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ARTICLE

Radioprotection studies for the ARCHADE carbon therapy center

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The Advanced Resource Centre for Hadrontherapy in Europe will be equipped with a superconducting cyclotron delivering 400 MeV per nucleon ^{12}C ion beams and 250 MeV proton beams. Shielding requirements and potential concrete activation in the facility are compared for these two types of beams.

Keywords: activation; PHITS; MCNPX; hadron therapy

1. Introduction

The Ion Beam Applications (IBA) Company works on the development of a superconducting cyclotron called the C400. Devoted to cancer therapy, it will be able to deliver ^{12}C ion beams with a fixed energy of 400 MeV per nucleon (MeV/u) and proton beams with energy of 250 MeV. The beams are extracted from the cyclotron with maximum energy and the energy modulation is performed by a graphite degrader located at the exit of the cyclotron.

The prototype of this machine will be installed in the Advanced Resource Centre for HADrontherapy in Europe (ARCHADE), close to the GANIL centre in Caen, France. The centre presented in **Figure 1** consists of a cyclotron room, a treatment room equipped with a horizontal fixed beam line, and a experiment room for research purposes.

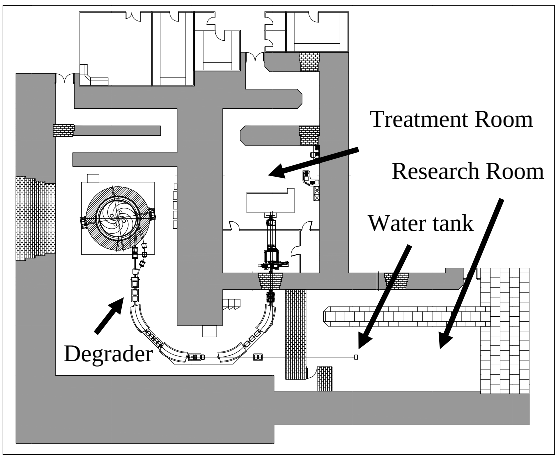

Figure 1. Layout of the proposed ARCHADE.

Radioprotection studies have been performed to evaluate the shielding requirements of the various rooms for ^{12}C beams [1]. In this paper, ambient dose equivalents obtained with ^{12}C and protons beams are compared. The generation of radioactive nuclides in the shielding concrete of the cyclotron room is also described, both for ^{12}C and proton beams.

The production of secondary neutrons and charged particles due to the passage of the primary beams in the degrader is discussed in section 2. The shielding requirements imposed by the ^{12}C ion and proton beams are compared in section 3. The evaluation of the concrete activation obtained in the cyclotron room for these two types of beams is described in section 4.

2. Secondary neutron and charged particle sources

The emission of secondary neutrons by high-energy ^{12}C or proton beams stopping in thick targets is evaluated using the Particle and Heavy-Ion Transport code System, PHITS [2]. The simulated energy and angular spectra obtained for 100 MeV/u to 400 MeV/u ^{12}C ions stopping in carbon and copper target are in rather good agreement with data measured at HIMAC, both in shape and in energy-integrated yields [3]. As an example, PHITS predictions and HIMAC data are compared in **Figure 2** for 400 MeV/u ^{12}C ions stopping in thick graphite target. The PHITS predictions appear to underestimate the neutron production in the very forward region (0°), without clear explanations.

The emission of secondary neutrons from 400 MeV/u ^{12}C ions passing through the energy degrader is also studied with PHITS. In addition to neutrons, the primary ion fragmentation leads to the production of secondary charged particles escaping the degrader. The evolution of the neutron multiplicity as a function of the ion transmitted energy is compared in **Figure 3** to the multiplicities obtained for the main secondary charged particles. Ions with a higher Z value can also be produced but with a yield smaller than 0.1 per primary particle.

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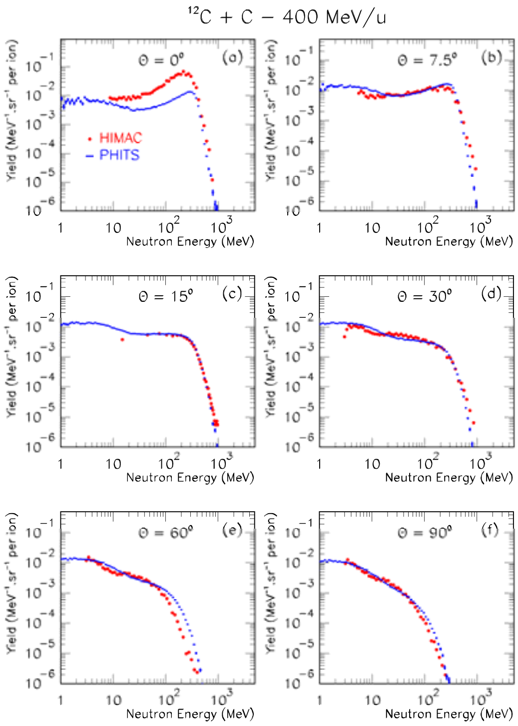

Figure 2. Comparison of the neutron double differential thick-target yields calculated with PHITS and the HIMAC data obtained for 400 MeV/u ^{12}C ions on carbon target [3].

