Establishment of 350–450 kV wide spectrum and high air-kerma rate X-ray radiation mass

Bo Wang1,2, Jinjie Wu2,3, Haiyan Du3, Siming Guo2, Shwei Ren1
1Hebei University of Science and Technology, Shijiazhuang, People’s Republic of China
2National Institute of Metrology, Beijing, People’s Republic of China
3Shanghai Jiao Tong University, Shanghai, People’s Republic of China
E-mail: wujj@nim.ac.cn

Abstract: In recent years, the measurement of X-rays has attracted much attention. Especially in the aspects of environmental monitoring, radiation protection, and radiation therapy, to obtain more accurate measurement values, it is necessary to set up a corresponding reference device to trace the magnitude. This paper aims to establish a 350–450 kV wide spectrum and high air-kerma rate X-ray radiant mass. First, the Monte Carlo simulation was used to simulate the establishment of a model of the light engine, and the energy spectra of different tube voltages and different additional filters were calculated to obtain the average photon energy. Then the average photon energy was compared with the extrapolated average photon energy so that the deviation was within ±5%. Finally, half-value measurements are made on additional filters that meet the requirements.

1 Introduction
Nuclear technology is widely used in medical diagnostics, radiotherapy, industrial non-destructive testing, nuclear power generation, radiation processing, materials analysis and scientific research. However, ionising radiation can cause serious damage to the human body. Therefore, it is necessary to carry out radioactive environmental monitoring and radiation protection of nuclear radiation to protect the health of people. Radiation protection and environmental monitoring instruments, as compulsory verification instruments, must be periodically tested in X-ray, Am-241, Cs-137 and Co-60 radiation sources. The international standard ISO 4037 [1] (equivalent to GB 12162 in China) specifies the technical conditions and calibration methods for calibration of radiation protection and environmental monitoring instruments. The verification system procedures and technical requirements for domestic JJG2043, JJG2095, JJG393, JJG962, JJG521, JJG593, and other verification system tables and procedures have been established [2]. It is imperative to establish X-ray and gamma ray-based standard devices to solve the traceability of measurement values.

Internationally, the German PTB has established a 50–400 kV X-ray air-kerma energy national benchmark. The benchmark uses a flat-plate free-air ionisation chamber. The distance between the plates is 58 cm, the high voltage is 10,000 V, the leakage current is <50 μA, and the air is reproduced. Relative standard uncertainty of kinetic energy is 0.65% (k = 2) [3] (see Fig. 1).

In this paper, ‘Radiation protection and environmental standards’ published by Metrologia magazine in 2009 [4], X-ray radiation protection was given, and the upper limit of energy was 400 kV.

At this stage, China has built a 10–60 kV X-ray air-kerma benchmark, 60–250 kV X-ray air-kerma benchmark, 1.25 MeV Co-60 gamma-ray air-kerma benchmark, and has basically completed molybdenum Target X-ray air-kerma energy reference, 662 kV Cs-137 gamma-air-kerma energy reference and accelerator high energy X-ray X-ray water absorption dose reference [5–7]. There is an urgent need to establish a 250–450 kV X-ray air-kerma energy national benchmark to address the traceability of various types of radiation protection, environmental monitoring and radiotherapy measurement instruments in this energy segment.

2 Simulation of the energy spectrum
For a specific series of reference radiation, the average photon energy is linearly related to the tube voltage. Whereas the tube voltage is higher than the specified range in the standard, the average photon energy of the reference radiation is the relationship between the average photon energy in the low energy region and the tube voltage. Linear extrapolation: The range of tube voltage included in the wide spectrum and high air-kerma rate series in ISO 4037-1 is 60–300 and 10–300 kV [8]. According to the standard, the relationship between the average photon energy of two series of reference radiation and the tube voltage is shown in Fig. 2.

Subsequently, the average photon energy of the reference energy of the high energy region is extrapolated, as shown in Table 1.

![Fig. 1 PTB 50–400 kV air-kerma benchmark photo](image1)

![Fig. 2 Relationship between tube voltage and average photon energy](image2)

---

**Table 1.** Relationship between tube voltage and average photon energy

| Tube Voltage (kV) | Average Photon Energy (keV) |
|-------------------|-----------------------------|
| 60                | 200                         |
| 100               | 180                         |
| 200               | 160                         |
| 300               | 140                         |

---

This is an open access article published by the IET under the Creative Commons Attribution License (http://creativecommons.org/licenses/by/3.0/)

