147th Meeting of the LHCC, 1-2 September 2021

RD50 Status Report

- September 2021 -

Radiation hard semiconductor devices for very high luminosity colliders

Gianluigi Casse (FBK & Uni Liverpool), Michael Moll (CERN)
for the RD50 Collaboration

Outline:

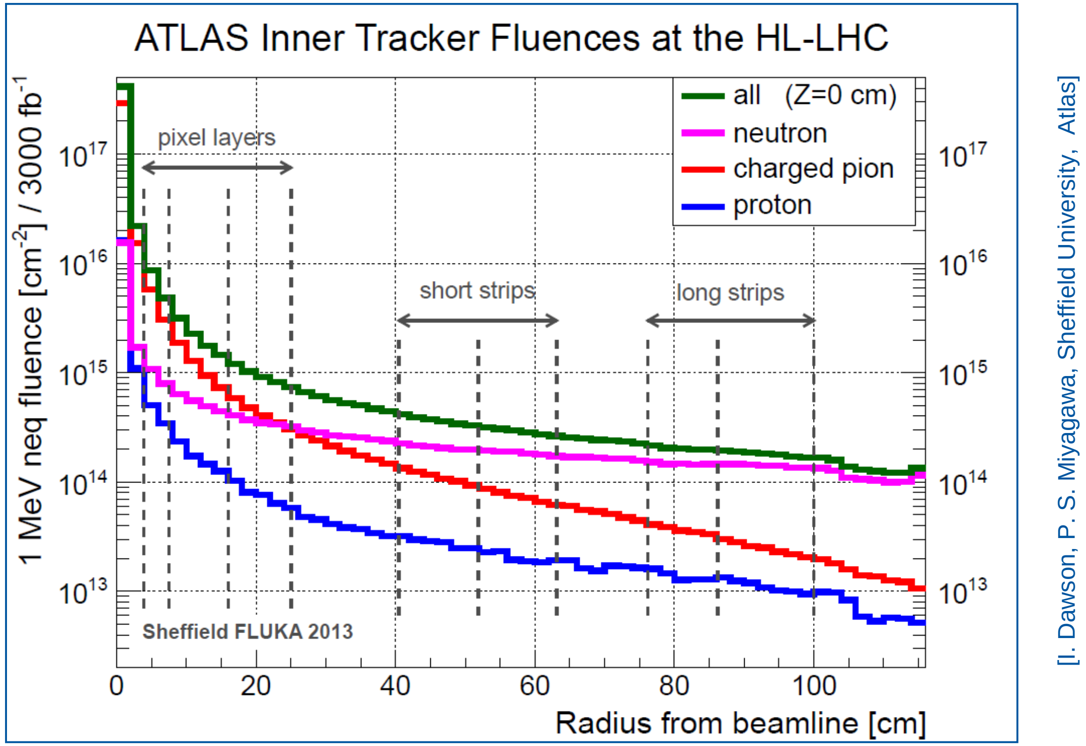
- RD50 Collaboration
- Scientific results 2019/21 (selected highlights)
  - Defect and Material Characterization
  - Detector Characterization
  - New Detector Structures
  - Full Detector Systems
- Summary
- Annex
  - RD50 - 5 Year Work Plan 2018-2023
  - List of ‘RD50 common projects’
  - Request to 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 (~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



- **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 and/or 4D tracking capabilities**

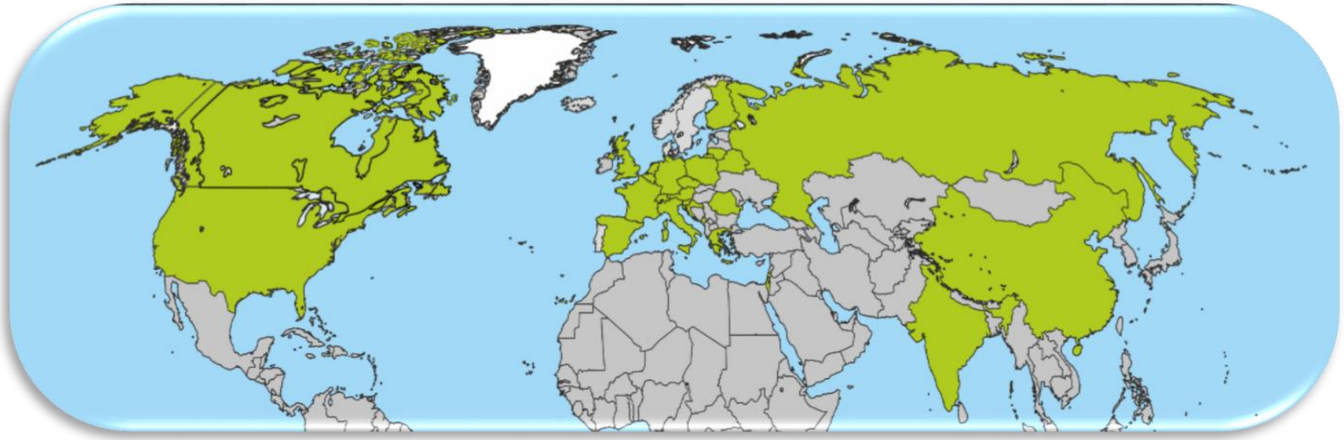
The RD50 Collaboration

no changes since last LHCC report in Sept.2020

- 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

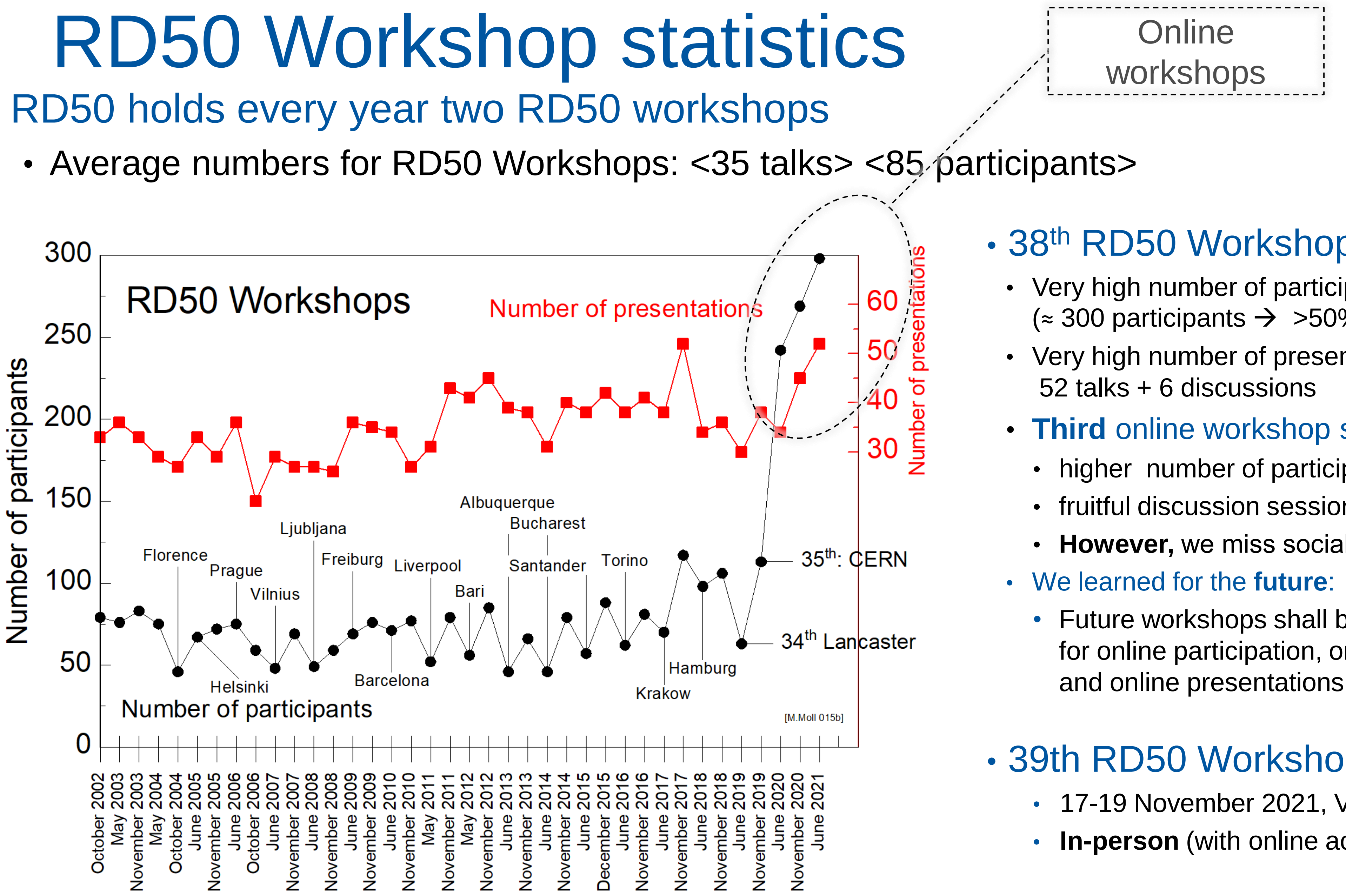
Israel (Tel Aviv)

4 Asian institutes

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

RD50 Workshop statistics

- RD50 holds every year two RD50 workshops
  - Average numbers for RD50 Workshops: <35 talks> <85 participants>



- 38th RD50 Workshop (June 2021)
  - Very high number of participants (≈ 300 participants → >50% of collaboration);
  - Very high number of presentations/discussion sessions 52 talks + 6 discussions
  - **Third** online workshop since June 2020:
    - higher number of participants
    - fruitful discussion sessions are possible
    - **However,** we miss social contacts & ‘coffee meetings’
  - We learned for the **future**:
    - Future workshops shall be tailored as well for online participation, online discussions and online presentations.

