Energy-reduced beta radiation fields from $^{90}\text{Sr}/^{90}\text{Y}$ for the BSS 2

R. Behrens

Physikalisch-Technische Bundesanstalt (PTB),
Bundesallee 100, 38116 Braunschweig, Germany

E-mail: Rolf.Behrens@PTB.de

ABSTRACT: For decades, the irradiation facility for beta radiation, the Beta Secondary Standard BSS 2 developed at PTB, has been in worldwide use to irradiate dosemeters, detectors and other devices with calibrated beta sources. In this work two energy-reduced radiation fields based on the $^{90}\text{Sr}/^{90}\text{Y}$ source are described. Their electron and photon particle spectra are made available as data files. In addition, angular distributions and the depth dose profiles are given. The spectra were determined using the Monte Carlo particle transport code EGSnrc/BEAMnrc and are provided in the supplementary data.

KEYWORDS: Models and simulations; Dosimetry concepts and apparatus
1 Introduction

For decades, the Beta Secondary Standard BSS 2 developed at PTB [1, 2], and commercially available [3] has been in worldwide use to perform irradiations with calibrated beta sources according to ISO 6980 [4–6]. Furthermore, the particle spectra, the depth dose profiles and the angular distributions of its radiation fields are available for the BSS 2 sources and corresponding geometries [7], see tables 1 and 2, respectively.

From table 1 it is obvious that there is a gap with respect to energy between $^{85}$Kr and $^{90}$Sr/$^{90}$Y. Therefore, two energy-reduced radiation fields from $^{90}$Sr/$^{90}$Y sources with absorbers between the radiation source and the reference plane for irradiation were suggested [8, 9], complementing the reference beta-particle radiation fields. Their absorber thickness (3 and 4 mm, respectively, for the two new radiation fields) and geometry are indicated in table 2 together with the further radiation fields of the BSS 2 (with or without beam-flattening filter). In this work, their characteristics mentioned above, i.e. their particle spectra, the depth dose profiles and the angular distributions, were determined using the Monte Carlo methods described earlier [7]. To compare the new radiation fields with those of the BSS 2, some of the data and graphs shown in this work are materials from the author’s previous work [7].

---

1 A consolidated version is available at PTB: https://www.ptb.de.
2 The phase space files are available at the corresponding websites for download at supplementary data.
Table 1. Types of radiation source of the BSS 2 and their main characteristics.

| Radionuclide | Mean; maximum beta energy MeV | Nominal activity GBq | Half-life y |
|--------------|-------------------------------|----------------------|------------|
| $^{147}$Pm   | 0.07 ; 0.23                  | 3.7                  | 2.62 (958.2 d) |
| $^{85}$Kr    | 0.25 ; 0.69                  | 3.7                  | 10.7 (3915 d)  |
| $^{90}$Sr/$^{90}$Y | 0.8 ; 2.3               | 0.46                 | 28.8 (10523 d) |
| $^{106}$Ru/$^{106}$Rh | 1.2 ; 3.5         | 0.02                 | 1.02 (373.59 d) |

Table 2. Radiation field geometries of the BSS 2 for which phase space files are available.

| Radionuclide (source) | 11 cm without filter | 20 cm without filter | 20 cm with filter or absorber | 30 cm without filter | 30 cm with filter | 50 cm without filter | 50 cm with filter |
|-----------------------|----------------------|----------------------|-------------------------------|----------------------|-------------------|----------------------|-------------------|
| $^{147}$Pm            | x                    | x                    | x                             | x                    | x                 | x                    | x                 |
| $^{85}$Kr             |                      |                      | x                             | x                    | x                 | x                    | x                 |
| $^{90}$Sr/$^{90}$Y    | x                    | x                    | 3 mm absorber                 | 4 mm absorber        | x                 | x                    | x                 |
| $^{106}$Ru/$^{106}$Rh | x                    | x                    | x                             | x                    | x                 | x                    | x                 |
| Distance of the phase space file plane from the front of the source$^{a}$ | 2 cm | 15 cm |
| Distance of the phase space file plane from the reference plane$^{a}$ | 9 cm | 18 cm | 5 cm | 15 cm | 35 cm |

