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Beam Dump for High Current Electron Beam at JNC

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Abstract

High current electron beams are required for transforming fission products with gamma-rays. Elemental technology to build a linac that can accelerate a high current beam in an efficient and stable manner, is being developed at the Japan Nuclear Cycle development institute (JNC).

This paper presents the design and performance of a beam dump for a high current, low energy beam (20 mA of a 10 MeV electron beam). A ring and disk (RD) structure was adopted to analyze the condition of the beam in real-time, as well as to absorb the beam safely. The absorbed dose rate for photons averaged over all directions is found to be 12.2 $\pm$ 0.07 Gy/h using the EGS4 code when the beam with average beam current of 20 mA enters into the beam dump.

The performance of the beam dump was evaluated using a beam of 7 MeV and an average current of 0.84 mA. Comparison of 1 cm dose equivalent rate from the dose meter with that from EGS4 code shows that the values from the EGS4 code at the beam energy of 7 MeV well reproduce the experimental data.

1 Introduction

High current electron beams are required for transforming fission products with gamma-rays. Elemental technology to build a linac that can accelerate a high current beam in an efficient and stable manner, is being developed at the Japan Nuclear Cycle development institute (JNC)[1].

The conceptual design of the accelerator was started in 1989. The test operation of the linac was started aiming at the permitted average current of 10.5 mA, in October 1999, after many research efforts. Main specification of the accelerator is shown in Table 1.

Table 1 Main specification of the JNC linac

Parameters	Design values
Energy	10 MeV
Maximum Beam Current	100 mA
Average Beam Current	20 mA
Pulse Length	0.1~4 msec
Pulse Repetition	0.1~50 Hz
Duty Factor	0.001~20 %
Norm. Emittance	50 π mm mrad *
Energy Spread	0.5 % *

$*$ estimated value by simulation

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Since the beam from the JNC linac is a very high current, low energy beam, energy loss induced in the material irradiated by the beam becomes very large, and resulting power density of heat generation is also quite high.

Therefore, it is of utmost importance from the viewpoint of safety for the JNC beam dump to be secured to dissipate and remove the generated heat efficiently. At the same time, shielding of the radiation generated from the beam dump is also of major concern in order to minimize the possible induction of radioactivity. Since the beam dump is installed on the beam line at about 10 m downstream of the exit of the accelerator tube, it is also possible to utilize it as a beam monitor for directly monitoring the condition of the beam.

2 Design

2.1 Conceptual Design

The conceptual design [2] of the JNC beam dump is based on the following four criteria:

(1) to disperse the beam by electromagnets disposed in front of the beam entry

(2) to stop the beam by absorbing it in spatially separated target blocks

(3) to minimize the possibility of the induction of radioactivity

(4) to add the function of a beam monitor for the high current beam.

The first criterion is for making the current density of the beam smaller by spreading the beam with quadrupole electromagnets. It is also assuring to avoid mishaps of the pin point beam hitting the target and destroying it. The second criterion is for making the energy loss per unit volume of the target smaller by absorbing the power of the spread beam in spatially distributed target. The third criterion reduces the amount of material that is directly in the passage of the beam or near the beam in order to reduce the possible induction of radioactivity. In particular, since the amount of cooling water circulating to the heat exchanger tends to be large, care should be taken so that the cooling water is not irradiated directly with the beam. The last criterion is to enable the direct monitoring of the beam with average beam current of 20 mA. This is difficult with a conventional beam monitor. It is especially important to grasp the situation immediately when the beam condition such as the direction of the beam changes.

2.2 Target

It is a major feature of the JNC beam dump that the target for absorbing the beam is separated into 22 plates. Each plate is made from Oxygen Free High-purity Copper (OFHC), and has thickness of 5 cm. Fig. 1 shows the cross section of the beam dump including the plates.

The structure of the plates is such that 18 rings with each having slightly different inside diameter are arranged on the upstream side and 4 disks having no hole are arranged on the downstream side. This structure of the JNC beam dump will be hereafter referred to as Ring and Disk (RD) structure.

