EP R&D Day 2021, 11-12 November 2021

WP1.4. Silicon Detectors Characterization and Simulation

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Michael Moll, Sebastian Pape, Vendula Subert

on behalf of the WP1.4. team

WP 1.4. Simulation & Characterization

- The WP aims for enabling a fundamental understanding and optimization of the performance of particle detectors
- Increasingly complex sensors and readout ASICs require improved characterization, modelling and simulation, including radiation effects

Radiation-damage models

- Defect characterization
- Damage models & simulation
- Radiation hard devices
- LGAD and p-type silicon

Characterization Infrastructure Development

- Flexible readout systems
- Laser test stands (TPA-TCT)
- Defect characterization tools

Radiation monitoring techniques

- New radiation sensors
- Revision of NIEL scaling
- Dosimetry for ultra-high radiation levels

Advanced detector simulations

- Charge & damage creation
- Device physics, signal formation
- Front-end response
- Simulation of data stream

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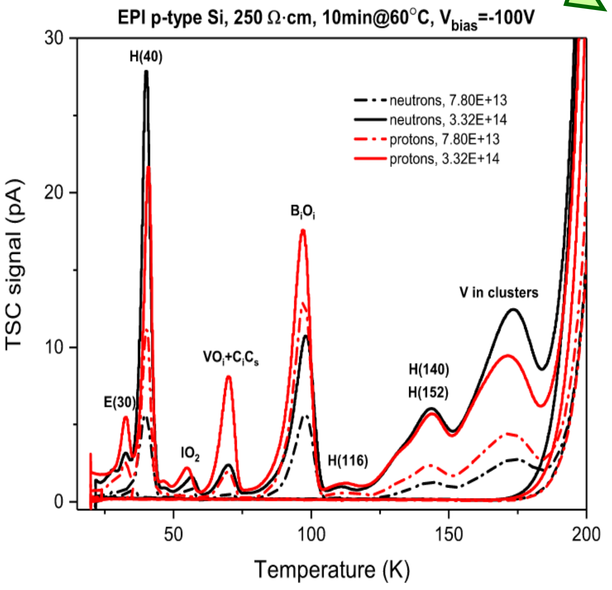
Highlight: Study of defects responsible for the radiation hardness limits of timing detectors for HL-LHC



Method: Thermally Stimulated Currents

Observation: De-activation of acceptors

Boron → Boron-oxygen complexes

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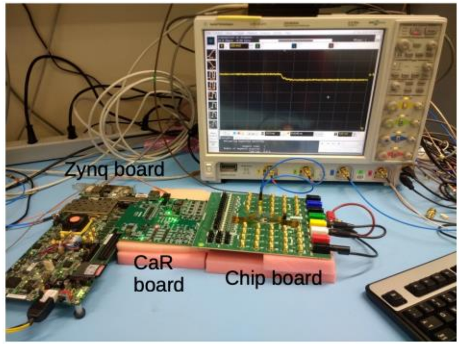
Highlight: Caribou DAQ
FPGA based flexible readout system development



Caribou DAQ for the new ATTRACT FASTpix technology demonstrator;

serves as template for dedicated WP 1.2 ASIC developments in the pipeline

WP1.4. Highlight presentations

- Characterization of radiation damage to LGAD sensors
  - Esteban Curras Rivera (Fellow)

- Two-Photon Absorption TCT measurements on silicon sensors
  - Sebastian Pape (DOCT)

- Revising the NIEL- Non Ionizing Energy Loss Hypothesis
  - Vendula Subert (DOCT)

- Resources
  - Core resources WP1.4. (2020/21)
    - 0.5 FTE Fellow: Radiation Damage Characterization
    - 0.5 FTE Fellow: DAQ & Caribou Development
    - 1 FTE PhD: Rad.Monitoring & Damage Simulations
    - 75 KCHF/year material budget
  - Further resources through other funds/programs:
    - CERN PCB Fellow, EP/DT, Gentner, AIDAinnova, RD50, ..
    - Close collaboration with the other EP-RD silicon WPs
- Participants (non exclusive)
  - ..see WP1.4. website + many more collaborators
    https://ep-rnd.web.cern.ch/topic/simulation-and-characterization

Eric Buschmann (Fellow)
…working on Caribou (also WP1.2)

- Anja Himmerlich (Fellow)
- Julian Boell (DOCT)
- Justus Braach (DOCT)
- …
- ..many more collaborators

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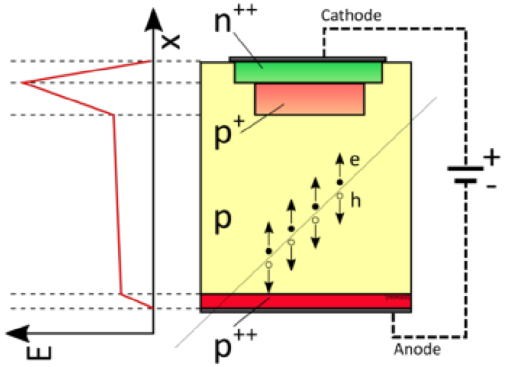
Low Gain Avalanche Detector (LGAD)

- An LGAD is a detector with internal multiplication of charge:
  - Improve the signal-to-noise ratio (SNR).
  - Improve the timing capabilities.
- A highly doped p^+ gain layer, creates a high electric field region in the multiplication layer:
  - Amplification of the charge by impact ionization.
  - Gain highly depends on:
    - Doping profile of the gain layer (GL).
    - Bias voltage.
    - Temperature.

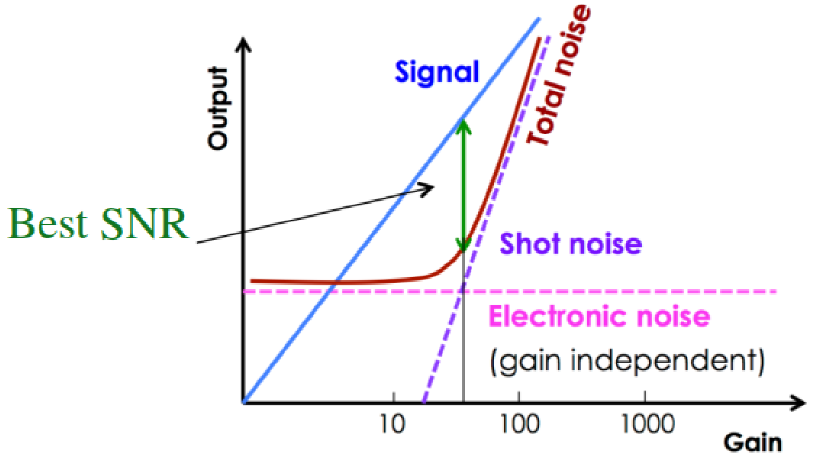


$$\sigma_{jitter} = \frac{Noise}{dV/dt} \approx \frac{t_{rise}}{S/N}$$

LGADs will be used at ATLAS-HGTD and CMS-ETL as timing detectors

Radiation tolerance: up to ~ 2.5x10^{15} n_{eq}/cm^2.

