MODELIZATION OF RADIATION-INDUCED DAMAGE IN FLUKA AND MATERIAL DAMAGE ESTIMATES FOR CERN INJECTORS AND FUTURE FACILITIES

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1st Workshop of ARIES WP17 PowerMat – 27-28/11/2017

FLUKA

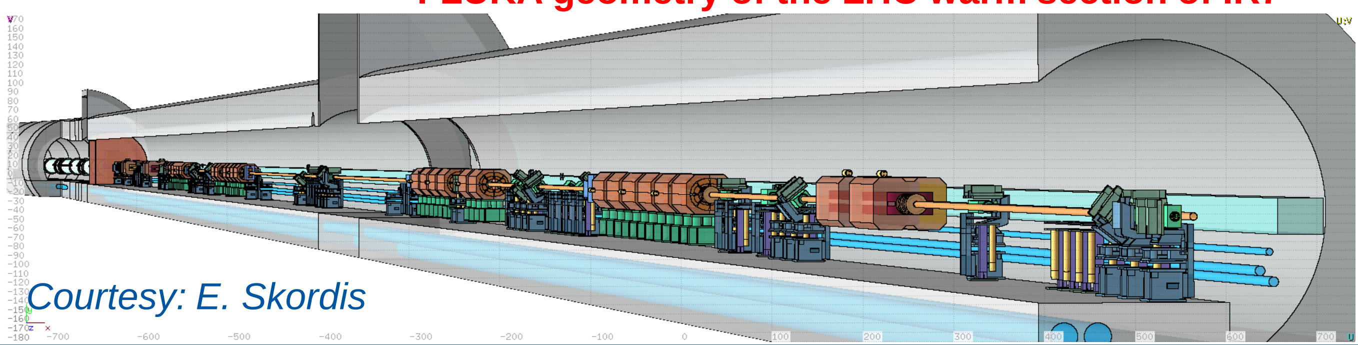
FLUKA is a Monte Carlo code for calculations of particle transport and interactions with matter.

- Wide range of applications:

  Proton and electron accelerator shielding, target design, calorimetry, activation, dosimetry, detector design, Accelerator Driven Systems, cosmic rays, neutrino physics, Radiotherapy, etc.

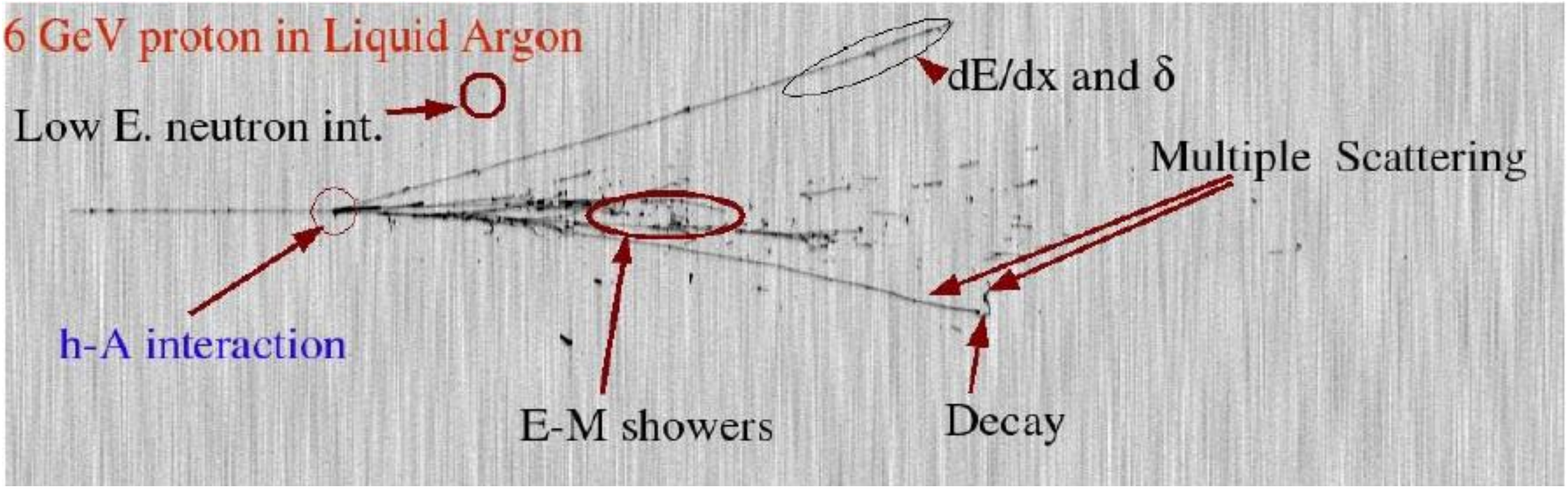
- **Extensively used at CERN for:**
  - Beam-machine interactions
  - Radio-Protection calculations
  - Facility design of future projects

FLUKA geometry of the LHC warm section of IR7



Courtesy: E. Skordis

Interaction and Transport Monte Carlo Code



- Hadron-nucleus interactions
- Nucleus-Nucleus interactions
- Electron interactions
- Photon interactions
- Muon interactions (inc. photonuclear)
- Neutrino interactions
- Decay
- Low energy neutrons

- Ionization
- Multiple scattering
- Combinatorial geometry
- Voxel geometry
- Magnetic field
- Analogue or biased
- On-line buildup and evolution of induced radioactivity and dose

- User-friendly GUI thanks to *Flair*

Info: **http://www.fluka.org**

Different kinds of damage

from Radiation-Matter interaction

Precious materials (healthy/tragic damage)

energy (dose) deposition, radioisotope production and decay & positron annihilation and photon pair detection

Oxidation by generation of chemically active radicals (e.g. PVC de-hydrochlorination by X and g-rays, radiolysis,…)

Accidents energy (power) deposition

Degradation energy (dose) deposition, particle fluence, DPA

Gas production residual nuclei production

Electronics high energy hadron fluence, neutron fluence, energy (dose) deposition

Activation residual activity and dose rate

F.Cerutti

DPA as Radiation Damage Estimator

The **dpa** quantity is a measure of the amount of radiation damage in irradiated materials. It means the **average number of displacements that every atom in the crystal structure has suffered**.

$$dpa = \frac{A}{N_A \rho} N_F$$

A is the mass number

N_A is the Avogadro number

ρ is the density

N_F is the number of defects or ***Frenkel pairs***.

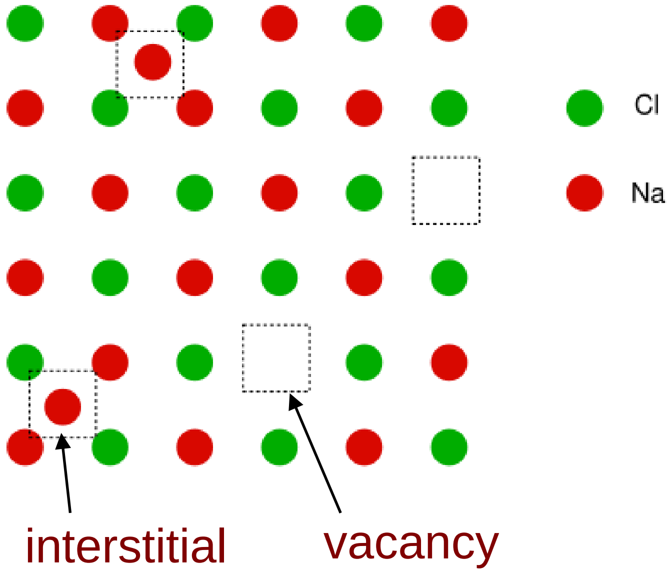
Experimentally: no direct determination. Indirect through study of macroscopic effects (electric and thermal conductivities, radiation hardening, swelling…)

Amount of dpa ↔ Macroscopic effects

Frenkel pairs

- Frenkel pair N_F (defect or disorder), is a compound crystallographic defect formed when an atom or ion leaves its place in the lattice (leaving a **vacancy**), and lodges nearby in the crystal (becoming an **interstitial**)

$$N_{NRT} \equiv N_F = \kappa \frac{\xi(T)T}{2E_{th}}$$



N_{NRT} Defects by Norgert, Robinson and Torrens

$\kappa=0.8$ is the displacement efficiency

T kinetic energy of the primary knock-on atom (PKA)

$\xi(T)$ partition function (LSS theory)

$\xi(T)\,T$ directly related to the NIEL(non ionizing energy loss)

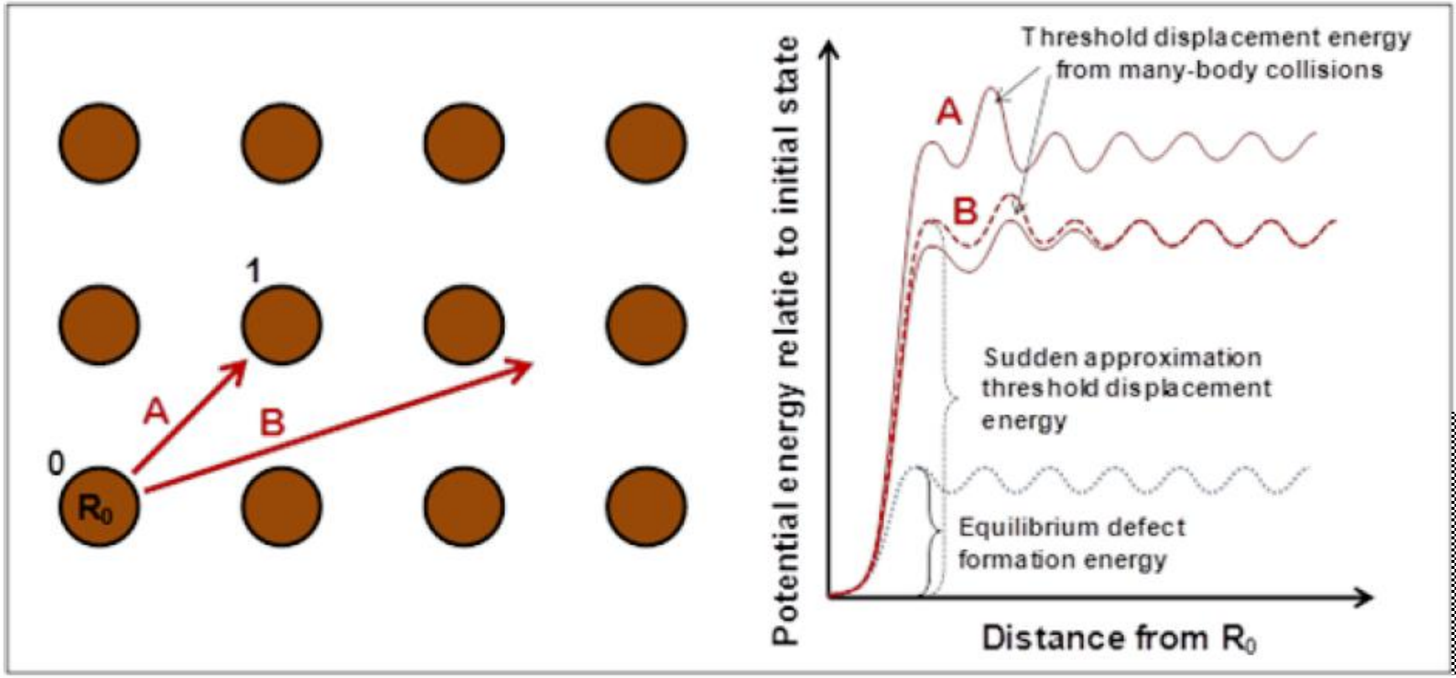
E_{th} damage threshold energy

Damage Threshold

$$N_{NRT} \equiv N_F = \kappa \frac{\xi(T)T}{2E_{th}}$$

From: NEA/NSC/DOC(2015)9

- Damage threshold **depends on the direction of the recoil** in the crystal lattice.
- Also depends on the **compound combination**: e.g. NaCl: E_{th}(Na-Na), E_{th}(Na-Cl), E_{th}(Cl-Na), E_{th}(Cl-Cl)
- FLUKA use the **"average" threshold over all crystallographic directions** (user defined)
- **Sensitivity studies** using different E_{th} values can provide upper and lower limits on dpa

