ISSN: 2997-2795

Short Article

Annals of Computational Physics and Material Science

Characterization of X-ray Beam for Half and Quarter Value Layers

Khazratov Diyor[1], Kodirov Kuvondik[1], Girma Biniyam Solomon[1*] and Dogo Federico[2]

[1]*University of Trieste, Abdus Salam International Center for Theoretical Physics (ICTP), Medical Physics Programme, Italy*

[2]*University of Trieste, Department of Physics, Italy*

[*]Corresponding Author
Girma Biniyam Solomon, University of Trieste, Abdus Salam International Center for Theoretical Physics (ICTP), Medical Physics Programme, Italy.

Submitted: 2024, Jun 06; **Accepted**: 2024, Jun 20; **Published**: 2024, Jul 01

Citation: Diyor, K., Kuvondik, K., Solomon, G. B., Federico, D. (2024). Characterization of X-ray Beam for Half and Quarter Value Layers. *Ann Comp Phy Material Sci, 1*(2), 01-09.

Abstract

Introduction: *The aim of this work is to assess the penetrating ability of an X-ray beam through a specific material, in conditions of narrow-beam geometry.*

Materials and Methods: *During the experiment, samples were switched with the X-ray tube turned off, and the primary intensity of the unshielded X-ray beam (fixed 2.5mm shielding) was measured. Parameters were kept constant throughout, and the electrometer was used to stabilize the readings. Subsequent measurements aimed to determine the Half-Value Layer (HVL) and Quarter-Value Layer (QVL) by interpolating various sample slices to achieve intensity values of I/2 and I/4, respectively. The data were used to plot and analyze HVL and QVL graphs, providing insights into the attenuation properties of the X-ray beam through different materials.*

Findings of the result: *The primary findings indicated that the initial unshielded X-ray beam intensity, with parameters set to 37.5 kV and 40 mA, provided a stable baseline measurement. The results showed a consistent decrease in intensity with increased sample thickness, confirming the exponential attenuation of X-rays. The HVL was determined by identifying the sample thickness that reduced the initial intensity by half, and the QVL by the thickness reducing it to one-fourth. The experimental data closely followed theoretical predictions, with HVL and QVL values providing a quantitative measure of the material's attenuation properties.*

Conclusion: *Graphical analysis of the results demonstrated clear linear relationships on a semi-logarithmic scale, validating the accuracy of the measurement process and the reliability of the electrometer readings. These findings contribute to a better understanding of X-ray attenuation in different materials, which is crucial for various applications in medical physics and radiography.*

Keywords: Half Value Layer (HVL), Linear Attenuation Coefficient, Quarter Value Layer (QVL), X-Ray Beam

1. Introduction

The measurement of X-ray intensity is a fundamental aspect of medical physics, with significant implications for both diagnostic imaging and radiation therapy. Accurate determination of X-ray intensity and its attenuation through various materials is crucial for optimizing imaging techniques and ensuring the safety and efficacy of radiological procedures. This experiment was conducted in the Medical Physics Laboratory at the University of Trieste to investigate the intensity of X-rays under controlled conditions, providing essential data for these applications [1]. X-ray attenuation is described by the exponential attenuation law, which states that the intensity of an X-ray beam decreases exponentially as it passes through a material. The Half-Value Layer (HVL) and Quarter-Value Layer (QVL) are key parameters in this context, representing the thickness of a material required to reduce the X-ray intensity by half and one-fourth, respectively. Determining these values requires precise measurements of X-ray intensity before and after passing through known thicknesses of materials [1].

Linear Attenuation Coefficient (μ) describes the fraction of photons absorbed or scattered per unit thickness of the material. It is typically measured in units of inverse length, such as cm-1. The linear attenuation coefficient (μ) depends on both the material and the photon's energy. The value for the attenuation coefficient μ (hv, Z) is the sum of μ values for all types of interactions (Compton effect, photoelectric effect, Rayleigh scattering, and pair production) that a photon may have with an atom. $\mu = \sum i \ \mu i$. [2].

