Measurements and dosimetry of secondary neutrons for medical and industrial accelerators

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Date : 21/02/22 – 15/07/22

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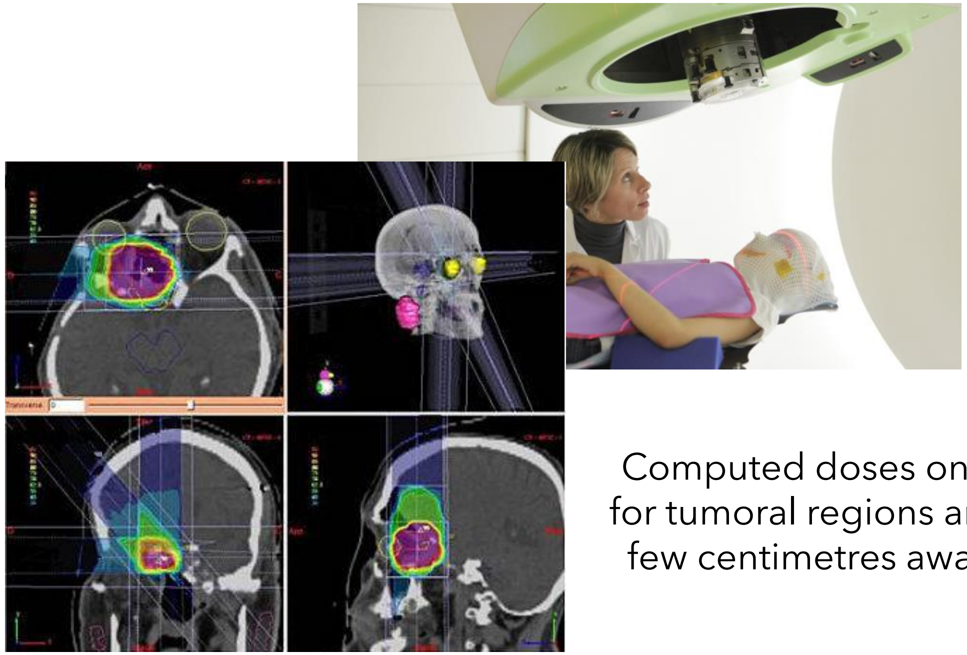
Particle accelerators for society

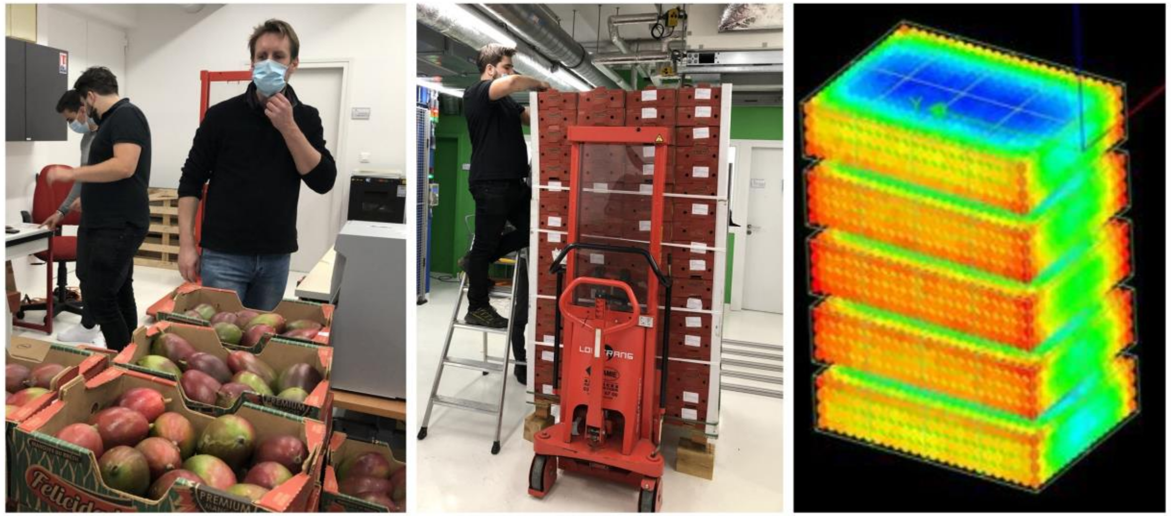
- **Hadrontherapy :**



Computed doses only for tumoral regions and few centimetres away

Secondary neutrons are **not taken into account** in the computations of **« out-of-field dose »**

- **Sterilization using X-rays :**



Activation computation not done for secondary neutrons

→ Access to produced neutrons distribution via Monte Carlo tools

A simulation tool

- **Monte Carlo** methods:

Based on probabilistic technics and high numbers of events, those algorithms allow to estimate possible results of a probabilistic event.

In this situation, allow to numerically reproduce radiation/matter interactions

- **GATE** :
  - ***Opensource*** *software* based on **Geant4**
  - Born of an **international collaboration** of 25 institutes, IPHC among them
  - Dedicated in **numerical simulations** in medical imaging and **radiotherapy**

- **Goal** :

Create a **mapping tool** of **neutrons** for an irradiation room using ***Monte Carlo*** *code, personalized for each accelerators, rooms, …*

Extension of GATE - functionnality

- Add the possibility to modify isotopic composition of materials

Old material table :

```
[Elements]
C:       S= C    ; Z=  6. ; A=  12.01  g/mole

[Materials]
CNat: d=2.1 g/cm3; n=1; state=solid
    +el: name=C; n=1
```

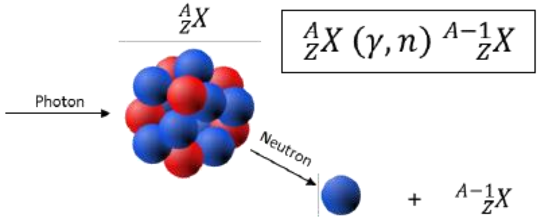
Only natural material available

New material table :

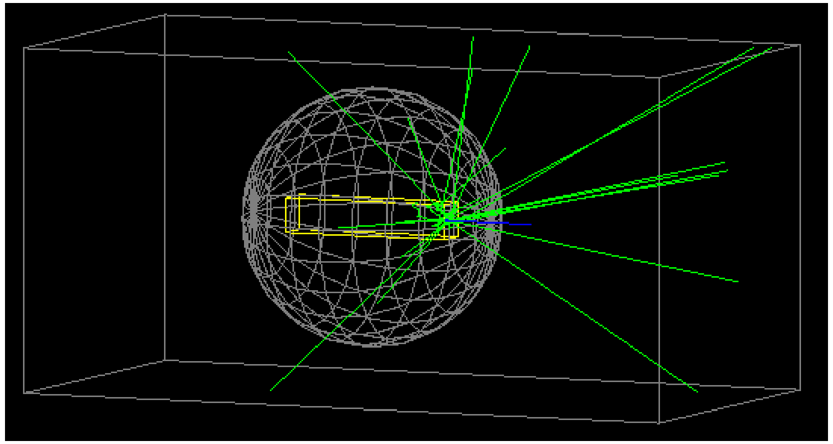
```
[Isotopes]
C12:     Z=6 ; N=12  ; A=  12.0000000 g/mole
C13:     Z=6 ; N=13  ; A= 13.00335483507 g/mole
C14:     Z=6 ; N=14  ; A= 14.0032419884 g/mole

[Elements]
C:      S= C    ; Z=  6. ; A=  12.01  g/mole
C12:     n=1     ; S=  C12
    +iso:   name=auto ; f=1
C13:     n=1     ; S=  C13
    +iso:   name=auto ; f=1
C14:     n=1     ; S=  C14
    +iso:   name=auto ; f=1

[Materials]
CNat: d=2.1 g/cm3; n=1; state=solid
    +el: name=C; n=1

CMod: d=2.1 g/cm3; n=3; state=solid
    +el: name=C12; f=0.7
    +el: name=C13; f=0.2
    +el: name=C14; f=0.1
```

