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Radiation protection measurements during the commissioning of the third-generation n_TOF neutron spallation target at CERN

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Abstract

The neutron Time-Of-Flight (n_TOF) facility, operational at CERN since 2000, is a pulsed neutron spallation source producing neutrons between a few meV and several GeV for two experimental stations located 185 m horizontally from the target and 20 m above the target. The neutron production target, made of pure lead, is impacted by the 20 GeV/c proton beam of the Proton Synchrotron. In 2018, the second-generation target reached the end of its lifetime, and the facility underwent a major upgrade during CERN's Long Shutdown 2 (2019-2021), which included the installation of the new third-generation spallation target. The previous targets were based on water-cooled massive lead blocks, whereas the new target is cooled by nitrogen gas slightly above atmospheric pressure to limit erosion-corrosion and contamination of the cooling circuit with radioactive lead spallation products. A radiation protection study, performed with the FLUKA Monte Carlo code, contributed to the optimisation of the target design and to assess the safe operation of the facility. In 2021, during the commissioning of the new target, the simulation results were complemented by dedicated radiation measurements, which are described in this work:

- Monitoring of stray radiation (neutrons and photons) in accessible areas by using fixed and mobile instrumentation (high-pressure ionisation chambers and the LUPIN extended range rem-counter, specifically conceived to measure pulsed neutrons) to ensure the compliance with the radiological area classification.
- Monitoring of residual dose rate to provide useful information for planning and optimising accesses and interventions.
- Monitoring of the nitrogen activation by means of a flow-through differential ionization chamber, for which a field calibration factor was calculated combining FLUKA simulations and experimental measurements.
- Activation studies for zoning purposes by installing in specific locations of the n_TOF facility samples of materials typically used in particle accelerators (aluminium, copper, stainless steel); during the Year End Technical Stop 2021-2022, their specific activity were measured by γ -spectrometry and compared against the

applicable CERN clearance limits.

Keywords: FLUKA, Monte Carlo simulations, Neutron spallation source, Radiation measurements, Radiation protection

Abstract in lingua italiana

L'esperimento n_TOF (neutron Time-Of-Flight), operativo al CERN dal 2000, consiste in una sorgente pulsata di neutroni di spallazione (con uno spettro energetico da pochi meV a diversi GeV) per due stazioni sperimentali, una situata a 185 m a valle dal bersaglio e l'altra a 20 m sopra di esso. I neutroni sono prodotti dall'interazione del fascio di protoni da 20 GeV/c proveniente dal Proton Synchrotron con il bersaglio fatto di piombo puro. Nel 2018, il bersaglio di seconda generazione è stato rimosso, e la struttura è stata sottoposta ad una riqualificazione durante il cosiddetto Long Shutdown 2 (2019-2021), durante il quale è stato installato un nuovo bersaglio di spallazione (terza generazione). I bersagli precedenti erano raffreddati ad acqua, mentre il nuovo bersaglio è stato concepito per essere raffreddato da azoto in forma gassosa per limitare l'erosione e la contaminazione del circuito di raffreddamento con i prodotti di spallazione provenienti dal piombo. Uno studio preliminare di radioprotezione, realizzato con il codice Monte Carlo FLUKA, ha contribuito all'ottimizzazione del progetto e alla valutazioni dei rischi radiologici. Nel 2021, durante la messa in servizio del nuovo bersaglio, i risultati delle simulazioni sono stati completati con misure sperimentali, descritte in questo lavoro:

- Monitoraggio della radiazione diretta (neutronica e fotonica) in aree accessibili utilizzando strumentazione fissa e mobile (camere di ionizzazione ad alta pressione e il LUPIN, un *extended – rangerem – counter* specificamente concepito per misurare i neutroni in campi pulsati), allo scopo di garantire la conformità con la classificazione radiologica degli ambienti dove le misure sono state effettuate.
- Monitoraggio della radiazione residua con lo scopo di fornire informazioni radiologiche rilevanti per pianificare e ottimizzare gli accessi nelle aree ove le misure sono state effettuate.
- Monitoraggio dell'attivazione dell'azoto con una camera di ionizzazione a flusso differenziale, per la quale è stato calcolato un fattore di calibrazione, combinando simulazioni FLUKA e misure sperimentali.
- Studi di attivazione mediante il posizionamento di campioni di materiali tipicamente utilizzati negli acceleratori di particelle (alluminio, rame, acciaio inossidabile). I

campioni sono stati temporaneamente rimossi durante lo stop di fine anno e la loro attività specifica è stata misurata attraverso spettrometria gamma e confrontata con i limiti di liberazione applicabili al CERN.

Parole chiave: FLUKA, Misure di radiazione, Radioprotezione, Simulazioni Monte Carlo, Sorgente di spallazione

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1 | Radiation protection at CERN

The HSE (Occupational Health Safety and Environmental Protection) Unit at CERN is responsible for:

- the establishment, update and interpretation of the Organization's regulatory framework in matters of Safety;
- Radiation Protection (RP);
- Occupational Medicine within the Organization;
- Fire and Rescue Services;
- The provision of advice and support in matters of occupational health and safety;
- The monitoring of - and reporting on the environmental impact of the Organization's activities;
- The granting of Safety clearance for Installations, including special equipment, activities, projects and CERN Experiments with major Safety implications.

The Radiation Protection (RP) group of the HSE Unit ensures that personnel on the CERN sites and the public are protected from potentially harmful effects of ionizing radiation linked to CERN activities. The RP Group fulfils its mandate in collaboration with the CERN departments owning or operating sources of ionizing radiation and having the responsibility for Radiation Safety of these sources [2]. The Radiation Protection Group is responsible for:

- assessing the hazards of ionizing radiation from CERN installations and their associated risks for personnel and members of the public and defines the appropriate protective measures;
- monitoring the implementation and the effectiveness of the protective measures by measuring radiation levels and ambient and personal doses;
- leading the implementation of the ALARA principle in the design, operation and decommissioning of CERN's accelerators and experiments;

- authorizing (suspending) the operation of an equipment, installation or activity generating ionizing radiation in case of compliance (non-compliance) with CERN's radiation protection rules;
- developing and maintaining tools, instruments and methods appropriate for the assessment of radiation hazards and risks particular to the CERN installations;
- providing expert advice and technical support to departments, to the experimental collaborations and to the CERN management in all matters of radiation protection;
- managing the interim storage, treatment and disposal of radioactive waste; being in charge of the Organization's regulatory framework in matters of radiation protection;
- contributing to the implementation of the Tripartite agreement on radiation protection and radiation safety.

The purpose of this chapter is to provide an overview about the CERN radiation protection framework, relevant for the work described in this thesis. The CERN RP framework is based on the well-known three RP principles:

- Justification: it requires that any practice involving radiation exposure produces enough benefit to the exposed individuals or society to compensate for the radiation harm it causes.
- Limitation: it requires that the dose to individuals should not exceed the appropriate limit.
- Optimization: it is defined as a process that keeps and optimizes the magnitude of individual doses and the number of people exposed As Low As Reasonably Achievable (ALARA), while accounting for economic and social factors. Concretely, optimizing entails balancing constraints on individual doses, risks, the number of people involved, and the consequences of potential failures.

1.1. Classification of personnel

CERN defines all persons who are occupationally exposed to radiation and set the corresponding effective dose limits [8]. The effective dose received in any consecutive 12-month period by any occupationally exposed person must not exceed 20 mSv. Occupationally exposed persons are classified in one of two categories:

- Category A: persons who may be exposed in the course of their profession to more

than 3/10 of the effective dose limit in 12 consecutive months.

- Category B: persons who may be exposed in the course of their profession to less than 3/10 of the effective dose limit in 12 consecutive months

Persons not occupationally exposed must not receive an effective dose greater than 1 mSv in any consecutive 12-month period.

1.2. Radiological area classification

The areas within CERN's perimeters are classified based on the effective dose that a person is likely to receive during his/her stay under normal working conditions. In practice, for each area, a limit in terms of ambient dose equivalent rate¹ is defined depending on the level of occupancy:

- permanent workplaces: a location that is always occupied. It is assumed that a person spends more than 20% of his working time in these areas.
- low-occupancy areas: any non-permanently occupied location. It is assumed that an individual spends less than 20% of his working time in these areas.

The radiological classification distinguishes three types of areas depending on dose rate limits:

1. An area is classified as Non-designated Area if under normal conditions a person cannot receive an effective dose in excess of 1 mSv in any 12-month period. The ambient dose equivalent rate, $H^*(10)$, at permanent workplaces must not exceed 0.5 $\mu\text{Sv/h}$ and in low-occupancy areas it must not exceed 2.5 $\mu\text{Sv/h}$.
2. An area must be classified as Supervised Radiation Area if a person may receive an effective dose in excess of 1 mSv, but less than 6 mSv in any consecutive 12-months period under normal working conditions. The ambient dose equivalent rate, $H^*(10)$, at permanent workplaces must not exceed 3 $\mu\text{Sv/h}$ and in low-occupancy areas it must not exceed 15 $\mu\text{Sv/h}$. A personal (passive) dosimeter is mandatory to access these areas.
3. An area must be classified as Controlled Radiation Area if a person may receive an effective dose in excess of 6 mSv in any consecutive 12-months period under normal working conditions. Controlled Radiation Areas are subdivided as follows:
 - Simple controlled radiation area: the ambient dose equivalent rate, $H^*(10)$, at

¹Additional limits in terms of surface and airborne contamination are also defined.

workplaces must not exceed 10 $\mu\text{Sv/h}$ and in low-occupancy areas it must not exceed 50 $\mu\text{Sv/h}$. A personal dosimeter is necessary to access these areas.

- Limited stay controlled radiation area: the ambient dose equivalent rate $H^*(10)$ must not exceed 2 mSv/h. Both personal and operational (active) dosimeters are mandatory to access these areas.
- High radiation area: the ambient dose equivalent rate $H^*(10)$ must not exceed 100 mSv/h. Both personal and operational (active) dosimeters are mandatory to access these areas.
- Prohibited radiation area: the ambient dose equivalent rate $H^*(10)$ exceeds 100 mSv/h. By definition, at any time, access to this area is prohibited.

Figure 1.1 summarises the radiological area classification at CERN ².

Area	Annual dose limit (year)	Ambient dose equivalent rate		Sign	Specific airborne radioactivity*	Specific surface contamination**
		permanent occupancy	low occupancy			
Non-designated	1 mSv	0.5 $\mu\text{Sv/h}$	2.5 $\mu\text{Sv/h}$		0.05 CA	1 CS
Radiation Area	Supervised	6 mSv	3 $\mu\text{Sv/h}$		0.1 CA	1 CS
	Simple Controlled	20 mSv	10 $\mu\text{Sv/h}$		0.1 CA	1 CS
	Limited Stay	20 mSv	-		100 CA	4000 CS
	High Radiation	20 mSv	-		1000 CA	40000 CS
	Prohibited	20 mSv	-		> 1000 CA	> 40000 CS

Figure 1.1: Synopsis of the radiological area classification at CERN [17].

1.3. CERN Clearance Limits for radionuclides of artificial origin

During facility operation, many materials can be activated and become radioactive. If a radioactive material fulfils the clearance conditions outlined below, it can be released from regulatory control. Thus, the material can be considered as non-radioactive. There

²CA and CS (from the French *Contamination de l'Air* and *Contamination Surfactive*) are the guidance values for the specific airborne activity and the specific surface contamination, respectively. The CA value is the activity concentration whose exposition for 40 hours per week and 50 weeks per year yields a committed effective dose of 20 mSv. The CS value is calculated on the basis of various scenarios, i.e. skin contamination, ingestion and inhalation, with the most unfavourable one being chosen [4].

are three requirements to meet the clearance limits: one for the activity/specific activity, one for residual dose rate and the last for surface contamination [28].

1.3.1. Activity and Dose Rate Requirements

In accordance with Article 106 of the Swiss Radiation Protection Legislation radioactive material can be removed from regulatory control if:

1. the ambient dose equivalent rate measured in 10 cm distance to the item is lower than 0.1 $\mu\text{Sv/h}$ after subtraction of the background
and
2. one of the following two conditions is fulfilled
 - the specific activity in Bq/g is below the CERN clearance limit as given in [28] (Table 2, column 2 of the Annex)
or
 - the total activity in Bq is below the CERN clearance limit as given in [28] (Table 2, column 3 of the Annex).

For radioactive material containing a mixture of radionuclides of artificial origin, the following sum rule must be applied to remove it from any further regulatory control:

$$\sum_{i=1}^n \frac{a_i}{LL_i} < 1 \quad (1.1)$$

where a_i is the specific activity (Bq/g) of the i^{th} radionuclide of artificial origin in the material, LL_i is the respective clearance limit (“Limit de Libération” = French for clearance limits) and n is the number of identified radio-nuclides [28].

1.3.2. Surface Contamination Requirement

In addition to the criteria indicated in Section 1.3.1, the following conditions about surface contamination must be met in order to allow for the clearance of material. Contamination levels of unidentified β - and γ -emitters must be lower than 1 Bq/cm² and 0.1 Bq/cm² in case of unidentified α -emitters. Once a radionuclide has been identified, then the CS-values (available in [28], Table 4 of the Annexe) must be used, and the following sum rule must be applied as a clearance criterion:

$$\sum_{i=1}^n \frac{c_i}{CS_i} < 1 \quad (1.2)$$

where c_i is the surface contamination value (Bq/cm²) of the i^{th} radionuclide, CS_i is its CS-value and n is the number of identified radio-nuclides [28].

1.4. The FLUKA Monte Carlo code

FLUKA (from the German *FLUkturiende KAscade*, i.e. fluctuating cascade) is a Monte Carlo code based on Fortran 77 developed as a result of a collaboration between CERN and INFN [6, 11, 18]. In 2019, CERN and INFN together decided to end their collaboration framework; as a consequence, CERN set up the FLUKA.CERN Collaboration. FLUKA is a general-purpose code, which can describe the transport and interaction of any particle and nucleus type in complex geometries over an energy range extending from thermal neutrons to ultra-relativistic hadron collisions [11]. FLUKA applications include but are not limited to radiation protection, dosimetry, medical physics, accelerator design. FLUKA can be combined with a graphical interface known as Flair (Fluka Advance Interface), which, for instance, allows the user to write the input file to be simulated, implement and visualize the geometry, execute external functions (routines).

FLUKA is widely used for radiation protection applications: characterisation of radioactive waste, shielding design, dosimetry and for the characterization of radiation detectors. In this work, FLUKA simulations were carried out to calculate the field calibration factor of an ionization chamber, which monitors the radioactivity concentration of the nitrogen gas used to cool the n_TOF spallation target (Section 3.2).

2 | The n_TOF facility

2.1. Facility overview

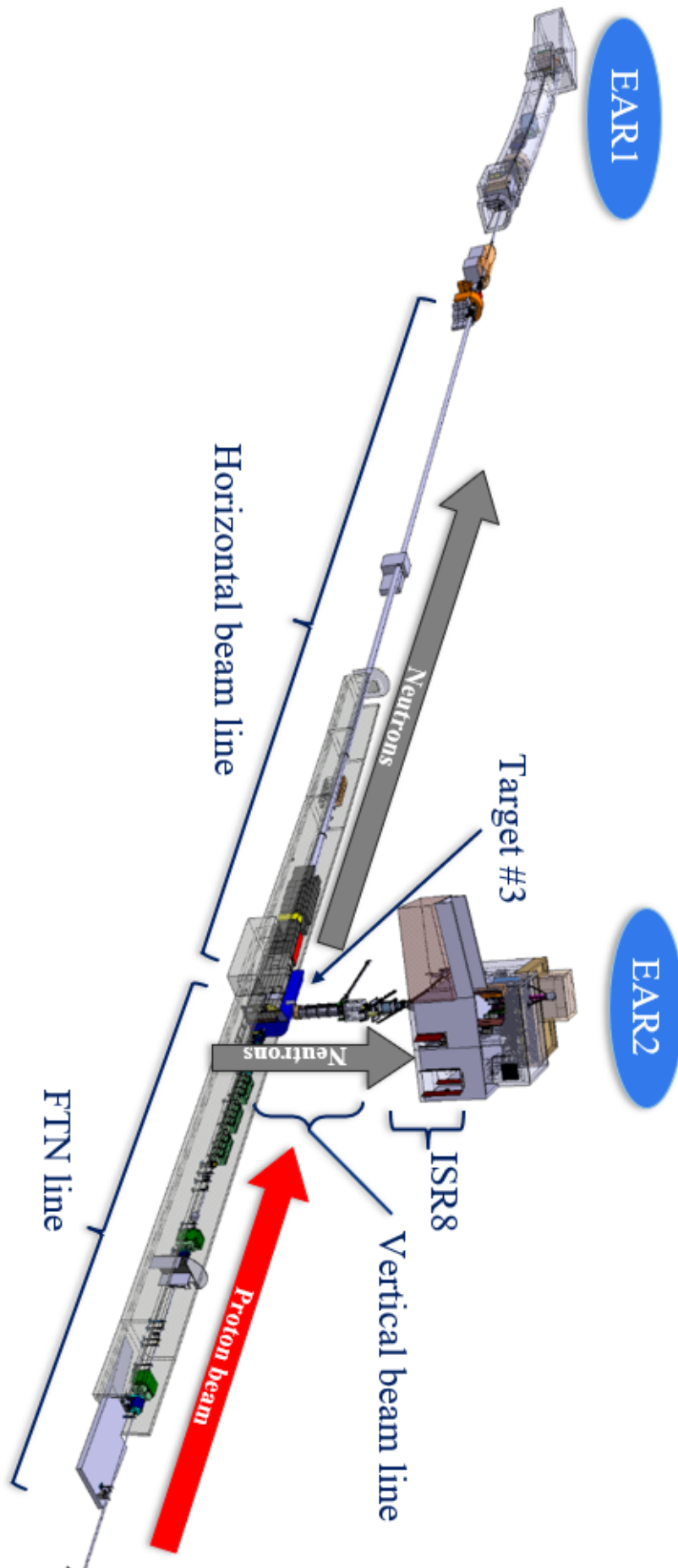
The neutron Time-Of-Flight (n_TOF) facility, operational at CERN since 2000, is a pulsed neutron spallation source producing neutrons between a few meV and several GeV for two experimental stations. Experiments performed at n_TOF find applications in nuclear astrophysics, nuclear technology and medical research.