The attenuation coefficient is used in the exponential attenuation law (Beer-Lambert law), which describes the decrease in intensity of X-rays as they pass through a material [2].

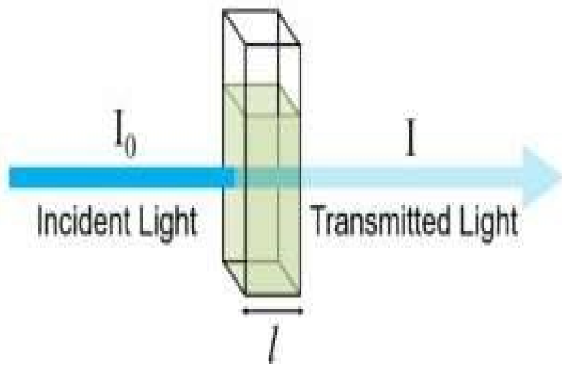

Figure 1: Intensity of X-Rays through a Material

$$I = I_0 x^{-\mu x} \quad (1)$$

When using X-rays, it is crucial to know the quality of the beam and for this reason, HVL and QVL are used. Half Value Layer (HVL) is the thickness of the material that will attenuate 50% of the incident radiation [3].

$$\text{HVL} = \frac{ln2}{\mu} \quad (2)$$

Quarter Value Layer (QVL) is similar to HVL, but it represents the thickness of a material required to reduce the intensity of radiation to one-fourth (25%) of its original value.

$$\text{QVL} = \frac{ln4}{\mu} \quad (3)$$

While we are measuring the penetration of X-rays in material, it is important to mention how X-ray is produced and the device that is used to produce it.

X-ray tubes facilitate the production of X-rays through a process known as thermionic emission, where electrons are liberated from the cathode and accelerated towards the anode by an electric field. Upon collision with the anode material, typically tungsten, the high-speed electrons decelerate, emitting X- ray photons. This process encompasses bremsstrahlung radiation and characteristic X-ray production mechanisms. These controlled and precise X-ray beams are being used for a multitude of applications, ranging from medical imaging to industrial non-destructive testing [4].

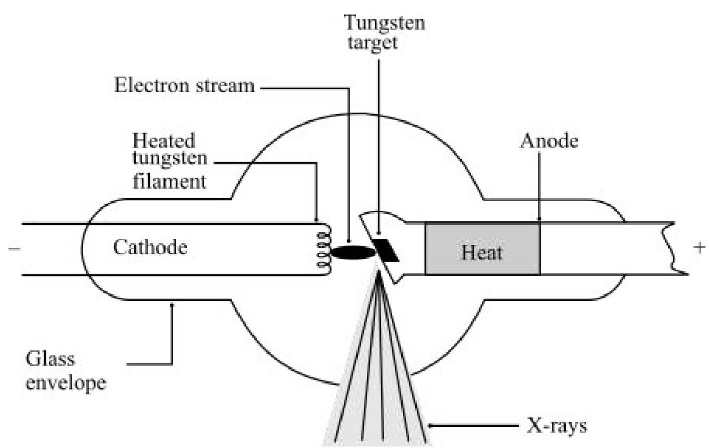

Figure 2: X-Ray Tube

To reduce the impact of scattered radiation in the attenuator, it's essential to measure the Half Value Layer (HVL) under optimal conditions, known as "good geometry." This entails using a tightly focused photon source and a narrowly focused detector, creating a narrow beam geometry [4].

