MONTE-CARLO SIMULATIONS FOR ESTIMATION OF THE RADIATION ENVIRONMENT AROUND THE MODERNIZED NUCLOTRON

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Abstract

The essential condition of the NICA (Nuclotron-based Ion Collider fAcility) project implementation is designing an appropriate radiation shields of its structural units, first of all – the upper shield of the Nuclotron tunnel. The crucial point determining the NICA shielding design is indispensable condition to keep the yearly equivalent dose < 1 mSv on the border of the Laboratory site. The radiation situation around the NICA will be formed by neutrons escaped from the shielding of the NICA radiation sources and multiscattered in air and ground ("skyshine" neutrons).

The calculations of the "skyshine" neutron radial distributions around the modernized Nuclotron at the acceleration of protons (12 GeV), ^{12}C (6 GeV/n), ^{238}U (3.5 and 4.5 GeV/n) and uniformly distributed along the accelerator ring beam losses are presented for different situations. The calculations have been carried out by the FLUKA and GEANT4 codes for the simplified model of the accelerator placed within the synchrophasotron tunnel.

The calculation of the NICA booster local shields (in the synchrophasotron linear spaces) at the acceleration of uranium nuclei to energy 0.5 GeV/n has been carried out as well.

The variant of the Nuclotron shielding design with the use of the synchrophasotron magnet element is proposed.

At the NICA (Nuclotron-based Ion Collider fAcility) several locations a high level of neutron production can be expected: the booster ring, the ion beam stripper between the booster and the Nuclotron ring; the Nuclotron, the ion beam transport channel between the Nuclotron and the collider, the ion collider rings and the ion beam stoppers. It is assumed now the acceleration at the NICA of ions with a wide mass distribution from protons (12 GeV) up to ^{238}U (3.5 (4.5) GeV/n). The main task of the NICA will be the experiments with MPD nuclei to the maximum energy. The total duration $4 \cdot 10^3$ hours of the NPD runs per year is supposed. Nuclotron and the collider, the ion collider rings and the ion beam stoppers. It is assumed now the acceleration at the NICA of ions with a wide mass distribution from protons (12 GeV) up to ^{238}U (3.5 GeV/n). The main task of the NICA will be the experiments with MPD (Mixed Phase Detector) at the acceleration of uranium nuclei to the maximum energy. The total duration $4 \cdot 10^3$ hours of the NPD runs per year is supposed.

The radiation shielding design of every element will have the specific character, but the radiation environment around the NICA must be determined for the sum radiation sources at the most danger operating mode. The crucial problem for radiation shielding design at heavy-ion accelerator facilities with beam energies to several GeV/n is the source term problem. At present, not many Monte-Carlo universal transport codes can be used for this purpose in principle. The verification of the codes with available experimental data is very important for selection of the most reliable code for practical tasks. Such verification with the unique experimental data on double differential neutron yields from the thick Fe target bombarded with 1 GeV/n uranium nuclei [1] has been done previously for the FLUKA, GEANT4 and SHIELD codes [2].

The GEANT4 and SHIELD codes demonstrate the better agreement with the experiment at large emission angles. As a result, the majority of the estimations of the radiation situations at the future NICA complex have been performed by the GEANT4 code.

The crucial point determining the NICA shielding design is indispensable condition for keeping the yearly equivalent dose < 1 mSv on the border of the Laboratory site (in compliance with the national radiation standard [3, 4]). Moreover, at the design of a new nuclear installation this limit must be reduced to halve for reserve. The average radius of the Nuclotron ring is 39.7 m. The distance between the Nuclotron centre and the site border is only 100 m roughly. The Nuclotron ring, mounded within the circular cable tunnel of the old synchrophasotron, has not now the special radiation shielding. The synchrophasotron building has ordinary walls with great windows and light roof. Therefore the building can not relax noticeably the penetrative radiation as well.

The acceptable radiation environment is ensured now only due to the small currents of the ion beams and limited time of the experimental runs per year. The radiation field around the Nuclotron is formed by neutrons escaped from the lengthy radiation source within the tunnel and multiscattered in air and ground (skyshine neutrons).

