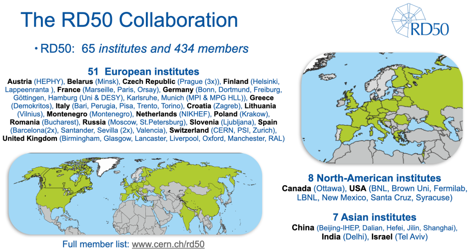
Silicon Detectors for Future Experiments - RD50 Status Report

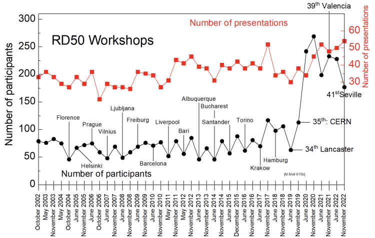
Marta Baselga on behalf of RD50 collaboration

VERTEX 2023 - Sestri Levante, 19th October 2023

RD50 collaboration

- RD50 collaboration is a CERN based collaboration for Radiation hard semiconductor devices for very high luminosity colliders
- It started the first workshop at 2001, as a continuation of ROSE collaboration
- Currently is having 2 annual workshops
- This November is going to be the 43rd RD50 workshop, it will be the last one
- RD50 activities will continue within the new DRD3 collaboration (Check the nice talk by N. Cartiglia!!)





[Plots by M. Moll]

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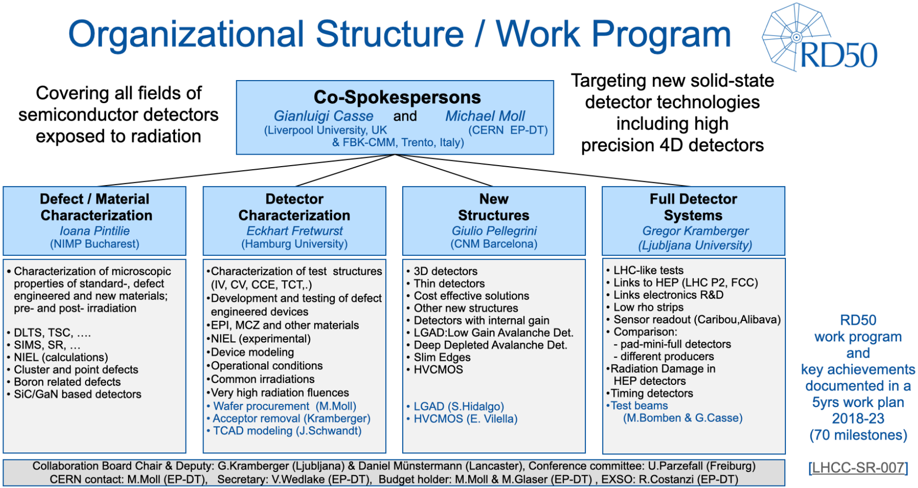
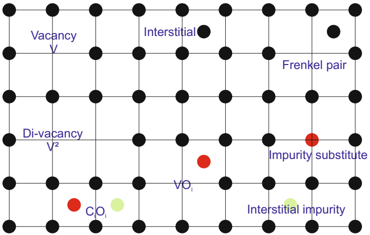
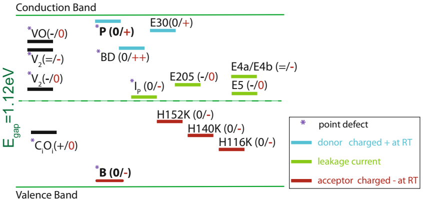
RD50 Structure



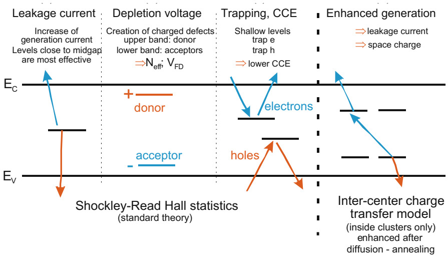
Slide thanks to Michael Moll

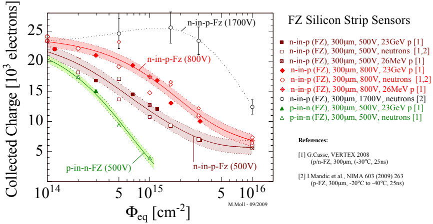
Connecting the microscopic with the macroscopic effects





[F. Hartmann, Evolution of Silicon Sensor Technology in Particle Physics, Springer 2017]





