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Evaluation of long-term activation in view of future decommissioning of the CNAO hadron therapy, new proton therapy and BNCT facilities by means of Monte Carlo simulations

Valutazione dell'attivazione a lungo termine in vista del futuro decommissioning delle strutture dell'attuale adroterapia, della nuova protonterapia e della BNCT del CNAO, mediante simulazioni Monte Carlo

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*"Guardate lontano,
e anche quando crederete di star guardando lontano,
guardate ancora più lontano!"
B.P.*

Abstract

Since the 21st century, the use of particle accelerators for the treatment of complex oncological diseases has significantly advanced. The National Center for Oncological Hadron Therapy (CNAO), located in Pavia, Italy, is one of the only six centers worldwide that uses protons and carbon ions for the treatment of rare tumors.

CNAO is currently undergoing an expansion. The commissioning of the third ion source, AISHa, is in progress, enabling the production and acceleration of helium ions within the existing synchrotron. In the future, additional ion species, including oxygen, iron and lithium, are expected to be introduced. Furthermore, new facilities are under construction, including a proton therapy synchrotron provided by Hitachi and a tandem accelerator supplied by TAE Life Sciences for Boron Neutron Capture Therapy (BNCT).

As a part of the initial authorization process for a facility, a decommissioning plan is developed to assess the feasibility of dismantling operations and estimate the associated costs. Nuclear decommissioning is the technical and administrative process through which a nuclear facility is progressively dismantled, until no further radiological protection measures are required.

This thesis work, carried out at the CNAO Radiation Protection Office, aims to identify the generated radionuclides and to determine their specific activities after a 30-year irradiation period, which corresponds to the typical operational lifespan of these accelerators, followed by a 1-year cooling time for the most activated components of all three facilities. To obtain these results, the FLUKA Monte Carlo simulation code was applied, allowing for the modeling of various scenarios and for the evaluation of radiation-induced activation levels.

Abstract in lingua italiana

A partire dal XXI secolo, l'utilizzo degli acceleratori di particelle per il trattamento di patologie oncologiche complesse ha registrato un notevole sviluppo. Il Centro Nazionale di Adroterapia Oncologica (CNAO), situato a Pavia (Italia), è uno dei sei centri al mondo che impiega sia protoni sia ioni carbonio per il trattamento di tumori rari.

Attualmente, il CNAO è in fase di espansione. È in corso il commissioning della terza sorgente (AISHa), che permetterà la produzione e l'accelerazione di ioni elio nell'attuale sincrotrone. In futuro, è prevista l'introduzione di ulteriori specie ioniche, tra le quali ossigeno, ferro e litio. Inoltre, sono in costruzione nuove strutture che ospiteranno un sincrotrone per la protonterapia, fornito da Hitachi, e un acceleratore tandem di TAE Life Sciences per la Boron Neutron Capture Therapy (BNCT).

Come parte del processo autorizzativo iniziale di un impianto, viene sviluppato un piano di decommissioning per valutare la fattibilità dello smantellamento e stimarne i costi. Il decommissioning nucleare è il processo tecnico e amministrativo con cui un impianto nucleare viene progressivamente smantellato, fino a non richiedere più misure di radioprotezione.

Questo lavoro di tesi, svolto presso l'Ufficio di Radioprotezione del CNAO, ha l'obiettivo di identificare i radionuclidi generati e le loro attività specifiche dopo un tempo di irraggiamento di 30 anni, tipico ciclo di vita di questi acceleratori, seguito da un tempo di raffreddamento di un anno per i componenti più attivati di tutti e tre gli impianti. Per ottenere questi risultati, è stato utilizzato il codice Monte Carlo FLUKA, che permette di simulare diversi scenari e valutare i livelli di attivazione indotta dalla radiazione.

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1 | CNAO Foundation

According to the statistics from the Proton Cooperative Group, updated in January 2025, there are currently 121 proton therapy centers and 15 carbon ion therapy centers in operation worldwide. Among them, the National Center for Oncological Hadrontherapy (CNAO), located in Pavia, Italy, is the only facility in the country, and one of just six worldwide, capable of treating patients with both proton (p) and carbon ion (C^{6+}) therapy[14].

CNAO was inaugurated on February 15th, 2010 and, after the initial commissioning, began treating patients in 2011. Since then, the center has treated over 4000 patients, averaging between 500 and 700 per year [16].

CNAO is currently expanding its facilities by adding a proton therapy unit equipped with a rotating gantry and a Boron Neutron Capture Therapy (BNCT) facility. Additionally, the current synchrotron will expand its capabilities to accelerate helium, lithium, oxygen, and iron ions for both therapeutic and research purposes.

1.1. Hadron Therapy

Hadron therapy is an advanced form of radiotherapy used to treat inoperable or radiation-resistant tumors. Unlike conventional radiotherapy, which relies on X-rays or electrons, hadron therapy exploits hadrons, particles composed of quarks.

The primary advantage over conventional radiotherapy (X-rays and electrons) is its ability to precisely target the tumor while minimizing damage to the surrounding healthy tissues, thus reducing the treatment side effects. A charged hadron interacts with matter mainly through excitation and ionization.

As the particle moves from the body surface into deeper tissues, it loses energy by interacting with atoms along its path. The depth at which the particles stop is known as the particle range, while the energy loss per unit distance [$\text{keV}/\mu\text{m}$] is defined as the Stopping Power.

The particle energy loss along the path can be estimated using the Bethe-Bloch equation:

$$\frac{-dE}{\rho dx} = 2\pi N_a r_e^2 m_e c^2 \frac{Z}{A} \frac{z^2}{\beta^2} \left[\ln \frac{2m_e \gamma^2 v^2 W_{max}}{I^2} - 2\beta^2 - \delta - 2\frac{C}{Z} \right] \quad (1.1)$$

According to this equation, energy loss depends on the charge of the particle (z), is inversely proportional to its mass, and decreases with increasing velocity ($\frac{1}{\beta^2}$). In denser materials with a higher atomic number (Z), the incident particle releases more energy compared to those with a lower Z . Fast-moving particles release less energy, while highly charged particles deposit more energy into the medium.

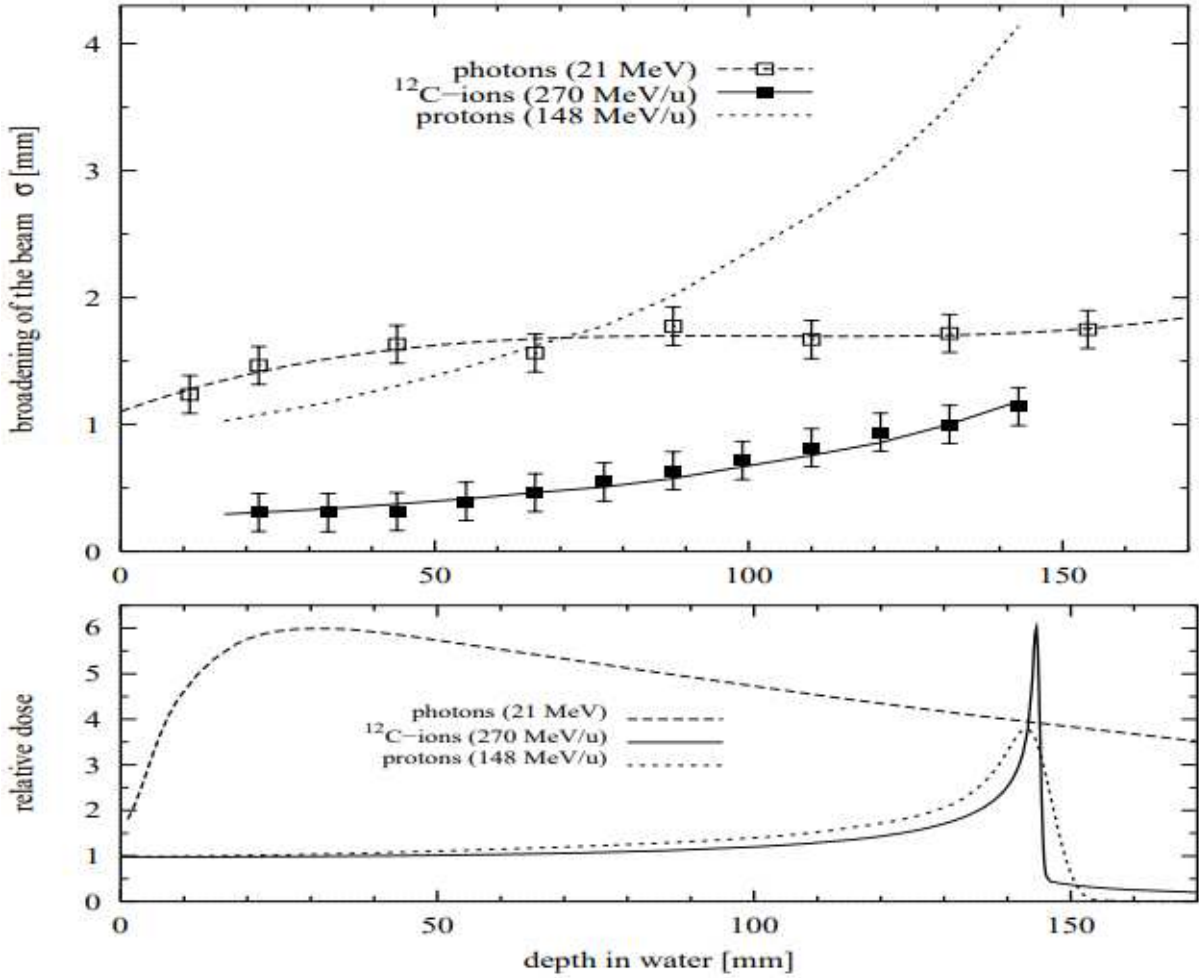


Figure 1.1: Comparison of the lateral scattering of photon, proton and carbon beams as a function of the penetration depth (top) and the depth dose correlation (Bragg peak) (bottom) [11].

As the particle slows down, its energy loss rate increases. Initially, interactions are brief,

resulting in lower energy transfer. However, toward the end of the particle path, energy deposition reaches a peak known as the Bragg peak [Figure 1.1]. This allows for a concentrated release of energy near the tumor, followed by a rapid decline to zero for protons or near zero for heavier ions. This precise targeting capability makes hadrons, particularly protons, ideal for treating tumors located near critical organs (e.g., eye tumors) and pediatric cancers. This energy deposition pattern differs significantly from that of photons and electrons, which release most of their energy on the patient's skin, making them more suitable for superficial treatments. In clinical practice, the dose is defined as the amount of energy deposited per unit mass of tissue, measured in Gray [Gy].

However, using a single Bragg peak is insufficient for tumor treatment, as the peak width is only a few millimeters, whereas tumors can extend over several centimeters. To ensure an even dose distribution, a Spread-Out Bragg Peak (SOBP) is created by overlapping multiple Bragg peaks [see Figure 1.2]. This is achieved using beams of varying energies, allowing optimal dose coverage across the tumor's depth. To further refine treatment precision, two beam modulation techniques are used: passive and active. The preferred method is active scanning, where beam range is adjusted by varying its energy at the accelerator. A system of magnets shapes the beam into a 'pencil beam', ensuring point-by-point tumor coverage.

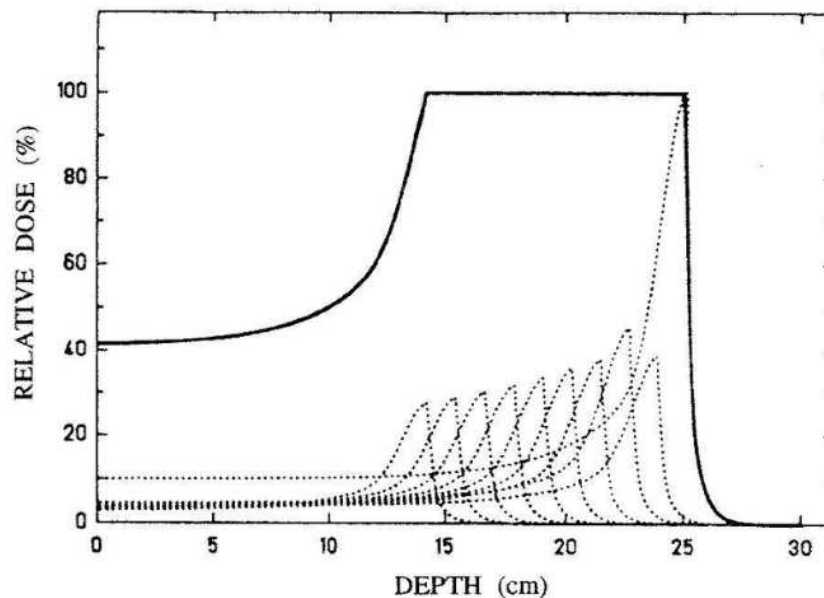


Figure 1.2: The Spread out Bragg peak.[3]

Carbon ions (and helium ions) interact differently with tissue compared to protons or X-rays. Being high-LET (Linear Energy Transfer) particles, they induce complex DNA

damage (double-strand breaks, DSB) that is harder for cells to repair, increasing the probability of cell death. This effect is quantified using the Relative Biological Effectiveness (RBE):

$$RBE = \frac{D_{ref}}{D} \quad (1.2)$$

where D_{ref} is the reference radiation dose (usually photons), and D is the dose of the radiation under study required to achieve the same biological effect. The RBE for protons is approximately 1.1, whereas for carbon ions, it is around 3. This means that carbon ions can achieve the same level of tumor cell damage with a dose three times lower than that required by protons.

Another key factor in treatment effectiveness is the Oxygen Enhancement Ratio (OER):

$$OER = \frac{D_{hyp}}{D_{oxy}} \quad (1.3)$$

where D_{hyp} is the absorbed dose required to induce a biological effect in hypoxic tissue, and D_{oxy} is the dose needed to achieve the same effect in fully oxygenated tissue under standard atmospheric pressure. The impact of oxygen, quantified by the OER, decreases with increasing LET. This suggests a clinical advantage for heavy ion therapy, such as carbon ion therapy, which has an OER close to 1. This property makes ion therapy particularly effective for treating hypoxic, radiation-resistant tumors that respond poorly to both X-ray and proton therapy.

Lighter ions (e.g., helium) are also being studied for therapeutic applications. They could offer advantages by exhibiting intermediate properties between carbon ions and protons. Helium ions experience less nuclear fragmentation at the end of their range compared to carbon ions and have reduced lateral scattering effects, which are more common with proton beams.

1.2. CNAO Synchrotron

Nowadays, the heart of CNAO is its synchrotron (Figure 1.3), located in a 1600 square meters bunker. The synchrotron has a 25 meter diameter and an 80 meter circumference, and it is isolated from the rest of the structure by radiation shielding made of concrete, ranging in thickness from 2 to 6 meters. These shields are essential to protect personnel and visitors from radiation exposure [15].

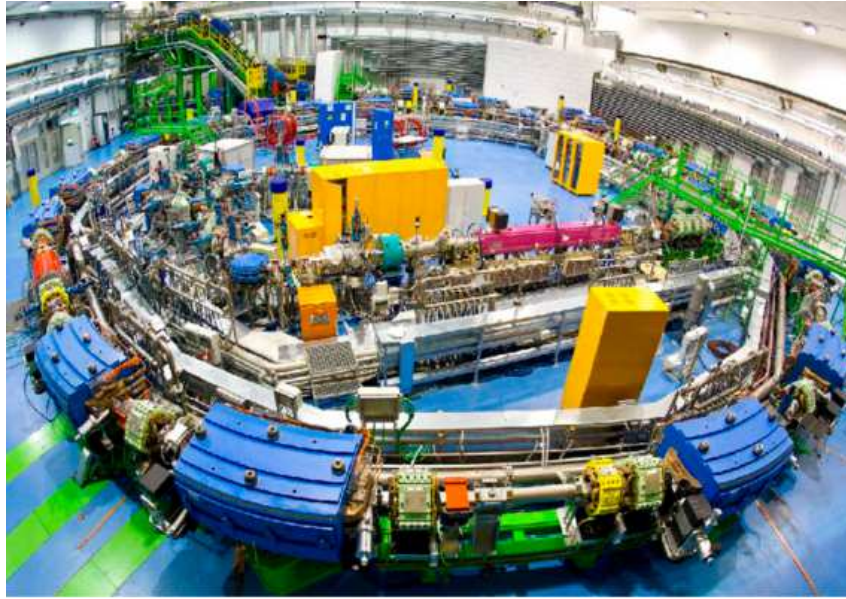


Figure 1.3: View of the synchrotron hall.

Inside the synchrotron ring, two identical Electron Cyclotron Resonance (ECR) sources are in operation: one using hydrogen (H_2) gas and the other one using carbon dioxide (CO_2) gas. By simply changing the gas used to generate plasma and optimizing parameters such as radiofrequency (RF) power and extraction electrode potential, different types of ion beams can be produced. Each source is designed to compensate for the possible unavailability of the other one. To generate helium, lithium, oxygen, and iron ions, a third ECR source, called AISHa (Advanced Ion Source for Hadron Therapy), was installed in September 2024.

The ion beams produced by these sources are then directed to a radiofrequency quadrupole (RFQ), which prepares the beam for further acceleration in the linear accelerator (LINAC). The RFQ accelerates longitudinally bunches, and transversely focuses the beam, increasing its energy from 8 keV/u at the input to 400 keV/u at the output.

The LINAC further accelerates the beam from 400 keV/u to 7 MeV/u in a 3.8 meter long tank. After this pre-acceleration stage, the beam is injected into the synchrotron, where it is accelerated to its final kinetic energy: up to 250 MeV for protons and up to 400 MeV/u for carbon ions. Figure 1.4 illustrates the synchrotron layout, including the ion sources and treatment rooms. Once acceleration is complete, the beam is directed to three treatment rooms (TR1, TR2, TR3) and one experimental research room (XPR). TR1 and TR3 are equipped with fixed horizontal beam lines. TR2 has both horizontal and vertical beam lines. XPR features a fixed beam line with four isocenters, allowing for flexible experimental setups.

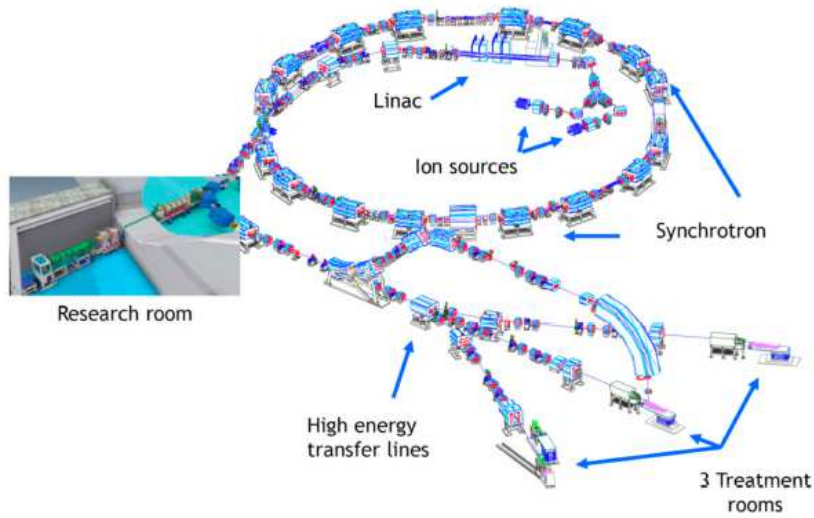


Figure 1.4: Model of the compact layout of the CNAO synchrotron: the injection chain is inside the ring and three horizontal beamlines are selected by a single fan-out magnet. Additionally, the experimental room is shown. [16]

1.3. New Proton therapy with HITACHI synchrotron

On December 2019, CNAO Foundation signed a contract with Hitachi Ltd. for the supply of a new synchrotron and a proton gantry. With this expansion, CNAO will become the only hadron therapy center in the world equipped with both a synchrotron for multiple ions (protons and carbon ions) and a dedicated proton synchrotron with a gantry [16].

The new system, developed by Hitachi, delivers Proton Beam Therapy using a technique called Intensity Modulated Proton Therapy (IMPT). This method reduces radiation exposure to healthy tissues by precisely modulating the intensity of the beam. In addition, the introduction of the gantry allows the beam to be delivered from any direction, optimizing the geometric aspects of the treatment. The decision to pair the gantry with a dedicated accelerator ensures independent treatments from the existing synchrotron. This setup also provides continuity of operation in the event of maintenance or technical issues affecting either machine.

The new facility, currently under installation, covers an area of approximately 6,000 m². It will include a dedicated proton therapy zone, along with spaces for patients, caregivers, and medical staff.



Figure 1.5: Model of the proton therapy technology proposed by Hitachi [16].

The main components of the Hitachi accelerator system are: the LINAC, four bending magnets, the electrostatic septum (ESD), the magnetic septum for passage through the High Energy Beam Transport (HEBT) system, the Gantry Beam Transfer Line (GABT), the isocenter. The LINAC is where protons are accelerated to an energy of 3.5 MeV, before being injected into the synchrotron. Inside the synchrotron, protons are accelerated in a vacuum vessel to the energy needed for the treatment up to 230 MeV. The HEBT carries the beam to the GABT and is where beam and profile measurements occur. The GABT transfers the protons to the patient. The presence of a gantry introduces the possibility of irradiating the patients from different angles and optimizing the geometric aspects, while the patient remains fixed.

1.4. Boron Neutron Capture Therapy - BNCT

Boron Neutron Capture Therapy (BNCT) is an innovative oncological therapy that was first applied in vitro to tumor fragments in 1940 by Kruger, eight years after Chadwick's discovery of the neutron. The idea of BNCT is based on the capture reaction of a thermal neutron by boron-10 (^{10}B), a natural isotope of boron with a concentration of 20% in nature. This reaction was first observed in 1935 by Taylor & Goldhaber.

During the interaction, a thermal neutron is absorbed by a ^{10}B nucleus, which has a capture cross-section of 3837 barns (b) at an energy of 25 meV ($1 \text{ barn} = 10^{-24}\text{cm}^2$). This

absorption produces an excited boron-11 nucleus ($^{11}\text{B}^*$), which then decays through two main pathways. With a 6% Branching Ratio (BR), it emits a lithium-7 (^7Li) nucleus with an energy of 1.01 MeV (in its ground state) and an alpha particle of 1.78 MeV. With a 94% BR, the $^{11}\text{B}^*$ nucleus decays by emitting a ^7Li nucleus in an excited state with 0.84 MeV, which quickly de-excites by releasing a 478 keV gamma photon.

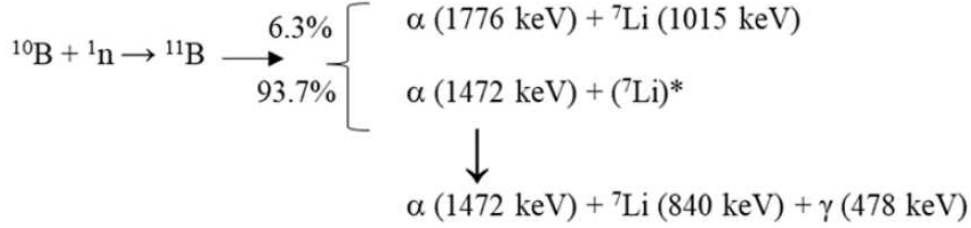


Figure 1.6: The boron neutron capture reaction [8].

Both the ^7Li and α particles have a short range, approximately $5 \mu\text{m}$ and $9 \mu\text{m}$, respectively. This is crucial because these distances are comparable to the typical diameter of a human cell ($10 \mu\text{m}$). Additionally, since these are high-LET (Linear Energy Transfer) particles, they cause double-strand breaks (DSBs) in the DNA molecule, which are difficult for the cells to be repaired. As a result, affected tumor cells lose their ability to divide, and undergo cell death.

BNCT is similar to external hadron therapy, but the tumour cells are killed by (charged) particles produced inside the body by the aforementioned neutron capture reaction. Boron-10 is injected into tumor cells and the therapeutic particles are generated directly within the patient. This provides a major advantage: BNCT can be highly selective and particularly suitable for treating metastatic tumors. The effectiveness of BNCT depends on the selective delivery and accumulation of boron in tumors. Moreover, the efficacy of BNCT depends not only on the boron concentration, but also on the localization of boron agents at the cell level.

An ideal BNCT agent should have low systemic toxicity and achieve higher uptake into the tumor tissue than the normal one. The concentration ratios of tumor to normal tissue (T/N) and tumor to blood (T/B) should be higher than 3–5:1 for optimal effectiveness. Other desirable properties are a tumor concentration of 20–35 mg $^{10}\text{B}/\text{g}$, as well as a rapid clearance from blood and normal tissues and a persistence in the tumor during the treatment. Nonetheless, the optimal parameters regarding the boron distribution and the boron levels in the tumor for a successful BNCT efficacy should continue to be a focus of research [17].

There are currently three generations of boron compounds. However, the two that are most commonly used in clinical practice are:

- Mercapto-undecahydro-closo-dodecaborate (BSH);
- 4-borono-L-phenylalanine (BPA) .

For BNCT, it is important to have a thermal neutron beam targeting cancerous cells. Superficial tumors are treated using thermal neutron beams ($E < 0.5$ eV), while deeper tumors require epithermal neutron beams ($E = 0.5$ eV to 10 keV). As these epithermal neutrons interact with the various elements in the human body (such as H, N, etc.), they slow down, generating a thermal neutron flux in boron-rich areas.

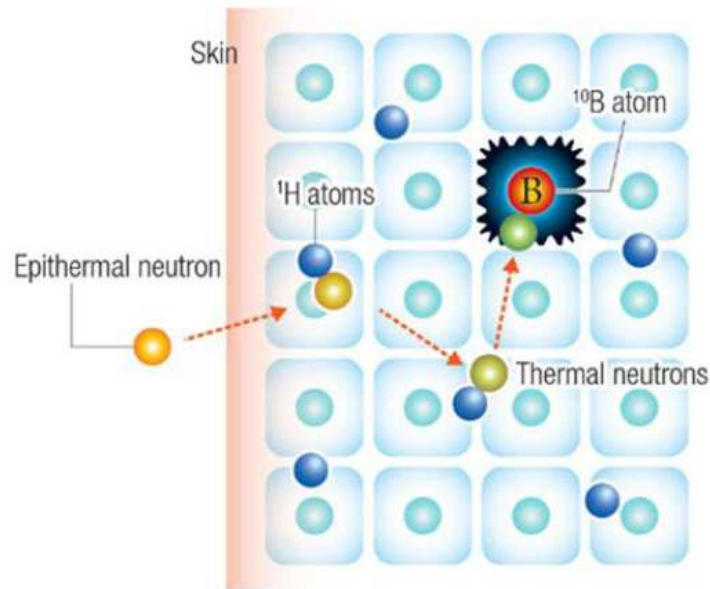


Figure 1.7: Schematic diagram of the interaction of an individual epithermal neutron being moderated by the hydrogenous tissue to thermal energies and thereafter being captured by a ^{10}B atom, triggering the therapeutic α decay [8].

In the last two decades there has been significant progress in the development of high intensity, accelerator-based neutron sources for BNCT (AB-BNCT) and other applications. The aim is to inaugurate the era of hospital-based BNCT facilities, moving progressively away from reactor-based facilities which, according to the prevailing consensus, are more costly, more difficult to operate and license, and, more importantly, more difficult to install in hospitals [8].

Neutron production reactions using accelerators can be either endothermic or exothermic. Typically, light projectiles (such as protons and deuterons) are used on specific targets to

ensure that the emitted neutrons have low energies, thus making beam moderation easier. The most commonly used projectile target reactions include:



In the future AB-BNCT facility at CNAO, neutron production will be based on proton capture reactions with lithium [Eq 1.4]. It is an endothermic reaction with a Q value of -1.65 MeV and a threshold energy of 1.88 MeV.

The cross-section trend exhibits a pronounced resonance at 2.25 MeV, reaching a peak value of 560 mbarn, as shown in Fig.1.8.

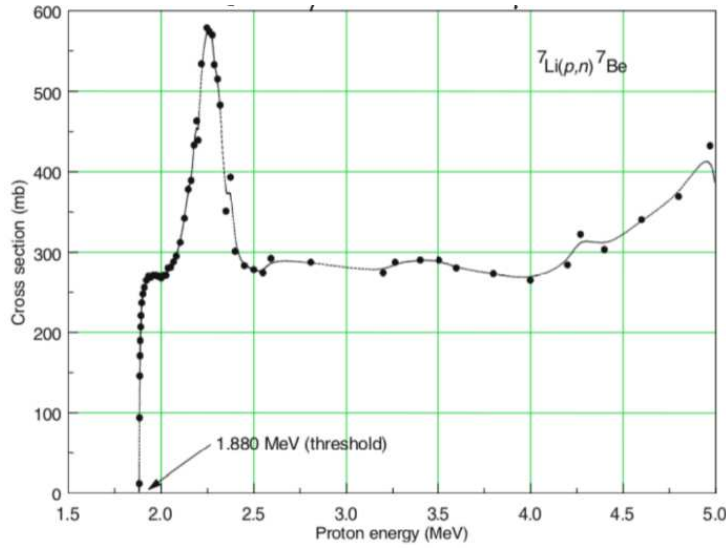


Figure 1.8: ${}^7\text{Li}(p,n){}^7\text{Be}$ cross section.

A disadvantage of using a lithium target is its low melting point and the production of ${}^7\text{Be}$, a radioactive isotope, which implies risks associated with the target decommissioning and with the possible contamination of the system. The neutrons produced in the lithium target can have energies above a few hundred keV, sometimes even reaching the MeV range. To create a well-shaped neutron field that meets the recommended characteristics in Fig.1.9 and achieves the desired beam energy, a Beam Shaping Assembly (BSA) is used.

Beam quality component	Symbol or definition	Reference value	Section	Ref.
Therapeutic epithermal flux ^a	ϕ_{epi}	$\geq 5 \times 10^8 \text{ cm}^{-2}\cdot\text{s}^{-1}$ (e)	3.1	[1, 78 ^e]
Thermal to epithermal flux ratio	$\phi_{\text{th}} / \phi_{\text{epi}}$	≤ 0.05	3.1	[1]
Beam directionality ^b	J / ϕ_{epi}	≥ 0.7	3.1	[1]
Fast neutron dose per unit epithermal fluence ^c	$D_{\text{H}} / \int \phi_{\text{epi}}(t) \cdot dt$	$\leq 7 \times 10^{-13} \text{ Gy}\cdot\text{cm}^2$	3.2.1	Table 27
Gamma dose per unit epithermal fluence ^{c,d}	$D_{\gamma} / \int \phi_{\text{epi}}(t) \cdot dt$	$\leq 2 \times 10^{-13} \text{ Gy}\cdot\text{cm}^2$	3.2.5	[1]

^a ϕ_{epi} refers to the flux of epithermal neutrons in the energy range typically defined for BNCT (Table 1).

^b Much lower values (e.g., 0.3) can be used for treatment of melanomas with more thermalized beams.

^c These are doses per unit fluence of epithermal neutrons, where epithermal fluence is defined as $\int \phi_{\text{epi}}(t) \cdot dt$, in units of cm^{-2} .

^d The range reported in reactor based BNCT facilities is $1\text{--}13 \times 10^{-13} \text{ Gy}\cdot\text{cm}^2$.

^e Ref. [78] reports $\int \phi_{\text{epi}}(t) \cdot dt = 5.3 \times 10^{11} \text{ cm}^{-2}$ used clinically in $t = 17 \text{ min}$, corresponding to $\phi_{\text{epi}} = 5.2 \times 10^8 \text{ cm}^{-2}\cdot\text{s}^{-1}$.

Figure 1.9: Reference neutron beam quality factors.

Figure 1.10 shows a schematic image of a typical BSA that generates an epithermal neutron beam. It consists of the following components:

- A high-energy neutron filter (made by Fe or Pb) installed after the target;
- Immediately downstream is the moderator (made by MgF_2 , AlF_3 or CaF) used to further reduce the neutron energies to the therapeutic range: this is typically the largest component;
- Next, thermal neutron (made by Cd or ^6Li) and gamma ray filters (made by Pb or Bi) are installed just upstream of the beam collimator to remove thermal neutron and photon contamination, respectively;
- Neutrons, with appropriately adjusted energy spectrum, pass through a collimator, and are emitted from a beam aperture with appropriate directionality, spectrum and flux;
- Surrounding these components is shielding.

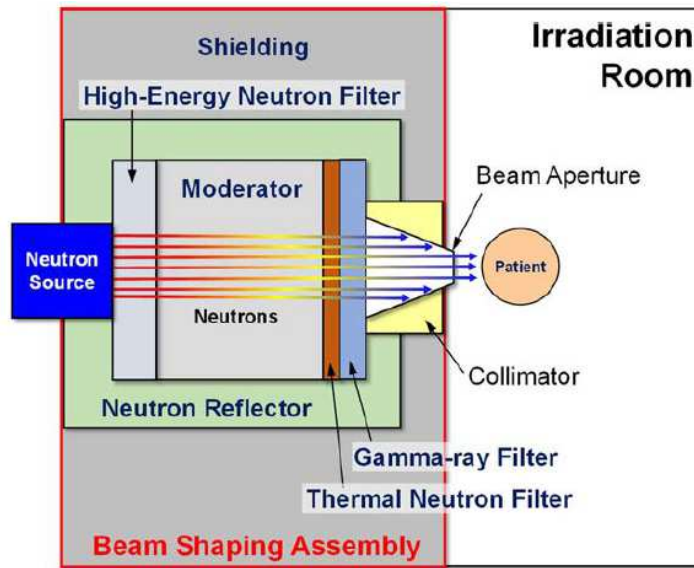


Figure 1.10: Typical beam shaping assembly for an epithermal neutron beam. All the components enclosed by the red line are usually counted as part of the BSA.

In the case of a BSA that generates a thermal neutron beam, the thermal neutron filter is not included in the BSA, but the size of the moderator required to further reduce the neutron energy may increase. In October 2020, a clinical and research collaboration was established between CNAO and TAE Life Sciences (TLS) to develop a new AB-BNCT facility. TLS has designed a compact neutron source based on a tandem accelerator to provide a complete BNCT solution. The accelerator is an electrostatic tandem [Fig. 1.11] for negative ions, from which a current higher than 10 mA of protons is generated with a stripping foil and subsequently accelerated to an energy of 2.5 MeV. To generate neutrons, TLS uses proton capture on a solid lithium target.



Figure 1.11: Tandem accelerator with source (on the left) and beamlines.

2 | Activation processes

2.1. Radiation Interactions with matter

The different types of ionizing radiation, from a physical point of view, can be classified into two main categories: charged radiation and neutral radiation. Charged radiation, or charged particles, interacts continuously with matter, losing most of its energy through inelastic collisions with electrons. These interactions produce ionizations and excitations of atoms and molecules in the target matter, as well as other processes such as radiative energy losses. Neutral radiation includes photons and neutrons. Photons interact with matter through different mechanisms depending on their energy; the most important ones are photoelectric effect, Compton effect, and pair production. The latter dominates at high energies and is responsible for the propagation of the electromagnetic cascade. Neutrons, on the other hand, interact exclusively through nuclear interactions, which are highly energy-dependent. However, when particle energy becomes very high, like in an accelerator where particles reach hundreds of MeV, nuclear interactions become dominant. A high-energy hadronic particle can interact not only with atomic nuclei but also with individual nucleons. This chapter focuses on these types of interactions, which are essential for understanding the radiation field near a hadron accelerator [2].

2.1.1. Nuclear reactions

A typical nuclear reaction is written as:

$$a + X \rightarrow Y + b + Q \quad (2.1)$$

where a is the accelerated projectile, X is the target, Q is the Q -value of the reaction, Y and b are the reaction products. Generally, a and b will be nucleons or light nuclei, but occasionally b will be a γ ray. The possibility of a nuclear reaction occurring is determined by conservation laws, which require that certain physical quantities remain unchanged as the system transitions from the initial to the final state. In general, these quantities include conservation of total energy, linear momentum, angular momentum, electric charge, and

baryon number.

Nuclear reactions can be classified in many ways, based on their type or the incident energy. In the first case, if the incident and outgoing particles are the same, and correspondingly X and Y are the same nucleus, it is a scattering process, which is elastic if Y and b are in their ground states, or inelastic if Y or b is in an excited state, from which it will generally quickly decay by γ emission. Finally, in a transfer reaction, one or two nucleons are transferred between projectile and target, such as an incoming deuteron turning into an outgoing proton or neutron, thereby adding one nucleon to the target X to form Y [12].

As mentioned earlier, nuclear reactions can also be classified on the basis of the incident energy. At high energies, around 100 MeV/u, nuclear reactions can be assumed to occur in a single step. In the semi-classical picture, the projectile experiences only a slight deflection from its trajectory, resulting in forward-peaked angular distributions. In addition, in these reactions, incident particles can transfer a significant amount of energy to the target nucleons, leading to the formation of an intranuclear cascade within the nucleus. At the opposite extreme, low-energy reactions, around 1 MeV/u, are characterized by much longer interaction times. In these cases, the large number of collisions creates a thermalized composite system formed by the projectile and the target, known as a compound nucleus. The compound nucleus survives long enough to lose memory of its formation process and decays into a final state that is independent of the initial state. At intermediate energies, between 1 and 100 MeV/u, pre-equilibrium reactions, also known as multi-step reactions, occur.

Intranuclear Cascade

When incident particles transfer a significant amount of energy to nucleons, an intranuclear cascade develops within the nucleus. In this process, nucleons gain enough energy to move inside the nucleus and interact with each other. As a result, some nucleons may be emitted almost immediately, within a time scale of about 10^{-21} s, with very high kinetic energies. At longer timescales, around 10^{-16} s, additional delayed emission processes can occur:

- Some nucleons or new nuclei may be emitted in the spallation process;
- The nucleus may split into two or more fragments in high-energy fission;
- If multiple light ions are emitted, the process is called fragmentation.

Furthermore, for energies above approximately 300 MeV/u, meson production is possible,

including pions, with energies reaching the GeV scale.

Pre-equilibrium

When the energy of all nuclei and nucleons drops below a few tens of MeV, the intranuclear cascade fades, giving way to pre-equilibrium processes. In this phase, the projectile's energy is dissipated both through scattering with nuclei and interactions with nearby nucleons. As a result, nucleons are emitted from the target with an energy comparable to that of the projectile and a strongly forward-peaked angular distribution.

Compound nucleus

At low energies, the particles involved in the reaction have a relatively long time to interact. As a result, the system undergoes complete thermalization, meaning that the projectile and the target form a compound nucleus, where energy and angular momentum are statistically distributed among all nucleons. Under these conditions, the system loses memory of the initial reaction, retaining only the total excitation energy, making the final state independent of the initial state. The compound nucleus de-excites mainly through the isotropic emission of nucleons and photons. However, above a certain energy threshold, nucleon emission is significantly more likely. Additionally, the probability of proton emission is lower than that of neutron emission due to the Coulomb barrier. In general, the emission probabilities follow the relation $\mathbf{P}(\mathbf{n}) > \mathbf{P}(\mathbf{p}) > \mathbf{P}(\gamma)$, where $\mathbf{P}$ represents the probability of emission. This emission process is often referred to as nuclear evaporation, due to its similarity with molecular evaporation. The final phase of de-excitation is characterized by γ -ray emission, resulting from transitions between energy levels of the residual nucleus, which often remains in an excited state before reaching its ground state. Finally, some of the final products may include radionuclides, which decay by emitting delayed β and γ radiation.

2.1.2. Hadronic Cascade

As discussed in previous sections, a high-energy neutron or proton can interact with a nucleus, producing one or more new particles. These secondary particles may then undergo further interactions, producing additional hadrons and initiating a self-sustaining process known as a nuclear or hadronic cascade. The main contributors to the cascade's propagation are nucleons and pions. A simplified representation of this process is shown in Figure 2.1. As successive nuclear interactions occur, the energy of the hadrons gradually decreases. The cascade terminates when their energy drops below the threshold required

for nuclear interactions, leaving only possible interactions with atomic electrons or elastic scattering. In the case of neutrons, the process often concludes with a (n,γ) reaction.

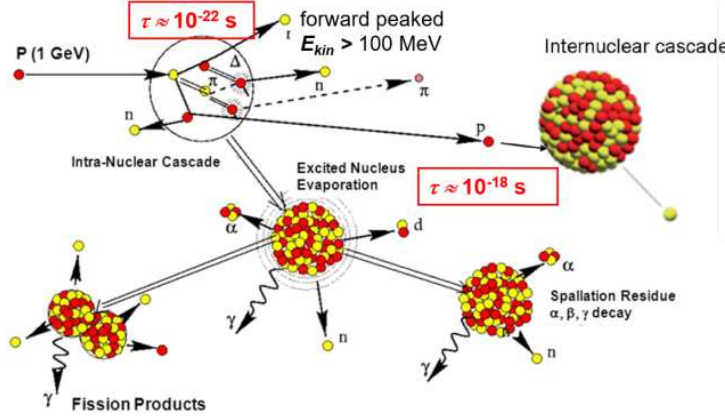


Figure 2.1: The reaction product by the spallation of protons of 1 GeV energy on a heavy target. [6]

The spatial development of a cascade, both in the longitudinal and transverse directions, is characterized by the interaction length, λ , measured in g/cm² and dependent on the material. The longitudinal spread increases logarithmically with the initial energy, while the transverse extent remains confined within a cylindrical region with a radius comparable to one interaction length. Finally, these processes lead to the formation of various radionuclides, which contribute to the problem of induced radioactivity.

2.1.3. Electromagnetic Cascade

Electromagnetic cascades can be initiated by a single high-energy electron or photon. Through bremsstrahlung and pair production processes, these particles generate a multiplying effect, leading to the production of a large number of electrons and gamma photons. This process is somewhat analogous to a hadronic cascade, with the key distinction that it is driven by particles undergoing electromagnetic interactions, such as electrons, positrons, and photons, rather than hadrons. In practice, both types of cascades coexist. For example, nuclear reactions often produce gamma rays, which can initiate an electromagnetic cascade. On the other hand, a high-energy photon interacting with a nucleus may trigger the emission of a nucleon through a photonuclear reaction. As a result, both cascades contribute to the overall radiation field, with their relative significance depending on the specific context. In a proton accelerator, hadronic cascades dominate, whereas in an electron accelerator, electromagnetic cascades play the primary role.

2.1.4. Neutron interaction

Neutrons are neutral particles, meaning they do not interact with atomic electrons but only with nuclei through nuclear interactions. Unlike electromagnetic interactions, the strong nuclear force has a very short range, in the order of 10^{-13} cm. As a result, neutrons must pass extremely close to a nucleus to interact with it. Given the small size of the nucleus compared to the entire atom, the probability of interaction is generally low, allowing neutrons to travel significant distances through matter [10].

Neutrons can be produced with a wide range of energies, and their interactions with matter depend strongly on their energy. As neutron energy increases, different interaction processes become possible, overlapping with one another. Neutrons are conventionally classified based on their energy as follows:

1. Low-energy or thermal neutrons: $E_n < 0.1$ eV
2. Intermediate energy or epithermal neutrons: $0.1\text{eV} < E_n < 10$ keV
3. High energy or fast neutrons: $E_n > 10$ keV

At low energies, neutrons primarily interact through elastic scattering and radiative capture. As their energy increases, additional interaction processes can occur. However, elastic scattering and radiative capture remain possible at all energy levels, though their probability decreases. In elastic scattering, a neutron collides with a target nucleus and is deflected in a different direction. The neutron loses energy, which is transferred to the target nucleus, causing it to recoil. The amount of energy transferred depends inversely on the mass of the target nucleus, which is why neutron moderators are typically composed of light, hydrogen-rich materials. Radiative capture involves (n, γ) reactions, where the incident neutron is absorbed by the target nucleus, forming a compound nucleus that de-excites by emitting a gamma photon within approximately 10^{-16} s. The resulting nuclei, often beta and gamma emitters, contribute to delayed radiation. At low energies, the neutron capture cross-section, as shown in Figure 2.2, follows a $1/v$ trend. At higher energies, it shows multiple resonance peaks. These peaks appear when the neutron's kinetic energy, combined with the nucleon binding energy, matches an energy level of the compound nucleus. According to the shell model, neutron absorption is more likely in these cases. If the excitation energy of the compound nucleus is higher than the nucleon binding energy, the nucleus tends to release a nucleon rather than a gamma photon. As neutron energy increases further, additional reactions become possible, such as inelastic scattering (n, n') , where a compound nucleus emits a neutron n' with lower energy than the incident neutron n . Other possible reactions include (n, p) , (n, α) , and $(n, 2n)$, where

different particles are emitted.

