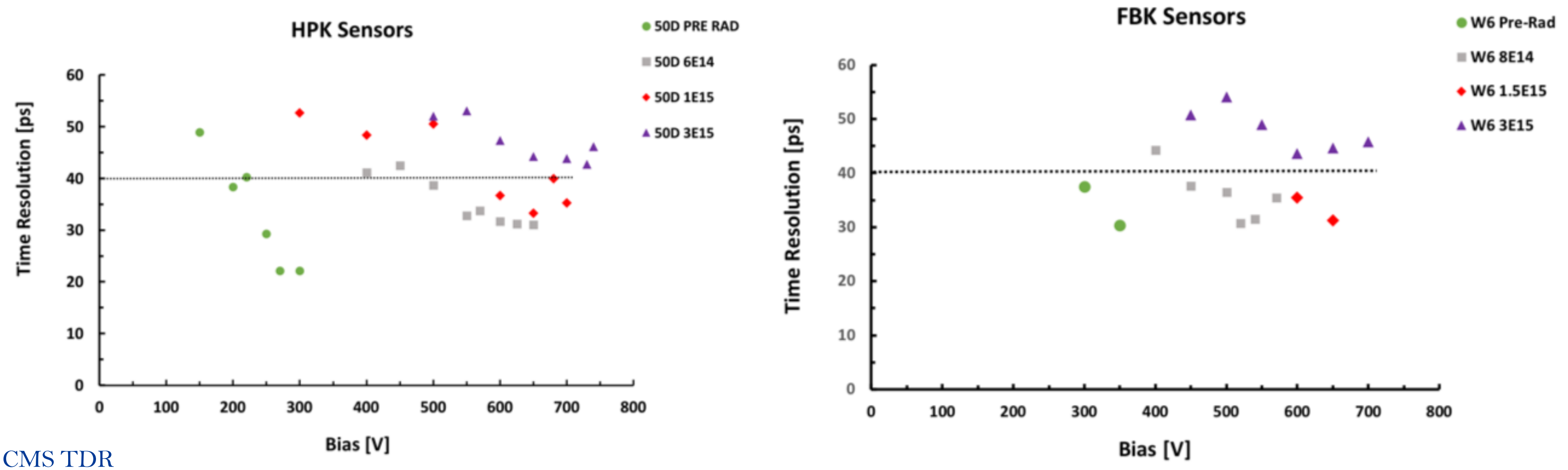
  - **Timing performance**
    - Optimization: sensor thickness, gain layer profile and signal homogeneity
  - **Fill factor and signal homogeneity**
    - Gain layer needs protection against breakdown (JTE) causing non-efficient area
    - Mitigation: New and optimized LGAD concepts investigated
  - **Radiation Hardness:**
    - Problem: Field in gain layer dropping due to "acceptor removal"
      - Defect Engineering of the gain layer
        - Use Gallium instead of Boron or Carbon co-implant to impact on defect kinetics
      - Modification of gain layer profile



LGAD: Time resolution

- Example: Studies for the CMS Endcap Timing Layer (ETL)
  - Time resolution for both sensor families shown (HPK and FBK) remains in the interval σ_t = 30–40 ps throughout the HL-LHC lifetime of the ETL detector
  - A moderate degradation to σ_t = 40–50 ps at a fluence of 3×10^{15} n_{eq}/cm^2 is observed, which is beyond the maximum ETL fluence (with safety factor).

LGAD σ_t versus voltage for different fluences



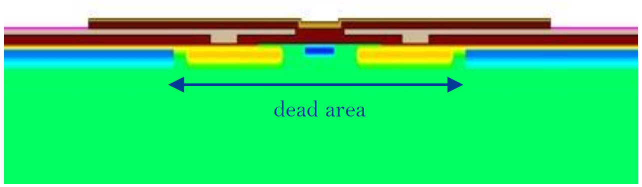
CMS TDR

- RD50 is collaborating closely with ATLAS (HGTD) and CMS (ETL) in the LGAD development

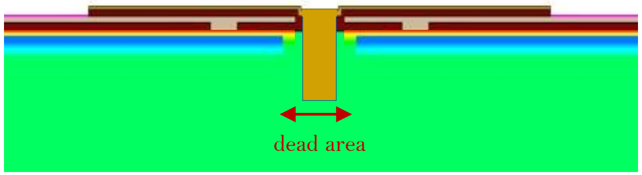
LGAD: Fill factor improvements

- Two opposing requirements:
  - To have a good timing reconstruction the signal must be homogeneous, i.e. no dead areas and homogeneous weighting field
  - A pixel-border termination is necessary to host all structures controlling the electric field
- Several new approaches to optimize/mitigate followed:

Trench Isolation

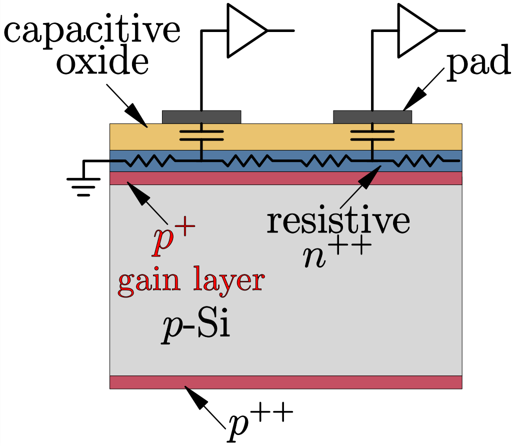


traditional gain isolation



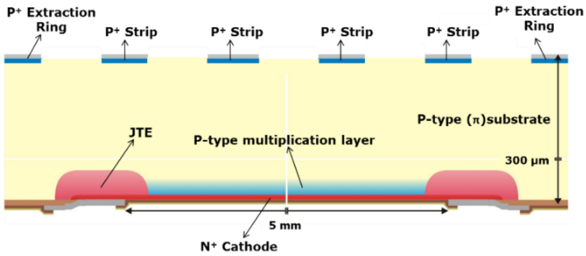
trenches isolation (HD-LGAD)

AC-LGAD



Invers LGAD

Front: segmented readout



Back: gain layer

- All above concepts simulated, designed, produced and tested in 2018/19
- Full qualification, irradiations and timing performance tests ongoing

