Journal of NUCLEAR SCIENCE and TECHNOLOGY, Supplement 1, p. 146–149 (March 2000)

Shielding Design of RIKEN RI Beam Factory

Yoshitomo UWAMINO*,†, Nobuhisa FUKUNISHI* and Koji OISHI**

*RIKEN
**Shimizu Corporation

Construction of the RIKEN RI Beam Factory is started, and the phase 1 will be finished by the end of March 2003. Two ring cyclotrons including one superconducting machine and two Big RIPSs will be constructed in the phase 1. Heavy ions of proton to uranium will be accelerated up to 400 MeV/u (A < 40) and 150 MeV/u for uranium at an intensity of 10^{13} pps.

Neutron production by the 400-MeV/u ^{20}Ne beam was measured at HIMAC of NIRS and it was used for the source term of the shielding calculations. The deep penetration of high-energy neutrons was calculated by using the ANISN code with the DLC-119/HILO86R group constants and also by using the HETC code. The ANISN results were modified by using the HETC results and the shielding experiment at ISIS, and they were fitted by a simple formula for practical use.

High-energy neutron penetrations of slantwise injection and the reflection probabilities of iron slab were calculated with the HETC code, and these results were used for the estimation of the thickness for the iron local shielding of Big RIPSs. Induced radioactivity in the air, accelerator components and the building, and the skyshine effect were also estimated.

KEYWORDS: RI Beam Factory, deep penetration, albedo, high-energy neutron, HETC, ANISN

I. The RI Beam Factory

Construction of the RIKEN RI (Radioactive Isotope) Beam Factory (RIBF) which is a facility-expanding project has been started. The existing facility consists of a heavy ion linear accelerator, RILAC, an AVF cyclotron, and a 4-sector ring cyclotron, RRC. RILAC and AVF are mainly used as the injectors of RRC. The maximum energy of the existing facility is 210 MeV for protons, 135 MeV/u for light-heavy ions (A < 40), and 15 MeV for uranium ion. We, however, have not a license for the uranium acceleration.

The expanding facility consists of two ring cyclotrons, IRC and SRC which is superconducting, projectile-fragment separators which are the RI beam production devices, Big RIPSs (RIKEN Projectile-fragment Separator), an accumulation cooler ring, ACR, double storage ring, DSR, and a booster synchrotron ring, BSR. The maximum beam energy of SRC is 400 MeV/u for ions lighter than Ar and 150 MeV/u for uranium ions of the high charge state, and this energy makes the projectile fragmentation possible up to uranium. The beam intensity will be 10^{13} particles/s for any element. The maximum beam power will be 24 kW for the uranium beam.

The construction schedule of the RIBF is divided into 3 phases. IRC, SRC and Big RIPSs will be constructed in phase 1, which is already approved, ACR and DSR in phase 2, and BSR in phase 3. Phase 1 will be finished by March 2003, phase 2 by 2007, and phase 3 by 2010.

II. Dose Limit Criteria

The Japanese legislation for radiation safety will be soon revised to meet the ICRP-60 recommendation. The dose limit criteria for RIBF were fixed as **table 1** with considering this revision. The value for the site boundary is an engagement with the local government.

III. Beam Loss

The beam loss is the most ambiguous parameter in the accelerator shielding design. Here, however, it was assumed as **table 2**. The low beam loss rate, total 2 % at SRC, for example, must be kept by the monitoring of beam loss.

IV. High-Energy Neutron Production by Heavy Ions

The high-energy neutron production is the most fundamental data for the safety design of RIBF. High-energy heavy ion beams are available at HIMAC of the National Institute of Radiological Sciences, and the neutron production at thick graphite, aluminum, copper and lead targets bombarded by the 400-MeV/u ^{20}Ne beam were measured(1). The data of the copper target are shown in **Fig. 1**. The neutron spectra spread to higher energies, and the angular distribution of high-energy neutrons

Table 1 Criteria of effective dose for the RIBF design.

item (boundary)	dose limit
non-restricted area in radiation controlled area	25 μSv/h (1 mSv/w)
radiation controlled area	2.6 μSv/h (1.3 mSv/3m)
office in site	0.5 μSv/h (250 μSv/3m)
site	50 μSv/y