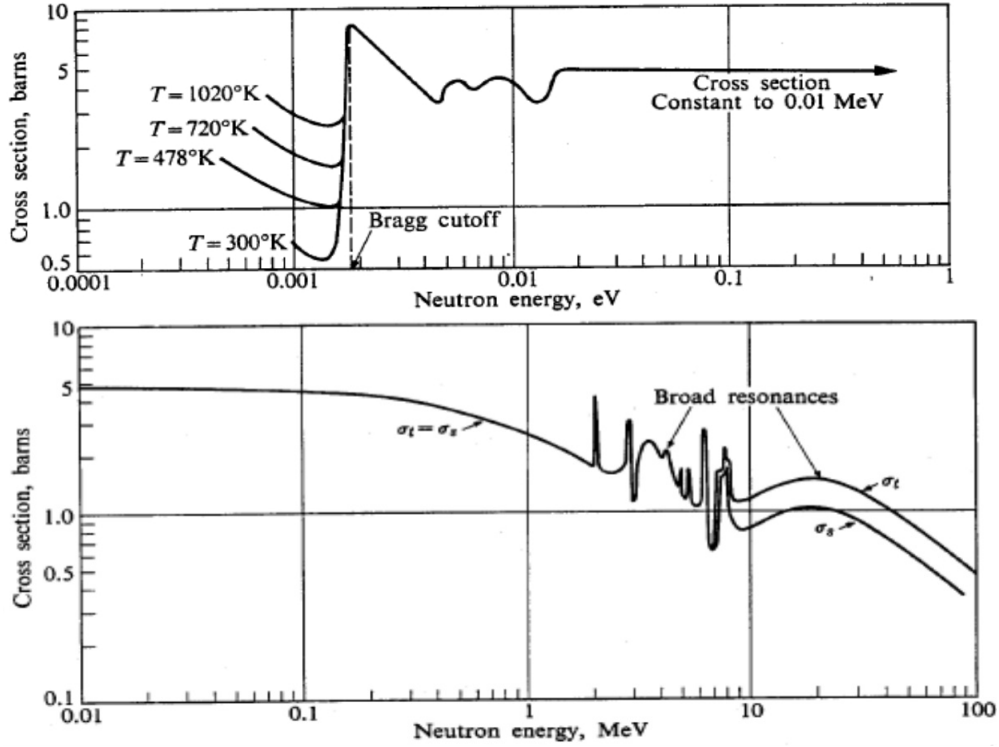


Figure 2.2: The total and elastic scattering cross section of C^{12} .

At even higher energies, pre-equilibrium reactions become increasingly significant, followed by direct reactions and intranuclear cascade processes, as discussed in the previous paragraphs.

2.2. Induced Radioactivity and Activity

The type of nuclides and secondary particles produced in nuclear reactions depends on the target atom, the projectile type, and its energy. In some cases, the resulting nuclide may be unstable, even if the original target atom was a stable isotope. When this happens, the nuclide emits radiation, leading to a phenomenon known as material activation or induced radioactivity. Activation is measured as the number of new unstable atoms produced due to the irradiation of the material. The number of nuclei made radioactive in an interval of time dt is given by :

$$dN_{act} = \phi N_t \sigma dt \quad (2.2)$$

where:

- N_t is the number of target atoms.

- ϕ is the flux of incident projectiles per unit time.
- σ is the capture cross-section, indicating the probability of forming a new nuclide.

Taking into account the nuclei produced that decay over time during irradiation, and considering λ as the decay constant of the activated nuclide, the resulting expressions are exponential:

$$N_{act}(t_i) = \frac{\phi N_t \sigma}{\lambda} (1 - e^{-\lambda t_i}) \quad (2.3)$$

where:

- t_i is the irradiation time.

The Activity, A , is the total number of these decays in the time unit and is equal to:

$$A(t_i) = \frac{-dN_{act}}{dt} = \lambda N_{act}(t_i) \quad (2.4)$$

The activity unit is the Becquerel [Bq], whose unit in SI is $[s^{-1}]$. For long irradiation times ($t_i \gg 1/\lambda$), the exponential term of eq 2.3 tends to zero, and the radioactivity reaches a steady-state value, known as the saturation activity (A_{sat}).

Once irradiation stops, the newly formed radionuclides decay exponentially, so after a time t , called cooling time, the remaining activity is:

$$A(t) = \lambda N_{act}(t_i) e^{-\lambda t} \quad (2.5)$$

A key factor influencing material activation is the reaction cross-section, which represents the probability that the projectile is captured and forms a new radionuclide.

The cross-section can vary by several orders of magnitude, depending on the reaction and the projectile-target combination. Additionally, it depends on the projectile energy. In endothermic reactions involving charged particles, there is an energy threshold below which the reaction cannot occur. As the projectile energy increases, new reaction thresholds are surpassed, leading to the formation of additional nuclides. However, in high-energy hadron interactions, the cross-sections vary slowly and remain within the same order of magnitude (around tens of millibarns, mb), regardless of the specific hadron used.

Finally, even radionuclides with low cross-sections can become relevant if the material is exposed to a high-intensity particle flux ϕ [2].

2.2.1. Specific activity

The specific activity of a radionuclide in a sample is defined as its activity A divided by the total mass m of the sample. It is typically expressed in units of [Bq/g]:

$$A_s = \frac{A}{m} \quad (2.6)$$

If the sample consists of a single element, its mass is given by:

$$m = \frac{N_{act}M}{N_a} \quad (2.7)$$

where:

- M is the molar mass of the element,
- N_a is the Avogadro number.

3 | Monte Carlo method and FLUKA

3.1. Monte Carlo method

The Monte Carlo Method refers to any numerical approach that uses random numbers to solve a problem probabilistically. This method is used in scientific fields to simulate stochastic processes, model the response of experimental instruments, and perform approximate numerical calculations.

Although probabilistic methods have a long history, systematic studies began only after 1945, leading to significant advancements. The idea of applying probabilistic techniques to neutron diffusion problems, which is the foundation of the Monte Carlo method, is generally attributed to the mathematician Stanislaw Ulam (1947), a key figure in the Manhattan Project, the program that led to the development of the atomic bomb during World War II [13].

The mathematical foundation of the Monte Carlo method is based on the Central Limit Theorem, which allows for the estimation of physical observables by sampling a set of particle trajectories, random paths, according to interaction cross-sections. The core component of all Monte Carlo codes is the pseudorandom number generator (PRNG), which produces sequences of numbers with a uniform distribution, starting from one or more seeds. In a Monte Carlo simulation, each particle follows its own history. During transport, at each interaction event, the cross-section and mean free path of the radiation are randomly sampled until the radiation is absorbed and its history ends. As the number of simulated particles increases, so does the number of histories considered, leading to greater accuracy in the final result. However, this results in a significantly long total runtime for the simulation.

3.2. The FLUKA Code

FLUKA (FLUktuierende KAskade) is a Monte Carlo simulation code written in FORTRAN (FORmula TRANslator). It was developed in the 1960s through a collaboration between CERN and INFN. This code is designed to simulate, in a complete and precise way, the transport and interaction of elementary particles and ions in complex geometries and materials.

FLUKA can simulate hadron-hadron, hadron-nucleus, leptonic, and electromagnetic interactions within an energy range from 1 keV (or 1 keV/n for ions) up to 10^{21} eV, except for photons and neutrons, which can be transported down to 100 eV and 10^{-5} eV, respectively.

These features make FLUKA particularly suitable for radiation protection applications, such as the study of induced radioactivity, the production of radionuclides, and the transport of residual radiation.

The following sections will outline some of the key physical models implemented in FLUKA, focusing only on those relevant to this study and providing a general overview of the software's functionality.

3.2.1. The Physics of FLUKA

FLUKA incorporates advanced physical models for particle transport across different energy ranges. A detailed description of nuclear and atomic interaction models, as well as their transport mechanisms, can be found in [4].

Hadron-nucleon interactions at energies below a few GeV are described by the isobar model, which accounts for the production and decay of hadronic resonances, along with elastic scattering, charge exchange, and strangeness exchange processes. For energies above a few GeV, the Dual Parton Model (DPM) is used.

Among the nuclear interaction models, one of the most accurate for intermediate energies ($E < 5$ GeV) is PEANUT (Pre-Equilibrium Approach to Nuclear Thermalization). This model includes:

- Glauber-Gribov Cascade, which describes multiple interactions between an incoming hadron and target nucleons;
- Generalized Intra-Nuclear Cascade (GINC);
- The pre-equilibrium stage;

- The evaporation and final de-excitation stage of the nucleus.

For low-energy neutron transport ($E < 20$ MeV), FLUKA employs a multigroup algorithm, where particles are assigned to discrete energy groups. The FLUKA cross-section library currently includes 260 energy groups, 31 of which are specifically dedicated to thermal neutrons. Starting from FLUKA 2021, the point-wise fully correlated neutron transport model has been introduced, significantly improving the accuracy of neutron reaction simulations.

3.2.2. Input file

FLAIR (Fluka Advanced Interface) is a graphical interface designed to simplify the use of the FLUKA code. It allows users to modify routines, manage code execution, visualize geometry in real time, and analyze output files. The input is divided into different categories in which the user can activate different CARDS. The following paragraphs introduce these categories, with a description of the main CARDS used [18].

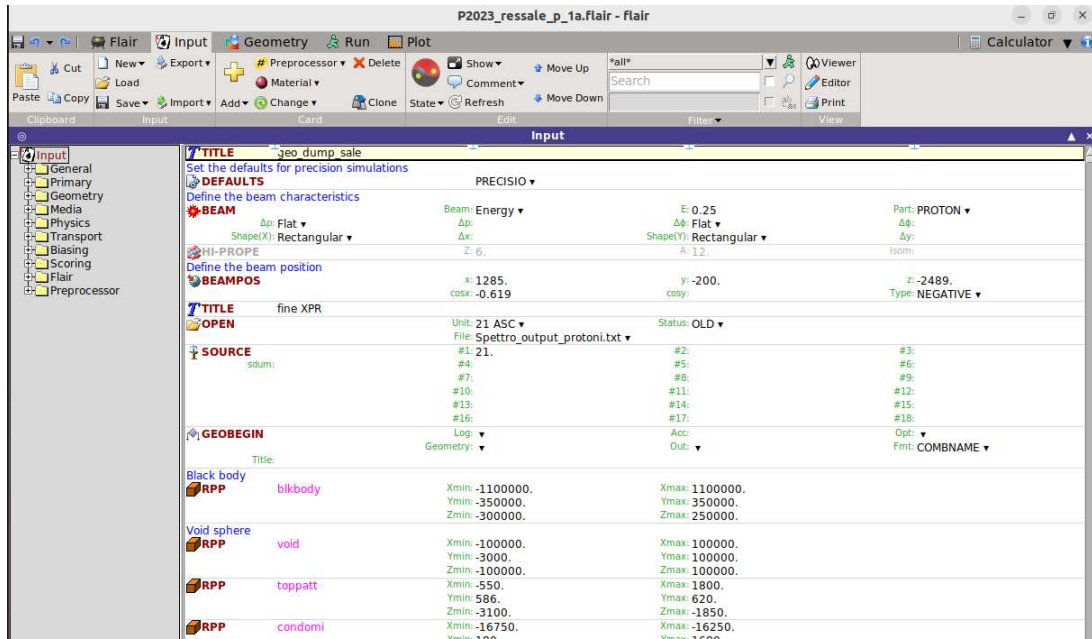


Figure 3.1: FLAIR input interface.

General

Here the user can configure the general settings of the problem. A title can be assigned to the simulation using the TITLE CARD, while the DEFAULT CARD with the PRECISIO option selects the physics models used. This option ensures high computational

accuracy, low-energy neutron transport, and heavy fragment production. Additionally, the RANDOMIZE CARD sets the seeds for the random number generators.

Primary

Here, the user can find CARDS that define the primary starting particles:

- BEAM: defines the primary beam characteristics, including energy, particle type, and beam dimensions.
- HI-PROP: when selecting heavyion in the BEAM CARD to simulate a heavy ion beam, this card specifies the atomic number (Z) and mass number (A) of the ion.
- BEAMPOS: allows setting the initial beam position, defining its coordinates and direction.
- SOURCE: instructs FLUKA to use a custom source routine implemented separately in FORTRAN. This allows the user to bypass FLUKA's standard CARD setup and create a different configuration. In this thesis work, the source routine was modified multiple times to introduce emissions with specific spectra and positions within the geometries.
- START: sets the number of primary particles in the simulation, affecting statistics and normalization of scoring CARDS.

Geometry

FLUKA uses a combinatorial geometry system, where standard-shaped objects (cylinders, spheres, parallelepipeds, planes, etc.) called BODIES are combined using Boolean operations to create complex structures.

The intersection, subtraction, and union of these bodies define REGIONS, which can be assigned specific materials. To prevent the simulation from running indefinitely by tracking particles endlessly, it is essential to include an outer region enclosed by a closed body (e.g., a sphere) and assign it the Black Hole material. Any particle entering this region will be absorbed.

Media

Here, there are cards for the definition of materials, and the user can assign them to geometric regions.

- **MATERIAL:** used to define a new material or compound if it is not already available in the FLUKA library. It requires assigning a name and density (g/cm^3). The assigned name will then be used in the ASSIGNMA and COMPOUND CARDS.
- **COMPOUND:** allows the creation of a compound using materials from the Flair file, defining its composition by weight or atomic percentage.
- **LOW-MAT:** sets the correspondence between FLUKA materials and low-energy neutron cross-sections.
- **ASSIGNMA:** establishes the actual association between a material and its corresponding region within the geometry.

Physics

Here, the user can control specific physical processes for selected particles using the PHYSICS card.

Transport

The following CARDS allow the activation of radioactive decay simulation:

- **DCYTIMES:** sets the decay times for scoring radioactive products.
- **IRRPROFI:** defines the irradiation profile for radioactive decay calculations.
- **RADDECAY:** enables the simulation of radioactive decays and configures the related biasing and transport settings.

Scoring

FLUKA includes several predefined CARDS that allow users to record and analyze various quantities, such as energy deposition and particle fluence. The most commonly used CARDS for this work are:

- **USERBIN:** records spatial distributions of deposited energy (GeV/cm^3), fluence (particles/ cm^2 per primary weight), activity (Bq), and specific activity (Bq/g), in a binning structure independent from the geometry.
- **RESNUCLEI:** scores residual nuclides after inelastic hadronic interactions.
- **DCYSCORE:** links specific scoring detectors of a selected estimator type to user-defined decay times [5].

4 | Nuclear Decommissioning

In the nuclear field, decommissioning refers to all administrative and technical actions taken when a nuclear facility reaches the end of its operational life. The goal is to restore the site for future use, either as a 'green field' site, allowing unrestricted use such as parks, housing, or parking areas, or as a 'brown field' site, where the land can be repurposed for industrial activities, such as new energy production.

According to the International Atomic Energy Agency (IAEA), decommissioning involves administrative and technical measures that enable the removal of some or all regulatory controls from a facility. The process assumes that the facility will no longer be used for its original purpose. Decommissioning activities must ensure the safety of workers, the public, and the environment by effectively managing residual radioactivity. This typically includes reducing radionuclide levels to allow safe release and possible reuse of materials and buildings [9].

The decommissioning process is complex and requires careful planning and execution. It includes site characterization, decontamination, dismantling, and waste management.

4.1. Decommissioning of particle accelerators

Over a service life that can reach decades, accelerators and their surroundings become activated due to the impact of primary and secondary particles on the equipment and the structures housing the accelerators.

The radioactive inventory and the complexity of decommissioning challenges depend heavily on the type of accelerator, its operational history, and its application. This complexity can range from minimal to significant. Since accelerators have a limited operational lifespan, they must be designed, built, and managed with decommissioning in mind.

The decommissioning of accelerators is a challenge for several reasons, including the following:

- The range of residual activation is highly variable. Additionally, activation is not

uniform within a facility, and hot spots are likely to be present.

- National and international clearance criteria are very strict, making the measurement and evaluation of residual activation particularly difficult.
- Clearance regulations differ from country to country, complicating the decommissioning process.
- Radiological conditions at the end of an accelerator's life depend on factors such as operational history, custom modifications, and the presence of specific radioisotopes. This variability makes it difficult to apply standardized decommissioning plans.

Radiological characterization

Activated materials are generated in accelerator facilities through various processes, including:

- Interaction of the primary beam with targets, collimators, or other materials that are intentionally struck by the beam.
- Unintentional beam interactions with the accelerator structure due to beam losses. These may occur from loss of control over particle trajectories or from smaller, more frequent losses, such as the scraping of the beam's outer edges (the "halo") along beamlines and components.
- Radiation emission from beam bending, such as synchrotron radiation or bremsstrahlung, which can interact with the accelerator structure or ancillary components.
- Secondary radiation generated by the above mechanisms, which can also induce activation (e.g., secondary neutrons or high-energy photons).

A variety of nuclear reactions contribute to activation. The most significant are reactions caused by beam particles interacting with absorbing materials. Common examples include (p, n) and (p, α) reactions, which occur when protons interact with collimators or targets in proton accelerators.

Secondary radiation, such as neutron-induced nuclear reactions, photonuclear reactions (γ , n), and hadronic interactions (e.g., spallation), also plays a role in activation. However, activation products in accelerators differ from those in nuclear reactors due to differences in primary and secondary particles, energy spectra, and materials.

Unlike reactors, accelerators do not produce fission products, and the production of alpha emitters is minimal, occurring only in high-Z materials. Most activation products in ac-

celerators are beta and gamma emitters with short to intermediate half-lives. As a result, the majority of activated materials contain low activity concentrations and are classified as very low-level or low-level waste.

Irradiated material	Radionuclides
Plastics, oils	^3H , ^7Be , ^{11}C
Concrete and aluminium	^3H , ^7Be , ^{11}C , ^{22}Na , ^{24}Na , ^{32}P , ^{42}K , ^{45}Ca , ^{152}Eu
Iron and steel	^3H , ^7Be , ^{11}C , ^{22}Na , ^{24}Na , ^{32}P , ^{42}K , ^{45}Ca , ^{44}Sc , $^{44\text{m}}\text{Sc}$, ^{46}Sc , ^{47}Sc , ^{48}Sc , ^{48}V , ^{51}Cr , ^{52}Mn , $^{52\text{m}}\text{Mn}$, ^{54}Mn , ^{56}Mn , ^{57}Co , ^{58}Co , ^{60}Co , ^{57}Ni , ^{55}Fe , ^{59}Fe , ^{63}Ni
Copper	^3H , ^7Be , ^{11}C , ^{22}Na , ^{24}Na , ^{32}P , ^{42}K , ^{45}Ca , ^{44}Sc , $^{44\text{m}}\text{Sc}$, ^{46}Sc , ^{47}Sc , ^{48}Sc , ^{48}V , ^{51}Cr , ^{52}Mn , $^{52\text{m}}\text{Mn}$, ^{54}Mn , ^{56}Mn , ^{57}Co , ^{58}Co , ^{60}Co , ^{57}Ni , ^{63}Ni , ^{65}Ni , ^{55}Fe , ^{59}Fe , ^{61}Cu , ^{64}Cu , ^{63}Zn , ^{65}Zn

Figure 4.1: Radionuclides commonly identified in solid materials irradiated around accelerators. [7]

Over time, activation products can form at different depths within the shielding materials, which can become a concern during decommissioning. To assess activation penetration, samples of structural materials (e.g. drill cores or equipment parts) can be collected for analysis.

Although a wide range of radionuclides can be produced, only a small number are significant for radiological protection and decommissioning. Radionuclides with short half-lives are primarily a concern during accelerator operation and maintenance, but not during decommissioning.

Shielding is essential to reduce radiation exposure to safe levels, ensuring compliance with dose limits and optimizing protection for workers and the public. While shielding design primarily aims to provide radiation protection, secondary effects such as activation of shielding materials must also be considered. During accelerator operation, concrete walls gradually become radioactive due to the activation of trace metals in the concrete and reinforcement bars. As part of early decommissioning planning, this radioactivity must be fully characterized [7].

Decommissioning strategies

IAEA has defined three decommissioning strategies: immediate dismantling, deferred dismantling, and entombment. The option of "no action" is not considered as an acceptable strategy. Immediate dismantling begins soon after the facility is shut down, following a

short transition period if necessary. Decommissioning proceeds in phases or as a single project until the facility or site reaches the approved final state, including its release from regulatory control.

In contrast, deferred dismantling involves placing the facility in a safe condition for several years or even decades before decontamination and dismantling take place. During this period, a surveillance and maintenance program is implemented to ensure safety.

Entombment is a strategy where the remaining radioactive materials are permanently sealed on-site, effectively turning the facility into a low, and intermediate, level waste repository. In this case, the site must comply with the requirements and controls for waste repository establishment, operation, and closure [9].

Ideally, the operating organization should decide on the most suitable decommissioning strategy early in the life cycle of the particle accelerator and use this decision as a basis for future planning. The chosen strategy must align with national decommissioning and waste management policies and follow a graded approach based on the hazards associated with decommissioning the specific type of accelerator.

Immediate dismantling would normally be the preferred strategy for Class 1 particle accelerators, for which typically no benefit will be gained from a ‘delay and decay’ approach. Conversely, a staged approach, including periods allowing for the decay of shorter half-life radionuclides, might be justified, typically for Class 2–4 particle accelerators. In deferred dismantling, security during the period of safe closure is an important consideration, especially in premises such as hospitals where the public has access to the site.

Class	Energy range ^a	Type of accelerator	Examples
Class 1	Low energy (2–30 MeV)	Electron linacs and electrostatic accelerators	• Radiotherapy linacs • Van de Graaff, tandem accelerators, Pelletron, with a potential lower than 10 MV
Class 2	Medium energy (10–100 MeV)	Proton, H ⁻ or multiple particle cyclotrons and linacs	• Cyclotrons for PET/single photon emission computed tomography (SPECT) radionuclide production • Cyclotrons for neutron sources • Other accelerators (linacs and cyclotrons) in physics research (injectors) • Some cyclotrons or synchrotrons for radiotherapy
Class 3	High energy (100–several hundred MeV)	Proton cyclotrons and synchro-cyclotrons and linear high energy accelerators	• Proton therapy • Accelerators for physics research (injectors) • Neutron spallation sources
Class 4	Very high energy (range GeV–TeV)	High energy synchrotrons, storage rings, colliders	• Fundamental physics research • Wide range of interdisciplinary research with light sources

^a For ions: kinetic energy per nucleon.

Figure 4.2: Accelerators classified by energy range [7].

In general, the staged approach adopted in the phased decommissioning strategy will permit time for access to the necessary resources, decay of short half-life radionuclides so as to reduce occupational exposures, provision of the required management arrangements, and resolution of outstanding technical issues. The staged approach would also provide a period during which radionuclide decay in buildings and materials might reduce the activity level to allow free release.

For particle accelerators, a combination of immediate and deferred dismantling may be appropriate, leading to phased decommissioning. After characterization, parts of the machine and its activated components can be dismantled and sorted into radioactive and non-radioactive waste streams. Depending on the activation levels, the accelerator hall, shielding, and other materials may be left for a decay period before being considered for clearance.

5 | FLUKA simulation of the CNAO Synchrotron

This chapter presents the results obtained from Monte Carlo simulations, performed with FLUKA, on the activation of the CNAO synchrotron and the materials composing the building that houses it.

5.1. Comparison between reality and FLUKA geometry

This section describes the general layout of the CNAO synchrotron facility used in the Monte Carlo simulations, along with a visual comparison between the simulated geometry and real-world images.

The geometry used in these simulations was provided by CNAO, with some modifications applied.

In FLAIR, the main facility structures are implemented, including the synchrotron ring, the HEBT, the three treatment rooms and the experimental research room (XPR) (see Figs. 5.1 and 5.2). The goal is to model the main elements of the facility as accurately as possible. The choice of materials is important because even small differences in composition can affect the radionuclides produced after irradiation. If a material is not specified in this section, the standard FLUKA material library is used. The building is made of 2 to 6 meters of Portland concrete (light blue in all geometry figures) to shield the outside from neutron radiation. Large-volume regions (e.g. walls, floor) are further divided into smaller blocks with an area of approximately 1 to 1.5 square meters and a variable thicknesses between 0.40 and 1 meters. This modification of the geometry provides more realistic activation data and facilitates material transport during decommissioning. The more uniform regions are divided using a Fortran77 code, which generated input files later integrated into the geometry.

The standard FLUKA composition (Table 5.1) for Portland concrete is used, with addi-

tional concentrations of Co and Eu based on reference [19].

Portland concrete ($\rho=2.34 \text{ g/cm}^3$)

Element	Weight fraction
Oxygen	0.529102
Silicon	0.337018
Calcium	0.044
Aluminum	0.0338713
Sodium	0.016
Iron	0.014
Potassiu	0.013
Hydrogen	0.01
Magnesi	0.002
Carbon	0.001
Cobalt	0.000008
Europium	0.0000007

Table 5.1: Portland concrete composition.

Synchrotron ring

The synchrotron ring consists of 16 dipoles that ensure a closed trajectory, 24 quadrupoles that maintain the beam stability in the longitudinal and radial focal directions, 5 sextupoles for chromatic correction, and 20 correctors. The schematized components of the synchrotron ring are shown in Fig. 5.3 [15].

The particle beam is contained within a vacuum chamber made of stainless steel, with a thickness of 1 cm, positioned in the zx plane at $y = -200$. The standard FLUKA composition is used for stainless steel (hereafter referred to as inox). This vacuum chamber extends throughout the entire ring, passing through all synchrotron components. The sextupoles, quadrupoles, betatron, and radiofrequency cavity are modeled as cylinders (RCC) of different sizes, the first three being made of iron and the last one of copper.

The dipoles, dumps, screen, electrostatic septa, and magnetic septa are modeled as rectangular parallelepipeds (RPP), each made of different materials such as iron, tungsten, inox and copper.

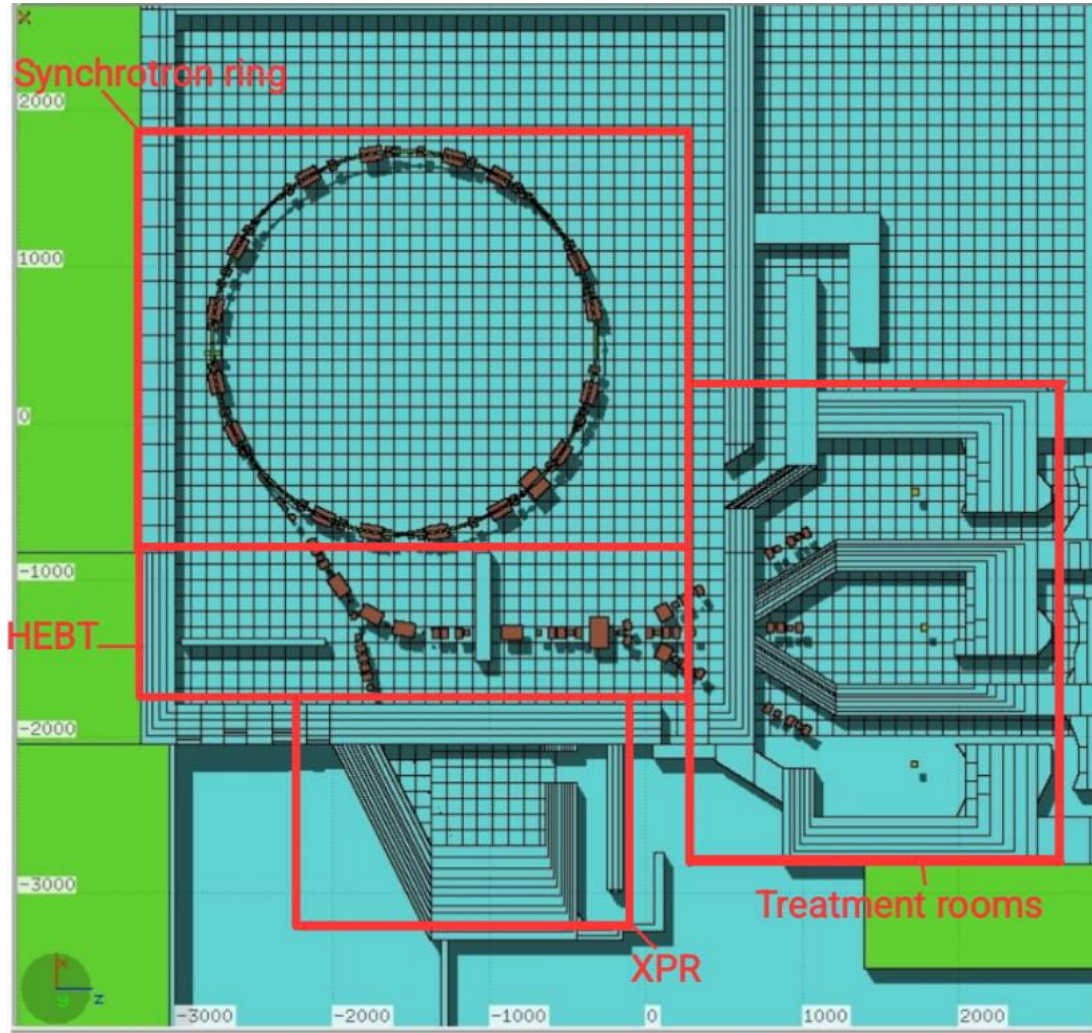


Figure 5.1: 3D view of the layout of the CNAO synchrotron, plane x-z with $y=-200$.

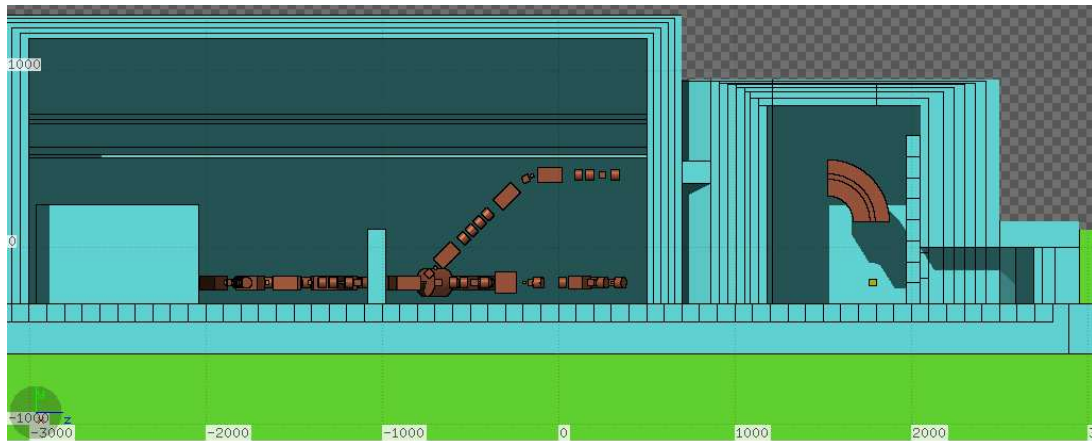


Figure 5.2: 3D view of the CNAO synchrotron, plane y-z with $x=-1400$.

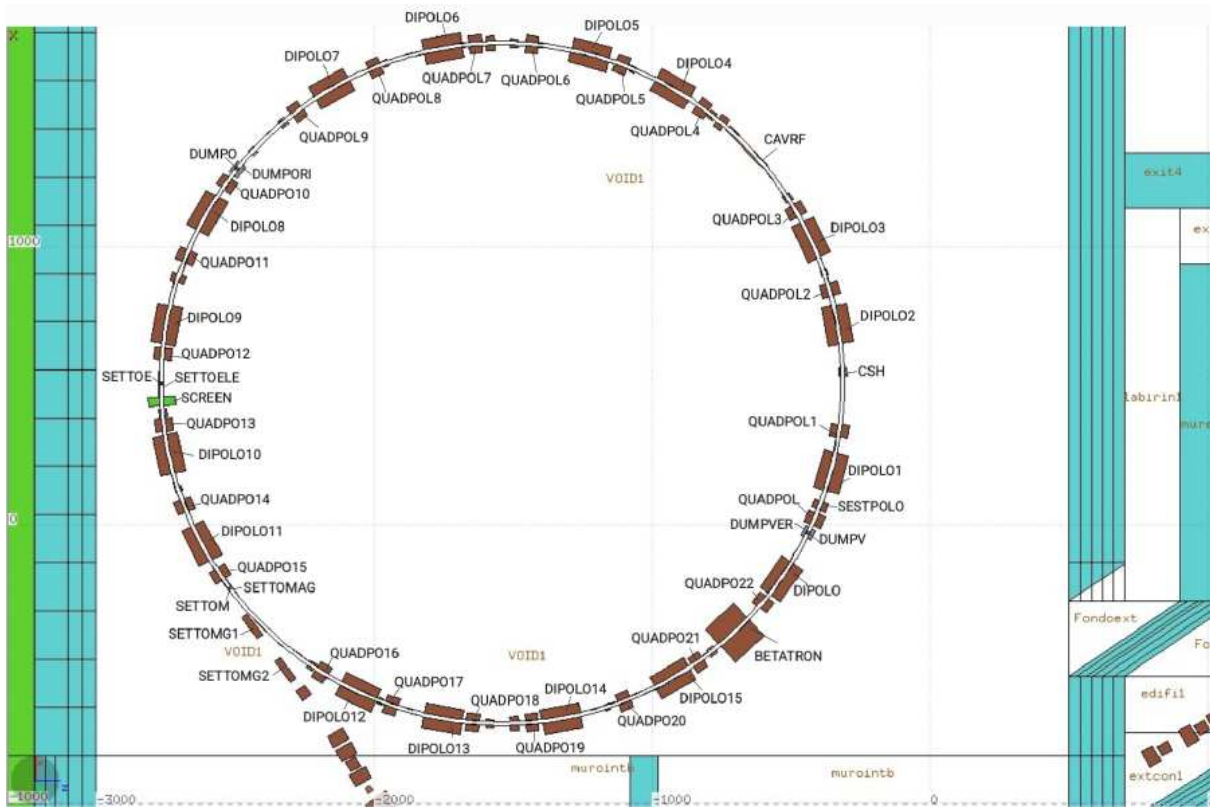


Figure 5.3: 2D view of the synchrotron ring, plane x-z with $y=-200$.

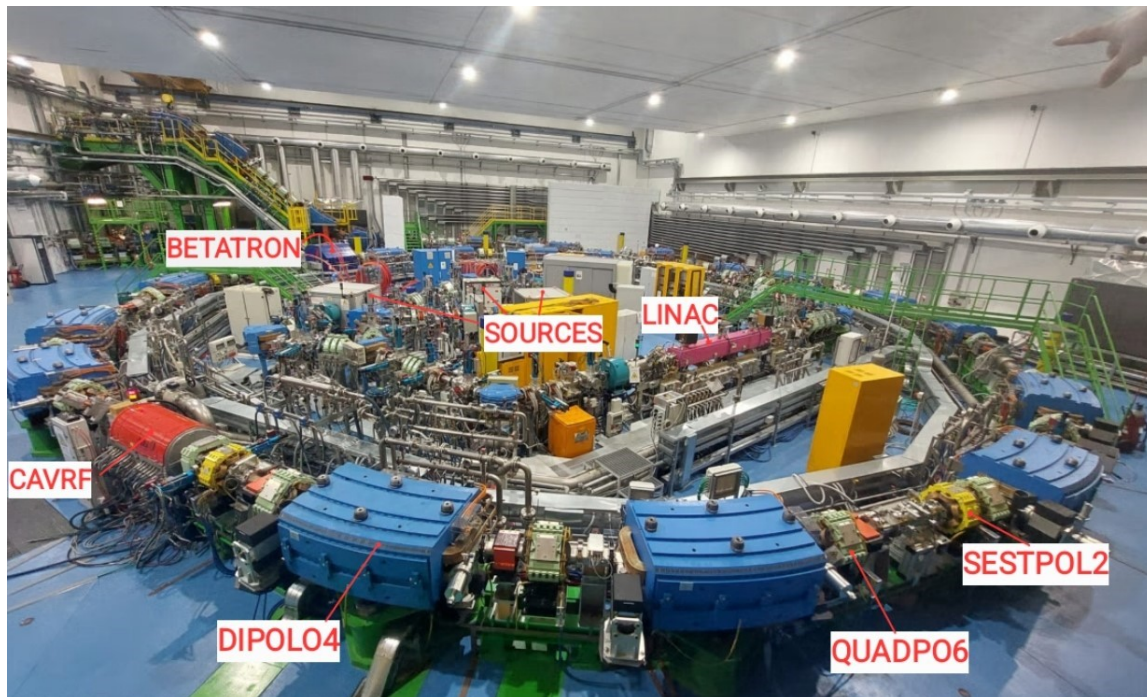


Figure 5.4: Photograph of the CNAO synchrotron with some components of the ring highlighted.

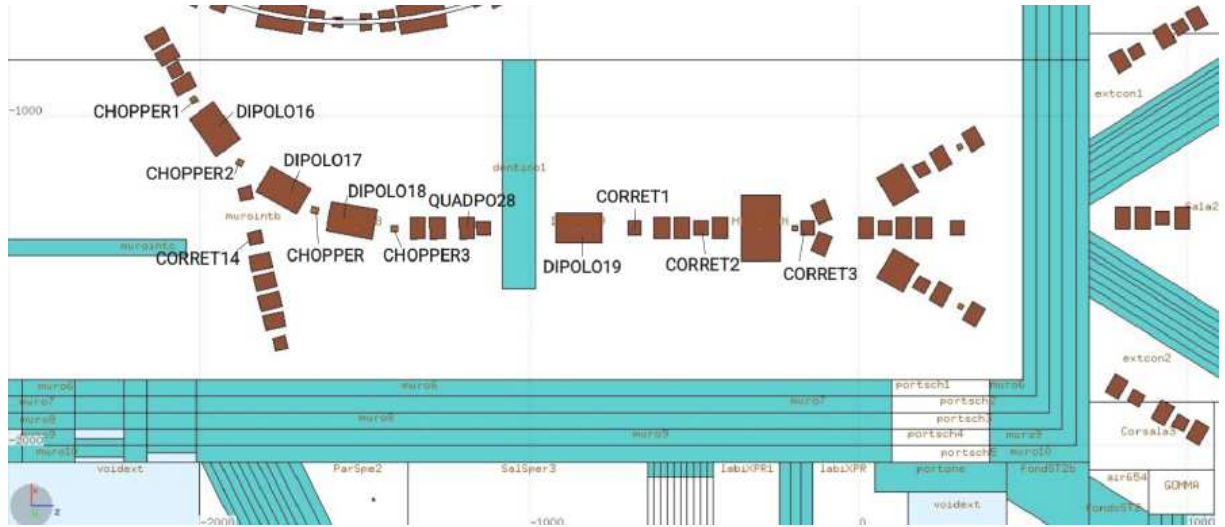


Figure 5.5: 2D view of HEBT, plane x-z with $y=-200$.

High Energy Beam Transport - HEBT

At CNAO, beam extraction is performed by operating the machine near resonance. The particles are moved out of a stable region through the action of the betatron, pushing them beyond the electrostatic and magnetic septa, allowing them to be transported to the treatment rooms. This task is carried out by the High Energy Beam Transport (HEBT) lines. In total, there are five lines, with the High Energy Experimental Line (HEBT XPR) branching off from the treatment room lines at the exchange dipole 16 [15].

In this section, in addition to diagnostic elements, the beamlines are equipped with four fast magnets (Chopper, Chopper1, Chopper2, and Chopper3). When activated, these magnets deflect the beam, directing it to the absorber (dump) and interrupting its path. The choppers are a high-speed system capable of switching the beam on and off in less than $260 \mu\text{s}$. The HEBT components are shown in Fig. 5.5. The choppers are made of copper. The other components are made of iron.



Figure 5.6: Photograph of the initial section of the HEBT in the CNAO synchrotron.

Treatment rooms and XPR

Treatment rooms and XPR components transport and direct the beam to the patient from the horizontal direction, and for TR2, also from the vertical direction. At the end of the beam lines, the patient is modeled as a square parallelogram (yellow in figure 5.10) with a 40 cm side, made of tissue-equivalent material. The dumps (orange in figure 5.10), on the walls of the treatment rooms, are modeled as RPP made of stainless steel (316 alloy). In the XPR room, there is no beam dump on the wall along the beamline, as the wall is built with removable blocks that can be easily replaced if activated. The four isocenters in the XPR room (orange in figure 5.8) are modeled as RCC cylinders made of copper.

Beam Losses

The FLUKA source definition is implemented using a Fortran77 user routine (SOURCE.f). This routine defines all loss positions and their average percentages (indicated in Tab.5.2). For each primary particle, a random number between 0 and 1 is selected. Based on this value, the routine determines the loss location and sets the particle's starting position and direction.



Figure 5.7: 3D view of treatment room, plane y-x with $z=1700$.

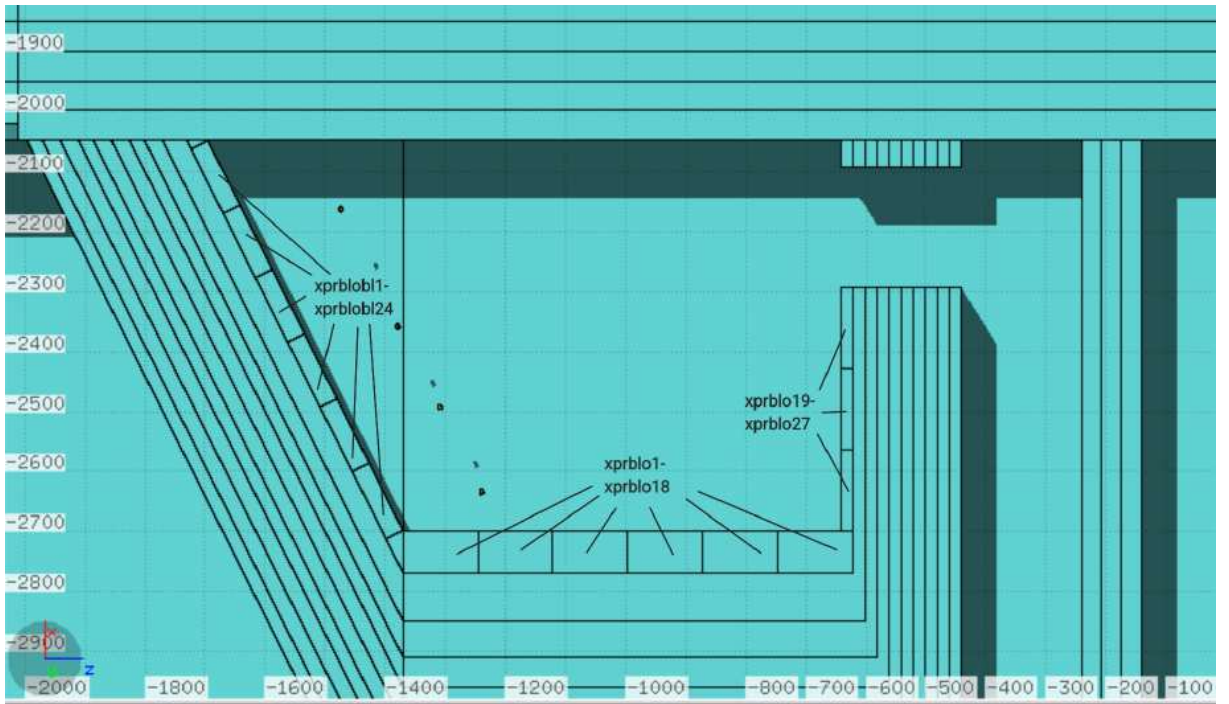


Figure 5.8: 3D view of XPR room, plane x-z with $y=-200$.

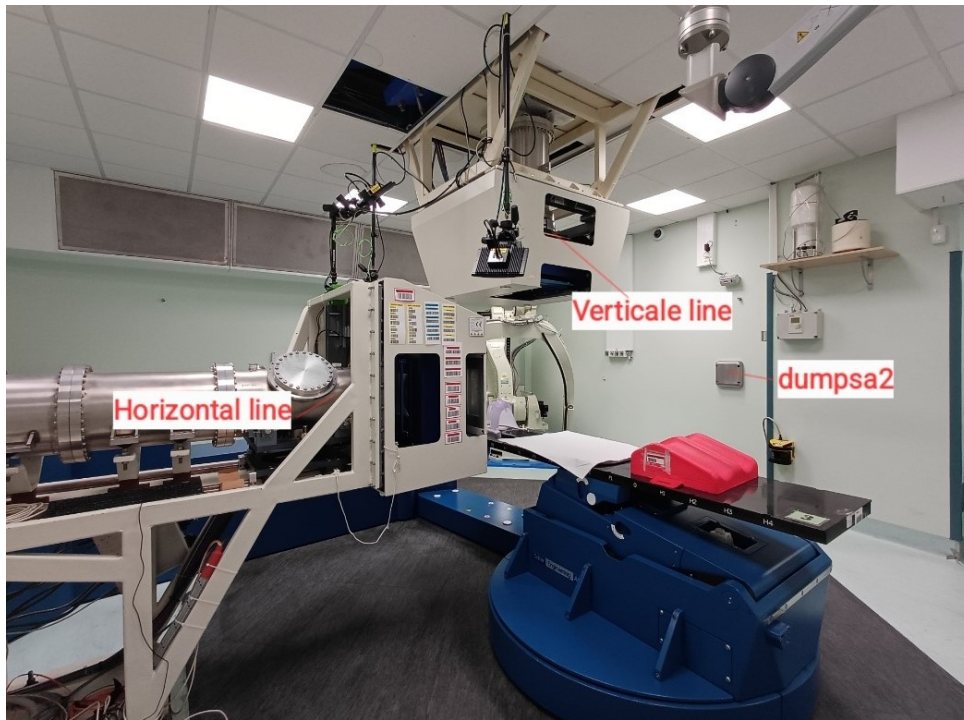


Figure 5.9: Photograph of Treatment Room 2, showing both the horizontal and the vertical beam line.



Figure 5.10: Photograph of Treatment Room 3.

