V. Maulerova-Subert, I. Dawson,
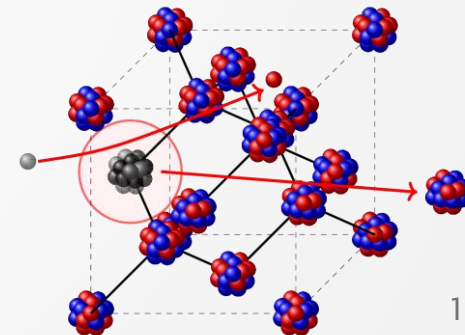E. Garutti, M.Moll, A. Himmerlich,
Y. Gurimskaya

NIEL (non-ionizing energy loss)

Geant4 simulations and OPTICS algorithm towards more complex
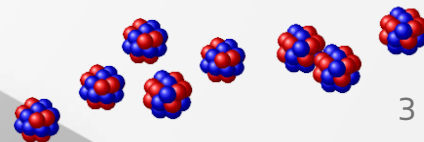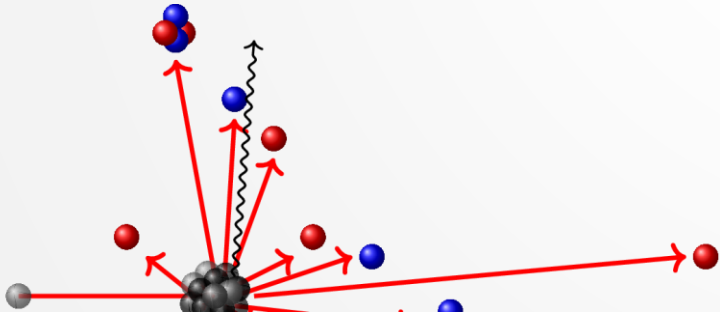NIEL concept for radiation damage modelling and prediction

The 40th RD-50 workshop, CERN, 21.06.2022

1

CONTENTS

The NIEL hypothesis

NIEL (non-ionizing energy loss)

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

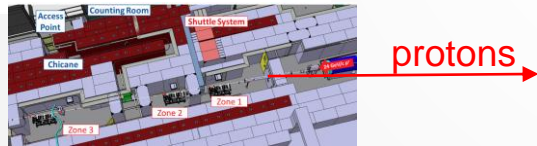- **NIEL scaling assumption is used by most of the LHC experiments**

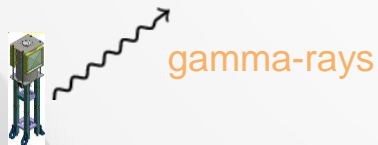Long term goal: to revisit the damage factor stated by different irradiation facilities
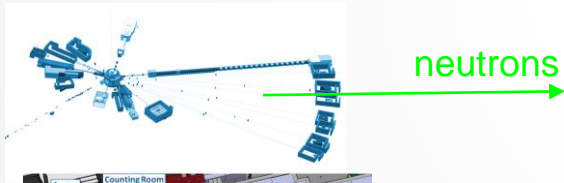
ESS neutrons

IRRAD protons

GIF++ gamma-rays

NIEL (non-ionizing energy loss)

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

- **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 giving the fraction of **T** that is going into further displacements
- **N_A** : Avogadro number
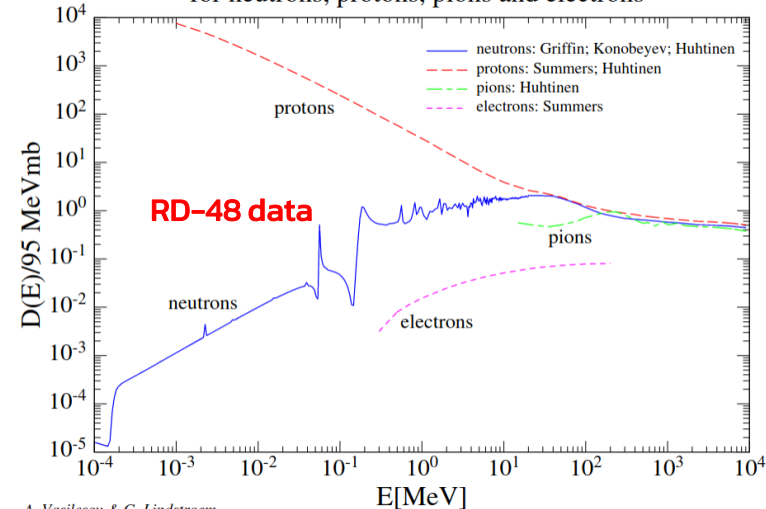- **A :** atomic mass of target atom

Displacement damage function

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

MeV cm²/g

MeV mb 1,2,3,4,5

Displacement damage in Silicon for neutrons, protons, pions and electrons

- neutrons: Griffin; Konobeyev; Huhtinen
- protons: Summers; Huhtinen
- pions: Huhtinen
- electrons: Summers

RD-48 data

A. Vasilescu & G. Lindstroem

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.
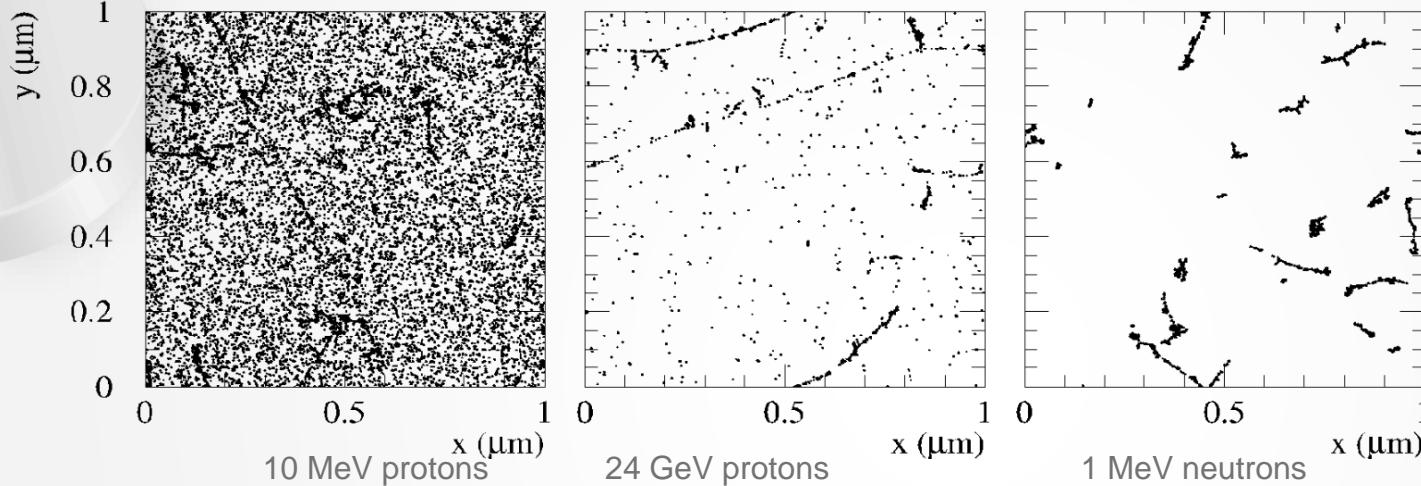
Revisiting NIEL

Simulations of radiation damage by M. Huhtinen[6].

36824 vacancies — 10 MeV protons
4145 vacancies — 24 GeV protons
8870 vacancies — 1 MeV neutrons

Radiation Damage in P-Type EPI Silicon Pad Diodes Irradiated with Protons and Neutrons[7].
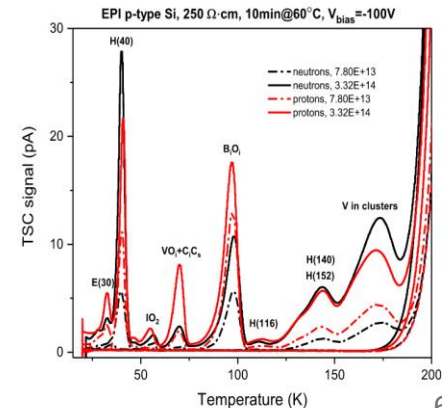

- NIEL doesn't distinguish between cluster and point displacement, i.e. the same displacament energy has a very different distribution of damage on the microscopic level.
- NIEL scaling violation reported in oxygen enriched silicon samples (CERN RD-48), differences between neutron's and proton's damage
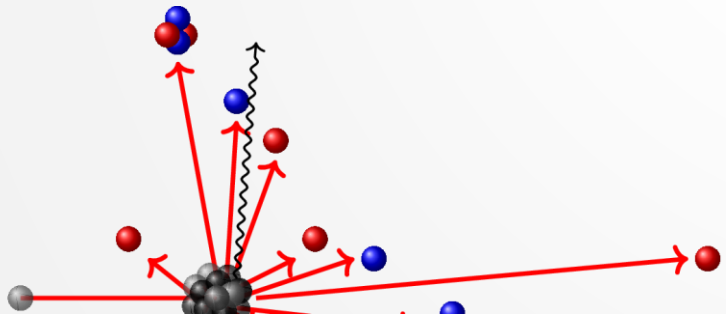
6) Huhtinen, M. "Simulation of Non-Ionising Energy Loss and Defect Formation in Silicon." Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, vol. 491, no. 1, Sept. 2002, pp. 194–215. ScienceDirect, https://doi.org/10.1016/S0168-9002(02)01227-5.
7) 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.
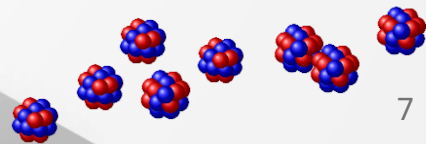
Geant4 simulations
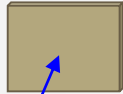
Geant4 simulation framework

Geant4[8,9] (for GEometry ANd Tracking) is a Monte Carlo simulation platform for the passage of particles through matter.