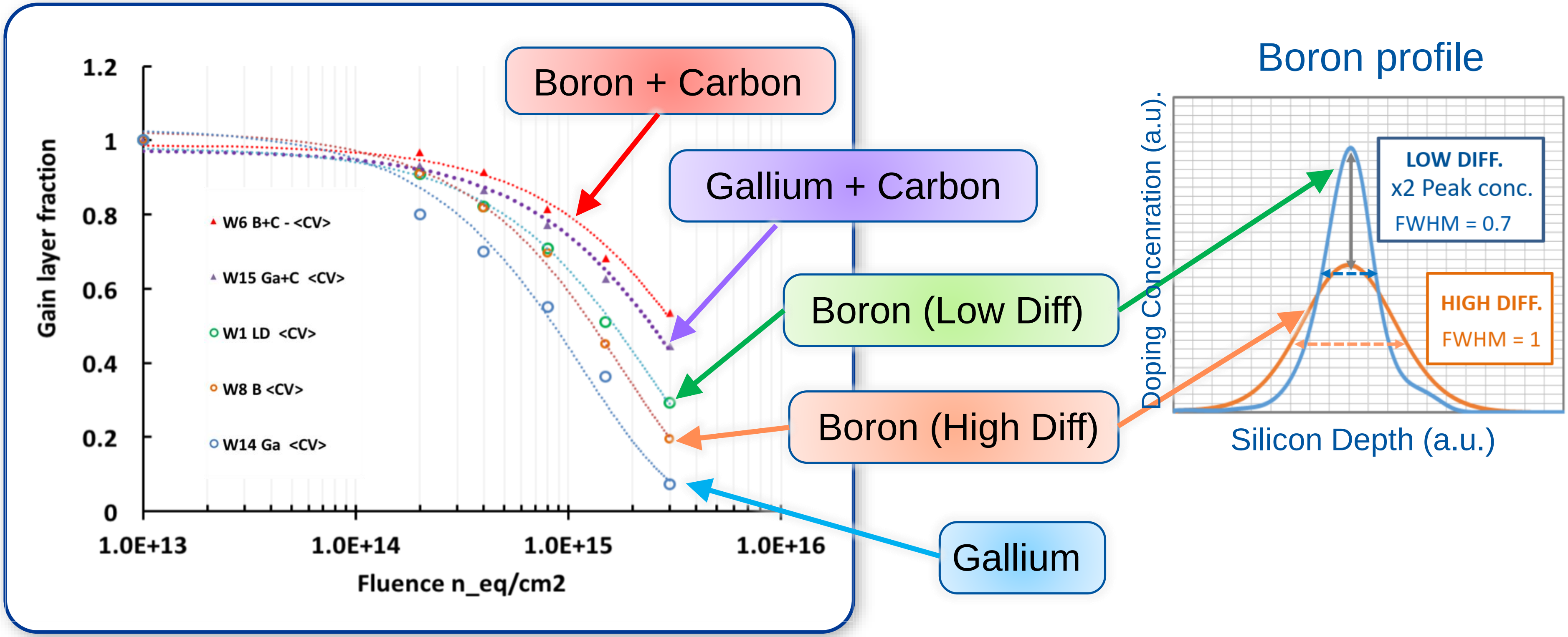
LGAD: Gain layer engineering

Defect Engineering of the gain layer

- **Carbon** co-implantation mitigates the gain loss after irradiation
- Replacing Boron by **Gallium** did not improve the radiation hardness

Modification of the gain layer profile

- Narrower **Boron doping profiles** with high concentration peak (Low Thermal Diffusion) are less prone to be inactivated



Boron + Carbon

Gallium + Carbon

Boron (Low Diff)

Boron (High Diff)

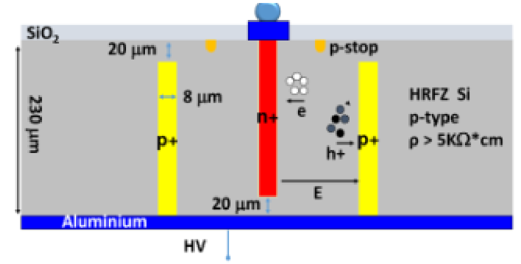
Gallium

Boron profile

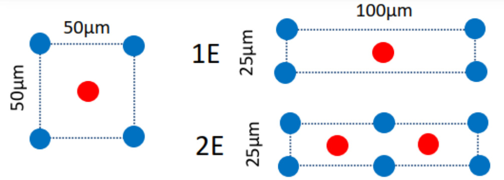
[G.Paternoster, FBK, Trento, Feb.2019]

3D sensors for ATLAS/CMS

- RD50 contributes to the 3D sensor developments for HL-LHC
  - Evaluation of different column geometries for the RD53 ASIC
    - 25x100 µm (2E) production has yield problems; production using a stepper instead of full wafer mask under way
  - Radiation Hardness evaluation in test beams at CERN
    - ATLAS and CMS testbeams on 150 µm double sided and single sided 3D sensors with different column geometries and irradiated to fluences of up to 1e16 n_{eq}/cm^2 demonstrated hit efficiencies > 97 % in normal incidence (>98% under 15º).



Double sided 3D sensor

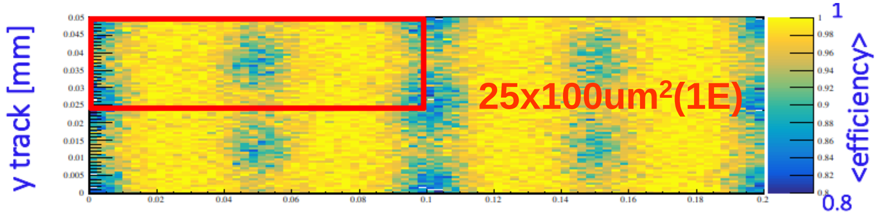


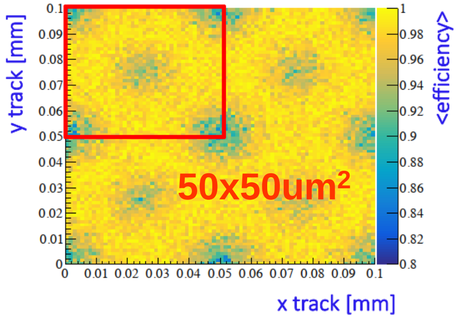
RD53 compatible column geometries

CMS

$1e16 n_{eq}/cm^2$ Efficiency 96.6%

Normal incidence. V = 124V. T = -36ºC





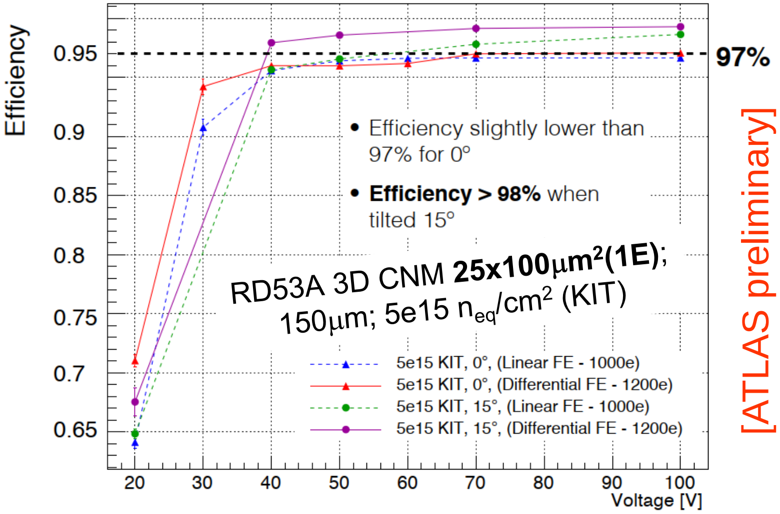
Efficiency 97.5%

Normal incidence.