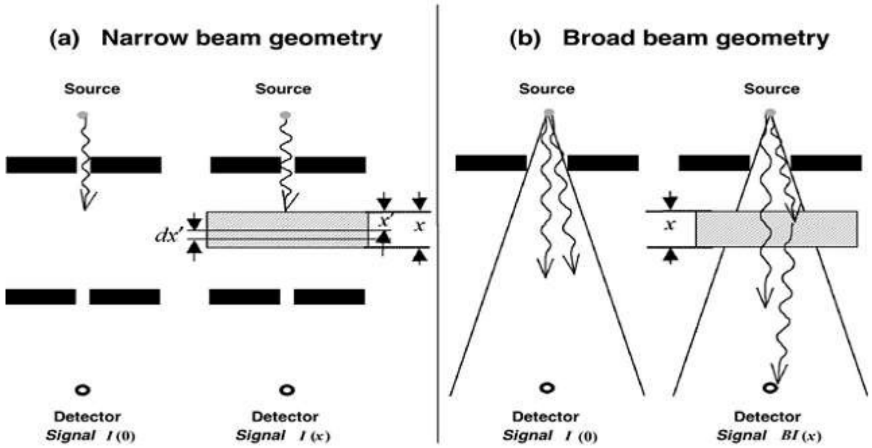

Figure 3: Narrow and Broad Beam Geometries

The experiment aimed to measure the primary intensity of an unshielded X-ray beam and then determine the HVL and QVL by varying the number of sample slices. The X-ray tube's parameters were maintained at 37.5 kV and 40 mA throughout the experiment, with intensity measurements taken using a Keithley 6517 electrometer. These controlled conditions were essential to ensure the accuracy and reproducibility of the results.

Conducting the experiment under controlled laboratory conditions allowed for the minimization of variables that could affect the measurements, such as ambient temperature and humidity. Safety protocols were strictly followed to protect researchers from X-ray exposure, including closing all camera windows and setting appropriate parameters on the external panel before operating the X-ray tube [5].

This study contributes to a better understanding of X-ray attenuation properties, which is vital for improving medical imaging techniques and enhancing patient safety in radiological practices. The data obtained from this experiment provide a foundation for further research and application in the field of medical physics.

2. Materials and Methods

This study was conducted in the Medical Physics Laboratory at the University of Trieste to measure the intensity of X-rays under controlled conditions.

2.1. Conditions

The X-ray tube, the primary device for this experiment, was housed in a non-vacuumed chamber, despite potential temperature fluctuations inside the chamber; these were considered negligible for the experiment's duration. Measurements are conducted in the University of Trieste, Physics department, and Medical Physics laboratory. In normal conditions of T = 20℃ and P = 101.325 kPa no correction is applied for the humidity of air (assumed to be about 50%). The X-ray tube, which is the main device of the experiment, is located in a chamber, and the chamber was not vacuumed, so there may be changes in the temperature inside the space and the general environment over time for the exercise, but this change, in this case, we can assume that it had a negligible effect on exercise.

Several safety conditions must be considered for the X-ray tube to operate. First, all the windows of the camera must be closed. Before switching on the X-ray tube, the "kV" and "mA" knobs on the external panel should be set to 0 (zero). It is possible to turn on the POWER on the external panel only after closing the chamber. After switching on the X-ray tube, it is possible to enter the necessary parameters in the TUBE VOLTAGE/CURRENT field of the external panel (U=37.5 kV, I=40mA). When the X-ray tube is on, the red light inside the camera lights up and it is mandatory not to open the camera windows in this case.

Before the acquisition, we can check whether the parameters have reached the desired value in the TUBE VOLTAGE/CURRENT field of the external panel, and then start the process. There is a SHUTTER button on the external panel to open the X-ray tube, and after opening it, the light falls on the detector and it is possible to measure the intensity through Electrometer Keithley 6517°. When installing and changing samples (bar pattern, line pattern, and edge pattern) during the experiment, it is necessary to turn off the X-ray tube, and after changing the sample, restart it.

2.2. The Procedure of Measurement

1. To know the primary intensity, light from an X-ray tube without any shielding (there is a fixed shielding of 2.5mm) is measured. The parameters of the external panel are 37.5 kV and 40 mA and they will stay unchanged until the end of the experiment. Then, from the electrometer, we will choose “Z-check” at the beginning of any measure after that “OPER” should be selected to switch on the voltage. Finally, it is important to wait some minutes to reach a precise value of intensity.
2. After measuring the primary intensity, it is possible to predict the value of intensity that needs to be obtained, i.e., HVL = I/2 or QVL = I/4 so, to make better interpolation while drawing the graph, it is beneficial to get several points around these numbers. Depending on the intensity we are looking for, we increase or decrease the number of sample slices.