Loss location	Loss percentage %
Synchrotron loss	3.69
dump chopper HEBT	3.60
ST1 magnet	0.07
ST2 magnet	0.03
ST3 magnet	0.03
magnetic septa	3.70
electrostatic septa	3.70
horizontal dump	36.99
vertical dump	2.22
isocenter xpr 1	7.79
isocenter xpr 2	7.80
isocenter xpr 3	7.79
isocenter xpr 4	7.80
isocenter ST1	4.67
dump ST1	0.05
isocenter ST2	4.67
dump ST2	0.05
isocenter ST3	4.67
dump ST3	0.05
chopper 1	0.38
chopper 2	0.12
chopper 3	0.09
point 17	0.01
point 18	0.02
point 19	0.01

Table 5.2: Beam losses of the synchrotron at CNAO.

5.2. FLUKA activation methodology

For the activation assessment, both a proton beam and a carbon ion beam were simulated. Protons were considered the most relevant for machine activation, while carbon ions were primarily analyzed for the activation of walls and materials in the beam path. This study

focused on these two beam types in relation to the new ions that will be used in the synchrotron.

The following subsections present the parameters implemented in the simulations with the primary and transport cards, the scoring cards used and an explanation of the data analysis methodology.

Primary and Transport CARDS

- Simulations were performed with both the maximum possible energy, 250 MeV for protons and 400 MeV/u for carbon ions, and the energy spectrum of protons and carbon ions used in 2023 at the CNAO synchrotron.
- The irradiation profile was defined using the IRRPROFI card, considering both the maximum authorized beam current (10^{10} p/s for protons and 4×10^8 p/s for carbon ions) and 15% of this maximum value, since the highest current is rarely achieved under operational conditions. The irradiation duration was set to 30 years, which represents the typical lifetime of an accelerator.
- A post-irradiation cooling time of 1 year was applied, based on literature data for the decommissioning of similar synchrotrons.

Scoring CARDS

- USERBIN-actomass cards were used to generate graphical representations of the specific activity [Bq/g] in selected spatial regions.
- The RESNUCLEI card was implemented to evaluate activation within specific regions and to identify the radionuclides produced.

Data analysis methodology

In the following figures, building maps with a color scale representing Actomass are shown. From these images, the hottest regions, meaning those with significant specific activity, were identified. A minimum color scale value of 0.1 Bq/g was used, as the analysis showed that no non-removable element had a specific activity below this threshold. For regions with specific activity greater than 0.1 Bq/g, RESNUCLEI analysis was performed. The data obtained from RESNUCLEI are reported and analyzed in numerous tables, which are available at the CNAO radiation protection office but are not all included here due to their high number. These tables contain:

- The inventory of radionuclides present after one year of cooling time, including their

activity (Bq) and associated percentage error.

- The material composition of the region analyzed, with density (g/cm³), mass (kg), and volume (m³).
- The total activity (Bq) and percentage error for the entire region.
- Calculation of specific activity (Bq/g) for each radionuclide.
- The assignment of values from Table 1b of Decreto Legislativo n.101 of July 31th, 2020, "Livelli di allontanamento per i materiali solidi", implemented with the CNAO authorization values for solid material clearance. For radionuclides not listed in these tables, a conservative clearance level of 0.01 was applied. In the following sections, radionuclides not included in these lists, subject to the most restrictive limit, are labeled as "unlisted" and highlighted in yellow.
- The calculation of the ratio between specific activity and the coefficients from the table.
- The half life ($T_{1/2}$) for each radionuclide.
- The summation of the specific activity to coefficient ratios ($\Sigma Att.sp./cf$).

According to Allegato 1 of Decreto Legislativo 101/2020, materials with a summation ratio greater than 1 cannot be cleared.

Materials with a ratio below 1 may be cleared if the Foundation has authorization to remove the present radionuclides. To facilitate this process, a final list of all radionuclides formed over 30 years that are present in removable blocks is provided in the results.

The assessments presented here are based on these assumptions and will need to be reviewed following decommissioning authorization and an evaluation of the actual workload at the end of the facility's operational life. If some components are classified as non-removable in these simulations only because they contain unlisted radionuclides, it may be possible, at the time of decommissioning, to request a less restrictive clearance level.

The following sections present the data analyzed using this methodology, specifically paragraphs 5.3.1 and 5.3.2 present the results of simulations performed with a carbon ion beam at the maximum energy of 400 MeV/u and the maximum authorized intensity of 4×10^8 p/s. For all cases, the section begins with representative images of specific activity obtained using the USERBIN-actomass card. Then paragraph 5.3.1 provides data analysis for the horizontal dump (hereafter referred to as dumpo), the external part of the dump (dumpori), the magnetic septa (settom and settomag), the chopper 1, the screen, the dipole8, the quadrupole (QUADPOL), the dump in Treatment Room 2 (dumps2), a sec-

tion of the wall of the XPR room (xprblo5) and a floor block (A0425), all of which are identified as non-removable components.

Paragraph 5.3.2 reports the data analysis of components classified as removable, including the dipole, quadrupole 23 and another wall block from the XPR room (xprblo6).

Paragraph 5.3.3 presents results from simulations conducted with a carbon ion beam using the actual energy spectrum employed by the machine in 2023, at the maximum authorized intensity of 4×10^8 p/s.

Paragraph 5.3.4 presents results from simulations performed under the same conditions as in Paragraph 5.3.3, but at 15% of the maximum authorized intensity.

Paragraphs 5.4.1 and 5.4.2 present the results of simulations conducted with a proton beam at the maximum energy of 250 MeV and the maximum authorized intensity of 10^{10} p/s.

As in the previous case, sections begin with representative images of specific activity obtained using the USERBIN-actomass card. Paragraph 5.4.1 then provides data analysis for the horizontal dump (dump), the external part of the dump (dumpori), the magnetic septa (settom and settomag), the chopper 1, the screen, the dipole8, the quadrupole, the dump in Treatment Room 2 (dumps2), a section of the XPR room wall (xprblo5), and a floor block (A0425), all of which were identified as non-removable components.

Paragraph 5.4.2 reports the data analysis of removable components, including the dipole, quadrupole 23, and another wall block from the XPR room (xprblo6).

Paragraph 5.4.3 presents results from simulations conducted with a proton beam using the actual energy spectrum employed by the machine in 2023, at the maximum authorized intensity of 10^{10} p/s.

Paragraph 5.4.4 presents results from simulations performed under the same conditions as in Paragraph 5.4.3, but at 15% of the maximum authorized intensity.

5.3. Carbon ions simulations

This section presents the data obtained from Monte Carlo simulations performed with FLUKA using a carbon ion beam for the following scenarios:

- Maximum authorized energy and intensity, considering both removable and non-removable components.
- Energy spectrum actually used in 2023 with the maximum authorized intensity.
- Energy spectrum actually used in 2023 with 15% of the maximum authorized intensity.

5.3.1. Non-removable components: simulations with maximum energy and maximum particle beam intensity.

Images 5.11-5.12 show the specific activity of the facility at beam level and floor level. The ceiling is not relevant to this study, as it is too far from the loss points and therefore not activated.

Figure 5.11 shows that the most activated areas are those surrounding the dumps in the synchrotron, the isocenters, and the walls in the treatment rooms, as well as the XPR, in the beam direction.



Figure 5.11: Visualization of the USERBIN-actomass in the x-z plane with $y=-200$, for a Carbon ion beam at maximum energy and intensity.

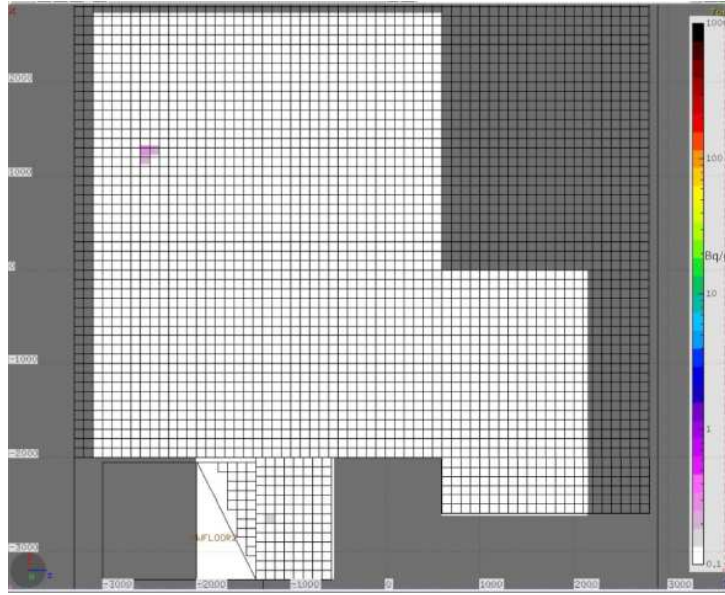


Figure 5.12: Visualization of the USERBIN-actomass in the x-z plane with $y=-350$, for a Carbon ion beam at maximum energy and intensity.

The following figures provide a detailed view of the activity of radionuclides generated after 30 years of irradiation. Tables are included for the most significant regions, ensuring that at least one table is provided for each type of material in the facility.

dumppo	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)				
179	73	2.92E+07	0.73	Ta	Ta-179	2.16E+03	0.01	2.16E+05	5.74E+07		V(m3)	tungsten	
173	71	6.14E+06	0.60	Lu	Lu-173	4.55E+02	0.01	4.55E+04	4.32E+07		7.00E-04	1.93E+01	1.35E+01
172	71	5.56E+06	1.29	Lu	Lu-172	4.11E+02	0.01	4.11E+04	5.79E+05		att. (Bq)		
172	72	5.50E+06	1.29	Hf	Hf-172	4.07E+02	0.01	4.07E+04	5.90E+07		1.16E+08 +/-		3.27E-01 %
145	61	4.42E+05	2.59	Pm	Pm-145	3.27E+01	0.01	3.27E+03	5.59E+08		att.sp. (Bq/g)		
175	72	4.27E+05	0.72	Hf	Hf-175	3.16E+01	0.01	3.16E+03	6.05E+06		8.61E+03		
3	1	3.88E+07	0.50	H	H-3	2.87E+03	1	2.87E+03	3.89E+08		Σatt.sp/cf		4.71E+05
145	62	3.13E+05	2.48	Sm	Sm-145	2.32E+01	0.01	2.32E+03	2.94E+07				
133	56	2.76E+05	6.08	Ba	Ba-133	2.04E+01	0.01	2.04E+03	3.33E+08				
174	71	2.19E+05	9.50	Lu	Lu-174	1.62E+01	0.01	1.62E+03	1.04E+08				
157	65	2.14E+05	2.77	Tb	Tb-157	1.58E+01	0.01	1.58E+03	2.24E+09				
148	64	1.98E+05	3.15	Gd	Gd-148	1.46E+01	0.01	1.46E+03	2.24E+09				
143	61	1.85E+05	2.16	Pm	Pm-143	1.37E+01	0.01	1.37E+03	2.29E+07				
159	66	1.81E+05	2.17	Dy	Dy-159	1.34E+01	0.01	1.34E+03	1.25E+07				
181	74	1.00E+07	0.50	W	W-181	7.41E+02	1	7.41E+02	1.05E+07				
88	39	6.45E+04	5.58	Y	Y-88	4.78E+00	0.01	4.78E+02	9.21E+06				
182	73	6.44E+05	1.10	Ta	Ta-182	4.77E+01	0.1	4.77E+02	9.91E+06				
151	64	6.20E+04	4.43	Gd	Gd-151	4.59E+00	0.01	4.59E+02	1.07E+07				
149	63	4.72E+04	2.49	Eu	Eu-149	3.49E+00	0.01	3.49E+02	8.04E+06				
183	75	4.72E+04	1.83	Re	Re-183	3.49E+00	0.01	3.49E+02	6.05E+06				
68	31	3.33E+04	10.59	Ga	Ga-68	2.47E+00	0.01	2.47E+02	4.06E+03				
68	32	3.33E+04	10.59	Ge	Ge-68	2.47E+00	0.01	2.47E+02	2.34E+07				
49	23	3.27E+04	3.85	V	V-49	2.42E+00	0.01	2.42E+02	2.85E+07				
101	45	3.04E+04	15.80	Rh	Rh-101	2.25E+00	0.01	2.25E+02	1.04E+08				
185	74	2.79E+06	0.39	W	W-185	2.06E+02	1	2.06E+02	6.49E+06				
184	75	2.39E+04	8.10	Re	Re-184	1.77E+00	0.01	1.77E+02	3.06E+06				
83	37	1.44E+04	4.15	Rb	Rb-83	1.06E+00	0.01	1.06E+02	7.45E+06				
88	40	1.03E+04	6.72	Zr	Zr-88	7.62E-01	0.01	7.62E+01	7.21E+06				
102	45	8.75E+03	15.74	Rh	Rh-102	6.48E-01	0.01	6.48E+01	1.79E+07				
42	18	8.44E+03	26.27	Ar	Ar-42	6.25E-01	0.01	6.25E+01	1.04E+09				
42	19	8.44E+03	26.27	K	K-42	6.25E-01	0.01	6.25E+01	4.45E+04				
91	41	8.09E+03	4.90	Nb	Nb-91	5.99E-01	0.01	5.99E+01	2.15E+10				
39	18	7.84E+03	4.58	Ar	Ar-39	5.80E-01	0.01	5.80E+01	8.46E+09				
163	67	7.48E+03	2.77	Ho	Ho-163	5.54E-01	0.01	5.54E+01	1.44E+11				
146	61	6.89E+03	27.39	Pm	Pm-146	5.10E-01	0.01	5.10E+01	1.75E+08				
22	11	6.56E+04	9.07	Na	Na-22	4.85E+00	0.1	4.85E+01	8.21E+07				
60	27	6.18E+04	3.93	Co	Co-60	4.58E+00	0.1	4.58E+01	1.66E+08				
144	61	5.18E+03	35.67	Pm	Pm-144	3.83E-01	0.01	3.83E+01	3.14E+07				
32	14	4.96E+03	14.92	Si	Si-32	3.67E-01	0.01	3.67E+01	4.95E+09				
168	69	4.96E+03	9.57	Tm	Tm-168	3.67E-01	0.01	3.67E+01	8.04E+06				
54	25	4.76E+04	12.57	Mn	Mn-54	3.53E+00	0.1	3.53E+01	2.70E+07				
146	63	4.49E+03	3.25	Eu	Eu-146	3.32E-01	0.01	3.32E+01	3.98E+05				
146	64	4.06E+03	3.25	Gd	Gd-146	3.01E-01	0.01	3.01E+01	4.17E+06				
65	30	3.51E+04	6.30	Zn	Zn-65	2.60E+00	0.1	2.60E+01	2.11E+07				
158	65	3.39E+03	9.42	Tb	Tb-158	2.51E-01	0.01	2.51E+01	5.68E+09				
150	63	2.03E+03	40.82	Eu	Eu-150	1.50E-01	0.01	1.50E+01	1.16E+09				
153	64	1.88E+05	3.64	Gd	Gd-153	1.39E+01	1	1.39E+01	2.08E+07				
154	63	1.82E+04	12.56	Eu	Eu-154	1.34E+00	0.1	1.34E+01	2.71E+08				
169	70	1.61E+03	0.67	Yb	Yb-169	1.19E-01	0.01	1.19E+01	2.77E+06				
109	48	1.47E+05	3.09	Cd	Cd-109	1.09E+01	1	1.09E+01	3.99E+07				
A/Z/m Isomers:													
181	73	7.40E+06	0.50	Ta	Ta-181	5.48E+02	0.01	5.48E+04	2.10E-04				
172	71	5.50E+06	1.29	Lu	Lu-172	4.07E+02	0.01	4.07E+04	7.90E+01				
172	71	6.19E+05	1.29	Lu	Lu-172	4.58E+01	0.01	4.58E+03	7.90E+01				
109	47	1.47E+05	3.09	Ag	Ag-109	1.09E+01	0.01	1.09E+03	3.98E+01				

Figure 5.13: Radionuclides generated in dumppo with their respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, see Data analysis methodology paragraph).

Fig.5.13 shows a partial activity table of the horizontal dump, dumppo, composed of tungsten. Due to the high number of generated radionuclides, only those with an att.sp/cf ratio greater than $1.00 \times 10^{+01}$ are listed. However, the total activity and Σ att.sp/cf calculations include all generated radionuclides. The most significant long-lived radionuclides due to the high specific activity of the component are ^{179}Ta , ^{173}Lu , ^{172}Hf , ^{145}Pm , ^3H , ^{145}Sm , ^{133}Ba , ^{174}Lu , ^{157}Tb , ^{148}Gd , ^{143}Pm , ^{159}Dy , ^{181}W , ^{151}Gd , ^{68}Ge , ^{49}V , ^{101}Rh and short-lived radionuclides ^{172}Lu , ^{175}Hf , ^{88}Y , ^{182}Ta , ^{149}Eu , ^{183}Re , ^{68}Ga , ^{185}W , ^{184}Re , ^{83}Rb and ^{146}Eu . Here, short-lived radionuclides (half-life < 1 year) are continuously produced during irradiation. Their detection after a year of cooling time is due to ongoing production, the decay of longer-lived parent isotopes, and secondary activation processes.

dumpori	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)		lead	
	195	79	4.83E+05	2.35	Au-195	8.35E-01	0.01	8.35E+01	1.61E+07	V(m3)	ro(g/cm3)	m(Kg)
	194	79	5.69E+04	2.19	Au-194	9.85E-02	0.01	9.85E+00	1.37E+05		5.09E-02	1.14E+01
	194	80	5.69E+04	2.19	Hg-194	9.85E-02	0.01	9.85E+00	1.41E+10	att. (Bq)		5.78E+02
	3	1	3.16E+06	1.09	H-3	5.46E+00	1	5.46E+00	3.89E+08		7.32E+06 +/-	6.99E-01 %
	204	81	3.06E+06	1.03	Tl-204	5.29E+00	1	5.29E+00	1.19E+08	att.sp. (Bq/g)		
	106	45	1.98E+04	9.89	Rh-106	3.43E-02	0.01	3.43E+00	3.01E+01		1.27E+01	
	179	73	9.33E+03	14.92	Ta-179	1.61E-02	0.01	1.61E+00	5.74E+07	Σ att.sp/cf		1.31E+02
	202	82	8.37E+03	0.59	Pb-202	1.45E-02	0.01	1.45E+00	1.66E+12			
	173	71	4.35E+03	36.85	Lu-173	7.52E-03	0.01	7.52E-01	4.32E+07			
	207	83	3.36E+04	10.30	Bi-207	5.81E-02	0.1	5.81E-01	9.96E+08			
	193	78	2.78E+05	6.20	Pt-193	4.80E-01	1	4.80E-01	1.58E+09			
	172	71	2.23E+03	61.23	Lu-172	3.86E-03	0.01	3.86E-01	5.79E+05			
	172	72	2.21E+03	61.23	Hf-172	3.82E-03	0.01	3.82E-01	5.90E+07			
	106	44	1.98E+04	9.89	Ru-106	3.43E-02	0.1	3.43E-01	3.21E+07			
	101	45	1.34E+03	57.77	Rh-101	2.32E-03	0.01	2.32E-01	1.04E+08			
	133	56	1.29E+03	61.24	Ba-133	2.23E-03	0.01	2.23E-01	3.33E+08			
	183	75	9.09E+02	21.13	Re-183	1.57E-03	0.01	1.57E-01	6.05E+06			
	174	71	7.12E+02	99.00	Lu-174	1.23E-03	0.01	1.23E-01	1.04E+08			
	88	39	6.31E+02	53.70	Y-88	1.09E-03	0.01	1.09E-01	9.21E+06			
	208	84	6.29E+02	99.00	Po-208	1.09E-03	0.01	1.09E-01	9.15E+07			
	125	51	5.60E+03	36.82	Sb-125	9.69E-03	0.1	9.69E-02	8.71E+07			
	121	50	5.01E+02	90.19	Sn-121	8.67E-04	0.01	8.67E-02	9.73E+04			
	102	45	4.72E+02	99.00	Rh-102	8.16E-04	0.01	8.16E-02	1.79E+07			
	68	31	3.14E+02	99.00	Ga-68	5.44E-04	0.01	5.44E-02	4.06E+03			
	68	32	3.14E+02	99.00	Ge-68	5.43E-04	0.01	5.43E-02	2.34E+07			
	123	50	2.43E+02	92.75	Sn-123	4.21E-04	0.01	4.21E-02	1.12E+07			
	90	39	2.25E+04	21.49	Y-90	3.89E-02	1	3.89E-02	2.31E+05			
	90	38	2.25E+04	21.49	Sr-90	3.89E-02	1	3.89E-02	9.12E+08			
	175	72	2.17E+02	22.35	Hf-175	3.74E-04	0.01	3.74E-02	6.05E+06			
	121	52	1.72E+02	99.00	Te-121	2.97E-04	0.01	2.97E-02	1.66E+06			
	85	36	1.17E+04	17.99	Kr-85	2.02E-02	1	2.02E-02	3.39E+08			
	134	55	1.14E+03	99.00	Cs-134	1.98E-03	0.1	1.98E-02	6.52E+07			
	151	64	1.04E+02	99.00	Gd-151	1.79E-04	0.01	1.79E-02	1.07E+07			
	188	74	8.50E+01	46.77	W-188	1.47E-04	0.01	1.47E-02	6.03E+06			
	202	81	8.29E+03	0.59	Tl-202	1.43E-02	1	1.43E-02	1.06E+06			
	205	82	8.23E+01	0.38	Pb-205	1.42E-04	0.01	1.42E-02	5.36E+14			
	88	40	7.69E+01	61.24	Zr-88	1.33E-04	0.01	1.33E-02	7.21E+06			
	60	27	6.86E+02	99.00	Co-60	1.19E-03	0.1	1.19E-02	1.66E+08			
	149	63	5.86E+01	99.00	Eu-149	1.01E-04	0.01	1.01E-02	8.04E+06			
	A/Z/m Isomers:											
	207	82	2.82E+04	10.30	Pb-207	4.88E-02	0.01	4.88E+00	8.06E-01			
	181	73	2.32E+03	20.41	Ta-181	4.01E-03	0.01	4.01E-01	2.10E-04			
	172	71	2.21E+03	61.23	Lu-172	3.82E-03	0.01	3.82E-01	7.90E+01			
	109	47	1.39E+03	66.67	Ag-109	2.40E-03	0.01	2.40E-01	3.98E+01			
	121	50	6.46E+02	90.19	Sn-121	1.12E-03	0.01	1.12E-01	1.39E+09			
	113	48	2.70E+02	24.69	Cd-113	4.68E-04	0.01	4.68E-02	4.45E+08			
	119	50	2.60E+02	33.39	Sn-119	4.50E-04	0.01	4.50E-02	2.53E+07			
	172	71	2.49E+02	61.23	Lu-172	4.30E-04	0.01	4.30E-02	7.90E+01			
	121	52	1.71E+02	99.00	Te-121	2.96E-04	0.01	2.96E-02	1.42E+07			
	174	71	1.35E+02	99.00	Lu-174	2.33E-04	0.01	2.33E-02	1.23E+07			
	88	39	7.69E+01	61.24	Y-88	1.33E-04	0.01	1.33E-02	9.21E+06			

Figure 5.14: Radionuclides generated in dumpori with their respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, see Data analysis methodology paragraph).

Fig.5.14 shows a partial activity table of the external part of the dump, dumpori, composed of lead. Due to the high number of generated radionuclides, only those with an att.sp/cf ratio greater than 1.00×10^{-02} are listed. However, the total activity and Σ att.sp/cf calculations include all generated radionuclides. The most significant long-lived radionuclides due to the high specific activity of the component are ^{195}Au , ^{194}Hg , ^3H , ^{204}Tl , ^{179}Ta , ^{202}Pb and short-lived radionuclides ^{194}Au and ^{106}Rh .

settom	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)		copper	
	49	23	1.39E+05	4.17	V	V-49	2.22E+01	0.01	2.22E+03	2.85E+07	V(m3)	ro(g/cm3)
	60	27	5.50E+05	6.07	Co	Co-60	8.77E+01	0.1	8.77E+02	1.66E+08	7.00E-04	8.96E+00
	3	1	4.19E+06	1.74	H	H-3	6.69E+02	1	6.69E+02	3.89E+08	att. (Bq)	m(Kg)
	54	25	2.31E+05	1.94	Mn	Mn-54	3.68E+01	0.1	3.68E+02	2.70E+07	6.83E+06 +/-	1.29E+00
	55	26	7.04E+05	2.16	Fe	Fe-55	1.12E+02	1	1.12E+02	8.66E+07	att.sp. (Bq/g)	%
	44	22	7.04E+03	21.73	Ti	Ti-44	1.12E+00	0.01	1.12E+02	1.87E+09	1.09E+03	
	57	27	5.09E+05	1.40	Co	Co-57	8.11E+01	1	8.11E+01	2.35E+07	Σ att.sp/cf	4.82E+03
	63	28	3.56E+05	1.31	Ni	Ni-63	5.68E+01	1	5.68E+01	3.19E+09		
	39	18	3.31E+03	14.94	Ar	Ar-39	5.28E-01	0.01	5.28E+01	8.46E+09		
	65	30	3.15E+04	4.37	Zn	Zn-65	5.01E+00	0.1	5.01E+01	2.11E+07		
	42	18	3.08E+03	22.46	Ar	Ar-42	4.92E-01	0.01	4.92E+01	1.04E+09		
	42	19	3.08E+03	22.46	K	K-42	4.92E-01	0.01	4.92E+01	4.45E+04		
	22	11	1.78E+04	23.39	Na	Na-22	2.83E+00	0.1	2.83E+01	8.21E+07		
	56	27	1.43E+04	6.04	Co	Co-56	2.28E+00	0.1	2.28E+01	6.67E+06		
	68	31	9.43E+02	66.67	Ga	Ga-68	1.50E-01	0.01	1.50E+01	4.06E+03		
	68	32	9.43E+02	66.67	Ge	Ge-68	1.50E-01	0.01	1.50E+01	2.34E+07		
	44	21	7.04E+03	21.73	Sc	Sc-44	1.12E+00	0.1	1.12E+01	1.46E+04		
	32	14	5.06E+02	31.62	Si	Si-32	8.07E-02	0.01	8.07E+00	4.95E+09		
	58	27	3.89E+04	1.74	Co	Co-58	6.21E+00	1	6.21E+00	6.12E+06		
	46	21	3.51E+03	7.24	Sc	Sc-46	5.59E-01	0.1	5.59E+00	7.24E+06		
	45	20	4.22E+03	14.14	Ca	Ca-45	6.72E-01	1	6.72E-01	1.40E+07		
	7	4	2.41E+03	5.48	Be	Be-7	3.83E-01	1	3.83E-01	4.60E+06		
	41	20	1.51E+01	12.04	Ca	Ca-41	2.40E-03	0.01	2.40E-01	3.14E+12		
	35	16	1.32E+03	22.97	S	S-35	2.11E-01	1	2.11E-01	7.55E+06		
	32	15	5.06E+02	31.62	P	P-32	8.07E-02	1	8.07E-02	1.23E+06		
	59	28	4.72E+02	1.05	Ni	Ni-59	7.52E-02	1	7.52E-02	2.40E+12		
	10	4	1.98E+00	6.20	Be	Be-10	3.15E-04	0.01	3.15E-02	4.77E+13		
	59	26	1.79E+02	14.85	Fe	Fe-59	2.85E-02	1	2.85E-02	3.84E+06		
	14	6	1.48E+02	3.57	C	C-14	2.36E-02	1	2.36E-02	1.80E+11		
	51	24	4.48E+01	5.64	Cr	Cr-51	7.13E-03	1	7.13E-03	2.39E+06		
	37	18	3.24E+01	6.56	Ar	Ar-37	5.17E-03	1	5.17E-03	3.02E+06		
	26	13	2.55E-01	22.27	Al	Al-26	4.07E-05	0.01	4.07E-03	2.26E+13		
	60	26	2.16E-01	11.76	Fe	Fe-60	3.44E-05	0.01	3.44E-03	8.27E+13		
	36	17	5.80E+00	10.54	Cl	Cl-36	9.24E-04	1	9.24E-04	9.51E+12		
	53	25	3.42E+00	2.53	Mn	Mn-53	5.45E-04	1	5.45E-04	1.17E+14		
	33	15	1.47E+00	3.95	P	P-33	2.35E-04	1	2.35E-04	2.19E+06		
	48	23	2.26E-02	3.53	V	V-48	3.61E-06	1	3.61E-06	1.38E+06		
	40	19	1.69E-03	10.82	K	K-40	2.70E-07	1	2.70E-07	3.94E+16		
	A/Z/Isomers:											
	44	21	7.01E+03	21.73	Sc	Sc-44	1.12E+00	0.1	1.12E+01	2.11E+05		
	60	27	2.16E-01	11.76	Co	Co-60	3.44E-05	0.1	3.44E-04	6.28E+02		
	45	21	8.01E-02	14.14	Sc	Sc-45	1.28E-05	0.01	1.28E-03	3.26E-01		

Figure 5.15: Radionuclides generated in settom with respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, see Data analysis methodology paragraph).

Fig.5.15 shows the activity table of settom, composed of copper. The most significant long-lived radionuclides due to the high specific activity of the component are ^{49}V , ^{60}Co , ^3H , ^{54}Mn , ^{55}Fe and ^{44}Ti .

settomag	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)				
	49	23	2.69E+05	3.84	V	V-49	8.34E-01	0.01	8.34E+01	2.85E+07	V(m3)	ro(g/cm3)	m(Kg)
	54	25	1.28E+06	1.46	Mn	Mn-54	3.96E+00	0.1	3.96E+01	2.70E+07	4.09E-02	7.87E+00	3.22E+02
	55	26	4.19E+06	1.32	Fe	Fe-55	1.30E+01	1	1.30E+01	8.66E+07	att. (Bq)		
	3	1	4.20E+05	5.68	H	H-3	1.31E+00	1	1.31E+00	3.89E+08	6.17E+06	+/-	9.90E-01 %
	44	22	3.05E+03	15.38	Ti	Ti-44	9.47E-03	0.01	9.47E-01	1.87E+09	att.sp. (Bq/g)		
	39	18	9.50E+02	30.30	Ar	Ar-39	2.95E-03	0.01	2.95E-01	8.46E+09	1.92E+01		
	44	21	3.05E+03	15.38	Sc	Sc-44	9.47E-03	0.1	9.47E-02	1.46E+04	Σ att.sp/cf		1.39E+02
	46	21	2.53E+03	16.50	Sc	Sc-46	7.87E-03	0.1	7.87E-02	7.24E+06			
	56	27	1.03E+03	23.89	Co	Co-56	3.19E-03	0.1	3.19E-02	6.67E+06			
	45	20	2.36E+03	23.69	Ca	Ca-45	7.33E-03	1	7.33E-03	1.40E+07			
	41	20	4.35E+00	14.13	Ca	Ca-41	1.35E-05	0.01	1.35E-03	3.14E+12			
	57	27	3.15E+02	99.00	Co	Co-57	9.79E-04	1	9.79E-04	2.35E+07			
	35	16	1.81E+02	44.37	S	S-35	5.62E-04	1	5.62E-04	7.55E+06			
	51	24	1.18E+02	2.27	Cr	Cr-51	3.66E-04	1	3.66E-04	2.39E+06			
	7	4	4.81E+01	42.86	Be	Be-7	1.49E-04	1	1.49E-04	4.60E+06			
	58	27	4.49E+01	61.24	Co	Co-58	1.40E-04	1	1.40E-04	6.12E+06			
	53	25	1.34E+01	1.81	Mn	Mn-53	4.15E-05	1	4.15E-05	1.17E+14			
	37	18	7.53E+00	41.42	Ar	Ar-37	2.34E-05	1	2.34E-05	3.02E+06			
	14	6	6.18E+00	92.98	C	C-14	1.92E-05	1	1.92E-05	1.80E+11			
	59	26	5.41E+00	61.24	Fe	Fe-59	1.68E-05	1	1.68E-05	3.84E+06			
	10	4	2.20E-02	61.24	Be	Be-10	6.84E-08	0.01	6.84E-06	4.77E+13			
	36	17	7.73E-01	17.50	Cl	Cl-36	2.40E-06	1	2.40E-06	9.51E+12			
	59	28	2.19E-01	99.00	Ni	Ni-59	6.80E-07	1	6.80E-07	2.40E+12			
	33	15	1.84E-01	54.77	P	P-33	5.72E-07	1	5.72E-07	2.19E+06			
	48	23	3.86E-02	3.50	V	V-48	1.20E-07	1	1.20E-07	1.38E+06			
	40	19	4.93E-04	22.85	K	K-40	1.53E-09	1	1.53E-09	3.94E+16			
	A/Z/m Isomers:												
	44	21	3.04E+03	15.38	Sc	Sc-44	9.43E-03	0.1	9.43E-02	2.11E+05			
	45	21	4.49E-02	23.69	Sc	Sc-45	1.39E-07	0.01	1.39E-05	3.26E-01			

Figure 5.16: Radionuclides generated in settomag with respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, see Data analysis methodology paragraph).

Fig. 5.16 shows the activity table of settomag, composed of iron. The most significant long-lived radionuclides due to the high specific activity of the component are ⁴⁹V, ⁵⁴Mn, ⁵⁵Fe and ³H.

chopper1	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)				
	49	23	2.53E+04	7.57	V	V-49	3.52E-01	0.01	3.52E+01	2.85E+07	V(m3)	copper	
	60	27	1.04E+05	6.97	Co	Co-60	1.45E+00	0.1	1.45E+01	1.66E+08	8.00E-03	8.96E+00	7.17E+01
	3	1	5.19E+05	5.55	H	H-3	7.24E+00	1	7.24E+00	3.89E+08	att. (Bq)		
	54	25	3.13E+04	6.38	Mn	Mn-54	4.37E-01	0.1	4.37E+00	2.70E+07	9.57E+05 +/-		5.45E+00 %
	55	26	1.07E+05	12.99	Fe	Fe-55	1.49E+00	1	1.49E+00	8.66E+07	att.sp. (Bq/g)		
	57	27	7.66E+04	5.77	Co	Co-57	1.07E+00	1	1.07E+00	2.35E+07	1.34E+01		
	63	28	7.44E+04	4.80	Ni	Ni-63	1.04E+00	1	1.04E+00	3.19E+09	Σ att.sp/cf		6.78E+01
	44	22	4.69E+02	61.24	Ti	Ti-44	6.54E-03	0.01	6.54E-01	1.87E+09			
	22	11	3.68E+03	31.18	Na	Na-22	5.13E-02	0.1	5.13E-01	8.21E+07			
	65	30	3.12E+03	26.50	Zn	Zn-65	4.35E-02	0.1	4.35E-01	2.11E+07			
	39	18	2.37E+02	46.77	Ar	Ar-39	3.31E-03	0.01	3.31E-01	8.46E+09			
	56	27	2.23E+03	8.39	Co	Co-56	3.11E-02	0.1	3.11E-01	6.67E+06			
	32	14	2.02E+02	99.00	Si	Si-32	2.82E-03	0.01	2.82E-01	4.95E+09			
	58	27	6.80E+03	6.44	Co	Co-58	9.48E-02	1	9.48E-02	6.12E+06			
	46	21	5.07E+02	41.42	Sc	Sc-46	7.07E-03	0.1	7.07E-02	7.24E+06			
	44	21	4.69E+02	61.24	Sc	Sc-44	6.54E-03	0.1	6.54E-02	1.46E+04			
	45	20	8.43E+02	63.25	Ca	Ca-45	1.18E-02	1	1.18E-02	1.40E+07			
	7	4	2.82E+02	11.82	Be	Be-7	3.93E-03	1	3.93E-03	4.60E+06			
	35	16	2.65E+02	48.59	S	S-35	3.69E-03	1	3.69E-03	7.55E+06			
	32	15	2.03E+02	99.00	P	P-32	2.83E-03	1	2.83E-03	1.23E+06			
	41	20	1.00E+00	31.18	Ca	Ca-41	1.40E-05	0.01	1.40E-03	3.14E+12			
	59	28	8.19E+01	7.79	Ni	Ni-59	1.14E-03	1	1.14E-03	2.40E+12			
	59	26	3.25E+01	28.26	Fe	Fe-59	4.53E-04	1	4.53E-04	3.84E+06			
	14	6	2.33E+01	15.31	C	C-14	3.25E-04	1	3.25E-04	1.80E+11			
	10	4	2.06E-01	27.78	Be	Be-10	2.88E-06	0.01	2.88E-04	4.77E+13			
	26	13	6.96E-02	40.82	Al	Al-26	9.71E-07	0.01	9.71E-05	2.26E+13			
	51	24	5.24E+00	19.29	Cr	Cr-51	7.31E-05	1	7.31E-05	2.39E+06			
	37	18	4.05E+00	36.42	Ar	Ar-37	5.65E-05	1	5.65E-05	3.02E+06			
	60	26	3.81E-02	31.18	Fe	Fe-60	5.31E-07	0.01	5.31E-05	8.27E+13			
	53	25	4.63E-01	3.85	Mn	Mn-53	6.45E-06	1	6.45E-06	1.17E+14			
	36	17	3.87E-01	28.57	Cl	Cl-36	5.39E-06	1	5.39E-06	9.51E+12			
	33	15	1.84E-01	44.72	P	P-33	2.57E-06	1	2.57E-06	2.19E+06			
	48	23	3.14E-03	14.91	V	V-48	4.38E-08	1	4.38E-08	1.38E+06			
	40	19	1.87E-04	20.82	K	K-40	2.60E-09	1	2.60E-09	3.94E+16			
	A/Z/ Isomers:												
	44	21	4.67E+02	61.24	Sc	Sc-44	6.52E-03	0.1	6.52E-02	1.46E+04			
	45	21	1.60E-02	63.25	Sc	Sc-45	2.23E-07	0.01	2.23E-05	3.26E-01			
	60	27	3.81E-02	31.18	Co	Co-60	5.31E-07	0.1	5.31E-06	6.28E+02			

Figure 5.17: Radionuclides generated in chopper1 with respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, see Data analysis methodology paragraph).

Fig. 5.35 shows the activity table of chopper1, composed of copper. The most significant long-lived radionuclides due to the high specific activity of the component are ⁴⁹V, ⁶⁰Co, ³H, ⁵⁴Mn, ⁵⁵Fe, ⁵⁷Co, ⁶³Ni and ⁴⁴Ti.

SCREEN	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)		inox		
	49	23	3.37E+05	3.39	V	V-49	1.81E-01	0.01	1.81E+01	2.85E+07	V(m3)	ro(g/cm3)	m(Kg)
	54	25	1.21E+06	1.19	Mn	Mn-54	6.51E-01	0.1	6.51E+00	2.70E+07	2.36E-01	7.90E+00	1.87E+03
	55	26	3.96E+06	1.65	Fe	Fe-55	2.12E+00	1	2.12E+00	8.66E+07	att. (Bq)		
	44	22	6.33E+03	7.41	Ti	Ti-44	3.39E-03	0.01	3.39E-01	1.87E+09	6.45E+06 +/-		1.56E+00 %
	44	21	6.33E+03	7.41	Sc	Sc-44	3.39E-03	0.01	3.39E-01	1.46E+04	att.sp. (Bq/g)		
	3	1	5.42E+05	4.64	H	H-3	2.91E-01	1	2.91E-01	3.89E+08	3.46E+00		
	57	27	2.79E+05	3.22	Co	Co-57	1.50E-01	1	1.50E-01	2.35E+07	Σ att.sp/cf		2.86E+01
	60	27	2.68E+04	17.86	Co	Co-60	1.44E-02	0.1	1.44E-01	1.66E+08			
	39	18	1.37E+03	24.40	Ar	Ar-39	7.31E-04	0.01	7.31E-02	8.46E+09			
	56	27	9.77E+03	4.38	Co	Co-56	5.24E-03	0.1	5.24E-02	6.67E+06			
	42	18	7.34E+02	61.24	Ar	Ar-42	3.93E-04	0.01	3.93E-02	1.04E+09			
	22	11	3.68E+03	40.82	Na	Na-22	1.97E-03	0.1	1.97E-02	8.21E+07			
	46	21	3.12E+03	8.84	Sc	Sc-46	1.67E-03	0.1	1.67E-02	7.24E+06			
	35	16	3.09E+02	36.42	S	S-35	1.65E-04	0.01	1.65E-02	7.55E+06			
	63	28	2.38E+04	9.54	Ni	Ni-63	1.27E-02	1	1.27E-02	3.19E+09			
	58	27	2.23E+04	4.58	Co	Co-58	1.20E-02	1	1.20E-02	6.12E+06			
	32	14	1.01E+02	99.00	Si	Si-32	5.42E-05	0.01	5.42E-03	4.95E+09			
	45	20	2.36E+03	17.50	Ca	Ca-45	1.27E-03	1	1.27E-03	1.40E+07			
	41	20	8.03E+00	18.22	Ca	Ca-41	4.30E-06	0.01	4.30E-04	3.14E+12			
	42	19	7.34E+02	61.24	K	K-42	3.93E-04	1	3.93E-04	4.45E+04			
	59	28	2.56E+02	4.39	Ni	Ni-59	1.37E-04	1	1.37E-04	2.40E+12			
	51	24	1.40E+02	2.48	Cr	Cr-51	7.50E-05	1	7.50E-05	2.39E+06			
	32	15	1.01E+02	99.00	P	P-32	5.42E-05	1	5.42E-05	1.23E+06			
	7	4	7.56E+01	17.01	Be	Be-7	4.05E-05	1	4.05E-05	4.60E+06			
	14	6	4.66E+01	18.22	C	C-14	2.50E-05	1	2.50E-05	1.80E+11			
	59	26	3.79E+01	20.82	Fe	Fe-59	2.03E-05	1	2.03E-05	3.84E+06			
	53	25	1.47E+01	1.99	Mn	Mn-53	7.86E-06	1	7.86E-06	1.17E+14			
	37	18	1.10E+01	28.10	Ar	Ar-37	5.89E-06	1	5.89E-06	3.02E+06			
	26	13	6.96E-02	40.82	Al	Al-26	3.73E-08	0.01	3.73E-06	2.26E+13			
	10	4	4.41E-02	46.77	Be	Be-10	2.36E-08	0.01	2.36E-06	4.77E+13			
	36	17	1.05E+00	12.89	Cl	Cl-36	5.62E-07	1	5.62E-07	9.51E+12			
	60	26	6.35E-03	99.00	Fe	Fe-60	3.40E-09	0.01	3.40E-07	8.27E+13			
	33	15	2.58E-01	42.86	P	P-33	1.38E-07	1	1.38E-07	2.19E+06			
	48	23	4.74E-02	3.81	V	V-48	2.54E-08	1	2.54E-08	1.38E+06			
	40	19	6.40E-04	13.82	K	K-40	3.43E-10	1	3.43E-10	3.94E+16			
	A/Z/ Isomers:												
	44	21	6.31E+03	7.41	Sc	Sc-44	3.38E-03	0.01	3.38E-01	2.11E+05			
	45	21	4.49E-02	17.50	Sc	Sc-45	2.40E-08	0.01	2.40E-06	3.26E-01			
	60	27	6.35E-03	99.00	Co	Co-60	3.40E-09	0.1	3.40E-08	6.28E+02			

Figure 5.18: Radionuclides generated in SCREEN with respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, see Data analysis methodology paragraph).

Fig. 5.18 shows the activity table of SCREEN, composed of inox. The most significant long-lived radionuclides due to the high specific activity of the component are ^{49}V , ^{54}Mn , ^{55}Fe , ^{44}Ti , ^3H , ^{57}Co , ^{60}Co and a short-lived radionuclide ^{44}Sc . Although ^{44}Sc has a half-life of only 4 hours, it is still detected after a cooling time of one year because it is continuously produced by the decay of ^{44}Ti . ^{44}Ti undergoes electron capture with a half-life of 59.1 years, creating a secular equilibrium state between the two isotopes.