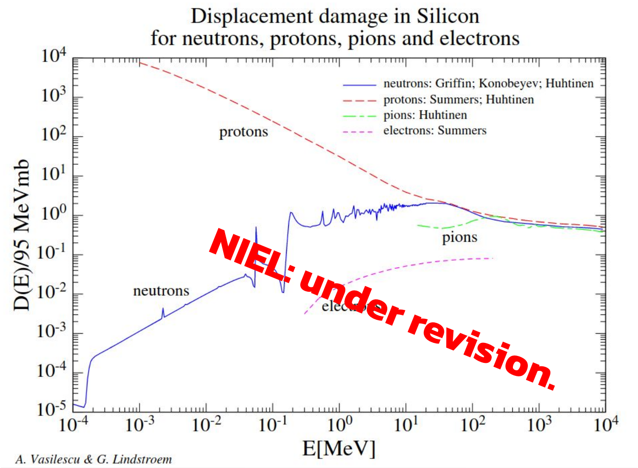
[M. Moll, Astroparticle, Particle and Space Physics, Detectors and Medical Physics Applications, 5: 101-110, 2010]

Defect characterization

NIEL(non-ionizing energy loss)

NIEL simulations do not distinguish between point or cluster defects

- NIEL is a simplification of the radiation damage
- Neutron and proton irradiation shows NIEL violation
- Simulations with Geant4 (PKA), TRIM (low energy recoil atoms) were corresponding to previous NIEL studies

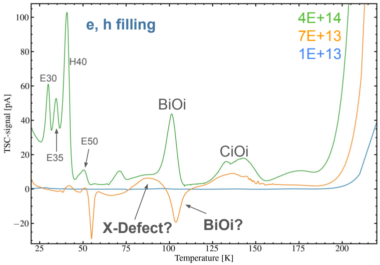


[V. Maulerova-Subert et al., 42nd RD50 Workshop]

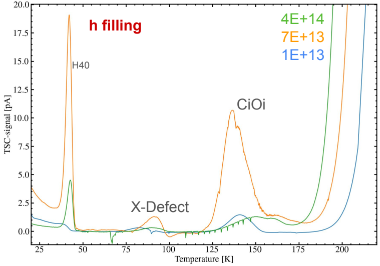
Negative TSC (Thermally Stimulated Current) results from CZ proton irradiated diodes

TSC Measurements of Thick Sensors (Electrical Filling)

1. Cooling down @-200V
2. **Forward bias filling (300V, 1mA)** @20K for 60s
3. Warming up @-200V



1. Cooling down @-200V
2. **0V filling** (majority carriers) @20K for 60s
3. Warming up @-200V



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[N. Sorgenfrei et al., 42nd RD50 Workshop]

- Negative TSC values corroborated with two setups
- Investigation of the origin cause ongoing

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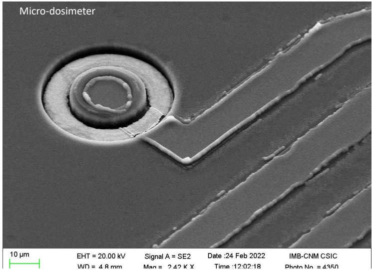
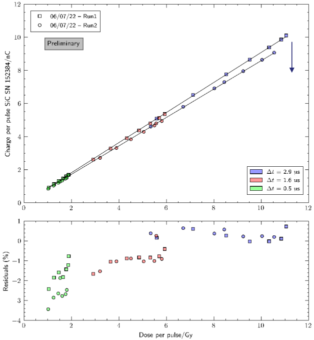
Other materials besides silicon

Ultra High Dose Dosimetry with Silicon Carbide

SiC for dosimetry of pulsed electron beams

- SiC as diamond has:
  - Low dark current
  - Radiation hardness
- Besides, SiC is cost effective for the quality of the crystal





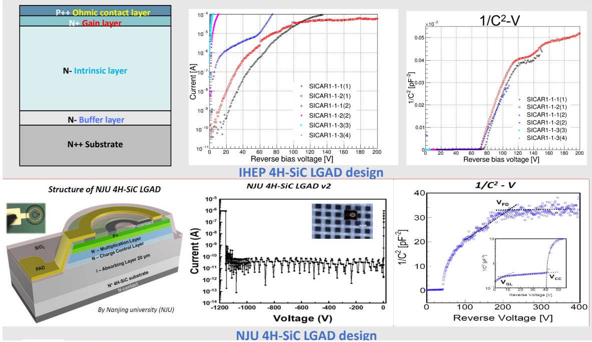
[G. Pellegrini et al., 42nd RD50 Workshop]

