My three-month internship at IBA

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The University of Manchester

Ion Beam Applications (IBA)

- Around 1500 employees, offices in Belgium, USA, Germany, China and Russia.

- 4 business units:
  - Proton therapy solutions (worldwide leader)
  - Dosimetry solutions
  - RadioPharma solutions (260 cyclotrons produced)
  - Industrial and sterilization solutions (250 electron and proton accelerators)

- Headquarters in Louvain-la-Neuve, Belgium.

My project: activation calculations for the KIUBE

- KIUBE: **18 MeV cyclotron** for the production of **radioisotopes** (Fluorine 18, Oxygen 15, Gallium 68, ...)

- Beam current from 100 μA to 300 μA, with 8 exit ports.

- Ex: production of **fluorine 18**: proton beam on enriched water $H_2{}^{18}O$

$$^{18}_{8}\mathrm{O} + {}^{1}_{1}\mathrm{p} \rightarrow {}^{18}_{9}\mathrm{F} + {}^{1}_{0}\mathrm{n} + \gamma$$

- Useful for **PET** (positron emission tomography): $^{18}_{9}\mathrm{F} \rightarrow {}^{18}_{8}\mathrm{O} + {}^{0}_{1}\mathrm{e}^{+}$

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➢ Beam current from 100 µA to 300 µA, with 8 exit ports.

➢ Ex: production of **fluorine 18**: proton beam on enriched water $H_2{}^{18}O$ ***What happens to those particles?***

$$^{18}_{8}O + ^{1}_{1}p \rightarrow ^{18}_{9}F + \boxed{^{1}_{0}n + \gamma}$$

➢ Useful for **PET** (positron emission tomography): $^{18}_{9}F \rightarrow ^{18}_{8}O + ^{0}_{1}e^{+}$

My project: activation calculations for the KIUBE

- Need to **track** the **particles** (neutrons, photons and electrons) passing through the materials of the KIUBE.

  ⟹ **Space** evolution with *MCNPX*

- Need to study the **impact** of those particles on the **materials**: **activation**.

  ⟹ **Time** evolution with *FISPACT II*

MCNPX

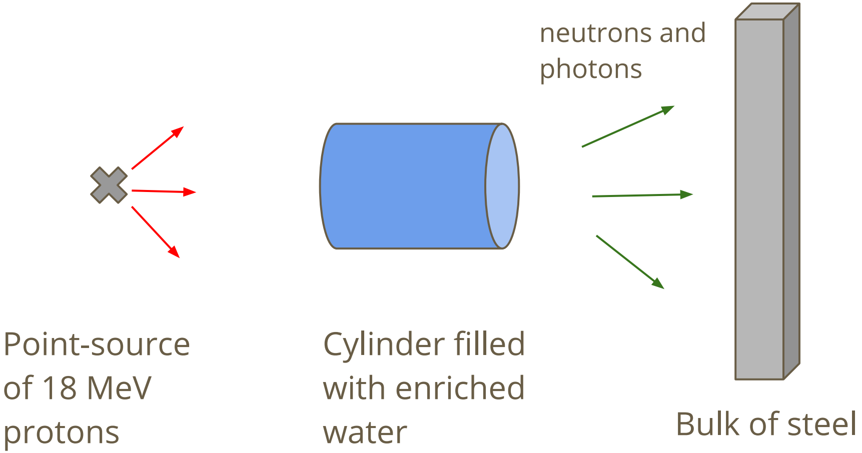
- ➢ Monte-Carlo (MC) code that models the **transport of neutral particles** (NP) through a medium. Tracks neutrons and photons, but also electrons, protons, …

- ➢ Created and maintained by Los Alamos National Laboratory.

- ➢ A lot of physics included: elastic and inelastic scattering, neutron capture, photon absorption, …

- ➢ Works with input files where one specifies:
  - Geometry: surfaces and cells
  - Materials of the cells: density, isotopic composition, cross-section library
  - Source of primary particles
  - Observables to be calculated (tallies)

MCNPX: an example



F4 tally: neutron (or photon) fluence averaged over the volume of the bulk (in 1 / cm²):

$$F4 = \frac{1}{V}\int_V dV \int_E dE \int_{4\pi} d\Omega\, \Phi(\mathbf{r}, E, \mathbf{\Omega})$$

Energy and angular distribution of the fluence as a function of the position

MCNPX estimates the F4 tally as:

$$F4 = \frac{1}{N}\sum_{i=1}^{N}\frac{W_i T_i}{V}$$

Weight of particle *i* (used for variance reduction)