Personalized material

Extension of GATE - benchmark

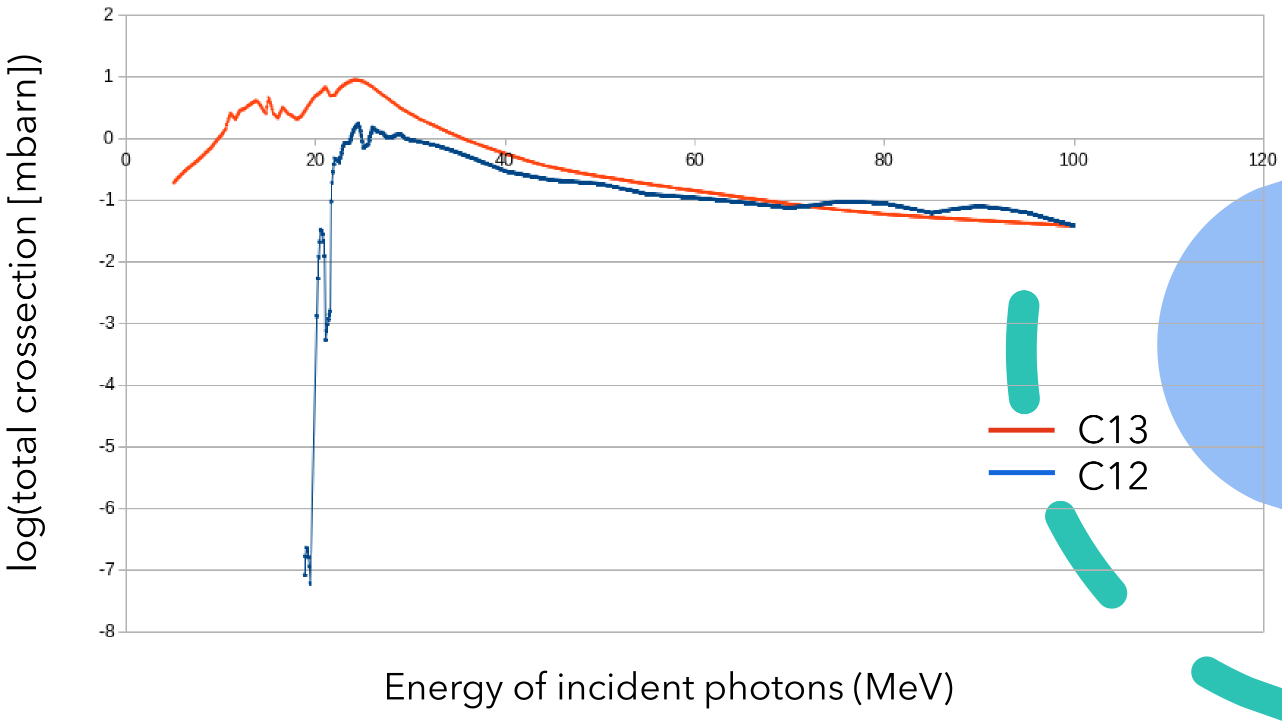


- Creation of a « benchmark » allowing to validate functionnality through software updates
  - Comparison of production rate between natural carbon and pure carbon isotope target
  - Use of a KillActor

