13th Terascale Detector Workshop
6-8 April 2021, Virtual at DESY

Recent results of the RD50 Collaboration

Radiation hard semiconductor devices for very high luminosity colliders

Michael Moll, CERN on behalf of RD50

Outline:

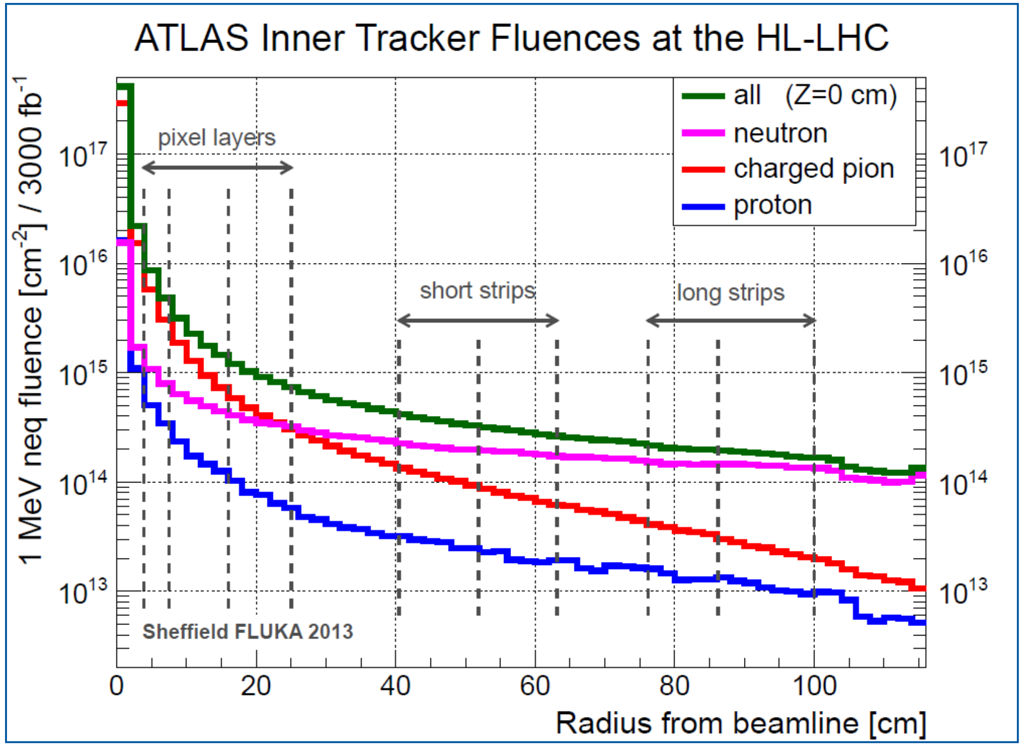
- RD50 Collaboration
- Scientific results 2020/21 (highlights)
  - Defect and Material Characterization
  - Detector Characterization
  - New Detector Structures
  - Full Detector Systems
- Summary and Outlook

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 (~2025-27);
    - 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**
  - ..also FCC-ee



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

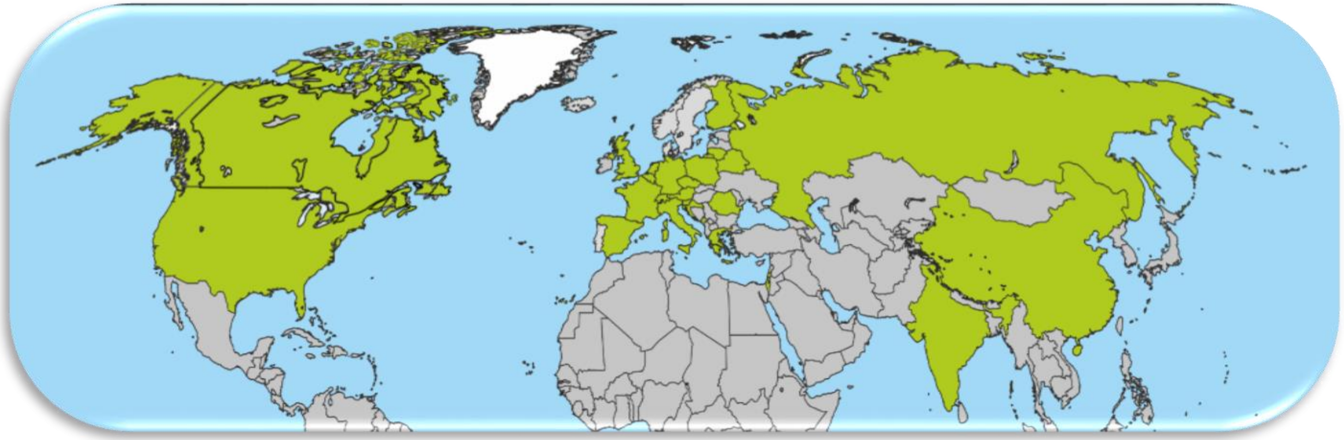
- **Increasing radiation levels**
  - Semiconductor detectors will face >10^{16} n_{eq}/cm^2 (HL-LHC) and >$7x10^{17}$ n_{eq}/cm^2 (FCC-hh)
    → detectors used at LHC cannot be operated after such irradiation
- **New requirement and new detector technologies**
  - New requirements or opportunities lead to new technologies (e.g. HV-CMOS, LGAD,…) which need to be evaluated and optimized in terms of radiation hardness

The RD50 Collaboration

- RD50: 64 *institutes and 410 members*

51 European institutes

Austria (HEPHY), **Belarus** (Minsk), **Czech Republic** (Prague (3x)), **Finland** (Helsinki, Lappeenranta), **France** (Marseille, Paris, Orsay), **Germany** (Bonn, Dortmund, Freiburg, Göttingen, Hamburg (Uni & DESY), Karlsruhe, Munich (MPI & MPG HLL)), **Greece** (Demokritos), **Italy** (Bari, Perugia, Pisa, Trento, Torino), **Croatia** (Zagreb), **Lithuania** (Vilnius), **Montenegro** (Montenegro), **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)



Full member list: www.cern.ch/rd50

8 North-American institutes

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

1 Middle East institute

Israel (Tel Aviv)

4 Asian institutes

China (Beijing-IHEP, Hefei, Jilin), **India** (Delhi)

Organizational Structure / Work Program

Covering all fields of semiconductor detectors exposed to radiation

Co-Spokespersons

Gianluigi Casse (Liverpool University, UK & FBK-CMM, Trento, Italy) and *Michael Moll* (CERN EP-DT)

Targeting new detector technologies including high precision 4D detectors

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/GaN 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
- Very high radiation fluences
- 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)

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 (Caribou,Alibava)
- Comparison:
  - pad-mini-full detectors
  - different producers
- Radiation Damage in HEP detectors
- Timing detectors
- Test beams (M.Bomben & G.Casse)

RD50 work program and key achievements documented in a 5yrs work plan 2018-23 (70 milestones)

[LHCC-SR-007]

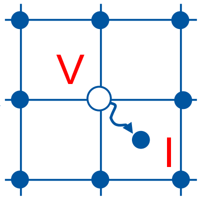
Collaboration Board Chair & Deputy: G.Kramberger (Ljubljana) & J.Vaitkus (Vilnius), Conference committee: U.Parzefall (Freiburg)
CERN contact: M.Moll (EP-DT), Secretary: V.Wedlake (EP-DT), Budget holder: M.Moll & M.Glaser (EP-DT) , EXSO: R.Costanzi (EP-DT)

Defect & Material Characterization

Recent results 2019/21

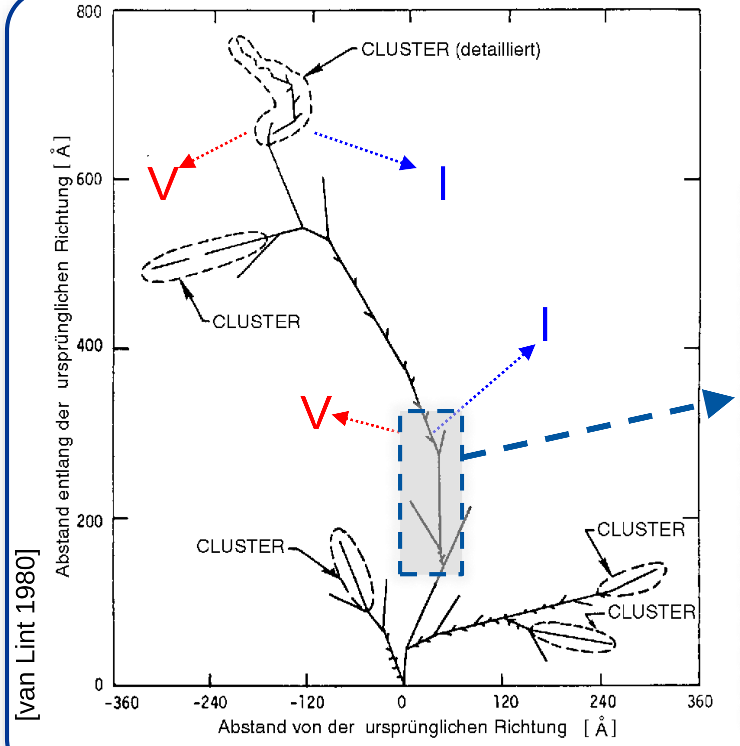
Displacement Damage

particle → Si_S → E_K>25 eV →



Vacancy
+
Interstitial → ..... *a wide range of* ***point defects***

E_K>5 keV → *point defects and clusters of defects*

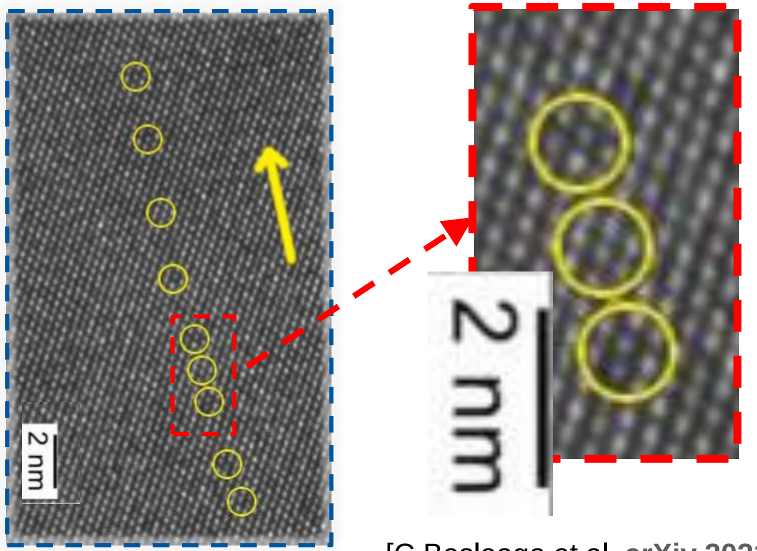


[van Lint 1980]

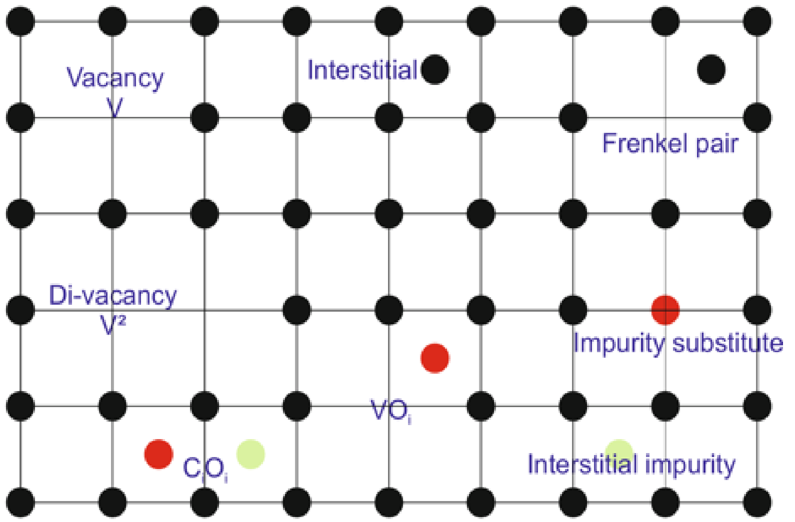
Can we see the defects?

