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# OPTIMAL GEOMETRIC DESIGN OF THE DIAPHRAGM OF A FREE-AIR IONIZATION CHAMBER FOR LOW-ENERGY X-RAYS

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***Abstract.*** *For reliable and comparable measurements of the dose quantity air kerma, dosimeter measurements must be traceable to a primary standard. Primary standard laboratories use free-air ionization chambers (FACs) for the primary realization of the unit of the air kerma free-in-air. Correction factors must be applied to convert measured charge to air kerma. One such correction factor is the correction factor for diaphragm effects (*$k_{dia}$*). This study investigated the impact of the geometry of the diaphragm on* $k_{dia}$*, as established FACs from different metrology institutes use different diaphragm geometries. The aim was to find the optimal diaphragm thickness and aperture shape to minimize the required diaphragm correction for the new PTB primary standard. Monte Carlo simulations were performed to determine* $k_{dia}$ *for various diaphragm geometries of a low-energy x-ray FAC. The influence of the diaphragm thickness and the aperture shape were investigated. The results showed that the diaphragm needs to be sufficiently thick to prevent transmission yet as thin as possible to reduce scattering at the inner surface of the aperture. The optimal diaphragm thickness, which depends on the air path length of the FAC, ranges from 0.8 mm to 1 mm. Using a diaphragm geometry with a more complex geometry than a simple 1 mm thick diaphragm with a cylindrical aperture is not advantageous.*

***Keywords:*** *free-air ionization chamber, primary standard, air kerma, diaphragm correction factor, Monte Carlo simulation*

## 1. Introduction

Diagnostic dosimeters are specialized instruments that measure the energy deposited by ionizing radiation in a material. These devices are used in acceptance and constancy testing to measure air kerma in diagnostic applications and thereby ensure compliance with regulatory safety standards. Regular calibration of diagnostic dosimeters is essential to maintain measurement accuracy, reliability, and comparability. National metrology institutes use free-air ionization chambers (FACs) as primary standards to realize the unit of the air kerma free-in-air. With the increasing demand for low-energy x-ray calibrations, particularly in the energy range of mammography, the Physikalisch-Technische Bundesanstalt (PTB) is currently developing a new primary standard for x-ray energies up to 50 keV.

The principle of a FAC is based on an x-ray beam entering the chamber through the entrance diaphragm and interacting with the air inside the FAC, thereby producing secondary electrons. The secondary electrons create ion pairs, which are subsequently measured as charge by an applied electric field. The measured charge can be converted into the air kerma using several correction factors that compensate for non-idealities in the geometry and operation of the FAC. The correction factors should always be as small as possible to minimize potential sources of errors or large uncertainties. Most correction factors depend on the geometry of the FAC and should be considered when designing a new primary standard.

According to ICRU Report 85 [1], kerma $K$ is defined as the mean sum of the initial kinetic energies $\mathrm{d}E_{tr}$ of all charged particles liberated in a mass $\mathrm{d}m$ of a material by uncharged particles, thus

$$K = \frac{\mathrm{d}E_{\mathrm{tr}}}{\mathrm{d}m}. \quad (1)$$

The unit of kerma is gray.

Consequently, air kerma only reflects dose contributions from secondary electrons generated by the interaction of the primary photon beam with the air inside the FAC. Dose contributions from particles that have interacted with the diaphragm – transmitted, scattered and fluorescence photons or electrons produced in the diaphragm by the incident photons – are excluded from the definition of air kerma. The diaphragm correction factor, denoted as $k_{dia}$, corrects for dose contributions from these secondary particles. Like several other correction factors, $k_{dia}$ depends on the geometry of the FAC. In particular, $k_{dia}$ is influenced by the geometry of the diaphragm itself [2–7]. In addition, the distance between the diaphragm and the collection volume is critical because it determines whether particles created by interactions with the diaphragm reach the collection volume and can contribute to the measured charge. To minimize photon attenuation in air this distance should be as small as possible for a low-

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energy x-ray primary standard [8]. This increases the correction for diaphragm effects. Therefore, it is important to reduce $k_{\mathrm{dia}}$ with an optimized diaphragm geometry.

This study systematically investigates the optimal diaphragm geometry to minimize the diaphragm correction factor for a low-energy x-ray FAC, with the aim of finding the best solution for the new PTB primary standard.