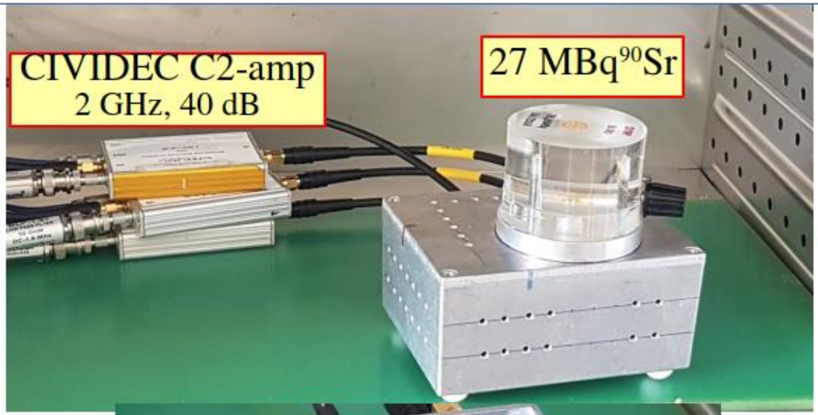
LGADs performance **after irradiation**:
- Time resolution < 50 - 70 ps per-hit in a MIP.
- Charge collected > 4 - 8 fC per MIP.
- Leakage current per pad < 5 uA.



V. Sola et al., JINST (2017) 12 C02072

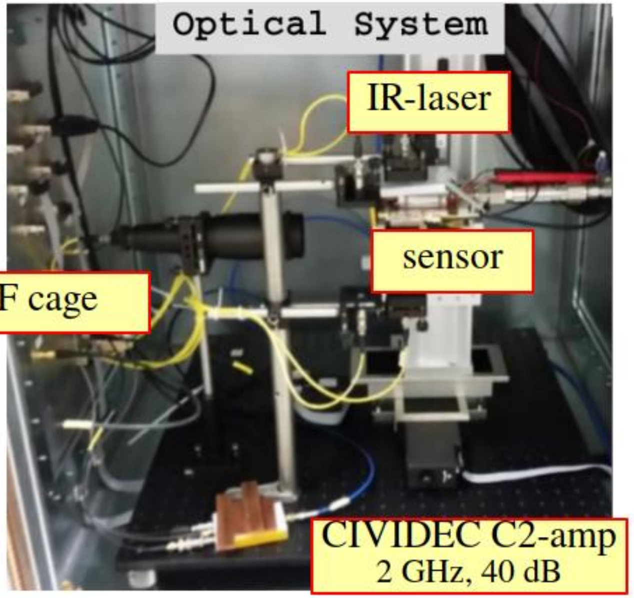
LGAD characterization at Solid State Detectors (SSD) lab

- ^{90}Sr and IR-laser setup used to measure time resolution, collected charge and noise.
  - ^{90}Sr: Landau noise
  - IR-laser: jitter



Set-up inside a RF cage and Climate Chamber

Osciloscope: Agilent DSO 9254, 2.5 GHz, 20 GSa/s



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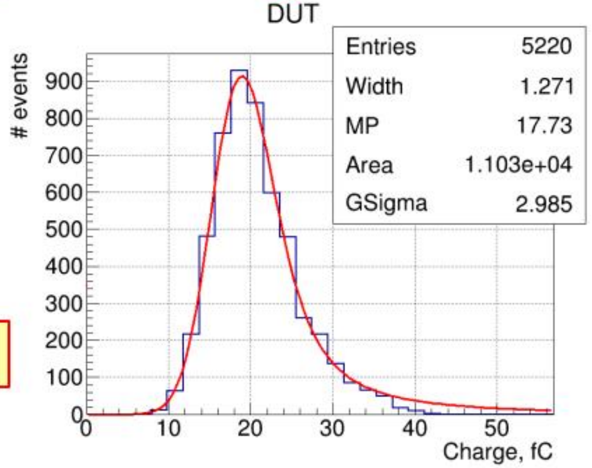
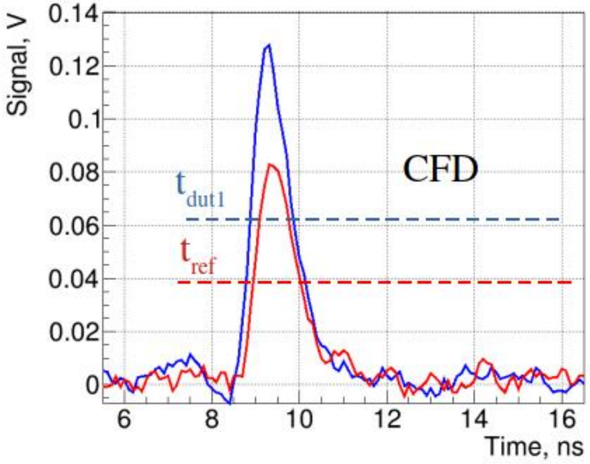
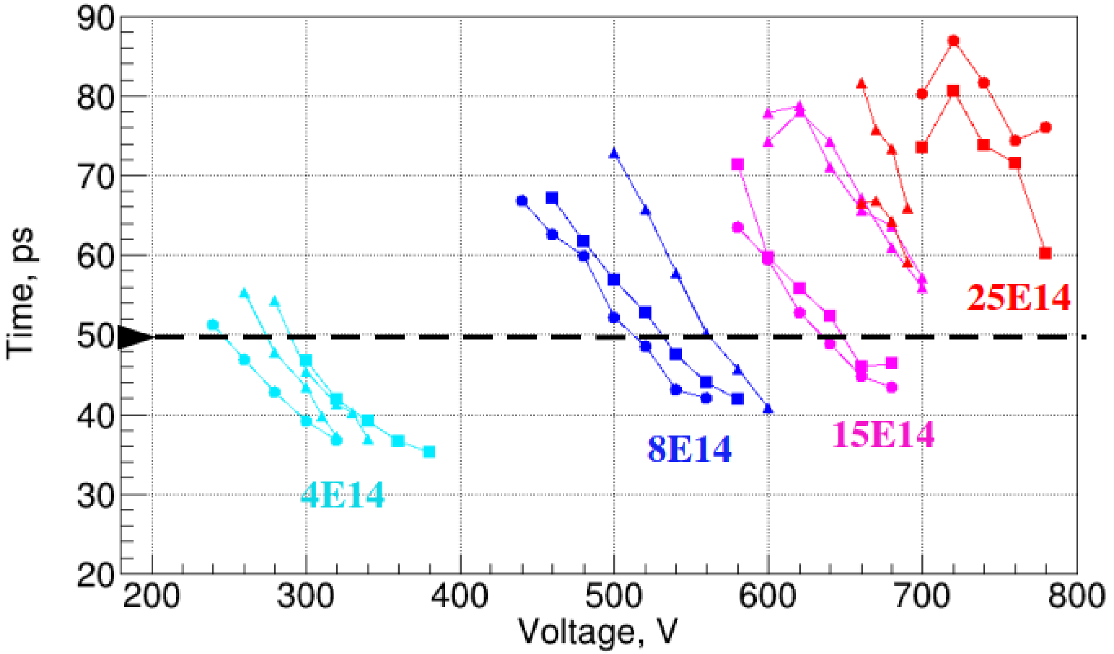
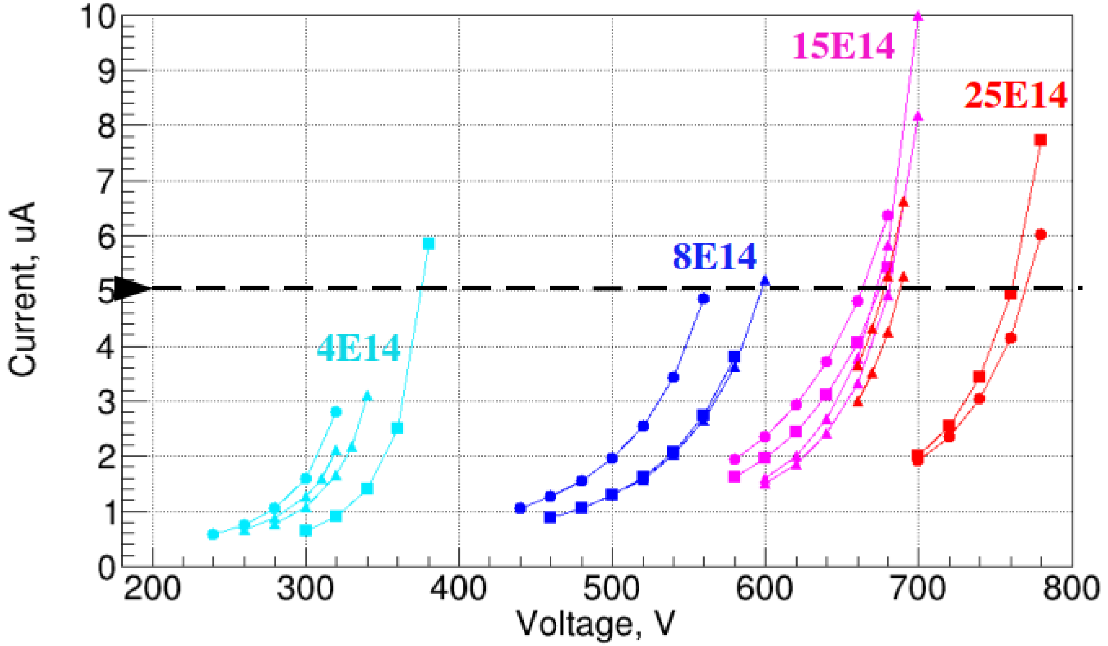


