EP R&D Day 2024, 22 May 2024

WP1.4. Solid-State Detectors

Characterization, Modelling and Radiation Hardening

Dominik Dannheim, Marcos Fernandez Garcia, Yana Gurimskaya, Veronika Kraus, **Michael Moll**, Younes Otarid, Faiza Rizwan, Niels Sorgenfrei, Peter Svihra, Moritz Wiehe

Alumni: Justus Braach, *Eric Buschmann, Esteban Curras, Katharina Dort, Anja Himmerlich, Jens Kroeger,* Vendula Maulerova-Subert, Magdalena Munker, *Sebastian Pape, Tomas Vanat*

on behalf of the WP1.4. team

WP1.4. Solid-State Detectors

Characterization, Modelling and Radiation Hardening

- The WP aims for enabling a fundamental understanding and performance optimization of solid-state detectors.
- The increasingly complex sensors, readout ASICs and monolithic devices require improved characterization techniques, detailed modelling and simulations and a better understanding and mitigation of radiation effects.

Radiation Damage & Mitigation Techniques

- radiation damage studies (modelling & defect characterization)
- radiation monitoring for irradiation facilities (NIEL project)
- radhard precision timing detectors (LGAD - Low Gain Avalanche Diodes)
- study of operation after extreme fluence exposure (FCC-hh)
- New materials: Silicon Carbide (4H-SiC) as new detector material

EP-RD

- WP1.1.
- WP1.2.
- WP1.3.
- WP1.4.

Solid-State Detectors - Characterization infrastructure

- provide characterization labs (EP-DT SSD lab & DAQ development lab)
- development of **new tools** and characterization campaigns:
  - laser testing; Two Photon Absorption–Transient Current Technique (**TPA-TCT**)
  - defect characterization tools; high temperature cryostat for SiC testing
  - modular and flexible readout systems: **CARIBOU** DAQ system
  - test beam infrastructure: test beam and telescope upgrades

WP1.4.: Resources & External Participants

- WP1.4. core resources (2024)
  - 1.5 FTE Graduates/Fellows
  - 1.2 FTE DOC/TECH students
  - 150 KCHF materials *(incl. special carry over for new cryostat)*
- Resources through other programs (essential!)
  - Close collaboration with other EP-RD silicon WPs
  - Gentner Prg., PCB Fellow prg., EP/DT labs & services
  - AIDAinnova, EUROLABS, RD50/DRD3, ..
    - common activities with external teams combining resources (e.g. common production runs)
- Participants
  - WP1.4.& WP1.x EP-RD teams at CERN
  - Several external collaborators (see slides on specific WP1.4. projects)

- AIDAinnova (2021-25)
  - WP1.4. members are leading tasks
  - CERN (WP1.4.) is beneficiary in:
    - **Task 3.5**. Development of common DAQ hardware [**Caribou project**]
    - **Task 4.3**. Common tools for irradiation facilities quality control [**NIEL project**]
    - **Task 4.4**. Design & development of a TPA-TCT characterisation system [**TPA-TCT project**]
    - **Task 6.3** Validation of common 3D and LGAD sensor productions [**LGAD project**]

- DRD3/RD50
  - WP1.4. projects are part of DRD3 work program
  - WP1.4. members hold management roles in DRD3
  - Several DRD3 projects with financial contribution:
    - Caribou common board production
    - TPA-TCT beam time at laser facilities
    - Common production of test structures (e.g. LGADs)

- EURO-LABS (2022-26)
  - TA to irradiation facilities

WP1.4. Team at CERN

- *Michael Moll & Dominik Dannheim (WP leaders)*
- *Marcos Fernandez-Garcia (IFCA, Spain, visiting scientist)*
- *Yana Gurimskaya (Solestial Inc., USA, visiting scientist)*
- *Ruddy Costanzi (Technical Engineer EP-DT, support)*

- **Moritz Wiehe** *[since Sept.22]*
  - Fellow, **WP1.4. funded**
  - defect & sensor studies


Moritz

- **Faiza Rizwan** *[since Sept.23]*
  - *Fellow, PCB program*
  - *SiC sensors*

Faiza


- **Niels Sorgenfrei** *[since Mar.23]*
  - DOCT, Gentner Prg.
  - defect characterization


Niels

- **Veronika Kraus** *[since May 23]*
  - DOCT, Austrian Prg.
  - LGAD, TPA-TCT


Veronika

- **Younes Otarid** *[since June 23]*
  - Quest Graduate **WP1.2./1.4. funded**
  - Caribou, DAQ, MAPS


Younes

- **Peter Svihra** *[Oct.21 - Sept.24]*
  - Fellow, WP1.3.
  - Test beam & lab hardware
  - Hybrid assembly testing

Peter


- **Justus Braach** *[Mar.21-Feb.24]*
  - DOCT, Gentner Prg.
  - Test-beam & lab hardware, MAPS


Justus

- **Vendula Subert** *[Nov.20 – Apr.24]*
  - DOCT, **WP1.4. funded**
  - NIEL studies, Geant4, TRIM

Vendula


+ many more collaborators ….

WP1.4. Alumni's: Eric Buschmann [Fellow, until Jul.23], Esteban Curras [Fellow, until Feb.23], Anja Himmerlich [Fellow, until Jan.23], Katarina Dort [DOCT, until June 22], Sebastian Pape [DOCT, until Feb. 24]


Sebastian


Eric

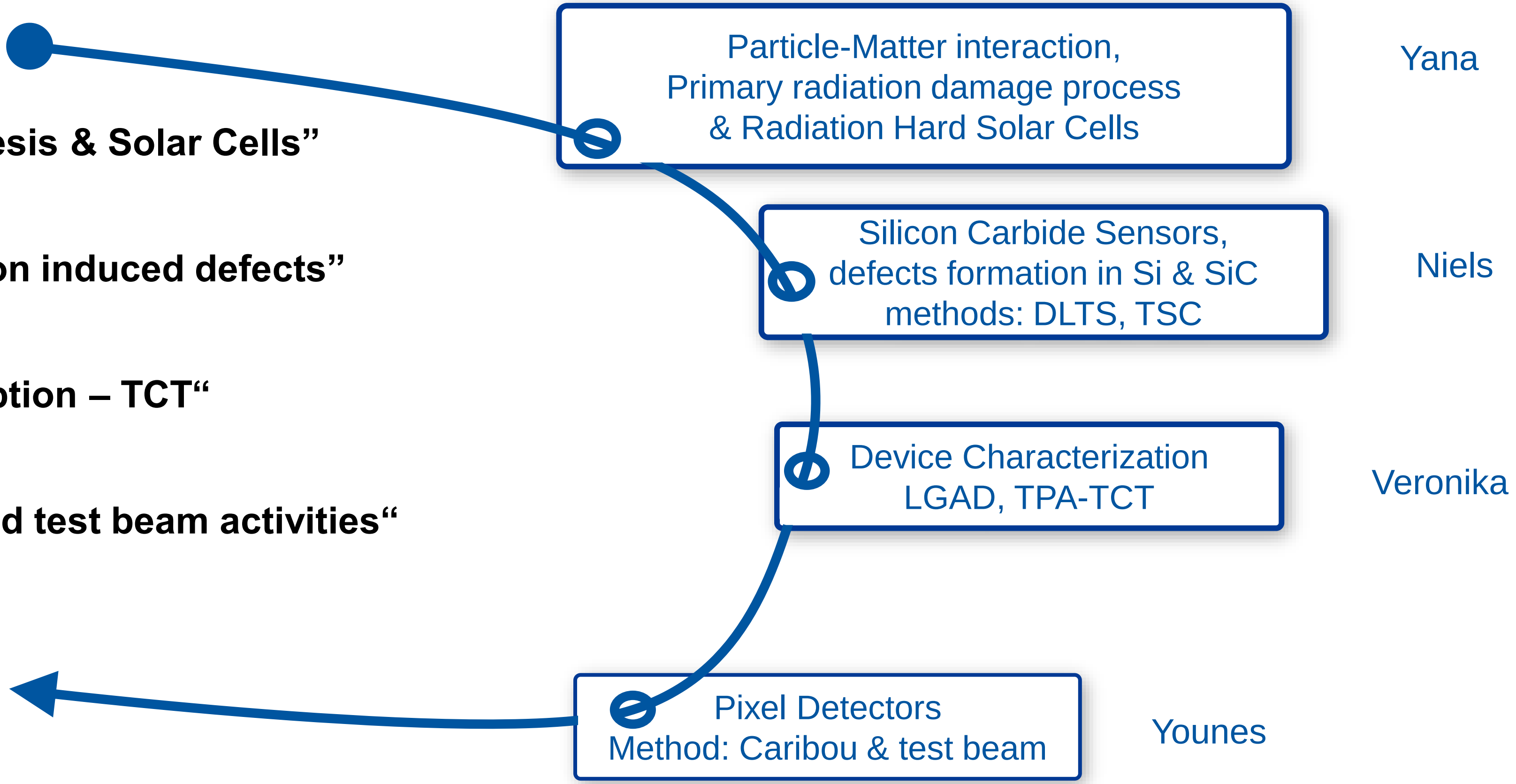

Esteban


Anja


Katharina

Todays WP1.4. Activity Overview

- Introduction (Scope, Resources, Collaborations, Team)
- **WP1.4. Activity Overview**
  - **“Revision of the NIEL Hypothesis & Solar Cells”**
    Yana Gurimskaya
  - **“SiC and Si sensors & radiation induced defects”**
    Niels Sorgenfrei
  - **“LGADs & Two Photon Absorption – TCT“**
    Veronika Kraus
  - **“Caribou, EP-RD telescope and test beam activities“**
    Younes Otarid



- Summary & Outlook
- Annex
  - Publication list [2022-24]
  - DRD3 collaboration on Solid State Detectors
  - WP1.4 main achievements

Revision of the NIEL Hypothesis
&
Silicon Solar Cells for Space Applications

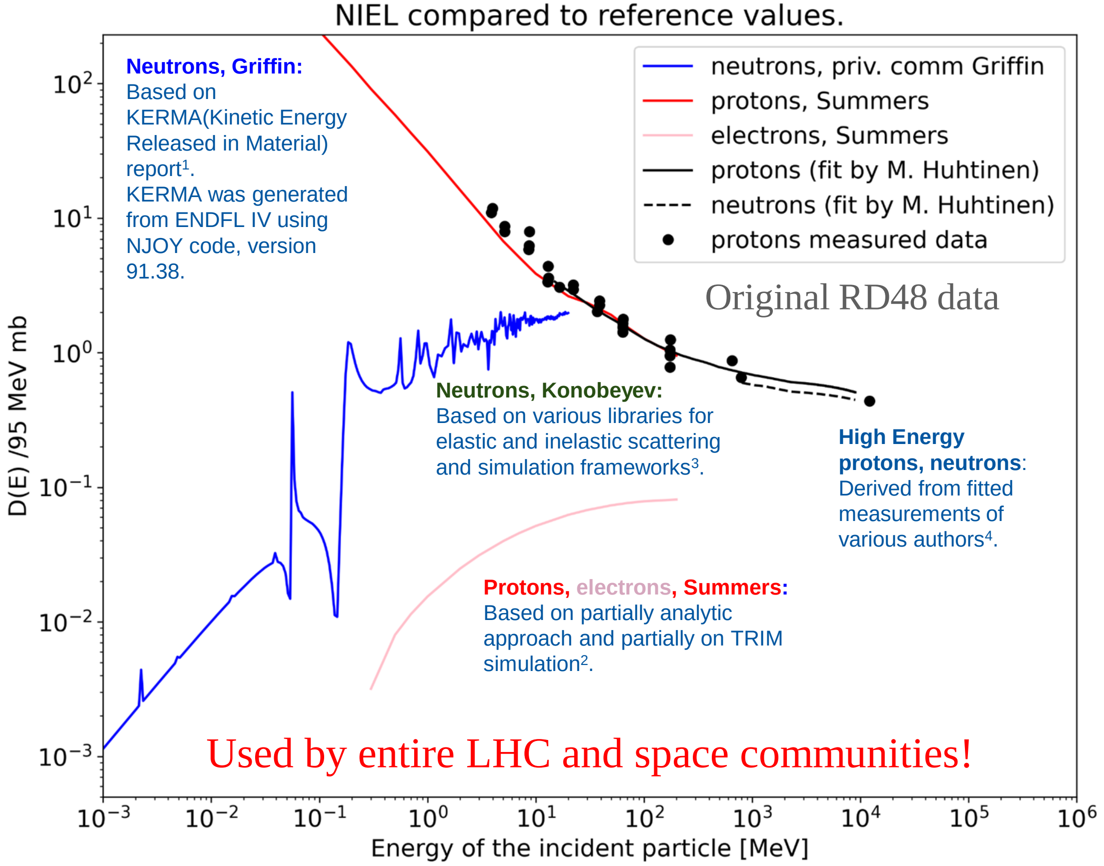
Yana Gurimskaya (Solestial Inc.)