J. Eng., 2019, Vol. 2019 Iss. 23, pp. 8824-8828

Received on 15th October 2018
Revised 22nd January 2019
Accepted on 7th February 2019
E-First on 24th October 2019
doi: 10.1049/joe.2018.9116
The X-ray tube used in this paper is produced by COMET. Its appearance and parameter table is shown in Fig. 3 and Table 2. Due to the high photon flux of X-rays generated by X-ray machines, it is difficult to use the detector directly to measure the energy spectrum. At present, the energy spectrum of Monte Carlo simulation is in good agreement with the experimental measurements. The Monte Carlo simulation program used in this paper is EGS (Electron–Gamma Shower), which can simulate photon energy from several keV to several GeV. EGSnrc is a Monte Carlo program designed to simulate the interaction between electrons and photons. It can quickly and easily model and set parameters. It mainly includes BEAMnrc, BEAMDP, egs.inprz, EGSnrcMP, DOSXYZnrc and other packages. This paper uses the BEAMnrc and BEAMDP packages in the EGSnrc simulation program [9, 10].

From the parameters of the X-ray machine, we can see that in the BEAMnrc package, the anode target of the photo-machine is tungsten, the anode target angle is 11°, and the inherent filtration is composed of 3 and 2 mm thick tantalum sheets, respectively, and the limiting beam is shielded. Good tungsten alloy metal material. The machine’s tube voltage is a maximum of 600 kV. The XTUBE and FLATFILT modules in BEAMnrc are used to set the tube voltage, filter material, and thickness of the light engine. The other major parameter settings are shown in the figure. Simulate X-ray fluence spectra under different tube voltages and additional filter specifications. In this simulation, the single-energy electrons generated by the tube voltage under different specifications were selected as the incident particles. The simulated particle number was $1 \times 10^9$, the electron cut-off energy $ECUT = 0.512$ MeV, and the photon cut-off energy was $PCUT = 0.001$ MeV. Other data use the default value. Compile and run eight sets of specifications and get the phase space files under the eight sets of specifications. After the BEAMnrc program is finished, the phase space file obtained after the run needs to use another package BEAMDP in EGSnrc to solve the phase space file to obtain the energy spectrum [11]. According to the ISO 4037 standard, the deviation of the average photon energy of the simulated energy spectrum from the extrapolated average photon energy is within $\pm 5\%$. The results are shown in Tables 3 and 4.

### Table 1 Linear average extrapolation of photon energy

| Tube voltage, kV | W series | Average energy, keV | H series |
|-----------------|----------|---------------------|----------|
| 350             | 240.70   | 174.62              |
| 400             | 274.62   | 198.58              |
| 450             | 308.54   | 222.74              |

### Table 2 Light pipe performance parameters

| Project                | Performance parameters |
|------------------------|------------------------|
| target material        | W                      |
| power                  | 700 W/1500 W           |
| focus size             | 0.5 mm/1.5 mm          |
| filament current       | 3.7 A/4.1 A            |
| tube voltage range     | 20–600 kV              |
| beam angle             | 40° × 30°              |
| target inclination     | 11°                    |
| inherent filtering     | 3 mm + 2 mm Be         |
| cooling medium         | oil                    |

### Table 3 Wide spectrum simulation result

| Tube voltage, kV | 350 | 400 | 450 |
|-----------------|-----|-----|-----|
| Additional filter, mm | Sn  |     |     |
|                  |     | 8   | 8.5 |
|                  |     | 9   | 10  |
|                  |     | 9.5 | 10  |
|                  |     | 10.5| 11.5|
|                  |     | 12.5| 14  |
|                  |     | 15  | 16  |
|                  |     | 18  |     |
|                  | Al  | 4   | 4   |
|                  |     | 4   | 4   |
|                  |     | 4   | 4   |
|                  |     | 4   | 4   |
|                  |     | 4   | 4   |
|                  |     | 4   | 4   |
|                  |     | 4   | 4   |
| average energy, keV | 234.04 | 236.13 | 241.78 |
| relative deviation, % | $-2.76$ | $-1.89$ | $-1.07$ |

### Table 4 High air-kerma rate simulation result

| Tube voltage, kV | 350 | 400 | 450 |
|-----------------|-----|-----|-----|
| Additional filter, mm | Sn  |     |     |
|                  |     | 3   | 3.5 |
|                  |     | 4   | 4   |
|                  |     | 4   | 4   |
|                  |     | 4   | 4   |
|                  |     | 5   | 5   |
|                  |     | 5.5 | 6   |
|                  | Al  | 4   | 4   |
|                  |     | 4   | 4   |
|                  |     | 4   | 4   |
|                  |     | 4   | 4   |
|                  |     | 4   | 4   |
| average energy, keV | 165.11 | 169.41 | 173.11 |
| relative deviation, % | $-5.44$ | $-2.98$ | $-0.86$ |