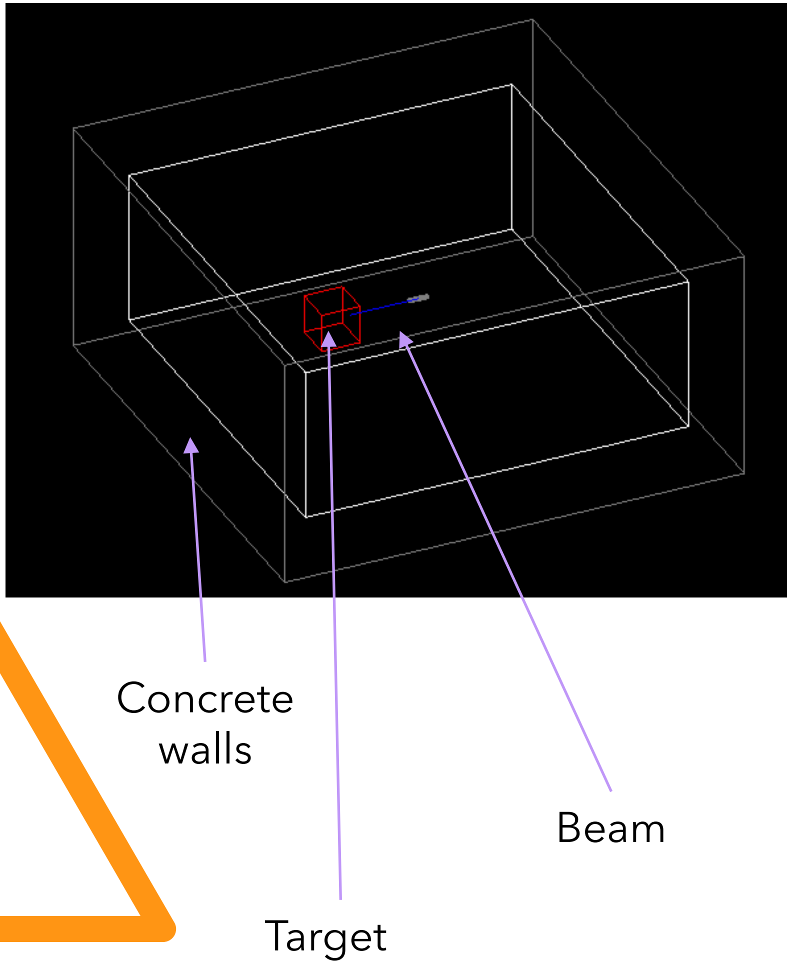


Situation modelled in the benchmark

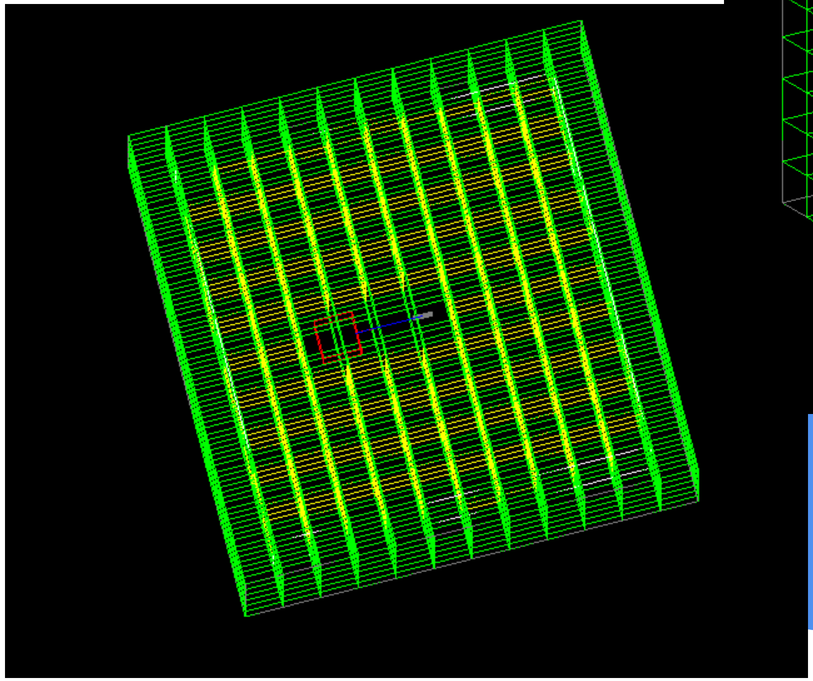
Total crossection of (γ,n) reaction for 12C and 13C



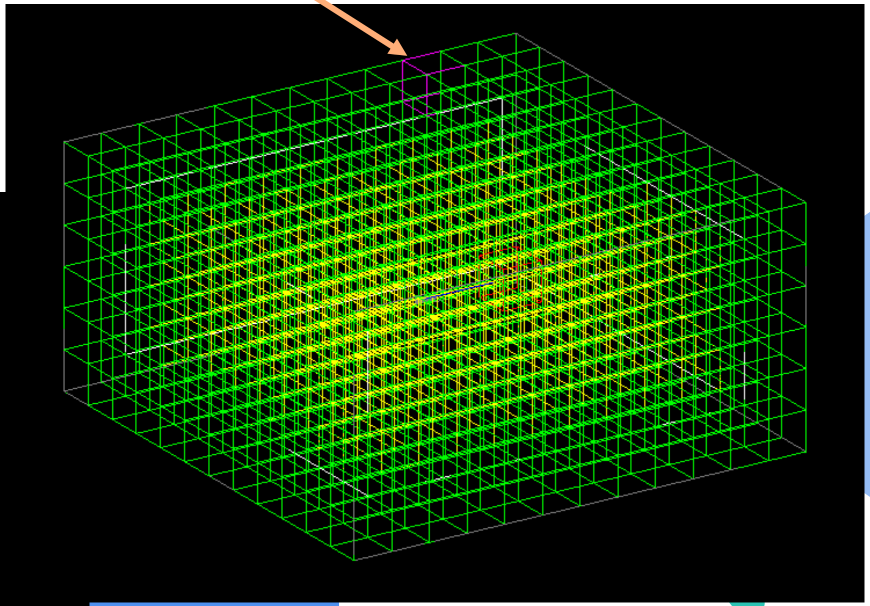
Automatic meshing - idea



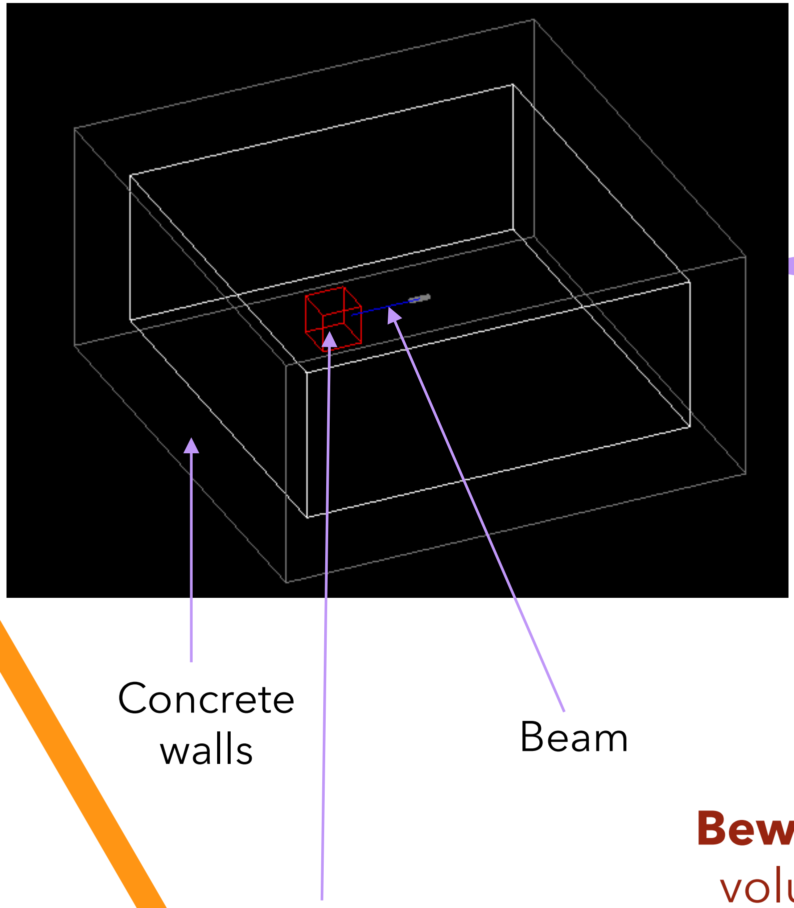
- Step 1 : room voxelization



- Step 2 : for each volume, association to a detector



Automatic meshing - behaviour



Beware of volumes **overlapping**

world
| - **Room**
| | - **BeamLine**
| | - **Target**
| | | - vox_Target-0
| | | - vox_Target-1
| | | - vox_Target-…
| | - vox_Room-0
| | - vox_Room-1
| | - vox_Room-…
| - vox_world-0
| - vox_world-1
| - vox_world-…

Tree struct

vox_Room-0 :

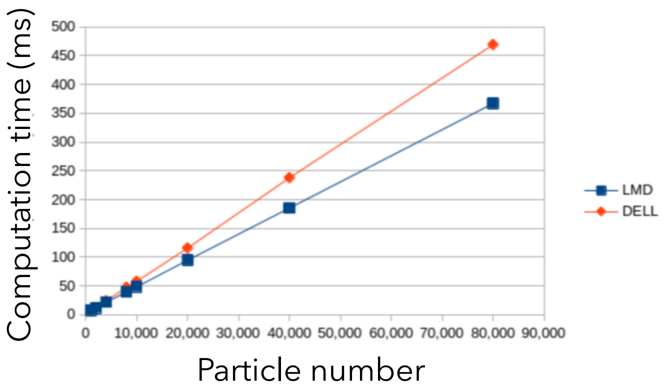
- Name of the volume
- Size of the box
- Position
- Material
- Output filename (for PhaseSpaceActor)