As described before, all the rings have different inside diameters which gradually decrease from upstream to downstream. (The spread beam passes through inside this ring.) The frontmost ring has the inside diameter of 19.6 cm and other rings have smaller diameters which successively decrease by 1.0 cm or 1.2 cm. The 18 rings are divided into two types according to the shape of the cross section in a plane parallel to the beam axis direction (hereinafter referred to as Z-axis direction) in which the beam travels. From No. 1 to No. 10 ring, the cross section of the ring is a rectangular shape, that is, the ring has equal thickness at the inside diameter and at the outside diameter. The cross section of the remaining 8 rings is a wedge of shape having stepwisely smaller thickness at the inside diameter compared to other portion. Fig. 2 shows the typical cross sections of the rings. The two types of cross sectional shape are adopted in order to examine the difference of the thermal conduction between two shapes, and to evaluate the method of thermal conduction analysis from the experimental data.

Since the density distribution of the current is a Gaussian distribution as a function of radius, as the beam travels, it is absorbed gradually beginning from the outside portion in the inner front edge of the ring, and finally all the beam is absorbed in the disks having no hole. The heat generated by the absorption of the beam is conducted to the outside of the plates, where the heat is transferred to the cooling water.

3 Estimation of the Dose of Photons

3.1 Conditions

The absorbed dose rate of photons generated from the beam dump is calculated using the electron-photon transport code EGS4[3]. The EGS4 code performs Monte Carlo simulations of the radiation transport of electrons, positrons and photons in any materials. We applied the PRESTA (Parameter Reduced Electron-Step Transport Algorithm)[4], which was developed to improve the electron transport in EGS4 in the low energy region. Computational conditions for EGS4 code are mainly as follows.

(1) In order to model the 22 axial-symmetric plates as one structural unit, the EGS4 code employs a cylinder-slab geometry that is defined by 30 coaxial cylinders and 67 plates orthogonal to them. Model of the vacuum jacket and lead shield is added to the plates. As a rule, design data are used for the shapes and dimensions of these structures. The material of the vacuum jacket made from stainless steel is substituted with iron. The pipes and stands in the vacuum jacket are omitted since they cannot be modeled as a cylinder-slab geometry presumed in the EGS4 code.

(2) As described before, the current density distribution of the beam is assumed to be a Gaussian distribution. The standard deviation σ is assumed to be 1/3 of the beam radius. (This distribution will be hereafter denoted by "3σ".)

(3) The diameter of the beam spreads as it travels from the electromagnet Q2 to the plates, from 1.0 cm to 20 cm. Therefore, each electron is not transported in parallel to Z axis, but enters into the plates at an angle of 1.16 ± 0.59 degrees relative to Z axis.

(4) The region A (Fig. 2) is assumed to have a length of 0.5 cm in the direction of Z axis. This is determined such that about 80 % of the energy of the beam (beam energy of 10.51 MeV) is lost in it.

(5) The cut-off energies for electrons, positrons and photons are assumed to be 100 keV, 100 keV and 10 keV, respectively.

(6) The center of the ring and disk structure, that is, a point on Z axis 56.5 cm downstream of the No.1 ring is denoted by O, and with the point O as the origin, orthogonal coordinates (O-xyz) and spherical coordinates (O-$r\theta\phi$) are set. Here, Y axis is taken in vertically upward direction, and θ is the angle from the direction of Z axis. Fig. 3 shows the O-xyz coordinates and the typical angle θ.

(7) A sphere of radius 3.0 m with the origin O as the center (hereafter referred to as evaluating sphere) is set so as to enclose the lead shield. In the EGS4 code, energy and position of photons at the evaluating sphere are calculated for photons passing through the evaluating sphere.