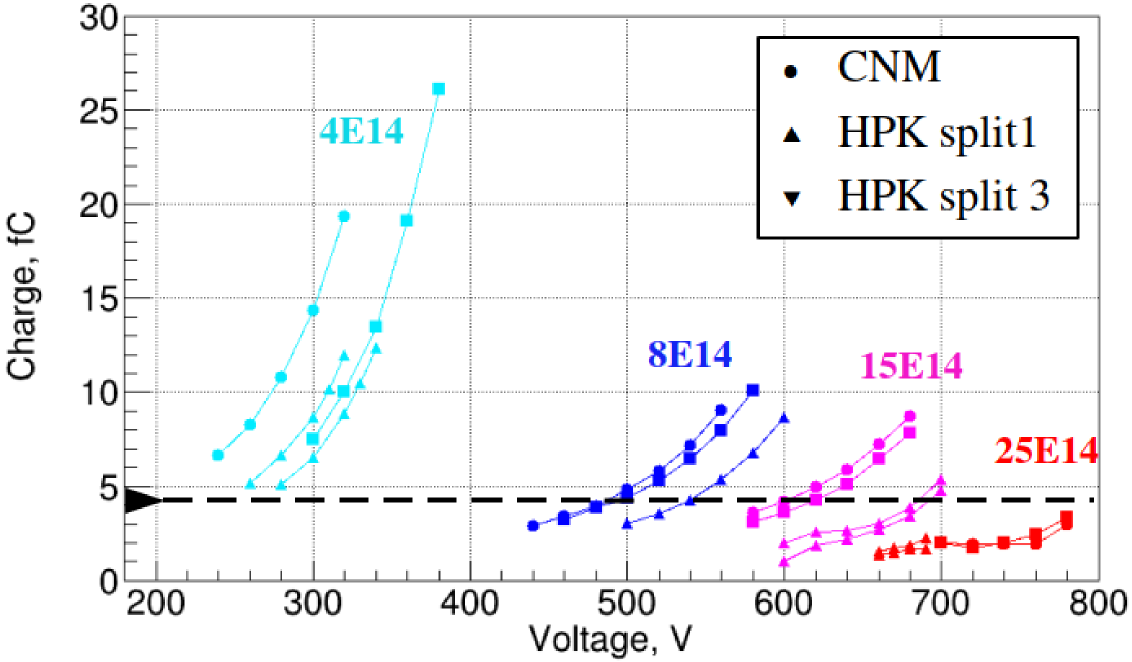


Neutron irradiation results:

- 50 um thick LGADs irradiated with neutrons at Ljubljana, fluences:
  - 4, 8, 15, 25x10^{14} n_{eq}/cm^2
- Almost 200 samples characterized at SSD before irradiation for distribution between different groups in the collaboration:
  - HPK LGADs: 4 different splits with different GL doping profiles.
  - CNM LGADs.
  - FBK LGADs: different gain layouts.
- Ongoing more irradiations to understand the difference between p$^+$ and n, and the mortality issue experienced at high fluences.