Number of events

Volume of the bulk

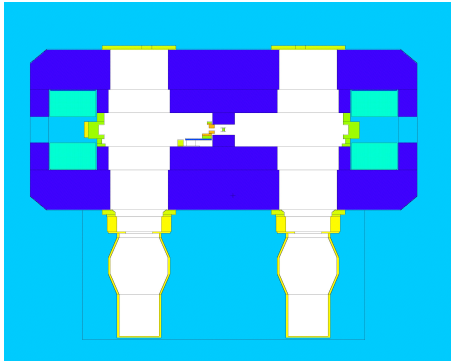
Track-length of particle *i* through the bulk

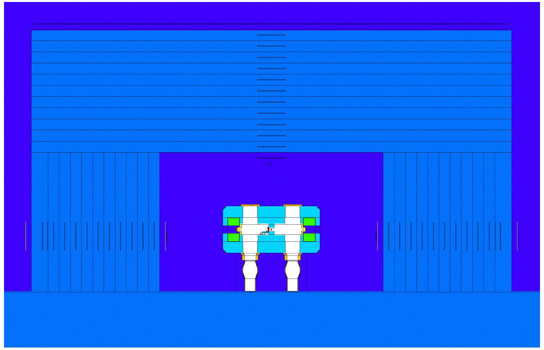
Neutron transport through the cells of the KIUBE

➢ The geometry of the KIUBE was implemented inside MCNPX and divided into **235 cells**.

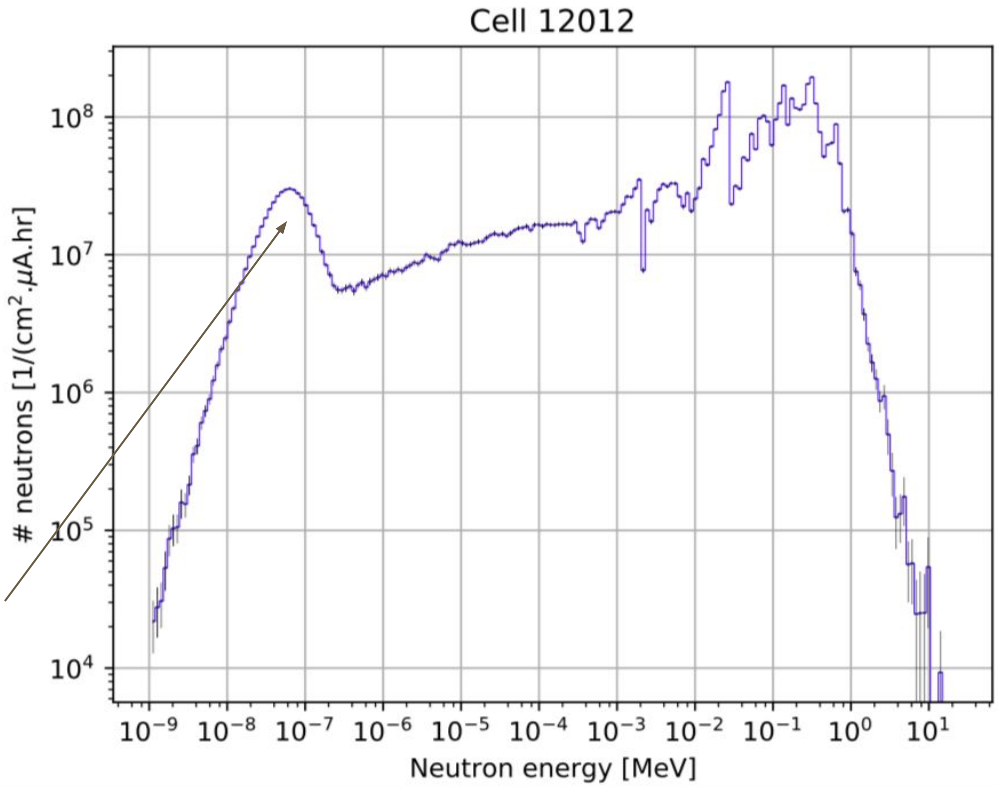
➢ Use a source of **18 MeV protons** on **enriched water**.

➢ We studied the **transport of the neutrons** through all the cells of the KIUBE. Use F4 tally on each cell (with energy bins) to get the **neutron fluence**.





