Displacement damage modelling with the FLUKA Monte Carlo code

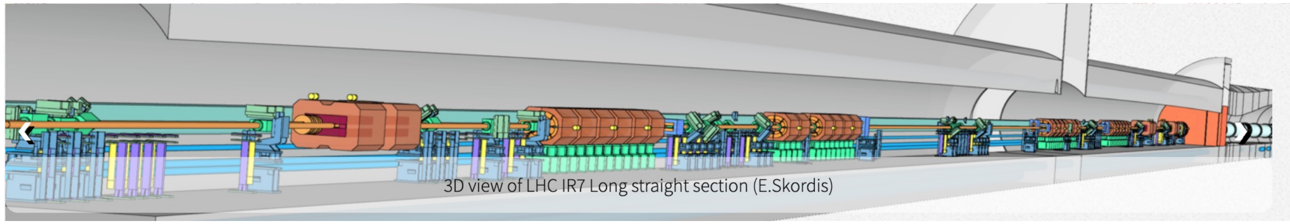
Francesc Salvat Pujol and Vasilis Vlachoudis

On behalf of the FLUKA.CERN Collaboration

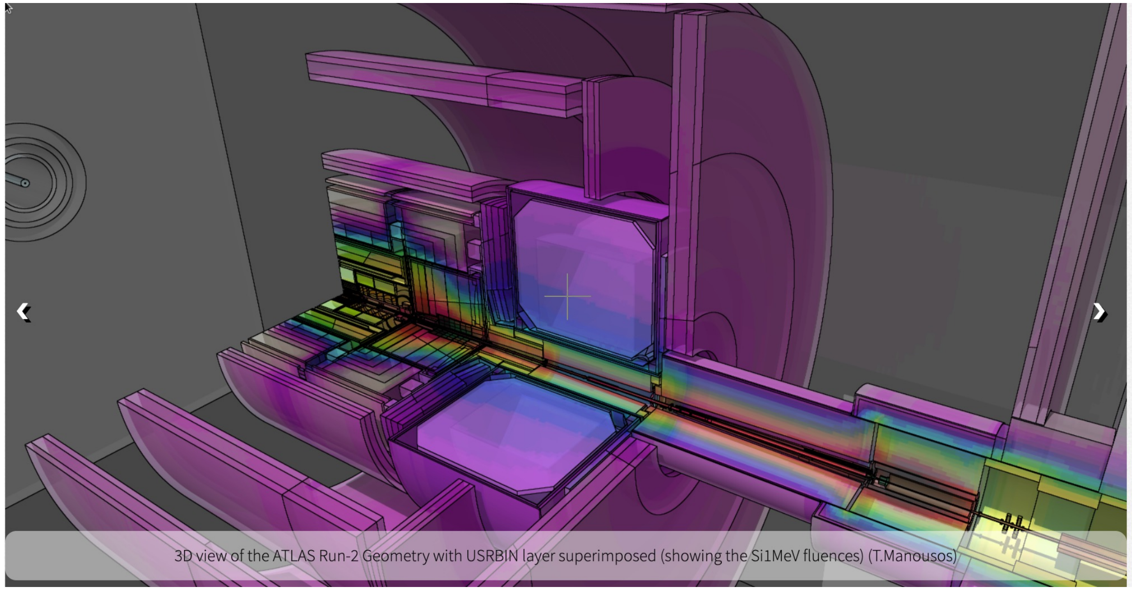
RADSUM – Topical Workshop on RADiation effects in SUperconducting Magnets
Jan 16, 2025 @ CERN

Outline

- Capabilities of the FLUKA particle transport code
- Condensed particle-history simulation
- Focus on radiation-damage-related quantities in FLUKA
- NIEL and DPA in FLUKA



3D view of LHC IR7 Long straight section (E.Skordis)



3D view of the ATLAS Run-2 Geometry with USRBIN layer superimposed (showing the Si1MeV fluences) (T.Manousos)

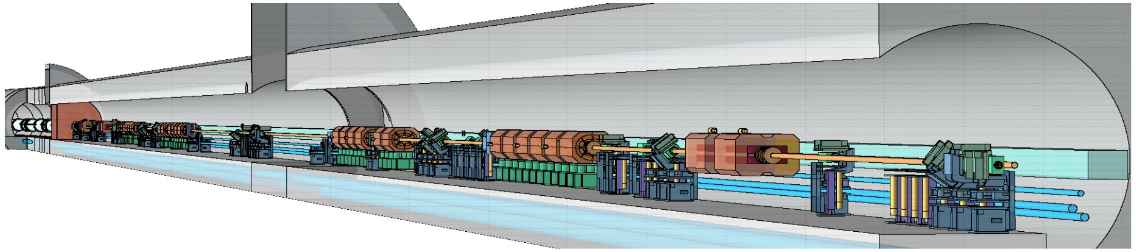
An overview of the
FLUKA particle transport code

The FLUKA particle transport code

https://fluka.cern

- Monte Carlo (MC) code for the ***simulation of coupled hadronic and electromagnetic particle showers in matter***
- Born in the 1960s at CERN
- Actively developed and maintained by the FLUKA.CERN Collaboration (CERN + ELI ERIC)
- Standard tool at CERN for problems involving radiation-matter interaction in present and future colliders:
  - Targetry studies, beam intercepting devices, beam-loss assessments, radiation protection, radiation damage, radiation effects in electronics, etc.

- Serving a worldwide community of thousands of users working in:
  - Shielding, dosimetry, medical applications, space applications, etc
- User support and training:
  - https://fluka-forum.web.cern.ch
    https://fluka.cern/support/courses-and-events



https://doi.org/10.23732/CYRCP-2018-002.17
https://cds.cern.ch/record/1481554

FLUKA in a nutshell (overly simplified!)

- FLUKA handles the transport+interaction of:

Photons	Leptons	Hadrons	Ions
	$e^{\pm}, \mu^{\pm}, \tau^{\pm}$ $\nu_X, \bar{\nu}_X$	$\pi^*, K^*, p, \bar{p}$, $n, \bar{n}, \Lambda, \ldots$	${}^A_Z X$

from the keV to the PeV
(γ down to 100 eV)
(n down to 0.01 meV)

- Rich physics engine with state-of-the-art modelling of all relevant radiation-matter interaction mechanisms:

https://indico.cern.ch/event/1444491/timetable/#20241202
https://flukafiles.web.cern.ch/manual/chapters/quick_look.html

Photon interactions	Coulomb scattering	Bremsstrahlung	Ionization	Nuclear elastic scattering
Hadron-nucleus inelastic interactions	Ion-ion inelastic interactions	Radioactive nuclei production and decay	Unstable particle decay	Transport in electromagnetic fields

+ …

Photo- and lepto-nuclear interactions as well!

- Secondary particle production (particle showers)

Radiation challenges for magnets in present and future colliders (HL-LHC, FCC, Muon Collider)	*Anton Lechner*
30/7-018 - Kjell Johnsen Auditorium, CERN	14:30 - 14:50

MC workflow (1/3): geometry and material definition

- Combinatorial geometry, built from union/subtraction operations on basic geometrical bodies
- As of FLUKA v4-5.0 (Q1 2025), tetra-, penta-, and hexahedral unstructured meshes are supported
- ***<u>Materials in FLUKA are assumed homogeneous and isotropic</u>***
- **No coherent scattering effects in general**
- (Ad-hoc account of molecular / crystalline binding environment for thermal neutrons, and channeling of positively charged particles in bent crystals)

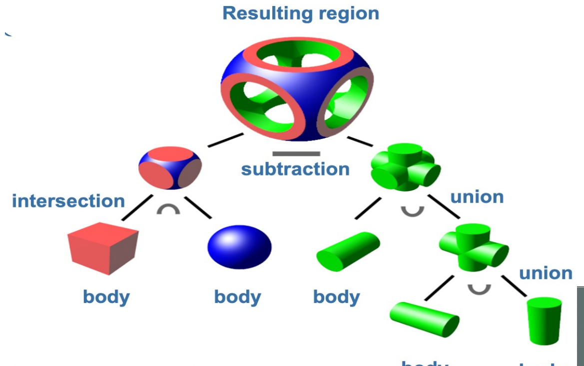
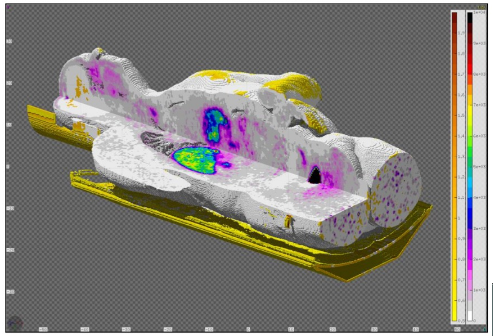
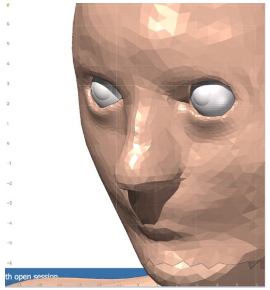
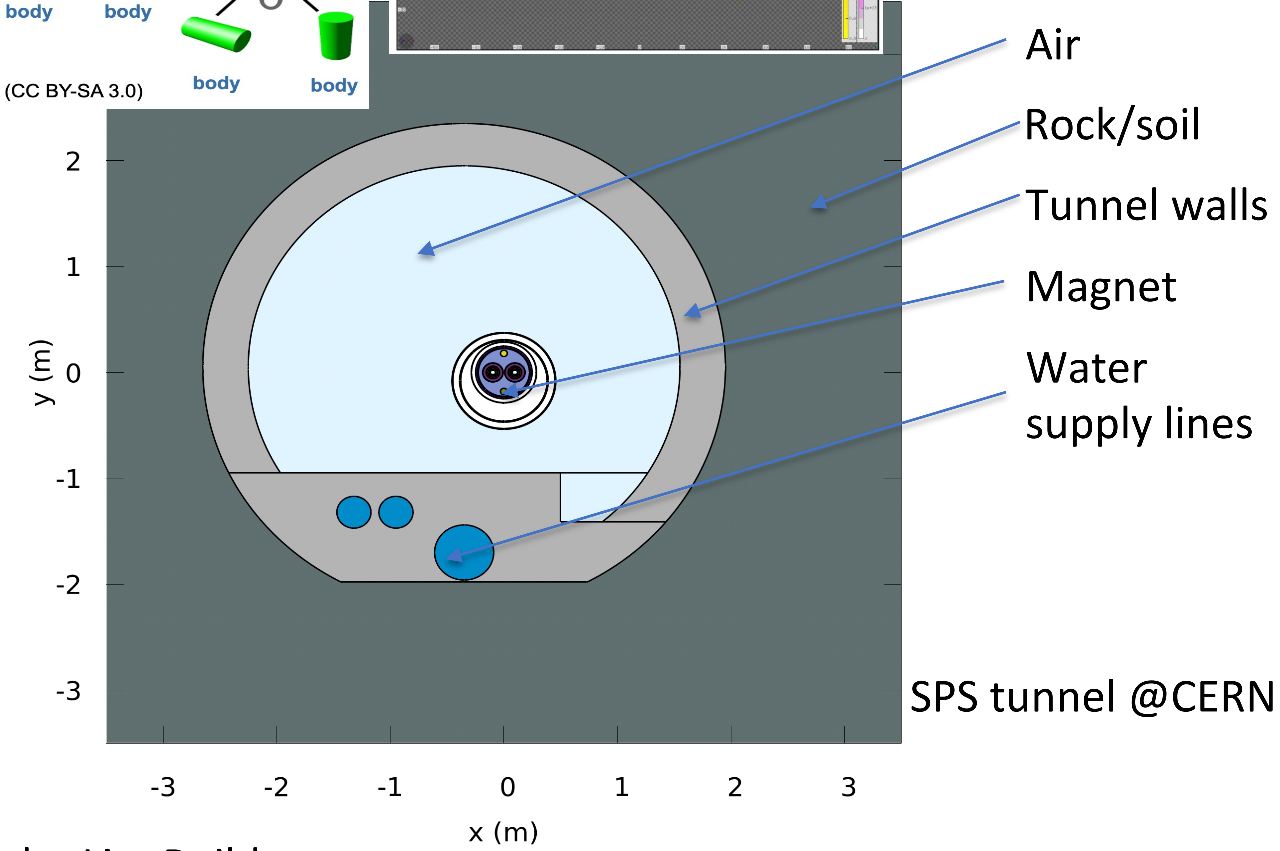