Revision of NIEL hypothesis

- **NIEL** is a physical quantity describing non-ionizing energy loss as the particle travels through the medium
- The amount of **NIEL** can be correlated to the amount of radiation damage (NIEL scaling) and therefore to predict the lifetime of detectors
- Fluence is expressed in 1 MeV neutron eq. ∽95 MeV mb

$$NIEL(T_0) = \frac{N_A}{A} \sum_i \int_{T_{min}}^{T_{max}} Q(T)T\left(\frac{d\sigma}{dT}\right)_i dT$$

- T_0: energy of incident particle
- T: energy transferred to the recoil atom
- $(d\sigma/dT)$: differential partial cross section for a particle with energy T_0 to create a recoil atom with energy T in the i-th reaction
- $Q(T)$: partition factor giving the fraction of T that is going into further displacements
- N_A: Avogadro number
- A: atomic mass of target atom



Revision of NIEL hypothesis

Radiation damage in p-type Si pad diodes

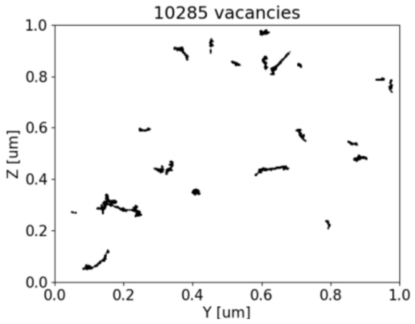
Shortcomings:

- **NIEL** doesn't describe cluster to point defect formation
- macroscopic **NIEL** violation reported in oxygen-enriched Silicon (CERN RD48)
- **NIEL** doesn't describe difference between proton vs neutron damage

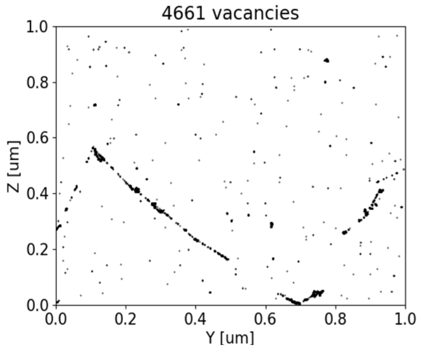
PhD thesis output:

- Re-calculate **NIEL** & reproduce RD48 curves
- Benchmark experimental **NIEL** against theoretical **NIEL**
- **NIEL** hypothesis revision with efforts to produce 2-parameters scaling including partition of NIEL into clusters and point-defects contribution
- Good understanding of full radiation damage process:
  - Primary interactions and **PKA energy distribution**
  - Spatial distribution of displaced **interstitials** and **vacancies**
  - Stable **point** and **cluster** defects formation

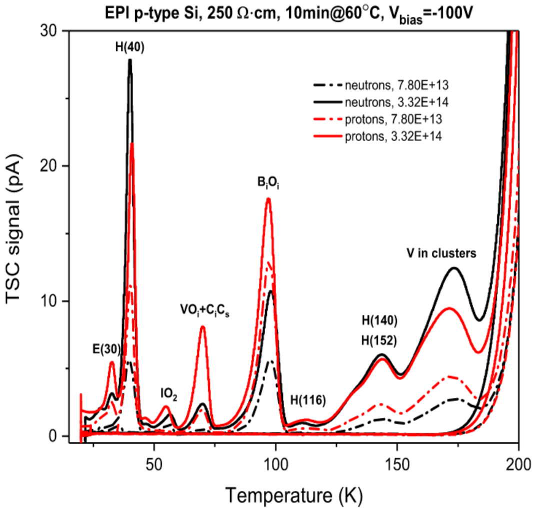
Recent simulations of radiation damage with GEANT4+TRIM



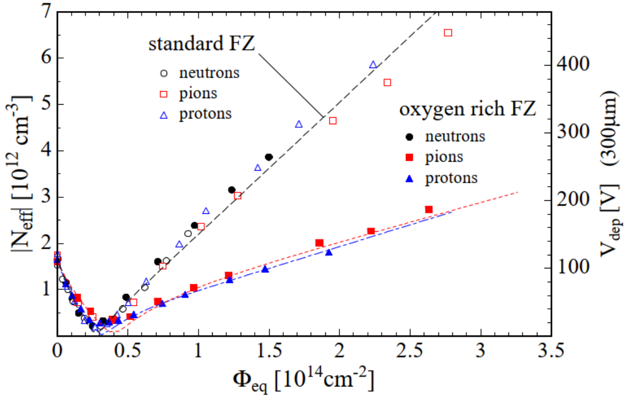
1 MeV neutrons



24 GeV protons



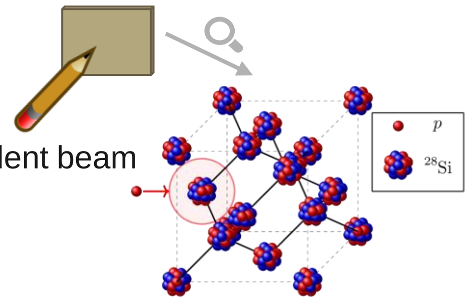
CERN RD48 : O-enriched silicon sensors



NIEL - simulations workflow

GEANT4

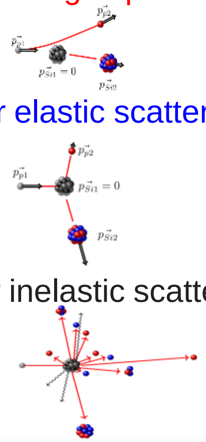
Incident beam



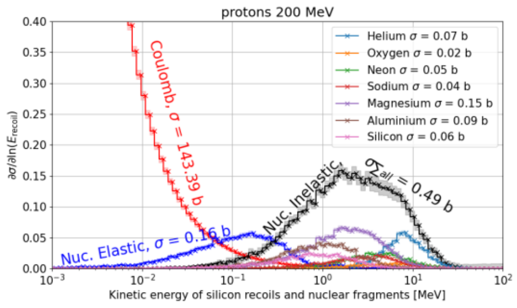
1. Coulomb elastic scattering (only charged particles)

2. Nuclear elastic scattering

3. Nuclear inelastic scattering

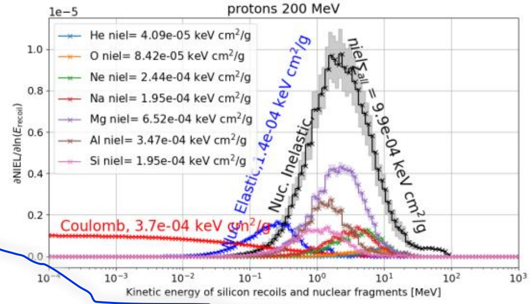


PKA distribution



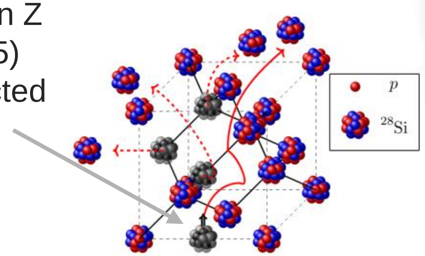
Area below the curve corresponds to cross section, DD threshold 21 eV

NIEL/NIEL$_{vac}$ distribution for high *E* particles

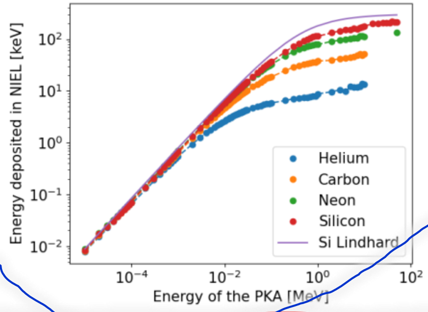


TRIM

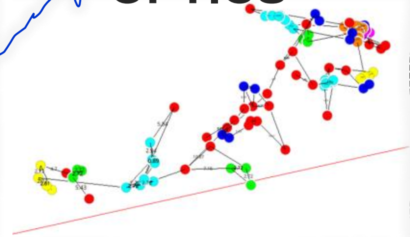
Ion in Z (1,15) injected



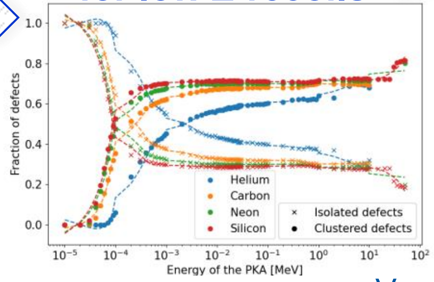
NIEL of low E recoils



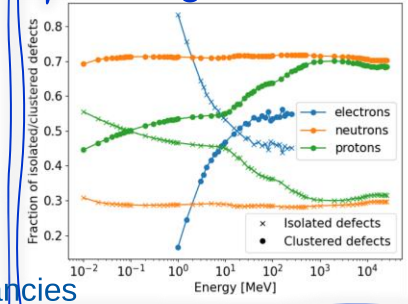
OPTICS



Isolated/Clustered for low *E* recoils



Isolated/Clustered for high *E* recoils



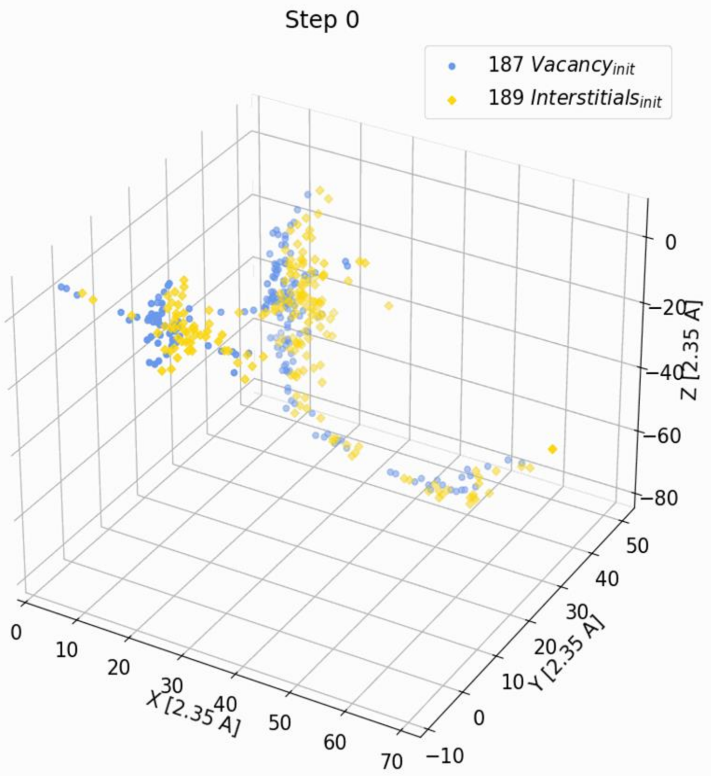
Vacancies

- Combination of different simulation tools allows better understanding of Displacement Damage mechanisms
- Clustering tool established

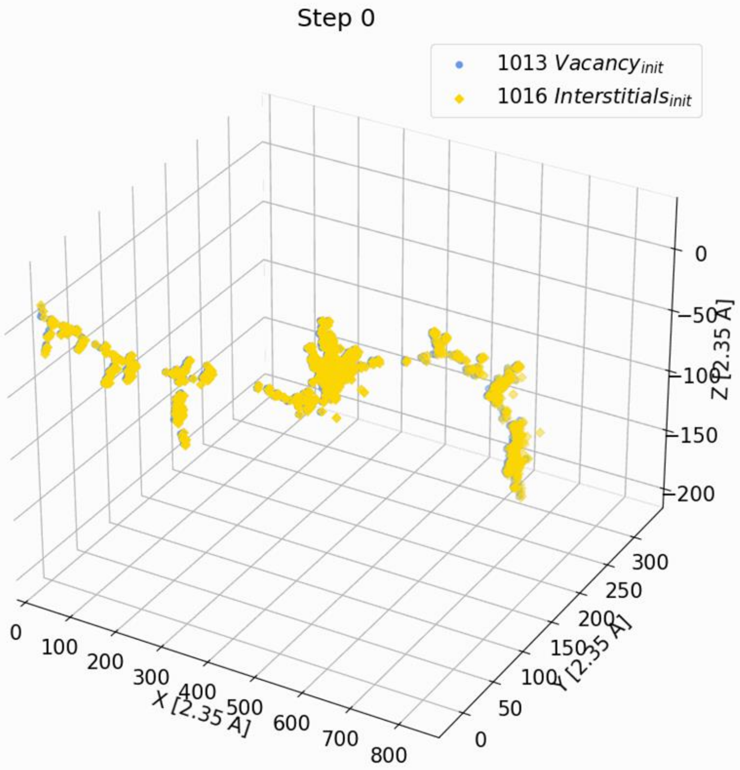
NIEL curves (CERN RD48) can be reproduced!