DIPOL08	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)			
	49	23	2.60E+05	4.59	V	V-49	3.33E-02	0.01	3.33E+00	2.85E+07	V(m3)	
	54	25	1.03E+06	1.79	Mn	Mn-54	1.32E-01	0.1	1.32E+00	2.70E+07	9.90E-01	7.87E+00
	55	26	4.61E+06	1.48	Fe	Fe-55	5.91E-01	1	5.91E-01	8.66E+07	att. (Bq)	7.80E+03
	3	1	4.31E+05	5.53	H	H-3	5.53E-02	1	5.53E-02	3.89E+08	6.36E+06 +/-	1.12E+00
	44	21	3.75E+03	22.96	Sc	Sc-44	4.81E-04	0.1	4.81E-02	1.46E+04	att.sp. (Bq/g)	%
	44	22	3.75E+03	22.96	Ti	Ti-44	4.81E-04	0.01	4.81E-02	1.87E+09	8.15E-01	
	39	18	1.01E+03	19.95	Ar	Ar-39	1.29E-04	0.01	1.29E-02	8.46E+09	Σ att.sp/cf	5.47E+00
	42	18	3.67E+02	99.00	Ar	Ar-42	4.71E-05	0.01	4.71E-03	1.04E+09		
	46	21	2.85E+03	11.58	Sc	Sc-46	3.65E-04	0.1	3.65E-03	7.24E+06		
	35	16	8.82E+01	61.24	S	S-35	1.13E-05	1	1.13E-03	7.55E+06		
	22	11	6.13E+02	99.00	Na	Na-22	7.86E-05	0.1	7.86E-04	8.21E+07		
	56	27	5.73E+02	30.46	Co	Co-56	7.35E-05	0.1	7.35E-04	6.67E+06		
	45	20	1.86E+03	9.09	Ca	Ca-45	2.38E-04	1	2.38E-04	1.40E+07		
	57	27	6.30E+02	61.24	Co	Co-57	8.08E-05	1	8.08E-05	2.35E+07		
	41	20	4.35E+00	11.21	Ca	Ca-41	5.58E-07	0.01	5.58E-05	3.14E+12		
	42	19	3.67E+02	99.00	K	K-42	4.71E-05	0.01	4.71E-05	4.45E+04		
	59	26	3.38E+02	5.93	Fe	Fe-59	4.33E-05	1	4.33E-05	3.84E+06		
	51	24	1.14E+02	3.44	Cr	Cr-51	1.47E-05	1	1.47E-05	2.39E+06		
	7	4	4.12E+01	61.24	Be	Be-7	5.29E-06	1	5.29E-06	4.60E+06		
	53	25	1.19E+01	1.85	Mn	Mn-53	1.53E-06	1	1.53E-06	1.17E+14		
	14	6	5.83E+00	61.24	C	C-14	7.47E-07	1	7.47E-07	1.80E+11		
	10	4	4.41E-02	46.77	Be	Be-10	5.65E-09	0.01	5.65E-07	4.77E+13		
	37	18	4.05E+00	28.57	Ar	Ar-37	5.20E-07	1	5.20E-07	3.02E+06		
	36	17	9.39E-01	27.28	Cl	Cl-36	1.20E-07	1	1.20E-07	9.51E+12		
	33	15	7.36E-02	61.24	P	P-33	9.44E-09	1	9.44E-09	2.19E+06		
	48	23	4.05E-02	7.23	V	V-48	5.20E-09	1	5.20E-09	1.38E+06		
	40	19	4.40E-04	16.32	K	K-40	5.64E-11	1	5.64E-11	3.94E+16		
	A/Z/m isomers:											
	44	21	3.74E+03	22.96	Sc	Sc-44	4.79E-04	0.1	4.79E-02	2.11E+05		
	45	21	3.52E-02	9.09	Sc	Sc-45	4.52E-09	0.01	4.52E-07	3.26E-01		

Figure 5.19: Radionuclides generated in dipolo8 with respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, see Data analysis methodology paragraph).

Fig. 5.19 shows the activity table of DIPOL08, composed of iron. The most significant long-lived radionuclides due to the high specific activity of the component are ^{49}V , ^{54}Mn and ^{55}Fe .

QUADPOL	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)			
	49	23	1.13E+05	1.37	V	V-49	1.01E-01	0.01	1.01E+01	2.85E+07	V(m3)	
	54	25	4.45E+05	2.81	Mn	Mn-54	3.98E-01	0.1	3.98E+00	2.70E+07	ro(g/cm3)	
	55	26	1.59E+06	3.30	Fe	Fe-55	1.42E+00	1	1.42E+00	8.66E+07	m(Kg)	
	3	1	1.85E+05	8.28	H	H-3	1.65E-01	1	1.65E-01	3.89E+08	att. (Bq)	
	44	21	9.38E+02	72.89	Sc	Sc-44	8.38E-04	0.1	8.38E-03	1.46E+04	2.34E+06 +/-	
	44	22	9.38E+02	72.89	Ti	Ti-44	8.38E-04	0.01	8.38E-02	1.87E+09	att.sp. (Bq/g)	
	39	18	4.16E+02	36.42	Ar	Ar-39	3.71E-04	0.01	3.71E-02	8.46E+09	2.09E+00	
	42	18	3.67E+02	99.00	Ar	Ar-42	3.28E-04	0.01	3.28E-02	1.04E+09	Σ att.sp/cf	
	46	21	1.13E+03	8.45	Sc	Sc-46	1.01E-03	0.1	1.01E-02	7.24E+06		1.59E+01
	22	11	6.13E+02	99.00	Na	Na-22	5.47E-04	0.1	5.47E-03	8.21E+07		
	56	27	1.81E+02	40.82	Co	Co-56	1.62E-04	0.1	1.62E-03	6.67E+06		
	45	20	8.43E+02	54.77	Ca	Ca-45	7.53E-04	1	7.53E-04	1.40E+07		
	42	19	3.67E+02	99.00	K	K-42	3.28E-04	0.01	3.28E-02	4.45E+04		
	57	27	3.15E+02	99.00	Co	Co-57	2.81E-04	1	2.81E-04	2.35E+07		
	41	20	1.67E+00	15.81	Ca	Ca-41	1.49E-06	0.01	1.49E-04	3.14E+12		
	51	24	5.21E+01	2.99	Cr	Cr-51	4.65E-05	1	4.65E-05	2.39E+06		
	59	26	3.52E+01	15.38	Fe	Fe-59	3.14E-05	1	3.14E-05	3.84E+06		
	7	4	2.06E+01	66.67	Be	Be-7	1.84E-05	1	1.84E-05	4.60E+06		
	53	25	4.95E+00	4.59	Mn	Mn-53	4.42E-06	1	4.42E-06	1.17E+14		
	14	6	2.91E+00	99.00	C	C-14	2.60E-06	1	2.60E-06	1.80E+11		
	26	13	2.32E-02	99.00	Al	Al-26	2.07E-08	0.01	2.07E-06	2.26E+13		
	37	18	2.32E+00	46.77	Ar	Ar-37	2.07E-06	1	2.07E-06	3.02E+06		
	10	4	2.20E-02	99.00	Be	Be-10	1.97E-08	0.01	1.97E-06	4.77E+13		
	36	17	4.97E-01	32.39	Cl	Cl-36	4.44E-07	1	4.44E-07	9.51E+12		
	33	15	1.10E-01	40.82	P	P-33	9.86E-08	1	9.86E-08	2.19E+06		
	48	23	1.54E-02	4.23	V	V-48	1.38E-08	1	1.38E-08	1.38E+06		
	40	19	2.00E-04	23.57	K	K-40	1.79E-10	1	1.79E-10	3.94E+16		
	A/Z/m Isomers:											
	44	21	9.34E+02	72.89	Sc	Sc-44	8.35E-04	0.1	8.35E-03	2.11E+05		
	45	21	1.60E-02	54.77	Sc	Sc-45	1.43E-08	0.01	1.43E-06	3.26E-01		

Figure 5.20: Radionuclides generated in QUADPOL with respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, see Data analysis methodology paragraph).

Fig. 5.20 shows the activity table of QUADPOL, composed of iron. The most significant long-lived radionuclides due to the high specific activity of the component are ⁴⁹V, ⁵⁴Mn, ⁵⁵Fe.

dumpsa2	A	Z	ATT(Bq)	err%	elemento	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)		inox316		
	49	23	6.46E+04	6.76	V	V-49	1.61E+00	0.01	1.61E+02	2.85E+07	V(m3)	ro(g/cm3)	m(Kg)
	54	25	1.00E+05	6.03	Mn	Mn-54	2.50E+00	0.1	2.50E+01	2.70E+07	5.02E-03	8.00E+00	4.02E+01
	55	26	3.45E+05	5.79	Fe	Fe-55	8.58E+00	1	8.58E+00	8.66E+07	att. (Bq)		
	3	1	1.97E+05	6.46	H	H-3	4.91E+00	1	4.91E+00	3.89E+08	7.57E+05 +/-		4.40E+00 %
	88	39	1.63E+03	15.31	Y	Y-88	4.06E-02	0.01	4.06E+00	9.21E+06	att.sp. (Bq/g)		
	44	22	9.38E+02	61.24	Ti	Ti-44	2.33E-02	0.01	2.33E+00	1.87E+09	1.88E+01		
	42	18	7.34E+02	61.24	Ar	Ar-42	1.83E-02	0.01	1.83E+00	1.04E+09	sommatoria di att.sp/cf	2.16E+02	
	42	19	7.34E+02	61.24	K	K-42	1.83E-02	0.01	1.83E+00	4.45E+04			
	39	18	4.16E+02	28.57	Ar	Ar-39	1.03E-02	0.01	1.03E+00	8.46E+09			
	91	41	3.33E+02	30.93	Nb	Nb-91	8.30E-03	0.01	8.30E-01	2.15E+10			
	57	27	3.09E+04	10.78	Co	Co-57	7.69E-01	1	7.69E-01	2.35E+07			
	88	40	3.08E+02	15.31	Zr	Zr-88	7.65E-03	0.01	7.65E-01	7.21E+06			
	56	27	1.73E+03	12.15	Co	Co-56	4.31E-02	0.1	4.31E-01	6.67E+06			
	83	37	1.29E+02	66.89	Rb	Rb-83	3.20E-03	0.01	3.20E-01	7.45E+06			
	22	11	1.23E+03	61.24	Na	Na-22	3.05E-02	0.1	3.05E-01	8.21E+07			
	46	21	1.09E+03	15.57	Sc	Sc-46	2.72E-02	0.1	2.72E-01	7.24E+06			
	44	21	9.38E+02	61.24	Sc	Sc-44	2.33E-02	0.1	2.33E-01	1.46E+04			
	60	27	6.88E+02	99.00	Co	Co-60	1.71E-02	0.1	1.71E-01	1.66E+08			
	63	28	2.07E+03	39.77	Ni	Ni-63	5.14E-02	1	5.14E-02	3.19E+09			
	58	27	2.00E+03	17.63	Co	Co-58	4.99E-02	1	4.99E-02	6.12E+06			
	45	20	1.35E+03	15.31	Ca	Ca-45	3.36E-02	1	3.36E-02	1.40E+07			
	90	39	4.02E+02	99.00	Y	Y-90	1.00E-02	1	1.00E-02	2.31E+05			
	90	38	4.02E+02	99.00	Sr	Sr-90	1.00E-02	1	1.00E-02	9.12E+08			
	41	20	3.51E+00	27.56	Ca	Ca-41	8.75E-05	0.01	8.75E-03	3.14E+12			
	35	16	3.09E+02	36.42	S	S-35	7.69E-03	1	7.69E-03	7.55E+06			
	85	36	1.36E+02	99.00	Kr	Kr-85	3.39E-03	1	3.39E-03	3.39E+08			
	85	38	7.83E+01	53.75	Sr	Sr-85	1.95E-03	1	1.95E-03	5.60E+06			
	7	4	4.12E+01	40.82	Be	Be-7	1.03E-03	1	1.03E-03	4.60E+06			
	93	42	3.73E+01	20.79	Mo	Mo-93	9.29E-04	1	9.29E-04	1.26E+11			
	10	4	2.64E-01	15.31	Be	Be-10	6.58E-06	0.01	6.58E-04	4.77E+13			
	51	24	2.33E+01	6.58	Cr	Cr-51	5.79E-04	1	5.79E-04	2.39E+06			
	59	28	1.95E+01	9.96	Ni	Ni-59	4.85E-04	1	4.85E-04	2.40E+12			
	14	6	1.15E+01	25.04	C	C-14	2.85E-04	1	2.85E-04	1.80E+11			
	59	26	8.11E+00	66.67	Fe	Fe-59	2.02E-04	1	2.02E-04	3.84E+06			
	37	18	6.37E+00	33.40	Ar	Ar-37	1.59E-04	1	1.59E-04	3.02E+06			
	82	37	3.68E-02	99.00	Rb	Rb-82	9.16E-07	0.01	9.16E-05	7.55E+01			
	82	38	3.68E-02	99.00	Sr	Sr-82	9.16E-07	0.01	9.16E-05	2.19E+06			
	26	13	2.32E-02	99.00	Al	Al-26	5.78E-07	0.01	5.78E-05	2.26E+13			
	53	25	1.37E+00	3.88	Mn	Mn-53	3.40E-05	1	3.40E-05	1.17E+14			
	36	17	1.33E+00	17.92	Cl	Cl-36	3.30E-05	1	3.30E-05	9.51E+12			
	94	41	8.19E-01	99.00	Nb	Nb-94	2.04E-05	1	2.04E-05	6.41E+11			
	99	43	7.09E-01	20.79	Tc	Tc-99	1.77E-05	1	1.77E-05	6.66E+12			
	95	41	5.77E-01	99.00	Nb	Nb-95	1.43E-05	1	1.43E-05	3.02E+06			
	92	41	4.79E-04	99.00	Nb	Nb-92	1.19E-08	0.01	1.19E-06	1.10E+15			
	48	23	1.16E-02	13.41	V	V-48	2.90E-07	1	2.90E-07	1.38E+06			
	93	40	1.03E-02	99.00	Zr	Zr-93	2.57E-07	1	2.57E-07	5.08E+13			
	86	37	1.01E-03	99.00	Rb	Rb-86	2.51E-08	1	2.51E-08	1.61E+06			
	40	19	5.07E-04	16.95	K	K-40	1.26E-08	1	1.26E-08	3.94E+16			
	A/Z/m Isomers:												
	88	39	3.08E+02	15.31	Y	Y-88	7.65E-03	0.01	7.65E-01	9.21E+06			
	44	21	9.34E+02	61.24	Sc	Sc-44	2.33E-02	0.1	2.33E-01	2.11E+05			
	85	37	7.57E+01	52.98	Rb	Rb-85	1.88E-03	0.01	1.88E-01	1.02E-06			
	91	41	5.62E+01	27.20	Nb	Nb-91	1.40E-03	0.01	1.40E-01	5.26E+06			
	83	36	9.34E+01	66.89	Kr	Kr-83	2.32E-03	1	2.32E-03	6.59E+03			
	93	41	1.52E+01	20.79	Nb	Nb-93	3.78E-04	1	3.78E-04	5.09E+08			
	45	21	2.56E-02	15.31	Sc	Sc-45	6.38E-07	0.01	6.38E-05	3.26E-01			

Figure 5.21: Radionuclides generated in dumpsa2 with respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, see Data analysis methodology paragraph).

Fig. 5.39 shows the activity table of the treatment room 2 dump, dumpsa2, composed of inox316. The most significant long-lived radionuclides due to the high specific activity of the component are ^{49}V , ^{54}Mn , ^{55}Fe , ^3H , ^{44}Ti , ^{49}Ar , ^{39}Ar and short-lived radionuclides ^{88}Y , ^{42}K .

xprblo5	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)		concrete	
	22	11	6.52E+05	5.21	Na	Na-22	2.77E-01	0.1	2.77E+00	8.21E+07	V(m3)	ro(g/cm3)
	3	1	3.69E+06	2.22	H	H-3	1.57E+00	1	1.57E+00	3.89E+08	1.01E+00	2.34E+00
	39	18	1.72E+04	9.32	Ar	Ar-39	7.31E-03	0.01	7.31E-01	8.46E+09	att. (Bq)	
	49	23	1.04E+04	18.39	V	V-49	4.42E-03	0.01	4.42E-01	2.85E+07	4.82E+06 +/-	1.95E+00 %
	152	63	5.25E+04	13.99	Eu	Eu-152	2.23E-02	0.1	2.23E-01	4.27E+08	att.sp. (Bq/g)	
	54	25	4.09E+04	10.65	Mn	Mn-54	1.74E-02	0.1	1.74E-01	2.70E+07	2.05E+00	
	55	26	2.79E+05	3.44	Fe	Fe-55	1.18E-01	1	1.18E-01	8.66E+07	Σ(att.sp/cf)	6.22E+00
	60	27	2.68E+04	13.69	Co	Co-60	1.14E-02	0.1	1.14E-01	1.66E+08		
	154	63	6.05E+03	36.85	Eu	Eu-154	2.57E-03	0.1	2.57E-02	2.71E+08		
	41	20	5.52E+02	2.45	Ca	Ca-41	2.34E-04	0.01	2.34E-02	3.14E+12		
	45	20	2.65E+04	7.64	Ca	Ca-45	1.12E-02	1	1.12E-02	1.40E+07		
	32	14	2.02E+02	61.24	Si	Si-32	8.60E-05	0.01	8.60E-03	4.95E+09		
	7	4	7.94E+03	3.85	Be	Be-7	3.37E-03	1	3.37E-03	4.60E+06		
	26	13	3.94E+01	1.87	Al	Al-26	1.68E-05	0.01	1.68E-03	2.26E+13		
	14	6	3.90E+03	1.67	C	C-14	1.65E-03	1	1.65E-03	1.80E+11		
	46	21	1.56E+02	46.77	Sc	Sc-46	6.62E-05	0.1	6.62E-04	7.24E+06		
	35	16	1.46E+03	22.27	S	S-35	6.18E-04	1	6.18E-04	7.55E+06		
	56	27	9.05E+01	40.82	Co	Co-56	3.84E-05	0.1	3.84E-04	6.67E+06		
	10	4	6.69E+00	4.90	Be	Be-10	2.84E-06	0.01	2.84E-04	4.77E+13		
	37	18	4.30E+02	4.24	Ar	Ar-37	1.82E-04	1	1.82E-04	3.02E+06		
	32	15	2.03E+02	61.24	P	P-32	8.60E-05	1	8.60E-05	1.23E+06		
	36	17	2.64E+01	4.03	Cl	Cl-36	1.12E-05	1	1.12E-05	9.51E+12		
	59	26	1.62E+01	61.24	Fe	Fe-59	6.89E-06	1	6.89E-06	3.84E+06		
	51	24	5.07E+00	7.29	Cr	Cr-51	2.15E-06	1	2.15E-06	2.39E+06		
	33	15	6.62E-01	6.80	P	P-33	2.81E-07	1	2.81E-07	2.19E+06		
	53	25	5.56E-01	2.83	Mn	Mn-53	2.36E-07	1	2.36E-07	1.17E+14		
	40	19	8.03E-02	1.03	K	K-40	3.41E-08	1	3.41E-08	3.94E+16		
	48	23	2.41E-03	18.95	V	V-48	1.02E-09	1	1.02E-09	1.38E+06		
	A/Z/m Isomers:											
	45	21	5.03E-01	7.64	Sc	Sc-45	2.14E-07	0.01	2.14E-05	3.26E-01		

Figure 5.22: Radionuclides generated in xprblo5 with respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, see Data analysis methodology paragraph).

Fig. 5.22 presents the activity table of xprblo5, made of concrete. The most significant long-lived radionuclides due to the high specific activity of the component are ²²Na, ³H, ³⁹Ar, ⁴⁹V, ¹⁵²Eu, ⁵⁴Mn, ⁵⁵Fe and ⁶⁰Co.

A0425	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)		concrete	
	152	63	8.58E+04	2.01	Eu	Eu-152	3.66E-02	0.1	3.66E-01	4.27E+08	V(m3)	ro(g/cm3)
	39	18	6.24E+03	2.15	Ar	Ar-39	2.67E-03	0.01	2.67E-01	8.46E+09		2.34E+00
	60	27	4.33E+04	2.86	Co	Co-60	1.85E-02	0.1	1.85E-01	1.66E+08	att. (Bq)	2.34E+03
	55	26	2.52E+05	1.24	Fe	Fe-55	1.08E-01	1	1.08E-01	8.66E+07	5.43E+05 +/-	8.06E-01 %
	22	11	2.41E+04	3.23	Na	Na-22	1.03E-02	0.1	1.03E-01	8.21E+07	att.sp. (Bq/g)	
	41	20	8.44E+02	0.34	Ca	Ca-41	3.61E-04	0.01	3.61E-02	3.14E+12	2.32E-01	
	3	1	7.94E+04	2.01	H	H-3	3.39E-02	1	3.39E-02	3.89E+08	Σ att.sp/cf	1.18E+00
	154	63	7.89E+03	6.14	Eu	Eu-154	3.37E-03	0.1	3.37E-02	2.71E+08		
	54	25	3.97E+03	6.55	Mn	Mn-54	1.70E-03	0.1	1.70E-02	2.70E+07		
	45	20	3.92E+04	1.44	Ca	Ca-45	1.67E-02	1	1.67E-02	1.40E+07		
	49	23	2.93E+02	25.64	V	V-49	1.25E-04	0.01	1.25E-02	2.85E+07		
	35	16	8.82E+01	16.48	Si	Si-35	3.77E-05	0.01	3.77E-03	7.80E-01		
	14	6	2.40E+02	2.51	C	C-14	1.02E-04	1	1.02E-04	1.80E+11		
	26	13	1.92E+00	2.85	Al	Al-26	8.18E-07	0.01	8.18E-05	2.26E+13		
	7	4	1.35E+02	5.46	Be	Be-7	5.76E-05	1	5.76E-05	4.60E+06		
	37	18	9.19E+01	1.60	Ar	Ar-37	3.93E-05	1	3.93E-05	3.02E+06		
	59	26	2.90E+01	6.42	Fe	Fe-59	1.24E-05	1	1.24E-05	3.84E+06		
	10	4	1.81E-01	5.97	Be	Be-10	7.73E-08	0.01	7.73E-06	4.77E+13		
	56	27	1.59E+00	99.00	Co	Co-56	6.79E-07	0.1	6.79E-06	6.67E+06		
	36	17	4.15E+00	2.15	Cl	Cl-36	1.77E-06	1	1.77E-06	9.51E+12		
	51	24	2.44E-01	12.53	Cr	Cr-51	1.04E-07	1	1.04E-07	2.39E+06		
	40	19	1.06E-01	0.28	K	K-40	4.53E-08	1	4.53E-08	3.94E+16		
	53	25	3.09E-02	9.89	Mn	Mn-53	1.32E-08	1	1.32E-08	1.17E+14		
	33	15	2.13E-02	36.24	P	P-33	9.10E-09	1	9.10E-09	2.19E+06		
	A/Z/Isomers:											
	45	21	7.45E-01	1.44	Sc	Sc-45	3.18E-07	0.01	3.18E-05	3.26E-01		

Figure 5.23: Radionuclides generated in floor block A0425 with respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, see Data analysis methodology paragraph).

Figure 5.23 shows the activity table for A0425, one of the few non-removable concrete floor pieces. It is a section of floor located under the dumpo. The most significant long-lived radionuclides, due to the high specific activity of the component, are ^{152}Eu , ^{39}Ar , ^{60}Co , ^{55}Fe and ^{22}Na .

5.3.2. Removable components: simulations with maximum energy and maximum particle beam intensity.

The following figures present data analyses of certain facility elements with a $\Sigma \text{Att.sp./cf}$ below one, making them removable. Additionally, the tables show similar elements of the synchrotron or the same material, which are non-removable but located in different positions within the machine. Since these elements are far from the beam loss points, they qualify for clearance removal.

DIPOLO	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)				
	49	23	3.01E+04	14.92	V-49	3.86E-03	0.01	3.86E-01	2.85E+07	V(m3)	iron		
	54	25	1.35E+05	2.53	Mn-54	1.73E-02	0.1	1.73E-01	2.70E+07	9.90E-01	ro(g/cm3)	7.87E+00	7.80E+03
	55	26	7.33E+05	4.19	Fe-55	9.40E-02	1	9.40E-02	8.66E+07	att. (Bq)			
	3	1	5.12E+04	11.84	H-3	6.56E-03	1	6.56E-03	3.89E+08	9.52E+05	+/-	3.71E+00	%
	44	21	4.69E+02	61.24	Sc-44	6.02E-05	0.1	6.02E-04	1.46E+04	att.sp. (Bq/g)			
	44	22	4.69E+02	61.24	Ti-44	6.02E-05	0.01	6.02E-03	1.87E+09	1.22E-01			
	39	18	1.19E+02	99.00	Ar-39	1.52E-05	0.01	1.52E-03	8.46E+09	Σ att.sp/cf		6.69E-01	
	35	16	8.82E+01	61.24	S-35	1.13E-05	1	1.13E-05	7.55E+06				
	46	21	2.73E+02	53.45	Sc-46	3.50E-05	0.1	3.50E-04	7.24E+06				
	56	27	1.81E+02	48.59	Co-56	2.32E-05	0.1	2.32E-04	6.67E+06				
	57	27	3.15E+02	99.00	Co-57	4.04E-05	1	4.04E-05	2.35E+07				
	45	20	1.69E+02	99.00	Ca-45	2.16E-05	1	2.16E-05	1.40E+07				
	59	26	5.14E+01	21.05	Fe-59	6.59E-06	1	6.59E-06	3.84E+06				
	41	20	5.02E-01	66.67	Ca-41	6.44E-08	0.01	6.44E-06	3.14E+12				
	51	24	1.31E+01	8.31	Cr-51	1.69E-06	1	1.69E-06	2.39E+06				
	14	6	5.83E+00	61.24	C-14	7.47E-07	1	7.47E-07	1.80E+11				
	10	4	3.31E-02	40.82	Be-10	4.24E-09	0.01	4.24E-07	4.77E+13				
	53	25	1.28E+00	2.78	Mn-53	1.64E-07	1	1.64E-07	1.17E+14				
	37	18	5.79E-01	99.00	Ar-37	7.42E-08	1	7.42E-08	3.02E+06				
	36	17	1.10E-01	99.00	Cl-36	1.42E-08	1	1.42E-08	9.51E+12				
	48	23	4.08E-03	22.72	V-48	5.23E-10	1	5.23E-10	1.38E+06				
	A/Z/Isomers:												
	44	21	4.67E+02	61.24	Sc-44	5.99E-05	0.1	5.99E-04	2.11E+05				
	45	21	3.20E-03	99.00	Sc-45	4.11E-10	0.01	4.11E-08	3.26E-01				

Figure 5.24: Radionuclides generated in DIPOLO with respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, see Data analysis methodology paragraph).

Fig. 5.24 shows the activity table of the DIPOLO, composed of iron. The same radionuclides generated in DIPOLO8 and iron components are also found here, but with lower specific activities. This reduction allows the dipole to be cleared for removal from the structure.

QUADPOL23	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)			
	49	23	1.49E+03	25.00	V	V-49	1.33E-03	0.01	1.33E-01	2.85E+07	V(m3)	ro(g/cm3)
	54	25	5.69E+03	11.69	Mn	Mn-54	5.08E-03	0.1	5.08E-02	2.70E+07		m(Kg)
	55	26	5.59E+04	11.79	Fe	Fe-55	4.99E-02	1	4.99E-02	8.66E+07	1.42E-01	7.87E+00
	39	18	5.94E+01	99.00	Ar	Ar-39	5.30E-05	0.01	5.30E-03	8.46E+09	att. (Bq)	1.12E+03
	3	1	4.32E+03	17.50	H	H-3	3.85E-03	1	3.85E-03	3.89E+08	6.75E+04 +/-	9.55E+00 %
	46	21	3.90E+01	99.00	Sc	Sc-46	3.48E-05	0.1	3.48E-04	7.24E+06	att.sp. (Bq/g)	
	56	27	3.02E+01	99.00	Co	Co-56	2.70E-05	0.1	2.70E-04	6.67E+06	6.03E-02	
	59	26	2.70E+00	99.00	Fe	Fe-59	2.42E-06	1	2.42E-06	3.84E+06	Σ att.sp/cf	2.43E-01
	51	24	1.20E+00	26.25	Cr	Cr-51	1.07E-06	1	1.07E-06	2.39E+06		
	53	25	9.79E-02	18.46	Mn	Mn-53	8.74E-08	1	8.74E-08	1.17E+14		
	33	15	3.68E-02	99.00	P	P-33	3.29E-08	1	3.29E-08	2.19E+06		
	48	23	4.19E-04	25.00	V	V-48	3.74E-10	1	3.74E-10	1.38E+06		

Figure 5.25: Radionuclides generated in QUADPOL23 with respective analysis.

Fig. 5.25 shows the activity table of the QUADPOL23, composed of iron. The same radionuclides generated in QUADPOL and iron components are also found here, but with lower specific activities.

xprblo6	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)			
	22	11	9.62E+04	7.23	Na	Na-22	4.09E-02	0.1	4.09E-01	8.21E+07	V(m3)	ro(g/cm3)
	3	1	4.07E+05	1.63	H	H-3	1.73E-01	1	1.73E-01	3.89E+08		m(Kg)
	39	18	3.27E+03	17.95	Ar	Ar-39	1.39E-03	0.01	1.39E-01	8.46E+09	1.01E+00	2.34E+00
	49	23	2.60E+03	36.42	V	V-49	1.10E-03	0.01	1.10E-01	2.85E+07	att. (Bq)	2.35E+03
	152	63	1.13E+04	29.30	Eu	Eu-152	4.82E-03	0.1	4.82E-02	4.27E+08	5.98E+05 +/-	8.57E-01 %
	60	27	6.87E+03	15.82	Co	Co-60	2.92E-03	0.1	2.92E-02	1.66E+08	att.sp. (Bq/g)	
	55	26	5.47E+04	15.41	Fe	Fe-55	2.32E-02	1	2.32E-02	8.66E+07	2.54E-01	
	54	25	5.33E+03	34.96	Mn	Mn-54	2.26E-03	0.1	2.26E-02	2.70E+07	Σ att.sp/cf	9.69E-01
	35	16	2.65E+02	61.24	S	S-35	1.12E-04	1	1.12E-04	7.55E+06		
	154	63	1.35E+03	61.24	Eu	Eu-154	5.71E-04	0.1	5.71E-03	2.71E+08		
	41	20	1.31E+02	4.98	Ca	Ca-41	5.56E-05	0.01	5.56E-03	3.14E+12		
	45	20	7.42E+03	14.99	Ca	Ca-45	3.15E-03	1	3.15E-03	1.40E+07		
	7	4	1.02E+03	10.69	Be	Be-7	4.35E-04	1	4.35E-04	4.60E+06		
	46	21	7.80E+01	99.00	Sc	Sc-46	3.31E-05	0.1	3.31E-04	7.24E+06		
	26	13	5.96E+00	6.20	Al	Al-26	2.53E-06	0.01	2.53E-04	2.26E+13		
	14	6	5.33E+02	6.78	C	C-14	2.26E-04	1	2.26E-04	1.80E+11		
	10	4	9.81E-01	8.59	Be	Be-10	4.16E-07	0.01	4.16E-05	4.77E+13		
	37	18	7.06E+01	13.63	Ar	Ar-37	3.00E-05	1	3.00E-05	3.02E+06		
	59	26	5.41E+00	61.24	Fe	Fe-59	2.30E-06	1	2.30E-06	3.84E+06		
	36	17	4.36E+00	19.45	Cl	Cl-36	1.85E-06	1	1.85E-06	9.51E+12		
	51	24	6.01E-01	53.45	Cr	Cr-51	2.55E-07	1	2.55E-07	2.39E+06		
	33	15	1.10E-01	66.67	P	P-33	4.69E-08	1	4.69E-08	2.19E+06		
	53	25	8.01E-02	25.76	Mn	Mn-53	3.40E-08	1	3.40E-08	1.17E+14		
	40	19	1.86E-02	3.46	K	K-40	7.92E-09	1	7.92E-09	3.94E+16		
	32	15	1.89E-04	44.88	P	P-32	8.02E-11	1	8.02E-11	1.23E+06		
	48	23	1.05E-04	99.00	V	V-48	4.44E-11	1	4.44E-11	1.38E+06		
	A/Z/Isomers:											
	45	21	1.41E-01	14.99	Sc	Sc-45	5.99E-08	0.01	5.99E-06	7.55E+04		

Figure 5.26: Radionuclides generated in xprblo6 with respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, see Data analysis methodology paragraph).

Fig. 5.26 shows the concrete block of the wall of the xpr room (see Fig. 5.8). The same radionuclides found in xprblo5 and other concrete blocks are present here, but with lower specific activities.

5.3.3. Simulations with energy spectrum and maximum particle beam intensity.

The same simulations were repeated using the energy spectrum employed in 2023 in the synchrotron with the Carbon ions beam. The OPEN CARD was used to introduce the energy spectrum into the input.

Images 5.27-5.28 show the specific activity of the facility at beam level and floor level. The ceiling is not relevant to this study, as it is too far from the loss points and therefore not activated.

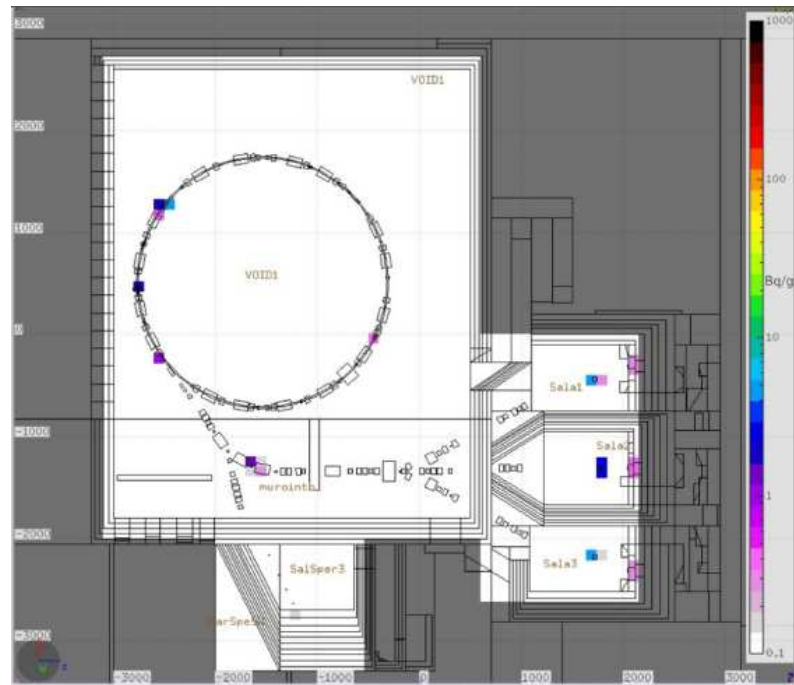


Figure 5.27: Visualization of the USERBIN-actomass in the x-z plane with $y=-200$, for a Carbon ion beam with energy spectrum and maximum intensity.

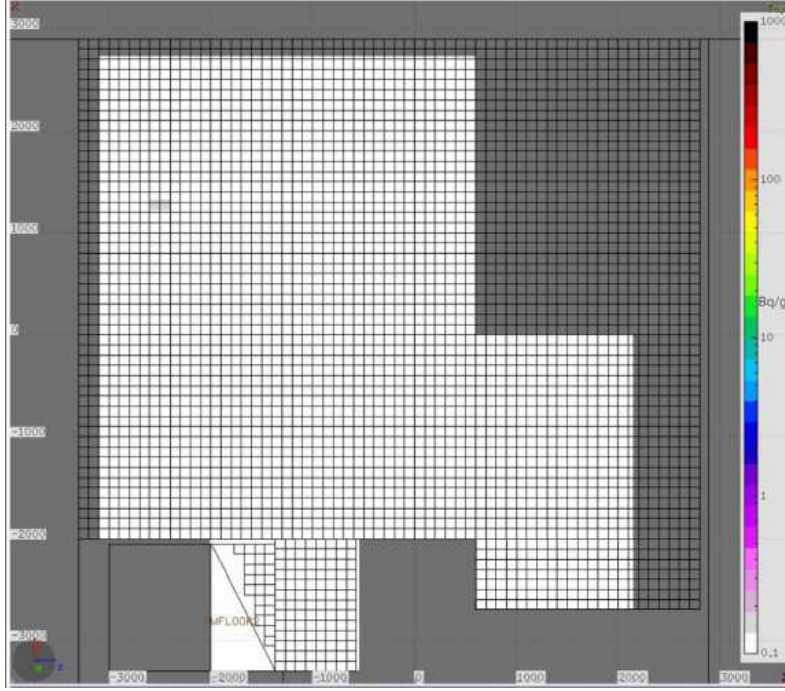


Figure 5.28: Visualization of the USERBIN-actomass in the x-z plane with $y=-350$, for a Carbon ion beam with energy spectrum and maximum intensity.

Once the RESNUCLEI files were obtained, all files were analyzed using tables identical to those generated with the maximum energy beam.

5.3.4. Simulations with energy spectrum and 15% of maximum beam intensity.

The same simulations were repeated using the energy spectrum employed in 2023 in the synchrotron with the Carbon ion beam and a 6×10^7 p/s beam current.

Once the RESNUCLEI files were obtained, all files were analyzed using tables identical to those generated with the maximum energy beam.

5.4. Protons simulations

This section presents the data obtained from Monte Carlo simulations performed with FLUKA using a proton beam for the following scenarios:

- Maximum authorized energy and intensity, considering both removable and non-removable components.

- Energy spectrum actually used in 2023 with the maximum authorized intensity.
- Energy spectrum actually used in 2023 with 15% of the maximum authorized intensity.

5.4.1. Non-removable components: simulations with maximum energy and maximum particle beam intensity.

Images 5.29-5.30 illustrate the specific activity of the facility at beam level and floor level for a Proton beam. The ceiling is not relevant to this study, as it is too far from the loss points and therefore not activated.

Figure 5.29 shows that the most activated areas, although exhibiting different specific activity concentrations, are the same as in the case of carbon ions. In particular, these include the regions surrounding the dumps in the synchrotron, the isocenters, the walls of the treatment rooms, and the XPR along the beam direction.

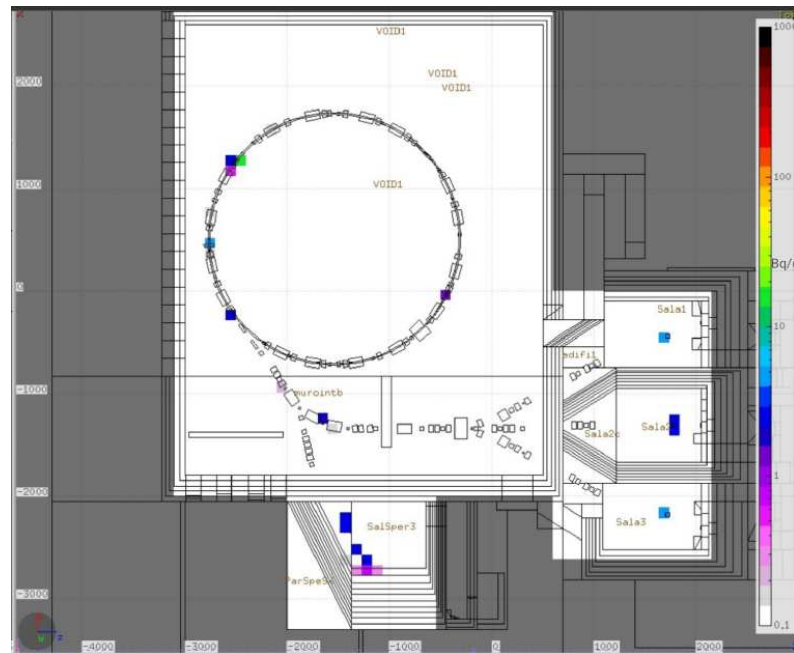


Figure 5.29: Visualization of the USERBIN-actomass in the x-z plane with $y=-200$, for a proton beam at maximum energy and intensity.

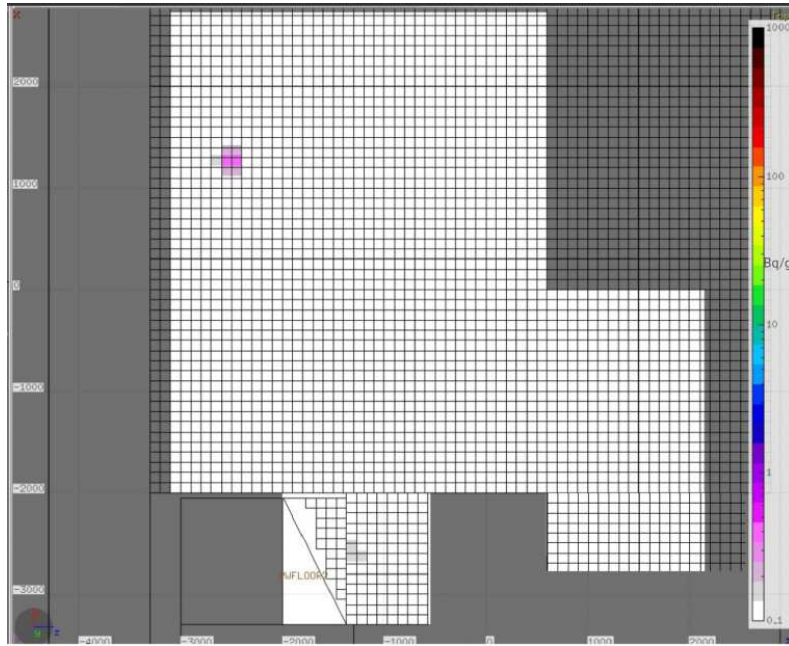


Figure 5.30: Visualization of the USERBIN-actomass in the x-z plane with $y=-350$, for a proton beam at maximum energy and intensity.

The following figures provide a detailed view of the specific activity of radionuclides generated after 30 years of irradiation. Tables are presented for the most significant regions, along with those from the previously reported carbon ion case, to allow for a comparison of the radionuclides produced and the activity values obtained with different particle beams.

dumpo	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)		tungsten	
	179	73	1.04E+08	0.34	Ta	Ta-179	7.73E+03	0.01	7.73E+05	5.74E+07	V(m3)	ro(g/cm3)
	173	71	3.44E+07	0.93	Lu	Lu-173	2.55E+03	0.01	2.55E+05	4.32E+07	7.00E-04	1.93E+01
	172	71	3.22E+07	0.62	Lu	Lu-172	2.38E+03	0.01	2.38E+05	5.79E+05	att. (Bq)	
	172	72	3.19E+07	0.62	Hf	Hf-172	2.36E+03	0.01	2.36E+05	5.90E+07	3.52E+08 +/-	1.85E-01 %
	175	72	2.37E+06	0.21	Hf	Hf-175	1.76E+02	0.01	1.76E+04	6.05E+06	att.sp. (Bq/g)	
	183	75	5.93E+05	0.81	Re	Re-183	4.39E+01	0.01	4.39E+03	6.05E+06	2.60E+04	
	3	1	5.82E+07	0.26	H	H-3	4.31E+03	1	4.31E+03	3.89E+08	Σ att.sp/cf	1.94E+06
	184	75	2.95E+05	3.60	Re	Re-184	2.19E+01	0.01	2.19E+03	3.06E+06		
	181	74	2.49E+07	0.24	W	W-181	1.84E+03	1	1.84E+03	1.05E+07		
	174	71	2.10E+05	9.09	Lu	Lu-174	1.55E+01	0.01	1.55E+03	1.04E+08		
	182	73	1.23E+06	1.22	Ta	Ta-182	9.08E+01	0.1	9.08E+02	9.91E+06		
	159	66	6.86E+04	6.61	Dy	Dy-159	5.08E+00	0.01	5.08E+02	1.25E+07		
	185	74	6.28E+06	0.22	W	W-185	4.65E+02	1	4.65E+02	6.49E+06		
	157	65	4.32E+04	14.52	Tb	Tb-157	3.20E+00	0.01	3.20E+02	2.24E+09		
	163	67	1.07E+04	2.50	Ho	Ho-163	7.92E-01	0.01	7.92E+01	1.44E+11		
	169	70	7.09E+03	1.51	Yb	Yb-169	5.25E-01	0.01	5.25E+01	2.77E+06		
	88	39	6.32E+03	21.45	Y	Y-88	4.68E-01	0.01	4.68E+01	9.21E+06		
	151	64	3.86E+03	22.88	Gd	Gd-151	2.86E-01	0.01	2.86E+01	1.07E+07		
	102	45	2.95E+03	44.72	Rh	Rh-102	2.18E-01	0.01	2.18E+01	1.79E+07		
	83	37	2.86E+03	15.04	Rb	Rb-83	2.12E-01	0.01	2.12E+01	7.45E+06		
	148	64	2.58E+03	41.43	Gd	Gd-148	1.91E-01	0.01	1.91E+01	2.24E+09		
	145	61	1.35E+03	99.00	Pm	Pm-145	1.00E-01	0.01	1.00E+01	5.59E+08		
	168	69	1.06E+03	31.87	Tm	Tm-168	7.81E-02	0.01	7.81E+00	8.04E+06		
	178	74	1.03E+03	0.34	W	W-178	7.59E-02	0.01	7.59E+00	1.87E+06		
	106	45	1.01E+03	99.00	Rh	Rh-106	7.49E-02	0.01	7.49E+00	3.01E+01		
	145	62	9.68E+02	99.00	Sm	Sm-145	7.17E-02	0.01	7.17E+00	2.94E+07		
	49	23	9.29E+02	99.00	V	V-49	6.87E-02	0.01	6.87E+00	2.85E+07		
	149	63	7.20E+02	55.72	Eu	Eu-149	5.33E-02	0.01	5.33E+00	8.04E+06		
	60	27	6.87E+03	46.79	Co	Co-60	5.08E-01	0.1	5.08E+00	1.66E+08		
	91	41	5.96E+02	15.99	Nb	Nb-91	4.41E-02	0.01	4.41E+00	2.15E+10		
	65	30	4.25E+03	48.59	Zn	Zn-65	3.15E-01	0.1	3.15E+00	2.11E+07		
	88	40	3.84E+02	46.77	Zr	Zr-88	2.85E-02	0.01	2.85E+00	7.21E+06		
	54	25	2.67E+03	40.82	Mn	Mn-54	1.97E-01	0.1	1.97E+00	2.70E+07		
	90	39	2.21E+04	23.40	Y	Y-90	1.64E+00	1	1.64E+00	2.31E+05		
	90	38	2.21E+04	23.40	Sr	Sr-90	1.64E+00	1	1.64E+00	9.12E+08		
	85	36	1.91E+04	19.68	Kr	Kr-85	1.41E+00	1	1.41E+00	3.39E+08		
	39	18	1.48E+02	99.00	Ar	Ar-39	1.10E-02	0.01	1.10E+00	8.46E+09		
	153	64	1.48E+04	19.08	Gd	Gd-153	1.10E+00	1	1.10E+00	2.08E+07		
	A/Z/Isomers:											
	172	71	3.19E+07	0.62	Lu	Lu-172	2.36E+03	0.01	2.36E+05	7.90E+01		
	181	73	1.84E+07	0.24	Ta	Ta-181	1.36E+03	0.01	1.36E+05	2.10E-04		
	172	71	3.59E+06	0.62	Lu	Lu-172	2.66E+02	0.01	2.66E+04	7.90E+01		
	184	75	3.06E+05	3.67	Re	Re-184	2.26E+01	0.01	2.26E+03	1.46E+07		
	184	74	7.80E+04	3.67	W	W-184	5.77E+00	0.01	5.77E+02	8.33E-06		
	174	71	1.18E+04	19.17	Lu	Lu-174	8.71E-01	0.01	8.71E+01	1.23E+07		
	175	71	5.46E+03	0.21	Lu	Lu-175	4.04E-01	0.01	4.04E+01	9.80E-04		
	113	48	4.46E+03	66.15	Cd	Cd-113	3.30E-01	0.01	3.30E+01	4.45E+08		
	109	47	2.31E+03	61.24	Ag	Ag-109	1.71E-01	0.01	1.71E+01	3.98E+01		
	178	72	1.91E+03	99.00	Hf	Hf-178	1.42E-01	0.01	1.42E+01	9.78E+08		
	178	72	1.91E+03	99.00	Hf	Hf-178	1.42E-01	0.01	1.42E+01	9.78E+08		
	73	32	1.11E+03	26.09	Ge	Ge-73	8.22E-02	0.01	8.22E+00	4.77E+01		
	73	32	1.11E+03	26.09	Ge	Ge-73	8.22E-02	0.01	8.22E+00	4.77E+01		
	178	73	1.03E+03	0.34	Ta	Ta-178	7.59E-02	0.01	7.59E+00	8.50E+03		
	85	37	8.83E+02	18.10	Rb	Rb-85	6.54E-02	0.01	6.54E+00	1.02E-06		
	181	73	8.21E+02	7.46	Ta	Ta-181	6.07E-02	0.01	6.07E+00	2.10E-04		
	151	63	3.96E+02	22.88	Eu	Eu-151	2.93E-02	0.01	2.93E+00	5.89E-05		
	88	39	3.84E+02	46.77	Y	Y-88	2.85E-02	0.01	2.85E+00	9.21E+06		
	177	72	3.24E+02	99.00	Hf	Hf-177	2.40E-02	0.01	2.40E+00	3.08E+03		

Figure 5.31: Radionuclides generated in dumpo with respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, see Data analysis methodology paragraph).