The most uncertain problem at the new accelerator design is the problem of correct assignment of the particle losses in process of acceleration, beam extraction, transportation etc. It can be expected that the high-energy ^{238}U beam losses will consist some percents within the Nuclotron ring owing to various causes: "vacuum" losses due to the charge-exchange with the molecules of the residual gas and "halo" losses due to large amplitudes of

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betatron oscillations. For example, the total uranium beam loss 10% was accepted at the SIS100/300 (GSI) tunnel shielding design [5, 6]. Based on the necessary conservatism at the beam loss admission the value of $1\cdot10^8$ uranium nuclei per second (9%) uniformly distributed within the Nuclotron vacuum chamber may be accepted as first approach.

At the Monte-Carlo simulations of the radiation field around the Nuclotron the simplified model of the vacuum chamber and surrounding equipment was implied. It is supposed that the particle projectiles with maximum energy are lost to the inner surface of the vacuum chamber with 1^o degree of incidence relative to the surface. The vacuum chamber with surrounding equipment is imitated by copper tore with square cross-section (Fig. 1). The differences of the cooling, magnetic elements and their irregularity are ignored and the total mass of the equipment is supposed uniformly distributed along the ring. The linear mass of the imitating ring is approximately compared with the average linear mass of the real vacuum chamber with the equipment (~ 300 kg/m).

All details of the tunnel, building and synchrophasotron magnet yoke that were taken into account at the simulations are shown in Fig. 2.

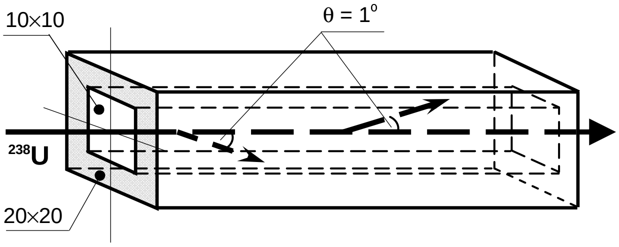

Fig. 1. The imitating element of the Nuclotron ring used at the Monte-Carlo simulations. All dimensions are in cm.

The radial distributions of the “skyshine” neutron fluence and equivalent equivalent dose around the Nuclotron were calculated by the FLUKA and GEANT4 codes for the regime of ^{238}U nuclei acceleration on conditions that the upper shielding of the tunnel is absent (the present situation). The geometrical model of the calculations is presented in Fig. 3. The high-energy neutrons have a large free path in air (several hundred meters). Because of it the volume of air with radius 1500 m was taking into account. The layer of the soil with

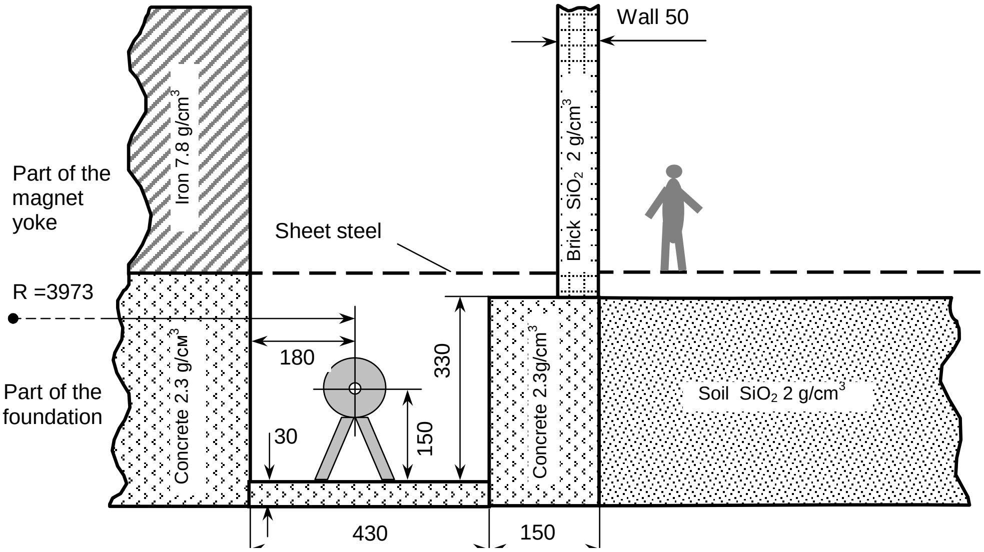

Fig. 2. The Nuclotron simplified geometry employed at the simulations. All dimensions are in cm.

