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GEANT4 Code Application for Radiation Environment Prediction at the NICA Complex

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The operation of a high-energy ion facility provokes secondary radiation along an accelerator ring and especially at the local sites of maximum beam losses (outlet devices, targets, and beam dumps). An essential condition for the commissioning of a relativistic heavy ion accelerator is appropriate radiation shielding for every radiation element of the complex. The shielding design is connected with two crucial problems: the estimation of the source term and the prognostication of the neutron fluence and equivalent dose distributions around the shielding.

As regards the first problem, the experimental data on the double differential cross section and secondary neutron production in thick targets for a primary uranium beam with the energy of several GeV/n are practically lacking. Few Monte Carlo multipurpose codes able to simulate the uranium ion interaction with, and transport into, the matter are now available. A comparison of FLUKA, GEAT4, and SHIELD simulations with unique experimental data on neutron production in a 1GeV/n ^{238}U beam interaction with a thick Fe target was performed to find the most suitable code. As a result, the GEANT4 code was chosen to carry out a simulation of the NICA (Nuclotron-Based Ion Facility at JINR) complex radiation shielding. Forming the secondary radiation field inside and behind the ordinary concrete shielding was analyzed as well. Some regularities of the secondary neutron field generation in a 4.5 GeV/n uranium beam interaction with thick targets are discussed.

As concerns the second problem, it was found that the crucial point determining the NICA shielding design is that the yearly equivalent dose at the border of the Laboratory site must not exceed 1 mSv. The radiation situation at long distances from NICA will be formed by neutrons which escaped from the shielding of the NICA radiation sources and were then multiscattered in the air and ground (“skyshine” neutrons). The GEANT4 calculations of the “skyshine” neutron radial distributions around all the elements of the NICA complex were carried out, and guidelines for the shielding construction were worked out for different operation modes of the complex.

Key words and phrases: Monte Carlo code, shielding data, relativistic heavy ions, secondary radiation field, thick target, neutron yield, attenuation curve, neutron fluence and equivalent dose.

1. Introduction

The design of the NICA radiation shielding and prognostication of radiation situation around it is a rather complicated task owing to the uncommon primary source terms, proximity to the border of radiation control area, and a collection of radiation sources of various types (the booster, Nuclotron, stripping station, collider, beam transport channels, beam stoppers, and MPD) disposed over the large territory of the Veksler and Baldin Laboratory of High Energy Physics (VBLHEP). The general layout of the NICA acceleration complex with the main beam parameters is shown in Fig. 1. The NICA complex is intended to accelerate heavy ions with A $\sim$ 200 and energy up to 4.5 GeV/n for ^{197}Au and ^{238}U. It is planned to build the booster inside the synchrophasotron magnet at the place of its vacuum chamber. Ions with an energy $\sim$ 0,5 GeV/n coming from the booster will be stripped by a thin target with efficiency about 40%. The beam of non-fully stripped ions will be blocked within the station

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stopper. The collider will accumulate 17 bunches × 10^9 ions of ^{197}Au × 2 rings for ~ 2 min; then it will be keeping the beam during one hour; afterwards, it will unload the beam into the stopper.

