Simulation of FOOT at CNAO for radioprotection issues

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In order to speed up procedures, the radioprotection service of CNAO has requested a FLUKA simulation of the activation of FOOT materials
For this purpose, we have prepared a new kind of FOOT simulation, oriented to measure material activation, implementing all the specifications received from them.

They asked the following irradiation profile:

- $50 \cdot 10^6$ primaries delivered in only 1 second
- 1 day of “cooling time” after irradiation

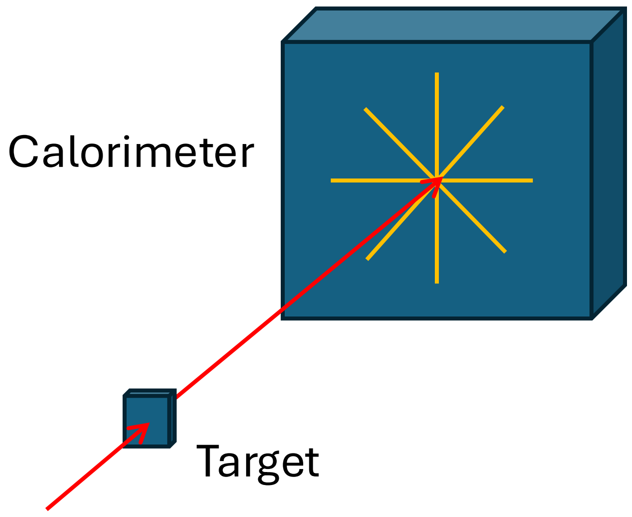
Required scorings at the end of cooling time:

1. list of residual nuclei and their activity/volume
2. specific activity as a function of coordinates
3. equivalent dose from neutrons

What we caught about the legal regulation

For objects exposed to **primary beam**
Tolerated activation threshold : milli Bq/g

For objects exposed to **secondaries** (charged fragments, neutrons)
For carbon ions E < 200 MeV/u and primary Nr < $3 \cdot 10^8$
Limit = 10 micro Sv @ 30 cm from the beam axis

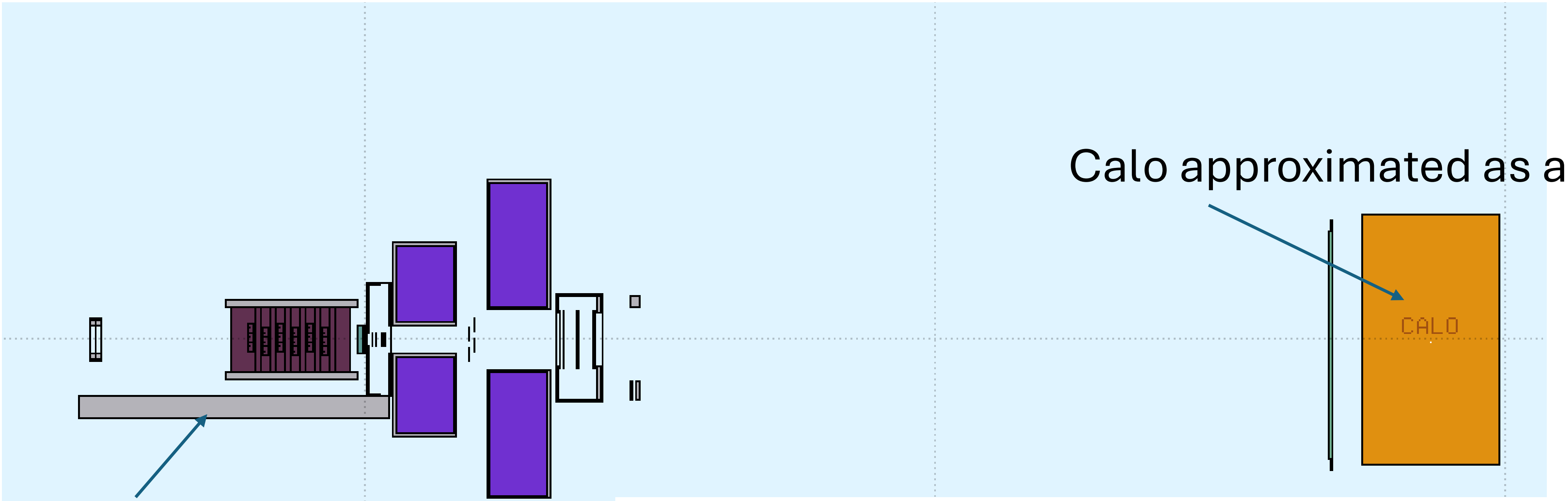


In our case, only the calorimeter is considered as the **neutron source**.
As a first approximation the target is neglected (~ 3% of the interactions)

Nothing we have concluded can be considered safe without feedback from CNAO radiation protection unit

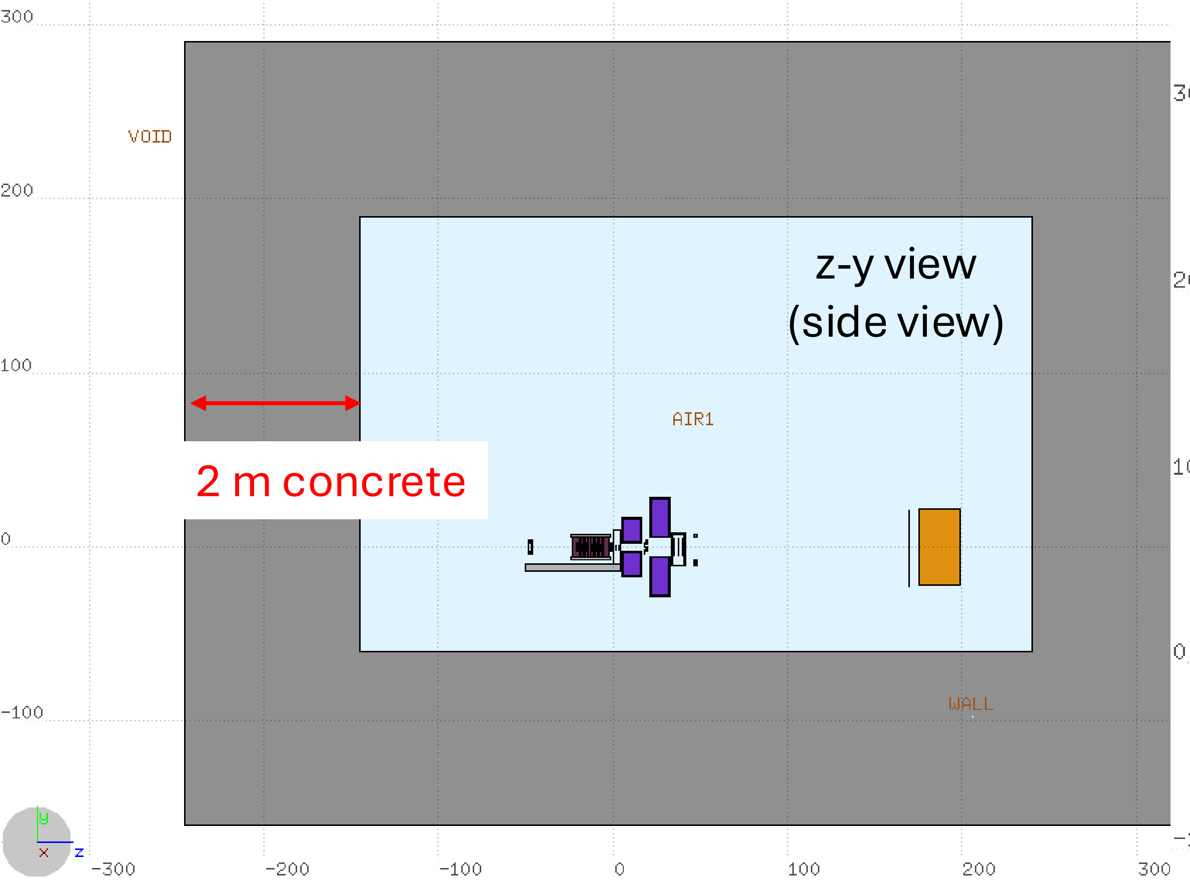
Simplified FOOT geometry

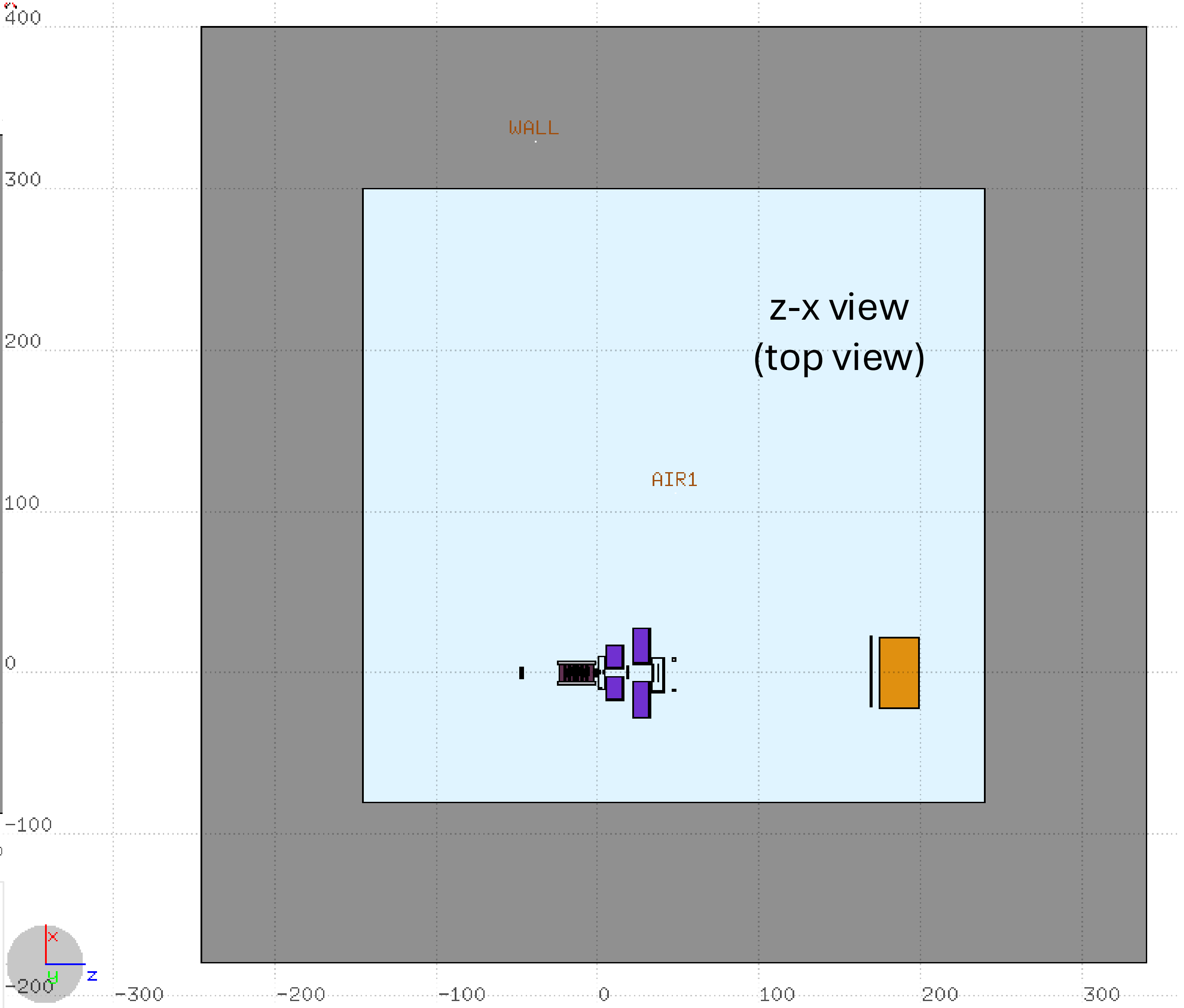
Segmentation of detectors is ignored:
all equal materials of a given detector are grouped together as a single region.
For example: the 4 Si sensors of VTX are considered together



