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Hybrid monitoring and measurement of concrete shielding activation at the ProtherWal proton therapy centre

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Abstract

Proton therapy systems produce large fluxes of energetic secondary particles when tailoring the beam energy and transverse profile to the specificities of each irradiation plan. A Low Activation Concrete (LAC) mix is foreseen for parts of the shielding of the Ion Beam Applications (IBA) Proteus® One (P1) compact system at the ProtherWal proton therapy centre in Charleroi, Belgium, to limit the long-term activation of the concrete shielding. To experimentally monitor the long-term activation and validate the beneficial impact of the LAC mix, a setup of four removable cores to be placed at critical locations in the cyclotron vault is optimised. We report on the experimental and simulation monitoring setup design. Our validated BDSIM/FISPACT-II methodology combines particle tracking and Monte-Carlo particle-matter interactions simulations using Beam Delivery Simulation (BDSIM) and the computation of the activation using FISPACT-II. We show that the evaluation of the short-term activation of the cores is essential to the measurement analysis. We detail a hybrid workflow based on numerical simulations that uses logging data of the workloads of the clinical and research beam production and experimental measurements to evaluate and monitor the short- and long-term activation at any point during the centre lifetime and decommissioning period. The activation of the cores using a realistic foreseen irradiation pattern is studied, allowing for the characterisation of the measurement process and radiation protection considerations related to the measurement campaign. The final experimental setup and the supporting online simulation tools are discussed in detail.

1 Introduction

Fixed-energy cyclotron-based proton therapy machines generate significant fluxes of secondary particles, mainly neutrons [1], particularly due to losses during acceleration and energy degradation. The produced secondary neutrons have a continuous energy spectrum from thermal energy up to the proton beam top energy and interact with the beamline elements or the concrete shielding via nuclear reactions, mainly neutron capture and spallation [2], to produce radioactive nuclides. Some of those nuclides are long-lived and responsible for the system long-term activation and shielding. In-depth activation studies are therefore required to design the concrete shieldings and foresee the radioactive waste generated during the entire exploitation period.

The Walloon Region ProtherWal proton therapy facility is in construction in Charleroi, Belgium [3, 4]. The proton therapy centre is an Ion Beam Applications (IBA) Proteus® One (P1) system. The superconducting synchrocyclotron (S2C2) accelerates protons to 230 MeV. Using the rotating-wheel energy degrader blocks, it delivers beams to the isocentre using a rotating gantry with a 220 degrees rotation range at any desired energy between 230 and 70 MeV. In addition to the clinical beam time, an extensive experimental research program is foreseen to be carried out, from radiobiology to material research for space missions. These research activities will require larger energy spans, higher beam currents, and longer irradiation times than clinical treatment beams, producing more secondary particles per unit volume and time than in clinical treatment plans.

A new methodology for the activation computation of any accelerator-based system, with application to proton therapy systems, was presented in Ref. [5]. It couples Beam Delivery SIMulation (BDSIM) [6], a Geant4-based code tracking primary and secondary particles inside beamline structures with realistic geometries while considering the particle-matter interactions, with the code system and library database

FISPACT-II. The latter code solves the rate equations using ENDF-compliant group library data for nuclear reactions, particle-induced or spontaneous fission yields, and radioactive decay. The methodology was validated against prior MNCPX [7] Monte-Carlo simulations for the concrete shielding of the proton therapy centre of Charleroi using the newly developed Low Activation Concrete (LAC) introduced to decrease the radioactive waste gathered at the centre decommissioning. The LAC was developed based on neutron activation analysis of different aggregates, sand and types of cement at the BR1 nuclear reactor from SCK-CEN in Belgium [8]. In that study, the concentrations in Eu, Co and Cs were measured two months after the irradiations using a high-purity germanium spectrometer and the activity generated inside the LAC was observed to be lower compared to regular concrete as it exhibits low concentration in the trace elements at the origin of long-lived nuclides. The reduction factor for the concentration of the trace elements Eu, Co and Cs are respectively 30, 100 and 30 compared to regular concrete. The detailed BDSIM model of the P1 system used in the methodology was previously developed and validated against experimental data in Ref. [9].

We designed an experimental setup comprising four removable concrete cores placed strategically in the cyclotron vault shielding walls. Detailed simulations of the experimental technique, using our newly developed BDSIM/FISPACT-II simulation package, are reported in this paper and highlight the efficiency of LAC in reducing the amount of radioactive waste during decommissioning.

To support the research program throughout the centre lifetime and to experimentally monitor the long-term activation of the concrete shielding, we developed a hybrid workflow coupling numerical evaluations of the activation of the cores and expected measurement results that follow the actual beam workloads and experimental measurements.

We refer to the back-and-forth exchange between the numerical simulations and the experimental measurements as "hybrid worflow" in the sense that the numerical simulations are first used to prepare the measurement campaign for precision, measurement techniques and radiation protection purposes. Second, the experimental measurements are used to validate and improve the model and its activation computation. Then, in between the experimental measurements, the numerical activation results are updated each time the machine is operated by using the exact irradiation properties (duration, beam current and beamline characteristics), and the cool-down period since the previous activation computation. Therefore, the simulations and the experiment work jointly with the numerical simulations used to monitor "in real time" the shielding activity and the repetitive experimental measurements used as comparative checks.

Predictions of the cores long- and short-term activation are provided, from which the position of the cores, the activation measurement method, and the radiation protection considerations related to the measurement campaign are studied. The experimental agreement between the BDSIM/FISPACT-II methodology and the experimental results will support its use for evaluating the entire beamline and concrete shielding activation all along the centre lifetime and predicting radiation protection quantities for personnel work dose planning during the cores extraction and measurements, critical situations or unusual irradiation patterns.