Image from Wikipedia (CC BY-SA 3.0)







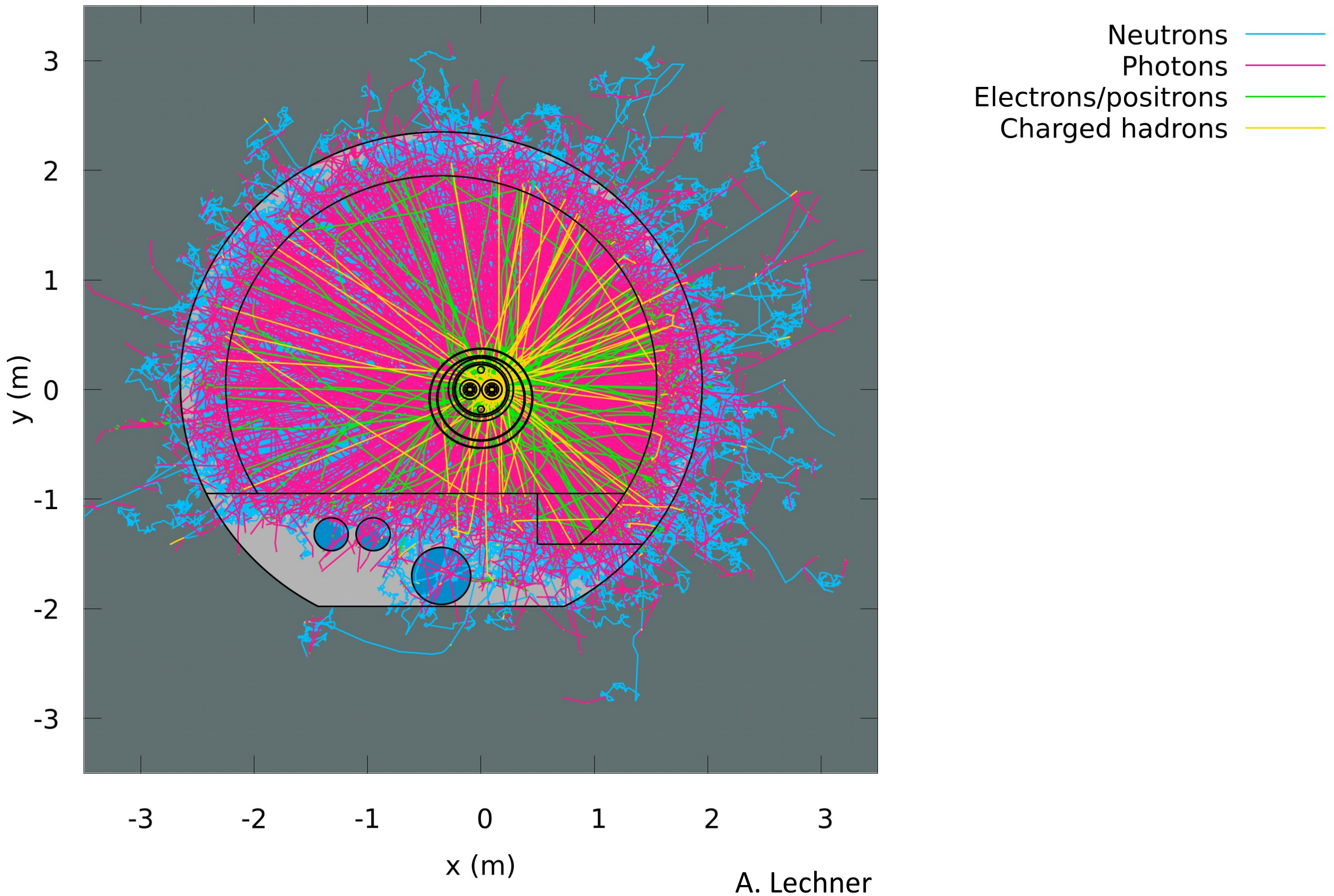
See also the LineBuilder https://accelconf.web.cern.ch/ipac2012/papers/weppd071.pdf

MC workflow (2/3): source definition + particle history simulation

- Simulate a large ensemble of particle ***random walks*** according to the cross sections and mean free paths of all relevant interaction mechanisms (and decay where applicable)

- All particles are transported until they either exit the geometry, or their energy drops below a preset threshold

450 GeV/c proton beam loss

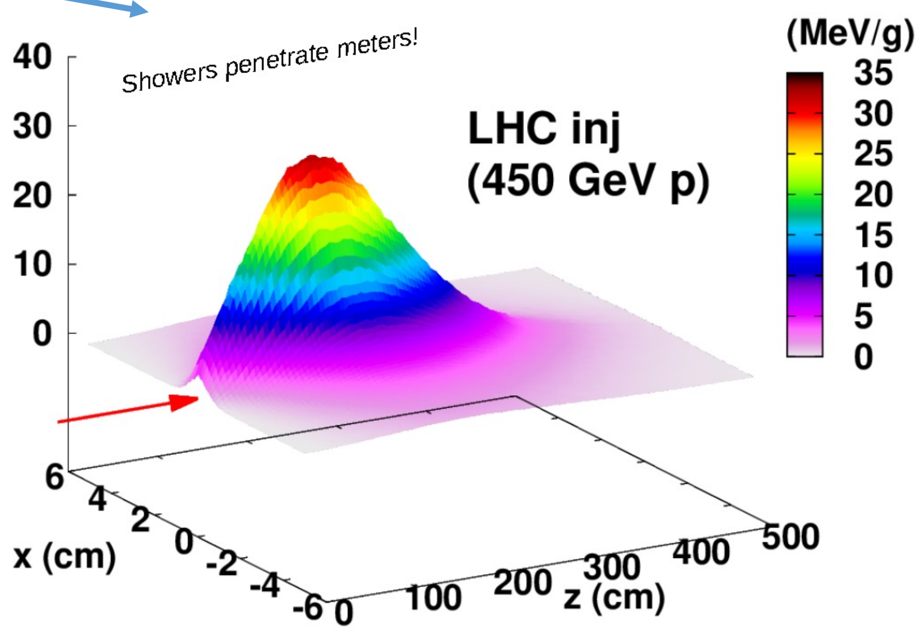


A. Lechner

MC workflow (3/3): extract physical observables

- Every simulated particle history contributes to **statistical estimators** of relevant physical quantities requested by the user, featuring:
  - Particle fluences/currents in a volume or across a surface (differential in position, energy, angle, etc)
  - Energy deposition (heat, power, dose, …)
  - Radionuclide inventories, including their time evolution in a single FLUKA run + associated protection quantities
  - Damage-related quantities: **NIEL**, Si 1-MeV-n equivalent fluence, **DPA-NRT, arc-DPA**
- NB: FLUKA contains built-in scoring capabilities for all of them, no coding involved, just an input-file option.
- ***No on-line material degradation: every particle history sees the same new, pristine, ideal material***

Dose profile in graphite



FLUKA benchmarking and validation

https://doi.org/10.1051/epjconf/202328416006

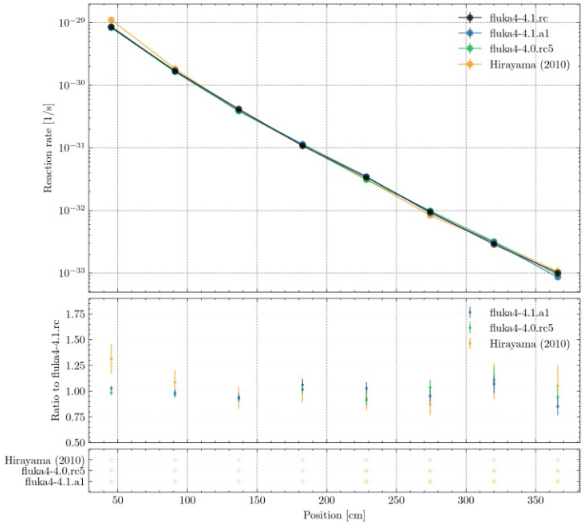
EPJ Web of Conferences **284**, 16006 (2023)
ND2022

FLUKAVAL – A validation framework for the FLUKA radiation transport Monte Carlo code

Markus Widorski[1,*], *Davide* Bozzato[1,2], *Robert* Froeschl[1], and *Vasiliki* Kouskoura[1]

[1]CERN, European Organization for Nuclear Research, 1211 Geneva 23, Switzerland
[2]Karlsruher Institut für Technologie (KIT), Kaiserstraße 12, 76131 Karlsruhe, Germany

p 24GeV, Concrete shield, Bi-206 yield



R. Froeschl et al.

- ***Dedicated workpackage (Code development support)***
- Regular participation in code benchmarking campaigns, among others within SATIF workshops

https://doi.org/10.1103/PhysRevAccelBeams.22.071003

PHYSICAL REVIEW ACCELERATORS AND BEAMS **22**, 071003 (2019)