Fig. 5.31 shows a partial activity table of the horizontal dump, dumpo, composed of tungsten. Due to the high number of generated radionuclides, only those with an att.sp/cf ratio greater than 1.00 are listed. However, the total activity and Σ att.sp/cf calculations include all generated radionuclides. The most significant long-lived radionuclides due to the high specific activity of the component are ^{179}Ta , ^{173}Lu , ^{172}Hf , ^3H , ^{181}W , ^{174}Lu , ^{159}Dy , ^{157}Tb , ^{163}Ho , ^{151}Gd , ^{102}Rh , ^{148}Gd , ^{145}Pm and short-lived radionuclides ^{172}Lu , ^{175}Hf , ^{183}Re , ^{184}Re , ^{182}Ta , ^{185}W , ^{169}Yb , ^{88}Y , ^{83}Rb . Here, short-lived radionuclides (half-life < 1 year)

are continuously produced during irradiation. Their detection after a year of cooling is due to ongoing production, the decay of longer-lived parent isotopes, and secondary activation processes.

dumpori	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)		lead	
	195	79	2.02E+05	6.58	Au	Au-195	3.49E-01	0.01	3.49E+01	1.61E+07	V(m3)	ro(g/cm3)
	204	81	2.76E+06	3.39	Tl	Tl-204	4.77E+00	1	4.77E+00	1.19E+08	5.09E-02	1.14E+01
	194	79	1.99E+04	8.00	Au	Au-194	3.44E-02	0.01	3.44E+00	1.37E+05	att. (Bq)	5.78E+02
	194	80	1.99E+04	8.00	Hg	Hg-194	3.44E-02	0.01	3.44E+00	1.41E+10	4.98E+06 +/-	2.39E+00 %
	3	1	1.78E+06	1.44	H	H-3	3.07E+00	1	3.07E+00	3.89E+08	att.sp. (Bq/g)	
	106	45	1.01E+04	15.81	Rh	Rh-106	1.75E-02	0.01	1.75E+00	3.01E+01	8.62E+00	
	202	82	8.43E+03	1.33	Pb	Pb-202	1.46E-02	0.01	1.46E+00	1.66E+12	Σ att.sp/cf	5.82E+01
	207	83	2.74E+04	19.96	Bi	Bi-207	4.74E-02	0.1	4.74E-01	9.96E+08		
	106	44	1.01E+04	15.81	Ru	Ru-106	1.75E-02	0.1	1.75E-01	3.21E+07		
	193	78	7.25E+04	9.78	Pt	Pt-193	1.25E-01	1	1.25E-01	1.58E+09		
	121	50	5.99E+02	99.00	Sn	Sn-121	1.04E-03	0.01	1.04E-01	9.73E+04		
	102	45	5.90E+02	99.00	Rh	Rh-102	1.02E-03	0.01	1.02E-01	1.79E+07		
	123	50	2.82E+02	99.00	Sn	Sn-123	4.87E-04	0.01	4.87E-02	1.12E+07		
	88	39	1.86E+02	99.00	Y	Y-88	3.22E-04	0.01	3.22E-02	9.21E+06		
	90	39	1.51E+04	23.57	Y	Y-90	2.61E-02	1	2.61E-02	2.31E+05		
	90	38	1.51E+04	23.57	Sr	Sr-90	2.61E-02	1	2.61E-02	9.12E+08		
	83	37	1.06E+02	99.00	Rb	Rb-83	1.83E-04	0.01	1.83E-02	7.45E+06		
	205	82	1.04E+02	0.57	Pb	Pb-205	1.79E-04	0.01	1.79E-02	5.36E+14		
	85	36	8.64E+03	25.15	Kr	Kr-85	1.49E-02	1	1.49E-02	3.39E+08		
	202	81	8.34E+03	1.33	Tl	Tl-202	1.44E-02	1	1.44E-02	1.06E+06		
	A/Z/Isomers:											
	207	82	2.30E+04	19.96	Pb	Pb-207	3.98E-02	0.01	3.98E+00	8.06E-01		
	121	50	7.71E+02	99.00	Sn	Sn-121	1.33E-03	0.01	1.33E-01	1.39E+09		
	119	50	1.44E+02	48.91	Sn	Sn-119	2.49E-04	0.01	2.49E-02	2.53E+07		
	113	48	1.42E+02	0.00	Cd	Cd-113	2.45E-04	0.01	2.45E-02	4.45E+08		

Figure 5.32: Radionuclides generated in dumpori with respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, see Data analysis methodology paragraph).

Fig.5.32 shows a partial activity table of the external part of the dump, dumpori, composed of lead. Due to the high number of generated radionuclides, only those with an att.sp/cf ratio greater than 1.00×10^{-02} are listed. However, the total activity and Σ att.sp/cf calculations include all generated radionuclides. The most significant long-lived radionuclides due to the high specific activity of the component are ^{195}Au , ^{204}Tl , ^{194}Hg , ^3H , ^{202}Pb and short-lived radionuclides ^{194}Au and ^{106}Rh .

settom	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)	copper			
	49	23	3.09E+05	4.10	V	V-49	4.93E+01	0.01	4.93E+03	2.85E+07	V(m3)	ro(g/cm3)	m(Kg)
	60	27	1.26E+06	3.24	Co	Co-60	2.01E+02	0.1	2.01E+03	1.66E+08	7.00E-04	8.96E+00	6.27E+00
	54	25	9.18E+05	3.54	Mn	Mn-54	1.46E+02	0.1	1.46E+03	2.70E+07	att. (Bq)		
	3	1	4.18E+06	0.96	H	H-3	6.66E+02	1	6.66E+02	3.89E+08	1.45E+07 +/-		7.54E-01 %
	55	26	3.70E+06	1.35	Fe	Fe-55	5.90E+02	1	5.90E+02	8.66E+07	att.sp. (Bq/g)		
	57	27	2.81E+06	2.17	Co	Co-57	4.49E+02	1	4.49E+02	2.35E+07	2.31E+03		
	65	30	1.98E+05	6.61	Zn	Zn-65	3.16E+01	0.1	3.16E+02	2.11E+07	Σ att.sp/cf		1.09E+04
	56	27	9.43E+04	2.38	Co	Co-56	1.50E+01	0.1	1.50E+02	6.67E+06			
	63	28	7.74E+05	0.81	Ni	Ni-63	1.23E+02	1	1.23E+02	3.19E+09			
	44	22	4.69E+03	46.77	Ti	Ti-44	7.48E-01	0.01	7.48E+01	1.87E+09			
	58	27	1.85E+05	1.16	Co	Co-58	2.95E+01	1	2.95E+01	6.12E+06			
	39	18	1.04E+03	36.42	Ar	Ar-39	1.66E-01	0.01	1.66E+01	8.46E+09			
	42	18	9.18E+02	99.00	Ar	Ar-42	1.46E-01	0.01	1.46E+01	1.04E+09			
	42	19	9.18E+02	99.00	K	K-42	1.46E-01	0.01	1.46E+01	4.45E+04			
	44	21	4.69E+03	46.77	Sc	Sc-44	7.48E-01	0.1	7.48E+00	1.46E+04			
	46	21	3.51E+03	13.47	Sc	Sc-46	5.59E-01	0.1	5.59E+00	7.24E+06			
	59	28	2.58E+03	1.86	Ni	Ni-59	4.11E-01	1	4.11E-01	2.40E+12			
	45	20	1.69E+03	46.77	Ca	Ca-45	2.69E-01	1	2.69E-01	1.40E+07			
	41	20	3.77E+00	32.39	Ca	Ca-41	6.00E-04	0.01	6.00E-02	3.14E+12			
	35	16	3.31E+02	66.67	S	S-35	5.28E-02	1	5.28E-02	7.55E+06			
	7	4	3.26E+02	12.89	Be	Be-7	5.20E-02	1	5.20E-02	4.60E+06			
	59	26	3.25E+02	16.99	Fe	Fe-59	5.17E-02	1	5.17E-02	3.84E+06			
	51	24	1.33E+02	2.28	Cr	Cr-51	2.12E-02	1	2.12E-02	2.39E+06			
	60	26	2.38E-01	10.54	Fe	Fe-60	3.80E-05	0.01	3.80E-03	8.27E+13			
	14	6	2.19E+01	66.67	C	C-14	3.48E-03	1	3.48E-03	1.80E+11			
	53	25	1.42E+01	1.17	Mn	Mn-53	2.26E-03	1	2.26E-03	1.17E+14			
	37	18	5.79E+00	61.24	Ar	Ar-37	9.23E-04	1	9.23E-04	3.02E+06			
	10	4	5.51E-02	61.24	Be	Be-10	8.78E-06	0.01	8.78E-04	4.77E+13			
	36	17	5.52E-01	46.77	Cl	Cl-36	8.80E-05	1	8.80E-05	9.51E+12			
	33	15	9.20E-02	99.00	P	P-33	1.47E-05	1	1.47E-05	2.19E+06			
	48	23	4.75E-02	5.47	V	V-48	7.57E-06	1	7.57E-06	1.38E+06			
	40	19	6.33E-04	19.34	K	K-40	1.01E-07	1	1.01E-07	3.94E+16			
	A/Z/ Isomers:												
	44	21	4.67E+03	46.77	Sc	Sc-44	7.45E-01	0.1	7.45E+00	2.11E+05			
	45	21	3.20E-02	46.77	Sc	Sc-45	5.11E-06	0.01	5.11E-04	3.26E-01			
	60	27	2.38E-01	10.54	Co	Co-60	3.80E-05	0.1	3.80E-04	6.28E+02			

Figure 5.33: Radionuclides generated in settom with respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, see Data analysis methodology paragraph).

Fig. 5.33 shows the activity table of settom, composed of copper. The most significant long-lived radionuclides due to the high specific activity of the component are ⁴⁹V, ⁶⁰Co, ⁵⁴Mn, ³H, ⁵⁵Fe, ⁵⁷Co, ⁶³Ni, ⁶⁵Zn and a short-lived radionuclides ⁵⁶Co.

settomag	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)			
	49	23	1.67E+05	9.09	V	5.19E-01	0.01	5.19E+01	2.85E+07	V(m3)	ro(g/cm3)	m(Kg)
	54	25	1.36E+06	1.10	Mn	4.24E+00	0.1	4.24E+01	2.70E+07	4.09E-02	7.87E+00	3.22E+02
	55	26	4.56E+06	1.39	Fe	1.42E+01	1	1.42E+01	8.66E+07	att. (Bq)		
	3	1	2.70E+05	9.73	H	8.38E-01	1	8.38E-01	3.89E+08	6.37E+06	+/-	1.10E+00 %
	44	22	5.86E+02	99.00	Ti	1.82E-03	0.01	1.82E-01	1.87E+09	att.sp. (Bq/g)		
	46	21	1.95E+03	23.72	Sc	6.05E-03	0.1	6.05E-02	7.24E+06	1.98E+01		
	44	21	5.86E+02	99.00	Sc	1.82E-03	0.1	1.82E-02	1.46E+04	Σ att.sp/cf		1.10E+02
	56	27	4.53E+02	40.82	Co	1.41E-03	0.1	1.41E-02	6.67E+06			
	45	20	2.11E+03	44.72	Ca	6.55E-03	1	6.55E-03	1.40E+07			
	35	16	1.10E+02	99.00	S	3.43E-04	1	3.43E-04	7.55E+06			
	51	24	1.04E+02	2.73	Cr	3.22E-04	1	3.22E-04	2.39E+06			
	41	20	8.37E-01	61.24	Ca	2.60E-06	0.01	2.60E-04	3.14E+12			
	59	26	1.35E+01	61.24	Fe	4.20E-05	1	4.20E-05	3.84E+06			
	53	25	1.25E+01	2.36	Mn	3.88E-05	1	3.88E-05	1.17E+14			
	37	18	1.45E+00	99.00	Ar	4.49E-06	1	4.49E-06	3.02E+06			
	36	17	2.76E-01	99.00	Cl	8.58E-07	1	8.58E-07	9.51E+12			
	48	23	2.56E-02	9.49	V	7.96E-08	1	7.96E-08	1.38E+06			
	40	19	1.67E-04	31.62	K	5.18E-10	1	5.18E-10	3.94E+16			
	A/Z/ Isomers:											
	44	21	5.84E+02	99.00	Sc	1.81E-03	0.1	1.81E-02	2.11E+05			
	45	21	4.00E-02	44.72	Sc	1.24E-07	0.01	1.24E-05	3.26E-01			

Figure 5.34: Radionuclides generated in settomag with respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, see Data analysis methodology paragraph).

Fig. 5.34 shows the activity table of settomag, composed of iron. The most significant long-lived radionuclides due to the high specific activity of the component are ^{49}V , ^{54}Mn , ^{55}Fe , ^3H and ^{44}Ti .

chopper1	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)			
	49	23	2.79E+04	19.00	V	3.89E-01	0.01	3.89E+01	2.85E+07	V(m3)	ro(g/cm3)	m(Kg)
	60	27	1.92E+05	7.57	Co	2.68E+00	0.1	2.68E+01	1.66E+08	8.00E-03	8.96E+00	7.17E+01
	54	25	1.13E+05	15.43	Mn	1.57E+00	0.1	1.57E+01	2.70E+07	att. (Bq)		
	3	1	4.79E+05	5.17	H	6.69E+00	1	6.69E+00	3.89E+08	1.74E+06 +/-		2.21E+00 %
	55	26	4.11E+05	3.91	Fe	5.74E+00	1	5.74E+00	8.66E+07	att.sp. (Bq/g)		
	57	27	3.44E+05	2.07	Co	4.80E+00	1	4.80E+00	2.35E+07	2.42E+01		
	65	30	1.28E+04	27.22	Zn	1.78E-01	0.1	1.78E+00	2.11E+07	Σ att.sp/cf		1.04E+02
	63	28	1.24E+05	5.11	Ni	1.73E+00	1	1.73E+00	3.19E+09			
	56	27	9.23E+03	9.57	Co	1.29E-01	0.1	1.29E+00	6.67E+06			
	58	27	2.02E+04	2.42	Co	2.82E-01	1	2.82E-01	6.12E+06			
	46	21	2.92E+02	66.67	Sc	4.08E-03	0.1	4.08E-02	7.24E+06			
	59	28	2.81E+02	1.96	Ni	3.92E-03	1	3.92E-03	2.40E+12			
	41	20	1.26E+00	40.82	Ca	1.75E-05	0.01	1.75E-03	3.14E+12			
	7	4	5.15E+01	66.67	Be	7.19E-04	1	7.19E-04	4.60E+06			
	59	26	4.73E+01	36.42	Fe	6.60E-04	1	6.60E-04	3.84E+06			
	51	24	1.37E+01	5.74	Cr	1.92E-04	1	1.92E-04	2.39E+06			
	10	4	2.75E-02	99.00	Be	3.84E-07	0.01	3.84E-05	4.77E+13			
	60	26	1.59E-02	99.00	Fe	2.21E-07	0.01	2.21E-05	8.27E+13			
	53	25	1.49E+00	4.92	Mn	2.08E-05	1	2.08E-05	1.17E+14			
	36	17	1.38E-01	99.00	Cl	1.93E-06	1	1.93E-06	9.51E+12			
	48	23	5.23E-03	20.92	V	7.30E-08	1	7.30E-08	1.38E+06			
	A/Z/ Isomers:											
	60	27	1.59E-02	99.00	Co	2.21E-07	0.1	2.21E-06	6.28E+02			

Figure 5.35: Radionuclides generated in chopper1 with respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, see Data analysis methodology paragraph).

Fig. 5.35 shows the activity table of chopper1, composed of copper. The most significant long-lived radionuclides due to the high specific activity of the component are ^{49}V , ^{60}Co , ^{54}Mn , ^3H , ^{55}Fe , ^{57}Co , ^{65}Zn , ^{63}Ni and a short-lived radionuclides ^{56}Co .

SCREEN	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)		inox		
	49	23	1.58E+05	7.38	V	V-49	8.46E-02	0.01	8.46E+00	2.85E+07	V(m3)	ro(g/cm3)	m(Kg)
	54	25	8.72E+05	4.49	Mn	Mn-54	4.67E-01	0.1	4.67E+00	2.70E+07	2.36E-01	7.90E+00	1.87E+03
	55	26	3.14E+06	3.65	Fe	Fe-55	1.68E+00	1	1.68E+00	8.66E+07	att. (Bq)		
	60	27	2.75E+04	18.24	Co	Co-60	1.47E-02	0.1	1.47E-01	1.66E+08	4.71E+06 +/-		3.22E+00 %
	3	1	2.43E+05	5.97	H	H-3	1.30E-01	1	1.30E-01	3.89E+08	att.sp. (Bq/g)		
	57	27	2.10E+05	3.86	Co	Co-57	1.12E-01	1	1.12E-01	2.35E+07	2.52E+00		
	44	22	1.17E+03	61.24	Ti	Ti-44	6.29E-04	0.01	6.29E-02	1.87E+09	Σ att.sp/cf		1.54E+01
	56	27	7.05E+03	9.34	Co	Co-56	3.78E-03	0.1	3.78E-02	6.67E+06			
	63	28	3.32E+04	12.04	Ni	Ni-63	1.78E-02	1	1.78E-02	3.19E+09			
	39	18	2.97E+02	61.24	Ar	Ar-39	1.59E-04	0.01	1.59E-02	8.46E+09			
	58	27	1.50E+04	6.81	Co	Co-58	8.02E-03	1	8.02E-03	6.12E+06			
	46	21	1.27E+03	35.67	Sc	Sc-46	6.79E-04	0.1	6.79E-03	7.24E+06			
	44	21	1.17E+03	61.24	Sc	Sc-44	6.29E-04	0.1	6.29E-03	1.46E+04			
	45	20	4.22E+02	99.00	Ca	Ca-45	2.26E-04	1	2.26E-04	1.40E+07			
	59	28	3.75E+02	4.09	Ni	Ni-59	2.01E-04	1	2.01E-04	2.40E+12			
	59	26	1.08E+02	22.96	Fe	Fe-59	5.80E-05	1	5.80E-05	3.84E+06			
	51	24	9.28E+01	5.19	Cr	Cr-51	4.97E-05	1	4.97E-05	2.39E+06			
	41	20	8.37E-01	99.00	Ca	Ca-41	4.48E-07	0.01	4.48E-05	3.14E+12			
	14	6	7.28E+01	15.81	C	C-14	3.90E-05	1	3.90E-05	1.80E+11			
	7	4	1.72E+01	99.00	Be	Be-7	9.21E-06	1	9.21E-06	4.60E+06			
	53	25	9.89E+00	3.34	Mn	Mn-53	5.30E-06	1	5.30E-06	1.17E+14			
	48	23	2.57E-02	9.90	V	V-48	1.37E-08	1	1.37E-08	1.38E+06			
	A/Z/ Isomers:												
	44	21	1.17E+03	61.24	Sc	Sc-44	6.26E-04	0.1	6.26E-03	2.11E+05			
	45	21	8.01E-03	99.00	Sc	Sc-45	4.29E-09	0.01	4.29E-07	3.26E-01			

Figure 5.36: Radionuclides generated in SCREEN with respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, see Data analysis methodology paragraph).

Fig. 5.36 shows the activity table of SCREEN, composed of inox. The most significant long-lived radionuclides due to the high specific activity of the component are ⁴⁹V, ⁵⁴Mn, ⁵⁵Fe, ⁶⁰Co, ³H and ⁵⁷Co.

DIPOL08	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)		iron		
	49	23	1.16E+05	8.67	V	V-49	1.49E-02	0.01	1.49E+00	2.85E+07	V(m3)	ro(g/cm3)	m(Kg)
	54	25	5.80E+05	5.16	Mn	Mn-54	7.44E-02	0.1	7.44E-01	2.70E+07	9.90E-01	7.87E+00	7.80E+03
	55	26	4.35E+06	1.17	Fe	Fe-55	5.58E-01	1	5.58E-01	8.66E+07	att. (Bq)		
	3	1	1.59E+05	14.77	H	H-3	2.04E-02	1	2.04E-02	3.89E+08	5.21E+06 +/-		7.21E-01 %
	46	21	1.17E+03	21.25	Sc	Sc-46	1.50E-04	0.1	1.50E-03	7.24E+06	att.sp. (Bq/g)		
	56	27	6.79E+02	40.82	Co	Co-56	8.70E-05	0.1	8.70E-04	6.67E+06	6.68E-01		
	57	27	7.88E+02	99.00	Co	Co-57	1.01E-04	1	1.01E-04	2.35E+07	Σ att.sp/cf		2.81E+00
	59	26	6.02E+02	6.97	Fe	Fe-59	7.72E-05	1	7.72E-05	3.84E+06			
	41	20	1.26E+00	40.82	Ca	Ca-41	1.61E-07	0.01	1.61E-05	3.14E+12			
	51	24	4.79E+01	5.70	Cr	Cr-51	6.14E-06	1	6.14E-06	2.39E+06			
	7	4	1.72E+01	99.00	Be	Be-7	2.20E-06	1	2.20E-06	4.60E+06			
	53	25	6.17E+00	4.30	Mn	Mn-53	7.92E-07	1	7.92E-07	1.17E+14			
	36	17	2.76E-01	61.24	Cl	Cl-36	3.54E-08	1	3.54E-08	9.51E+12			
	48	23	1.73E-02	10.55	V	V-48	2.21E-09	1	2.21E-09	1.38E+06			
	40	19	1.33E-04	72.89	K	K-40	1.71E-11	1	1.71E-11	3.94E+16			

Figure 5.37: Radionuclides generated in dipolo8 with respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, see Data analysis methodology paragraph).

Fig. 5.37 shows the activity table of DIPOL08, composed of iron. The most significant long-lived radionuclides due to the high specific activity of the component are ⁴⁹V, ⁵⁴Mn and ⁵⁵Fe.

QUADPOL	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)				
	49	23	7.52E+04	9.03	V	V-49	6.72E-02	0.01	6.72E+00	2.85E+07	V(m3)		
	54	25	3.52E+05	7.64	Mn	Mn-54	3.14E-01	0.1	3.14E+00	2.70E+07	ro/g/cm3	7.87E+00	1.12E+03
	55	26	1.37E+06	2.53	Fe	Fe-55	1.22E+00	1	1.22E+00	8.66E+07	m(Kg)		
	3	1	9.55E+04	1.98	H	H-3	8.53E-02	1	8.53E-02	3.89E+08	att. (Bq)		
	44	21	5.86E+02	99.00	Sc	Sc-44	5.24E-04	0.1	5.24E-03	1.46E+04	1.90E+06 +/-		2.99E+00 %
	44	22	5.86E+02	99.00	Ti	Ti-44	5.24E-04	0.01	5.24E-02	1.87E+09	att.sp. (Bq/g)		
	46	21	5.85E+02	48.59	Sc	Sc-46	5.22E-04	0.1	5.22E-03	7.24E+06	1.69E+00		
	56	27	3.02E+02	25.00	Co	Co-56	2.70E-04	0.1	2.70E-03	6.67E+06	Σ att.sp/cf		1.13E+01
	57	27	7.88E+02	99.00	Co	Co-57	7.04E-04	1	7.04E-04	2.35E+07			
	59	26	5.41E+01	25.00	Fe	Fe-59	4.83E-05	1	4.83E-05	3.84E+06			
	41	20	4.18E-01	99.00	Ca	Ca-41	3.74E-07	0.01	3.74E-05	3.14E+12			
	51	24	3.11E+01	9.32	Cr	Cr-51	2.78E-05	1	2.78E-05	2.39E+06			
	53	25	3.44E+00	6.74	Mn	Mn-53	3.07E-06	1	3.07E-06	1.17E+14			
	48	23	1.05E-02	8.93	V	V-48	9.36E-09	1	9.36E-09	1.38E+06			
	A/Z/ Isomers:												
	44	21	5.84E+02	99.00	Sc	Sc-44	5.22E-04	0.01	5.22E-02	2.11E+05			

Figure 5.38: Radionuclides generated in QUADPOL with respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, see Data analysis methodology paragraph).

Fig. 5.38 shows the activity table of QUADPOL, composed of iron. The most significant long-lived radionuclides due to the high specific activity of the component are ⁴⁹V, ⁵⁴Mn and ⁵⁵Fe.

dumpsa2	A	Z	ATT(Bq)	err%	elemento	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)				
	49	23	2.79E+03	40.82	V	V-49	6.93E-02	0.01	6.93E+00	2.85E+07	V(m3)		
	54	25	7.11E+03	42.39	Mn	Mn-54	1.77E-01	0.1	1.77E+00	2.70E+07	ro/g/cm3	8.00	4.02E+01
	88	39	5.10E+02	99.00	Y	Y-88	1.27E-02	0.01	1.27E+00	9.21E+06	att. (Bq)		
	60	27	1.72E+03	99.00	Co	Co-60	4.27E-02	0.1	4.27E-01	1.66E+08	3.23E+04 +/-		2.72E+01 %
	55	26	1.55E+04	41.83	Fe	Fe-55	3.86E-01	1	3.86E-01	8.66E+07	att.sp. (Bq/g)		
	88	40	9.61E+01	99.00	Zr	Zr-88	2.39E-03	0.01	2.39E-01	7.21E+06	8.03E-01		
	91	41	6.02E+01	99.00	Nb	Nb-91	1.50E-03	0.01	1.50E-01	2.15E+10	Σ att.sp/cf		1.15E+01
	57	27	1.58E+03	61.24	Co	Co-57	3.92E-02	1	3.92E-02	2.35E+07			
	3	1	1.54E+03	99.00	H	H-3	3.84E-02	1	3.84E-02	3.89E+08			
	56	27	7.54E+01	99.00	Co	Co-56	1.88E-03	0.1	1.88E-02	6.67E+06			
	63	28	7.38E+02	61.24	Ni	Ni-63	1.84E-02	1	1.84E-02	3.19E+09			
	45	20	4.22E+02	99.00	Ca	Ca-45	1.05E-02	1	1.05E-02	1.40E+07			
	59	28	2.74E+00	31.62	Ni	Ni-59	6.81E-05	1	6.81E-05	2.40E+12			
	51	24	1.72E+00	25.00	Cr	Cr-51	4.28E-05	1	4.28E-05	2.39E+06			
	95	41	1.52E+00	99.00	Nb	Nb-95	3.78E-05	1	3.78E-05	3.02E+06			
	53	25	1.22E-01	39.10	Mn	Mn-53	3.04E-06	1	3.04E-06	1.17E+14			
	A/Z/ Isomers:												
	45	21	8.01E-03	99.00	Sc	Sc-45	1.99E-07	0.01	1.99E-05	3.26E-01			
	88	39	9.61E+01	99.00	Y	Y-88	2.39E-03	0.01	2.39E-01	9.21E+06			

Figure 5.39: Radionuclides generated in dumpsa2 with respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, see Data analysis methodology paragraph).

Fig. 5.39 shows the activity table of the treatment room 2 dump, dumpsa2, composed of inox316. The most significant long-lived radionuclides due to the high specific activity of the component are ⁴⁹V, ⁵⁴Mn and a short-lived radionuclide ⁸⁸Y.

xprblo5	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)		concrete		
	22	11	2.94E+05	8.05	Na	Na-22	1.25E-01	0.1	1.25E+00	8.21E+07	V(m3)	ro(g/cm3)	m(Kg)
	39	18	1.50E+04	6.72	Ar	Ar-39	6.37E-03	0.01	6.37E-01	8.46E+09	1.01E+00	2.34E+00	2.35E+03
	3	1	1.36E+06	3.29	H	H-3	5.77E-01	1	5.77E-01	3.89E+08	att. (Bq)		
	49	23	8.36E+03	11.11	V	V-49	3.55E-03	0.01	3.55E-01	2.85E+07	2.04E+06 +/-		2.43E+00
	152	63	5.07E+04	10.81	Eu	Eu-152	2.15E-02	0.1	2.15E-01	4.27E+08	att.sp. (Bq/g)		
	54	25	3.02E+04	15.00	Mn	Mn-54	1.28E-02	0.1	1.28E-01	2.70E+07	8.68E-01		
	60	27	2.58E+04	27.88	Co	Co-60	1.09E-02	0.1	1.09E-01	1.66E+08	Σ att.sp/cf		3.43E+00
	55	26	2.27E+05	6.26	Fe	Fe-55	9.63E-02	1	9.63E-02	8.66E+07			
	41	20	5.84E+02	2.44	Ca	Ca-41	2.48E-04	0.01	2.48E-02	3.14E+12			
	154	63	5.04E+03	66.67	Eu	Eu-154	2.14E-03	0.1	2.14E-02	2.71E+08			
	45	20	2.53E+04	13.69	Ca	Ca-45	1.07E-02	1	1.07E-02	1.40E+07			
	7	4	2.73E+03	6.85	Be	Be-7	1.16E-03	1	1.16E-03	4.60E+06			
	26	13	1.88E+01	5.66	Al	Al-26	7.98E-06	0.01	7.98E-04	2.26E+13			
	14	6	1.76E+03	3.61	C	C-14	7.48E-04	1	7.48E-04	1.80E+11			
	35	16	5.52E+02	31.62	S	S-35	2.34E-04	1	2.34E-04	7.55E+06			
	10	4	3.58E+00	15.43	Be	Be-10	1.52E-06	0.01	1.52E-04	4.77E+13			
	37	18	2.95E+02	7.41	Ar	Ar-37	1.25E-04	1	1.25E-04	3.02E+06			
	36	17	1.57E+01	7.13	Cl	Cl-36	6.68E-06	1	6.68E-06	9.51E+12			
	59	26	6.76E+00	99.00	Fe	Fe-59	2.87E-06	1	2.87E-06	3.84E+06			
	51	24	3.87E+00	25.76	Cr	Cr-51	1.64E-06	1	1.64E-06	2.39E+06			
	33	15	4.60E-01	44.72	P	P-33	1.95E-07	1	1.95E-07	2.19E+06			
	53	25	4.11E-01	3.31	Mn	Mn-53	1.75E-07	1	1.75E-07	1.17E+14			
	40	19	7.61E-02	2.41	K	K-40	3.23E-08	1	3.23E-08	3.94E+16			
	48	23	5.23E-04	61.24	V	V-48	2.22E-10	1	2.22E-10	1.38E+06			
	32	15	2.75E-04	36.42	P	P-32	1.17E-10	1	1.17E-10	1.23E+06			
A/Z/m Isomers:													
	45	21	4.81E-01	13.69	Sc	Sc-45	2.04E-07	0.01	2.04E-05	3.26E-01			

Figure 5.40: Radionuclides generated in xprblo5 with respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, see Data analysis methodology paragraph).

Fig. 5.40 presents the activity table of xprblo5, made of concrete. The most significant long-lived radionuclides due to the high specific activity of the component are ²²Na, ³⁹Ar, ³H, ⁴⁹V, ¹⁵²Eu, ⁵⁴Mn and ⁶⁰Co.

Att425	A	Z	ATT(Bq)	err%	element		ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)		concrete	
	154	63	1.56E+04	7.70	Eu	Eu-154	6.68E-03	0.1	6.68E-02	2.71E+08		V(m3)	ro(g/cm3)
	152	63	1.68E+05	2.28	Eu	Eu-152	7.19E-02	0.1	7.19E-01	4.27E+08		1.00E+00	2.34E+00
	60	27	8.83E+04	3.57	Co	Co-60	3.77E-02	0.1	3.77E-01	1.66E+08		att. (Bq)	2.34E+00
	59	26	5.97E+01	8.19	Fe	Fe-59	2.55E-05	1	2.55E-05	3.84E+06		9.80E+05 +/-	8.06E-01 %
	58	27	3.30E+00	99.00	Co	Co-58	1.41E-06	1	1.41E-06	6.12E+06		att.sp. (Bq/g)	
	55	26	5.23E+05	1.45	Fe	Fe-55	2.24E-01	1	2.24E-01	8.66E+07		4.19E+05	
	54	25	3.50E+03	11.25	Mn	Mn-54	1.50E-03	0.1	1.50E-02	2.70E+07		Σ att.sp/cf	2.05E+00
	53	25	2.42E-02	15.59	Mn	Mn-53	1.03E-08	1	1.03E-08	1.17E+14			
	51	24	1.90E-01	25.41	Cr	Cr-51	8.10E-08	1	8.10E-08	2.39E+06			
	49	23	5.46E+01	99.00	V	V-49	2.33E-05	0.01	2.33E-03	2.85E+07			
	45	20	8.32E+04	1.86	Ca	Ca-45	3.56E-02	1	3.56E-02	1.40E+07			
	41	20	1.76E+03	0.41	Ca	Ca-41	7.51E-04	0.01	7.51E-02	3.14E+12			
	40	19	2.19E-01	0.29	K	K-40	9.35E-08	1	9.35E-08	3.94E+16			
	39	18	9.72E+03	2.78	Ar	Ar-39	4.15E-03	0.01	4.15E-01	8.46E+09			
	37	18	1.38E+02	2.37	Ar	Ar-37	5.88E-05	1	5.88E-05	3.02E+06			
	36	17	6.43E+00	4.12	Cl	Cl-36	2.75E-06	1	2.75E-06	9.51E+12			
	35	16	4.54E+01	36.42	Si	Si-35	1.94E-05	0.01	1.94E-03	7.80E-01			
	33	15	1.08E-02	70.29	P	P-33	4.62E-09	1	4.62E-09	2.19E+06			
	26	13	1.59E+00	4.37	Al	Al-26	6.81E-07	0.01	6.81E-05	2.26E+13			
	22	11	2.13E+04	6.67	Na	Na-22	9.09E-03	0.1	9.09E-02	8.21E+07			
	14	6	3.44E+02	3.41	C	C-14	1.47E-04	1	1.47E-04	1.80E+11			
	10	4	1.26E-01	11.13	Be	Be-10	5.40E-08	0.01	5.40E-06	4.77E+13			
	7	4	8.59E+01	12.30	Be	Be-7	3.67E-05	1	3.67E-05	4.60E+06			
	3	1	6.44E+04	3.70	H	H-3	2.75E-02	1	2.75E-02	3.89E+08			
	A/Z/m Isomers:												
	45	21	1.58E+00	1.86	Sc	Sc-45	6.76E-07	0.01	6.76E-05	3.26E-01			

Figure 5.41: Radionuclides generated in floor block A0425 with respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, see Data analysis methodology paragraph).

Figure 5.41 shows the activity table for A0425, one of the few non-removable concrete floor pieces. It is a section of floor located under the dumpo. The most significant long-lived radionuclides, due to the high specific activity of the component, are ^{154}Eu , ^{152}Eu and ^{60}Co .

5.4.2. Removable components: simulations with maximum energy and maximum particle beam intensity

The following figures present data analyses of certain facility elements with a $\Sigma \text{Att.sp./cf}$ below one, making them removable. Additionally, the tables show similar elements of the synchrotron or the same material, which are non-removable but located in different positions within the machine. Since these elements are far from the beam loss points, they qualify for clearance removal.

DIPOLO	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	$T_{1/2}$ (s)				
	55	26	1.07E+06	3.84	Fe	Fe-55	1.37E-01	1	1.37E-01	8.66E+07	V(m3)	iron	
	54	25	1.42E+05	7.06	Mn	Mn-54	1.82E-02	0.1	1.82E-01	2.70E+07		ro/g/cm3	m(Kg)
	3	1	2.93E+04	19.34	H	H-3	3.75E-03	1	3.75E-03	3.89E+08	9.90E-01	7.87E+00	7.80E+03
	49	23	2.69E+04	11.44	V	V-49	3.45E-03	0.01	3.45E-01	2.85E+07	att. (Bq)		
	56	27	6.79E+02	27.22	Co	Co-56	8.70E-05	0.1	8.70E-04	6.67E+06	1.27E+06 +/-		4.12E+00 %
	46	21	1.95E+02	61.24	Sc	Sc-46	2.50E-05	0.1	2.50E-04	7.24E+06	att.sp. (Bq/g)		
	59	26	1.08E+02	20.73	Fe	Fe-59	1.39E-05	1	1.39E-05	3.84E+06	1.62E-01		
	51	24	1.14E+01	8.76	Cr	Cr-51	1.46E-06	1	1.46E-06	2.39E+06	Σ att.sp/cf		6.69E-01
	53	25	1.44E+00	11.85	Mn	Mn-53	1.84E-07	1	1.84E-07	1.17E+14			
	48	23	3.92E-03	36.51	V	V-48	5.03E-10	1	5.03E-10	1.38E+06			

Figure 5.42: Radionuclides generated in DIPOLO with respective analysis.

Fig. 5.42 shows the activity table of the DIPOLO, composed of iron. The same radionuclides generated in DIPOLO8 and iron components are also found here, but with lower specific activities. This reduction allows the dipole to be cleared for removal from the structure.

QUADPOL23	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	$T_{1/2}$ (s)				
	55	26	8.85E+04	19.93	Fe	Fe-55	7.91E-02	1	7.91E-02	8.66E+07	V(m3)	iron	
	54	25	8.00E+03	11.11	Mn	Mn-54	7.15E-03	0.1	7.15E-02	2.70E+07		ro/g/cm3	m(Kg)
	49	23	2.79E+03	66.67	V	V-49	2.49E-03	0.01	2.49E-01	2.85E+07	1.42E-01	7.87E+00	1.12E+03
	3	1	1.54E+03	99.00	H	H-3	1.38E-03	1	1.38E-03	3.89E+08	att. (Bq)		
	56	27	7.54E+01	99.00	Co	Co-56	6.74E-05	0.1	6.74E-04	6.67E+06	1.01E+05 +/-		1.97E+01 %
	59	26	2.03E+01	66.67	Fe	Fe-59	1.81E-05	1	1.81E-05	3.84E+06	att.sp. (Bq/g)		
	51	24	1.50E+00	36.42	Cr	Cr-51	1.34E-06	1	1.34E-06	2.39E+06	9.02E-02		
	53	25	4.45E-02	25.00	Mn	Mn-53	3.97E-08	1	3.97E-08	1.17E+14	Σ att.sp/cf		4.01E-01
	48	23	2.62E-04	99.00	V	V-48	2.34E-10	1	2.34E-10	1.38E+06			

Figure 5.43: Radionuclides generated in QUADPOL23 with respective analysis.

Fig. 5.43 shows the activity table of the QUADPOL23, composed of iron. The same radionuclides generated in QUADPOL and iron components are also found here, but with lower specific activities.

xprblo6	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)		concrete		
	3	1	2.74E+05	9.51	H	H-3	1.16E-01	1	1.16E-01	3.89E+08	V(m3)	ro/g/cm3	m(Kg)
	55	26	1.04E+05	11.94	Fe	Fe-55	4.42E-02	1	4.42E-02	8.66E+07	1.01E+00	2.34E+00	2.35E+03
	22	11	6.13E+04	3.95	Na	Na-22	2.60E-02	0.1	2.60E-01	8.21E+07	att. (Bq)		
	152	63	2.09E+04	20.82	Eu	Eu-152	8.87E-03	0.1	8.87E-02	4.27E+08	5.02E+05 +/-	3.84E+00	%
	60	27	1.55E+04	20.76	Co	Co-60	6.56E-03	0.1	6.56E-02	1.66E+08	att.sp. (Bq/g)		
	54	25	1.07E+04	31.18	Mn	Mn-54	4.53E-03	0.1	4.53E-02	2.70E+07	2.13E-01		
	45	20	9.70E+03	21.30	Ca	Ca-45	4.12E-03	1	4.12E-03	1.40E+07	Σ att.sp/cf		8.07E-01
	39	18	3.12E+03	27.56	Ar	Ar-39	1.32E-03	0.01	1.32E-01	8.46E+09			
	49	23	9.29E+02	99.00	V	V-49	3.94E-04	0.01	3.94E-02	2.85E+07			
	14	6	4.44E+02	11.12	C	C-14	1.89E-04	1	1.89E-04	1.80E+11			
	7	4	4.30E+02	10.95	Be	Be-7	1.82E-04	1	1.82E-04	4.60E+06			
	35	16	3.31E+02	40.82	S	S-35	1.41E-04	1	1.41E-04	7.55E+06			
	41	20	2.27E+02	4.73	Ca	Ca-41	9.65E-05	0.01	9.65E-03	3.14E+12			
	37	18	7.38E+01	19.21	Ar	Ar-37	3.13E-05	1	3.13E-05	3.02E+06			
	59	26	1.35E+01	61.24	Fe	Fe-59	5.74E-06	1	5.74E-06	3.84E+06			
	36	17	4.83E+00	26.73	Cl	Cl-36	2.05E-06	1	2.05E-06	9.51E+12			
	26	13	3.94E+00	18.69	Al	Al-26	1.68E-06	0.01	1.68E-04	2.26E+13			
	51	24	1.72E+00	25.00	Cr	Cr-51	7.30E-07	1	7.30E-07	2.39E+06			
	10	4	7.44E-01	29.05	Be	Be-10	3.16E-07	0.01	3.16E-05	4.77E+13			
	33	15	1.84E-01	61.24	P	P-33	7.81E-08	1	7.81E-08	2.19E+06			
	53	25	1.33E-01	25.00	Mn	Mn-53	5.67E-08	1	5.67E-08	1.17E+14			
	40	19	3.04E-02	4.58	K	K-40	1.29E-08	1	1.29E-08	3.94E+16			
	32	15	1.18E-04	40.82	P	P-32	5.01E-11	1	5.01E-11	1.23E+06			
A/Z Isomers:													
	45	21	1.84E-01	21.30	Sc	Sc-45	7.82E-08	0.01	7.82E-06	3.26E-01			

Figure 5.44: Radionuclides generated in xprblo6 with respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, see Data analysis methodology paragraph).

Fig. 5.44 shows the concrete block of the wall of the xpr room (see Fig. 5.8). The same radionuclides found in xprblo5 and other concrete blocks are present here, but with lower specific activities.

5.4.3. Simulations with energy spectrum and maximum particle beam intensity

The same simulations were repeated using the energy spectrum employed in 2023 in the synchrotron with the proton beam. The OPEN CARD was used to introduce the energy spectrum into the input.

Images 5.45-5.46 show the specific activity of the facility at beam level and floor level. The ceiling is not relevant to this study, as it is too far from the loss points and therefore not activated.