2 Simulation

2.1 Method of simulation

The simulations were carried out using the Monte Carlo particle transport code package BEAMnrc [10, 11]. The transport parameters are the same as in the simulations for the radiation fields listed in tables 1 and 2 [7]. For the sake of completeness, they are repeated here anyway: the cross-sectional data for the electron transport (where the condensed history technique is applied) are: standard EGSnrc (based on the Bethe-Bloch theory) for the collision stopping power and Bethe-Heitler cross sections for the radiative stopping power. For photons, the XCOM cross sections are used. The maximum energy loss per electron step is 25 % (ESTEPE = 0.25) and photons and electrons are followed down to an (kinetic) energy of 10 keV as this proved to be small enough. The exact boundary-crossing algorithm and the PRESTA-II electron-step algorithm were used, see references for details [10, 11], while the bare $^{90}$Sr/$^{90}$Y spectra (electrons and photons) were taken from ICRP 38 [12]. The number of Monte Carlo histories varies from $10^9$ for the radiation field with the 3 mm absorber for the phase space files up to $10^{12}$ for the radiation field with the 4 mm absorber for the depth dose simulations for the primary electron contribution and slightly less for the primary photon contribution taking up to 5 years of CPU time per simulation (for the primary electron contribution for the radiation field with the 4 mm absorber).

The simulations were performed separately for both the primary electron and the primary photon radiations emitted by the radiation sources. From the combination of both contributions, several results were deduced:

1. the total dose to tissue at 40 different depths from 1 µm to 20 mm on a nearly logarithmic scale and radii of the tissue phantom;
2. the contribution to the dose due to primary and secondary photon radiations (gammas and
Figure 1. Overall geometry comprising the BSS 2 source, the PMMA absorber, a phantom made of ICRU 4-element tissue and the surrounding air. The geometry is rotational with respect to the z-axis. The figure was produced using BEAMnrc [10, 11] (all numbers in cm). The figure is symmetric to the central vertical axis as the geometry is rotationally symmetric.

X-rays emitted by the radionuclide and bremsstrahlung produced in the source and its surroundings), and

3. the angular particle distributions in front of and at different depths and radii of the tissue phantom.

2.2 Geometry and material

The suggested radiation fields consist of the typical $^{90}$Sr/$^{90}$Y source supplied with the BSS 2 with an absorber made of polymethyl methacrylate (PMMA, C$_5$O$_2$H$_8$), placed at a distance of 4 cm from the source. For two different radiation fields, a PMMA absorber of 3 mm and 4 mm in thickness and 200 mm in diameter is used, respectively [8, 9]. A specific density of 1.19 g/cm$^3$ yields areal masses of 357 mg/cm$^2$ and 476 mg/cm$^2$, respectively, for the PMMA absorbers. Figure 1 shows the corresponding overall geometry of the simulation.

Figure 2 and table 3 give an overview of the simulated dose rates (at a tissue depth of 70 μm) for the different source types and irradiation geometries of the BSS 2 for the nominal activities as specified in table 1. The two new source types described in this paper perfectly fill the gap with respect to energy between $^{85}$Kr and normal $^{90}$Sr/$^{90}$Y sources.

2.3 Verification of the simulations

To verify the simulations, the calculated depth dose curves (dose to tissue) were compared to measurements with the primary extrapolation chamber of PTB on the center axis of the radiation field. The ionization volume of the chamber has a diameter of 3 cm, the same was chosen for the simulated depth dose curves. In figure 3, a comparison of simulated and measured data is shown for two well-established source geometries of $^{90}$Sr/$^{90}$Y and the two new source types. The uncertainties
Figure 2. Simulated dose rates (at 70 µm tissue depth) for the different sources and geometries at the nominal source activities, see Table 1. The colors represent different radionuclides: red: $^{147}$Pm; green: $^{85}$Kr; black: $^{90}$Sr/$^{90}$Y; blue: $^{106}$Ru/$^{106}$Rh. The olive/yellow and magenta backgrounds indicate the two new $^{90}$Sr/$^{90}$Y radiation fields with a 3 and 4 mm PMMA absorber, respectively. These colors are (partly) used in the following figures. The statistical uncertainties are much smaller than the symbols, i.e. less than 1 %, and therefore not shown.