- 39th RD50 Workshop (November 2021)
  - 17-19 November 2021, Valencia, Spain
  - **In-person** (with online access)

Organizational Structure / Work Program

RD50

Co-Spokespersons

Gianluigi Casse and *Michael Moll*

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

(CERN EP-DT)

Spokespersons and management team were re-elected for two years in June 2021

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)

Covering all fields of semiconductor detectors exposed to radiation

Targeting new detector technologies including high precision 4D detectors

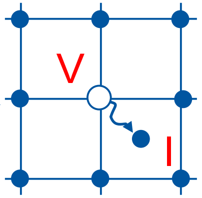
Collaboration Board Chair & Deputy: G.Kramberger (Ljubljana) & tbc, Conference committee: U.Parzefall (Freiburg)
CERN contact: M.Moll (EP-DT), Secretary: V.Wedlake (EP-DT), Budget holder: M.Moll & M.Glaser (EP-DT) , EXSO: R.Costanzi (EP-DT)

Defect & Material Characterization

Recent results 2019/21

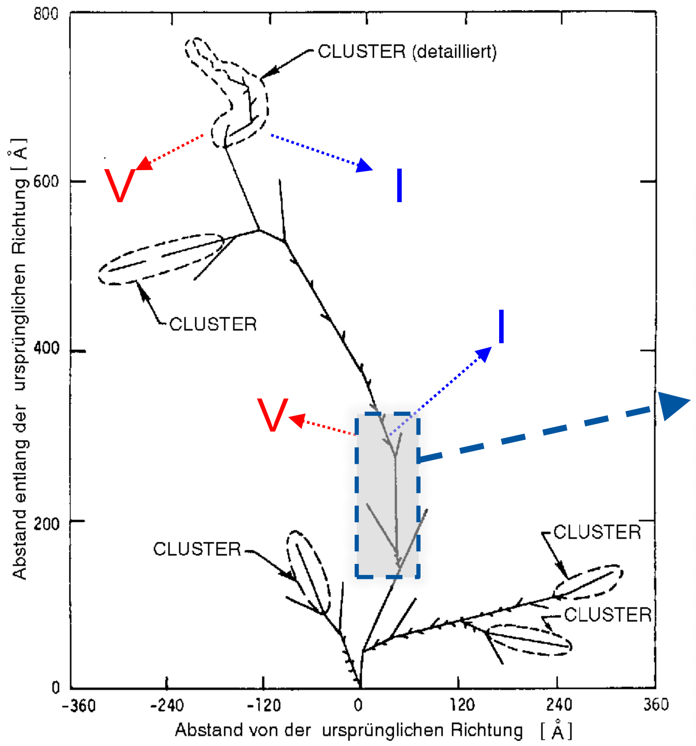
Displacement Damage

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*

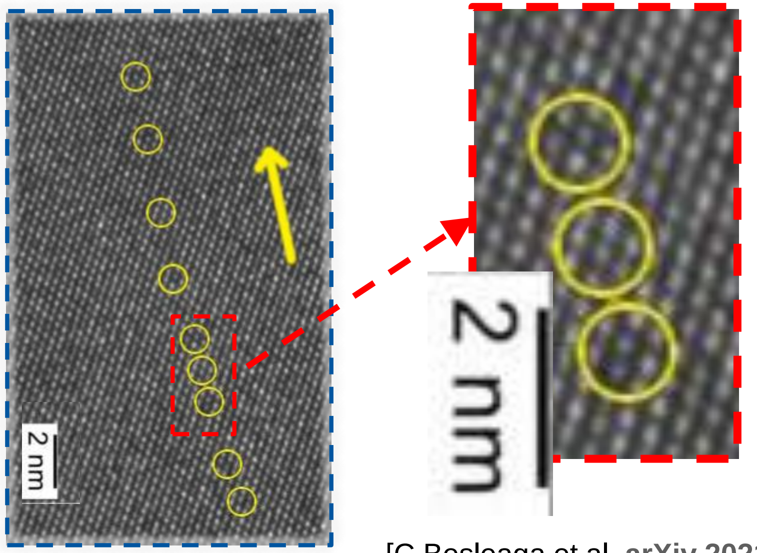


[van Lint 1980]

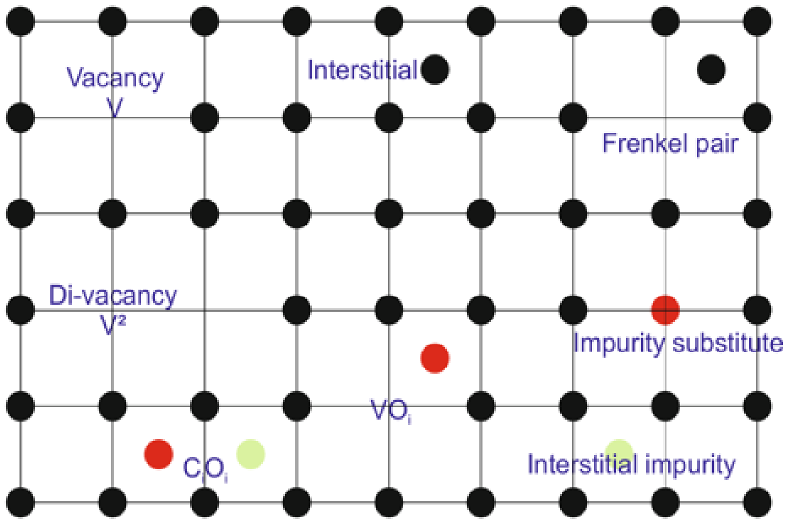
Can we see the defects?

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: $V+O \rightarrow VO$; $V+P \rightarrow VP$ ← "dopant removal"

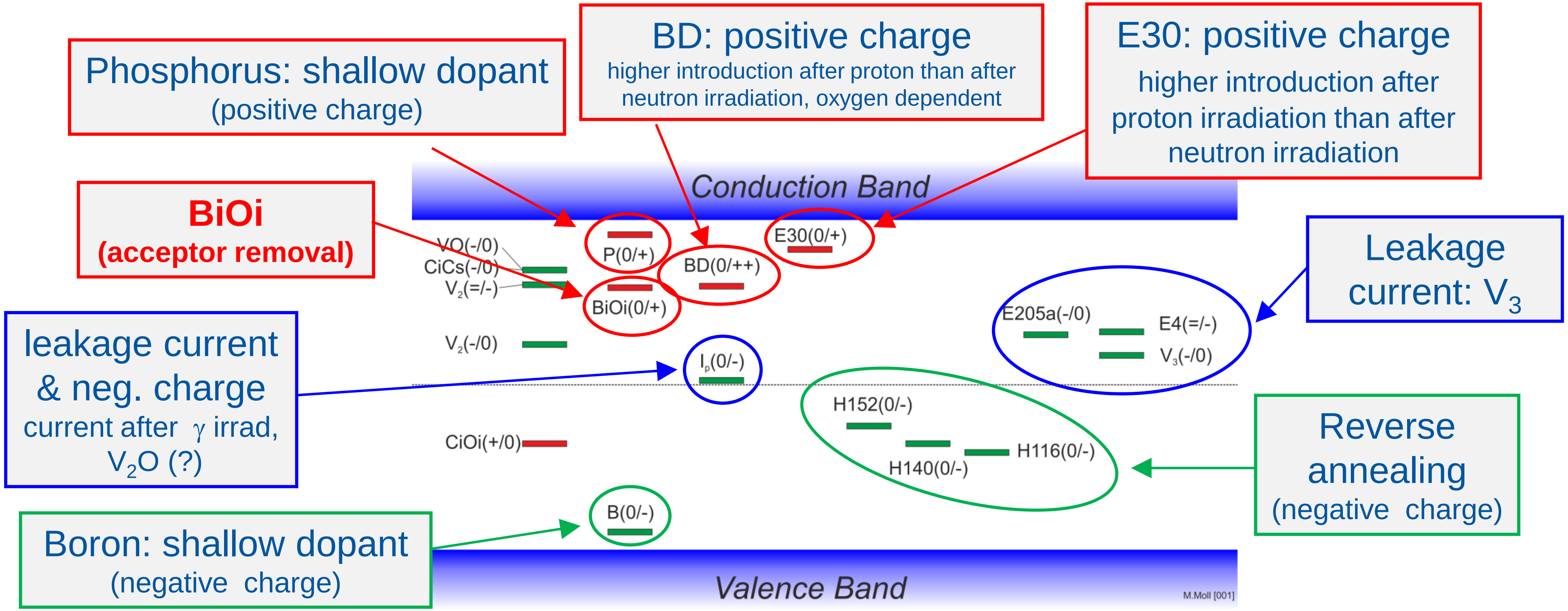
I: $I+C_S \rightarrow C_i \rightarrow C_i + O \rightarrow C_iO_i$

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

… many more reactions!

Radiation induced defects with impact on device performance

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



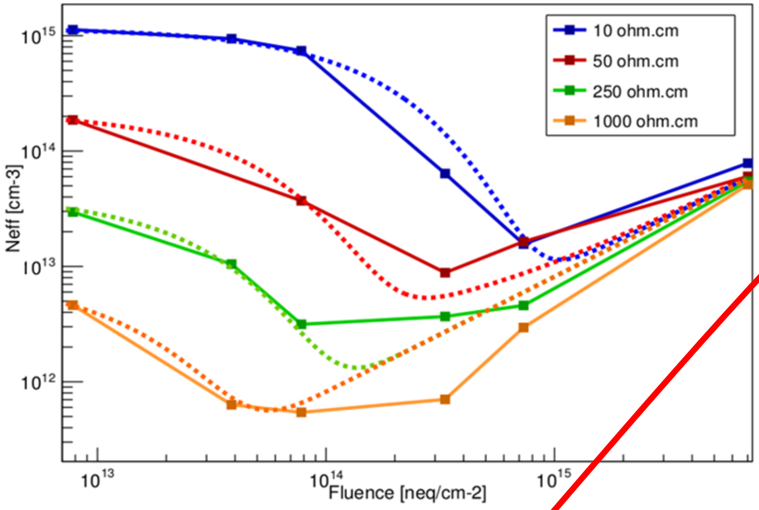
- Trapping: Indications that E205a and H152K are important (further work needed)
- Converging on consistent set of defects observed after p, π, n, γ and e irradiation.
- Defect introduction rates are depending on particle type and energy, and some on material!