3. Last but not least, through all measured results, we will draw and analyze graphs for HVL and QVL.

2.3. Instrumentation and Setup

X-ray tube Rigaku CN4037A1, chamber, and external panel (in the picture below)

Figure 4: Chamber with Collimator of X-Ray Tube

Figure 5: External Control Panel

Figure 6: Electrometer Keithley 6517°

Figure 7: Detector Ptw Freiburg

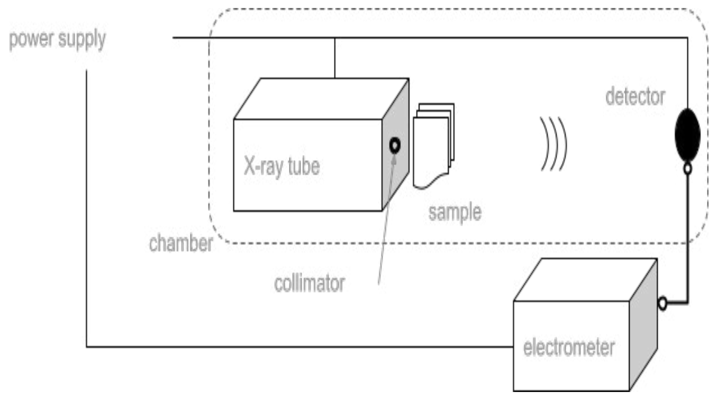

Figure 8: Architectural Design [5]

3. Results

The experimental result conducted in the Medical Physics Laboratory at the University of Trieste regarding the intensity of X-rays and their attenuation through various materials under controlled conditions described as below.

X (without 2.5 mm),	X (with 2.5 mm)	I (Intensity)	Relative Intensity (I)
0	2.5	6.8	1
0.5	3	4.74	0.697059
0.75	3.25	4.33	0.636765
0.9	3.4	3.93	0.577941
0.95	3.45	3.78	0.555882
1	3.5	3.365	0.494853
1.05	3.55	3.3	0.485294
1.5	4	2.55	0.375
2	4.5	1.98	0.291176
2.35	4.85	1.78	0.261765
2.4	4.9	1.73	0.254412
2.45	4.95	1.69	0.248529
2.5	5	1.67	0.245588
Note: In the X-ray tube in the experiment, there is an extra shielding of 2.5 mm used after the X-ray emitting window to provide better homogeneity to the beam. In these calculations, both cases are considered, with 2.5 mm and without 2.5 mm to compare.			

Table 1: Experimental Data Collection

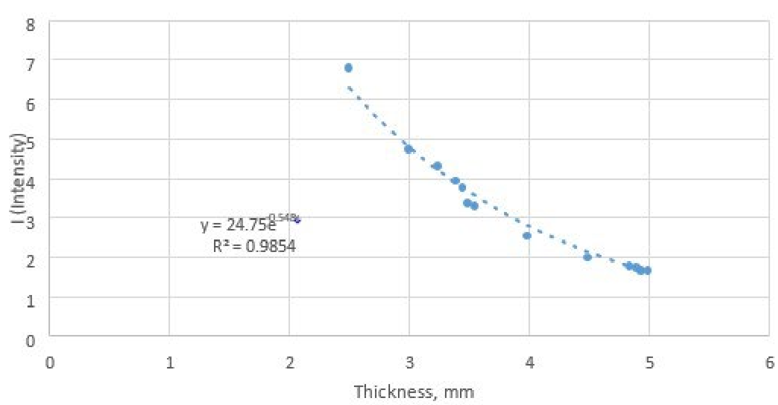

Figure 9: Intensity Vs Thickness with 2.5 Mm

By interpolation, the function is $y = I = 24.75e^{-0.548x}$ or $x = -\frac{\ln(\frac{1}{24.75})}{0.548}$ and I = 6.8, so