Editors' Suggestion

Validation of energy deposition simulations for proton and heavy ion losses in the CERN Large Hadron Collider

A. Lechner,* B. Auchmann,† T. Baer,‡ C. Bahamonde Castro, R. Bruce, F. Cerutti, L. S. Esposito, *et al.*

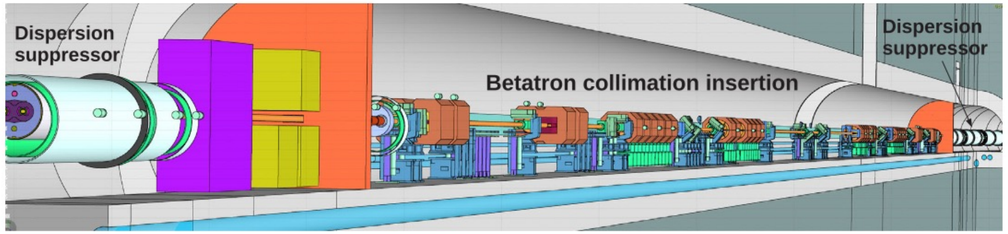
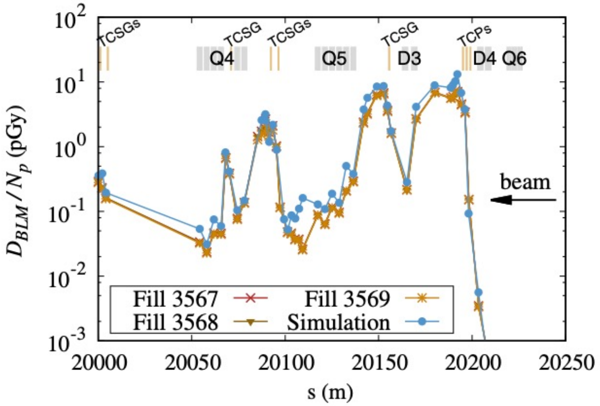
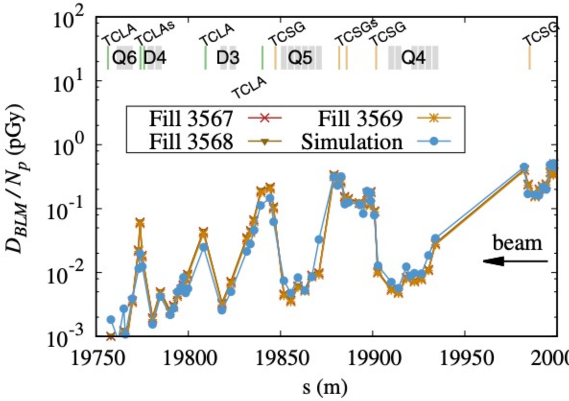


FIG. 8. Geometry model of the LHC betatron cleaning insertion and the first superconducting magnets in the dispersion suppressors



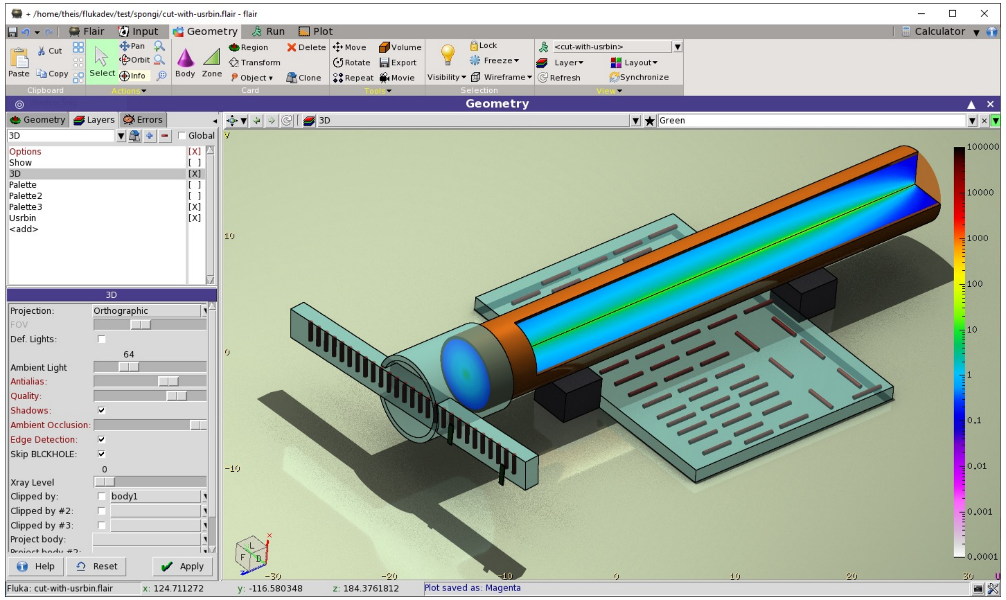


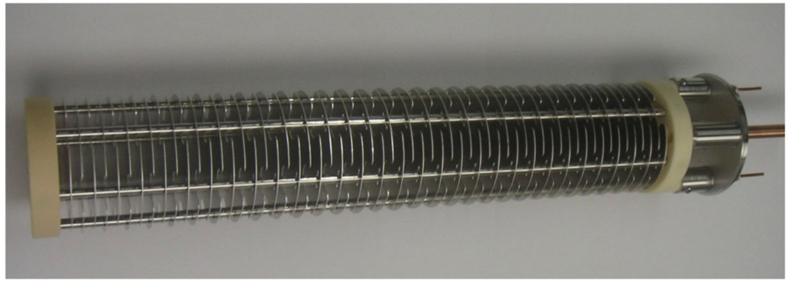
Radiation hardness requirements for organic materials in magnets and radiation environments in muon colliders, FCC, ...
Francesco Cerutti (tomorrow)

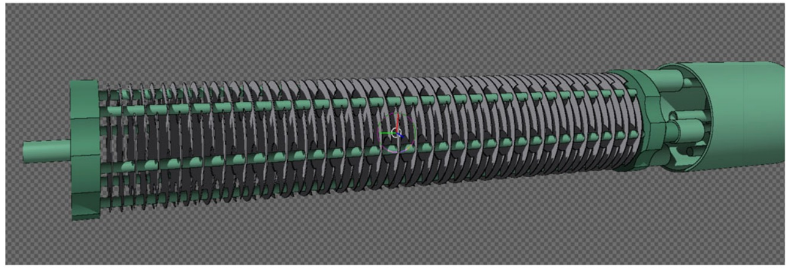
Flair – a one-stop shop for FLUKA simulations

https://flair.cern

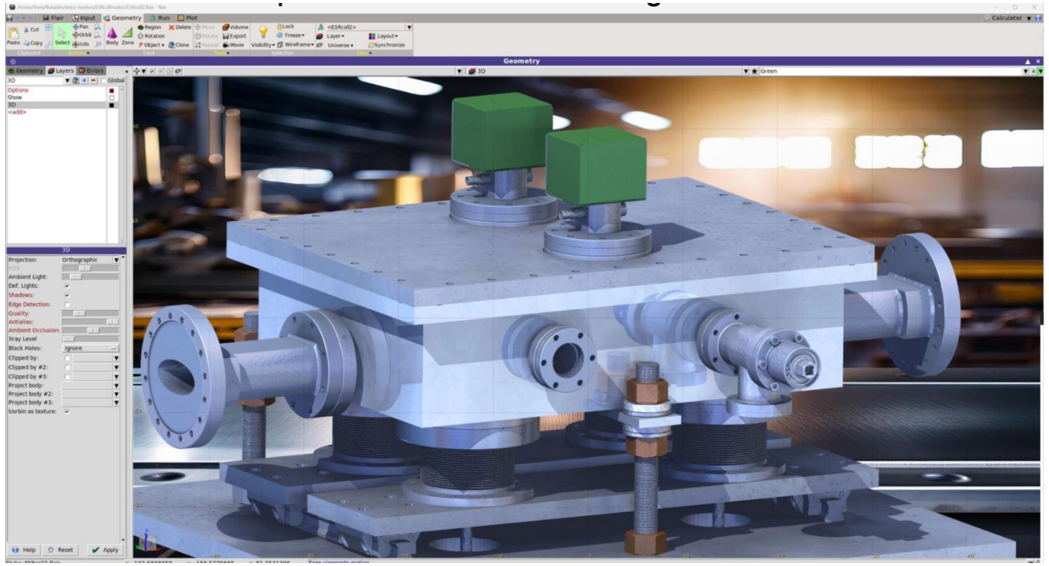
- Advanced graphical user interface
- **Allows users to edit/debug/render geometries, prepare the input file, set up the run (even in parallel / across cluster nodes), process results, plot physical observables**
- FARM: Flair advanced render module







https://doi.org/10.1103/PhysRevAccelBeams.22.071003



https://indico.cern.ch/event/1444491/contributions/6234932/attachments/2977548/5241983/01_Introduction_to_FLUKA_2024_CERN.pdf

Displacement-damage modeling in FLUKA

FLUKA focuses not only on the description of radiation fields, but also on their effect in matter (within the approximations pointed out above)

Instantaneous effects and related quantities in FLUKA

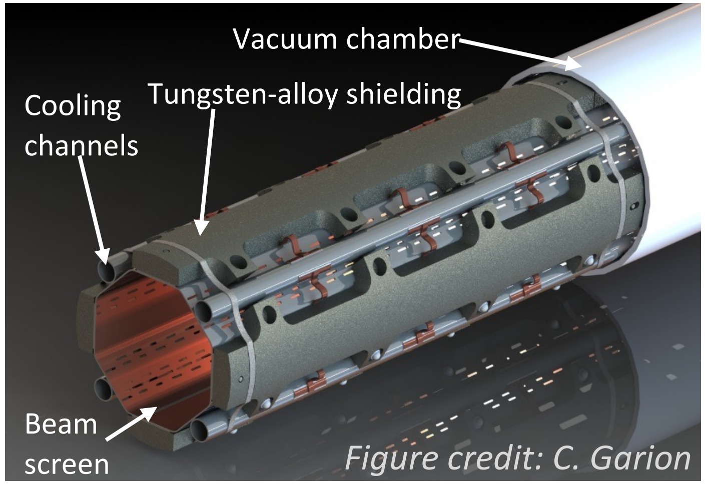
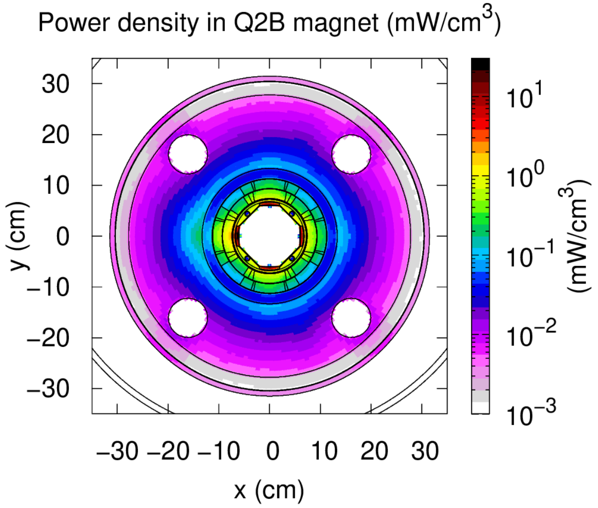
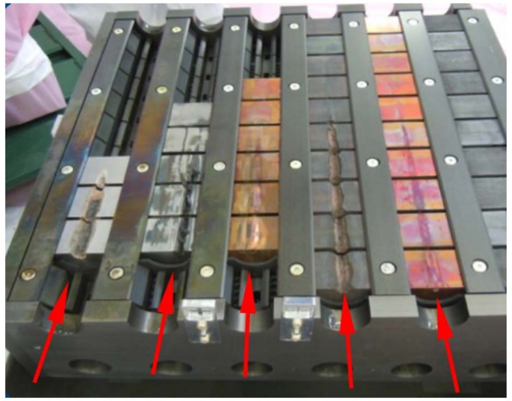


Figure credit: C. Garion



- Power deposition (mW/cm³) → local hot spots and SC magnet quench limits
- Total deposited energy → Cryogenics constrains
- Accidental beam loss and consequences
- Single-event effects in electronics
- ….