RD50: Dedicated acceptor removal studies

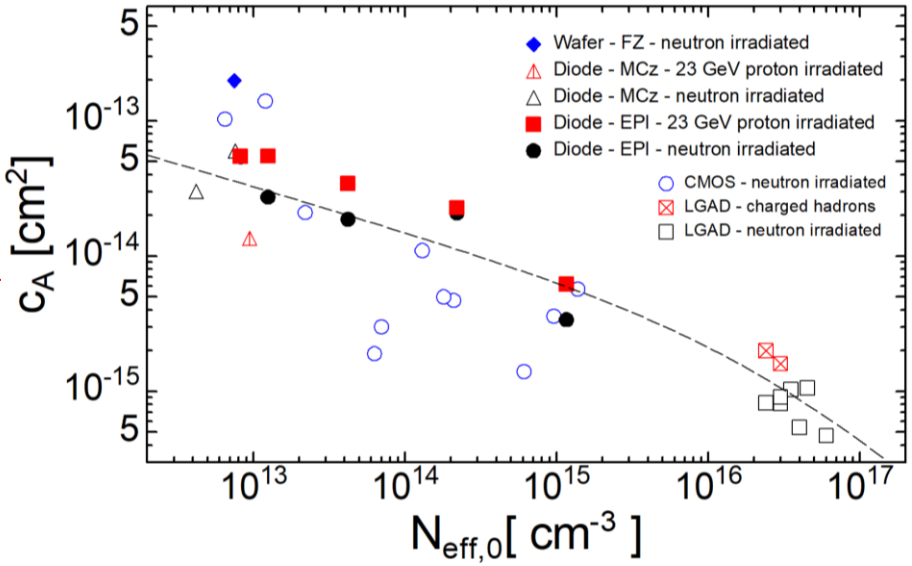
2020

- **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



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



[M.Moll – PoS(Vertex2019)027]

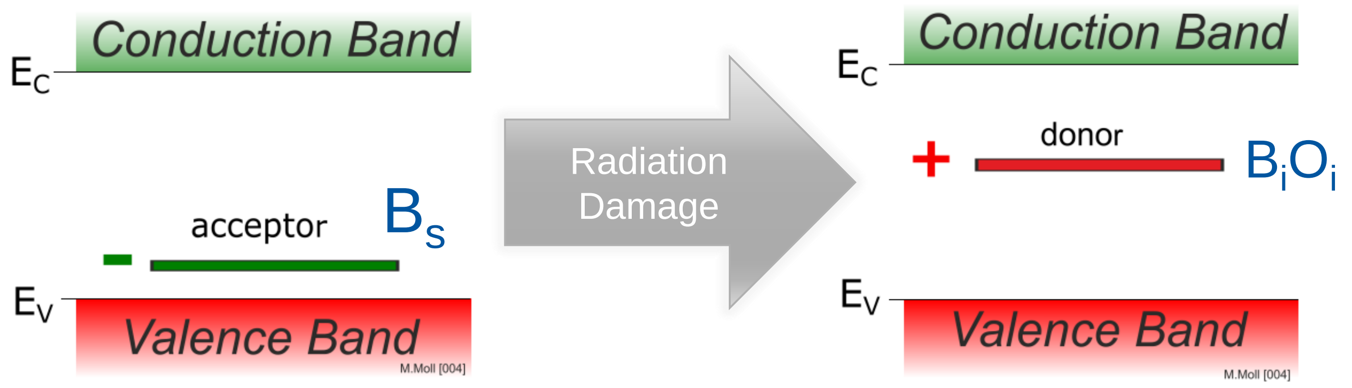
- Acceptor removal coefficients obtained on a wide range of sensor types
  - pin diodes (epi, FZ, MCZ, …), LGAD detectors, CMOS sensors
  - after charged hadron irradiation (red) and neutron irradiation (black/blue)

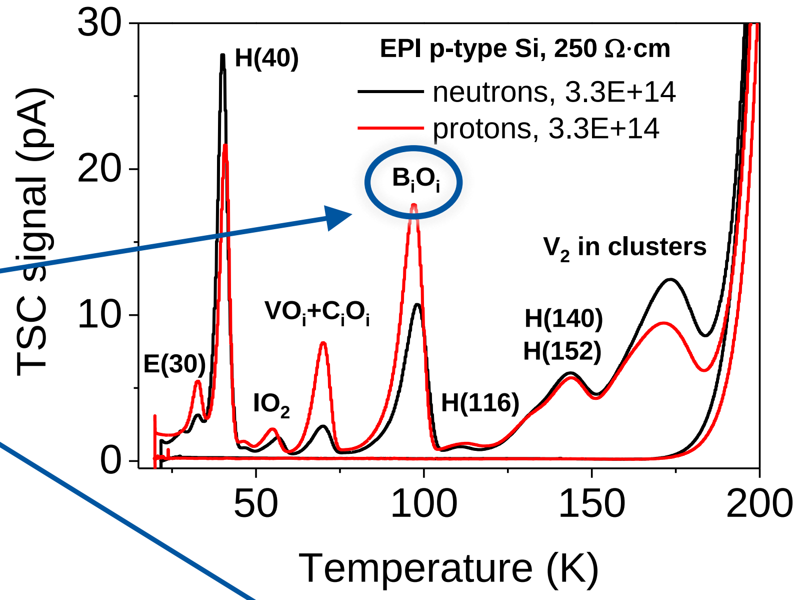
- **Parameterization of acceptor removal established within RD50**
  - covering the range [B]=10^{12} to 10^{18} cm^{-3} (10 kΩcm to 5 mΩcm) i.e. damage predictions can be done

Defect studies: Acceptor Removal

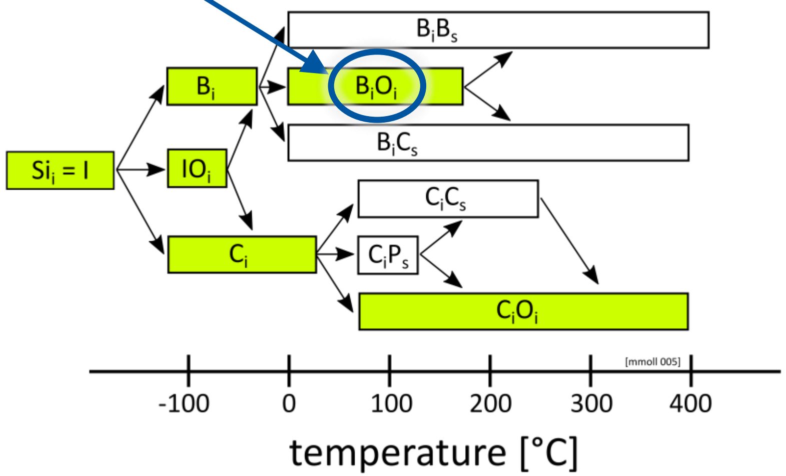
2020

- 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.

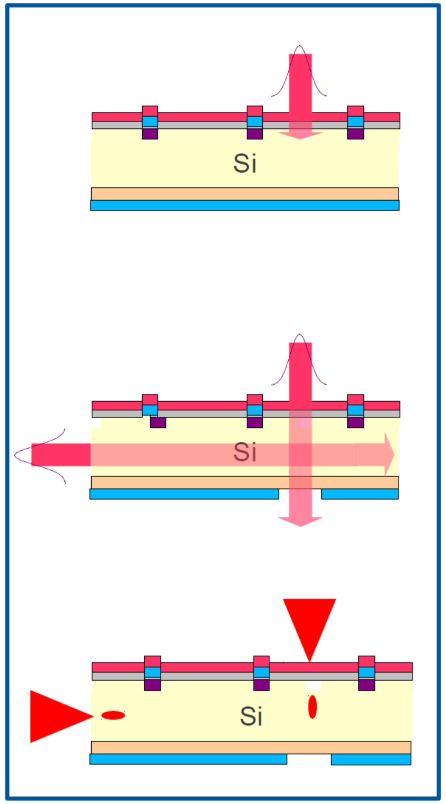


Detector Characterization

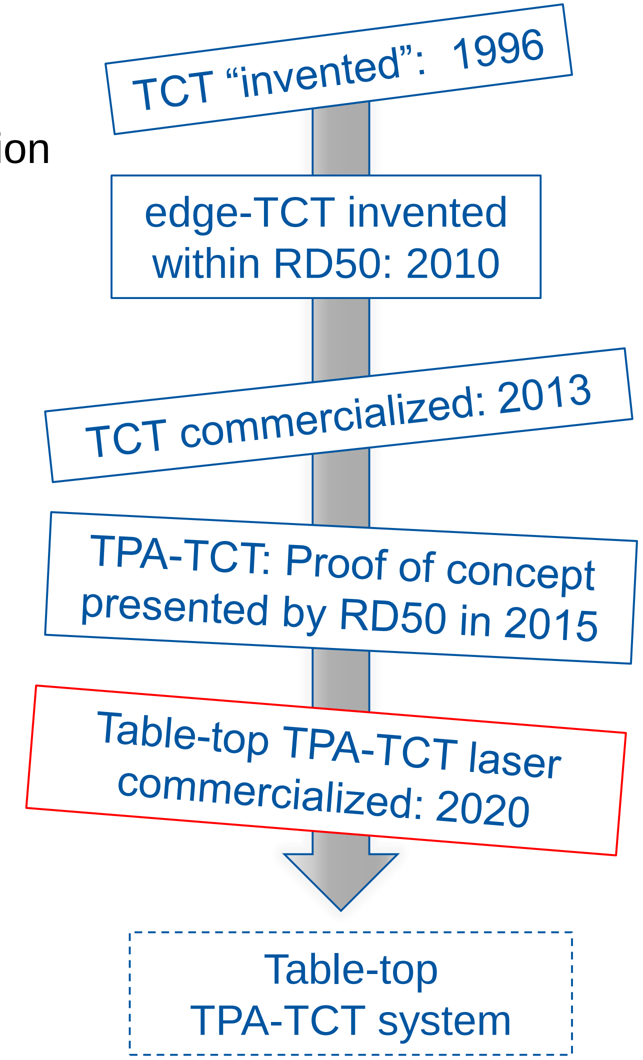
Recent results 2019/21

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

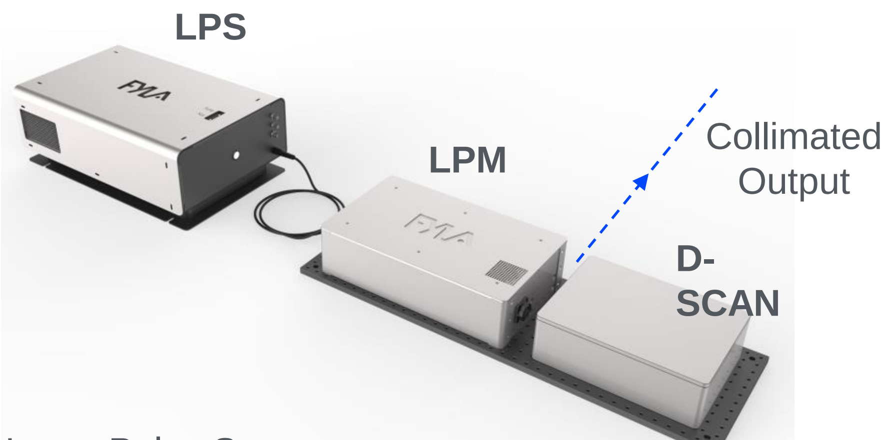


- **TCT (red laser)**
  - short penetration length (650nm = 1.9eV)
  - carriers deposited in a few μm from surface
  - front and back TCT: study electron and hole drift separately
  - 2D spatial resolution (5-10μm)
- **TCT (infrared laser)**
  - long penetration (1064nm = 1.17 eV)
  - similar to MIPs (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)



TPA-TCT laser development

CURRENT (2020/21)
LFC1500X commercial model



- **LPS:** Laser Pulse Source
  - All-fiber CPA femtosecond pulses generation
  - Pulse rep rate selection. **Single shot to 8 MHz**
- **LPM**: Laser Pulse Management module
  - Pulse energy modulation: **<10 pJ to > 10 nJ**
  - Synchronized shutter**. rise/fall time < 1 us**
- **D-SCAN:** Dispersion scanning
  - Pulse duration tuning: **300 fs to 600 fs**
  - Pulse temporal properties characterization