The complete BDSIM model of the proton therapy centre of Charleroi is presented in Sect. 2. The experimental setup for the removable concrete cores is presented in Sect. 3. The detailed simulation methodology of the BDSIM/FISPACT-II coupling is briefly recalled in Sect. 4. The experimental setup is assessed and optimised in Sect. 5 for its ability to perform long-term activation measurements. The expected measurements are simulated and reported in Sect. 6 to provide an understanding of the foreseen experimental conditions. Conclusions on the final removable cores setup, its efficiency to experimentally validate the beneficial impact of the LAC inserts, and the proposed hybrid monitoring and measurement methodology are discussed in detail in Sect. 7.

2 BDSIM model of the ProtherWal proton therapy centre

The complete BDSIM model of the ProtherWal proton therapy centre combines the BDSIM P1 system model developed in Ref. [9] and the concrete shielding model presented in Ref. [5]. A 3D visualisation of the complete model is shown in Fig. 1. The concrete shielding is implemented using *PYG4OMETRY*, a Python library to programmatically create GDML-based geometry [10]. The regular and recently developed Low Activation Concrete (LAC) are modelled following their atomic composition presented in Table 1 and their concentration in trace elements at the origin of the major long-lived nuclides produced by neutron capture detailed in Table 2.

The beam losses can be divided into the beamline losses and the cyclotron losses. First, the beamline losses are obtained by simulating the propagation of the primary beam through the entire beamline. The energy depositions along the beamline for a primary proton beam of 100 MeV, which is anticipated to be the most used energy in terms of protons produced per year, is shown in Fig. 2.[1] The "primary first hits", which represent the fraction of the primary beam that undergoes its first interaction, and the primary loss, which describes the fractionnal losses per unit length, are also depicted. BDSIM capabilities in terms of particle tracking in magnetic fields and through matter lead to a continuous beam loss pattern distributed along the beamline and to the continuous production of secondary particles. We observe that the most important source of secondary particles in the

[1] Analysis of the beamline loss patterns at 70 MeV and 210 MeV can be found in Ref. [5].

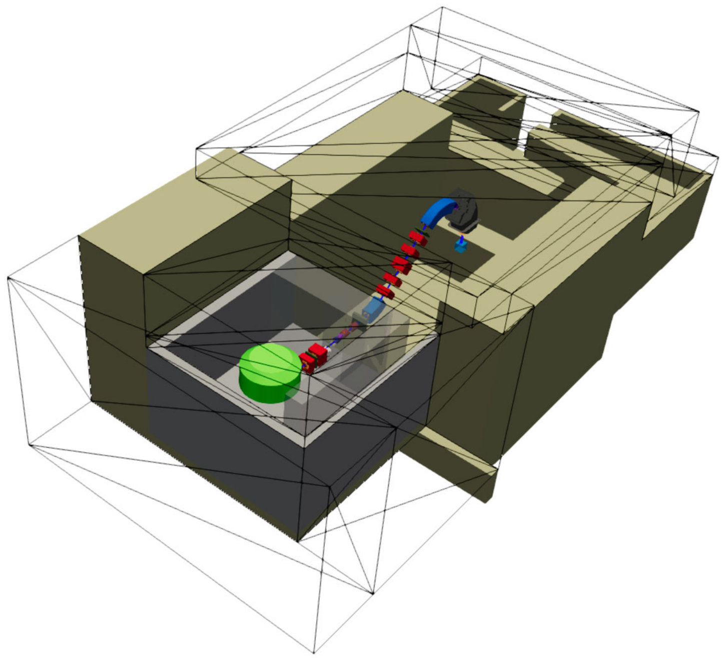

Figure 1 BDSIM model of the P1 proton therapy centre (Charleroi, Belgium), including the beam transport elements and the details of the concrete shielding. Regular concrete is shown in light brown, while the Low Activation Concrete is in light grey. Selected walls are shown as transparent mesh for visualization purposes

Table 1 Atomic composition in weight fractions of the main elements in regular and Low Activation Concrete [8]

Element	Standard Concrete	LAC
H	1.00%	0.721%
C	0.10%	8.915%
O	52.91%	47.772%
Na	1.60%	0.076%
Mg	0.20%	0.240%
Al	3.39%	0.275%
Si	33.70%	1.241%
K	1.30%	0.033%
Ca	4.40%	40.514%
Fe	1.40%	0.063%
S	0	0.088%
Cu	0	0.008%
Sr	0	0.034%
Ru	0	0.02%

Table 2 Concentration of trace elements in regular and Low Activation Concrete (LAC) [8]

Concrete Type	Eu(ppm)	Co(ppm)	Cs(ppm)
Regular	1.08	21.9	3.21
LAC	0.0316	0.2066	0.0942

beamline are the slits (SL1E, SL1-3G—collimators protecting downstream elements), the energy degrader (P1E) and the circular collimator (COL), stopping the particles scattered at large angles during the energy degradation process.

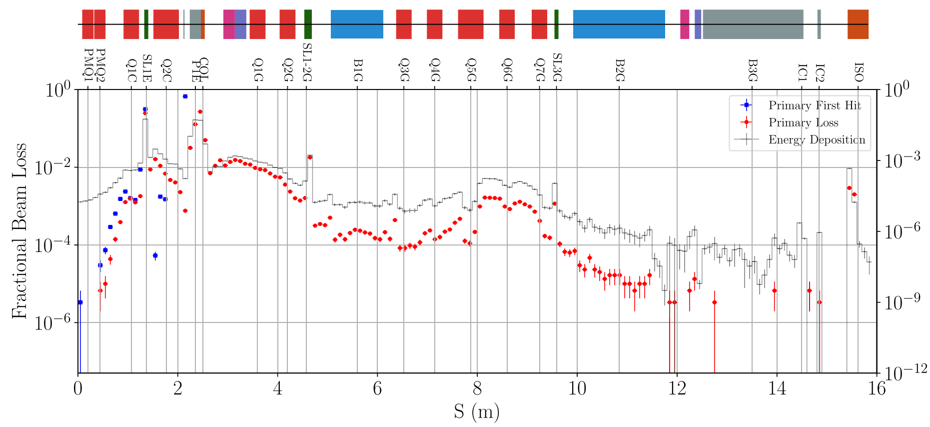

Figure 2 Beam loss pattern along the beamline for a beam energy of 100 MeV. "Primary first hits", in blue, represent the fraction of the primary beam that undergoes its first interaction. "Primary loss", in red, represents the fractional beam losses per unit length. The energy deposition represents the energy deposited by the primaries and the secondaries. All the particles interact with the degrader (annotated "P1E"), resulting in the absence of downstream "primary first hits"