Define a geometry:

For most of the simulations:
1mm x 1 mm x 100 µm

Choose a physics list:

1. For PKA:
   a. *QGSP_BERT_HP* (Nuclear scattering)
   b. *QGSP_BERT_HP__SS* (Coulomb scattering)
2. For subsequent cascade:
   a. *Custom PhysicsList*[10]

Launch a simulation:

QGSP_BERT_HP
QGSP_BERT_HP_

_SS

Custom Physics[10]

Define a beam profile:

1. For PKA: Monochromatic pencil beam of protons and neutrons of various energies.
2. For subsequent cascade: Single Si particles of various energies being injected
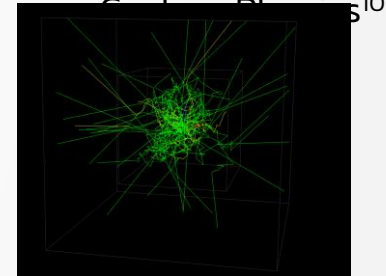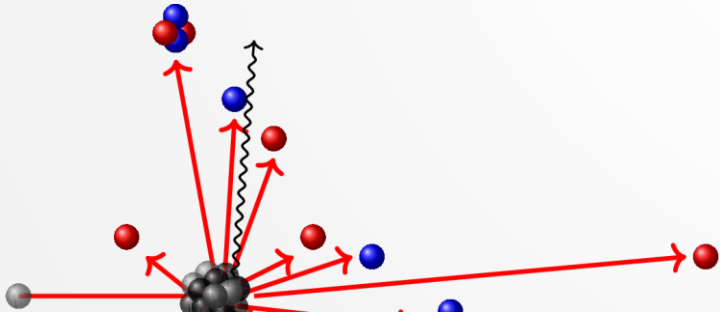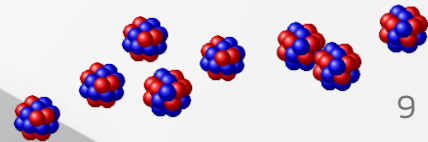
Analyze (c++, python)

8)   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.
9)   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.
10)   Raine, Melanie, et al. "Simulation of Single Particle Displacement Damage in Silicon - Part I: Global Approach and Primary Interaction Simulation." IEEE Transactions on Nuclear Science, vol. 64, no. 1, Oct. 2016, pp. 133–40. HAL Archives Ouvertes, https://doi.org/10.1109/TNS.2016.2615133.
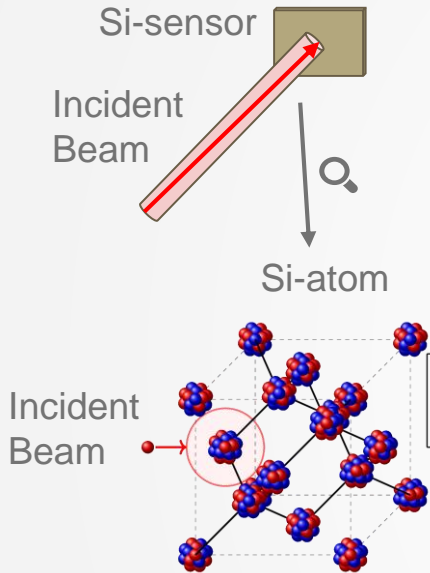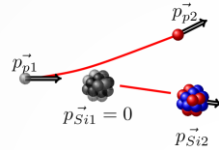
PKA (Primary knocked-on atoms)

PKA cross section example

Incident Beam → Si-sensor

Si-atom

Incident Beam

p — ^{28}Si

1) Coulomb elastic scattering (only charged particles)
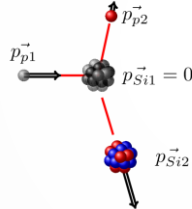
$\vec{p_{p1}}$ $\vec{p_{p2}}$ $p_{\vec{Si1}} = 0$ $\vec{p_{Si2}}$

2) Nuclear elastic scattering

$\vec{p_{p1}}$ $\vec{p_{p2}}$ $p_{\vec{Si1}} = 0$ $\vec{p_{Si2}}$

3) Nuclear inelastic scattering

FLUKA cross–comparison

GEANT4

protons 200.0 Elastic, $\sigma=1.54e{-}01$
protons 200.0 Inelastic, $\sigma=5.51e{-}01$
protons 200.0 Coulomb, $\sigma=1.35e{+}02$
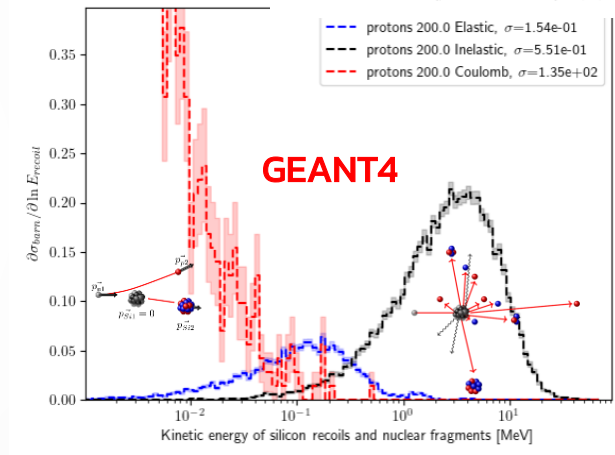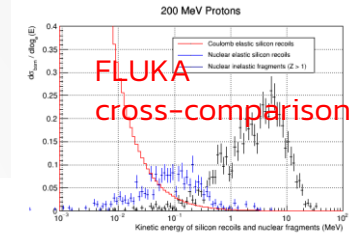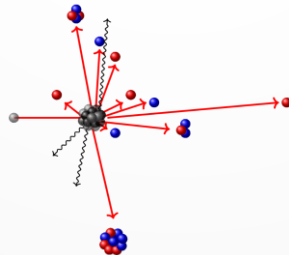
Area below the curve corresponds to the cross section.

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

PKA cross section example

Si-sensor

Incident Beam

Si-atom

Incident Beam

$\bullet$ p

^{28}Si

1) Coulomb elastic scattering (only protons)

$\vec{p_{p1}}$ $\vec{p_{p2}}$

$\vec{p_{Si1}} = 0$ $\vec{p_{Si2}}$

2) Nuclear elastic scattering

$\vec{p_{p1}}$ $\vec{p_{p2}}$

$\vec{p_{Si1}} = 0$

$\vec{p_{Si2}}$

3) Nuclear inelastic scattering

FLUKA cross-comparison

GEANT4

- Elastic
- Inelastic
- Coulomb

$\partial \text{NIEL}/\partial \ln(E_{recoil})$

Kinetic energy of silicon recoils and nuclear fragments [MeV]
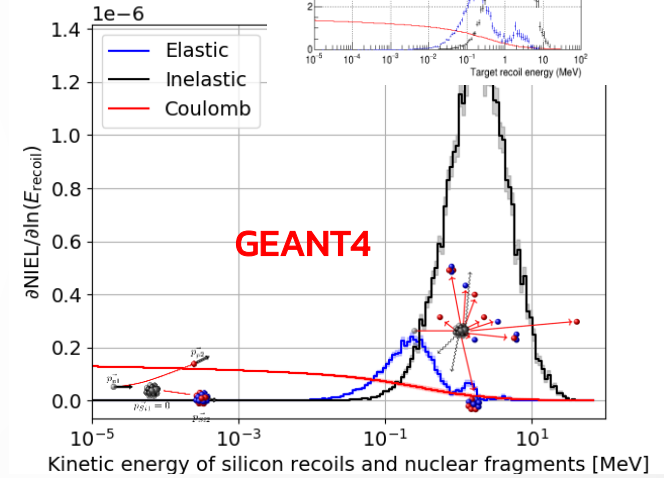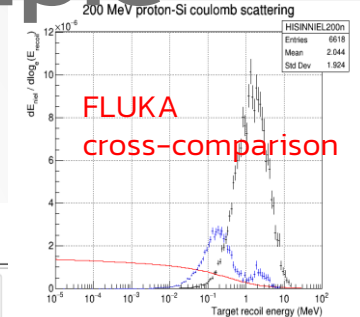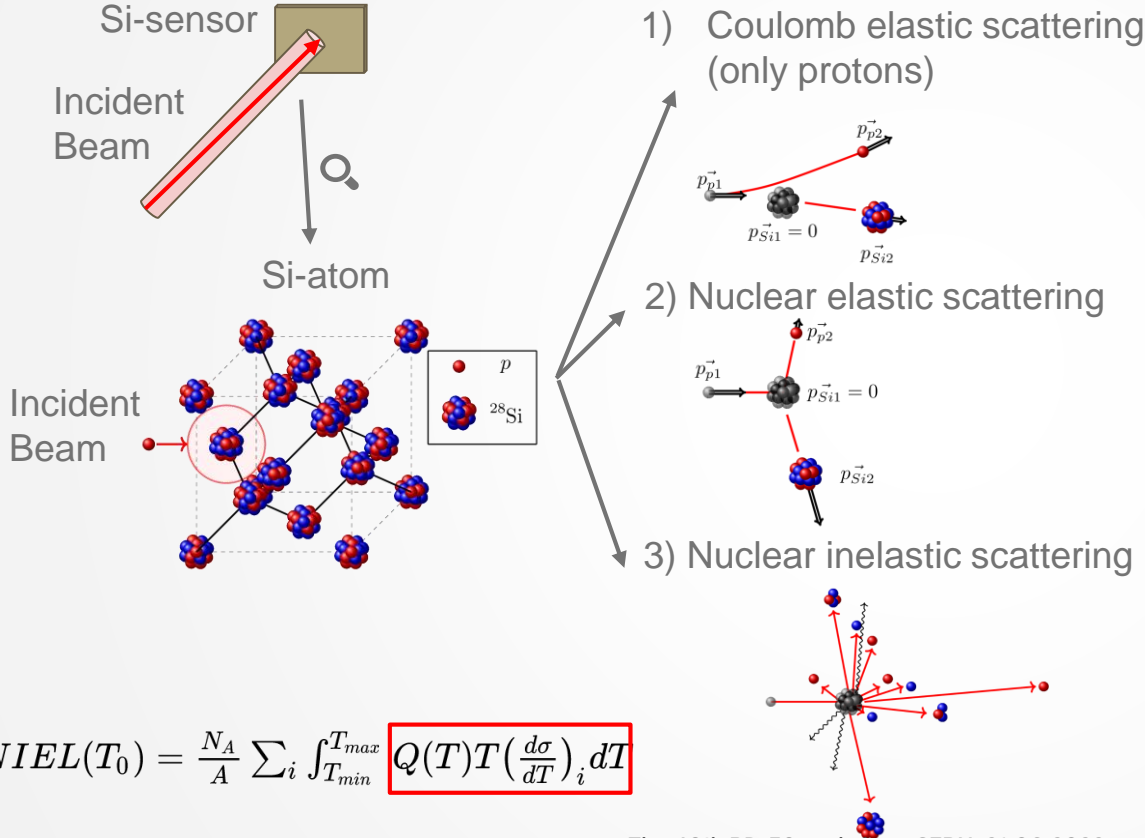
Area below the curve corresponds to the NIEL for respective reaction.

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

NIEL

NIEL compared to reference values.