➔ *What is really important in this kind of simulation is to know the* ***material composition****, the* ***weight*** *and the* ***volume*** *of each region (=detector element with homogenous material)*

A simplified room environment is also considered

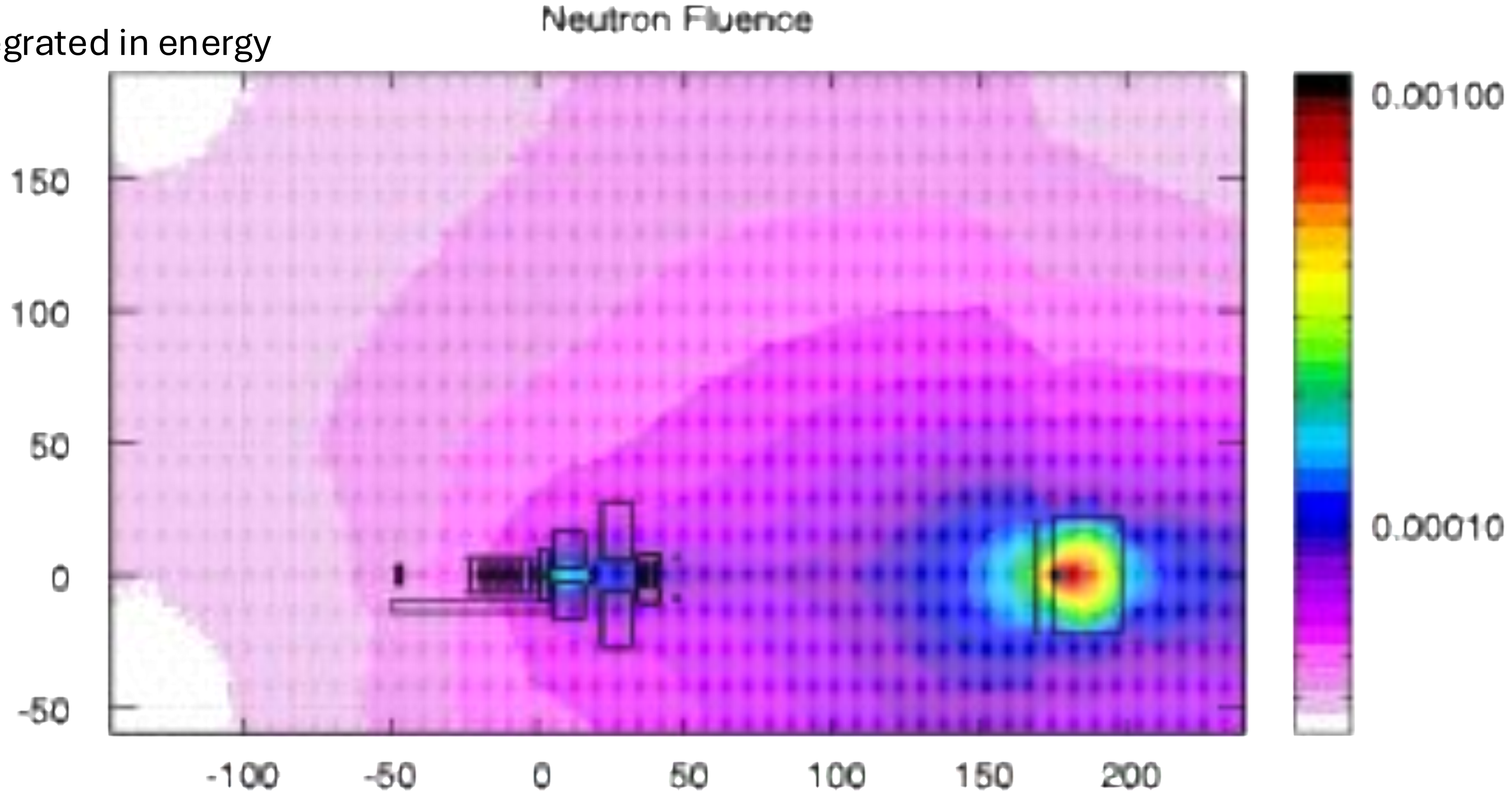




The room volume is then divided in 2x2x2 cm^3 voxels to measure dose, activity and specific activity

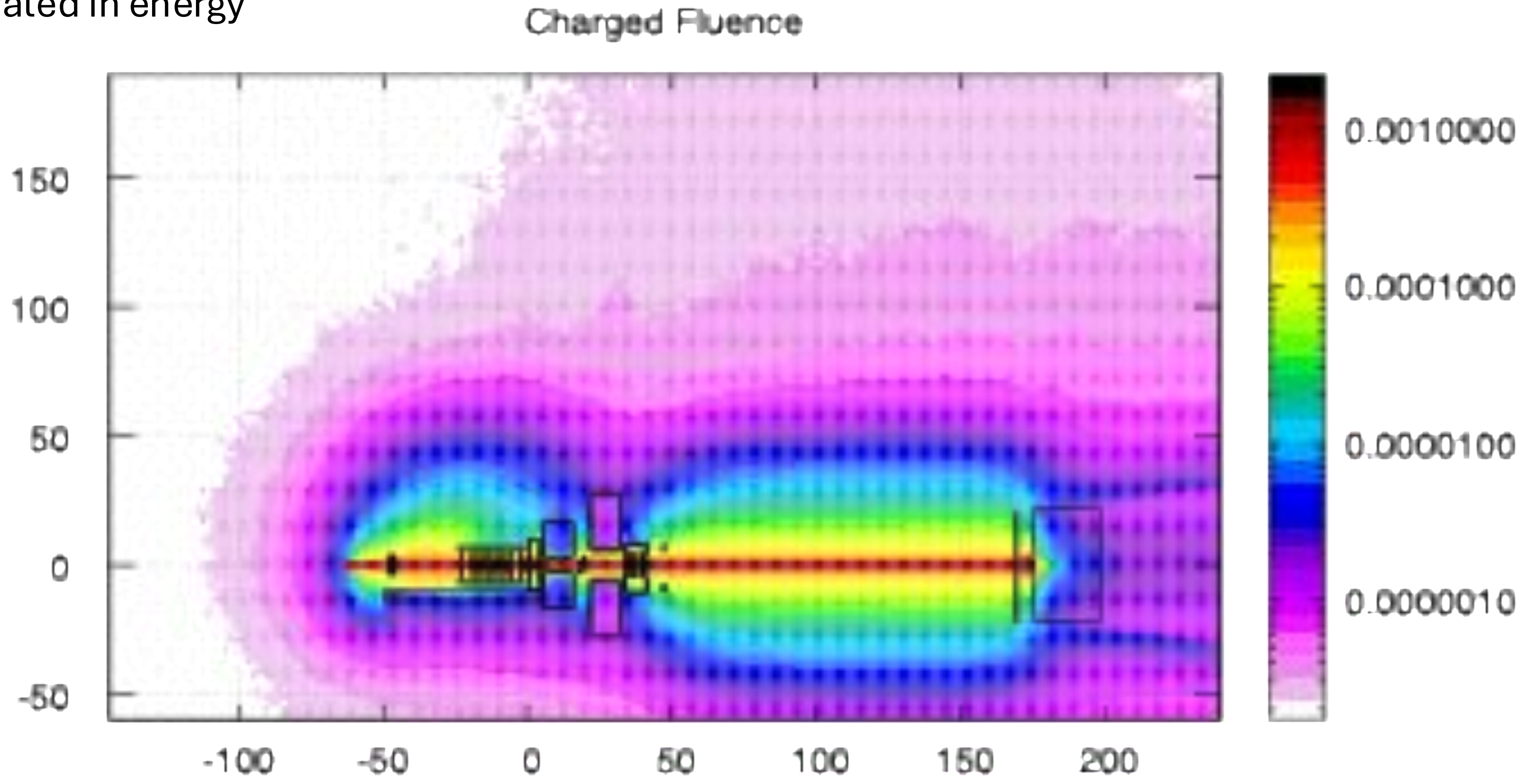
Neutron fluence (neutron/cm^3/primary)

