Proton therapy beamline activation of the IBA Proteus One using BDSIM and FISPACT-II

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Cyclotron-based proton therapy systems generate large fluxes of secondary particles due to the beam interactions with the beamline elements, with the energy degrader being the dominant source. Compact systems exacerbate these challenges for concrete shielding and beamline element activation. Our implementation of the Rigorous Two-Step method uses Beam Delivery Simulation (BDSIM), a Geant4-based particle tracking code, for primary and secondary particles transport and fluence scoring and FISPACT-II for time-dependent nuclear inventory and solving the rate equations. This approach is applied to the Ion Beam Applications (IBA) Proteus®ONE (P1) system, for which a complete model has been built, validated, and used for shielding activation simulations. We detail the first simulations of the activation on quadrupole magnets in high-fluence locations downstream of the degrader. Results show the evolution of the long-lived nuclide concentrations for short and long timescales throughout the facility lifetime for a typical operation scenario.

1. BDSIM simulation of the P1 secondary neutrons and lost protons

The P1 proton therapy system has already been modelled in BDSIM and validated against experimental data in Ref. [1]. The primary beam tracking is done from the exit of the accelerator (S2C2) to the isocentre.

The interaction of the primary beam with the degrader allows to deliver proton beams from 230 MeV to 70 MeV. However, as a counterpart, it **scatters some of the primary protons and produces a large number of secondary particles, mainly neutrons [2], which interact with the beamline elements via nuclear reactions, mainly capture and spallation, producing radioactive nuclides**.

2. BDSIM/FISPACT-II methodology

The BDSIM/FISPACT-II methodology, thoroughly described in Ref. [3] and inspired by the Rigorous Two-Step (R2S) [4], **was proposed to characterise the beamline activation during a typical centre lifetime of 20 years**.

The method is illustrated on the first quadrupole of the rotating gantry, Q1G, which was modelled using a cylindrical default geometry made of iron provided by BDSIM.

Figure 1 shows the BDSIM model of the vault of the proton therapy centre of Charleroi with the S2C2, the extraction line with the quadrupoles, slits and degrader and the start of the rotating gantry with the collimator and Q1G.

4. Secondary neutron differential fluence

Primary beam tracking simulations from the exit of the S2C2 to the isocenter have been realised using the BDSIM model with the degrader calibrated for a delivered beam energy of 100 MeV.

The differential fluence of the secondary neutrons and lost protons are scored following respectively the predefined energy group structures "CCFE-709" and "CCFE-162" **in the cylindrical scorer mesh presented in Fig. 2 using the 4D-Scoring BDSIM feature** [5]. The neutron and proton differential fluence is presented in Fig. 3 at different depths.

- **The neutron fluence variation with depth is less important than the proton fluence variation**, which is expected behaviour due to the finite range of protons in iron.

The level scheme observed in the neutron and proton differential fluences can be directly linked to the variation in energy bin widths of their respective energy group structure.

5. Activation results

The activity of a compound is determined by its clearance index. The clearance index is defined as the sum A_i/CL_i over all the material radionuclides with A the specific activity and CL the clearance level allowed by the Belgian legislation. If the clearance index exceeds the value of 1, the compound is considered radioactive waste.

Using the differential fluence of the secondary neutrons and lost protons, FISPACT-II computes the activation of Q1G over an irradiation and a cooling period of 20 years separately for each type of particle. The results are combined to characterise the total activation of Q1G at the end of the centre lifespan.

- Figure 4 shows that the **neutron activation dominates at all depths with only a small impact of the proton activation in the first centimetres**.
- Figure 5 shows the evolution of the clearance index of the Q1G structure during the irradiation and the cooling periods. **The radioactivity is mainly induced by ^{54}Mn**. The evolution of the clearance index induced by the other radioactive nuclides is also presented.

The high clearance index value shows that **the quadrupole structure will be highly activated at the decommissioning time of the centre. A cooling period of 15 years will be required for Q1G to be considered normal waste.**

This activation study can be extrapolated to the other critical elements of the beamline or the movable parts brought in the vault or the treatment room for specific treatment plans or research activities.

Conclusion and outlook

The BDSIM/FISPACT-II methodology was applied to the specific case of the activation of an element of the P1 beamline. The first quadrupole of the rotating gantry, Q1G, has been chosen as its position behind the degrader leads to significant irradiation of scattered protons and secondary neutrons. The results showed that the neutron-induced activation dominated proton-induced activation. The analysis of the evolution of radioactive nuclide concentrations showed that ^{54}Mn was the primary source of activity and that a cooling period of 15 years after the centre decommissioning was required for the Q1G structure to be considered normal waste.