Box struct

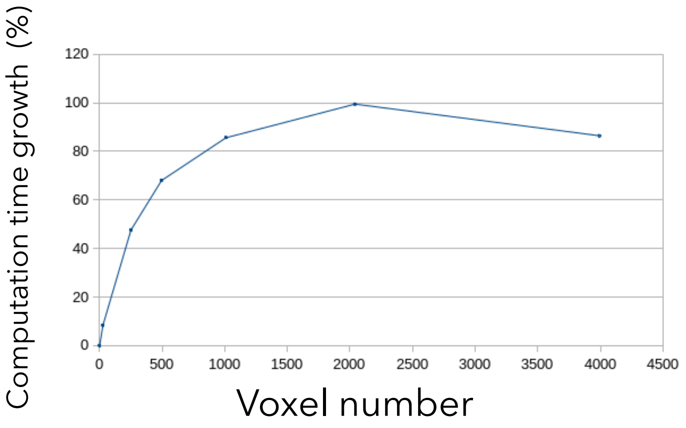
Automatic meshing - optimization

« Software » approach

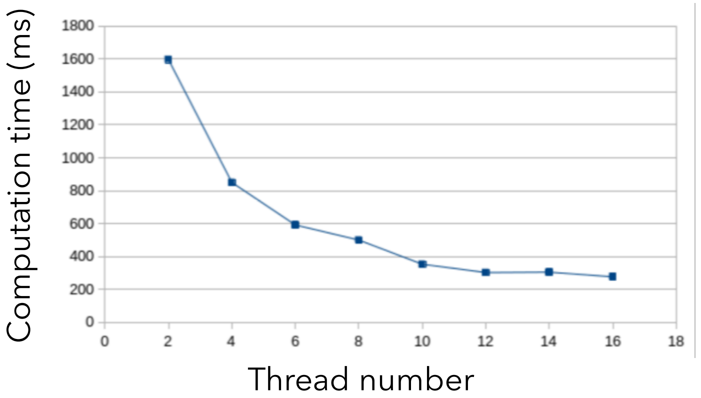
- Particle number :



- Voxel number :



- File-writting → 20-30% of time optimization
- Parallelisation :

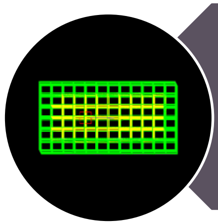


« Physics » approach

- Particles elimination → 10 % speed loss
  - But associated with process deactivation → 15% gain
- Energy cuts → amelioration up to a factor of 4
- …

- Removal of air in the room → factor 4 gain
- Modification of isotopic composition → up to 1/(isotopic fraction)
  example : up to 10,000 when considering 2H
- …

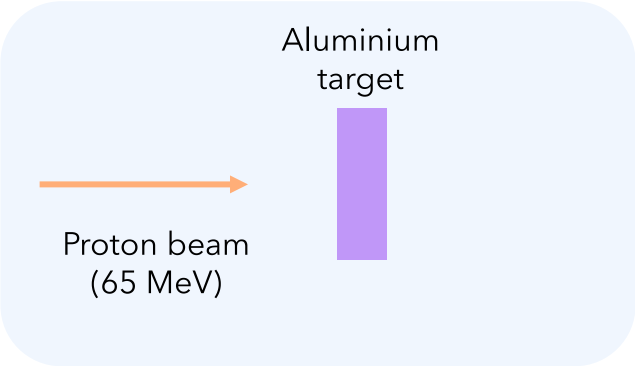
Energy spectrum extraction

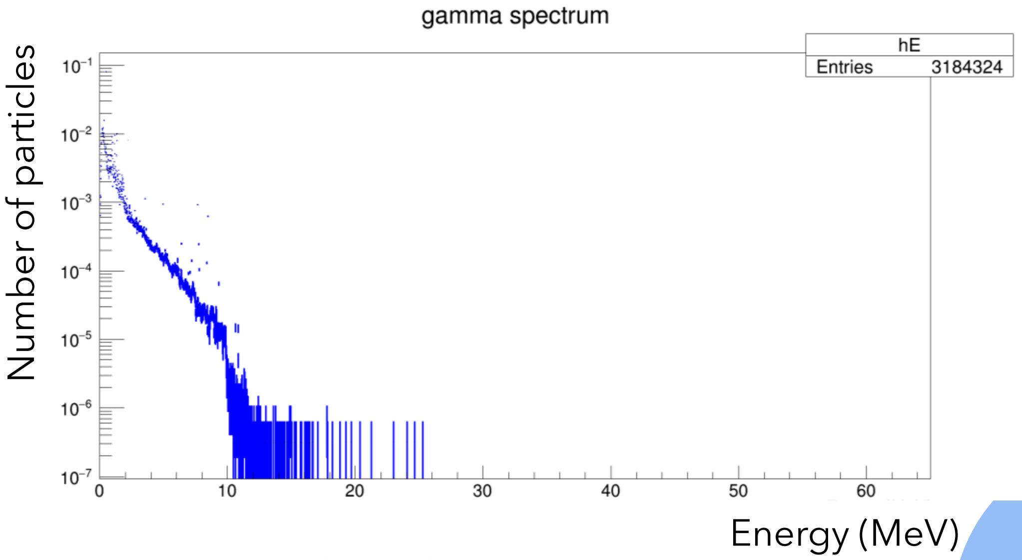


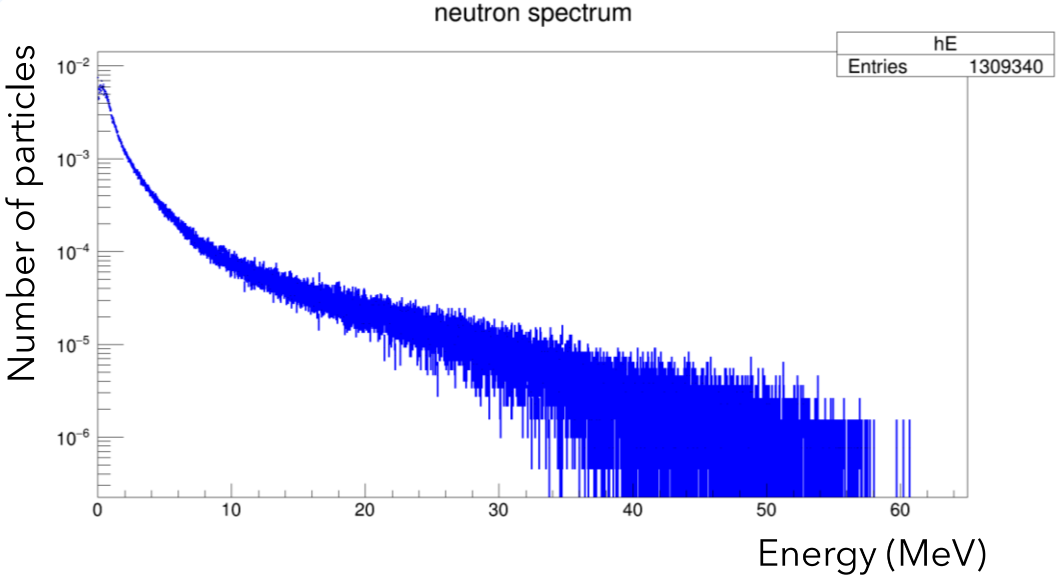
Meshing

Data extraction

Typical example : (here with 4π-detector)