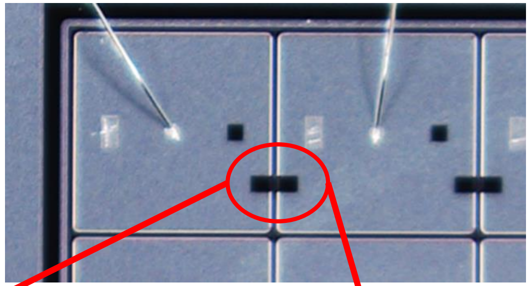
RD50/AIDA INNOVA (2026)
Single box fully all-fiber with system

- **LPS + LPM + D-SCAN** in single box fully all-fiber
  - Pulse duration goal < 100 fs
  - Fiber-based tunable dispersion compensation: < 100 fs to 1 ps
  - Fiber-pigtailed AOM functionalites:
    - Energy modulation
    - Pulse rep rate selection
    - Sync shutter
  - Dispersion-less fiber output delivery to TPA-TCT optical sub- system

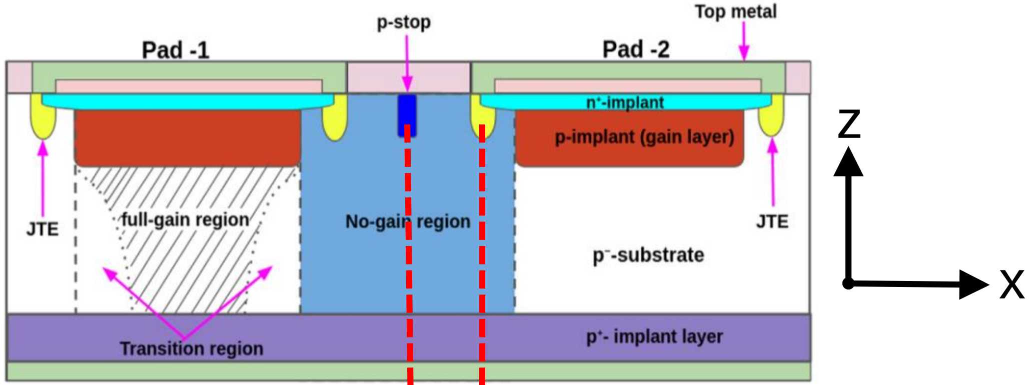
2021: 5 RD50 institutes equipped with this laser

Inter-pad region of LGAD sensors

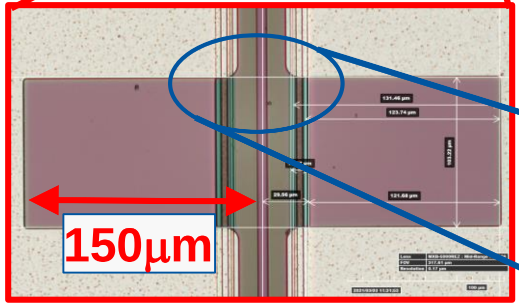
- **top-TPA-TCT** on the inter-pad region of an HPK2-LGAD matrix

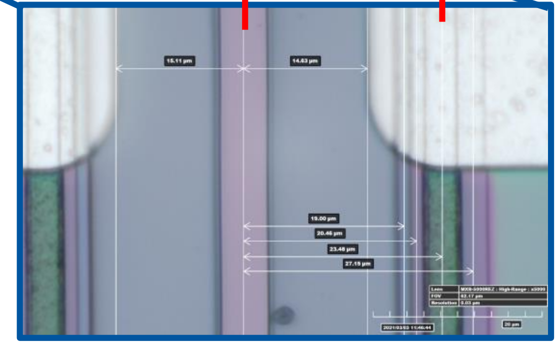


schematic cut through device



Drawing: S. Bharthuar et.al. https://doi.org/10.1016/j.nima.2020.164494

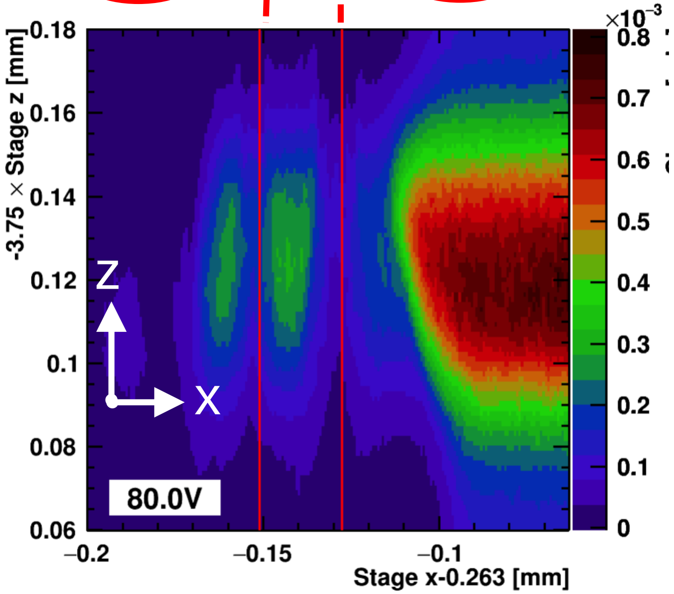




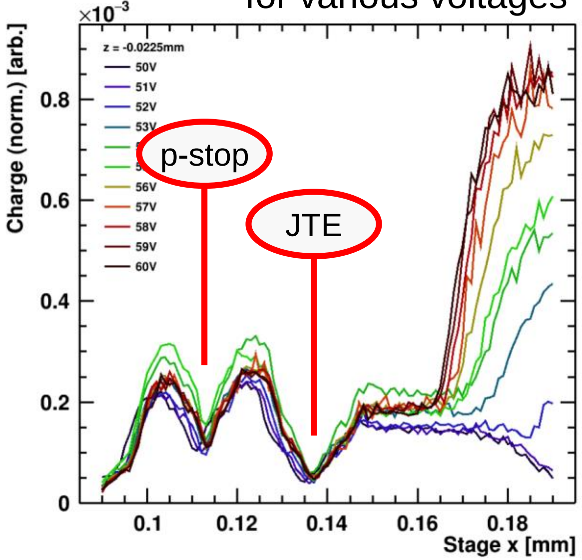
Images with Hirox microscope taken at CERN EP-DT QART lab

HPK2-W28-S1-LGAD-P14

LG 5x5-SE3-IP5-UBM



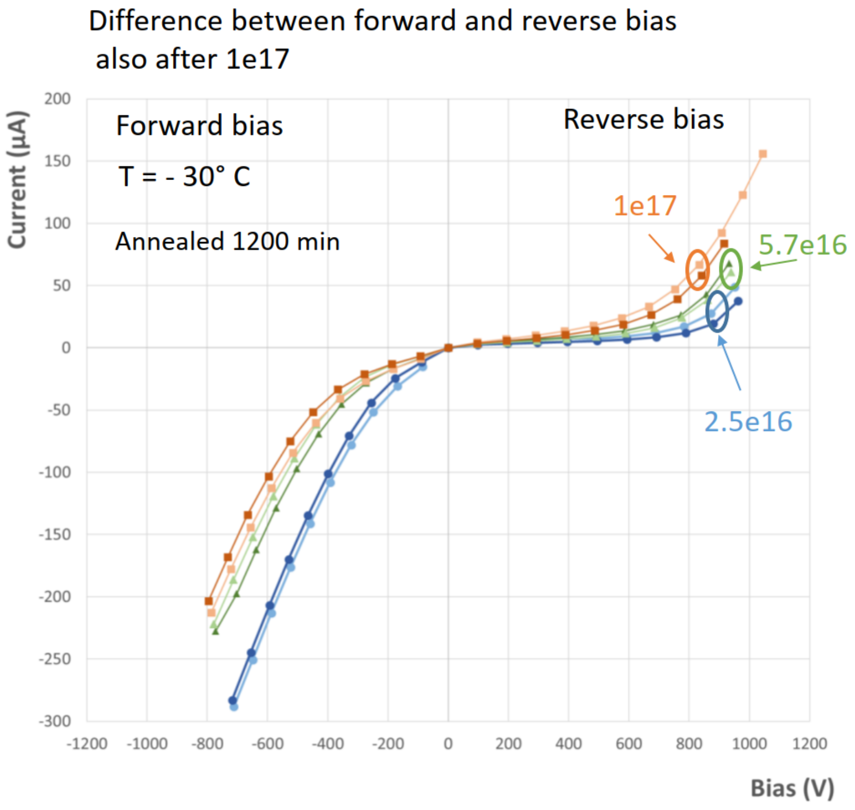
x scan at fixed depth for various voltages

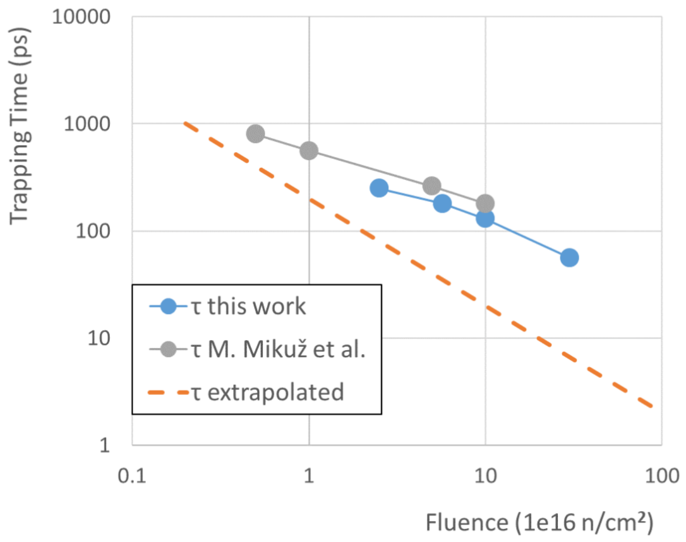


Extreme fluences (planar sensors)

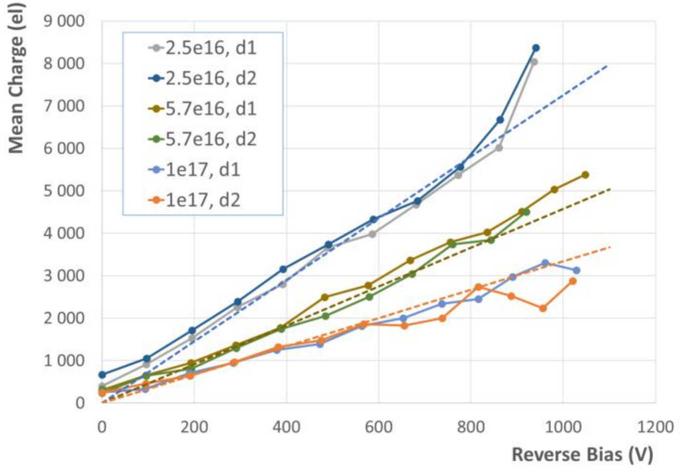
- Study of silicon detectors at extreme particle fluences of **10^{17} n_{eq}/cm^2 and beyond**
- Motivation: Development of tracking detectors for FCC-hh (or other high fluence environments)

