

ISO 4037 narrow spectrum X-ray reference field: Simulation and measurement

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ABSTRACT

The paper presents the characteristics of the ISO-4037 narrow spectrum X-ray reference fields in 02 different manners: simulation using the SpekPy and measurement using a calibrated ionization chamber. The physical (air Kerma rate) and radiation (X-ray fluence-spectrum-averaged energy, the first and the second half value layers, as well as the beam homogeneity coefficient) quantities were simulated using the SpekPy web-based simulation toolkit. In addition, air Kerma rates were measured by the ionization chamber. The characteristics of the ISO-4037 narrow spectrum X-ray reference fields were determined for various X-ray beam qualities (i.e., N-40, 60, 80, 100, 120, and 150) at 250 cm from the X-ray focal spot. The air Kerma rate tendency was deduced by comparing simulation and measurement data. The combined standard uncertainty of measured air Kerma rate was investigated and presented.

Keywords: Averaged energy; Air Kerma; SpekPy; Homogeneity coefficient.

1. INTRODUCTION

The International Organization for Standardization (ISO) has released the ISO-4037 series [1-3] to guide the establishment of photon (X-ray and gamma) reference fields that are applied in photon metrology. In which, the guidance for establishing the narrow spectrum X-ray reference fields (referred to “N-series”) is recommended.

Many laboratories have established the ISO 4037 N-series X-ray reference fields in different approaches (i.e., using Monte Carlo simulations and/or measurements) [5-11]. For the secondary standard dosimetry laboratories (SSDLs), the air Kerma rate is the most important quantity being used in calibrations, which is also the concerned one, among others, in this work.

There have been several intercomparisons between different laboratories on air Kerma rates caused by the ISO 4037 N-series X-ray reference fields as well as on operational dosimetric quantity (e.g., ambient dose equivalent rate, $\dot{H}^*(10)$ [12].)

In this work, the physical (air Kerma rate - \dot{K}_{SpekPy}) and radiation (X-ray fluence-spectrum-averaged energy - \bar{E} ; the first - HVL_1 , and the second - HVL_2 , half value layers as well as the beam homogeneity coefficient - $h = HVL_1/HVL_2$) quantities of the ISO-4037 N-series X-ray reference fields have been established using the SpekPy web-based simulation toolkit. Moreover, the air Kerma rates (\dot{K}_{IC}) measured by an ionization chamber were also performed, accompanied by their investigated combined standard uncertainties. The comparison between values of \dot{K}_{SpekPy} and \dot{K}_{IC} was done to show the air Kerma rate tendency of the ISO 4037 N-series X-ray reference fields.

2. MATERIAL AND METHOD

2.1. X-ray system and SpekPy simulation toolkit

The Institute for Nuclear Science and Technology (INST, Hanoi – Viet Nam) was equipped with the MXR-160/22 model Hopewell Design Inc. (USA) X-ray system, which was manufactured in 2020. The X-ray system was designed with an anode-cathode axis as 5.2° tilt back to the emitted

X-ray direction (in comparison with the vertical axis). The X-ray system has a tungsten anode with a tilt angle of 20° (to the electron incident angle). The information designed for this X-ray system was taken care of when performing simulations using the SpekPy web-based simulation toolkit.

The SpekPy (version 2.0.8) web-based simulation toolkit was used to generate N-series X-ray fluence spectra at 250 cm from the X-ray focal spot. Out of related information about the X-ray system, the following setting parameters were chosen in the SpekPy simulations: physics model (kqp); attenuation data (Penelope); energy bin (0.5 keV); X-ray component included (Bremsstrahlung and characteristic); filtration (taking information from the ISO-4037-1 [1] for different beam qualities).

As a result, the output X-ray spectra are in the form of “fluence.keV⁻¹.mAs⁻¹” were achieved and converted to the form of “fluence.mAs⁻¹” (unit in cm⁻².mAs⁻¹). In addition, the following quantities were also derived as outputs of the SpekPy: \dot{K}_{SpekPy} , \bar{E} , HVL_1 , HVL_2 , $h = HVL_1/HVL_2$. Those simulated physical and radiation quantities were presented in this work.