Effect of accumulated dose:

- Two runs, around 26 kGy accumulated dose
- Response linearity not affected
- 5% reduction sensitivity
- The saturation of the device response is associated to the series resistance

Combination of LGAD 4H-SiC sensors

p-in-n implant with an n+ multiplication layer



IHEP LGAD:
- obvious gain
- high breakdown voltage

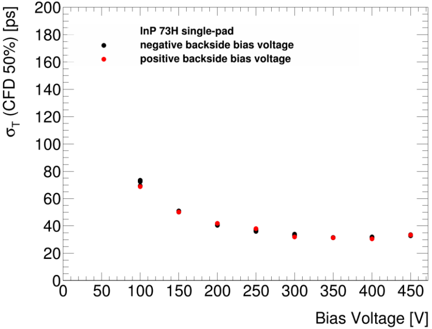
NJU LGAD:
- No gain
- High breakdown voltage

[Congcong Wang et al., 42nd RD50 Workshop]

- Good results with LGAD 4H-SiC sensors, showing the top ones gain, more investigation further
- TCAD Simulations should also be adapted to new materials (Philipp Gaggl et al., 42nd RD50 Workshop)

Characterization of Indium Phosphide sensors for future large-scale thin film detectors

Laser measurement with different polarity

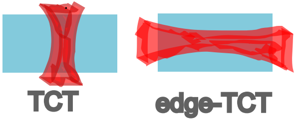


[J. Ott et al., 42nd RD50 Workshop]

- Indium phosphide is under investigation as thin-film material: single pad and multipad arrays were fabricated on bulk material and studied with several methods
- InP electron mobility 4500 $cm^2/Vs \rightarrow$ more than 3 times faster than Silicon

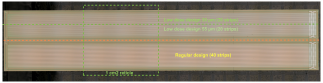
- High electron mobility leads to very fast signals and interesting timing resolution (substrate of 350 µm InP:Fe wafer)
- Reported timing resolution of 33 ps, more measurements to be confirmed

TCT- Transient Current Technique



TPA TCT for passive CMOS strips with stitching

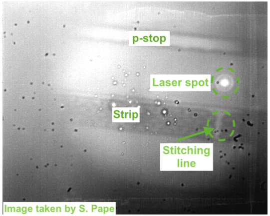
Stitched Passive Strips



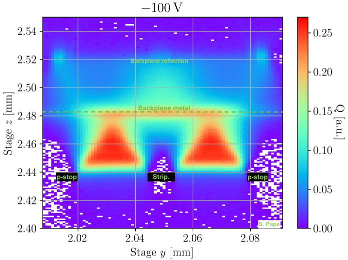
- TPA-TCT measurements were performed at CERN SSD
- The charge in stitching and outside stitching does not show any difference

More in this S. Pape et al., 41st RD50 Workshop, M. Baselga et al., 41st RD50 Workshop and M. Baselga et al, VERTEX23

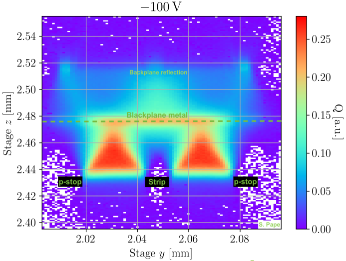
IR image



TPA-TCT in the stitch area

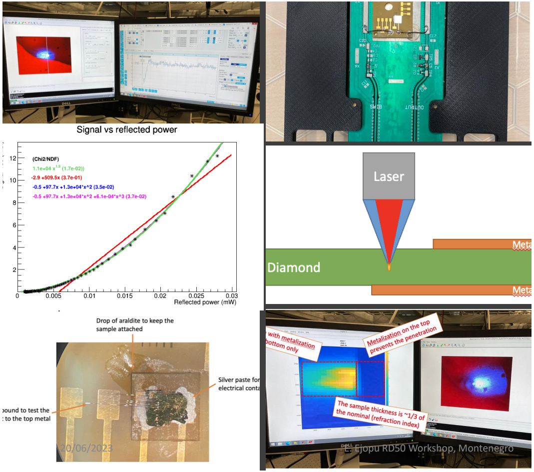


TPA-TCT outside the stitch



Performed TPA characterisation for Silicon diodes, LGADs and Diamond

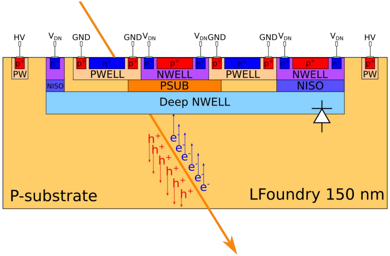
TPA TCT results for diamond detector



- Diamond E_{gap}=5.47 eV
- Laser wavelength λ=400 nm (~3.1 eV)
- Strong indication of TPA (quadratic nature of the curve)