The n_TOF spallation target is based on high-purity lead owing to its superior performances in terms of reduced photon background with respect to other spallation materials, due its low neutron capture cross sections. The target is impacted by the 20 GeV/c pulsed proton beam delivered by CERN's Proton Synchrotron (PS) with typically 7×10^{12} protons per pulse, yielding about 300 neutrons per incident proton through spallation reactions. The resulting neutron beam can be moderated by either demineralised or borated water, broadening the neutron energy spectrum down to the epithermal and thermal regions. The neutron beam is therefore directed to two experimental areas where neutron cross sections measurements are performed; the first one (EAR1) is located 185 metres downstream the target, whereas the second one (EAR2) is 20 metres above the target (EAR2). The n_TOF complex is composed of:

- The FTN beam line: it is the proton transfer line, which, by means of the TT2 transfer tunnel, connects the PS accelerator with the target.
- The n_TOF target area, where the spallation target, the NEAR experimental station and the mobile shielding wall are located.
- The cooling station: it hosts three hydraulic systems essential for the target operation:
 - Two water-based moderation circuits (one for each neutron beam line). The water of the circuits is physically separated from the target, preventing water and lead from coming into contact.
 - One cooling circuit: the heat transfer fluid is nitrogen gas;

- The ISR8 (8th octant of the former Intersecting Storage Ring): this is the area where the cooling station is located.
- The horizontal neutron beam line: it is 185 m long and is equipped with a permanent magnet (to remove charged particles from the neutron beam line), collimators, a filter box (which contains filters to blank out different neutron energies from the beam or attenuate the in-beam photons) and shielding (especially to minimize the muon contribution). This beam line ends in EAR1.
- The vertical beam line: it is 20 m long and passes through a zone called "technical gallery" (where another permanent magnet and filter box are installed) before reaching EAR2.
- EAR1: it is located at the end of the horizontal beam line. The kinetic energy of the incoming neutron is estimated by measuring their time-of-flight across a defined and well-known distance, i.e. the length of the horizontal beam line (185 m). This approach may be used to determine the energy-dependent capture cross-section across a wide range of energies.
- EAR2: it is the experimental station where the 20 m vertical beam line ends. Due to its proximity to the spallation target, EAR2 has superior neutron flux compared to EAR1 [9].

The 3D layout of the facility is reported in the next page.



2.2. Proton generation for n_TOF

The CERN accelerator complex is a series of particle accelerators (called in CERN jargon "machines") with increasing accelerating energy. In order to produce the protons that impinge on the n_TOF target the following process is performed:

- negative hydrogen ions are produced and accelerated in the Linac4 up to an energy of 160 MeV;
- at injection in Proton Synchrotron Booster (PSB), the negative hydrogen ions are stripped of the two electrons, and the resulting proton beam is accelerated up to 2 GeV;
- then, the proton beam is injected into the Proton Synchrotron, which can accelerate the protons up to 26 GeV/c;
- the pulsed proton beam sent to n_TOF is fast extracted at 20 GeV/c from the PS and sent via the TT2 extraction line to the n_TOF target.

;

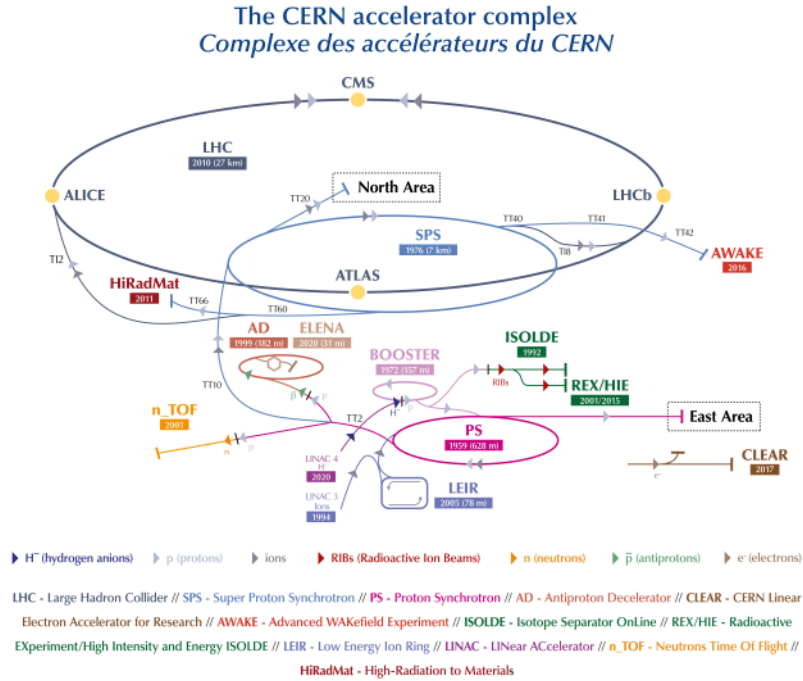


Figure 2.1: The CERN Accelerator Complex [1]. The beam that reaches n_TOF target is generated into the Linac4 and then is fed into two synchrotrons (Booster and PS). After being accelerated, the beam is directed towards n_TOF via a transfer line.

2.3. FTN beam transfer line

From the TT2 extraction line, the n_TOF proton beam enters in the FTN beam transfer line, which is part of the beam line just upstream the n_TOF target. In the FTN beam line, bending magnet and focusing/defocusing quadrupoles are installed to prepare the proton beam before the impact with the spallation target. In addition, the line is equipped with beam instrumentation like beam loss monitors and a SEM (Secondary Emission Monitor) grid, which allows to evaluate the beam position and size. The monitoring of beam position, size and intensity is of paramount to guarantee that design average and peak deposited powers are not exceeded and thus to ensure the safe operation of the target from the thermo-mechanical standpoint. Periodic radiation surveys are performed in FTN (during beam-off periods) to measure residual dose rates and identify potential beam loss locations. The FTN beam line is located in building 801, and its 3D CAD model is represented in Figure 2.2¹.

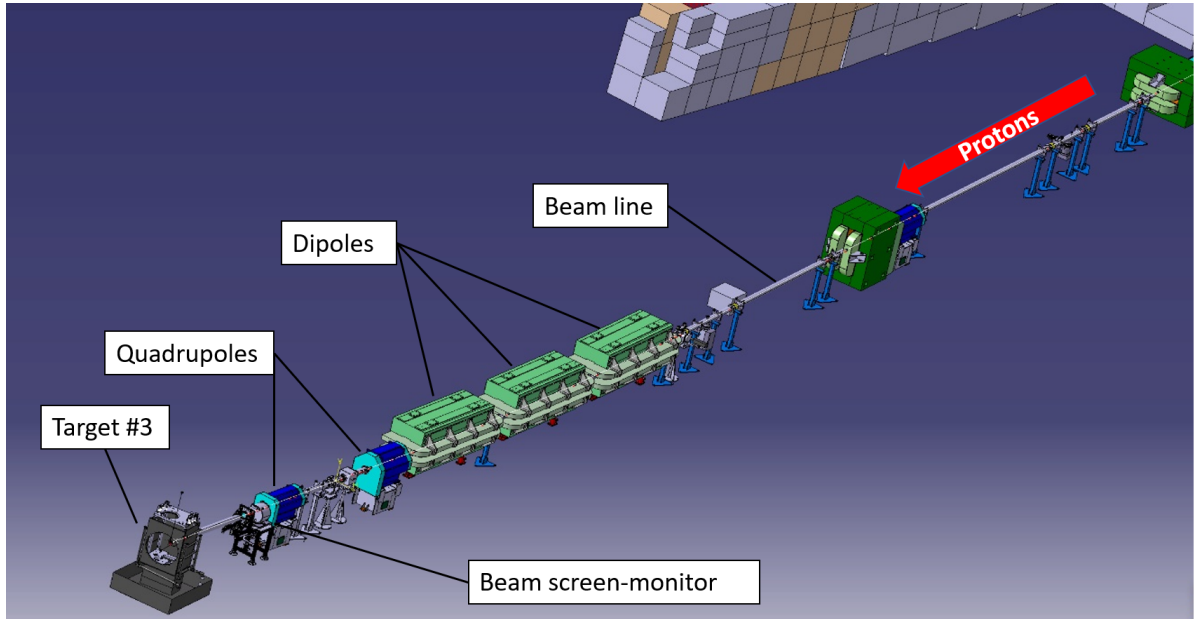


Figure 2.2: The FTN beam transfer line.

2.4. Operational beam parameters

The beam to the n_TOF target is an intense single proton bunch that is sent into the TT2 and subsequent FTN lines by fast extraction from the PS at a nominal momentum of 20 GeV/c. An RF bunch rotation before extraction reduces the total bunch length to

¹It should be noted that at the beginning of 2022 the last two quadrupoles were removed in order to reduce the beam aperture restrictions in the beam line.

about 25 ns. Two different variants exist, a dedicated (TOF) and a so-called parasitic beam. The bunch intensity is of the order of $700 - 850 \times 10^{10}$ protons on the dedicated cycle, and of the order of $300 - 350 \times 10^{10}$ protons on the parasitic cycle. The average intensity that can be sent to the target is mainly limited by the maximum power dissipation on the target, and to the acceptable radiation level around the n_TOF complex. Presently, the operational limit is set to 1.66×10^{12} protons/second. The minimum repetition period is 1.2 seconds, the operational repetition rate is less due to the average intensity limit but can be even lower due to the sharing of the PS Booster (PSB) and PS Supercycles with other PSB and PS users. The beam intensity is measured with a Beam Current Transformer (BCT) located upstream the target with an interlock threshold of 1.66×10^{12} p/s, which corresponds to the maximum average beam intensity acceptable for the n_TOF target. The beam is focused through a set of quadrupoles located in FTN line, and its spot size on the target in 2021 was of about 15 mm x 15 mm in horizontal and vertical directions.

2.5. Target

Since it was originally commissioned in 2001, three spallation targets have been employed:

- target #1 (2001-2004): a pile of lead bricks cooled by water, which was also used as moderator;
- target #2 (2008-2018): a cylindrical monolithic lead block water-cooled inside an aluminum vessel, with an independent moderator assembly made from aluminum alloy;
- target #3 (2021-): a six-lead slices core cooled by nitrogen gas and surrounded by a stainless steel vessel.

Target #3 was installed in the target pit in Spring 2021, and it received the first proton beam in July 2021. Figure 2.3, Figure 2.4 and Figure 2.5 show the design of target 3 [27]:

- six lead slices: they constitute the target core;
- seven aluminium plates: they form the cooling channels for the nitrogen gas and act as anti-creep structures;
- twelve aluminium stiffeners: they use four tie rods to support the lead blocks and anti-creep plates in the longitudinal direction;
- aluminium cradle: it provides support for the above-mentioned components and contains the two nitrogen manifolds;

- two aluminium supports for the two moderators (one vertical and one horizontal).
- low-cobalt stainless steel vessel: it houses the cradle assembly, supports the moderators and provides the interfaces for cooling system.

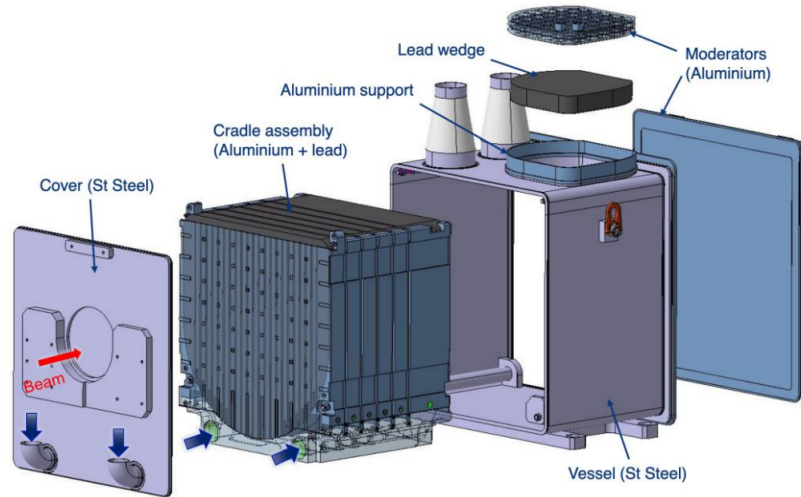


Figure 2.3: n_TOF spallation target#3: exploded model [27].

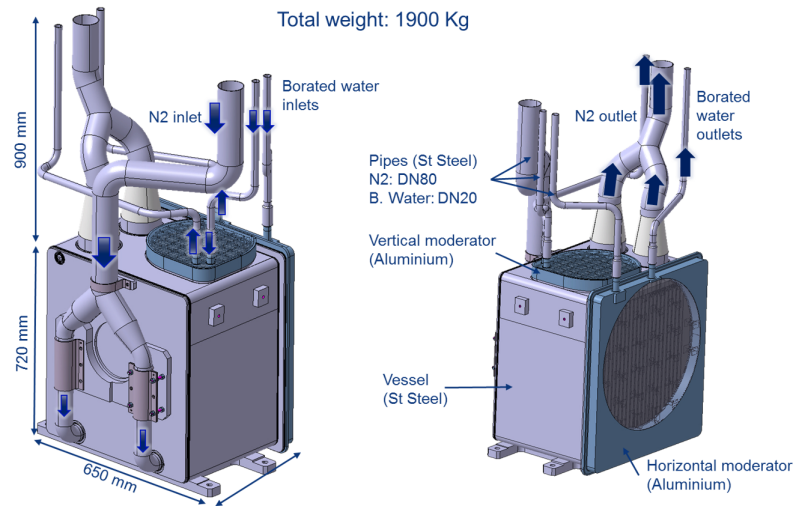


Figure 2.4: n_TOF spallation target #3: vessel and pipework design. Aluminium moderators can be supplied with either demineralized or borated water [27].

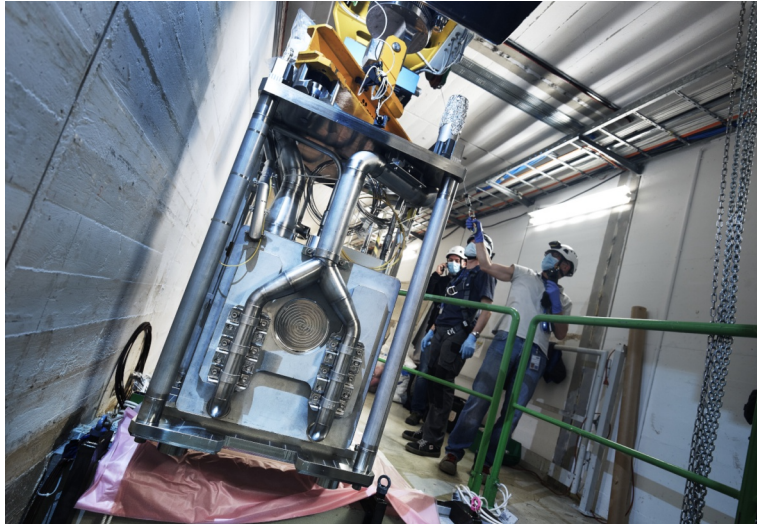


Figure 2.5: Picture of n_TOF spallation target #3.

Target #3 design was optimized from an RP standpoint taking into account the return on experience from the two previous targets. One of the critical RP aspects of the operation of target #1 and target #2 was the direct contact between the cooling water and the lead; due to erosion, corrosion and out-diffusion effects, spallation products from lead activation migrated into the cooling water (e.g. Hg-194, Bi-208, Gd-148, Po-208, Po-209 and Po-210). The water cooling circuit was equipped with nuclear-grade cartridges to filter some of these radionuclides and reduce the circuit contamination. The cartridges, concentrating such radionuclides, became very radioactive (several mSv/h) and represented a source of external exposure and potential contamination during maintenance activities in the cooling station. The change from water to nitrogen gas, coupled with the presence of HEPA (High Efficiency Particulate Air filter), and active carbon filters in the circuit (see Section 2.8) reduces the presence of lead spallation products and improves the radiological safety of the whole cooling station.

In view of the final target disposal, the use of aluminum over stainless steel for the target vessel would have offered reduced activation and residual dose rate, but lead to additional constraints that would have cancelled these benefits. In fact, chemical reactions may happen between aluminum and the concrete-based mortar used to prepare the waste, producing hydrogen gas that may damage the package in the long term. For this reason, it was decided to limit the amount of aluminum in the new target and to build the new vessel in stainless steel. The main cause of the higher residual dose rate of stainless steel is its cobalt content, with the production of Co-60 ($t_{1/2} = 5.3$ y) from thermal neutron capture on Co-59. In order to avoid safety issues with the target disposal and at the same time optimize the target residual dose rate, the vessel was made of stainless steel with a

cobalt concentration lower than 0.1 % in mass.

2.6. The lateral mobile shielding and the NEAR experimental station

The target is laterally shielded by a wall in order to limit air activation in the target area during beam operation and subsequent release into the environment and to reduce the residual activation levels in the area during accesses. Until 2019, the wall was made of fixed concrete blocks, for a maximum thickness of 200 cm. In 2020, the shielding was modified in order to fit a mobile version (Figure 2.6) allowing to access the target pit and flexible enough for potential future uses: in fact, a new experimental station was created, called NEAR, to perform irradiation in a mixed-radiation field [23, 26]. To compensate the reduced thickness of the new shielding wall, its first layer was made of 40 cm thick iron followed by 80 cm thick concrete blocks and finally 20 cm thick marble blocks (the latter to reduce the residual activation). In addition, several openings were included in the shielding design to access the target with endoscopes and radiation probes and to allow, in the future, the installation of a pneumatic irradiation station. A 3D-view of the mobile shielding is represented in Figure 2.7.



Figure 2.6: The mobile shielding: (a) in the closed position (b) in the open position [25].