## 2. Materials and Methods

To investigate the optimal geometric design of the diaphragm of a low-energy x-ray FAC, a simplified FAC was modeled in the Monte Carlo simulation environment EGSnrc [9]. The FAC model consisted of a housing, two plane-parallel electrodes, and a tungsten diaphragm with 10 mm aperture diameter. A sketch of the FAC model is shown in Figure 1.

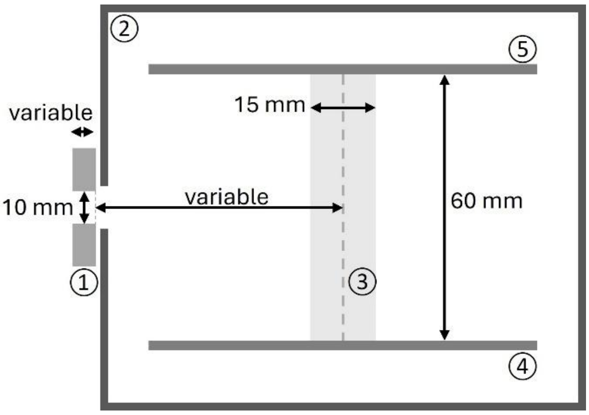


Figure 1. Cross-sectional sketch of the Monte Carlo simulation model of the free-air ionization chamber with variable entrance diaphragm ① geometry. The air path length (the distance between the reference plane of the FAC, defined by the diaphragm, and the middle of the collecting volume ③) is variable. The housing ② contains the ground ④ and the high-voltage electrode ⑤.

In the Monte Carlo simulations, the diaphragm thickness and the aperture shape of the diaphragm were varied. The diaphragm thickness was varied between 0.4 mm and 10 mm for a FAC model with variable air path length. The air path length is defined as the distance between the reference plane of the FAC, which is located at the downstream end of the diaphragm, and the middle of the collecting volume. Air path lengths between 40 mm and 100 mm were chosen based on common dimensions of established low-energy x-ray FACs from various metrology institutes [8]. For this part of the study, the aperture of the diaphragm was cylindrical.

To further evaluate the optimal design for the aperture of the diaphragm, three different aperture shapes (see Figure 2) were compared: cylindrical, conical, and hybrid. For the hybrid shape, the upstream half of the diaphragm was cylindrical, and the downstream half was conical. The opening angles for conical and hybrid apertures ranged from 0.15° to 45°. For this part of the study, the air path length of the FAC model was 60 mm, and the diaphragm thickness was between 1 mm and 10 mm.

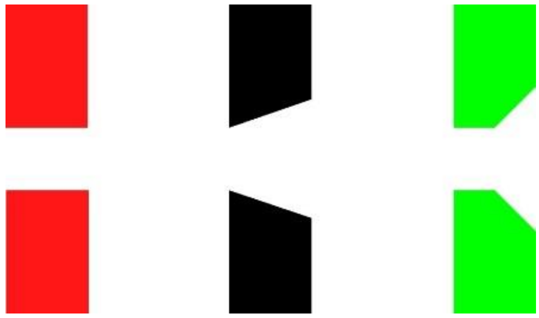

Figure 2. Different aperture shapes of the diaphragm of a free-air ionization chamber: cylindrical (left), conical (middle), hybrid (right).

Monte Carlo simulations were carried out with the EGSnrc user code egs_fac [10] to calculate the correction factor for diaphragm effects $k_{\mathrm{dia}}$. $k_{\mathrm{dia}}$ was calculated as follows:

$$k_{\mathrm{dia}} = \frac{E1}{Eg}, \qquad (2)$$

where $Eg$ is the total energy deposited in the collecting volume and $E1$ is the energy deposited in the collecting volume without the contribution of the particles that have interacted with the diaphragm or been generated by such interactions. Accordingly, $E1$ excludes energy contributions caused by transmission through the diaphragm, as well as by both scattering at the diaphragm and fluorescence.

A monoenergetic x-ray beam with an energy of 50 keV was simulated to analyze the influence of the diaphragm geometry. A point source was defined at a distance of one meter from the reference plane of the FAC. The beam diameter at the reference plane was 12 mm. The applied Monte Carlo simulation parameters are listed in Table 1.