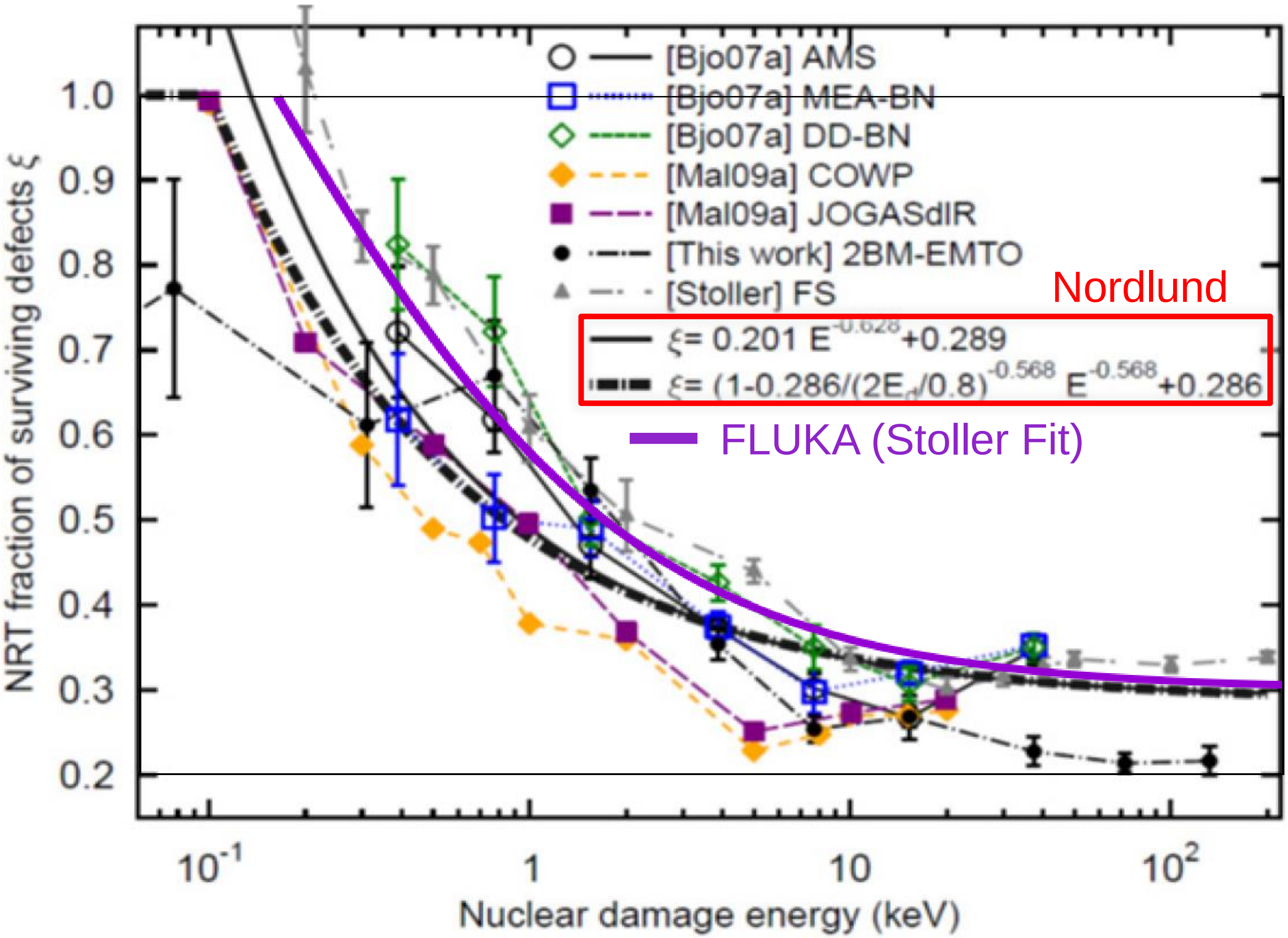


Typical values used in NJOY99 code

Element	Eth (eV)	Element	Eth (eV)
Lithium	10	Co	40
C in SiC	20	Ni	40
Graphite	30..35	Cu	40
Al	27	Nb	40
Si	25	Mo	60
Mn	40	W	90
Fe	40	Pb	25

Displacement efficiency
κ Stoller vs Nordlund

$$N_{NRT} \equiv N_F = \kappa \frac{\xi(T)T}{2E_{th}}$$



Recombination from overlap of collision cascades, "athermal recombination-corrected" dpa: Arc-dpa

Stoller results Comes from Molecular Dynamics simulations

Thermal recombination of defects not considered

↓

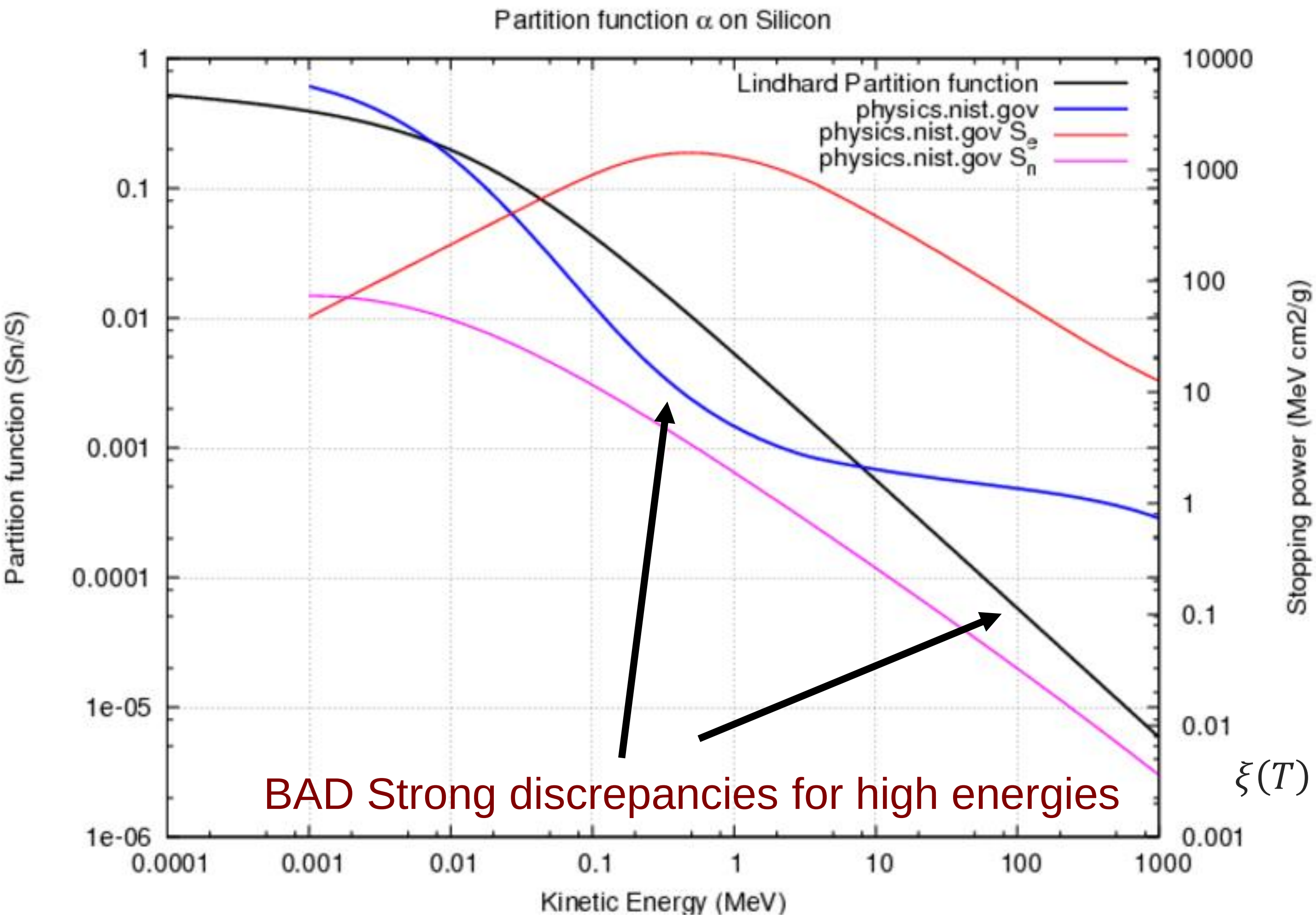
becomes relevant for high temperatures

↓

Overestimation of dpa's

Lindhard partition function ξ

$$N_F = \kappa \frac{\xi(T)T}{2E_{th}}$$



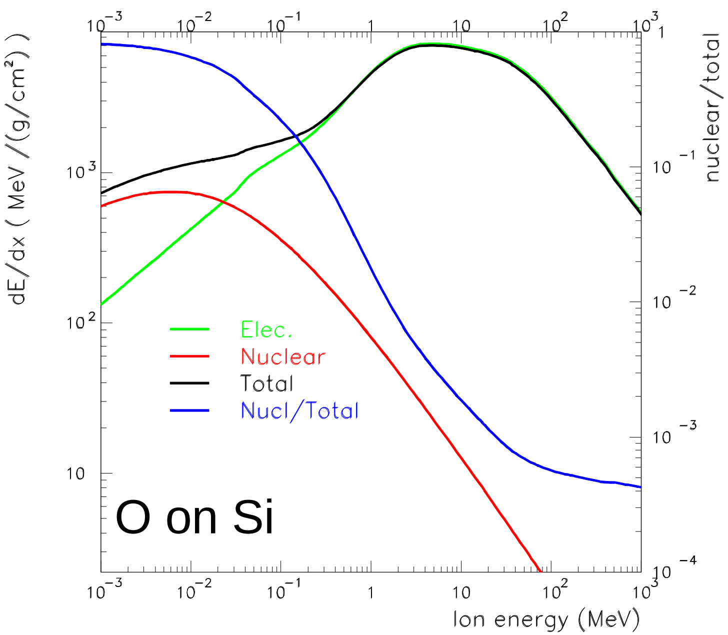
Fraction of stopping power *S(T)* going into NIEL (non-ionizing energy loss)

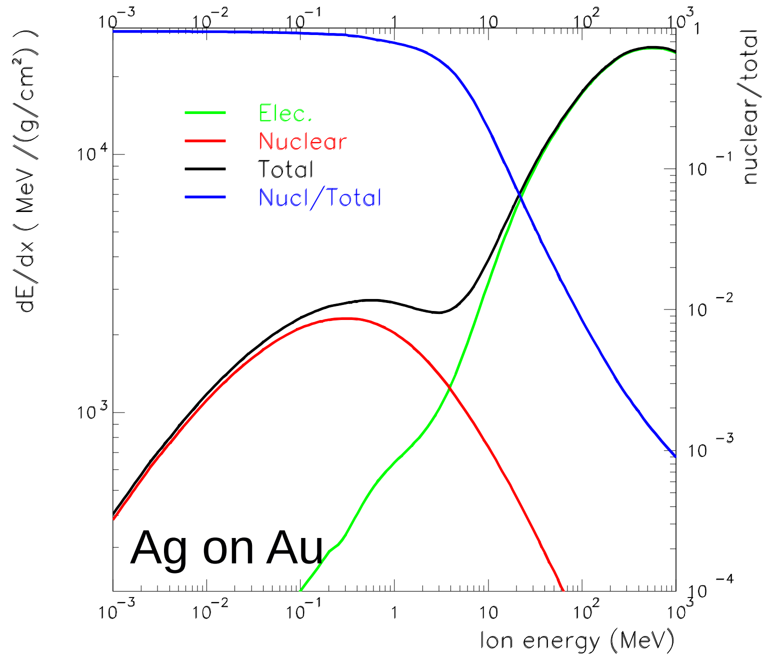
$$\xi(T) = \frac{S_n(T)}{S(T)} = \frac{S_n(T)}{S_n(T) + S_e(T)}$$

Nuclear Stopping Power

$$\xi(T) = \frac{S_n(T)}{S(T)}$$

$$N_F = \kappa \frac{\xi(T)\,T}{2E_{th}}$$





The total ***(S)***, nuclear ***(S_n)*** and electronic ***(S_e)*** stopping power. The **partition function *$S_n/(S_n+S_e)$*** is also plotted. The abscissa is the ion total kinetic energy

Partition function decreases with energy
And increases with charge

→ NIEL/DPA are dominated by
Low energy (heavy) recoils

F.Cerutti

Restricted Nuclear Stopping Power

$$N_F = \kappa \frac{\xi(T)T}{2E_{th}}$$

- Lindhard approximation uses the unrestricted NIEL. Including all the energy losses also those below the threshold E_{th} → ***Overestimation of DPAs***
- FLUKA is using a more accurate way by employing the restricted nuclear losses

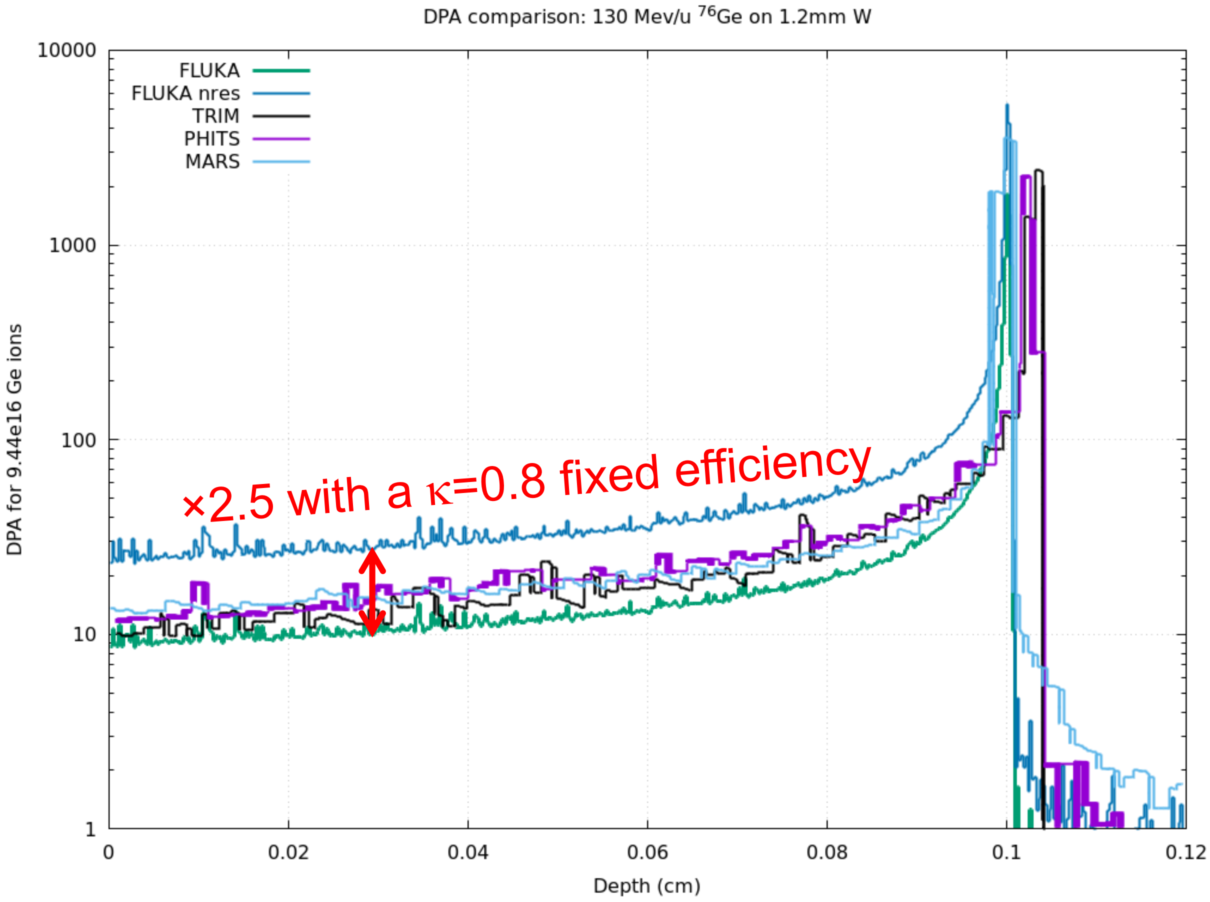
$$S(E,E_{th}) = N\int_{E_{th}}^{\gamma E} T\left(\frac{d\sigma}{dT}\right)dT$$

where:

$S(E,E_{th})$	is the restricted energy loss
N	atomic density
T	energy transfer during ion-solid interaction
$d\sigma/dT$	differential scattering cross section
$\gamma = \dfrac{2E(2m+E)}{M+\dfrac{m^2}{M}+2(m+E)}$	maximum fraction of energy transfer during collision

Comparison with other simulation codes

^{76}Ge ion pencil beam of 130 MeV/*A* uniform in W target a disc of R=0.3568 mm, 1.2 mm thickness



Non-restricted provides higher values if we consider fixed Displ. Effic.