As BDSIM is not used to simulate the acceleration and extraction processes in the S2C2, the distribution of the cyclotron losses is based on conservative assumptions which considers an efficiency of 30% for the S2C2 extraction. We model them as primary protons inside the S2C2 yoke geometry to simulate the production of secondaries. The lost proton distribution is defined in two parts. The first part, representing 25% of the initial beam, is uniformly distributed along the S2C2 circumference at an energy of 230 MeV. The second part, representing 45% of the initial beam, is lost at the location of the extraction septum. The exact lost protons distribution inside the S2C2 structure is unknown, and different proton loss distributions can be modelled while following the main loss pattern described by the conservative design. The S2C2 secondary particle generation simulation is presented in Fig. 3. Ref. [11] discusses the impact of the proton loss distribution choice on the concrete shielding activation results and concludes that the variation between the loss models can be characterised as a systematic error and has no significant impact on the results. These expected loss patterns will be assessed during the commissioning of the facility, in particular using transmission measurements.

3 Experimental setup for the removable concrete cores

The experimental setup of the removable concrete cores is optimised based on the neutron fluence and activation simulation results of Ref. [5] to achieve the following criteria. First, the experimental cores are placed in different regions of the vault that exhibit specific activation levels due to different irradiation sources: S2C2 extraction losses (North and East walls, see Fig. 4) and combined losses from the energy degrader and the beamline transport (South left wall, see Fig. 4). Second, the cores must be placed at the location of the highest activation in their respective wall to allow a conservative measurement of the shielding activation. Third, two of the cores should be placed in locations experiencing similar irradiation conditions to provide a direct experimental validation of the efficiency of the LAC compared to regular concrete in mitigating the production of long-lived radioactive nuclides responsible for the classification as radioactive waste. This condition will be referred to as the "iso-flux" hypothesis in Sect. 5.

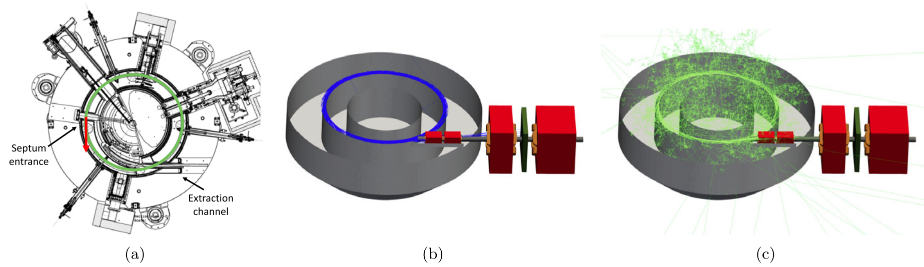

Figure 3 Illustration of the S2C2 losses in the BDSIM model. Figure 3(**a**) schematically displays the two sources of proton losses in the S2C2: the uniformly distributed losses along the accelerator circumference (green) and the extraction losses located at the septum (red). In Figures, 3(**b**) and 3(**c**), the blue and green lines respectively represent the positively charged particles (protons) and the neutral particles (neutrons and photons). The extraction line quadrupoles are represented in red with their coils represented in orange. The so-called "extraction slits", horizontal collimators protecting the downstream elements, are represented in dark green. Figure 3(**c**) illustrates the results obtained from the primary losses simulations. The important number of tracks with short step lengths shows that most of the neutral particles generated are neutrons

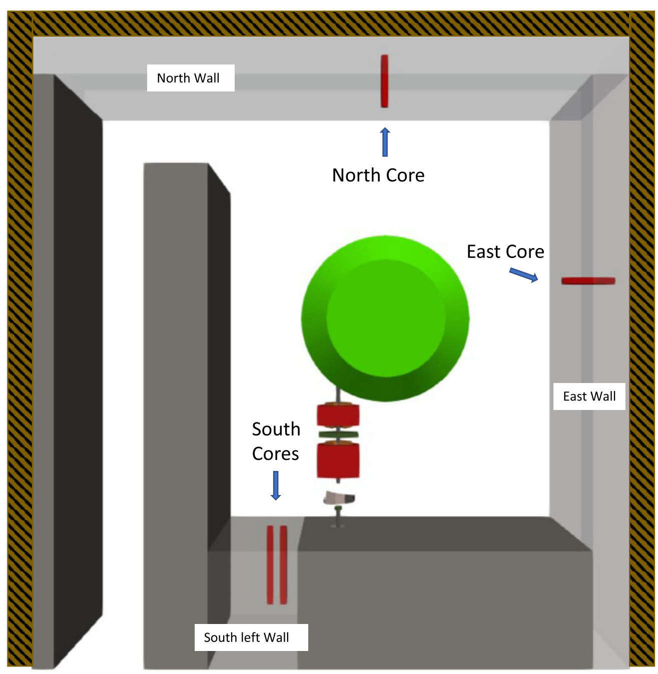

Figure 4 Removable core position in the vault concrete shielding. The shielding walls in Low Activation Concrete are shown in light grey. Some walls are shown as transparent for visualization purposes. The first part of the P1 BDSIM model is shown with the S2C2 in green, the quadrupoles in red, the slits in dark green and the degrader wheel in grey

An initial configuration is shown in Fig. 4. Two 0.8 m long cores are placed in the East and North walls. Their compositions follow the one of the shielding wall: a first layer of LAC of 0.5 m followed by 0.3 m of regular concrete as shown in Fig. 5. These will provide a direct measurement of the activation in those two walls. Two cores of 1.2 m long, one entirely made of LAC, and the other in regular concrete as shown in Fig. 6, are placed in the South left wall, assuming that the neutron fluence is identical at both locations, to compare the activation levels between the shielding materials. As shown in Sect. 5, it turns