V=150V. T = -35°C

[A.Garcia Alonso et al. – RD50 Nov.2018]

ATLAS



- Efficiency slightly lower than 97% for 0°
- **Efficiency > 98%** when tilted 15°

RD53A 3D CNM **25x100µm²(1E)**; 150µm; 5e15 n_{eq}/cm^2 (KIT)

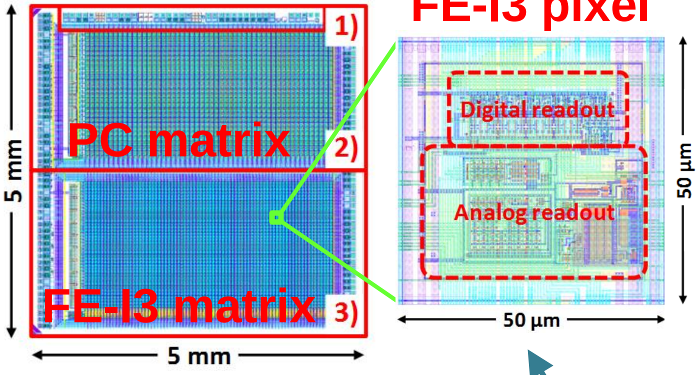
[ATLAS preliminary]

[Giulia Giannini et al. – RD50 Nov.2018]

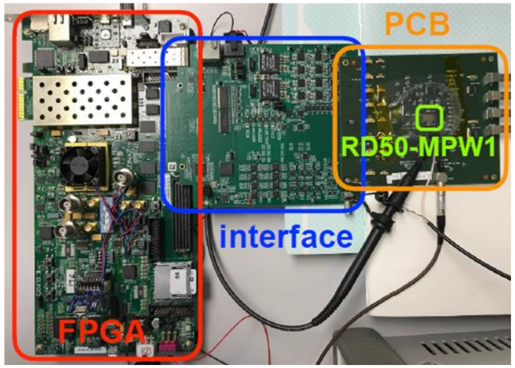
CMOS

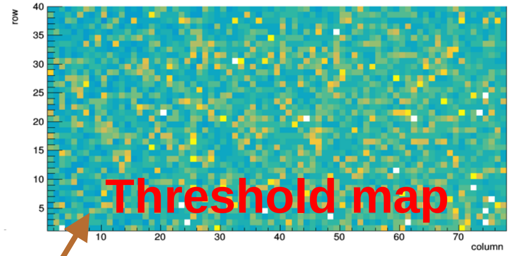
RD50-MPW1

FE-I3 pixel

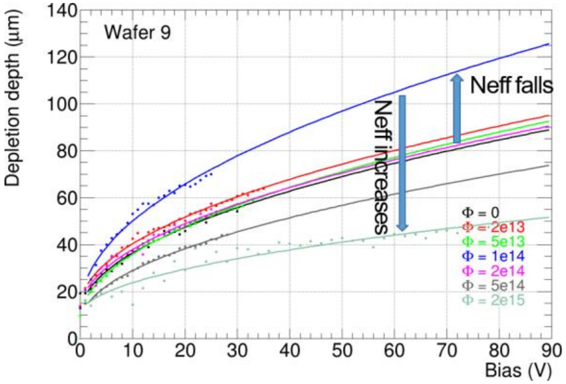


RD50 DAQ (Caribou)

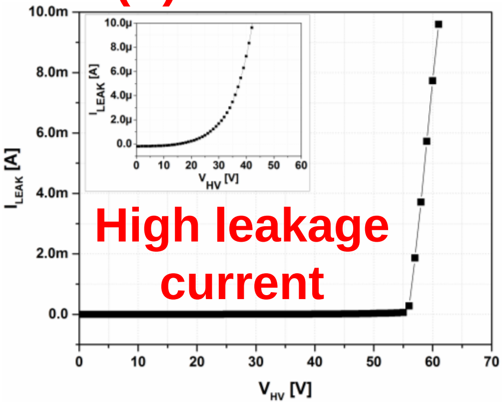




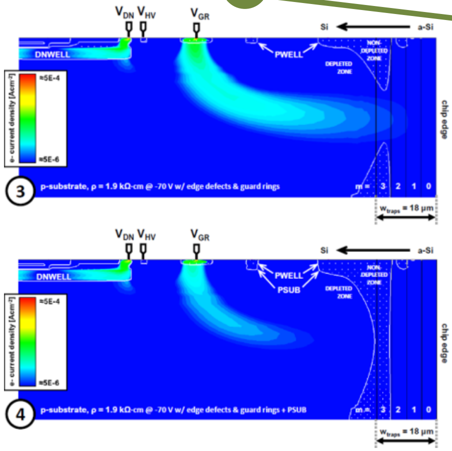
eTCT measurements



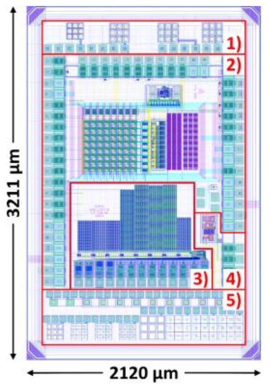
I(V) RD50-MPW1



TCAD simulations (to develop methodologies to reduce leakage current)