Integrated in energy



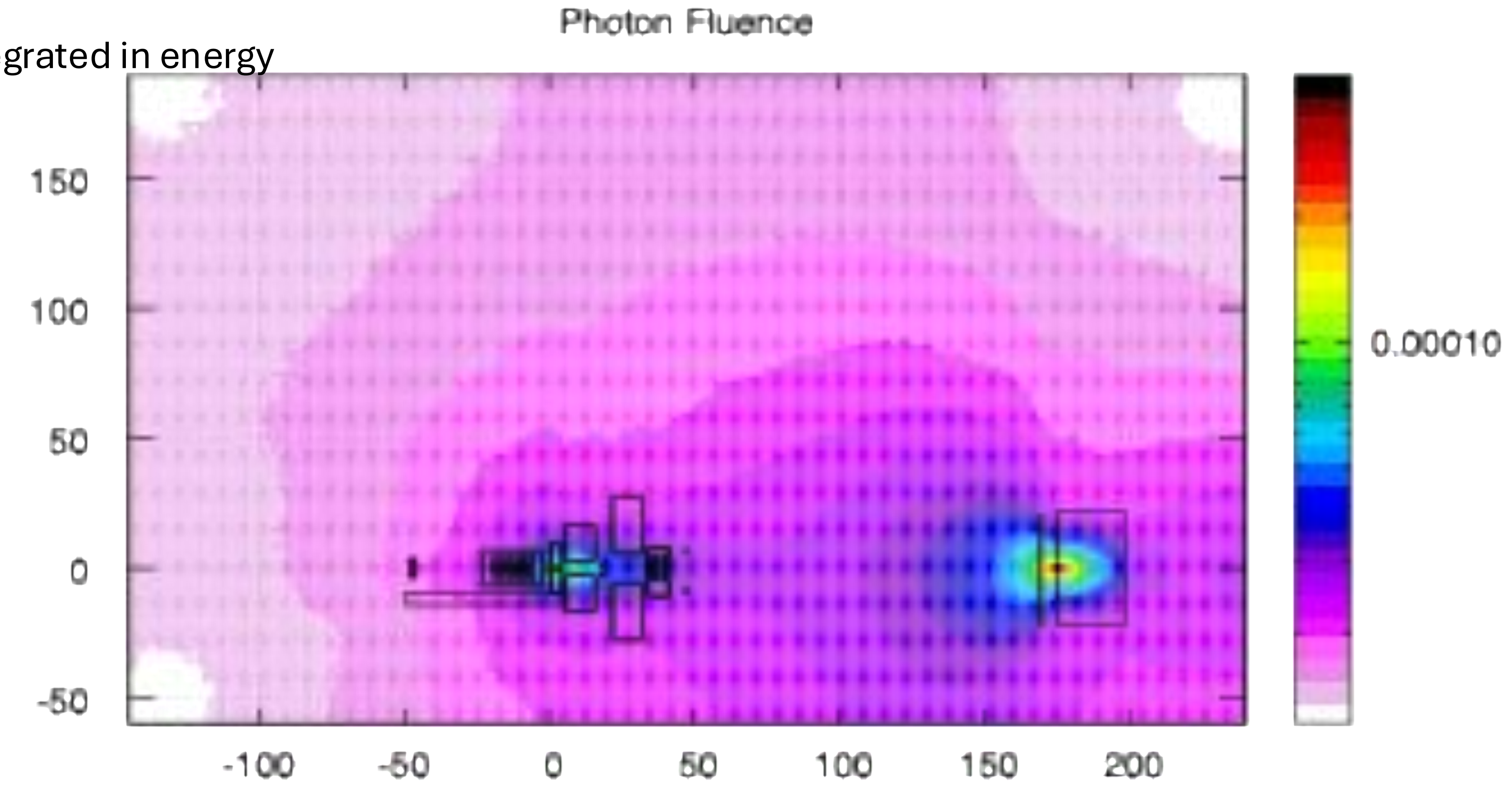
Charged part. fluence (particles/ cm^3/primary)

Integrated in energy

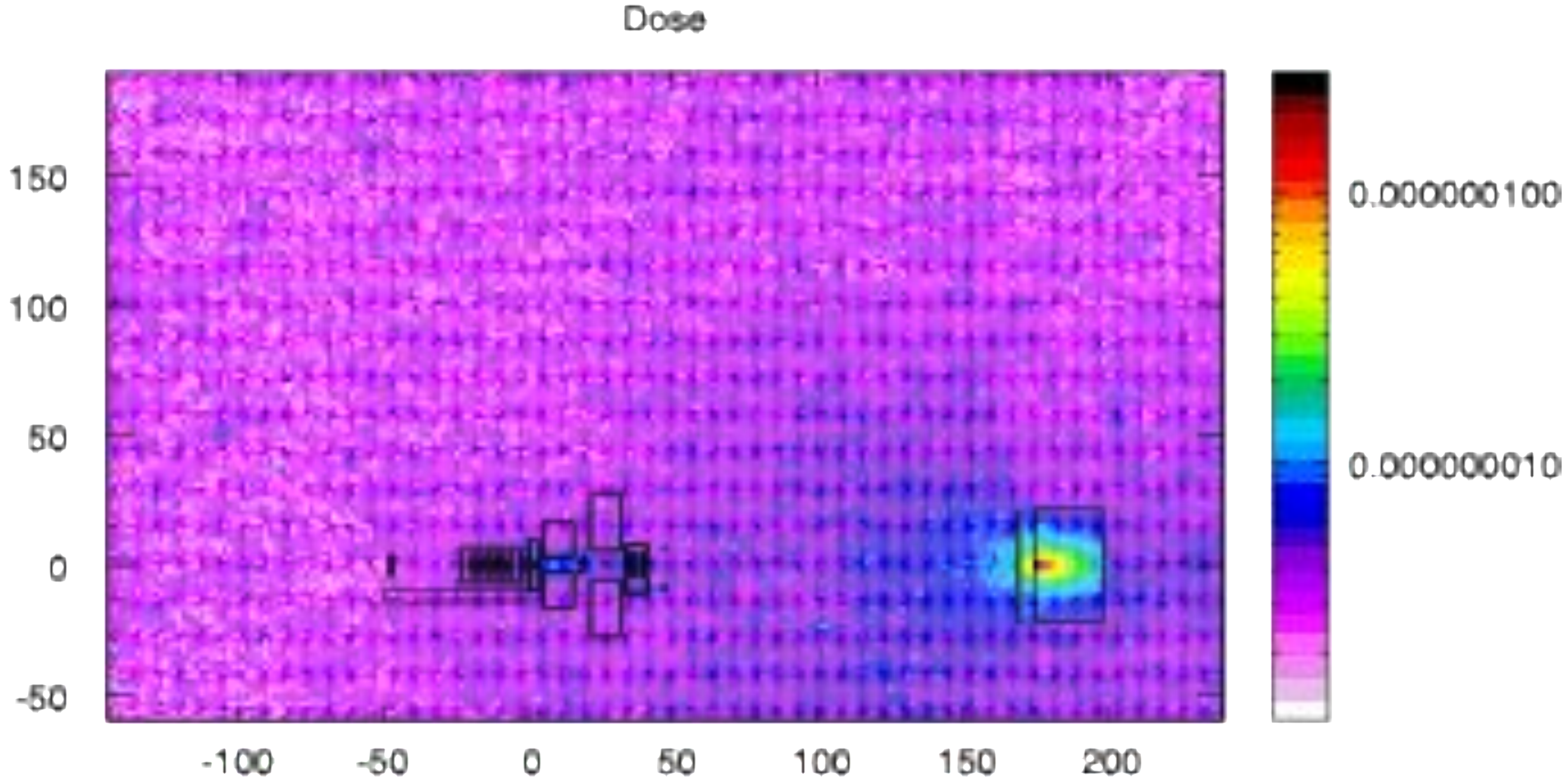


Photon fluence (photons/cm^3/primary)

Integrated in energy

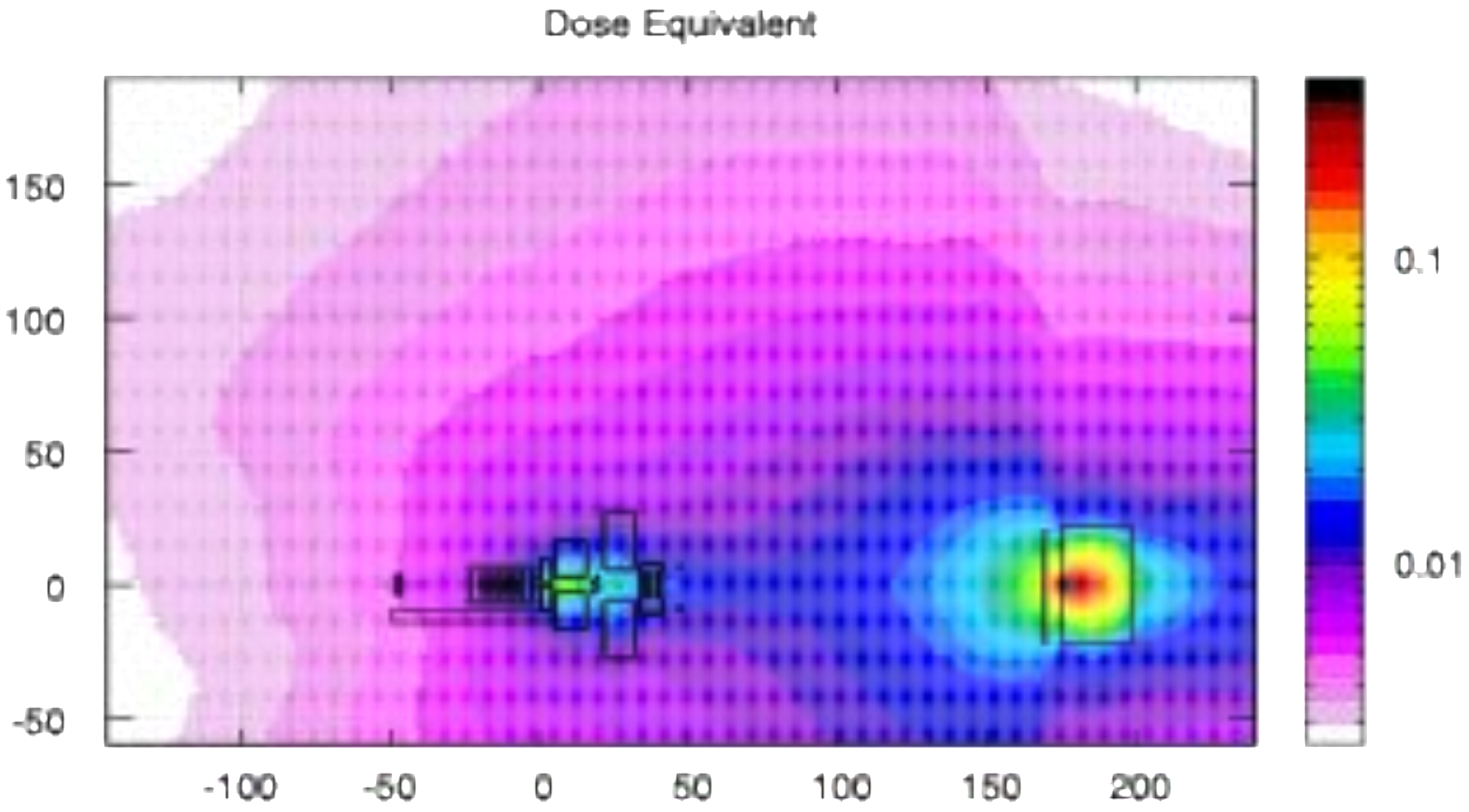


Dose (GeV/g)