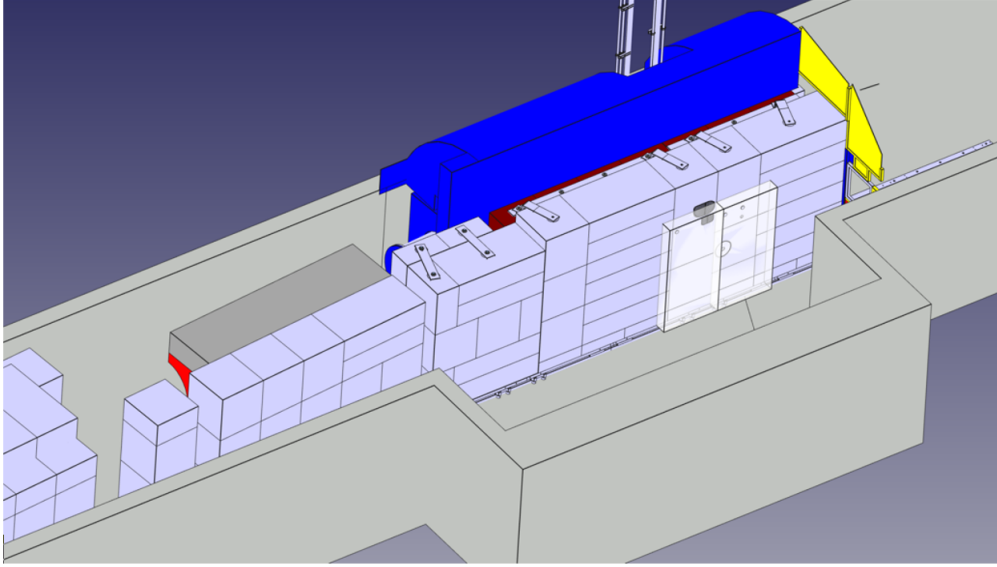


Figure 2.7: 3D-view of the mobile shielding [10]. The new experimental station NEAR was located in front of the mobile shielding, in order to perform neutron measurements in a highly fluent pulsed field.

2.7. ISR8

The ISR8 area, located in building 375, hosts several equipment and systems associated to the operation of the n_TOF facility, such as:

- the cooling station (375/T8-I74 and 375/T8-I75), classified as Controlled Radiation Area – Limited Stay and not accessible during beam operation;
- the n_TOF temporary storage (375/T8-A79), classified as Controlled Radiation Area – Limited Stay;
- the technical gallery (375/T8-203), classified as Controlled Radiation Area – Simple and not accessible during beam operation;
- the air handling units, and filters for the target area ventilation (375/T8-402), classified as Controlled Radiation Area - Simple.

The rest of ISR8 is classified as Supervised Radiation Area and can be accessed by authorised personnel during beam operation. The main sources of exposure in ISR8 are the neutron stray radiation from the vertical beam line and the stray and residual radiation from the cooling station (from the ion exchange resins of the water moderator circuits) [16]. Layouts of floor S and R of building 375 are represented in Figure 2.8 and Figure 2.9,

while Figure 2.10 shows a side view of the FLUKA geometry of the vertical beam line including ISR8.

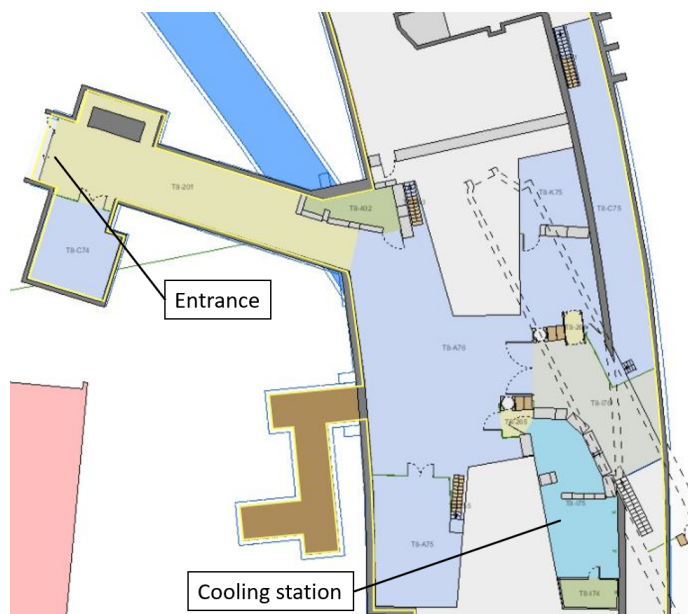


Figure 2.8: Building 375 layout (floor S).

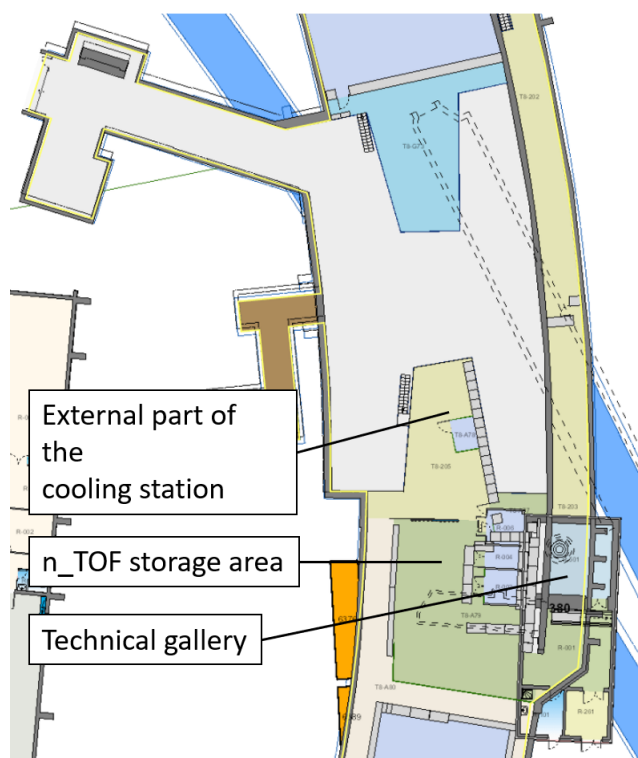


Figure 2.9: Building 375 layout (floor R).

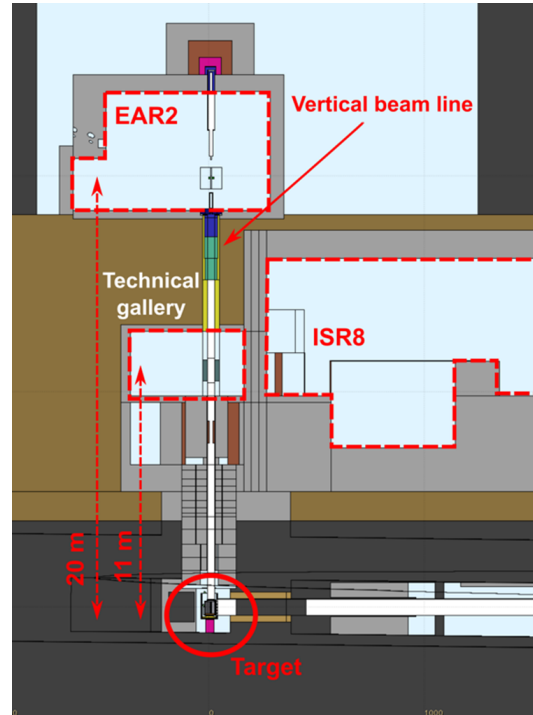


Figure 2.10: Side view of the FLUKA geometry of the vertical beam line including ISR8 [16].

2.8. Cooling station

As mentioned above, the cooling station is located in ISR8 and hosts three circuits:

- two water moderator circuits (horizontal and vertical) using either demineralized or borated water;
- the nitrogen cooling circuit, which ensure that the target temperature stays within safe operational values.

The main characteristics of the three circuits are summarized in Table 2.1.

Characteristic	Unit	Cooling circuit	Horizontal moderator	Vertical moderator
Medium	[-]	Nitrogen gas	Water	Water
Supply temperature	[°C]	20 ± 2	20 ± 2	20 ± 2
Nominal flow rate	[m ³ /h]	780 (Nm ³ /h)	0.7	0.7
Maximum pressure at equipment inlet	[bar]	0.5	2	2

Table 2.1: Main characteristics of the cooling and moderator circuits [14].

2.8.1. Moderator circuits

The two moderator circuits are independent of each other and have separate sampling locations for water analysis (γ -spectrometry and tritium measurement). Depending on the physics requirements, the moderator skids may work with either demineralized water or borated water. All the components are compatible with both types of water, and the skids are designed in such a way that water exchange from one type to the other can be carried out via a manual process.

2.8.2. Cooling circuit

The nitrogen cooling system is a closed circuit; the nitrogen coming from the target is filtered by two filtering units: an High Efficiency Particulate (HEPA) filter for particulate/aerosols and a charcoal filter to trap volatile species (e.g. iodines). The area housing the filtration units is under dynamic confinement at -20 Pa to prevent any leak of radioactive species into the ISR8. Regarding fluid dynamic aspects, the velocity of the nitrogen flow is subjected to constraints: a higher velocity may have a beneficial thermal effect, but it must remain below the 110 m/s erosion threshold. This fact directly affects some RP aspects because erosion can cause the presence of lead spallation products in the cooling circuit. Nitrogen gas is also continuously analysed by a differential ionization chamber, which provides information about the radioactivity concentration (Section 3.2).

The following figures represent some parts of the cooling station, such as circuits and filtering units.

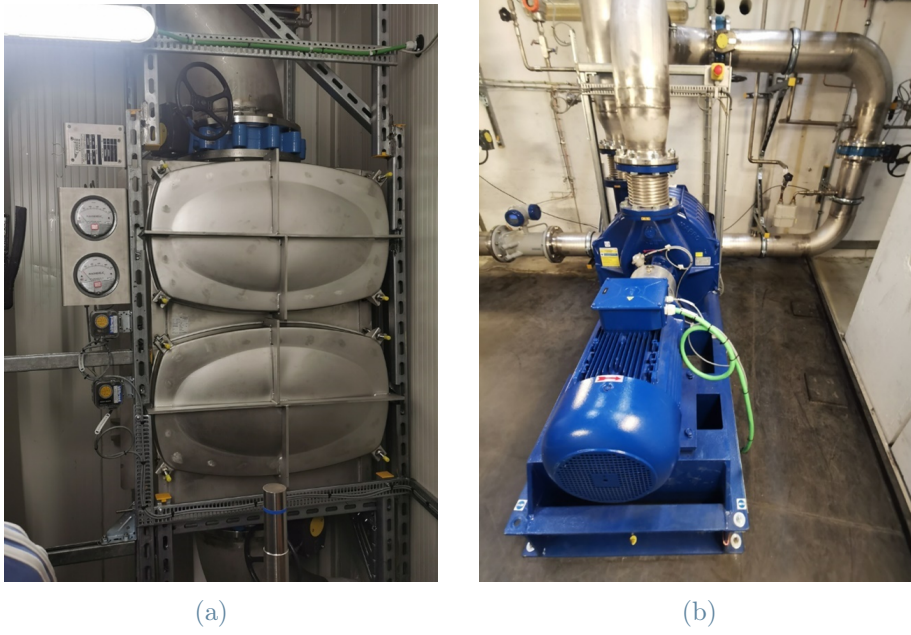


Figure 2.11: (a) Filter units. (b) Nitrogen blower.



Figure 2.12: Moderator water skids.

2.9. n_TOF radiological measurement campaign

After the Long Shutdown 2 (LS2, 2019-2021), the n_TOF facility resumed operation in 2021 with the first proton beam sent on the new spallation target in July. Extensive radiation protection measurements (stray and residual radiation) were carried out to monitor radiation levels and verify the conformity with the radiological area classification of the

n_TOF facility. In addition, the monitoring of the radioactivity concentration in the nitrogen gas, required a field characterisation of the differential ionisation chamber by means of Monte Carlo simulations and benchmark with experimental measurements. The measurement campaign is presented in the following order:

1. Instrument calibration:
 - LUPIN BF_3 : it is an extended neutron rem-counter, specially conceived to work in pulsed-radiation fields, used for the monitoring of neutron stray radiation; it was calibrated in the CERN RP calibration laboratory by means of an Am-Be source.
 - BM8 differential ionization chamber: employed for measuring the radioactivity concentration inside the nitrogen coolant. Its field response was assessed through FLUKA simulations and validated against experimental analysis.
2. Stray radiation measurements with the LUPIN, an organic scintillator typically used for operational radiation protection and hydrogen- and argon-filled ionisation chambers.
3. Residual dose rate measurements performed during radiation surveys in areas not accessible during beam operation.
4. Radioactive waste zoning, by installing metallic samples (copper, cobalt, aluminum) in specific locations along the neutron beam lines and by performing γ -spectrometry measurements once retrieved.

The work presented in this thesis refers to the 2021 beam operation period, namely from 19/07/2021 (first beam on target), to 15/11/2021, when the beam was stopped for the Year End Technical Stop (YETS).

3 | Detector calibration and characterisation

The calibration and characterisation of radiation detectors is fundamental to ensure the correct monitoring of radiation. The purpose of this chapter is to describe the calibration procedures implemented for two detectors used in the measurement campaign:

- the extended-range neutron rem-counter LUPIN BF_3 , which was calibrated with the reference Am-Be neutron source of the CERN RP calibration laboratory [15];
- the differential ionisation chamber BM8 (used to monitor the radioactivity concentration in the nitrogen gas), for which a field calibration factor was established by means of Monte Carlo simulations and validated against experimental measurements.

3.1. LUPIN BF_3 calibration

3.1.1. LUPIN BF_3

The neutron prompt radiation field at n_TOF may extend up to the GeV energy range and for this reason the LUPIN BF_3 extended-range rem-counter was used in the measurement campaign. In fact, its high-Z insert made of lead promotes (n,xn) reactions, making the LUPIN able of reliably measuring the ambient dose equivalent up to energies of several hundred MeV.

In addition, the LUPIN, manufactured by ELSE Nuclear (Italy) is suitable for working in pulsed neutron fields. The detector consists of a cylindrical BF_3 proportional counter placed at the centre of a polyethylene equilateral cylindrical moderator of 25 cm in diameter. Cadmium and lead layers are placed inside the moderator material. The structure is completed by two polyethylene inserts and electrostatic shielding, constituted by an aluminium cylinder 1.5 mm thick. Figure 3.1 reports the design of LUPIN BF_3 , while the main detector specifications are listed in Table 3.1 [7].

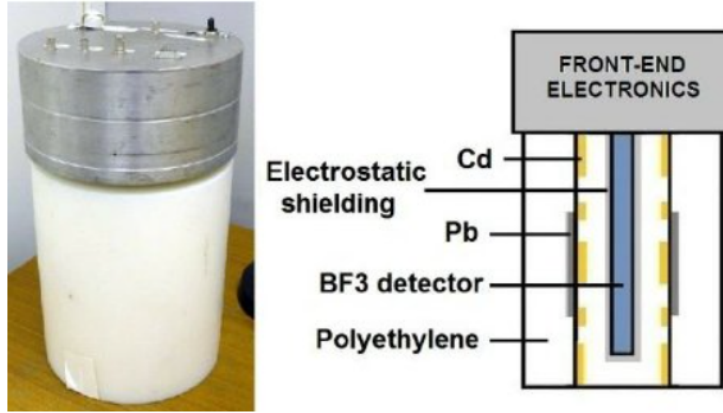


Figure 3.1: Picture and scheme of the LUPIN BF_3 [21].

Table 3.1: Technical specifications of the LUPIN.

Energy range	0.025 eV to 10 GeV
H*(10) range	10 nSv/h to 100 mSv/h
Nominal neutron sensitivity	0.6 cps/(μ Sv/h) (AmBe)
Gamma sensitivity	$< 0.5 \mu$ Sv/h at 50 mSv/h, 662 keV
Angular dependence	$< 20\%$
Serial number	SN 115

3.1.2. Calibration

The detector calibration was carried out at the CERN RP calibration laboratory, located in the building 772 (layout in Figure 3.2). The neutron calibration room is the R-401.

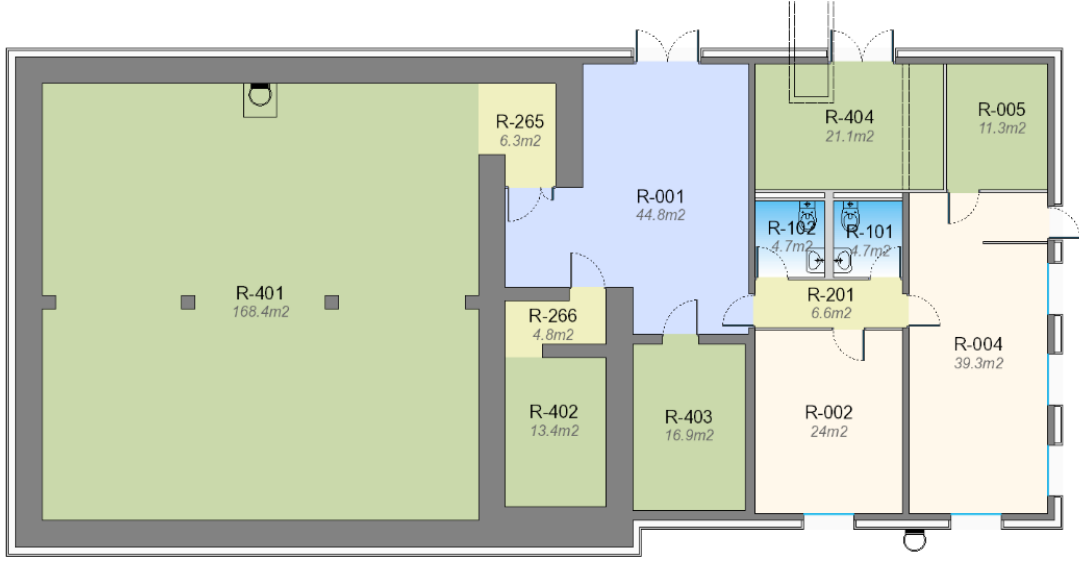


Figure 3.2: Calibration laboratory floor plan (Building 772-R)

The calibration was performed with the 888 GBq (nominal activity in 2015) Am-Be source with the detector located on the calibration bench located between the neutron and the photon irradiators (Track 1). All the source-to-detector distances were previously characterized with the SmartREM detector, a secondary standard neutron rem-counter [5, 15]. Table 3.2 shows the reference ambient dose equivalent rate, $H_{REF,i}^*(10)$, for the four selected distances.

Table 3.2: $H_{REF,i}^*(10)$ and corresponding source-to-detector distances.

Measurement ID, i	Source-to-detector distance [cm]	$H_{REF,i}^*(10)$ [$\mu\text{Sv/h}$]
1	101.8	650
2	131.6	400
3	192.6	200
4	292.6	100

Measurement set-up

The LUPIN calibration was monitored through the LabVIEW interface of the detector [13]. The measurement time was chosen for each measurement in order to integrate about 10'000 counts, resulting in 1% statistical uncertainty. The LUPIN was tested in vertical configuration as shown in Figure 3.3; the alignment was carried out by means of the available laser system, assuming that the centre of the BF_3 detector is placed at half the

height of the polyethylene moderator.