HRTEM on Si: n-irradiated 10^{19} n_{eq}/cm^2

High Resolution Transmission Electron Microscopy



[C.Besleaga et al. arXiv 2021]



- example of point defect reactions:

V: *V+O → VO; V+P → VP* ← "dopant removal"

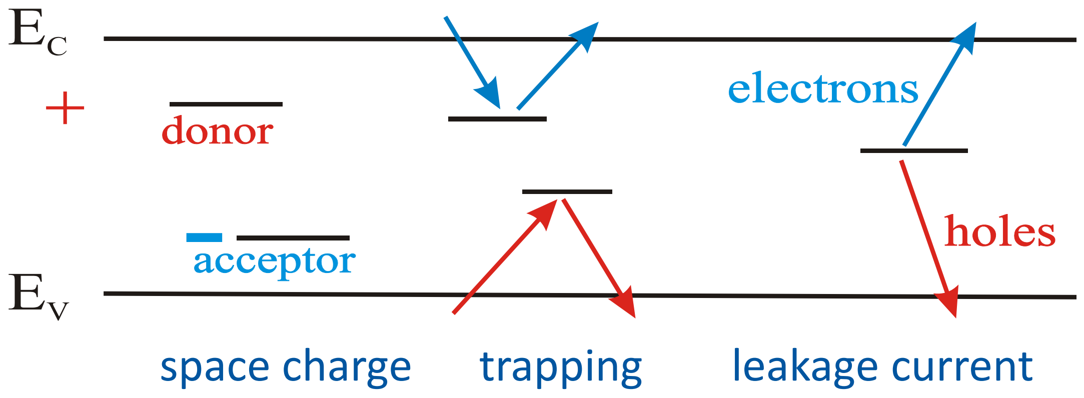
I: $I+C_S \rightarrow C_i \rightarrow C_i + O \rightarrow C_iO_i$

$I+B_S \rightarrow B_i \rightarrow B_i + O \rightarrow B_iO_i$

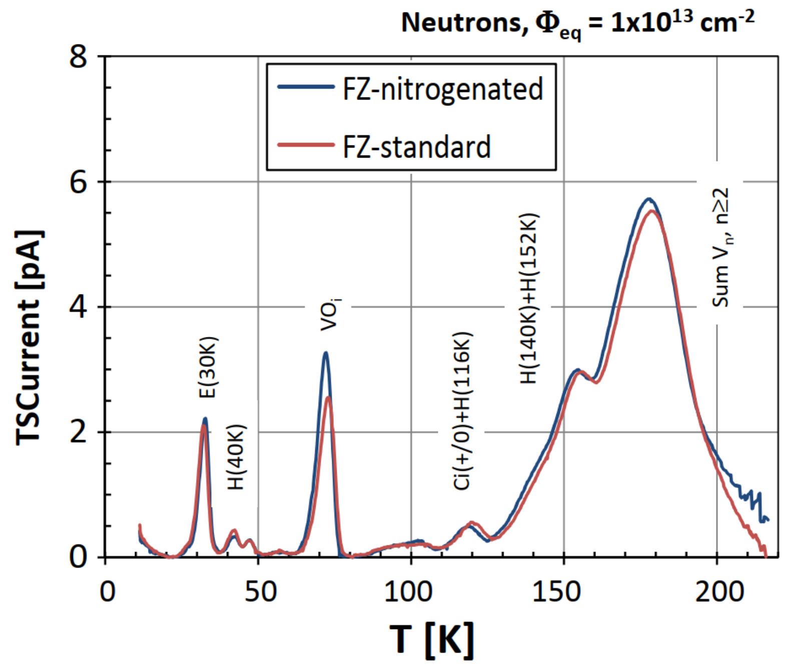
... many more reactions!

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



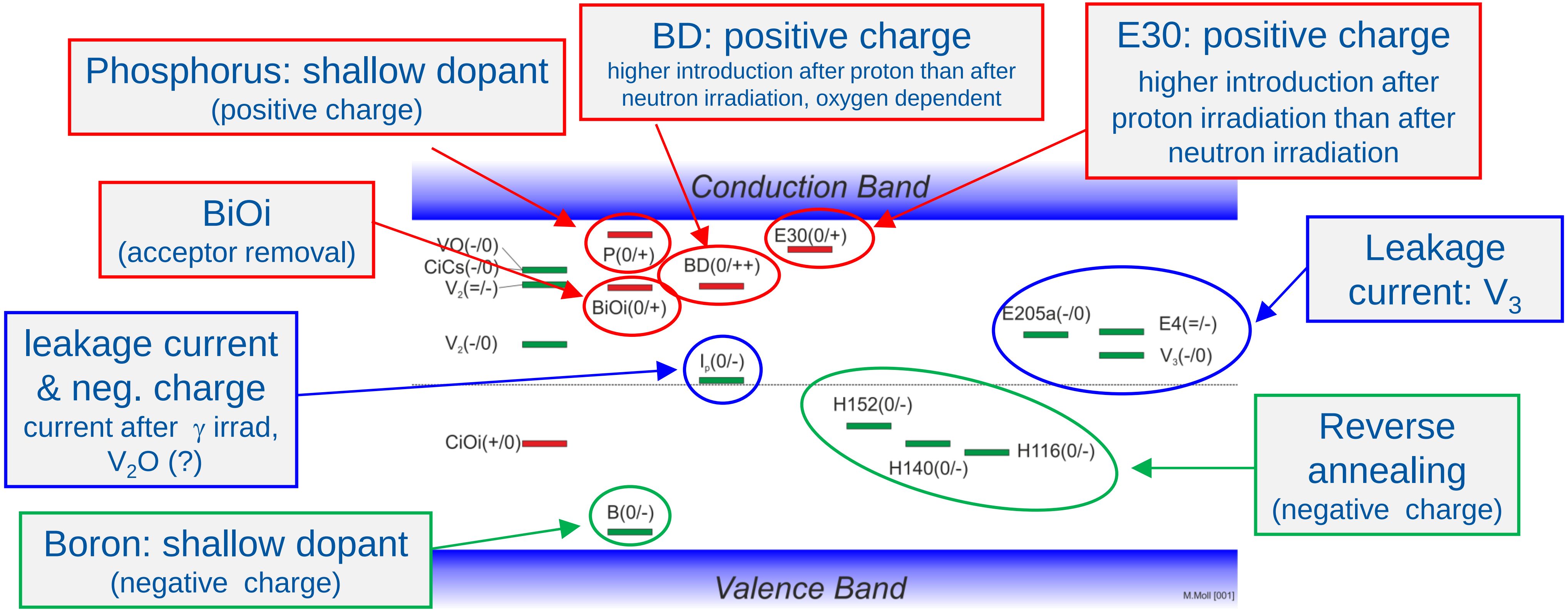
- Defect Characterization performed with various tools:
  - **DLTS** (Deep Level Transient Spectroscopy)
  - **TSC** (Thermally Stimulated Currents)
  - **PITS** (Photo Induced Transient Spectroscopy)
  - **FTIR** (Fourier Transform Infrared Spectroscopy)
  - **EPR** (Electron Paramagnetic Resonance)
  - **TCT** (Transient Current Technique)
  - **CV/IV** (Capacitance/Current-Voltage Measurement)
  - **MW-PC** (Microwave Probed Photo Conductivity)
  - **PC, PL, I-DLTS, TEM,… and simulations**
  - RD50: several hundred samples irradiated with protons, neutrons, electrons, ^{60}Co-γ



[E.Fretwurst et al. – RD50 Nov.2018]

Radiation induced defects with impact on device performance

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

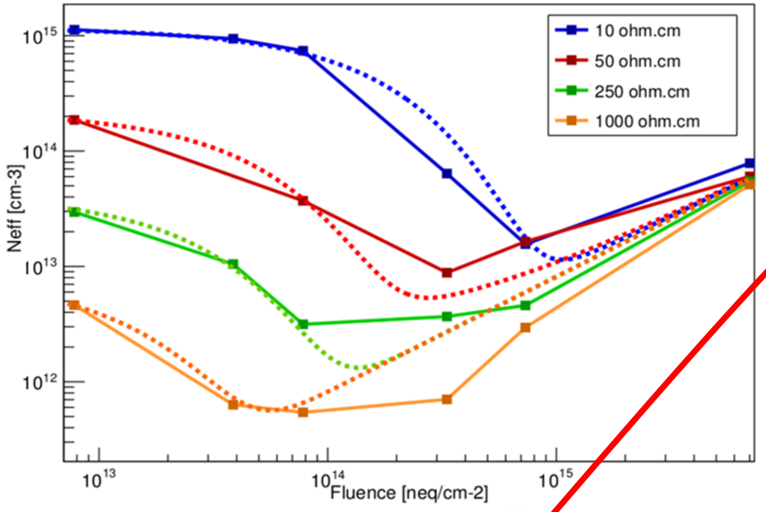


- Trapping: Indications that E205a and H152K are important (further work needed)
- Converging on consistent set of defects observed after p, π, n, γ and e irradiation.
- Defect introduction rates are depending on particle type and energy, and some on material!