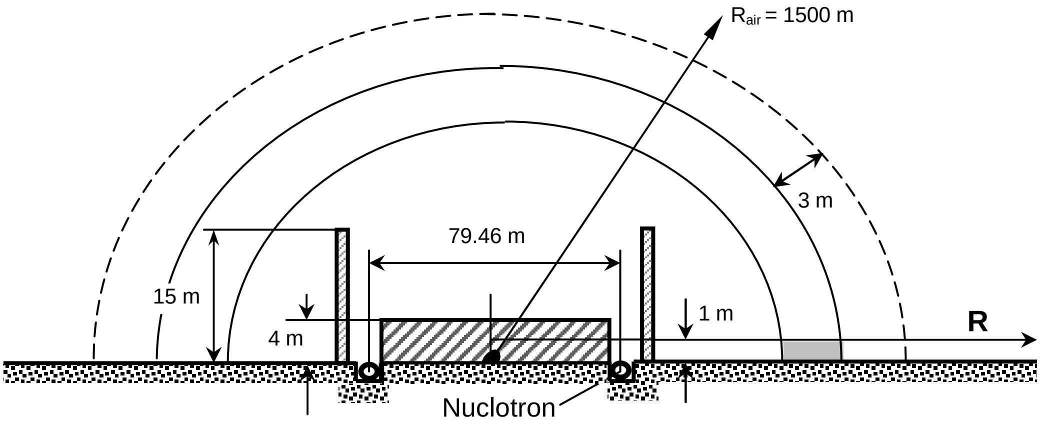

Fig. 3. The geometry of the simulations of the “skyshine” neutron dose spatial distributions around the Nuclotron.

thickness of 0.5 m was considered as well. The values of the neutron fluence and dose were averaged into the concentric circles with height 1 m above the soil and with radial bin 3 m.

At the abovementioned assumption about the level of the ^{238}U beam loss and the yearly experimental run summary dose on the border of the Laboratory site (approximately 100 m from the ring centre) will be about 43 mSv at present situation without the ring upper shielding (Fig. 4). The data are normalized to 1 uranium nucleus with energy 3.5 GeV/n interacting with the vacuum chamber. The incidence points are distributed uniformly over the vacuum chamber inner surface. The distance is counted off from the Nuclotron ring centre. The effective dose was determined by the convolution of the neutron energy spectra with the energy-depended conversion coefficients (up to 20 MeV by [5], above it by [8]) for isotropic field of radiation.

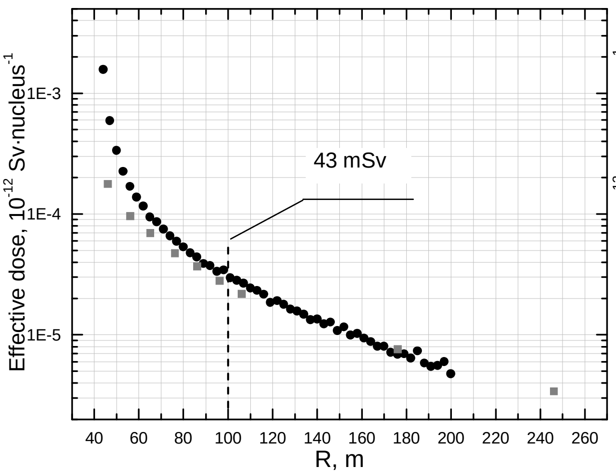

Fig. 4. The “skyshine” neutron effective dose radial distribution at the absence of the upper shielding of the Nuclotron ring.

The simulations were made in the presence of the upper shielding of the Nuclotron ring from ordinary concrete ($\rho = 2.3$ g/cm^3) with thickness 2 and 3 meters as well. The neutron relaxation length in concrete is about 122 g/cm^2 that is typically for relaxation of the high-energy neutrons within light concrete.