  - 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)

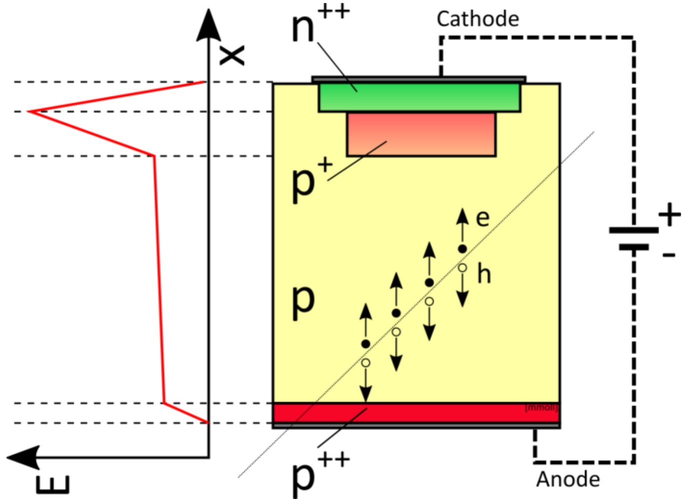
New Structures

Recent results 2019/21

2020

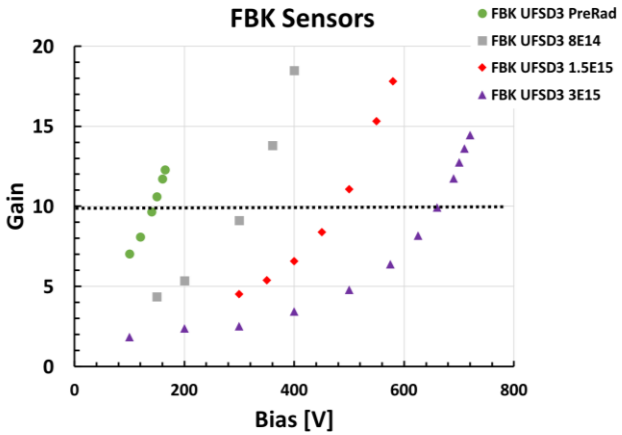
Sensors for 4D tracking
LGAD: Low Gain Avalanche Detectors

- **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
  - Will 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, ….)



Producers of LGADs

Producer	LGAD	Resistive readout (RSD)
IMB-CNM (Spain)*+	✓	✓
FBK (Italy)*+	✓	✓
Micron Semiconductors Ltd (UK) °	✓	
HPK (Japan)°	✓	✓
BNL (US)*+		✓
NDL (China)*+	✓	
IME (China)*+	✓	

* RD50 member
\+ RTO (Research and Technical Organisation)
° Commercial manufacturer

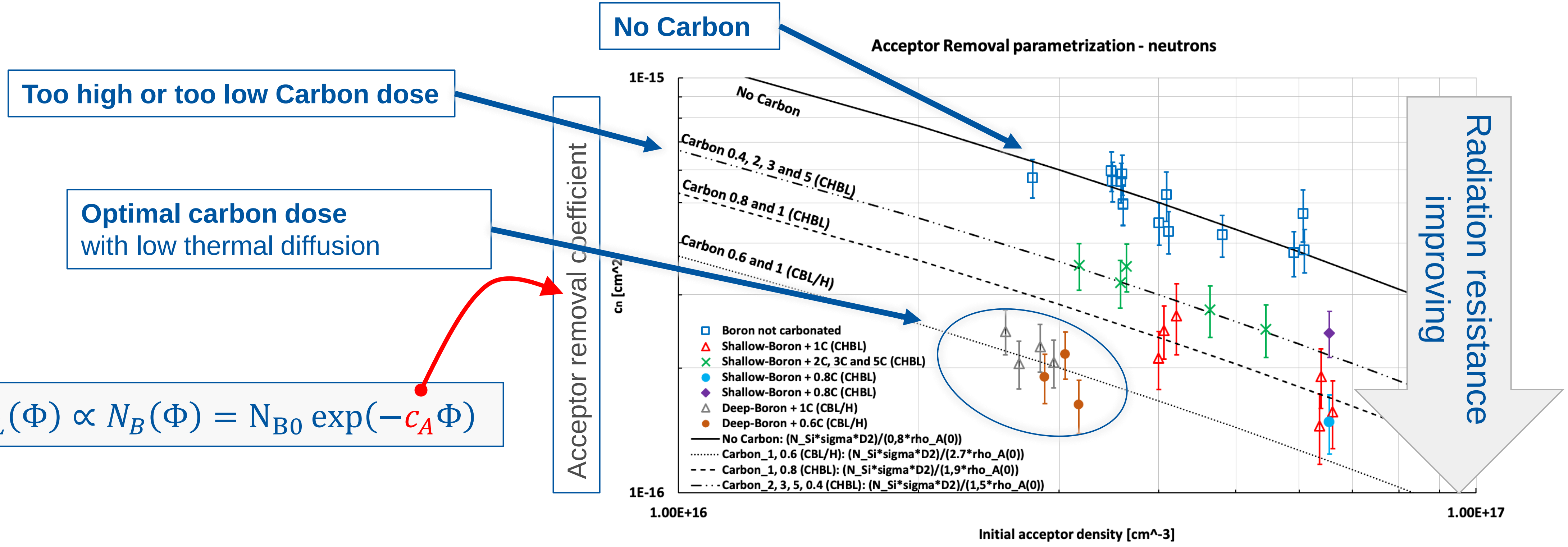
LGAD: Gain layer engineering

Defect Engineering of the gain layer

- **Carbon** co-implantation mitigates the gain loss after irradiation -> The mitigation effect depends on the Carbon dose.
- 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



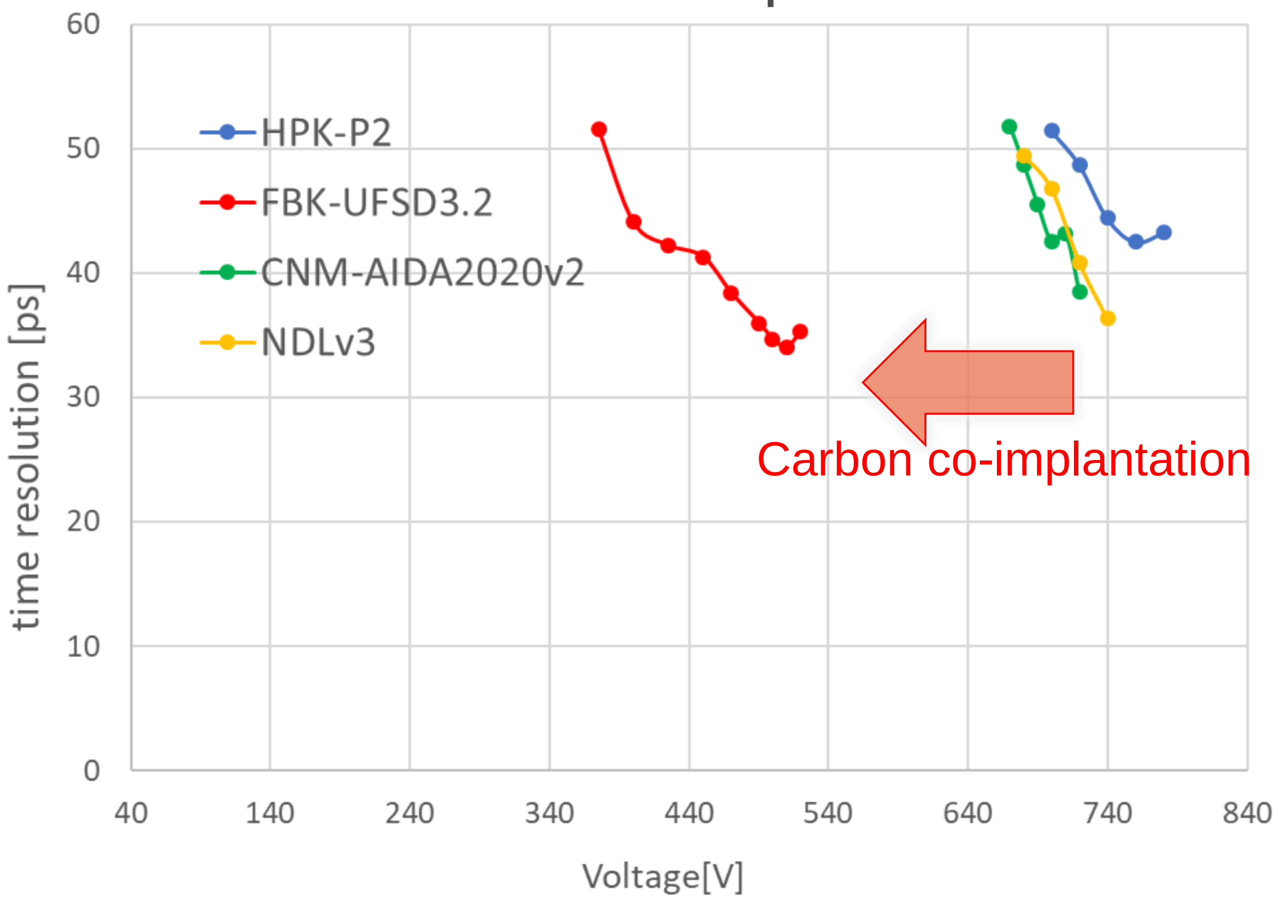
$$V_{GL}(\Phi) \propto N_B(\Phi) = \mathrm{N}_{\mathrm{B0}}\exp(-c_A\Phi)$$

[M. Ferero, INFN To, 37th RD50 Workshop]

LGAD: Time resolution after irradiation

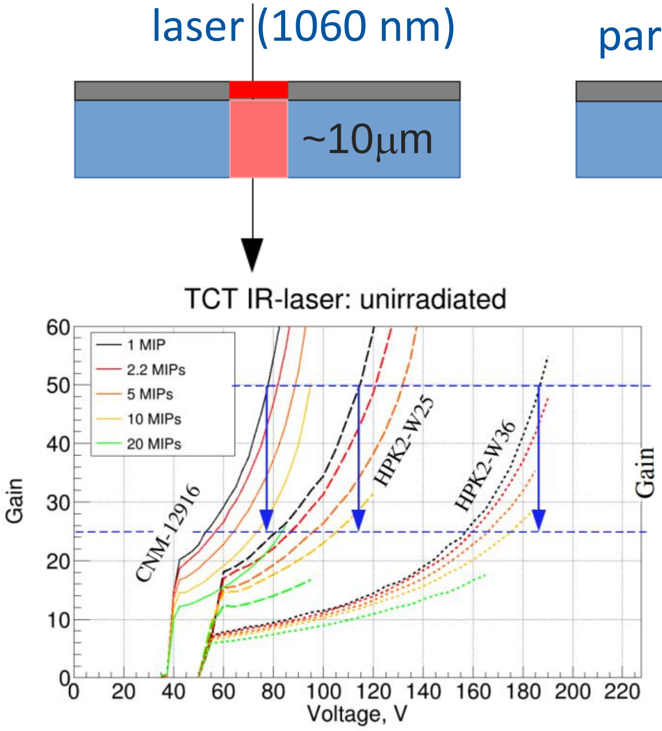
- Carbon co-implantation allows to reach an exceptional time resolution (~ 30 ps) after irradiation (2.5e15 $n_{eq}cm^{-2}$) using about 300 Volts less wrt not carbonated samples.

