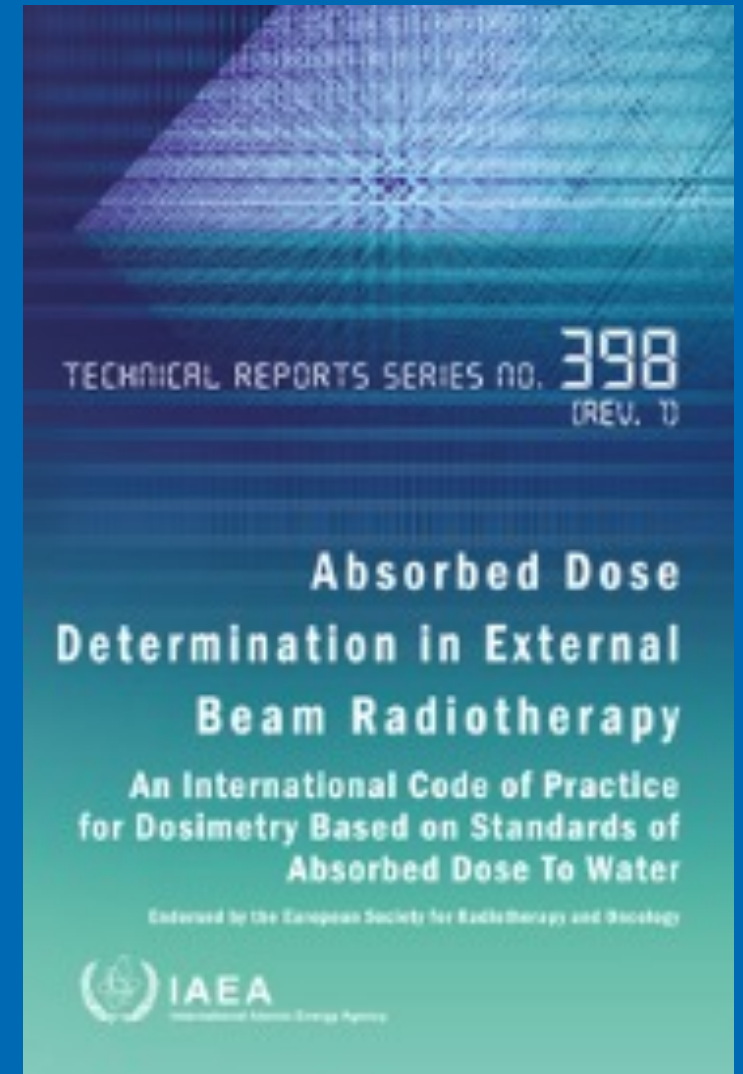


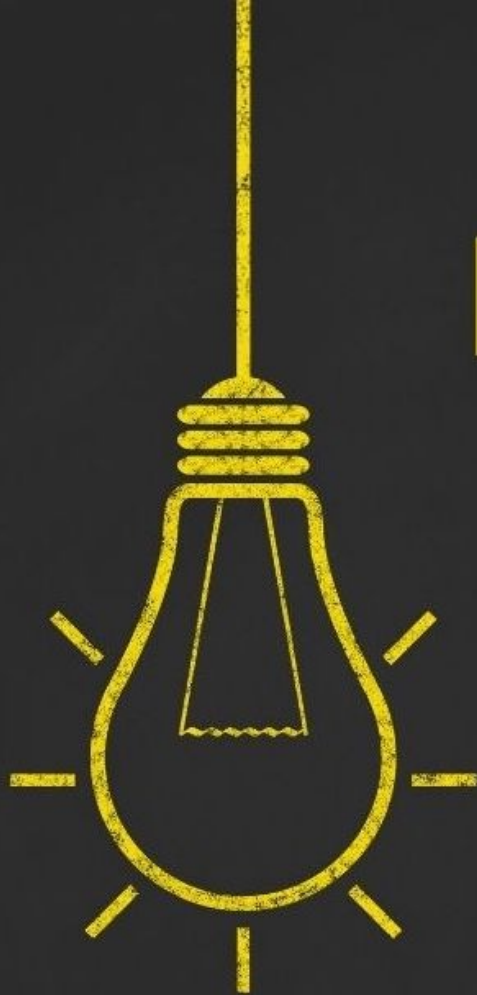
**Low and medium energy X-ray dosimetry
according to TRS-398 (rev. 1)
by
Karen Christaki**

Acknowledgement to Robin Hill



- 1 Background
- 2 Primary standards for low and medium energy X rays.
- 3 Medium energy X rays dosimetry₄
- 4 Low energy X ray dosimetry.
- 5 Beam quality index