2.2. Measurement of air Kerma rate using ionization chamber and uncertainty

Measurements were performed with a measuring assembly consisting of an ionization chamber (US Standard Imaging, Exradin A4, with an active volume of 30 cm³) and an electrometer (US Standard Imaging, SuperMax), which was calibrated with the N-series X-ray reference fields (in terms of air Kerma rate) at the Dutch Metrology Institute, VSL.

For the purpose of calibrations of radiation protection measuring devices, the conventional true values of air Kerma rates (\dot{K}_{IC}) at points of interest are calculated as Eq. (1), based on the following data: (i) measured values of C_0 per unit mAs (derived from measured values in appropriate duration with statistical uncertainties less than 1%); (ii) the calibration factor of the measuring assembly at a specific X-ray beam quality, N_K (taken from the VSL certificate); and (iii) the correction factor for other influence quantities (i.e., environmental conditions, k_1 ; ionization chamber influence factors, k_2 ; and from radiation field influence factors, k_3).

$$\dot{K}_{IC} = C_0 \cdot N_K \cdot k_1 \cdot k_2 \cdot k_3 \quad (1)$$

Applying the uncertainty propagation principle, the combined standard uncertainty of \dot{K}_{IC} in Eq. (1) - u_K , can be estimated based on the following uncertainty budgets: (1) from environmental conditions, k_1 (consisting of influence factors from: temperature - k_T , pressure - k_P , humidity - k_H); (2) from ionization chamber influence factors, k_2 (including reading resolution, linearity response, stability, chamber aging, leakage current, recombination of ions, polarity, etc. – all of them are normally negligible, for the ease of this case, all these influence factors are included in the statistical uncertainty of the value C_0 , k_C). Thus, the values of k_2 is considered as included in k_C); and (3) from radiation field influence factors, k_3 (including uniformity of the field - k_u , beam quality - k_Q , range of measuring quantity - k_r). In addition to that, there is a type B uncertainty budget originating from N_K , k_N . The value of u_K is analyzed applying the NIST uncertainty web-based computer software [13] with the following variables: $k_1 = 0.17\%$ (caused by: $k_T = 0.10\%$, $k_P = 0.10\%$, $k_H = 0.10\%$); $k_2 = k_C = 2.00\%$; $k_3 = 2.08\%$ (caused by: $k_u = 2.00\%$, $k_Q = 0.30\%$, $k_r = 0.50\%$); and $k_N = 0.50\%$. Therefore, the value of u_K was derived as 2.93%.

3. RESULT AND DISCUSSION

3.1. X-ray spectrum

Fig. 1 demonstrates the ISO 4037 N-series X-ray spectra at 250 cm from the X-ray focal spot, which was generated by the SpekPy web-based simulation toolkit (black dot line, data from this work with $\pm 3.0\%$ error bars) in comparison with those from published data, red line [14]. They are consistent with each other. That means the SpekPy simulation data are believable.

From Fig. 1, ones can figure out that the N-80 and N-100 X-ray spectra have characteristic X-ray peaks while others do not (or just with a negligible magnitude). If these spectra are used for the calculation of spectral resolution, the characteristic X-ray peaks must be excluded, following the recommendations in Ref. [1].