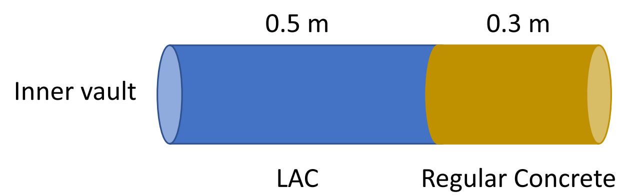

Figure 5 North and East cores inner composition

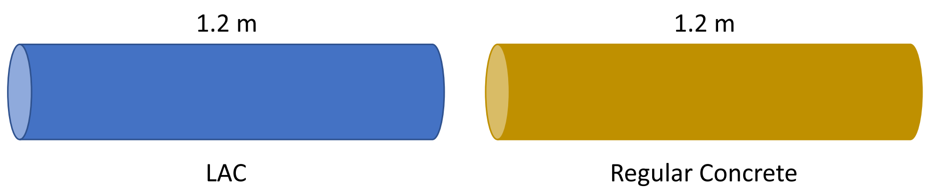

Figure 6 South cores inner composition

out that the configuration for these last two cores does not fulfil the "iso-flux" hypothesis. Detailed simulations presented in Sect. 5 allowed to propose a final configuration where these two cores are placed on top of each other, symmetrically to the horizontal beamline reference plane.

Integration studies confirmed that the final configuration ensures the compatibility between the machine configuration, maintenance operations and the removal of the cores for experimental measurements.

4 Methodology and hypotheses for activation simulations

The activation in the experimental cores is computed in two steps. First, the differential fluence of the secondary neutrons, required by FISPACT-II, is extracted from the BDSIM simulation using a 4D fluence scorer [12] where the energy bins follow the predefined energy group structure CCFE-709. The beam delivery energy is set to 100 MeV in the BDSIM simulations to be representative of the expected most used or average energy. This beam energy is in contrast to the 70 MeV value, which was conservatively chosen for the shielding design and activation studies [5]. Following the same hypotheses used for dimensioning the shielding walls, the S2C2 extracted current is set at 150 nA, and the total beam-on time is fixed at 300 hours per year. Finally, this differential fluence is input to FISPACT-II for the activation computation.

The activity of a material is determined by its clearance index (CI), defined as the sum A_i/CL_i over all the material composite radionuclides with A the specific activity and CL the clearance level allowed by the Belgian legislation. The material is considered radioactive waste if the CI exceeds the value 1. The major isotopes produced in concrete are listed in Table 3 with their corresponding clearance level.

5 Assessment of the experimental setup for long-term activation measurement

The activation of the experimental cores is studied during the typical 20 years of operation for a proton therapy centre to assess and optimise the ability of the experimental setup

Table 3 Clearance levels for the main isotopes produced in concrete [8]. The values correspond to the clearance level allowed by the Belgian legislation

Nuclide	CL (Bq/g)	Nuclide	CL (Bq/g)
^{3}H	100	^{60}Co	0.1
^{7}Be	10	^{134}Cs	0.1
^{22}Na	0.1	^{152}Eu	0.1
^{54}Mn	0.1	^{154}Eu	0.1

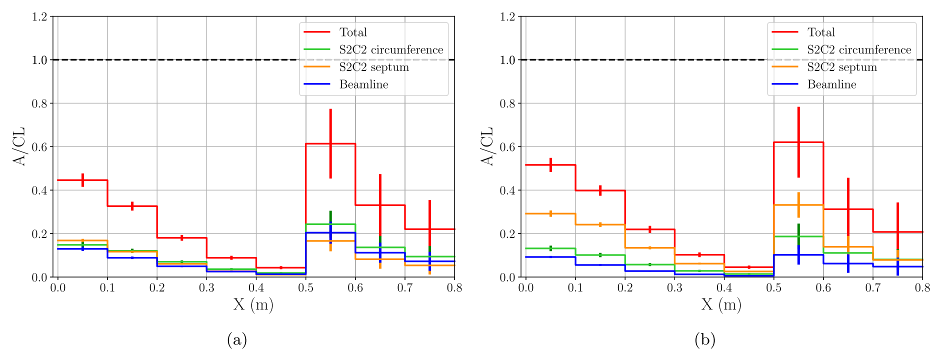

Figure 7 Evolution of the CI along the length of the East (left) and North (right) cores. The contributions from the S2C2 and beamline losses to the CI are respectively represented in green and blue, while the total is in red. The CI limit characterising radioactive waste is shown as a dashed line in black

to measure the long-term activation of the shielding efficiently. This detailed procedure is part of the future experimental workflow supported by numerical simulations taking into account the actual beam workload and source terms. Only long-lived nuclides are considered. The activation results for the East and North cores can be directly computed and are shown in Fig. 7. As expected by their respective position in the vault, the activation related to the S2C2 losses is more important than the activation related to the beamline losses for both cores and the North core is more activated by the extraction septum losses than the East core. The effect of the change of material from LAC to regular concrete in the cores is observed by an increase in the CI after 0.5 m along the cores length X. The limit value of 1, characterising radioactive waste, is never reached as predicted by the shielding activation study [5].

On the other hand, the long-term activation study on the two South cores first required the validation of the "iso-flux" hypothesis. These two cores will be referred to as the "South left" and "South right" cores. The placement configuration initially considered for these two cores is shown in Fig. 8.

The "iso-flux" hypothesis is tested by comparing the secondary particles energy-differential fluence between the two South cores as shown in Fig. 9.