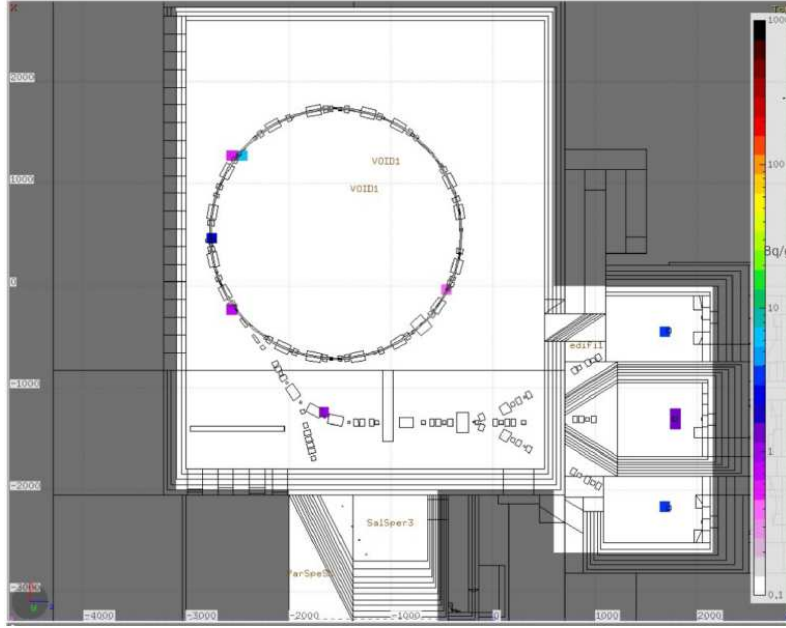


Figure 5.45: Visualization of the USERBIN-actomass in the x-z plane with $y=-200$, for a proton beam with energy spectrum and maximum intensity.

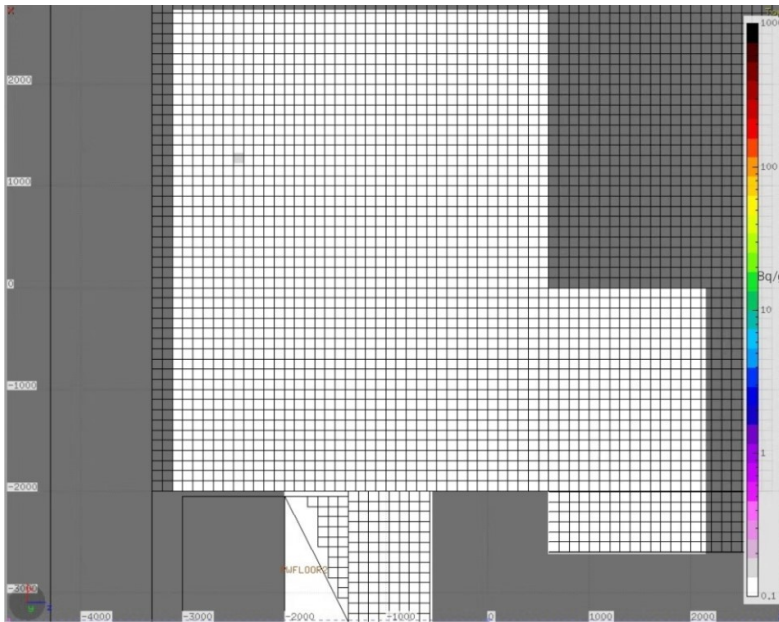


Figure 5.46: Visualization of the USERBIN-actomass in the x-z plane with $y=-350$, for a proton beam with energy spectrum and maximum intensity.

Once the RESNUCLEI files were obtained, all files were analyzed using tables identical to those generated with the maximum energy beam.

5.4.4. Simulations with energy spectrum and 15% of maximum beam intensity

The same simulations were repeated using the energy spectrum employed in 2023 in the synchrotron with the Proton beam and a 1.5×10^9 p/s beam current.

Once the RESNUCLEI files were obtained, all files were analyzed using tables identical to those generated with the maximum energy beam.

5.5. Results

Figure 5.47 shows the names of all components of the CNAO synchrotron structure, treatment rooms, and experimental room (XPR) that cannot be removed. These components are compared across all analyzed cases.

The cases, listed in the same order as in the table, include:

- Simulations with a carbon ion beam at maximum energy and maximum intensity;
- Simulations with a proton beam at maximum energy and maximum intensity;
- Simulations with a carbon ion beam using the energy spectrum applied in treatments in 2023 and maximum intensity;
- Simulations with a proton beam using the energy spectrum applied in treatments in 2023 and maximum intensity;
- Simulations with a carbon ion beam using the same energy spectrum and 15% of the maximum authorized intensity;
- Simulations with a proton beam using the same energy spectrum and 15% of the maximum authorized intensity.

max_E_C	max_E_P	C_E_spect.	P_E_spect.	C_15%int_sp	P_15%int_sp	Material	Volume (m ³)
dumpv	dumpv	dumpv	dumpv	dumpv	dumpv	tungsten	7.00E-04
dumpv	dumpv	dumpv	dumpv	dumpv	dumpv	lead	5.09E-02
dumpo	dumpo	dumpo	dumpo	dumpo	dumpo	tungsten	7.00E-04
dumpori	dumpori	dumpori	dumpori	dumpori	dumpori	lead	5.09E-02
settom	settom	settom	settom	settom	settom	copper	7.00E-04
settomag	settomag	settomag	settomag	settomag	settomag	iron	4.09E-02
settoe	settoe	settoe	settoe	settoe	settoe	copper	7.00E-04
settoele	settoele	settoele	settoele	settoele	settoele	iron	9.59E-03
settomg1	settomg1	settomg1	settomg1	settomg1	settomg1	iron	5.41E-02
settomg2	settomg2	settomg2	settomg2	settomg2	settomg2	iron	5.41E-02
chopper	chopper	chopper	chopper	chopper	chopper	copper	8.00E-03
chopper1	chopper1	chopper1	chopper1	chopper1	chopper1	copper	8.00E-03
chopper2	chopper2	chopper2	chopper2	chopper2	chopper2	copper	8.00E-03
chopper3	chopper3	chopper3	chopper3	chopper3	chopper3	copper	8.00E-03
ring	ring	ring	ring	ring	ring	inox	1.04E-01
Screen	Screen	Screen	Screen	Screen	Screen	inox	2.36E-01
S1_BLO3	S1_BLO3	S1_BLO3	S1_BLO3	S1_BLO3	S1_BLO3	concrete	1.12E+00
S2_BLO1	S2_BLO1	S2_BLO1	S2_BLO1	S2_BLO1	S2_BLO1	concrete	7.83E-01
S2_BLO2	S2_BLO2	S2_BLO2	S2_BLO2	S2_BLO2	S2_BLO2	concrete	7.83E-01
S2_BLO3	S2_BLO3	S2_BLO3	S2_BLO3	S2_BLO3	S2_BLO3	concrete	7.83E-01
S2_BLO4	S2_BLO4	S2_BLO4	S2_BLO4	S2_BLO4	S2_BLO4	concrete	7.83E-01
S2_BLO7	S2_BLO7	S2_BLO7	S2_BLO7	S2_BLO7	S2_BLO7	concrete	7.83E-01
S2_BLO8	S2_BLO8	S2_BLO8	S2_BLO8	S2_BLO8	S2_BLO8	concrete	7.83E-01
S3_BLO2	S3_BLO2	S3_BLO2	S3_BLO2	S3_BLO2	S3_BLO2	concrete	1.12E+00
xprblo1	xprblo1	xprblo1	xprblo1	xprblo1	xprblo1	concrete	1.01E+00
xprblo2	xprblo2	xprblo2	xprblo2	xprblo2	xprblo2	concrete	1.01E+00
xprblo4	xprblo4	xprblo4	xprblo3	xprblo3	xprblo3	concrete	1.01E+00
xprblo5	xprblo5	xprblo5	xprblo5	xprblo5	xprblo5	concrete	1.01E+00
xprblo7	xprblo7	xprblo7	xprblo7	xprblo7	xprblo7	concrete	1.01E+00
xprblo8	xprblo8	xprblo8	xprblo8	xprblo8	xprblo8	concrete	1.01E+00
xprblo19	xprblo19	xprblo19	xprblo19	xprblo19	xprblo19	concrete	2.97E-02
xprblo20	xprblo20	xprblo20	xprblo20	xprblo20	xprblo20	concrete	2.97E-02
xprblo21	xprblo21	xprblo21	xprblo21	xprblo21	xprblo21	concrete	2.97E-02
xprblo22	xprblo22	xprblo22	xprblo22	xprblo22	xprblo22	concrete	2.97E-02
xprblo23	xprblo23	xprblo23	xprblo23	xprblo23	xprblo23	concrete	2.97E-02
xprblo24	xprblo24	xprblo24	xprblo24	xprblo24	xprblo24	concrete	2.97E-02
xprblo25	xprblo25	xprblo25	xprblo25	xprblo25	xprblo25	concrete	2.97E-02
xprblo26	xprblo26	xprblo26	xprblo26	xprblo26	xprblo26	concrete	2.97E-02
xprblo27	xprblo27	xprblo27	xprblo27	xprblo27	xprblo27	concrete	2.97E-02
xprblo10	xprblo10	xprblo10	xprblo10	xprblo10	xprblo10	concrete	2.92E-01
xprblo11	xprblo11	xprblo11	xprblo11	xprblo11	xprblo11	concrete	2.92E-01
xprblo12	xprblo12	xprblo12	xprblo12	xprblo12	xprblo12	concrete	3.05E-01
xprblo15	xprblo15	xprblo15	xprblo15	xprblo15	xprblo15	concrete	2.92E-01
xprblo16	xprblo16	xprblo16	xprblo16	xprblo16	xprblo16	concrete	2.92E-01
xprblo17	xprblo17	xprblo17	xprblo17	xprblo17	xprblo17	concrete	2.92E-01
xprblo18	xprblo18	xprblo18	xprblo18	xprblo18	xprblo18	concrete	3.05E-01
xprblo122	xprblo122	xprblo122	xprblo122	xprblo122	xprblo122	concrete	2.92E-01
xprblo123	xprblo123	xprblo123	xprblo123	xprblo123	xprblo123	concrete	2.92E-01
xprblo124	xprblo124	xprblo124	xprblo124	xprblo124	xprblo124	concrete	3.05E-01
A0425	A0425	A0425	A0425	A0425	A0425	concrete	1.00E+00
A0426	A0426	A0426	A0426	A0426	A0426	concrete	1.00E+00
A0376	A0376	A0376	A0376	A0376	A0376	concrete	1.00E+00
A0377	A0377	A0377	A0377	A0377	A0377	concrete	1.00E+00
dumpsa1	dumpsa1	dumpsa1	dumpsa1	dumpsa1	dumpsa1	inox316	5.02E-03
dumpsa2	dumpsa2	dumpsa2	dumpsa2	dumpsa2	dumpsa2	inox316	5.02E-03
dumpsa3	dumpsa3	dumpsa3	dumpsa3	dumpsa3	dumpsa3	inox316	5.02E-03
DIPOL08	DIPOL08	DIPOL08	DIPOL08	DIPOL08	DIPOL08	iron	9.90E-01
DIPOL010	DIPOL010	DIPOL010	DIPOL010	DIPOL010	DIPOL010	iron	9.90E-01
DIPOL013	DIPOL013	DIPOL013	DIPOL013	DIPOL013	DIPOL013	iron	9.90E-01
DIPOL018	DIPOL018	DIPOL018	DIPOL018	DIPOL018	DIPOL018	iron	9.90E-01
QUADPOL	QUADPOL	QUADPOL	QUADPOL	QUADPOL	QUADPOL	iron	1.42E-01
QUADPOL1	QUADPOL1	QUADPOL1	QUADPOL1	QUADPOL1	QUADPOL1	iron	1.42E-01
QUADPOL2	QUADPOL2	QUADPOL2	QUADPOL2	QUADPOL2	QUADPOL2	iron	1.42E-01
QUADPOL3	QUADPOL3	QUADPOL3	QUADPOL3	QUADPOL3	QUADPOL3	iron	1.42E-01
QUADPOL4	QUADPOL4	QUADPOL4	QUADPOL4	QUADPOL4	QUADPOL4	iron	1.42E-01
QUADPOL5	QUADPOL5	QUADPOL5	QUADPOL5	QUADPOL5	QUADPOL5	iron	1.42E-01
QUADPOL6	QUADPOL6	QUADPOL6	QUADPOL6	QUADPOL6	QUADPOL6	iron	1.42E-01
QUADPOL7	QUADPOL7	QUADPOL7	QUADPOL7	QUADPOL7	QUADPOL7	iron	1.42E-01
QUADPOL8	QUADPOL8	QUADPOL8	QUADPOL8	QUADPOL8	QUADPOL8	iron	1.42E-01
QUADPOL9	QUADPOL9	QUADPOL9	QUADPOL9	QUADPOL9	QUADPOL9	iron	1.42E-01
QUADPOL10	QUADPOL10	QUADPOL10	QUADPOL10	QUADPOL10	QUADPOL10	iron	1.42E-01
QUADPOL11	QUADPOL11	QUADPOL11	QUADPOL11	QUADPOL11	QUADPOL11	iron	1.42E-01
QUADPOL12	QUADPOL12	QUADPOL12	QUADPOL12	QUADPOL12	QUADPOL12	iron	1.42E-01
QUADPOL13	QUADPOL13	QUADPOL13	QUADPOL13	QUADPOL13	QUADPOL13	iron	1.42E-01
QUADPOL14	QUADPOL14	QUADPOL14	QUADPOL14	QUADPOL14	QUADPOL14	iron	1.42E-01
QUADPOL15	QUADPOL15	QUADPOL15	QUADPOL15	QUADPOL15	QUADPOL15	iron	1.42E-01
QUADPOL16	QUADPOL16	QUADPOL16	QUADPOL16	QUADPOL16	QUADPOL16	iron	1.42E-01
QUADPOL17	QUADPOL17	QUADPOL17	QUADPOL17	QUADPOL17	QUADPOL17	iron	1.42E-01
QUADPOL18	QUADPOL18	QUADPOL18	QUADPOL18	QUADPOL18	QUADPOL18	iron	1.42E-01
QUADPOL19	QUADPOL19	QUADPOL19	QUADPOL19	QUADPOL19	QUADPOL19	iron	1.42E-01
QUADPOL20	QUADPOL20	QUADPOL20	QUADPOL20	QUADPOL20	QUADPOL20	iron	1.42E-01
QUADPOL21	QUADPOL21	QUADPOL21	QUADPOL21	QUADPOL21	QUADPOL21	iron	1.42E-01
QUADPOL22	QUADPOL22	QUADPOL22	QUADPOL22	QUADPOL22	QUADPOL22	iron	1.42E-01

Figure 5.47: Comparison of synchrotron components that cannot be removed when using carbon ion or proton beams, for all analyzed cases.

For each component, the corresponding volume and material are reported. Based on this data, the total volume of each material classified as non-removable and requiring disposal as radioactive waste, was calculated. This allows for an estimation of future decommissioning costs. In figure 5.47, non-removable components are highlighted in red, while removable components are highlighted in green.

Volume (m ³)						
Material	max_E_C	max_E_P	C_E_spect.	P_E_spect.	C_15%int_sp	P_15%int_sp
tungsten	1.40E-03	1.40E-03	1.40E-03	1.40E-03	1.40E-03	1.40E-03
lead	1.02E-01	1.02E-01	1.02E-01	5.09E-02	5.09E-02	\\
copper	3.34E-02	3.34E-02	3.34E-02	3.34E-02	3.34E-02	3.34E-02
iron	7.45E+00	6.35E+00	4.08E+00	3.35E-01	3.89E-01	1.93E-01
concrete	1.65E+01	1.52E+01	7.27E+00	2.35E+00	2.35E+00	7.83E-01
inox316	1.51E-02	1.51E-02	1.51E-02	1.51E-02	1.51E-02	1.51E-02
inox	3.41E-01	3.41E-01	3.41E-01	3.41E-01	3.41E-01	1.04E-01

Figure 5.48: Summation of non-removable volumes, classified by material and case type.

Finally, the radionuclides generated in the removable components, for which the structure will need to request authorization for release, include ²⁶Al, ³⁷Ar, ³⁹Ar, ¹⁹⁴Au, ¹⁹⁵Au, ¹⁰Be, ⁷Be, ²⁰⁵Bi, ²⁰⁷Bi, ²⁰⁸Bi, ¹⁴C, ⁴¹Ca, ⁴⁵Ca, ¹¹³Cd, ³⁶Cl, ⁵⁶Co, ⁵⁷Co, ⁵⁸Co, ⁶⁰Co, ⁵¹Cr, ¹⁵²Eu, ¹⁵⁴Eu, ⁵⁵Fe, ⁵⁹Fe, ³H, ¹⁹⁴Hg, ²⁰³Hg, ¹²⁹I, ⁴⁰K, ⁸³Kr, ⁸⁵Kr, ⁵²Mn, ⁵³Mn, ⁵⁴Mn, ²²Na, ⁹³Nb, ⁹⁵Nb, ⁵⁹Ni, ³²P, ³³P, ²⁰²Pb, ²⁰⁵Pb, ²⁰⁷Pb, ¹⁰⁷Pd, ¹⁹³Pt, ⁸³Rb, ⁸⁵Rb, ⁸⁶Rb, ¹⁰³Rh, ¹⁰⁶Rh, ¹⁰³Ru, ¹⁰⁶Ru, ³⁵S, ⁴⁴Sc, ⁴⁵Sc, ⁴⁶Sc, ⁴⁷Sc, ³²Si, ⁹⁰Sr, ⁴⁴Ti, ²⁰²Tl, ²⁰⁴Tl, ⁴⁸V, ⁴⁹V, ⁹⁰Y, ⁹¹Y, ⁹³Zr and ⁹⁵Zr.

6 | FLUKA simulation of the new HITACHI proton therapy facility

This chapter presents the results obtained from Monte Carlo simulations, performed with FLUKA, on the activation of the new proton therapy facility at CNAO. This facility will host a Hitachi synchrotron, with the linear accelerator (Linac), the high-energy beam transfer line (HEBT), and the gantry beam transfer line (GABT).

The machine layout is shown in Figure 6.1. The synchrotron is located in the back of the treatment room. Along the extraction line, just downstream of the Fast Faraday Cup (FFC) and the beam dumper, there is a partition wall designed to separate the two environments and shield the most radiation-exposed areas of the accelerator. The synchrotron consists of a source integrated with pre-acceleration stages (RFQ, Linac), which pre-accelerates the beam up to 3.5 MeV. The beam is then injected through the injection septum, accelerated in the synchrotron to treatment energies ranging from 60 to 230 MeV, and subsequently extracted and delivered to the patient through the transport line and gantry system. The synchrotron is equipped with an active scanning system, which distributes the beam over the patient positioned at the isocenter. This is achieved using scanning magnets and a nozzle that controls the dose delivery system.

6.1. FLUKA geometry

This section describes the general layout of the proton therapy facility used in the Monte Carlo simulations. In FLAIR, the main structures of the facility have been implemented, including the HITACHI synchrotron, the LINAC, the HEBT, and the GABT. The building measures 37 m x 20 m, with a maximum height of 19 m. The goal was to model the main elements of the facility as accurately as possible. The choice of materials is important because even small differences in composition can affect the radionuclides produced after irradiation. If a material is not specified in this section, the standard FLUKA material

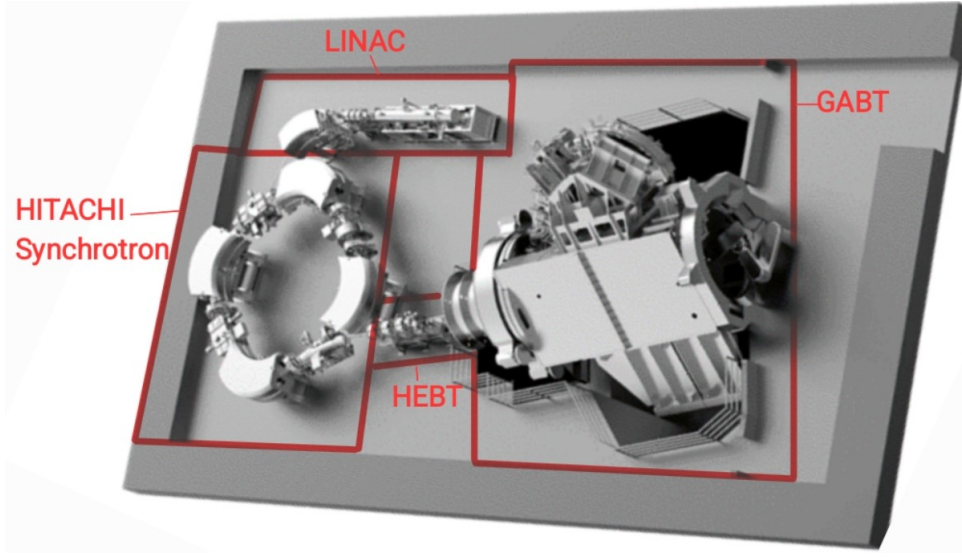


Figure 6.1: New proton therapy layout [16].

library was used. The building is made of 4 meters of Portland concrete to shield the outside from neutron radiation. For its composition (Table 6.1), the standard FLUKA composition was used, with additional concentrations of Co and Eu based on reference [19].

Portland concrete ($\rho = 2.34g/cm^3$)

Element	Weight fraction
Oxygen	0.529102
Silicon	0.337018
Calcium	0.044
Aluminum	0.0338713
Sodium	0.016
Iron	0.014
Potassiu	0.013
Hydrogen	0.01
Magnesi	0.002
Carbon	0.001
Cobalt	0.000008
Europium	0.0000007

Table 6.1: Portland concrete composition.

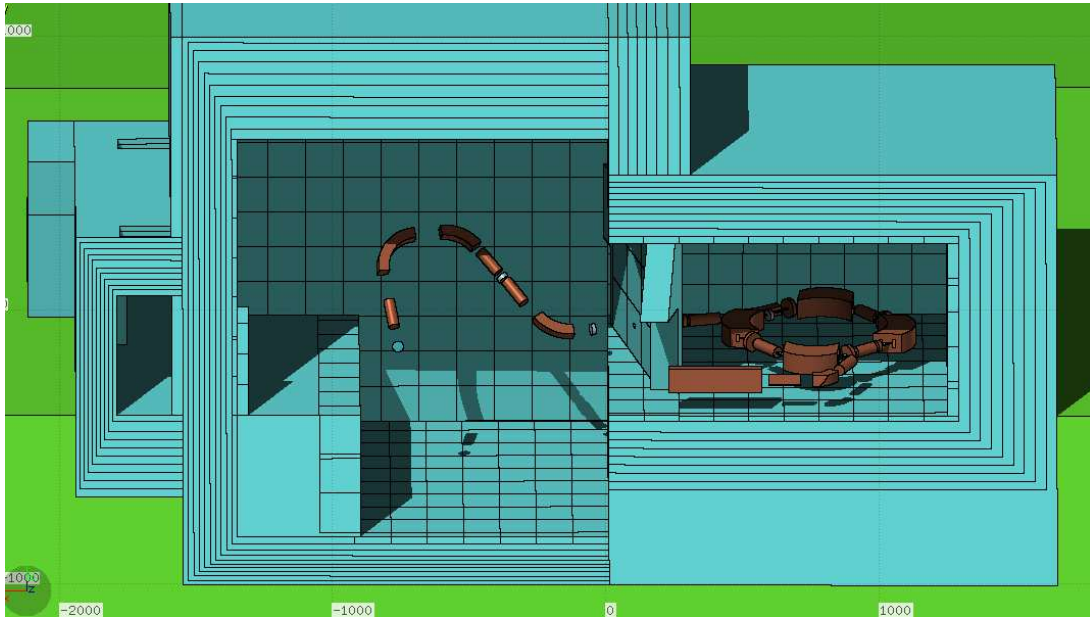


Figure 6.2: 3D representation of the facility geometry, reconstructed in FLUKA.

LINAC

The LINAC was modeled as a pure iron structure (Fig. 6.3). The other components responsible for transporting and injecting protons into the synchrotron are also made of iron.

HITACHI Synchrotron

The schematized components of the HITACHI synchrotron are shown in Fig. 6.4. The proton beam is contained in a vacuum vessel made of stainless steel and lies in the z - x plane at $y = 200$ cm. The FLUKA standard composition is used for stainless steel. A transversal section of the four bending magnets (BM1, BM2, BM3, and BM4) is shown in Fig. 6.5. These magnets have an "H" structure made of copper, with an iron outside cover. The vacuum vessel runs through all synchrotron components. Other elements focus the beam and make measurements. In the model, they were simplified and made of iron.

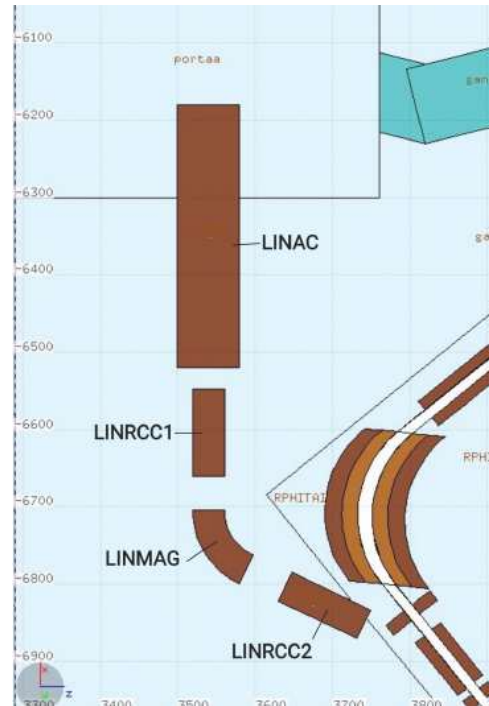


Figure 6.3: 2D view of LINAC, plane x-z with $y=-200$.

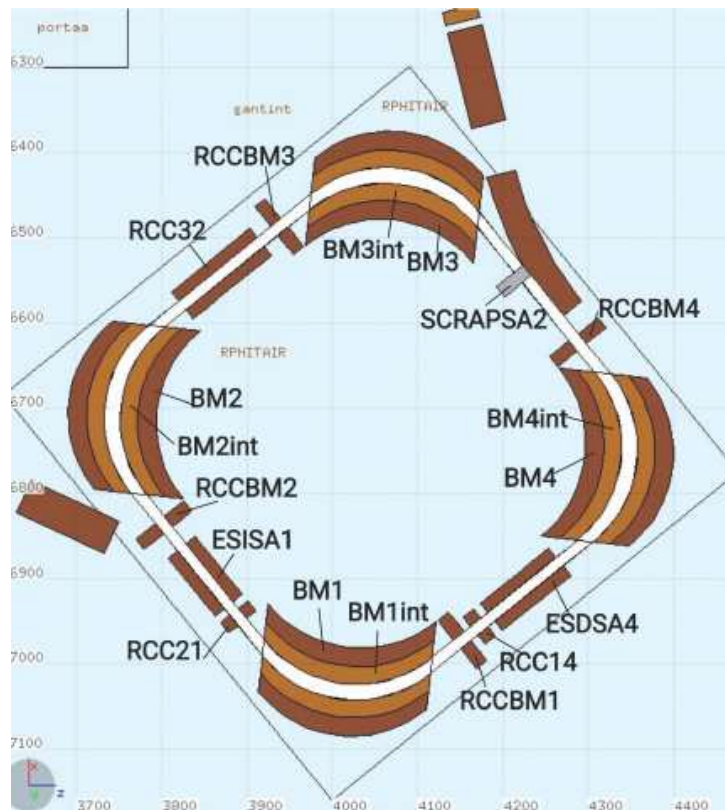


Figure 6.4: 2D view of HITACHI synchrotron, plane x-z with $y=-200$.

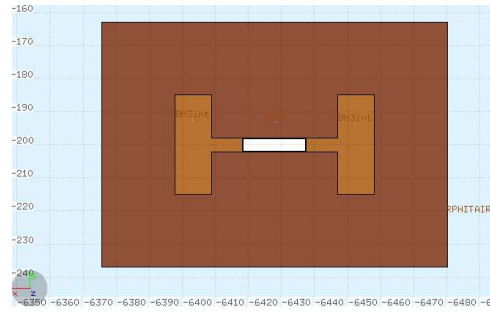
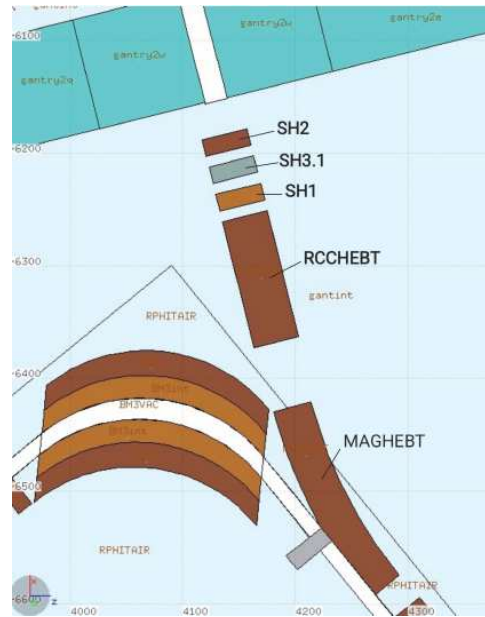


Figure 6.5: 2D view of BM3, plane x-y.

HEBT

The HEBT components are shown in Fig. 6.6. SH1, where beam measurement occurs, is made of copper. SH2 is a beam dump and is made of iron. SH3.1 is a profile monitor and is made of tungsten. The other components are made of iron.

Figure 6.6: 2D view of HEBT, plane x-z with $y=-200$.

GABT

The GABT components (Fig. 6.7) transport and direct the beam to the patient from different angles. Except for SH3.2 and SH3.3, which are made of tungsten, all components are made of iron. At the end of the gantry, the patient is represented as a 20 cm radius sphere made of water.

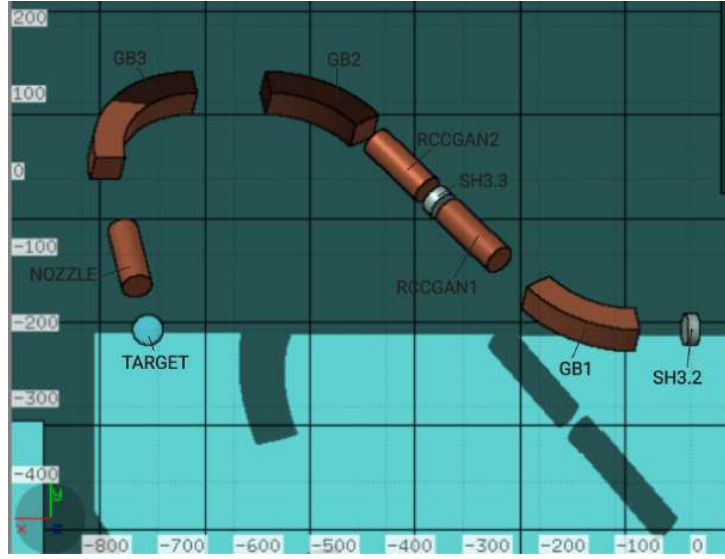


Figure 6.7: 3D view of GABT, plane x-y with $z=3500$.

Beam losses

The FLUKA source definition is implemented using a Fortran77 user routine (SOURCE.f). This routine defines all loss positions and their average percentages (indicated in Tab.6.2). These include the extraction septa (ESDSA4), the four synchrotron magnets, the Fast Faraday Cup (SH1), the beam dumper (SH2), the profile monitors (SH3.1-SH3.2-SH3.3) and the isocenter.

For each primary proton, a random number between 0 and 1 is selected. Based on this value, the routine determines the loss location and sets the proton starting position and direction.

Loss location	Loss percentage %
BM1	5.72
BM2	5.72
BM3	5.72
BM4	5.72
ESDSA4	7.72
SH1	6.57
SH2	6.29
SH3.1	0.87
SH3.2	0.87
SH3.3	0.86
TARGET	53.94

Table 6.2: Proton beam losses of the new proton therapy facility at CNAO.

6.2. FLUKA activation simulations

The following subsections present the parameters implemented in the simulations with the primary and transport cards, the scoring cards used and an explanation of the data analysis methodology.

Primary and Transport CARDS

- Proton beam energy was considered at both the maximum possible energy of 230 MeV, and the proton energy spectrum used in 2023 with the CNAO synchrotron.
- The irradiation profile was introduced using the IRRPROFI card, considering the maximum authorized current of 10^{10} p/s, with an irradiation time of 30 years, which is the typical lifetime of the accelerator.
- The cooling time was set to 1 year after the end of irradiation.

Scoring CARDS

- USERBIN-actomass cards were used for the graphical visualization of specific activity [Bq/g] in selected spatial areas.
- RESNUCLEI cards were implemented to evaluate activation within specific regions

and to identify the radionuclides produced.

Data analysis methodology

In the following figures, building maps with a color scale representing Actomass are shown. From these images, the hottest regions, meaning those with significant specific activity, were identified. Large-volume regions (e.g., walls) were further divided into smaller areas by modifying the geometry to obtain more realistic data and facilitate material transport during decommissioning. A minimum color scale value of 0.1 Bq/g was used, as the analysis showed that no non-removable element had a specific activity below this threshold. For regions with specific activity greater than 0.1 Bq/g, RESNUCLEI analysis was performed. The data obtained from RESNUCLEI are reported and analyzed in numerous tables, which are available at the CNAO radiation protection office but are not all included here due to their large number. These tables contain:

- The inventory of radionuclides present after one year of cooling time, including their activity (Bq) and associated percentage error.
- The material composition of the analyzed region, with density (g/cm³), mass (kg), and volume (m³).
- The total activity (Bq) and percentage error for the entire region.
- Calculation of specific activity (Bq/g) for each radionuclide.
- The assignment of values from Table 1b of Decreto Legislativo n.101 of July 31th, 2020, "Livelli di allontanamento per i materiali solidi", implemented with the CNAO authorization values for solid material clearance. For radionuclides not listed in these tables, a conservative clearance level of 0.01 was applied. In the following sections, radionuclides not included in these lists, subject to the most restrictive limit, are labeled as "unlisted" and highlighted in yellow.
- The calculation of the ratio between specific activity and the coefficients from the table.
- The half life ($T_{1/2}$) for each radionuclide.
- The summation of the specific activity-to-coefficient ratios ($\Sigma Att.sp./cf$).

According to Allegato 1 of Decreto Legislativo 101/2020, materials with a summation ratio greater than 1 cannot be cleared.

Materials with a ratio below 1 may be cleared if the Foundation has authorization to remove the present radionuclides. To facilitate this process, a list of all radionuclides formed

over 30 years that are present in removable blocks is provided in the results.

The assessments presented here are based on these assumptions and will need to be reviewed following decommissioning authorization and an evaluation of the actual workload at the end of the facility's operational life. If some components are classified as non-removable in these simulations only because they contain unlisted radionuclides, it may be possible, at the time of decommissioning, to request a less restrictive clearance level.

The following sections present the data obtained from Monte Carlo simulations performed with FLUKA using a proton beam for the following scenarios:

- Maximum authorized energy and intensity, considering both removable and non-removable components (Paragraphs 6.2.1 and 6.2.2);
- Energy spectrum actually used in 2023 with the maximum authorized intensity (Paragraph 6.2.3).

Specifically, paragraph 6.2.1 presents the data analysis for Synchrotron Magnet 2, including both its external (BM2) and internal (BM2int) parts, as well as for the Fast Faraday Cup (SH1), the Beam Dumper (SH2), the Profile Monitor (SH3.1) and a floor block (SO147) located under Magnet 2. All of these components are classified as non-removable.

Paragraph 6.2.2 reports the data analysis for removable components, including Synchrotron Magnet 1 (both external (BM1) and internal (BM1int) parts) and a wall section (Gantry2W) through which the beam passes, separating the synchrotron hall from the treatment room.

Paragraph 6.2.3 presents the simulation results for a proton beam at the maximum authorized intensity, using the actual energy spectrum employed in the CNAO existing proton therapy facility.

For both Sections 6.2.1 and 6.2.3, the results begin with representative images of specific activity distributions, obtained from the USERBIN-actomass card.

6.2.1. Non-removable components: simulations with maximum energy and maximum particle beam intensity

Images 6.8 and 6.9 show the specific activity of the facility at beam level and floor level.

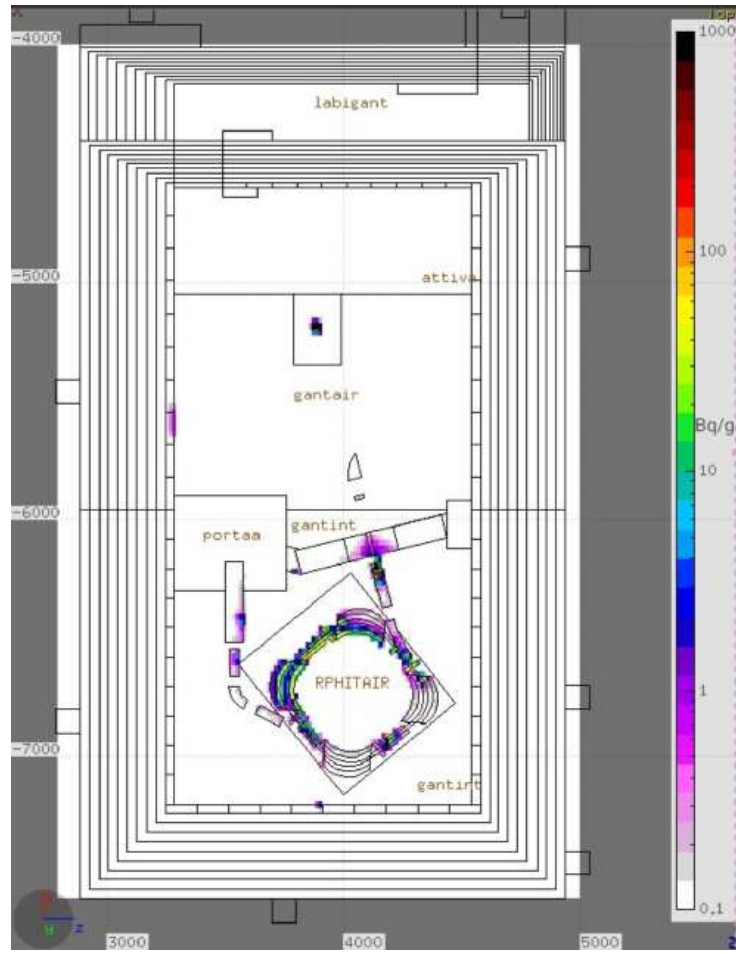


Figure 6.8: Visualization of the USERBIN-actomass in the x-z plane with $y=-200$, for a proton beam at maximum energy of 230 MeV.

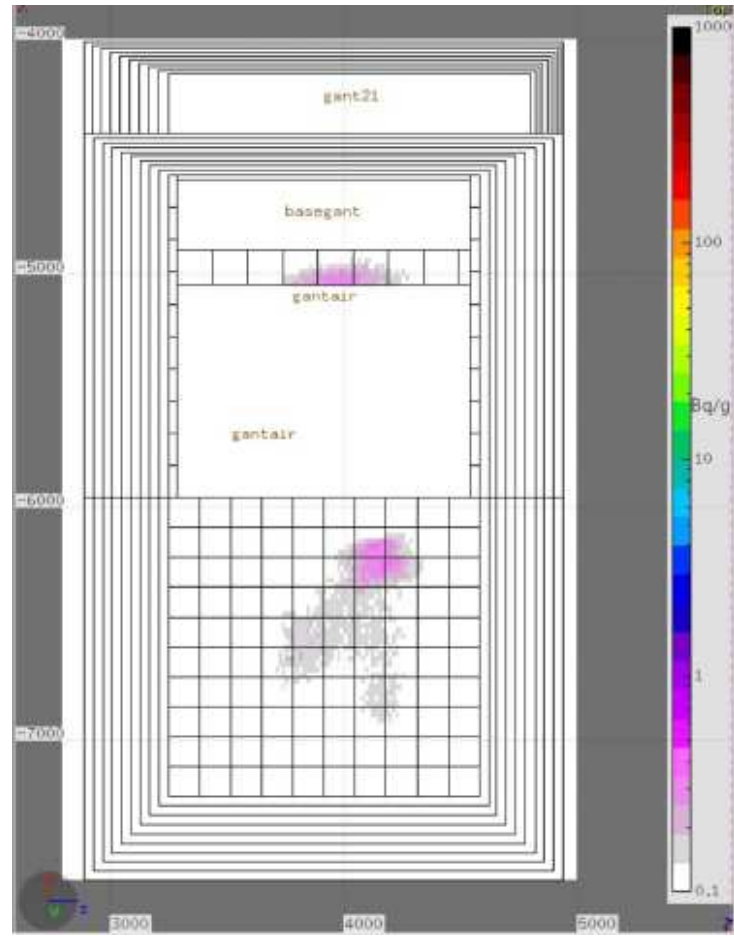


Figure 6.9: Visualization of the USERBIN-actomass in the x-z plane with $y=-330$, for a proton beam at maximum energy of 230 MeV.

Figure 6.8 shows that the most activated areas are the synchrotron and the HEBT.

The following figures provide a detailed view of the specific activity of radionuclides generated after 30 years of irradiation. Tables are included for the most significant regions, ensuring that at least one table is provided for each type of material in the facility.

BM2	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)		iron	
	49	23	2.26E+06	0.21	V	V-49	2.11E-01	0.01	2.11E+01	2.85E+07	V(m3)	ro(g/cm3)
	54	25	8.88E+06	0.10	Mn	Mn-54	8.33E-01	0.1	8.33E+00	2.70E+07	1.35E+00	7.87E+00
	55	26	3.87E+07	0.08	Fe	Fe-55	3.63E+00	1	3.63E+00	8.66E+07	att. (Bq)	1.07E+04
	44	22	2.95E+04	1.37	Ti	Ti-44	2.77E-03	0.01	2.77E-01	1.87E+09	5.22E+07	+/-
	3	1	2.19E+06	0.27	H	H-3	2.05E-01	1	2.05E-01	3.89E+08	att.sp. (Bq/g)	6.68E-02 %
	56	27	4.84E+04	0.40	Co	Co-56	4.54E-03	0.1	4.54E-02	6.67E+06	4.90E+00	
	39	18	3.09E+03	1.97	Ar	Ar-39	2.90E-04	0.01	2.90E-02	8.46E+09	Σ(att.sp/cf)	3.37E+01
	44	21	2.95E+04	1.37	Sc	Sc-44	2.77E-03	0.1	2.77E-02	1.46E+04		
	46	21	1.68E+04	0.73	Sc	Sc-46	1.57E-03	0.1	1.57E-02	7.24E+06		
	42	19	2.02E+02	22.91	K	K-42	1.89E-05	0.01	1.89E-03	4.45E+04		
	42	18	2.02E+02	22.91	Ar	Ar-42	1.89E-05	0.01	1.89E-03	1.04E+09		
	57	27	1.83E+04	2.31	Co	Co-57	1.72E-03	1	1.72E-03	2.35E+07		
	45	20	8.05E+03	2.16	Ca	Ca-45	7.55E-04	1	7.55E-04	1.40E+07		
	22	11	6.28E+02	15.54	Na	Na-22	5.89E-05	0.1	5.89E-04	8.21E+07		
	32	14	5.31E+01	22.75	Si	Si-32	4.98E-06	0.01	4.98E-04	4.95E+09		
	41	20	3.21E+01	1.13	Ca	Ca-41	3.01E-06	0.01	3.01E-04	3.14E+12		
	59	26	1.53E+03	0.69	Fe	Fe-59	1.43E-04	1	1.43E-04	3.84E+06		
	51	24	9.93E+02	0.16	Cr	Cr-51	9.31E-05	1	9.31E-05	2.39E+06		
	35	16	4.66E+02	5.04	S	S-35	4.37E-05	1	4.37E-05	7.55E+06		
	7	4	2.20E+02	2.93	Be	Be-7	2.06E-05	1	2.06E-05	4.60E+06		
	58	27	1.57E+02	5.54	Co	Co-58	1.47E-05	1	1.47E-05	6.12E+06		
	53	25	1.11E+02	0.10	Mn	Mn-53	1.04E-05	1	1.04E-05	1.17E+14		
	32	15	5.32E+01	22.75	P	P-32	4.98E-06	1	4.98E-06	1.23E+06		
	37	18	2.58E+01	2.39	Ar	Ar-37	2.42E-06	1	2.42E-06	3.02E+06		
	14	6	1.97E+01	5.80	C	C-14	1.84E-06	1	1.84E-06	1.80E+11		
	10	4	8.81E-02	5.44	Be	Be-10	8.27E-09	0.01	8.27E-07	4.77E+13		
	36	17	3.94E+00	1.67	Cl	Cl-36	3.69E-07	1	3.69E-07	9.51E+12		
	26	13	8.12E-03	28.75	Al	Al-26	7.62E-10	0.01	7.62E-08	2.26E+13		
	48	23	3.45E-01	0.30	V	V-48	3.23E-08	1	3.23E-08	1.38E+06		
	59	28	3.06E-01	12.26	Ni	Ni-59	2.87E-08	1	2.87E-08	2.40E+12		
	33	15	2.11E-01	7.22	P	P-33	1.98E-08	1	1.98E-08	2.19E+06		
	40	19	2.71E-03	1.17	K	K-40	2.54E-10	1	2.54E-10	3.94E+16		
	A/Z/ Isomers:											
	44	21	2.94E+04	1.37	Sc	Sc-44	2.76E-03	0.1	2.76E-02	2.11E+05		
	45	21	1.53E-01	2.16	Sc	Sc-45	1.43E-08	0.01	1.43E-06	3.26E-01		

Figure 6.10: Radionuclides generated in BM2 with corresponding analysis.