Acquisition of spatial and energetic mapping for secondary particles (neutrons)

Hadrontherapy :
Conversion coefficients for access to dose

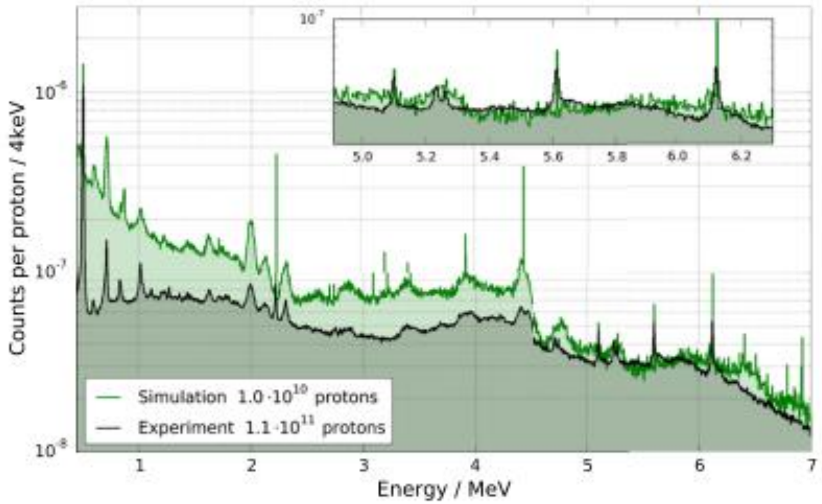
$$\omega_R(E_n) = \begin{cases} 2,5 + 18,2e^{-\frac{\ln^2(E_n)}{6}} & E_n < 1\ MeV \\ 5,0 + 17,0e^{-\frac{\ln^2(2E_n)}{6}} & 1\ MeV < E_n \leq 50\ MeV \\ 2,5 + 3,25e^{-\frac{\ln^2(0.04E_n)}{6}} & E_n > 50\ MeV \end{cases}$$

Sterilisation :
Activation software (FISPACT-II)

Digital tool limitations

Simulations very sensitive to :

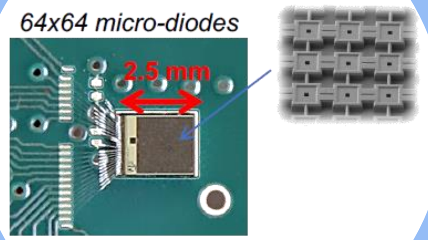
- Considered models of physics
- Volumes geometry
- Considered materials



Quantitative comparison of measured and simulated summed γ-ray emission spectrum from about 0.5 MeV–7 MeV for the full absorption PMMA measurement [A. Schumann et al., Physics in Medicine and Biology (2015)]

Experimental measurements allowed by DeSIs-developed device :

- Real-time fast and thermal neutron detector **AlphaRad** (quasi transparency to photons, small-sized, small energy requirements)



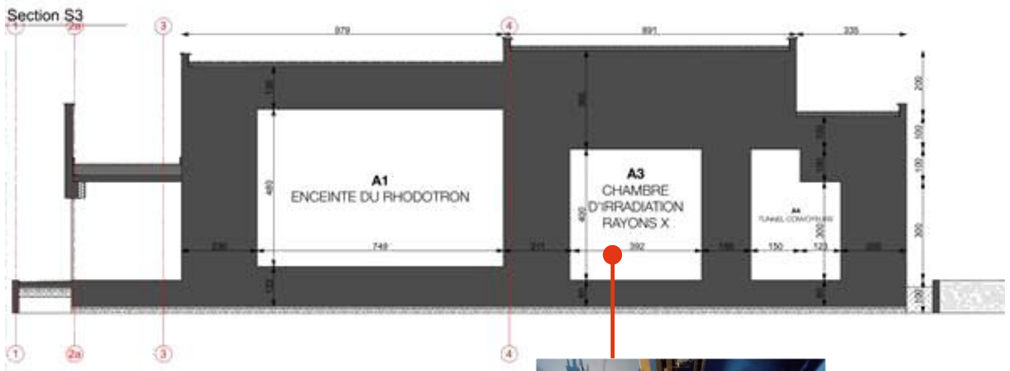
Convolution of resulting map with AlphaRad efficiency :

- Draft of **measurements protocols** associating the developed tool and detectors for validation of the tool

Application to partner platforms

Experimental irradiation platform : **FEERIX**

- Real geometry:

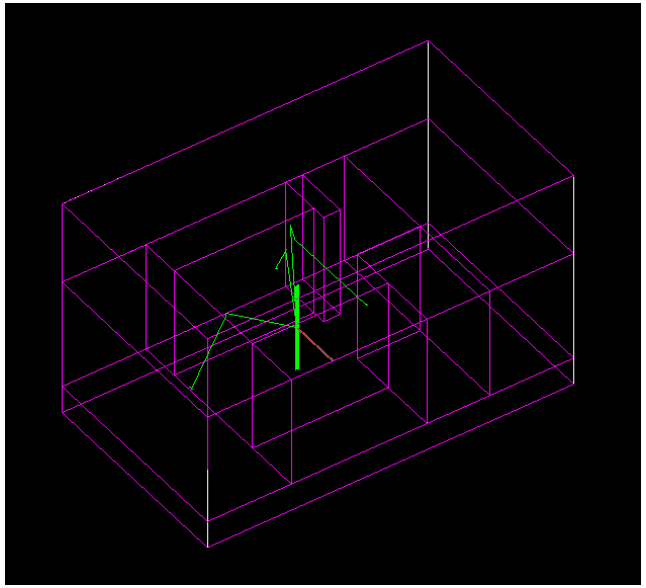


7 MeV electron input

Tantalum target for X-ray conversion

Irradiation area (mango position)