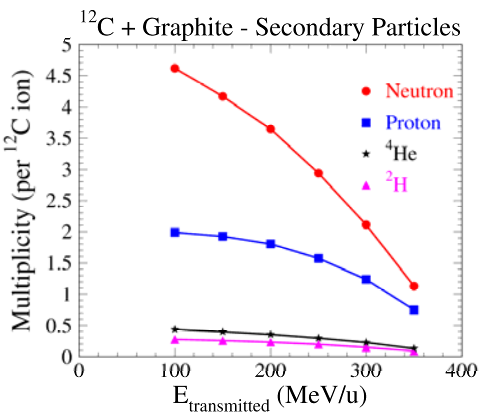

Figure 3. Evolution of secondary particle multiplicities as a function of ^{12}C transmitted energy through a graphite degrader.

3. Shielding requirements

In order to be able to compare shielding requirements needed in proton and carbon mode, the dose rates obtained in a thick water absorber (40x40x40 cm^3) for these two types of beam have been compared. The beam currents needed to obtain an average physical dose rate of 2 Gy/min in a water volume of 10x10x10 cm^3 have been determined, the 10 cm depth being aligned on the Bragg peak distal edges.

Neutron and charged particle transport inside ARCHADE model is performed with MCNPX 2.5.0 [4].

In the cyclotron room, ambient dose equivalents H*(10) are computed for beams with transmitted energy of 100 MeV/u for ^{12}C and 100 MeV for ^{1}H, corresponding to a degrader thickness of 27.9 g/cm^2 and 28.6 g/cm^2, respectively. The H*(10) values are computed with ICRP 74 fluence-to-dose conversion factors below 200 MeV [5] and with factors from M. Pelliccioni at higher energy [6]. The currents extracted from the cyclotron, I_{cyclo}, are chosen to deliver an average dose rate of 2 Gy/min in the irradiation volume. They take into account the transmission efficiency of the degrader [1] and are given in **Table 1** in particle-nA (pnA).

The evolution of H*(10) inside the walls is shown in **Figure 4**, in the directions Θ=0° and Θ=90° with respect to the primary beam direction, Θ being the polar angle of the emitted neutrons. Secondary charged particles emitted by the degrader are strongly forward-peaked and will stop in the first magnet following the degrader. The neutrons emitted by these charged particles contribute less than 5% to the total neutron dose.

The values of H*(10) in the walls of the research room are compared in **Figure 5** for ^{12}C beams of 400 MeV/u and ^{1}H beams of 250 MeV. The beam currents reaching the water absorber, I_{treat}, also correspond to an average dose rate of 2 Gy/min (see Table 1). The differences between ^{1}H and ^{12}C results in the lateral shielding are due to the harder neutron energy spectrum obtained with ^{12}C ions.

At large depth, H*(10) values obtained with ^{12}C beams exceed those obtained with ^{1}H beams in all cases, even if the difference is more pronounced in Θ=0° direction than in Θ=90°. The shielding design can thus be based upon ^{12}C beams only.

Table 1. Beam currents needed to obtain a dose rate of 2 Gy/min in water absorber.

Beam current	^{1}H mode	^{12}C mode
I_{cyclo} (pnA)	19.94	0.316
I_{treat} (pnA)	0.651	0.0304

4. Concrete activation

There are many elements in standard concrete that become activated when irradiated by neutrons produced in the cyclotron vault or in the irradiation rooms. Only a few of the resulting nuclides are long-lived. They are identified in **Table 2**. These radioactive species build up over time from neutron capture reactions in trace amounts of stable Europium, Cobalt, and Cesium which are present in concrete in concentrations of a few parts per million or less by weight.

Table 2. Long-lived radioactive nuclides produced in standard concrete per neutron capture.