Revision of NIEL hypothesis

Silicon 10 keV PKA



Silicon 100 keV PKA



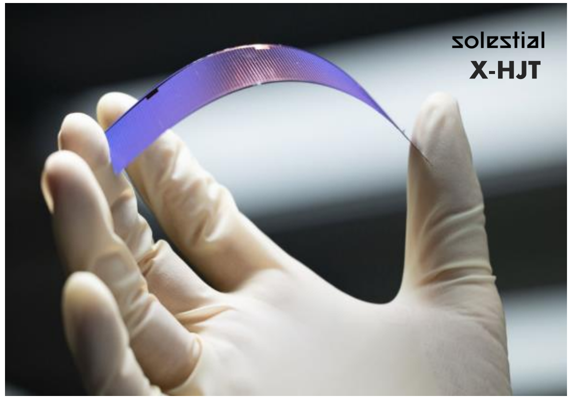
Isolated vs. clustered vacancies and interstitials

Outlook:

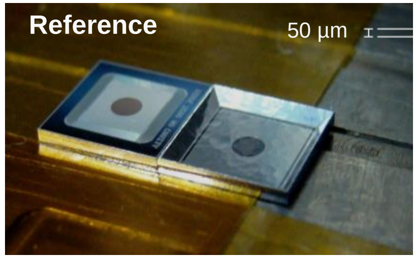
- Comparison of results to FLUKA by external project partners
- Production of dosimeters and custom test structures for NIEL scaling and hardness factor evaluation
- Characterisation after ultra-high fluences >1E+16 n_{eq}/cm^2
- Dosimetry concept and monitoring sensors for ultra-high fluences

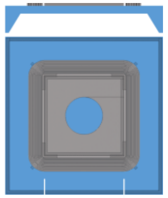
Silicon Solar Cells for Space

CERN KT Collaboration Agreement KN5705/KT/EP/263C



- Rad-Hard Silicon solar cells – 'X-HJT'
- Defect-engineered B-doped CZ Si, 20 µm
- Self-curing of radiation damage at operational temperatures (60-90°C)

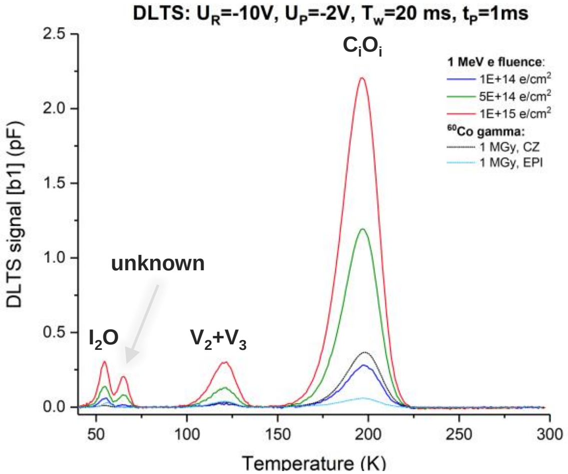


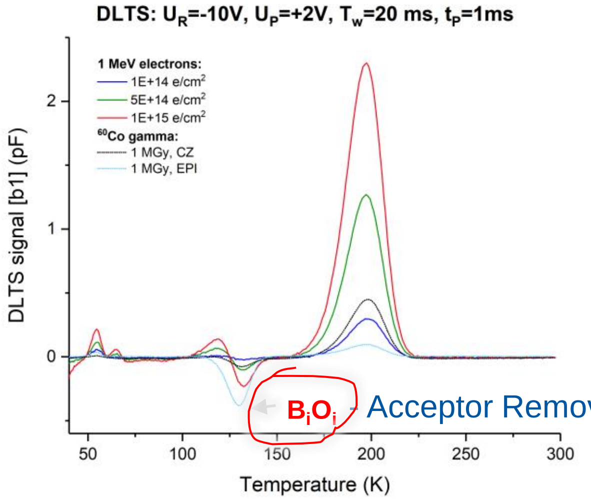


CiS Forschungsinstitut für Mikrosensorik GmbH

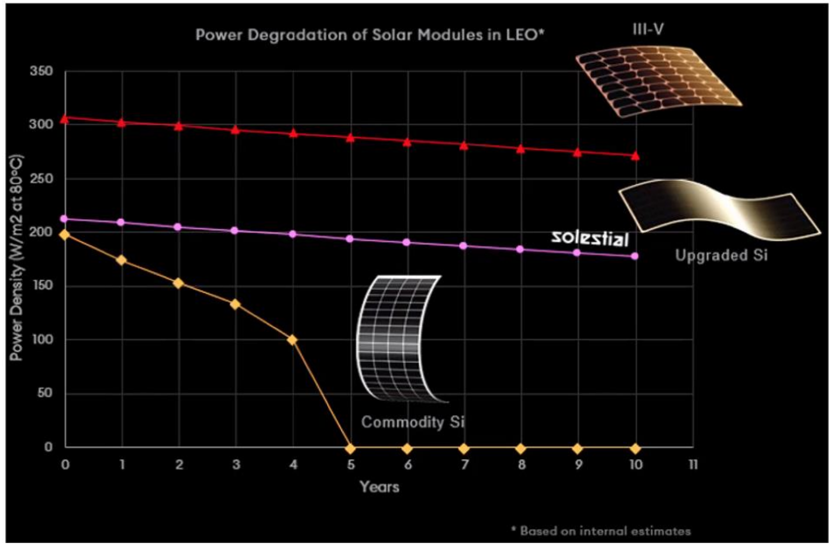
- Reference test structures
- B-doped CZ p-Si with known B, C and O content

- Radiation/annealing testing
- Defect spectroscopy → fundamental damage mechanism:





Acceptor Removal candidate – see Niels's presentation



- Space PV Standards revised in 2023
  - 1 MeV $\bar{e}$: 1E+14 - 1E+16 e/cm²
  - 100 keV - 3 MeV p: 1E+10 - 1E+12 p/cm²

→ **NIEL violation for low *E* and high φ**

- Need to re-evaluate dosimetry methods → Si solar cell as radiation detectors

Outlook: New test structures in production

solestial

EP R&D Day 2024, 22 May 2024

Silicon Carbide (4H-SiC) as Detector Material
&
Defect Spectroscopy on Si and SiC

Niels Sorgenfrei (CERN, University of Freiburg)

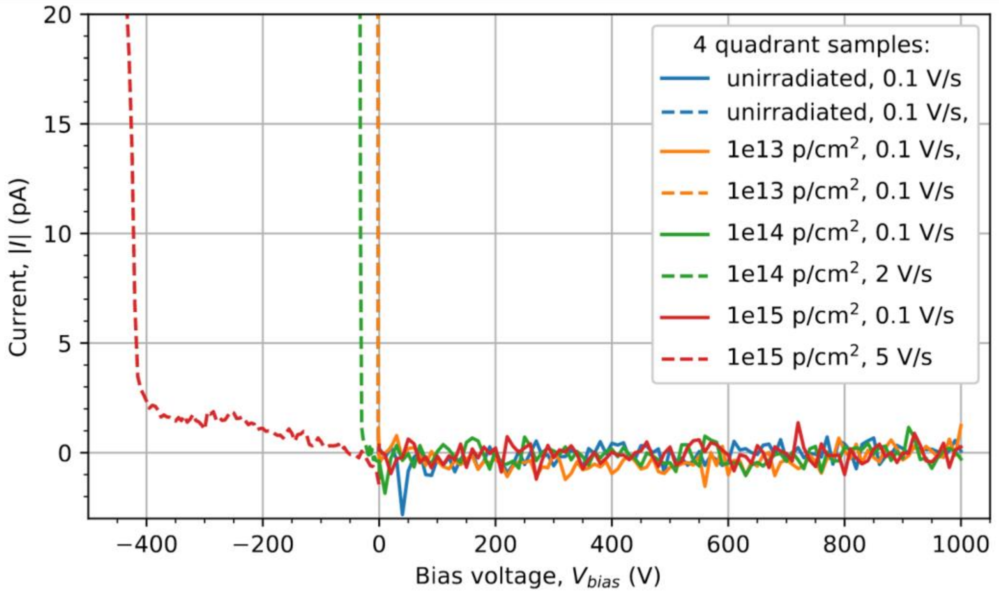
SPONSORED BY THE
Federal Ministry of Education and Research

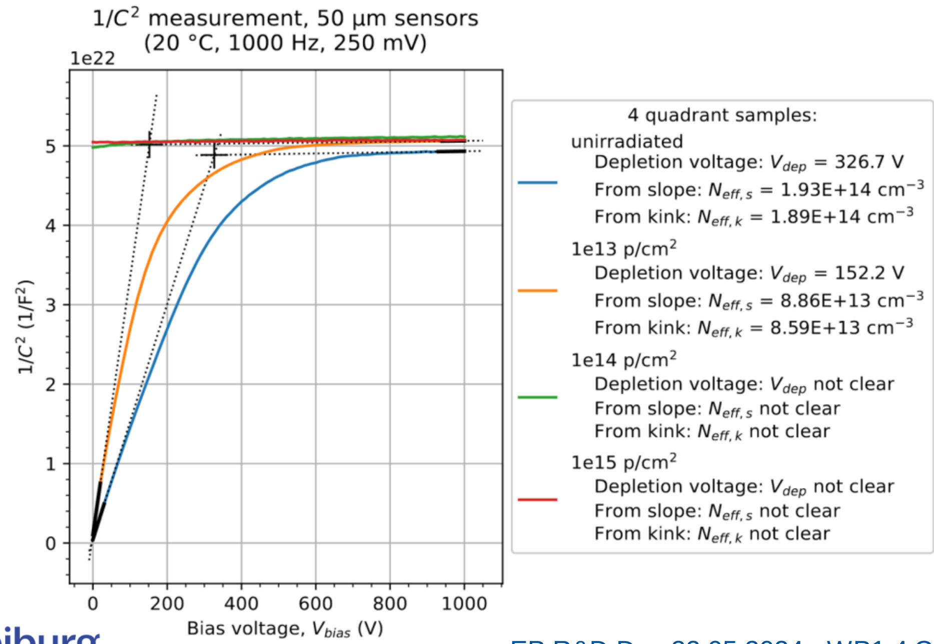
New Activity: Silicon Carbide

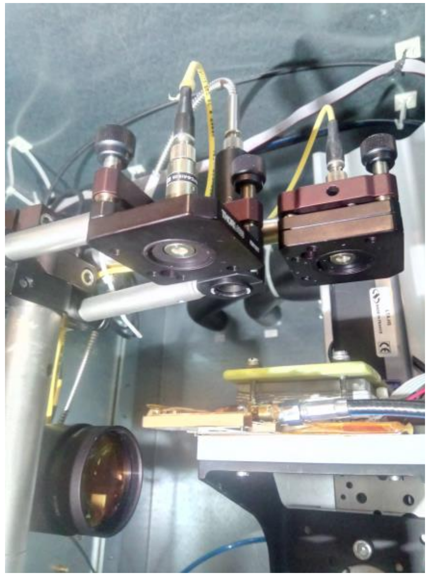
Property (@ 300 K)	Si	4H-SiC
Bandgap [eV]	1.12	3.27
Threshold displacement energy [eV]	21	30–40
Breakdown electric field [V/cm]	$3 \cdot 10^5$	$3–4 \cdot 10^6$
Thermal Conductivity [W/K cm]	1.5	4.9
Electron Saturation Velocity [cm/s]	$0.8 \cdot 10^7$	$2 \cdot 10^7$
Electron mobility [cm^2/V s]	1450	800
Hole mobility [cm^2/V s]	450	115
Relative Permittivity	11.7	9.7

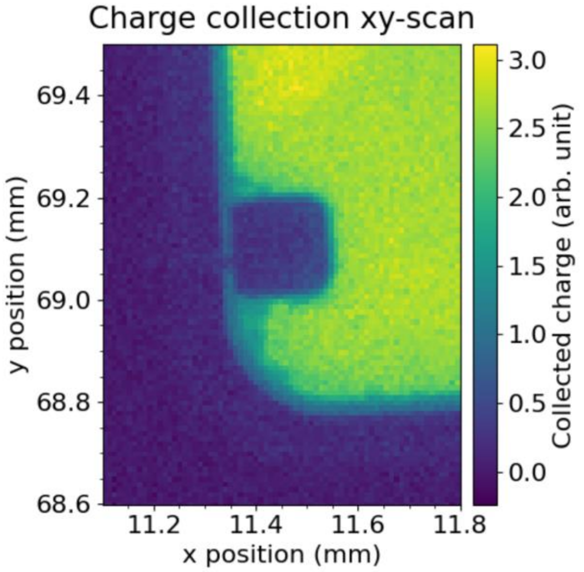
- extremely low leakage currents
  - at elevated temperatures
  - under ambient light
- excellent thermal conductivity
- SiC is not a replacement for Si per se, but good for specific applications (e.g. neutron detectors)