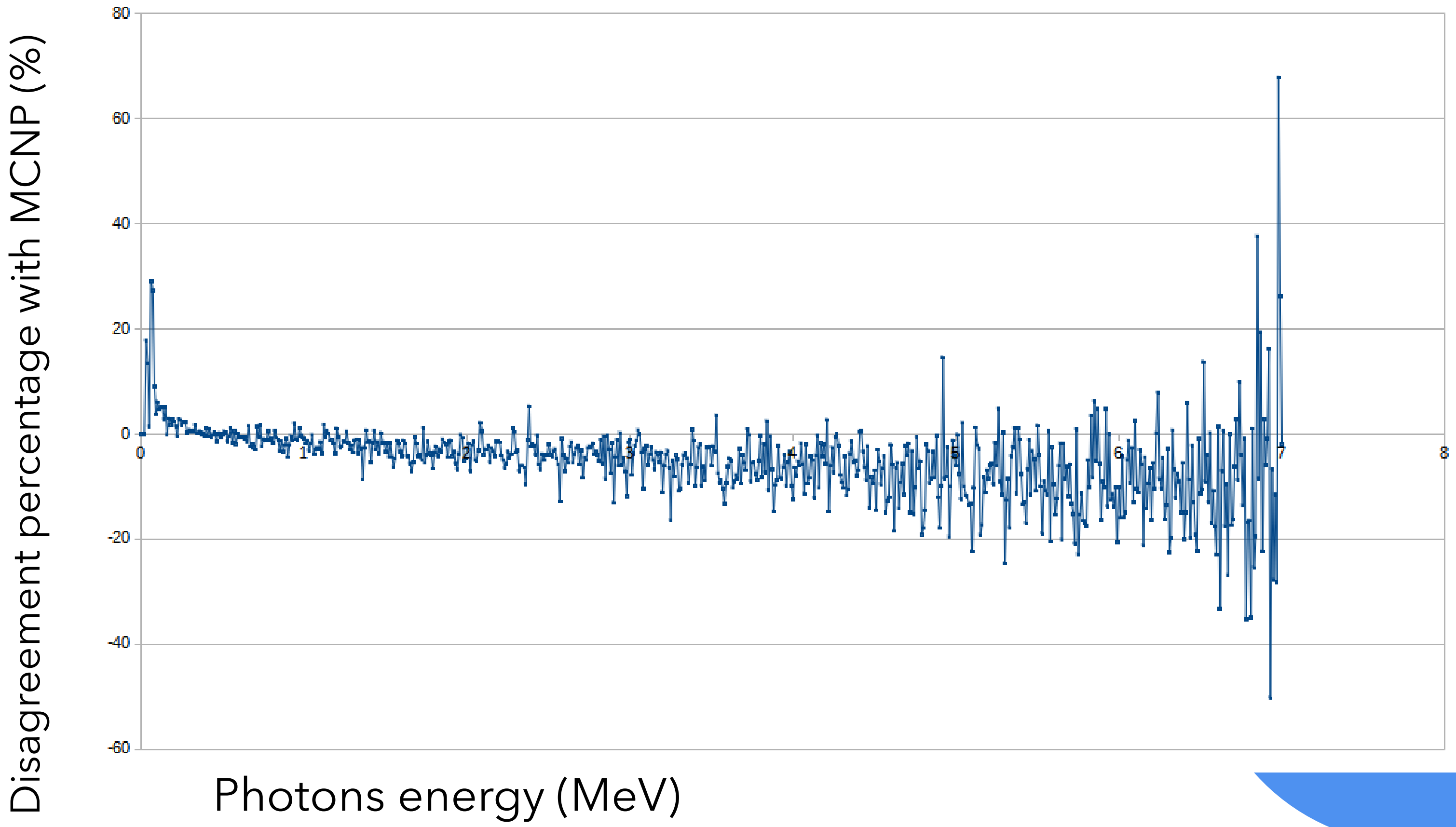
- GATE modelling :



Merci de votre attention

Modelling FEERIX platform

No agreement between MCNP, GATE/Geant4 and PENELOPE for X-ray spectrum :



N.B. : 0 to 7 MeV

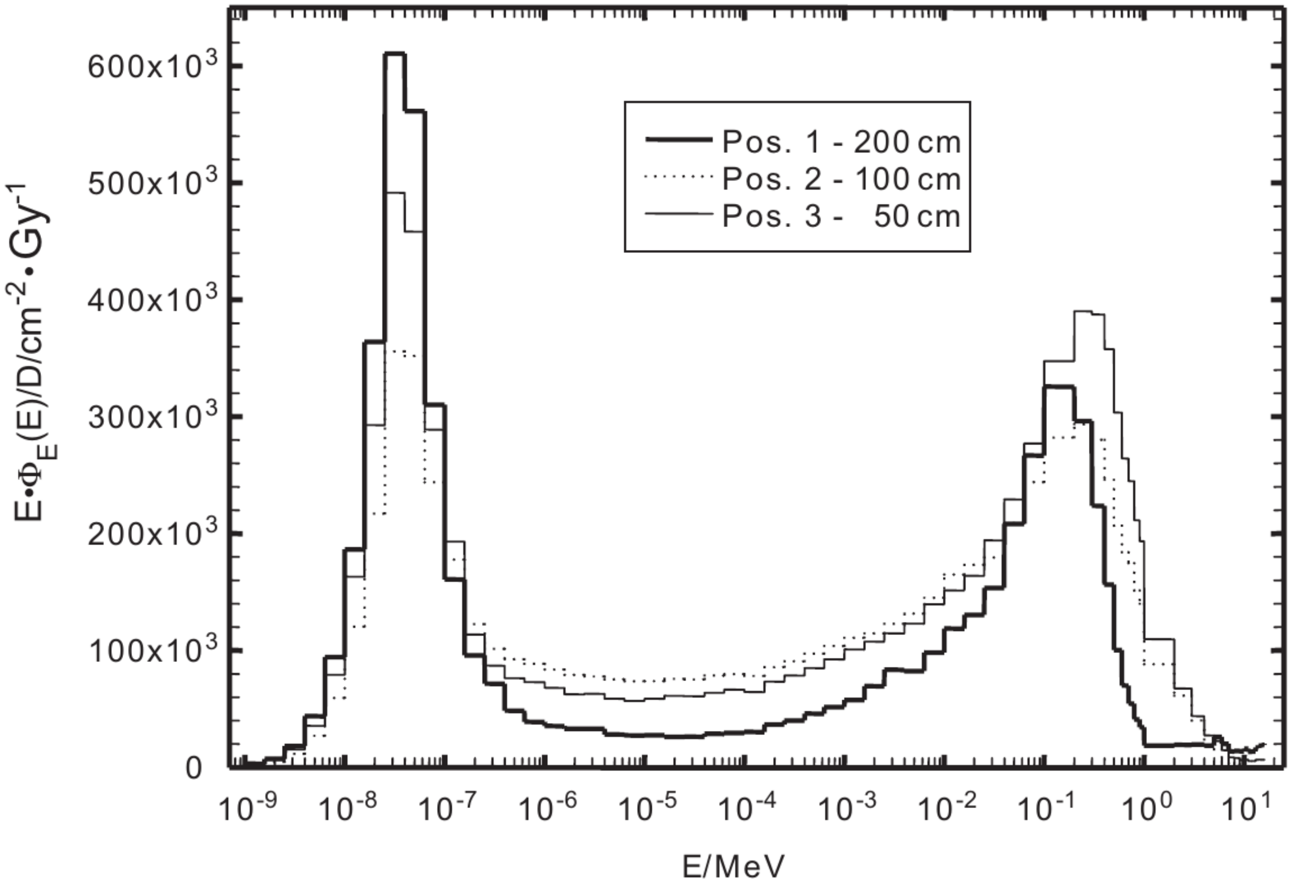
Annexe : exemple code GATE

```
#==================================================================
# Geometry
#==================================================================
/gate/geometry/setMaterialDatabase» {data}/GateMaterials.db

#-------------------------------
#----World----------------------
#-------------------------------
/gate/world/setMaterial              {MatWorld}
/gate/world/geometry/setXLength      260 cm
/gate/world/geometry/setYLength      260 cm
/gate/world/geometry/setZLength      330 cm

#-------------------------------
#----Room-----------------------
#-------------------------------
/gate/world/daughters/name           Room
/gate/world/daughters/insert         box
/gate/Room/geometry/setXLength       220 cm
/gate/Room/geometry/setYLength       220 cm
/gate/Room/geometry/setZLength       290 cm
/gate/Room/placement/setTranslation  0 0 0 cm
/gate/Room/setMaterial               {MatRoom}
/gate/Room/vis/setVisible            1
/gate/Room/vis/setColor              white
```

```
#==================================================================
# Physics part one
#==================================================================

/gate/physics/addPhysicsList {phyList}

/control/execute {mac}/{phyFile_I}.mac

#==================================================================
# Actors
#==================================================================

#-----------------------------
#----Phase_Space--------------
#-----------------------------

/gate/actor/addActor PhaseSpaceActor                 phaseSpace1
/gate/actor/phaseSpace1/save                         {output}/{filePS}
/gate/actor/phaseSpace1/attachTo                     Det
/gate/actor/phaseSpace1/enableEkine                  true
/gate/actor/phaseSpace1/enableYPosition              true
/gate/actor/phaseSpace1/enableZPosition              true
/gate/actor/phaseSpace1/enableXDirection             false
/gate/actor/phaseSpace1/enableYDirection             false
/gate/actor/phaseSpace1/enableZDirection             false
/gate/actor/phaseSpace1/enableProductionVolume       true
/gate/actor/phaseSpace1/enableProductionProcess      true
/gate/actor/phaseSpace1/enableParticleName           true
/gate/actor/phaseSpace1/storeSecondaries             true
/gate/actor/phaseSpace1/enableWeight                 true


#-----------------------------
#----Particles_statistics------
#-----------------------------

/gate/actor/addActor    SimulationStatisticActor»   stat
/gate/actor/stat/save   {output}/{fileStat}
```

