EP-RD - 21 June 2022

Revision of the NIEL Hypothesis

Vendula Subert
(EP-DT-DD)

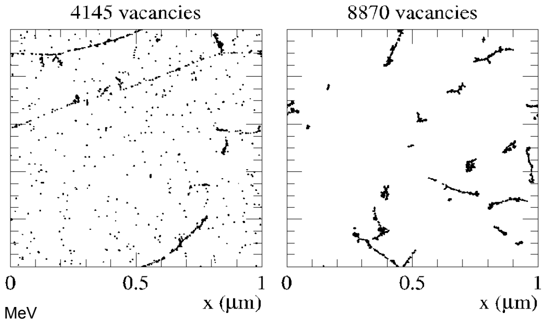
NIEL (non-ionizing energy loss)

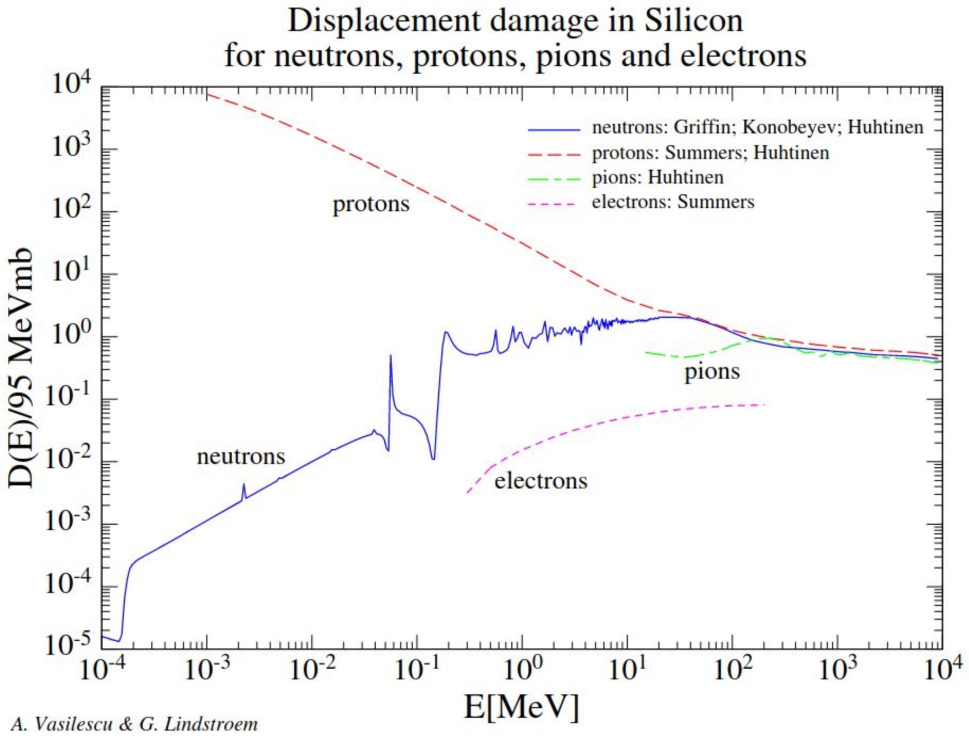
- **NIEL** is a physical quantity describing the non-ionizing energy loss as the particle travels to the medium.
- The amount of **NIEL** can be correlated to the radiation damage and can therefore predict the life time of the detectors in the experiments.
- **NIEL** is usually expressed as an equivalent to **NIEL** of 1 MeV neutrons.

- **NIEL is used by the LHC experiments (for damage predictions)**

NIEL for Silicon was standardized based on multiple sources 20 years ago by A. Vasilescu and G. Linstrom[1-5] (RD-48 data).