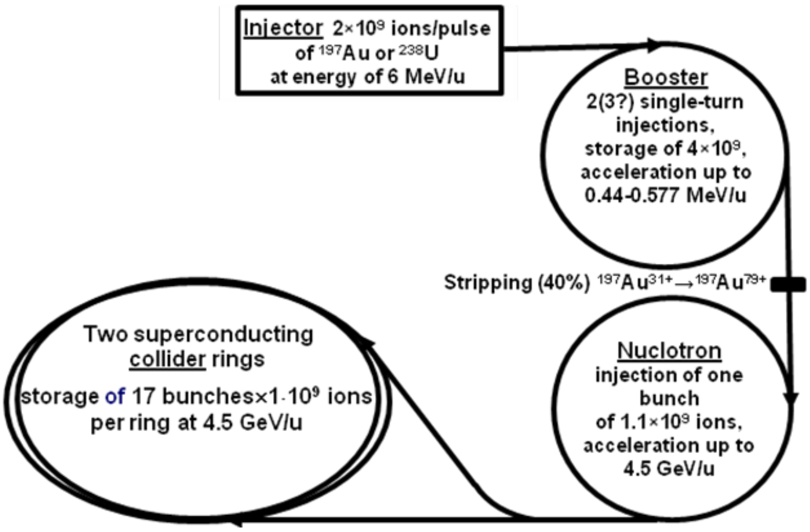

Figure 1. **The principal scheme of the NICA complex**

The placement of the structural elements of the complex (radiation sources) is shown in Fig. 2. The crucial point determining the NICA shielding design is meeting the indispensable requirement that the yearly equivalent dose be < 1 mSv on the border of the LHEP site [1]. The radiation situation around the NICA complex will be formed by the neutrons escaped from the shielding of the NICA radiation sources and multiscattered in the air and ground (“skyshine” neutrons).

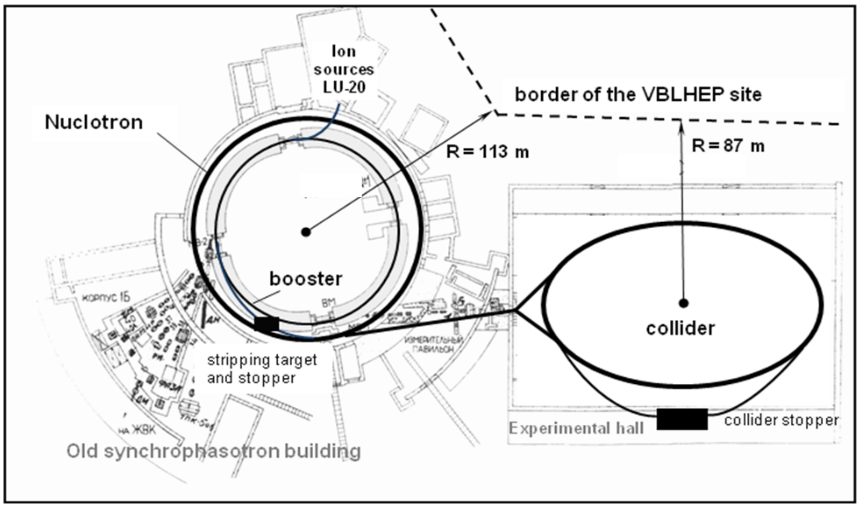

Figure 2. **The placement of the NICA complex at the VBLHEP site**

In order to reduce the dose level at the border of the Laboratory site, it was first proposed to arrange the ion stripping station with the stopper near the second magnet quadrant. It was also proposed to combine both collider stoppers consisting of two rings into a single bidirectional stopper with the iron core and arrange it behind the collider (as is shown in Fig. 2). The iron of the synchrophasotron magnet will be the perfect radiation shielding of the booster ring, but the shielding has to overlap the open linear spaces of the synchrophasotron magnet. The main radiation sources contributing to the dose at the border of the Laboratory site will be the Nuclotron, collider, and beam transport channels. It is necessary to mount the thick upper shielding of the Nuclotron ring, which is placed within the former cable tunnel around the synchrophasotron. The coupled collider rings and beam transport channels also have to be surrounded by thick compact shielding owing to the immediate vicinity of the control area border.

The total annual effective dose of "skyshine" neutrons and gammas from all radiation sources at the NICA control area border must be less than 0.5 mSv with the reserve coefficient 2 [2]. The real annual dose level will depend on several parameters: beam losses at all stages of ion acceleration and storage, yearly NICA schedule for all modes of its operation, shielding efficiency, distance from each source to the control area border, and so on. The choice of the appropriate method for the source term description and calculating the internuclear cascade within the shielding matter is very important as well in order to reliably simulate neutron leakage from the source shielding.

2. Simulation

The simulation of the accelerated ^{238}U and ^{197}Au ions interaction with the beam guide material and the internuclear cascade within the shielding were carried out with the GEAN4 code after verification of some codes with available experimental data [3].