The parts highlighted in yellow indicate unlisted radionuclides (further details can be found in the paragraph on Data analysis methodology).

Fig.6.10 shows the activity table of the BM2 magnet, composed of iron. The most significant long-lived radionuclides due to the high specific activity of the magnet are ⁴⁹V, ⁵⁴Mn, ⁵⁵Fe, ⁴⁴Ti and ³H.

BM2int	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)				
	49	23	1.90E+05	0.69	V	V-49	1.46E-01	0.01	1.46E+01	2.85E+07			
	60	27	1.55E+06	0.34	Co	Co-60	1.19E+00	0.1	1.19E+01	1.66E+08			
	54	25	8.02E+05	0.35	Mn	Mn-54	6.15E-01	0.1	6.15E+00	2.70E+07			
	3	1	3.37E+06	0.20	H	H-3	2.59E+00	1	2.59E+00	3.89E+08			
	55	26	3.31E+06	0.21	Fe	Fe-55	2.54E+00	1	2.54E+00	8.66E+07			
	57	27	2.83E+06	0.16	Co	Co-57	2.17E+00	1	2.17E+00	2.35E+07			
	65	30	2.42E+05	0.54	Zn	Zn-65	1.86E-01	0.1	1.86E+00	2.11E+07			
	63	28	1.05E+06	0.18	Ni	Ni-63	8.06E-01	1	8.06E-01	3.19E+09			
	56	27	8.51E+04	0.33	Co	Co-56	6.53E-02	0.1	6.53E-01	6.67E+06			
	58	27	1.98E+05	0.18	Co	Co-58	1.52E-01	1	1.52E-01	6.12E+06			
	44	22	1.69E+03	6.40	Ti	Ti-44	1.30E-03	0.01	1.30E-01	1.87E+09			
	39	18	2.87E+02	6.88	Ar	Ar-39	2.86E-04	0.01	2.86E-02	8.46E+09			
	46	21	1.71E+03	2.54	Sc	Sc-46	1.31E-03	0.1	1.31E-02	7.24E+06			
	44	21	1.69E+03	6.40	Sc	Sc-44	1.30E-03	0.1	1.30E-02	1.46E+04			
	22	11	3.68E+02	21.45	Na	Na-22	2.82E-04	0.1	2.82E-03	8.21E+07			
	59	28	2.81E+03	0.14	Ni	Ni-59	2.15E-03	1	2.15E-03	2.40E+12			
	42	19	2.75E+01	57.15	K	K-42	2.11E-05	0.01	2.11E-03	4.45E+04			
	42	18	2.75E+01	57.15	Ar	Ar-42	2.11E-05	0.01	2.11E-03	1.04E+09			
	45	20	9.65E+02	6.75	Ca	Ca-45	7.40E-04	1	7.40E-04	1.40E+07			
	59	26	3.57E+02	1.36	Fe	Fe-59	2.74E-04	1	2.74E-04	3.84E+06			
	32	14	2.53E+00	99.00	Si	Si-32	1.94E-06	0.01	1.94E-04	4.95E+09			
	7	4	2.46E+02	2.73	Be	Be-7	1.89E-04	1	1.89E-04	4.60E+06			
	41	20	2.20E+00	4.60	Ca	Ca-41	1.68E-06	0.01	1.68E-04	3.14E+12			
	51	24	9.47E+01	0.45	Cr	Cr-51	7.27E-05	1	7.27E-05	2.39E+06			
	35	16	6.73E+01	12.31	S	S-35	5.16E-05	1	5.16E-05	7.55E+06			
	14	6	2.07E+01	6.65	C	C-14	1.59E-05	1	1.59E-05	1.80E+11			
	60	26	1.99E-01	2.66	Fe	Fe-60	1.53E-07	0.01	1.53E-05	8.27E+13			
	10	4	1.23E-01	4.37	Be	Be-10	9.40E-08	0.01	9.40E-06	4.77E+13			
	53	25	1.12E+01	0.32	Mn	Mn-53	8.56E-06	1	8.56E-06	1.17E+14			
	32	15	2.53E+00	99.00	P	P-32	1.94E-06	1	1.94E-06	1.23E+06			
	37	18	2.24E+00	8.01	Ar	Ar-37	1.72E-06	1	1.72E-06	3.02E+06			
	36	17	3.45E-01	6.72	Cl	Cl-36	2.65E-07	1	2.65E-07	9.51E+12			
	26	13	1.16E-03	70.35	Al	Al-26	8.90E-10	0.01	8.90E-08	2.26E+13			
	33	15	2.94E-02	16.55	P	P-33	2.26E-08	1	2.26E-08	2.19E+06			
	48	23	2.47E-02	0.93	V	V-48	1.90E-08	1	1.90E-08	1.38E+06			
	40	19	2.50E-04	3.61	K	K-40	1.92E-10	1	1.92E-10	3.94E+16			
	A/Z/ Isomers:												
	44	21	1.68E+03	6.40	Sc	Sc-44	1.29E-03	0.1	1.29E-02	2.11E+05			
	45	21	1.83E-02	6.75	Sc	Sc-45	1.41E-08	0.01	1.41E-06	3.26E-01			
	60	27	1.99E-01	2.66	Co	Co-60	1.53E-07	0.1	1.53E-06	6.28E+02			

	copper		
V(m3)	ro(g/cm3)	m(Kg)	
1.46E-01	8.96E+00	1.30E+03	
att. (Bq)			
1.36E+07	+/-	1.07E-01	%
att.sp. (Bq/g)			
1.05E+01			
Σ(att.sp/cf)		4.36E+01	

Figure 6.11: Radionuclides generated in BM2int with respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, please see the Data analysis methodology paragraph).

Fig.6.11 shows the activity table of the BM2int magnet, composed of copper. The most significant long-lived radionuclides due to the high specific activity of the magnet are ⁴⁹V, ⁶⁰Co, ⁵⁴Mn, ³H, ⁵⁵Fe, ⁵⁷Co and ⁶⁵Zn.

SH1	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)			
	49	23	3.24E+05	0.51	V	V-49	1.83E+00	0.01	1.83E+02	2.85E+07	V(m3)	
	60	27	2.88E+06	0.26	Co	Co-60	1.62E+01	0.1	1.62E+02	1.66E+08	ro(g/cm3)	
	54	25	1.30E+06	0.23	Mn	Mn-54	7.33E+00	0.1	7.33E+01	2.70E+07	m(Kg)	
	3	1	5.40E+06	0.14	H	H-3	3.04E+01	1	3.04E+01	3.89E+08	att. (Bq)	
	55	26	5.29E+06	0.18	Fe	Fe-55	2.98E+01	1	2.98E+01	8.66E+07	2.27E+07 +/-	7.45E-02 %
	57	27	4.44E+06	0.13	Co	Co-57	2.50E+01	1	2.50E+01	2.35E+07	att.sp. (Bq/g)	
	65	30	3.56E+05	0.40	Zn	Zn-65	2.01E+00	0.1	2.01E+01	2.11E+07	1.28E+02	
	63	28	2.29E+06	0.14	Ni	Ni-63	1.29E+01	1	1.29E+01	3.19E+09	Σ(att.sp/cf)	5.49E+02
	56	27	1.35E+05	0.22	Co	Co-56	7.59E-01	0.1	7.59E+00	6.67E+06		
	44	22	3.63E+03	3.94	Ti	Ti-44	2.05E-02	0.01	2.05E+00	1.87E+09		
	58	27	3.17E+05	0.15	Co	Co-58	1.78E+00	1	1.78E+00	6.12E+06		
	39	18	6.56E+02	4.60	Ar	Ar-39	3.70E-03	0.01	3.70E-01	8.46E+09		
	44	21	3.63E+03	3.94	Sc	Sc-44	2.05E-02	0.1	2.05E-01	1.46E+04		
	46	21	3.01E+03	1.95	Sc	Sc-46	1.69E-02	0.1	1.69E-01	7.24E+06		
	22	11	5.36E+02	14.85	Na	Na-22	3.02E-03	0.1	3.02E-02	8.21E+07		
	42	19	4.59E+01	43.81	K	K-42	2.59E-04	0.01	2.59E-02	4.45E+04		
	42	18	4.59E+01	43.81	Ar	Ar-42	2.59E-04	0.01	2.59E-02	1.04E+09		
	59	28	4.37E+03	0.11	Ni	Ni-59	2.46E-02	1	2.46E-02	2.40E+12		
	45	20	1.92E+03	4.49	Ca	Ca-45	1.08E-02	1	1.08E-02	1.40E+07		
	32	14	7.59E+00	57.15	Si	Si-32	4.28E-05	0.01	4.28E-03	4.95E+09		
	59	26	5.87E+02	0.99	Fe	Fe-59	3.31E-03	1	3.31E-03	3.84E+06		
	41	20	4.77E+00	2.50	Ca	Ca-41	2.69E-05	0.01	2.69E-03	3.14E+12		
	7	4	4.11E+02	2.04	Be	Be-7	2.32E-03	1	2.32E-03	4.60E+06		
	51	24	1.60E+02	0.39	Cr	Cr-51	8.99E-04	1	8.99E-04	2.39E+06		
	35	16	1.21E+02	11.23	S	S-35	6.84E-04	1	6.84E-04	7.55E+06		
	14	6	3.61E+01	3.68	C	C-14	2.04E-04	1	2.04E-04	1.80E+11		
	60	26	3.37E-01	1.91	Fe	Fe-60	1.90E-06	0.01	1.90E-04	8.27E+13		
	10	4	2.15E-01	3.87	Be	Be-10	1.21E-06	0.01	1.21E-04	4.77E+13		
	53	25	1.82E+01	0.24	Mn	Mn-53	1.03E-04	1	1.03E-04	1.17E+14		
	32	15	7.59E+00	57.15	P	P-32	4.28E-05	1	4.28E-05	1.23E+06		
	37	18	4.11E+00	5.90	Ar	Ar-37	2.32E-05	1	2.32E-05	3.02E+06		
	36	17	7.67E-01	4.64	Cl	Cl-36	4.32E-06	1	4.32E-06	9.51E+12		
	26	13	1.16E-03	70.35	Al	Al-26	6.54E-09	0.01	6.54E-07	2.26E+13		
	33	15	4.78E-02	15.09	P	P-33	2.70E-07	1	2.70E-07	2.19E+06		
	48	23	4.46E-02	0.82	V	V-48	2.51E-07	1	2.51E-07	1.38E+06		
	40	19	4.77E-04	3.07	K	K-40	2.69E-09	1	2.69E-09	3.94E+16		
	A/Z/ Isomers:											
	44	21	3.62E+03	3.94	Sc	Sc-44	2.04E-02	0.1	2.04E-01	2.11E+05		
	45	21	3.65E-02	4.49	Sc	Sc-45	2.06E-07	0.01	2.06E-05	3.26E-01		
	60	27	3.37E-01	1.91	Co	Co-60	1.90E-06	0.1	1.90E-05	6.28E+02		

Figure 6.12: Radionuclides generated in SH1 with respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, please see the Data analysis methodology paragraph).

Fig.6.12 shows the activity table of the Fast Faraday Cup, SH1, composed of copper. The most significant long-lived radionuclides due to the high specific activity of the component are ^{49}V , ^{60}Co , ^{54}Mn , ^3H , ^{55}Fe , ^{57}Co , ^{65}Zn , ^{63}Ni , ^{44}Ti and short-lived radionuclides ^{56}Co , ^{58}Co .

SH2	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)		iron		
	49	23	4.43E+06	0.15	V	V-49	2.84E+01	0.01	2.84E+03	2.85E+07	V(m3)	ro(g/cm3)	m(Kg)
	54	25	1.12E+07	0.09	Mn	Mn-54	7.15E+01	0.1	7.15E+02	2.70E+07	1.98E-02	7.87E+00	1.56E+02
	55	26	4.15E+07	0.07	Fe	Fe-55	2.66E+02	1	2.66E+02	8.66E+07	att. (Bq)		
	44	22	7.03E+04	0.89	Ti	Ti-44	4.51E-01	0.01	4.51E+01	1.87E+09	6.17E+07 +/-		5.56E-02 %
	3	1	4.14E+06	0.19	H	H-3	2.66E+01	1	2.66E+01	3.89E+08	att.sp. (Bq/g)		
	56	27	1.14E+05	0.25	Co	Co-56	7.28E-01	0.1	7.28E+00	6.67E+06	3.96E+02		
	39	18	7.43E+03	1.42	Ar	Ar-39	4.76E-02	0.01	4.76E+00	8.46E+09	Σ(att.sp/cf)		3.92E+03
	44	21	7.03E+04	0.89	Sc	Sc-44	4.51E-01	0.1	4.51E+00	1.46E+04			
	46	21	3.38E+04	0.50	Sc	Sc-46	2.17E-01	0.1	2.17E+00	7.24E+06			
	57	27	4.10E+04	1.25	Co	Co-57	2.63E-01	1	2.63E-01	2.35E+07			
	42	18	3.21E+02	15.92	Ar	Ar-42	2.06E-03	0.01	2.06E-01	1.04E+09			
	42	19	3.21E+02	15.92	K	K-42	2.06E-03	0.01	2.06E-01	4.45E+04			
	45	20	1.68E+04	1.54	Ca	Ca-45	1.08E-01	1	1.08E-01	1.40E+07			
	22	11	1.39E+03	8.99	Na	Na-22	8.94E-03	0.1	8.94E-02	8.21E+07			
	32	14	1.04E+02	15.54	Si	Si-32	6.65E-04	0.01	6.65E-02	4.95E+09			
	41	20	7.54E+01	0.74	Ca	Ca-41	4.83E-04	0.01	4.83E-02	3.14E+12			
	51	24	1.76E+03	0.13	Cr	Cr-51	1.13E-02	1	1.13E-02	2.39E+06			
	35	16	1.07E+03	3.31	S	S-35	6.87E-03	1	6.87E-03	7.55E+06			
	7	4	5.08E+02	1.89	Be	Be-7	3.25E-03	1	3.25E-03	4.60E+06			
	58	27	3.71E+02	4.15	Co	Co-58	2.38E-03	1	2.38E-03	6.12E+06			
	53	25	1.79E+02	0.09	Mn	Mn-53	1.15E-03	1	1.15E-03	1.17E+14			
	60	27	1.72E+01	99.00	Co	Co-60	1.10E-04	0.1	1.10E-03	1.66E+08			
	32	15	1.04E+02	15.54	P	P-32	6.66E-04	1	6.66E-04	1.23E+06			
	59	26	8.13E+01	2.70	Fe	Fe-59	5.21E-04	1	5.21E-04	3.84E+06			
	37	18	6.05E+01	1.26	Ar	Ar-37	3.88E-04	1	3.88E-04	3.02E+06			
	14	6	4.15E+01	4.47	C	C-14	2.66E-04	1	2.66E-04	1.80E+11			
	10	4	2.00E-01	3.81	Be	Be-10	1.28E-06	0.01	1.28E-04	4.77E+13			
	36	17	9.57E+00	1.20	Cl	Cl-36	6.14E-05	1	6.14E-05	9.51E+12			
	26	13	4.18E-02	11.69	Al	Al-26	2.68E-07	0.01	2.68E-05	2.26E+13			
	48	23	7.23E-01	0.20	V	V-48	4.63E-06	1	4.63E-06	1.38E+06			
	59	28	6.51E-01	8.50	Ni	Ni-59	4.18E-06	1	4.18E-06	2.40E+12			
	33	15	5.11E-01	4.30	P	P-33	3.27E-06	1	3.27E-06	2.19E+06			
	40	19	6.35E-03	0.61	K	K-40	4.07E-08	1	4.07E-08	3.94E+16			
	A/Z/ Isomers:												
	44	21	7.00E+04	0.89	Sc	Sc-44	4.49E-01	0.1	4.49E+00	2.11E+05			
	45	21	3.19E-01	1.54	Sc	Sc-45	2.05E-06	0.01	2.05E-04	3.26E-01			

Figure 6.13: Radionuclides generated in SH2 with respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, please see the Data analysis methodology paragraph).

Fig.6.13 shows the activity table of the beam dumper, SH2, composed of iron. The most significant long-lived radionuclides due to the high specific activity of the component are ⁴⁹V, ⁵⁴Mn, ⁵⁵Fe, ⁴⁴Ti, ³H, ³⁹Ar and short-lived radionuclides ⁵⁶Co, ⁴⁶Sc, ⁴⁴Sc. Although ⁴⁴Sc has a half-life of only 4 hours, it is still detected after a cooling time of one year because it is continuously produced by the decay of ⁴⁴Ti. ⁴⁴Ti undergoes electron capture with a half-life of 59.1 years, creating a secular equilibrium state between the two isotopes.

SH3.1	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)
	179	73	9.61E+06	0.13	Ta	2.51E+01	0.01	2.51E+03	5.74E+07
	173	71	2.10E+06	0.23	Lu	5.49E+00	0.01	5.49E+02	4.32E+07
	172	71	1.81E+06	0.27	Lu	4.74E+00	0.01	4.74E+02	5.79E+05
	172	72	1.79E+06	0.27	Hf	4.70E+00	0.01	4.70E+02	5.90E+07
	175	72	1.65E+05	0.16	Hf	4.32E-01	0.01	4.32E+01	6.05E+06
	183	75	4.20E+04	0.35	Re	1.10E-01	0.01	1.10E+01	6.05E+06
	3	1	3.34E+06	0.20	H	8.75E+00	1	8.75E+00	3.89E+08
	181	74	2.78E+06	0.11	W	7.28E+00	1	7.28E+00	1.05E+07
	184	75	2.15E+04	1.48	Re	5.62E-02	0.01	5.62E+00	3.06E+06
	185	74	2.01E+06	0.07	W	5.25E+00	1	5.25E+00	6.49E+06
	174	71	1.62E+04	3.10	Lu	4.24E-02	0.01	4.24E+00	1.04E+08
	182	73	1.52E+05	0.39	Ta	3.97E-01	0.1	3.97E+00	9.91E+06
	159	66	1.91E+03	4.68	Dy	5.01E-03	0.01	5.01E-01	1.25E+07
	157	65	9.91E+02	5.93	Tb	2.59E-03	0.01	2.59E-01	2.24E+09
	163	67	3.61E+02	1.44	Ho	9.44E-04	0.01	9.44E-02	1.44E+11
	169	70	3.48E+02	0.53	Yb	9.12E-04	0.01	9.12E-02	2.77E+06
	88	39	2.87E+02	9.52	Y	7.52E-04	0.01	7.52E-02	9.21E+06
	106	45	1.52E+02	27.42	Rh	3.97E-04	0.01	3.97E-02	3.01E+01
	102	45	1.36E+02	20.31	Rh	3.56E-04	0.01	3.56E-02	1.79E+07
	101	45	1.26E+02	32.72	Rh	3.30E-04	0.01	3.30E-02	1.04E+08
	83	37	1.03E+02	10.91	Rb	2.69E-04	0.01	2.69E-02	7.45E+06
	178	74	8.78E+01	0.13	W	2.30E-04	0.01	2.30E-02	1.87E+06
	168	69	7.25E+01	13.77	Tm	1.90E-04	0.01	1.90E-02	8.04E+06
	145	61	7.05E+01	42.00	Pm	1.84E-04	0.01	1.84E-02	5.59E+08
	151	64	6.54E+01	17.91	Gd	1.71E-04	0.01	1.71E-02	1.07E+07
	148	64	6.14E+01	31.32	Gd	1.61E-04	0.01	1.61E-02	2.24E+09
	145	62	5.01E+01	41.99	Sm	1.31E-04	0.01	1.31E-02	2.94E+07
	133	56	4.84E+01	57.15	Ba	1.27E-04	0.01	1.27E-02	3.33E+08
A/Z/ Isomers:									
	181	73	2.06E+06	0.11	Ta	5.39E+00	0.01	5.39E+02	2.10E-04
	172	71	1.79E+06	0.27	Lu	4.70E+00	0.01	4.70E+02	7.90E+01
	184	75	2.22E+04	1.52	Re	5.82E-02	0.01	5.82E+00	1.46E+07
	184	74	5.67E+03	1.52	W	1.48E-02	0.01	1.48E+00	8.33E-06
	174	71	8.85E+02	5.84	Lu	2.31E-03	0.01	2.31E-01	1.23E+07
	175	71	3.80E+02	0.16	Lu	9.94E-04	0.01	9.94E-02	9.80E-04
	178	72	2.87E+02	16.75	Hf	7.50E-04	0.01	7.50E-02	9.78E+08
	109	47	1.39E+02	27.22	Ag	3.63E-04	0.01	3.63E-02	3.98E+01
	102	45	1.16E+02	36.63	Rh	3.03E-04	0.01	3.03E-02	1.18E+08
	181	73	9.85E+01	2.45	Ta	2.58E-04	0.01	2.58E-02	2.10E-04
	178	73	8.78E+01	0.13	Ta	2.30E-04	0.01	2.30E-02	8.50E+03
	113	48	4.93E+01	50.89	Cd	1.29E-04	0.01	1.29E-02	4.45E+08

tungsten		
V(m3)	ro(g/cm3)	m(Kg)
1.98E-02	1.93E+01	3.82E+02
att. (Bq)		
2.79E+07	±/-	8.73E-02 %
att.sp. (Bq/g)		
7.31E+01		
Σ(att.sp/cf)		5.11E+03

Figure 6.14: Radionuclides generated in SH3.1 with respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, please see the Data analysis methodology paragraph).

Fig.6.14 shows a partial activity table of the profile monitor, SH3.1, composed of tungsten. Due to the high number of generated radionuclides, only those with an Att.sp/cf ratio greater than 1.00×10^{-02} are listed. However, the total activity and Σ att.sp/cf calculations include all generated radionuclides. The most significant long-lived radionuclides due to the high specific activity of the component are ^{179}Ta , ^{173}Lu , ^{172}Hf , ^3H , ^{181}W , ^{174}Lu and short-lived radionuclides ^{172}Lu , ^{175}Hf , ^{183}Re , ^{184}Re , ^{185}W , ^{182}Ta . Although ^{172}Lu has a short half-life, it is still present after one year of cooling because it is continuously produced by ^{172}Hf , reaching a state of secular equilibrium.

so147	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)				
	152	63	3.31E+04	1.51	Eu	Eu-152	4.16E-02	0.1	4.16E-01	4.27E+08			
	39	18	2.47E+03	1.67	Ar	Ar-39	3.10E-03	0.01	3.10E-01	8.46E+09			
	60	27	1.79E+04	2.15	Co	Co-60	2.25E-02	0.1	2.25E-01	1.66E+08			
	55	26	9.87E+04	0.79	Fe	Fe-55	1.24E-01	1	1.24E-01	8.66E+07			
	22	11	7.12E+03	3.77	Na	Na-22	8.93E-03	0.1	8.93E-02	8.21E+07			
	41	20	3.35E+02	0.27	Ca	Ca-41	4.21E-04	0.01	4.21E-02	3.14E+12			
	154	63	3.04E+03	5.45	Eu	Eu-154	3.82E-03	0.1	3.82E-02	2.71E+08			
	3	1	2.24E+04	1.83	H	H-3	2.81E-02	1	2.81E-02	3.89E+08			
	45	20	1.53E+04	1.27	Ca	Ca-45	1.92E-02	1	1.92E-02	1.40E+07			
	54	25	1.28E+03	5.75	Mn	Mn-54	1.60E-03	0.1	1.60E-02	2.70E+07			
	49	23	1.11E+02	22.25	V	V-49	1.40E-04	0.01	1.40E-02	2.85E+07			
	42	19	4.59E+00	99.00	K	K-42	5.76E-06	0.01	5.76E-04	4.45E+04			
	42	18	4.59E+00	99.00	Ar	Ar-42	5.76E-06	0.01	5.76E-04	1.04E+09			
	14	6	7.80E+01	2.14	C	C-14	9.80E-05	1	9.80E-05	1.80E+11			
	26	13	5.46E-01	2.00	Al	Al-26	6.85E-07	0.01	6.85E-05	2.26E+13			
	7	4	4.41E+01	4.53	Be	Be-7	5.53E-05	1	5.53E-05	4.60E+06			
	37	18	3.79E+01	1.36	Ar	Ar-37	4.76E-05	1	4.76E-05	3.02E+06			
	35	16	2.37E+01	15.59	S	S-35	2.98E-05	1	2.98E-05	7.55E+06			
	59	26	1.24E+01	5.33	Fe	Fe-59	1.55E-05	1	1.55E-05	3.84E+06			
	56	27	7.54E-01	70.35	Co	Co-56	9.47E-07	0.1	9.47E-06	6.67E+06			
	10	4	5.01E-02	5.01	Be	Be-10	6.29E-08	0.01	6.29E-06	4.77E+13			
	57	27	3.94E+00	99.00	Co	Co-57	4.94E-06	1	4.94E-06	2.35E+07			
	36	17	1.69E+00	2.11	Cl	Cl-36	2.12E-06	1	2.12E-06	9.51E+12			
	51	24	5.26E-02	13.76	Cr	Cr-51	6.60E-08	1	6.60E-08	2.39E+06			
	40	19	4.19E-02	0.19	K	K-40	5.25E-08	1	5.25E-08	3.94E+16			
	53	25	8.51E-03	8.28	Mn	Mn-53	1.07E-08	1	1.07E-08	1.17E+14			
	33	15	2.76E-03	39.78	P	P-33	3.46E-09	1	3.46E-09	2.19E+06			
	A/Z/Isomers:												
	45	21	2.91E-01	1.27	Sc	Sc-45	3.65E-07	0.01	3.65E-05	3.26E-01			

	concrete		
V(m3)	ro(g/cm3)	m(Kg)	
3.40E-01	2.34E+00	7.97E+02	
att. (Bq)			
2.02E+05 +/-		5.37E-01 %	
att.sp. (Bq/g)			
2.54E-01			
Σ(att.sp/cf)		1.32E+00	

Figure 6.15: Radionuclides generated in so147 with respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, please see the Data analysis methodology paragraph).

Fig.6.15 presents the activity table of so147, the only concrete block identified as non-removable. It is a section of floor located under BM2. The most significant long-lived radionuclides due to the high specific activity of the component are ¹⁵²Eu, ³⁹Ar, ⁶⁰Co, ⁵⁵Fe and ²²Na.

6.2.2. Removable components: simulations with maximum energy and maximum particle beam intensity.

BM1	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)		iron		
	55	26	1.86E+06	0.27	Fe	Fe-55	1.75E-01	1	1.75E-01	8.66E+07	V(m3)	ro(g/cm3)	m(Kg)
	49	23	1.38E+04	2.46	V	V-49	1.30E-03	0.01	1.30E-01	2.85E+07	1.35E+00	7.87E+00	1.07E+04
	54	25	1.11E+05	0.96	Mn	Mn-54	1.04E-02	0.1	1.04E-01	2.70E+07	att. (Bq)		
	44	22	1.47E+02	19.17	Ti	Ti-44	1.37E-05	0.01	1.37E-03	1.87E+09	2.00E+06 +/-		2.47E-01 %
	3	1	1.40E+04	3.54	H	H-3	1.32E-03	1	1.32E-03	3.89E+08	att.sp. (Bq/g)		
	39	18	2.08E+01	28.75	Ar	Ar-39	1.95E-06	0.01	1.95E-04	8.46E+09	1.88E-01		
	56	27	1.94E+02	6.04	Co	Co-56	1.82E-05	0.1	1.82E-04	6.67E+06	Σ(att.sp/cf)		4.11E-01
	44	21	1.47E+02	19.17	Sc	Sc-44	1.37E-05	0.1	1.37E-04	1.46E+04			
	46	21	1.08E+02	8.39	Sc	Sc-46	1.01E-05	0.1	1.01E-04	7.24E+06			
	59	26	2.30E+02	1.80	Fe	Fe-59	2.15E-05	1	2.15E-05	3.84E+06			
	57	27	1.02E+02	28.21	Co	Co-57	9.60E-06	1	9.60E-06	2.35E+07			
	45	20	5.90E+01	26.90	Ca	Ca-45	5.53E-06	1	5.53E-06	1.40E+07			
	41	20	1.42E-01	20.99	Ca	Ca-41	1.33E-08	0.01	1.33E-06	3.14E+12			
	51	24	7.56E+00	1.70	Cr	Cr-51	7.09E-07	1	7.09E-07	2.39E+06			
	35	16	1.10E+00	99.00	S	S-35	1.03E-07	1	1.03E-07	7.55E+06			
	53	25	9.91E-01	1.10	Mn	Mn-53	9.29E-08	1	9.29E-08	1.17E+14			
	14	6	8.74E-01	27.22	C	C-14	8.20E-08	1	8.20E-08	1.80E+11			
	58	27	5.62E-01	99.00	Co	Co-58	5.27E-08	1	5.27E-08	6.12E+06			
	7	4	3.44E-01	70.35	Be	Be-7	3.22E-08	1	3.22E-08	4.60E+06			
	37	18	1.16E-01	34.08	Ar	Ar-37	1.09E-08	1	1.09E-08	3.02E+06			
	10	4	2.75E-04	99.00	Be	Be-10	2.58E-11	0.01	2.58E-09	4.77E+13			
	36	17	8.28E-03	39.78	Cl	Cl-36	7.77E-10	1	7.77E-10	9.51E+12			
	48	23	1.80E-03	3.73	V	V-48	1.69E-10	1	1.69E-10	1.38E+06			
	33	15	9.20E-04	99.00	P	P-33	8.63E-11	1	8.63E-11	2.19E+06			
	A/Z/ Isomers:												
	44	21	1.46E+02	19.17	Sc	Sc-44	1.37E-05	0.1	1.37E-04	2.11E+05			
	45	21	1.12E-03	26.90	Sc	Sc-45	1.05E-10	0.01	1.05E-08	3.26E-01			

Figure 6.16: Radionuclides generated in BM1 with respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, please see the Data analysis methodology paragraph).

BM1int	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)		copper		
	60	27	2.87E+03	7.37	Co	Co-60	2.20E-03	0.1	2.20E-02	1.66E+08	V(m3)	ro(g/cm3)	m(Kg)
	49	23	5.57E+01	39.78	V	V-49	4.27E-05	0.01	4.27E-03	2.85E+07	1.46E-01	8.96E+00	1.30E+03
	54	25	4.18E+02	15.26	Mn	Mn-54	3.20E-04	0.1	3.20E-03	2.70E+07	att. (Bq)		
	63	28	2.90E+03	3.58	Ni	Ni-63	2.22E-03	1	2.22E-03	3.19E+09	1.19E+04 +/-		3.84E+00 %
	3	1	2.30E+03	8.23	H	H-3	1.76E-03	1	1.76E-03	3.89E+08	att.sp. (Bq/g)		
	57	27	1.60E+03	7.84	Co	Co-57	1.23E-03	1	1.23E-03	2.35E+07	9.13E-03		
	55	26	1.49E+03	12.20	Fe	Fe-55	1.14E-03	1	1.14E-03	8.66E+07	Σ(att.sp/cf)		3.68E-02
	65	30	7.08E+01	36.24	Zn	Zn-65	5.43E-05	0.1	5.43E-04	2.11E+07			
	56	27	3.77E+01	12.87	Co	Co-56	2.89E-05	0.1	2.89E-04	6.67E+06			
	58	27	1.59E+02	6.48	Co	Co-58	1.22E-04	1	1.22E-04	6.12E+06			
	45	20	4.22E+00	99.00	Ca	Ca-45	3.23E-06	1	3.23E-06	1.40E+07			
	59	28	1.92E+00	5.63	Ni	Ni-59	1.47E-06	1	1.47E-06	2.40E+12			
	59	26	3.38E-01	43.81	Fe	Fe-59	2.59E-07	1	2.59E-07	3.84E+06			
	51	24	5.15E-02	20.62	Cr	Cr-51	3.95E-08	1	3.95E-08	2.39E+06			
	60	26	3.17E-04	70.35	Fe	Fe-60	2.43E-10	0.01	2.43E-08	8.27E+13			
	10	4	2.75E-04	99.00	Be	Be-10	2.11E-10	0.01	2.11E-08	4.77E+13			
	53	25	4.67E-03	14.43	Mn	Mn-53	3.58E-09	1	3.58E-09	1.17E+14			
	A/Z/ Isomers:												
	45	21	8.01E-05	99.00	Sc	Sc-45	6.14E-11	0.01	6.14E-09	3.26E-01			
	60	27	3.17E-04	70.35	Co	Co-60	2.43E-10	0.1	2.43E-09	6.28E+02			

Figure 6.17: Radionuclides generated in BM1int with respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, please see the Data analysis methodology paragraph).

Fig.6.16-6.17 show the activity tables of the BM1-BM1int magnet, composed of iron and copper. The same radionuclides generated in BM2, BM2int and iron/copper components are also found here, but with lower specific activities. This reduction allows the magnet to be cleared for removal from the structure.

gantry2w	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)		concrete	
	22	11	2.81E+05	0.81	Na Na-22	2.89E-02	0.1	2.89E-01	8.21E+07	V(m3)	ro(g/cm3)	m(Kg)
	39	18	1.59E+04	1.01	Ar Ar-39	1.63E-03	0.01	1.63E-01	8.46E+09	4.16E+00	2.34E+00	9.73E+03
	152	63	1.50E+05	1.10	Eu Eu-152	1.54E-02	0.1	1.54E-01	4.27E+08	att. (Bq)		
	3	1	1.15E+06	0.41	H H-3	1.18E-01	1	1.18E-01	3.89E+08	2.32E+06 +/-		2.90E-01 %
	60	27	7.95E+04	1.63	Co Co-60	8.18E-03	0.1	8.18E-02	1.66E+08	att.sp. (Bq/g)		
	49	23	5.49E+03	4.54	V V-49	5.64E-04	0.01	5.64E-02	2.85E+07	2.39E-01		
	55	26	5.17E+05	0.57	Fe Fe-55	5.32E-02	1	5.32E-02	8.66E+07	Z(att.sp/cf)		9.86E-01
	54	25	2.87E+04	2.16	Mn Mn-54	2.95E-03	0.1	2.95E-02	2.70E+07			
	41	20	1.55E+03	0.18	Ca Ca-41	1.59E-04	0.01	1.59E-02	3.14E+12			
	154	63	1.34E+04	3.91	Eu Eu-154	1.37E-03	0.1	1.37E-02	2.71E+08			
	35	16	7.81E+02	3.32	S S-35	8.03E-05	1	8.03E-05	7.55E+06			
	45	20	7.28E+04	0.81	Ca Ca-45	7.49E-03	1	7.49E-03	1.40E+07			
	44	22	4.56E+01	40.64	Ti Ti-44	4.69E-06	0.01	4.69E-04	1.87E+09			
	32	14	3.09E+01	32.26	Si Si-32	3.18E-06	0.01	3.18E-04	4.95E+09			
	42	18	3.06E+01	56.41	Ar Ar-42	3.14E-06	0.01	3.14E-04	1.04E+09			
	42	19	3.06E+01	56.41	K K-42	3.14E-06	0.01	3.14E-04	4.45E+04			
	7	4	2.43E+03	0.81	Be Be-7	2.50E-04	1	2.50E-04	4.60E+06			
	26	13	1.90E+01	0.56	Al Al-26	1.96E-06	0.01	1.96E-04	2.26E+13			
	14	6	1.86E+03	0.61	C C-14	1.91E-04	1	1.91E-04	1.80E+11			
	44	21	4.56E+01	40.64	Sc Sc-44	4.69E-06	0.1	4.69E-05	1.46E+04			
	46	21	3.68E+01	15.83	Sc Sc-46	3.79E-06	0.1	3.79E-05	7.24E+06			
	37	18	2.98E+02	0.72	Ar Ar-37	3.06E-05	1	3.06E-05	3.02E+06			
	10	4	2.89E+00	1.01	Be Be-10	2.97E-07	0.01	2.97E-05	4.77E+13			
	56	27	1.26E+01	28.60	Co Co-56	1.29E-06	0.1	1.29E-05	6.67E+06			
	59	26	5.81E+01	3.88	Fe Fe-59	5.97E-06	1	5.97E-06	3.84E+06			
	57	27	5.25E+01	38.44	Co Co-57	5.40E-06	1	5.40E-06	2.35E+07			
	32	15	3.09E+01	32.26	P P-32	3.18E-06	1	3.18E-06	1.23E+06			
	36	17	1.72E+01	0.85	Cl Cl-36	1.77E-06	1	1.77E-06	9.51E+12			
	51	24	2.72E+00	2.66	Cr Cr-51	2.80E-07	1	2.80E-07	2.39E+06			
	58	27	6.24E-01	99.00	Co Co-58	6.41E-08	1	6.41E-08	6.12E+06			
	33	15	3.36E-01	6.18	P P-33	3.46E-08	1	3.46E-08	2.19E+06			
	53	25	3.25E-01	2.10	Mn Mn-53	3.34E-08	1	3.34E-08	1.17E+14			
	40	19	1.96E-01	0.14	K K-40	2.02E-08	1	2.02E-08	3.94E+16			
	48	23	6.61E-04	6.46	V V-48	6.79E-11	1	6.79E-11	1.38E+06			
A/Z/Isomers:												
	44	21	4.54E+01	40.64	Sc Sc-44	4.67E-06	0.1	4.67E-05	2.11E+05			
	45	21	1.38E+00	0.81	Sc Sc-45	1.42E-07	0.01	1.42E-05	3.26E-01			

Figure 6.18: Radionuclides generated in gantry2w with respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, please see the Data analysis methodology paragraph).

Fig.6.18 shows the concrete block of the wall that separates the synchrotron from the treatment room and allows the beam to pass through (see Fig. 6.6). The same radionuclides found in sol147 and other concrete blocks are present here, but with lower specific activities.

6.2.3. Simulations with energy spectrum and maximum particle beam intensity

The same simulations were repeated using the energy spectrum employed in 2023 in the existing synchrotron with the proton beam. The OPEN CARD was used to introduce the

energy spectrum into the input. Image 6.19 shows the specific activity of the facility at beam level. The specific activity of the ceiling and floor is not shown, as these two do not exhibit activation levels within the reported range.

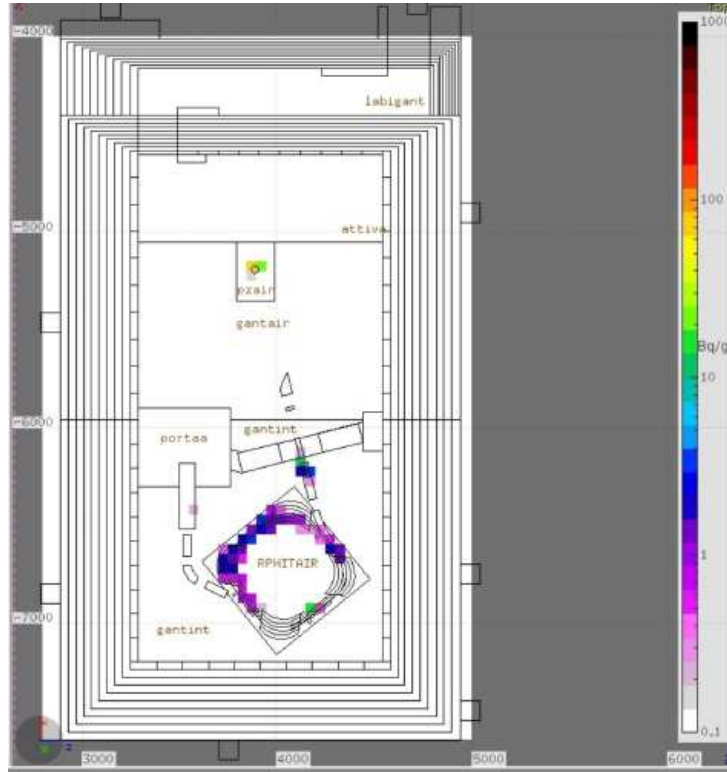


Figure 6.19: Visualization of the USERBIN-actomass in the x-z plane with $y=-200$, for a proton beam with energy spectrum.

Once the RESNUCLEI files were obtained, all files were analyzed using tables identical to those generated with the maximum energy beam.

6.2.4. Results

Figure 6.20 shows a comparison between the components exposed to the maximum energy beam that remain non-removable after one year of cooling time and those exposed to the energy spectrum, highlighting their corresponding materials and volumes.

Based on this comparison, the total volumes of each material to be disposed of as radioactive waste were calculated to estimate future decommissioning costs (Fig. 6.21).

In figure 6.20, non-removable components are highlighted in red, while removable components are highlighted in green.

max_E	E_spect.	Material	Volume (m ³)
linac	linac	iron	2.18E+00
linrcc1	linrcc2	iron	1.49E-01
RCCHEBT	RCCHEBT	iron	1.52E-01
SH1	SH1	copper	1.98E-02
SH2	SH2	iron	1.98E-02
SH3.1	SH3.1	tungsten	1.98E-02
SH3.2	SH3.2	tungsten	1.98E-02
MAGHEBT	MAGHEBT	iron	2.07E-01
RCCBM3	RCCBM3	iron	6.10E-02
RCC32	RCC32	iron	1.54E-01
RCCBM2	RCCBM2	iron	6.10E-02
ESISA1	ESISA1	iron	1.06E-01
RCC21	RCC21	iron	1.86E-02
RCC14	RCC14	iron	1.86E-02
RCCBM1	RCCBM1	iron	6.10E-02
ESDSA4	ESDSA4	iron	1.24E-01
RCCBM4	RCCBM4	iron	6.10E-02
BM2	BM2	iron	1.35E+00
BM2int	BM2int	copper	1.46E-01
BM3	BM3	iron	1.35E+00
BM3int	BM3int	copper	1.46E-01
BM4	BM4	iron	1.35E+00
BM4int	BM4int	copper	1.46E-01
nozzle	nozzle	iron	1.32E-01
so147	so147	concrete	3.40E-01

Figure 6.20: Comparison of the Hitachi facility components that remain non-removable with maximum energy and with the energy spectrum.

Volume (m ³)		
Material	max_E	E_spect.
iron	7.56E+00	5.04E+00
copper	4.56E-01	4.56E-01
tungsten	3.96E-02	3.96E-02
concrete	3.40E-01	\\

Figure 6.21: Summation of non-removable volumes, classified by material and case type.

Finally, the radionuclides generated in the removable components, for which the structure

will need to request authorization for release, include ^{26}Al , ^{37}Ar , ^{39}Ar , ^{42}Ar , ^{10}Be , ^7Be , ^{14}C , ^{41}Ca , ^{45}Ca , ^{47}Ca , ^{36}Cl , ^{56}Co , ^{57}Co , ^{58}Co , ^{60}Co , ^{51}Cr , ^{152}Eu , ^{154}Eu , ^{55}Fe , ^{59}Fe , ^{60}Fe , ^{152}Gd , ^3H , ^{172}Hf , ^{174}Hf , ^{175}Hf , ^{181}Hf , ^{40}K , ^{42}K , ^{171}Lu , ^{172}Lu , ^{173}Lu , ^{174}Lu , ^{175}Lu , ^{52}Mn , ^{53}Mn , ^{54}Mn , ^{22}Na , ^{59}Ni , ^{63}Ni , ^{32}P , ^{33}P , ^{187}Re , ^{35}S , ^{44}Sc , ^{45}Sc , ^{46}Sc , ^{47}Sc , ^{177}Ta , ^{178}Ta , ^{179}Ta , ^{180}Ta , ^{181}Ta , ^{182}Ta , ^{183}Ta , ^{44}Ti , ^{48}V , ^{49}V , ^{178}W , ^{181}W , ^{183}W , ^{185}W , ^{169}Yb , ^{171}Yb and ^{65}Zn .

7 | FLUKA simulation of the BNCT facility

This chapter presents the results obtained from Monte Carlo simulations, performed with FLUKA, on the activation of the BNCT facility at CNAO. The proposed BNCT facility, developed by TAE, is based on TANDEM accelerator technology. It uses a proton beam with a variable energy of up to 2.5 MeV and a variable current of up to 15 mA (with an operating current of 10 mA). Neutrons are produced through the reaction (p,n) on a thin (100 μm) Li-7 target, which is deposited on a metallic substrate. From the TANDEM accelerator, the beam is transported along a dedicated beamline into the High Energy Beam Line (HEBL) area, where bending magnets direct it toward two treatment rooms. A separate beamline extends toward the beam dump. Between the HEBL and each treatment room, a Beam Shaping Assembly (BSA) is positioned. Each BSA ends at a beam port facing the corresponding treatment room. The beam transport lines terminate at the target inside the BSA. When the proton beam strikes the target, neutrons are generated through the (p,n) reactions on Li-7. These neutrons are then moderated and collimated within the BSA before passing through the beam port into the treatment room. The machine layout is shown in Figure 7.1.