Neutron transport through the cells of the KIUBE



Cell 12012: cavity of the radio-frequency system of the cyclotron. Made of copper with density 8.96 g/cm³.

Thermal peak: neutrons lost some kinetic energy by recoiling against the atoms of the medium.

FISPACT II

- Deterministic code that solves numerically problems of **activation**.
- The output is a **time-dependent inventory** of all the **radioisotopes** present in the material.
- Works with input files where one specifies:
  - Material: density, isotopic composition, cross-section library
  - Source of incident particles
  - Irradiation and cooling times.
- **No geometry** involved: the material is assumed to be homogeneous and infinite.

FISPACT II

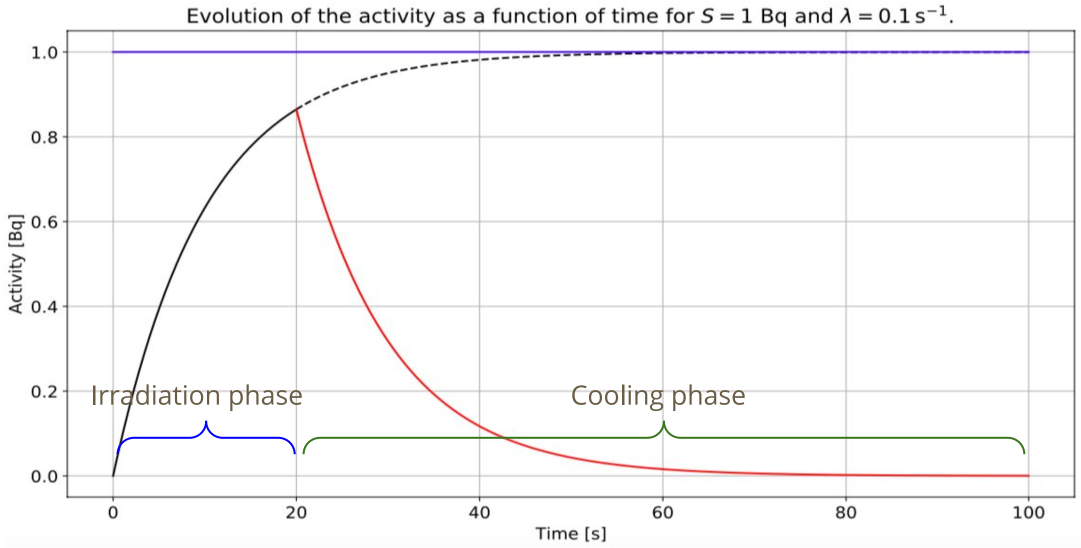
Number of a given isotope in a material follows:

$$\frac{\mathrm{d}N}{\mathrm{d}t} = -\lambda N(t) + S$$

Decay rate

Source term (activation rate)

- **Irradiation** phase: $S \neq 0 \quad A(t) = S\left(1 - e^{-\lambda t}\right)$
- **Cooling** phase: $S = 0 \quad A(t) = S\left(1 - e^{-\lambda t_{\mathrm{irr}}}\right) e^{-\lambda (t - t_{\mathrm{irr}})}$



Activity: number of decays per unit time

$$A(t) = \lambda N(t)$$

FISPACT II

- In fact:

$$S_i(t) = \phi \sum_{j \neq i} \sigma_i^j N_j(t)$$

Flux of incident particles

Cross-section for reactions on *j* producing *i*

- System of nested equations:

$$\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{N} = \mathcal{M}\boldsymbol{N}(t)$$