To test the neutron source term, considered was, first of all, secondary neutron production in the interaction of the projectiles with different atomic masses and the same energy per nucleon (4.5 GeV/n) with a thick Fe target (10×10×20 cm). A Fe target was chosen since iron is a typical material of an accelerator vacuum chamber. Neutron yields from the target in different energy and angular ranges are shown in Fig. 3 depending on the projectile mass (relative to neutron yields from 4.5-GeV protons). The factors in the round brackets are the neutron yields per proton required to obtain the absolute values of the neutron yields for projectiles.

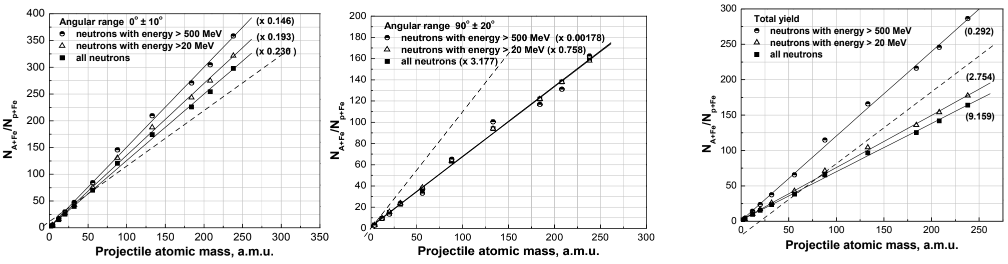

Figure 3. **Relative secondary neutron yields from a thick Fe target bombarded by beam projectiles with different atomic masses and an energy of 4.5 GeV/n. NA+Fe is the neutron yield for the beam projectiles, Np+Fe is the neutron yield for a 4.5-GeV proton beam. The solid lines are linear approximations. The dashed lines show the A-equivalent proton approaches**

The neutron yield from a thick target in 4π sr and in the whole energy range per one uranium ion with an energy of 4.5 GeV is about $1.5{\cdot}10^3$. The forward flying neutrons spread up to energies higher than the initial projectile energy per nucleon owing to the cumulative effect. This effect is shown in Fig. 4. At large emission angles, the lower energy neutrons dominate in the yields due to the evaporation process. As a consequence, the changes in the neutron yield and the spectrum shape related to an increase in projectile energy are weaker in the lateral direction than in the forward direction.

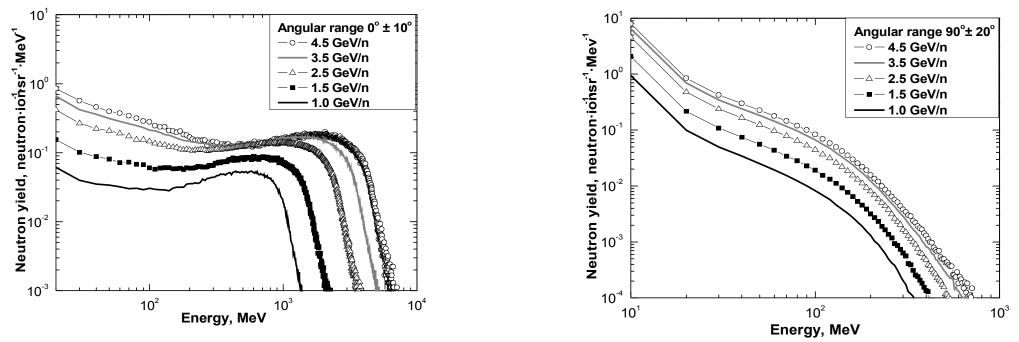

Figure 4. **Dependences of the neutron spectra from a thick Fe target on uranium projectile energy in the forward and lateral directions**

The target material dependences of the neutron spectra generated by 4.5-GeV/n uranium ions in the forward and lateral directions are shown in Fig. 5. All spectra are normalized to one neutron emitted from the target. It is clear that the hardest spectra in the forward direction correspond to a light target.