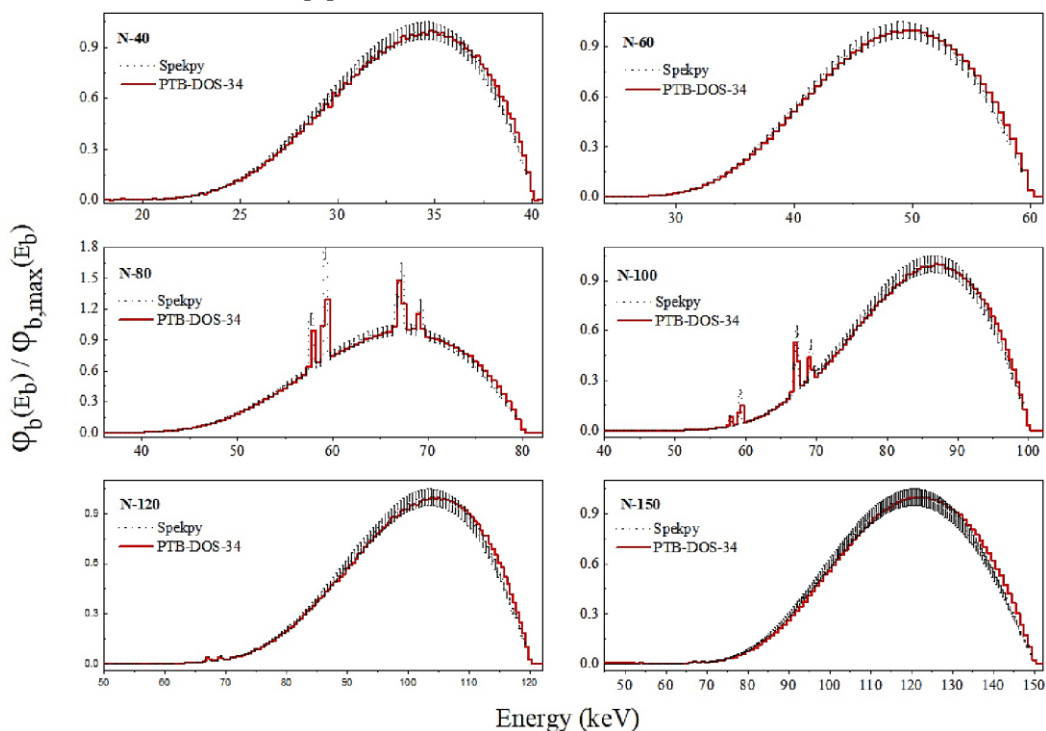


Figure 1. Different ISO 4037 N-series X-ray spectra at 250 cm from the focal spot. Data generated by the SpekPy web-based simulation toolkit (black dot line, data from this work, with $\pm 3.0\%$ error bars) and published ones [14].

3.2. Physical and radiation quantity

Table 1 shows the physical quantities of \dot{K}_{SpekPy} (generated by the SpekPy web-based simulation toolkit); and of \dot{K}_{IC} (measured by the ionization chamber) together with radiation quantities (\bar{E} , HVL_1 , HVL_2 , $h = HVL_1/HVL_2$) at 250 cm from the X-ray focal spot.

Table 1. Physical and radiation quantities of the ISO 4037 N-series X-ray reference fields at 250 cm from the X-ray focal spot.

N-series	HVL_1 (mmCu)	HVL_2 (mmCu)	HVL_1/HVL_2	\bar{E} (keV)	\dot{K}_{SpekPy} ($\mu Gy/mAs$)	\dot{K}_{IC} ($\mu Gy/mAs$)
N-40	0.054	0.065	0.84	33	0.15	0.16
N-60	0.240	0.260	0.89	48	0.26	0.25
N-80	0.580	0.620	0.93	65	0.13	0.13
N-100	1.100	1.200	0.95	83	0.06	0.07
N-120	1.700	1.800	0.96	100	0.07	0.07
N-150	2.300	2.500	0.96	120	0.53	0.51

Notation: HVL_1 , HVL_2 : The first and the second half value layers, respectively;
 $h = HVL_1/HVL_2$: The beam homogeneity coefficient;
 \bar{E} : X-ray fluence-spectrum-averaged energy;
 \dot{K}_{SpekPy} , \dot{K}_{IC} : Air Kerma rates were obtained from the SpekPy and measurements.

If one performs a comparison between physical and radiation quantities obtained from this work to those published in Ref. [1], a good agreement can be found. That means the data obtained from this work are reliable and can be used as the conventional true values applied in the calibration process.

The simulated values of physical and radiation quantities were generated by the SpekPy web-based simulation toolkit without their uncertainty. Thus, in this work, the combined standard uncertainties of simulated data were not mentioned.