2.5e15 n_{eq} cm^{-2}

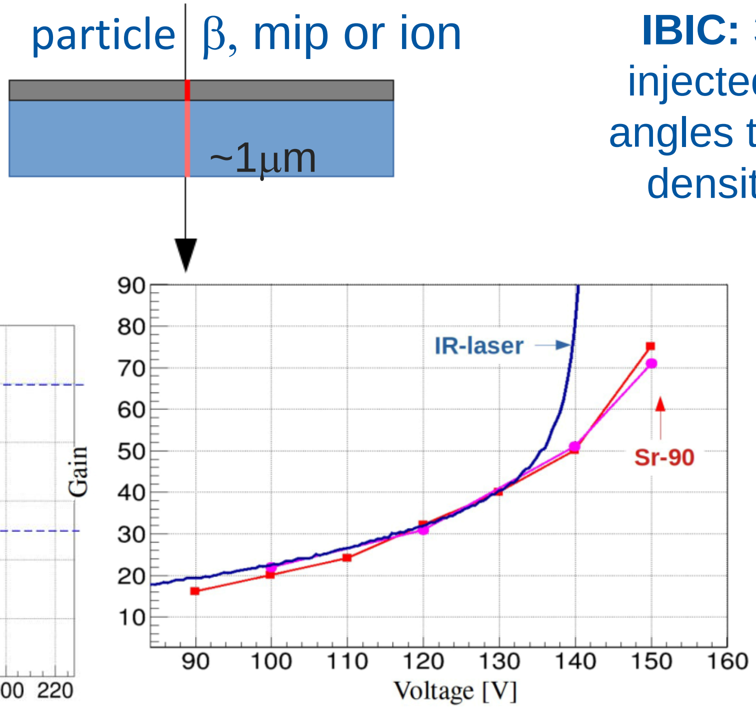


Gain suppression

- Ionization density matters for the gain (timing performance) of LGAD sensors
  - Signals obtained with a laser, a minimum ionizing particle or an ion are very different

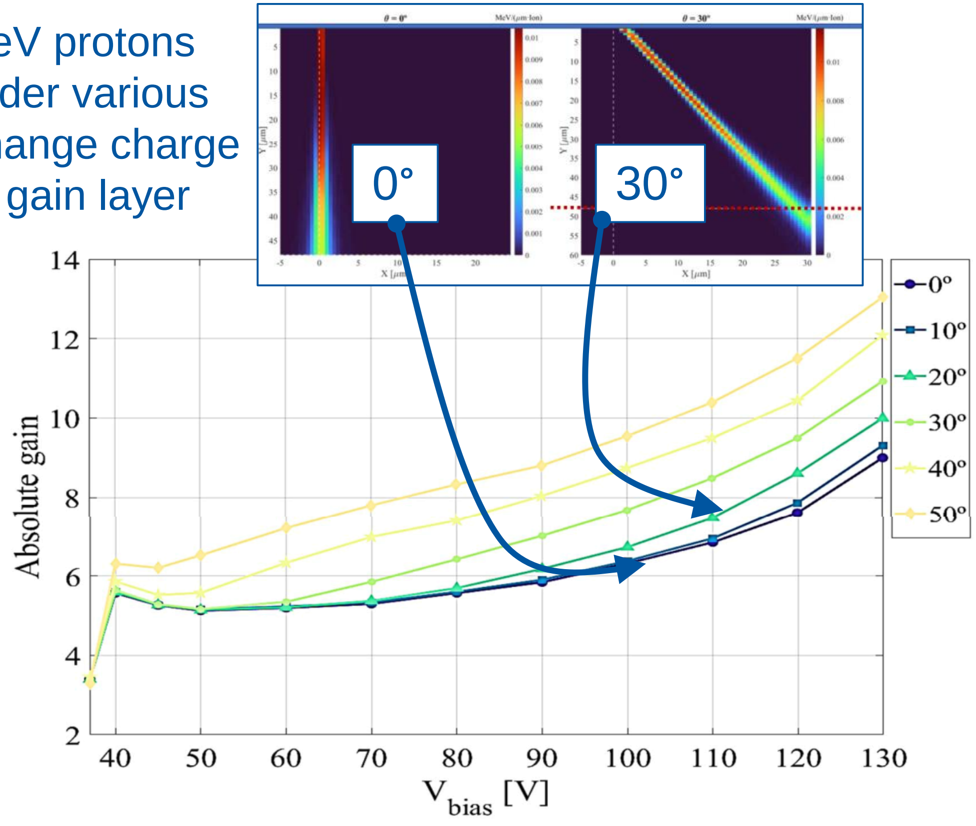


gain reduced with increasing laser intensity



impossible to match laser and Sr-90 over voltage range

IBIC: 3 MeV protons injected under various angles to change charge density at gain layer



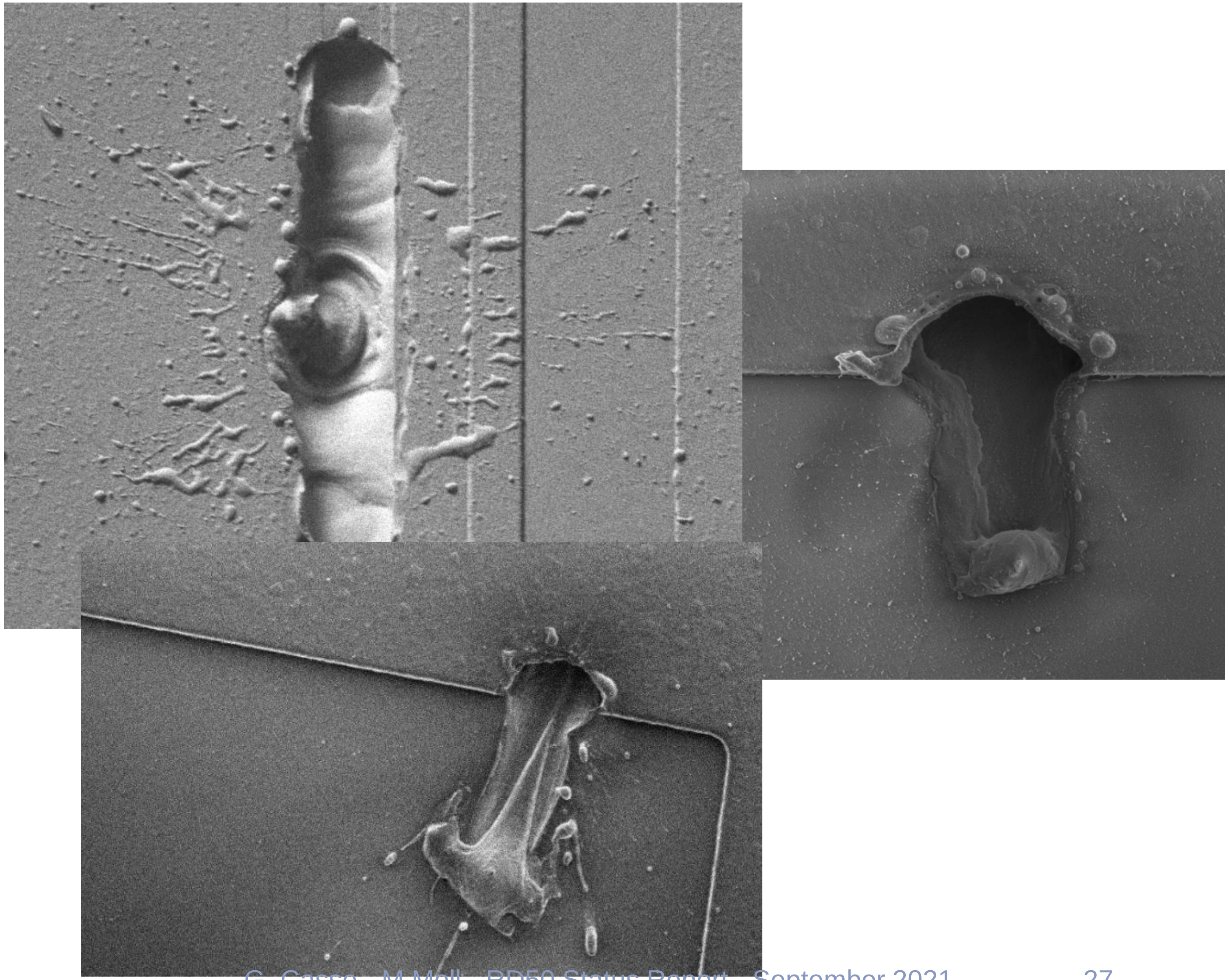
[E.Curras – RD50 Workshop – 6/2021]

[M.C. Jiménez-Ramos – RD50 Workshop – 6/2021]

- **Conclusion:** Evaluation of timing performance to be done in test beams (or with β-source)

LGAD Mortality during Test Beam

- There is an evidence for death of highly irradiated LGADs at test beam
- Fatal voltage: > 600V for 50 um Sensors
- Mortality is function of sensor thickness and voltage only (Gain is not necessary for death mechanism)
- Probably due to rare, large ionization events producing large current in narrow path
- Carbon co-implantation (lower operative bias!) or using thicker substrates should reduce the sensor mortality
- Studies performed in close collaboration with ATLAS and CMS timing detectors teams

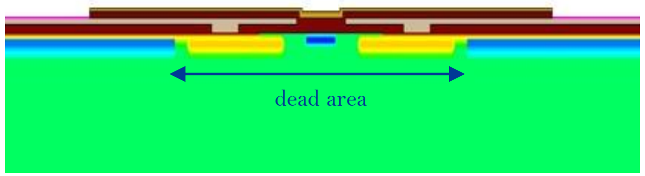


[Ryan Heller, 38th RD50 Workshop]
[Gordana Lastovicka-Medin, 38th RD50 Workshop]

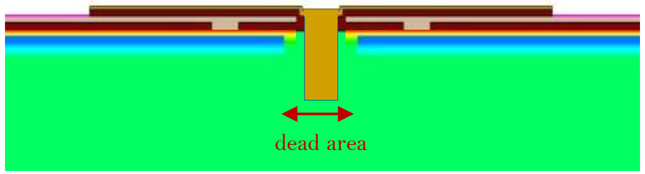
LGAD: Fill factor & performance improvements