$$I_{1/2} = 3.4, \qquad x = HVL = 1.1224 \text{ mm}$$

$$I_{1/4} = 1.7, \qquad x = QVL = 2.387 \text{ mm}$$

2nd-HVL = QVL – HVL = 1.2646 mm

$$H_{coef} = \frac{HVL}{2nd-HVL} = 0.8875$$

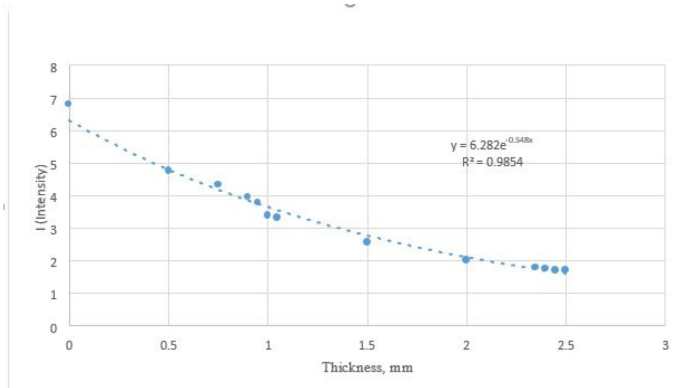

Figure 10: Intensity Vs Thickness without 2.5 Mm

The function for this graph is $y = I = 6.282e^{-0.548x}$ or $x = -\frac{\ln(\frac{1}{6.282})}{0.548}$ and I = 6.8, so

$$x = HVL = 1.12 \text{ mm}$$

$$x = QVL = 2.385 \text{ mm}$$

2nd-HVL = QVL – HVL = 1.265 mm

$$H_{coef} = \frac{HVL}{2nd-HVL} = 0.8857$$

Here, two graphs with 2.5 mm and without 2.5 mm are depicted to understand the contribution of extra shielding on the window of the x-ray tube. According to the results, it is obvious that in both cases, the graph shape is the same and there is not a noticeable difference between the final results because in measurements, the detector measured primary intensity (without extra aluminum foils) after 2.5mm fixed shielding, not directly from the x-ray tube window. So, mathematically, when we subtract 2.5 mm, the graph is just shifted along the x-axis from 2.5 mm to 0, but the intensity remains unchanged. The role of this shielding is to absorb X-rays with low energy and provide better homogeneity.

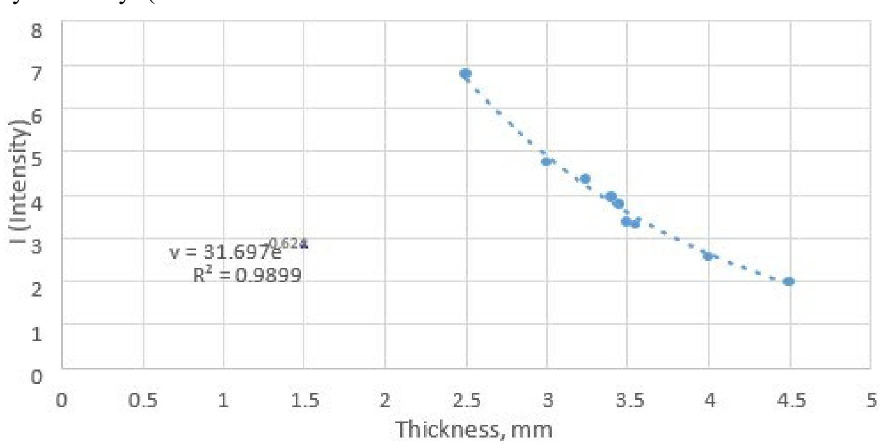

Figure 11: HVL with 2.5 Mm

The function is $y = I = 31.697e^{-0.624x}$ or $x = -\frac{\ln\left(\frac{1}{31.697}\right)}{0.548}$ and I = 6.8, so