Table 1. Parameters applied for the Monte Carlo simulations according to [11].

| Parameter | Description | Ref. |
|---|---|---|
| Code | EGSnrc release version 2021 | [9] |
| Timing | PTB computing cluster (CPU), approx. $10^7$-$10^8$ histories per hour | |
| Cross-sections | mcdf-xcom | |
| Transport parameters | Electron cutoff 0.512 MeV, photon cutoff 0.001 MeV | |
| Variance reduction | Photon splitting, Russian Roulette | [12] |
| Histories | $10^9$-$10^{11}$ histories per simulation | |
| Statistical uncertainty | ≤ 0.01 % for $k_{\mathrm{dia}}$ | |
| Postprocessing | OriginPro 2023b | |

## 3. Results

The aim of this study was to determine the optimal diaphragm geometry, in terms of diaphragm thickness and aperture shape, using Monte Carlo simulations. The influence of the geometric design on the diaphragm correction factor $k_{dia}$ was evaluated by systematically varying these parameters. The results of the Monte Carlo simulation study are presented in the following sections.

### *3.1. Diaphragm thickness*

The diaphragm thickness for FAC models with air path lengths ranging from 40 mm to 100 mm was varied between 0.4 mm and 10 mm. For each air path length of the FAC, an optimal diaphragm thickness was determined at which the value of $k_{dia}$ is closest to 1 (see Figure 3). As the air path length of the FAC model increased, the optimal diaphragm thickness also increased slightly. For instance, an optimal thickness of 0.8 mm was found for an air path length of 40 mm, while it was 1 mm at 100 mm air path length. For diaphragm thicknesses below these optimal values, a steep drop in $k_{dia}$ was observed, indicating that more correction of diaphragm effects is required. Conversely, for diaphragm thicknesses exceeding the optimal value, a continuous moderate decrease in the value of $k_{dia}$ was observed. However, this decrease was steeper for an air path length of 40 mm.

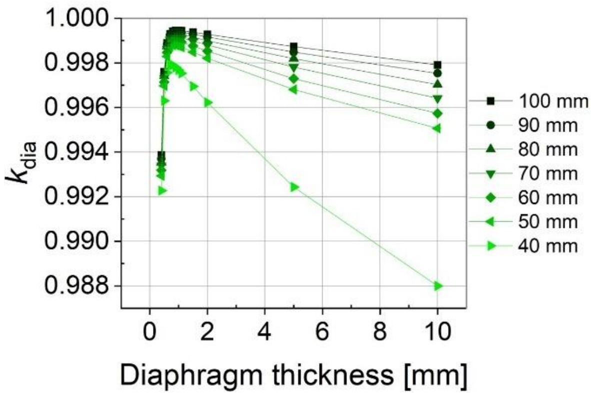


Figure 3. Diaphragm correction factor $k_{dia}$ as a function of the diaphragm thickness, plotted for several air path lengths of the free-air ionization chamber model.

### *3.2. Aperture shape*

The impact of three different aperture shapes (cylindrical, conical and hybrid) on the diaphragm correction factor $k_{dia}$ was analyzed. Figure 4 shows the values of $k_{dia}$ in dependence on the aperture shape and the diaphragm thickness for a FAC model with an air path length of 60 mm. For a 1 mm thick diaphragm with a cylindrical aperture, $k_{dia}$ was 0.9990. For conical and hybrid apertures with opening angles of 0.3°, $k_{dia}$ approached 1. The thicker the diaphragm, the greater the observed difference between 0° and 0.3°. The best value for $k_{dia}$ (0.9997) was observed for a 10 mm thick diaphragm with conical aperture and an opening angle of 0.3°. This indicates a 0.4% reduction in diaphragm correction when compared with a 10 mm diaphragm with cylindrical aperture. Compared to a 1 mm diaphragm with cylindrical aperture, this is a 0.07% reduction in diaphragm correction.