Table 3. Dose rates (at 70 µm tissue depth) in mGy/h at the nominal source activities, see Table 1, of the sources and geometries listed in Table 2. The statistical uncertainties are less than 1 %.

| Radionuclide (source) | 11 cm without filter | 20 cm without filter | 20 cm with filter or absorber | 30 cm without filter | 30 cm with filter | 50 cm without filter | 50 cm with filter |
|-----------------------|----------------------|----------------------|-------------------------------|----------------------|-------------------|-------------------|------------------|
| $^{147}$Pm             | 931                  | 10.7                 |                               |                      |                   |                   |                  |
| $^{85}$Kr              |                       |                      |                               |                      |                   |                   |                  |
| $^{90}$Sr/$^{90}$Y     | 444                  | 137                  | 3 mm: 32.0                    | 60.8                 | 38.9              | 21.5              | 14.1             |
| $^{106}$Ru/$^{106}$Rh  | 27.7                 | 8.68                 | (37 times lower activity)     |                      |                   |                   |                  |

of the simulation (lines) and measurements (squares) are represented by the small variations of the data points at (nearly) the same depth in the phantom. At large depths very small dose rates occur, on the order of 0.1 mGy/h, see bottom right part of figure 3 (the same data as in the top and bottom left parts but on a logarithmic scale). As the corresponding ionization currents are also very small, on the order of 0.1 fA ($10^{-16}$ A), the measured values considerably vary from one measurement to another.

The simulations were performed for the nominal source activities according to the manufacturer’s information, see Table 1. As the real source activities are not known exactly (and differ from one source to another) the measured values were normalized to the simulated ones at the reference
depth of 70 µm³ (specific for each source and geometry). The normalization factors for the two new source geometries are between 1 and 2. According to the manufacturer, the nominal source activities meet the real ones by about ±15 %. However, as the results of this work are not influenced by the absolute dose agreement, no further investigation was undertaken to improve the absolute dose agreement.

More important is (it can be seen in figure 3; especially in the top and bottom left part) that the shapes of the simulated and measured depth dose curves agree quite well. This demonstrates that the simulation code with the chosen geometries, materials and particle transport parameters appropriately describes the particle transport from the radioactive material (source) to the point of test (position where an object to be irradiated is placed). As the scattering and absorption of electrons strongly depend on their energy, the shape of a depth dose curve is strongly correlated with the corresponding energy spectrum. Therefore, it is assumed that the electron spectra deduced from the simulations meet the real ones.

Furthermore, the maximum penetration depth of electrons in material is limited. Therefore, the depth dose curves drop down to a nearly zero dose rate at a certain depth (see top and bottom left part of figure 3). Only a very small contribution of photons penetrates deeper into the material (see right part of figure 3). It is obvious that the simulated and measured values agree sufficiently well even at depths larger than the maximum penetration depth of the electrons. Therefore, it is assumed that also this small photon contribution is adequately simulated and, consequently, the photon spectra deduced from the simulations also meet the real ones (discussed in section 3.2).

3 Results

3.1 Simulated depth dose profiles

In order to interpret (and optimize) the response of instruments to beta radiation, the knowledge of the dose or dose rate at different positions in the instrument is of interest. Therefore, the depth dose profiles in an ICRU tissue phantom are shown in figure 4 for the BSS 2 sources for several irradiation geometries. In principle, these profiles are only valid for an ICRU tissue phantom. However, they are assumed to be comparable in all materials with low atomic numbers, Z, e.g., plastics; only a conversion to the corresponding tissue equivalent depth is necessary. At least for the irradiation of most types of passive personal dosemeters being irradiated on a slab phantom, the shown depth dose profiles are assumed to be representative. For materials with higher atomic numbers the amount of bremsstrahlung produced in the material increases and, therefore, results in slightly different depth dose profiles. In case more precise knowledge of the dose distribution in an instrument is necessary, a detailed simulation needs to be performed.

The graphs of the depth dose profiles in figure 4 are normalized to the source and geometry specific mean dose at the following region: a depth of 70 µm and a radius of 1.5 cm around the center of the phantom. This region was chosen because the reference depth in beta dosimetry is 70 µm in tissue and because at a radius of 1.5 cm the dose profile is nearly homogeneous within ±2 % for all sources.

370 µm is the reference depth for beta radiation in radiation protection as the radiation sensitive part of human skin is located approximately at that depth.
Figure 3. Comparison of simulated and measured depth dose curves (absorbed dose to tissue) on the central axis of the radiation beam (average over an area with a radius of 1.5 cm) for two well-established geometries from $^{90}$Sr/$^{90}$Y of the BSS 2 as well as for the two new source types (top and bottom left: linear ordinate; bottom right: logarithmic ordinate). The measurements (squares) are normalized to the simulations (solid lines) at a depth of 70 µm (red cross) as only nominal activities of the sources are available. The dose due to photons is shown (dotted lines).