RD-48
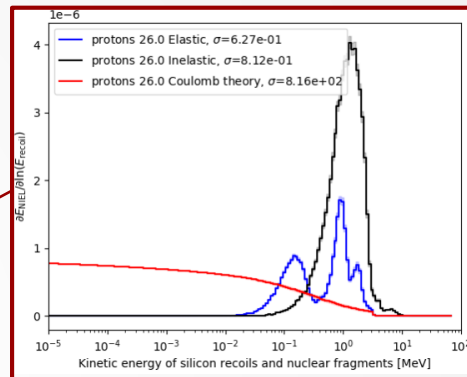
Geant4
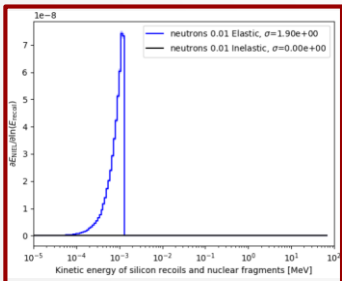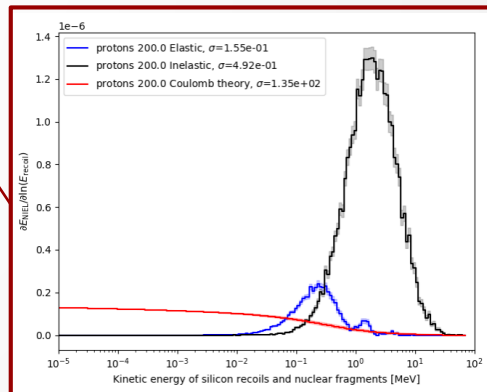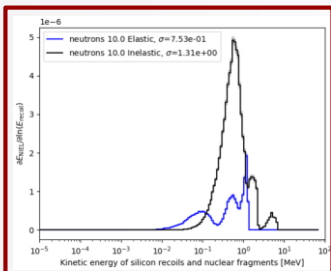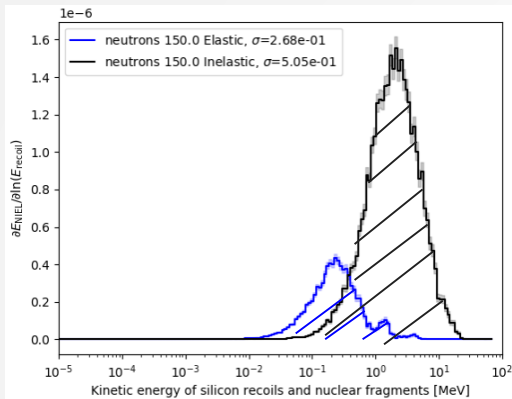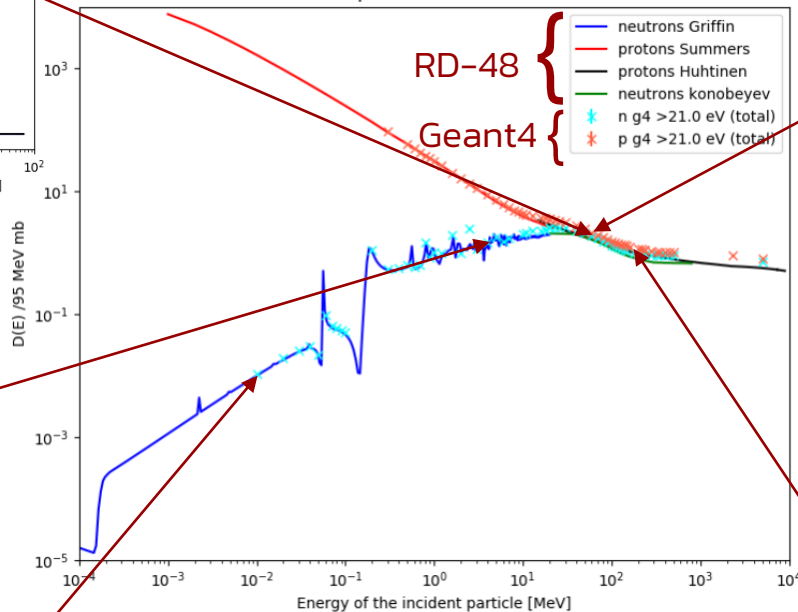
Recoils < 5 keV: point displacements
Recoils > 5 KeV: point displacements+ cluster displacements

NIEL
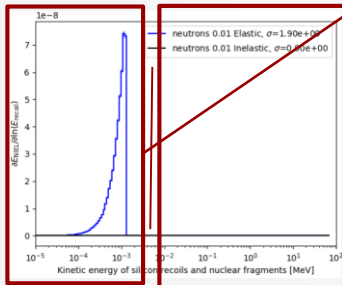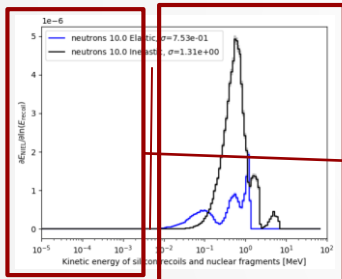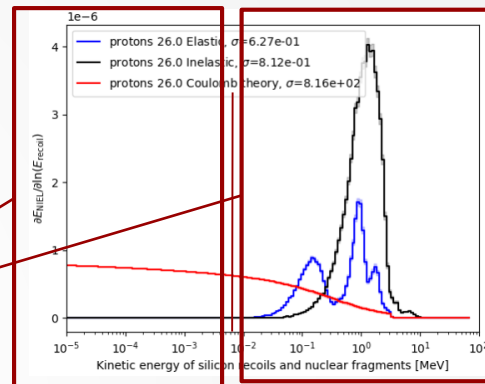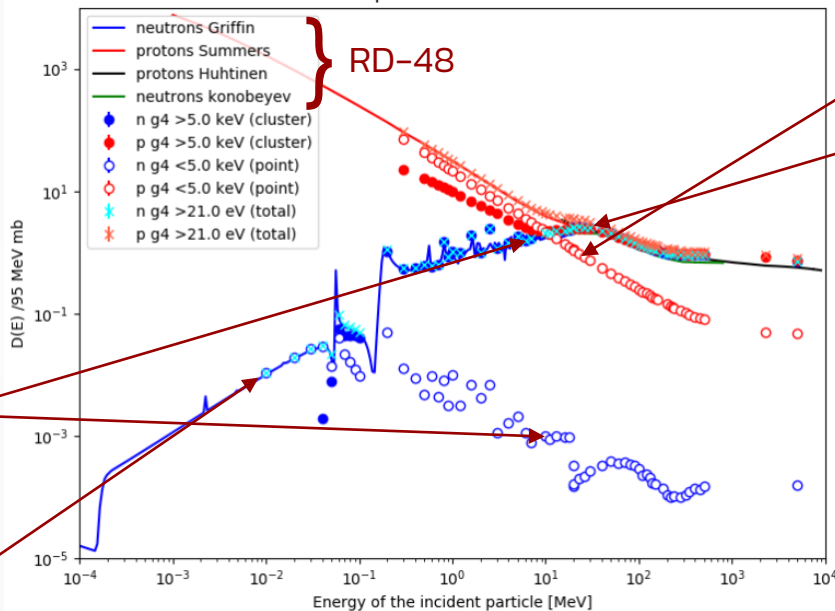
SKA Secondary knocked-on atoms)
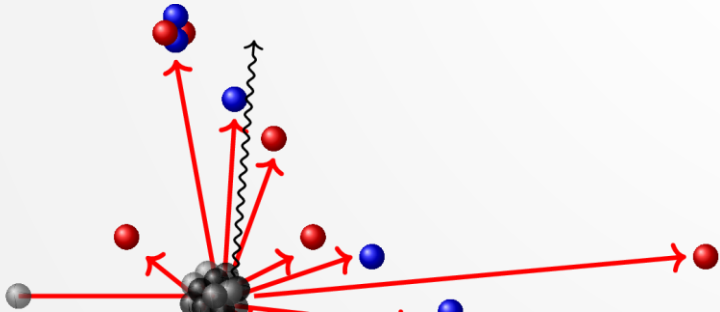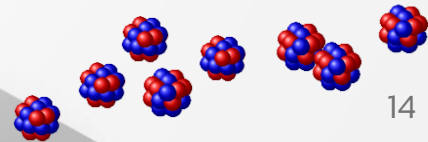
How to define a cluster? What algorithm to choose?

- Geant4 studies with Screened Nuclear Recoil process[10]
- focus on the propagation of Si–recoil in Silicon (no incident beam)
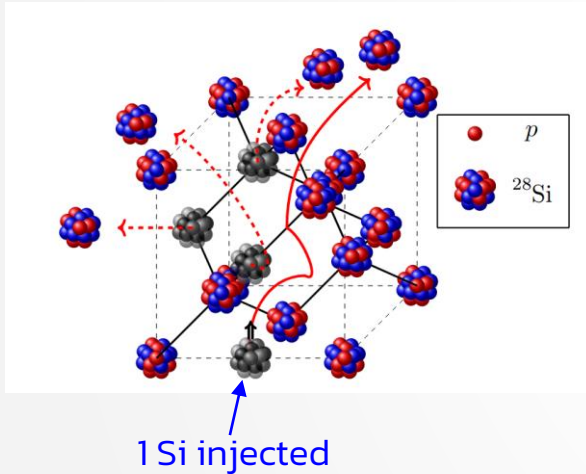
Example:
- 100 keV Silicon track
- originating from the blue cross (position 0,0,0)
- initial momentum in +z direction
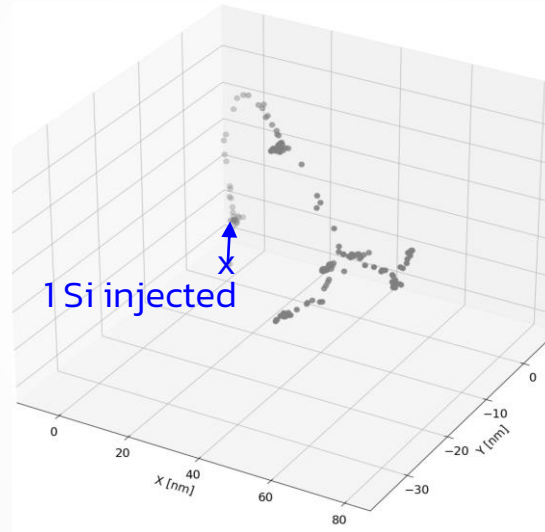
Grey dots: isolated displacements
Colored dots: clustered displacements
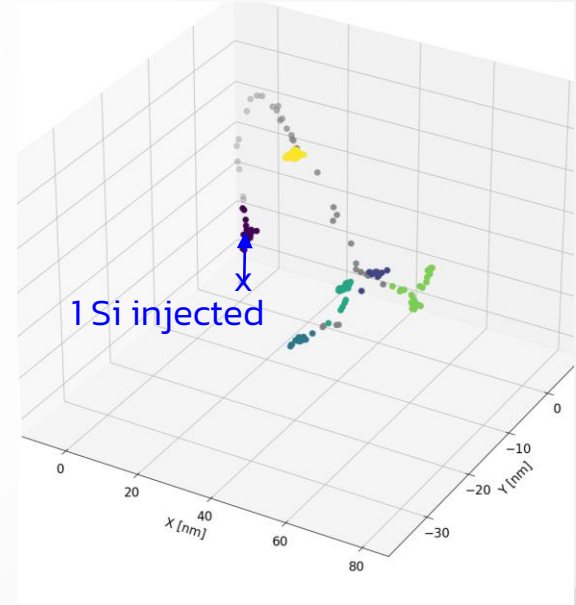
1 Si injected

10)   Raine, Melanie, et al. "Simulation of Single Particle Displacement Damage in Silicon - Part I: Global Approach and Primary Interaction Simulation." IEEE Transactions on Nuclear Science, vol. 64, no. 1, Oct. 2016, pp. 133–40. HAL Archives Ouvertes, https://doi.org/10.1109/TNS.2016.2615133.

Clusters

- Cluster detection is a big topic in machine learning and mathematics
- Depending on its application, different algorithms are the best fit.