↓

Overestimation of DPA

$$N_F = \kappa \frac{\xi(T)T}{2E_{th}}$$

FLUKA Implementation

Charged particles and heavy ions

- **During transport**
  Calculate the restricted non ionizing energy loss
- **Below threshold**
  Calculate the integrated nuclear stopping power with the Lindhard partition function
- **At (elastic and inelastic) interactions**
  Calculate the recoil, to be transported or treated as below threshold

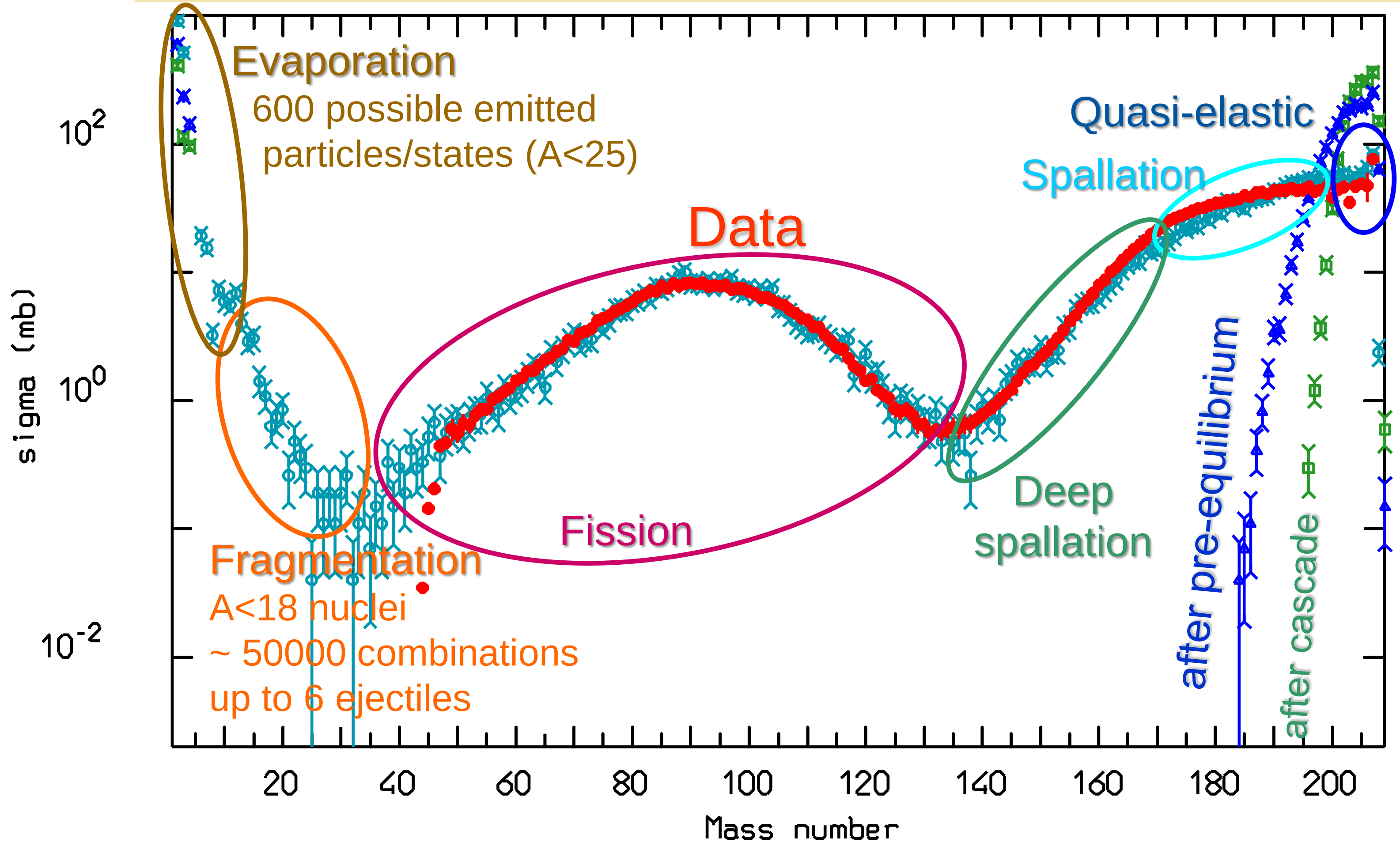
Neutrons:

- **High energy E_n>20 MeV**
  - Calculate the recoils after interaction
    Treat recoil as a "normal" charged particle/ion
- **Low energy E_n≤20 MeV (group-wise)**
  - Calculate the NIEL from NJOY
- **Low energy E_n≤20 MeV (point-wise)**
  - Calculate the recoil if possible
    Treat recoil as a "normal" charged particle/ion

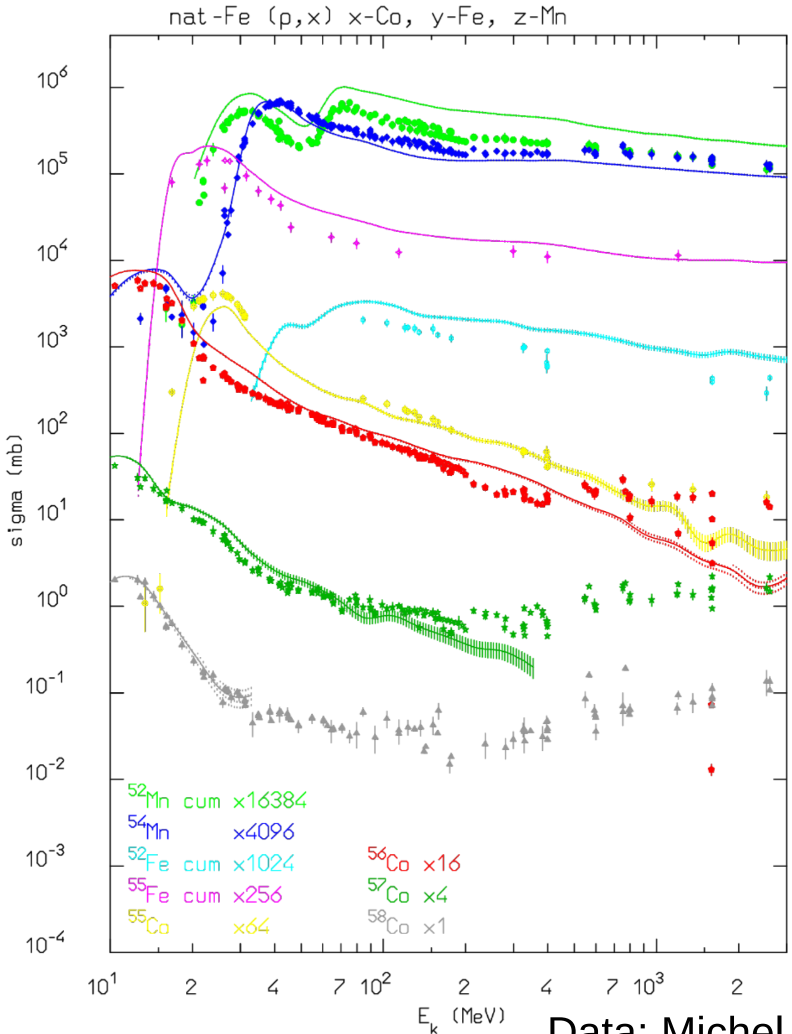
Implementation in FLUKA: A. Fasso et al. Prog. In Nucl. Science and Technology, Vol. 2, p769-775 (2011)

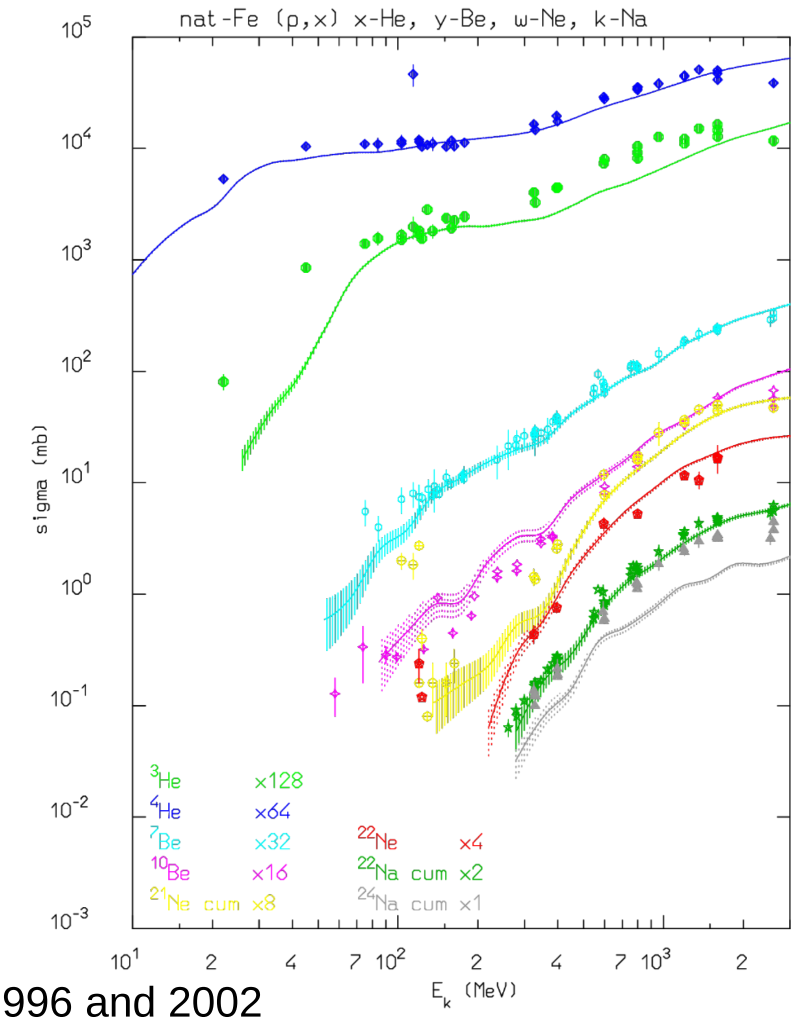
Example of fission/evaporation

1 A GeV ^{208}Pb + p reactions Nucl. Phys. A 686 (2001) 481-524



Isotope production for $^{nat}Fe(p,x)$:





Data: Michel et al. 1996 and 2002

Estimates for CERN injectors and future facilities

- Beam Dump Facility
- BLIP capsule
- PS Internal Beam Dumps

Beam Dump Facility (BDF)

Beam:

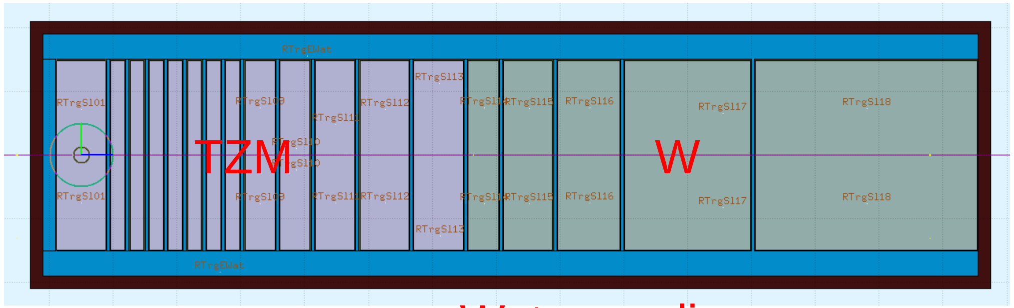
- Protons: 400 GeV/c
- Sweep pattern:
  - radius 3 cm
  - 1σ 0.6 cm

Geometry:

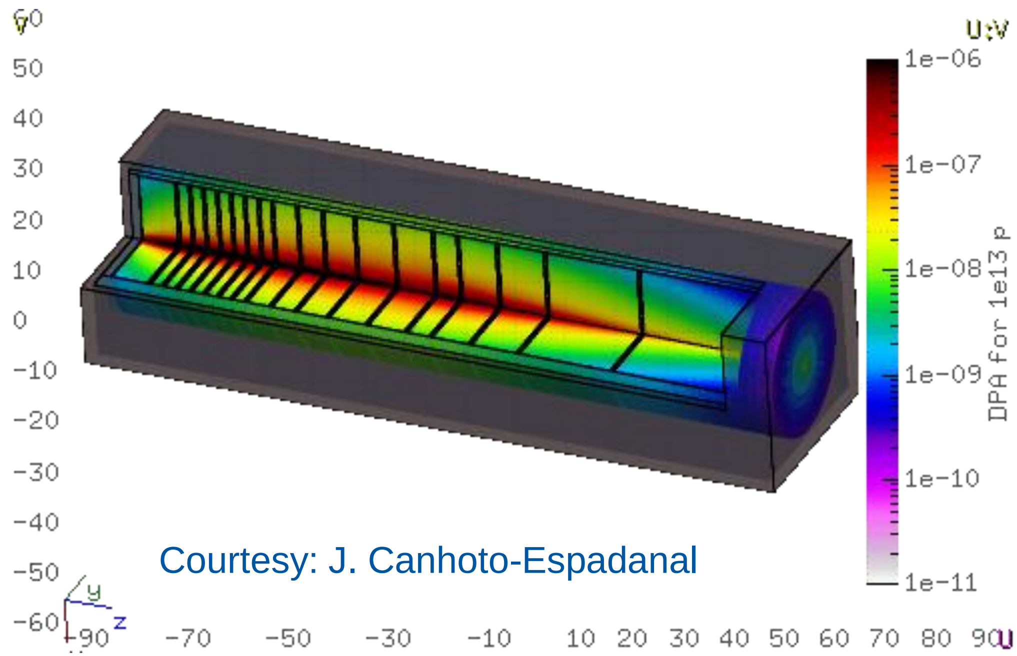
- 1.4 m long cylinder discs of
  TZM enclosed in Ta
  W enclosed in Ta
  1.5 mm Ta cladding and
  5 mm water gaps

Materials:

- Tungsten E_d=90 eV
- SS 316N E_d=40 eV
- Tantalum E_d=53 eV
- TZM (Mo,Zr,Ti…) E_d=60 eV