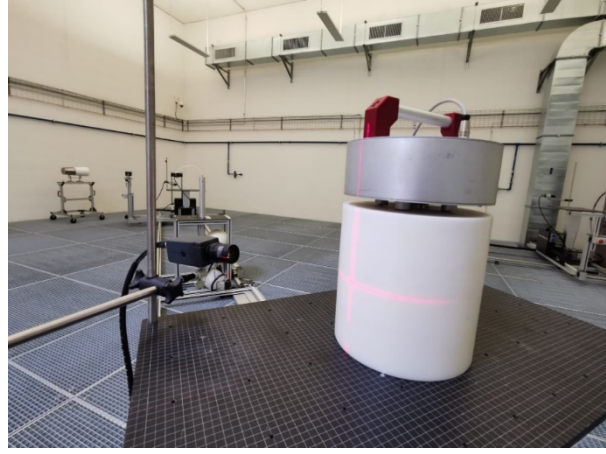


Figure 3.3: The LUPIN rem-counter installed on Track1.

Figure 3.4 shows the raw ambient dose equivalent rate measured by the LUPIN, $H_{LUPIN}^*(10)$, versus time, compared with $H_{REF}^*(10)$.

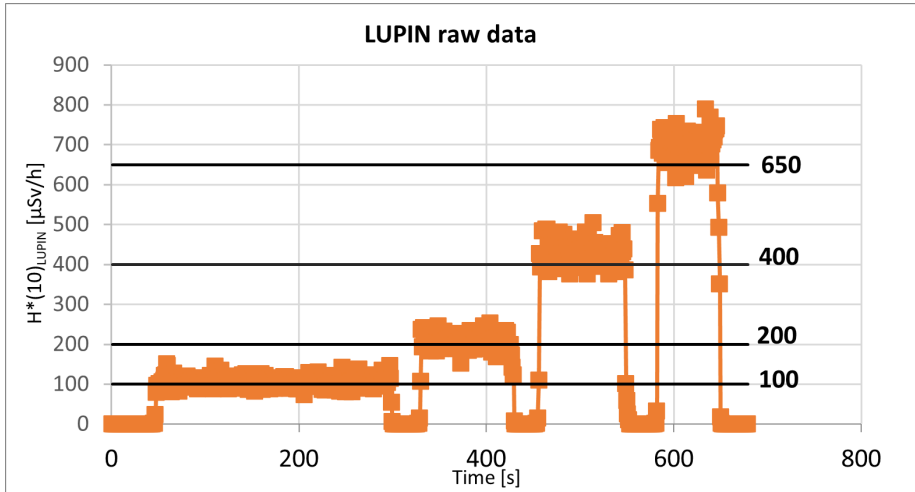


Figure 3.4: $H_{LUPIN}^*(10)$ versus time; $H_{REF}^*(10)$ used in the calibration procedure is also indicated with black lines.

Calibration

The LUPIN software provides as output the $H^*(10)$ in $\mu\text{Sv/h}$; consequently, the calibration procedure consisted in determining a correction factor CF_{LUPIN} , i.e. a factor that

modifies the $H_{LUPIN}^*(10)$ to obtain the conventional true value of the ambient dose equivalent rate. The output data of the LUPIN were recorded and the average $H_{LUPIN,i}^*(10)$ was calculated for each reference measurement i (see Table 3.2). Then, for each reference measurement i , $CF_{LUPIN,i}$ was computed as the ratio between the $H_{LUPIN,i}^*(10)$ and the reference $H_{REF,i}^*(10)$ as shown in Equation 3.1.

$$CF_{LUPIN,i} = \frac{H_{LUPIN,i}^*(10)}{H_{REF,i}^*(10)} \quad (3.1)$$

The correction factor CF_{LUPIN} was calculated as the average value of the single correction factors $CF_{LUPIN,i}$, as shown in Equation 3.2.

$$CF_{LUPIN} = \frac{1}{n} * \sum_{i=1}^{n=4} CF_{LUPIN,i} \quad (3.2)$$

The uncertainty on the correction factor was determined considering the following uncertainties:

- Statistical uncertainty on the LUPIN measured counts (ranging between 0.62% and 0.94%, type A);
- Systematic uncertainty on the $H_{REF,i}^*(10)$ (4%, type B).

The uncertainties associated with $CF_{LUPIN,i}$ and CF_{LUPIN} were quantified through the error propagation formula (Equation 3.3, [19]): if $x, y, z, \dots$ are directly measured counts or related variables for which the respective standard deviations $\sigma_x, \sigma_y, \sigma_z, \dots$ are known, the standard deviation for any quantity u derived from these variables can be computed as:

$$\sigma_u = \sqrt{\left(\frac{\partial u}{\partial x}\right)^2 * \sigma_x^2 + \left(\frac{\partial u}{\partial y}\right)^2 * \sigma_y^2 + \left(\frac{\partial u}{\partial z}\right)^2 * \sigma_z^2 + \dots} \quad (3.3)$$

The resulting correction factor is 1.057 ± 0.013 .

Figure 3.5 shows the correction factors for each reference measurement together with the average value at one standard deviation; the numerical results are listed in Table 3.3.

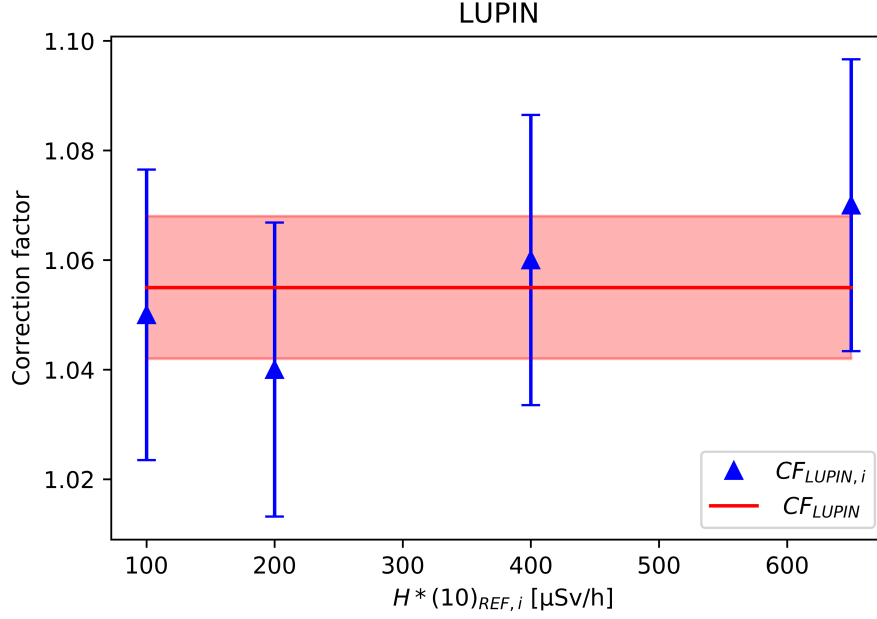


Figure 3.5: $CF_{LUPIN,i}$ versus $H^*_{REF,i}(10)$ together with the average value $CF_{LUPIN} \pm$ one standard deviation.

Table 3.3: Results of the LUPIN calibration.

Source-to-detector distance [cm]	$H^*_{REF,i}(10)$ [$\mu\text{Sv/h}$]	$H^*_{LUPIN,i}(10)$ [$\mu\text{Sv/h}$]	$CF_{LUPIN,i}$ [-]
101.8	650	698.63 ± 4.33	1.075 ± 0.027
131.6	400	425.83 ± 2.79	1.065 ± 0.027
192.6	200	208.10 ± 1.96	1.041 ± 0.027
292.6	100	104.81 ± 0.84	1.048 ± 0.027

3.2. Response characterization of the differential ionisation chamber BM8

The BM8 detector is a flow-through differential ionization chamber used to measure the radioactivity concentration of the nitrogen gas used to cool the third-generation spallation target at n_TOF. The manufacturer provides a calibration factor for the measurement of tritium in air with nitrogen as supporting gas; therefore, the calibration factor for the specific radioactive gas mixture in which the detector is employed was assessed.

3.2.1. Description of BM8 detector and calculation of the in-field calibration factor

The BM8 (Figure 3.6) consists of two ionisation chambers, which are identical in construction: the reference chamber is sealed and filled with non-radioactive air, while the measurement chamber is connected to the gas cooling circuit.

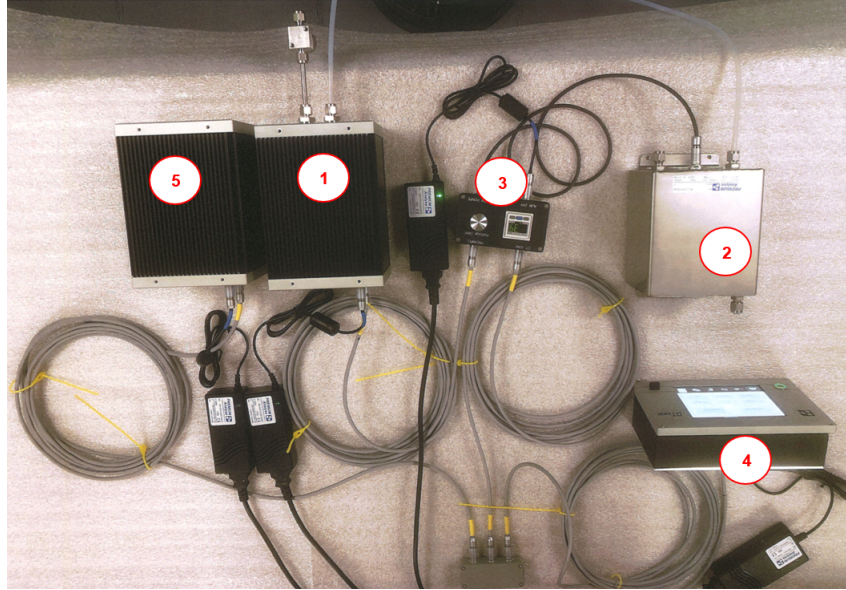


Figure 3.6: The BM8 detector. The fluid is pumped in the measurement chamber (1) by means of a pump (2), whose mass flow rate can be adjusted by a manual control (3). The screen (4) allows to display historical and real-time measurements, and enables to set the calibration factor. The background is measured by the reference chamber (5), and it is subtracted from the measurement chamber signal.

The net current, i.e. current measured by the measurement chamber minus the current measured by the reference chamber, is converted via a specific calibration factor to volumic activity (Bq/m^3). The manufacturer provides the detector calibrated for H-3 in air (calibration factor of $7.282\text{e}4 \text{ Bq}/\text{m}^3/\text{fA}$ [24]). However, additional radionuclides are expected in the nitrogen cooling gas, which may contribute differently to the charge produced in the measurement chamber and subsequently to the measured signal. Therefore, the detector response was evaluated for the real mixture of radioactive gas and the corresponding field calibration factor was calculated.

3.2.2. FLUKA simulations

Simulation parameters

The measurement chamber of the BM8 detector was modeled with the FLUKA Monte Carlo code to estimate its response to various radioisotopes. The chamber was filled with a gas mixture composed by 97.3% of nitrogen (N) and 2.7% of argon (Ar) in weight, with a density of 0.0011465 g/cm^3 [3, 16]. It should be noted that the presence of argon was not indicated in the user's requirements for the target #3 cooling system HI-PROPERTIprodctiinter[14] and it was discovered only during the facility commissioning by means of mass spectrometer and radiation decay measurements. With the present nitrogen generator system, argon presence cannot be avoided.

The decay properties of the specific radionuclides are simulated using the BEAM card with particle type set to ISOTOPE and the HI-PROPErties card, where the mass and atomic number of the radionuclide are defined. Each radionuclide¹ (H-3, C-11, N-13, Ar-41, Kr-79, Kr-85m, Kr-87, Xe-125 and Xe-127) is individually treated in a dedicated simulation. In addition to the radionuclides expected in the nitrogen gas, for the sake of completeness and for future reference, O-15, Cl-38 and Cl-39 were also considered (these radionuclides are typically relevant for air activation at particle accelerators). The location of the radionuclide decay is homogeneously sampled within the active volume of the chamber via a *source.f* user-routine. The user-routine samples the decay location in a volume slightly larger than the active volume of the chamber but the decay is simulated only if the location belongs to the active volume. In this way, any simulation issue that may arise if the location of the radionuclide decay is generated at the boundaries between two FLUKA regions is avoided. The decay particles and the secondary electrons/photons are propagated through the active volume including surrounding walls to consider backscattering. The production and transport kinetic energy thresholds were set to 1 keV for photons and to 4 keV for electrons and positrons. Finally, the deposited energy from the propagation and interaction of the decay particles and their secondaries is scored with the USRBIN card in the active volume of the chamber.

Deposited energy results

Figure 3.7 and Table 3.4 show the deposited energy in the active volume of the BM8 for each radionuclide.

¹The list of the radionuclides was defined using information from previous FLUKA activation studies for the nitrogen gas [16] and from the results of γ -spectrometry measurements on nitrogen samples.

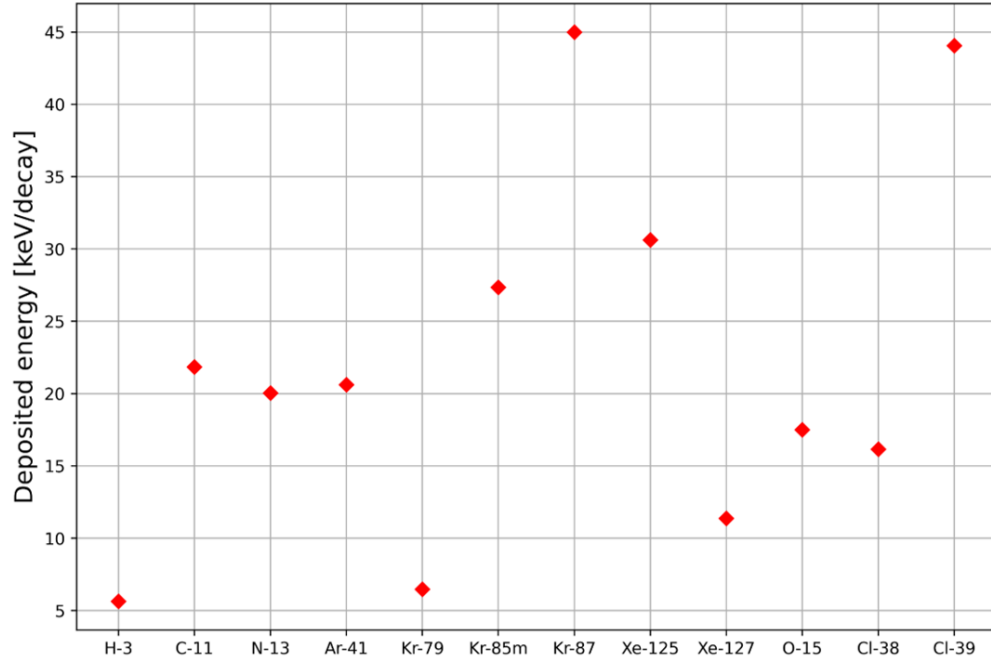


Figure 3.7: Deposited energy in keV per decay per radionuclide. The statistical uncertainty of the simulations is always lower than 1% and, for this reason, the error bars are not shown.

Table 3.4: Deposited energy in keV per decay.

Radionuclide	Half-life	Deposited energy [keV/decay]	Statistical uncertainty
H-3	12.3 y	5.64	<0.1%
C-11	20.4 min	21.85	<0.1%
N-13	10 min	20.05	0.1%
Ar-41	1.8 h	20.62	0.1%
Kr-79	1.5 d	6.48	0.2%
Kr-85m	4.5 h	27.35	<0.1%
Kr-87	1.3 h	44.99	<0.1%
Xe-125	16.9 h	30.62	<0.1%
Xe-127	36.4 d	11.38	0.3%
O-15	2.0 min	17.5	<0.1%
Cl-38	37.2 min	16.17	0.2%
Cl-39	55.6 min	44.06	<0.1%

In addition to the statistical uncertainty (which is always <1%), the systematic uncertainties are related to the modeling process, i.e.:

- difference between the real geometry and the one reproduced in the Monte Carlo code;
- charge collection efficiency (assumed to be 100%).

To estimate the systematic uncertainty introduced by the modeling process a comparison with the experimental calibration factor, i.e. the calibration factor for tritium (H-3) in air given by the manufacturer, is performed. In this way it is possible to quantify the deviation between the experimental and the simulated phenomena for a calibration, and then apply the same deviation to the calculations for the other radionuclides. The calibration factors are weighted by using the same scaling factor computed through the comparison for tritium in air, with the approximation that the systematic uncertainty due to the modeling process is independent from the radionuclide.

3.2.3. Calibration factors

The calibration factor for each radionuclide can be determined from its deposited energy in the active volume of the chamber. By using the average energy to produce an ion pair (W-factor) in the specific n_TOF gas mixture², i.e. 34.6 ± 0.2 eV [22], the number of produced electron-ion pairs is calculated. By multiplying this number times the elementary charge (1.602×10^{-19} C), the total charge generated per decay in the active volume is computed. Then, the charge is converted into an electric current and multiplied by the active volume, i.e. 0.664 L; the inverse of the result is the calibration factor expressed in Bq/m³ per A. These steps are summarized in Figure 3.8.

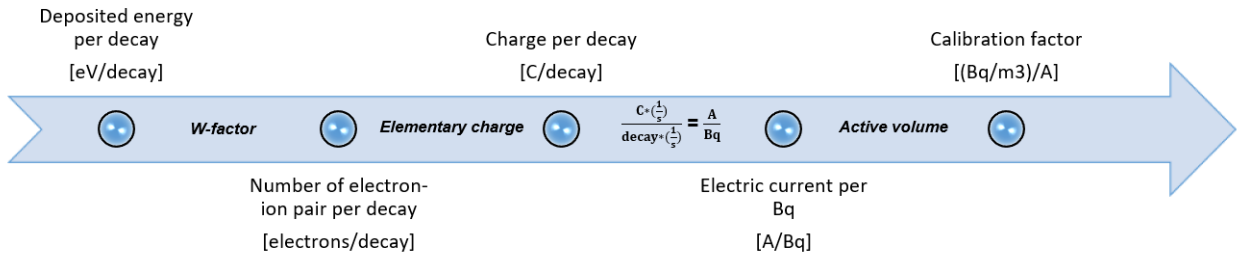


Figure 3.8: The calibration factor is obtained starting from the deposited energy per decay computed from the simulation.

As mentioned before, the tritium response in air is also calculated to compare it with the

²The average energy to produce an ion pair is calculated by weighting the W-values for nitrogen, i.e. 34.8 ± 0.2 eV, and for argon, i.e. 26.31 ± 0.18 eV, against the respective fractions in the gas mixture, i.e. 97.3% of N and 2.7% of Ar.

calibration factor provided by the manufacturer. The comparison is shown in Table 3.5.