Image from[11,12]
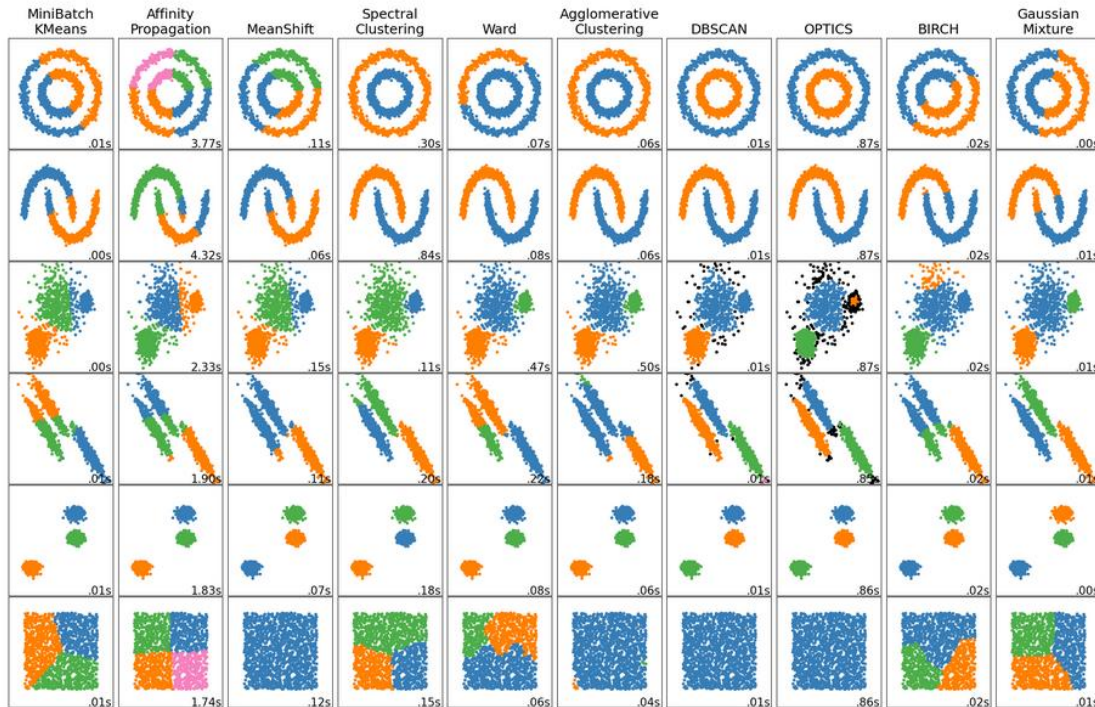
- Various clustering algorithms applied to 6 different sample datasets
- aim : identify clusters
- Algorithm must be able to process:
  - samples with large number of "outliers" (=single displacements for us)
  - samples with clusters of different shapes
  - samples with clusters with various densities

11) Pedregosa, F., Varoquaux, G., Gramfort, A., Michel, V., Thirion, B., Grisel, O., … Duchesnay, E. (2011). Scikit-learn: Machine Learning in Python. *Journal of Machine Learning Research*, *12*, 2825–2830.
12)https://scikit-learn.org/stable/auto_examples/cluster/plot_cluster_comparison.html#sphx-glr-auto-examples-cluster-plot-cluster-comparison-py

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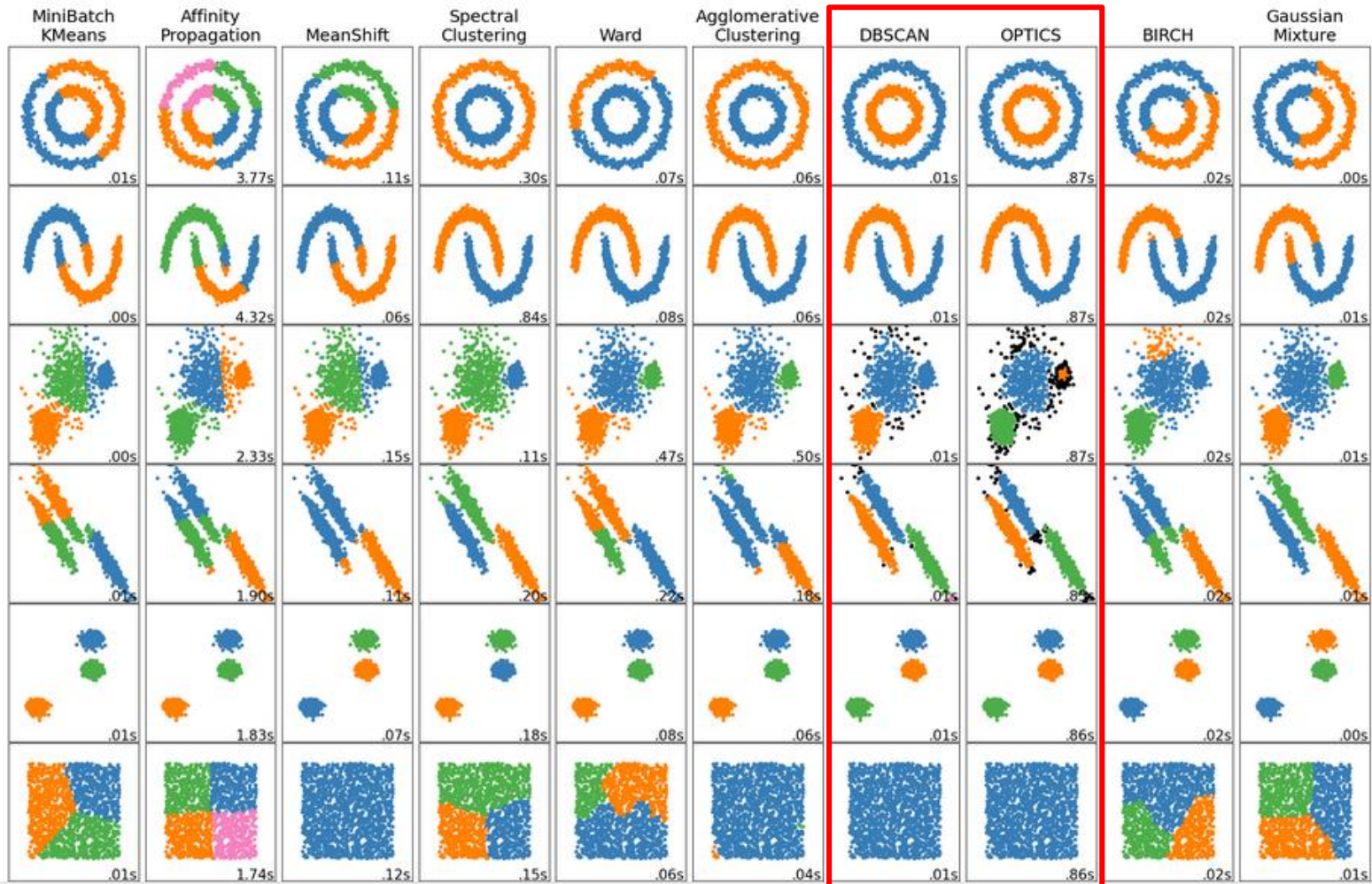
Image from[11,12]

OPTICS performs better then DBSCAN for clusters with **varying densities**[13].

11) Pedregosa, F., Varoquaux, G., Gramfort, A., Michel, V., Thirion, B., Grisel, O., … Duchesnay, E. (2011). Scikit-learn: Machine Learning in Python. *Journal of Machine Learning Research*, *12*, 2825–2830.
12)https://scikit-learn.org/stable/auto_examples/cluster/plot_cluster_comparison.html#sphx-glr-auto-examples-cluster-plot-cluster-comparison-py
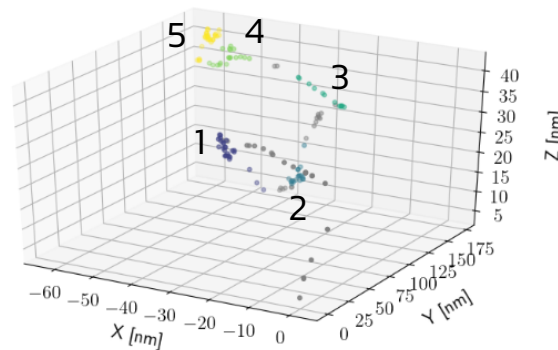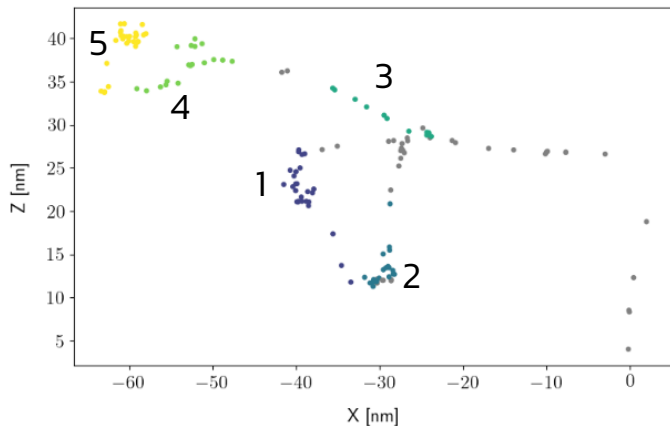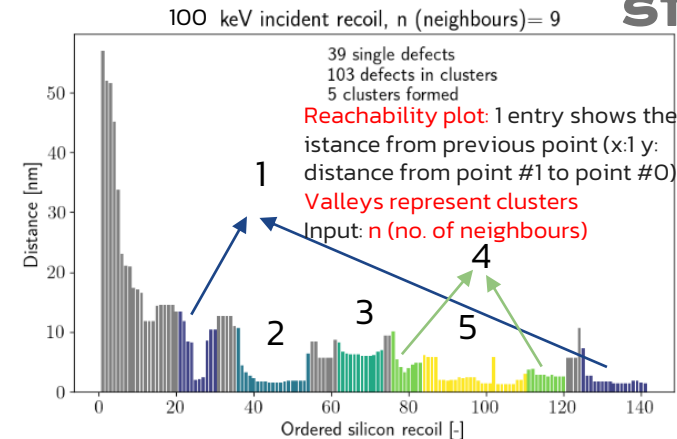13)https://scikit-learn.org/stable/modules/clustering.html#optics

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

100 keV incident recoil, n (neighbours) = 9

39 single defects
103 defects in clusters
5 clusters formed

Reachability plot: 1 entry shows the distance from previous point (x:1 y: distance from point #1 to point #0)
Valleys represent clusters
Input: n (no. of neighbours)

- Algorithm flow explain in the Appendix (Slide 31)
- Basic idea:
  - Ordering points and plotting their distances produces **Reachability plot**
  - Valleys in the reachability plot represent clusters
- Algorithm needs a user input: minimum number of samples to create cluster