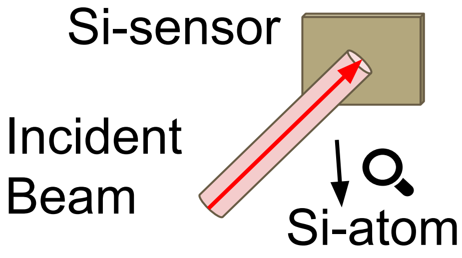
NIEL does not distinguish in point defects/ cluster defects, NIEL violation has been reported. [6-7]->need to **revisit NIEL**

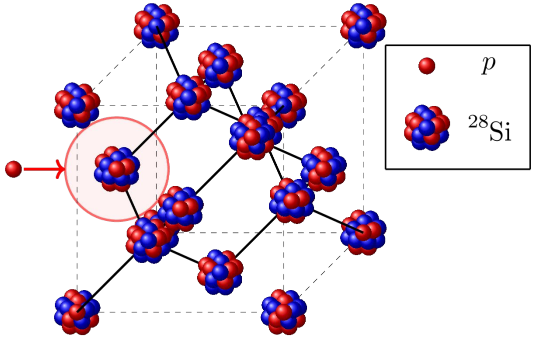




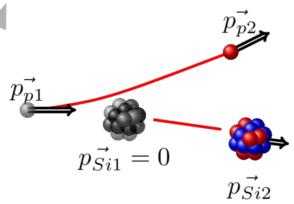
1) Data from A. Vasilescu (INPE Bucharest) and G. Lindström (Univ. of Hamburg)
2) P.J. Griffin et al., SAND92-0094 (Sandia Natl. Lab.93), priv. comm. 1996: E = 1.025E-10 - 1.995E+01 MeV
3) Konobeyev, Alexander Yu., et al. "Nuclear Data to Study Damage in Materials under Irradiation by Nucleons with Energies up to 25 GeV." Journal of Nuclear Science and Technology, vol. 39, no. sup2, Aug. 2002, pp. 1236–39. Taylor and Francis+NEJM, https://doi.org/10.1080/00223131.2002.10875327.
4) Huhtinen, M., and P. A. Aarnio. "Pion Induced Displacement Damage in Silicon Devices." Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, vol. 335, no. 3, Nov. 1993, pp. 580–82. ScienceDirect, https://doi.org/10.1016/0168-9002(93)91246-J.
5) Summers, G. P., E. A. Burke, P. Shapiro, et al. "Damage Correlations in Semiconductors Exposed to Gamma, Electron and Proton Radiations." IEEE Transactions on Nuclear Science, vol. 40, no. 6, Dec. 1993, pp. 1372–79. IEEE Xplore, https://doi.org/10.1109/23.273529.
6) Huhtinen, M. "Simulation of Non-Ionising Energy Loss and Defect Formation in Silicon." Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, vol. 491, no. 1, Sept. 2002, pp. 194–215. ScienceDirect, https://doi.org/10.1016/S0168-9002(02)01227-5.

Primary knocked-on atoms[7,8]

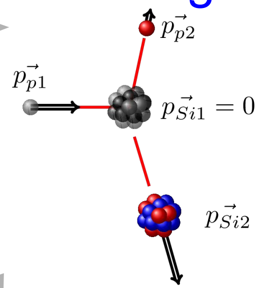




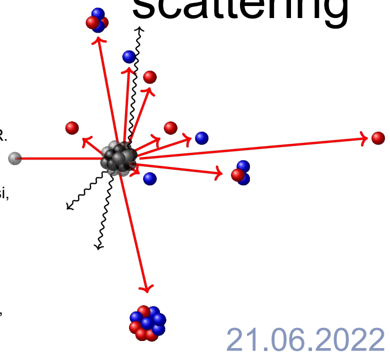
1) Coulomb elastic scattering (only charged particles)