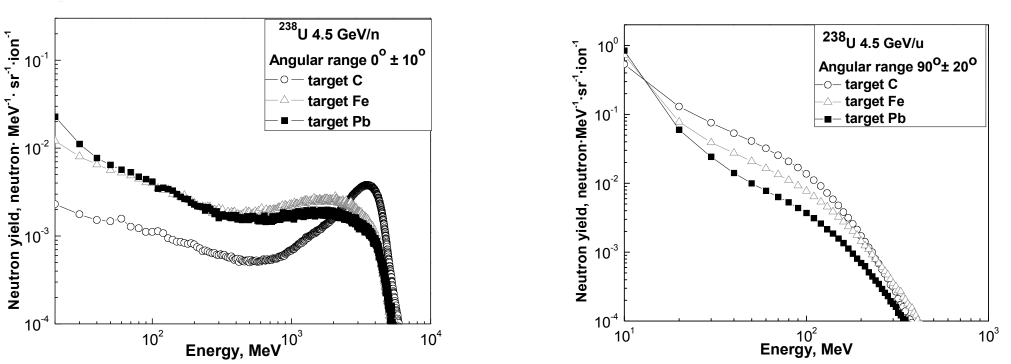

Figure 5. **Dependences of the neutron spectra from 4.5-GeV/n uranium ions on the target material in the forward and lateral directions**

The Nuclotron, collider, and surrounding equipment were simulated by an iron torus pipe with 5-cm thick walls for the calculation of the vacuum chambers of the booster. The angles of the ion loss emission from the beam used for the calculation were within the statistical sampling of 0^o–1^o. The secondary hadrons from the vacuum chambers irradiate the internal surfaces of the lateral concrete shielding. The detailed geometries of the shielding design and the simulation of “skyshine” neutron fields around every NICA element are given in [4].

In the real geometry of the lateral thick shielding irradiation by an extended source of secondary neutrons (a circular vacuum chambers of the accelerators and collider), the attenuation curves for the neutron fluence within the shielding don’t have build-up maximums (contrary to the case of normal irradiation) and slightly change with the energy of heavy ions increasing from 1 to 4.5 GeV/n. For example, the attenuation curves for the concrete ($\rho = 2.34 g{\cdot}\mathrm{cm}^{-3}$) shielding of the collider are shown in Fig. 6 for two energies of the uranium beam. The geometry of shielding iiradiation is schematically shown in the inset in Fig. 6.

For the booster and Nuclotron shielding, simulations of near-real energy distributions of the ion beam losses were taken into account. Then the radial distributions of the “skyshine” neutron effective dose were simulated for each NICA element. The spatial dose rate distributions around the Nucloton with the upper 3-m concrete shielding are presented in Fig. 7A for different energies of lost uranium ions (normalized to one

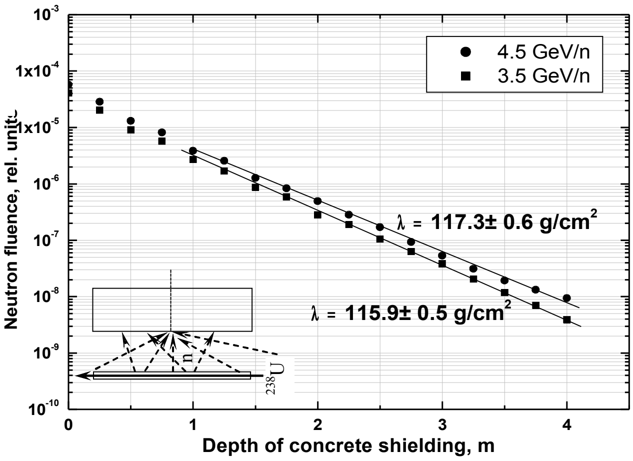

Figure 6. **Total neutron fluence attenuation inside ordinary concrete shielding of the collider depending on uranium ion energy**

ion lost along the vacuum chamber ring per one second). In Fig. 7B, the similar spatial distribution of neutron dose rate around the collider is shown.