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.
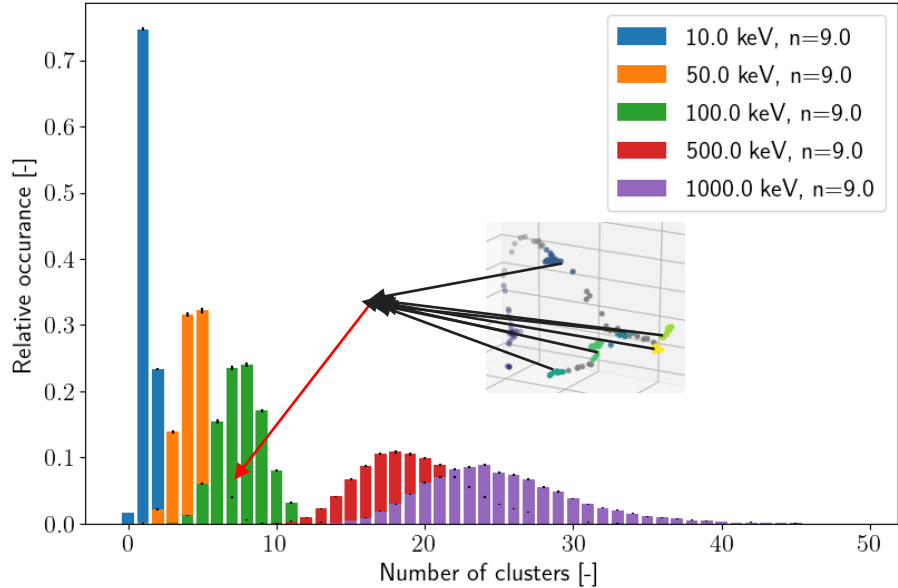14) Schubert, Erich, Michael Gertz. "Improving the Cluster Structure Extracted from OPTICS Plots." Proc. of the Conference "Lernen, Wissen, Daten, Analysen" (LWDA) (2018): 318-329.
15) https://www.youtube.com/watch?v=CV0mWaHOTA8&t=133s tutorial
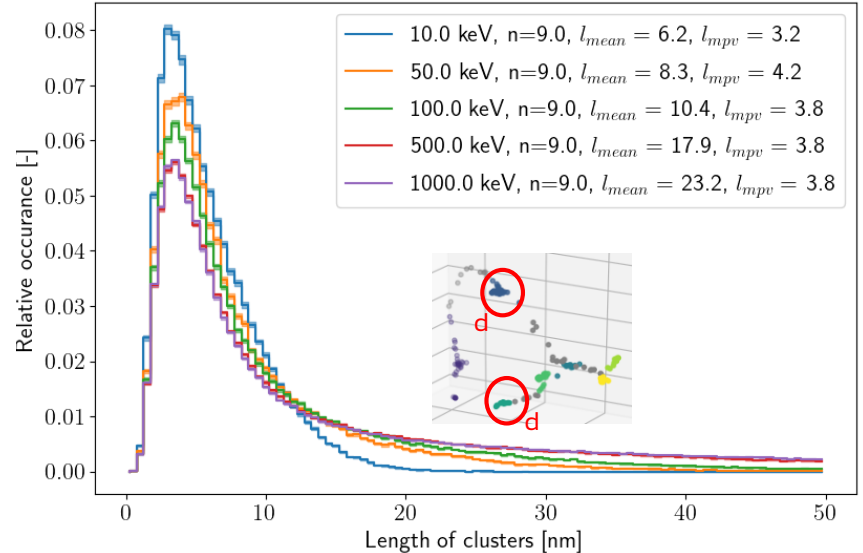
RESULTS

How many clusters?

Relative occurance of a particular number of clusters being created per event.

How large are the clusters?

Length := diameter of the smallest enclosed sphere around the cluster

Relative occurance of a particular length of clusters being created per event.

Legend for length plot:
- 10.0 keV, n=9.0, $l_{mean} = 6.2$, $l_{mpv} = 3.2$
- 50.0 keV, n=9.0, $l_{mean} = 8.3$, $l_{mpv} = 4.2$
- 100.0 keV, n=9.0, $l_{mean} = 10.4$, $l_{mpv} = 3.8$
- 500.0 keV, n=9.0, $l_{mean} = 17.9$, $l_{mpv} = 3.8$
- 1000.0 keV, n=9.0, $l_{mean} = 23.2$, $l_{mpv} = 3.8$

Legend for number plot:
- 10.0 keV, n=9.0
- 50.0 keV, n=9.0
- 100.0 keV, n=9.0
- 500.0 keV, n=9.0
- 1000.0 keV, n=9.0

- If the cluster is too big, the algorithm prefers to break the cluster down into a smaller subclusters.
- While the cluster size remains similar with energy, the number of clusters increases.
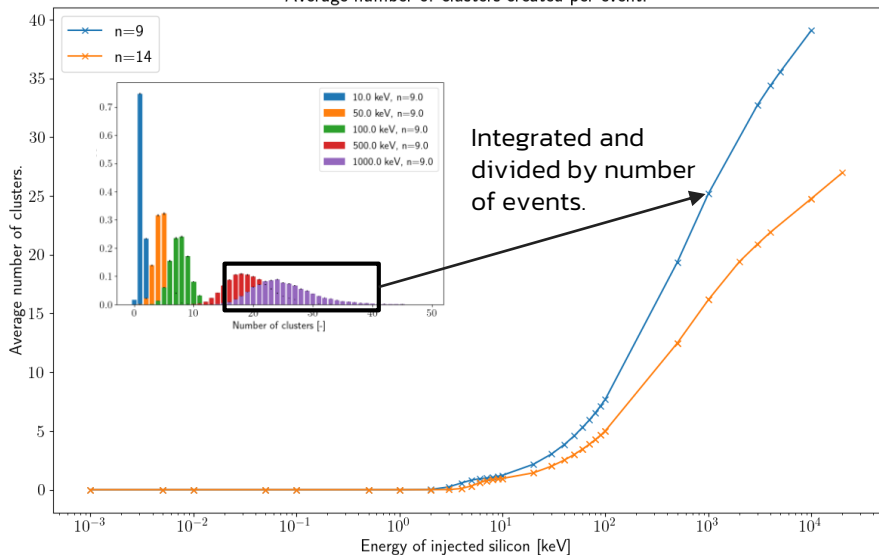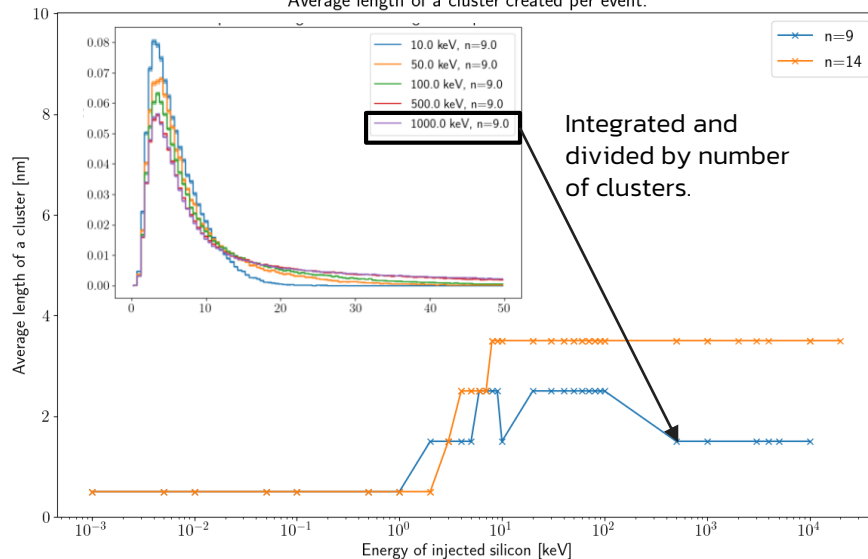
RESULTS

How many clusters?

Average number of clusters created per event.

Integrated and divided by number of events.

How large are the clusters?

Length := diameter of the smallest enclosed sphere around the cluster


Average length of a cluster created per event.
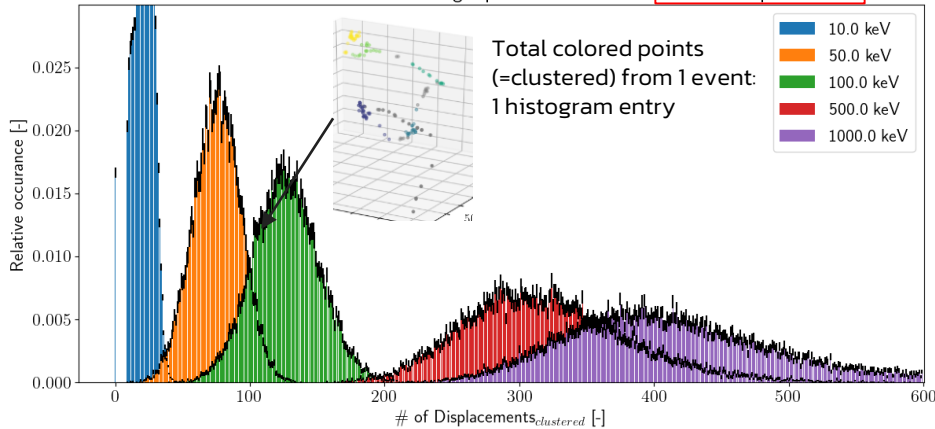
Integrated and divided by number of clusters.

- For Si > 10 keV the length of the cluster for n=14 ~ 3 nm, for Si > 10 keV the length of the cluster for n=9 ~ 1–2 nm.
- For n=9 the algorithm detects higher number of clusters with smaller sizes, for n=14 it is the opposite.
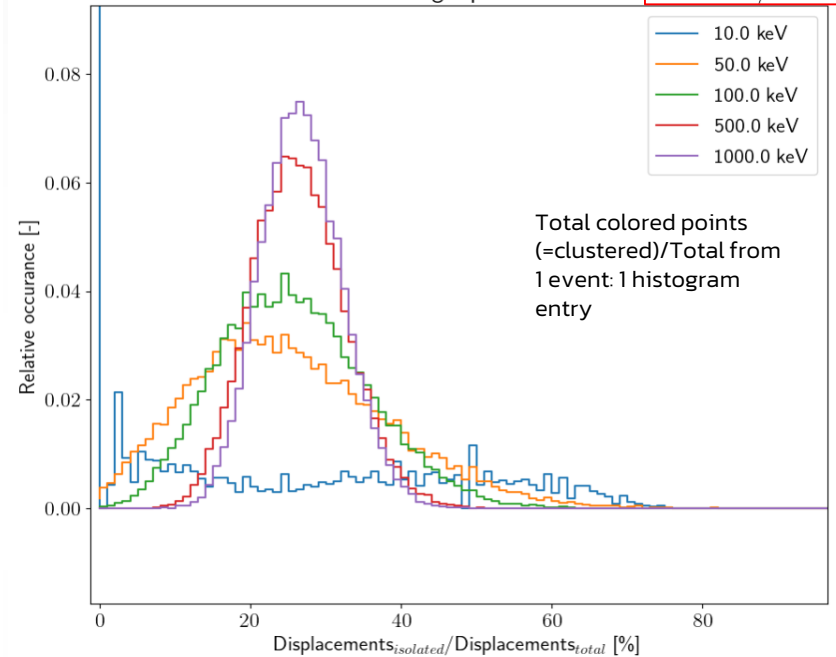
RESULTS

Relative occurance of Si event creating a particular number of isolated displacements.