Dose
150
100
50
0
-50
-100
-50
0
50
100
150
200
0.000000100
0.000000010

Equivalent dose from neutrons (pSv, 1 day cooling time)

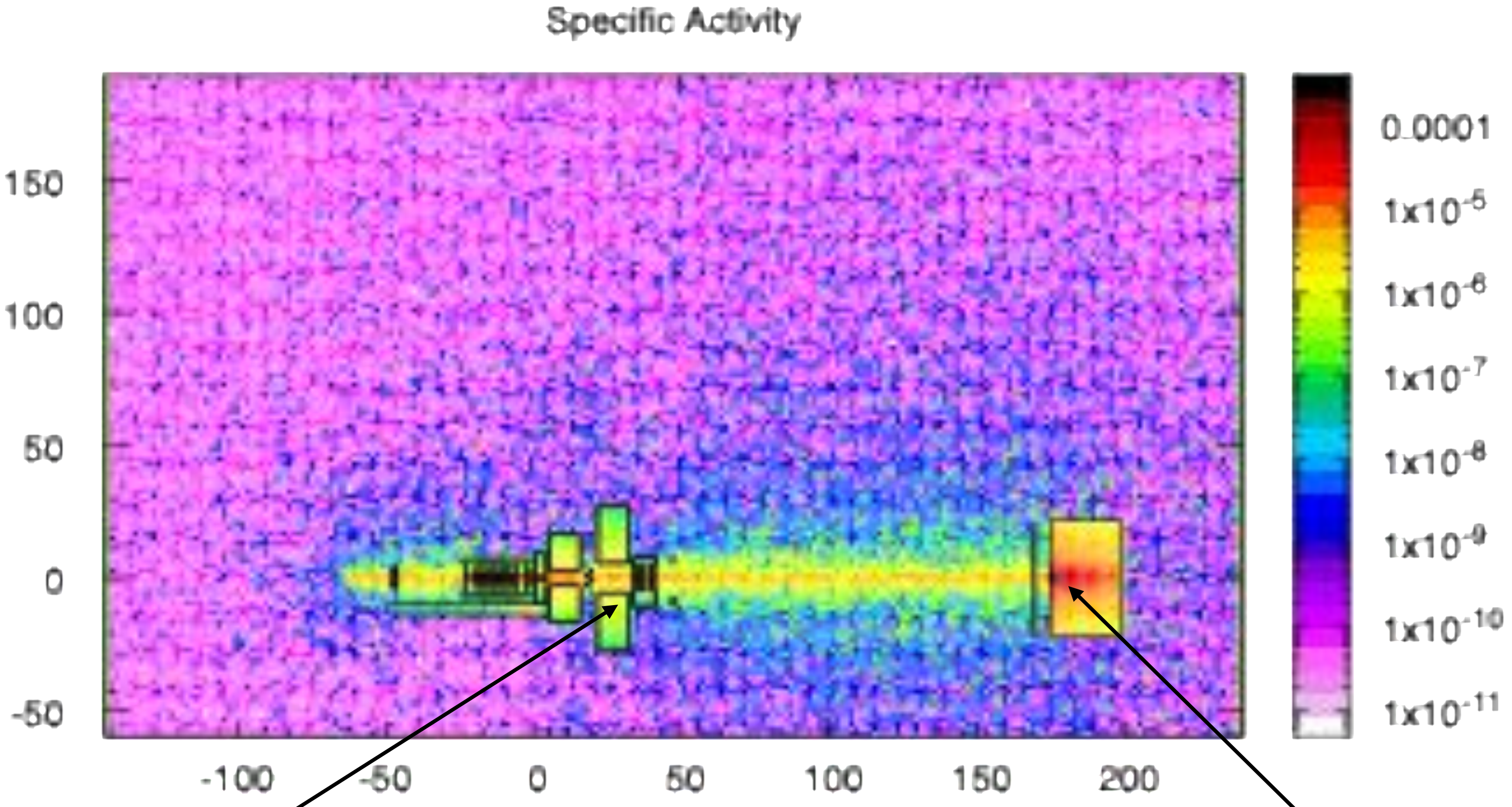


Fluence to dose conversion using coefficients taken from:

M. Pelliccioni, "Overview of fluence-to-effective dose and fluence-to-ambient dose equivalent conversion coefficients for high energy radiation calculated using the FLUKA code", Radiation Protection Dosimetry 88 (2000) 279-297

Specific activity (Bq/g, 1 day cooling time)

Air is not a problem:
in simulation it is necessarily static,
in reality there is a continuous flow



Even if the magnet is outside the beam axis, it is activated since it is a sort of dump for many charged fragments emitted at large angle (and neutrons as well)

Our hot point:
0.0392 Bq/g

Limit < milli Bq/g

Calculation of time evolution of the system

For an arbitrary irradiation pattern, the time evolution of the system (build-up and decay during the irradiation and cooling) is obtained runtime *for fixed cooling times* via the exact analytical solution of the **Bateman equations**:

$$\frac{dN_i}{dt} = -\sum_{j \neq i} \left[\lambda_{ji}^{d} + \bar{\sigma}_{ji} \bar{\varphi} \right] N_i + \sum_{j \neq i} \left[\lambda_{ij}^{d} + \bar{\sigma}_{ij} \bar{\varphi} \right] N_j$$

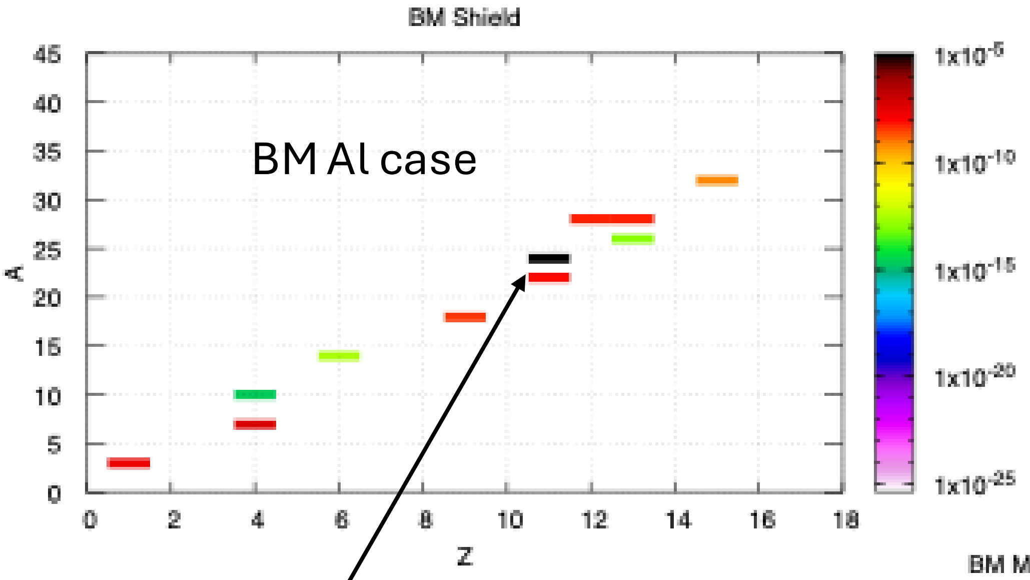
where for each radionuclide in the material:

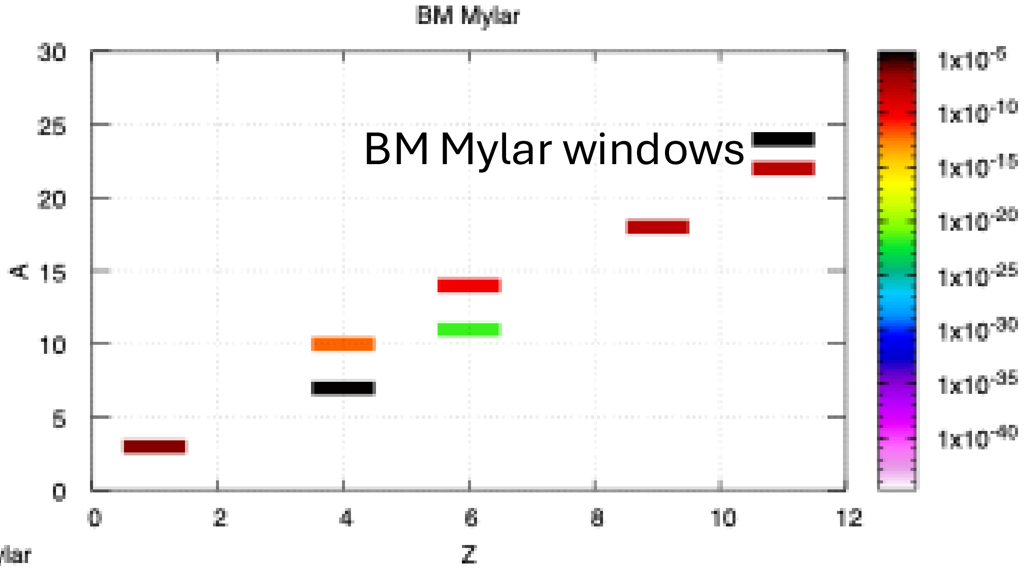
λ_{ji}^{d} → decay probability of the residual nucleus i in the residual nucleus j