ISSI SRAM tester. Courtesy of G. Lerner.



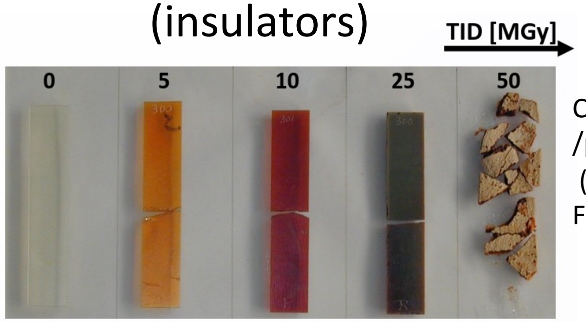
See:

Radiation challenges for magnets in present and future colliders (HL-LHC, FCC, Muon Collider)	*Anton Lechner*
30/7-018 - Kjell Johnsen Auditorium, CERN (yesterday)	14:30 - 14:50

Cumulative effects

Total ionizing dose

- Affects chemical bonds
- Relevant for organic materials (insulators)



Cylinders of alanine /polymer mixture (~4 cm length)
From: M. Brugger

(see these talks tomorrow)

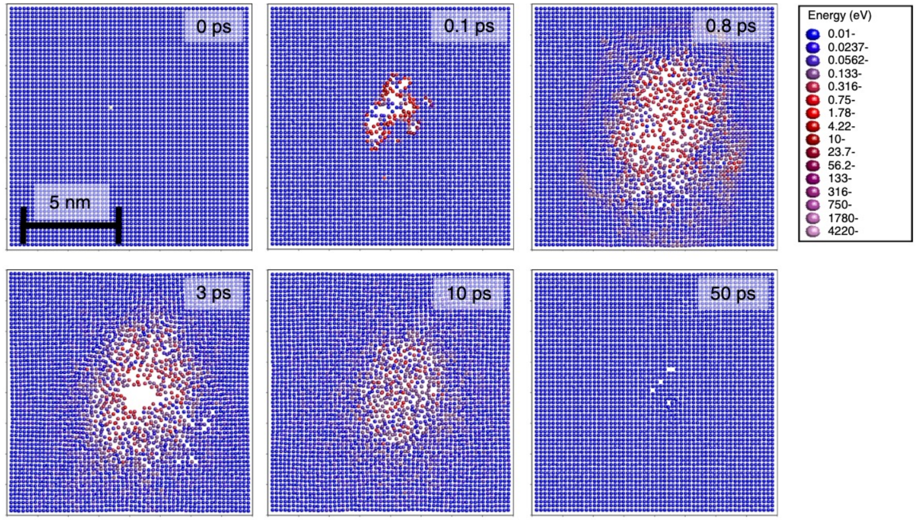
Magnet shielding design in present and future colliders — *Daniele Calzolari*
30/7-018 - Kjell Johnsen Auditorium, CERN — 11:25 - 11:45

Radiation hardness requirements for organic materials in magnets and radiation environments in muon colliders, FCC, …
Francesco Cerutti

Gas production

- Production of H and He
- Correlated with production of "bubbles"/cracks in the material

Atomic displacements



https://doi.org/10.1038/s41467-018-03415-5

- Primary knock-on atom (PKA) is transferred a recoil kinetic energy
- Cascade of ion-hole pairs
- Recombination
- Net displacement damage
- **Degradation of transport properties**

Nb_3Sn wires

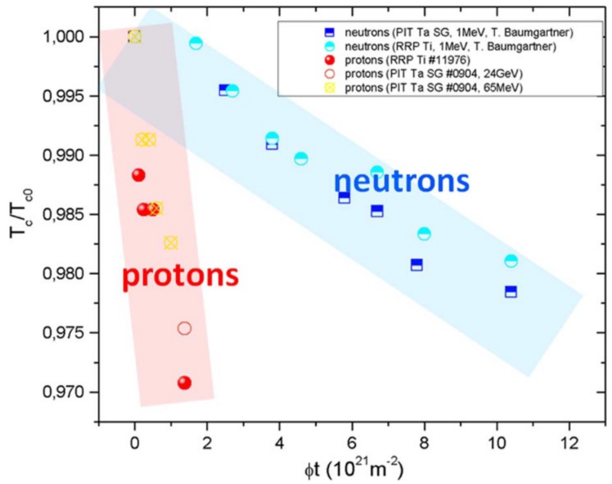


Fig. 1. T_c versus fluence for the same Nb_3Sn wires (#0904, PIT, Ta alloyed and #11976, RRP, Ti alloyed) after irradiation by high-energy protons (60 MeV and 24 GeV) [6] and neutrons (> 0.1 MeV) [4].

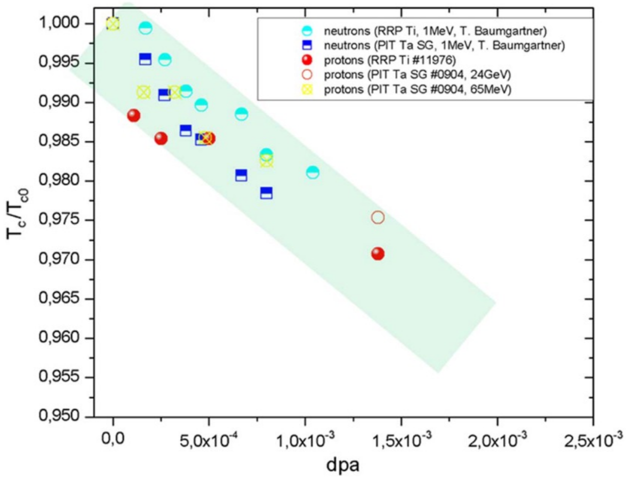
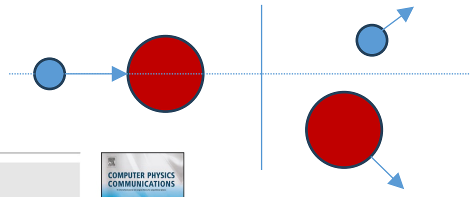


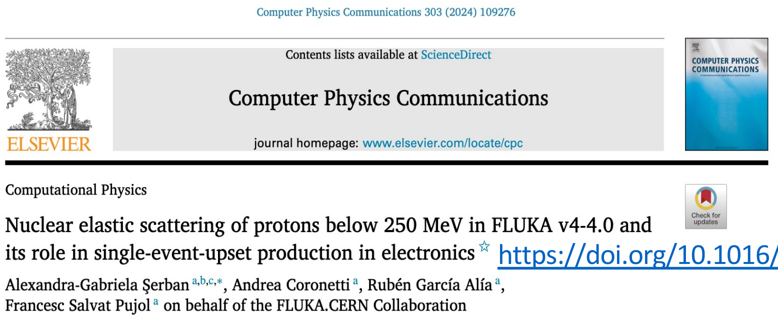
Fig. 2. T_c versus *dpa*, after replacing the fluence in Fig. 1 by the *dpa* values determined from the FLUKA code (see Table II).

http://dx.doi.org/10.1109/TASC.2016.2549858

Relevant primary knock-on source: elastic scattering



- Elastic scattering on the **electrostatic** potential:
  - **Mostly small deflections, large cross section**
  - **Mean free paths O(nm-um)**
- **We can in general *not* afford to sample individual Coulomb scatterings in FLUKA***
- Instead, multiple Coulomb scattering theory (Molière) gives effective angular distribution after a macroscopic particle step
- Recoil: see next slide
- Elastic scattering on the **nuclear** potential:
  - **Mostly large deflections, lower cross section**
  - **Mean free paths O(1-10) cm**
  - **Explicit recoil transport in FLUKA (if above threshold)**


Computer Physics Communications 303 (2024) 109276

Contents lists available at ScienceDirect

Computer Physics Communications

journal homepage: www.elsevier.com/locate/cpc

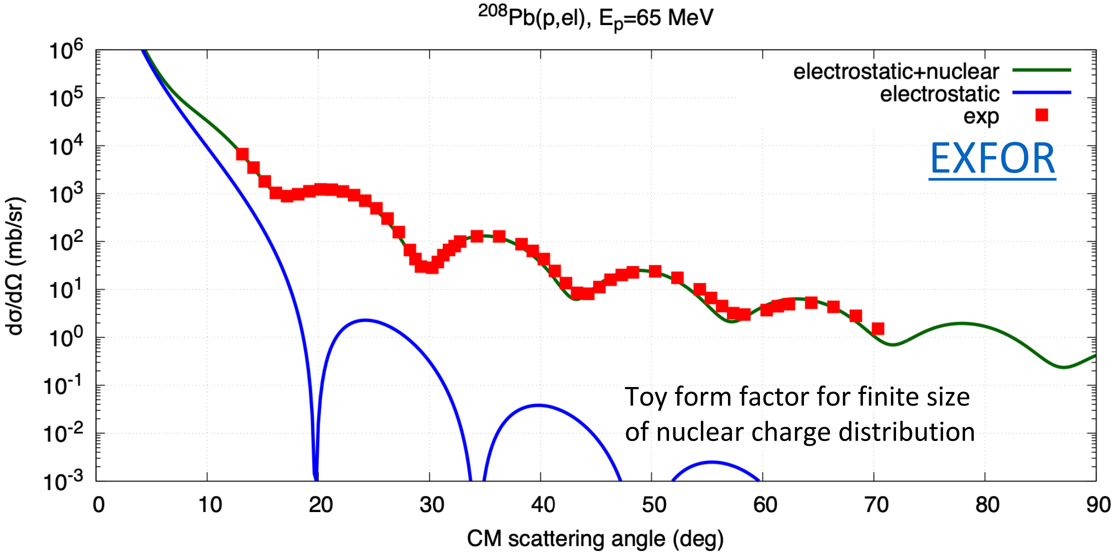
ELSEVIER

Computational Physics

Nuclear elastic scattering of protons below 250 MeV in FLUKA v4-4.0 and its role in single-event-upset production in electronics ☆