Nuclide	Parent	σ(n,γ)	Half-life
^{152}Eu	^{151}Eu	9198 barns	13.33 y
^{154}Eu	^{153}Eu	312 barns	8.5 y
^{60}Co	^{59}Co	37 barns	5.27 y
^{134}Cs	^{133}Cs	29 barns	2.065 y

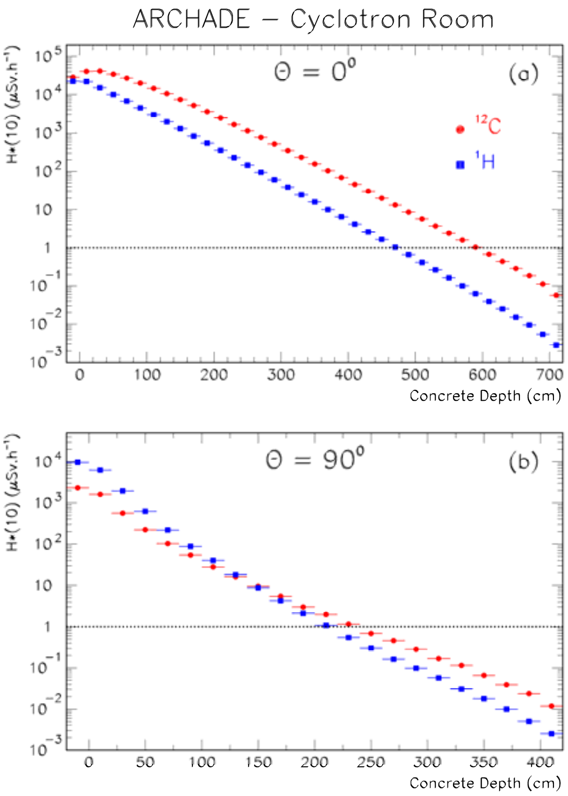

Figure 4. Evolution of the ambient dose equivalent in the walls of the cyclotron room as a function of concrete depth: (a) wall facing the degrader; (b) side wall.

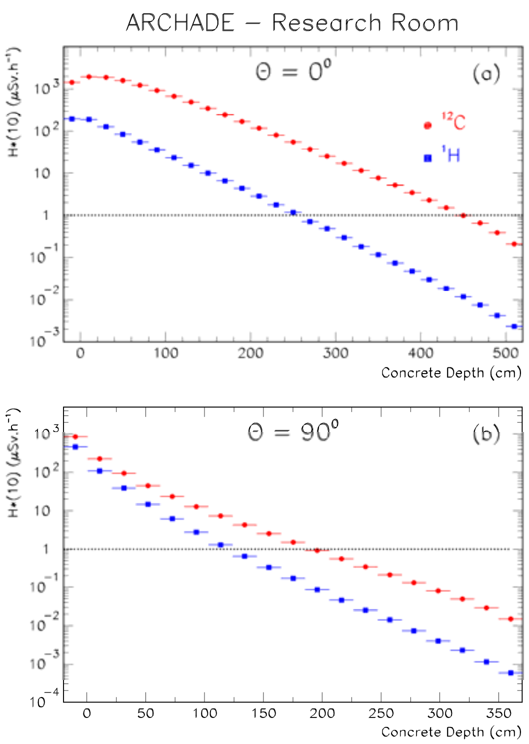

Figure 5. Evolution of the ambient dose equivalent in the walls of the research room as a function of concrete depth: (a) wall facing the beam absorber; (b) side wall.

In this study, we use the concentrations of stable Eu, Co and Cs in concrete as found in the analysis of activated concrete coming from a PET cyclotron vault [7]. Based upon the measured specific activity of the 4 isotopes listed in Table 2, they derived the weight fraction of natural Eu (0.29 ppm), Co (2.5 ppm) and Cs (1.5 ppm) in the original concrete before irradiation.

Because of the extremely low beam currents used in particle therapy, it is very unlikely to produce significant activation in the treatment rooms. However, the case of the cyclotron room is different: for low energy beams, the transmission efficiency of the degrader is about 1-2% and thus, the currents extracted from the cyclotron are 50 to 100 times larger than in the irradiation rooms. We consider beams with an energy of 100 MeV/u after the degrader, which is the lowest beam energy usually used. To further enhance these currents, we consider irradiation conditions corresponding to a maximal dose rate of 40 Gy/min in a water phantom located inside the treatment room. Using an operating time of 1000 h/year, this leads to an annual workload of 2.2 particle-µA.h and 150 µA.h for ^{12}C and proton beams, respectively.

The total specific activity per gram of concrete is obtained by summing the activities of the 4 nuclides listed in Table 2. It is computed at saturation and for a period of 20 years, typical for a particle therapy centre. **Figure 6** shows the evolution of the total saturated specific activity as a function of concrete depth. This result is obtained in a surface of 1 m^2 right in front of energy degrader, corresponding to the direction Θ=0° with respect to primary beam. The depth-activity profiles obtained with proton and carbon beams are clearly different, due to the different energy spectra of secondary neutrons emitted by these two beams. The transversal profiles of the generated activity are also rather different between proton and carbon beams. The transversal activity profile obtained with ^{12}C beams at a depth of 30 to 40 cm is shown in **Figure 7** while the activity profile obtained with proton beams at a depth of 10 to 20 cm is displayed in **Figure 8**.