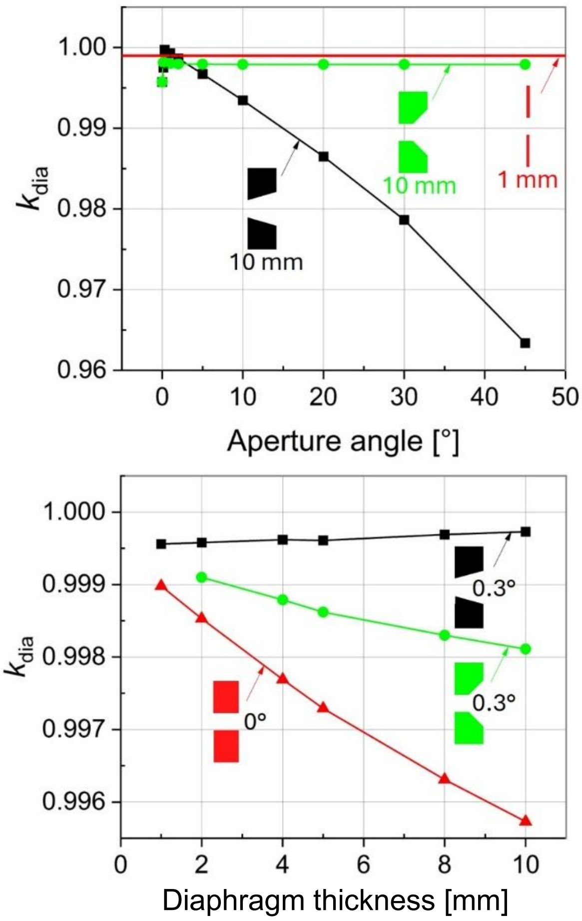


Figure 4. Top: $k_{dia}$ as a function of the aperture opening angle for a 10 mm thick diaphragm with conical or hybrid aperture. For comparison, the $k_{dia}$ value for a 1 mm thick diaphragm with cylindrical aperture is given as a constant. Bottom: $k_{dia}$ as a function of the diaphragm thickness for diaphragms with cylindrical or conical and hybrid apertures with opening angles of 0.3°.

## 4. DISCUSSION

The diaphragms in established FACs of different metrology institutes have different geometric designs regarding diaphragm thickness and aperture shape. Figure 5 shows the technical drawings of the diaphragms of three different FACs – two from PTB and one from the Bureau International des Poids et Mesures (BIPM). Furthermore, the literature is inconsistent regarding the dependence between the diaphragm correction factor and the diaphragm thickness or the aperture shape. These inconsistencies will be addressed in the following sections.

### *4.1. Diaphragm thickness*

The results of the Monte Carlo simulations with the FAC with cylindrical diaphragm and varying diaphragm thickness, see Figure 3, show that the diaphragm must be thick enough to prevent transmission through the diaphragm body. At the same time, it must be as thin as possible to reduce the inner surface of the aperture

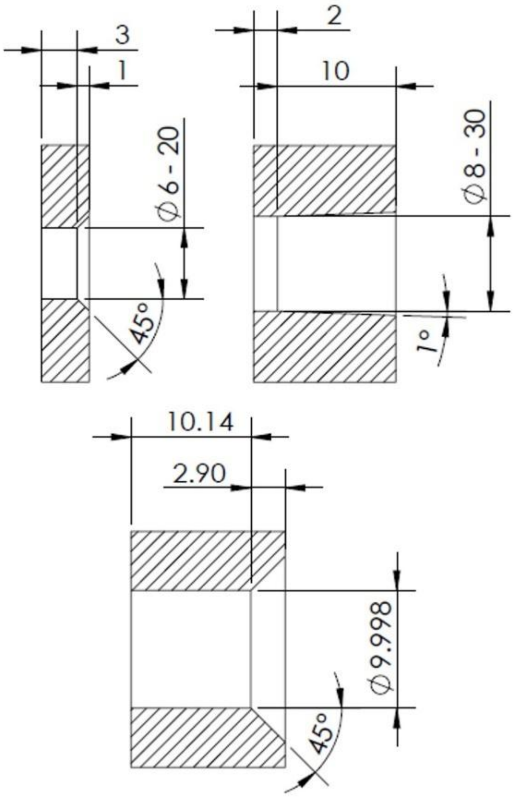


Figure 5. Technical drawings of the diaphragms of PTB's PK100 (top left) and FK (top right) [13], and of BIPM's FAC-L-02 (bottom) [14]. Dimensions are given in mm.

where photons can interact with the diaphragm material. The optimal diaphragm thickness is slightly dependent on the air path length of the FAC. For a FAC with an air path length of 40 mm, an optimal diaphragm thickness of 0.8 mm was determined, while for a FAC with an air path length of 100 mm, a value of 1 mm was determined. This shows that the optimal dimension for a cylindrical diaphragm is dependent on other design aspects of the FAC. The observed steeper decrease of $k_{dia}$ for thicknesses greater than 0.8 mm for a FAC with an air path length of 40 mm can be attributed to the fact that this air path length is insufficient to prevent electrons produced in the diaphragm by the incident photons from reaching the collecting volume [8].