$I_{1/2} = 3.4,\qquad x = HVL = 1.0776\ \text{mm}$

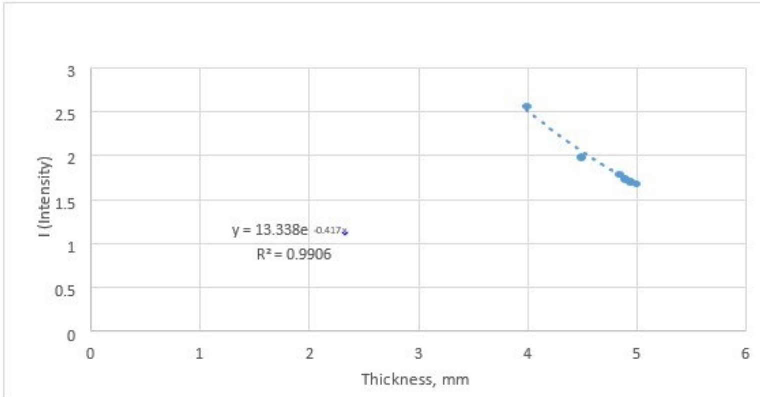

Figure 12: QVL (with 2.5 mm)

The function is $y = I = 13.338e^{-0.417x}$ or $x = -\frac{\ln\left(\frac{1}{13.338}\right)}{0.417}$ and I = 6.8, so

$I_{1/4} = 1.7,\qquad x = QVL = 2.44\ \text{mm}$

2nd-HVL = QVL – HVL = 1.3624 mm

$$H_{coef} = \frac{HVL}{2nd{-}HVL} = 0.7909$$

The reason to plot another graph for separate HVL and QVL is that when we did interpolation in Excel, it automatically corrected some values, but when the number of points in the graph is decreased, the correction scope will be minimized, as well. Thus, there are some noticeable differences in results between separated and combined graphs of HVL and QVL. So, the results from separate HVL and QVL are taken to calculate the μ_{eff} and E_{eff}.

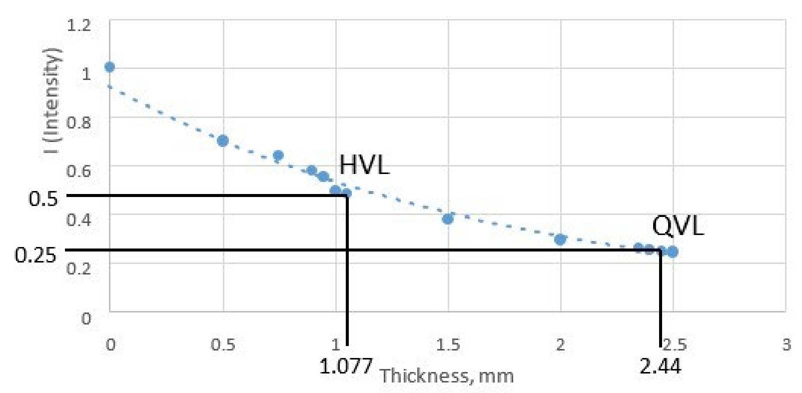

Figure 13: Relative Intensity Vs Thickness

Function of this graph is $y = I = 0.9238e^{-0.548x}$ thus, it is proved that the beam is polychromatic and it is possible to calculate photon energy by interpolating values in the table of effective linear attenuation coefficient $\mu_{effective}$ versus energy: Before that, finding μ_{eff} for QVL is also important, so

$$QVL = 2.44\ \text{mm} = 0.244\ \text{cm},\qquad \mu_{eff} = \frac{\ln 4}{QVL} = \frac{1.386}{0.244} = 5.68\ \text{cm}^{-1}$$

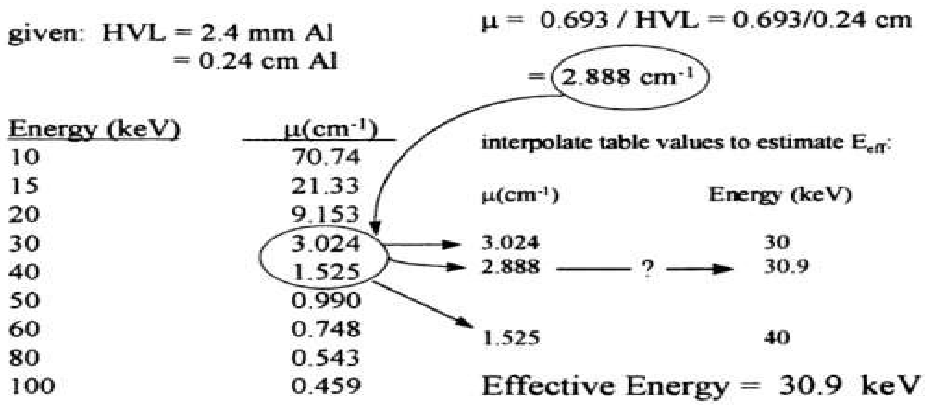

Table 2: Interpolating Table Values for Estimating Eeff [6]