The following characteristics of the depth dose profiles can be seen in figure 4:

- The smaller the distance between the radiation source and the phantom, $d_{s-ph}$, the more inhomogeneous the dose profile. This is due to the divergence of the particles: the diameter of the sources is on the order of 1 cm or below which is much less than the distance $d_{s-ph}$, which is at least 11 cm. Therefore, the divergence of the particles is quite similar to that of a point source resulting in a dose profile according to the quadratic distance law (see top left of figure 4);

- The maximum of the depth dose profiles is located at larger depths than the 70 µm reference depth due to multiple scattering of electrons in the phantom resulting in a dose build-up effect. In case no beam-flattening filter is in place, the maximum is of an elliptical shape; with a beam-flattening filter it is rather a rectangular region;
Figure 4. Simulated depth dose profiles (absorbed dose to tissue) in an ICRU tissue phantom (normalized to a 70 µm depth, \(d\), and a radius of \(r = 1.5\) cm) for two well-established geometries from \(^{90}\text{Sr}/^{90}\text{Y}\) of the BSS 2 (top) as well as for the two new source types (bottom). A horizontal line is plotted at a phantom depth of 70 µm; the region in which the dose rate is within ±2% of the one at \(d = 70\) µm and \(r = 1.5\) cm is marked magenta. The color scale represents steps of 0.04. The graphs are symmetric to the central vertical axis as the geometry is rotationally symmetric, see figure 1.

- The reference region is located at a 70 µm depth and a radius of 1.5 cm (i.e. around the center of the radiation beam at the reference depth). In all graphs, the region with nearly the same dose as in the reference region is marked magenta.

- The two graphs at the bottom of figure 4 show the beam profiles of the two new source geometries. Due to the rather thick absorbers, the profiles are quite inhomogeneous. This was expected as the absorbers were not optimized with respect to beam homogeneity;

- As expected, in case a beam-flattening filter is in place (see top right of figure 4, i.e. \(d_{\text{s-ph}} = 30\) cm and the beam-flattening filter present), the dose profile is much more homogenous than for the two new radiations fields (i.e. \(d_{\text{s-ph}} = 20\) cm and an additional rather thick absorbers to reduce the mean energy but without beam-flattening filter);

In summary, in figure 5 the beam profiles at a depth of 70 µm and 3 mm in an ICRU tissue phantom are shown for \(H_p(0.07)\) and \(H_p(3)\), respectively.
Figure 5. Simulated dose profiles (absorbed dose to tissue) in an ICRU tissue phantom (normalized to a 70 µm and 3 mm depth and a radius of 1.5 cm, left and right, respectively) for all geometries of the BSS 2 as well as for the two new source types. Note, that the ordinates of the top figures are broken at a value of 0.9 with different scales before and after the break. The bottom figures show the same data as the top figures on a larger scale. All graphs are symmetric to the central vertical axis as the geometry is rotationally symmetric, see figure 1.

3.2 Simulated and measured particle spectra

3.2.1 Spectra at the beam centre and at reference distance from the source

In order to perform a detailed particle transport simulation within an instrument, the particle spectrum incident on the instrument needs to be well known. Therefore, the particle spectra of four BSS 2 sources with beam-flattening filter together with those of the two new source geometries are shown in figure 6. The spectra are valid for a circular beam with a radius of 1.5 cm around the beam center and are normalized to a source and geometry specific total dose of \( H_p(0.07) = 1 \) mSv. The beta and photon spectra in the reference plane at the top, and the beta spectra at 0.07 mm and 3 mm depth in an ICRU tissue phantom at the bottom left and right, respectively, are shown. The spectra at the bottom do contain radiation scattered back from the ICRU tissue phantom while those at the top do not. At the front of the phantom the ratio of the total electron fluence with and without radiation scattered back from the phantom is 1.21, 1.13, 1.06 and 1.04 for \(^{147}\text{Pm}\), \(^{85}\text{Kr}\), \(^{90}\text{Sr}/^{90}\text{Y}\) and \(^{106}\text{Ru}/^{106}\text{Rh}\), respectively. I.e., the more backscatter the smaller the electron’s energy due to the more dominant multiple scattering process of low energy electrons.
The following characteristics of the particle spectra can be seen in figure 6:

1. For $^{147}$Pm the maximum electron fluence is reduced by about a factor of four from the front of the phantom, top left, compared to a depth of 0.07 mm, bottom left. This is due to the absorption and scattering of the rather low energetic electrons from $^{147}$Pm in 0.07 mm tissue. For the other nuclides there is approximately no fluence reduction in 0.07 mm tissue, due to the larger electron energies of those radionuclides.