Table 3.5: Comparison between the simulated tritium calibration factor in air and the one provided by the manufacturer.

Isotope	Calibration factor (simulation) [Bq/m ³ /A]	Calibration factor (manufacturer) [Bq/m ³ /A]	Scaling Factor (SF) Simulation/Manufacturer
H-3 (in air)	5.64e19	7.28e19	0.77

The simulated calibration factor is 23% lower than the one provided by the manufacturer; this discrepancy could be originated from:

- the difference between the real and the modeled geometry (including material composition differences impacting the scattering behavior);
- physics model in the FLUKA code;
- the assumption that the charge collection efficiency is 100%, since we are neglecting the phenomena that compete to worsen it, such as the recombination effects.

The calibration factors for the other radionuclides were scaled, assuming the same systematic deviation. The results are listed in Table 3.6.

Table 3.6: Calibration factors and scaled calibration factors. The uncertainties consider the statistical uncertainty from the simulations and the uncertainty on the W-value.

Isotope	Calibration factor [Bq/m ³ /A]	Uncertainty	Scaled calibration factor [Bq/m ³ /A]
H-3	5.77e19	0.6%	7.45e19
C-11	1.49e19	0.6%	1.92e19
N-13	1.62e19	0.6%	2.09e19
Ar-41	1.58e19	0.6%	2.04e19
Kr-79	5.02e19	0.6%	6.48e19
Kr-85m	1.19e19	0.6%	1.54e19
Kr-87	7.23e18	0.6%	9.33e18
Xe-125	1.06e19	0.6%	1.37e19
Xe-127	2.86e19	0.6%	3.69e19
O-15	1.86e19	0.6%	2.40e19
Cl-38	2.01e19	0.6%	2.60e19
Cl-39	7.38e18	0.6%	9.53e18

3.2.4. Field calibration factor

To obtain the field calibration factor, the individual calibration factors were weighted according to the expected relative contribution of each radionuclide to the total activity

in the cooling circuit. The relative contribution was calculated by folding the particle spectral fluences (for protons, neutrons, photons and charged pions) in the nitrogen surrounding target #3 [16] with the nuclide production cross sections in the nitrogen gas (97.3% of nitrogen and 2.7% of argon); the nuclide production yields were then used to evaluate the activity present in the circuit for a beam intensity of 1.66×10^{12} protons per second and an irradiation time of 210 days, which is representative of a typical n_TOF operational year. The results are listed in Table 3.7 and the related statistical uncertainties are lower than 1%. It should be noted that some of the radionuclides (not listed in Table 3.7) are not expected to be encountered in the nitrogen circuit at the level of the BM8 since they are likely trapped by the HEPA and charcoal filters installed in the circuit, and therefore they were neglected for the calculation of the field calibration factor. The field calibration factor is calculated using the radionuclides with a relative contribution higher than 0.1%, i.e. H-3, C-11, N-13 and Ar-41 and results in $2.06 \times 10^{19} (\pm 1\%) \text{ Bq/m}^3/\text{A}$.

Table 3.7: Results of ActiWiz calculations. The relative contributions to the total activity are estimated by neglecting the radionuclides trapped by the HEPA and charcoal filter of the circuit.

Isotope	Half-life	Activity [Bq]	Volumic activity [Bq/m ³]	Relative contribution to the activity	Relative contribution to the field calibration factor
H-3	12.3 y	2.93e05	1.47e05	0.17%	0.6%
C-11	20.4 min	2.44e07	1.22e07	14.37%	13.4%
N-13	10 min	8.79e07	4.40e07	51.81%	52.7%
C-14	5700 y	1.18e05	5.90e04	0.07%	-
O-15	2 min	3.13e04	1.57e04	0.02%	-
Ar-41	1.8 h	5.69e07	2.85e07	33.56%	33.2%

3.2.5. Nitrogen decay study

The dominant contributions of C-11, N-13 and Ar-41 to the radioactivity may be demonstrated experimentally by analysing the decay of the radioactivity concentration in the nitrogen circuit during beam-off periods, which can be fitted with an exponential function. From the fitting procedure, one obtains an estimation of the decay constant, that could be used for computing the half-life of the dominant (in terms of radioactivity concentration) radionuclide (Equation 3.4).

$$T_{1/2} = \frac{\ln(2)}{\lambda} \quad (3.4)$$

Since the radioactivity concentration in the nitrogen gas is expected to be dominated by three radionuclides, i.e. C-11, N-13 and Ar-41, it was decided to fit the current measured by the the BM8 with a sum of three exponential functions (Equation 3.5):

$$f(t) = C_1 e^{-\lambda_1 t} + C_2 e^{-\lambda_2 t} + C_3 e^{-\lambda_3 t} \quad (3.5)$$

The fitting function $f(t)$ represents the signal of the BM8 (expressed in current) as a function of time; it consists of three exponential terms, in which λ_i ($i=1,2,3$) are the decay constants, multiplied by three coefficients C_1 , C_2 and C_3 . These coefficients add up when $t=0$, giving the initial current $f(0)$. The analysis was performed at the beginning of the Year-End Technical Stop (YETS) (15th November 2021). A period of 360 minutes has been taken as a reference, from 06:00 to 12:00. The fitting was performed with Python3 and the results are reported in Table 3.8 and plotted in Figure 3.9 and Figure 3.10.

Table 3.8: Results of the fitting.

C_1 [fA]	0.00017
C_2 [fA]	0.00024
C_3 [fA]	0.00043
λ_1 [1/min]	0.027
λ_2 [1/min]	0.006
λ_3 [1/min]	0.076
Half life 1 [min]	25.35
Half life 2 [min]	119.67
Half life 3 [min]	9.17

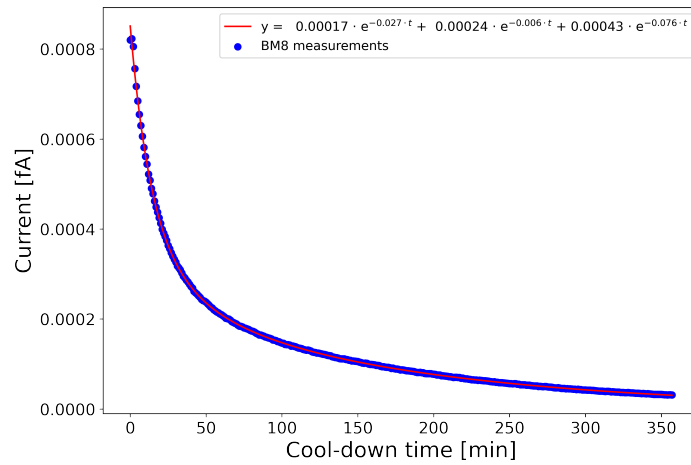


Figure 3.9: BM8 signal over 360 minutes during a shut-down phase (YETS). The fitting is performed through a three-exponential function.

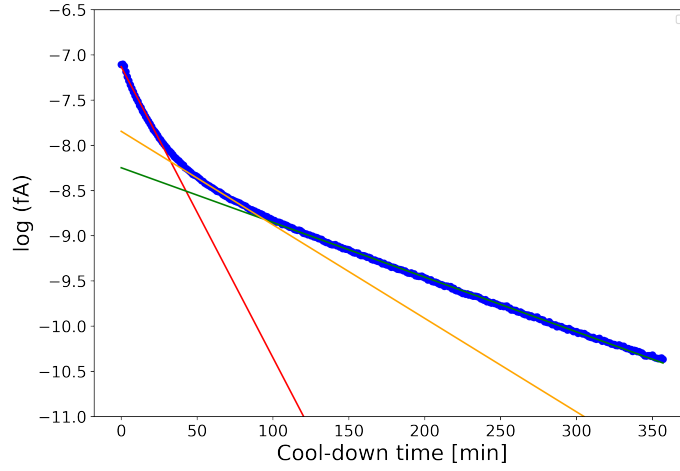


Figure 3.10: Logarithmic representation of the BM8 signal. The variation in slope indicates the change in the contribution to the signal of radionuclides over time, according to the own half-life.

Figure 3.10 gives a good representation of the changes over time of each individual radionuclide to the signal. If only a single-radionuclide had been present in the circuit, the curve would have been linear (in logarithmic scale). The three half-lives obtained from the fitting procedure are compatible with the ones of C-11 (20 min), N-13 (10 min) and Ar-41 (110 min) (Table 3.9); this provide an empirical confirmation of the assumptions taken above.

Table 3.9: Comparison between the experimental half-lives and the ones found in the scientific literature.

Radionuclide	Experimental half-life [min]	Theoretical half-life [min]	Ratio (experimental/theoretical)
C-11	25.35	20.4	1.24
N-13	9.17	10	0.92
Ar-41	119.67	109.34	1.09

3.2.6. Comparison with experimental measurements

During the operation of target #3 in 2021, three nitrogen gas samples were taken and measured by γ -spectroscopy. The sampling was performed by connecting a 0.4 litre volume bottle to the circuit just upstream the BM8. The bottle was then sent to the RP radioanalytical laboratory and measured by γ -spectrometry; the activity was reported to the moment when the sample was taken in order to correlate the results with the reading

of the BM8. Unfortunately, only one out of the three samples could be taken during relative stable beam conditions and can be used for this comparison. The γ -spectrometry results of the sample taken on 14/10/2021 at 11:00 are given in Table 3.10. The activity of H-3, C-11 and N-13 can be estimated from the measured activity of Ar-41 (if the latter is at saturation), using the expected relative contribution of the three radionuclides given in Table 3.7; this results in an activity concentration of:

- 2.35e4 Bq/ m^3 for H-3;
- 1.99e6 Bq/ m^3 for C-11;
- 7.16e6 Bq/ m^3 for N-13.

One can neglect the contribution of the other radionuclides measured in the nitrogen sample, i.e. Kr-79, Kr-85m, Kr-87, Xe-125 and Xe-127, because their relative contribution to the radioactivity concentration is much lower (at least two order of magnitudes) than the ones from C-11, N-13 and Ar-41 and the respective calibration factors listed in Table 3.6 are within a factor of 3 with respect to the field calibration factor. The total activity in the circuit is estimated to be 1.38e7 Bq/ m^3 . When the nitrogen sample was taken, the BM8 was measuring an activity concentration of 6.00e7 Bq/ m^3 . This value needs to be corrected by the field calibration factor, using Eq:

$$BM8_{corr}[Bq/m^3] = BM8 * \frac{C_{infield}}{C_{3H}} \quad (3.6)$$

where $BM8_{corr}$ is the reading of the BM8 corrected by the field calibration factor $C_{infield}$, and BM8 is the reading of the BM8 making use of the calibration factor from the manufacturer, C_{3H} . This results in 1.70e7 Bq/ m^3 , which is sufficiently consistent with the estimated value of 1.38e7 Bq/ m^3 .

Table 3.10: γ -spectrometry results on the nitrogen sample taken on 14/10/2021 at 11:00.

Radionuclide	$t_{1/2}$	A [Bq/ m^3]	Uncertainty at 2 σ
Ar-41	1.8 h	4.64e6	5%
Kr-79	1.5 d	1.22e4	31%
Kr-85m	4.5 h	1.55e4	42%
Kr-87	1.3 h	1.80e4	52%
Xe-125	16.9 h	5.31e3	18%
Xe-127	36.4 d	1.19e4	9%

Tritium is not detectable by γ -spectrometry since it is a pure β^+ emitter. However, after about two weeks from the end of beam at n_TOF , i.e. around the 30/11/2021, the BM8 was measuring an activity concentration of about $1.7\text{e}5 \text{ Bq}/m^3$. If one attributes this signal completely to tritium because of its longer half-life with respect to the other radionuclides, its contribution to the radioactivity concentration in the nitrogen circuit is still negligible compared to Ar-41, C-11 and N-13 during beam operation.

4 | Radiation measurement campaign

This chapter describes the radiological measurement campaign performed in ISR8 and in the n_TOF target area during the first operational year of the third-generation spallation target. The ambient dose equivalent rate in areas accessible during beam operation was measured by means of mobile and fixed instrumentation to validate the conformity with the radiological area classification. The residual dose rate measurements were carried out in the target area, cooling station and technical gallery.

4.1. Instrumentation

The employed instrumentation can be divided into two categories:

- Portable detectors for stray radiation measurements (Figure 4.1):
 - IG5 trolley, composed of:
 1. a CENTRONIC high-pressure ionization chamber IG5-H20 (hydrogen-filled at 20 bar), which has a high neutron sensitivity and a lower sensitivity to photons.
 2. a CENTRONIC high-pressure ionization chamber IG5-A20 (argon-filled at 20 bar), which has a high photon sensitivity and a lower sensitivity to neutrons.
 - LUPIN (described in Section 3.1) [20].
 - Automess 6150AD-b/E (AD-b): it is a portable cylindrical three-by-three-inch organic scintillator. When coupled with a dose rate meter 6150AD, it can measure the ambient dose equivalent from photon radiation. A router was connected with the detector to stream the measured data to the REMUS¹

¹REMUS is the software designed to monitor the devices of the radiation and environmental monitoring system 365 days a year, 24/7; it allows the monitoring of real-time measured values, alarms and

supervision.

- Fixed monitors ²(Figure 4.2 - Figure 4.4):
 - PAXNT112: in front of the PAD (Personnel Access Device) in ISR8;
 - PAXNT211: on top of the cooling station, ISR8;
 - PAXNT212: adjacent to the wall separating the n_TOF storage area from the vertical beam line, ISR8;
 - PAHNT211: next to the ion exchange resins in the cooling station, ISR8;
 - PAHNT212: next to water pipes in the room under dynamic confinement of the cooling station, ISR8;
 - PAHNT214: at the entrance of the cooling station close to the nitrogen blower, ISR8;
 - PMINT211: in the technical gallery close to the permanent magnet of the vertical beam line;
 - PMINT101: close to the new SEM (Secondary Emission Monitors) grid in the FTN beam line;
 - PMINT201: in front of the mobile shielding in n_TOF target area;
 - PMINT301: at the entrance of the n_TOF target area;

In addition, dedicated radiation surveys were performed with the Automess 6150AD detector, sensible to gamma and X radiation in a range between 45 keV and 2.6 MeV.

operational states of device. Furthermore, it also allows the display of historical data by ensuring the recovery of measured values recorded locally in the measuring devices [12].

²PAHNT-devices are Geiger-Muller counters mounted on a support, PAXNT-devices are high pressure ionization chamber hydrogen-filled and PMINT-devices are air-filled ionization chambers.



Figure 4.1: Portable detectors installed ISR8: the LUPIN (white cylinder) and the IG5 trolley (on the right hand side with respect to the LUPIN) with the hydrogen- and argon-filled high-pressure ionization chambers.

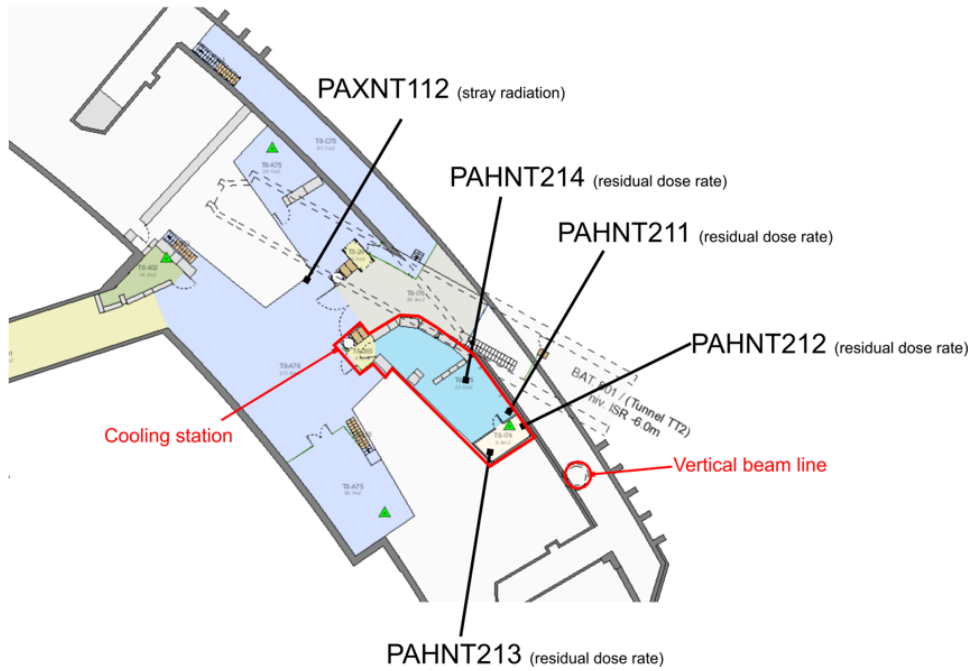


Figure 4.2: Fixed RP monitor locations in ISR8 (S-floor).

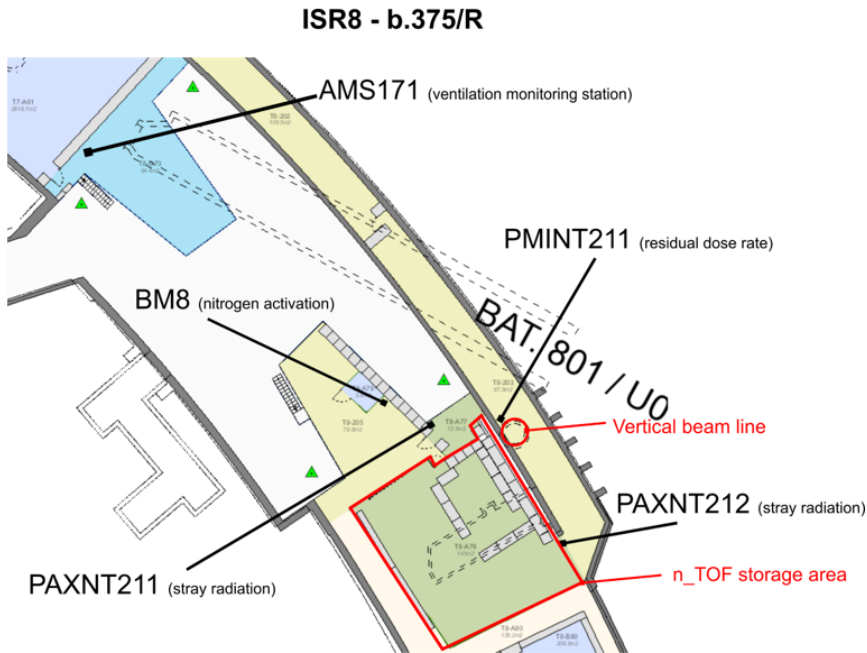


Figure 4.3: Fixed RP monitor locations in ISR8 (R-floor).