Table 2 Assumed beam loss rate at RIBF

position	IRC	SRC	Big RIPS
beam loss	2 %	2 %	100 %

* *2-1, Hirosawa, Wako, Saitama 351-0198*
** *3-4-17, Etchujima, Koto-ku, Tokyo 135-8530*
† Corresponding author, Tel.+81-48-467-9292, Fax.+81-48-462-4616, E-mail: uwamino@postman.riken.go.jp

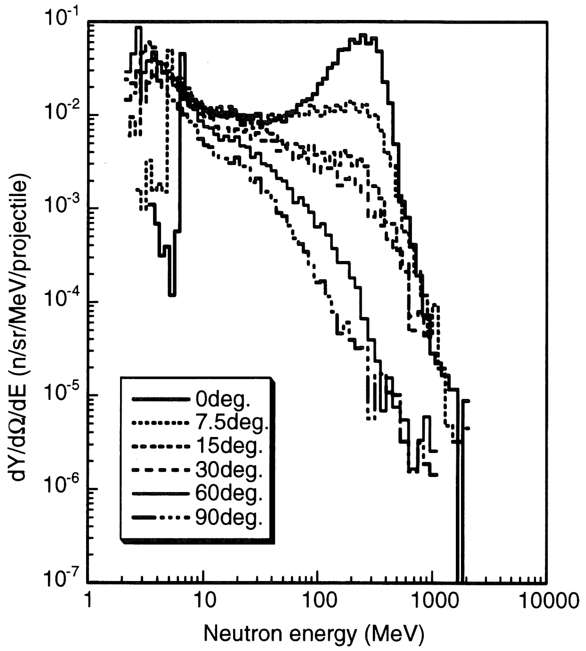

Fig. 1 The measured neutron production at a thick Cu target bombarded by 400-MeV/u ^{20}Ne beam.

Table 3 Relative thick target neutron yield of the SRC beam.

ion	beam energy (MeV/u)	intensity (pμA)	neutron yield
$^{16}O^{7+}$	400	1	0.80
$^{20}Ne^{9+}$	400	1	1.00
$^{40}Ar^{17+}$	400	1	2.00
$^{84}Kr^{30+}$	300	1	2.36
$^{129}Xe^{38+}$	200	1	1.61
$^{238}U^{49+}$	100	1	0.74
$^{238}U^{58+}$	150	0.2	0.33

have a strong forwardness.

RIBF will accelerate all the elements, and we must know which element will produce the largest amount of high-energy neutrons. This estimation was performed on the assumption that the neutron yield is in proportion to [E^2•A], where E is the beam energy in MeV/u and A is mass number, and the result are shown in **table 3** in the relative value.

In table 3 the neutron production is highest for the $^{84}Kr^{30+}$ beam, and the result of the ^{20}Ne beam was corrected by multiplying a factor of 2.4 [=$(300/400)^2$•(84/20)].

V. Deep Penetration of High-Energy Neutrons

1. HETC Calculation

A several-meter-thick iron slab is necessary for the 0-degree shield at a dump of a 1-particle mA heavy ion beam. The neutrons very heavily attenuate after such a thick shield, and some biasing method must be incorporated into a Monte Carlo transport calculation.

The "multi-layer" method was incorporated into the HETC-3step code[2] and the one-dimensional transportation was calculated. The "multi-layer" method is explained as in the following.

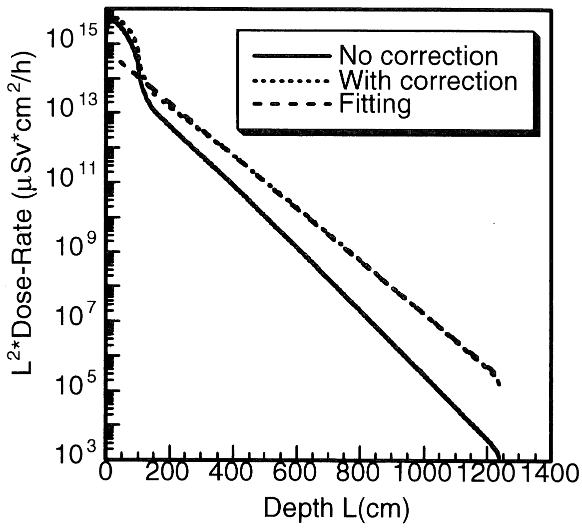

Fig. 2 Effective Dose distribution in a 1-m-thick iron and 12-m thick ordinary concrete slab calculated with the ANISN code, its corrected result with Eq. (1), and the fitting with Eq. (2).