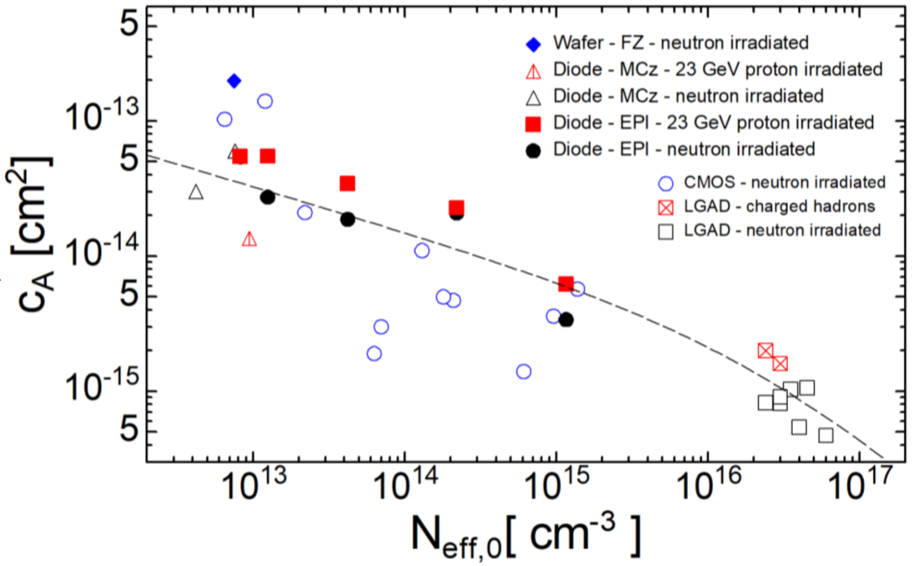
RD50: Dedicated acceptor removal studies

- **Acceptor removal:** Radiation induced de-activation of acceptors (p-type doping, Boron)
- Impact:
  - Change of silicon conductivity; Change of sensor depletion voltage and/or active volume
  - **Loss of gain in LGAD sensors,** sets radiation harness limits for timing detectors (ETL, HGTD)
- Macroscopic studies:

Example: 23 GeV proton irradiated epi diodes



$$N_{eff}(\Phi) = \mathrm{N_{B0}} \exp(-c_A \Phi) + g \cdot \Phi$$



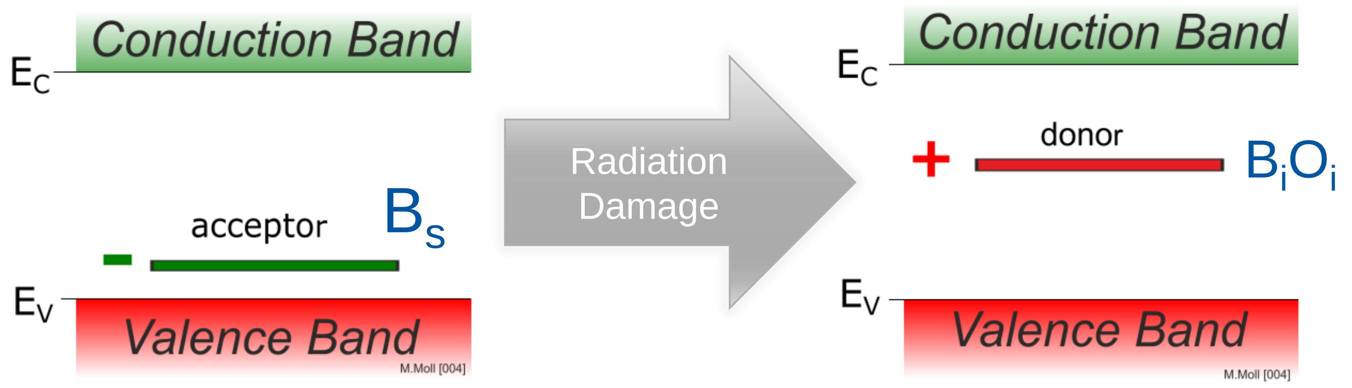
[M.Moll – PoS(Vertex2019)027]

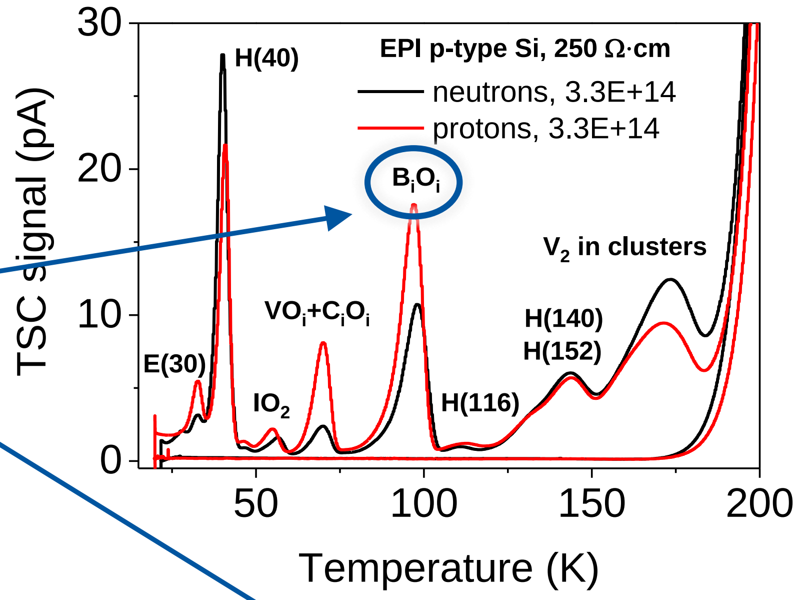
- Acceptor removal coefficients obtained on a wide range of sensor types
  - pin diodes (epi, FZ, MCZ, …), LGAD detectors, CMOS sensors
  - after charged hadron irradiation (red) and neutron irradiation (black/blue)

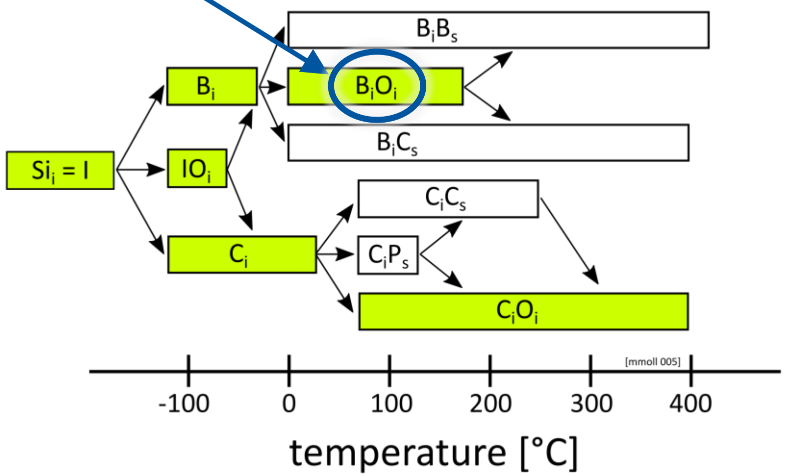
- **Parameterization of acceptor removal established within RD50**
  - covering the range [B]=10^{12} to 10^{18} cm^{-3} (10 kΩcm to 5 mΩcm) i.e. damage predictions can be done

Defect studies: Acceptor Removal

- Microscopic origin:
  - Formation of defects containing Boron that no longer acts as shallow dopant







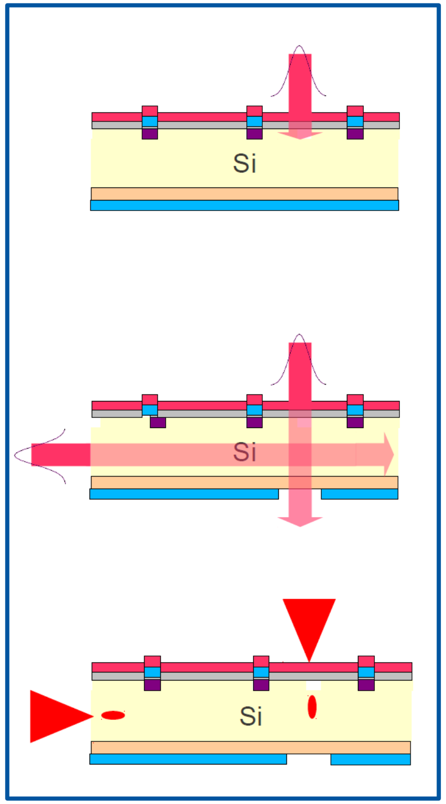
- Status
  - Large amount of data (Wafers, Detectors, CMOS, LGAD)
  - Acceptor removal is parametrized over 6 orders of magnitude in resistivity
    - Damage predictions are possible
  - Defect engineering (with Carbon) works
    but microscopic understanding needs more work!
    - Measured defect concentrations do not fully explain the macroscopic observations.

Detector Characterization

Recent results 2019/21

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)

TCT “invented”: 1996

edge-TCT invented within RD50: 2010

TCT commercialized: 2013

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

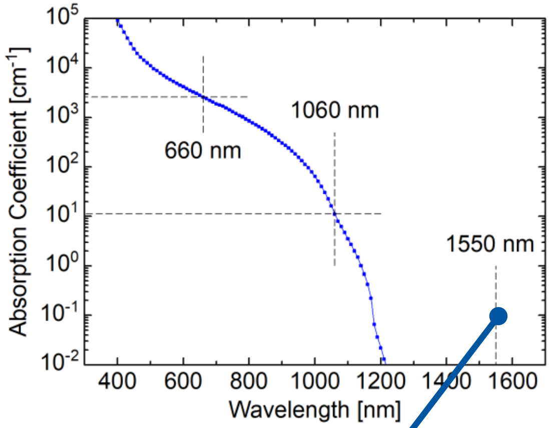
Table-top TPA-TCT laser commercialized: 2020

Table-top TPA-TCT system

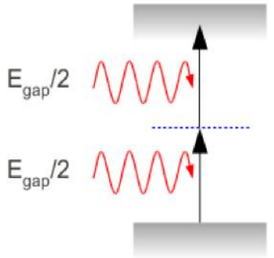
Table-top TPA-TCT system

- Development of a customized fiber-laser (1550 nm, ~ 200 fs) with external company (Seed funding: CERN KT-Fund grant)
- 2019/20 proof of concept achieved at CERN & commercialization started
- 2020: 2nd laser installed at IFCA, Santander, Spain, … system optimization and development ongoing

Si: Single Photon absorption



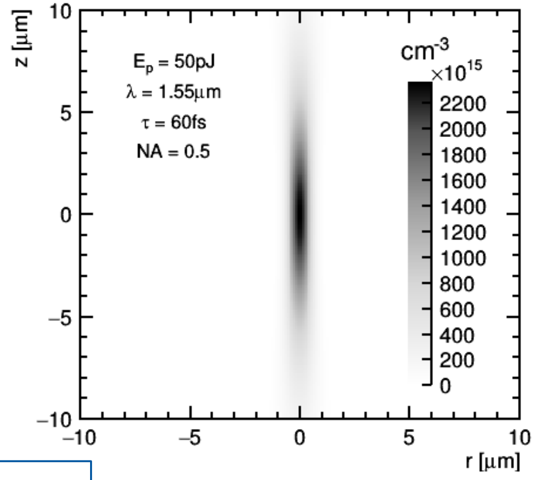
no absorption unless two photons are absorbed at same time (within fs)



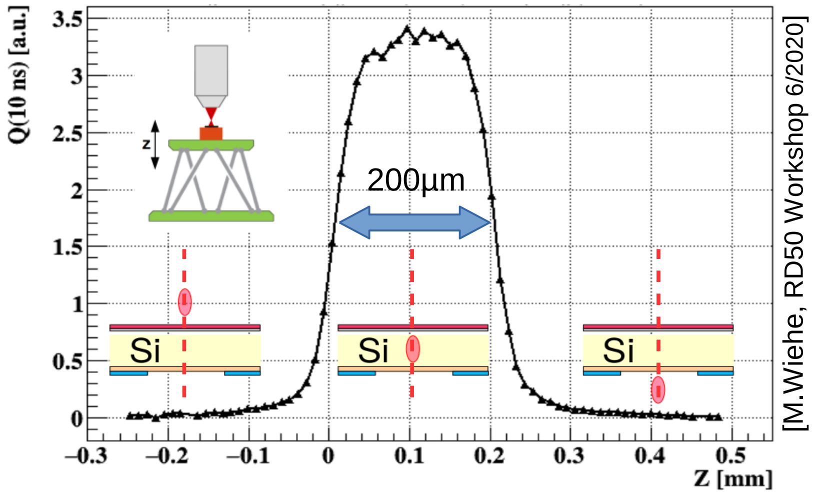
$$\frac{dI(r,z)}{dt} = -\alpha I - \beta I^2(r,z)$$

no SPA TPA

charge carrier density

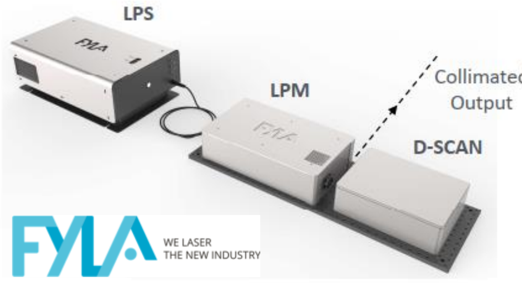


z-scan measurement at CERN



- Characterization of un-/irradiated silicon sensors
- charge generation only at focal point
- very good spatial resolution (1 x 1 x 10 μm³)
- 3D mapping of sensors possible