A significant difference is observed between the two cores, especially for high-energy neutrons (above 10 MeV). Neutrons at these energies are responsible for most of the activation from spallation reactions. To verify the impact of this difference on the future measurements, the activation of the two cores is computed. Furthermore, to ensure that the comparison between regular concrete and LAC is pertinent, we compute the long-term activation for these two locations, assuming that the two samples are composed of LAC. The results are depicted in Fig. 10. We observe a significant difference between the

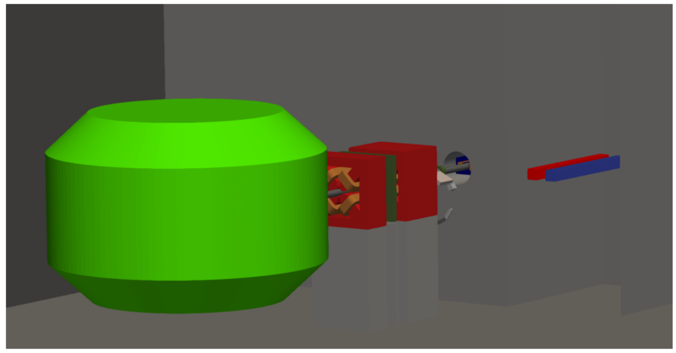

Figure 8 South left (blue) and south right (red) cores positions in the South left Wall

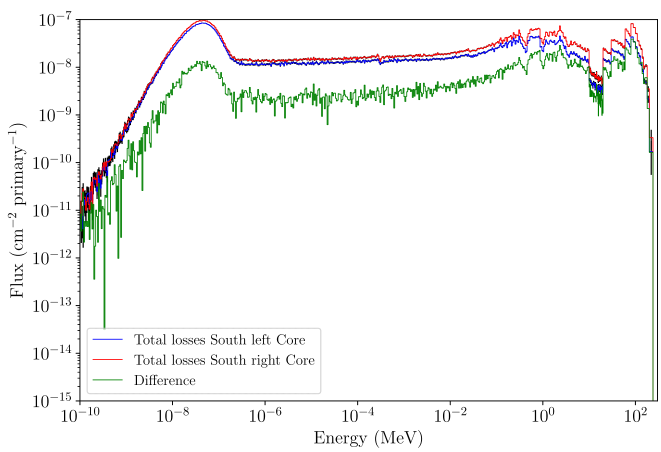

Figure 9 Comparison of the differential secondary neutron fluences extracted from the South left (blue) and South right (red) cores. The difference is represented in green

results obtained for the two cores: the activation depth reached after 20 years of operation reaches a difference factor of two between the cores.

BDSIM/FISPACT-II simulations of alternative core placements are used to optimise the final configuration. A Paraview [13] representation of the BDSIM model superposed with the activated thickness results of the entire South left Wall is shown in Fig. 11. The final cores are placed symmetrically along a vertical axis centred on that plane.

The configuration of the two new cores referred to as “South up” and “South down”, is presented in Fig. 12.

The comparison of the resulting secondary particles energy-differential fluences for the two new cores is shown in Fig. 13. The differences are minimized and subsist only marginally above 10 MeV. These slight variations can be explained by the asymmetry of the beam delivered from the S2C2 inducing asymmetric protons loss distribution around the beamline.

A final conclusion that these two cores will allow a consistent and direct comparison is reached when considering the simulated activation results with identical LAC compositions, as shown in Fig. 14. Therefore, a comparison between the LAC and the regular concrete is experimentally possible in this new configuration.

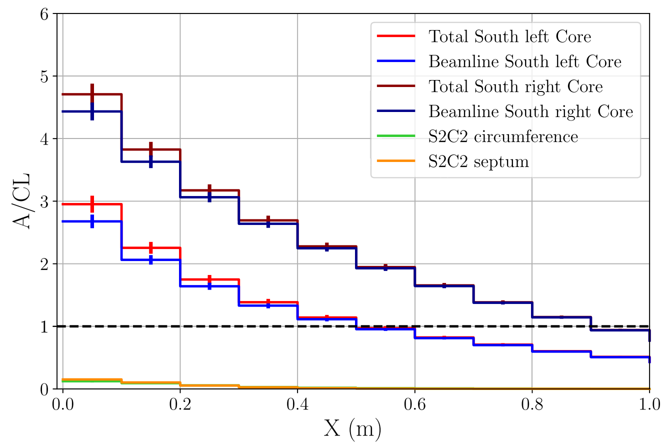

Figure 10 Evolution of the CI along the length of the South left and South right cores in the initial configuration. Both cores are composed of LAC. The contributions of the S2C2 losses to the CI are shown in green and orange for the two samples and are nearly equal. However, the contributions of the beamline losses to the CI of the two cores are shown in dark and light blue with a factor of two difference. The CI limit characterising radioactive waste is shown as a dashed line in black

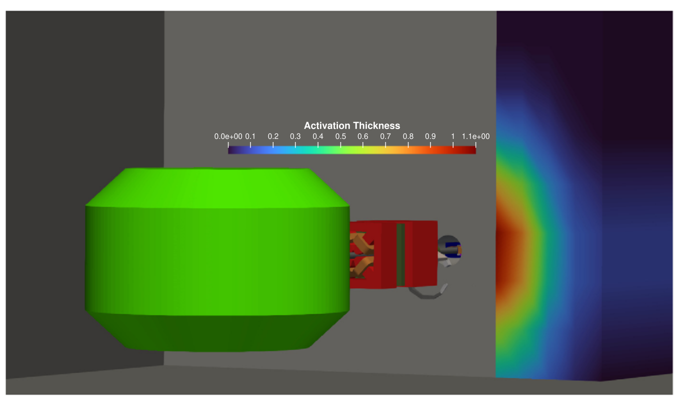

Figure 11 Paraview representation of the P1 BDSIM beamline and the vault shielding. The results of the activation study in the south left wall is represented through the visualisation of the activated thickness in the wall

The activation of the cores South up and South down when respectively made in LAC and regular concrete at the end of the future centre lifetime is shown in Fig. 15. This is expected behaviour due to their positions with respect to the degrader. Both results show that beamline losses are the most critical source of activation.