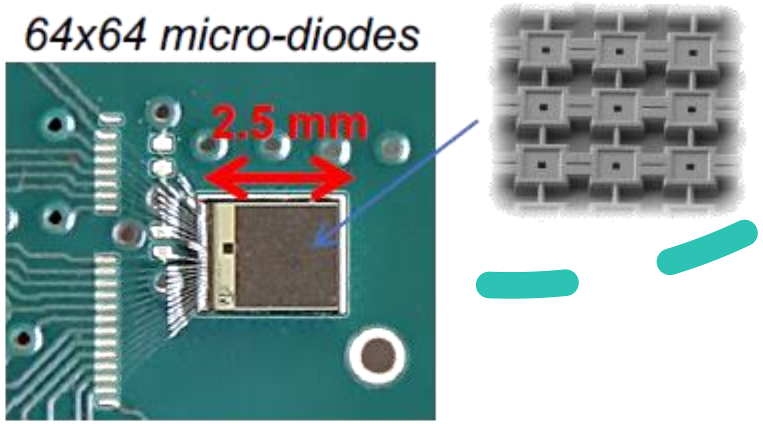
```
#==================================================================
# Initialization
#==================================================================

/gate/run/initialize

#==================================================================
# Beam
#==================================================================

/gate/source/addSource                  pBeam gps
/gate/source/pBeam/gps/particle         proton
/gate/source/pBeam/gps/ene/type         Mono
/gate/source/pBeam/gps/energy           65 MeV
/gate/source/pBeam/gps/pos/type         Volume
/gate/source/pBeam/gps/pos/shape        Cylinder
/gate/source/pBeam/gps/pos/centre       0 0 -85 cm
/gate/source/pBeam/gps/pos/radius       2 cm
/gate/source/pBeam/gps/pos/halfz        0.1 cm
/gate/source/pBeam/gps/direction        0 0 1

#==================================================================
# Physics part two
#==================================================================

/control/execute {mac}/{phyFile_II}.mac

#==================================================================
# Main program
#==================================================================

#-----------------------------
#----Visualisation------------
#-----------------------------

/control/if {bVisu} == 1 {mac}/visu_I.mac

#-----------------------------
#----Random-------------------
#-----------------------------

/gate/random/setEngineName MersenneTwister
/gate/random/setEngineSeed auto

#-----------------------------
#----Start-------------------
#-----------------------------

/gate/application/setTotalNumberOfPrimaries {nbPart}
/gate/application/start
```

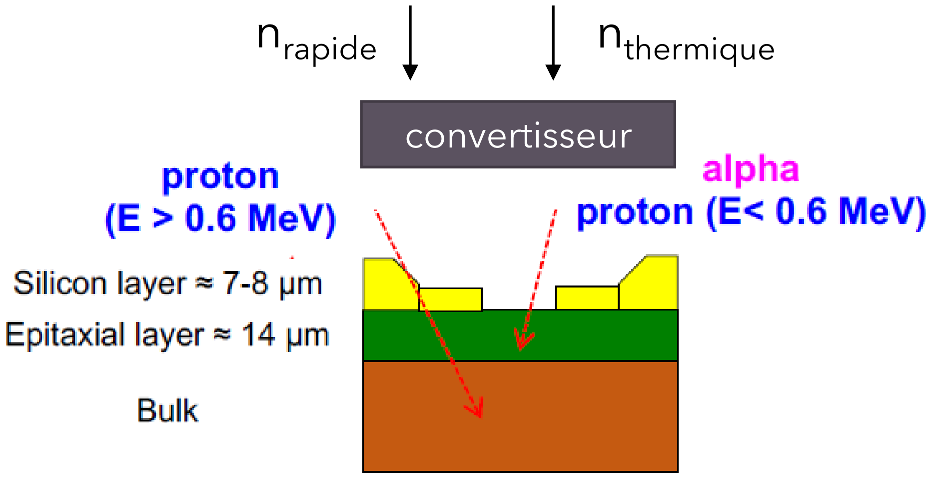
Annexe : spectre neutrons typique

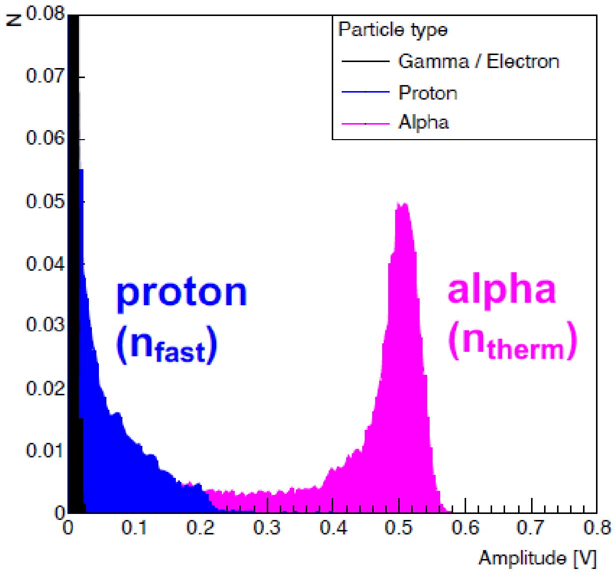


Annexe : l'AlphaRad

Avantages principaux
- Transparent aux photons
- Compact
- Faible consommation
- Vitesse de lecture