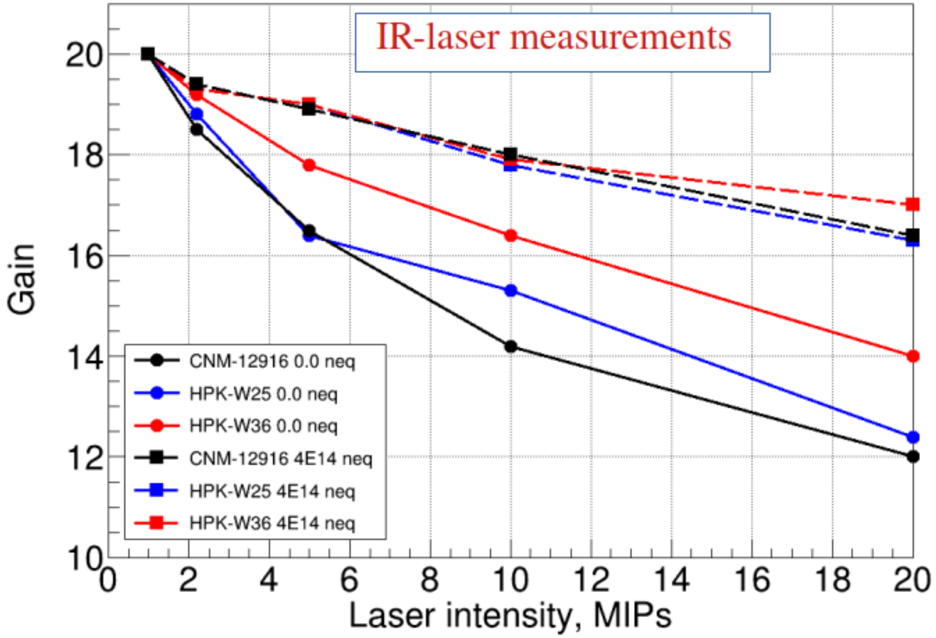




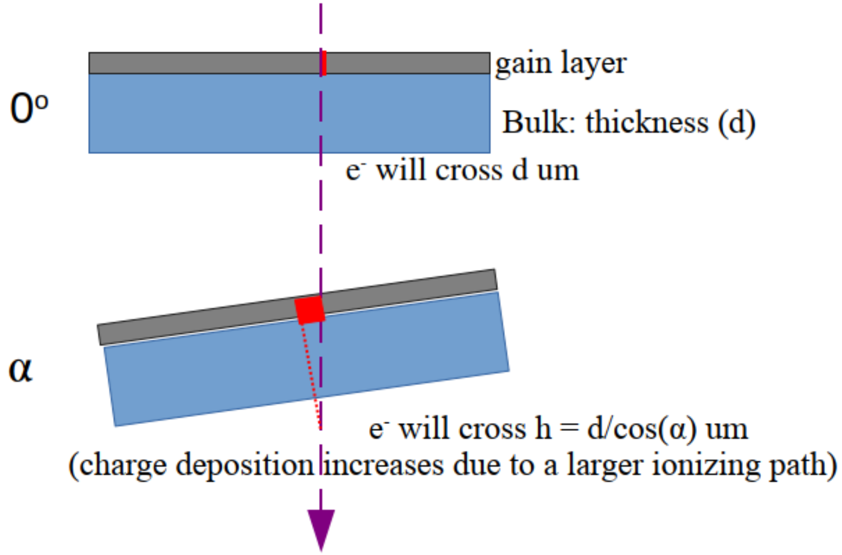


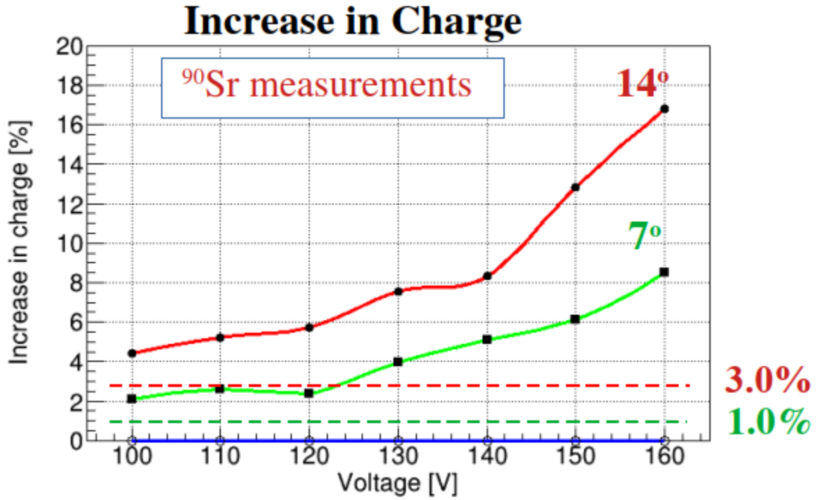
Important discovery: Gain suppression mechanism

- Already known: the gain strongly depends on the temperature and applied voltage in the LGADs.
- Several test done at the lab showed that the gain also depends on the charge density arriving to the gain layer:
  - High charge density signals will reduce the gain.
- Published: https://arxiv.org/abs/2107.10022



For a gain > 20, this reduction is more dramatic !





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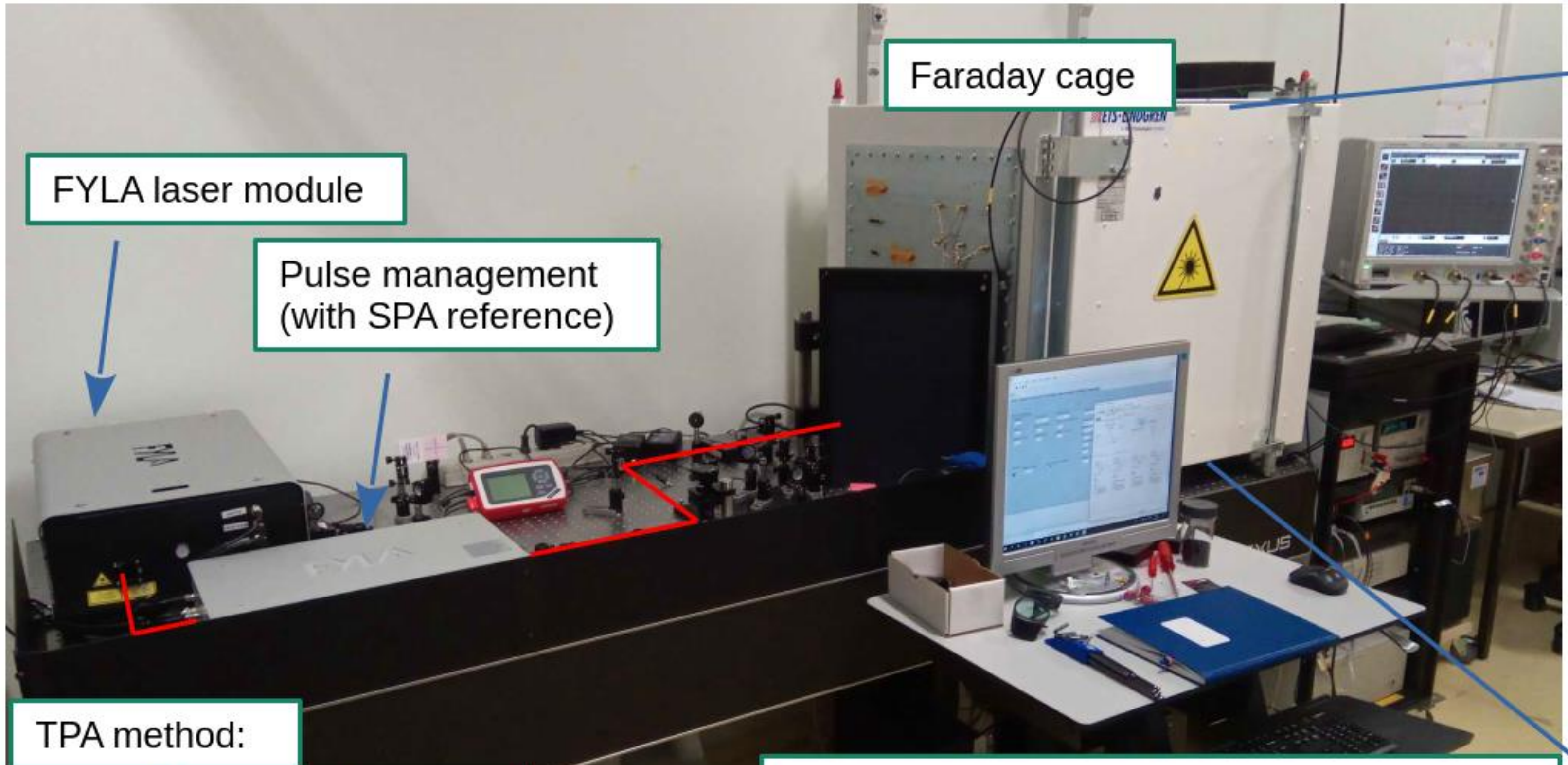
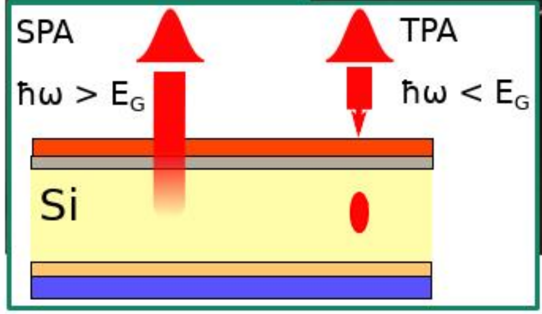
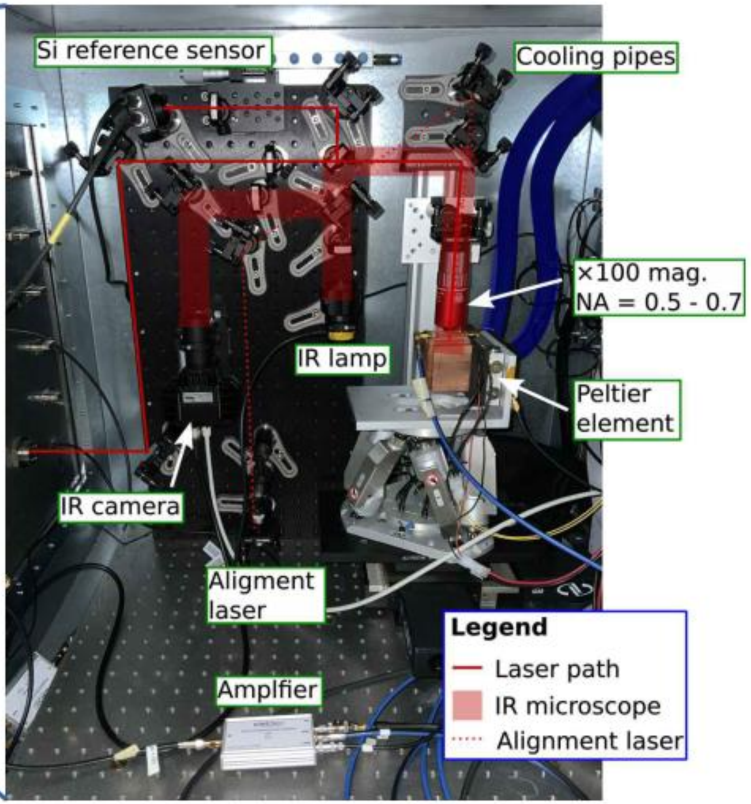
TPA-TCT setup at the SSD lab