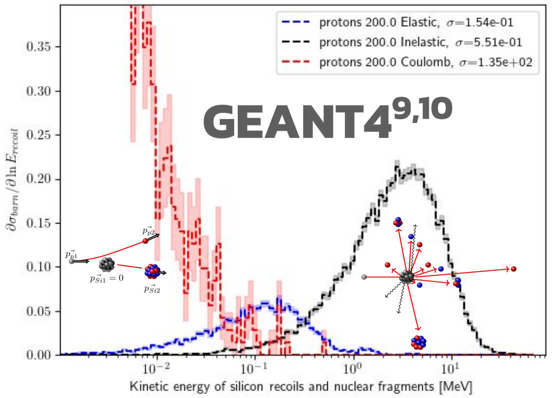
2) Nuclear elastic scattering

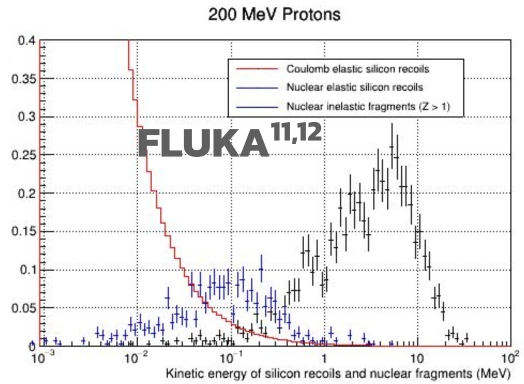


3) Nuclear inelastic scattering

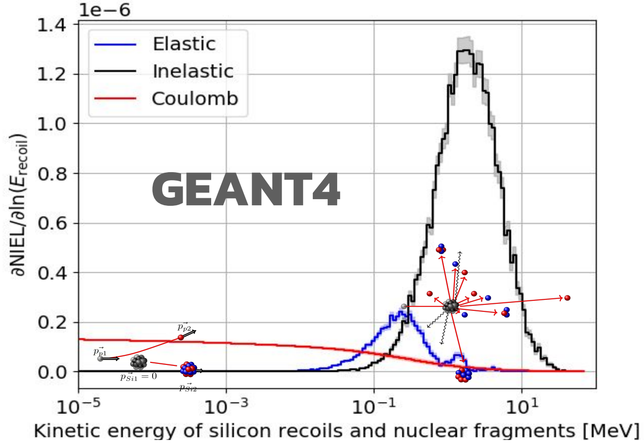


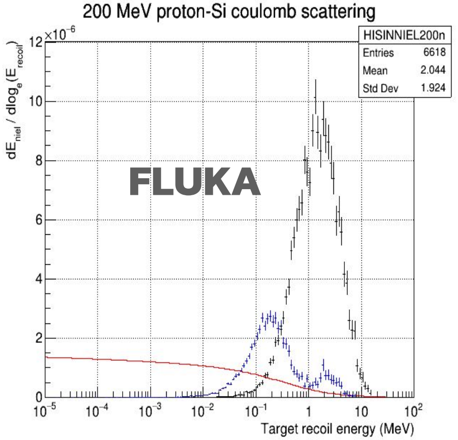
Area below the curves ~ **cross section**.





Area below the curves corresponds to the **NIEL**.