2. The low energy electrons of $^{147}$Pm and $^{85}$Kr are totally absorbed by 3 mm tissue. Therefore, they are not shown in the graph with the spectra at 3 mm depth, i.e. bottom right.

3. From the bottom graphs, it is also obvious that the higher the electron energy, the smaller the reduction factor due to the penetration of 3 mm tissue: for $^{106}$Ru/$^{106}$Rh it is about a factor of two while it is more than about a factor of ten for $^{90}$Sr/$^{90}$Y with a 4 mm PMMA
absorber. This trend is confirmed by the dose rates at the nominal activities shown in figure 2 in which also a significant reduction is obvious comparing the dose rate of $^{90}$Sr/$^{90}$Y at 20 cm distance without filter to that of $^{90}$Sr/$^{90}$Y with a 3 mm PMMA absorber (as the absorption and scattering in 3 mm PMMA is comparable to that in 3 mm ICRU tissue).

4. Furthermore, the endpoint energies are reduced at 3 mm depth compared to 0.07 mm: for $^{90}$Sr/$^{90}$Y with a 4 mm PMMA absorber by a factor of almost two (from about 1.4 MeV to about 0.8 MeV) and for a $^{106}$Ru/$^{106}$Rh source only slightly by a factor of 1.2 (from about 3.2 MeV to about 2.7 MeV). This reduction is caused by the continuous energy loss and multiple scattering of electrons when penetrating material. As expected, these effects are more dominant, the smaller the initial electron energy is.

5. Finally, the photon fluences for the new radiation fields are significantly larger than for the normal $^{90}$Sr/$^{90}$Y field (top right). The reason for this is the normalization to a source and geometry specific dose of $H_p(0.07) = 1$ mSv: the betas are significantly absorbed in 3 mm or 4 mm PMMA while the photons are not — as discussed above. Thus, the photon fluences relative to a total dose of $H_p(0.07) = 1$ mSv are the largest, the more the betas are absorbed.

3.2.2 Electron spectra outside the beam centre

As mentioned at the beginning of section 3.2.1, figure 6 shows particle spectra valid for a circular beam with a radius of 1.5 cm around the beam center at the reference distance. In order to assess the spectral dependence on the beam radius and on the depth in material, figure 7 shows electron spectra for different radial regions, $r$, and at different depths, $d$, in an ICRU tissue phantom. As mentioned above, this tissue is assumed to be representative for all materials with low atomic numbers, $z$, e.g. plastics. Information on how to scale the depth in different material to one another can be found in ICRU Report 56 [13]. Spectra are shown for the following phantom depths: at the surface, $d = 0$ mm, and at depths relevant for the quantities $H_p(0.07)$ and $H_p(3)$, i.e. $d = 0.07$ mm and 3 mm. Due to the rather small amount of scattering and absorption of photons, no photon spectra are shown in this section. The particles scattered back from behind the depths for which each spectrum is shown are not included.

The following characteristics of the electron spectra can be seen in figure 7:

1. Due to their rather high energy, the spectra are nearly independent of the radius; only at a depth of 3 mm in the phantom a slight decrease of the mean energy (by about 10 %) at a radial region of 9–12 cm is observed because of the rather long way (more than 3 mm) through the material.

2. A much larger decrease of the mean energy is apparent with increasing depth (from 0 to 3 mm). At 3 mm the mean energy is 25 % to 30 % smaller than at the surface. This is, of course, due to the large amount of scattering and absorption (and with this an energy loss) in the phantom material.
Figure 7. Simulated electron spectra for different positions in an ICRU tissue phantom for different geometries. In the legend the mean energy and fluence relative to the reference fluence, i.e. the fluence at the front center of the phantom, \( \{ \Phi_{r, d} / \Phi_{ref} \} \), are given. All spectra are normalized to an area of unity.
3.3 Simulated angular distributions