Laser output pulse properties:

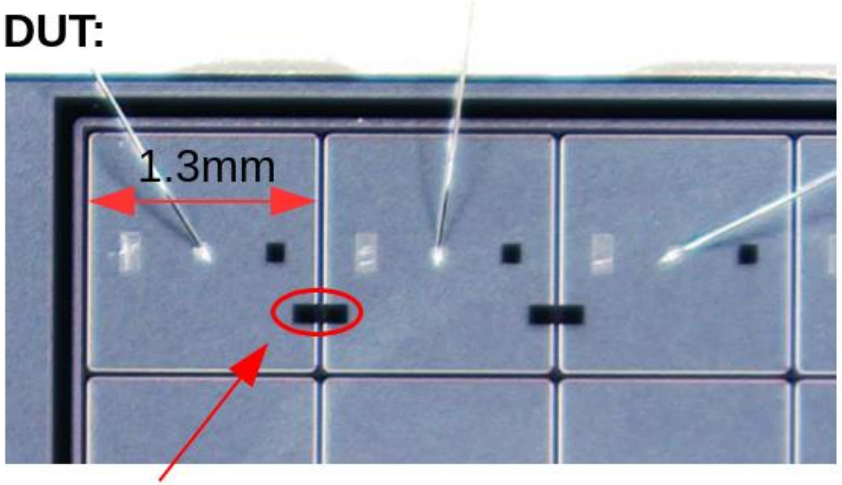
- approx. 430 fs width
- pulse frequency 8 MHz to single pulse
- pulse energy up to 10 nJ
- central wavelength 1.55 µm



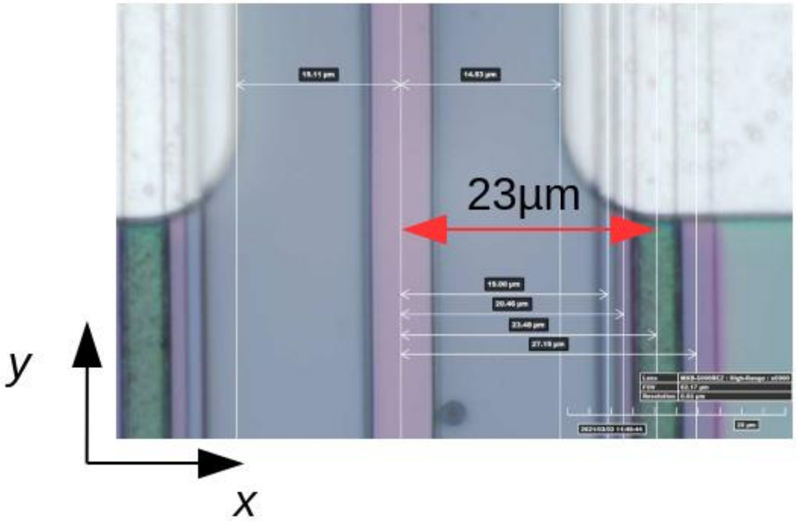
M. Wiehe et al., "Development of a Tabletop Setup for the Transient Current Technique Using Two-Photon Absorption in Silicon Particle Detectors", doi: 10.1109/TNS.2020.3044489.

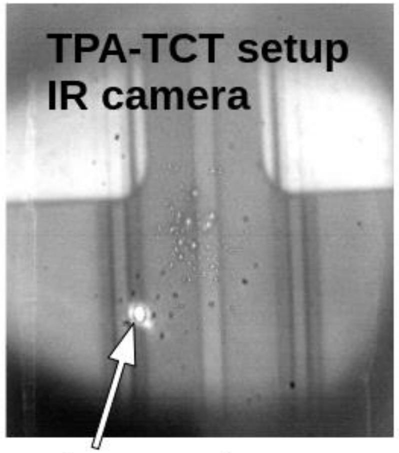
Inter-pad region of a HPK multipad LGAD

DUT:



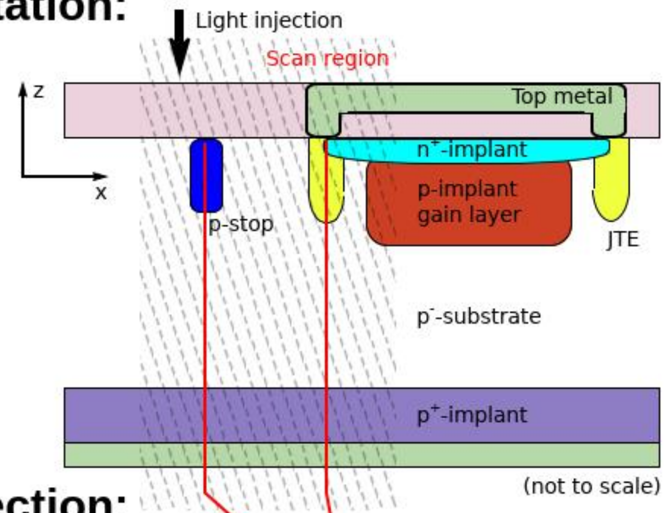
Inter-pad region: (microscope view)