RD50-MPW2



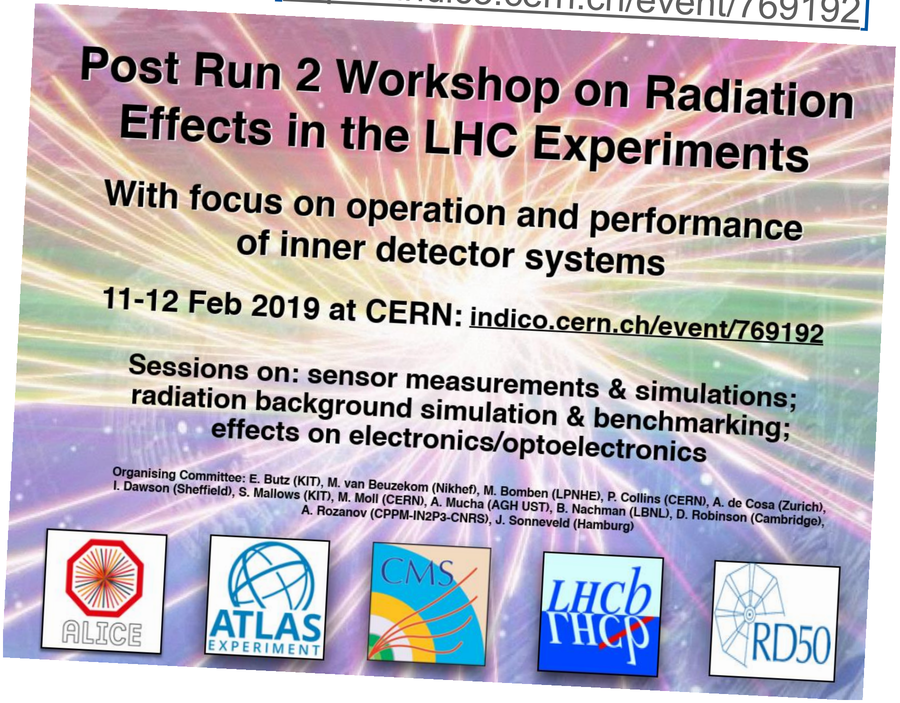
Full Detector Systems

Recent results 2018/19

Radiation Effects in LHC Experiments

- 5th Workshop on Radiation Effects at LHC Experiments and Impact on Operation and Performance [CERN, 11-12 February 2019]
  - Common Workshop: (ALICE), ATLAS, CMS, LHCb, RD50
    - Sensor Measurements
    - Electronics/Optoelectronics
    - Radiation Simulation and Monitoring
    - Sensor Simulation

[https://indico.cern.ch/event/769192]



Post Run 2 Workshop on Radiation Effects in the LHC Experiments

With focus on operation and performance of inner detector systems

11-12 Feb 2019 at CERN: indico.cern.ch/event/769192

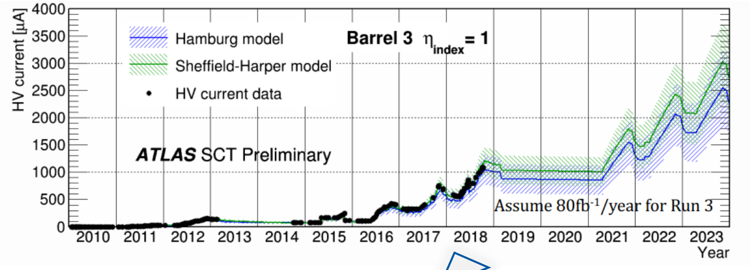
Sessions on: sensor measurements & simulations; radiation background simulation & benchmarking; effects on electronics/optoelectronics

Organising Committee: E. Butz (KIT), M. van Beuzekom (Nikhef), M. Bomben (LPNHE), P. Collins (CERN), A. de Cosa (Zurich), I. Dawson (Sheffield), S. Mallows (KIT), M. Moll (CERN), A. Mucha (AGH UST), B. Nachman (LBNL), D. Robinson (Cambridge), A. Rozanov (CPPM-IN2P3-CNRS), J. Sonneveld (Hamburg)

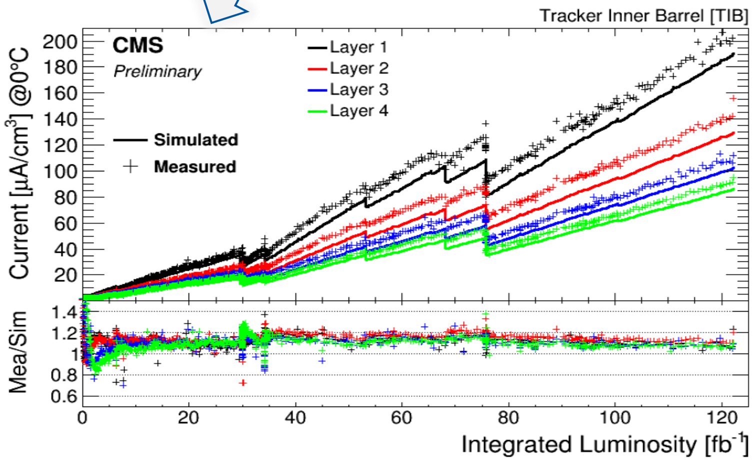
- Workshop statistics (Feb 2019/ April 2018):
  - 108/124 participants
  - 30/32 talks and discussion sessions
- Outcome and follow-up:
  - Generally good agreement between damage predictions by RD50 models ("Hamburg model") and radiation damage observed by the experiments
  - Coherent approach in data analyses agreed
  - Modelling will have to be refined in some areas for run 3
  - Report under preparation to summarize observations, compare results of different experiments against each other, list open questions and outline further work

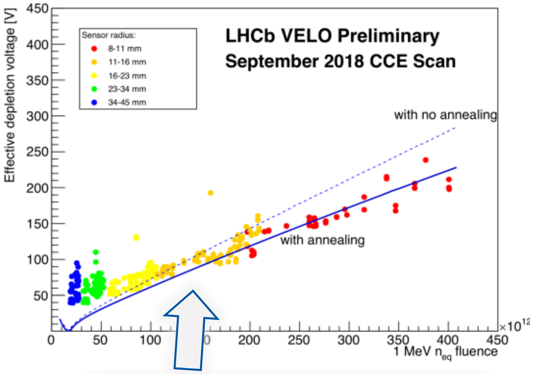
Radiation Effects in LHC Experiments

- Workshop on radiation effects in LHC Experiments (Feb.2019)