The BDSIM/FISPACT-II methodology will be used for a complete activation study of all the P1 beamline elements and experimental setup structures of the future proton therapy centre of Charleroi.

Acknowledgments

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Modelling of the vault of the Charleroi proton therapy centre

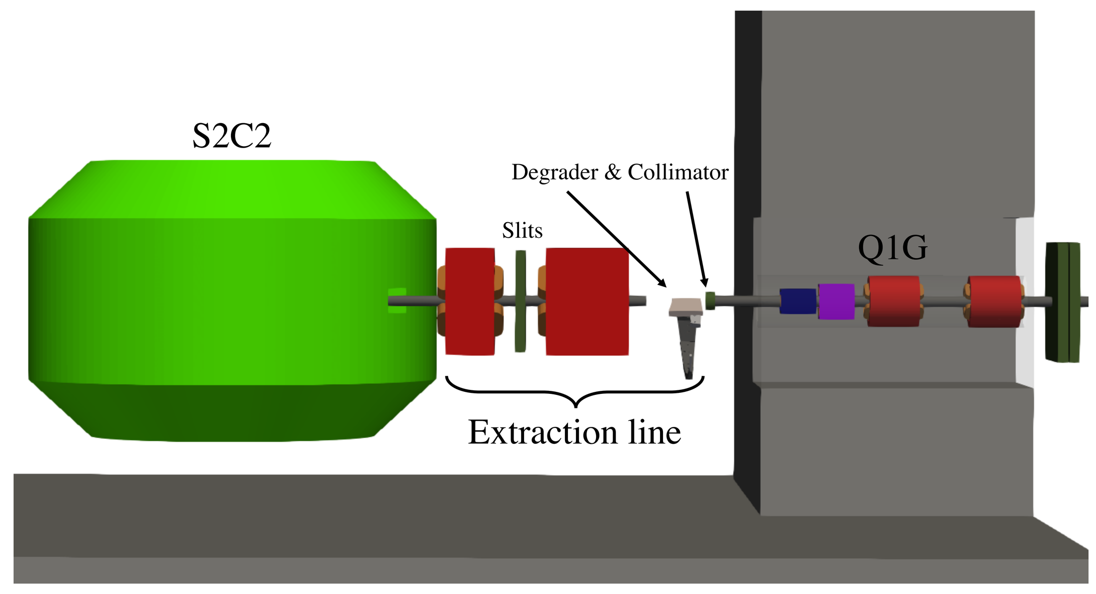

Figure 1: BDSIM model of the vault extraction line and its shielding. The superconducting synchro-cyclotron (S2C2) and the energy degradation system are shown. The concrete shielding wall separating the cyclotron vault from the treatment area is visible, with the beamline elements fit through a cylindrical cut.

Cylindrical 4D-Scoring of the proton and neutron fluence

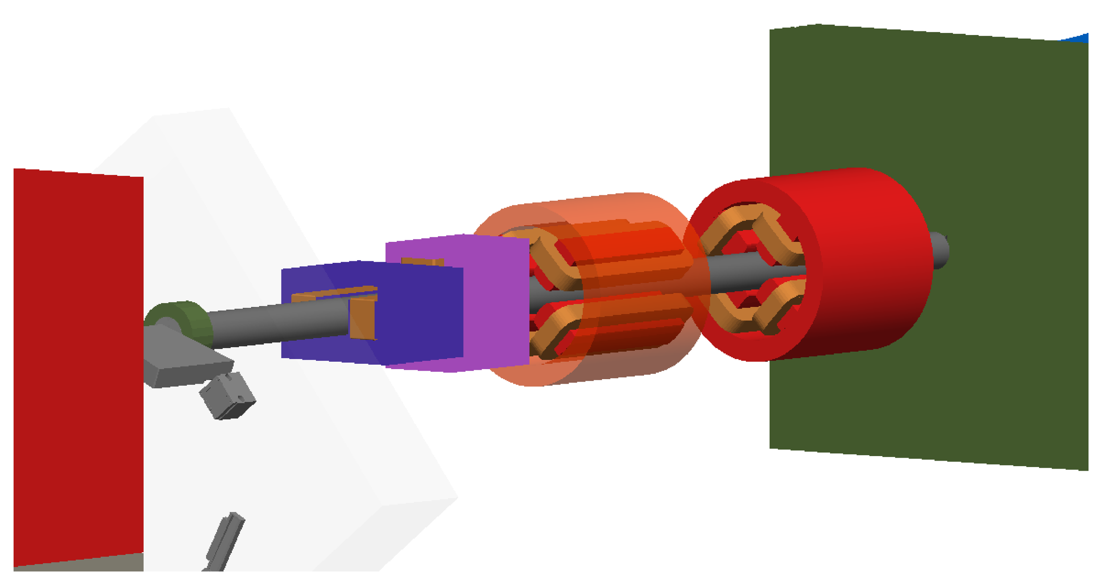

Figure 2: Detailed model of the energy degrader and the beginning of the rotating gantry. A cylindrical 4D-Scoring is placed on the Q1G quadrupole. The last radial bin fits the iron external geometry of the magnet. On the figure, the external geometry of Q1G was removed and the last bin of the scoring mesh was highlighted in red.