[E. Ejopu et al., 42nd RD50 Workshop]

Monolithic


HV
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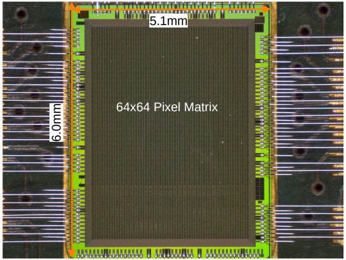
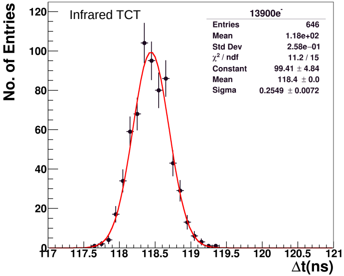
HV
PW
PWELL
NWELL
PWELL
NWELL
PW
NISO
PSUB
NISO
Deep NWELL
P-substrate
LFoundry 150 nm

RD50 MWP3 time results

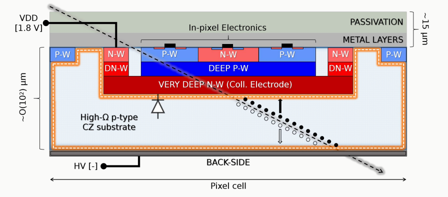




- CMOS chip with full analogue and digital electronics
- 1.9 kΩ cm and 3 kΩ cm resistivities
- 320 MHz input clock
- Large discrepancy between achievable time resolution between test pulses O(800ps) and bottom TCT O(250ps)

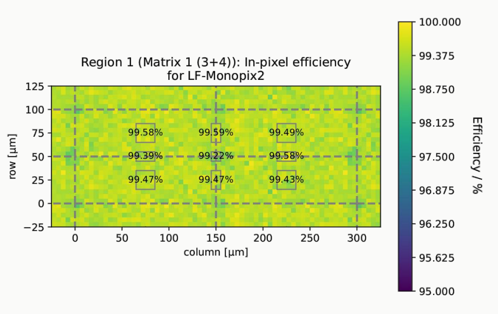
[U. Kramer, 42nd RD50 Workshop]

Characterization and radiation-hardness of the LF-Monopix2 DMAPS prototype



- *PROS*: Short drift distances, strong E field
- *CONS*: Large detector capacitance, high analogue power and ENC

- NIEL damage $1 \times 10^{15}\,n_{eq}/cm^2$
- Mean hit efficiency of 99.5 %

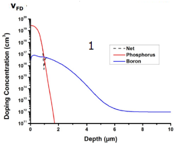


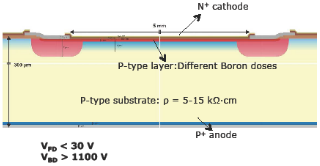
Covered by Lars Schall talk

[I. Caicedo, 42nd RD50 Workshop]

- Fully functional DMAPS in 150 nm CMOS process and large electrode pixel design

LGAD - Low Gain Avalanche Detectors





[S. Hidalgo, 22nd RD50 Workshop]

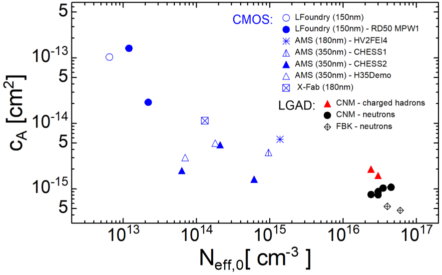
LGADs overview (Low Gain Avalanche Detectors)

- LGADs have been developed for more than 10 years (first time named LGADs in an RD50 workshop!)
- Incredible results for timing measurements (UFSD, thin detectors)
- Acceptor removal after irradiation dramatically affecting the multiplication layer. Mitigation strategies:
  - Efforts to implant Gallium → Discarded since it was not beneficial
  - Boron multiplication layer with carbon mitigates acceptor removal
  - Defect characterization with TSC to understand the process
- Small active area (reduced fill factor). Mitigation strategies:
  - iLGAD (multiplication at the backplane) → difficult to process thin backside wafers
  - TI-LGAD
  - AC-LGAD
  - DC-RSD, DJ-LGAD and more structures being developed
- Gain suppression
- Fast detectors competing with 3D detectors (drifting time defined by the distance between columns)