When a neutron penetration through a 3-m-thick iron slab is calculated, the slab is separated into three 1-m slabs. The source neutrons are generated at the center of the left surface of the 1st 1-m slab, and the neutron penetration is calculated. The energy-angular distributions of the leakage neutrons, protons, and negative pions from the right surface are obtained, and they are used as the source term for the next 1-m slab calculation. The particle penetration through the 2nd 1-m slab is calculated by using this point directional source placed at the center of the left surface. The deep penetration is calculated by repeating this procedure.

2. ANISN Calculation

ANISN is the most powerful code for the practical shielding design because of its short calculation time, and was used with the DLC-119/HILO86R group constants[3].

3. Correction and Fitting of the Calculated Results

The shielding experiment at ISIS[4] showed the HETC and the ANISN codes give considerable underestimation for the high-energy neutron transport. The ANISN results were corrected by using the C/E (Calculation/Experiment) value of the ISIS experiment. We obtained the following correction formula for the ANISN results.

$$H_{\text{corrected}} = He^{Rt} \qquad (1)$$

Where R is $1.21\text{x}10^{-3}$ g^{-1} cm^2.

The calculated results of the iron-concrete slabs were corrected with the formula (1), and the dose distributions in the thick concrete backing were fitted by using the following exponential formula.

$$Hr^2 = H_0 e^{-t/\lambda} \qquad (2)$$

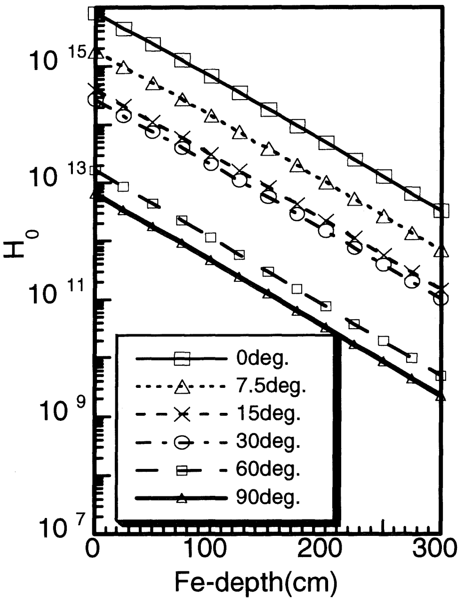

Fig. 3 H_0 parameters as functions of primary iron shield thickness.

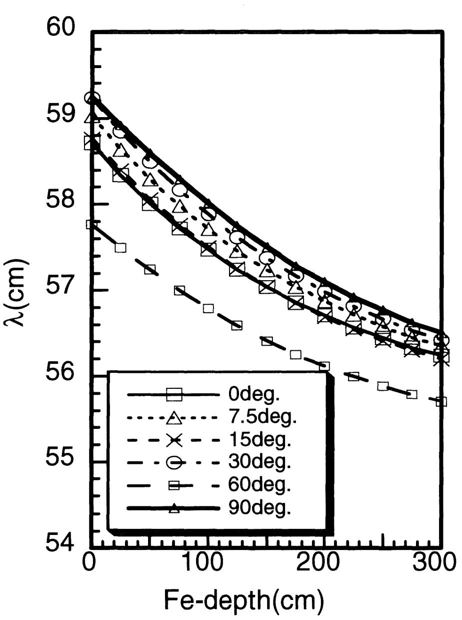

Fig. 4 λ parameters as functions of primary iron shield thickness.

Figure 2 shows the ANISN result, the corrected results with Eq. (1), and the fitting of Eq. (2) for the case of 1-m-iron+12-m-concrete shield. The H_0 and λ parameters as functions of primary iron shield thickness are shown in **Figs. 3** and **4** for the various emission angles of the secondary neutrons. The Eq. (2) was used in the practical shielding design, and, for example, the result of the effective dose distribution on the SRC roof is shown in **Fig. 5**.