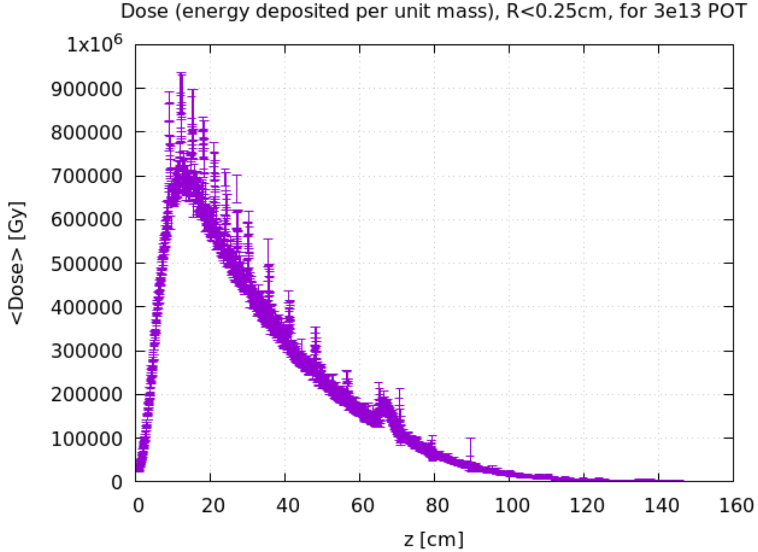


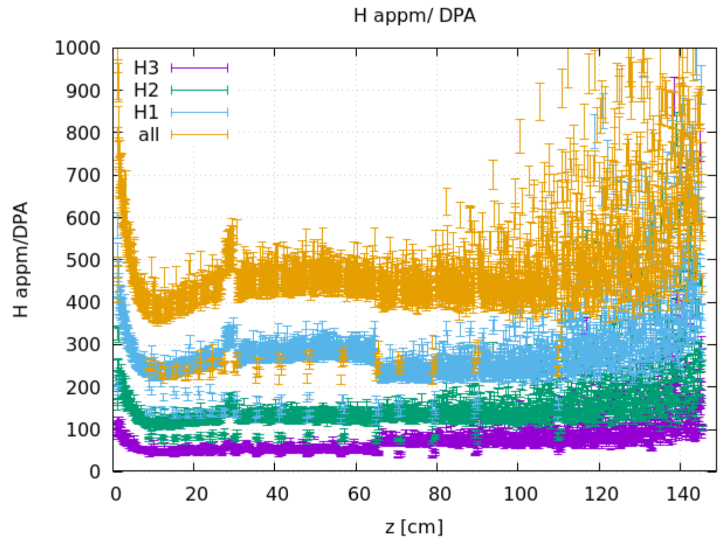
Ta cladding Water cooling

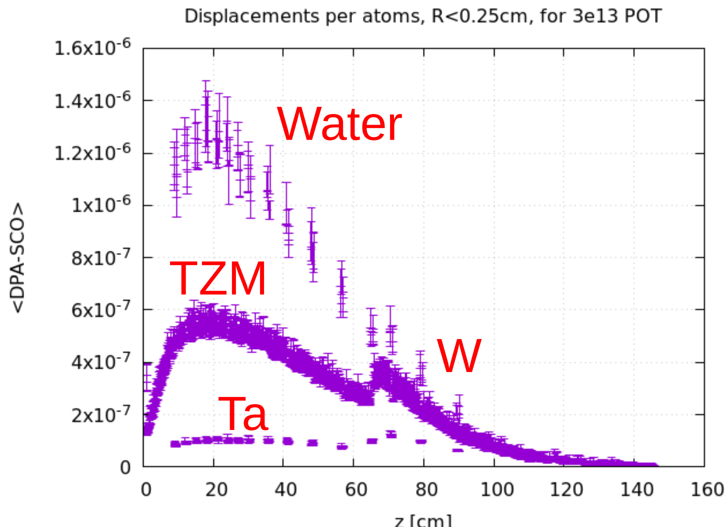


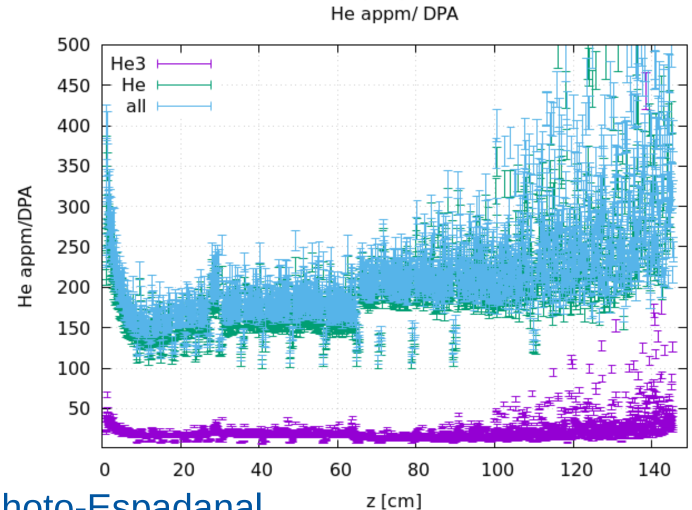
Courtesy: J. Canhoto-Espadanal

BDF Results: H/He[appm] vs DPA







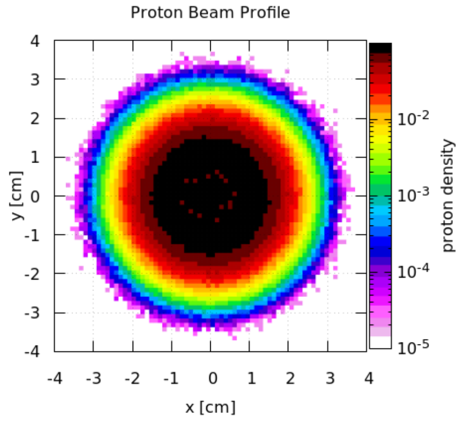


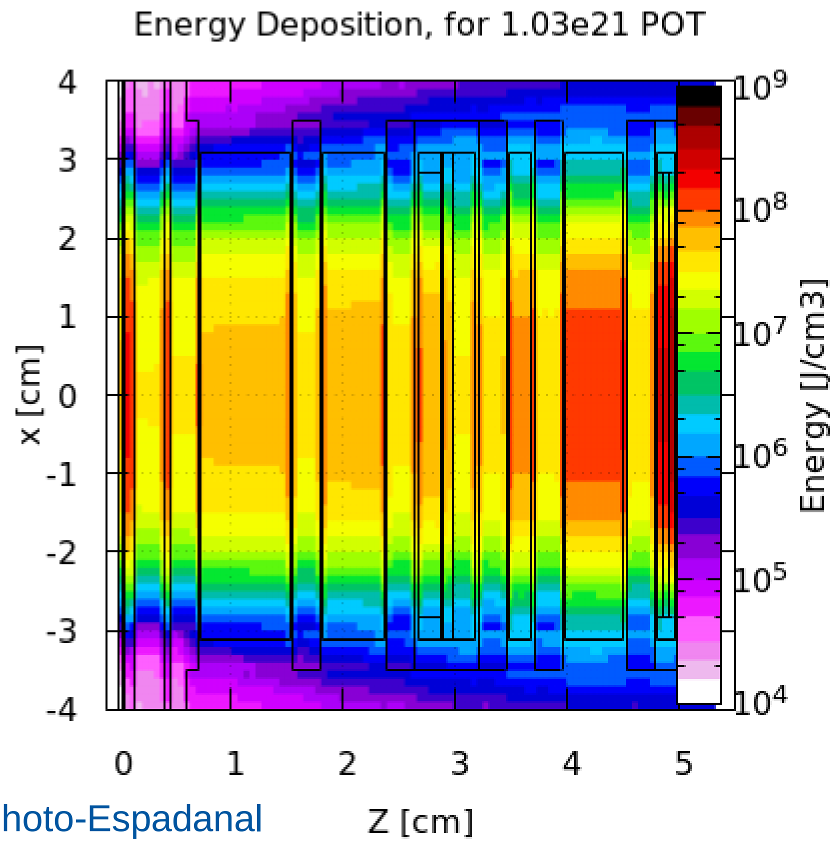
Courtesy: J. Canhoto-Espadanal

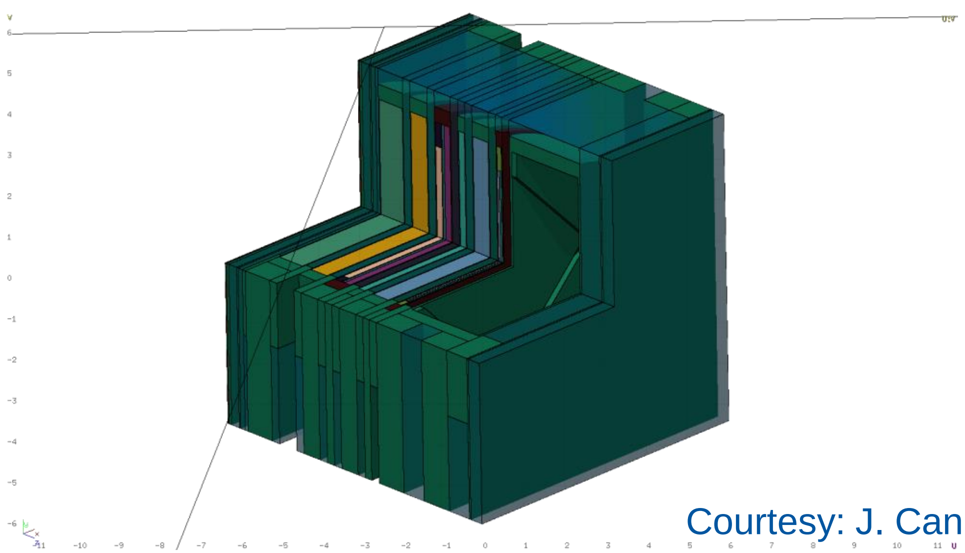
BLIP capsule

- Beam
  - Proton E=181 MeV
  - $\sigma_{x,y}$ = 5.1 mm
- Geometry: Layers of

Window SS304L	0.3mm
TZM	0.5mm
CuCrZr	0.5mm
Ir	0.5mm
Graphite(0.85g/cm3)	0.1mm

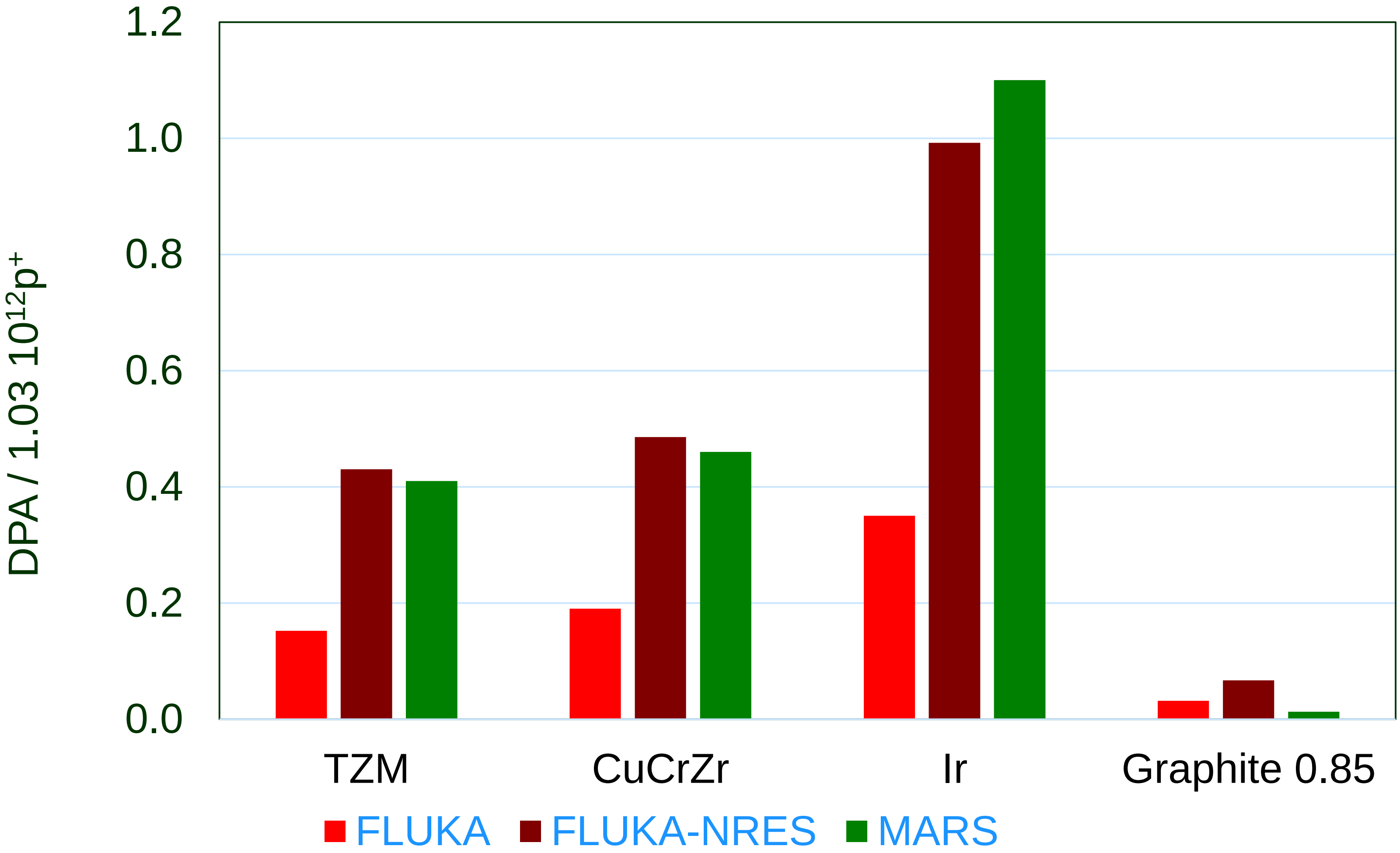






Courtesy: J. Canhoto-Espadanal

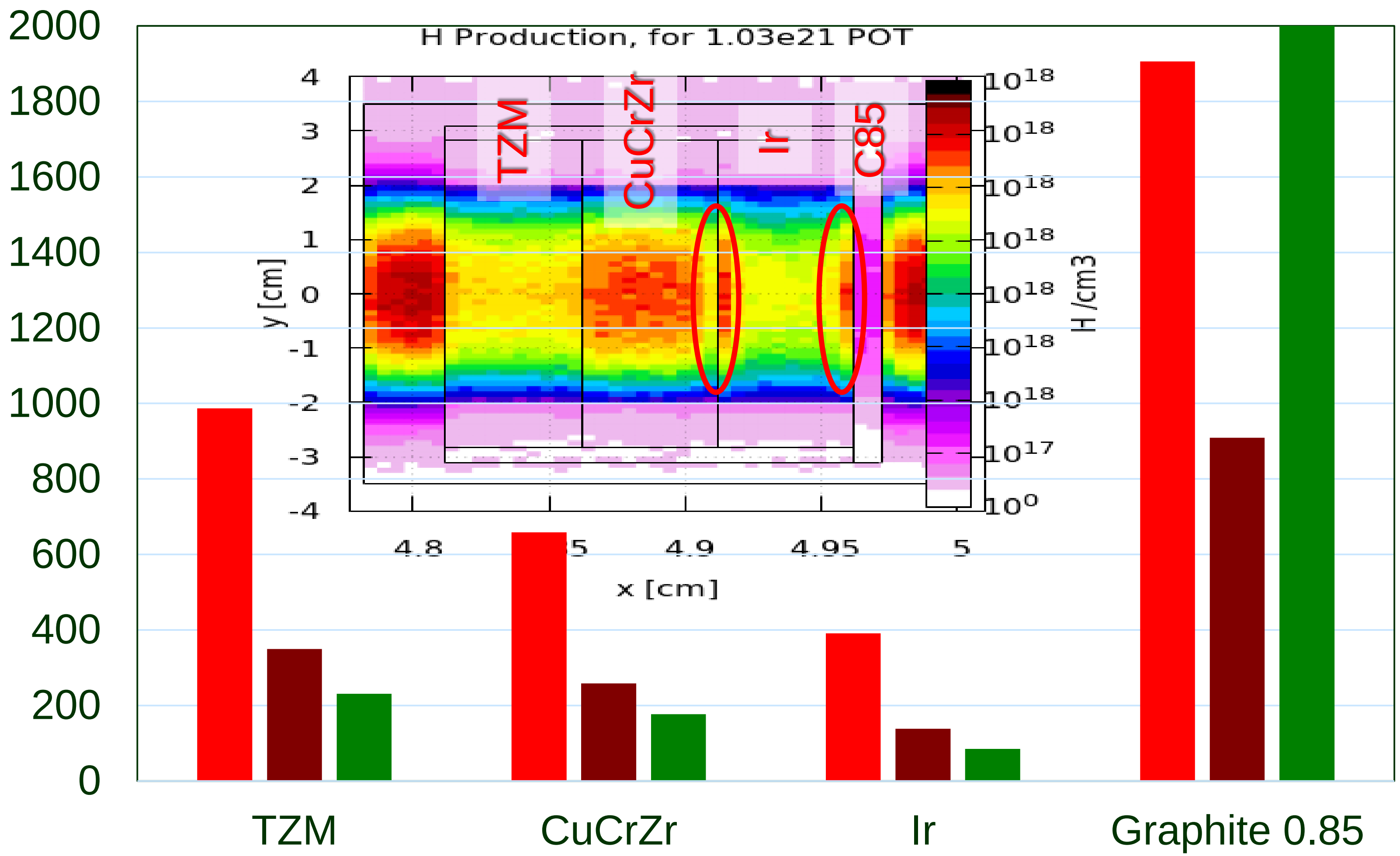
DPA High-Z BLIP [FLUKA vs MARS]



Courtesy: J. Canhoto-Espadanal

Note: NRT model of MARS

H appm/DPA High-Z BLIP

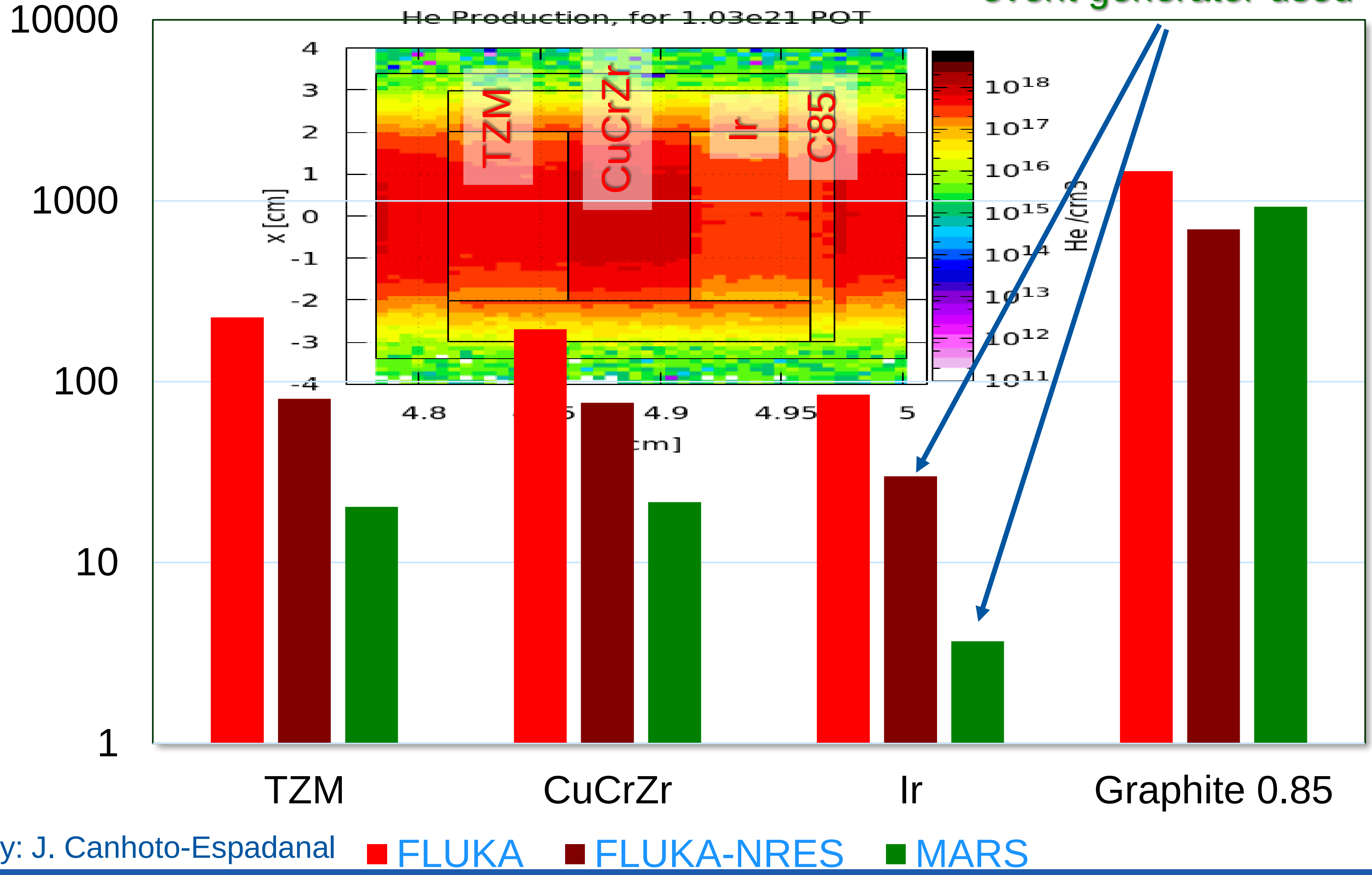


Courtesy: J. Canhoto-Espadanal ■ FLUKA ■ FLUKA-NRES ■ MARS

He appm/DPA High-Z BLIP

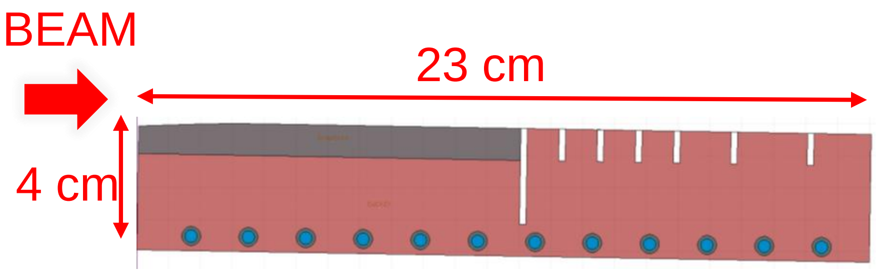
Probably due to "Old" MARS event generator used