Alexandra-Gabriela Şerban [a,b,c,*], Andrea Coronetti [a], Rubén García Alía [a], Francesc Salvat Pujol [a] on behalf of the FLUKA.CERN Collaboration

https://doi.org/10.1016/j.cpc.2024.109276



- One-to-one correspondence between θ_{CM} and **recoil energy transfer T:**

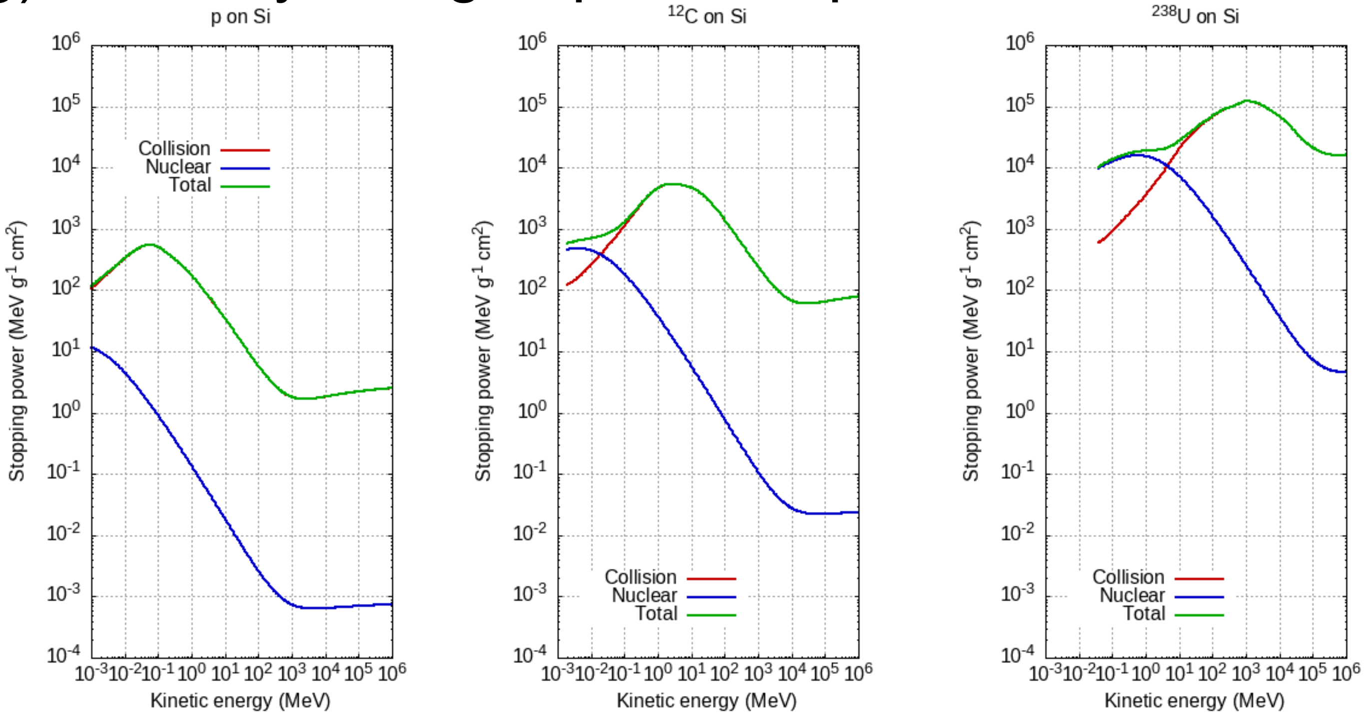
$$T = \frac{p_{CM}^2(1-\cos\theta_{CM})}{m_t} \qquad \frac{d\sigma}{d\Omega} \rightarrow \frac{d\sigma}{dT}$$

Nuclear stopping power

- With a condensed-history approach, one loses the possiblity of an event-by-event explicit production of primary knock-on atoms (PKAs) from Coulomb scattering
- FLUKA accounts for the specific energy transfer to the material as a result of Coulomb scattering via the **nuclear stopping power,** (average energy loss per unit path length due to Coulomb scattering) for every charged particle species:

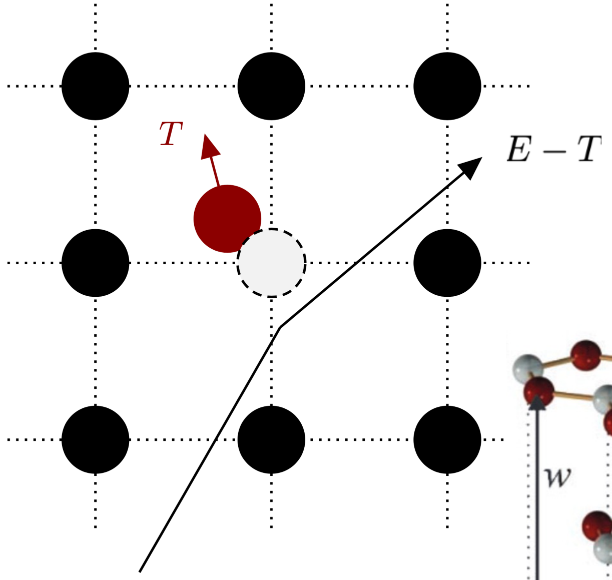
$$\left.\frac{\mathrm{d}E}{\mathrm{d}x}\right|_{\mathrm{nuc}} = \frac{N_A \rho}{A_w} \int_0^{T_{\max}} \mathrm{d}T\, T \frac{\mathrm{d}\sigma(E)}{\mathrm{d}T} \quad \text{(GeV/cm)}$$

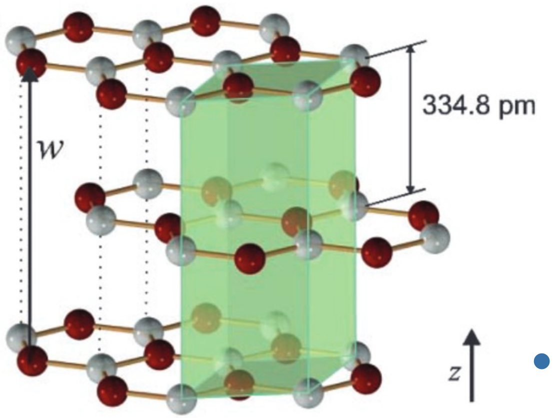
E: particle energy (GeV)
x: path length (cm)
T: Energy transfer to PKA (GeV)
N_A: Avogadro number (mol^{-1})
ρ: material density ($g\ cm^{-3}$)
A_w: atomic weight ($g\ mol^{-1}$)
T_{max}: maximum recoil energy (GeV)
$d\sigma/dT$: diff. cross section for elastic scattering on electrostatic potential of target atom ($cm^2\ GeV^{-1}$)



Not every *T* dislodges atoms: damage threshold energy

- Only recoil energies above the **damage threshold E_d** (typically 10s of eV) dislodge the target ion from its lattice site (*PKA*)





https://doi.org/10.1073/pnas.2134173100

- **Considerable variation of E_d as a function of lattice site, momentum-transfer direction, etc**

https://doi.org/10.1016/j.nucet.2017.08.007

Estimated and adopted ("A") E_{dmin} values in eV.

3 Li	9 ± 7	39 Y	15 ± 3 A	69 Tm	16 ± 3 A
4 Be	15 ± 5	40 Zr	22 ± 5 A	70 Yb	9 ± 2 A
5 B	19 ± 5	41 Nb	32 ± 6 A	71 Lu	17 ± 3 A
6 C	25 ± 5 A	42 Mo	34 ± 7 A	72 Hf	27 ± 5
11 Na	7 ± 4	43 Tc	32 ± 6	73 Ta	32 ± 6 A
12 Mg	10 ± 2 A	44 Ru	34 ± 7	74 W	41 ± 8 A
13 Al	16 ± 3 A	45 Rh	33 ± 7	75 Re	44 ± 9 A
14 Si	13 ± 3 A	46 Pd	34 ± 7 A	76 Os	46 ± 9
15 P	10 ± 4	47 Ag	25 ± 5 A	77 Ir	46 ± 9 A
16 S	10 ± 3	48 Cd	19 ± 4 A	78 Pt	34 ± 7 A
19 K	7 ± 5	49 In	10 ± 2 A	79 Au	34 ± 7 A
20 Ca	10 ± 3	50 Sn	22 ± 4 A	80 Hg	14 ± 5
21 Sc	14 ± 3 A	51 Sb	18 ± 4	81 Tl	16 ± 3
22 Ti	19 ± 4 A	52 Te	15 ± 3	82 Pb	14 ± 3 A
23 V	26 ± 5 A	53 I	11 ± 3	83 Bi	13 ± 3 A
24 Cr	28 ± 6 A	55 Cs	7 ± 4	84 Po	13 ± 3
25 Mn	18 ± 4	56 Ba	11 ± 2	85 At	16 ± 4
26 Fe	17 ± 3 A	57 La	15 ± 3	87 Fr	21 ± 6
27 Co	22 ± 4 A	58 Ce	14 ± 3	88 Ra	14 ± 3
28 Ni	23 ± 5 A	59 Pr	10 ± 2 A	89 Ac	24 ± 5
29 Cu	20 ± 4 A	60 Nd	9 ± 2 A	90 Th	35 ± 7 A
30 Zn	14 ± 3 A	61 Pm	13 ± 4	91 Pa	33 ± 9
31 Ga	12 ± 2 A	62 Sm	10 ± 2 A	92 U	36 ± 8
32 Ge	15 ± 3 A	63 Eu	8 ± 2 A		
33 As	15 ± 3	64 Gd	14 ± 3 A		
34 Se	12 ± 2	65 Tb	15 ± 3 A		
35 Br	9 ± 3	66 Dy	15 ±		
37 Rb	7 ± 4	67 Ho	15 ±		
38 Sr	10 ± 3	68 Er	16 ±		

Estimated and adopted ("A") averaged displacement threshold energy E_d values in eV.