Total grey points (=isolated) from 1 event: 1 histogram entry
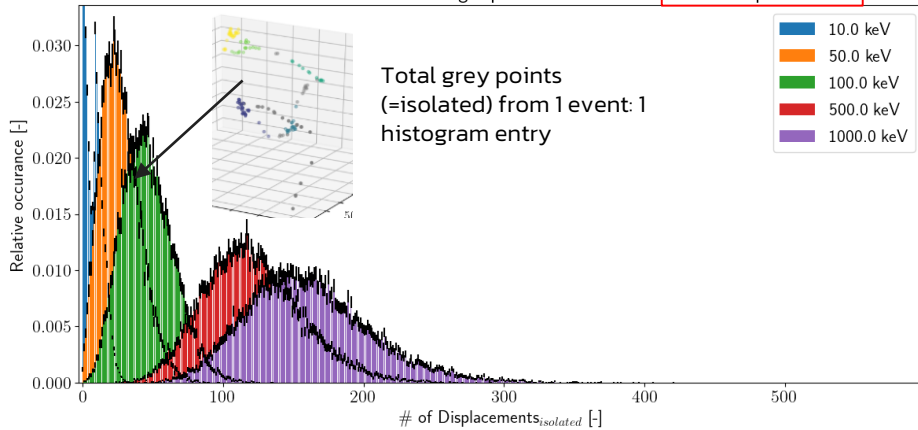
Relative occurance of Si event creating a particular number of clustered displacements.

Total colored points (=clustered) from 1 event: 1 histogram entry

Relative occurance of Si event creating a particular ratio of ISOLATED/TOTAL.

Total colored points (=clustered)/Total from 1 event: 1 histogram entry

- For E>500 keV, ~25% of the displacements are point-like
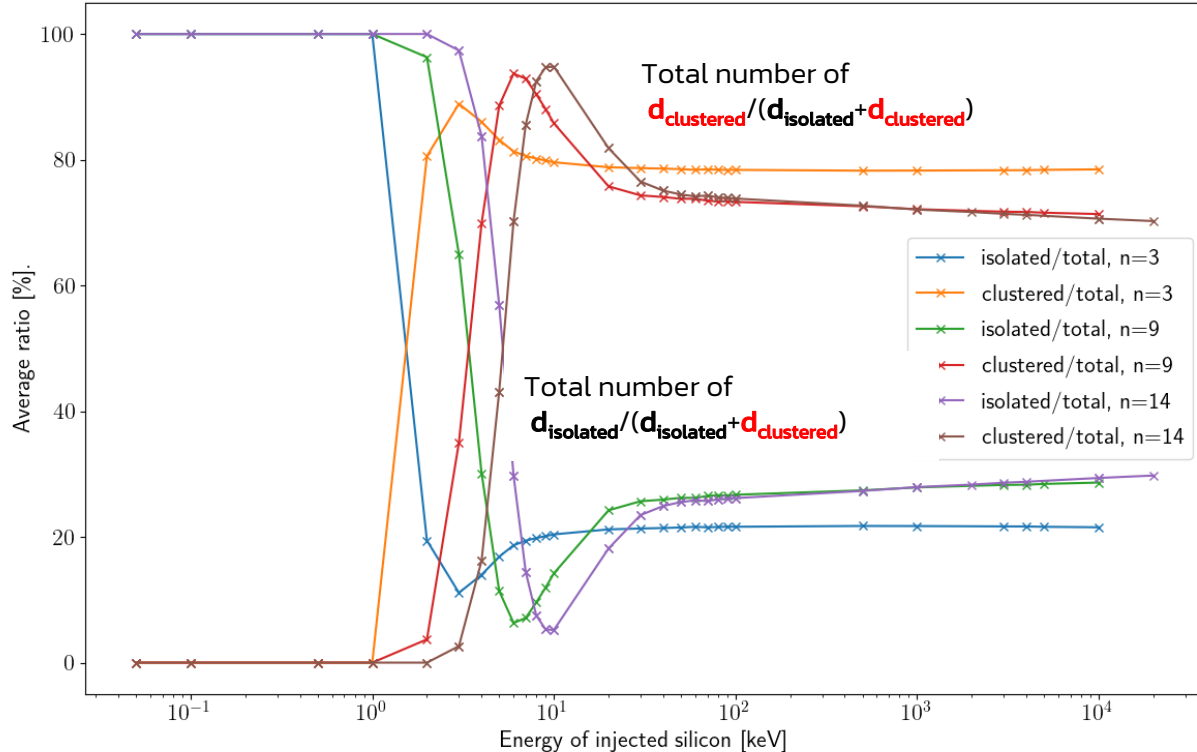- For E<500 keV, the fluctuations are larger. Event can create between 0–60% point like defects.

By integrating plots from previous slide for respective energies and dividing by the number of histogram entried, we gain 1 point on the plot on the right plot.

d$_{isolated}$
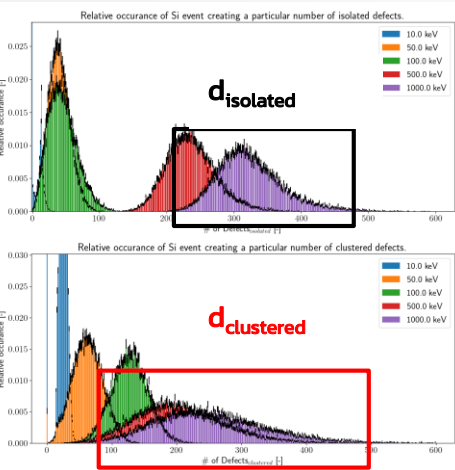
d$_{clustered}$

- For E > 50 keV stable ratio of point-like and cluster displacements are independent of the choice of n
- The threshold energy for creating stable ratio of point-like and cluster displacements depends on the algorithm parameter.
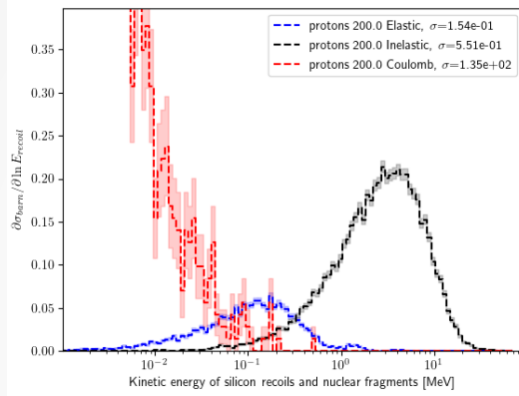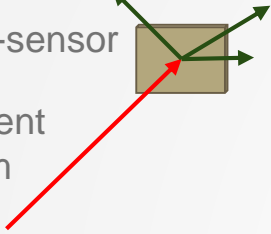
RESULTS

Average ratio of isolated and clustered displacements created per event.

Total number of
d$_{clustered}$/(**d$_{isolated}$**+**d$_{clustered}$**)

Total number of
d$_{isolated}$/(**d$_{isolated}$**+**d$_{clustered}$**)

isolated/total, n=3
clustered/total, n=3
isolated/total, n=9
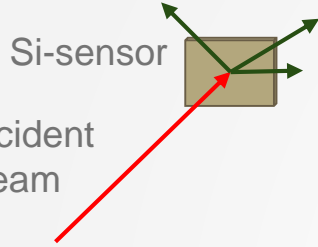clustered/total, n=9
isolated/total, n=14
clustered/total, n=14

Goal

Si-sensor

Incident
Beam

PKA characterized

Goal

Si-sensor

Incident
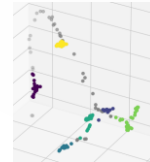Beam
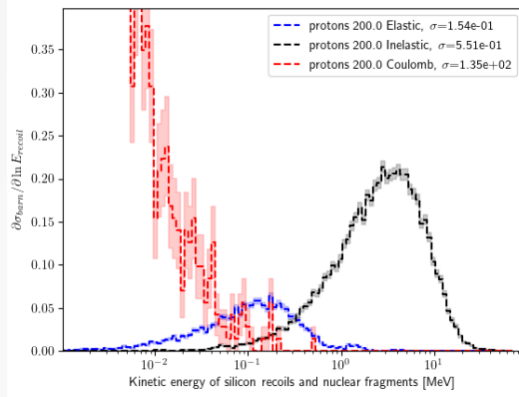


1) PKA characterized

Si-sensor
• Si injection
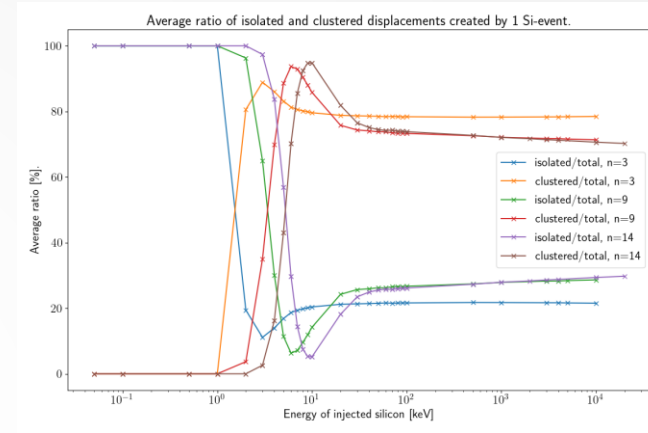
2) Subsequent Si cascade characterized

3) Goal:
- take the output of 1) for all projectile energies and apply the output of 2) subsequent Si cascade.
- A revised version of RD48 should show the cluster vs isolated defect contribution.
- At this point benchmark with measurements will be possible.

I need revision.

A. Vasilescu & G. Lindstroem
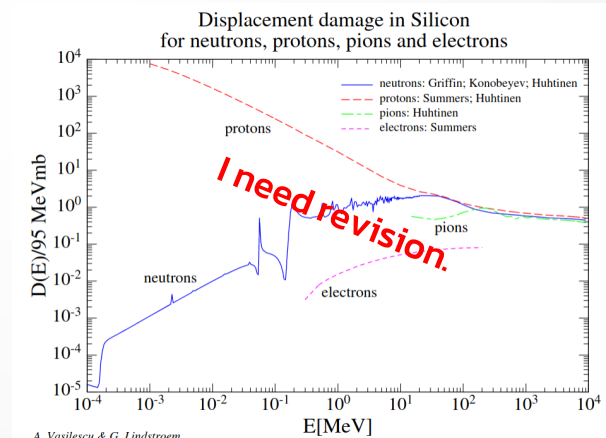
Outlook & next steps

Si-recoil, 50 keV

100 nm
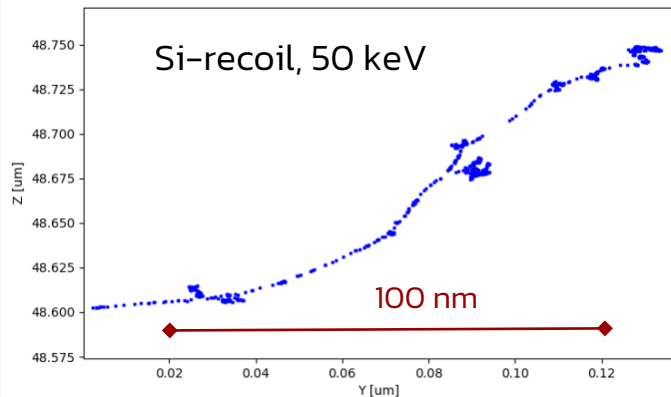
- A Geant4–based simulations and analysis are being carried out together with FLUKA to revisit the RD–48 NIEL curves.
- NIEL curves in literature with Geant4 and Fluka simulations successfully reproduced
- Algorithm for identifying clustered versus point defect damage implemented.
- For Si recoil of the energy above 50 keV energy threshold the cluster to point defect ration remains constant, in agreement with the literature[14].
- 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.