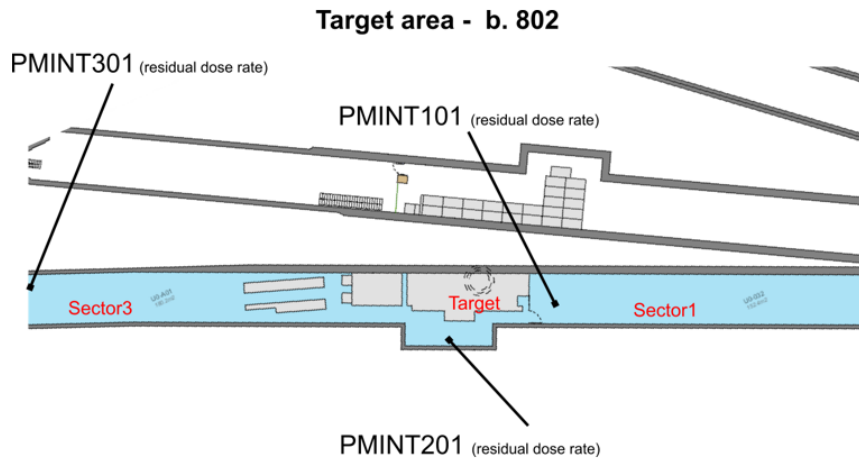


Figure 4.4: Fixed RP monitor locations in the target area.

4.2. Measurements and data analysis

Two types of radiation measurements were performed:

- Stray radiation measurements: they are relatively long measurements (lasting several days) that were correlated with the beam intensity and were carried out using portable detectors and fixed monitors (PAXNT-devices).

- Residual dose rate measurements: residual dose rate maps were obtained by means of dedicated radiation surveys during beam off periods; in addition, information from the radiation surveys were complemented by the analysis of fixed monitors for residual dose rate (PMINT- and PAHNT-devices).

4.2.1. Stray radiation measurements

Stray radiation measurements were made through fixed monitors (PAXNT-devices) and portable detectors. The latter was placed at selected locations for a specific amount of time. All the instruments, except the LUPIN, were connected to the REMUS supervision. The LUPIN data recording was performed via a dedicated LabVIEW interface running on a portable laptop connected to the detector. In order to normalize the stray radiation measurements, beam intensity information was obtained from the beam current transformer³ installed in the FTN beam line via TIMBER, an interactive GUI application to query data from the CERN Logging Service (CALS). To obtain the ambient dose equivalent rate at a specific location due to stray radiation and compare it with the radiological area classification, the following analysis was performed:

1. A set of relatively stable beam periods was selected. The number of periods is indicated with J and the associated index is $j=1,2,3,\dots,J$.
2. For each period j , a normalized ambient dose equivalent rate, $H_{j,N}^*(10)$, was calculated by dividing the average ambient dose equivalent rate measured by the instrument in the period j , $H_j^*(10)$, by the average beam intensity in the period j , I_j .

$$H_{j,N}^*(10) = \frac{H_j^*(10)}{I_j} \quad (4.1)$$

$H_{j,N}^*(10)$ is the ambient dose equivalent rate normalized at 1 proton per second in the period j , and it is expressed in $[(\mu\text{Sv/h}) / (\text{p/s})]$.

3. The mean value $H_N^*(10)$ is computed as the average of all the $H_{j,N}^*(10)$.

$$H_N^*(10) = \frac{1}{J} \sum_{j=1}^J H_{j,N}^*(10) \quad (4.2)$$

$H_N^*(10)$ is the average ambient dose equivalent rate normalized at 1 proton per second for a certain location, and it is expressed in $[(\mu\text{Sv/h}) / (\text{p/s})]$.

³The TIMBER variable is named FTN.BCT.477:TOTAL_INTENSITY.

4. In order to compare the measurements with the radiological area classification, the results were scaled to the maximum average beam intensity at n _TOF, i.e. $1.66e12$ p/s [16]. The obtained value is indicated as $H_{N,max}^*(10)$ and it is expressed in $\mu\text{Sv/h}$.

$$H_{N,max}^*(10) = H_N^*(10) * 1.66e12 \quad (4.3)$$

4.2.2. Residual dose rate measurements

Radiation surveys

Radiation surveys were performed in the cooling station and in the target area during beam off periods, e.g. technical stops. Radiation surveys are a versatile method to assess residual dose rates, evaluate possible hot-spots and complete information provided by fixed monitors.

Fixed monitor analysis

A detailed analysis of the residual dose rate in the cooling station and in the target area was performed during several beam off periods⁴. The chosen periods were:

- 21/07/2021 (beam off at 20:00 for 12 hours).
- 26/08/2021 (beam off at 05:00 for 4 hours).
- 14/09/2021 (beam off at 07:40 for 30 hours for the Injector Technical Stop 2, ITS2).
- 15/11/2021 (beam off at 06:00 for the start of Year End Technical Stop, YETS).

4.2.3. Measurement locations

ISR8

Table 4.1⁵, Figure 4.5 and Figure 4.6 show the locations where radiation measurements were performed in ISR8 (with portable detectors and fixed monitors). In addition, radiation surveys were performed inside the cooling station at specific locations; these are detailed in Section 4.3.2.

⁴It should be noted that in 2021 the n _TOF facility started its operation with the proton beam on 19/07 at 09:30. For n _TOF the YETS started on 15/11 at 06:00.

⁵The measurements performed in location n°11 with the IG5 trolley could not be exploited due to a high photon background from activated equipment stored nearby.

Table 4.1: Locations of radiation measurements in ISR8.

Position	Detector	Portable/Fixed	Room	Position description
1	PAXNT112	Fixed	375/T8-A76	In front of the PAD
2	PAHNT211	Fixed	375/T8-I75	Ion exchange resin of cooling station
3	PAHNT212	Fixed	375/T8-I74	Water pipes in the cooling station
4	PAHNT213	Fixed	375/T8-I74	HEPA/charcoal filters in the cooling station
5	PAHNT214	Fixed	375/T8-I75	Entrance of cooling station
6	LUPIN/IG5s	Mobile	375/T8-C75	ISR8 ground floor towards buffer area
7	PAXNT211	Fixed	375/T8-205	Top of cooling station
8	AD-b	Mobile	375/T8-A76	On the platform above the PAXNT112
9	LUPIN/IG5s	Mobile	375/T8-A76	Next to the PAD
10	LUPIN/IG5s	Mobile	375/T8-201	Next to the ventilation filters
11	LUPIN/IG5s	Mobile	375/T8-A79	n_TOF storage area
12	LUPIN/IG5s	Mobile	375/T8-A80	Close to the shielding wall of the technical gallery (outside the storage area)
13	AD-b	Mobile	375/T8-A79	n_TOF storage area on top of the shielding
14	AD-b	Mobile	375/T8-A78	On the platform where the BM8 is installed
15	AD-b	Mobile	375/T8-205	On the platform where the BM8 is installed
16	LUPIN/IG5s	Mobile	375/T8-205	On the platform where the BM8 is installed
17	PAXNT212	Fixed	375/T8-A79	Adjacent to the wall separating the n_TOF storage area from the vertical beam line
21	PMINT211	Fixed	375/T8-203	Technical gallery

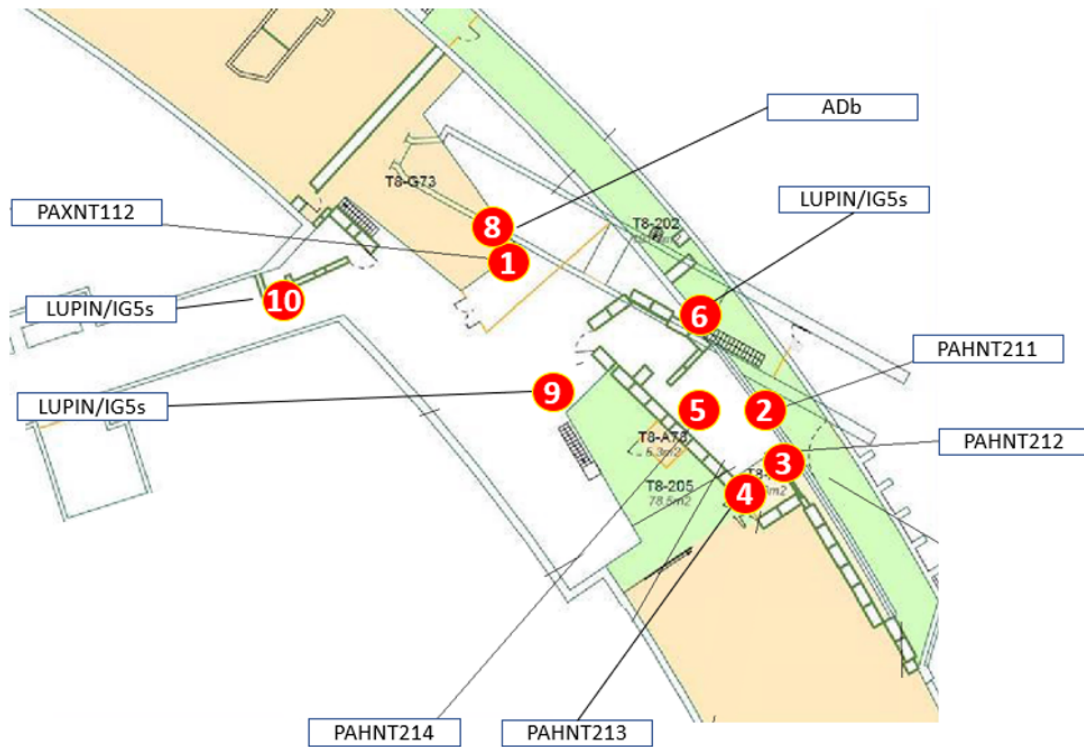


Figure 4.5: Radiation measurements positions in ISR8 (Building 375, floor S).

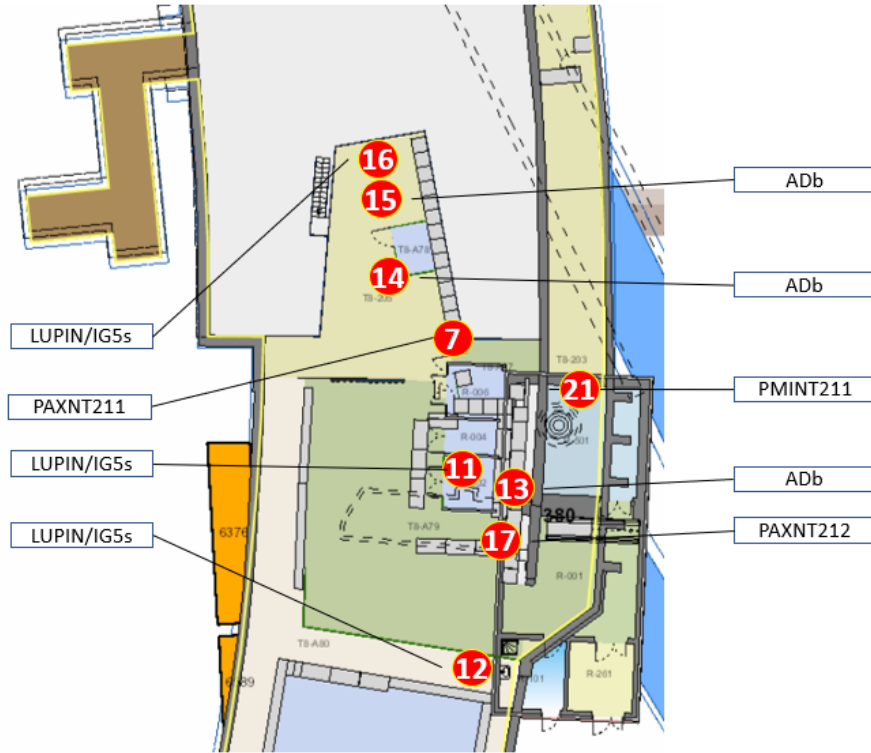


Figure 4.6: Radiation measurements positions in ISR8 (Building 375, floor R).

Target area

The locations of the monitors in target area are given in Table 4.2 and shown in Figure 4.7. Radiation survey locations and their results are given in Section 4.3.2.

Table 4.2: Location of the fixed monitors in the target area.

Position	Detector	Mobile/Fixed	Room	Area description
18	PMINT301	Fixed	802/U0-A01	Entrance of target area
19	PMINT101	Fixed	802/U0-A01	Proximity of the SEM grid (FTN line)
20	PMINT201	Fixed	802/U0-A01	In front of the mobile shielding

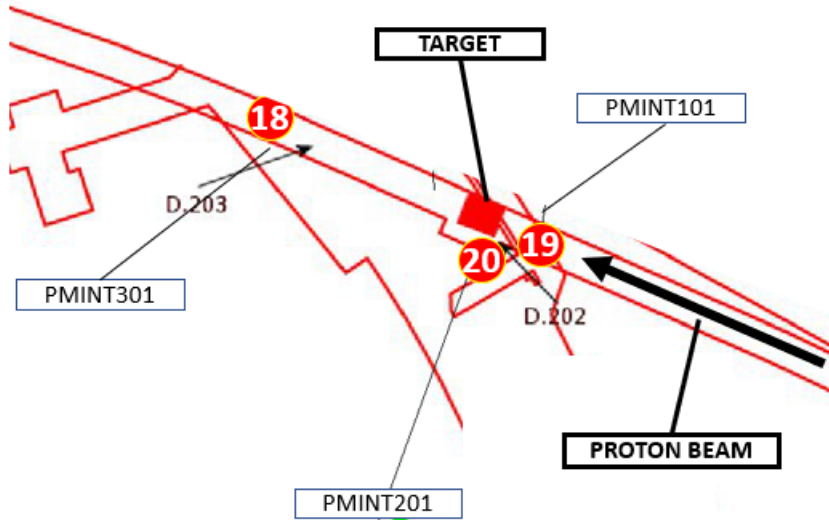


Figure 4.7: Radiation measurements positions in the target area (building 802, floor U0).

4.3. Results

4.3.1. Stray radiation measurements

The computed ambient dose equivalent rates for each detector and location are shown in Table 4.3 (fixed monitors) and Table 4.4 (portable detectors), and then indicated in Figure 4.8 and Figure 4.9. The measurements are normalized to the maximum average beam intensity of 1.66×10^{12} protons per second. The measurements performed with the IG5 trolley in the storage area (position 11) are not reported because the dose rate values were affected by the presence of radioactive material (photon contribution) temporarily stored in the area. It is important to underline that the calibration factor of the IG5H and PAXNT-devices (which are hydrogen-filled ionization chambers as the IG5H) fixed monitors is determined for both photon (Cs-137) and neutron (Am-Be) reference fields; the current measured by the chamber is converted to ambient dose equivalent using the neutron calibration factor, which is usually about a factor of three higher than the photon calibration factor. If the chamber is exposed to a mixed photon/neutron field (as it is the case in ISR8), it provides a conservative estimate of the ambient dose equivalent, since the photon contribution is overestimated. This also explains why the LUPIN⁶ values are usually lower than the ones measured by the IG5H. The only exception is position 12,

⁶The LUPIN has a Cs-137 equivalent gamma sensitivity of $< 0.5 \mu\text{Sv/h}$ at 50 mSv/h [7].

where the ambient dose equivalent rate measured by the LUPIN is higher than the one measured by the IG5H; this because the LUPIN was placed at a different height with respect to the IG5 trolley to verify the impact on the ambient dose equivalent of a small aperture in the shielding of the technical gallery. For all positions, the ambient dose equivalent rates are well below the limit for Supervised Area – Low occupancy, i.e. $15 \mu\text{Sv/h}$. In addition, the following considerations can be made for position 15 and position 17:

- Position 15 (on the platform where the BM8 is installed): the ADb shows a value a photon ambient dose equivalent of $1.9 \mu\text{Sv/h}$, which comes from photon stray radiation from the cooling station.
- Position 17 (top of technical gallery shielding): the PAXNT212, which is installed on the wall separating the vertical beam line from the storage area at 4 m above the ground level, shows an ambient dose equivalent rate of about $5.9 \mu\text{Sv/h}$. This value is still conformed with the radiological classification of the area and is likely to be overestimated due to the photon contribution from the cooling station (the monitor is in the line of sight with the cooling station). It should be noted that the neutron ambient dose equivalent in the storage area at few metres from PAXNT212, measured by the LUPIN in position 11 at ground level, is below $< 0.1 \mu\text{Sv/h}$.

Table 4.3: Ambient dose equivalent rates, $H^*(10)$, in $\mu\text{Sv/h}$, normalized to $1.66\text{e}12 \text{ p/s}$, measured by the fixed monitors installed in ISR8.

Position	Detector	Position description	$H^*(10)$ normalized to $1.66\text{e}12 \text{ p/s}$ [$\mu\text{Sv/h}$]	Uncertainty
1	PAXNT112	In front of the PAD	1.3	14%
7	PAXNT211	Top of cooling station	2.9	8%
17	PAXNT212	Top of technical gallery shielding	5.9	<1%

Table 4.4: Ambient dose equivalent rates, $H^*(10)$, in $\mu\text{Sv/h}$, normalized to $1.66\text{e}12$ p/s, measured by the portable detectors.