Acceptor removal coefficient study: Comparison between samples

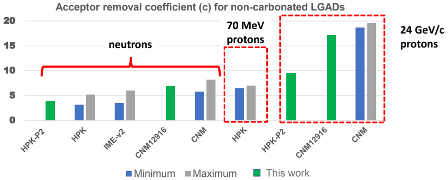
Acceptor removal coefficient measurements

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



[M. Moll, PoS Vertex2019]

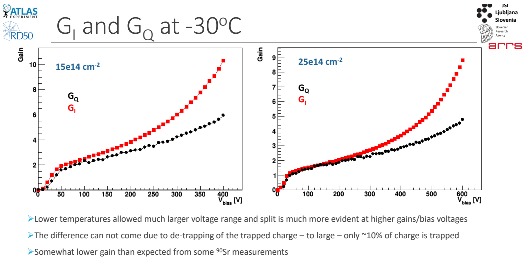
c (10^{-16} cm^{-2})	c_n	c_p	c_p/c_n
CNM-12916	6.91 ± 0.05	17.1 ± 0.77	2.475
HPK-P2	3.85 ± 0.24	9.51 ± 0.51	2.470
c_{CNM}/c_{HPK}	1.795	1.798	-

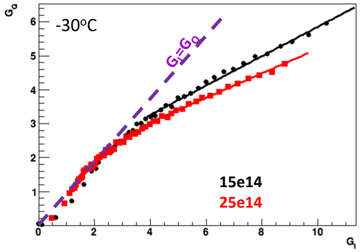


- 24 GeV protons introduce damages in gain layer almost 2.5 times higher than neutrons

[F. Zareef et al., 42nd RD50 Workshop]

Correlation between charge and current gain in LGADs (G_Q and G_I)



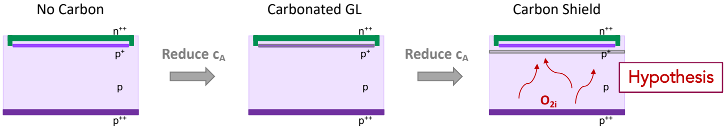


[G. Kramberger et al., 42nd RD50 Workshop]

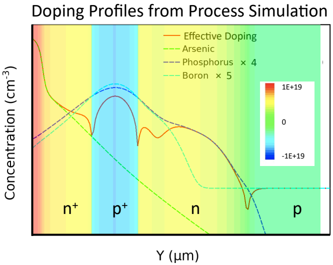
- Measurements of the Gain: charge gain, capacitance measurement gain, current gain
- For non-irradiated devices a deviation from G_Q=G_I is observed only at very high gains (voltages) and is attributed to charge screening effects observed before
- The ratio G_Q /G_I decreases with fluence at given gain, which is in agreement with Sr90 measurements
- Probably due to “field-quenching” because of trapped holes

Exflu, LGADS for high fluences

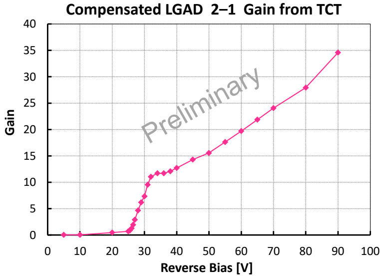
Carbonated shilding LGAD



Compensated LGAD



Laser stimulus on a LGAD-PiN structure from W6 (2 – 1)



[V. Sola et al., 42nd RD50 Workshop]

- Thickness ranging from 15 µm to 45 µm
- Compensated LGADs might be interesting for radiation hard measurements

Conclusions

- During 21 years, RD50 have been active and very fruitful in results of silicon studies (and other materials)
- Highly motivated in radiation damage but also fast detectors, new materials, new setups (TCT, e-TCT, TPA-TCT), simulations, ...
- Very strong bonding between collaboration members and with HEP experiment teams
- Future .... to move forward to DRD3 for future experiments, to continue the collaboration and knowledge exchange
- Last opportunity to attend the RD50 Workshop at CERN (28th November - 1st December 2023)!!!!!!!!
  - Registration → https://indico.cern.ch/event/1334364/overview

Thanks for your attention

Backup

LGADs for proton-CT

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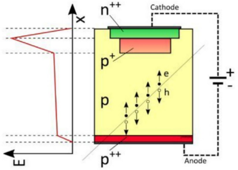
Motivation