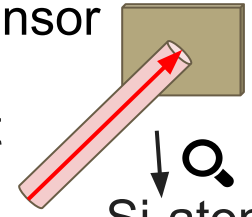
7) V. Maulerova et al., the 39th RD50 workshop, Valencia 17-19 Nov 2021, presentation, https://indico.cern.ch/event/1074989/
8) V. Subert-Maulerova et al., the 40th RD50 workshop, CERN 22-25 Jun 2022, presentation, https://indico.cern.ch/event/1157463/
9) Agostinelli, S., et al. "Geant4—a Simulation Toolkit." Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, D Detectors and Associated Equipment, vol. 506, no. 3, July 2003, pp. 250–303. ScienceDirect, https://doi.org/10.1016/S0168-9002(03)01368-8.
10) Allison, J., K. Amako, J. Apostolakis, H. Araujo, et al. "Geant4 Developments and Applications." IEEE Transactions on Nuclear Science, vol. 53, no. 1, Feb. 2006, pp. 270–78. IEEE Xplore, https://doi.org/10.1109/TNS.2006.869826.
11) C. Ahdida, D. Bozzato, D. Calzolari, F. Cerutti, N. Charitonidis, A. Cimmino, A. Coronetti, G. L. D'Alessandro, A. Donadon Servelle, L. S. Esposito, R. Froeschl, R. García Alía, A. Gerbershagen, S. Gilardoni, D. Horváth, G. Hugo, A. Infantino, V. Kouskoura, A. Lechner, B. Lefebvre, G. Lerner, M. Magistris, A. Manousos, G. Moryc, F. Ogallar Ruiz, F. Pozzi, D. Prelipcean, S. Roesler, R. Rossi, M. Sabaté Gilarte, F. Salvat Pujol, P. Schoofs, V. Stránský, C. Theis, A. Tsinganis, R. Versaci, V. Vlachoudis, A. Waets, M. Widorski, "New Capabilities of the FLUKA Multi-Purpose Code", Frontiers in Physics 9, 788253 (2022).
12) G. Battistoni, T. Boehlen, F. Cerutti, P.W. Chin, L.S. Esposito, A. Fassò, A. Ferrari, A. Lechner, A. Empl, A. Mairani, A. Mereghetti, P. Garcia Ortega, J. Ranft, S. Roesler, P.R. Sala, V. Vlachoudis, G. Smirnov, "Overview of the FLUKA code", Annals of Nuclear Energy 82, 10-18 (2015).

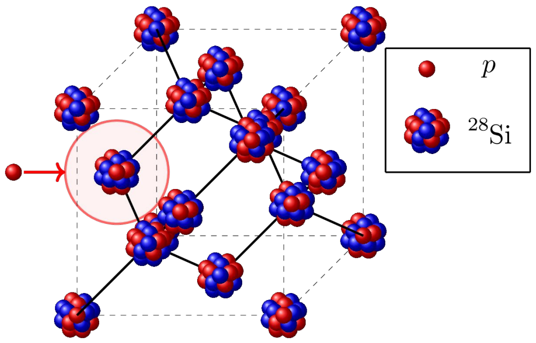
Primary knocked-on atoms

Si-sensor

Incident Beam

Si-atom





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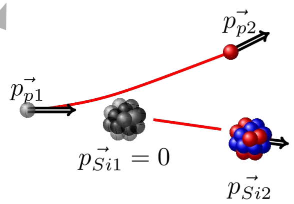
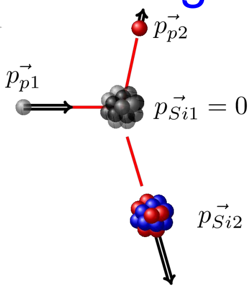
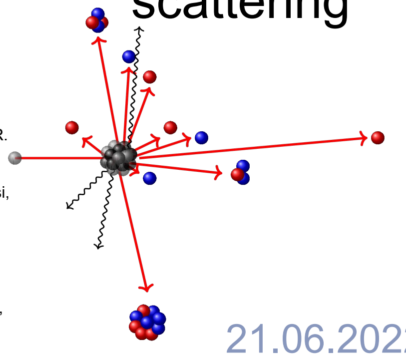


