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Shielding data for hadron-therapy ion accelerators: Attenuation of secondary radiation in concrete

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ABSTRACT

The secondary radiation field produced by seven different ion species (from hydrogen to nitrogen), impinging onto thick targets made of either iron or ICRU tissue, was simulated with the FLUKA Monte Carlo code, and transported through thick concrete shields: the ambient dose equivalent was estimated and shielding parameters evaluated. The energy for each ion beam was set in order to reach a maximum penetration in ICRU tissue of 290 mm (equivalent to the therapeutic range of 430 MeV/amu carbon ions). Source terms and attenuation lengths are given as a function of emission angle and ion species, along with fits to the Monte Carlo data, for shallow depth and deep penetration in the shield. Trends of source terms and attenuation lengths as a function of neutron emission angle and ion species impinging on target are discussed. A comparison of double differential distributions of neutrons with results from similar simulation works reported in the literature is also included. The aim of this work is to provide shielding data for the design of future light-ion radiation therapy facilities.

1. Introduction

A growing number of proton accelerators with energies typically up to 250 MeV are being installed in hospitals worldwide for cancer radiation therapy, exploiting the better dose distributions allowed by protons over photons and electrons. Hadrons heavier than protons can further improve precision and effectiveness of the treatment: on the one hand, the sharper Bragg peak and the lower lateral scattering allow even better sparing of healthy tissues; on the other hand, their higher relative biological effectiveness (RBE) increases the radiation response of a certain class of tumours (see e.g. Ref. [1]). At present a few medical facilities using carbon ions up to 430 MeV/amu are operational or at the planning stage, and it cannot be excluded that the use of other light ions will be investigated for future clinical use (hadron therapy) [2,3].

The radiation field which dictates the shielding requirements at hadron accelerators is dominated by the secondary neutrons produced by the interaction of the beam with the structures of the accelerator, of the beam transfer lines, of the beam delivery system (such as collimators and field-shaping devices), and with the patient himself, where the beam is ultimately lost [4]. Ducts and mazes should also be designed mainly to attenuate neutron streaming through them (see, for example, Refs. [5,6]). In spite of the growing interest in intermediate-energy ion accelerators, there are not so many shielding data available in the literature except for protons. The aim of this paper is to provide an extensive set of computational data for concrete for shielding light ion (up to nitrogen) accelerators, complementing existing data for protons [7,8] and other ions [9–12], in order to anticipate possible needs for the design of future light-ion radiation therapy facilities.

In the present work, the attenuation through concrete of the total dose equivalent produced by several ion beams impinging on thick iron and ICRU tissue equivalent targets was calculated with the FLUKA Monte Carlo code [13,14]. The calculations reproduce the dominant secondary radiation field created by the beam impacting on the target. Iron is chosen as representative of other materials of similar density and atomic number, such as copper and stainless steel, main constituents of accelerator components; tissue is chosen to represent the patient. The dose equivalent behind the shield includes contribution from all particles emitted by the target over the entire solid angle, as well as secondary particles produced in the concrete shield itself. The results of the calculations were fitted by the classical two-parameter formula of a point-source line-of-sight model. Neutron yields and energy spectra produced by the impact of the selected ions on the chosen targets were calculated. The results are compared with available literature data and discrepancies explained. The complete set of

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source terms and attenuation length data, specifically conceived to be directly employed in shielding calculations, are given in Appendix B. The full results (neutron energy spectra for all combinations of ion species and targets, attenuation curves and respective fits, plots showing the variation of the source terms and attenuation lengths as a function of the scoring angular bin and of the atomic number of the impinging ion Z_{ion}) can be found in Ref. [15].

2. Monte Carlo simulations

The simulations were performed with the version 2011.2 of the FLUKA Monte Carlo code [13,14]. Secondary particles produced by a mono-energetic "pencil" ion beam impinging on a thick target and emitted over the entire solid angle were transported through a large, spherical, concrete shield. The ambient dose equivalent was estimated online, folding the particle fluence with built-in fluence-to-dose equivalent conversion coefficients [16,17], provided in the FLUKA code. The energy of each ion beam was chosen in order to reach a maximum penetration in ICRU tissue of 290 mm, corresponding to the range of 430 MeV/amu carbon ions. The SRIM code [18] was used to set the ion energies. Fully stripped ions were simulated as primary beam. Table 1 lists the chosen ions and their energies.

The target was cylindrical, coaxial with the incoming beam, and slightly thicker than the ion range at the given energy for the given material: 60 mm for the iron target, 350 mm for the tissue target. Table 2 gives the elemental composition of the ICRU tissue [19] used in the simulations. The geometry of a right cylinder (i.e. diameter equal to the length) was adopted because it ensures a sufficiently conservative combination between neutron yield and spectrum hardness [4,7]. In general, shielding data for thin targets are conservative, since the emitted neutron spectrum is harder and thus more penetrating, with no self-absorption in the target itself. In contrast, the secondary particle yield is higher for a thick target, featured by a more intense low-energy component. In real situations the beam is usually lost in a rather thick target (e.g. a magnet or a collimator) and thick-target data should normally be used [5].