Position	Detector	Position description	$H^*(10)$ normalized to $1.66\text{e}12$ p/s [$\mu\text{Sv/h}$]	Uncertainty
6	LUPIN	ISR8 ground floor close to the buffer area	0.77	17%
	IG5H		1.49	10%
	IG5A		0.51	6%
8	ADb	Above PAXNT112 (on the platform)	0.89	8%
9	LUPIN	Next to the PAD	0.21	20%
	IG5H		0.77	10%
	IG5A		0.14	17%
10	LUPIN	Next to ventilation filters	1.09	9%
	IG5H		1.30	8%
	IG5A		0.25	4%
11	LUPIN	n_TOF storage area	<0.1	-
12	LUPIN	Close to the shielding wall of the technical gallery (outside the storage area)	1.08	10%
	IG5H		0.89	10%
	IG5A		0.16	14%
14	ADb	On the platform where the BM8 is installed	0.63	19%
15	ADb	On the platform where the BM8 is installed	1.87	8%
16	LUPIN	On the platform where the BM8 is installed	0.30	12%
	IG5H		1.22	4%
	IG5A		0.52	3%

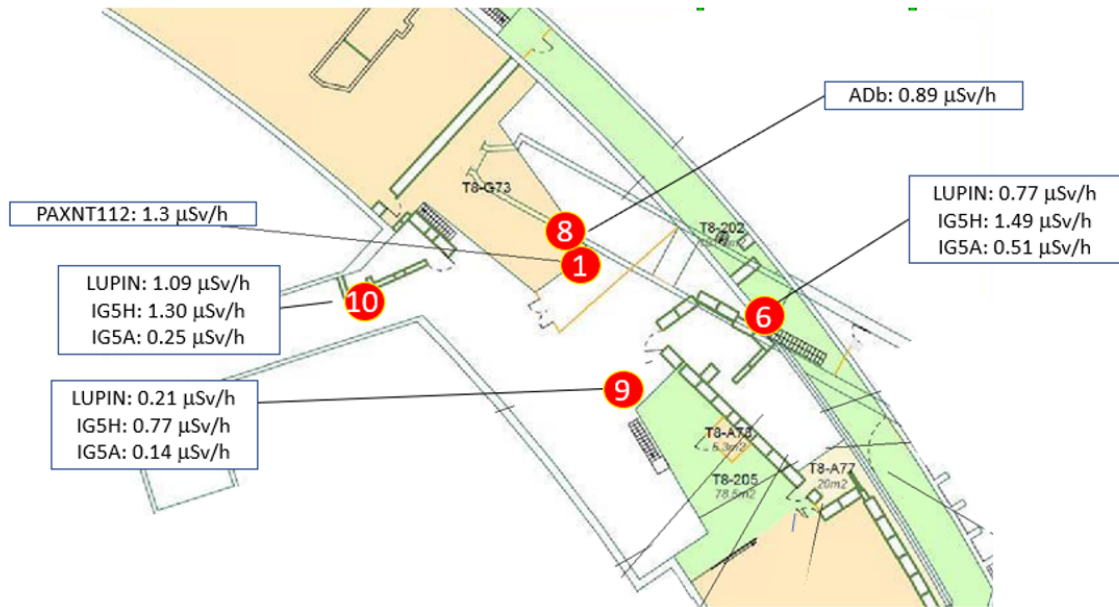


Figure 4.8: Stray radiation measurement locations and ambient dose equivalent rates normalized to $1.66\text{e}12$ p/s in ISR8 (floor S).

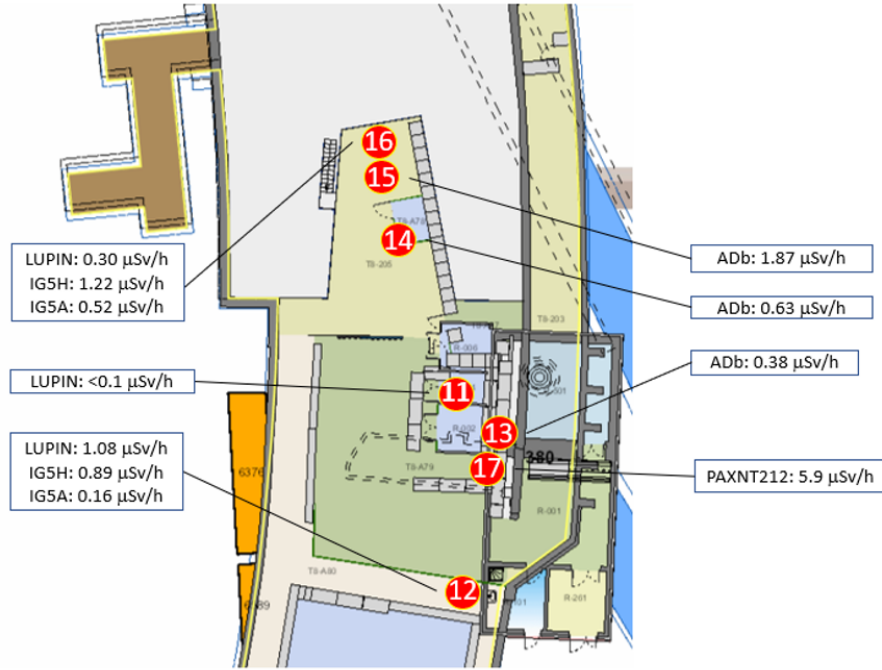


Figure 4.9: Stray radiation measurement locations and ambient dose equivalent rates normalized to 1.66×10^{12} p/s in ISR8 (floor R).

4.3.2. Residual dose rate measurements

Target area

Figure 4.10 and Figure 4.11 show the ambient dose equivalent rates, $H^*(10)$, for each radiation survey, expressed in $\mu\text{Sv/h}$. The residual dose rate is rather low, a few $\mu\text{Sv/h}$ at the entrance of Sector 3, whereas higher values are measured in the proximity of the shielding wall in the correspondence of shielding weaknesses. The highest value is in front of the NEAR collimator where, after 30 hours of cool-down time, the residual dose rate is about 2 mSv/h, which decreases at 120 $\mu\text{Sv/h}$ at one metre (the measurement of 750 $\mu\text{Sv/h}$ on 15/09/2021 was not done in contact with the collimator due to the presence of equipment for NEAR irradiations preventing the access to the collimator itself).

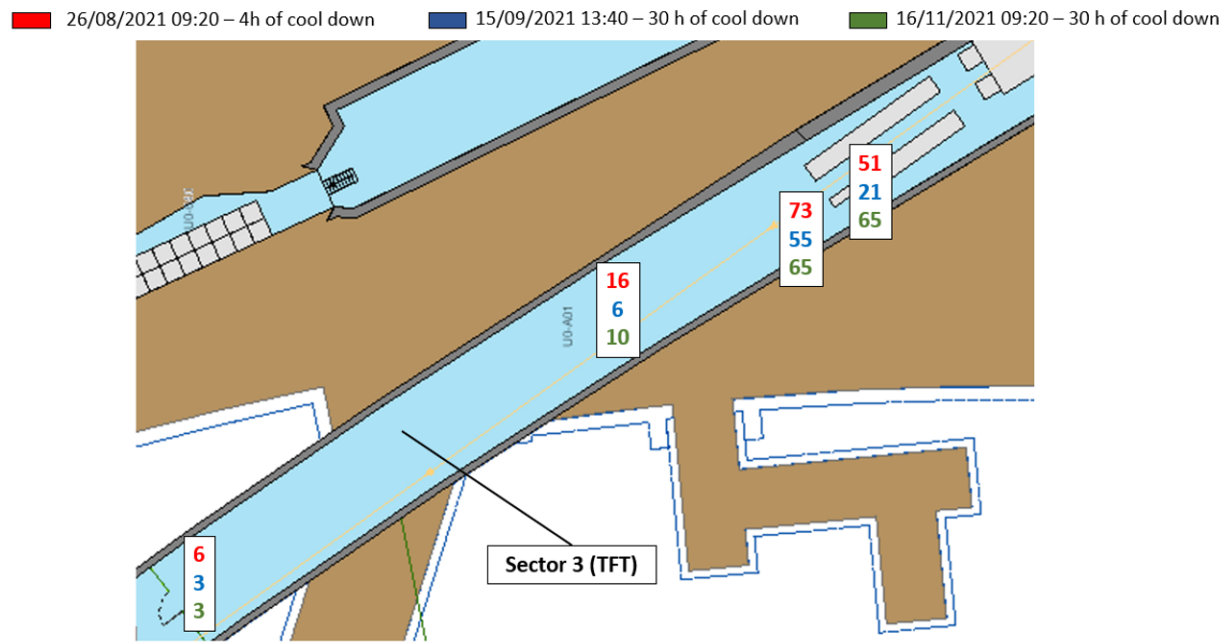


Figure 4.10: Ambient dose equivalent rate, $H^*(10)$, expressed in $\mu\text{Sv/h}$ from radiation surveys performed around the neutron beam line downstream the target.

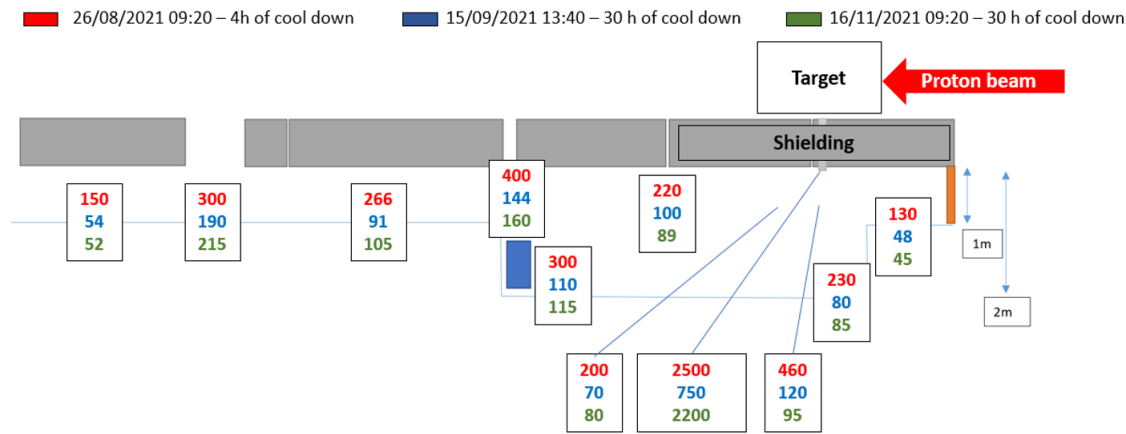


Figure 4.11: Ambient dose equivalent rates, $H^*(10)$, expressed in $\mu\text{Sv/h}$, in the area in front of the target shielding wall (grey rectangles indicate the blocks of the shielding wall, the blue rectangle represents an electrical rack). The measurement of $750 \mu\text{Sv/h}$ on 15/09/2021 was not done in contact with the collimator due to the presence of equipment for NEAR irradiations preventing the access to the collimator itself.

Table 4.5 reports the ambient dose equivalent rate values between 1 hour and 30 hours of cool down time in the n_TOF target area during four periods of beam stop, in July,

August, September and November. It should be noted that despite the increased irradiation time, the values between September and November are rather similar for PMINT301 and PMINT201 and lower in November for PMINT101; this is likely to be correlated with reduced beam losses in the FTN beam line upstream the target.

Table 4.5: Ambient dose equivalent rate in $\mu\text{Sv/h}$ for several cool-down times (between 1 hour and 30 hours) in n_TOF target area, during four periods of beam off in July, August, September and November.

Position	Detector	Position description	Cool-down time	July [$\mu\text{Sv/h}$]	August [$\mu\text{Sv/h}$]	September [$\mu\text{Sv/h}$]	November [$\mu\text{Sv/h}$]
18	PMINT301	Entrance of Sector 3	1 h	2.0	5.8	7.1	7.3
			4h	1.6	4.5	5.5	5.3
			12 h	1.2	-	4.0	4.0
			24 h	-	-	2.9	3.0
			30 h	-	-	2.6	2.8
19	PMINT101	In the proximity of the SEM grid (FTN line)	1 h	175.8	553.3	709.5	611.6
			4h	121.4	397.4	515.7	443.2
			12 h	70.9	-	338.5	295.7
			24 h	-	-	244.2	221.6
			30 h	-	-	216.9	199.9
20	PMINT201	In front of the mobile shielding	1 h	77.2	253.8	314.5	304.4
			4h	56.7	188.8	235.2	224.2
			12 h	34.6	-	144.4	137.5
			24 h	-	-	85.7	83.0
			30 h	-	-	67.7	66.5

Technical gallery

The residual dose rate in the technical gallery measured by PMINT211, installed close to the permanent magnet, is rather low, about $\mu\text{Sv/h}$, after already one hour of cool-down time.

Table 4.6: Ambient dose equivalent rate in $\mu\text{Sv/h}$ for several cool-down times (between 1 hour and 30 hours) in the technical gallery, during four periods of beam off in July, August, September and November.

Position	Detector	Cool-down time	July [$\mu\text{Sv/h}$]	August [$\mu\text{Sv/h}$]	September [$\mu\text{Sv/h}$]	November [$\mu\text{Sv/h}$]
21	PMINT211	1 h	0.9	1.1	1.1	0.9
		4h	0.7	1.0	0.9	0.9
		12 h	0.6	-	0.7	0.7
		24 h	-	-	0.8	0.6
		30 h	-	-	0.7	0.5

Cooling station

Fifteen locations were selected in the cooling station for residual dose rate measurements (at contact of equipment) using the dose rate meter 6150AD. Figure 4.12 illustrates all the measuring points, which are labelled with a letter, as well as the fixed stations, which are instead labelled with a number.

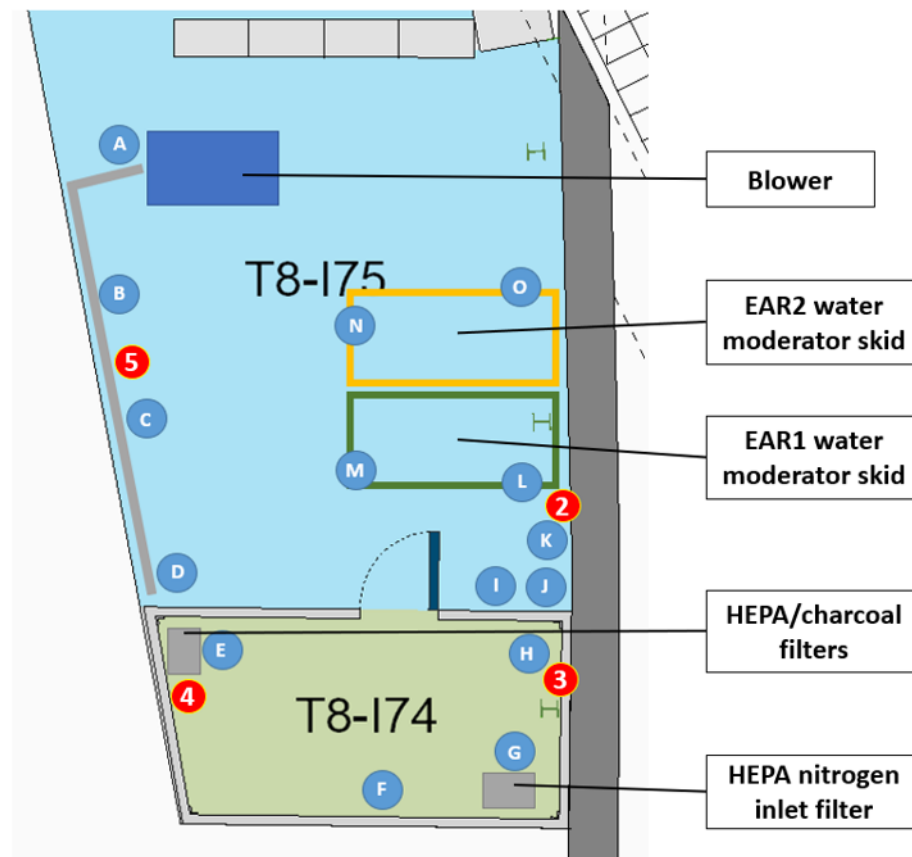


Figure 4.12: ISR8 cooling station (inside) layout. The selected spots for the surveys are labelled with a letter, while the fixed stations are marked with a number.

Two radiation surveys were made between August and September:

- 26/08/2021: at 09:00 (4 hours of cool down)
- 15/09/2021: at 11:40 (4 hours of cool down)

Table 4.7 summarizes the results of the surveys, while Table 4.8 shows the results from the fixed monitors. The highest residual dose rate is found in contact of the ion exchange resins, i.e. max. $730 \mu\text{Sv/h}$ (which decreases to about $20 \mu\text{Sv/h}$ at about 40 cm). It

should be underlined that the HEPA and charcoal filters of the nitrogen circuit shows a rather low residual dose rate, i.e. $10 \mu\text{Sv/h}$ at contact.

Table 4.7: Results of the radiation surveys performed in the cooling station.

Position	Description	Date: 26/08/2021	Date: 15/09/2021
		Cool-down time: 4 h	Cool-down time: 4 h
		H*(10) [$\mu\text{Sv/h}$]	H*(10) [$\mu\text{Sv/h}$]
A	Nitrogen blower	0.1	0.3
B	Nitrogen pipe	0.5	0.3
C	Nitrogen pipe	0.5	0.5
D	Wall of the dynamically confined room (blower side)	4	3
E	HEPA/charcoal filters	10	9
F	Pipes going down to the target area	4	-
G	HEPA nitrogen inlet filter	-	2
H	Air extraction from the room dynamically confined	-	1.6
I	Resin cartridge	21	54
J	Resin cartridge	440	730
K	Resin cartridge	23	52
L	EAR1 water moderator skid	4	6
M	EAR1 water moderator skid	2	2
N	EAR2 water moderator skid	-	1
O	EAR2 water moderator skid	0.5	0.9

Table 4.8: Ambient dose equivalent rate values in $\mu\text{Sv/h}$ between 1 hour and 30 hours of cool down time in the cooling station, during 4 periods of beam stop made respectively in July, August, September and November.

Position label	Detector	Cooling time	July [$\mu\text{Sv/h}$]	August [$\mu\text{Sv/h}$]	September [$\mu\text{Sv/h}$]	November [$\mu\text{Sv/h}$]
2	PAHNT211	1 h	18.2	62.9	95.1	162.3
		4h	0.7	7.2	12.2	21
		12 h	0.5	-	11	19.9
		24 h	-	-	10.3	19.4
		30 h	-	-	10.4	19.3
3	PAHNT212	1 h	9.6	27.6	34.9	56
		4h	0.5	3.4	5	7.3
		12 h	0.3	-	4.1	6.7
		24 h	-	-	4.1	6.6
		30 h		-	4.2	6.4
4	PAHNT213	1 h	0.2	9.6	14.5	16.3
		4h	<0.1	1.2	6.4	6.1
		12 h	<0.1	-	5.4	5.9
		24 h	-	-	4.4	5.3
		30 h	-	-	4.1	4.9
5	PAHNT214	1 h	1	3.1	3.5	5.3
		4h	0.2	0.3	0.5	0.6
		12 h	0.2	-	0.4	0.5
		24 h	-	-	0.4	0.5
		30 h	-	-	0.4	0.5

4.4. Conclusions

The results of stray radiation measurements confirmed the conformity of the radiological area classification of ISR8 (Supervised Radiation Area). Residual dose rate measurements and radiation surveys in the cooling station, in the target area and in the technical gallery provided useful information for planning and optimizing accesses and interventions (e.g. NEAR related accesses, maintenance activities in the cooling station). In addition, the residual dose rate near the nitrogen filters is presently rather low (a few of $\mu\text{Sv/h}$); this might indicate a limited presence of lead spallation products in the cooling circuit (especially if compared with the nuclear cartridges used for target #2 water cooling circuit,

where a few mSv/h could be measured).