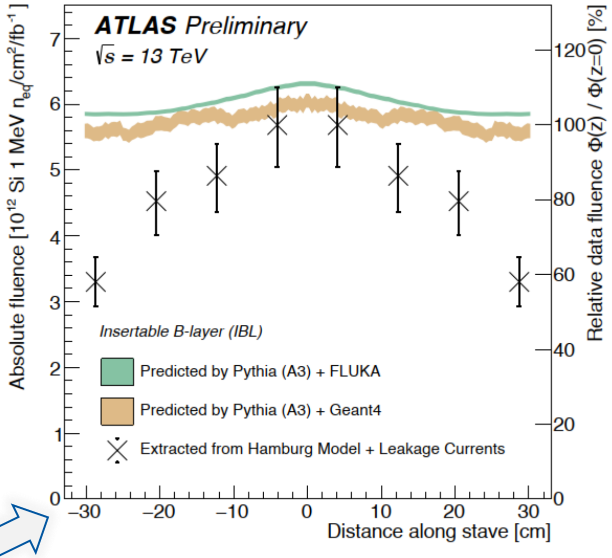


Leakage currents in **ATLAS SCT** and **CMS tracker** and model predictions



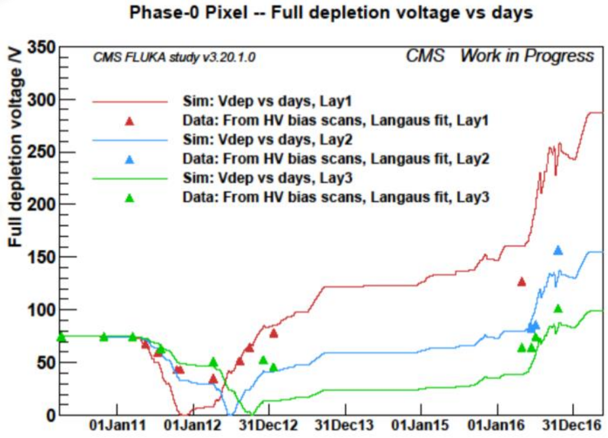


LHCb Velo depletion voltage reduced by annealing; according to model



ATLAS B-layer data vs. MC&NIEL strong z-dependence; unexpected

CMS pixel layers; deviation of V_{dep} from modelling at high fluences



Plots: Radiation Effects Workshop Feb.2019 https://indico.cern.ch/event/769192
K.Mochizuki(ATLAS SCT) J.L.Agram (CMS Tracker), Aiden Grummer (ATLAS Pixel) ,
G.Sarpis (LHCb Velo) , F.Feindt (ATLAS Pixel)

RD50 – 5 Year Work Plan

- **5 year work program submitted in May 2018**
  - Approved by CERN Research Board in June 2018
- **Workplan [70 milestones]**
  - **Defect and Material Characterization [16 MS]**
    - p-type silicon [7 MS]
    - Cluster defects [4 MS]
    - Theory of defects [5 MS]
  - **Device Characterization & Device Simulation [21MS]**
    - Silicon materials [5 MS]
    - Extreme fluences [5 MS]
    - Experimental techniques [3 MS]
    - Surface damage [1 MS]
    - TCAD simulations [7 MS]
  - **New structures [21 MS]**
    - 3D sensors [6 MS] ; LGAD [4 MS]
    - CMOS [6 MS] ; New Materials [5 MS]
  - **Full Detector Systems [12 MS]**
    - LHC [7 MS]; HL-LHC [3 MS]
    - FCC [2 MS]

RD50 Prolongation Request: May 2018

CERN, 31 May 2018

CERN-LHCC-2018-017 / LHCC-SR-007
31/05/2018

RD50 Prolongation Request

– May 2018 –

The RD50 Collaboration

Abstract

With this document, we request the prolongation of the CERN RD50 research program for 5 years. A very brief historical review of the RD50 research program since the RD50 project approval by the Research Board in the year 2002 is presented and the biggest RD50 achievements are highlighted. The present composition of the collaboration, its organizational structure, and the research methodology are described. The role of RD50 in the present various upgrade and research programs of the LHC Experiments community is given and the overall work plan explained. Finally, a detailed 5-years work program with precise milestones and deliverables for the various research activities is presented. We conclude with our prolongation request towards the LHCC.

https://cds.cern.ch/record/2320882/files/LHCC-SR-007.pdf

Outlook & Request to LHCC

- RD50 outlook:
  - Roadmap given in 5 Year Workplan (2018-2023) https://cds.cern.ch/record/2320882
  - Milestone status discussed in depth with LHCC referee on 2.9.2019
- RD50 MOU
  - New “Memorandum of Understanding”: signed by CERN Research DG in May 2019
- Resources:
  - Every RD50 institution is contributing 2kCHF/year to the RD50 common fund (CF).
  - The CF is used to finance common projects and to support common activities.
  - "RD50 common projects" receive a financial contribution from the CF within rules defined in the MOU. Remaining costs are shared between the institutions participating in the project.
  - Most RD50 projects are performed as in-kind contributions supported by other funding (national funding agencies, successful competitive funding proposals,….).
  - RD50 is planning to continue this funding concept.
- Resources from CERN (Host lab) (as previous years)
  - Access to EP-DT facilities: Irradiation facilities, Bond Lab, Solid State Detector Lab,…
  - Administrative support at CERN through EP-DT secretariat
- Acknowledgement:
  - The CERN RD50 team is supported through the EP Department and looking forward to participate in the CERN EP R&D program for future experiments.