The radial distributions of the neutron effective dose for these situations are shown in Fig. 5. The 3 m shielding thickness is quite sufficient for the acceptable yearly dose of neutrons at the abovementioned assumption (the similar “skyshine” gamma-ray dose is usually no more than 10% from the neutron dose at the same distance). However, it is necessary to take into account that some of the NICA sources will be placed closer to the Lab site border than the Nuclotron – the collider ring and the collider beam stoppers.

The other radiation source of the NICA complex will be the booster that will accelerate the uranium nuclei up to 450 MeV/n. It is proposed to arrange the Nuclotron booster inside the cynchrophasotron on the place of its chamber. The massive cynchrophasotron magnets will be a good biological shielding. The radiation source of the “skyshine” neutrons in that case will be the only fur linear spaces between the cynchrophasotron magnets with the length of 8 m each.

The simulations of the neutron effective dose radial distributions at the absence of the shielding of the booster linear spaces and with their lateral and upper shielding from ordinary concrete with 1 m thickness were carried out. The conditions of the secondary neutrons generation were the same as for the Nuclotron. The results of the simulation are presented in Fig. 6. At the uranium beam loss $1 \cdot 10^8$ nuclei per second distributed uniformly along the booster vacuum chamber the contribution of the booster to the summary yearly dose at 100 m distance will be 0.08 mSv at the presence of the booster linear spaces shielding.

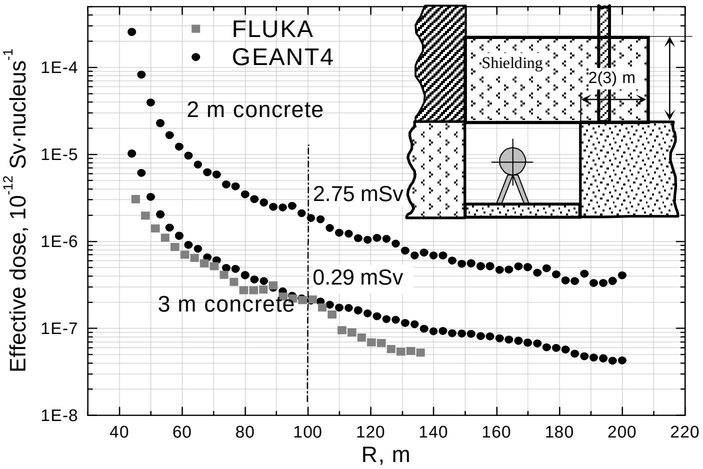

Fig. 5. The “skyshine” neutron effective dose radial distributions at the presence of the upper concrete shielding of the Nuclotron ring with thickness 2 and 3 m.

The radial distributions of the “skyshine” neutron effective dose were simulated for the proton beam (12 GeV) and carbon beam (6 GeV/n) at the upper concrete

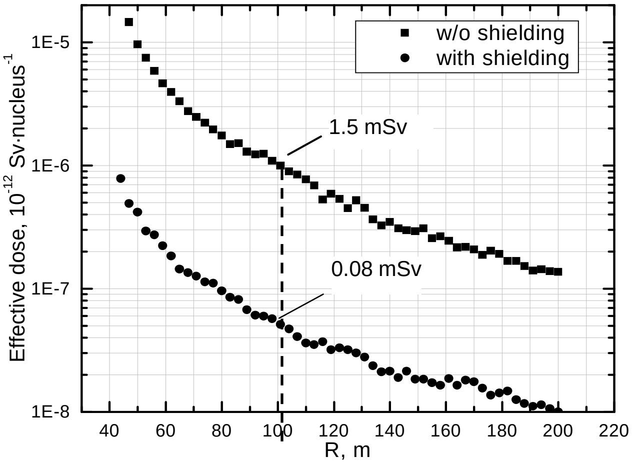

Fig. 6. The “skyshine” neutron effective dose radial distributions at the presence of the booster linear spaces shielding from 1m concrete and without the shielding.