Silicon Carbide: Diode Characterisation

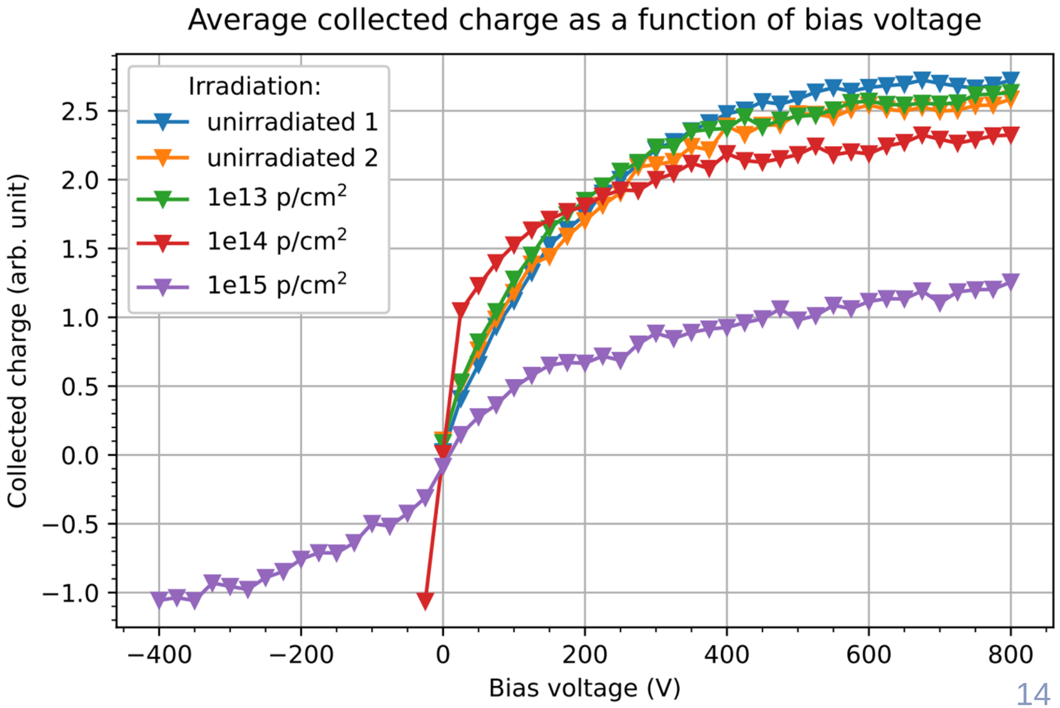




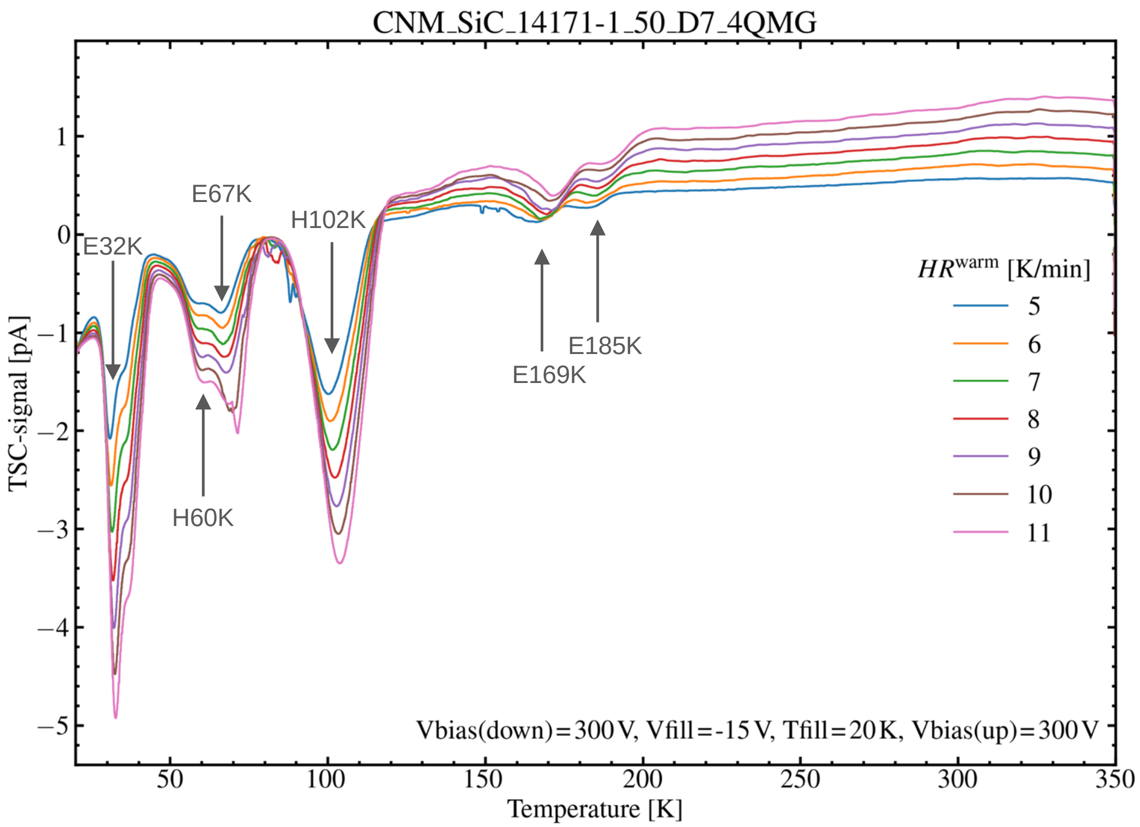


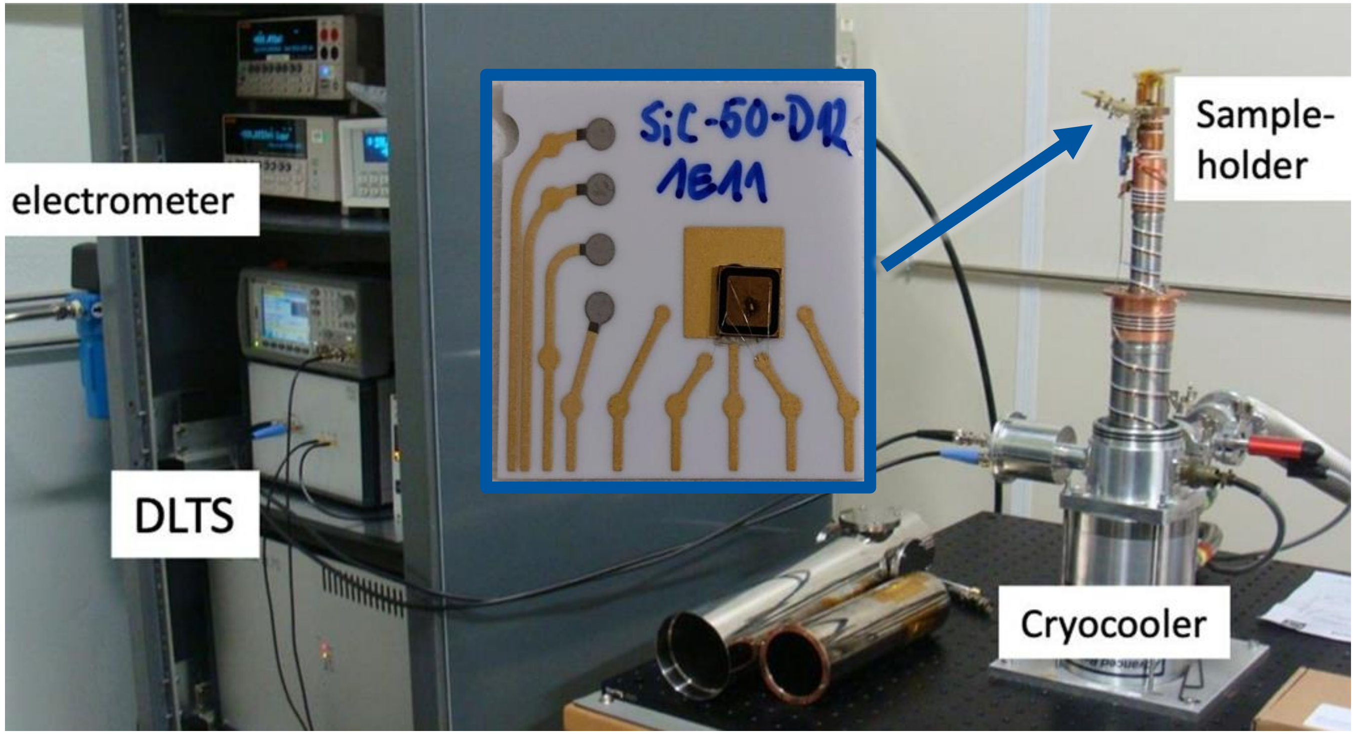


new UV laser installed in TCT+ setup



Silicon Carbide: Defect Spectroscopy (TSC & DLTS)





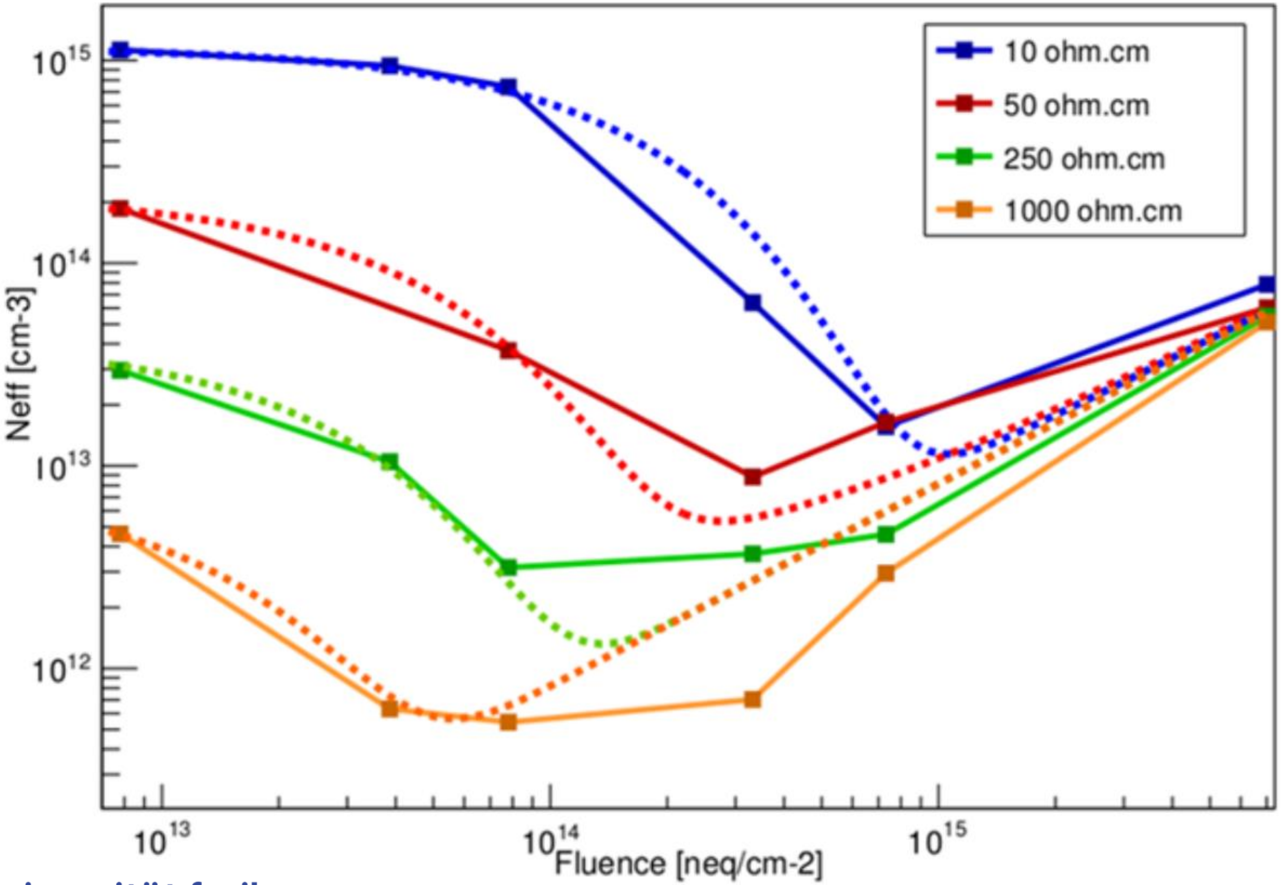
- limited in temperature to 350K
  - for full bandgap need up to 800K
- high temperature cryostat purchased (delivery this summer)
- study of SiC-LGADs (production under way)

Silicon: Acceptor Removal

apparent deactivation of doping/acceptors (Boron) due to radiation

$$N_{eff}(\phi_{eq}) = N_{A,0}\exp(-c_A\phi_{eq}) + g\phi_{eq}$$

$$W_{depl} \approx \sqrt{\frac{2\cdot\varepsilon}{q_0\,|N_{eff}|}\cdot V_{bias}}$$



neg. space charge

neutral

$Si_i + B_s \rightarrow B_i \rightarrow B_i + O_i \rightarrow B_iO_i$

pos. space charge

For every removed Boron an acceptor is lost and a donor is created (factor 2)

Mechanism for the reduction of gain in LGADs

LGAD

Low Gain Avalanche Detectors

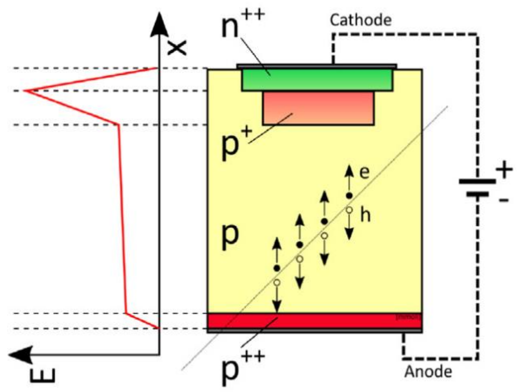
&

TPA-TCT

Two Photon Absorption Transient Current Spectroscopy

Veronika Kraus (CERN, TU Vienna)

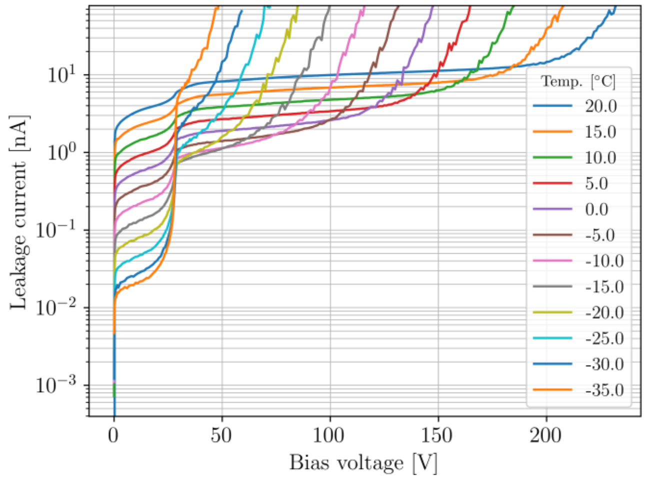
Low Gain Avalanche Detectors (LGADs)



Schematic cross-section of a Low Gain Avalanche Detector (LGAD)

Why LGADs?

- Semiconductor detectors with signal amplification: in a highly-doped gain layer a high electric field is created → avalanche multiplication of primary electrons
- Improved Signal-to-Noise Ratio
- Improved timing capabilities (< 30 ps) for thin LGADs (~ 50 μm)
- Used for HL-LHC CMS and ATLAS timing detectors, promising technology for future detectors



Exemplary IV measurements of LGADs. The rise between 0 and 50 V is a typical LGAD characteristic, that represents the depletion of the gain layer. The temperature dependence of the breakdown voltage indicates the temperature dependence of impact ionization happening in the gain layer.

Current challenges: LGADs suffer from radiation induced performance degradation (loss of signal gain) due to acceptor removal and therefore need a more profound theoretical understanding and further design optimizations!