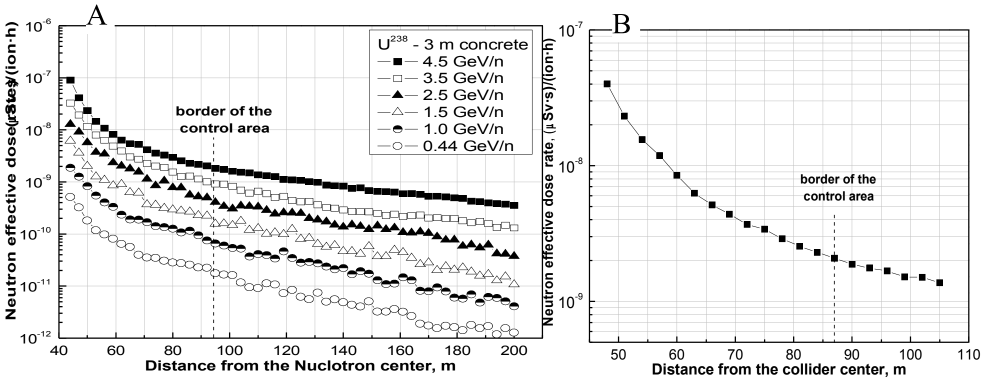

Figure 7. **Uranium ion energy dependences of the radial distribution of the "skyshine" neutron effective dose rate around the Nuclotron with 3-m concrete upper shielding of the tunnel (A) and the radial distribution of the "skyshine" neutron effective dose rate around the collider with 3-m compact concrete shielding surrounding the coupled rings (B)**

Analogous spatial distributions were obtained for other NICA radiation sources both for uranium and gold ions. Different variants of the Nuclotron and collider shielding design were tested as well. For the Nuclotron tunnel upper shielding, 0.77-m thick steel was considered as one of the variants. A self-sunk design of the collider located near the Nuclotron was also examined. This variant combines the concrete and ground shielding of the rings as shown in Fig. 8A. The dependences of the neutron effective dose rate around the underground collider on the thickness of the ground layer are presented in Fig. 8B.

Estimations of radiation conditions at the border of the NICA control area were done for different designs of the Nuclotron and collider shielding. The values of the

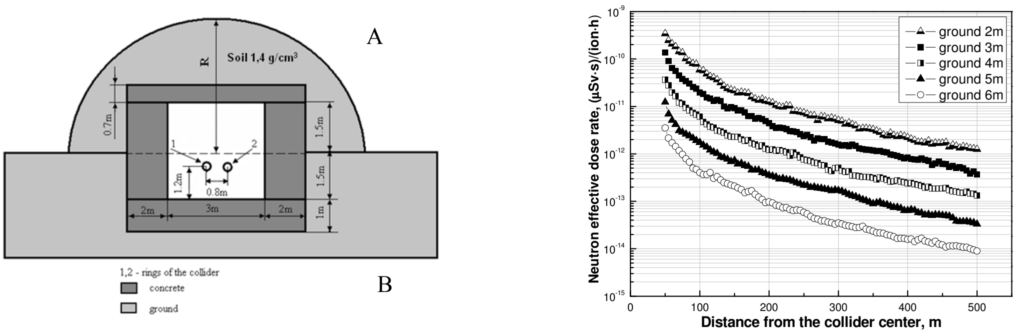

Figure 8. **A design of the collider semi-sunk in the ground (A) and spatial distributions of the "skyshine" neutron effective dose rate depending on the ground layer under the rings (B)**

uniformly distributed beam losses were taken as follows: the booster accounts for 5% (E > 50 MeV/n), the ion stripping station – 60% (E = 0.45 GeV/n), the Nuclotron — 5% (0.45 < E < 4.5 GeV/n), the beam transport channel — 3% (E = 4.5 GeV/n), and the collider — 20% (E = 4.5 GeV/n) during one hour of the beam storage. The ion stripping station stopper will be holding $6{\cdot}10^8$ ion$\cdot$s^{-1} with an energy of 0.45 GeV/n, and the single bidirectional stopper of the collider will damp $1.12 \cdot 10^{11}$ ions with an energy 4.5 GeV/n once in an hour. A total of 4000 hours of the annual operation of the complex with uranium or gold ions accelerated to 4.5 GeV/n and additionally 500 hours of tuning time were taken in consideration. The results of estimations for uranium and gold ions are presented in Tables 1 and 2.

Table 1

The total annual neutron effective dose and the partial contributions to it at the border of the NICA control area associated with the acceleration of uranium and gold ions for different designs of the Nuclotron and collider shielding (within Building 205).