6 Activation monitoring in experimental conditions

The BDSIM/FISPACT-II methodology is then used to devise the required performance of the experimental measurement and to simulate the response in terms of activation measurement for the four experimental cores. The cores removal and the activation measurement will be performed at regular intervals during the centre lifetime and decommissioning period. We use a typical beam workload scenario to evaluate this procedure in simulations. As part of the proposed hybrid workflow described in Sect. 7, these simulation

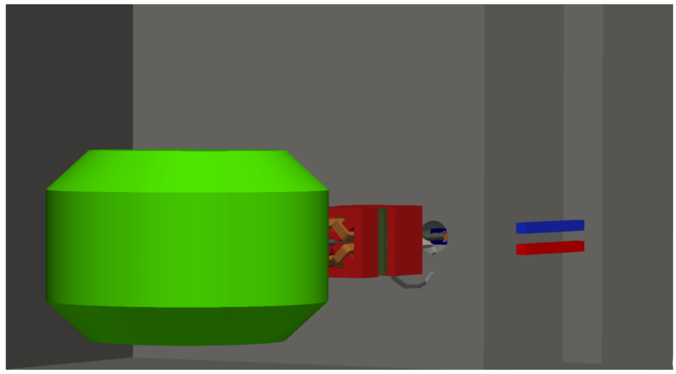

Figure 12 South up (blue) and south down (red) cores positions in the South left Wall

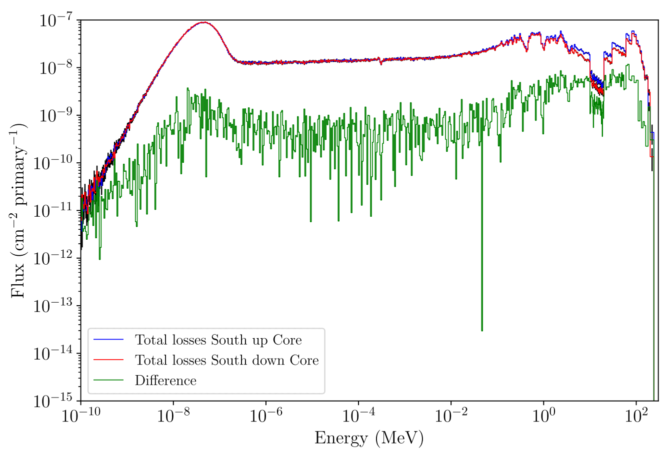

Figure 13 Comparison of the differential secondary neutron fluences extracted from the South up (blue) and South down (red) cores. The difference is represented in green

results will also be recomputed at regular intervals based on the actual machine logging data on the beam current and energy. The evolution of the activation per main long-term nuclides for both South cores next to the degrader—one in LAC and the other in regular concrete—when considering the average expected workload of the centre (300 hours of irradiation per year at 100 MeV) is shown in Fig. 16. ^{22}Na is observed to be the main radioactive nuclide for both concrete compositions. As expected, we observe that the two concrete compositions major contributors to the total activity are different.

A key point of the BDSIM/FISPACT-II methodology is that the most time-consuming operation, the BDSIM simulations, is dissociated from the fast FISPACT-II computations. Once the secondary particles differential fluences are extracted, FISPACT-II can perform the activation computation for any atomic composition and total irradiation fluence (the differential fluence is normalised). Therefore, the actual workload of the centre can be used to follow in a day-to-day or even hour-to-hour manner the evaluation of the activation of the concrete shielding.[2] Such capability allows better assessments of the system actual activation level, improving the quality of the related radiation protection studies

[2]Or of the beamline elements [14].

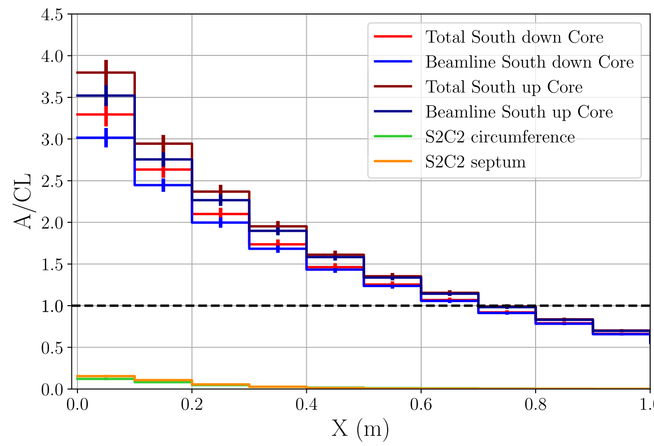

Figure 14 Evolution of the CI along the length of the South up and South down cores with identical LAC compositions for comparison. The contributions of the S2C2 losses to the CI are shown in green and orange for the two samples and are nearly equal. The contributions of the beamline losses to the CI of the two cores are shown in dark and light blue. The CI limit characterising radioactive waste is shown as a dashed line in black

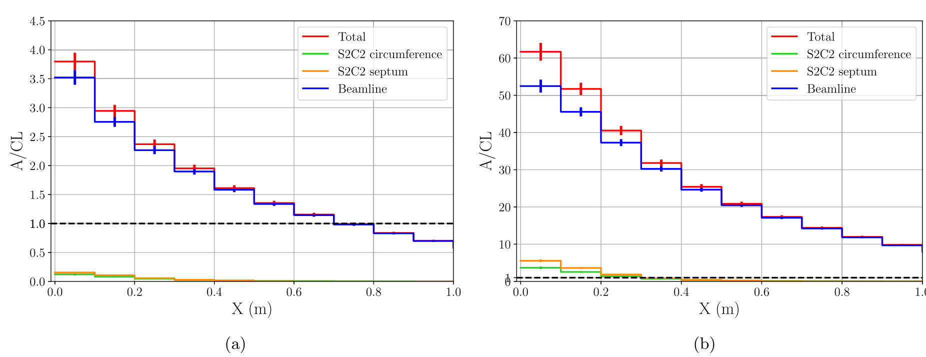

Figure 15 Evolution of the CI along the length of the South up (left) and South down (right) cores in their respective material: LAC and regular concrete. The contributions of the S2C2 losses to the CI are shown in green and orange. The contributions of the beamline losses to the CI are shown in blue. The CI limit characterising radioactive waste is shown as a dashed line in black

and allowing a targeted decommissioning of the concrete shielding. It is also of primary importance when preparing the removal of the cores and their measurements at a given time; to allow for determining the expected activity of the different nuclides and the expected spectrometry results.