5 | Activation studies

On 14th July 2021, six sets of four metallic samples were installed at different locations in the n_TOF complex in order to experimentally study activation phenomena. Each set consisted of:

- one 100 g stainless steel disk (thickness of 0.44 cm, radius of 3 cm and density of 7.9 g/cm^3).
- one 100 g copper disk (thickness of 0.39 cm, radius of 3 cm and density of 9 g/cm^3).
- one 100 g aluminium disk (thickness of 1.3 cm, radius of 3 cm and density of 2.7 g/cm^3).
- one 10 g Kovar alloy disk (thickness of 0.1 cm, radius of 2 cm and density of 8 g/cm^3).

The four materials were packed in a single plastic bag, as shown in Figure 5.1.



(a)



(b)

Figure 5.1: Left: the four samples set; right: the samples placed inside the plastic bag.

The aim is performing activation studies on the samples: aluminium, copper and stainless steel are typical materials used in the accelerators, while kovar, that contains 10% of cobalt, can be used for evaluating conservatively irradiation situations of materials, since cobalt is contained as impurity in many materials employed.

5.1. Sample locations

All the samples are traced with TREC (Traceability of Radioactive Equipment at CERN), which is the system used at CERN to trace potentially radioactive equipment. Six different locations were chosen for the placement of samples:

- 1st collimator (802/U0-A02) towards Experimental Area 1 (EAR-1).



Figure 5.2: 1st collimator.



Figure 5.3: Positioning of the sample upstream the 1st collimator.

- 2nd collimator (802/U0-A20) towards EAR-1.



Figure 5.4: 2nd collimator.



Figure 5.5: Positioning of the sample upstream the 2nd collimator.

- Permanent magnet (802/U0-A20) towards EAR-1.



Figure 5.6: Permanent magnet.



Figure 5.7: Positioning of the sample upstream the permanent magnet.

- Experimental Area 2 (EAR-2, 380/R-501) aside of the vertical beam line (380/R-501).



Figure 5.8: Experimental Area 2 (EAR-2).



Figure 5.9: Positioning of the sample in the EAR-2 bunker.

- Experimental Area 2 (EAR-2, 380/R-501) in the proximity of the vertical beam line.



Figure 5.10: Positioning of the sample in the proximity of the vertical line of EAR-2.

- Technical gallery (375/T8-203) below the permanent magnet.



Figure 5.11: Technical gallery.

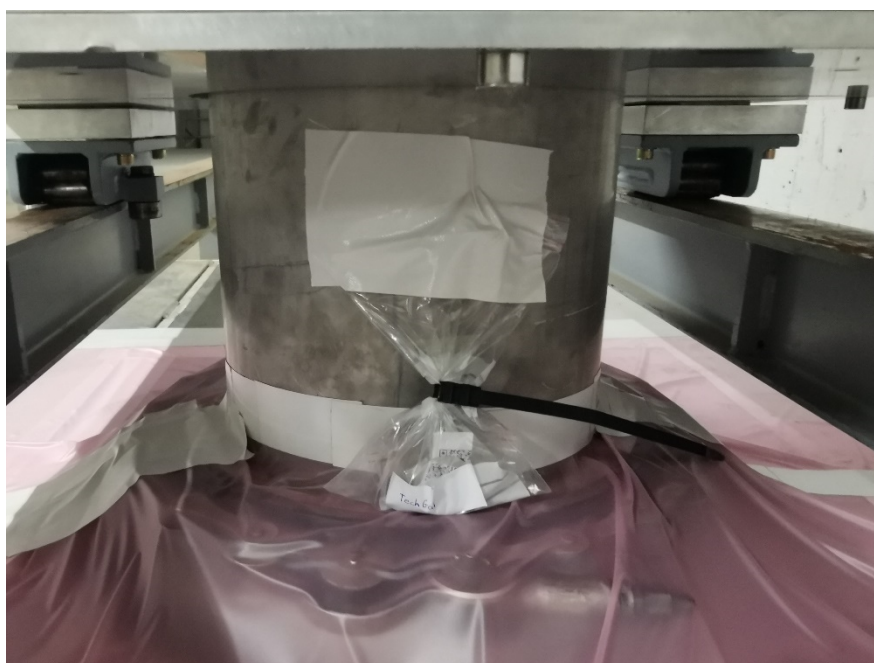


Figure 5.12: Positioning of the sample in the technical gallery below the permanent magnet.

5.2. γ -spectrometry results

The samples were retrieved in January 2022 (during the Year End Technical Stop), after 119 days of irradiation, 8.2×10^{18} protons on target and about 70 days of cool-down time. The γ -spectrometry analysis was performed in RP radio-analytical laboratory. The results expressed in Bq/g were compared against the CERN clearance limits, otherwise called LL (see Section 1.3 for more details about the clearance procedure at CERN). For each sample material, a figure-of-merit (FOM, see Equation 1.1) was calculated; if the FOM is above one, the material has to be considered as radioactive. γ -spectrometry results are schematically reported with the specific activities in Bq/g, LL limits and the respective MDA (Minimum Detectable Activity).

5.2.1. EAR-2 (beam line) samples

Table 5.1: Irradiation profile.

Measurement date	18/01/2022
Cool-down time	64 days

Table 5.2: γ -spectrometry results on samples placed in the last part of EAR-2 beam line.

Material	Radionuclide	Half life	LL [Bq/g]	Specific activity [Bq/g]	Uncertainty [%]	MDA [Bq/g]	Specific activity/LL	FOM
Copper	Co-58	70.86 d	1.00E+00	1.27E-02	26.7%	4.02E-03	0.013	0.013
Stainless-steel	Mn-54	312.30 d	1.00E-01	1.29E-02	19.9%	2.78E-03	0.129	0.134
	Co-58	70.86 d	1.00E+00	4.74E-03	33.1%	3.66E-03	0.005	
Aluminium	-	-	-	-	-	-	-	-
Kovar	Co-57	271.79 d	1.00E+00	2.36E-02	71.0%	2.69E-02	0.024	0.059
	Co-58	70.86 d	1.00E+00	3.52E-02	41.4%	3.56E-02	0.035	

For all materials, specific activity levels are always below clearance limits. No radionuclide was detected in the aluminium sample.

5.2.2. EAR-2 (wall) samples

γ -spectrometry measurements did not show the presence of artificial radionuclides, but only natural radionuclides, such as Th-232 and Ra-226.

5.2.3. Technical gallery samples

Table 5.3: Irradiation profile.

Measurement date	26/01/2022
Cool-down time	72 days

Table 5.4: γ -spectrometry results on the samples placed in the technical gallery.

Material	Radionuclide	Half life	LL [Bq/g]	Specific activity [Bq/g]	Uncertainty [%]	MDA [Bq/g]	Specific activity/LL	FOM
Copper	Mn-54	312.30 d	1.00E-01	1.43E-01	9.47%	9.73E-03	1.43	5.59
	Co-56	77.27 d	1.00E-01	1.30E-01	7.28%	1.02E-02	1.30	
	Co-57	271.79 d	1.00E+00	4.67E-01	8.97%	1.86E-02	0.47	
	Co-58	70.86 d	1.00E+00	1.38	6.33%	1.16E-02	1.38E+00	
	Fe-59	44.50 d	1.00E+00	7.85E-02	13.07%	1.64E-02	0.08	
	Co-60	5.27 y	1.00E-01	9.30E-02	8.25%	8.74E-03	0.93	
Stainless-steel	Sc-46	83.81 d	1.00E-01	4.07E-01	5.23%	1.80E-02	4.07	63.15
	V-48	15.97 d	1.00E+00	1.28E-01	7.65%	1.15E-02	0.13	
	Cr-51	27.70 d	1.00E+02	5.04E+00	10.08%	2.18E-01	0.05	
	Mn-54	312.30 d	1.00E-01	4.78E+00	6.01%	2.29E-02	47.80	
	Co-56	77.27 d	1.00E-01	4.98E-01	4.61%	1.76E-02	4.98	
	Co-57	271.79 d	1.00E+00	1.02E+00	8.10%	2.36E-02	1.02	
	Co-58	70.86 d	1.00E+00	1.49E+00	6.32%	2.37E-02	1.49	
	Fe-59	44.50 d	1.00E+00	6.19E-02	16.62%	2.83E-02	0.06	
Alluminium	Co-60	5.27 y	1.00E-01	3.55E-01	5.34%	1.10E-02	3.55	1.66
	Na-22	2.60 y	1.00E-01	1.38E-01	9.91%	7.72E-03	1.38	
Kovar	Mn-54	312.30 d	1.00E-01	2.78E-02	18.63%	7.51E-03	0.28	79.57
	Cr-51	27.70 d	1.00E+02	4.19E-01	33.83%	3.55E-01	0.004	
	Mn-54	312.30 d	1.00E-01	8.89E-01	9.72%	9.67E-02	8.89	
	Co-56	77.27 d	1.00E-01	4.17E-01	11.18%	9.69E-02	4.17	
	Co-57	271.79 d	1.00E+00	1.02E+00	8.62%	1.87E-02	1.02	
	Co-58	70.86 d	1.00E+00	2.09E+00	7.59%	9.30E-02	2.09	
	Fe-59	44.50 d	1.00E+00	1.00E-01	46.44%	1.17E-01	0.10	
	Co-60	5.27 y	1.00E-01	6.33E+00	4.37%	5.32E-02	63.30	

For all materials, the FOM is always above the unit.

5.2.4. 1st collimator samples

Table 5.5: Irradiation profile.

Measurement date	26/01/2022
Cool-down time	74

Table 5.6: γ -spectrometry results on the samples placed in the 1st collimator.

Material	Radionuclide	Half life	LL [Bq/g]	Specific activity [Bq/g]	Uncertainty [%]	MDA [Bq/g]	Specific activity/LL	FOM
Copper	Be-7	53.12 d	1.00E+01	2.33E-01	31.44%	3.10E-01	0.02	25.97
	Sc-46	83.81 d	1.00E-01	3.20E-01	5.53%	1.28E-02	3.20	
	V-48	15.97 d	1.00E+00	7.18E-02	9.72%	1.86E-02	0.07	
	Cr-51	27.7 d	1.00E+02	6.76E-01	15.72%	2.44E-02	0.01	
	Mn-54	312.30 d	1.00E-01	8.14E-01	6.63%	2.14E-02	8.14	
	Co-56	77.27 d	1.00E-01	6.48E-01	4.21%	2.07E-02	6.48	
	Co-57	271.79 d	1.00E+00	1.63E+00	8%	2.85E-02	1.63	
	Co-58	70.86 d	1.00E+00	3.5E+00	5.86%	2.27E-02	3.50	
	Fe-59	44.50 d	1.00E+00	1.95E-01	9.57%	2.53E-02	0.20	
Stainless-steel	Co-60	5.27 y	1.00E-01	1.98E-01	6.26%	1.07E-02	1.98	42.59
	Zn-65	244.26 d	1.00E-01	7.45E-02	19.01%	2.29E-02	0.75	
	Be-7	53.12 d	1.00E+01	2.98E-01	22.17%	1.88E-01	0.03	
	Na-22	2.6 y	1.00E-01	1.59E-02	3.65%	9.64E-03	0.16	
	Sc-46	83.81 d	1.00E-01	6.63E-01	4.78%	1.55E-02	6.63	
	V-48	15.97 d	1.00E+00	1.95E-01	6.45%	8.54E-03	0.20	
	Cr-51	27.7 d	1.00E+02	2.97E+00	10.16%	1.24E-01	0.03	
	Mn-54	312.30 d	1.00E-01	2.86E+00	6.09%	1.83E-02	28.60	
	Co-56	77.27 d	1.00E-01	4.27E-01	4.94%	1.66E-02	4.27	
Aluminium	Co-57	271.79 d	1.00E+00	7.10E-01	7.97%	9.04E-03	0.71	6.62
	Co-58	70.86 d	1.00E+00	1.03E+00	6.47%	1.74E-02	1.03	
	Fe-59	44.50 d	1.00E+00	2.00E-02	33.30%	2.96E-02	0.02	
	Co-60	5.27 y	1.00E-01	9.12E-02	9.12%	8.36E-03	0.91	
Kovar	Be-7	53.12 d	1.00E+01	6.98E-01	11.06%	6.35E-02	0.07	98.68
	Na-22	2.60 y	1.00E-01	5.75E-01	6.11%	6.31E-03	5.75	
	Sc-46	83.81 d	1.00E-01	1.18E-02	19.89%	8.91E-03	0.12	
	Mn-54	312.30 d	1.00E-01	6.87E-02	10.26%	6.75E-03	0.69	
	Be-7	53.12 d	1.00E+01	5.14E-01	34.97%	9.26E-01	0.05	
	Sc-46	83.81 d	1.00E-01	3.57E-01	11.47%	1.04E-01	3.57	
	V-48	15.97 d	1.00E+00	1.36E-01	20.59%	9.74E-02	0.14	
	Cr-51	27.70 d	1.00E+02	1.39E+00	17.94%	4.62E-01	0.01	
	Mn-54	312.30 d	1.00E-01	2.29E+00	7.49%	9.71E-02	22.90	
Kovar	Co-56	77.27 d	1.00E-01	1.29E+00	6.48%	9.62E-02	12.90	98.68
	Co-57	271.79 d	1.00E+00	2.57E+00	8%	2.43E-02	2.57	
	Co-58	70.86 d	1.00E+00	5.27E+00	6.58%	9.50E-02	5.27	
	Fe-59	44.50 d	1.00E+00	1.69E-01	25.66%	1.74E-01	0.17	
	Co-60	5.27 y	1.00E-01	5.11E+00	4.52%	6.42E-02	51.10	

For all materials, the FOM is above the unit.

5.2.5. 2nd collimator samples

γ -spectrometry measurements did not show the presence of artificial radionuclides, but only the presence of natural radioactivity (Ra-226).

5.2.6. Permanent magnet samples

Table 5.7: Irradiation profile.

Measurement date	26/01/2022
Cool-down time	72 days

Table 5.8: γ -spectrometry results on the samples placed on the magnet.

Material	Radionuclide	Half life	LL [Bq/g]	Specific activity [Bq/g]	Uncertainty [%]	MDA [Bq/g]	Specific activity/LL	FOM
Copper	Mn-54	312.30 d	1.00E-01	4.37E-03	37.21%	4.93E-03	0.044	0.096
	Co-56	77.27 d	1.00E-01	3.16E-03	37.71%	3.60E-03	0.032	
	Co-57	271.79 d	1.00E+00	7.13E-03	17.76%	2.15E-03	0.007	
	Co-58	70.86 d	1.00E+00	1.38E-02	20.50%	3.59E-03	0.014	
Stainless-steel	Sc-46	83.81 d	1.00E-01	3.08E-03	49.81%	5.60E-03	0.031	0.176
	Mn-54	312.30 d	1.00E-01	1.20E-02	22.94%	4.15E-03	0.120	
	Co-56	77.27 d	1.00E-01	2.02E-03	65.23%	5.02E-03	0.020	
	Co-57	271.79 d	1.00E+00	2.71E-03	29.66%	2.29E-03	0.003	
	Co-58	70.86 d	1.00E+00	2.62E-03	52.33%	4.75E-03	0.003	
Aluminium	-	-	-	-	-	-	-	-
Kovar	Co-57	271.79 d	1.00E+00	9.60E-03	46.09%	1.78E-02	0.010	0.034
	Co-58	70.86 d	1.00E+00	2.42E-02	47.72%	3.49E-02	0.024	

For all materials, the FOM is below the unit. No artificial radionuclides were detected in the aluminium sample.

5.3. Conclusion

The technical gallery and the region around the 1st collimator are locations where material activation can be expected. The samples located close to the permanent magnet and in EAR2 beam line showed traces of artificial radionuclides, while no artificial radionuclides were detected in the samples placed in the 2nd collimator and on EAR2 wall. The results are summarized in Figure 5.13.

The samples were re-installed in their original locations before the restart of n_TOF operation in 2022. The activation trends will be monitored again in the next years and correlated with the operation of the n_TOF facility, allowing to establish a robust radioactive waste zoning approach.

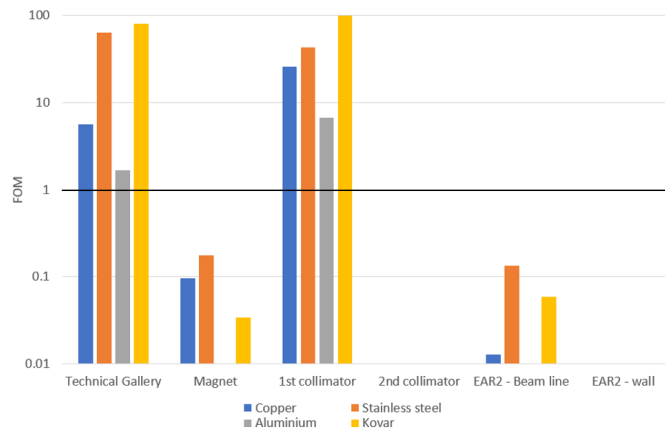


Figure 5.13: γ -spectrometry results. The FOM (calculated with Equation 1.1) should be below the limit of 1.

6 | Conclusions and future perspectives

This work described the radiation protection studies and measurements performed during the first operational year of the nitrogen-cooled third-generation spallation target. The results confirm that radiation protection is properly implemented at n_TOF. The RP study focused on four main aspects:

1. Response characterisation of the ionisation chamber used to monitor the radioactivity concentration of the nitrogen circuit and its validation against experimental measurements. The presently used source term shall be continuously monitored and, if needed (e.g. presence of lead spallation products like noble gases due to outdiffusion from the target) updated to ensure the reliably measurements of radioactivity concentration.
2. Monitoring of stray radiation to verify the compliance with the radiological area classification; results confirmed the conformity of ISR8 classification (Supervised Radiation Area).
3. Monitoring of residual dose rate to provide useful information for planning and optimising accesses and interventions. The evolution with time and operation of residual dose rate shall be ensured in order to provide up-to-date data.
4. Activation studies for zoning purposes by placing samples of materials. As for the residual dose rate measurements, activation levels shall be followed-up by regularly measure (ideally once per year) the samples. Such information will be of paramount importance to radiologically classify materials in case of dismantling/decommissioning.

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