- 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:

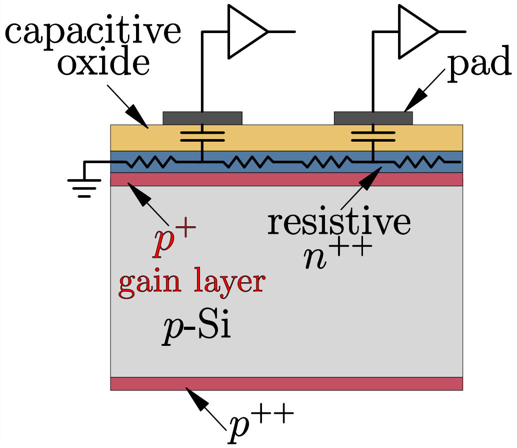
Trench Isolation LGAD	AC-LGAD	Invers LGAD	Deep Junction LGAD



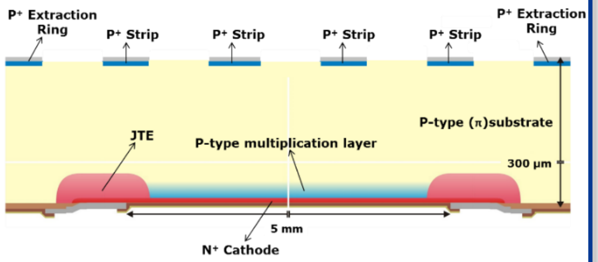
traditional gain isolation



trenches isolation (HD-LGAD)

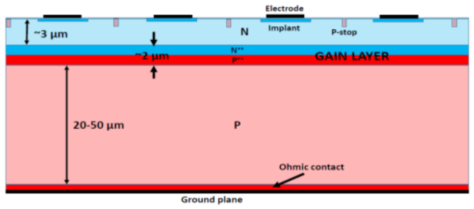


Front: segmented readout



Back: gain layer

Front: segmented readout



Gain layer located deep under front electrodes

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

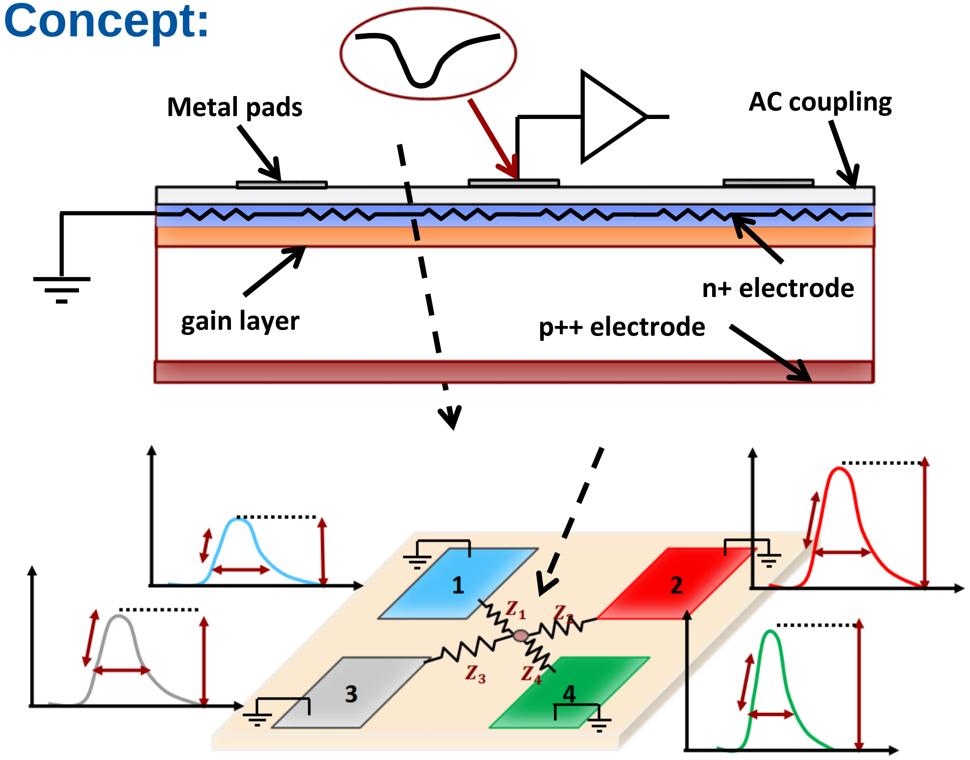
..new concept 2020

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

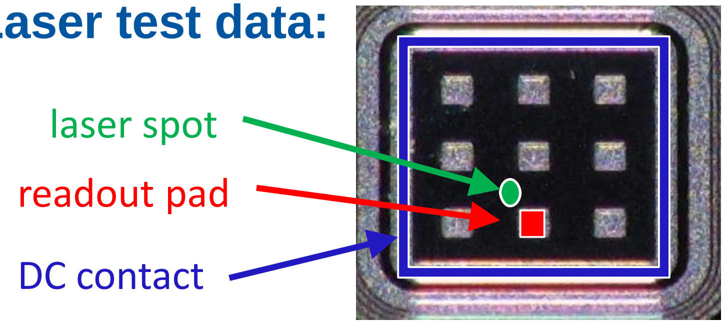
Resistive AC-coupled LGAD

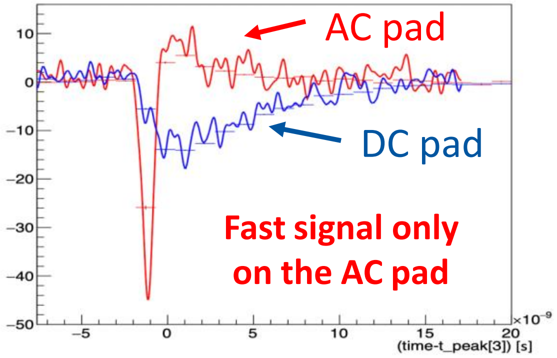
- Combining internal gain with internal signal sharing
  - Keep 100% fill factor (with continuous n^+ layer and continuous p^+ gain layer)
  - **Example: RSD project**: aim for resolution in position < 5μm and in time ~20-30 ps

Concept:



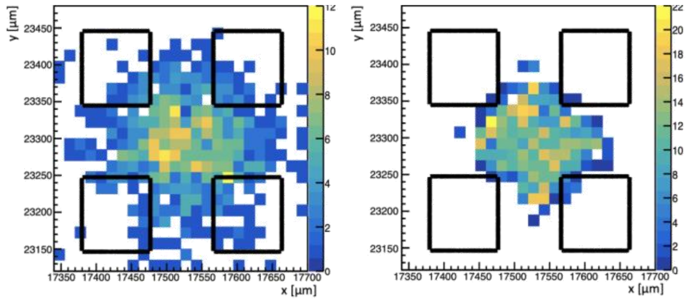
Laser test data:

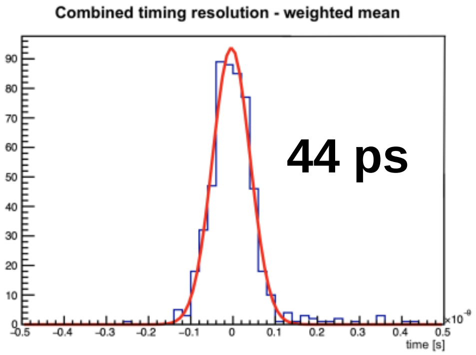




Test beam data:

Tracker coordinates – Sensor coordinates





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

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

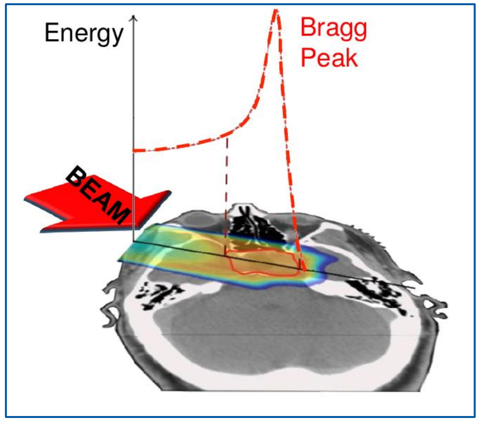
[M.Tornaga et al. – arXiv Feb/2021]

LGAD: Exploring applications outside HEP

RD50

Hadrontherapy: beam monitoring

- QA; Energy measure (TOF); Particle counting; Beam profile
- requirements similar to HEP but TOF using several particles



Development within the MoVeIT project

MoVe IT

Soft X-ray detection in synchrotrons and FELs

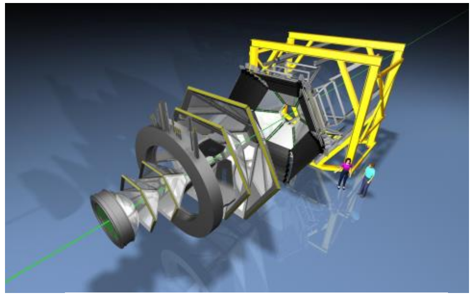
- Detection of soft X-rays (250 eV – 2 keV)
- Gain to:
  - lower detection limit of photon counting detectors
  - Improve SNR of charge-integrating detectors
  - Beam profile measurement
- Fully depleted sensors with thin entrance window must be developed

Development in collaboration with PSI

PAUL SCHERRER INSTITUT PSI

Nuclear Physics: HADES@GSI

- LGAD has been used to design and construct prototypes of time-zero detector for experiments utilizing proton and pion beams with High Acceptance Di-Electron Spectrometer (HADES) at GSI Darmstadt, Germany.
- The systems based on prototype LGAD detector operated at room temperature and equipped with leading-edge discriminators reach a time precision below 50 ps.