Activation results from cumulative irradiation periods can be obtained as incremental results. We use a hypothetical one-week beam workload to illustrate this workflow. We consider a continuous beam usage of 1.15 hours per day for five consecutive days per week. The results for the evolution of the activation of the two cores of the South left Wall considering such irradiation pattern for 20 weeks is shown in Fig. 17. The radioactive nuclide composition at any location in the shielding can be extracted at any time. This feature of our computation package can be used to study subsequent irradiation or cool-down periods without repeating the simulations from the start over the whole period.

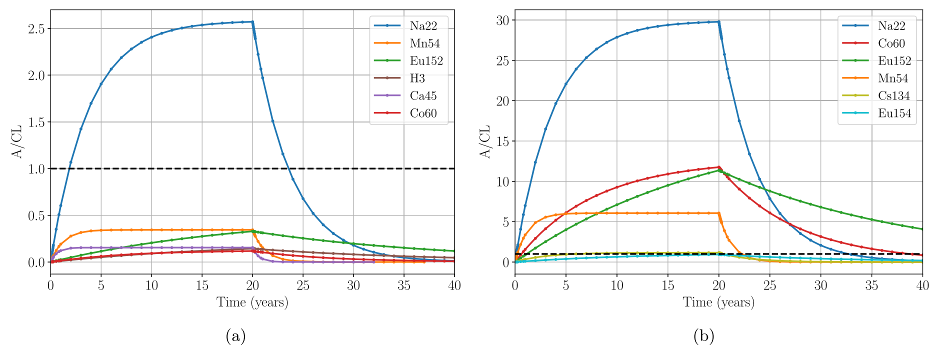

Figure 16 Time evolution of the CI for the South up (left) LAC core and the South down regular concrete core (right). The contributions from the six most active nuclides are shown. The CI limit characterising radioactive waste is shown as a dashed line in black

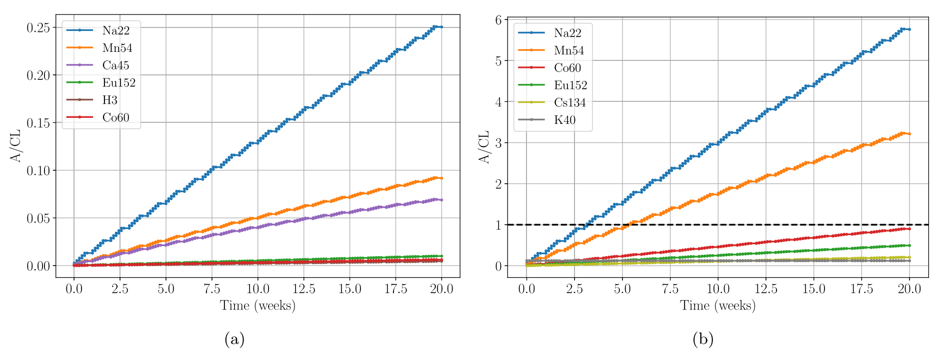

Figure 17 Time evolution of the CI for the South up (left) LAC core and the South down regular concrete core (right). The contributions from the six most active nuclides are shown. The irradiation and cooling patterns follow a typical week workload. The CI limit characterising radioactive waste is shown as a dashed line in black

This methodology will be fully exploited at the Charleroi centre. The machine log files will be used to reconstruct the complete workload scenario, including beam energy and beam current, and to obtain detailed snapshots of the shielding and experimental cores radioactive nuclei composition and clearance levels at any time. These simulation data will guide the experimental program to provide inputs regarding the required cool-down time prior to new measurements and expectations regarding the spectrometry results. These two aspects are analysed for the typical workload described above.

The activation monitoring can be realised by analysing measured γ spectra from cores fragments [15, 16]. The γ intensities will allow us to derive the nuclides activities and compute the CI of the experimental core fragments. A theoretical γ spectrum can be extracted from the FISPACT-II output files analysis using the python library ActiGamma [17]. ActiGamma produces γ spectra from the nuclides activities extracted from FISPACT-II simulations. The expected spectra of the γ emitted from the two South cores at the end of the centre lifespan are shown in Fig. 18. We observe a difference between the cores γ spectra as expected from the results of Fig. 16: the intensity of the South down core made in regular concrete is observed to be higher than the one of the South up core made in LAC as expected by their difference in CI and, in each spectrum, a coherent relative importance between the nuclides is obtained.

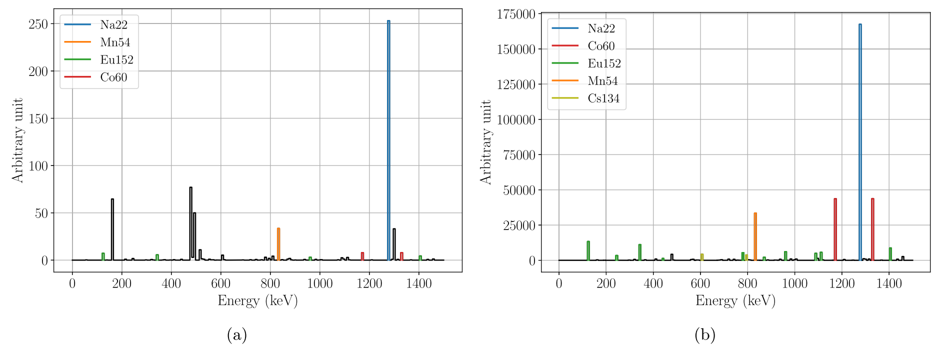

Figure 18 Expected γ spectrum expected at the most activated depth of the South up (left) and South down (right) at the end after 20 years of centre operation and an arbitrary ten-day cooling period. The γ spectra of the different nuclides contributing to the emission are colour-coded