Burns and Büermann [5] also stated that a diaphragm thickness of 1 mm is sufficient to prevent transmission through the diaphragm body for a 50 kV x-ray beam. However, they did not address that increasing the diaphragm thickness beyond 1 mm can lead to a higher diaphragm correction. McEwan [4] reported that diaphragm scatter is independent of diaphragm thickness. In contrast, Burns and Kessler [6] observed discrepancies between their findings and those of McEwan, attributing these differences to variations in diaphragm thickness.

### *4.2. Aperture shape*

Diaphragms with different aperture geometries were introduced to reduce the transmission and scattering of x-rays [5]. According to the analytic calculation method of Simons [2], the diaphragm transmission should be lower for an aperture with conical downstream edge. Burns and Kessler [6] did not find any substantial differences in $k_{dia}$ when they altered the orientation of a diaphragm (cylindrical aperture with a conical downstream edge) in their measurements and simulations. Burns and Büermann [5] also concluded that there is no benefit in using a geometry other than the simple cylindrical aperture.

The results presented in section 3.2. and discussed in the following are valid for a FAC with 60 mm of air path length. Figure 4 shows that conical apertures with opening angles greater than 0.3° are unsuitable. The opening angle creates a sharp corner on the upstream side of the diaphragm, where the material thickness becomes thin and allows photon transmission. The larger the aperture angle, the more pronounced this issue, leading to diaphragm corrections exceeding 1% for apertures with opening angles greater than 15°.

It was found that the required diaphragm correction can be reduced with an opening angle of 0.3° compared to a cylindrical aperture. However, the observed reduction depends on the thickness of the diaphragm. When using a 10 mm diaphragm, 0.4% less diaphragm effects need to be corrected. With a 1 mm thick diaphragm, the reduction is less than 0.1%.

For opening angles of 0.3°, diaphragms with hybrid apertures require greater diaphragm correction than those with 0.3°-conical apertures of equivalent diaphragm thickness. As the aperture correction factor remains constant for larger opening angles than 0.3° with hybrid aperture shapes, they are nevertheless preferable to conical apertures. However, compared to a 1 mm diaphragm with cylindrical aperture the diaphragm correction for hybrid apertures is the same or even increased.

The improvement with a 0.3° aperture opening angle results from the x-ray beam having an incidence angle of about 0.3° at the aperture in the described setup. This minimizes the interactions with the diaphragm when the x-ray beam passes through the aperture. Changing the distance between the x-ray source and the FAC alters the beam incidence angle, making 0.3° opening angle no longer optimal.

It has been shown that angled aperture shapes can result in a marginal reduction in the diaphragm correction compared to a diaphragm with cylindrical aperture. However, these reductions are negligible given the significantly increased manufacturing complexity for precise small taper angles in tungsten plates. Resulting mechanical inaccuracies increase the uncertainty associated with $k_{dia}$. Moreover, the positive effect of angled apertures is limited to a certain distance from the x-ray tube. Therefore, it is not generally applicable, making the measurements less robust for variable experimental setups.

## 5. Conclusion

Regular dosimeter calibration ensures consistency and comparability of dosimeter measurements through traceability to a primary standard. The first step in the development of the new PTB low-energy x-ray primary standard is the design of its geometry.

This study systematically investigated the optimal diaphragm geometry to minimize the diaphragm correction factor $k_{dia}$ for a low-energy x-ray FAC used as primary standard for the realization of the unit of the air kerma. Monte Carlo simulations were employed to calculate the diaphragm correction factor $k_{dia}$ for various diaphragm geometries. It was observed that $k_{dia}$ depends on the diaphragm thickness and the aperture shape. The optimal thickness for a tungsten diaphragm is between 0.8 mm and 1 mm, depending on the air path length of the FAC. The present results clearly show that there is no reason to prefer a diaphragm geometry with a more complex aperture shape over a simple 1 mm thick diaphragm with a cylindrical aperture. Consequently, the new PTB primary standard, a FAC with an air path length of 60 mm, employs a 1 mm tungsten diaphragm with cylindrical aperture.

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