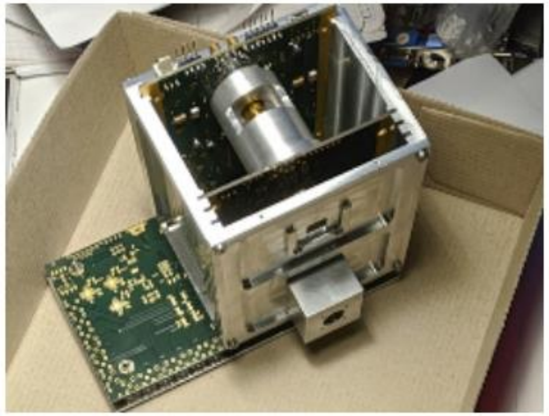


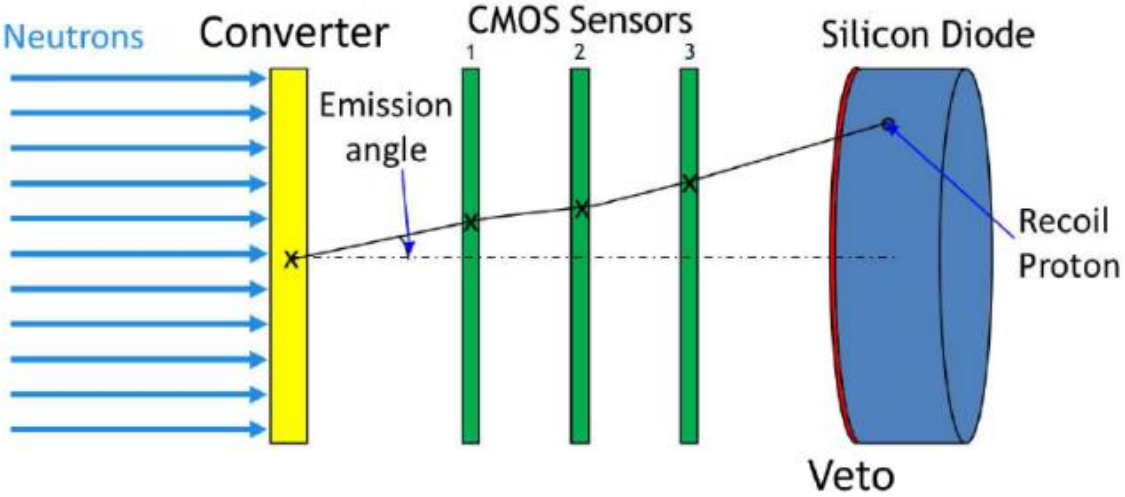




[N. Arbor et al., NIM A 888 (2018)]

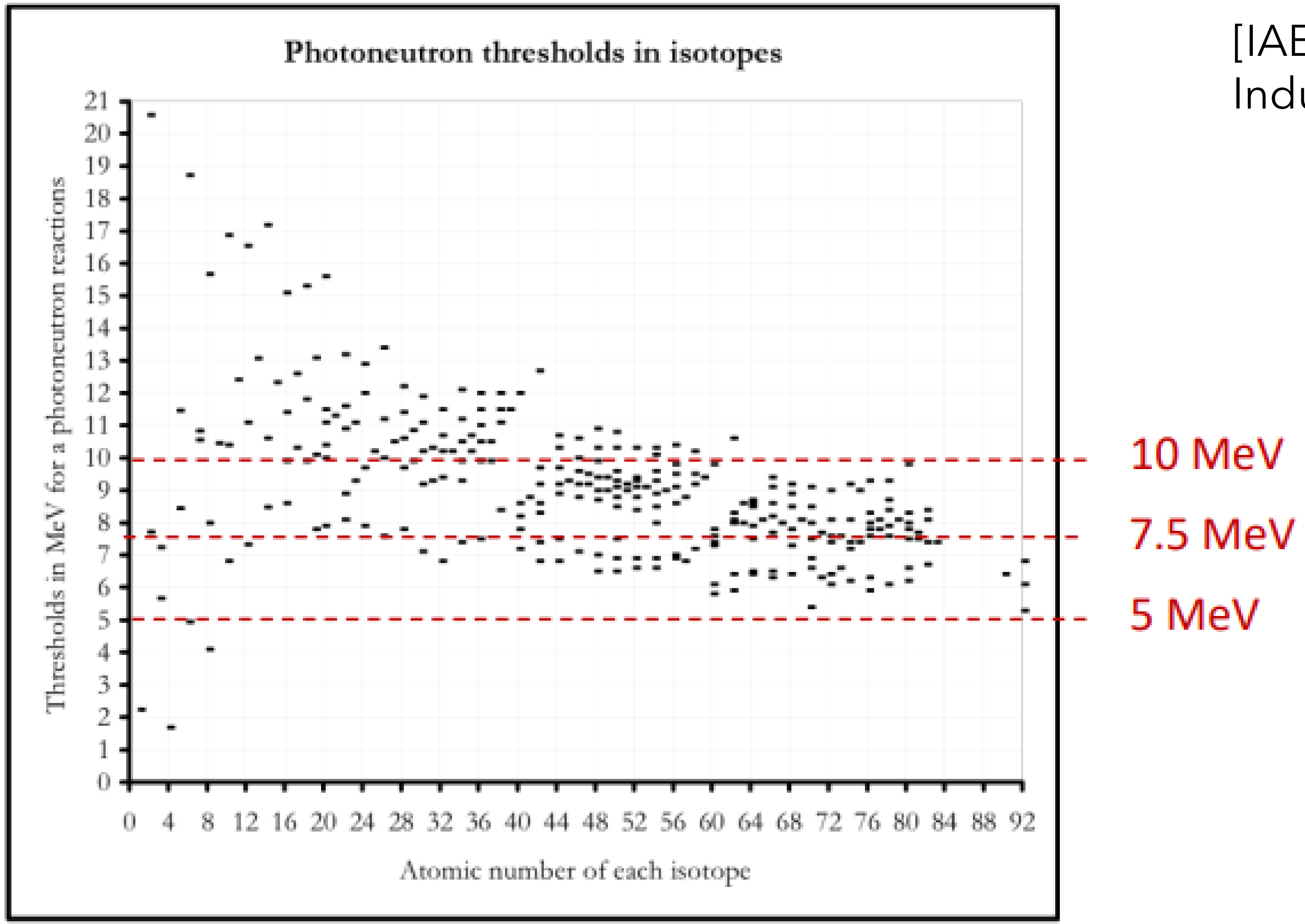
Annexe : Télescope à protons de reculs





$$E_n = E_p / \cos^2(\theta)$$

Annexe : seuil de production de photoneutrons



[IAEA TecDoc 1287, Natural and Induced Radioactvity in Food 2002]

Pourquoi augmenter ?

- Meilleur répartition de la dose
- Bremstrahlung plus efficace (8% 5 MeV – 14% 7 MeV)
- Accélération des procédés industriels