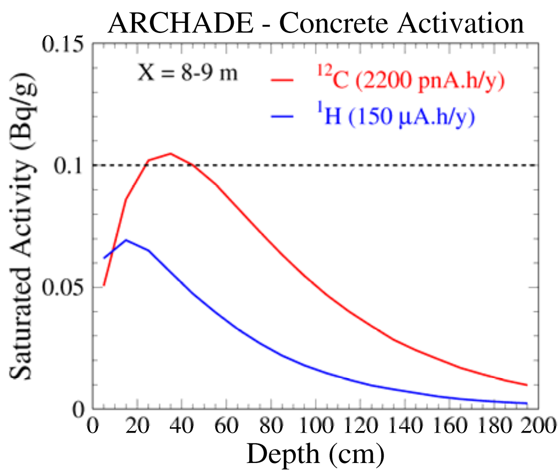

Figure 6. Evolution of saturated specific activity with concrete depth in front of the degrader for ^{12}C ions and protons.

As expected from the very forward-peaked angular distribution of secondary neutrons emitted by ^{12}C ions, the activity reaches its maximal value at X= 8 m, corresponding to the degrader location along the X axis but decreases rapidly when moving away from this position. The activity profile obtained with proton beams is much broader with a 4 m wide plateau around the degrader position. The activity decrease observed in the middle of this plateau is due to the presence of the bending magnet after the degrader, scattering or absorbing neutrons produced in the very forward region. This effect is less pronounced with ^{12}C ions because of the more forward -peaked neutron emission.

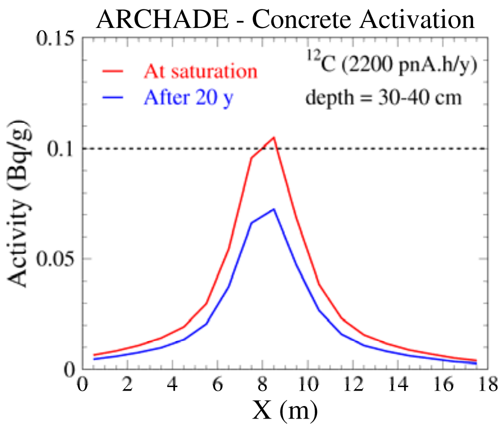

Figure 7. Variation of specific activity obtained along X axis at a depth of 30 to 40 cm for ^{12}C ions. Activities obtained after 20 years of operation and at saturation are shown.

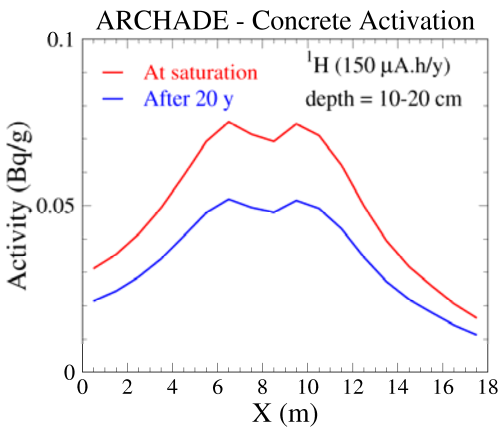

Figure 8. Variation of specific activity obtained along X axis at a depth of 10 to 20 cm for protons. Activities obtained after 20 years of operation and at saturation are shown.

The IAEA recommends values of activity concentration that can be used as limits for the exemption and the clearance of bulk amounts of material containing radionuclides of artificial origins [8]. For the nuclides considered in this study, this limit amounts to 0.1 Bq/g. Based upon the results presented in Figures 6 and 7, this limit is only reached for the saturated specific activity in a very small portion of the concrete when using ^{12}C beams. For a period of 20 years, the specific activity reaches a maximal value of 0.07 Bq/g, well below the exemption limit. For protons, the specific activity reached a maximal value of 0.05 Bq/g.

Considering the very conservative assumptions used in this study (1000 h/y of very low energy beams in the cyclotron room), these results demonstrate that the concrete used in ARCHADE centre can be treated as non-nuclear waste at the end of the lifetime of the centre.

5. Conclusions

The comparison of ambient dose equivalents obtained with ^{12}C and proton beams shows that, for beam currents leading to the same dose deposition inside a water absorber, ^{12}C ions always give larger radiation doses than protons behind a thick shielding (> 150 cm), both in the primary beam direction and at 90° from it.

For the same annual workload, carbon beams also generate more activation of long-lived nuclides in the cyclotron room concrete than proton beams. Nevertheless, even with very heavy workload, the specific activity obtained after 20 years of operation remains below IAEA limits defined for exemption and clearance of bulk materials.

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