7.1. FLUKA geometry

This section describes the general layout of the BNCT facility used in the Monte Carlo simulations. In FLAIR, the main structures of the facility have been implemented, including the accelerator room, HEBL room and two treatment rooms (see Fig. 7.2). The goal was to model the main elements of the facility as accurately as possible. The choice of materials is important because even small differences in composition can affect the radionuclides produced after irradiation. If a material is not specified in this section, the standard FLUKA material library was used. The building's walls consist of a 20 cm first layer of borated concrete (orange in Fig. 7.2), followed by 2 to 4 meters of Portland concrete (light blue in Fig. 7.2). The doors, hatches, and the materials surrounding the BSA

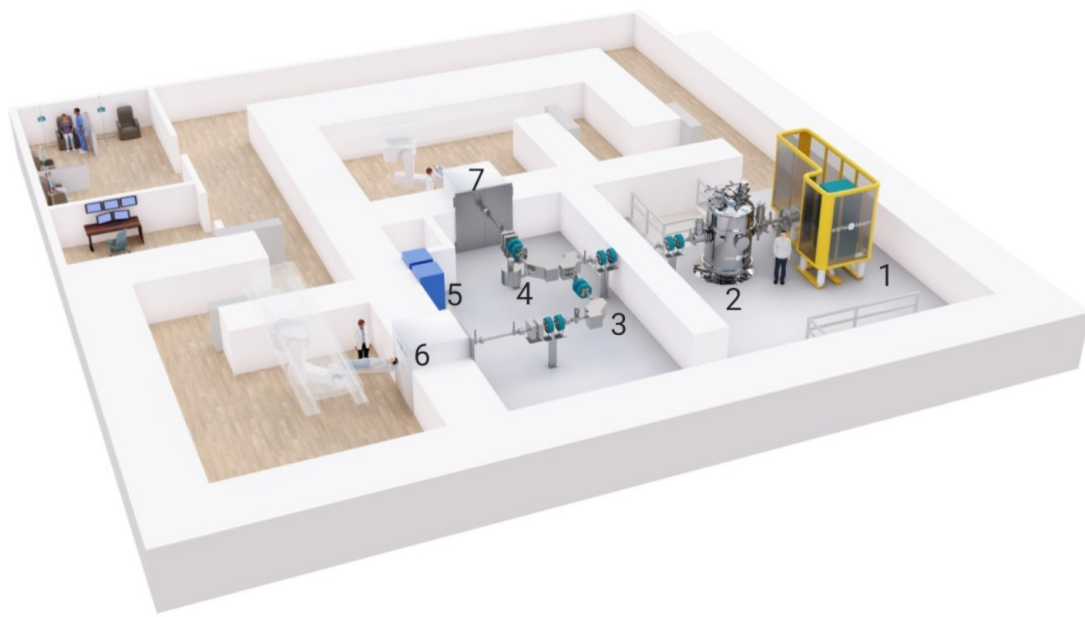


Figure 7.1: BNCT layout with beam lines. The figure illustrates the main components of the system: 1) Proton source; 2) TANDEM accelerator; 3) and 4) Bending magnets directing the beam to the two treatment rooms; 5) Beam dump; 6) and 7) Beam Shaping Assemblies (BSA), which contain the lithium targets where the proton beam is directed for neutron production [1].



Figure 7.2: 3D representation of the BNCT facility, cutting plane x-z at $y=0$, highlighting the rooms that compose it.

are made of barite concrete with an additional concentration of boron (dark grey in Fig. 7.2). The composition of these materials is detailed in Tables 7.1–7.3. Borated concrete is used to absorb thermal neutrons, while barite concrete provides radiation shielding against both gamma rays and neutrons.

Large-volume regions (e.g. walls, floor) are further divided into smaller blocks with an area of about 1 square meters and a variable thicknesses between 0.20 and 1 meters. This modification of the geometry provides more realistic activation data and facilitates material transport during decommissioning. The more uniform regions are divided using a Fortran77 code, which generated input files later integrated into the geometry.

Portland concrete ($\rho=2.34 \text{ g/cm}^3$)

Element	Weight fraction
Oxygen	0.529102
Silicon	0.337018
Calcium	0.044
Aluminum	0.0338713
Sodium	0.016
Iron	0.014
Potassiu	0.013
Hydrogen	0.01
Magnesi	0.002
Carbon	0.001
Cobalt	0.000008
Europium	0.0000007

Table 7.1: Portland concrete composition.

Borated concrete ($\rho=2.3 \text{ g/cm}^3$)

Element	Weight fraction
Oxygen	0.529107
Silicon	0.337021
Calcium	0.044
Aluminum	0.033872
Iron	0.014
Potassiu	0.013
Hydrogen	0.01
Boron	0.01
Sodium	0.006
Magnesi	0.002
Carbon	0.001

Table 7.2: Borated concrete composition.

Barite concrete with Boron (baritbor)($\rho=3.2 \text{ g/cm}^3$)

Element	Weight fraction
Barium	0.407
Oxygen	0.3489
Sulfur	0.0963
Calcium	0.0846
Silicon	0.0176
Iron	0.0104
Boron	0.0098
Hydrogen	0.0085
Aluminum	0.0061
Magnesium	0.0022
Sodium	0.0011

Table 7.3: Barite concrete with boron composition.

Accelerator room

The TANDEM accelerator is not included in the geometry, as these simulations use the neutrons produced at the lithium target as primary particles, being the main contributors to activation processes.

HEBL room

Figure 7.3 shows an image of the HEBL room. The HEBL is schematized with six magnets and one dump. Magnets 1 and 2 are modeled as simple rectangular parallelepipeds made of copper, while magnets 3, 4, 5 and 6 consist of two hollow cylinders with a copper inner section and an iron outer section. The dump is modeled as a rectangular parallelepiped RPP made of copper.

Treatment rooms

Figure 7.4 shows the FLUKA geometry of Treatment Room 1. Treatment Room 2 has the same features but is mirrored.

The solid lithium target is modeled as a small cylindrical body (RCC) with a height of

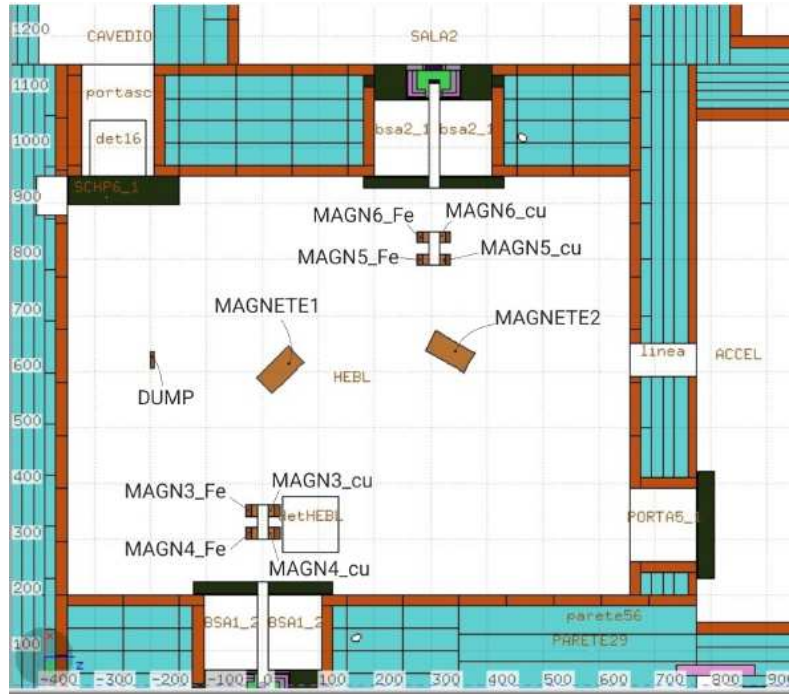


Figure 7.3: 2D representation of the HEBT room in the x-z plane at $y=0$.



Figure 7.4: 3D representation of Treatment Room 1, cutting the y-z plane at $x=-500$.

0.01 cm. Directly after the target, the Beam Shaping Assembly (BSA) begins. Surrounding the vacuum chamber and the lithium target, the BSA includes various components such as the moderator, reflector and filters. The detailed geometry of the BSA is not included here for privacy reasons. Infact, in the results section, non-removable BSA components are grouped into a region called BSA1 (or BSA2), made of an unspecified material labeled as BSA.

At the center of the room, the patient bed is modeled. It consists of a carbon fiber surface with a stainless steel frame, which is considered to be coated with a 3 mm layer of borated plastic to absorb neutrons. To allow movement within the room, the bed is mounted on a stainless steel rail system.

The compositions of Borated plastic is detailed in Table 7.4.

Borated plastic (Plastbor) ($\rho=1.127 \text{ g/cm}^3$)

Element	Weight fraction
Carbon	0.7255
Hydrogen	0.1013
Oxygen	0.0523
Boron	0.05
Nitrogen	0.0351
Calcium	0.0184
Fluorine	0.0174

Table 7.4: Borated plastic composition.

Beam losses

The FLUKA source definition is implemented using a Fortran77 user routine (SOURCE.f). This routine defines all loss positions, their average percentages and energy of primary paticle (indicated in Tab.7.5). For each primary particle, a random number between 0 and 1 is selected. Based on this value, the routine determines the loss location and sets the starting position, direction and energy of the particle.

Loss location	Loss percentage %	Energy [MeV]
BSA1	49.00	1
BSA2	49.00	1
Dump	0.33	0.5
Point1	0.33	0.5
Point2	0.33	0.5

Table 7.5: Neutron beam losses of BNCT facility at CNAO.

As previously mentioned, these simulations use the neutron beam as the primary source. Neutrons are generated from proton interactions with lithium in BSA1-BSA2 and from proton interactions with copper at beam loss points in the HEBT room.

7.2. FLUKA activation analysis

The following subsections present the parameters implemented in the simulations with the primary and transport cards, the scoring cards used, and an explanation of the data analysis methodology.

Primary and Transport CARDS

- The simulations were performed using fixed energies based on the positions of the primary neutrons, as shown in figure 7.5.
- The irradiation profile was introduced using the IRRPROFI card, considering a current of 10^{13} p/s. The irradiation duration was set to 30 years, which represents the typical lifetime of an accelerator.
- A post-irradiation cooling time of 1 year was applied.

Scoring CARDS

- USERBIN-actomass cards were used to generate graphical representations of the specific activity [Bq/g] in selected spatial regions.
- RESNUCLEI cards were implemented to evaluate activation within specific regions and to identify the radionuclides produced.

Data analysis methodology

In the following figures, building maps with a color scale representing Actomass are shown. From these images, the hottest regions, meaning those with significant specific activity, were identified.

A minimum color scale value of 0.1 Bq/g was used, as the analysis showed that no non-removable element had a specific activity below this threshold. For regions with specific activity greater than 0.1 Bq/g, RESNUCLEI analysis was performed. The data obtained from RESNUCLEI are reported and analyzed in numerous tables, which are available at the CNAO radiation protection office but are not all included here due to their large number. These tables contain:

- The inventory of radionuclides present after one year of cooling time, including their activity (Bq) and associated percentage error.
- The material composition of the region analyzed, with density (g/cm^3), mass (kg), and volume (m^3).
- The total activity (Bq) and percentage error for the entire region.
- Calculation of specific activity (Bq/g) for each radionuclide.
- The assignment of values from Table 1b of Decreto Legislativo n.101 of July 31th, 2020, "Livelli di allontanamento per i materiali solidi", implemented with the CNAO authorization values for solid material clearance. For radionuclides not listed in these tables, a conservative clearance level of 0.01 was applied. In the following sections, radionuclides not included in these lists, subject to the most restrictive limit, are labeled as "unlisted" and highlighted in yellow.
- The calculation of the ratio between specific activity and the coefficients from the table.
- The half life ($T_{1/2}$) for each radionuclide.
- The summation of the specific activity-to-coefficient ratios ($\Sigma Att.sp./cf$).

According to Allegato 1 of Decreto Legislativo 101/2020, materials with a summation ratio greater than 1 cannot be cleared.

Materials with a ratio below 1 may be cleared if the Foundation has authorization to remove the present radionuclides. To facilitate this process, a list of all radionuclides formed over 30 years that are present in removable blocks is provided in the results.

The assessments presented here are based on these assumptions and will need to be reviewed following decommissioning authorization and an evaluation of the actual workload

at the end of the facility's operational life. If some components are classified as non-removable in these simulations only because they contain unlisted radionuclides, it may be possible, at the time of decommissioning, to request a less restrictive clearance level.

The following sections present the data analyzed using this methodology, considering initial neutron energies of either 1 MeV or 0.5 MeV, depending on the emission point, and a beam current of 10^{13} p/s.

Both paragraphs begin with representative images of specific activity distributions, obtained from the USERBIN-actomass card.

Paragraph 7.2.1 provides the data analysis for several non-removable components of Treatment Room 1, including the lithium target of the BSA, the dump, synchrotron magnet 2, the outer iron casing of magnet 4 (MagnFe4), a borated concrete block surrounding BSA1 (BSA1BOR1), the rotating structure of the treatment bed (S1LETROT), the plastic shielding of the bed (PLASTBOR), a borated concrete wall block (A0017) and a concrete wall block (S0027).

Paragraph 7.2.2 presents the data analysis for removable components, including synchrotron magnet 1, an additional borated concrete wall block (A0002), and another concrete wall block (R0006).

Only the components of Treatment Room 1 are analyzed in these sections, as Treatment Room 2 has an identical but mirrored layout, leading to the same data.

Additionally, the analysis of the BSA components is not included due to privacy reasons. Instead, in the results section, the total volume of non-removable BSA components will be reported as a single material entity labeled "BSA".

7.2.1. Non-removable components

Images 7.5-7.6-7.7-7.8 show the specific activity of the facility at beam level, floor level, ceiling level and a lateral section.



Figure 7.5: Visualization of the USERBIN-actomass in the x-z plane with $y=0$.

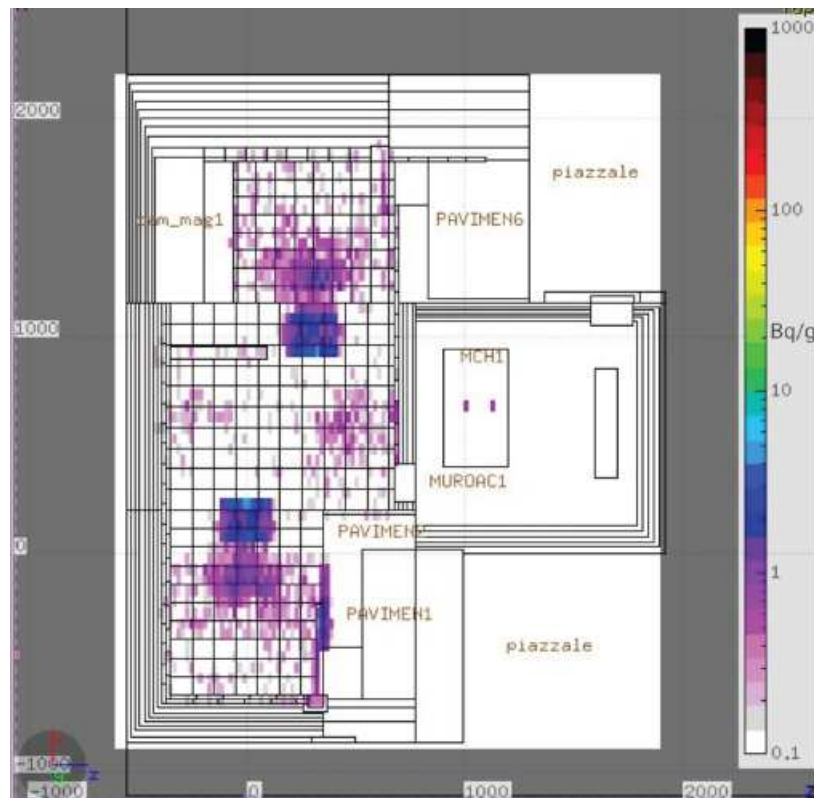


Figure 7.6: Visualization of the USERBIN-actomass in the x-z plane with $y=-155$.



Figure 7.7: Visualization of the USERBIN-actomass in the x-z plane with $y=450$.



Figure 7.8: Visualization of the USERBIN-actomass in the x-y plane with $z=0$.

Figures 7.5-7.6-7.7-7.8 show that the most activated areas are those around the BSA and the walls in the beam direction. The following figures provide a detailed view of the specific activity of radionuclides generated after 30 years of irradiation. Tables are included for the most significant regions, ensuring that at least one table is provided for each type of

material in the facility.

Li_BSA1	A	Z	ATT(Bq)	err%	element		ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)
	3	1	6.42E+08	0.4039	H	H-3	4.24E+08	1	4.24E+08	3.89E+08

	lithium		
V(m3)	ro(g/cm3)	m(Kg)	
2.84E-06	2.7	1.51E-03	
att. (Bq)			
6.42E+08	+/-	4.04E-01	%
att.sp. (Bq/g)		4.24E+08	
Σ att.sp/cf		4.24E+08	

Figure 7.9: Radionuclides generated in the Li target of BSA1 (Li_bsa1) with respective analysis.

Fig.7.9 shows the activity table of the Li target of treatment room 1, composed of lithium. The only long-lived radionuclide still present after one year of cooling time is ³H. It has a high specific activity, preventing the removal of the target.

DUMP	A	Z	ATT(Bq)	err%	element		ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)
	63	28	2.40E+06	3.77	Ni	Ni-63	1.79E+02	1	1.79E+02	3.19E+09

	copper		
V(m3)	ro(g/cm3)	m(Kg)	
1.50E-03	8.96	1.34E+01	
att. (Bq)			
2.40E+06	+/-	3.77E+00	%
att.sp. (Bq/g)		1.79E+02	
Σ att.sp/cf		1.79E+02	

Figure 7.10: Radionuclides generated in the DUMP with respective analysis.

Fig.7.10 shows the activity table of DUMP, composed of copper. The only long-lived radionuclide still present after one year of cooling time is ⁶³Ni. It has a high specific activity, preventing its removal.

MAGNETE2	A	Z	ATT(Bq)	err%	element		ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)
	63	28	1.76E+07	1.48	Ni	Ni-63	1.54E+01	1	1.54E+01	3.19E+09

	copper		
V(m3)	ro(g/cm3)	m(Kg)	
1.28E-01	8.96	1.15E+03	
att. (Bq)			
1.76E+07 +/-		1.48E+00	%
att.sp. (Bq/g)		1.54E+01	
Σ att.sp/cf		1.54E+01	

Figure 7.11: Radionuclides generated in the MAGNETE2 with respective analysis.

Fig.7.11 shows the activity table of MAGNETE2, composed of copper. The only long-lived radionuclide still present after one year of cooling time is ⁶³Ni. It has a high specific activity, preventing its removal.

MAGN4_Fe	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)		iron	
	55	26	8.56E+06	4.3	Fe	Fe-55	3.46E+01	1	3.46E+01	8.66E+07	V(m3)	ro(g/cm3)
	59	26	2.37E+03	16.9	Fe	Fe-59	9.56E-03	1	9.56E-03	3.84E+06	m(Kg)	
											3.14E-02	7.874
											att. (Bq)	
											8.56E+06 +/-	4.30E+00 %
											att.sp. (Bq/g)	3.46E+01
											Σ att.sp/cf	3.46E+01

Figure 7.12: Radionuclides generated in the MAGN4_Fe with respective analysis

Fig.7.12 shows the activity table of MAGN4_Fe, the outer part of Magnet 4, made of iron. It has a high specific activity, preventing its removal. The long-lived radionuclide produced and still present in this element is ⁵⁵Fe and a short-live radionuclide ⁵⁹Fe.

BSA1BOR1	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)		baritbor	
	133	56	1.89E+07	3.13	Ba	Ba-133	8.59E+00	0.01	8.59E+02	3.33E+08	V(m3)	ro(g/cm3)
	55	26	1.27E+06	11.01	Fe	Fe-55	5.78E-01	1	5.78E-01	8.66E+07	m(Kg)	
	41	20	1.26E+04	1.96	Ca	Ca-41	5.73E-03	0.01	5.73E-01	3.14E+12	6.89E-01	3.2
	45	20	5.99E+05	9.07	Ca	Ca-45	2.72E-01	1	2.72E-01	1.40E+07	att. (Bq)	
	3	1	1.08E+05	41.88	H	H-3	4.89E-02	1	4.89E-02	3.89E+08	2.10E+07 +/-	2.86E+00 %
	35	16	1.06E+05	9.59	S	S-35	4.80E-02	1	4.80E-02	7.55E+04	att.sp. (Bq/g)	9.54E+00
	14	6	5.83E+02	34.08	C	C-14	2.64E-04	1	2.64E-04	1.80E+11	Σ att.sp/cf	8.60E+02
	37	18	3.18E+02	21.01	Ar	Ar-37	1.44E-04	1	1.44E-04	3.02E+06		
	10	4	1.93E+00	36.63	Be	Be-10	8.75E-07	0.01	8.75E-05	4.77E+13		
	59	26	1.35E+02	70.35	Fe	Fe-59	6.13E-05	1	6.13E-05	3.84E+06		
	33	15	9.20E-01	99.00	P	P-33	4.17E-07	1	4.17E-07	2.19E+06		
	131	55	1.29E-01	1.83	Cs	Cs-131	5.84E-08	1	5.84E-08	8.37E+05		
	131	56	2.06E-02	1.83	Ba	Ba-131	9.33E-09	1	9.33E-09	9.94E+05		
	A/Z/ Isomers:											
	45	21	1.14E+01	9.07	Sc	Sc-45	5.16E-06	0.01	5.16E-04	3.26E-01		

Figure 7.13: Radionuclides generated in the BSA1BOR1 with respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, please see the Data analysis methodology paragraph).

Fig.7.13 shows the activity table of BSA1BOR1, a piece of borated concrete surrounding BSA1. The most significant long-lived radionuclides due to the high specific activity of the component are ¹³³Ba, ⁵⁵Fe, ⁴¹Ca and and a short-lived radionuclide ⁴⁵Ca .

S1LETROT	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)		stainless	
	55	26	6.58E+08	0.46	Fe	Fe-55	1.06E+02	1	1.06E+02	8.66E+07	V(m3)	ro(g/cm3)
	63	28	9.14E+07	0.68	Ni	Ni-63	1.48E+01	1	1.48E+01	3.19E+09	m(Kg)	
	59	28	6.60E+05	0.28	Ni	Ni-59	1.07E-01	1	1.07E-01	2.40E+12	7.93E-01	3.2
	59	26	1.48E+05	2.25	Fe	Fe-59	2.39E-02	1	2.39E-02	3.84E+06	att. (Bq)	
	51	24	1.14E+05	0.40	Cr	Cr-51	1.85E-02	1	1.85E-02	2.39E+06	7.50E+08 +/-	2.86E+00 %
	35	16	2.21E+03	70.35	S	S-35	3.57E-04	1	3.57E-04	7.55E+04	att.sp. (Bq/g)	1.21E+02
	32	15	5.47E-02	8.55	P	P-32	8.84E-09	1	8.84E-09	1.23E+06	Σ att.sp/cf	1.21E+02

Figure 7.14: Radionuclides generated in the S1LETROT with respective analysis.

Fig.7.14 shows the activity table of S1LETROT, the support structure of the rotating arm used to position the patient's bed in Treatment Room 1, made of stainless steel. The

most significant long-lived radionuclides due to the high specific activity of the component are ^{55}Fe , ^{63}Ni and ^{59}Ni .

PLASTBOR	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)				
	14	6	4.69E+04	4.48	C	C-14	1.63E+00	1	1.63E+00	1.80E+11	V(m3)	ro(g/cm3)	m(Kg)
	3	1	1.54E+04	99.00	H	H-3	5.35E-01	1	5.35E-01	3.89E+08	2.56E-02	1.127	2.88E+01
	45	20	1.26E+04	57.15	Ca	Ca-45	4.39E-01	1	4.39E-01	1.40E+07	att. (Bq)		
	41	20	8.79E+01	22.75	Ca	Ca-41	3.05E-03	0.01	3.05E-01	3.14E+12	7.50E+04 +/-		2.86E+00 %
	A/Z/ Isomers:										att.sp. (Bq/g)		2.60E+00
	45	21	2.40E-01	57.15	Sc	Sc-45	8.34E-06	0.01	8.34E-04	3.26E-01	Σ att.sp/cf		2.91E+00

Figure 7.15: Radionuclides generated in the PLASTBOR with respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, please see the Data analysis methodology paragraph).

Fig.7.15 shows the activity table of PLASTBOR, the plastic coating of the rotating arm used to position the patient's bed in Treatment Room 1, made of borated plastic (Plastbor). The most significant long-lived radionuclides due to the high specific activity of the component are ^{14}C , ^3H , ^{45}Ca and ^{41}Ca .

A0017	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)				
	55	26	4.35E+05	18.36	Fe	Fe-55	8.61E-01	1	8.61E-01	8.66E+07	V(m3)	ro(g/cm3)	m(Kg)
	41	20	1.16E+03	6.70	Ca	Ca-41	2.29E-03	0.01	2.29E-01	3.14E+12	2.20E-01	1.127	5.05E+02
	45	20	3.37E+04	34.08	Ca	Ca-45	6.68E-02	1	6.68E-02	1.40E+07	att. (Bq)		
	3	1	3.08E+04	70.35	H	H-3	6.10E-02	1	6.10E-02	3.89E+08	5.01E+05 +/-		1.76E+01 %
	59	26	2.70E+02	49.24	Fe	Fe-59	5.35E-04	1	5.35E-04	3.84E+06	att.sp. (Bq/g)		9.92E-01
	14	6	2.19E+02	74.23	C	C-14	4.33E-04	1	4.33E-04	1.80E+11	Σ att.sp/cf		1.22E+00
	37	18	2.90E+01	70.35	Ar	Ar-37	5.73E-05	1	5.73E-05	3.02E+06			
	36	17	1.38E+00	99.00	Cl	Cl-36	2.73E-06	1	2.73E-06	9.51E+12			
	40	19	1.22E-01	4.38	K	K-40	2.41E-07	1	2.41E-07	3.94E+16			
	A/Z/ Isomers:												
	45	21	6.41E-01	34.08	Sc	Sc-45	1.27E-06	0.01	1.27E-04	3.26E-01			

Figure 7.16: Radionuclides generated in the A0017 with respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, please see the Data analysis methodology paragraph).

Fig.7.16 shows the activity table of A0017, a piece of the first wall layer in the beam direction of Treatment Room 1, made of borated concrete (borato). The most significant long-lived radionuclides due to the high specific activity of the component are ^{55}Fe , ^{41}Ca , ^{45}Ca and ^3H .

S0027	A	Z	ATT(Bq)	err%	element		ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)		concrete	
	152	63	3.14E+04	70.33	Eu	Eu-152	6.77E-02	0.1	6.77E-01	4.27E+08	V(m3)	ro(g/cm3)	m(Kg)
	60	27	1.81E+04	99.00	Co	Co-60	3.89E-02	0.1	3.89E-01	1.66E+08	2.02E-01	2.3	4.64E+02
	55	26	2.12E+05	25.90	Fe	Fe-55	4.58E-01	1	4.58E-01	8.66E+07	att. (Bq)		
	45	20	5.33E+04	27.13	Ca	Ca-45	1.15E-01	1	1.15E-01	1.40E+07	3.17E+05 +/-	1.91E+01	%
	41	20	1083	5.74	Ca	Ca-41	2.33E-03	0.01	2.33E-01	3.14E+12	att.sp. (Bq/g)	6.82E-01	
	40	19	0.1108	5.89	K	K-40	2.39E-07	1	2.39E-07	3.94E+16	Σ att.sp/cf	1.87E+00	
	37	18	30.47	70.33	Ar	Ar-37	6.56E-05	1	6.56E-05	3.02E+06			
	14	6	230	57.12	C	C-14	4.95E-04	1	4.95E-04	1.80E+11			
	A/Z/ Isomers:												
	45	21	1.01E+00	27.13	Sc	Sc-45	2.18E-06	0.01	2.18E-04	3.26E-01			

Figure 7.17: Radionuclides generated in the S0027 with respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, please see the Data analysis methodology paragraph).

Fig.7.17 shows the activity table of S0027, a piece of the second wall layer in the beam direction of Treatment Room 1, made of concrete. The most significant long-lived radionuclides due to the high specific activity of the component are ¹⁵²Eu, ⁶⁰Co, ⁵⁵Fe, ⁴⁵Ca and ⁴¹Ca .

7.2.2. Removable components

MAGNETE1	A	Z	ATT(Bq)	err%	element		ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)		copper	
	63	28	1.48E+04	49.2	Ni	Ni-63	1.29E-02	1	1.29E-02	3.19E+09	V(m3)	ro(g/cm3)	m(Kg)
											1.28E-01	8.96	1.15E+03
											att. (Bq)		
											1.48E+04 +/-	4.92E+01	%
											att.sp. (Bq/g)	1.29E-02	
											Σ att.sp/cf	1.29E-02	

Figure 7.18: Radionuclides generated in the MAGNETE1 with respective analysis.

Fig. 7.18 shows the activity table of MAGNETE1, composed of copper. The same radionuclide, ⁶³Ni, generated in copper components is also found here, but with lower specific activities.

A0002	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)				
	55	26	1.86E+05	29.68	Fe	Fe-55	3.69E-01	1	3.69E-01	8.66E+07			
	41	20	757.2	7.52	Ca	Ca-41	1.50E-03	0.01	1.50E-01	3.14E+12			
	45	20	1.69E+04	49.24	Ca	Ca-45	3.34E-02	1	3.34E-02	1.40E+07			
	14	6	72.82	99.00	C	C-14	1.44E-04	1	1.44E-04	1.80E+11			
	59	26	67.6	99.00	Fe	Fe-59	1.34E-04	1	1.34E-04	3.84E+06			
	37	18	28.95	70.35	Ar	Ar-37	5.73E-05	1	5.73E-05	3.02E+06			
	36	17	1.38	99.00	Cl	Cl-36	2.73E-06	1	2.73E-06	9.51E+12			
	40	19	9.50E-02	5.97	K	K-40	1.88E-07	1	1.88E-07	3.94E+16			
	A/Z/Isomers:												
	45	21	0.3204	49.24	Sc	Sc-45	6.34E-07	0.01	6.34E-05	3.26E-01			

	borato		
V(m3)	ro(g/cm3)	m(Kg)	
2.20E-01	1.127	5.05E+02	
att. (Bq)			
2.04E+05	+/-	2.77E+01	%
att.sp. (Bq/g)		4.04E-01	
Σ att.sp/cf		5.53E-01	

Figure 7.19: Radionuclides generated in A0002 with respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, please see the Data analysis methodology paragraph).

Fig.7.19 shows the activity table of A0002, another piece of the first wall layer of Treatment Room 1. The same radionuclides found in A0017 and other borated concrete blocks are present here, but with lower specific activities.

R0006	A	Z	ATT(Bq)	err%	element	ATT. SP. (Bq/g)	cf. Tab 1.b	att.sp/cf	T _{1/2} (s)				
	152	63	1.57E+04	99	Eu	Eu-152	2.76E-02	0.1	2.76E-01	4.27E+08			
	60	27	1.81E+04	99	Co	Co-60	3.17E-02	0.1	3.17E-01	1.66E+08			
	55	26	1.14E+05	36.57	Fe	Fe-55	2.01E-01	1	2.01E-01	8.66E+07			
	45	20	2.22E+04	43.76	Ca	Ca-45	3.90E-02	1	3.90E-02	1.40E+07			
	41	20	268.6	12.31	Ca	Ca-41	4.72E-04	0.01	4.72E-02	3.14E+12			
	40	19	4.91E-02	8.05	K	K-40	8.62E-08	1	8.62E-08	3.94E+16			
	14	6	76.66	99	C	C-14	1.35E-04	1	1.35E-04	1.80E+11			
	A/Z/Isomers:												
	45	21	0.4216	43.76	Sc	Sc-45	7.40E-07	0.01	7.40E-05	3.26E-01			

	concrete		
V(m3)	ro(g/cm3)	m(Kg)	
2.48E-01	2.3	5.70E+02	
att. (Bq)			
1.71E+05	+/-	3.09E+01	%
att.sp. (Bq/g)		3.00E-01	
Σ att.sp/cf		8.80E-01	

Figure 7.20: Radionuclides generated in the R0006 with respective analysis.

The parts highlighted in yellow indicate unlisted radionuclides (for further details, please see the Data analysis methodology paragraph).

Fig.7.20 shows the activity table of R0006, a piece of the second wall layer in the beam direction of HEBT Room. The same radionuclides found in S0027 and other concrete blocks are present here, but with lower specific activities.

7.2.3. Results

Figure 7.21 presents all the elements that cannot be removed after 30 years of machine operation, considering a neutron field as described by the routine and one year of cooling time. For each analyzed region, the table provides the material type and volume.

Region	Material	Volume (m ³)	Region	Material	Volume (m ³)	Region	Material	Volume (m ³)	Region	Material	Volume (m ³)	Region	Material	Volume (m ³)
DUMP	copper	1.50E-03	A0009	borato	2.20E-01	S0019	concrete	2.02E-01	V00017	concrete	1.60E-01	V0025	concrete	3.94E-01
MAGNETE2	copper	1.28E-01	A0010	borato	2.20E-01	S0020	concrete	2.02E-01	V00018	concrete	1.60E-01	V0026	concrete	3.94E-01
MAGN3_Fe	iron	3.14E-02	A0017	borato	2.20E-01	S0021	concrete	2.02E-01	V00019	concrete	1.60E-01	V0027	concrete	3.94E-01
MAGN4_Fe	iron	3.14E-02	A0018	borato	2.20E-01	S0026	concrete	2.02E-01	V00020	concrete	1.60E-01	V0033	concrete	3.94E-01
MAGN5_Fe	iron	3.14E-02	A0025	borato	2.20E-01	S0027	concrete	2.02E-01	V00021	concrete	1.60E-01	V0034	concrete	3.94E-01
MAGN6_Fe	iron	3.14E-02	A0015	borato	1.71E-01	S0028	concrete	2.02E-01	V00025	concrete	1.60E-01	V0015	concrete	3.94E-01
U_BSA1	lithium	2.84E-06	E0020	borato	1.46E-01	S0029	concrete	2.02E-01	V00026	concrete	1.60E-01	V0021	concrete	3.94E-01
U_BSA2	lithium	2.84E-06	H0038	borato	2.00E-01	S0033	concrete	2.02E-01	V00027	concrete	1.60E-01	V0026	concrete	3.94E-01
BSA1BOR1	baritbor	6.89E-01	H0039	borato	2.00E-01	S0034	concrete	2.02E-01	V00028	concrete	1.60E-01	V0027	concrete	3.94E-01
BSA1BOR2	baritbor	6.89E-01	I0006	borato	2.04E-01	S0035	concrete	2.02E-01	V00031	concrete	1.60E-01	V0004	borato	1.35E-01
BSA1BOR3	baritbor	5.55E-01	I0014	borato	2.04E-01	S0036	concrete	2.02E-01	V00032	concrete	1.60E-01	V0005	borato	1.35E-01
BSA1BOR4	baritbor	5.55E-01	N0014	borato	1.97E-01	S0037	concrete	2.02E-01	V00033	concrete	1.60E-01	V0009	borato	1.35E-01
BSA2BOR1	baritbor	6.89E-01	N0015	borato	1.97E-01	S0041	concrete	2.02E-01	V00034	concrete	1.60E-01	V0010	borato	1.35E-01
BSA2BOR2	baritbor	6.89E-01	N0021	borato	1.97E-01	S0042	concrete	2.02E-01	V00035	concrete	1.60E-01	V0011	borato	1.35E-01
BSA2BOR3	baritbor	5.55E-01	N0026	borato	1.97E-01	S0043	concrete	2.02E-01	V00039	concrete	1.60E-01	V0014	borato	1.35E-01
BSA2BOR4	baritbor	5.55E-01	N0027	borato	1.97E-01	S0044	concrete	2.02E-01	V00040	concrete	1.60E-01	V0017	borato	1.35E-01
DENTINO3	baritbor	4.20E-02	O0031	borato	1.98E-01	T0019	concrete	3.50E-01	V00042	concrete	1.60E-01	V0018	borato	1.35E-01
DENTINO9	baritbor	4.20E-02	O0032	borato	1.98E-01	T0020	concrete	3.50E-01	V00043	concrete	1.60E-01	V0019	borato	1.35E-01
PORT1.1	baritbor	3.13E-01	O0039	borato	1.98E-01	T0021	concrete	3.50E-01	V00045	concrete	1.60E-01	V0020	borato	1.35E-01
PORT1.2	baritbor	3.13E-01	O0044	borato	1.98E-01	T0026	concrete	3.50E-01	V00046	concrete	1.60E-01	V0024	borato	1.35E-01
PORT1.3	baritbor	3.13E-01	R0004	concrete	2.48E-01	T0027	concrete	3.50E-01	V00047	concrete	1.60E-01	V0025	borato	1.35E-01
PORT1.4	baritbor	3.13E-01	R0005	concrete	2.48E-01	T0028	concrete	3.50E-01	V00048	concrete	1.60E-01	V0026	borato	1.35E-01
S1LETROT	stainless	0.7931	R0007	concrete	2.48E-01	T0029	concrete	3.50E-01	V00049	concrete	1.60E-01	V0027	borato	1.35E-01
S1LETTA1	stainless	4.28E-02	R0013	concrete	2.48E-01	T0033	concrete	3.50E-01	V00053	concrete	1.60E-01	V0028	borato	1.35E-01
S1LETTB1	stainless	4.49E-02	R0014	concrete	2.48E-01	T0034	concrete	3.50E-01	V00054	concrete	1.60E-01	V0029	borato	1.35E-01
S1LETTBR1	stainless	7.65E-02	R0015	concrete	2.48E-01	T0035	concrete	3.50E-01	V00059	concrete	1.60E-01	V0033	borato	1.35E-01
PLASTBOR	plastbor	2.56E-02	R0023	concrete	2.48E-01	T0036	concrete	3.50E-01	V00060	concrete	1.60E-01	V0034	borato	1.35E-01
S2LETROT	stainless	0.7931	R0024	concrete	2.48E-01	T0037	concrete	3.50E-01	V00061	concrete	1.60E-01	V0035	borato	1.35E-01
S2LETTA1	stainless	4.28E-02	R0025	concrete	2.48E-01	T0042	concrete	3.50E-01	V00068	concrete	1.60E-01	V0036	borato	1.35E-01
S2LETTB1	stainless	4.49E-02	R0026	concrete	2.48E-01	T0043	concrete	3.50E-01	V00072	concrete	1.60E-01	V0041	borato	1.35E-01
S2LETTBR1	stainless	7.65E-02	R0027	concrete	2.48E-01	T0044	concrete	3.50E-01	V00073	concrete	1.60E-01	V0042	borato	1.35E-01
PLASTBOR2	plastbor	2.56E-02	R0033	concrete	2.48E-01	T0045	concrete	3.50E-01	V00074	concrete	1.60E-01	V0043	borato	1.35E-01
BSA1	BSA	3.08E-01	R0034	concrete	2.48E-01	T0051	concrete	3.50E-01	V00075	concrete	1.60E-01	V0044	borato	1.35E-01
BSA2	BSA	3.08E-01	R0035	concrete	2.48E-01	T0052	concrete	3.50E-01	V00076	concrete	1.60E-01	V0050	borato	1.35E-01
I0069	borato	1.81E-01	R0036	concrete	2.48E-01	T0058	concrete	3.50E-01	V00077	concrete	1.60E-01	V0051	borato	1.35E-01
I0079	borato	1.81E-01	R0046	concrete	2.48E-01	T0060	concrete	3.50E-01	V00087	concrete	1.60E-01	V0052	borato	1.35E-01
I0059	borato	1.81E-01	R0047	concrete	2.48E-01	V0003	concrete	1.60E-01	V00088	concrete	1.60E-01	V0061	borato	1.35E-01
I0030	borato	1.81E-01	R0054	concrete	2.48E-01	V0004	concrete	1.60E-01	V00090	concrete	1.60E-01	V0009	borato	1.35E-01
g0061	borato	1.35E-01	R0055	concrete	2.48E-01	V0005	concrete	1.60E-01	V0101	concrete	1.60E-01	g0010	borato	1.35E-01
I0031	borato	1.81E-01	R0056	concrete	2.48E-01	V0003	concrete	1.60E-01	X0014	concrete	3.94E-01	g0012	borato	1.35E-01
g0058	borato	1.35E-01	R0058	concrete	2.48E-01	V0004	concrete	1.60E-01	X0015	concrete	3.94E-01	g0013	borato	1.35E-01
I0040	borato	1.81E-01	S0003	concrete	2.02E-01	V0005	concrete	1.60E-01	X0021	concrete	3.94E-01	g0019	borato	1.35E-01
g0050	borato	1.35E-01	S0009	concrete	2.02E-01	V0006	concrete	1.60E-01	X0026	concrete	3.94E-01	g0021	borato	1.35E-01
I0050	borato	1.81E-01	S0010	concrete	2.02E-01	V0007	concrete	1.60E-01	X0027	concrete	3.94E-01	g0022	borato	1.35E-01
S0018	concrete	2.02E-01	S0011	concrete	2.02E-01	V00012	concrete	1.60E-01	X0013	concrete	3.94E-01	g0035	borato	1.35E-01
V00015	concrete	1.60E-01	S0012	concrete	2.02E-01	V00013	concrete	1.60E-01	X0014	concrete	3.94E-01	g0036	borato	1.35E-01
V0021	concrete	3.94E-01	S0013	concrete	2.02E-01	V00014	concrete	1.60E-01	X0015	concrete	3.94E-01	g0044	borato	1.35E-01

Figure 7.21: Non-removable components of the BNCT facility.

From these data, the total volumes of each material were calculated for the components that will need to be disposed of as radioactive waste. This information is used to estimate the decommissioning costs of the facility (Fig. 7.22).

Material	Volume (m ³)
copper	1.30E-01
iron	1.26E-01
lithium	5.67E-06
baritbor	6.31E+00
stainless	1.91E+00
plastbor	5.12E-02
borato	1.08E+01
concrete	3.21E+01
BSA	6.16E-01

Figure 7.22: Summation of non-removable volumes, classifield by material.

Finally, the radionuclides generated in the removable components, for which the structure will need to request authorization for release, include ^{37}Ar , ^{39}Ar , ^{10}Be , ^{14}C , ^{41}Ca , ^{45}Ca , ^{36}Cl , ^{60}Co , ^{152}Eu , ^{154}Eu , ^{55}Fe , ^{59}Fe , ^3H , ^{40}K , ^{63}Ni , ^{205}Pb , ^{45}Sc and ^{47}Sc .

8 | Conclusions and future developments

This study presents the work carried out during an internship at the Radiation Protection Office of CNAO, as a part of a LM+ project. Decommissioning is a normal phase in the life cycle of a nuclear facility and must be considered from the early stages of its development. As a part of the initial authorization process, a decommissioning plan is developed to ensure its feasibility.

The objective of this work was to identify the radionuclides generated during operation and their specific activities under both conservative and more realistic beam energy and intensity conditions. This was achieved using the FLUKA Monte Carlo code, which allows for the simulation of different scenarios, providing data on activation levels and the list of produced radionuclides. The simulations were based on an irradiation period of 30 years, a typical operational lifespan for these accelerators. This time frame is necessary to determine whether a component qualifies as radioactive waste or can be safely removed during decommissioning. The assessment follows the criterion that the sum of the ratios between the specific activity of each radionuclide and its value from Table 1.b of Decreto Legislativo n. 101 of July 31, 2020, must be smaller than one.

The simulation results indicate that the most exposed components, forming radiation "hot spots", are those directly impacted by the beam and those near loss points due to secondary radiation. In the case of the CNAO existing synchrotron, the highest activity levels were found in the components surrounding beam dumps, isocenters and walls aligned with the beam direction. Concerning the expansion facilities, the highest activation in the new proton therapy structure occurs in components where proton losses take place, particularly in the synchrotron and the High Energy Beam Transport (HEBT) line. In the Boron Neutron Capture Therapy (BNCT) facility, the most activated components include the Beam Shaping Assembly (BSA) and the surrounding elements due to the high neutron flux generated at the lithium target, including the patient bed support and the walls in the beam direction. Regarding the estimation of radioactive waste, under the most conservative scenario, considering the carbon ion beam at maximum energy and

intensity, the total volume of radioactive waste from the CNAO existing hadron therapy facility was estimated at 24.5 m³, mainly from copper components. For the new Hitachi proton therapy facility, under the most conservative conditions with a high-energy proton beam, the total radioactive waste volume was 8.4 m³, mostly from iron components. In the BNCT facility, the estimated radioactive waste volume was 52.0 m³, mainly from barite concrete with boron and standard concrete walls.

The estimated waste volumes could potentially be lower, as the analysis identified several facility components with a sum of specific activity to clearance factor ratios ($\Sigma Att.sp./cf$) slightly above one. In many cases, this exceedance is due to the presence of unlisted radionuclides, which are not included in the official ministerial tables or the current CNAO authorizations. For these radionuclides, the most conservative clearance value was applied. Therefore, if less stringent clearance levels for these radionuclides will be required in the decommissioning authorizations, the assessment of whether certain materials can be cleared or must be classified as radioactive waste may change.

It is important to emphasize that this study provides a purely computational analysis. As indicated by IAEA, operational decommissioning planning is only possible after ex-post evaluations, conducted at the end of the facility operational phase. These assessments will take into account the actual workload, machine usage conditions, and experimental material characterization. Decommissioning can only proceed after an adequate cooling period, allowing short-lived radionuclides to decay as much as possible. The dismantling process will prioritize the removal of the most activated components first, minimizing radiation exposure for the personnel involved in the operations.

Future studies could further extend this work by improving the simulation geometry and incorporating the actual beam intensities and energies used in treatments and research with the new facilities. This would provide a more realistic and less conservative estimate of the activation levels and the resulting radioactive waste volumes.

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