Commercialization (2020)

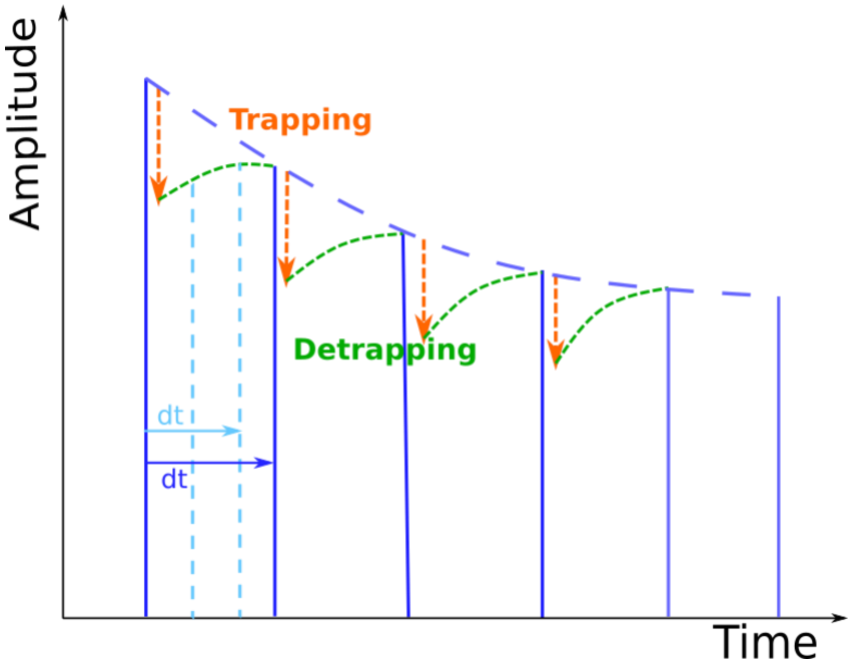


- **LPS: Laser Pulse Source**
  - All-fiber CPA fs pulses generation
  - Pulse rep. single shot to 8 MHz
- **LPM: Laser Pulse Management**
  - Pulse energy: <10 pJ to > 10 nJ
  - Synchronized shutter. rise/fall time < 1 us
- **D-SCAN: Dispersion scanning**
  - Pulse duration: 200 fs to 500 fs
  - Spectral and temporal pulse characterization

[P.Perez-Millan, Fyla – RD50 Workshop 6/2020]

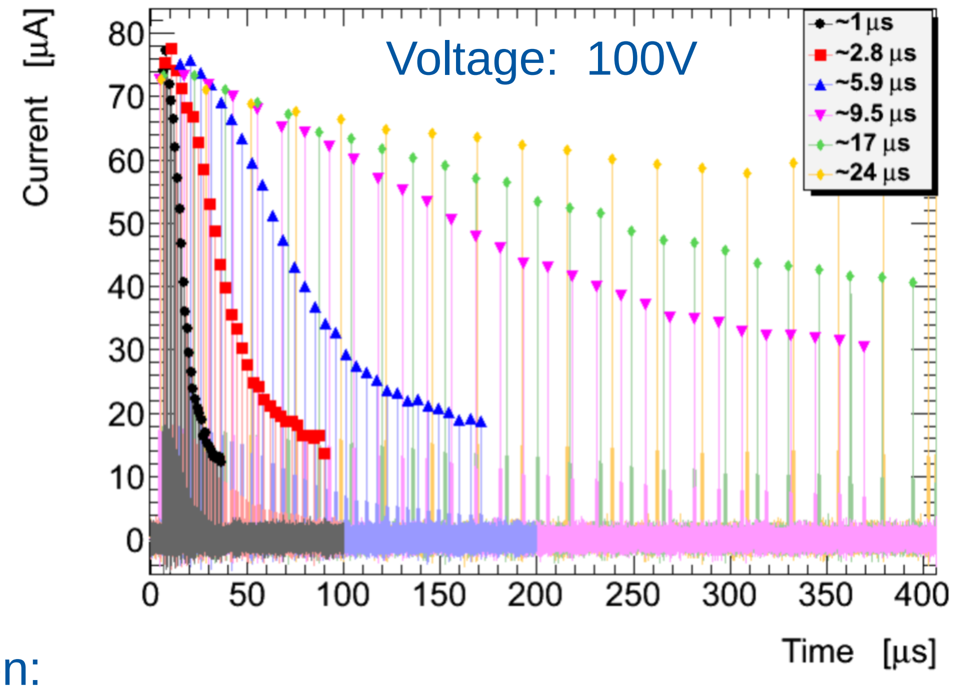
Studying Trapping & Detrapping by TCT

Concept: Use subsequent TCT laser pulses to inject charge carriers into irradiated silicon sensors and study the trapping and detrapping from defect levels by analyzing the TCT signal.



Example: p-type sensor, neutron irradiated (2×10^{15} n_{eq}/cm^2)

- variation of delay between TCT pulses



[L.Diehl, Freiburg – TREDI2021, Feb.2021]

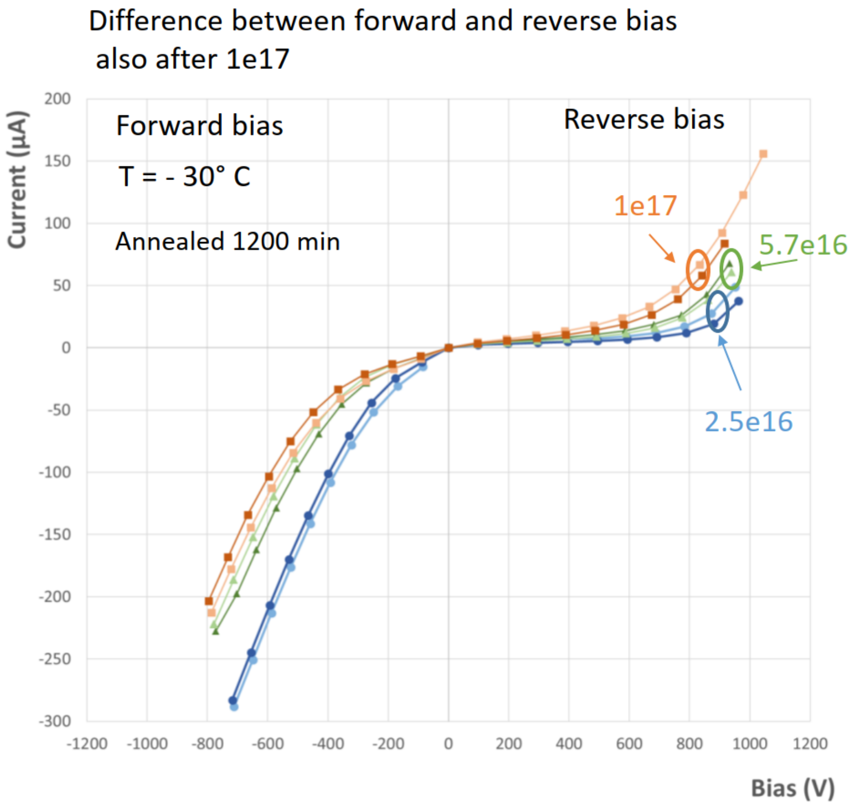
Conclusion:

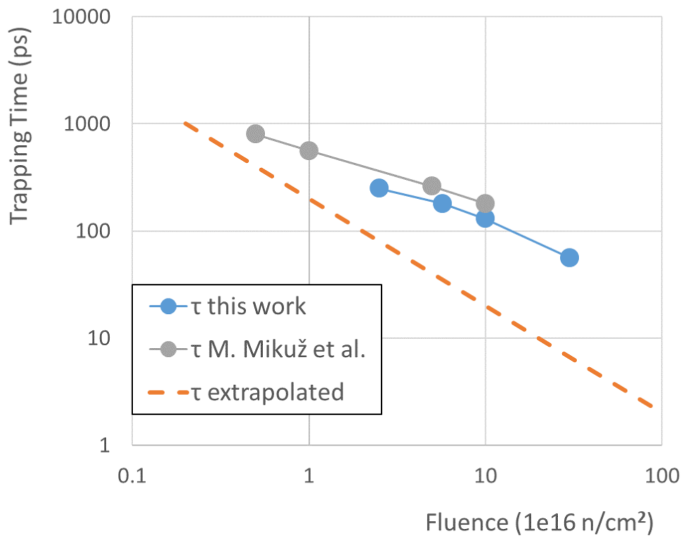
- Trapping has significant impact on TCT signals (as function of repetition frequency, laser intensity, temperature, voltage, ….)
- Excellent dataset for benchmark of sensor simulations
- Extraction of trapping/detrapping parameters possible

Extreme fluences (planar sensors)

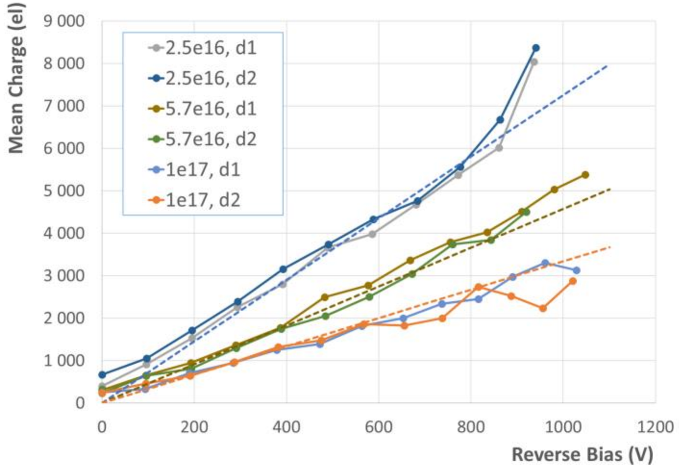
- Study of silicon detectors at extreme particle fluences of **10^{17} n_{eq}/cm^2 and beyond**
- Motivation: Development of tracking detectors for FCC-hh (or other high fluence environments)

  - 75 um LGAD studied with Sr^{90} source and TCT
    - behaves like thin diode after these fluences





beware: S/N = 0.5 to 1.0

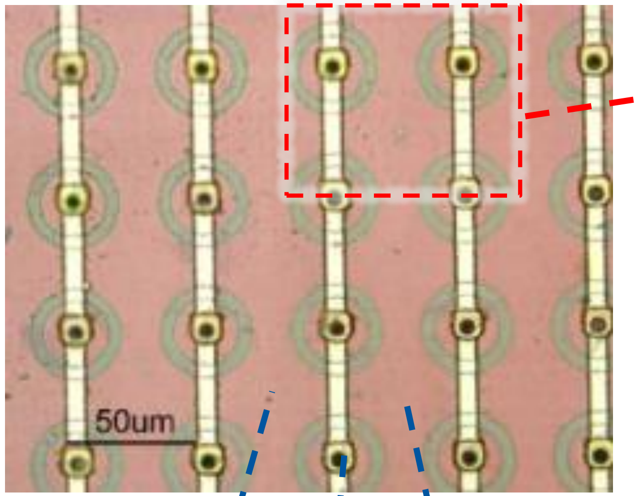


[I.Mandic, Ljubljana – JINST 2020]