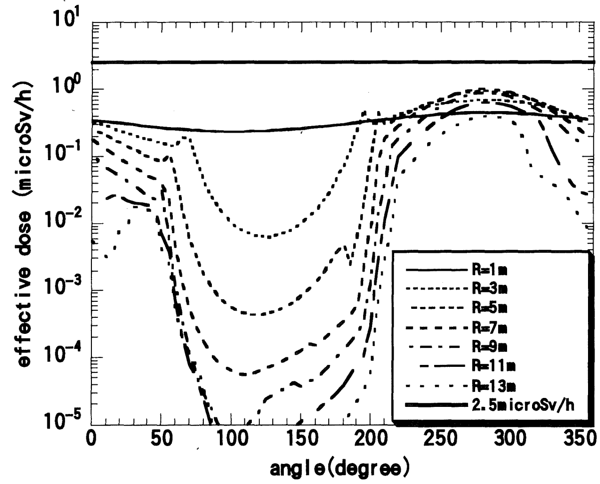

Fig. 5 Effective dose distribution on the SRC roof. R is the distance from the roof center, and the abscissa is the angle from the Big RIPS side direction.

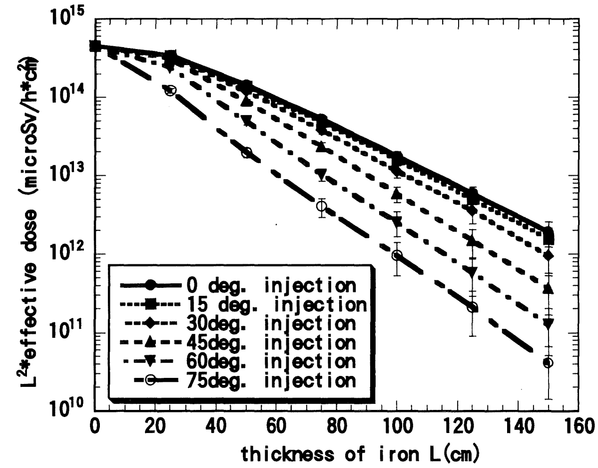

Fig. 6 Effective dose attenuation of the slantwise-injecting source neutrons.

VI. Shielding of Big RIPS

The beam loss at Big RIPS is 100 % and the shielding design is most difficult. In the Big RIPS, 20 % beam is lost at the fragmentation target, and the residual beam is lost in the 1st dipole magnet. Moreover, about 1.6 % beam will be stopped at the 1st focusing point. The local iron shielding for Big RIPS likes a square tunnel.

1. Direct Ray Shielding

The fast neutrons irradiate the inner surface of the tunnel with large angles in the area far from the beam loss point. The neutrons scatter many times in iron, and the direction is diffused. In this condition, the shielding thickness cannot be estimated with the factor of 1/cosθ.

The effective dose attenuation to the slantwise-injecting

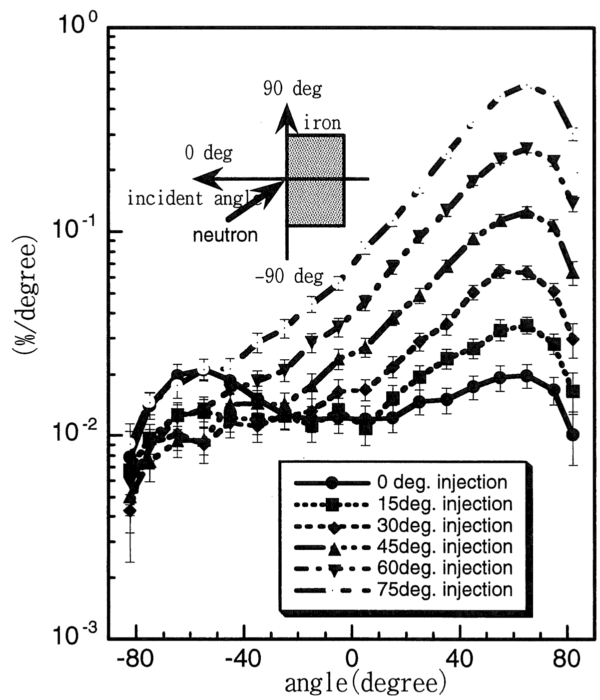

Fig. 7 Angular differential effective-dose albedo function of iron.

source neutrons was calculated with the HETC-3step code, and the results are shown in **Fig. 6**. The attenuation is slower than the 1/cosθ correction.