3.2 Result

Fig. 4 shows the energy E, scattering angle θ, and azimuth angle ϕ of 1.4×10^4 photons that pass through the evaluating sphere, when 2.0×10^7 electrons of beam energy 10.51 MeV are made to enter into the beam dump. In Fig. 4, (1) shows the relation between energy and scattering angle, and (2) shows the relation between energy and azimuth angle. As seen in Fig. 4, photons are localized in the two regions, upper left and lower right regions. However, distribution is uniform with respect to azimuth angle. Reason for the localization of photons in specified scattering angle lies in the difference of production process. The upper region of Fig. 4 (1) represents the photons produced by electrons incident on the plates in the back scattering from the atomic nucleus. On the other hand, lower right region represents photons which are produced by electrons traveling in the plates and which have passed the lead shield. Therefore, energy of former photons is about 0.6 MeV, while energy of the latter photons is about 2 MeV.

Fig. 5 shows energy spectra of photons falling in a specified range of scattering angle. In Fig. 5, vertical axis represents photon fluence, and solid angle is taken into account in (2). The scattering angles set in the figure are $0° \sim 180°$, $0° \sim 120°$, $177.5° \sim 180°$. Among them, photons having the scattering angle in $0° \sim 120°$ correspond to those photons in the lower right region of Fig. 4(1), and photons having scattering angles in $177.5° \sim 180°$ correspond to those photons in the upper region of the same figure. As can be seen from Fig. 5 (2), the number of photons per unit solid angle is asymmetric with respect to scattering angle. The intensity of photons scattered in the direction devoid of the lead shield, that is, in the backward direction, is higher than the intensity of photons scattered in the forward direction. For example, the intensity of photons having scattering angle in $177.5° \sim 180°$ is as much as 10^2 times higher than the intensity averaged over all directions.

From the above described result, when the beam with beam energy of 10.51 MeV and average beam current of 20 mA enters into the beam dump, the absorbed dose rate for photons averaged over all directions is found to be 12.2 ± 0.07 Gy/h. Fig. 6 shows absorbed dose rate averaged over a specified range of scattering angles. These values represent the absorbed dose rate at a distance of 1 m from the center of the beam dump, and were obtained by multiplying the value on the evaluating sphere by 9.

When average beam current of accelerator is low, the absorbed dose rate in the direction of 180° from the beam dump may be substituted by the value for the scattering angle of 90°, and evaluation performed accordingly. However, in the case of JNC accelerator where the average beam current is high, it is important from the viewpoint of radiation protection to evaluate the dose rate for arbitrary scattering angle. In the present study, the photons scattered backward from the JNC beam dump were evaluated using the EGS4 code, and the value of 3100 Gy/h was obtained for the absorbed dose rate.

4 Experimental Results and Discussion

4.1 General

In the test operation of the linac started in January 1999, beam current was increased aiming at the permitted average current of 10.5 mA. In December of the same year, the linac was operated for about 60 minutes with the average beam current of 3.5 mA (maximum beam current 100 mA, pulse width 1 msec, repetition frequency 35Hz). The nominal energy of the beam was 7.0 MeV as calculated from the decrease of the high frequency energy.

During this test operation, a test was performed to determine the characteristics of the beam dump for low current beam (the beam dump test). The average beam current in the beam dump test was set to 0.84 mA (maximum beam current 100 mA, beam width 0.24 msec, repetition frequency 35Hz) that allows electrons to be accelerated stably, since temperature of the plates need to be examined for a long period.

4.2 Measurement of Dose Equivalent Rate

In order to measure the 1 cm dose equivalent rate during the beam dump test for comparison with the result of the EGS4 code, film badges (FB) and thermoluminescence dosimeters (TLD) were installed on the surface (at the locations of six black circles in Fig. 3) of the shield of the beam dump.