14) S. 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
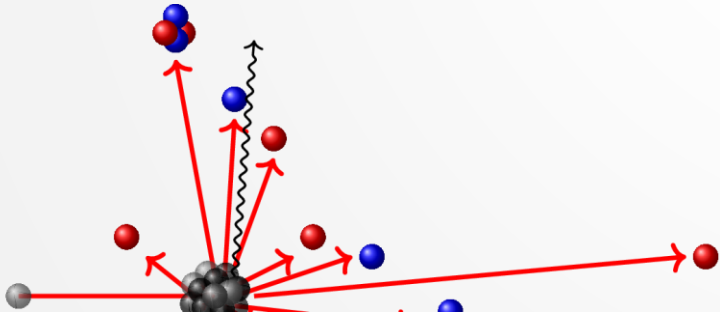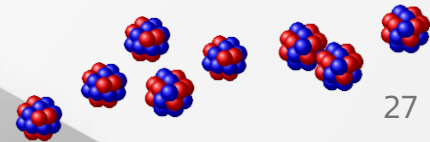
THANKS!

Do you have any questions?

Extra slides

Geant4 physics list, step functions

For physics list:
- AtRest functions: decay, e+ annihilation
- AlongStep functions: to describe continuous (inter)actions, occurring along the path of the particle, like ionisation
- PostStep actions: For describing point–like (inter)actions, like decay in flight, hard Radiation..

G4VProcess: can implement any combination of
AtRest, AlongStep, PostStep action

GetPhysicalInteractionLength():
• Used to limit the step size:
– either because the process « triggers » an interaction, a decay;
– Or any other reasons, like fraction of energy loss;
– geometry boundary;
– user's limit ..

8)   https://geant4.web.cern.ch/sites/default/files/geant4/collaboration/workshops/users2002/talks/lectures/PhysicsProcessesInGeneral.pdf

Geant4 physics list, step

The stepping:
- The stepping treats processes generically:
- The stepping does not know what processes it is Handling
- The stepping imposes on the processes to
    Cooperate in their AlongStep actions;
    Compete for PostStep and AtRest actions;
- Processes can optionally emit also a «signal» to require particular treatment:
    - notForced: «standard» case;
    - forced: PostStepDoIt action is applied anyway;
    - conditionallyForced: PostStepDoIt
    - applied if AlongStep has limited the step;

The stepping: Stepping Invocation Sequence of Processes for a particle travelling
1. At the beginning of the step, determine the step length: Consider all processes attached to the current G4Track; Define the step length as the smallest of the lengths among: All AlongStepGetPhysicalInteractionLenght()., All PostStepGetPhysicalInteractionLength()
2. Apply all AlongStepDoIt() actions, « at once »: Changes computed from particle state at the beginning of the step; Accumulated in the G4Step; Then applied to the G4Track, from the G4Step.
1. Apply PostStepDoIt() action(s) « sequentially », as long as the particle is alive: Apply PostStepDoIt() of process which proposed the smallest step length;
apply « forced » and « conditionally forced » actions

8) https://geant4.web.cern.ch/sites/default/files/geant4/collaboration/workshops/users2002/talks/lectures/PhysicsProcessesInGeneral.pdf
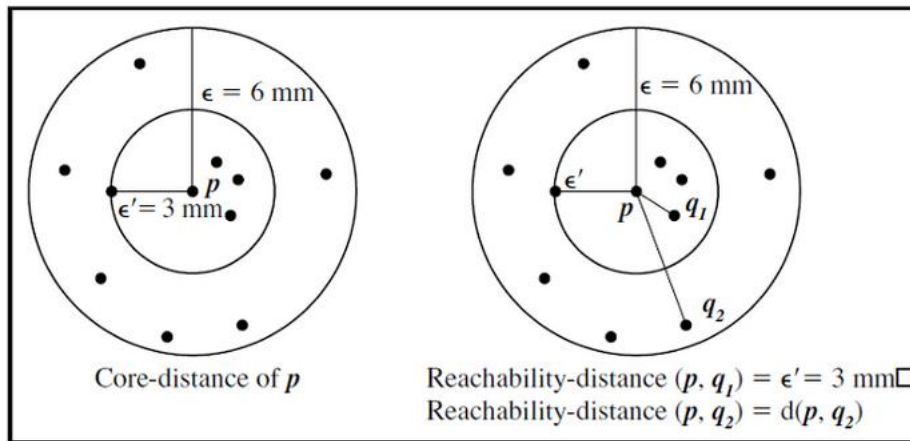
Geant4 physics list, step

At rest:

1. 1. If the particle is **at rest**, is stable and can'tannihilate, it is killed by the tracking:To be more accurate: if a particle at rest has no« AtRest » actions defined, it is killed.
2. Otherwise determine the lifetime: Take the smallest time among: All AtRestGetPhysicalInteractionLenght() Called «physical interaction length» but returns a time!
3. Apply the AtRestDoIt() action of the process which returned the smallest time.

https://geant4.web.cern.ch/sites/default/files/geant4/collaboration/workshops/users2002/talks/lectures/PhysicsProcessesInGeneral.pdf

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

Important concepts:

- **n (number of neighbours)**: user input
- **Core distance:** The minimum distance to make a point a core point, so that it contains number of neighbours n
- **Reachability-distance:**
  a.   If point < the core-distance reachability distance = core-distance
  b.   If point > core-distance, reachability distance = distance between the point and core point

If n = 4

Core-distance of p

Reachability-distance $(p, q_1) = \epsilon' = 3$ mm

Reachability-distance $(p, q_2) = d(p, q_2)$

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.
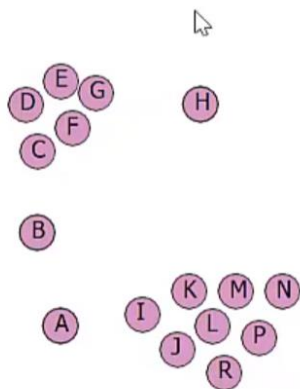
Explanation from:
https://www.youtube.com/watch?v=CVOmWaHOTA8&t=133s

Optics algorithm takes the points in a certain order and assigns them properties.

- $\varepsilon = 44, \quad MinPts = 3$
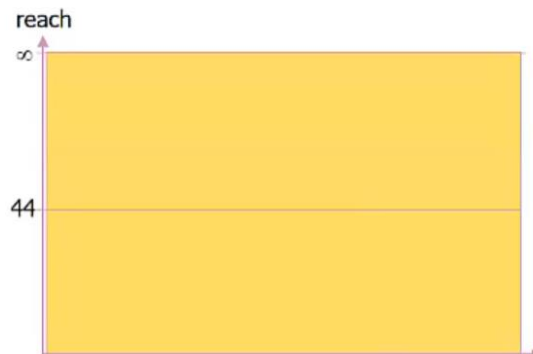
reach

∞

44

seedlist:

Min neighbours:2

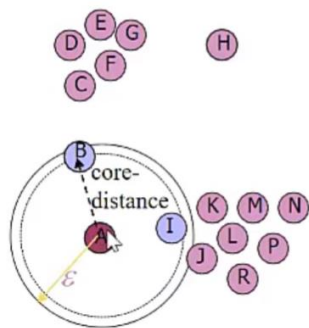# OPTICS

Explanation from:
https://www.youtube.com/watch?v=CVOmWaHOTA8&t=133s

• Example Database (2-dimensional, 16 points)
• $\varepsilon = 44$, $MinPts = 3$

seedlist: (B,40) (I, 40)

- A is the first point -> it's reachibility is infinite. (How far is the point from the last point?)
- B and C have are 40 units far away from A.

Min neighbours:2

OPTICS
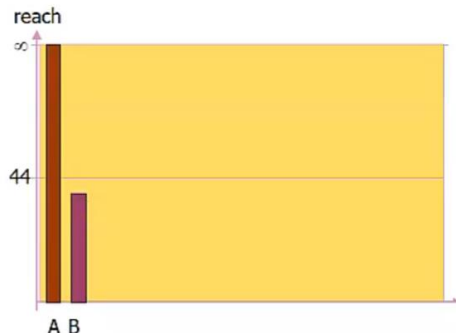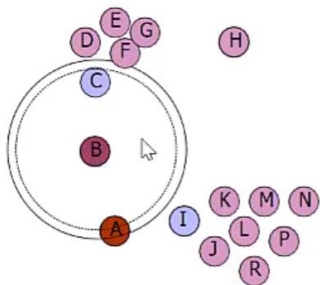
- Next point: B.
- Seedlist is updated and ordered by reachability.

- Example Database (2-dimensional, 16 points)
- $\varepsilon = 44$, $MinPts = 3$

seedlist: (I, 40) (C, 40)

Min neighbours:2

OPTICS

Explanation from:
https://www.youtube.com/watch?v=CVOmWaHOTA8&t=133s

- Next point I.
- The core distance is much smaller (K and J are close).
- The seedlist is updated and ordered by reachability.

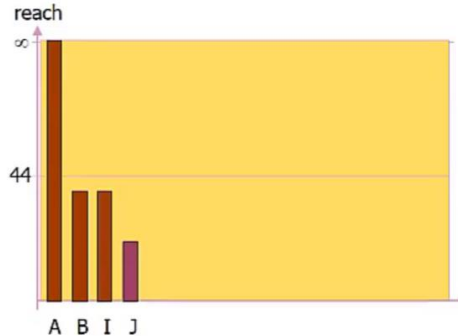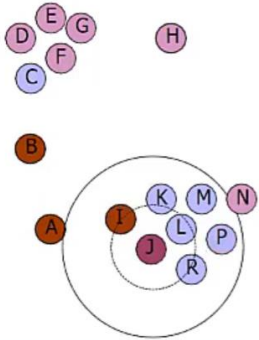- Example Database (2-dimensional, 16 points)
- $\varepsilon = 44$, $MinPts = 3$

seedlist: (J, 20) (K, 20) (L, 31) (C, 40) (M, 40) (R, 43)

Min neighbours:2

OPTICS

Explanation from:
https://www.youtube.com/watch?v=CVOmWaHOTA8&t=133s

- Next point J
- The seedlist is updated and ordered by the rechability.