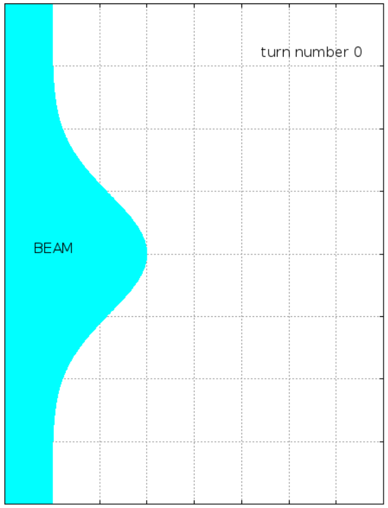
Warning: Log-scale



Courtesy: J. Canhoto-Espadanal

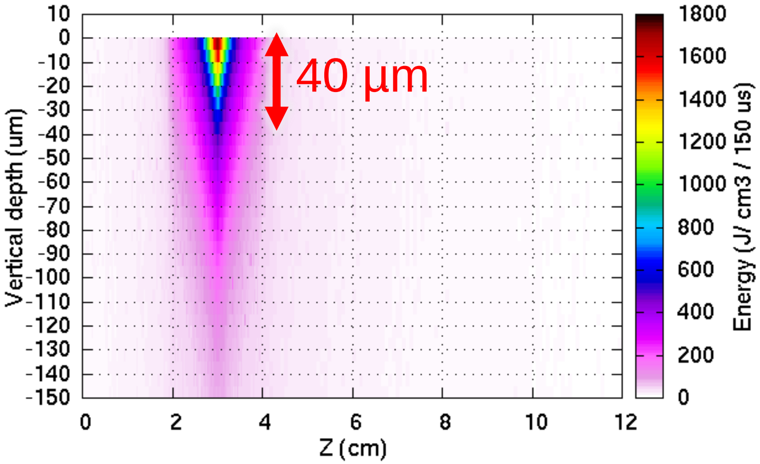
PS Internal Beam Dumps

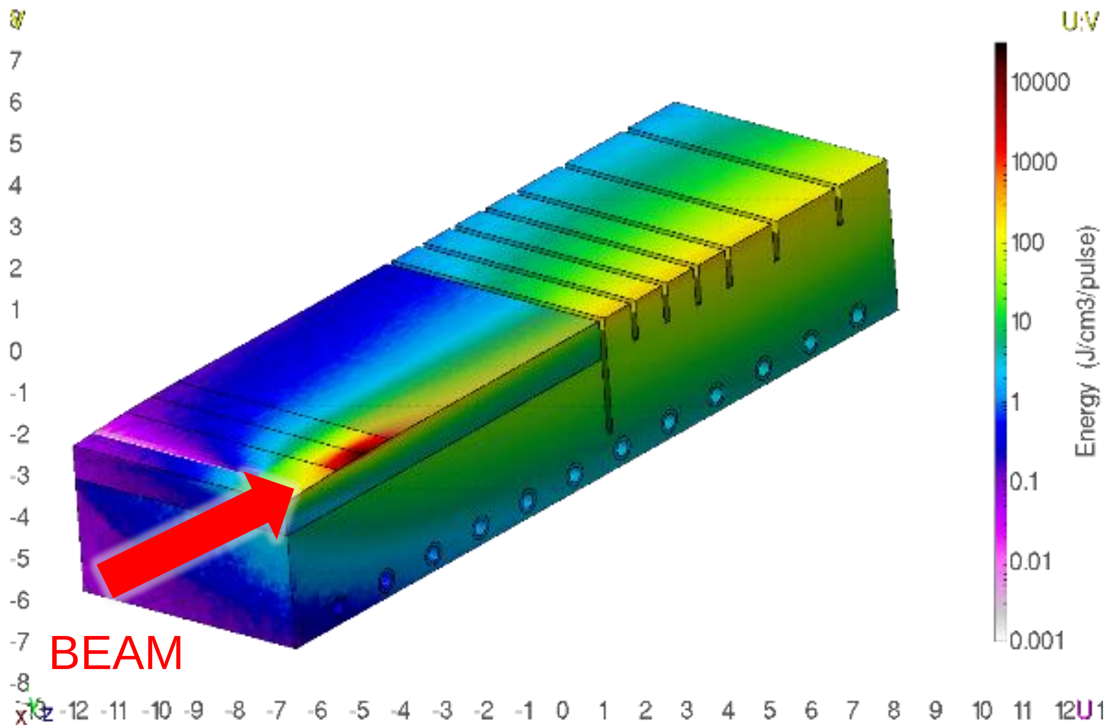




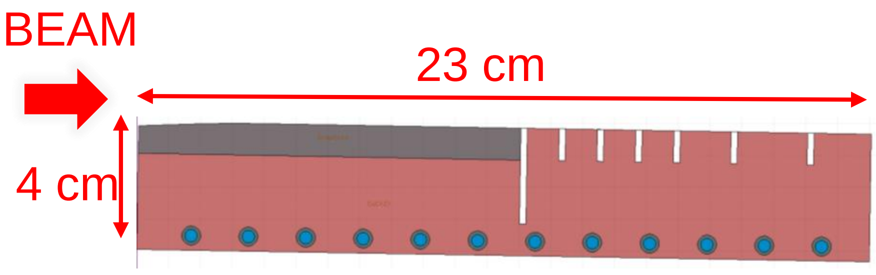
Challenging Energy density

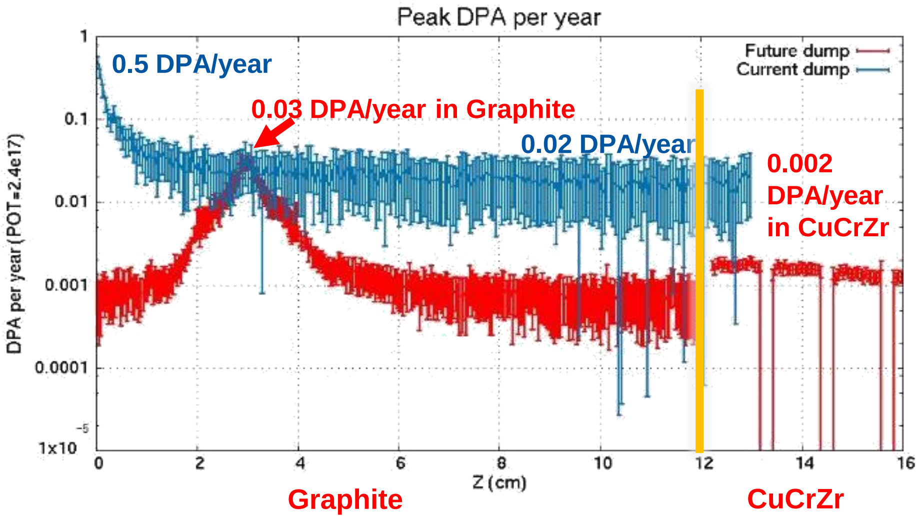
Superficial energy deposition





PS Internal Beam Dumps: Damage





Beam properties:

- 26 GeV/c proton beam
- 2.4e17 POT per year
- σ_h=1.74 mm σ_v=0.87 mm
- Beam is shaved in a thin top most layer

Damage threshold energies considered:
E_{th}(Graphite) = 30 eV - typical value 30-35 eV
E_{th}(CuCrZr and SS304L) = 40 eV

Graphite:
Experience at CERN with **CNGS** air cooled graphite target (SPS beam). About 1200°C reached for each pulse. At the end of operation: 1.5 DPA

→**No problem observed on graphite**

CuCrZr:
Literature on neutron irratiation indicated for **similar dpa damage some** possible radiation hardening and thermal conductivity **degradation but not dramatic** effects

Summary

- FLUKA dpa model uses a **restricted NIEL** computed during initialization and run time.
- **Not based on Lindhard** but reworked all formulas
- The **only free parameter** for the user is the **damage threshold.** It depends on the direction of the recoil. Simple averaging is not correct
- Uniform treatment from the transport threshold up to the highest energies
- Use of **Stoller displacement efficiency instead of a fixed 0.8** as NRT suggests
- Not considered thermal recombination of defects → **overestimation of dpa**. Improving the estimate would require Molecular Dynamics simulations

Summary

- **FLUKA is employed to evaluate radiation-induced damage** on new dumps facilities (BDF, BLIP) and elements of the CERN injector chain (PS internal dumps)
- Simulations provided a way of quantifying the damage through estimation of dpa and gas production (H, He)
- Comparison of **estimations of dpa (simulations)** and modifications of macroscopic quantities (experimental: thermal, electric, etc…, properties) helps to extract conclusions on radiation-induced damage

Possible Future improvements:

- Implementation of the Nordlund arc-dpa
- More accurate recoil momentum cross section for pair production and Bremsstrahlung
- Point wise treatment of low energy neutrons will provide correct recoil information
- Multiple damage thresholds for compounds

Thank you for your attention!

Any question?

Extra slides

E_{th} Damage Threshold Energy

$$N_F = \kappa \frac{\xi(T)T}{2E_{th}}$$

- E_{th} is the value of the threshold displacement energy averaged over all crystallographic directions or a minimum energy to produce a defect

Element	Eth (eV)	Element	Eth (eV)
Lithium	10	Co	40
C in SiC	20	Ni	40
Graphite	30..35	Cu	40
Al	27	Nb	40
Si	25	Mo	60
Mn	40	W	90
Fe	40	Pb	25

Typical values used in NJOY99 code

- The only variable requested for FLUKA

MAT-PROP *WHAT(1)* = E_{th} (eV)
WHAT(4,5,6) = Material range
SDUM = **DPA-ENER**

Damage Threshold in Compounds

- NJOY (MT=444) sums up the cross section multiplied by the damage energies, which is the damage production cross section representing the effective kinetic energy of recoiled atom for reaction types *i* at neutron energy E_n

$$(E\sigma)_{DPA} = \sum_i E_{th,i}\sigma_i(E_n)$$

Problematic:

- Damage threshold depends on the lattice structure
- Damage threshold can be quite different for each combination for the specific compound

  e.g. NaCl: E_{th}(Na-Na), E_{th}(Na-Cl), E_{th}(Cl-Na), E_{th}(Cl-Cl)
- Simple weighting with the atom/mass fraction doesn't work
- FLUKA's approximation is using a unique average damage threshold E_{th} for the compounds as well → **A sensitivity study can be performed**

Only free parameter for the FLUKA user is E_{th}

$$N_F = \kappa \frac{\xi(T)T}{2E_{th}}$$

κ displacement efficiency

- κ=0.8 value deviates from the hard sphere model (K&P), and compensates for the forward scattering in the displacement cascade

- The displacement efficiency κ can be considered as independent of *T* only in the range of *T*≤1−2 *keV*. At higher energies, the development of collision cascades results in defect migration and recombination of Frenkel pairs due to overlapping of different branches of a cascade which translates into decay of κ(*T*).

- From molecular dynamics (MD*) simulations of the primary cascade the number of surviving displacements, N_{MD}, normalized to the number of those from NRT model, N_{NRT}, decreases down to the values about 0.2–0.3 at *T*≈20−100 *keV*. The efficiency in question only slightly depends on atomic number Z and the temperature. $N_{MD}/N_{NRT} = 0.3–1.3$

- $$N_{MD} / N_{NRT} = 0.3 - 1.3\left(-\frac{9.57}{X} + \frac{17.1}{X^{4/3}} - \frac{8.81}{X^{5/3}}\right)$$

where X ≡ 20 T (in keV).

•Roger E. Stoller, J. Nucl. Mat., 276 (2000) 22

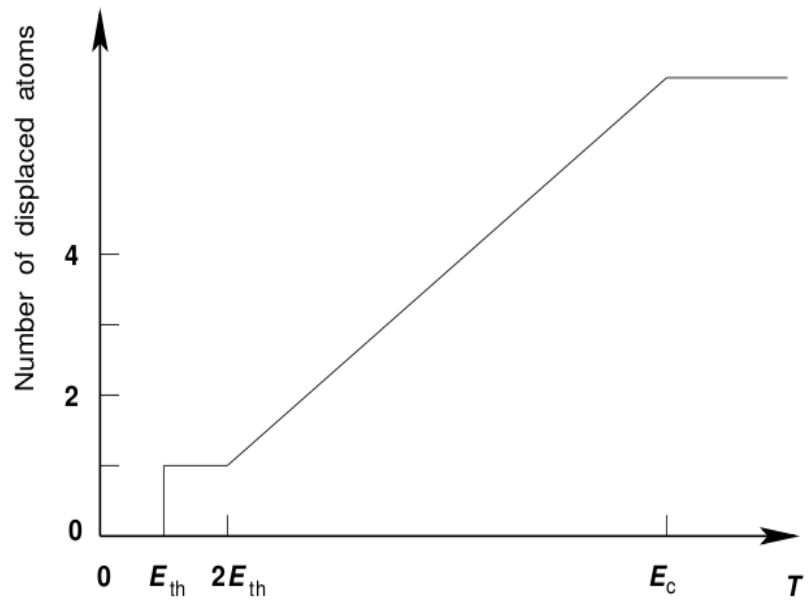
•D.J. Bacon, F. Gao and Yu.N. Osetsky, J. Comp.-Aided Mat. Design, 6 (1999) 225.

$$N_F = \kappa \frac{\xi(T)T}{2E_{th}}$$

Factor of 2 (Kinchin & Pease)

- The cascade is created by a sequence of two-body elastic collisions between atoms
- In the collision process, the energy transferred to the lattice is zero
- For all energies $T < E_c$ electronic stopping is ignored and only atomic collisions take place. No additional displacement occur above the cut-off energy E_c
- The energy transfer cross section is given by the hard-sphere model.

$\nu(T)=0$ for $0<T<E_{th}$ (phonons)
$\nu(T)=1$ for $E_{th}<T<2E_{th}$
$\nu(T)=T/2E_{th}$ for $2E_{th}<T<E_c$
$\nu(T)=E_c/2E_{th}$ for $T > E_c$



Schematic relation between the number of displaced atoms in the cascade and the kinetic energy T of the primary knock-on atom

Energy is equally shared between two atoms after the first collision
Compensates for the energy lost to sub threshold reactions

Lindhard partition function ξ [1/2]

$$N_F = \kappa \frac{\xi(T)T}{2E_{th}}$$

- The partition function gives the fraction of stopping power S that goes to NIEL
- Approximations used: Electrons do not produce recoil nuclei with appreciable energy, lattice binding energy is neglected, etc...

$$(S_n + S_e)E_n'(E) = \int E_n(T)\frac{d\sigma_n}{dT}dT$$

where

$$S_{ne}(E) = \int T_{ne} d\sigma_{ne}$$

- approximated to

$$\xi(T) = \frac{1}{1 + F_L \cdot \left(3.4008 \cdot \varepsilon(T)^{1/6} + 0.40244 \cdot \varepsilon(T)^{3/4} + \varepsilon(T)\right)}$$

$$F_L = 30.724 \cdot Z_1 \cdot Z_2 \sqrt{Z_1^{2/3} + Z_2^{2/3}}$$

$$\varepsilon(T) = \frac{T}{0.0793 \dfrac{Z_1^{2/3} \cdot \sqrt{Z_2}}{\left(Z_1^{2/3} + Z_2^{2/3}\right)^{3/4}} \cdot \dfrac{(A_1 + A_2)^{3/2}}{A_1^{3/2}\sqrt{A_2}}}$$

Z,A	charge and mass
1	projectile
2	medium
T	recoil energy (eV)

Nice feature: It can handle any projectile Z_1,A_1 whichever charged particle

Nuclear Stopping power

- Nuclear stopping power (unrestricted)

$$\frac{1}{\rho} S_n(E, E_{th}) = -2\pi N \int_0^{b\max} b \frac{db}{d\theta} W(\theta, E) db$$

- Energy transferred to recoil atom

$$W(\theta, T) = \gamma T \sin^2(\theta / 2)$$

- Deflection angle, by integrating over all impact parameters b

$$\theta = \pi - 2\int \frac{b dr}{r^2 \sqrt{1 - \frac{V(r)}{E_{cms}} - \frac{b^2}{r^2}}}$$

- Universal potential

$$V(r) = \frac{Z_1 Z_2 e^2}{r} F_s\left(\frac{r}{r_s}\right)$$

- where:

$F_s(x) = \Sigma a_i \exp(-c_i x)$ screening function

$r_s = 0.88534\, r_B / (Z_1^{0.23} + Z_2^{0.23})$ screening length

$r_s = 0.88534\, r_B Z_1^{-1/3}$ in case of particle

ICRU-49

Ziegler approximation

- Reduced kinetic energy ε (T in keV)

$$\varepsilon = \frac{32.536\ T}{\left(Z_1^{0.23}+Z_2^{0.23}\right)\left(1+\frac{M_1}{M_2}\right)Z_1 Z_2}$$

- Reduced stopping power

if $\varepsilon < 30$ $\quad \hat{S}_n(\varepsilon) = \frac{0.5\ \ln\left(1+1.1383\ \varepsilon\right)}{\varepsilon + 0.01321\ \varepsilon^{0.21226} + 0.19593\sqrt{\varepsilon}}$

if $\varepsilon \geq 30$ $\quad \hat{S}_n(\varepsilon) = \frac{\ln(\varepsilon)}{2\varepsilon}$

Important features of Reduced Stopping Power

- Independent from the **projectile** and **target** combination
- Accurate within **1%** for $\varepsilon<1$ and to within **5%** or better for $\varepsilon>3$