3 Li	19 ± 4	37 Rb	17 ± 4	65 Tb	36 ± 7
4 Be	31 ± 6	38 Sr	24 ± 5	66 Dy	34 ± 7
5 B	46 ± 9	39 Y	36 ± 7	67 Ho	36 ± 7
6 C	69 ± 14	40 Zr	40 ± 8 A	68 Er	37 ± 7
11 Na	17 ± 4	41 Nb	78 ± 16 A	69 Tm	36 ± 7
12 Mg	20 ± 4 A	42 Mo	65 ± 13 A	70 Yb	27 ± 5
13 Al	27 ± 5 A	43 Tc	58 ± 12	71 Lu	44 ± 9
14 Si	37 ± 7	44 Ru	60 ± 12	72 Hf	61 ± 12
15 P	20 ± 5	45 Rh	51 ± 10	73 Ta	90 ± 18 A
16 S	20 ± 4	46 Pd	41 ± 8 A	74 W	90 ± 18 A
19 K	16 ± 4	47 Ag	39 ± 8 A	75 Re	60 ± 12 A
20 Ca	23 ± 5	48 Cd	30 ± 6 A	76 Os	69 ± 14
21 Sc	33 ± 7	49 In	12 ± 2 A	77 Ir	58 ± 12
22 Ti	30 ± 6 A	50 Sn	20 ± 10	78 Pt	44 ± 9 A
23 V	57 ± 11 A	51 Sb	22 ± 6	79 Au	43 ± 9 A
24 Cr	40 ± 8 A	52 Te	20 ± 5	80 Hg	20 ± 5
25 Mn	33 ± 7	53 I	16 ± 4	81 Tl	24 ± 5
26 Fe	40 ± 8 A	55 Cs	15 ± 4	82 Pb	25 ± 5 A
27 Co	36 ± 7 A	56 Ba	22 ± 4	83 Bi	23 ± 5
28 Ni	33 ± 7 A	57 La	29 ± 6	84 Po	22 ± 4
29 Cu	30 ± 6 A	58 Ce	28 ± 6	85 At	22 ± 4
30 Zn	29 ± 6 A	59 Pr	27 ± 5	87 Fr	34 ± 6
31 Ga	23 ± 5	60 Nd	28 ± 6	88 Ra	24 ± 5
32 Ge	35 ± 7	61 Pm	30 ± 5	89 Ac	33 ± 7
33 As	31 ± 6	62 Sm	27 ± 5	90 Th	44 ± 9 A
34 Se	23 ± 5	63 Eu	24 ± 5	91 Pa	43 ± 7

Threshold Displacement Energies of Oxygen in YBa2Cu3O7: A Multi-Physics Analysis *Mr Ashley Dickson*

30/7-018 - Kjell Johnsen Auditorium, CERN 11:00 - 11:20

- FLUKA asks user for average displacement threshold (user-input or 30 eV by default)

Not all of *T* goes into atomic collisions: the partition function

- The PKA kinetic energy T will be lost to ionization (no displacement damage) and Coulomb scattering (displacement damage).

- **One needs an effective way to "discount" the fraction of T which would be spent on ionization: enter the Lindhard partition function**

- In FLUKA we rely on a parametrized function based on https://doi.org/10.1109/23.907581:

$$L(T) = \frac{1}{1 + F_L(3.4008\varepsilon^{1/6} + 0.402\,44\varepsilon^{3/4} + \varepsilon)}$$

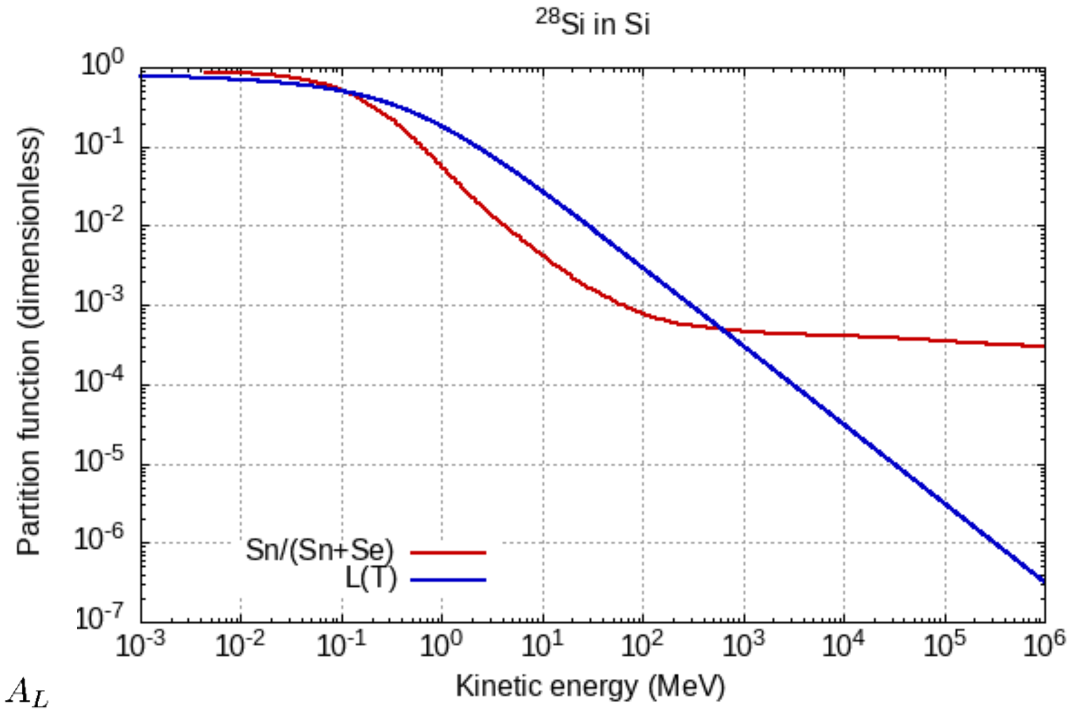
$$\varepsilon = \frac{T}{E_L}$$

(L: lattice atom)
(R: recoil atom)

$$E_L = 30.724 Z_R Z_L (Z_R^{2/3} + Z_L^{2/3})^{1/2} \frac{A_R + A_L}{A_L}$$

$$F_L = \frac{0.0793 Z_R^{2/3} Z_L^{1/2} (A_R + A_L)^{3/2}}{(Z_R^{2/3} + Z_L^{2/3})^{3/4} A_R^{3/2} A_L^{1/2}}.$$

- Approximations:
  - Recoil energy << Projectile kinetic energy
  - Electronic stopping << Nuclear stopping



Considerable differences wrt Sn/(Sn+Se) at high energies.

- **To minimize their impact, it's best to lower FLUKA ion transport cuts to lowest limit (~250 eV/u)**

Non-ionizing energy loss (NIEL) in FLUKA

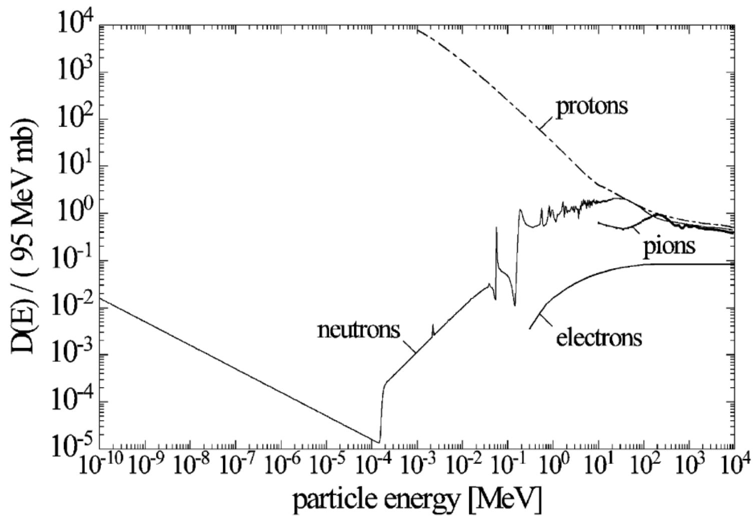
- The NIEL is a basic quantity accounting for both the damage threshold and the partition function:

$$\mathrm{NIEL}(E) = \frac{N_A \rho}{A_w} \int_{E_d}^{T_{\max}} \mathrm{d}T\, T \frac{\mathrm{d}\sigma(E)}{\mathrm{d}T} L(T)$$ (GeV/cm)

Particularly useful for Si as target material, i.e. for electronics

Conveniently recast in terms of a damage function D(E)

$$NIEL = \frac{N_A \rho}{A_w} \int dE\, D(E) \frac{d\Phi(E)}{dE}$$ (GeV/cm³)

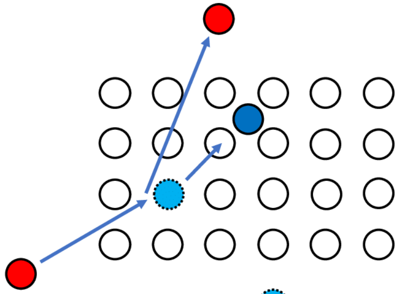


https://doi.org/10.1016/S0168-9002(98)01462-4

- Tabulated in FLUKA at initialization as a function of energy, apportioned among particle steps runtime.
- NIEL: quantifies the fraction of energy transferred to the material which might produce displacement damage.
- Although still in use, it is not the end of the story. ***Not all of the NIEL goes into displacement damage: some is dissipated as heat (phonons)***
- ***NIEL does not make any prediction of defect cascades***

Estimating displacement damage: DPA in FLUKA*

- The quantity *displacements per atom* (DPA) goes beyond the NIEL, in that it converts the energy available for displacement into a number of ion-hole (Frenkel) pairs
- Two variants available in FLUKA, both treated as "stopping-power-like" quantities, apportioned over macroscopic particle steps:
  - ***Norgett-Robinson-Torrens displacements per atom (DPA)*:***



http://dx.doi.org/10.15496/publikation-20433

$$\text{DPA-NRT}(E) \sim \frac{N_A \rho}{A_w} \int_{E_d}^{T_{\max}} \mathrm{d}T \, \frac{\mathrm{d}\sigma(E)}{\mathrm{d}T} N_{\mathrm{NRT}}(T_d), \qquad T_d = \text{“}L(T)\text{”}T, \qquad N_{\mathrm{NRT}}(T_d) = \begin{cases} 0 & \text{if } 0 < T_d < E_d, \\ 1 & \text{if } E_d < T_d < \frac{2E_d}{0.8}, \\ \frac{0.8 T_d}{2E_d} & \text{if } \frac{2E_d}{0.8} < T_d \end{cases}$$