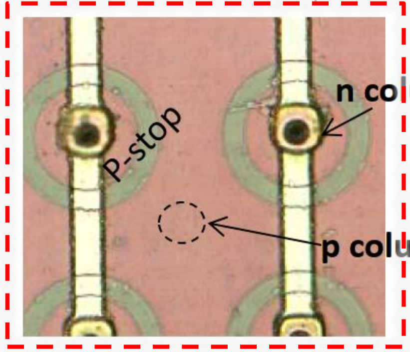
- IV with forward / reverse bias get more and more similar
- E-Field across whole detector already with 100V
- Less trapping than extrapolation from low fluence would predict
- Even after $1e17n_{eq}/cm2$ charge can be collected (2000e MP at 600V)

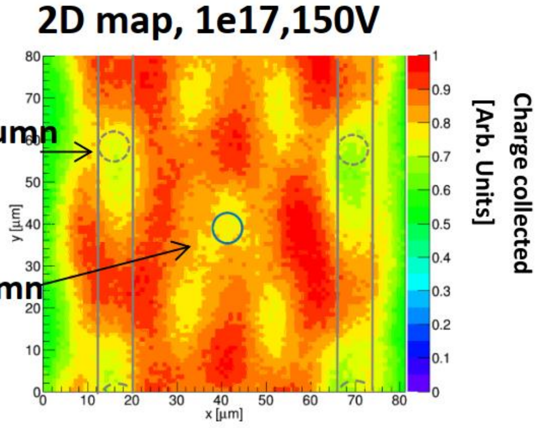
Extreme fluences (3D sensors)

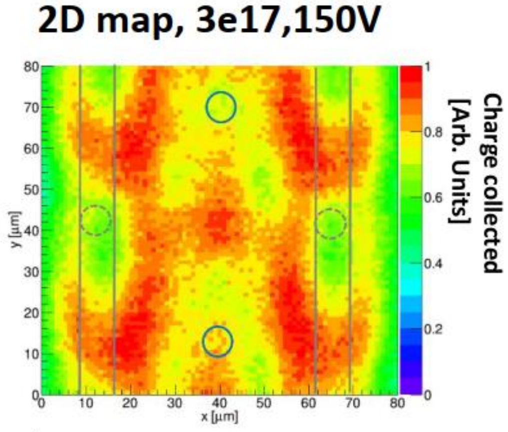
- 3D strip sensor (DS) irradiated up to $3\times10^{17} n_{eq}/cm^2$
  - TCT (1060nm) and Alibava Sr^{90}



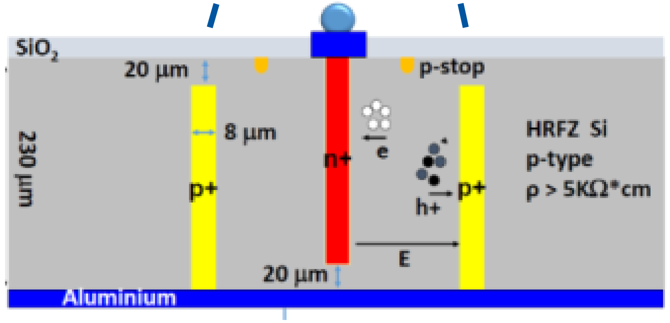
scan area: $80x80\mu m^2$

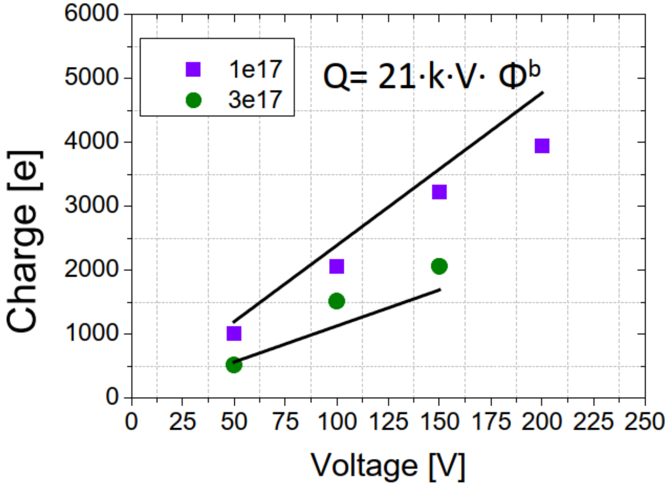






*Scaled to the maximum charge collected





- 3D still alive after $3\times10^{17} n_{eq}/cm^2$
- More charge collected than in planar devices
  - 3D provided up to 4000e after $10^{17} n_{eq}/cm^2$

- Conclusion:
  Silicon sensors “alive” after some $10^{17} n_{eq}/cm^2$

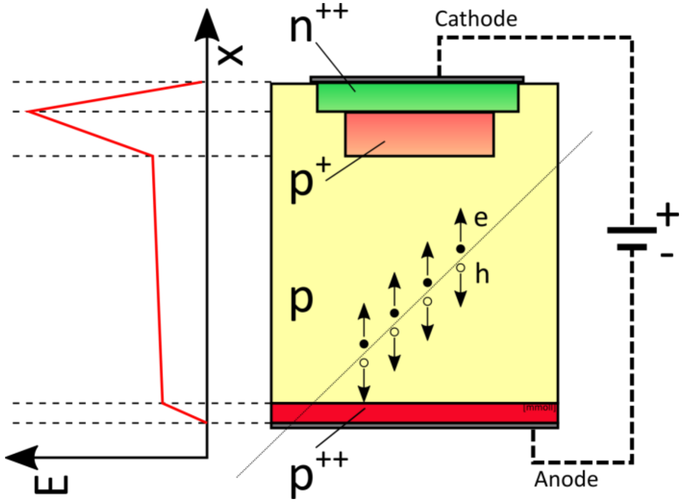
3D and LGAD sensors
see also presentation
of Gregor Kramberger

New Structures

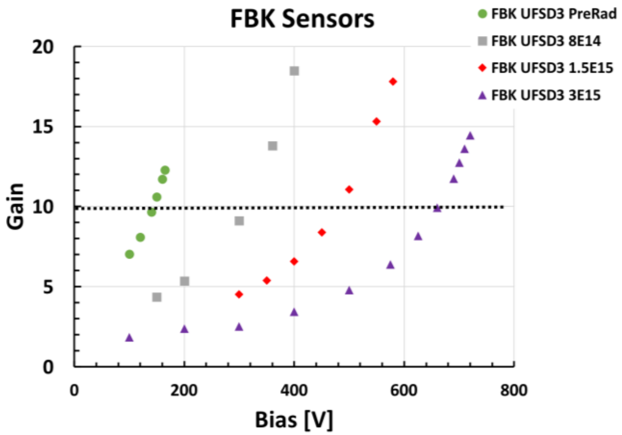
Recent results 2019/20

Sensors for 4D tracking
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), finely segmented for tracking
  - 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 in preparation: CIS(Erfurt, Germany)



$$\sigma_{jitter}^2 = \frac{Noise}{dV/dt} \approx \frac{t_{rise}}{S/N}$$



- **Areas of LGAD developments within RD50**
  - **Timing performance**
    - Optimization: sensor thickness, gain layer profile and signal homogeneity (weighting field)
  - **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 gain layer: Use ~~Ga instead of B~~ or C co-implantation
      - Modification of gain layer profile
  - **Performance Modelling**
    - Predictive model for operation performance (radiation, temperature, thickness, annealing, ….)

LGAD: Gain layer engineering

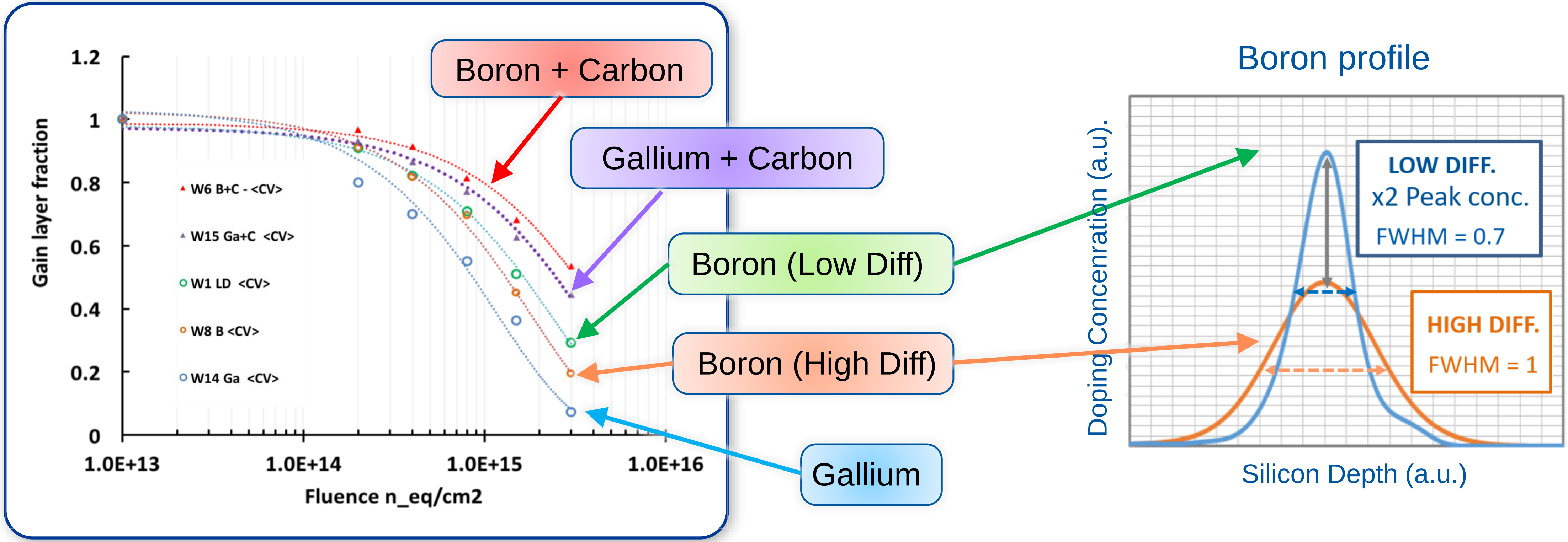
RD50

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 and implantation depth

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

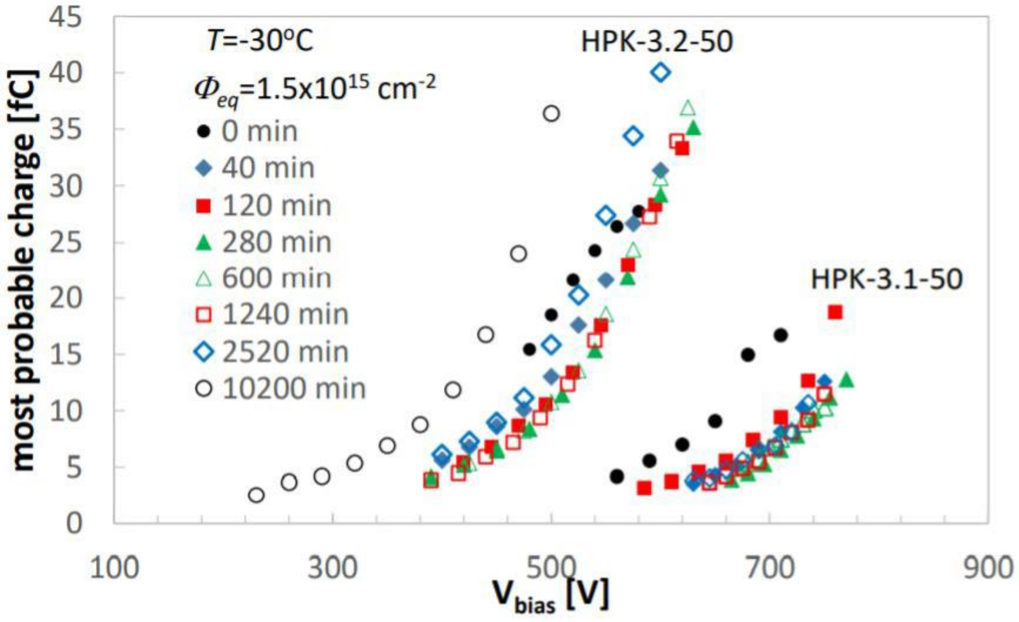


[G.Paternoster, FBK, Trento, Feb.2019]