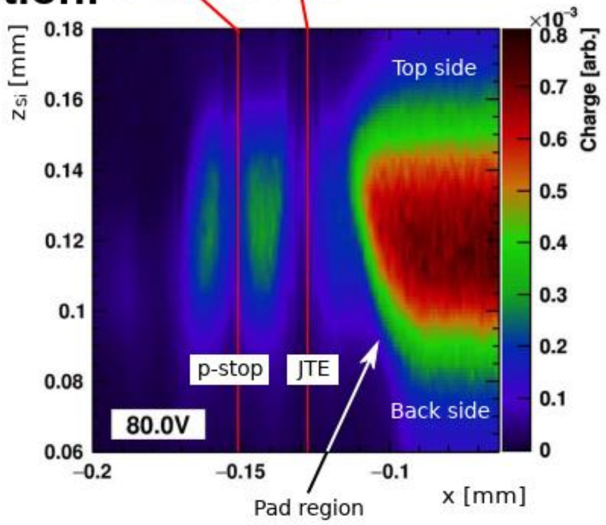


Laser beam spot

Implantation:

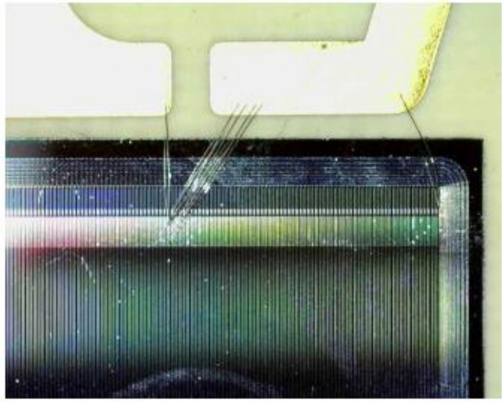


Charge collection:



Charge collection in a strip detector

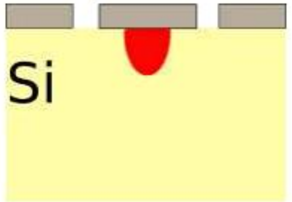
DUT:



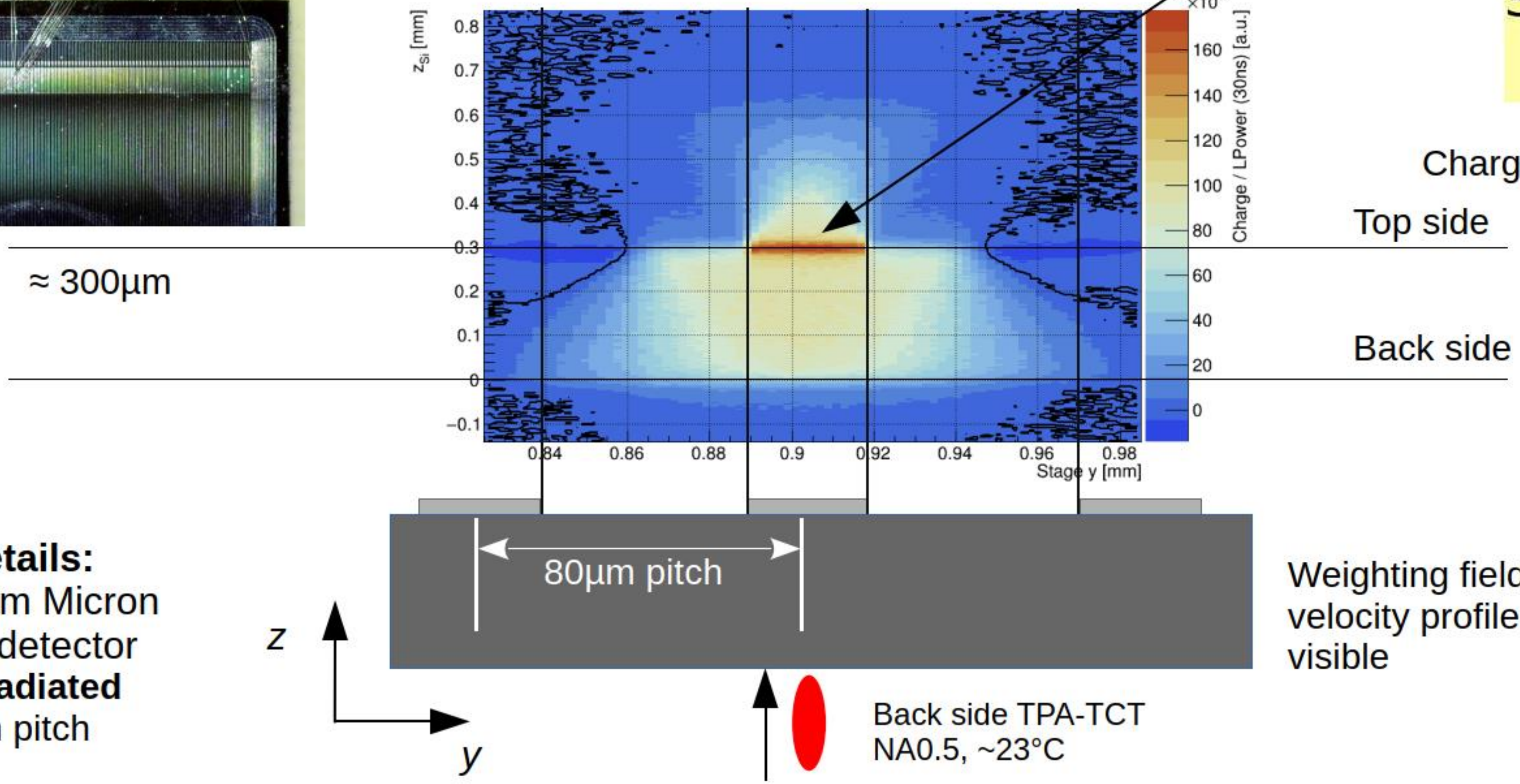
Charge collection:

Bias voltage: -50V

Reflection at strip metalization:



Charge highest: **$Q \sim I^2$**



Weighting field and drift velocity profile qualitatively visible

DUT details:
- 300µm Micron strip detector
- **unirradiated**
- 80µm pitch

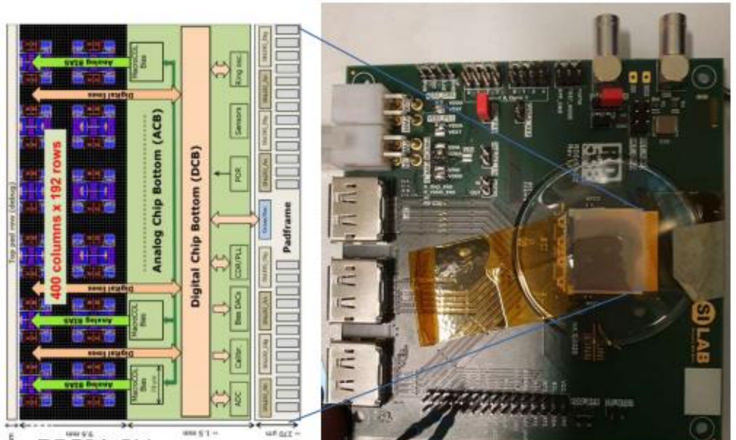
SEEs in a RD53B chip

Study SEEs in the RD53B chip in cooperation with the RD53 collaboration

Final goal: Check that events < 1nJ do not disturb or destroy the chip

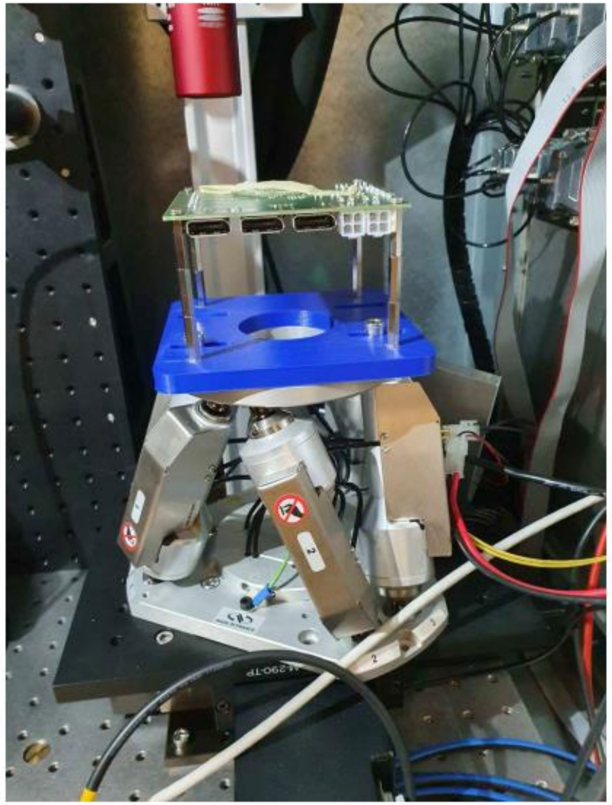
Possible to study SEEs with the TPA-TCT setup at CERN

RD53B chip + pixel sensor:

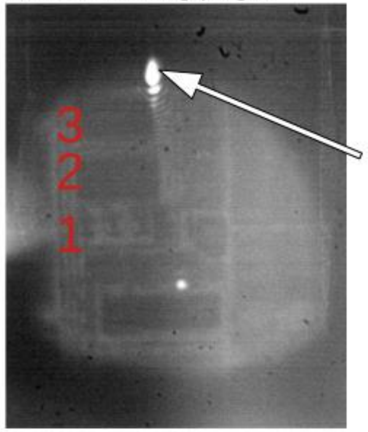


RD53A Chip

RD53 chip mounted in the setup with a custom made holder: (thanks to Ruddy Costanzi)

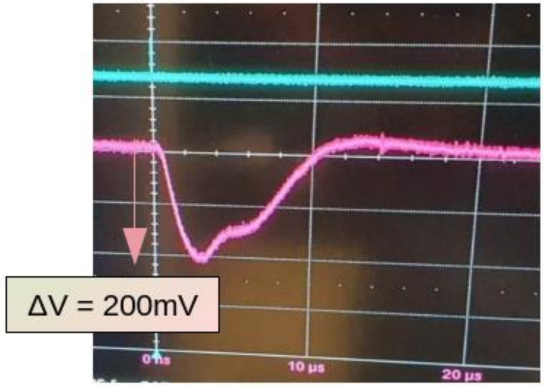


View under the IR microscope:
Transistors in the core bandgap region



Laser beam spot

SET found after injecting charge in the one of the transistors:



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Revisiting the NIEL

- **NIEL** is a physical quantity describing the non-ionizing energy loss as the particle travels to the medium.

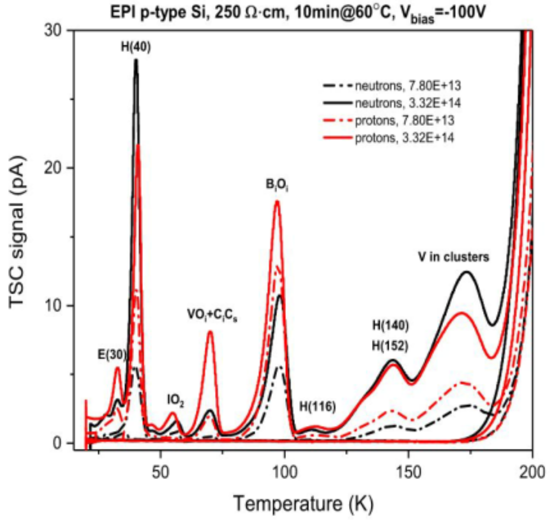
$$NIEL(T_0) = \frac{N_A}{A} \sum_i \int_{T_{min}}^{T_{max}} Q(T)T\left(\frac{d\sigma}{dT}\right)_i dT$$

- T_0: energy of incident particle, **T**: energy transferred to the recoil atom
- **(dσ/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 (fraction of **T** that is going into further displacements)
- N_A : Avogadro number, **A :** atomic mass of target atom

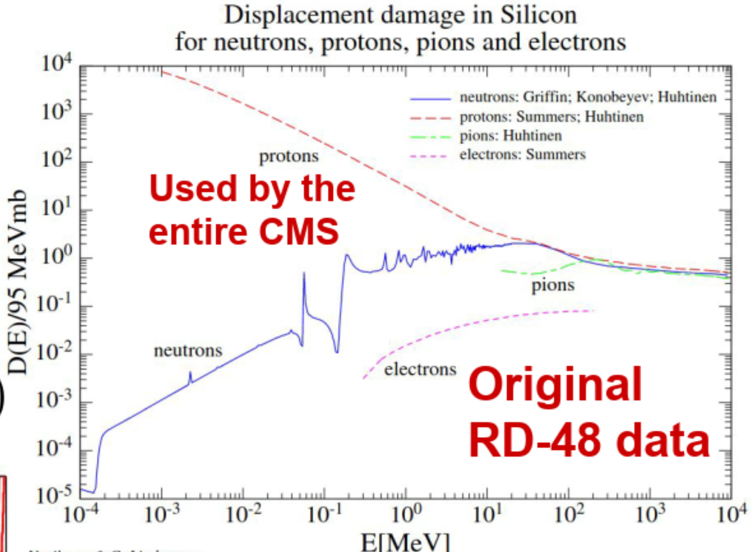
Displacement damage function for protons, neutrons and pions[1]

$$NIEL(T_0) = \frac{N_A}{A} D(T)$$

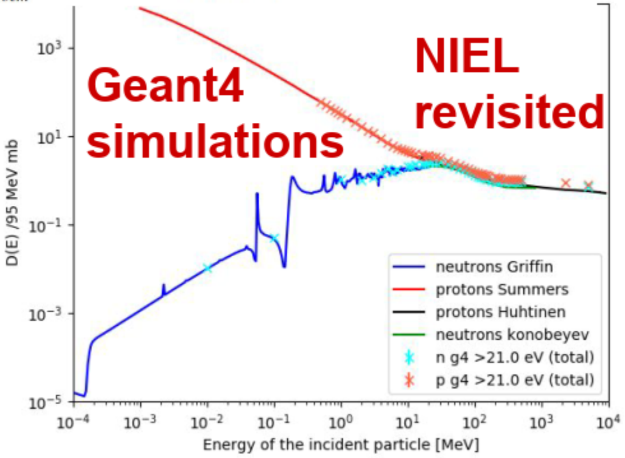
- NIEL doesn't describe cluster/ points defects, i.e. the same displacament energy has a very different distribution of damage on the microscopic level.
- NIEL violation reported in oxygen enriched silicon samples (CERN RD-48), differences between neutron's and proton's damage



Gurimskaya, Yana, et al. "Radiation Damage in P-Type EPI Silicon Pad Diodes Irradiated with Protons and Neutrons." Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, vol. 958, Apr. 2020, p. 162221. ScienceDirect, https://doi.org/10.1016/j.nima.2019.05.062.