(1/cm)

Ref: Nordlund K. *et al.*, Nat. Commun. **9** 1084 (2018)

Ref: Norgett M.J. *et al.*, Nucl Eng Des **33** 50-54 (1975)
https://doi.org/10.1016/0029-5493(75)90035-7

"The binary collision simulations used as the basis of the NRT-dpa model focused on the collisional phase of the displacement cascade and did not consider the dynamics of cascade evolution as atomic velocities fell"
(Overestimation of displacement damage)

Legacy binary collision model

The factor of 0.8 accounts for more realistic atomic potential instead of hard sphere scattering of original Kinchin-Pease calculations + crude recombination efficiency

*See however the following paper+slides for second-level sub-cascade treatment:

http://dx.doi.org/10.15669/pnst.2.769
https://indico.cern.ch/event/769192/contributions/3287282/attachments/1794339/2924300/RadiationEffectsLHCexperiments.pdf

Estimating displacement damage: DPA in FLUKA*

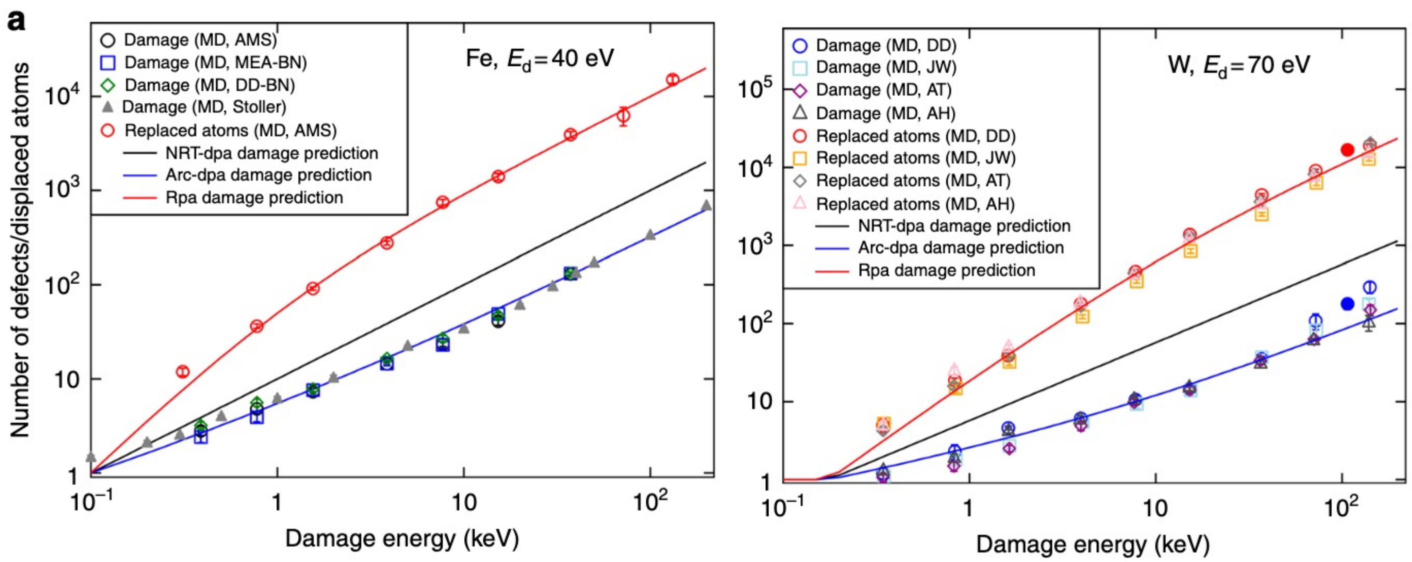
- ***Athermal-recombination-corrected DPA*:***

Ref: Nordlund K. *et al.*, Nat. Commun. **9** 1084 (2018)

$$\text{ARC-DPA}(E) \sim \frac{N_A \rho}{A_w} \int_{E_d}^{T_{\max}} \mathrm{d}T \, \frac{\mathrm{d}\sigma(E)}{\mathrm{d}T} N_{\text{arcDPA}}(T), \qquad T_d = L(T)T, \qquad N_{\text{arcDPA}}(T_d) = \begin{cases} 0 & \text{if } 0 < T_d < E_d, \\ 1 & \text{if } E_d < T_d < \frac{2E_d}{0.8}, \\ \frac{0.8T_d}{2E_d} \xi_{\text{arcDPA}}(T_d) & \text{if } \frac{2E_d}{0.8} < T_d \end{cases}$$

(1/cm)

$$\xi_{\text{arcdpa}}(T_\text{d}) = \frac{1 - c_{\text{arcdpa}}}{(2E_\text{d}/0.8)^{b_{\text{arcdpa}}}} T_\text{d}^{b_{\text{arcdpa}}} + c_{\text{arcdpa}}$$



https://doi.org/10.1038/s41467-018-03415-5

”b” and “c” parameters determined from MD or experiments for a given material

Lim b=0, c=0 of arc-DPA → DPA-NRT

Parameter compilation from Konobeyev et al., https://doi.org/10.1016/j.nucet.2017.08.007

*See however the following paper+slides for second-level sub-cascade treatment:

http://dx.doi.org/10.15669/pnst.2.769

https://indico.cern.ch/event/769192/contributions/3287282/attachments/1794339/2924300/RadiationEffectsLHCexperiments.pdf

For elementary materials…

Scoring of arc-DPA is available in FLUKA since v4-3.0 (Sep 2022)

DPA of all particles scored on equal footing in FLUKA

Charged particles:

a) **Transport step (condensed history)**: restricted NIEL/DPA over the step

b) **Below transport threshold**: estimate NIEL/DPA as integral over nuclear stopping power x L(T).

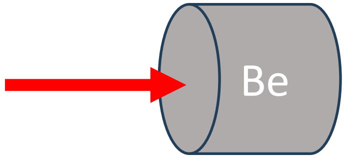
Recoils from nuclear elastic scattering (n,p,π,K) / residuals from nuclear reactions:

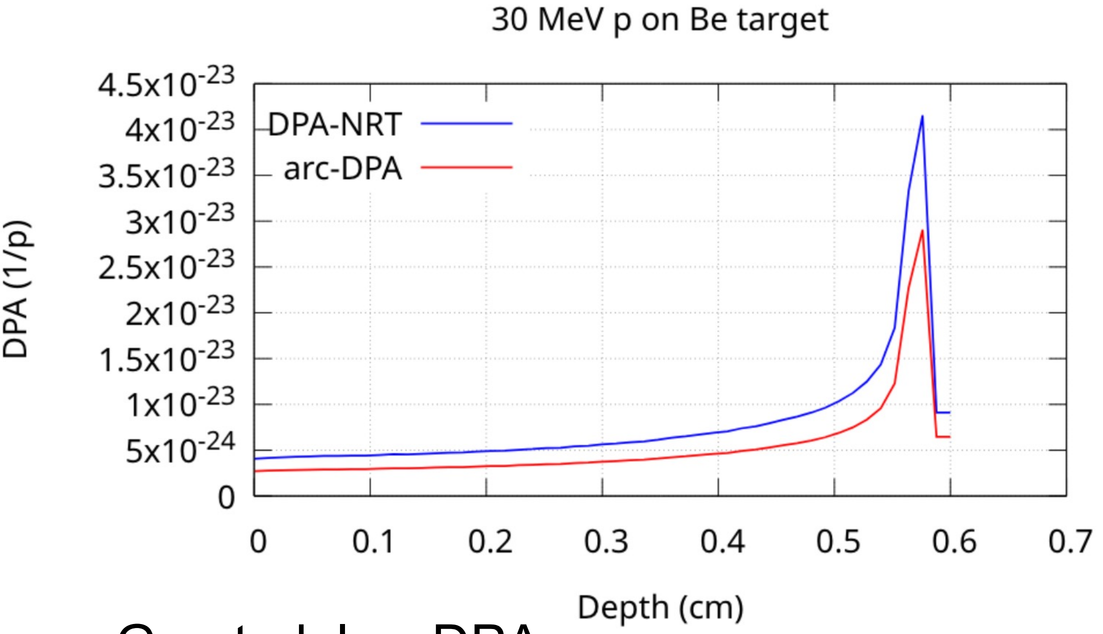
- Go to a) if its kinetic energy is above transport threshold, go to b) if below

NB: as of newly included point-wise treatment of neutron interactions below 20 MeV in FLUKA v4-4.0 (Feb 2024), their* contribution to NIEL/DPA is treated coherently with the rest of particles