The X-ray tube used in this paper is produced by COMET. Its appearance and parameter table is shown in Fig. 3 and Table 2. Due to the high photon flux of X-rays generated by X-ray machines, it is difficult to use the detector directly to measure the energy spectrum. At present, the energy spectrum of Monte Carlo simulation is in good agreement with the experimental measurements. The Monte Carlo simulation program used in this paper is EGS (Electron–Gamma Shower), which can simulate photon energy from several keV to several GeV. EGSnrc is a Monte Carlo program designed to simulate the interaction between electrons and photons. It can quickly and easily model and set parameters. It mainly includes BEAMnrc, BEAMDP, egs.inprz, EGSnrcMP, DOSXYZnrc and other packages. This paper uses the BEAMnrc and BEAMDP packages in the EGSnrc simulation program [9, 10].

From the parameters of the X-ray machine, we can see that in the BEAMnrc package, the anode target of the photo-machine is tungsten, the anode target angle is 11°, and the intrinsic filtration is composed of 3 and 2 mm thick tantalum sheets, respectively, and the limiting beam is shielded. Good tungsten alloy metal material. The machine’s tube voltage is a maximum of 600 kV. The XTUBE and FLATFILT modules in BEAMnrc are used to set the tube voltage, filter material, and thickness of the light engine. The other major parameter settings are shown in the figure. Simulate X-ray fluence spectra under different tube voltages and additional filter specifications. In this simulation, the single-energy electrons generated by the tube voltage under different specifications were selected as the incident particles. The simulated particle number was $1 \times 10^9$, the electron cut-off energy $ECUT = 0.512$ MeV, and the photon cut-off energy was $PCUT = 0.001$ MeV. Other data use the default value. Compile and run eight sets of specifications and get the phase space files under the eight sets of specifications. After the BEAMnrc program is finished, the phase space file obtained after the run needs to use another package BEAMDP in EGSnrc to solve the phase space file to obtain the energy spectrum [11]. According to the ISO 4037 standard, the deviation of the average photon energy of the simulated energy spectrum from the extrapolated average photon energy is within $\pm 5\%$. The results are shown in Tables 3 and 4.

### 3 Build-up radiation mass

The X-ray beam emitted by the X-ray tube is continuously distributed. The best way to describe X-ray radiation is to study the X-ray energy spectrum. However, the half-value layer (HVL) is usually used to represent the X-ray penetration ability. When single-energy narrow-beam X-rays pass through a substance, the change in X-ray air-kerma energy rate satisfies the law of exponential decay. When the incident X-ray air-kerma energy rate
is reduced to half of the initial value, the absorption body thickness is HVL. Because the X-ray emission spectrum is continuous and not mono-energy, the corresponding spectrum does not necessarily have to be the same even for the same HVL. For this reason, ISO 4037-1 also defines the second HVL (HLV₂nd), which is the thickness of the absorber minus the first half value when the air-kerma energy of the incident X-ray is reduced to a quarter of the initial value. **Thickness:** At the same time, the homogeneity coefficient \( h = \frac{\text{HLV}_{1st}}{\text{HLV}_{2nd}} \) is also defined.

The additional filtration that meets the requirements after the simulation is assembled and the HVL is measured. The schematic diagram of the HVL measuring device is shown in Fig. 4. During the measurement, the absorption sheet is placed in the approximately middle position between the X-ray focal spot and the ionisation chamber. Therefore, the absorption sheet is placed 60 cm away from the X-ray focal spot, and the measurement point distance between the focal spot and the light focal spot is 120 cm. The laser locator and measuring rod are used to measure the distance and position. The absorbent sheet is a copper sheet with a purity of better than 99.9% [12, 13]. The thickness of the absorbent sheet needs to be patched together. The maximum thickness of the absorbent sheet should be at least equal to less than a quarter of the current value.

The series of measurement results are as follows:

1. **Wide spectrum series** (see Fig. 5 and Table 5).
2. **High air-kerma rate series** (see Fig. 6 and Table 6).

### 4 Conclusion

The establishment of 350–450 kV broad spectrum and high air-kerma energy X-ray radiation can fill in the energy vacancy in the photon radiation field and solve all kinds of radiation protection, environmental monitoring and radiotherapy measurement instruments in this energy segment. Traceability provides a reference platform and lays an important foundation. However, it needs to be recognised that in the future, the absolute measurement of the X-ray air-kerma energy needs to be studied in detail.
This work was supported by National Key R&D Program of China under grant no. 2016YFF0200800, Research Fund for the Research on Key Measurement Standards and Traceability Technology of Aerospace.