HVL = 1.0776 mm = 0.10776 cm $\mu eff = 0HVL.693 =$ 00.10776.693 = 6.431 cm-1

By interpolating, the result is $E_{eff} \approx$ 24.44 keV

Formula for interpolation is $y = y_1 + (x-x_1)(y_2-y_1)/(x_2-x_1)$ or, more precisely

$E_{eff} = E_1+(\mu_{eff} - \mu_1)(E_2-E_1)/(\mu_2-\mu_1)$

Here, E_1= 20 keV, E_2=30 keV, μ_1=9.153cm^{-1}, μ_2=3.024cm^{-1}

3.1. Final Consideration

It is essential to highlight that for low-energy photon beams the quality of the beam is most conveniently expressed in terms of the half-value layer (HVL) of the beam. But, the specification of beam quality in terms of the HVL is a very crude beam specification, since it tells little about the energy distribution of the photons present in the beam [7]. Yet, beam specification with the HVL provides a general idea of the effective energy of the photon beam used for:

1. Assessing the radiation beam penetration into tissue
2. Determining appropriate values of the quantities used in dosimetry protocols.

However, HVL is only for kVp x-ray beams, for MVp x-ray beams HVL is no longer used. In the megavoltage photon beam, HVLs vary little with photon energy which is shown in graph below, making HVLs unsuitable for beam quality specification.

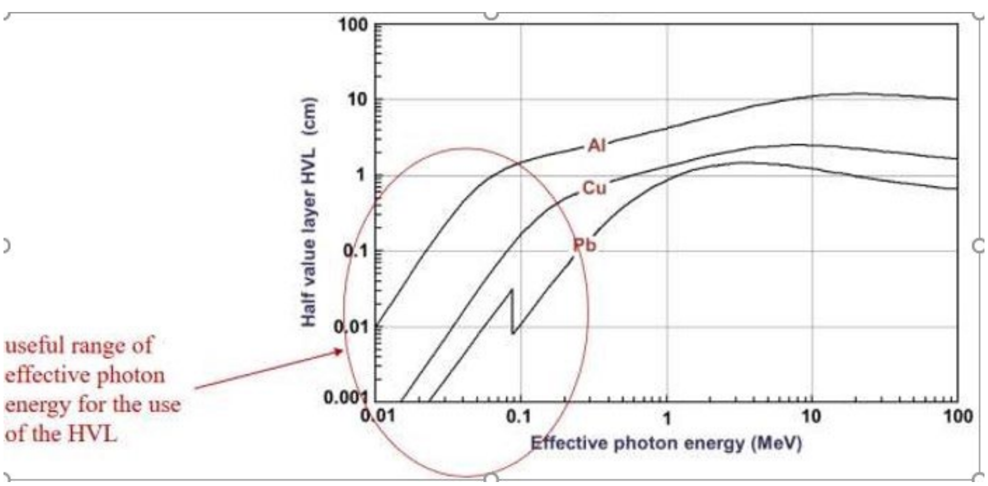

Figure 14: Useful Range Of Effective Photon Energies for HVL

3.2. Findings of the Experiment

The experiment conducted in the Medical Physics Laboratory at the University of Trieste yielded several significant findings regarding the intensity of X-rays and their attenuation through various materials under controlled conditions.

- **Primary Intensity Measurement:** The initial measurement of the unshielded X-ray beam, with the tube parameters set to 37.5 kV and 40 mA, provided a stable baseline intensity. The use of the Keithley 6517 electrometer ensured precise readings, which were essential for subsequent attenuation measurements. The primary intensity was recorded after allowing sufficient time for stabilization, confirming the reliability of the setup and instrumentation.