- Stopping power (MeV/g/cm^2)

$$\frac{1}{\rho} S_n(T) = \frac{5105.3\ Z_1 Z_2\ \hat{S}_n(\varepsilon)}{\left(Z_1^{0.23}+Z_2^{0.23}\right)\left(1+\frac{M_2}{M_1}\right)A}$$

Restricted Stopping Power

- The restricted nuclear stopping power is calculated the same way only integrating from 0 impact parameter up to a maximum b_{max} which corresponds to a transfer of energy equal to the
  $E_{th} = W_{min}(\theta_{min}, T)$

$$\frac{1}{\rho} S_n(E, E_{th}) = -2\pi N \int_0^{b\max} b \frac{db}{d\theta} W(\theta, E)\, db$$

- To find b_{max} we have to approximately solve the previous θ integral using an iterative approach for

$$\theta_{min} = 2\arcsin\left(\sqrt{\frac{E_{th}}{\gamma T}}\right)$$

This can be done either by integrating numerically for θ or using the magic scattering formula from Biersack-Haggmark that gives a fitting to $sin^2(\theta/2)$

Implementation: Charged Particles

- During the transport of all charged particles and heavy ions the dpa estimation is based on the restricted nuclear stopping power while for NIEL on the unrestricted one.
- For every charged particle above the transport threshold and for every Monte Carlo step, the number of defects is calculated based on a modified multiple integral
- Taking into account also the second level of sub-cascades initiated by the projectile

$$N(E) = \int_{E_{th}}^{\gamma E} \left[\xi_r(T, E_{th}) \left(\frac{d\sigma}{dT} \right)_E \int_{E_{th}}^{\gamma' T} \kappa(T') \xi(T') T' \left(\frac{d\sigma}{dT'} \right)_T dT' \right] dT$$

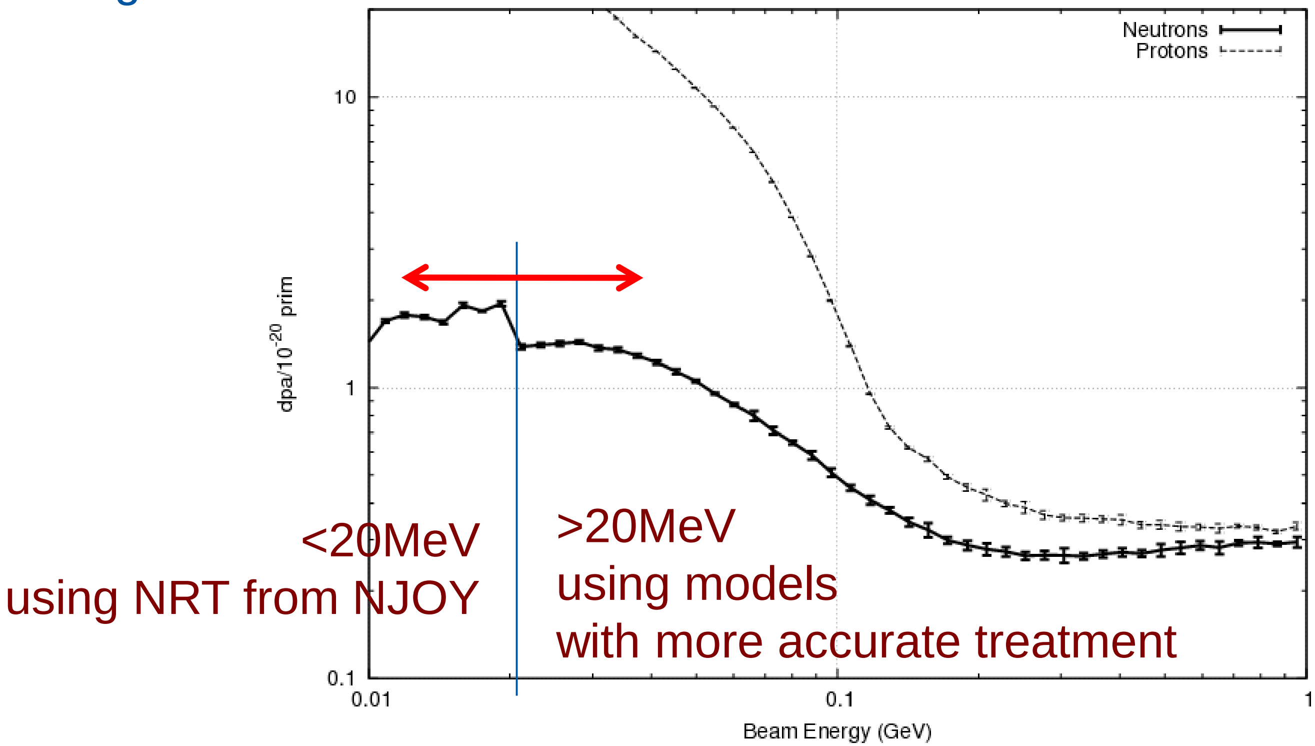
restricted partition function (ξ_r)

Lindhard partition function (κ)

- Below the transport threshold (1 keV) it employs the Lindhard approximation

Group Wise Neutron Artifacts

- Due to the group treatment of low-energy neutrons, there is no direct way to calculate properly the recoils.
- Therefore the evaluation is based on the KERMA factors calculated by NJOY, which in turn is based on the Unrestricted Nuclear losses from using the NRT model.



Implementation: others

For Bremsstrahlung and pair production the recoil is sampled randomly from an approximation of the recoil momentum cross section

Bremsstrahlung

$$\frac{d\sigma}{dp_\perp} = \frac{32a(Za)^2}{kp_\perp^3}\left[1-\frac{k}{E}+\frac{1}{2}\left(\frac{k}{E}\right)^2\right]\ln\left(\frac{p_\perp}{m_e}\right)$$

Pair production

$$\frac{d\sigma}{dp} = \frac{0.183\cdot 10^{-2} Z^2}{p^3}\left(\ln\left(p\right)+0.5\right)$$

both can be written in the same approximate way as

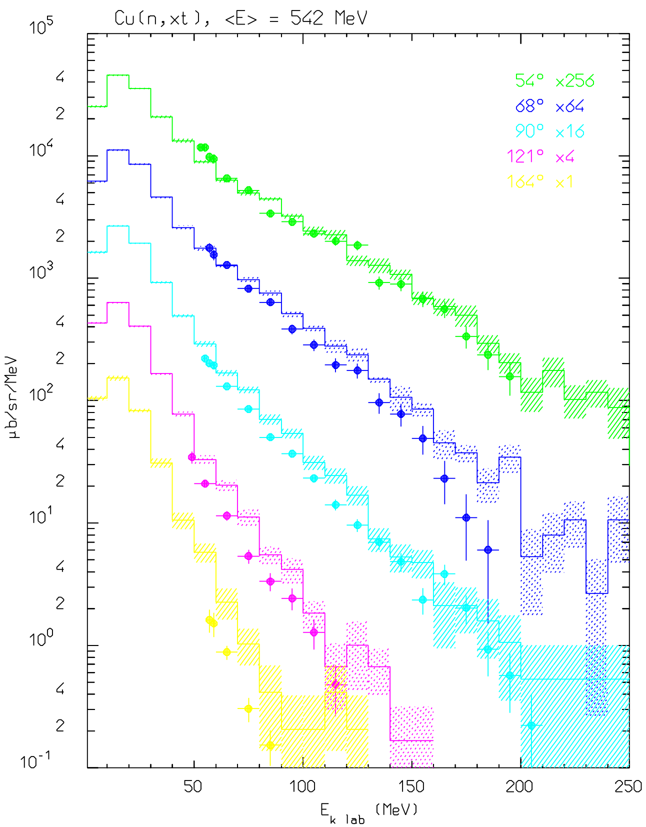
$$\frac{d\sigma}{dp} \propto \frac{\ln\left(p/c\right)}{p^3}$$

where the recoil momentum is sampled randomly by rejection from a similar function

Coalescence:

- d, t, ^{3}He, and alpha's generated during the (G)INC and preequilibrium stage
- All possible combinations of (unbound) nucleons and/or light fragments checked at each stage of system evolution
- FOM evaluation based on phase space "closeness" used to decide whether a light fragment is formed rather than not
  - FOM evaluated in the CMS of the candidate fragment at the time of minimum distance
  - Naively a momentum or position FOM should be used, but not both due to quantum non commutation
  - … however the best results are obtained with a Wigner transform FOM (assuming gaussian wave packets) which should be the correct way of considering together positions and momenta
- Binding energy redistributed between the emitted fragment and residual excitation (exact conservation of 4-momenta)

Coalescence



High energy light fragments are emitted through the coalescence mechanism: "put together" emitted nucleons that are near in phase space.

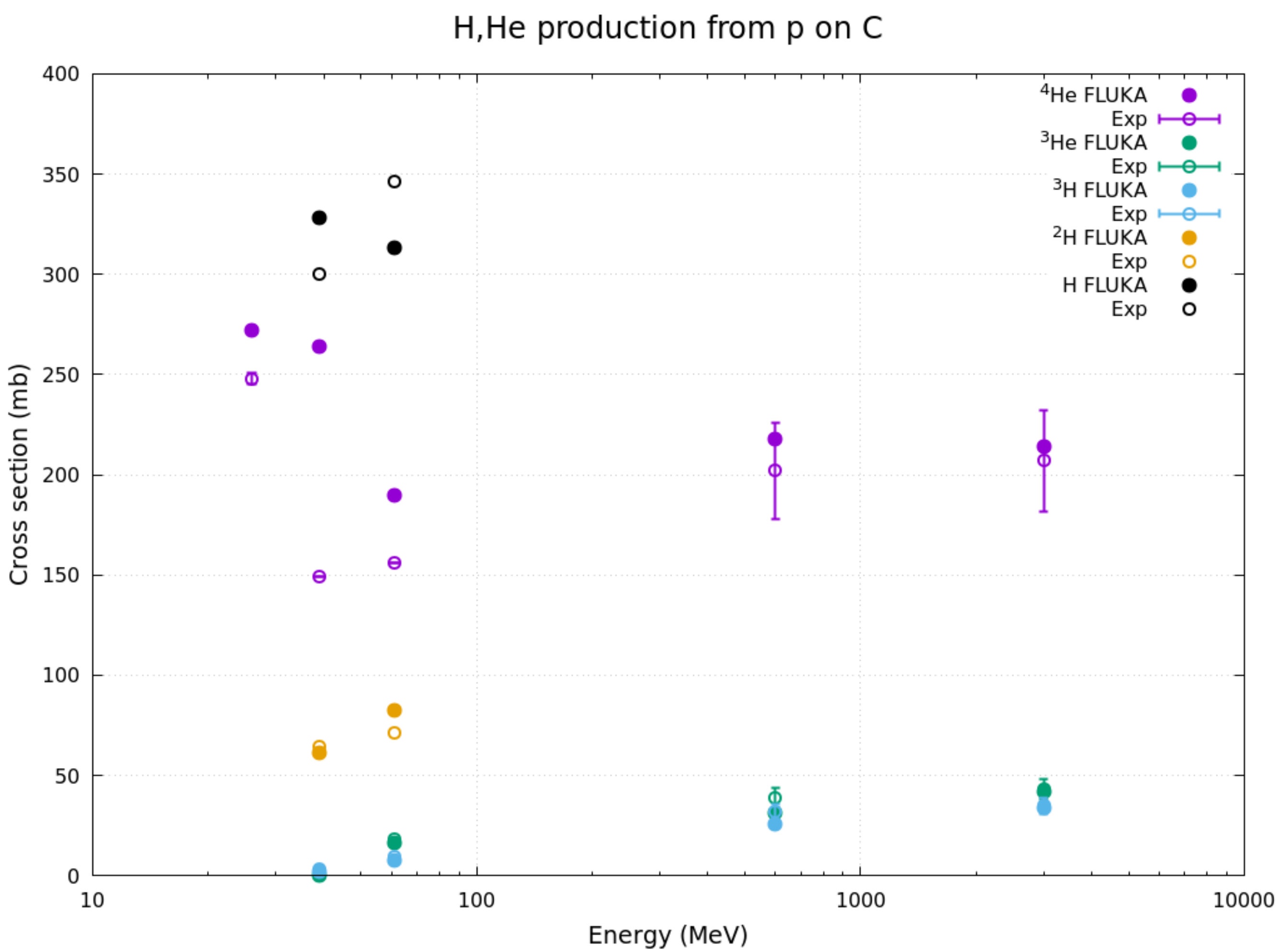
Example : double differential t production from 542 MeV neutrons on Copper

Warning: coalescence is OFF by default
Can be important, ex for . residual nuclei.
To activate it:

```
    PHYSICS 1.                                                    COALESCE
```

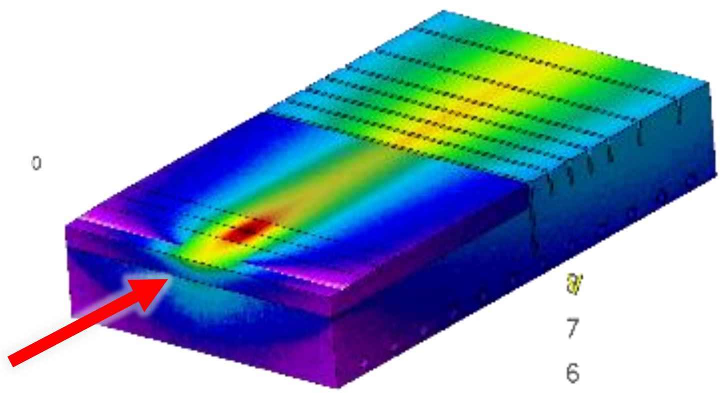
If coalescence is on, switch on Heavy ion transport and interactions (see later)