2. Scattered Ray Shielding

The backscattered neutrons from the tunnel wall hit again the shielding wall and go out through the tunnel. To estimate this effect the angular differential albedo function was calculated with the HETC-3step code, and the result is shown in **Fig. 7**. By using the data of Figs. 6 and 7, the thicknesses of iron local shielding and the "barrier" in the tunnel were obtained.

VII. Induced Radioactivity

1. Air Activation

The high-energy and thermal neutron fluxes in the cyclotron rooms, in the Big RIPS tunnel, and in the experimental rooms were obtained by using the ANISN code. The activation cross sections of air were quoted from Ref. 5. The air ventilation duct of the room is closed when the beam is on, and it is opened 2 hours later from the beam off. The ventilation rate is 0.5 replacements per hour. The air concentration was estimated on these conditions.

2. Activation of Accelerator Components and Building

Induced radioactivity produced by the primary heavy ions was measured at HIMAC[6]. These data are used for the evaluation of the exposure during the maintenance work.

Activation of the cyclotron yoke, local shieldings and the concrete building are evaluated by using the DCHAIN-SP code[7]. Radioactivity induced by high-energy neutrons (E_n > 20 MeV) was calculated by using the HETC-3step code and the result was put into the DCHAIN-SP Code. Low energy (E_n < 20 MeV) neutron fluence was calculated by the ANISN code, and the production of radioactivity was calculated by the DCHAIN-SP Code based on the calculated fluence and the cross section library in the code. The decay and the build up of the radioactivity and the gamma-ray emission were calculated by the DCHAIN-SP Code. The ambient dose due to the gamma rays was calculated by using the ANISN code.

VIII. Skyshine

The building of RIBF is below the ground level, and only roof can be seen from the outside. The skyshine radiation is the main component to the dose rate at the site boundary. The area of RIKEN is not large and houses and buildings surround it. A simple exponential fitting of the skyshine radiation distribution gives a considerable overestimation at short distances, and the following equation was obtained by using the data of Ref. 8.

$$H(r)=\frac{3.7\times10^{-2}hs}{r^2}e^{-2.38\times10^{-3}r}(1-e^{-1.7\times10^{-2}r}) \quad (3)$$

[μSv/h]

Where r is the distance [m], h is the mean dose rate [μSv/h] over the roof, and s is the area [m^2] of the roof.

The dose rate above the ground becomes larger than that on the ground[8], and the correction factor can be obtained by Eq. (4).

$$\frac{H(z)}{H(0)}=0.094\theta+1 \quad (4)$$

Where θ is elevation angle in degree, and θ=14 was adopted for RIBF.

IX. Conclusion

A primary safety design work was performed for RIKEN RI Beam Factory. Local shieldings and the 3.5-m-thick ordinary-concrete roof of SRC, for example, will keep the radiation level below the criteria.

— References —

(1) Kurosawa, T., *et al.* : *J. Nucl. Sci. Technol.*, **36**, 1 (1999).
(2) Yoshizawa, N., *et al.* : *J. Nucl. Sci. Technol.*, **32**, 601 (1995).
(3) Kotegawa, H., *et al.* : *JAERI-M* 93-020 (1993).
(4) Uwamino, Y., *et al.* : *Genshikaku Kenkyu*, **41** No. 3, 89 (1996).
(5) Sullivan, A. H. : "*A Guide to Radiation and Radioactivity Levels Near High Energy Particle Accelerators*", Nuclear Technology Publishing, Kent 138 (1992).
(6) Uwamino, U., *et al.* : *Proc. Int. Conf. Nucl. data for Sci. and Technol.*, p.1513 (1997).
(7) Takada, H., Kosako, K. : *JAERI-Data/Code* 99-008 (1999).
(8) Uwamino, Y., Nakamura, T. : *Particle Accelerators*, **21**, 157 (1987).