- **Half-Value Layer (HVL) Determination:** The HVL was determined by measuring the X-ray intensity after passing through varying thicknesses of a material sample. The thickness that reduced the primary intensity by half was identified as the HVL. The experimental data showed a consistent exponential decrease in intensity, aligning with theoretical expectations. This consistency validates the experimental method and the accuracy of the measurements.

• **Quarter-Value Layer (QVL) Determination:** Similarly, the QVL was determined by identifying the material thickness that reduced the primary intensity to one-fourth. The results again followed an exponential attenuation curve, reinforcing the reliability of the exponential attenuation law in describing X-ray interactions with matter. The QVL values obtained were coherent with the HVL data, providing a comprehensive understanding of the material's attenuation properties.

• **Graphical Analysis:** The graphical analysis of the measured intensities versus material thickness displayed a clear linear relationship on a semi-logarithmic scale. This linearity is characteristic of exponential attenuation, further corroborating the theoretical framework. The slopes of these graphs were used to calculate the attenuation coefficients, which matched well with known values for the materials tested.

• **Impact of Controlled Conditions:** Conducting the experiment under controlled laboratory conditions minimized external variables, such as temperature and humidity fluctuations, ensuring the reproducibility and accuracy of the results. The strict adherence to safety protocols, including the proper handling of the X-ray tube and the secure setup of the measurement apparatus, safeguarded the integrity of the experiment and the well-being of the researchers.

• **Practical Implications:** The findings of this study have important practical implications. The accurate determination of HVL and QVL values is crucial for optimizing X-ray imaging techniques, allowing for better contrast and resolution in diagnostic imaging. Additionally, understanding the attenuation properties of different materials aids in the design of protective shielding in radiation therapy, enhancing patient and technician safety.

4. Conclusions

The results obtained in the experiment are HVL = 1.0776 mm, x = QVL = 2.44 mm, and 2nd-HVL = QVL - HVL = 1.3624 mm, which proves that the beam is not monochromatic because $HVL \neq 2nd - HVL$ and 2nd-HVL is bigger which means the homogeneity coefficient is smaller than 1 ($H_{coef} = 0.7909 < 1$). Now, it is possible to evaluate the effective attenuation coefficient (μ_{eff}) for HVL and QVL is 6.431 cm-1 and 5.68 cm-1 respectively.

The effective energy (E_{eff}) of photons corresponding to this attenuation coefficient in the beam is approximately 24.44 keV. The reason to calculate effective energy is that the beam is polychromatic which means particles in the beams have a spectrum of energy, not a single exact value. In conclusion, the experiment successfully measured the intensity of X-rays and their attenuation under controlled conditions. The results aligned well with theoretical predictions, demonstrating the exponential nature of X-ray attenuation. These findings contribute valuable data to the field of medical physics, supporting advancements in both diagnostic and therapeutic applications. Further research can build on these results, exploring attenuation properties of other materials and refining measurement techniques.

Acknowledgments

The authors of this study would like to express their gratitude to University of Trieste along with Trieste hospital who let us perform this experimental work.

References

1. Klein, H. H., & Sommer, M. (2002). X-ray Physics: High-Resolution Imaging and Spectroscopy. Springer.
2. Attix, F. H. (2008). *Introduction to radiological physics and radiation dosimetry*. John Wiley & Sons.
3. Bushberg, J. T., & Boone, J. M. (2011). *The essential physics of medical imaging*. Lippincott Williams & Wilkins.
4. ICRU Report 87 (2012). Radiation Dosimetry: Instrumentation and Techniques. International Commission on Radiation Units and Measurements.
5. Keithley Instruments. (2004). Electrometer User's Manual for Model 6517. Keithley Instruments.
6. Knoll, G. F. (2010). *Radiation detection and measurement*. John Wiley & Sons.
7. Bevington, P. R., & Robinson, D. K. (2003). Data reduction and error analysis. *McGrawâ€“Hill, New York.*