Secondary differential fluences extracted using the Scoring-4D feature

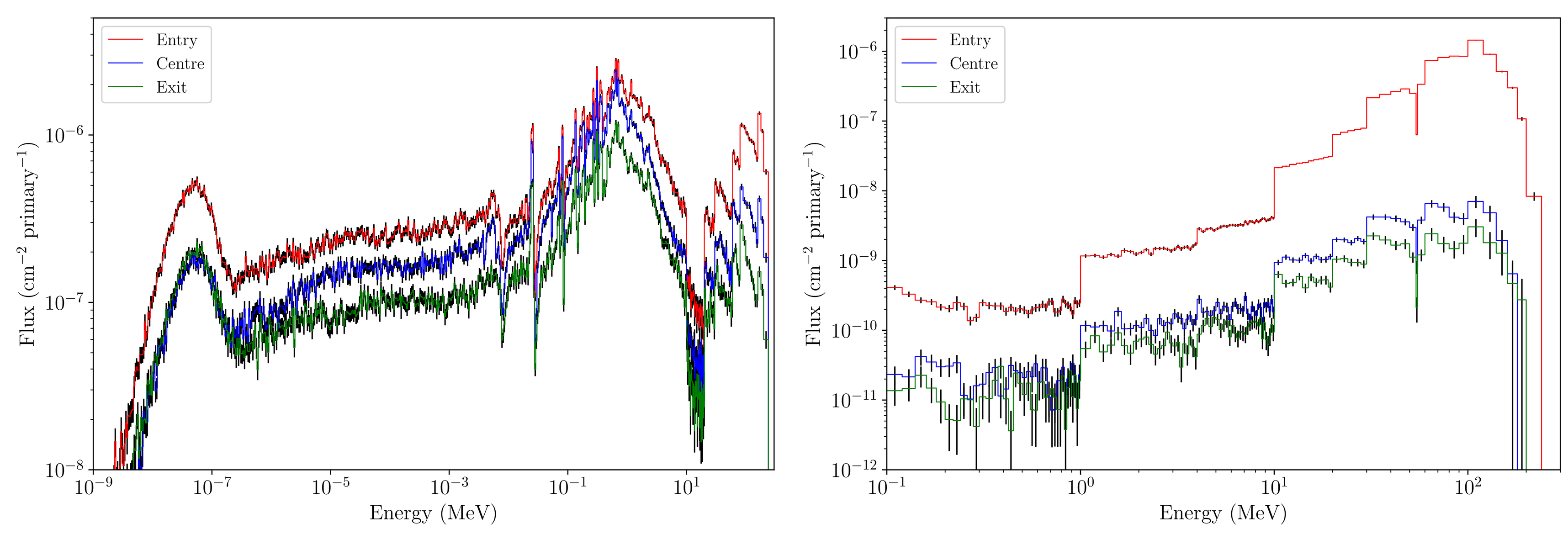

Figure 3: Differential secondary neutron fluence (left) and proton fluence (right) extracted from the Q1G external structure using the BDSIM 4D Scoring feature. The fluence has been extracted at the entry, the centre and the exit of the Q1G outer structure. The energy bins follow the CCFE-709 and CCFE-162 energy group structures, respectively.