Our current LGAD projects

Proton irradiation campaigns

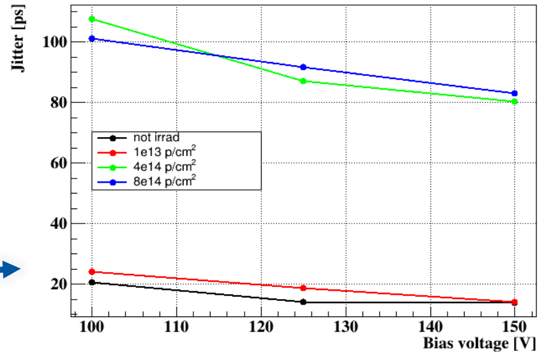
- Limited literature on the comparison of irradiation induced LGAD degradation with different proton energies
- **Of special interest: low energy protons,** different damage mechanisms → limits of the Non-Ionizing Energy Loss (NIEL) scaling *(For more information: Vendula Subert's soon coming PhD thesis!)*
- Proton irradiation at four facilities: CERN, LANSCE, University of Birmingham, Bern
- Over 100 samples (CNM and HPK)

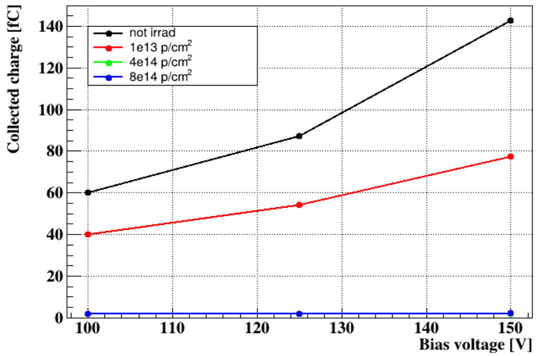
First results: low energy protons

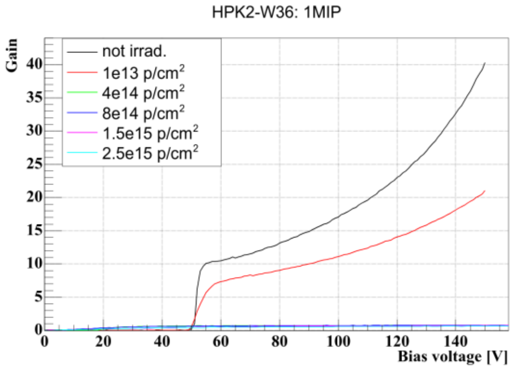
Timing, charge collection and gain measurements after irradiation show: 18 MeV protons are much more damaging than higher energies!

Investigating the novel nLGAD concept

Further information in the following slides and at the poster session :)



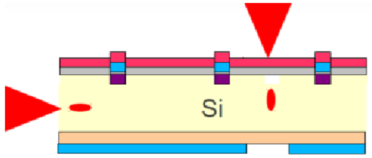




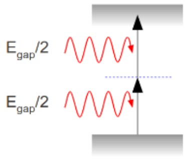
Two Photon Absorption – Transient Current Technique (TPA-TCT)

What we use for sensor characterization: IV/CV, Radioactive source measurements, Laser induced generation of charge carriers with TCT and **TPA-TCT**

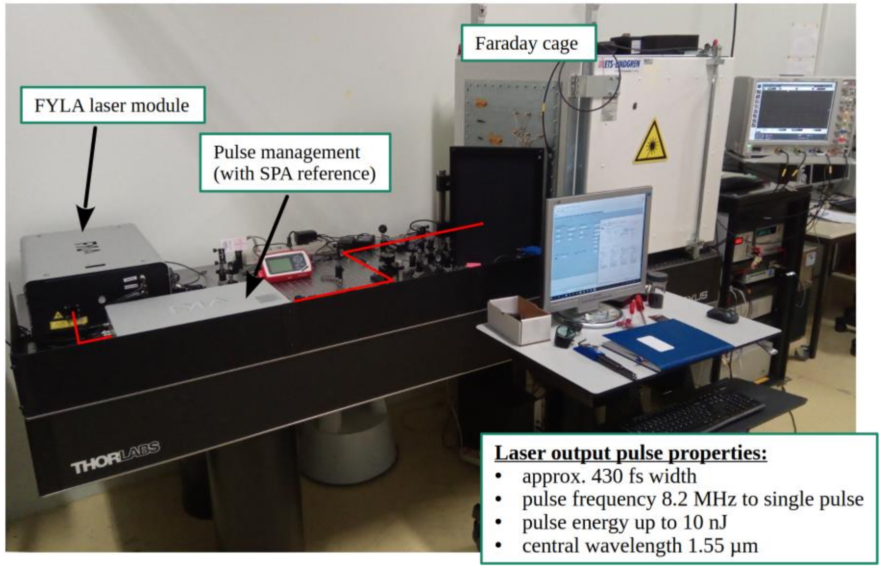
- 2 photons produce one electron-hole pair
- Point-like energy deposition in focal point
- **3D** spatial resolution (1 x 1 x 10 µm)



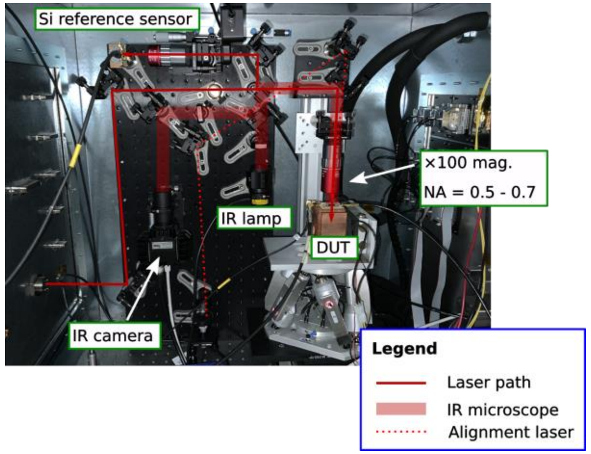
TPA (1550 nm):
No excitation if $E_{photon} < E_{gap}$ ~ 1 eV. But, if **two** photons arrive in ~100 attoseconds:



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

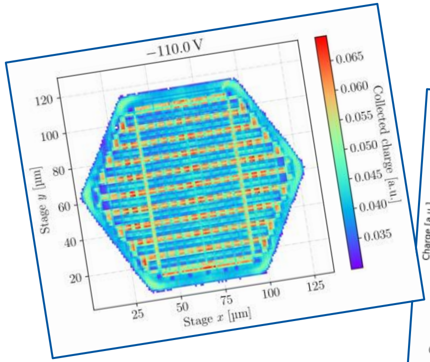


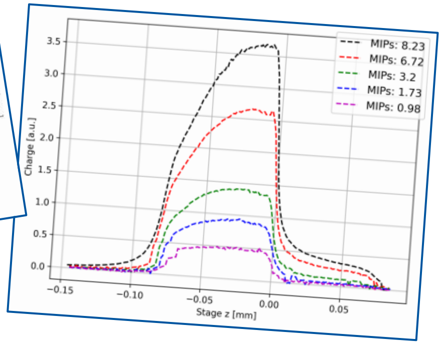
Laser output pulse properties:
- approx. 430 fs width
- pulse frequency 8.2 MHz to single pulse
- pulse energy up to 10 nJ
- central wavelength 1.55 µm



TPA-TCT setup at the SSD lab (left) and view into the Faraday cage (above)

Since completion of the system in 2021: Various interesting projects, including LGAD measurements.

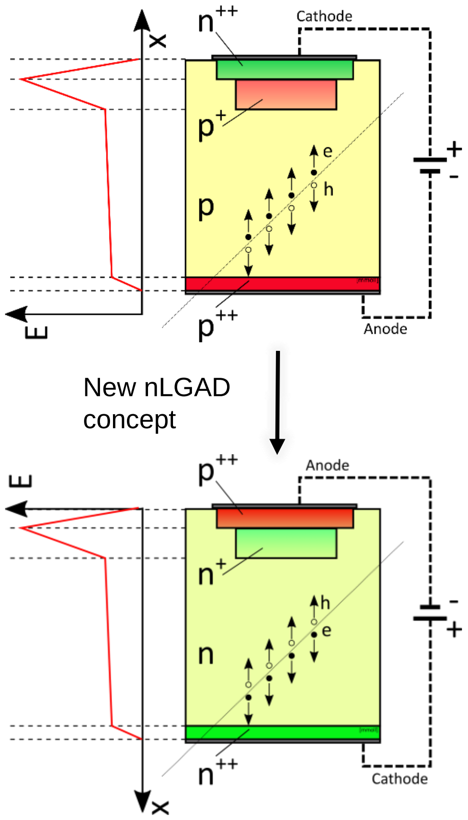


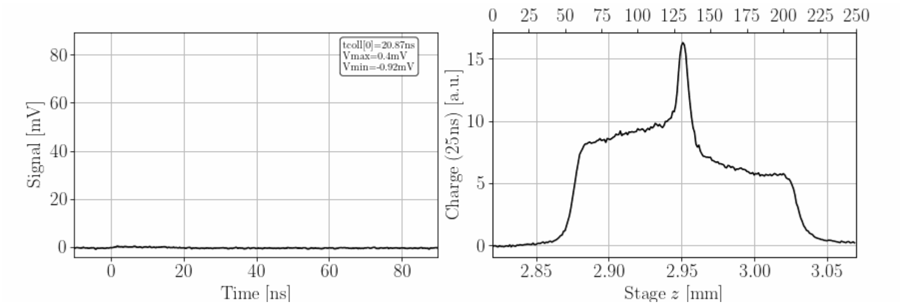


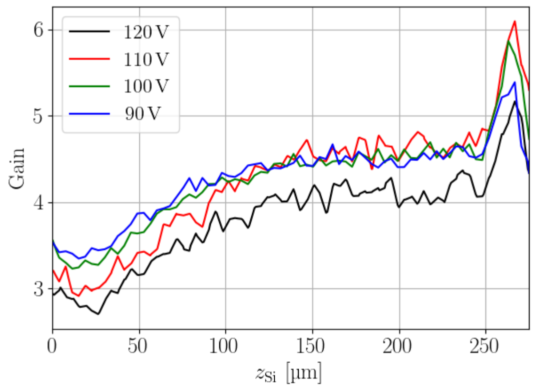
For more information: see PhD thesis M. Wiehe (2021), S. Pape (2024)

Studying nLGADs with TPA-TCT

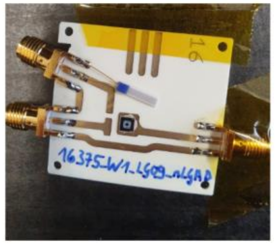
- Low Gain Avalanche Detectors (LGAD), implemented as $n^{++}-p^{+}-p$, show outstanding performance when detecting high-energy charged particles
- Due to the difference in multiplication mechanism for holes and electrons, the detection performance for low penetrating particles is significantly reduced. Therefore, the novel nLGAD concept was designed and fabricated at CNM and first tested at the CERN SSD group
- Interesting also for high-energy physics and R&D: first ever tests in such a structure!, impact ionization, donor-removal ↔ acceptor removal (eg. relevant for compensated LGADs), ...







Gain nLGADs (Q_{nLGAD}/Q_{pin}) against depth: comparing different V_{bias} up to 120 V



Outlook

Radiation hardening of sensors by device and defect engineering (RD50/DRD3):

- LGAD: deep junction, partially activated Boron gain layers, super-doped gain layers
- New material: SiC based LGADs in production

Characterization tools: TPA-TCT integration into optical cryostat (low T testing)

Caribou
&
EP-RD Telescope

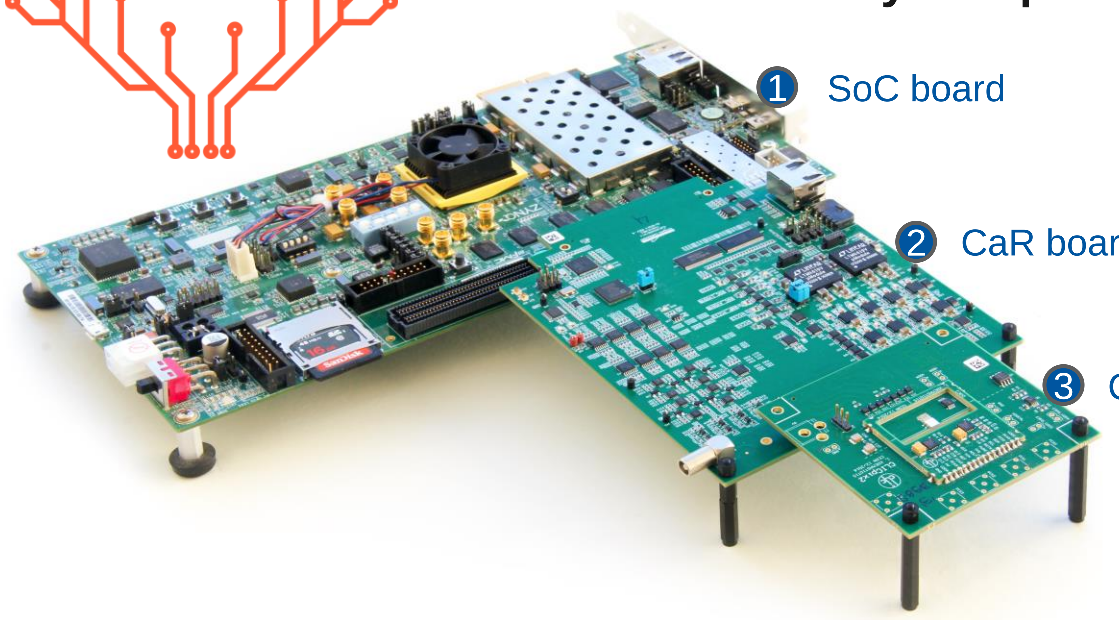
Younes Otarid (CERN)