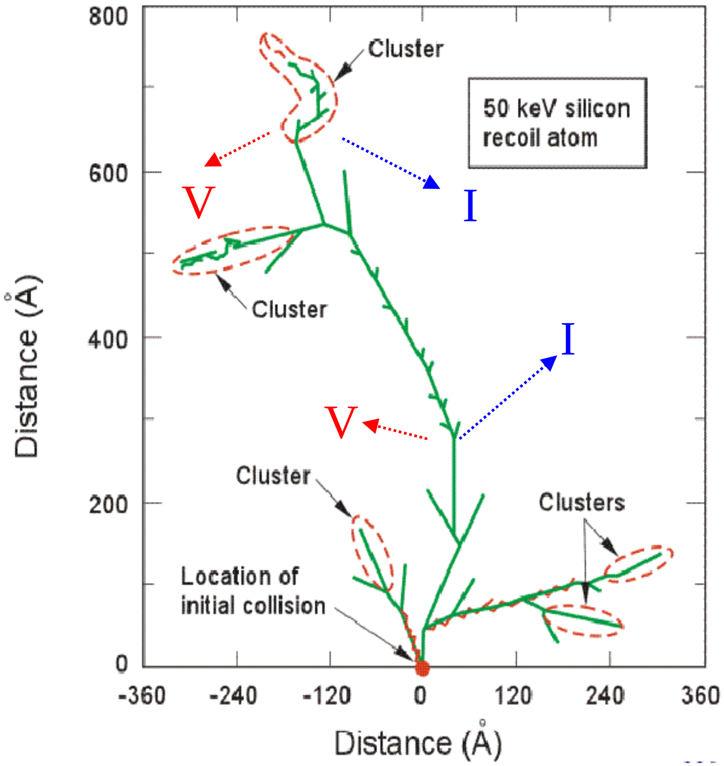
Spare Slides

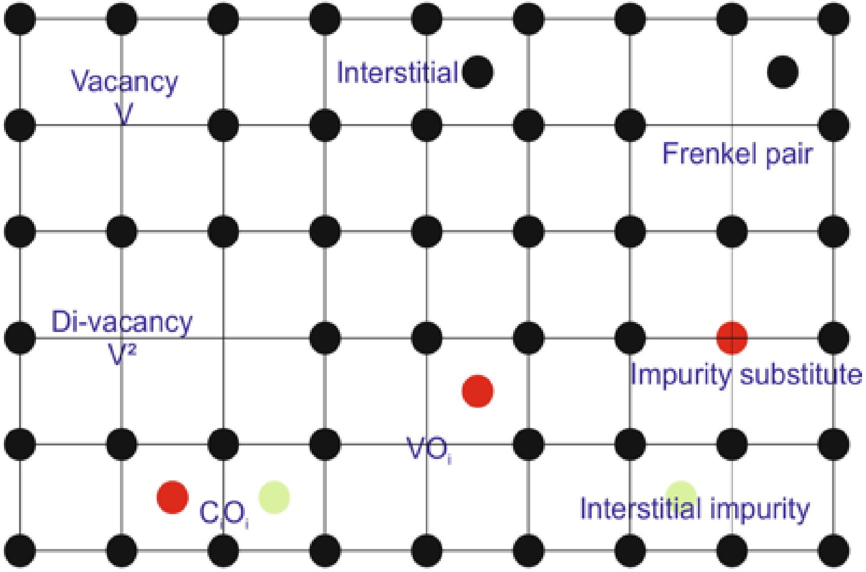
Recent results 2018/19

Displacement Damage

- Mechanism:
  - Primary interaction generates displacements (vacancies & interstitials)
  - **Vacancies** and **Interstitials** migrate, either recombine (~90%) or migrate and form stable defects (point and cluster defects)

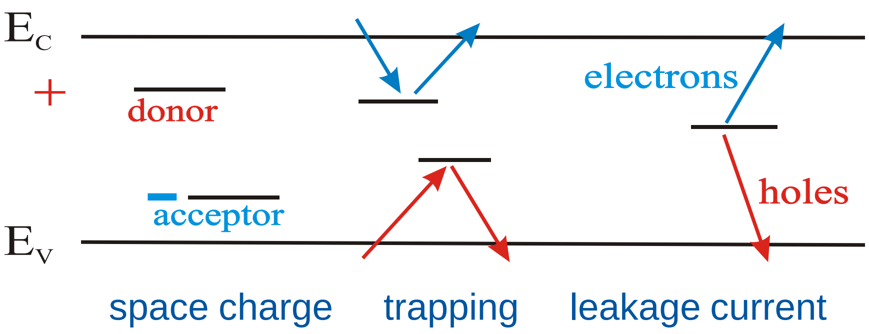
van Lint 1980





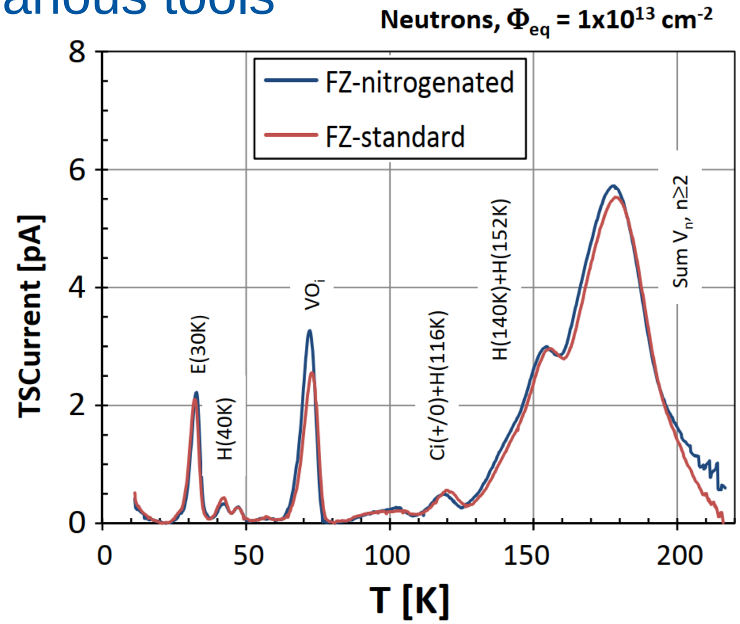
Defect Characterization

- Aim of defect studies:
  - Identify defects responsible for Change of N_{eff}, Change of E-Field, Trapping, Leakage Current
  - Understand if knowledge can be used to mitigate radiation damage (e.g. defect engineering)
  - Deliver input for device simulations to predict detector performance under various conditions



- Method: Defect Analysis performed with various tools
  - **DLTS** (Deep Level Transient Spectroscopy)
  - **TSC** (Thermally Stimulated Currents)
  - **PITS** (Photo Induced Transient Spectroscopy)
  - **FTIR** (Fourier Transform Infrared Spectroscopy)
  - **EPR** (Electron Paramagnetic Resonance)
  - **TCT** (Transient Current Technique)
  - **CV/IV** (Capacitance/Current-Voltage Measurement)
  - **MW-PC** (Microwave Probed Photo Conductivity)
  - **PC, RL, I-DLTS, TEM,… and simulations**

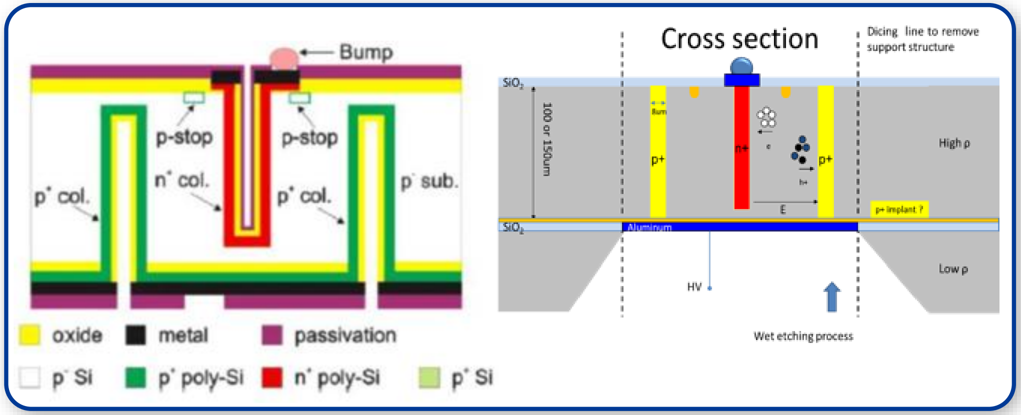
  - RD50: several hundred samples irradiated with protons, neutrons, electrons and ^{60}Co-γ



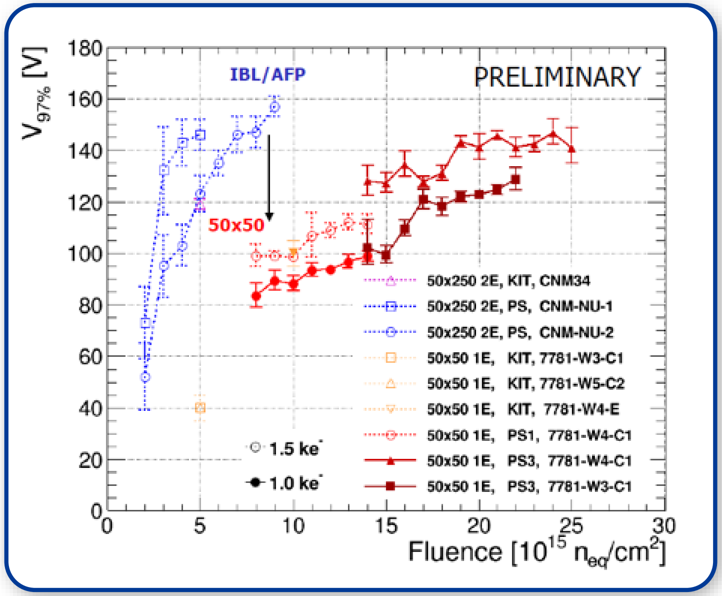
[E.Fretwurst et al. – RD50 Nov.2018]