In figures 8 and 9, the angular distributions of the radiation fields are shown for two different energy regions of the electron spectra, i.e. for the lower part (solid lines) and for the upper part (dotted lines), for two different regions of the radiation fields, i.e. for the central region of a 0–1.5 cm radius (squares) and for the outer region of a 9–12 cm radius (stars), and with and without the back scattered contribution, i.e. with those particles that passed the plane for which the angular distribution is valid more than once (multiple passers included, green and magenta lines) and without them (blue and
Figure 9. Simulated angular distributions at a phantom depth of 3 mm for $^{90}$Sr/$^{90}$Y in an ICRU tissue phantom (squares for the central region and stars for the outer region) for different source geometries. The solid and dotted lines give the distributions for the lower and upper energy parts of the spectra, respectively. The grey symbols with their vertical side lines represent the corresponding geometrical angle region for the central beam of a 0–1.5 cm radius (square) and the outer beam of a 9–12 cm radius (star). All distributions are normalized to an area of unity.

The red lines). Finally, the corresponding geometrical angle ranges (given by straight lines from the source to the area of the region) for the central region of a 0–1.5 cm radius (square) and for the outer region of a 9–12 cm radius (star) are shown in grey symbols. 0°, 90°, and 180° angles represent the direction from the source to the phantom (see figure 1), perpendicular to this direction (parallel to the phantom surface), and backwards (from the phantom to the source), respectively. Figure 8 shows the spectra at 0.07 mm ICRU tissue depth while figure 9 shows the spectra at 3 mm ICRU tissue depth.
The following features can be seen:

1. Especially for low energy electrons and once a significant amount of material is located between the source and the phantom, i.e. for the new radiation fields with a 3 and 4 mm PMMA absorber and for all spectra at 3 mm depth, the angular distributions of electrons are rather broad due to multiple scattering of electrons that occur between the source and the phantom. This greater amount of low energy scattering is also reflected in the contributions scattered back (see green lines) while the high energy parts are nearly not scattered back (see magenta lines). This is especially obvious at 3 mm tissue depth (see figure 9).

2. At 0.07 mm depth (figure 8) and for the high energy regions the maxima of the angular distributions are nearly located at the angular region following from the geometry (see grey symbols). Thus, one can conclude that on average these electrons penetrate through to the phantom nearly on a straight line. At 0.07 mm phantom depth and with a 3 or 4 mm PMMA absorber (lower part of figure 8) and at 3 mm phantom depth for all geometries (figure 9) rather broad angular distributions are present. The reason for this is that the more material is to be passed the more scattering events with many different scattering angles occur. Consequently, broad angular distributions follow.

4 Supplementary data supplied with this publication

In order to enable researchers to use the outcome of the simulations undertaken in this work, several fluence spectra are supplied as electronic ASCII data files with this publication. As one usually wants to simulate the irradiation of a device positioned at the reference distance, spectra are supplied for that distance and without the contribution of back scattered radiation, i.e. for the absence of the phantom. Spectra are supplied for areas with a radius of 0–1.5 cm, 3–6 cm, and 9–12 cm in units of “1/(cm² MeV) per source decay” for both electrons and photons, i.e. absolute values are given. The data are given in two ASCII formats:

Firstly, the EGSnrc and BEAMnrc format (ASCII) for spectra [11] not containing uncertainties is given, see figure 10 for an example: first line: title (up to 80 characters); second line: number of energy channels, lower energy of first bin (MeV), mode 1 (fluence per MeV); following lines: top of energy bin (MeV) and fluence (1/(cm² MeV)). In addition, two lines are given at the end of the file giving the total fluence of the spectrum. In addition, ASCII files containing additional details such as the statistical uncertainty of each fluence value are given. An example can be seen in figure 11.

| PTB-BS52-spec: Elec; Sr-90/Y-90; 20cm; with 3mm PMMA filt; 3-6cm radius; 2020 J. Instrum. | 200, 0.8, 1 | 0.011, 4.582E-07 |
| 0.022, 4.717E-06 | 2.2, 4.823E-09 | Total fluence in 1/cm²: 3.494E-05 |

Figure 10. Example of the EGSnrc and BEAMnrc format for the spectra in the supplementary data to this publication.
Of course, the angular distributions are not contained in the spectra. Therefore, if very accurate simulations shall be undertaken, the full information of the radiation fields is necessary, i.e. the position, the direction, the energy, and the type of particle (electron or photon). All this information is available on each single particle that ever crossed a specific plane during the simulation in the so-called phase space files. Consequently, these binary files are very large (altogether about 2 gigabytes for the irradiation geometries described in this article). They are given for planes with a cross-sectional diameter of 120 cm, see figure 1. These planes are located between the source and the reference plane, i.e. at a distance of 15 cm from the source with the reference plane being located at 20 cm from the source. By this it is possible to simulate the irradiation of objects at both normal and oblique angles of the radiation incidence. These files are also supplied and can be read, e.g. using EGSnrc or BEAMnrc. The format is described in the BEAMnrc manual [11].