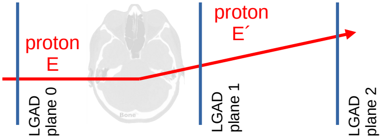


Low Gain Avalanche Detector

- Silicon detector with an additional highly doped p+ gain layer creating high electric field region for charge multiplication
- Intrinsic gain depends on:
  gain layer doping, bias voltage, temperature

Promising technology for **proton-CT**
LGADs offer fast signal collection
good spatial resolution
energy via time of flight

G.Kramberger LGAD sensors for application in proton CT, RAD2023



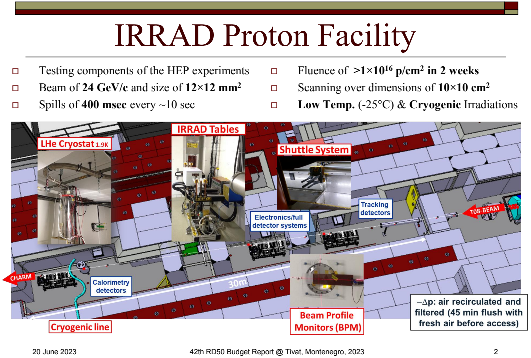
Why do we want to characterize LGADs with 30 MeV protons ?

- How does response depend on angle for highly ionizing particles?
- Can we see increased gain due to less screening for angled tracks?

Facilities

Facilities: ELI and IRRAD

- The Extreme Light Infrastructure is the world's largest and most advanced high-power laser infrastructure and a global technology and innovation leader in high-power, high-intensity, and short-pulsed laser systems



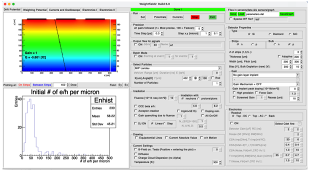
- User Portal: https://up.eli-laser.eu/

[M. Rebarz et al., 42nd RD50 Workshop]

Simulation: Microscopic effects for simulation models

Simulation software to adjust the radiation damage

- TRACS
- KDetSim
- Weightfield2
- RASER



TCAD Commercial software

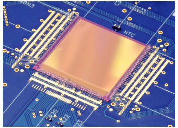
- Synopsys sentaurus
- Silvaco

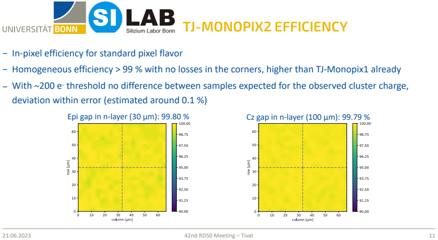
Radiation damage models

- Based on EVL
- Perugia models
- Pentatrap model
- LGAD

PERFORMANCE OF TJ-MONOPIX

- Latest iteration TJ-Monopix2: 33.04 µm pixel pitch in 512 x 512 pixel matrix (2 x 2 cm^2)
- 7 bit TOT resolution (40 MHz BCID clock - 25 ns timing)
- 3 bit in-pixel threshold tuning
- Communication via four differential lines
  - Command-based slow control (taken from RD53B)
  - 160 MHz data output rate (frame-based 8b10b encoding)
- bdaq53 readout board (from RD53A/B testing)
- Possible multi-chip readout not implemented yet





[C. Bespin, 42nd RD50 Workshop]

- Collected charge > 2000 e- for MIPs with efficiency > 99 % for unirradiated chips across front-end and substrate variants

NIEL(non-ionizing energy loss)

NIEL simulations do not distinguish between point or cluster defects

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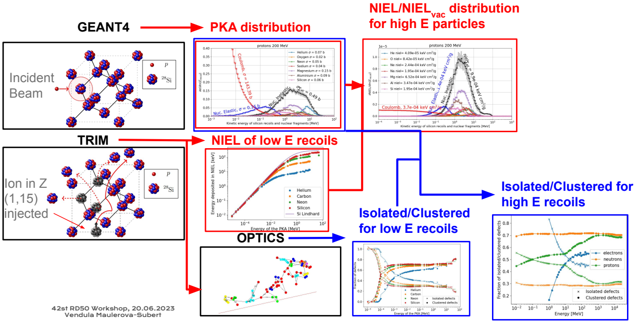
- Simulations with Geant4 (PKA), TRIM (low energy recoil atoms) were corresponding to previous NIEL studies



[V. Subert et al., 42nd RD50 Workshop]