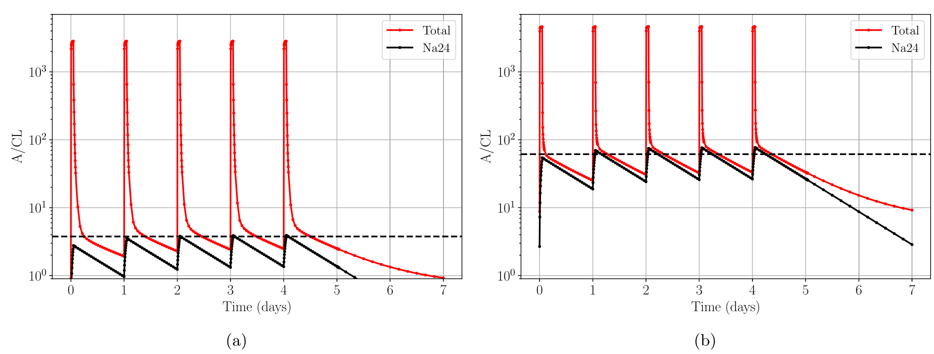

Figure 19 Evolution of the CI expected at the most activated depth of the South up LAC core (left) and the South down regular concrete core (right). Long- and short-term radioactive nuclides are considered in these results. The irradiation and cooling patterns follow the hypothetical one-week irradiation scenario discussed in the text. For each material, the CI value reached after 20 years of centre operation is represented in black for comparison purposes

Short-term studies using the BDSIM/FISPACT-II methodology are also required to distinguish short-term activation background from long-term contributions. Indeed, most computations related to activation only consider the radioactive nuclides with a half-life over three months. Such simplification has no impact on the long-term activation results that have been presented so far. However, the total amount of produced radioactive nuclides must be considered to be able to anticipate their impact as additional background on the spectrometry measurement result on the long-term activation.

The evolution of the two South cores CI during a typical week while considering both the long- and short-term radioactive nuclides is shown in Fig. 19. When considering the short-lived nuclides, we observe that the CI obtained in the cores—which can be related to the activation of the walls—reach some extremely high values largely above the limit of 1. For both South cores, the CI reached after 20 years of operation of the centre (when only considering the long-term nuclides) is shown in black dashed line for comparison purposes. These values, respectively of 4 and 61 for LAC and regular concrete, are crossed for the South up core in LAC, 4 hours after the end of the first beam and 11 hours after the end of the last beam before the weekend. The corresponding relaxation times for the

South down core in regular concrete are 2 and 7 hours. The increase in the relaxation time over the week shows that repetitive irradiation patterns, even separated by a day, can induce additive effects for short-term activation. This background contribution must be anticipated and accounted for in the measurement. It is important to note that the CI reached at the end of the week is similar to the values of the beginning of the week for this hypothetical workload scenario. This similarity is due to the significant decay of the short-lived nuclides.

The radioactive nuclides, which are major contributors to the total activation, are extracted from the simulations. ^{24}Na is the most active contributor to the short-term activation. It dominates the signal between each irradiation period. Other short-lived nuclides contributions decay (notably ^{38}K, ^{49}Ca, ^{11}C, ^{13}N, ^{34}Cl, ^{27}Mg, ^{44}K and ^{29}Al) below background before the next irradiation pattern. This is crucially relevant regarding radiation protection studies and preparation of the experimental measurements. Indeed, ^{24}Na most probable decay leads to an excited state of ^{24}Mg by the emission of a β^- of 1.392 MeV maximal energy followed by 2 relaxation γ of 2.754 MeV and 1.368 MeV [18]. Such emissions cannot be disregarded, especially at high disintegration rates, as they can contribute to an important dose deposition or temper the activation measurements, calibrated based on the long-term γ decay monitoring.

The activation study of the experimental cores allowed foreseeing the main long-term radioactive nuclides and their expected γ spectra, crucial for the measurement campaign preparation. The importance of the short-term nuclides contribution to the radiation protection studies and the quality of the experimental measurements was acknowledged by the cores activation study in a hypothetical experimental condition.

7 Conclusion

To support the complete clinical and experimental program of the ProtherWal proton therapy centre in Charleroi, Belgium, the BDSIM/FISPACT-II methodology has been applied to design and optimise an experimental setup to monitor the long-term shielding activation using a set of removable concrete cores placed at critical locations in the cyclotron vault.

The methodology was shown to be efficient in designing the experimental cores configurations based on the best-knowledge hypothetical irradiation workload. The capability to recompute complete "activation snapshots" of the shielding walls at any point during the centre lifetime based on logging information on the beam energy and current was illustrated. The long-term activation following a typical anticipated centre workload was thoroughly studied. Theoretical γ spectra were obtained using FISPACT-II output files to characterise the main radioactive nuclides whose activities can be correlated with measured γ intensities.

We have shown that the experimental setup will allow a direct comparison between LAC and regular concrete cores and experimentally validate the beneficial impact of the LAC in reducing the amount of radioactive waste at the end of the centre lifetime. A particular focus has been given to the short-term activation occurring after each irradiation when the cores clearance indexes at the depth of highest activation reach values that are orders of magnitude larger than those from the long-term contributions. Specific simulations will be performed prior to the measurement campaigns to quantity the detrimental effect of this background.

The final setup with the four removable cores will provide a rich dataset of measured results on shielding activation. This experimental campaign will be supported by computation from our simulation package using machine data, thus offering a complete hybrid—simulated and experimental—monitoring of the shielding activation.

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Availability of data and materials
The data generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare no competing interests.

Author contributions
ER: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing—Original Draft, Writing—Review & Editing. CH: Conceptualization, Methodology, Writing—Original Draft, Supervision, Writing—Review & Editing. RT: Conceptualization, Writing—Review & Editing. EG: Conceptualization, Writing—Review & Editing. NP: Writing—Review & Editing, Supervision. FS: Writing—Review & Editing. All authors read and approved the final manuscript.

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