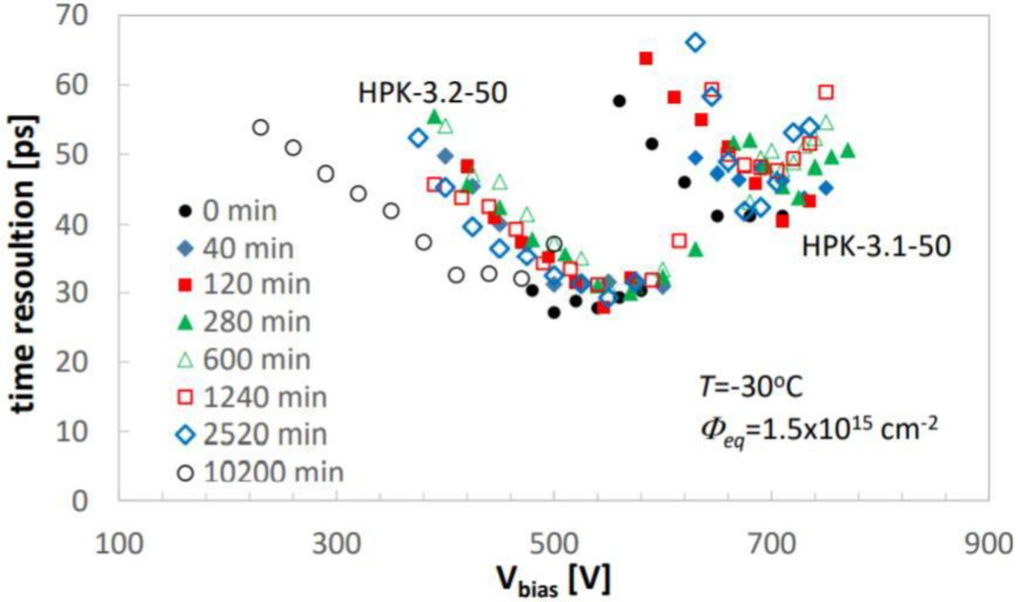
LGAD: Annealing after Irradiation

- Annealing changes N_{eff} with time after irradiation: check for influence on timing response.
- Important for temperature scenario in experiments!
  - Experiment: HPK LGAD sensors (1.3 x 1.3 mm^2), 50 μm thickness, neutron irradiated (4x10^{14} to 3 x 10^{15} n_{eq}/cm^2), annealing at 60°C

Charge collection (beta source)



time resolution



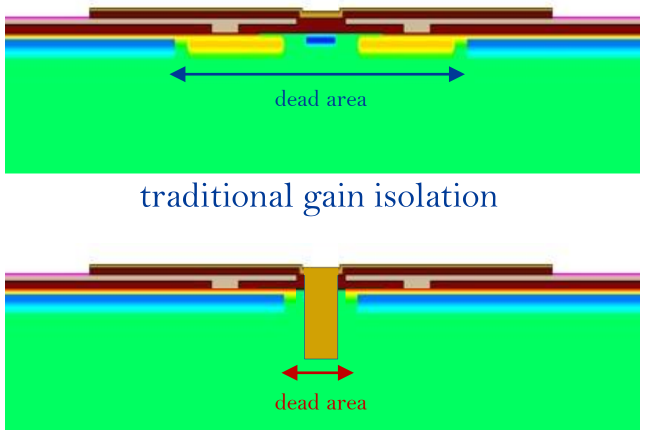
Better charge collection and time resolution for 0 min annealing;
after that no strong change (with exception of very long annealing > 10.000 min)

[G.Kramberger, JSI – 36th RD50 Workshop 6/2020]

LGAD: Fill factor & performance improvements

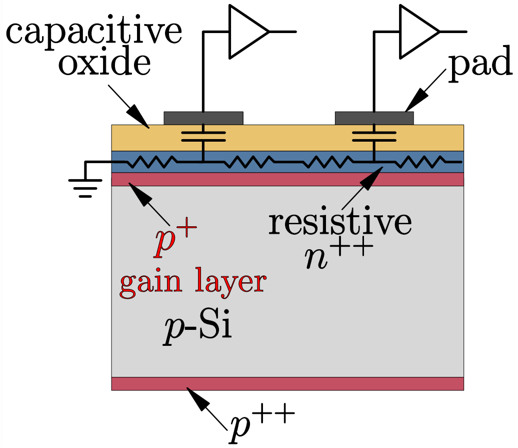
- Two opposing requirements:
  - Good timing reconstruction needs homogeneous signal (i.e. no dead areas and homogeneous weighting field)
  - A pixel-border termination is necessary to host all structures controlling the electric field
- Several new approaches to optimize/mitigate followed:

Trench Isolation LGAD



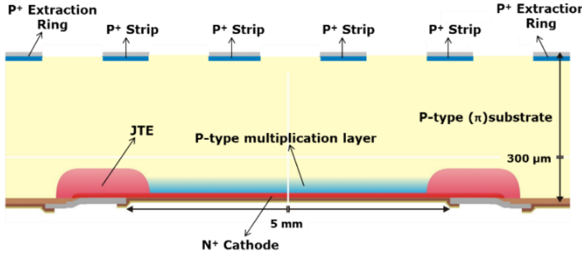
trenches isolation (HD-LGAD)

AC-LGAD



Invers LGAD

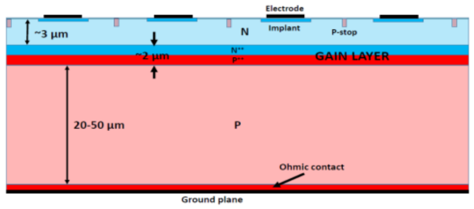
Front: segmented readout



Back: gain layer

Deep Junction LGAD

Front: segmented readout



Gain layer located deep under front electrodes

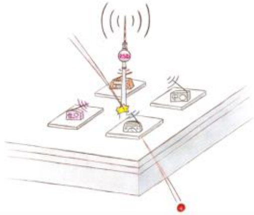
Concepts simulated, designed, produced and tested in 2018..2021

..new concept 2020

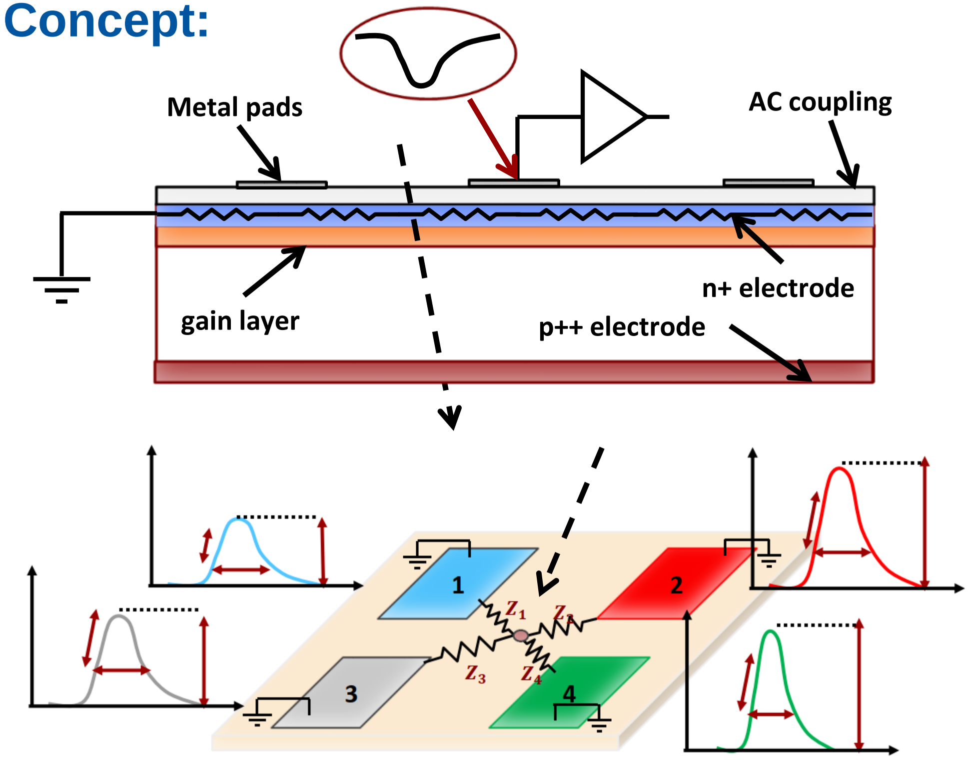
- Full qualification, irradiations and timing performance tests on all design flavours ongoing

Resistive AC-coupled LGAD

- Combining internal gain with internal signal sharing
  - Keep 100% fill factor (with continuous n^+ layer and continuous p^+ gain layer)
  - **Example: RSD project**: aim for resolution in position < 5μm and in time ~20-30 ps



Concept:

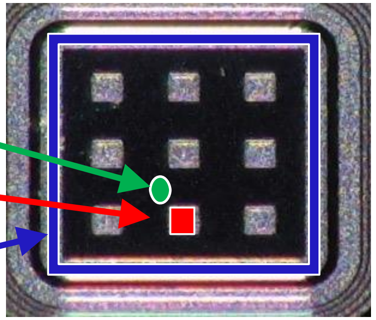


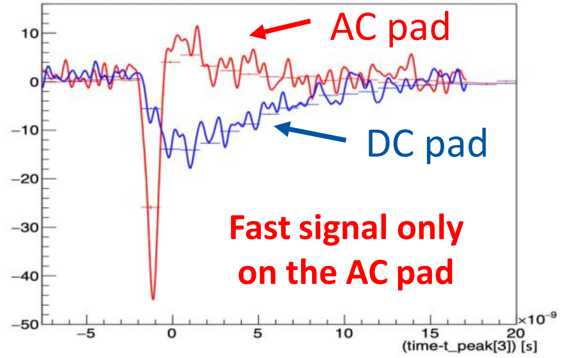
Laser test data:

laser spot

readout pad

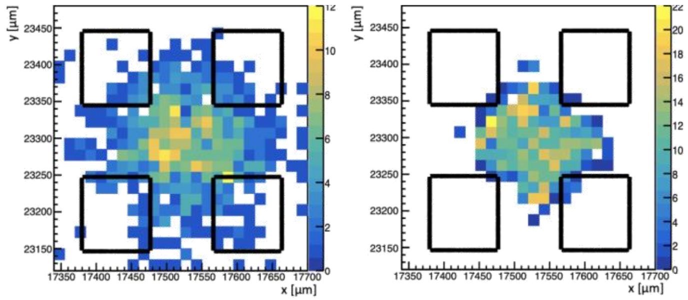
DC contact

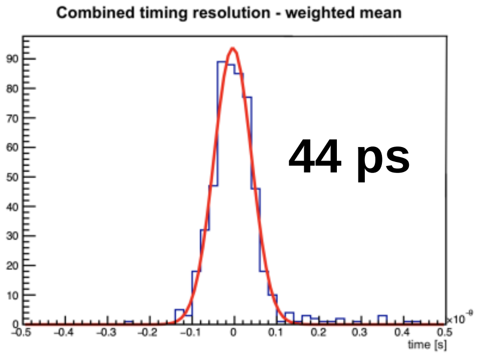




Test beam data:

Tracker coordinates – Sensor coordinates





Status: proof of concept achieved….many parameters to optimize

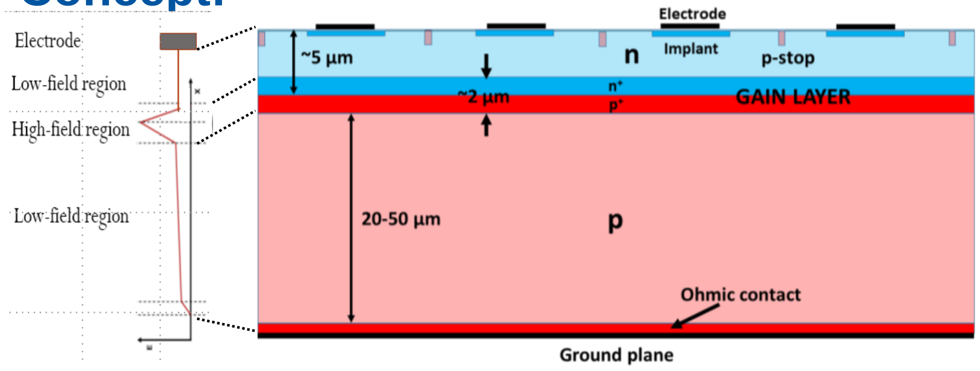
[N.Cartiglia,Torino – DESY Instrumentation Seminar 3/2021]

[M.Tornaga et al. – arXiv Feb/2021]

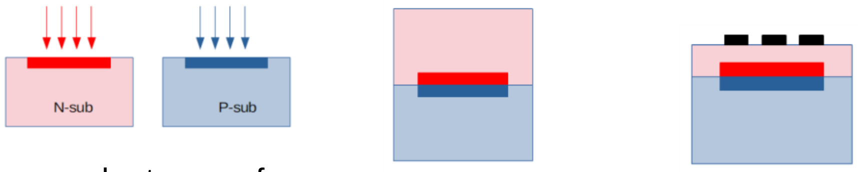
Deep Junction LGAD

- Push the high field region far away (e.g. 5μm) from the top electrodes
  - Keep 100% fill factor with a continuous deep junction n+/p+ gain layer
  - **Example: DJ-LGAD project**: aim for resolution in position < 5μm and in time ~17-50 ps

Concept:



Fabrication: Wafer bonding

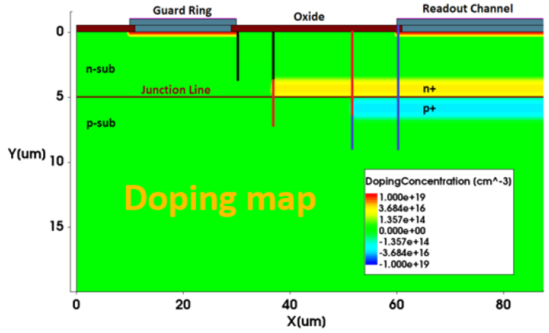


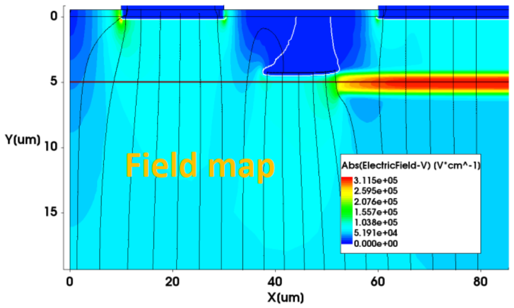
n- and p-type wafer implantation

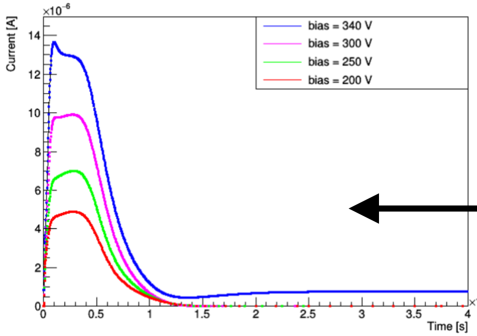
wafer bonding

thinning procesing

Device: design & simulations



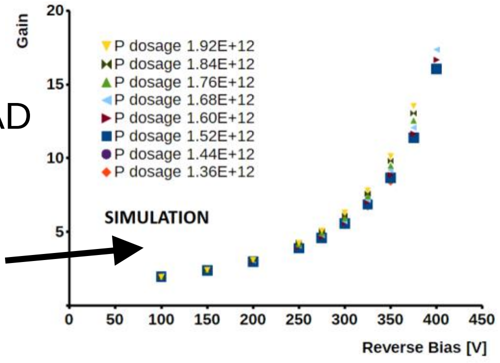




simulation:
mip on 50μm LGAD

signal(Voltage)

gain(Voltage)



Status: First devices in production; proof of concept to be achieved

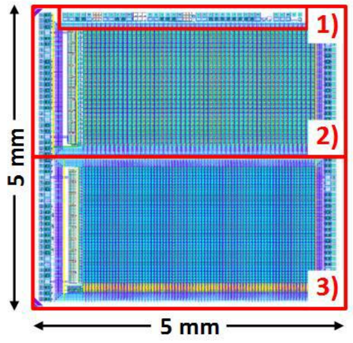
[Y.Zhao – RD50 6/2020; B.Schumm - CPAD 3/2021]

[S.Ayyoub et al. –arXiV Jan/2021]

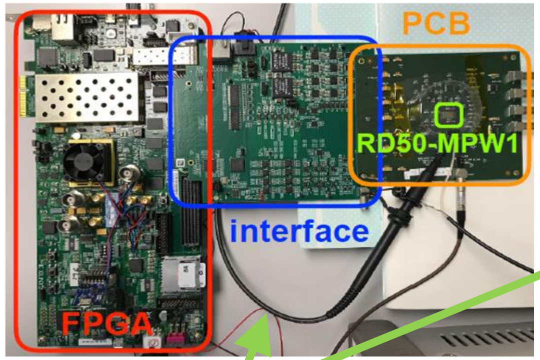
RD50: CMOS developments (150 nm)

Timeline: good results with MPW2, intense characterisation campaign, move design forward to frontier performance (speed, size, …)

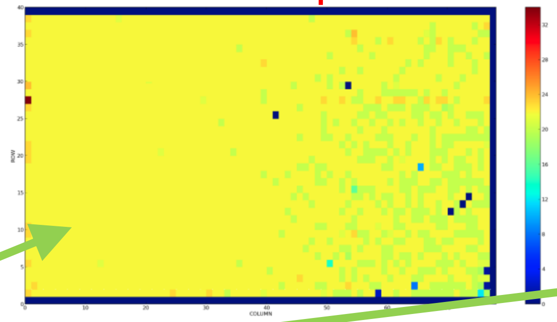
RD50-MPW1



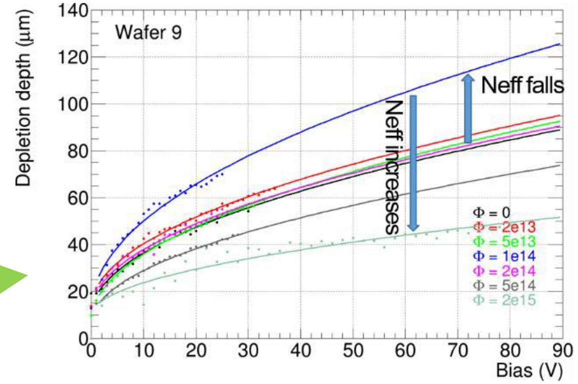
RD50-DAQ (Caribou)



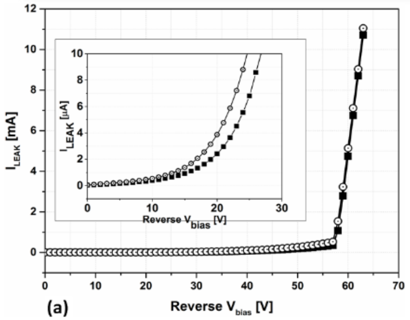
Hit map



e-TCT after irradiation

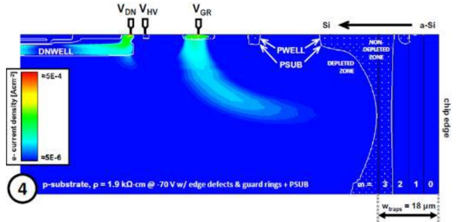


2021
MPW3

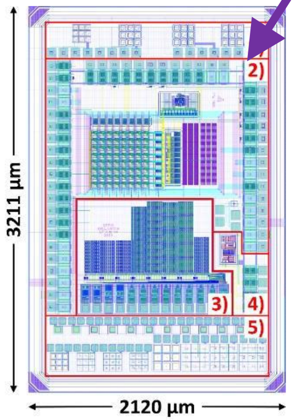


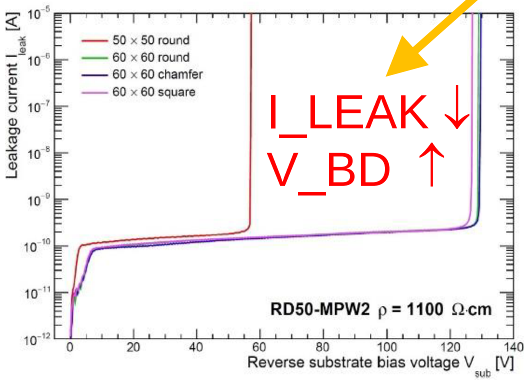
RD50-MPW1 I-V

TCAD

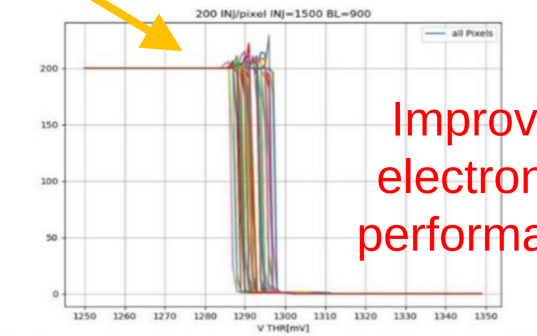


RD50-MPW2





I_LEAK ↓
V_BD ↑



Improved electronics performance

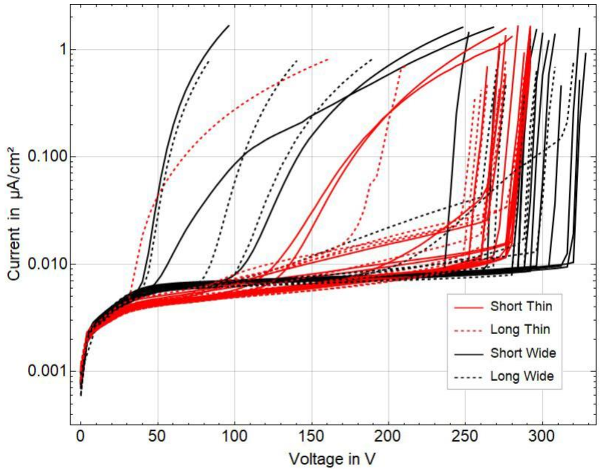
S-curves for all pixels with threshold variation. Trim DAC values adjusted. Injection amplitude 1500 mV.