In the present test, one FB and a pair of two TLD was installed at each measuring point, and irradiated by the beam for 172 minutes. As a result, two findings were obtained. First, the most of the energy of photons at each measuring point is equal to or greater than 80 keV. And second, the three dose equivalents obtained at each measuring point were averaged, and shown in Fig. 7 as 1 cm dose equivalent rate. The error of the dose equivalent rate was obtained from the error of FB 50 %, the error of TLD 5 %, and the fluctuation of the three measured values. When the measured value exceeded the measuring range of TLD, the value of FB was used. Especially, since the value for the scattering angle of 176° exceeded the measuring range of FB, the upper bound of FB (2 Sv) was used. In addition, 1 cm dose equivalent rate was calculated using the EGS4 code for each measuring point for average beam current of 0.84 mA, and shown in the same figure. Here, the computational conditions for the EGS4 code are as follows.

(1) The beam energies are 7.0 MeV and 10.51 MeV.

(2) In order to adjust the maximum beam current for each module obtained from the EGS4 code so as to coincide with the measured value, two cases for the density distribution of the current are considered, that is, the distribution "3σ", and the Gaussian distribution with 1/5 of the beam radius adopted as the standard deviation (hereafter, this distribution is referred to as "5σ").

(3) The photons at each measuring point are, considering the size of the pair of dosimeter, those falling in the range of $\pm$ 5 cm on the shield centered at the dosimeter, except in the case of 0°, where the range $\pm$ 15 cm is used.

(4) The photon detection efficiency of each dosimeter is set to 1, since the measured dose equivalent rate includes error of more than 50 % and the object of the present measurement is to evaluate the performance of the beam dump.

Comparison of 1 cm dose equivalent rate from the dose meter with that from the EGS4 code shows that the values from the EGS4 code at the beam energy of 7 MeV well reproduce the experimental data. Especially, under the condition of "7.0 MeV, 5σ", the two seem to be in agreement within a factor of about 2. For more detailed comparison, energy distribution of photons needs to be obtained.

5 Conclusion

A beam dump at JNC, employing the Ring and Disk structure, has been designed to absorb the beam (200 kW of 10 MeV electron) safely and to analyze the beam condition in real-time. The beam could be stopped at the inner edge of the rings which are cooled by water. The absorbed dose rate for photons averaged over all directions is found to be 12.2 $\pm$ 0.07 Gy/h using the EGS4 code when the beam with average beam current of 20 mA enters into the beam dump.

The performance of the beam dump was evaluated using a beam of 7 MeV and an average current of 0.84 mA. Comparison of 1 cm dose equivalent rate from the dosimeter with that from EGS4 code shows that the values from the EGS4 code at the beam energy of 7 MeV well reproduce the experimental data. Especially, under the condition of "7.0 MeV, 5σ", the two seem to be in agreement within a factor of about 2.

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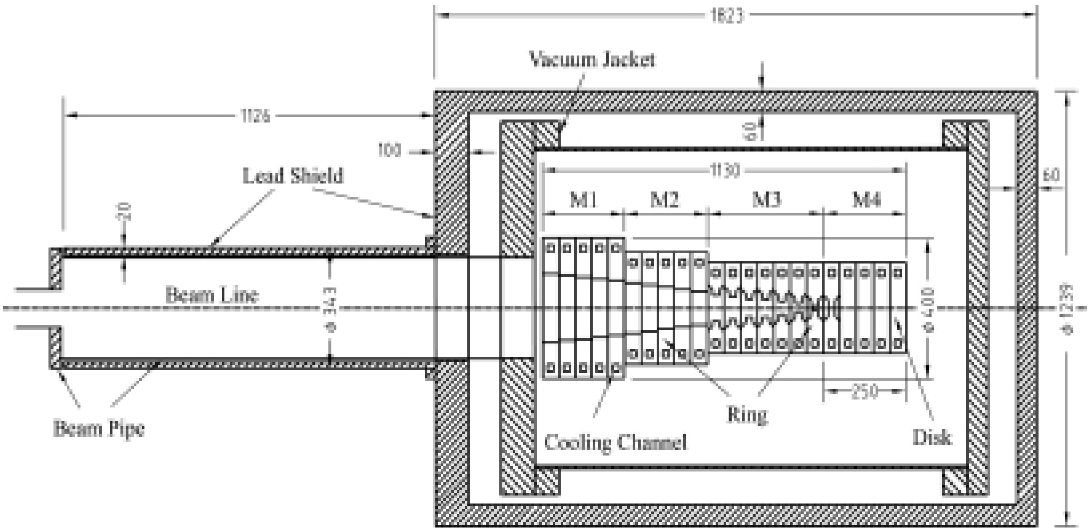

Figure 1: JNC beam dump in cross-section.