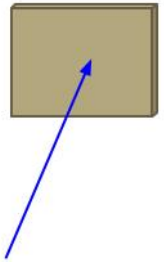
Vasilescu & G. Lindstroem



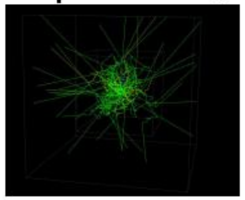
Revisiting the NIEL

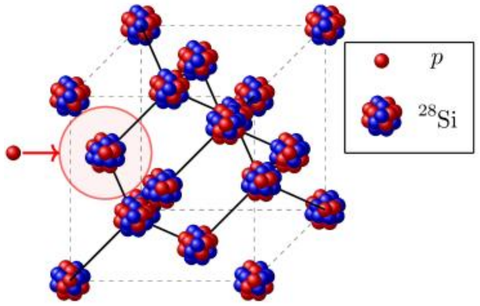
Geant4[4,5,6] (for GEometry ANd Tracking) is a Monte Carlo simulation platform for the passage of particles through matter.

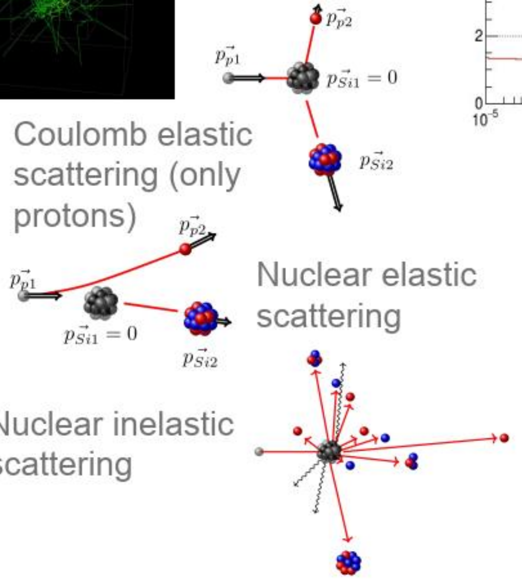
Define a geometry, beam:

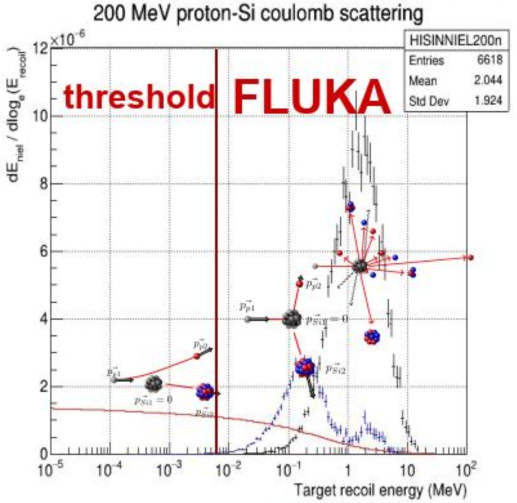


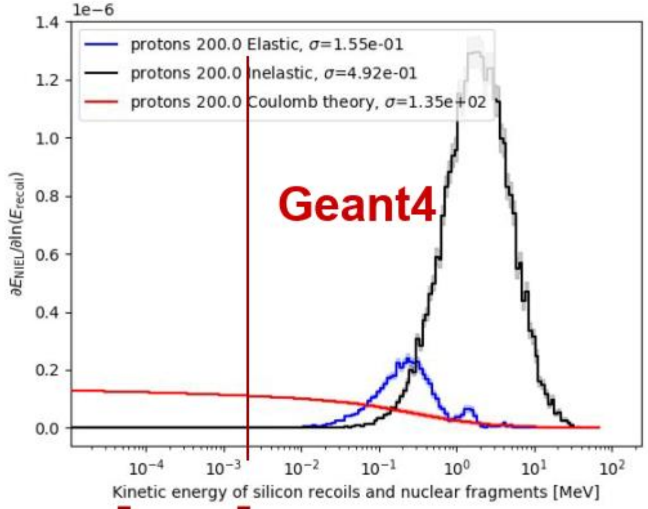
1mm x1 mm x100 µm
Pencil beam protons, neutrons

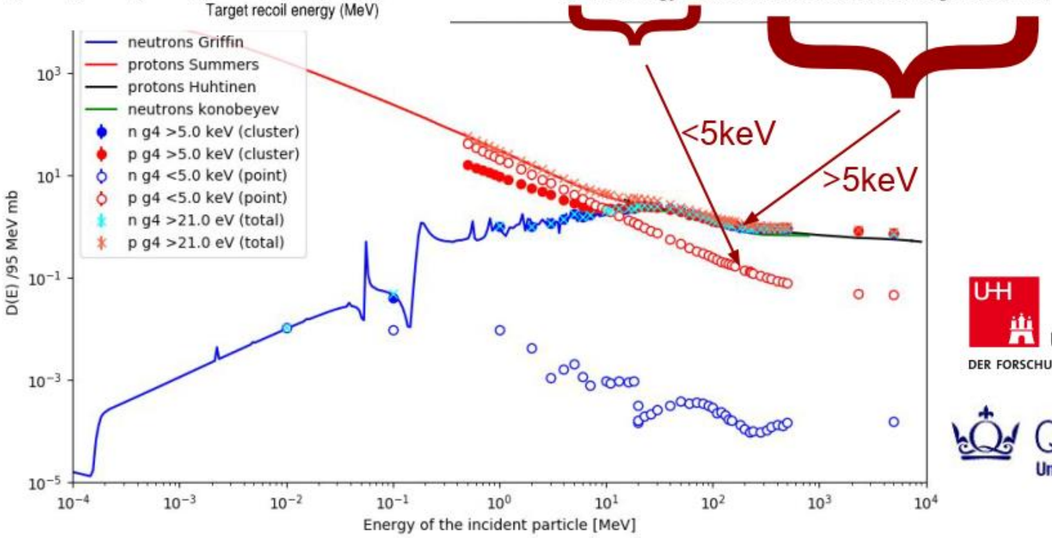












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Summary WP1.4.: Characterization & Simulation

- **Characterization tools** operational and made accessible to "clients/collaborators"
  - Tool development: TPA-TCT and Caribou DAQ system developed and fully operational
    - upgrades planned within WP1.4./AIDAinnova
  - Further equipment in operation in the SSD–Solid State Detectors lab (see backup slide):
    - CV/IV down to -30°C on cold chuck
    - CV/IV down to -70°C in climate chamber
    - Beta source measurements in climate chamber
    - TCT (standard and edge) 660nm and 1060nm
    - TPA-TCT (see this presentation)
    - Cryostat (10K to 370K) for defect spectroscopy
      - DLTS (Deep Level Transient Spectroscopy)
      - TSC (Thermally Stimulated Currents)
- **Characterization & Simulation** of sensors and radiation effects ongoing
  - **Aim:** Revision of NIEL hypothesis, Understand the "Acceptor Removal Effect" (i.e. degradation of LGADs), develop defect and device engineering approaches, build-up simulation models for simulations

CERN – SSD: Solid State Detectors lab