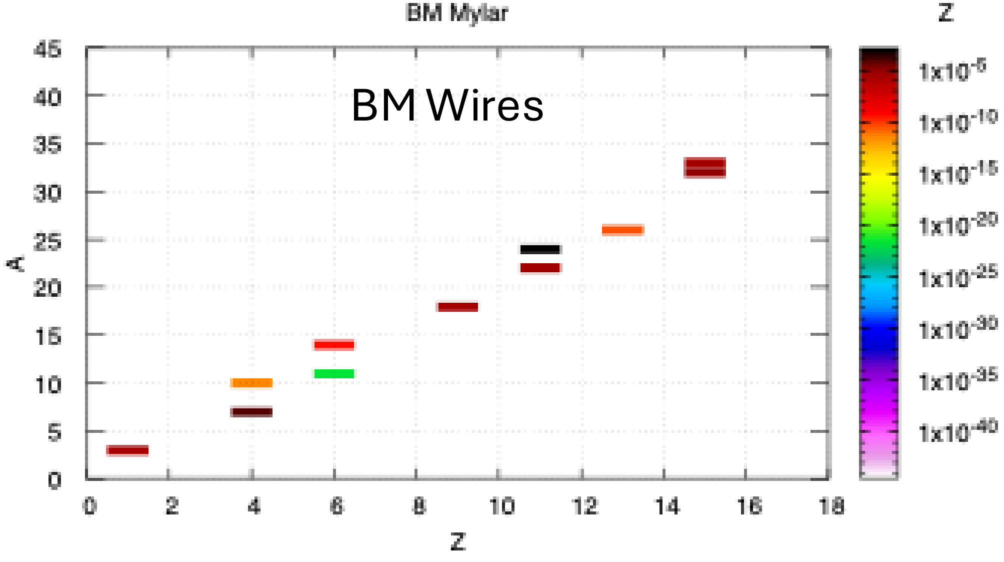
σ_{ji} → cross section for transmutation of the residual nucleus i in the residual nucleus j

$\bar{\varphi} = \int \varphi(E) dE$ $\quad\quad$ $\bar{\sigma}_{ji} = \frac{1}{\bar{\varphi}} \int \varphi(E) \sigma_{ji}(E) dE$

Example of residual nuclei table (the BM)







In aluminum, the most active residual nucleus turns out to be ^{24}Na.
It decays β^- with $t_{1/2}$ ~15 h

Summary table of residuals for BM

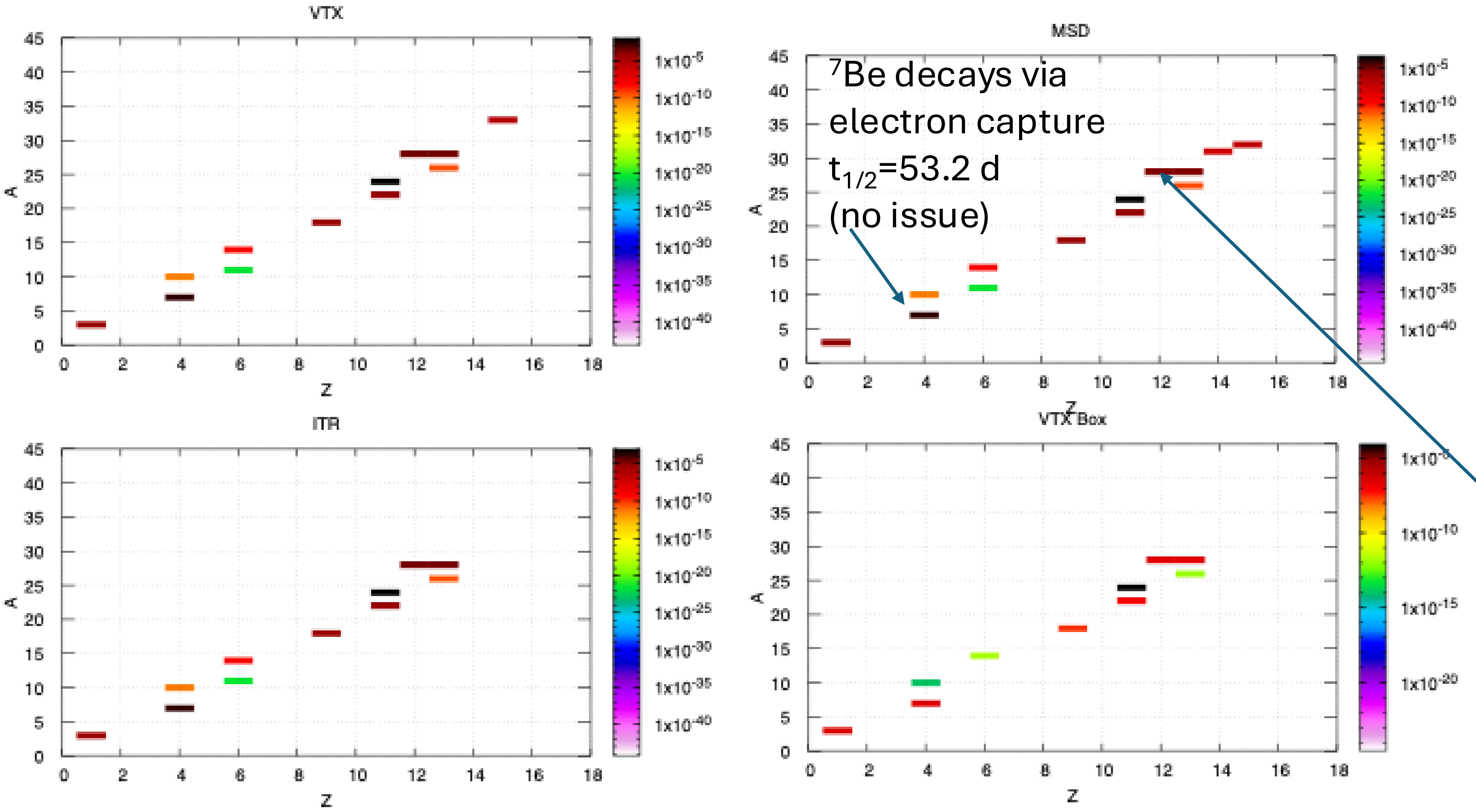
Z	A	Activity (Bq/cm^3)	err_%
1	3	9.95712e-07	5.82624
4	7	4.76318e-05	9.22462
4	10	1.11996e-12	17.5363
6	11	2.33232e-22	6.50857
6	14	1.43554e-10	23.8718
7	13	1.40198e-45	22.2344
9	18	3.20394e-08	90.6341
11	22	2.43088e-08	85.1634
11	24	5.33797e-05	43.0767
12	28	5.29825e-13	99
13	26	2.5007e-14	11.0482
13	28	5.30775e-13	99
15	32	9.82156e-09	70.3521
15	33	2.82331e-09	99
17	36	1.33679e-15	70.3526
17	38	1.30238e-17	70.3526
17	39	1.09418e-13	57.1489

BM Activity = 0.00010+/- 2.e-05 Bq/cm^3

In Bq/g is well below 10^{-3}, which is considered the zero threshold

Table Activity = 4.16e-06 +/- 7e-08

Activity of Silicon detector is dominated by their Al boxes



^{7}Be decays via electron capture $t_{1/2}$=53.2 d (no issue)

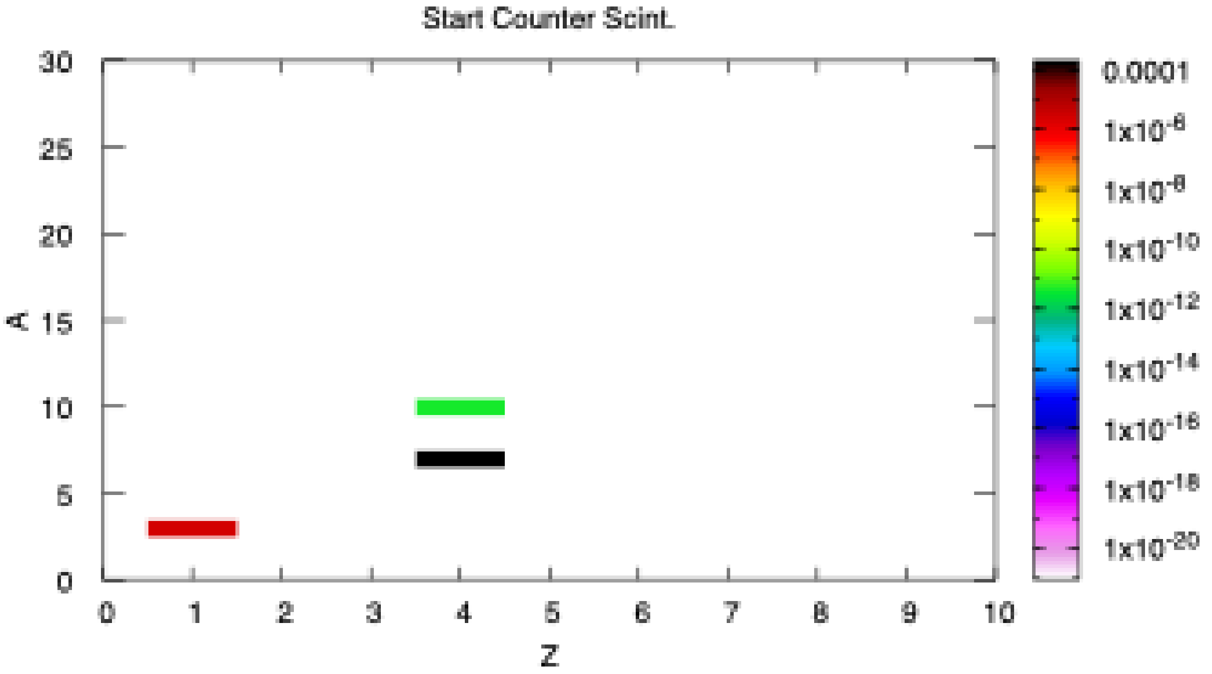
VT (+Box) Activity = 0.0154+/- 0.0011 Bq/cm^3