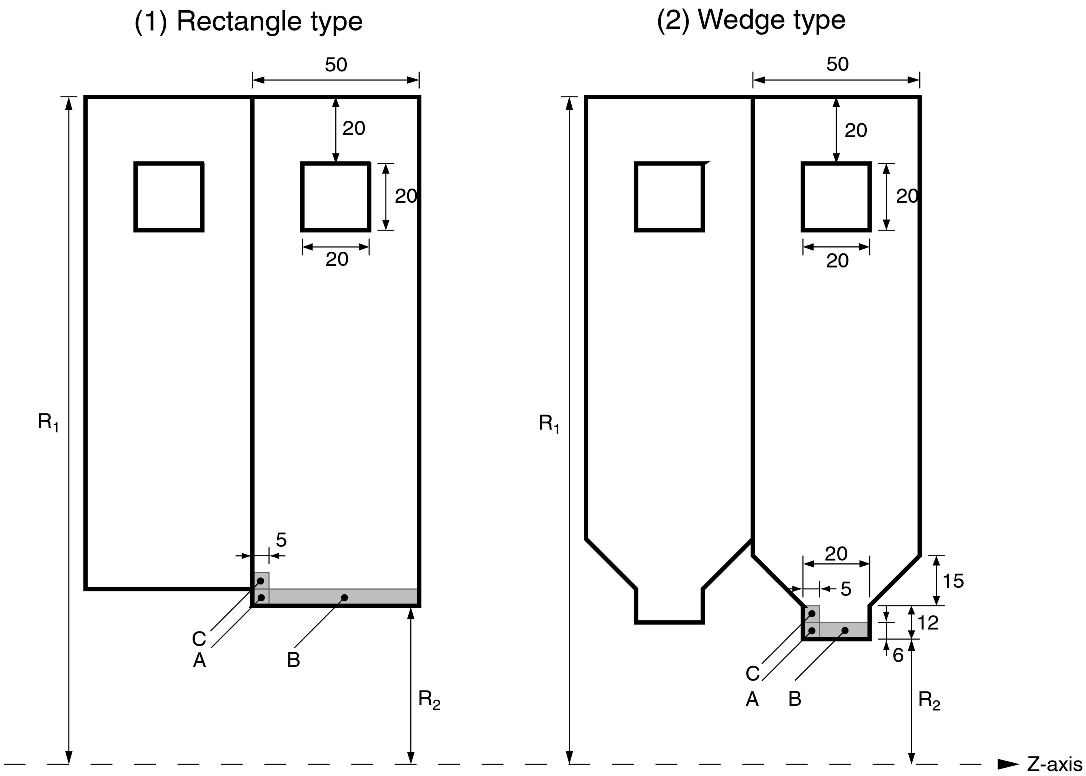

Figure 2: Typical cross sections of the rings.