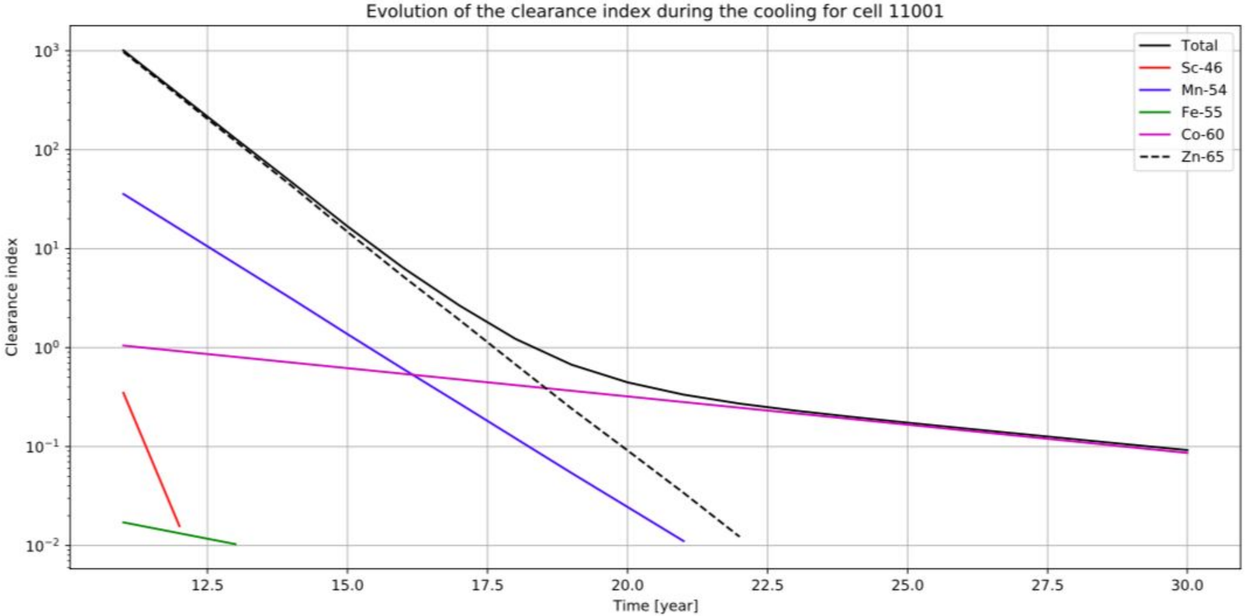
Isotopic vector

Matrix with decay and activation rates

Activation of the KIUBE

➢ The cells of the KIUBE are **irradiated by neutrons**. Use the energy spectra from MCNPX as energy distributions for the sources.

➢ **Isotopic vector** calculated for each cell of the KIUBE.



Clearance index:

$$\mathrm{CI}_i(t) = \frac{A_i(t)}{A_i^{\mathrm{ref}}}$$

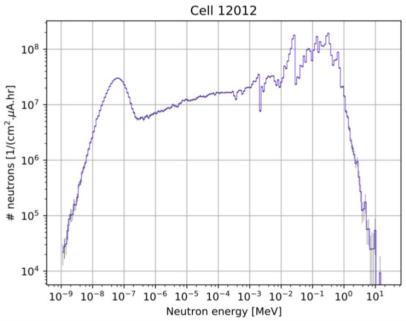
Safety standards:

$$\mathrm{CI}_i < 1$$

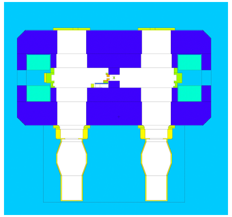
→ isotope *i* can be considered as **non-radioactive**

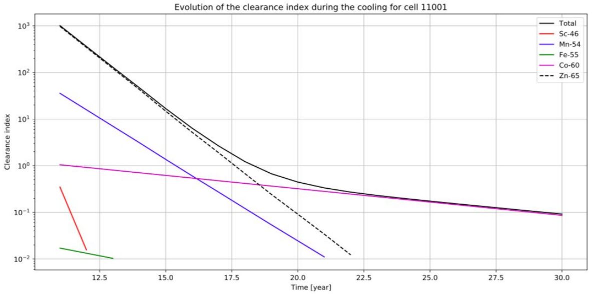
Summary[1]: activation calculations

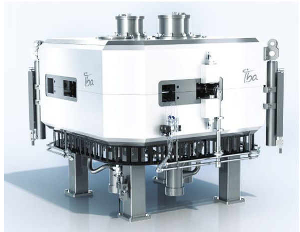
MCNPX



FISPACT II







Define geometry, materials and sources

[1]This work has received funding from the European Union's Horizon 2020 research and innovation programme as part of the Marie Sklodowska-Curie Innovative Training Network MCnetITN3 (grant agreement no. 722104).

My experience: it was interesting to

- Work in a company (different atmosphere, pace, expectations).
- Apply my theoretical knowledge of particle physics to an industrial case.
- Learn new methods of variance reduction and how to better assess errors (cf. MCNP primer), even though I was already familiar with Monte-Carlo methods.
- Set the safety standards as a priority in order to validate my results.
- Deal with different softwares and interface them.

References

- J. K. Shultis and R. E. Faw, An MCNP Primer.
- M. Fleming, T. Stainer, M. Gilbert, The Fispact-II User Manual, 2018.