As done in various previous studies [4,7,8,10,11,20], the target was located at the centre of a large spherical shield made of ordinary concrete (type TFS 5.5 [21], Table 3), the inner radius of which was sufficiently large (90 m) to ensure that curvature-related effects are negligible (Fig. 1). The volume of the cavity delimited by the inner surface of the shield was "filled" with vacuum.

The particle fluence was scored by means of inverse cosine-weighted boundary crossing estimators (i.e. fluence across a surface) at different depths inside the shield, taking into account only particles directed outwards ("one-way" scoring option) [4,7,8]. Profiting from the cylindrical symmetry of the problem, the entire solid angle was divided into 12 planar angular bins, each 15° wide; angles are defined with respect to the incident beam direction. A special routine (described in Appendix A) was written and linked to FLUKA, checking the farthest scoring surface reached by any tracked particle, and triggering the scoring only when the particle was traversing it for the first time. This routine was implemented to avoid overestimating the fluence by scoring neutrons scattering back and forth across a boundary estimator, typical when scoring inside a homogeneous medium but not occurring while scoring at the boundary between the shield and the air outside it. Consequently, it was possible to score the dose inside the medium as if any given scoring surface was the outermost one. It was thus possible to run one single simulation for each selected ion-target pair for all shielding thicknesses, saving considerable computing time.

Table 1
List of ions and corresponding energies considered in the present work.

Ion beam	Charge state	Energy (MeV/amu)
^{1}H	+1	215
^{4}He	+2	223
^{7}Li	+3	250
^{9}Be	+4	286
^{11}B	+5	342
^{12}C	+6	430
^{14}N	+7	469

Table 2
ICRU four-elemental composition (per cent by weight) and density.

	H	C	N	O
ICRU	10.1	11.1	2.6	76.2
Density (g cm^{-3})	1			

Table 3
Elemental composition of concrete TSF – 5.5 [21]. The nominal water content is 5.5% and the density is 2.31 g cm^{-3}.

Elemental composition (10^{21} atoms cm^{-3}) of concrete TSF – 5.5							
H	C	O	Mg	Al	Si	Ca	Fe
8.5	20.2	35.5	1.86	0.6	1.7	11.3	0.19

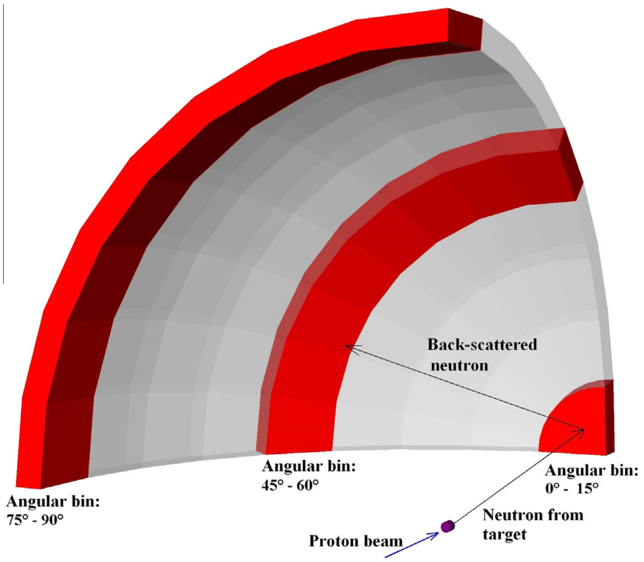

Fig. 1. FLUKA geometry plotted with SimpleGeo [22] showing the target, hit by the beam, located at the centre of the spherical shield, 90 m in radius, made of ordinary concrete. Only one octant of the 4π shield is shown. Three of the scoring angular bins (15° wide) are shown. The neutron "cross-talk" mentioned in Section 3.2, which represents the neutron transport in one angular bin after being back-scattered from another angular bin, is also sketched.

Variance reduction techniques were used, namely "geometry splitting" and "Russian roulette": each region was attributed an importance, increasing with the distance from the target, so as to maintain the fluence of particles approximately constant throughout the shield [4,7,8]. Biasing is a key ingredient for the convergence of results over a reasonable time-scale, especially in the case of deep penetration problems, and for emission directions far from the beam direction. Preliminary simulations were performed in order to reasonably tune the biasing throughout the shield for the various cases. For all ions but protons, the iron target was chosen since its spectrum is slightly harder than the one from tissue: biasing was thus tuned for the case of the iron target,