Caribou

A versatile data acquisiton system for silicon detector characterization

- A modular hardware plateform complemented by firmware and software suits
- Collaboratively developed and maintained, and supported by RD50 / DRD3 collaborations
- Suitable for laboratory and test-beam measurements

Laboratory setup



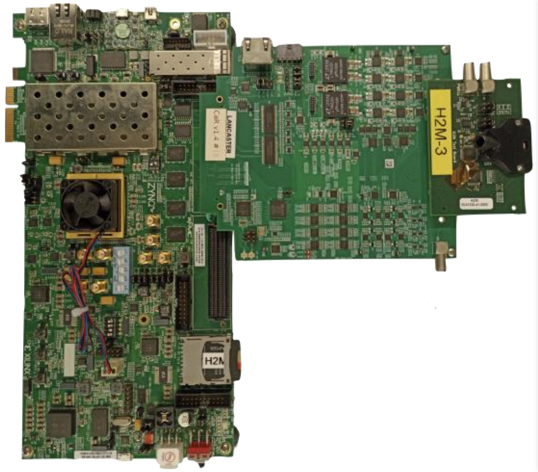
1. SoC board
2. CaR board
3. Chip board

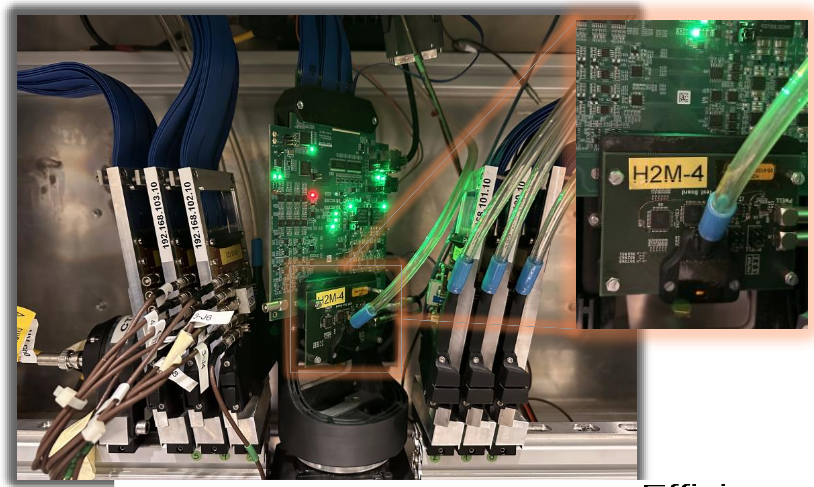
Test-beam setup

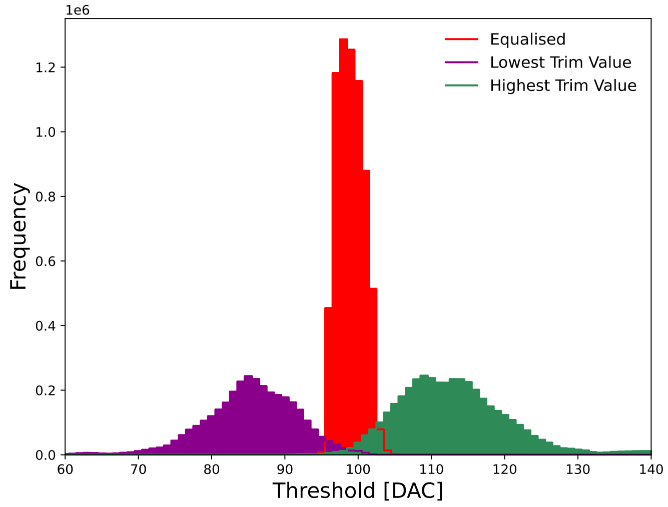
Caribou

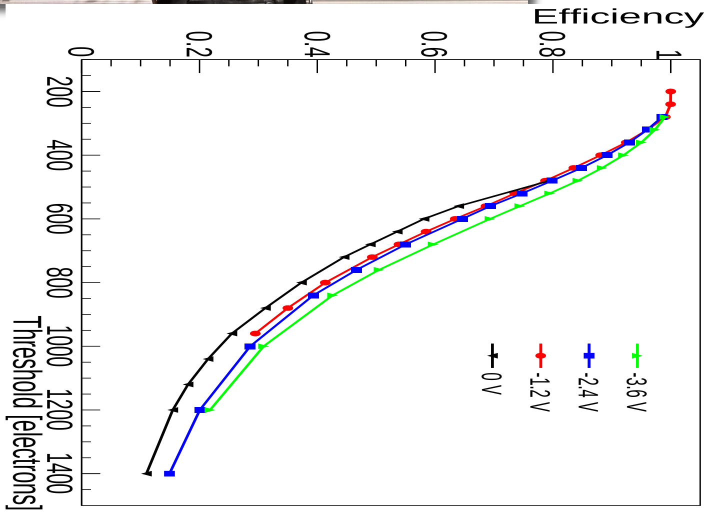
Latest developments

- **Hybrid-to-Monolithic (H2M) chip integration**
  - 65nm monolithic demonstrator chip from WP1.2
  - Active laboratory characterization
  - Multiple successful test-beam campaigns







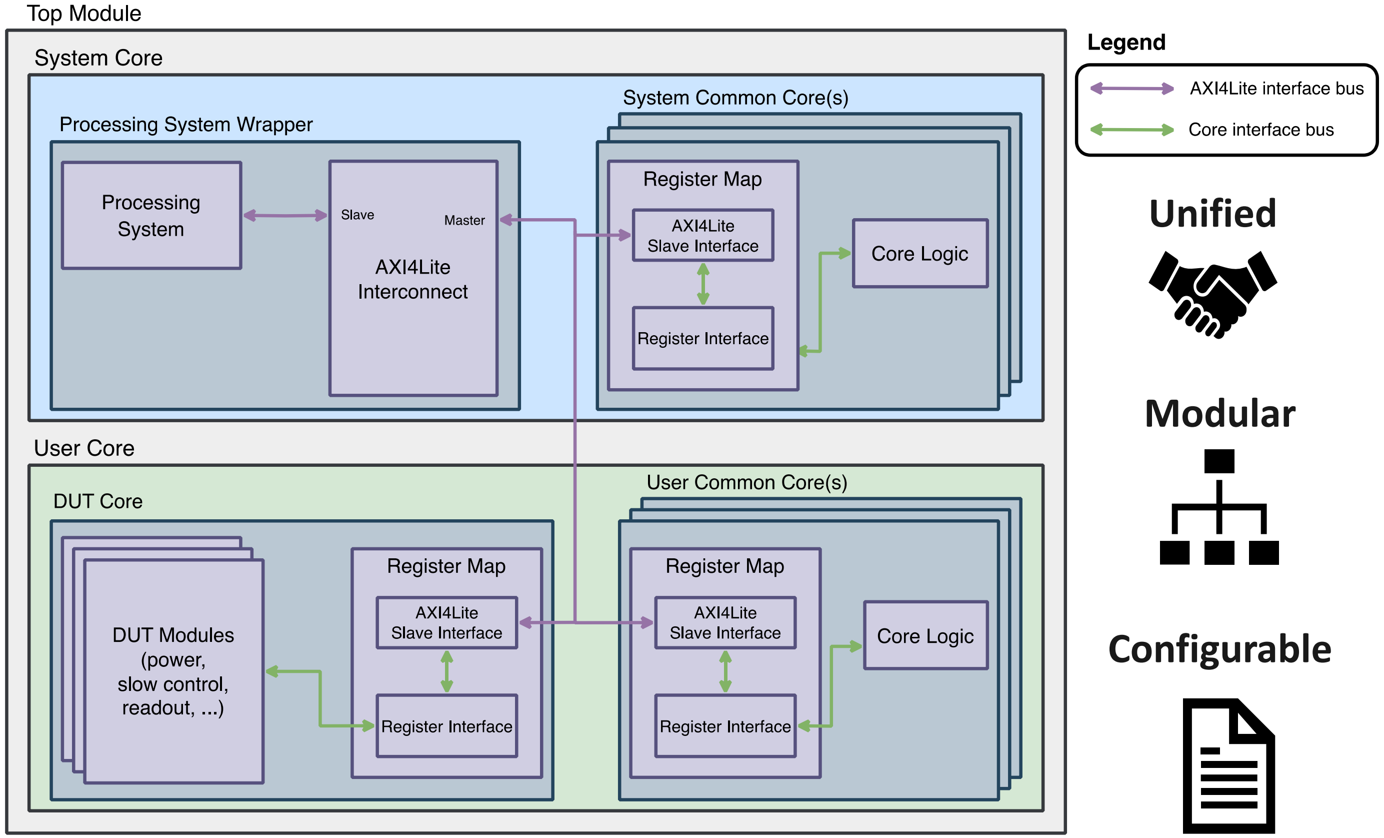


Caribou

Latest developments and milestones

- **Hybrid-to-Monolithic (H2M) chip integration**
  - 65nm monolithic demonstrator chip from WP1.2
  - Active laboratory characterization
  - Multiple successful test-beam campaigns

- **New firmware architecture – Boreal**
  - Unified, modular and configurable design
  - Streamlined development workflow
  - Pilot project in progress with Sevilla University



Caribou

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- **Respin of CaR board v1.4 → v1.5**
  - Credit to Eric Bushmann from BNL (WP1.4 Alumni)
  - Updated components
  - Various improvements and bug fixes
  - Combined purchase order for 31 boards in preparation

Caribou

Latest developments and milestones

- **Hybrid-to-Monolithic (H2M) chip integration**
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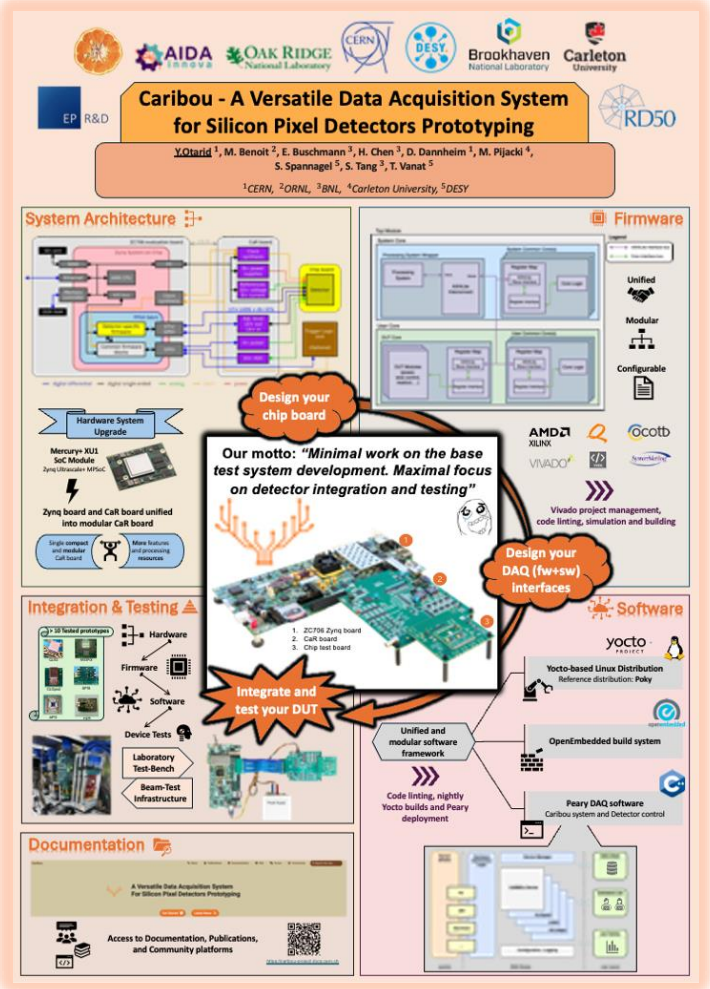
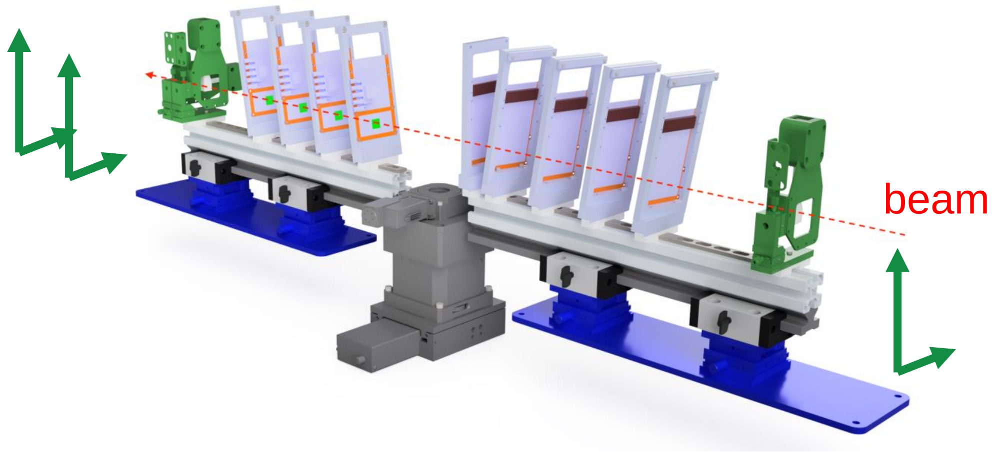
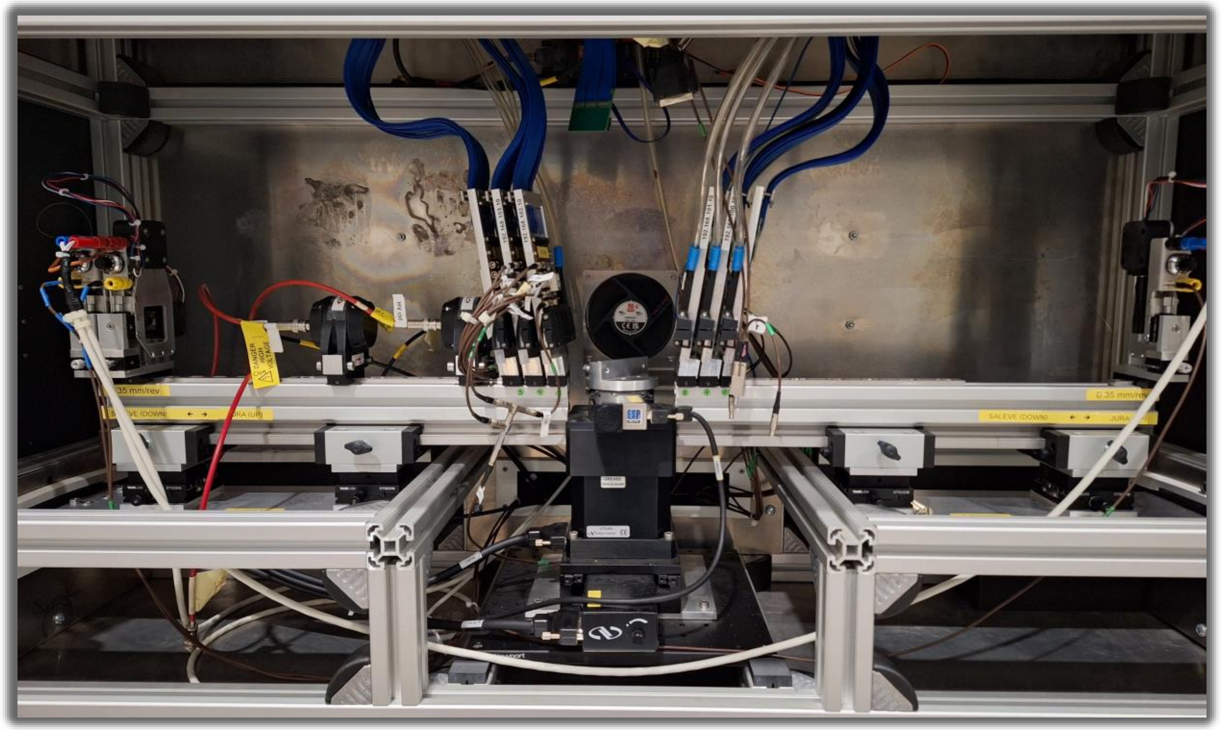
- **Poster presented during EP R&D day**
  - Meet Younes Otarid for more details about Caribou