GSI

GSI Helmholtzzentrum für Schwerionenforschung GmbH

Astro particles: Strip-like, LGAD-type sensors

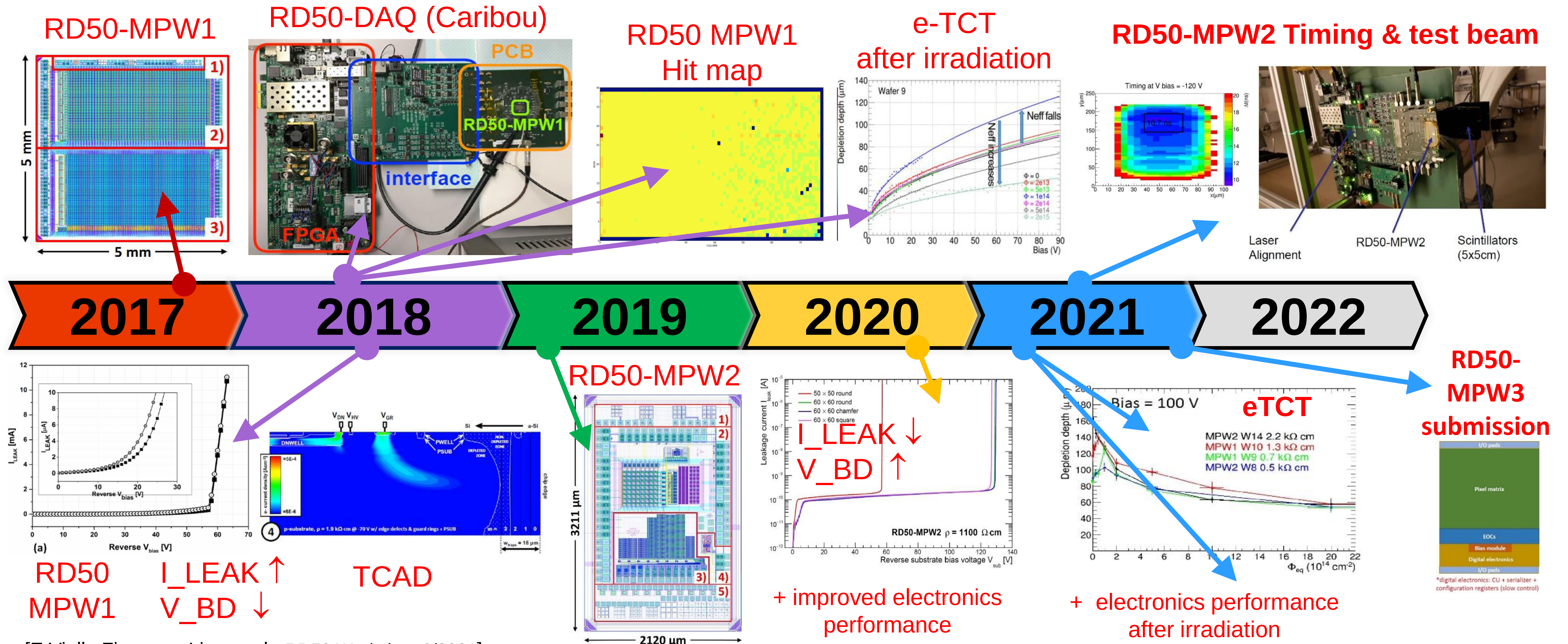
- high temporal (as well as spatial) resolution
- low material budget (thin silicon substrate)
- low power consumption (reduce number of channel)
- Low Earth Orbit experiment (radiation is not an issue)

In partnership with INFN

INFN

RD50: CMOS developments (150 nm)

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

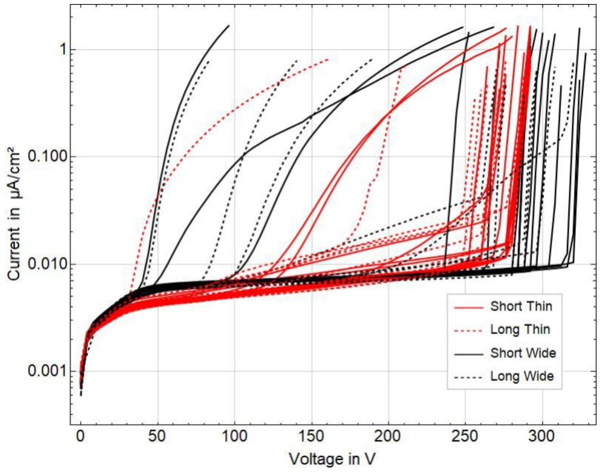


[E.Viella Figueras, Liverpool - RD50 Workshop 6/2021]

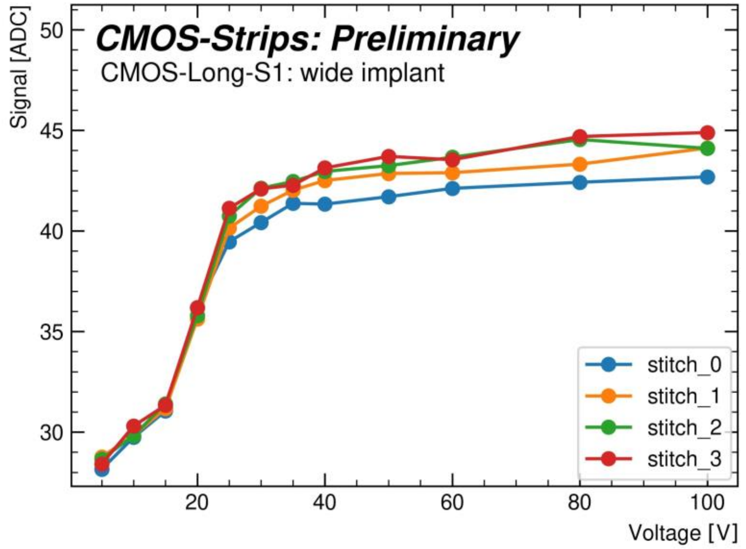
[P.Sieberer, HEPHY, Vienna –Trento Workshop 2/2021]

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

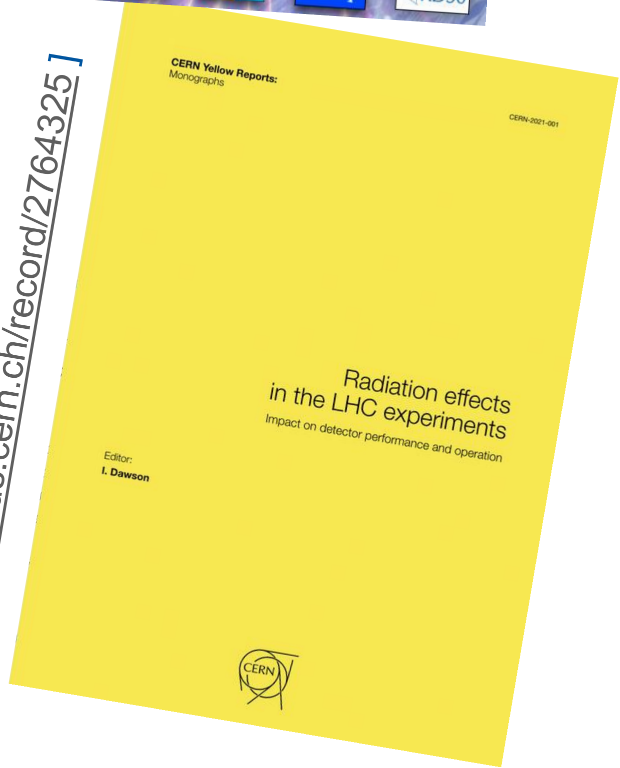
Recent results 2019/21

Radiation Effects in LHC Experiments

- 5 workshops on “Radiation Effects at LHC Experiments and Impact on Operation and Performance” organized (2011 - 2019)
  - Common Workshop: (ALICE), ATLAS, CMS, LHCb, RD50
    - Sensor Measurements
    - Electronics/Optoelectronics
    - Radiation Simulation and Monitoring
    - Sensor Simulation
- Outcome and follow-up:
  - Generally good agreement between RD50 damage prediction models (e.g.“Hamburg model”) and radiation damage observed by the LHC experiments.
  - More coherent approach in data analyses agreed and documented.
  - Modelling will have to be refined in some areas for run 3 !
- **CERN Yellow Report** written and edited by a team from RD50 & all LHC experiments has been published (154 pages, Radiation effects in the LHC experiments https://cds.cern.ch/record/2764325) summarizing observations, comparing results from different experiments against each other, listing open questions and outlining further work towards Run 3.

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

[https://cds.cern.ch/record/2764325]



Summary & RD50 achievements

- Presentation covered some highlights of ongoing work in the RD50 collaboration
  - ..selection of examples biased by the speaker ☺
  - ..detailed status of milestones in the RD50 workplan 5-years Workplan (2018-23) are given in the annex

- 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

- 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 fields (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.

Annex

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.

RD50 common projects

- Common Projects (2017 – 2021)
  - 2017-01 LGAD based on EPI wafers (G.Pellegini, CNM, Barcelona)
  - 2017-02 TPA TCT on CMOS sensors (I.Vila, Santander)
  - 2017-03 LGAD fabricated with epitaxial layer (G.Pellegrini, CNM, Barcelona)
  - 2017-04 RD50 CMOS submission (Gianluigi Casse, Liverpool, UK / Vitaliy Fadeyev, SCIPP, USA)
  - 2017-05 50 µm thin LGAD fabricated with Ga multiplication layer (Joern Lange, IFAE Barcelona)
  - 2017-06 Thin LGADs characterization using IBIC and time-resolved IBIC at CAN (Carmen Jiménez-Ramos, Sevilla)
  - 2017-07 MPW run with LFoundry (Eva Vilella, Liverpool)
  - 2017-08 50 µm thin AC-LGAD (Mar Carulla, CNM Barcelona)
  - 2018-01 Development of Segmented LGAD with small pixels and high Fill-Factor (Giovanni Paternoster, FBK)
  - 2019-01 RD50-MPW2 (Eva Vilella, Liverpool)
  - 2019-02 Proof of concept of 3D detectors fabricated in Silicon Carbide (SiC) semiconductor layers (Sofia Otero-Ugobono, CNM Barcelona)
  - 2019-03 Schottky diodes on Epitaxial Silicon for Radiation Damage Characterization of CMOS MAPS (Giulio Villani, STFC Rutherford Appleton Laboratory)
  - 2020-01 3D detectors optimized for timing applications (Gregor Kramberger, JSI,Ljubljana)
  - 2020-02 Proof-of-concept and radiation tolerance assessment of thin pixelated Inverse Low Gain Avalanche Detectors (ILGAD) (Ivan Vila, UC-CSIC, Santander)

3 new projects in 2021

- 2021-01 Production of Caribou CaR boards for the RD50 DMAPS (Dominik Dannheim, CERN)
- 2021-02 Characterization of GaN Based Materials, Electronics and Sensors, Subject to Large Radiation Doses (T.Koffas, Carleton)
- 2021-03 Defect engineering for sensors with intrinsic gain (Gkougkousis Evangelos – Leonidas, CERN)

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 26.8.2021
- RD50 MOU
  - RD50 Memorandum of Understanding (MoU) finalized and 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. [..a list of recent projects is given in the annex].
  - 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 requested from CERN (Host lab) (as previous years)
  - Operation of the RD50/Solid State Detectors Lab (1 physicist, 0.5 technician & 100kCHF/year)
  - Access to CERN and EP-DT facilities: Irradiation facilities, Bond Lab, Solid State Detector Lab,…
  - Administrative support at CERN through EP-DT secretariat
- Acknowledgement:
  - The CERN RD50 core team is supported through the EP Department and participates in the CERN EP R&D program for future experiments.

RD50 work plan
&
scientific projects

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

RD50

RD50 Prolongation Request

– May 2018 –

The RD50 Collaboration

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

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