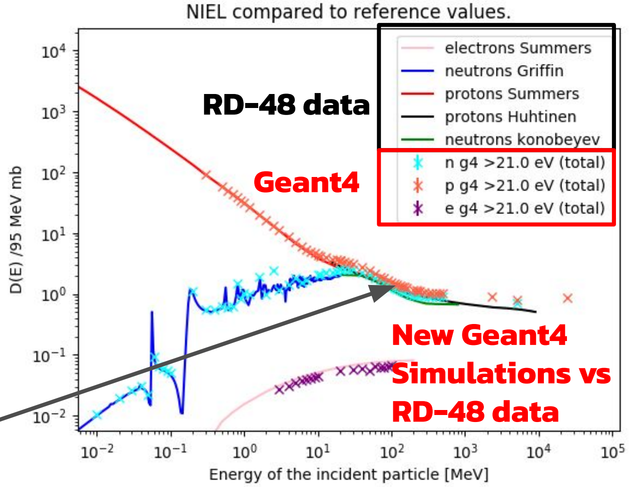
2) Nuclear elastic scattering

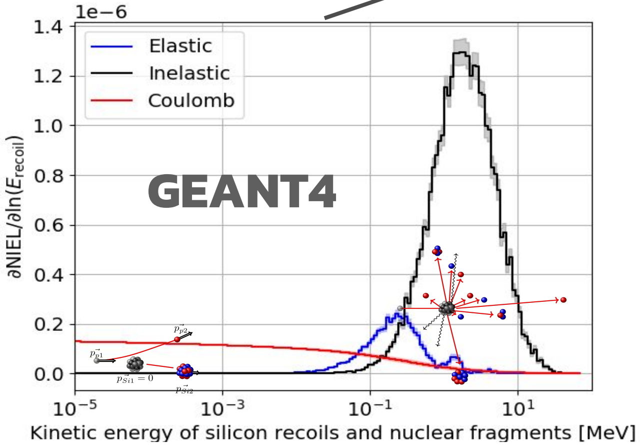


3) Nuclear inelastic scattering



Integrating area yields 1 point RD-48 plot.





7) V. Maulerova et al., the 39th RD50 workshop, Valencia 17-19 Nov 2021, presentation, https://indico.cern.ch/event/1074989/
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10) Allison, J., K. Amako, J. Apostolakis, H. Araujo, et al. "Geant4 Developments and Applications." IEEE Transactions on Nuclear Science, vol. 53, no. 1, Feb. 2006, pp. 270–78. IEEE Xplore, https://doi.org/10.1109/TNS.2006.869826.
11) C. Ahdida, D. Bozzato, D. Calzolari, F. Cerutti, N. Charitonidis, A. Cimmino, A. Coronetti, G. L. D'Alessandro, A. Donadon Servelle, L. S. Esposito, R. Froeschl, R. García Alía, A. Gerbershagen, S. Gilardoni, D. Horváth, G. Hugo, A. Infantino, V. Kouskoura, A. Lechner, B. Lefebvre, G. Lerner, M. Magistris, A. Manousos, G. Moryc, F. Ogallar Ruiz, F. Pozzi, D. Prelipcean, S. Roesler, R. Rossi, M. Sabaté Gilarte, F. Salvat Pujol, P. Schoofs, V. Stránský, C. Theis, A. Tsinganis, R. Versaci, V. Vlachoudis, A. Waets, M. Widorski, "New Capabilities of the FLUKA Multi-Purpose Code", Frontiers in Physics 9, 788253 (2022).
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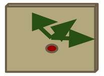
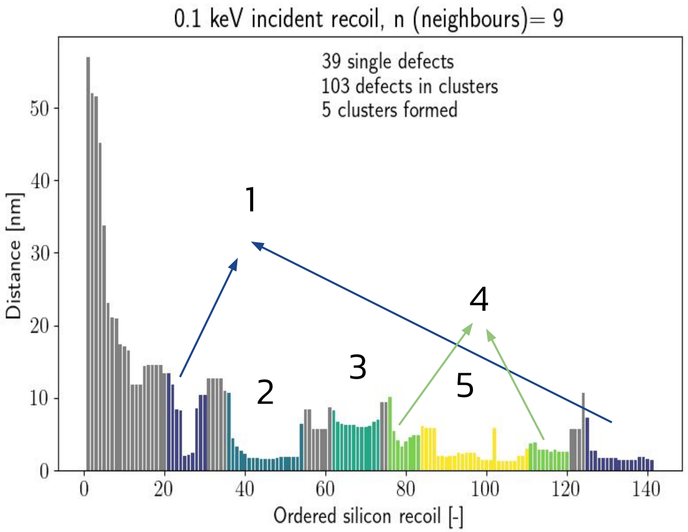
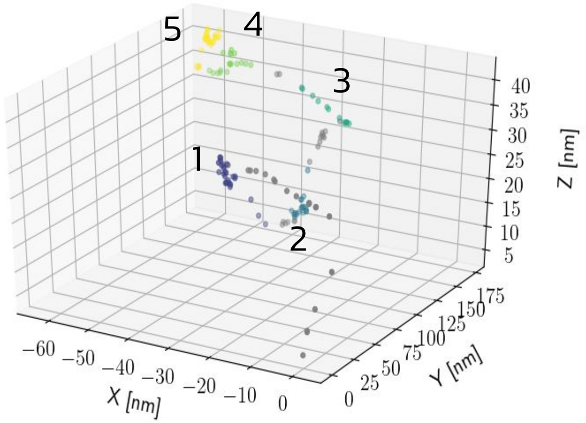
Subsequent Silicon Cascade