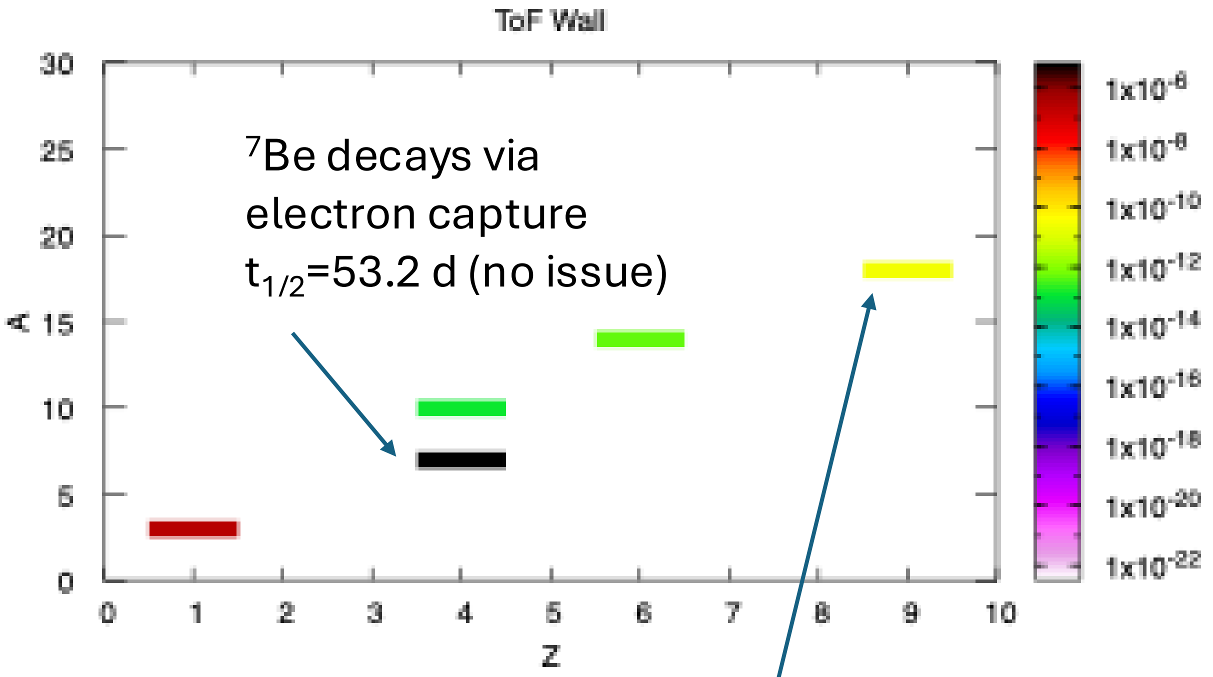
ITR Tot. Activity = 0.0014 +/- 0.0001 Bq/cm^3

MSD(+Box) Activity = 6.5e-05 +/- 1.4e-06 Bq/cm^3

^{28}Mg ($t_{1/2}$=20.9 h) and ^{28}Al ($t_{1/2}$=2.24 m) which decay β^-

Scintillators are not an issue



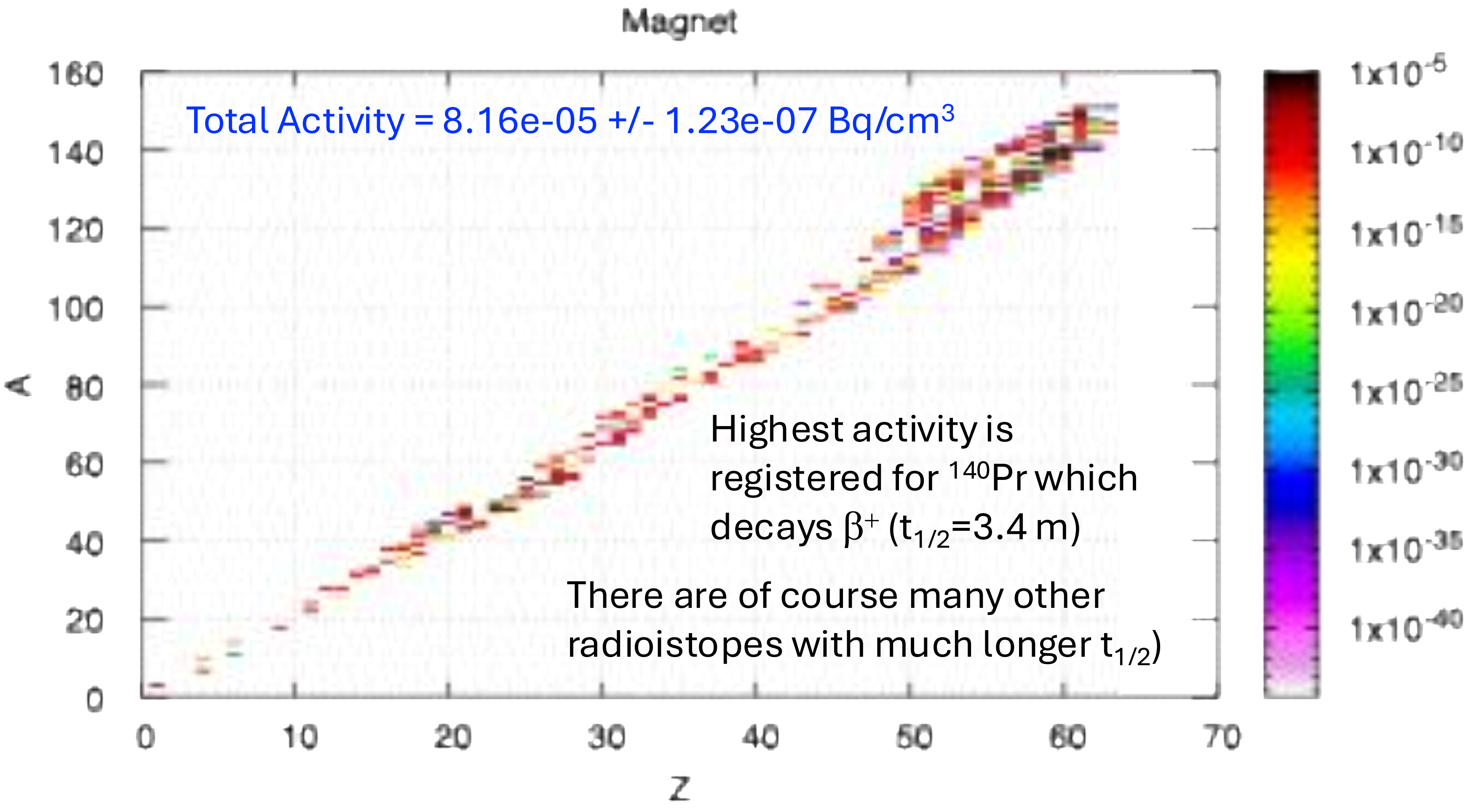


^{18}F ($t_{1/2}$=1.83 h)
which decay β^{+}

SC (+Al frame) Activity = = 0.000200 +/- 8.e-06 Bq/cm^3

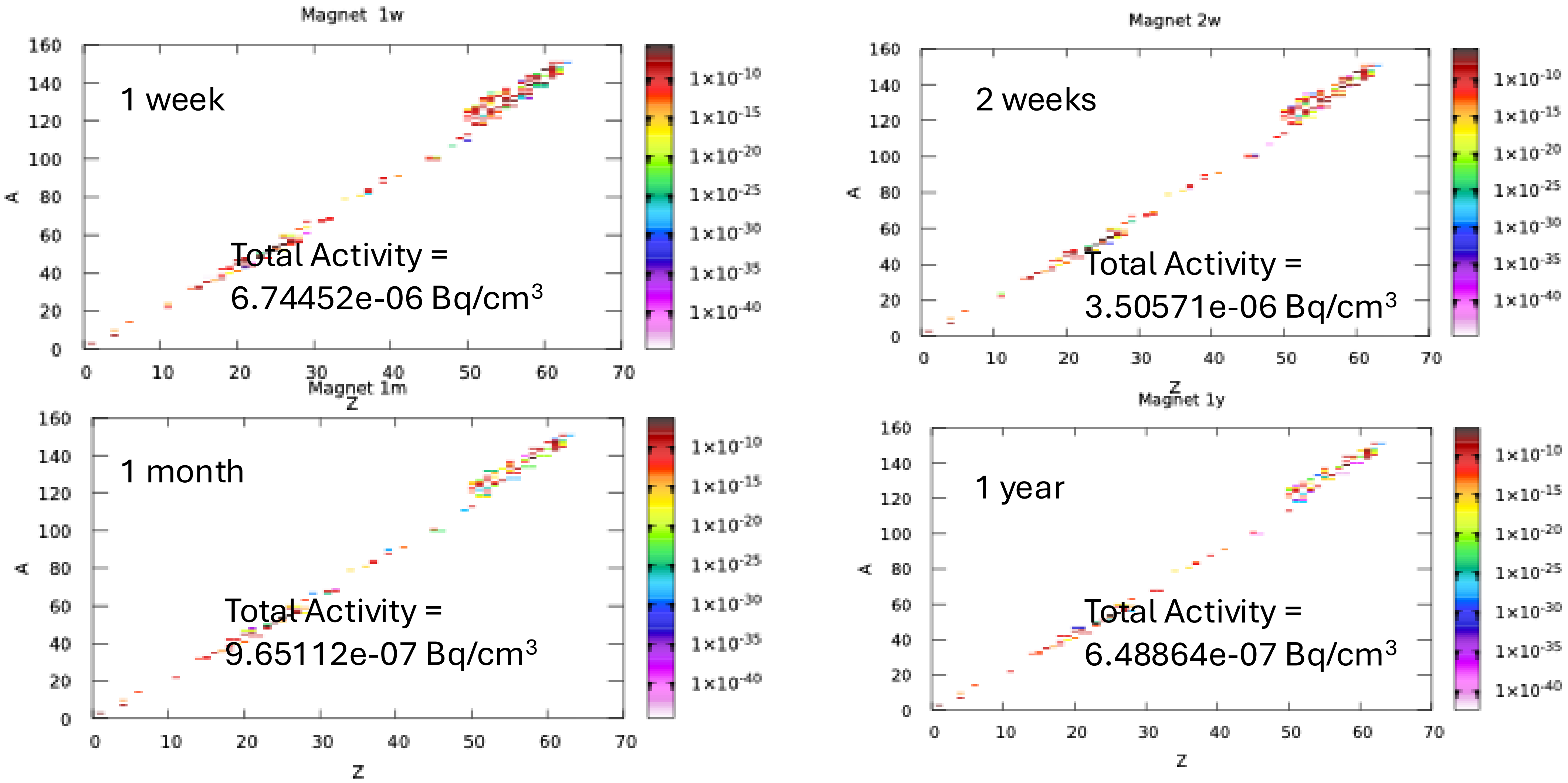
TW Activity = 17.54e-06 +/- 4.e-08 Bq/cm^3