[E.Viella Figueras, Liverpool - RD50 Workshop 6/2020]

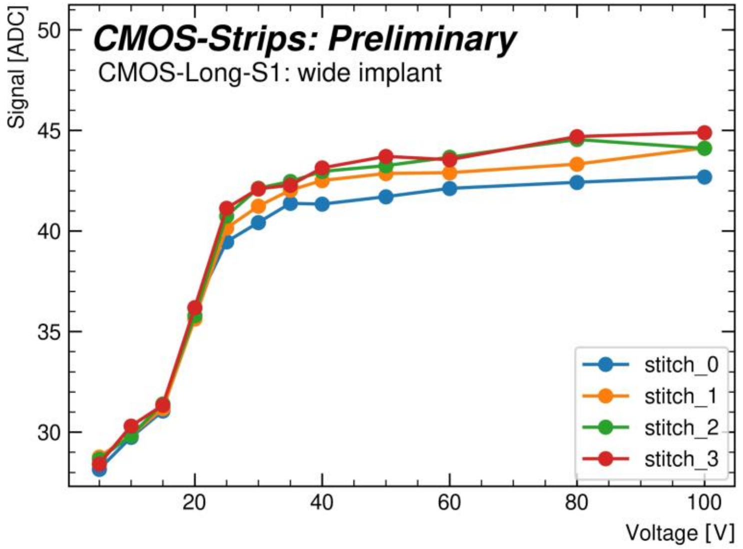
[P.Sieberer, HEPHY, Vienna –Trento Workshop 2/2021]

Passive CMOS Strip Sensors

- Stitched strip sensors on 8" wafer
  by a commercial high volume foundry
  - L-Foundry 150 nm process (deep N-well/P-well)
  - Up to 7 metal layers
  - Wafer Resistivity: > 2 kΩ·cm; Float-Zone silicon
  - Technology demonstrated to allow for production of passive CMOS pixel sensors within ATLAS ITK specs
    [D.Pohl, Bonn, Trento Workshop 2/2021]



- **Here**: 2 and 4 cm long strip sensors produced (by stitching)
  - 150µm thickness (after thinning)
- After optimization of backside implant and metallization, good breakdown behaviour obtained.
- Charge collection study (Sr-90 source) did not show any unusual behaviour
- **Conclusion:**
  Production of strip sensors with this technology looks feasible
  - Radiation tests still to be done but not expected to yield surprises



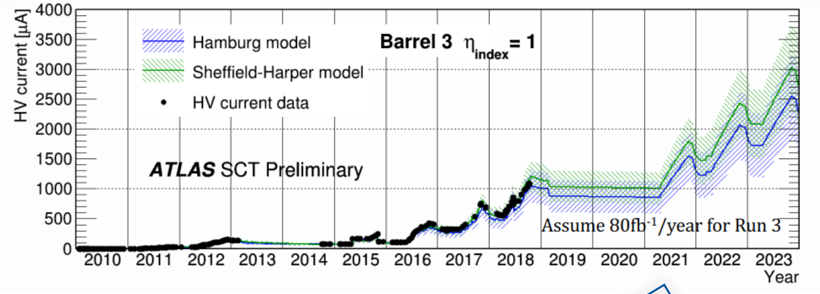
[A.Rodriguez Rodriguez, Freiburg, Trento Workshop 2/2021]

Full Detector Systems

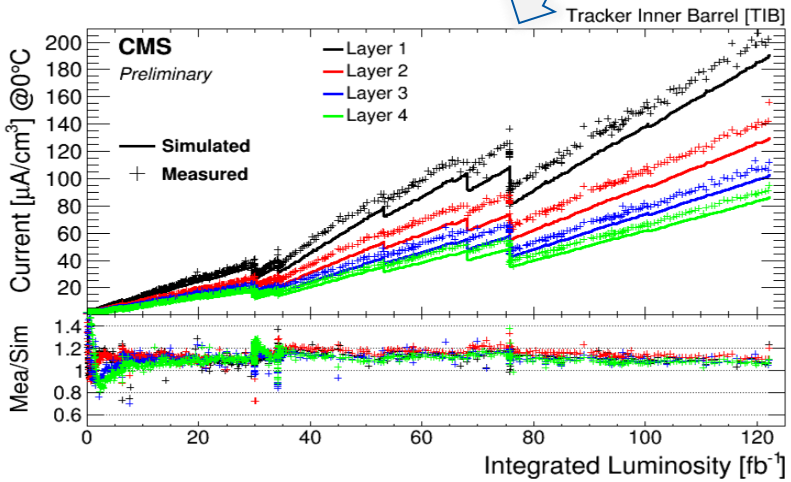
Recent results 2019/21

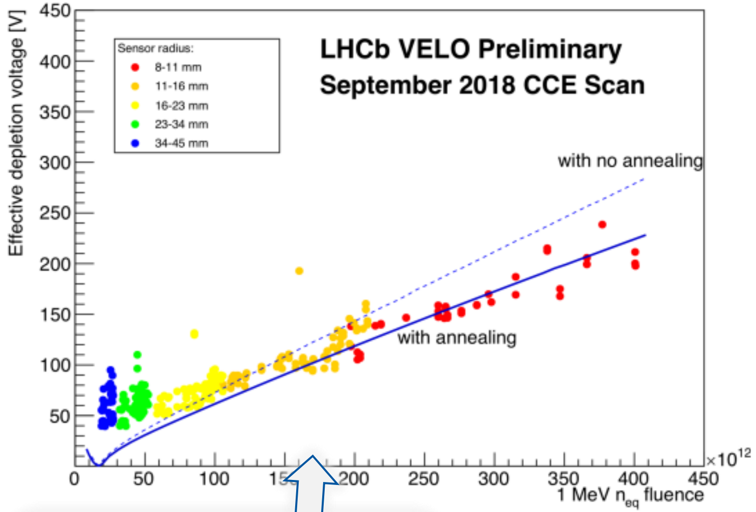
Radiation Effects in LHC Experiments

- Review of radiation effects in the LHC Experiments in several workshops [INDICO]
  - Common working group: RD50 & LHC experiments → Publication of a summary report in April 2021 [CERN Yellow Report; find preprint here]

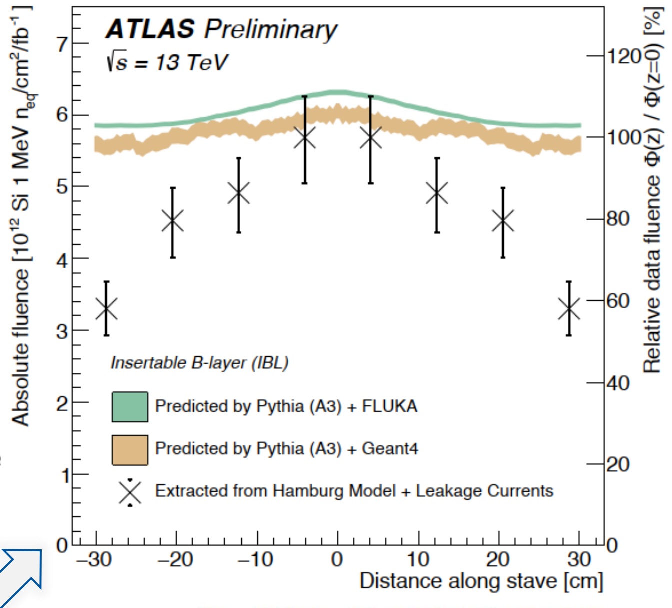


Leakage currents in **ATLAS SCT** and **CMS tracker** and model predictions

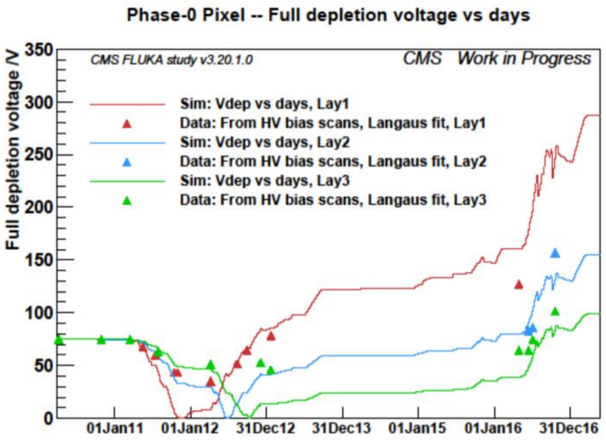




LHCb Velo depletion voltage reduced by annealing; according to model



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
K.Mochizuki(ATLAS SCT) J.L.Agram (CMS Tracker), Aiden Grummer (ATLAS Pixel) , G.Sarpis (LHCb Velo) , F.Feindt (ATLAS Pixel)

Summary & RD50 achievements

- Presentation covered some highlights of ongoing work in the RD50 collaboration
  - ..selection of examples biased by the speaker ☺
- RD50 original mission focussed on HL-LHC and is about to be completed very successfully!
  - Strong share in the development of **p-type sensors**, **3D sensors**, **LGAD sensors,** all essential for HL-LHC
  - Important contributions to solid-state physics landscape of radiation induced defects in silicon materials
  - Development of unique characterization methods and systems for sensor and material analyses
  - …more on spare slide ☺
- Focussing slowly on a new generation of colliders (FCC) with
  - (a) very extreme radiation conditions in the far future (FCC-hh) that will require a further decade of R&D
  - (b) very challenging sensor requirements for sensors in moderate radiation fileds (FCC-ee, …)
- … not forgetting that the LHC and HL-LHC experiments will have to cope with radiation issues
- **RD50 strength** lies in a community with a well established collaborative network of expertise and experience in the various fields of radiation damage and sensor R&D; reaching across all LHC experiments and interacting in a very open and innovative spirit.

RD50 achievements (Highlights)

- The RD50 collaboration was formed in 2001, building on previous R&D (RD48, RD2) projects and is “the place” to discuss radiation effects and new sensor concepts for solid state tracking detectors
- RD50 has given important contributions towards the LHC and LHC upgrade detectors:
  - **p-type silicon** (brought forward by RD50 community) is used for the ATLAS and CMS Strip Tracker upgrades
  - **MCZ and oxygenated silicon** (introduced by RD50) can improve performance in mixed radiation fields
  - Double column **3D detector technology** (developed within RD50 with CNM and FBK) was picked up by ATLAS and further developed for ATLAS IBL needs, followed by AFP and TOTEM and now also within CMS/ATLAS upgrades.
  - RD50 results on highly irradiated planar segmented sensors demonstrated: **planar devices are a feasible option for LHC upgrade**
  - RD50 data and **damage models** are essential input for operation scenarios of LHC experiments and sensor designs
  - Precision timing sensors: **LGAD (Low Gain Avalanche Detectors)** were developed within the RD50 community
  - **New characterization techniques** and simulation tools for the community:
    - Edge-TCT, Alivaba readout, TPA-TCT, … are now available through spin-off companies

- In all these developments, RD50 keeps a very close links to the LHC experiments collaborations:
  - Only few RD50 groups are not involved in ATLAS, CMS and LHCb upgrade activities (natural close contact).
  - Common projects with experiments: detector developments and detector characterization, irradiation campaigns, test beams, ….
  - Close collaboration with LHC experiments on radiation damage issues of present detectors.