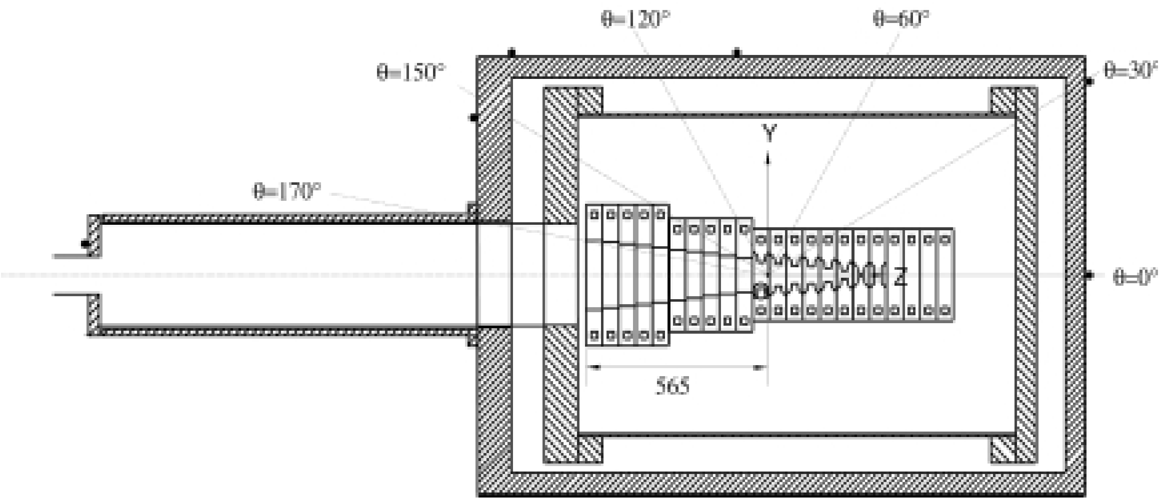

Figure 3: The O-xyz coordinates and the typical angle θ defined in the EGS4 code. Six black circles represent the locations of FB and TLD.

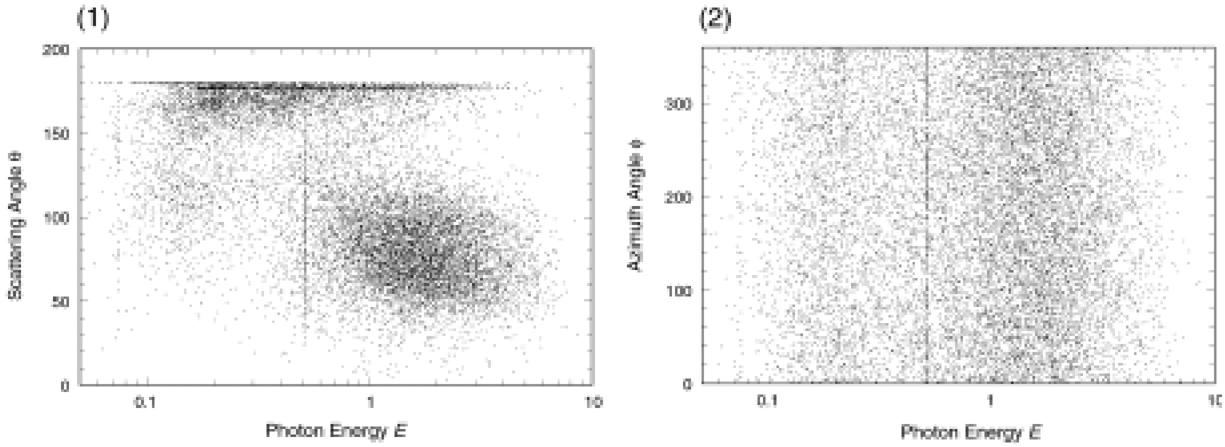

Figure 4: The relation of the energy, scattering angle, and azimuth angle of $1.4*10^4$ photons that pass through the evaluating sphere.