Residual nuclei table for the magnet

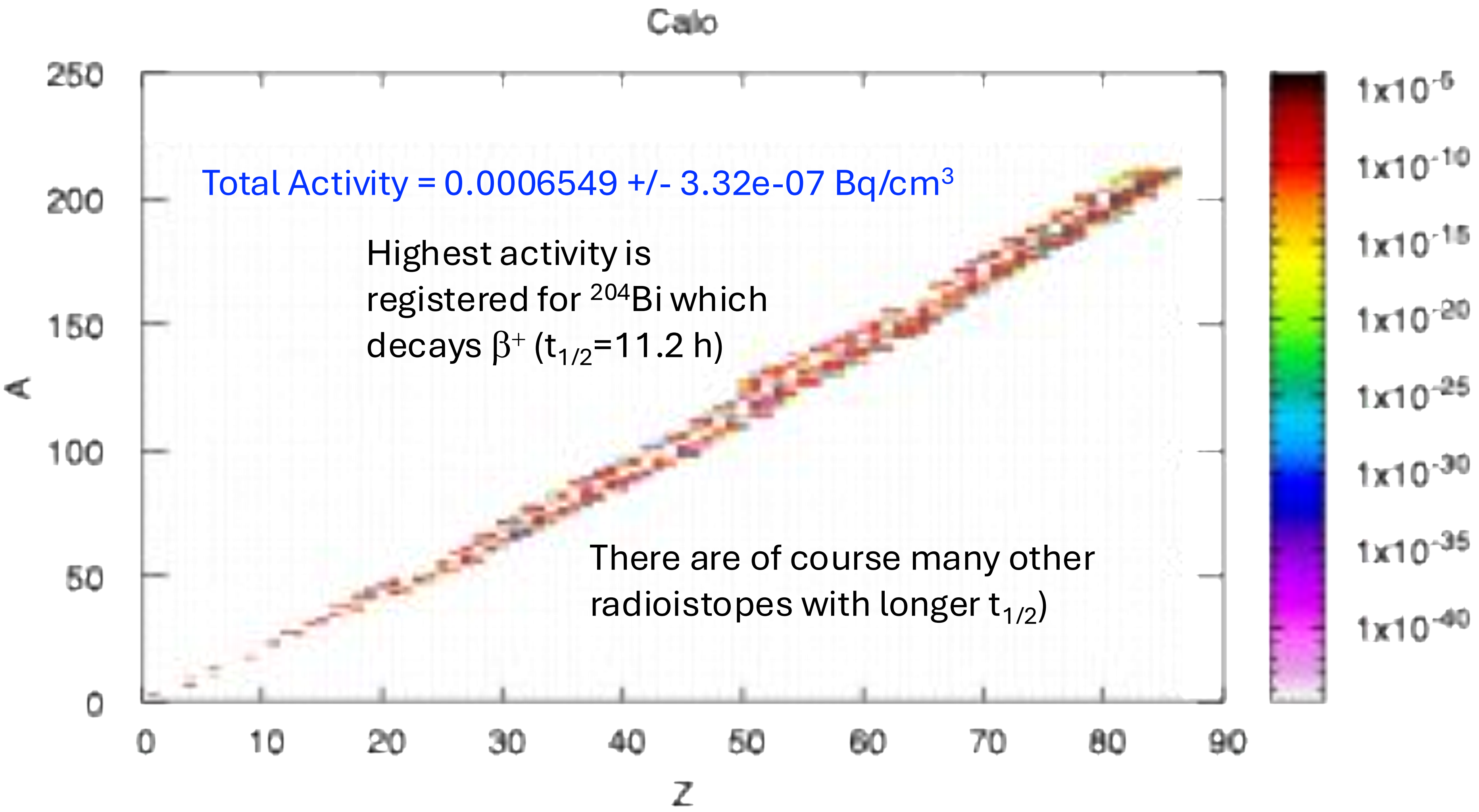


Here there might be a legal problem since there are radioisotopes with Z>31

Evolution in time for the magnet



Residual nuclei table for Calo



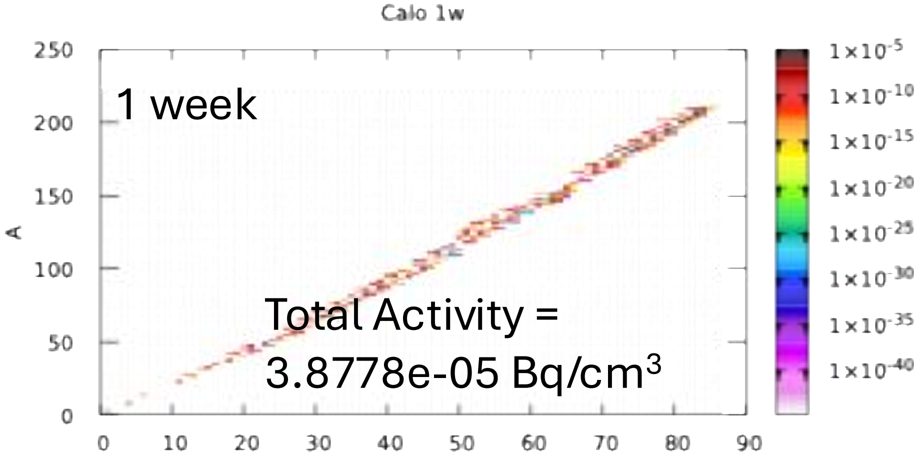
Total Activity = 0.0006549 +/- 3.32e-07 Bq/cm^3

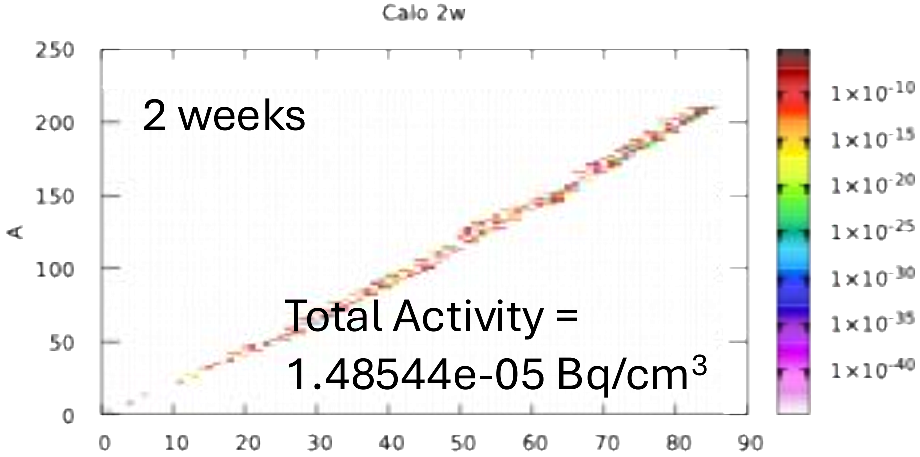
Highest activity is registered for ^{204}Bi which decays β^+ ($t_{1/2}$=11.2 h)

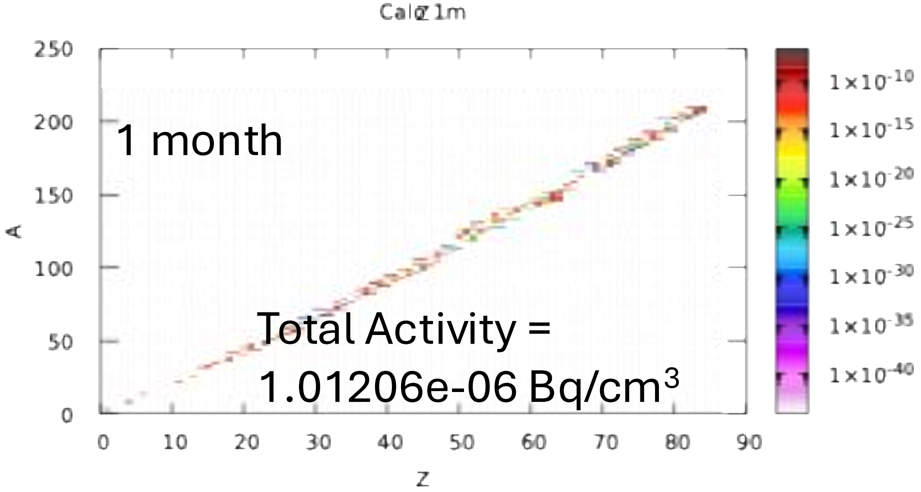
There are of course many other radioistopes with longer $t_{1/2}$)

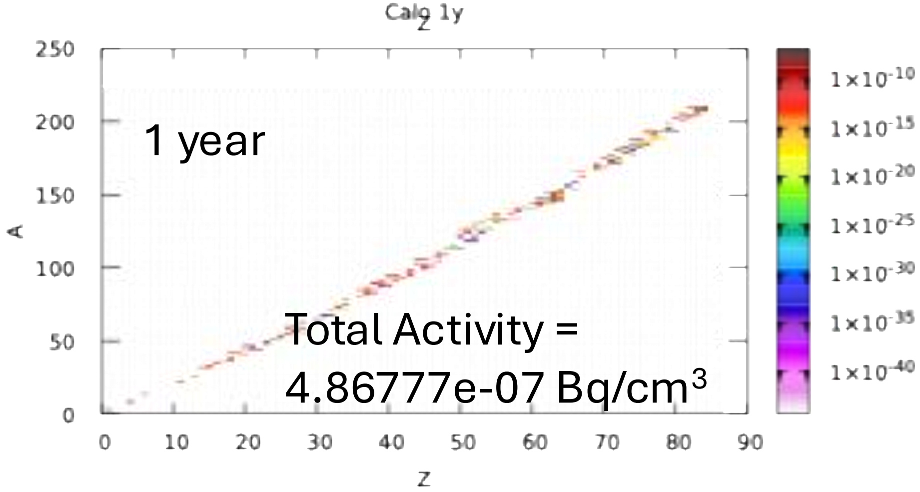
Here there might be a legal problem since there are radioisotopes with Z>31