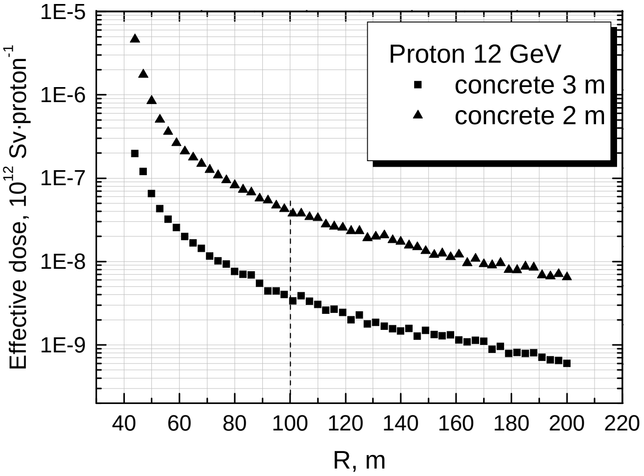

Fig. 7A. The “skyshine” neutron dose radial distribution for 12 GeV proton beam.

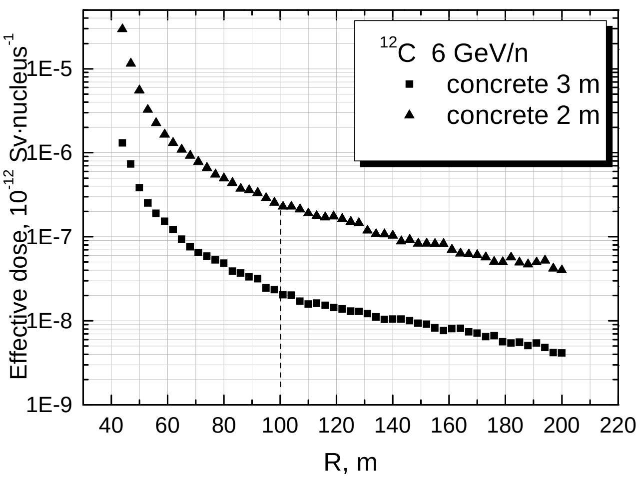

Fig. 7B. The “skyshine” neutron dose radial distribution for 6 GeV/n carbon beam.

shielding with 2 and 3 m thickness (Figs. 7, A and B).

The fixed thickness of the upper Nuclotron shielding will be defined after ascertainment of the beam loss values in the NICA design statement. However, there is a technical problem independently of the exact thickness of the Nuclotron shielding. This problem is connected with the unreliability of the synchrophasotron building foundation at the additional loading. As a result of it the Nuclotron upper shielding must not produce any pressure on the building foundation. The variant of the corbel back shielding is proposed in order to avoid this problem. The engineering solution envisages the use of the lower steel beams of the synchrophasotron magnets as the biological shielding of the Nuclotron tunnel. The lateral steel beams (77 cm thickness) of the synchrophasotron magnets are turned around, and the lower beams are moved forward at that. It is important as well that such shielding variant is essentially cheaper in comparison with the concrete shielding.

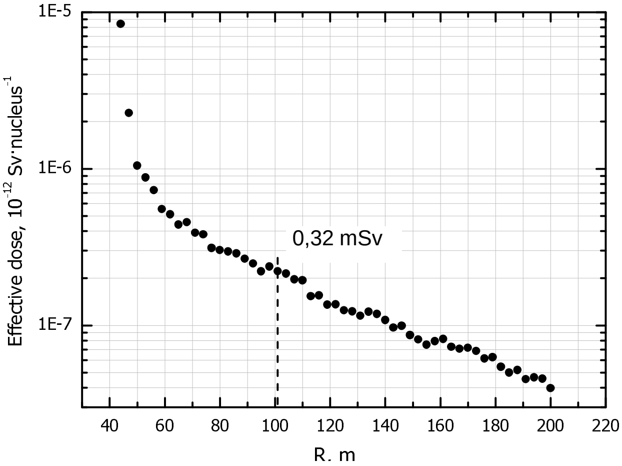

Fig. 8. The “skyshine” neutron effective dose radial distribution for the design variant with the steel corbel back shielding at the uranium nuclei acceleration.

The simulation of the “skyshine” neutron dose radial distribution for this shielding variant shows that the yearly dose on the Lab site border will be about 0.32 mSv that is closely related with 3 m concrete shielding result. The radial distribution of the neutron effective dose around the Nuclotron for this design variant is given in Fig. 8.

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