Table 5  Wide-spectrum series half-value measurement results

| Tube voltage, kV | Additional filtering, mm Cu | HVL_{1st}, mm Cu | HVL_{2nd}, mm Cu | Homogeneous coefficient | Effective energy, keV |
|-----------------|----------------------------|-----------------|-----------------|------------------------|---------------------|
| 350             | 9                          | 5.99            | 6.12            | 0.98                   | 254.15              |
| 350             | 10                         | 6.13            | 6.26            | 0.98                   | 261.76              |
| 400             | 11.5                       | 6.55            | 6.68            | 0.98                   | 284.6               |
| 400             | 12.5                       | 6.68            | 6.81            | 0.98                   | 291.95              |
| 450             | 14                         | 7.04            | 7.16            | 0.98                   | 308.7               |
| 450             | 15                         | 7.15            | 7.28            | 0.98                   | 319.24              |
| 450             | 16                         | 7.16            | 7.30            | 0.98                   | 319.81              |
| 450             | 18                         | 7.22            | 7.35            | 0.98                   | 323.71              |

Table 6  High air-kerma rate series half-value measurement results

| Tube voltage, kV | Additional filtering, mm Cu | HVL_{1st}, mm Cu | HVL_{2nd}, mm Cu | Homogeneous coefficient | Effective energy, keV |
|-----------------|----------------------------|-----------------|-----------------|------------------------|---------------------|
| 350             | 3.5                        | 4.39            | 5.07            | 0.86                   | 175.85              |
| 350             | 4                          | 4.54            | 5.14            | 0.88                   | 179.82              |
| 400             | 4.5                        | 5.06            | 5.57            | 0.91                   | 204.8               |
| 400             | 5                          | 5.08            | 5.69            | 0.89                   | 205.57              |
| 450             | 6                          | 5.55            | 6.11            | 0.91                   | 230.43              |

Fig. 6 High air-kerma rate X-ray attenuation curves from 250 kV to 450 kV
References

[1] Zhang, Q., Han, M., Huang, Y., et al.: ‘Establishment of filtered X-ray reference radiation based on ISO4037-1:1996 in CIRP’, *J. Nucl. Sci. Technol.*, 2008, 45, (sup5), pp. 278–281

[2] Wei, Y., Meng, Y., Ke, H., et al.: ‘Performance assessment of gamma-ray monitors for radiation protection monitoring in China’, *Radiat. Prot.*, 2014, 17, (5), p. 53

[3] Burns, D.T., Kessler, C.: ‘Key comparison BIPM.RI(I)-K3 of the air-kerma standards of the PTB, Germany and the BIPM in medium-energy x-rays’, *Metrologia*, 2014, 48, (1A), pp. 6004–6004

[4] Ambrosi, P.: ‘Radiation protection and environmental standards’, *Metrologia*, 2009, 46, (2), pp. S99–S111

[5] Sharma, S.D., Kumar, S., Srinivasan, P., et al.: ‘Establishment of air kerma reference standard for low dose rate Cs-137 brachytherapy sources’, *J. Appl. Clin. Med. Phys.*, 2011, 12, (4), p. 3553

[6] Pearce, J., Bass, G., Duane, S., et al.: ‘Short communication: revised correction factor for the UK national primary standard for air kerma for 137Cs and 60Co gamma-rays’, *Metrologia*, 2009, 46, (5), pp. L26–L26(1)

[7] Jun, L.I., Zhang, X.Z., Tan, F.: ‘Measurement and calculation of absorbed dose for high energy X-ray and electron beam’, *Chin. J. Med. Phys.*, 2008, 37, (3), p. 211

[8] Yasar, D., Kapdan, E., Korkmaz, M.: ‘Performance tests of active personal Dosemeter developed by CNRTC/NEL’, *Radiat. Prot. Dosim.*, 2017, 176, (4), pp. 380–387

[9] Kocsis, L., Szepesvári, C.: ‘Bandit based Monte-Carlo planning’, *Lect. Notes Comput. Sci.*, 2006, 4212, pp. 282–293

[10] Taylor, R.E., Rogers, D.W.: ‘An EGSnrc Monte Carlo-calculated database of TG-43 parameters’, *Med. Phys.*, 2008, 35, (9), pp. 4228–4241

[11] Ma, C.M., Rogers, D.W.O.: ‘BEAMDP as a general-purpose utility’. NRC Report PIRSE, 2009

[12] Boone, J.M., Burkett, G.W., Mckenney, S.E.: Apparatus and methods for determination of the half value layer of X-ray beams. US, US9008264, 2015

[13] Jeannot, S.: ‘Method and assembly for the manufacture of an absorbent sheet, and absorbent sheet obtained’. United States Patent 8012311