Clearance index evolution along Q1G thickness

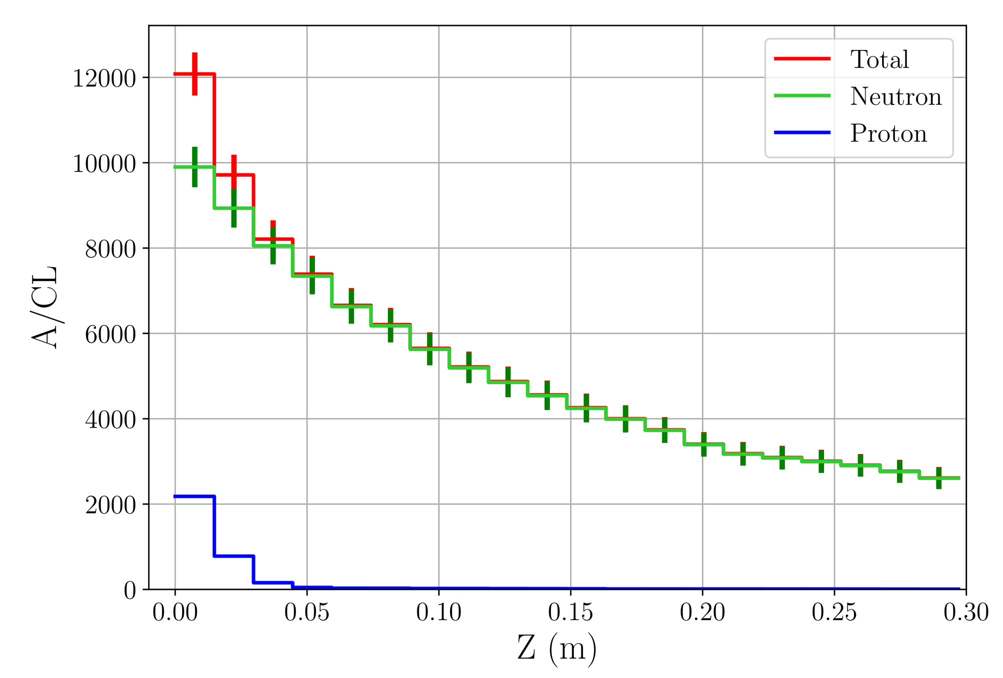

Figure 4: Evolution of the clearance index along with the thickness of the Q1G external structure. The clearance indexes related to the neutron and proton activation are represented in green and blue, while the total is represented in red.

Clearance index evolution with time of Q1G most radioactive part

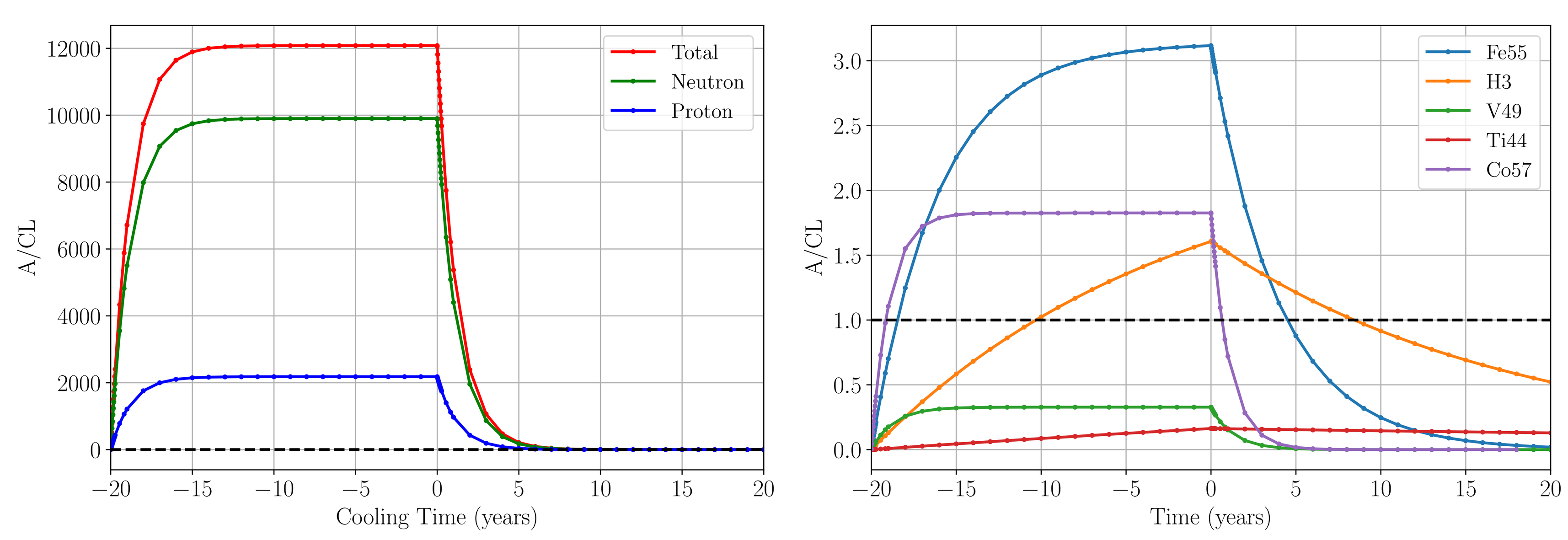

Figure 5: Evolution of the clearance index with time of the most radioactive part of the Q1G external structure following the incident particle (left) and the main radioactive nuclides, other than ^{54}Mn (right).