Evolution in time for Calo



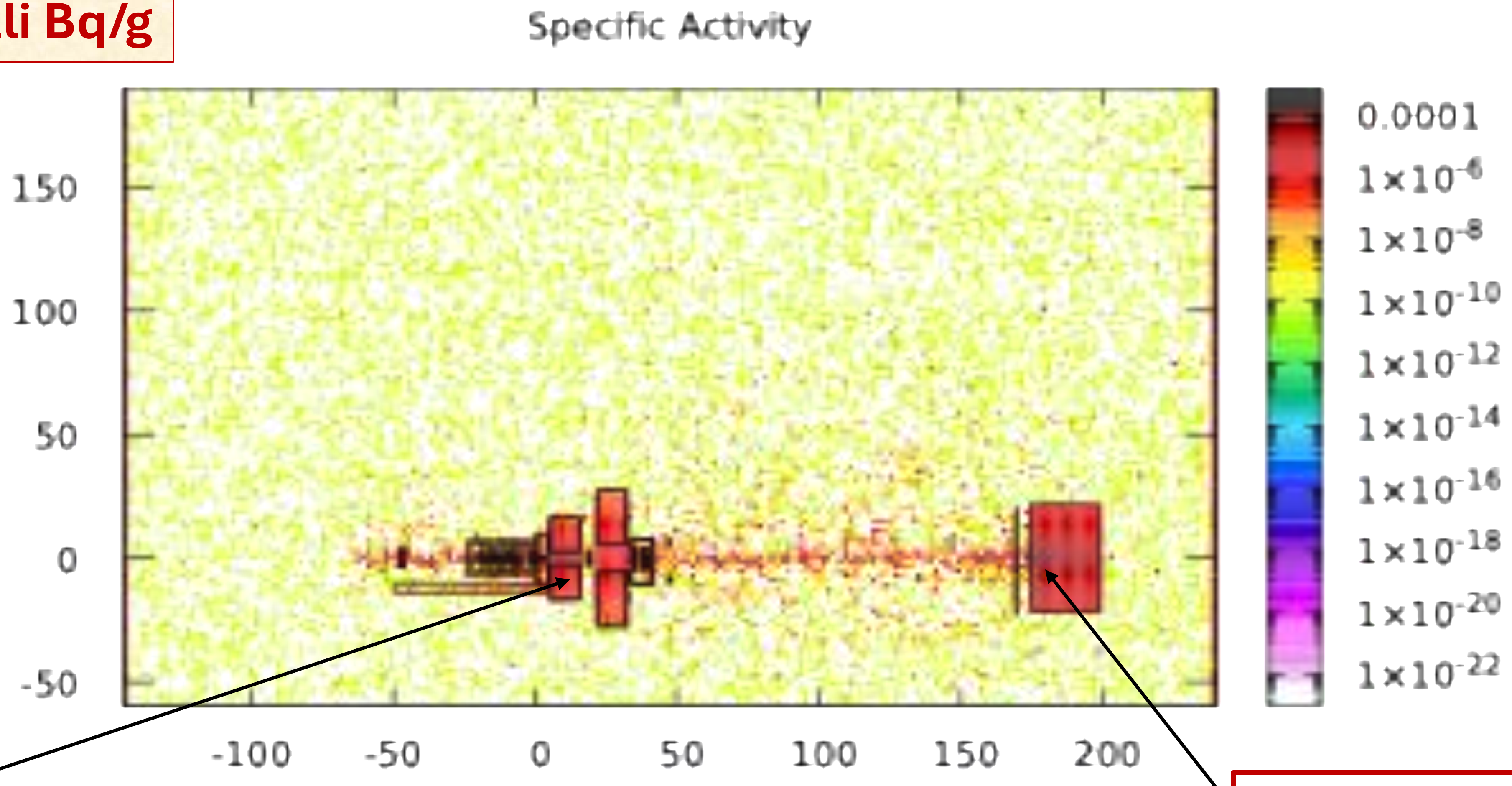






Specific activity (Bq/g, 1 day cooling time)

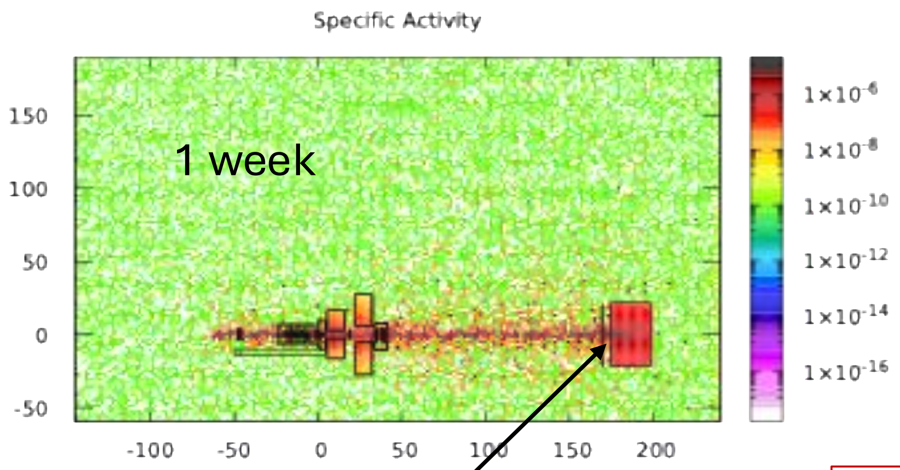
Limit < milli Bq/g



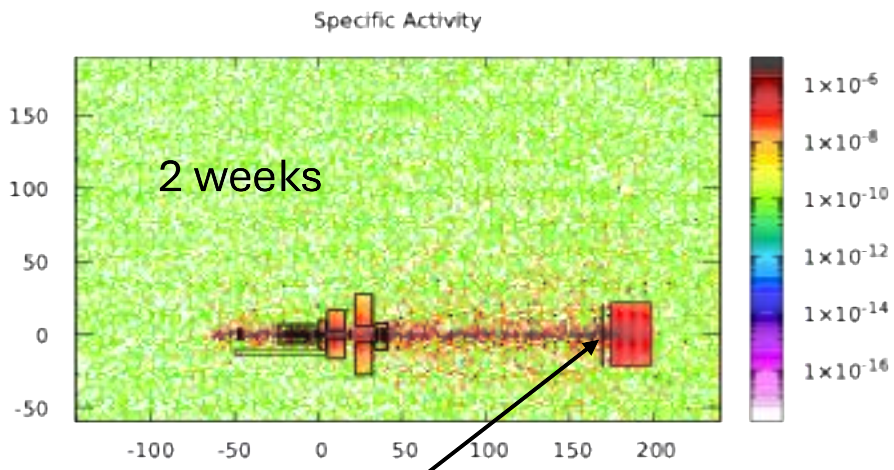
Even if the magnet is outside the beam axis, it is activated since it is a sort of dump for many charged fragments emitted at large angle (and neutrons as well)

Our hot point: 0.0392 Bq/g

Time evolution of specific activity of the hot point in Calo

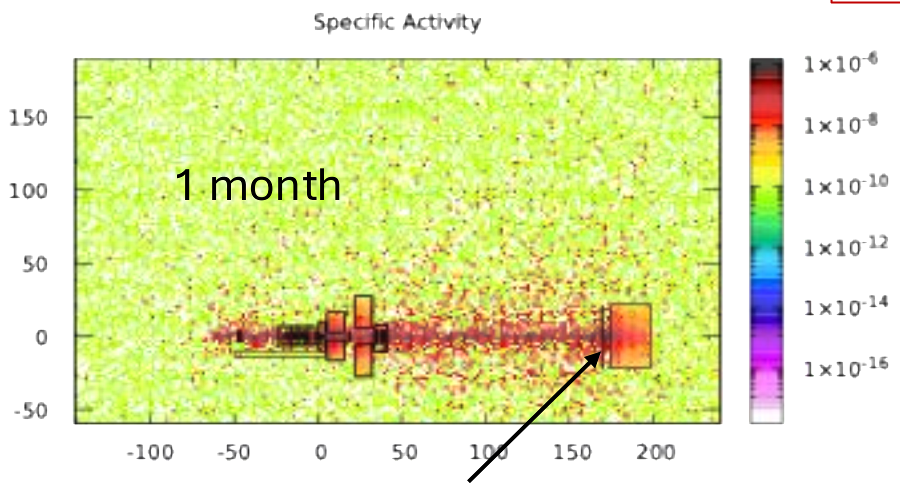


0.001976 Bq/g

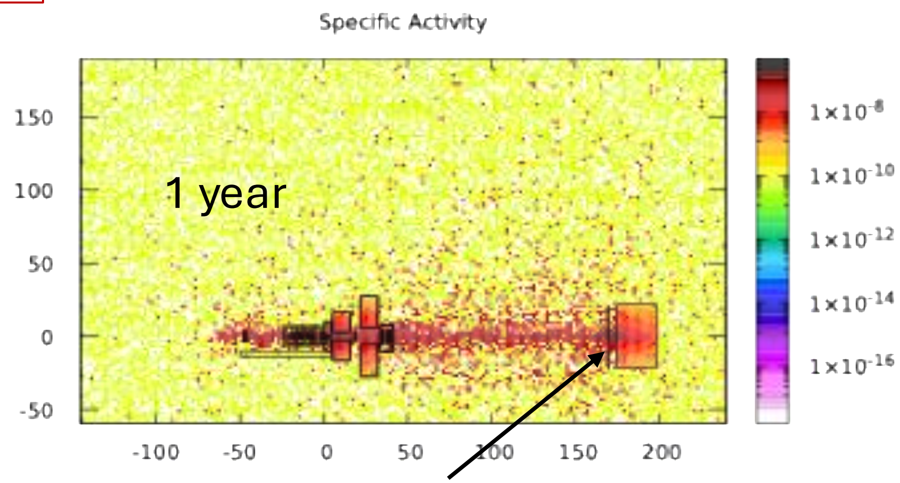


0.00099 Bq/g

Limit < milli Bq/g



0.000123 Bq/g



4.69e-05 Bq/g

Summary and conclusion

- A new kind of FOOT simulation had to be prepared to cope with the request of help coming from the radioprotection service of CNAO
- The amount of activation predicted for our detector seems to be below the threshold of attention
- However, there are at least two elements (Magnet and Calo) where the activation of $Z>31$ isotopes could trigger a problem related to the present status of the regulation
- We hope that our work will help to accelerate all the procedures
- Waiting for a feedback to draw the final conclusions