3D sensors

- Complicated fabrication: double- or single-sided process
- Efficient even after $3{\cdot}10^{16}\ n_{eq}\ /cm^2$



3D $V_{97\%}$ versus fluence

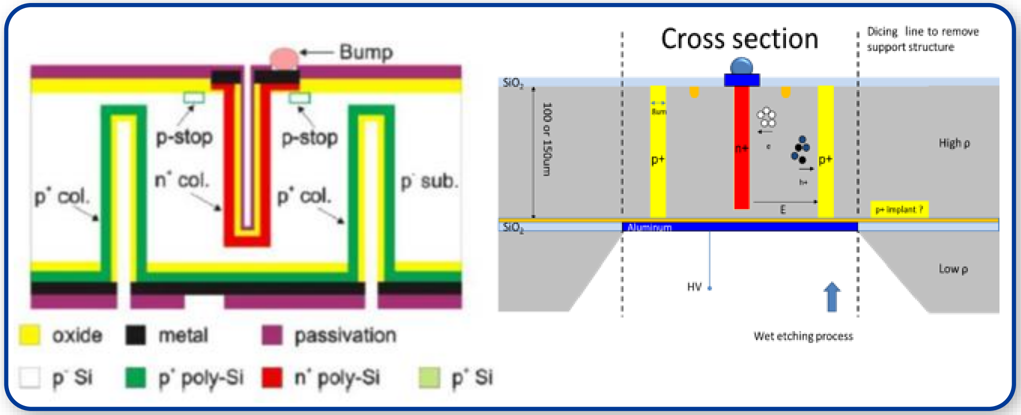


J. Lange, RD50 workshop, Nov 2017

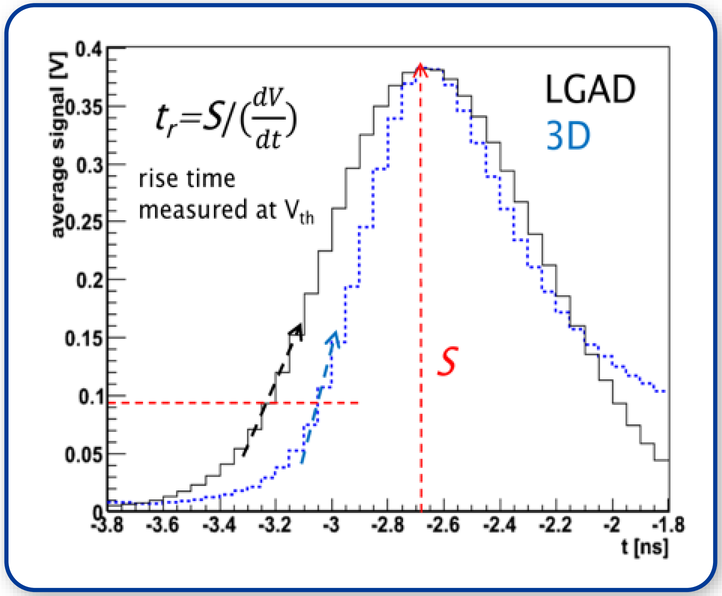
3D sensors

- Complicated fabrication: double- or single-sided process
- Efficient even after $3{\cdot}10^{16}\ n_{eq}\ /\mathrm{cm}^2$
- Very good timing performances: $\sigma_t \sim 30$ ps* ($V > 100$ V, $T = -20$°C)