Si-sensor 

Si injection

- OPTICS[13,14,15] (Ordering points to identify the clustering structure) algorithm

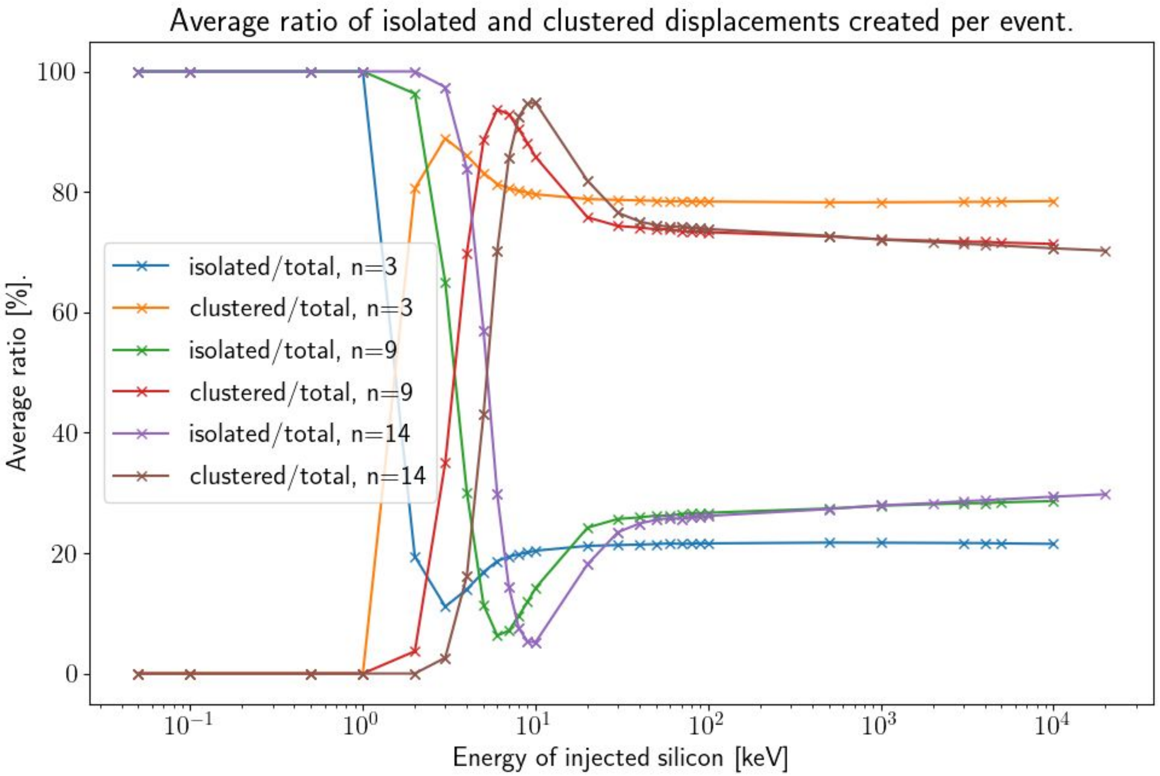




Reachability plot:

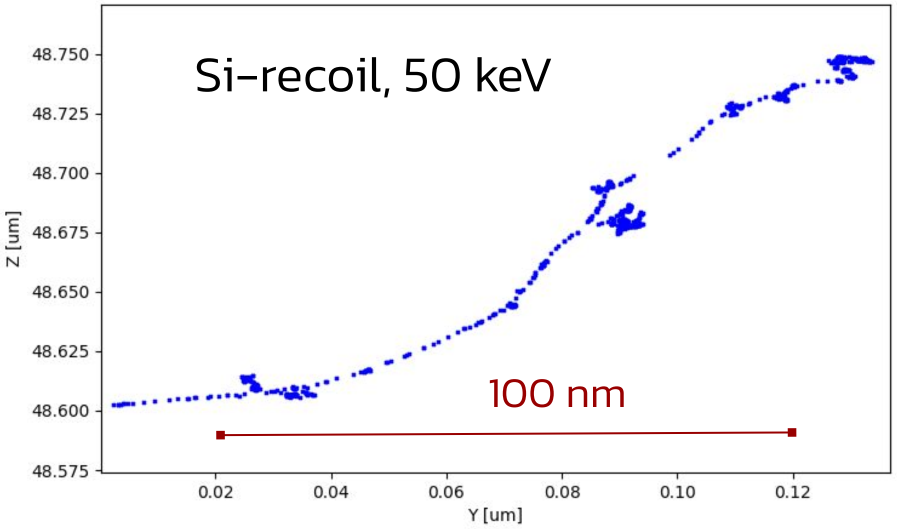
- 1 entry shows the istance from previous point (x:1 y: distance from point #1 to point #0)
- Valleys represent clusters
- User input: n (no. of neighbours)

- Conclusion: From certain threshold value of injected Si-recoil, the ratio cluster/isolated defects is constant.



13) Ankerst, Mihael, Markus M. Breunig, Hans-Peter Kriegel, and Jörg Sander. "OPTICS: ordering points to identify the clustering structure." ACM SIGMOD Record 28, no. 2 (1999): 49-60.
14) Schubert, Erich, Michael Gertz. "Improving the Cluster Structure Extracted from OPTICS Plots." Proc. of the Conference "Lernen, Wissen, Daten, Analysen" (LWDA) (2018): 318-329.
15) https://www.youtube.com/watch?v=CV0mWaHOTA8&t=133s tutorial

Outlook & next steps



- A Geant4-based simulations and analysis are being carried out together with FLUKA to revisit the RD-48 NIEL curves.
- NIEL curves in literature with Geant4 and Fluka simulations successfully reproduced
- Algorithm for identifying clustered versus point defect damage implemented.
- For Si recoil of the energy above 50 keV energy threshold the cluster to point defect ration remains constant, in agreement with the literature[13].
- Further developments of algorithm for damage differences between different particles are envisioned.
- Closure on cluster's parameter definition.
- Further studies and comparisons with FLUKA.
- Cluster/Isolated displacements containing update of the RD48 plot for protons and neutrons and extending studies to electrons and gammas.
- Benchmarking with DLTS measurements data.
- Determine fraction of cluster NIEL in irradiation facilities, e.g. CERN PS versus JSI research reactor.

13) J. R. Srour and J. W. Palko, "A framework for understanding displacement damage mechanisms in irradiated silicon devices," IEEE Trans. Nucl. Sci., vol. 53, no. 6, pp. 3610–3620, Dec. 2006