Moreover, radiation quantities are not directly dealt with by SSDL staff in the calibration process, but the physical quantity (air Kerma rate). Therefore, the tendency of air Kerma rate, as well as the combined standard uncertainty of \dot{K}_{IC} were analyzed and discussed in the next section.

3.3. Kerma tendency

Fig. 2 shows the tendency of air Kerma rates of the N-series X-ray reference fields at 250 cm from the X-ray focal spot in comparison between simulations (SpekPy) and measurement data.

From Fig. 2, one can figure out that the Kerma rate tendency between the simulated and the measured data is equivalent. That implies the reliability in the determination of air Kerma rates (both in simulation and measurement). This tendency must be found to be equivalent between different laboratories to ensure the quality of the calibration.

The combined standard uncertainty of measured air Kerma rate ($u_K = 2.93\%$) is presented in Fig. 2 as the filled area. This combined standard uncertainty in the determination of air Kerma rate at radiation protection level is considered acceptable for calibrations at the SSDLs.

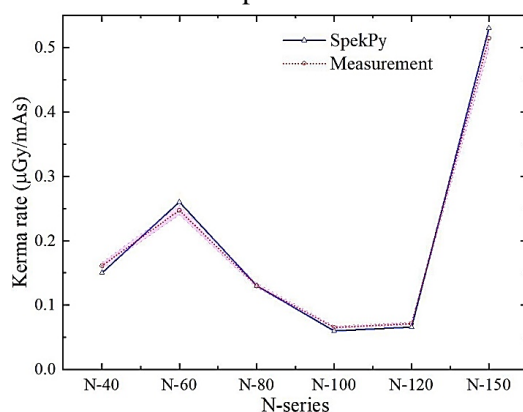


Figure 2. Tendency of air Kerma rates of the ISO 4037 N-series X-ray reference fields in comparison between the simulation (SpekPy) and measurement data.

4. CONCLUSIONS

The physical and radiation quantities of the ISO-4037 narrow spectrum X-ray reference fields were characterized for the beam qualities of N-40, N-60, N-80, N-100, N-120, N-150 using the SpekPy web-based simulation toolkit as well as measurements using the ionization chamber. The obtained results show the reliability in the determination of radiation quantities as well as air Kerma rates of the X-ray reference fields, which are the most important quantities applied for the calibration of X-ray measuring instruments.

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TÓM TẮT

Trường chuẩn bức xạ tia X phổ hẹp theo tiêu chuẩn ISO 4037: Mô phỏng và thực nghiệm

Bài báo này trình bày đặc trưng của trường bức xạ tia X phổ hẹp (chuỗi N) theo tiêu chuẩn ISO 4037, được xác định theo 02 phương pháp: Mô phỏng sử dụng phần mềm SpekPy và Thực nghiệm sử dụng buồng ion hóa (đã được hiệu chuẩn quốc tế). Đại lượng vật lý (suất Kerma trong không khí) và các đại lượng liên quan đến bức xạ (phổ bức xạ tia X và năng lượng trung bình của chúng, bề dày làm suy giảm một nửa lần 1 và lần 2, hệ số đồng nhất chùm tia) được xác định bằng mô phỏng sử dụng phần mềm SpekPy. Thêm vào đó, giá trị suất Kerma trong không khí được đo đạc sử dụng buồng ion hóa. Tính chất của các chuỗi tia X phổ hẹp (N-40, 60, 80, 100, 120, và 150) theo tiêu chuẩn ISO 4037 được xác định tại khoảng cách 250 cm so với tiêu điểm bóng tia X. Xu hướng của suất Kerma trong không khí được trình bày trong mối tương quan so sánh giữa giá trị mô phỏng và thực nghiệm. Độ không đảm bảo đo của giá trị thực nghiệm suất Kerma trong không khí cũng được đề cập trong nghiên cứu này.

Từ khóa: Năng lượng trung bình; Suất Kerma trong không khí; SpekPy; Hệ số đồng nhất chùm tia.