- Example Database (2-dimensional, 16 points)
- $\varepsilon = 44$, $MinPts = 3$

seedlist: (L, 19) (K, 20) (R, 21) (M, 30) (P, 31) (C, 40)

Min neighbours:2

OPTICS

Explanation from:
https://www.youtube.com/watch?v=CVOmWaHOTA8&t=133s

- Example Database (2-dimensional, 16 points)
- $\varepsilon = 44$, $MinPts = 3$

seedlist: (M, 18) (K, 18) (R, 20) (P, 21) (N, 35) (C, 40)
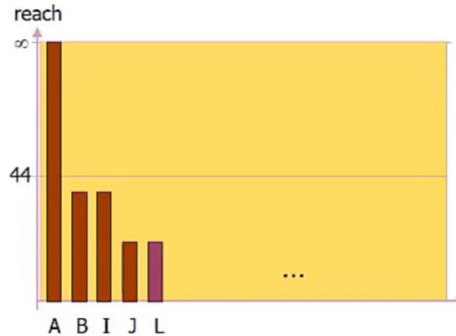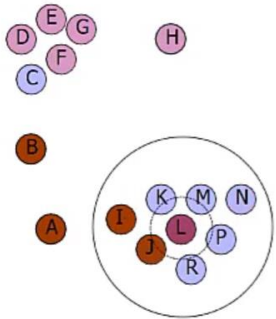
- Next point L
- The seedlist is updated and ordered by the rechability.

Min neighbours:2

Explanation from:
https://www.youtube.com/watch?v=CV0mWaHOTA8&t=133s
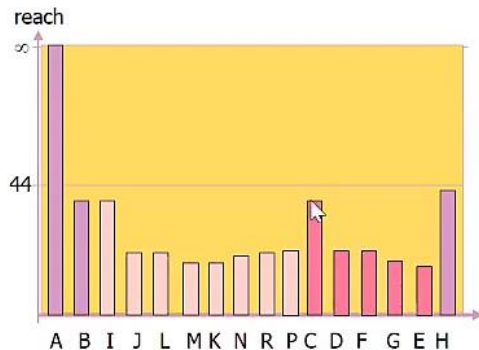
- The valleys represent the clusters.
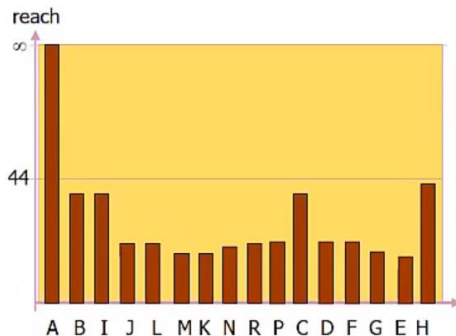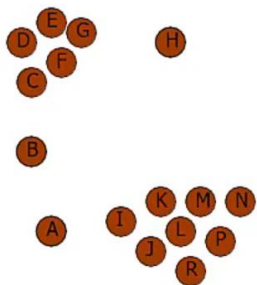
- Example Database (2-dimensional, 16 points)
- $\varepsilon = 44$, $MinPts = 3$

seedlist: -

Min neighbours:3

OPTICS

- The valleys represent the clusters.

- Example Database (2-dimensional, 16 points)

- $\varepsilon = 44$, *MinPts* = 3
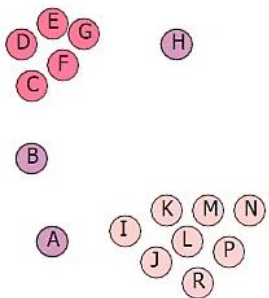
Min neighbours:2

note: representing y axis as $\partial\sigma_{barn}/\partial\ln(E)$

Linear binning, log x axis

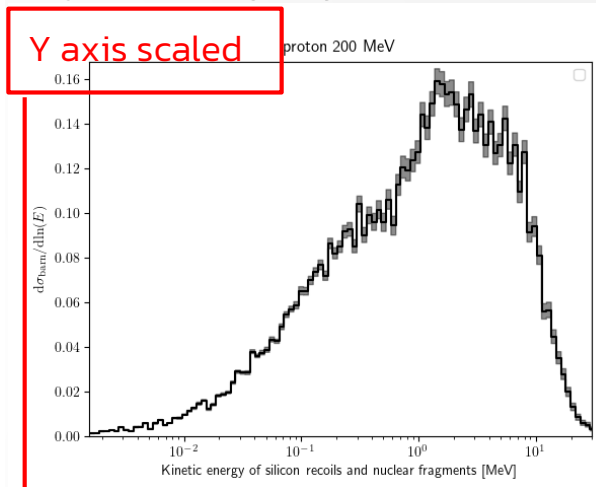**Same graph: Logarithmic binning, log x axis**

Y axis scaled
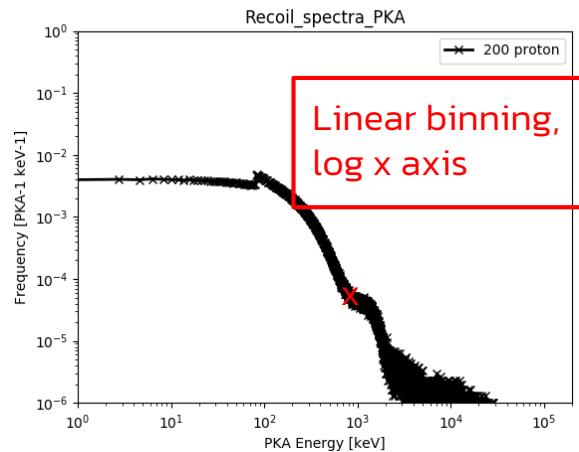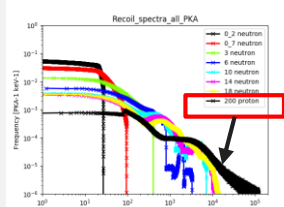
1) PKA are summed and divided by the number of incident particles.

Conversion from σ to probability:
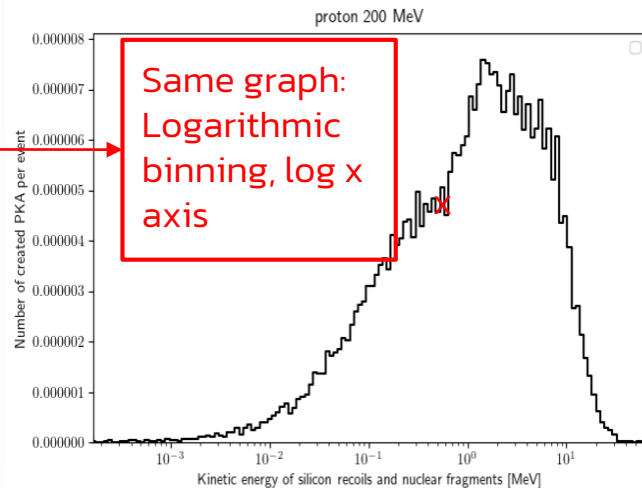
2) Logarithmic binning is used instead.

$$\frac{I_{scattered}}{I_{incident}} = \frac{N_A\rho_{Si}d}{m_{Si}}\sigma = 0.0005\sigma_{barn}$$

3) Each content in a bin is divided by the length of the bin. That makes the y-axis linear. Furthermore the y axis is scaled by:
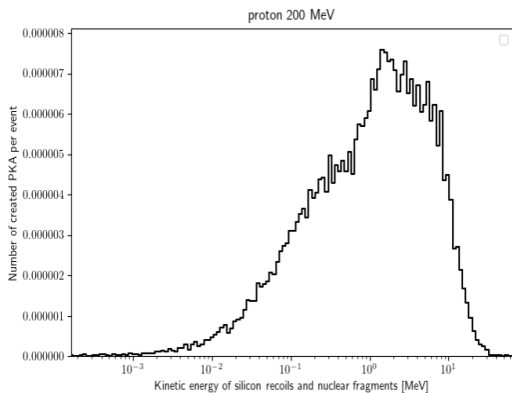
$$\frac{10^{24}}{N_{targ}d}$$

$d = 0.01\text{cm}$

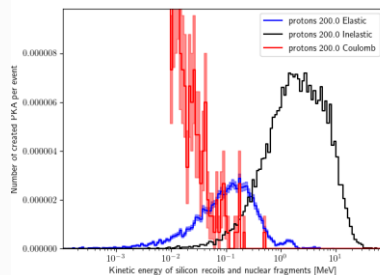$N_{targ} = \frac{N_A\rho_{Si}}{m_{Si}}$

so that the **total area** corresponds to the **total cross section** of creating the PKA.
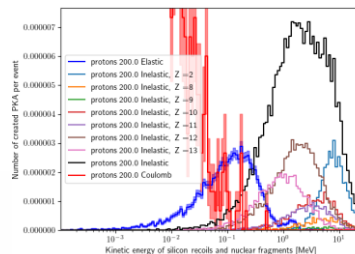
40

note: representing y axis as $\partial E_{NIEL}/\partial \ln(E_{recoil})$

proton 200 MeV

2) PKA are divided into Elastic and Inelastic parts (Coulomb part is added from QGSP_BIC_HP__SS simulation). Inelastic part is further divided into different spectra according to the Z

3) Inelastic part is further divided into different spectra according to the Z number.

4) For Coulomb, Elastic and Inelastic Si, Al and Mg recoils a Lindhard formulation is used[12].

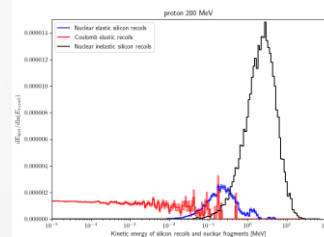For a recoil silicon in a silicon lattice, they read as:

$$E_{de} = \frac{E_{Si}}{1 + k \times g(\epsilon)}, \qquad (2)$$

with $k = 0.1462$, $\epsilon = 1.014 \times 10^{-2} \times Z_{Si}^{-7/3} \times E_{Si} = 2.147 \times 10^{-5} E_{Si}$ and the universal function

$$g(\epsilon) = 3.4008 \times \epsilon^{1/6} + 0.40244 \times \epsilon^{3/4} + \epsilon \qquad (3)$$

5) For alphas[13], Xapsos–Burke values were used to calculate NIEL.

6) Each content in a bin is divided by the length of the bin so that the **total area** corresponds to the **total NIEL**.

1) PKA are summed and divided by the number of incident particles. Logarithmic binning is used instead, that makes the y axis linear.

12) Bergmann, Benedikt, et al. "Ionizing Energy Depositions After Fast Neutron Interactions in Silicon." IEEE Transactions on Nuclear Science, vol. 63, Aug. 2016, pp. 2372–78. NASA ADS, https://doi.org/10.1109/TNS.2016.2574961.
13) Xapsos, M.A. & Burke, E.A. & Badavi, F.F. & Townsend, Lawrence & Wilson, John & Jun, I.. (2005). NIEL calculations for high-energy heavy ions. Nuclear Science, IEEE Transactions on. 51. 3250 - 3254. 10.1109/TNS.2004.839136.