*see G. Kramberger presentation at TREDI workshop 2019



3D / LGAD signals

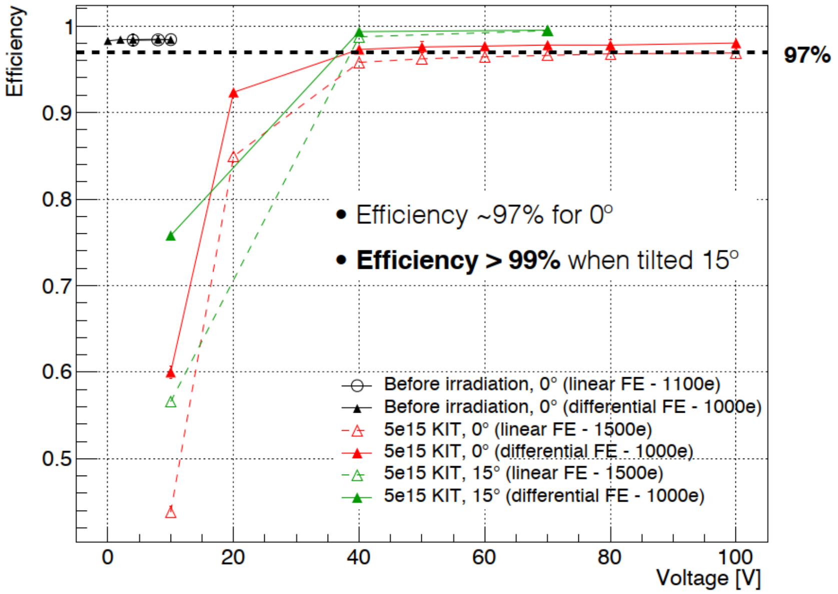


G. Kramberger, RD50 workshop, Nov 2018

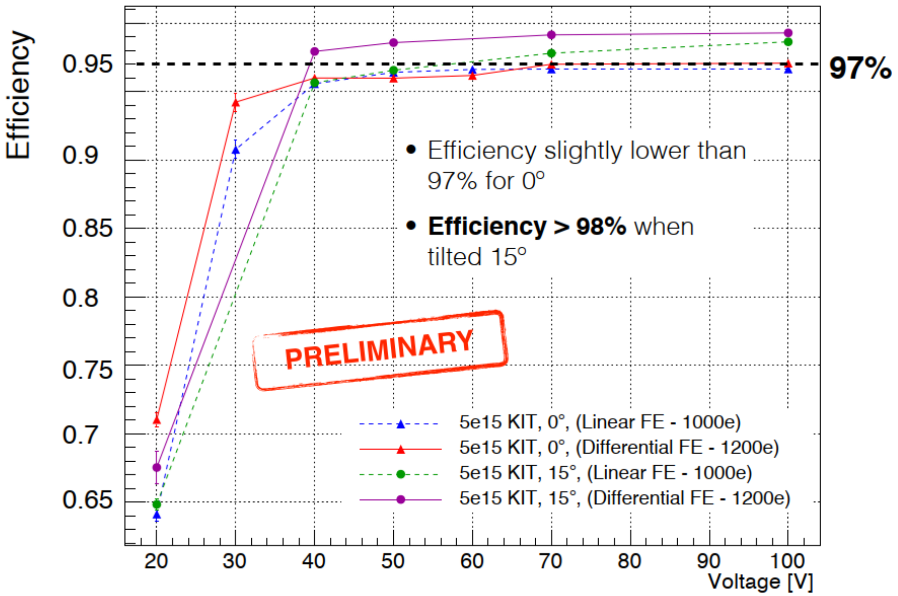
3D sensors for ATLAS/CMS

- Test beam at CERN (**ATLAS**,RD50,AIDA)
  - 3D detectors (150um) show outstanding radiation tolerance of all the different cell layouts
  - Hit efficiencies after qualification fluence of 5E15n_{eq}/cm^2 (protons, KIT)
    - 97% at 0º; 99% at 15º (>50V) for the 50x50 μm electrode
    - 97% at 0º; 98% at 15º (>70V) for the and for 25x100 μm electrode

RD53A 3D CNM **50x50μm^2**; 150μm; 5e15 n_{eq}/cm^2 (KIT)



RD53A 3D CNM **25x100μm^2(1E)**; 150μm; 5e15 n_{eq}/cm^2 (KIT)

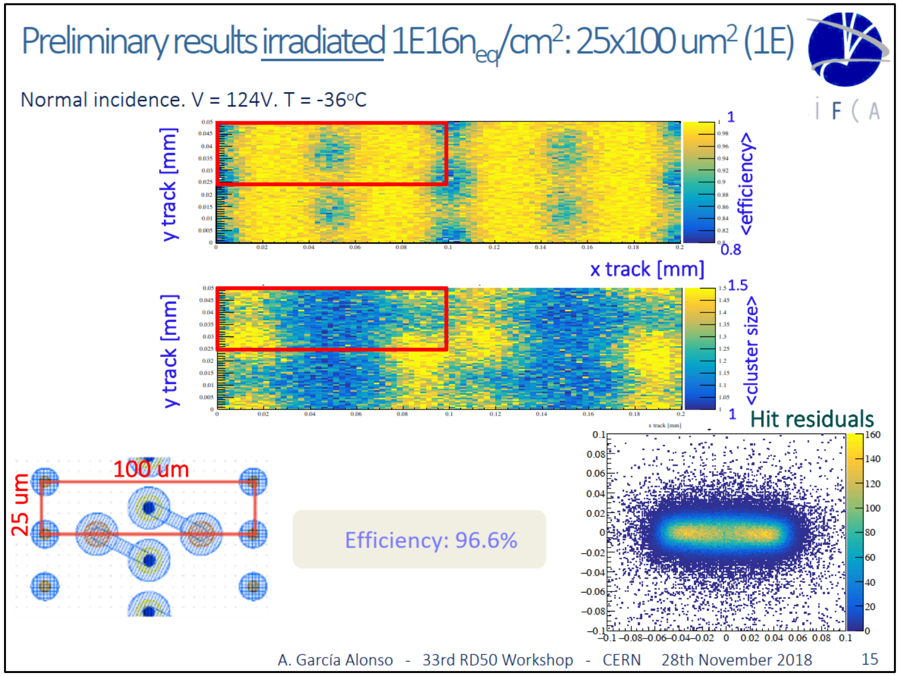


[Giulia Giannini et al. – RD50 Nov.2018]

3D sensors for ATLAS/CMS

- Test beam at CERN (CMS,RD50,AIDA,RD53)

Conclusion: 3D detectors show outstanding radiation tolerance of all the different cell layouts at 1E16n$_{eq}$/cm^2. Hit efficiency is 96,6% at 0º and 124V bias voltage for the 25x100 (1E) electrode and 97.5% at 0º and 150V after qualification fluence of 1E16n$_{eq}$/cm^2.



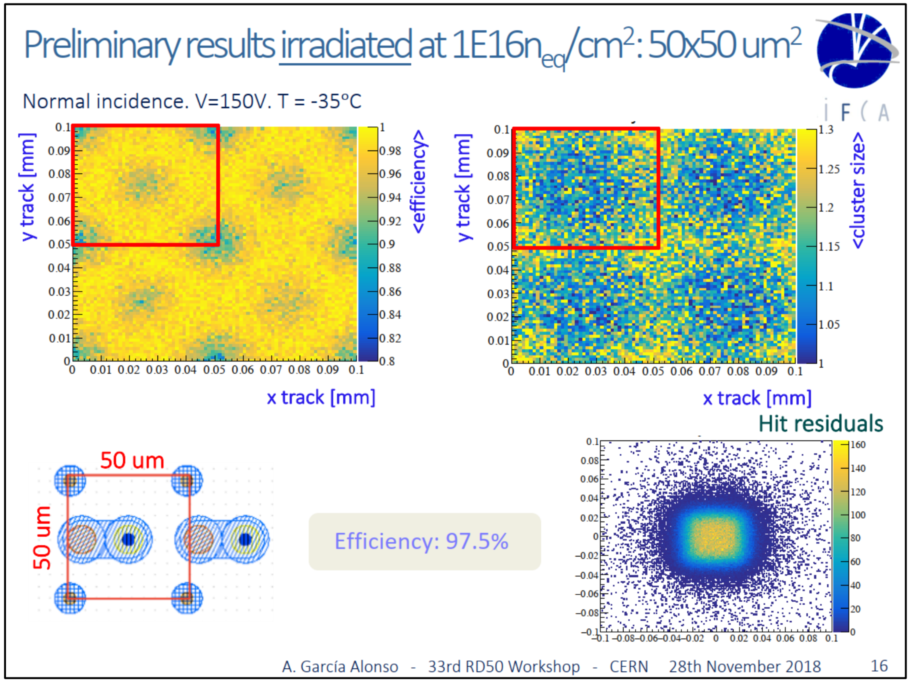
Preliminary results irradiated 1E16n$_{eq}$/cm^2: 25x100 um^2 (1E)

Normal incidence. V = 124V. T = -36ºC

Efficiency: 96.6%

Hit residuals

A. García Alonso - 33rd RD50 Workshop - CERN 28th November 2018 15



Preliminary results irradiated at 1E16n$_{eq}$/cm^2: 50x50 um^2

Normal incidence. V=150V. T = -35ºC

Efficiency: 97.5%

Hit residuals

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