5 Conclusions and outlook

In this work the complete radiation fields (i.e. electron and photon contributions) of two new energy-reduced radiation fields from \( ^{90}\text{Sr}/^{90}\text{Y} \) sources for the BSS 2 are simulated. The comparison to measurements (depth dose curves) demonstrates the validity of the results. Consequently, the resulting particle spectra can be used for a broad range of applications, e.g. the simulation of instrument responses or the determination of correction factors for measuring devices such as primary extrapolation chambers. By freely supplying the particle spectra as electronic data files, their use is unlimited to every user of the BSS 2. Finally, the given depth dose profiles enable the users of the BSS 2 to choose the appropriate irradiation geometry depending on the size of their radiation instrument.
In future, investigations regarding the determination of correction factors for primary dosimetry as well as for the operational quantities, the optimization of the dose profiles with respect to homogeneity by modification of the absorber or addition of a beam-flattening filter (not only for the two new radiation fields but also for others of the BSS 2, e.g. the one of $^{147}$Pm at 20 cm source distance), as well as the practical implementation of the two new radiation fields to the BSS 2 should be carried out.

Acknowledgments

Special thanks go to Gert Lindner (PTB Berlin) for his invaluable help in using the high-performance computer cluster (HPC) of PTB on which the simulations were carried out; without his help I would not have been able to use the HPC (by now nearly 2 000 CPU cores). The author is also thankful to George Winterbottom (PTB) for the production of the 3 and 4 mm PMMA absorbers including their holders, to Phil Brüggemann (PTB) for the measurements with the primary extrapolation chamber, to Susanne Eger (PTB) for English checking and to Annette Röttger (PTB) for valuable comments to the manuscript.

References

[1] P. Ambrosi, G. Buchholz and K. Helmstädt, The PTB Beta Secondary Standard BSS 2 for radiation protection, 2007 JINST 2 P11002.

[2] R. Behrens and G. Bucholz, Extensions to the PTB Beta Secondary Standard BSS 2, 2011 JINST 6 P11007 [Erratum ibid. 7 (2012) E04001].

[3] Eckert & Ziegler Strahlen- und Medizintechnik AG https://www.ezag.com.

[4] International Organization for Standardization, Reference beta-particle radiation — Part 1: methods of production, ISO 6980-1 (2006).

[5] International Organization for Standardization, Reference beta-particle radiation — Part 2: calibration fundamentals related to basic quantities characterizing the radiation field, ISO 6980-2 (2004).

[6] International Organization for Standardization, Reference beta-particle radiation — Part 3: calibration of area and personal dosemeters and the determination of their response as a function of beta radiation energy and angle of incidence, ISO 6980-3 (2006).

[7] R. Behrens, Simulation of the radiation fields of the Beta Secondary Standard BSS 2, 2013 JINST 8 P02019 [Addendum ibid. 14 (2019) A07001].

[8] S. Shimizu, Attenuation of β-ray absorption dose rate by clothes and gloves (in Janaese), Health physics in JAERI no. 35, JAERI-M-93-172 (1993).

[9] M. Kato and T. Kurosawa, Beta-particle fields with the mean energy between $^{85}$Kr and $^{90}$Sr/$^{90}$Y source, in preparation.

[10] D.W.O. Rogers et al., BEAM: a Monte Carlo code to simulate radiotherapy treatment units, Med. Phys. 22 (1995) 513.

[11] D.W.O. Rogers, B. Walters and I. Kawrakow, BEAMnrc users manual, NRCC Report PIRS-0509(A)revL.
[12] International Commission on Radiological Protection, *Radionuclide transformations — Energy and intensity of emissions*, ICRP Publication 38, Ann. ICRP 11-13 (1983).

[13] International Commission on Radiation Units and Measurements, *Dosimetry of external beta rays for radiation protection*, ICRU Report 56 (1997).