EP-R&D Timepix3 Telescope

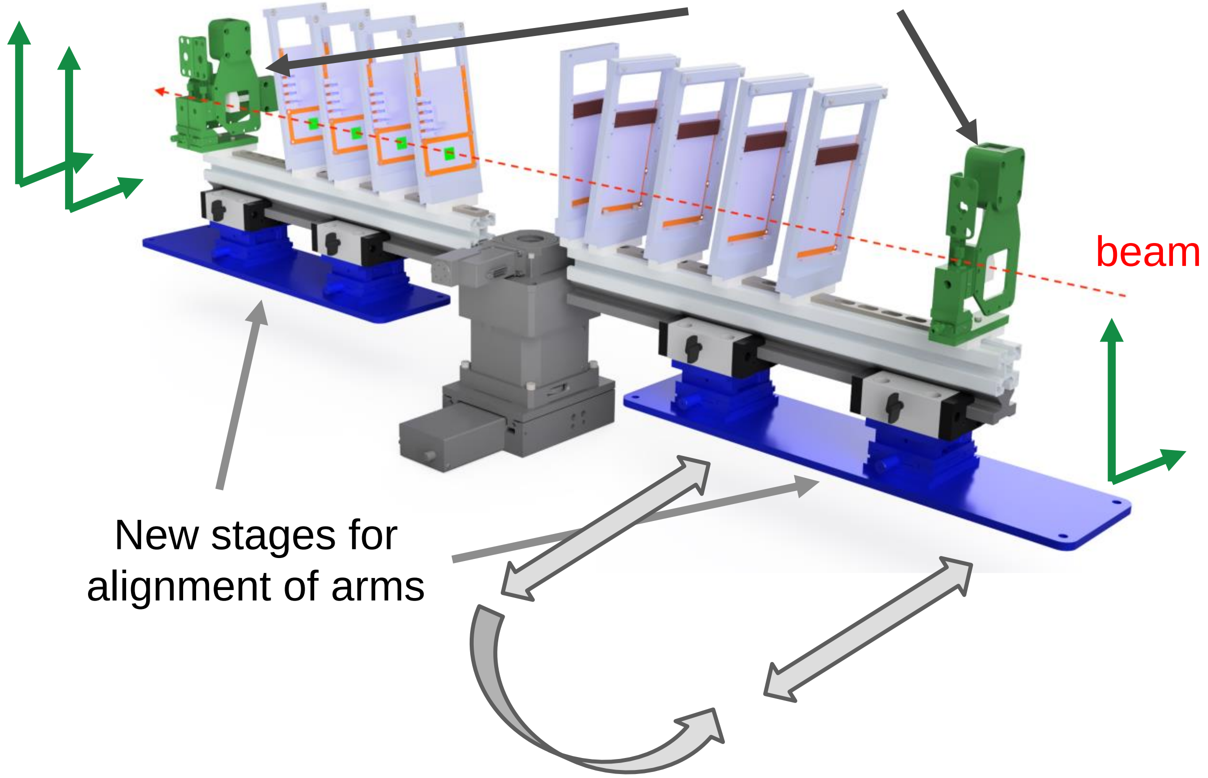


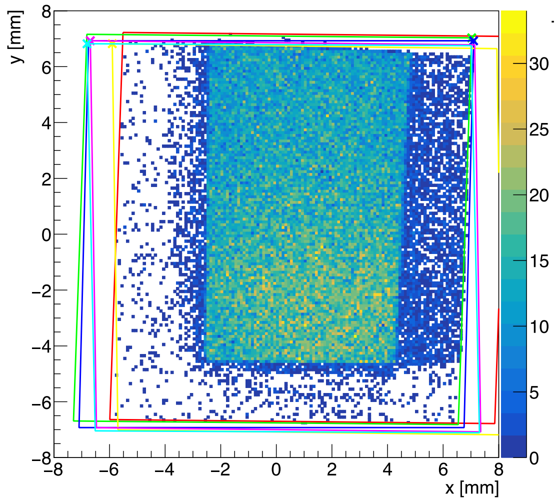


- Permanently installed in H6B beam line at SPS
- Used to characterize many devices (FASTPIX, iLGAD, H2M)
- Includes picosecond timing layer (MCP-PMT)

EP-R&D Timepix3 Telescope

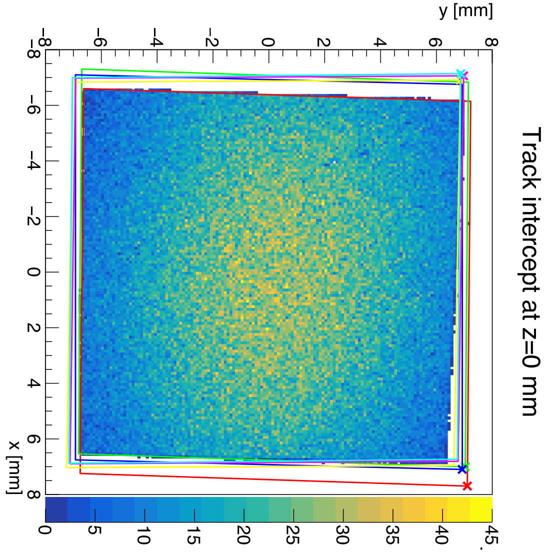
Mechanical improvements





Before modifications

After modifications



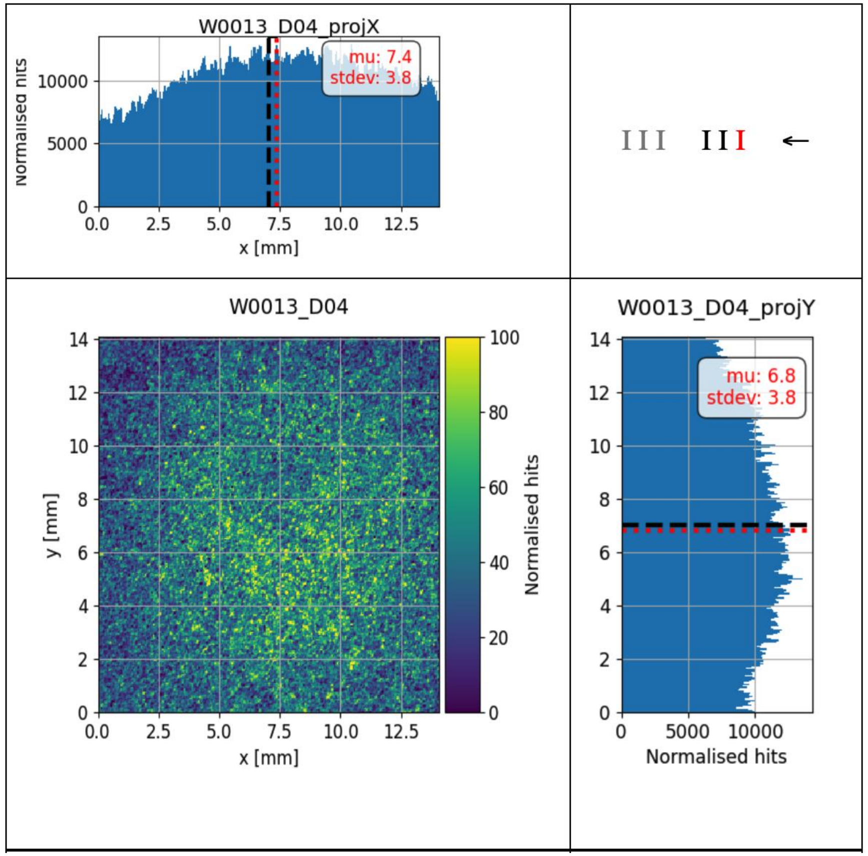
Largely improved telescope acceptance and thus data taking efficiency

EP-R&D Timepix3 Telescope

Online monitoring

Extensive Grafana monitoring of environmental data and DAQ status

Beam profile online monitoring

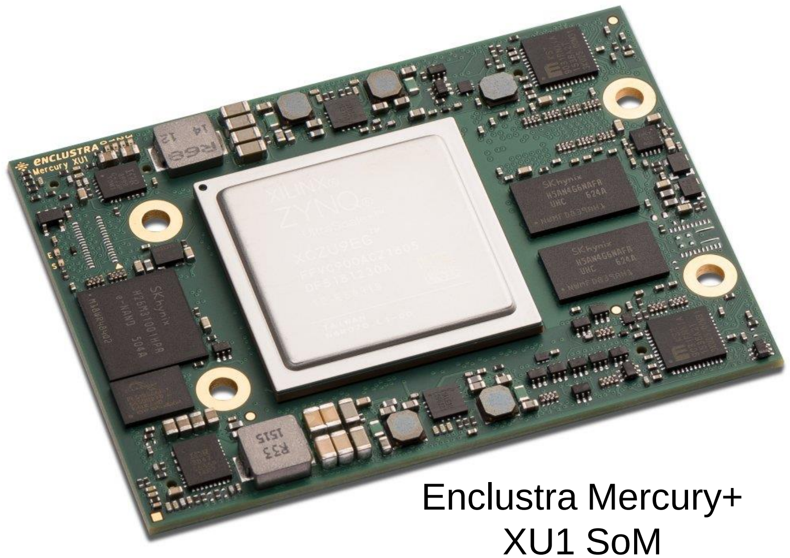


Available on a webpage and used for beam profile optimization

Outlook

Caribou:

- Caribou v2.0 : Merging SoC and CaR boards into a single compact and modular CaR board
- Use a cost-effective System-on-Module (SoM) commercial solution



Enclustra Mercury+
XU1 SoM

EP-RD Timepix3 Telescope:

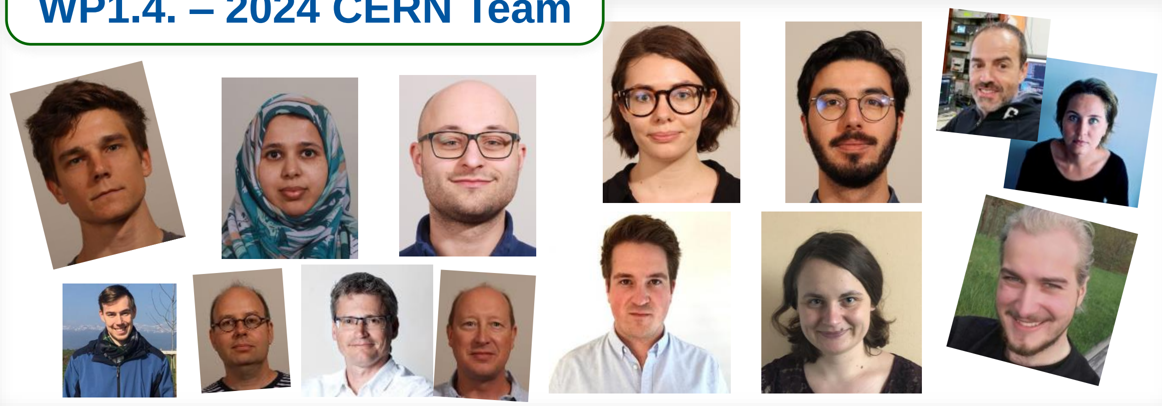
- Gradual upgrades and improvements of the beam-telescope
- Potential migration to new data acquisition system
- Preparation for unavailability of CERN test beams during LS3