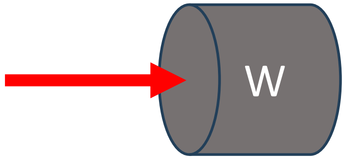
DPA-NRT vs arc-DPA

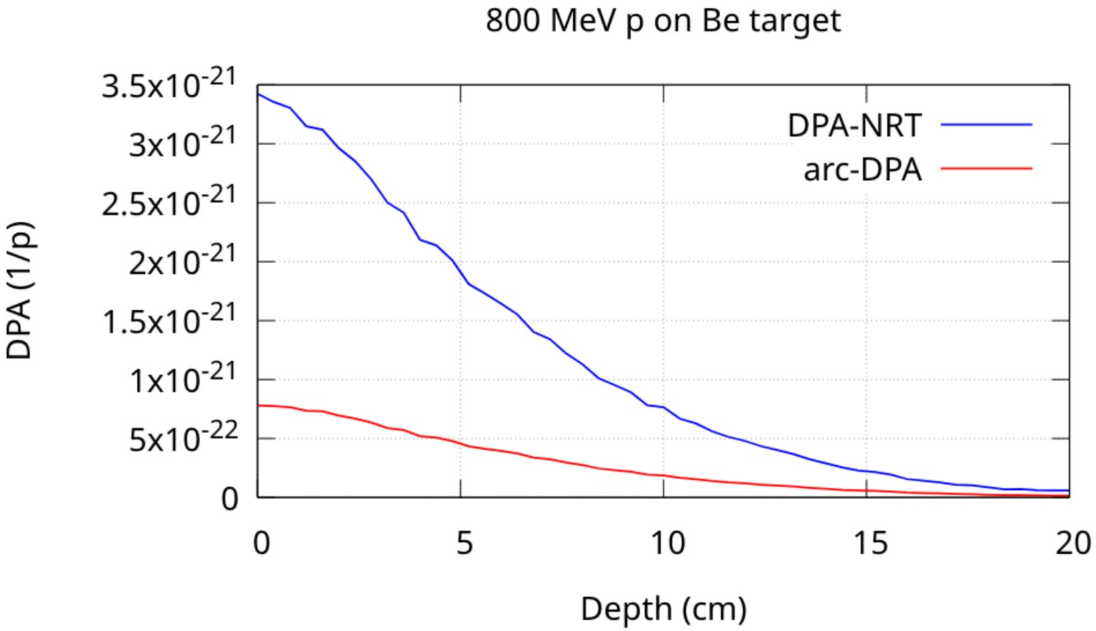
E_d=31 eV, b=-1, c=0.46





E_d=70 eV, b=-0.56 eV, c=0.12



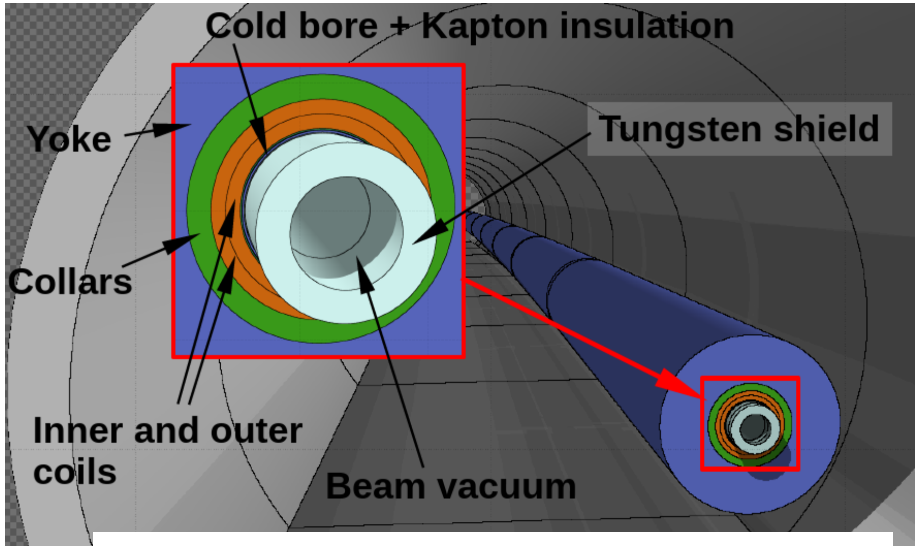


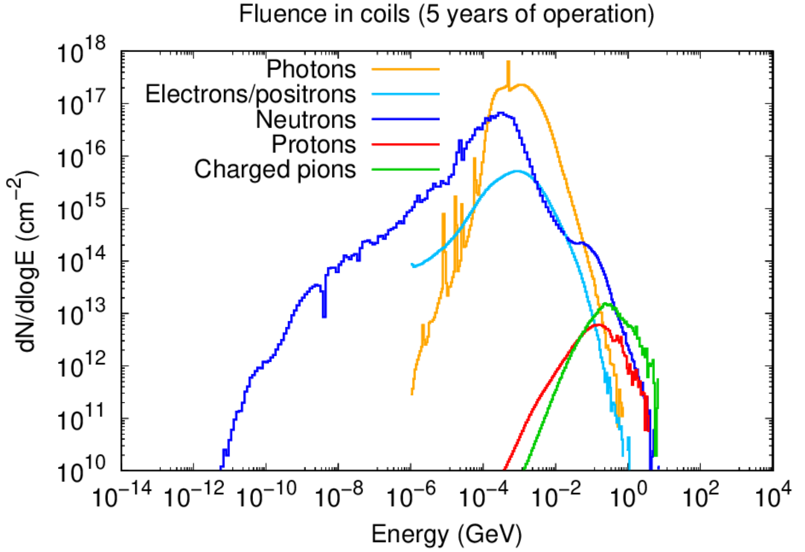
- Granted, low DPA.
- See this talk tomorrow for more consequent examples relevant for Muon Collider studies:

Magnet shielding design in present and future colliders	*Daniele Calzolari*
30/7-018 - Kjell Johnsen Auditorium, CERN	11:25 - 11:45

- See also SATIF15 code intercomparison for MC simulation of displacement damage https://www.oecd-nea.org/upload/docs/application/pdf/2024-05/satif15-session-7-and-8.pdf#page=25

Radiation to Muon-Collider ring magnets

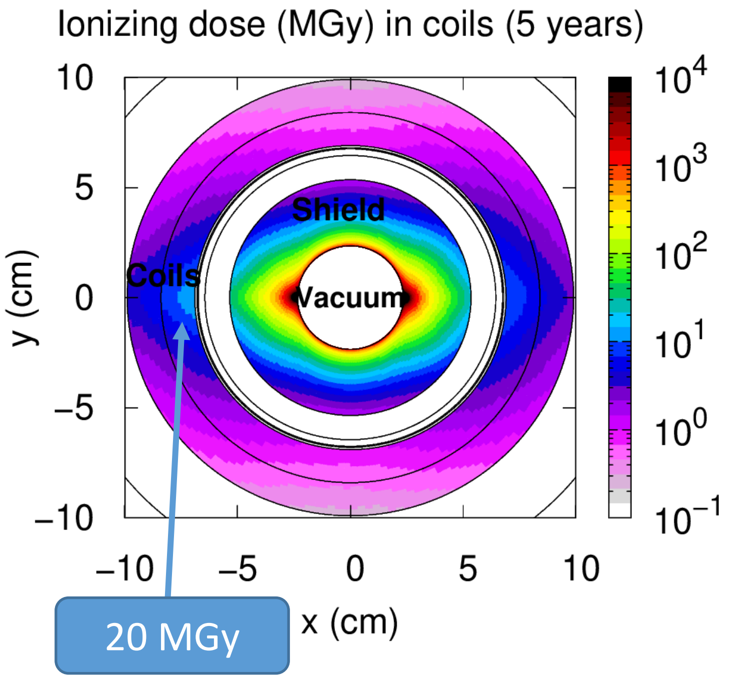


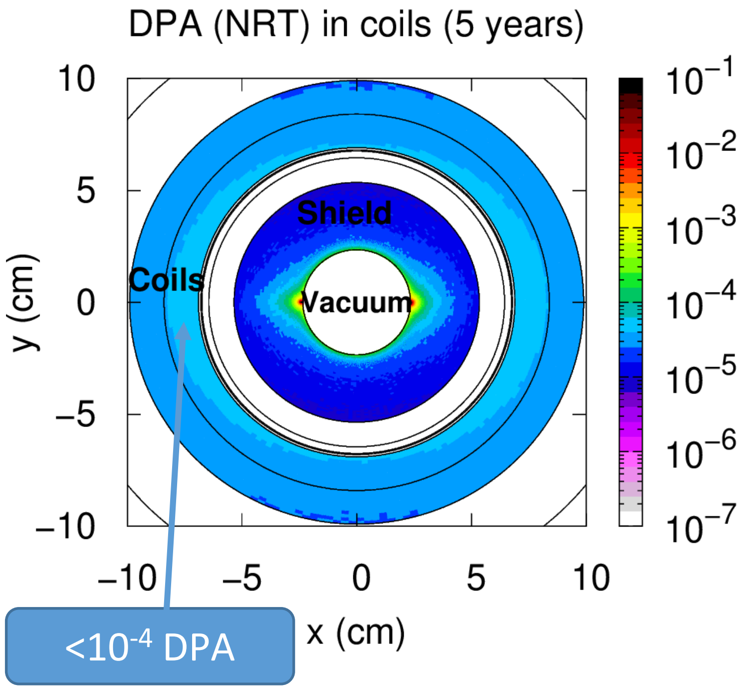


Radiation challenges for magnets in present and future colliders (HL-LHC, FCC, Muon Collider) — *Anton Lechner*

30/7-018 - Kjell Johnsen Auditorium, CERN — 14:30 - 14:50

*Cumulative dose and DPA in coils of arc dipoles after 5 yrs (with **3 cm thick tungsten shielding**):*





Dose in coils → mostly due to e-/γ

DPA in coils → mostly due to neutrons

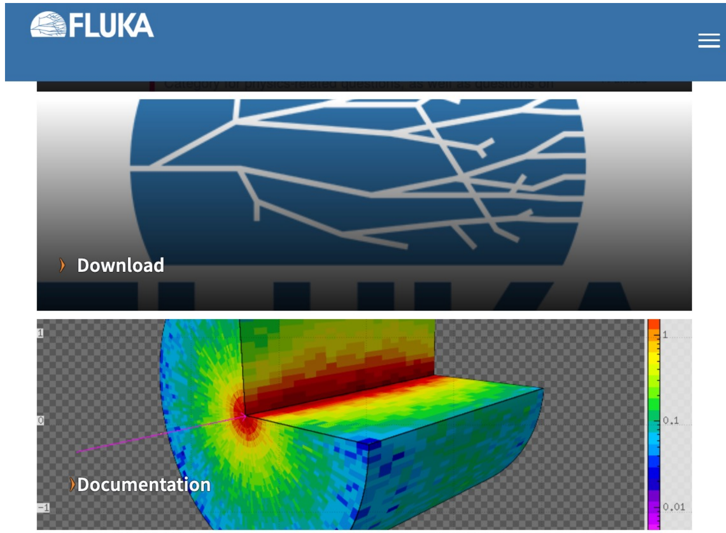
Assuming 5 years with 140 days of operation per year

Summary

- General overview of FLUKA
- Displacement damage modelling in FLUKA: NIEL and DPA
- Advantages and limitations
  - Coherent treatment across all particle species
  - Built-in scoring of NIEL, DPA-NRT, arc-DPA
  - Use of average damage thresholds
  - No on-line simulation of material degradation
- Still, effective DPA scoring as a probe of displacement damage

- Feel free to register and download FLUKA!
- If interested, consider attending one of our trainings!

https://fluka.cern/



https://fluka.cern/support/courses-and-events


FLUKA

Courses and events

FLUKA/Flair courses are typically organized once or twice a year. Future courses will be announced below. Presentations, demos and exercises from previous courses can be accessed on the respective course websites listed below under "Past events" (see links).

Upcoming/ongoing events:

Past events:

2024 FLUKA.CERN Beginner's course, Course website
CERN, Geneva, Switzerland
02 - 06 December 2024, FLUKA beginner's course

2024 FLUKA.CERN Topical course, Course website
CERN, Geneva, Switzerland
25 - 27 November 2024, FLUKA user workshop

2024 FLUKA.CERN Beginner's course, Course website
National Institute for Aerospatial Technologies, Madrid, Spain
15 - 19 April 2024, FLUKA beginner's course

2023 FLUKA.CERN Beginner's course, Course website
NEA, Boulogne-Billancourt, Paris, France
06 - 10 November 2023, FLUKA beginner's course

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