^{238}U

Radiation source, ^{238}U acceleration	Booster	Stripping station stopper	Nuclotron	Beam transport channels	Collider	Collider stopper	NICA Complex, total
Annual neutron dose, mSv	0.0018 0.0018	0.0166 0.0166	0.0082 (3 m concrete) 0.0604 (2 m concrete)	0.0501 0.0501	0.0347 (3 m concrete) 0.0943 (2.5 m concrete)	0.0562 0.0562	0.1676 0.2794

It is well known that the contribution of gammas to the total "skyshine" effective dose at large distances from high-energy accelerators does not exceed 10%. Thus, the proposed variants of the shielding of the NICA radiation sources will ensure that the annual equivalent dose at the border of the VBLHEP site will be less than 0,5 mSv (even taking into account a 10% contribution of gammas to the total dose). It will allow additional proton runs at the Nuclotron with a yearly duration of ~1500 h and the proton beam intensity of 10^{11} protons/cycle without exceeding the prescribed dose limit.

Table 2

The total annual neutron effective dose and the partial contributions to it at the border of the NICA control area associated with the acceleration of uranium and gold ions for different designs of the Nuclotron and collider shielding (within Building 205).

^{197}Au

Radiation source	Booster	Stripping station stopper	Nuclotron	Beam transport channels	Collider	Collider stopper	NICA Complex, total
Annual neutron dose, mSv	0.0015 0.0015	0.0137 0.0137	0.0499 (2 m concrete) 0.0034 (0.77 m steel)	0.0414 0.0414	0.0779 (2.5 m concrete) 0.0779 (2.5 m concrete)	0.0465 0.0465	0.231 0.185

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Применение программы GEANT4 для прогнозирования радиационной обстановки на комплексе NICA

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При работе высокоэнергетичного ускорителя тяжелых ионов генерируется вторичное излучение как по кольцу ускорителя, так и на локальных участках, где наблюдаются максимумы потерь пучка ядер (выводные устройства, мишени и ловушки пучка). Необходимым условием реализации проекта ускорителя тяжёлых ядер является создание радиационной защиты всех элементов ускорительного комплекса. Острыми проблемами при конструировании радиационной защиты такого комплекса являются проблема корректного описания источника излучения и проблема оценки флюенса и эквивалентной дозы нейтронов вокруг ускорителя.

Экспериментальные данные по двойным дифференциальным выходам нейтронов из толстых мишеней, бомбардируемых ядрами урана с энергией в несколько ГэВ/н, практически отсутствуют. В настоящее время существует несколько универсальных Монте-Карло транспортных программ, которые могут моделировать взаимодействия с веществом ядер урана. Для выбора наиболее адекватной программы было выполнено сравнение расчетов по программам FLUKA, GEANT4 и SHIELD с данными единственного

эксперимента по изучению выхода нейтронов из толстой Fe мишени, облучённой пучком ядер 238U с энергией 1 ГэВ/н. В результате сравнения для расчета радиационной защиты комплекса NICA в ОИЯИ была выбрана программа GEANT4. С её помощью был исследован механизм формирования полей вторичного излучения как внутри, так и за защитой из обычного бетона. В данной статье исследованы также некоторые особенности формирования полей вторичного нейтронного излучения при взаимодействии пучка ядер урана с энергией 4,5 ГэВ/н с толстыми мишенями.

При расчете защит ускорительного комплекса учитывалось, что годовая эффективная доза нейтронов на границе площадки Лаборатории (санитарно-защитной зоны) не должна превышать 1 мЗв. Радиационная обстановка на больших расстояниях от радиационных источников комплекса определяется нейтронами утечки из защит, многократно рассеянными в окружающей среде (воздухе и грунте). Приведены результаты расчетов радиальных распределений эффективной дозы таких нейтронов вокруг каждого элемента комплекса NICA для различных вариантов работы комплекса.

Ключевые слова: программа Монте-Карло, радиационная защита, релятивистские тяжелые ионы, поле вторичного излучения, толстая мишень, выход нейтронов, кривая ослабления, флюенс и эквивалентная доза нейтронов.