Summary: WP1.4. Scope & Outlook (2024-2028)

WP1.4. - Scope

- **Radiation Damage & Mitigation Techniques**
  - radiation damage studies (Modelling & Defect Characterization)
  - Precision Timing Detectors (LGAD - Low Gain Avalanche Diodes)
  - Silicon Carbide (4H-SiC) as new detector material
- **Characterization Infrastructure**
  - modular readout systems, test-beam infrastructure, laser testing

WP1.4. – 2024 CERN Team



WP1.4. - Outlook

- **Radiation Damage Mitigation and Precision Timing Detectors**
  - **Optimization of (Si) timing detectors with & without gain; device modelling**
    - **radiation hardening of sensors by device and defect engineering (RD50/DRD3)** (LGAD: Deep Junction, Partially Activated Boron gain layers, super-doped gain layers)
  - **Defect characterization; NIEL and damage modelling; extreme fluence studies; damage studies on segmented detectors**
    - **production of custom-made sensors for defect spectroscopy and NIEL measurements** *(status: both processing runs started at CNM and CIS)*
- **Silicon Carbide sensors**
  - **Study of silicon carbide as detector material** (new sensors to arrive in summer)
  - **SiC based LGAD sensors** (custom epi-layers in production)
- **Characterization tools**
  - **High temperature cryostat to cover the larger bandgap of SiC** (cryostat delivery expected for this summer)
  - **TPA-TCT integration into optical cryostat** (low T testing)
- **Development of DAQ (Caribou)**
  - **Cardboard v2 System-on-Module platform**
  - **Support of reference installations**
- **Beam telescope infrastructure**
  - **Telescope upgrades**
  - **Telescope support**
  - **Support of beam tests outside of CERN** (anticipating long shutdown 2027)

Annex

- Publications:
  - 22 articles published in scientific journals [2022-2024]
  - 2 PhD thesis and 2 PhD thesis in writing process
- ECFA roadmap & Major WP1.4. achievements

Achievements: Journal publications

Papers published in 2022:

A more detailed list for SSD incl. submitted manuscripts: link

1. **Technique for the investigation of segmented sensors using the Two Photon Absorption – Transient Current Technique**; *Sebastian Pape, Esteban Currás, Marcos Fernández García, Michael Moll*; Sensors 2023, 23(2), 962; *https://doi.org/10.3390/s23020962*
2. **Defect characterization studies on neutron irradiated boron-doped silicon pad diodes and Low Gain Avalanche Detectors**; Anja Himmerlich, Nuria Castello-Mor, Esteban Curras Rivera, Yana Gurimskaya, Vendula Maulerova-Subert, Michael Moll, Ioana Pintilie, Eckhart Fretwurst, Chuan Liao, Jörn Schwandt; Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment Volume 1048, March 2023, 167977 https://doi.org/10.1016/j.nima.2022.167977
3. **Fiber Laser System of 1550 nm Femtosecond Pulses with Configurable Properties for the Two-Photon Excitation of Transient Currents in Semiconductor Detectors**; *Azahara Almagro-Ruiz, Sebastian Pape, Hector Muñoz, Moritz Wiehe, Esteban Curras Rivera, Marcos Fernández-García, Michael Moll, Raúl Montero Santos, Rogelio Palomo, Cristian Quintana, Iván Vila Álvarez, Pere Pérez-Millán;* Applied Optics 61, 9386-9397 (2022); https://doi.org/10.1364/AO.470780
4. **Characterisation of irradiated and non-irradiated silicon sensors with a table-top Two Photon Absorption TCT system**; *S. Pape, M. Fernández García, M.Moll, R. Montero, F.R. Palomo, I. Vila and M. Wiehe;* Journal of Instrumentation, C08011, 2022, volume 17, number 08; https://doi.org/10.1088/1748-0221/17/08/c08011
5. **First observation of the charge carrier density related gain reduction mechanism in LGADs with the Two Photon Absorption – Transient Current Technique**; *S.Pape, E.Currás, M.Fernández García, M.Moll,R.Montero, F.R.Palomo, I.Vila, M.Wiehe, C.Quintana; July 2022;* NIMA 1040:167190; https://doi.org/10.1016/j.nima.2022.167190
6. **Increase of the photoconductivity quantum yield in silicon irradiated by neutrons to extremely high fluences**; *Juozas V Vaitkus, Michael Moll, Vaidotas Kažukauskas and Vilius Vertelis;* Journal of Physics D: Applied Physics; Volume 55; Number 39; 395104; https://doi.org/10.1088/1361-6463/ac7f65
7. **Gain reduction mechanism observed in Low Gain Avalanche Diodes;** *Esteban Curras, Marcos Fernandez and Michael Moll*, *NIMA, 4.March 2022, 166530, https://doi.org/10.1016/j.nima.2022.166530*
8. **The boron-oxygen (Bi Oi) defect complex induced by irradiation with 23 GeV protons in p-type epitaxial silicon diodes;** *C. Liao, E. Fretwurst, E. Garutti, J. Schwandt, M. Moll, A. Himmerlich, Y. Gurimskaya, I. Pintilie, A. Nitescu, Z. Li, L. Makarenko;* IEEE Transactions on Nuclear Science (Volume: 69, Issue: 3, March 2022); https://doi.org/10.1109/TNS.2022.3148030
9. **Plasma effects in silicon detectors and the Two Photon Absorption Transient Current Technique** *F.R. Palomo, M. Moll, M. Fernández-García, R. Montero, I. Vila; Proceedings of the 2021 21th European Conference on Radiation and Its Effects on Components and Systems (RADECS) https://doi.org/10.1109/RADECS53308.2021.9954488*
10. **Transient Monte Carlo simulations for the optimisation and characterisation of monolithic silicon sensors**; *R. Ballabriga, J. Braach, E. Buschmann, M. Campbell, D. Dannheim, K. Dort ,L. Huth, I. Kremastiotis, J. Kröger, L. Linssen, M. Munker, P. Schütze, W. Snoeys, S. Spannagel, T. Vanat, NIMA 1031, 11* May 2022, 166491; https://doi.org/10.1016/j.nima.2022.166491

2022: PhD Thesis:

1. **Simulation Studies and Characterisation of Monolithic Silicon Pixel-Detector Prototypes for Future Collider Detectors & Unsupervised Anomaly Detection in Belle II Pixel-Detector Data, thesis Katharina Dort** https://cds.cern.ch/record/2813457

Achievements: Journal publications

A more detailed list for SSD incl. submitted manuscripts: link

Papers published in 2023/24:

1. **Status and recent extensions of the Caribou DAQ system for picosecond timing with an FPGA TDC,** *E. Buschmann, 2023 JINST 18* C02005 https://iopscience.iop.org/article/10.1088/1748-0221/18/02/C02005
2. **Gain layer degradation study after neutron and proton irradiations in Low Gain Avalanche Diodes**, *E. Curras Rivera, A. La Rosa, M. Moll and F. Zareef; Journal of Instrumentation, 2023, volume 18, P10020; https://doi.org/10.1088/1748-0221/18/10/P10020*
3. **Ultrathin four-quadrant silicon photodiodes for beam position and monitor applications: Characterization and radiation effects;** *J.M. Rafí, D. Quirion, M. Duch, I. Lopez Paz, V. Dauderys, T. Claus, N. Moffat, B. Molas, I. Tsunoda, M. Yoneoka, K. Takakura, G. Kramberger, M. Moll, G. Pellegrini; Solid State Electronics; volume 209, November 2023, 108756; https://doi.org/10.1016/j.sse.2023.108756*
4. **Low Temperature Annealing of Electron, Neutron and Proton Irradiation Effects on SiC Radiation Detectors;** *Joan Marc Rafí, David Quirion, Marta Duch, Ivan Lopez Paz, Vainius Dauderys, Tobias Claus, Neil Moffat, Bernat Molas, Isao Tsunoda, Masashi Yoneoka, Kenichiro Takakura, Gregor Kramberger, Michael Moll, Giulio Pellegrini; IEEE Transactions on Nuclear Science, vol.70, no. 10, pp. 2285-2296, Oct. 2023, https://doi.org/10.1109/TNS.2023.3307932*
5. **Timing performance and gain degradation after irradiation with protons and neutrons of Low Gain Avalanche Diodes based on a shallow and broad multiplication layer in a float-zone 35µm and 50µm thick silicon substrate;** *Esteban Curras, Albert Doblas; Marcos Fernandez, David Flores, Javier Gonzalez, Salvador Hidalgo, Richard Jaramilo, Michael Moll, Efren Navarrete, Giulio Pellegrini, Ivan Vila; Nuclear Instruments and Methods in Physics Research Section A: Accelerators Spectrometers Detectors and Associated Equipment, Volume 1055, October 2023, 168522; https://doi.org/10.1016/j.nima.2023.168522*
6. **Investigation of the Boron removal effect induced by 5.5 MeV electrons on highly doped EPI- and Cz-silicon**; *C. Liao, E. Fretwurst, E. Garutti, J. Schwandt, L. Makarenko, I. Pintilie, L. Filip, A. Himmerlich, M. Moll, Y. Gurimskaya, Z. Li; Nuclear Instruments and Methods in Physics Research Section A: Accelerators Spectrometers Detectors and Associated Equipment, Volume 1056, November 2023, 168559; https://doi.org/10.1016/j.nima.2023.168559*
7. **Influence of temperature on measurements of the Two Photon Absorption – Transient Current Technique in silicon planar detectors using a 1550 nm femtosecond fibre laser**; *S. Pape, E.Currás, M.Fernández García, M. Moll, M. Wiehe, Nuclear Instruments and Methods in Physics Research Section A: Accelerators Spectrometers Detectors and Associated Equipment, Volume 1053, August 2023, 168387; https://doi.org/10.1016/j.nima.2023.168387*
8. **Study of impact ionization coefficients in silicon with Low Gain Avalanche Diodes;** *Esteban Curras and Michael Moll; IEEE Transactions on Electron Devices, Volume 70, Issue 6, June 2023, pp. 2919-2926, https://doi.org/10.1109/TED.2023.3267058*
9. **Technique for the investigation of segmented sensors using the Two Photon Absorption – Transient Current Technique;** *Sebastian Pape, Esteban Currás, Marcos Fernández García, Michael Moll; Sensors 2023, 23(2), 962; https://doi.org/10.3390/s23020962*
10. **Defect characterization studies on neutron irradiated boron-doped silicon pad diodes and Low Gain Avalanche Detectors**; *Anja Himmerlich, Nuria Castello-Mor, Esteban Curras Rivera, Yana Gurimskaya, Vendula Maulerova-Subert, Michael Moll, Ioana Pintilie, Eckhart Fretwurst, Chuan Liao, Jörn Schwandt; Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 1048, March 2023, 167977 https://doi.org/10.1016/j.nima.2022.167977*
11. **CERN: A Global Hub for Materials Science,** *Panagiotis Charitos, Paul Lecoq, Michael Moll, Cristoforo Benvenuti and Luca Bottura; Chapter in book: Between Science and Industry: Institutions in the History of Materials Research; May 2024;756 pages; Part of A World Scientific Encyclopedia of the Development and History of Materials Science https://doi.org/10.1142/13625*
12. **Investigation of high resistivity p-type FZ silicon diodes after ^{60}Co - γ irradiation**; *C. Liao, E. Fretwurst, E.Garutti, J. Schwandt, I. Pintilie, A. Himmerlich, M. Moll, Y. Gurimskaya, Z. Li; Nuclear Instruments and Methods in Physics Research Section A: Accelerators Spectrometers Detectors and Associated Equipment, Volume 1061, 2024, 169103; https://doi.org/10.1016/j.nima.2024.169103*

2024: PhD Thesis:

1. **Characterisation of Silicon Detectors Using the Two Photon Absorption – Transient Current Technique; thesis Sebastian Pape, TU Dortmund; https://cds.cern.ch/record/2889325**

ECFA roadmap & WP1.4 Achievements

- All present and future WP1.4. activities are **well aligned with the detector roadmap**
  - they are targeted in the roadmap **DRDT 3.2. “4D-solid state detectors”** and **DRDT 3.3. “extreme fluences”**
  - they are part of the DRD3 Solid-State Detectors proposal re-submitted on 15.5.24 to the DRDC
  - WP1.4. members participate in managing DRD3: M.Moll (deputy spokesperson); D.Dannheim (WG convener)

- **WP1.4. major achievements:**
  - Two Photon Absorption TCT (**TPA-TCT**) fully commissioned: A major step forward in sensor characterization.
  - **Significant contribution to develop and understand LGADs (High relevance for HI-LUMI LHC!)**
    - **An improved parameterization of the impact ionization coefficients in silicon – fundamental solid-state parameter!**
  - Significant progress in understanding **defect formation in p-type silicon** & impact on detector performance.
    - Defect engineering with **Carbon enrichment has enabled operation of LGADs for ATLAS/CMS phase II timing detectors**
  - Re-evaluation of NIEL initiated in the community, Geant4 + TRIM + Clustering toolset established.
  - Production of Silicon Carbide sensors and first radiation damage studies; Outlook: SiC LGADs in production
  - **Caribou readout system used** by a wide international (growing) user community (e.g. RD50/DRD3)
    - Several successful use cases with technology demonstrators within EP-RD silicon work packages
  - Advanced simulation tools (Allpix Squared, Garfield++ and 3D TCAD) were improved and validated against data.
    [WP1.4.: No further effort to give major push to the software tools; user level participation]