Particle production in C(p,x) reaction

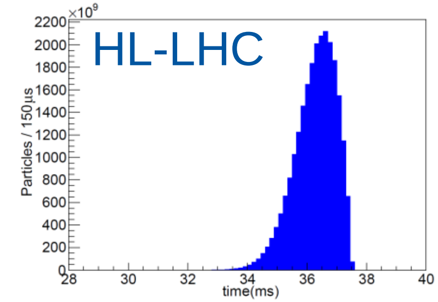


Data: JNST36 313 1999, PRC7 2179 1973

Energy Density Distribution from FLUKA



Values shown are accumulated per pulse



HL-LHC beam

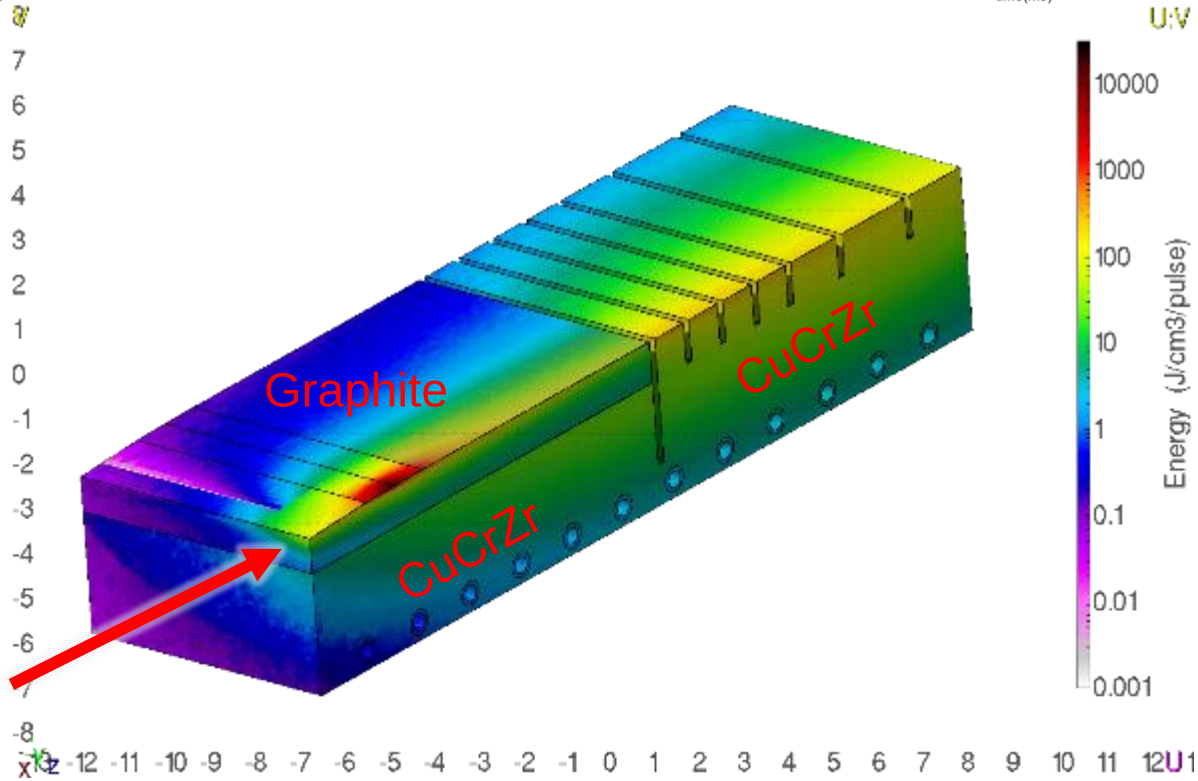
p=26 GeV/c

2.4e13 ppp

$\sigma_x x \sigma_y$=1.74 mm x 0.87 mm

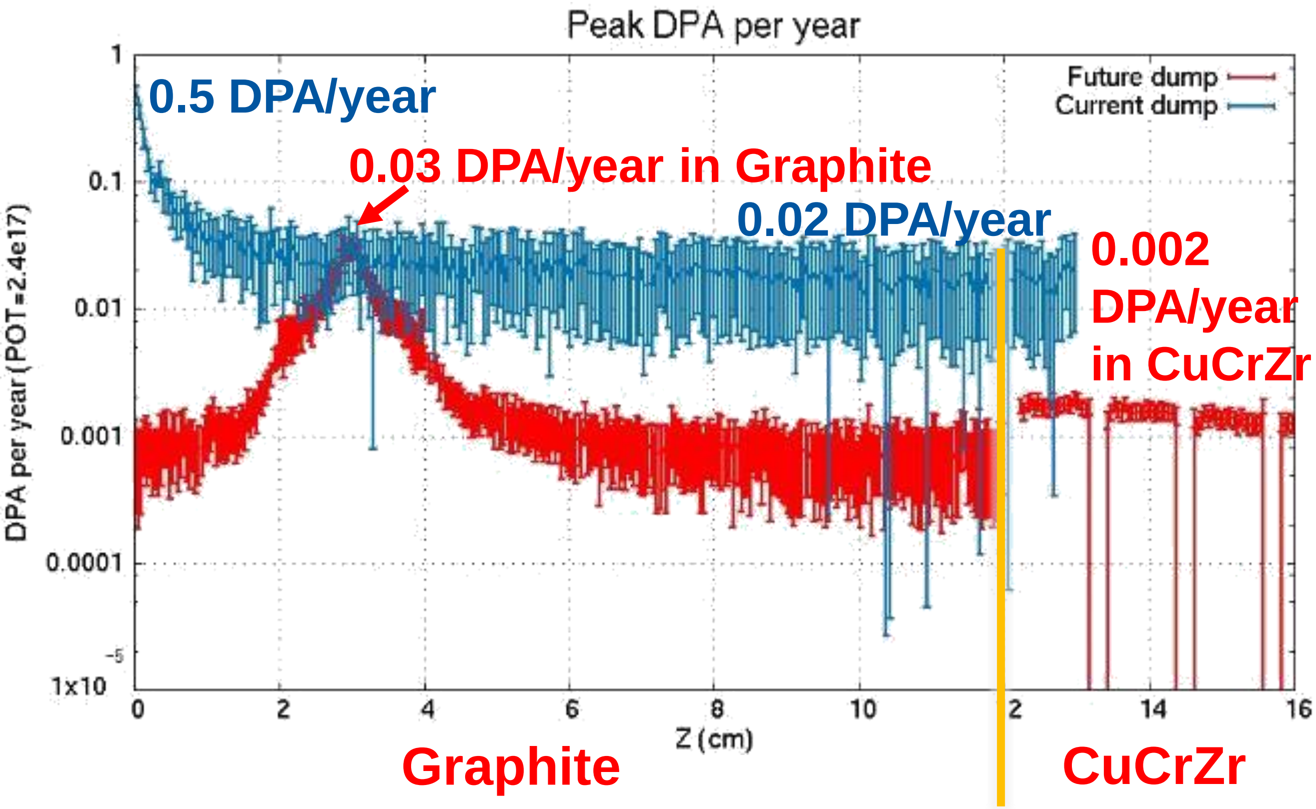
ε_x=1.8 mm mrad

ε_y=1.8 mm mrad



BEAM

Structural Damage on Dump Core



Lower general damage than current dump
(~1 order of magnitude)

Lower peak DPA on copper region than current dump
(~2 orders of magnitude)

Graphite protects the copper block from structural damage

Damage threshold energies considered:
E_{th}(Graphite) = 30 eV - typical value 30-35 eV
E_{th}(CuCrZr and SS304L) = 40 eV

POT=2.4e17 (assumed same POT for current and future dumps)

Irradiation on Graphite

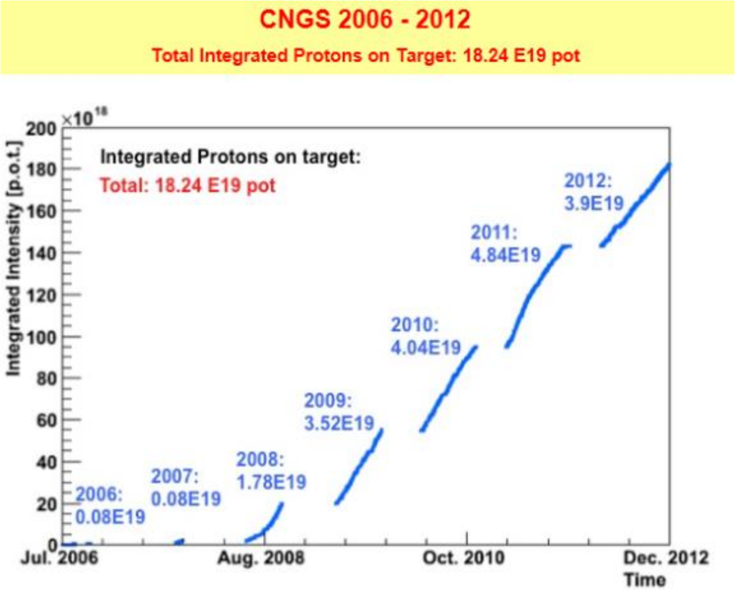
0.03 DPA/year estimated in Graphite block of PS dump

Experience at CERN: **CNGS air cooled graphite target (SPS beam)**

- → About 1200°C reached for each pulse
- → At the end of operation: **1.5 DPA**
- → **No problem observed on graphite**

→**3.5 x 10^{13} protons per pulse,**
→**10.5 µs pulse length < 1 mm spot size**
→2 extractions per cycle separated by 50 ms, **occurring every 6 s**
→ 2 000 000 extractions achieved by end of 2009
→ **4.5 x 10^{19} protons** at 400 GeV/c on CNGS target **per year**

Graphite rods 2020PT (Mersen)



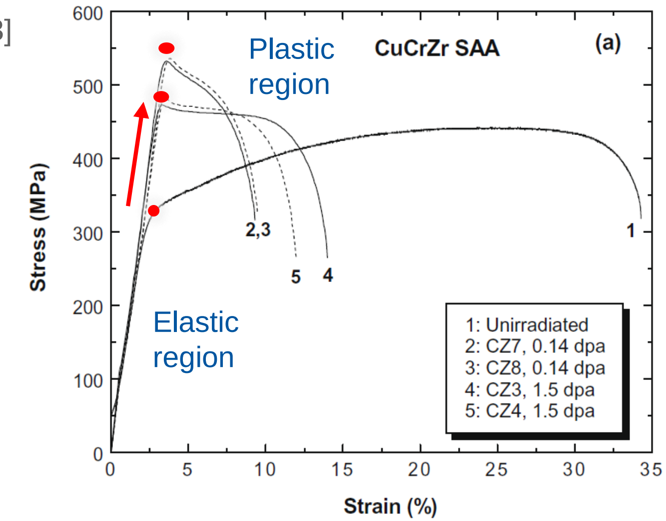
***[Ref]:** Spallation materials R&D for CERN's fixed target program, M. Calviani et al. IWSMT, Oct. 2014, Austria*

PS dump graphite irradiation shall not be a concern

Irradiation on CuCrZr

- Peak value obtained of 0.002 DPA per year (**0.04 DPA** in 20 years) in CuCrZr block of PS Dump
- **Localized peak DPA**
- Information for **neutron irradiation** found in literature
- CuCrZr shows **radiation hardening** until saturation values around 0.1 – 0.5 DPA [1][3] → Some hardening may occur
- CuCrZr is **void swelling resistant** [1][2]
(below 2% density change for up to 150 DPA [1])
- Some **thermal conductivity** degradation may occur (5 – 10 % reduction for doses > 0.1 DPA at < 150 °C [2])

[3]



[1]

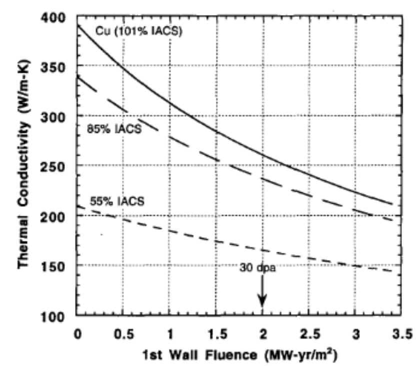


FIG. 21. Effect of solid transmutations on the thermal conductivity of copper at a fusion reactor first wall. The calculations were performed for three different initial conductivities, expressed in terms of percent International Annealed Copper Standard (IACS).

[2]

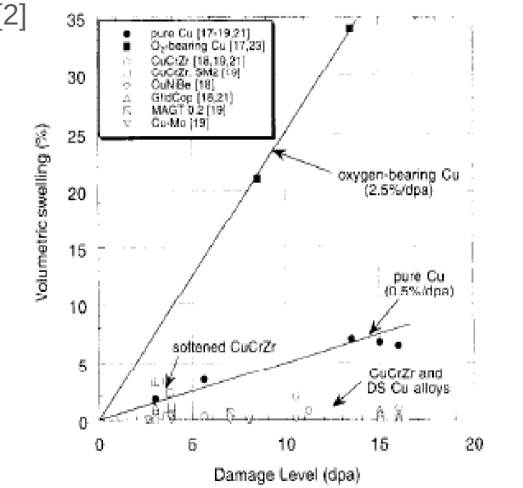


Fig. 3. Irradiation-induced swelling of neutron-irradiated copper and copper alloys. (a) Temperature dependence of void swelling in copper [20]. (b) Dose dependence of volumetric swelling in pure copper and copper alloys at ~ 400°C [17–19,21,23].

[1] C. Bobeldijk (ed.). (1994). Atomic and Plasma-Material Interaction Data for Fusion. Vol. 5. Supplement to the Journal Nuclear Fusion
[2] S.A. Fabritsiev & S.J. Zinkle & B.N. Singh. (1996). Evaluation of copper alloys for fusion reactor divertor and first wall components. Journal of Nuclear Materials. Vol. 233-237. pp. 127-137.
[3] M. Li & M.A. Sokolov & S.J. Zinkle. (2009). Tensile and fracture toughness properties of neutron-irradiated CuCrZr. Journal of Nuclear Materials. Vol. 393. pp. 36-46.