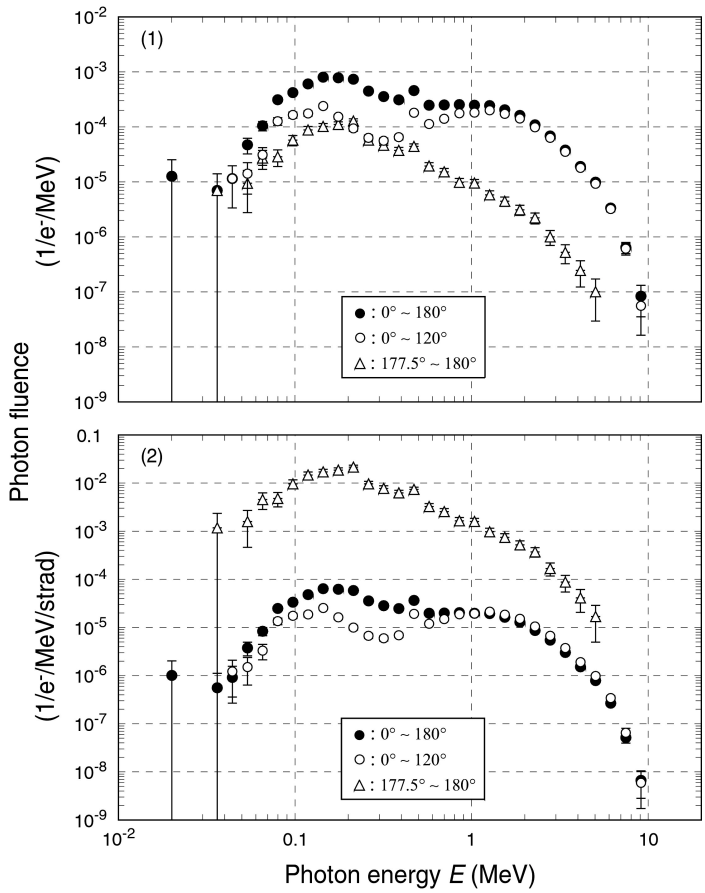

Figure 5: Energy spectra of photons falling in a specified range of scattering angle.

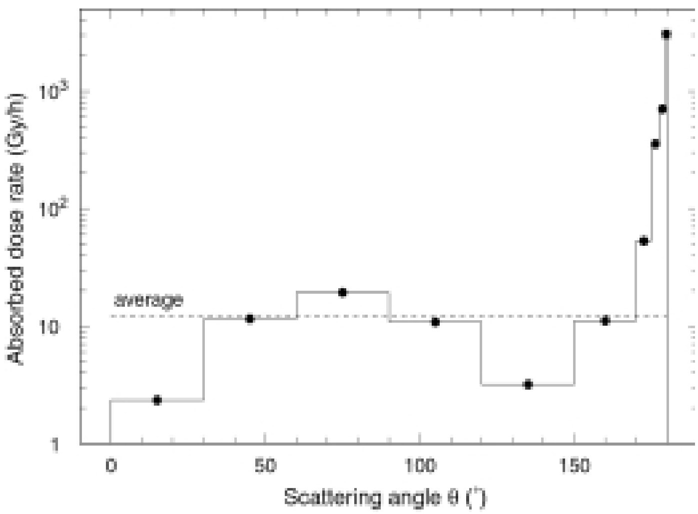

Figure 6: Absorbed dose rate at a distance of 1 m from the center of the beam dump.

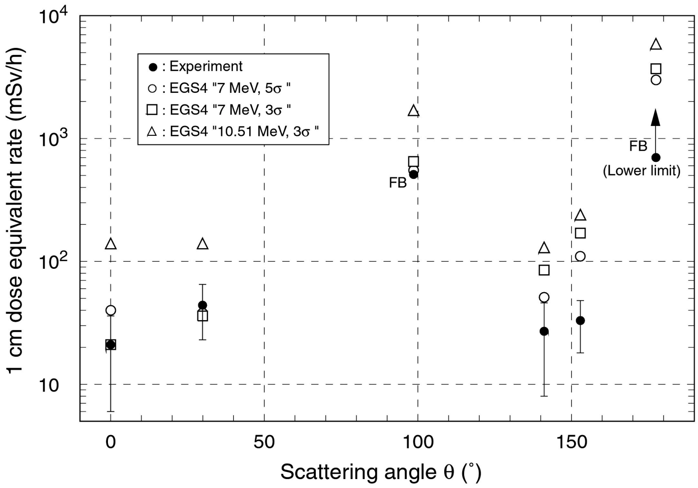

Figure 7: Comparison of 1 cm dose equivalent rate from the dose meter with that from the EGS4 code.