Background

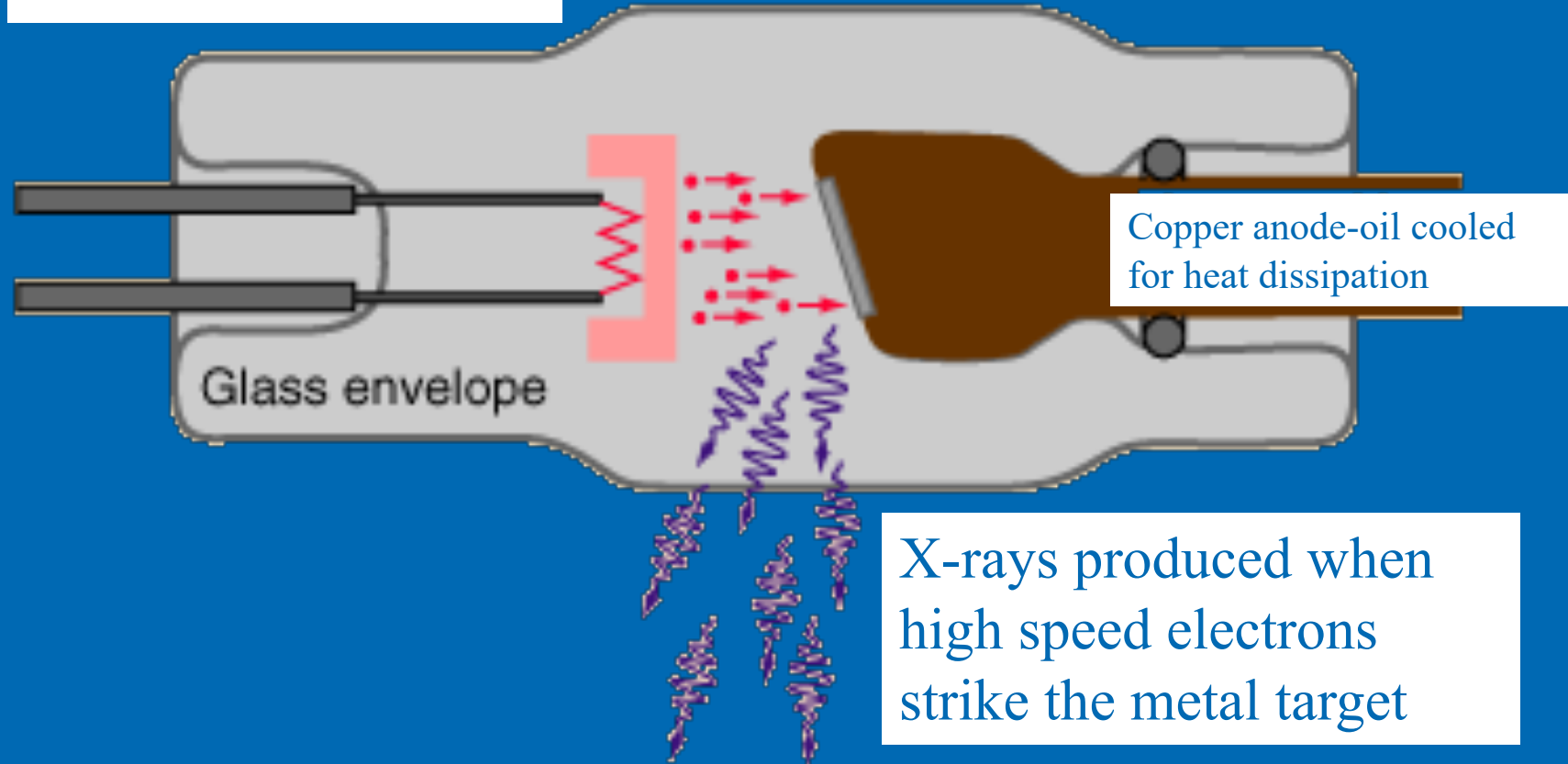


INFORMATION



Heated filament emits
electrons by
thermionic emission

Electrons are accelerated
by a high voltage



X-rays produced when
high speed electrons
strike the metal target

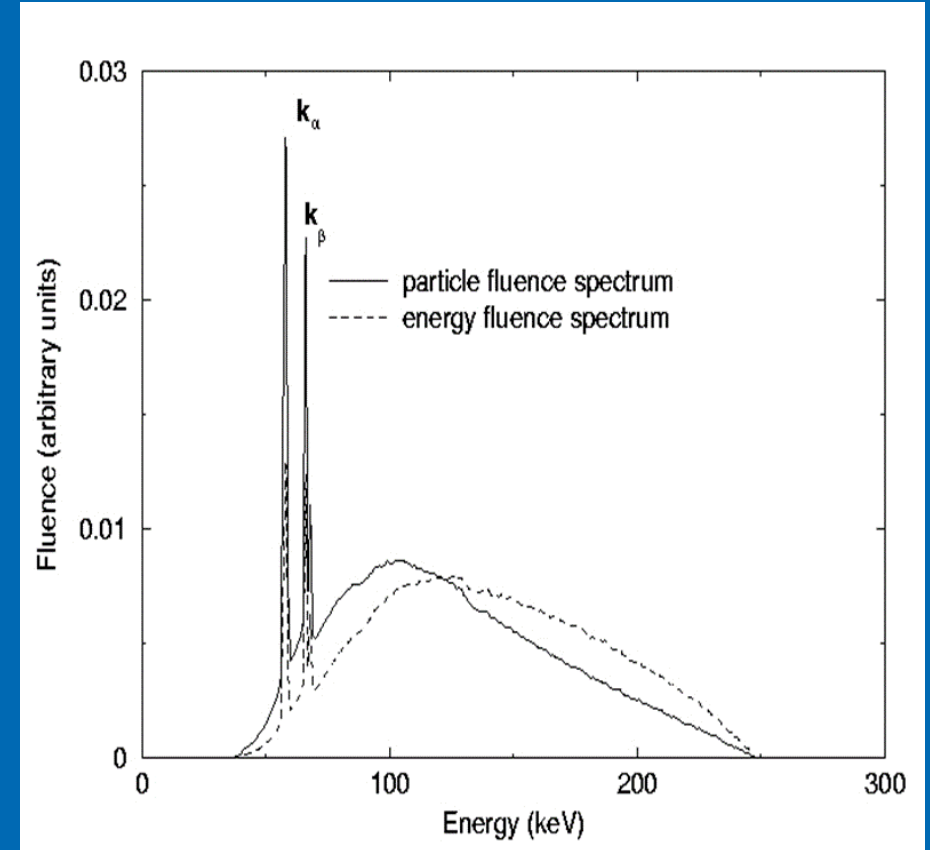
Definition of low and medium energy X rays.

Low energy X rays beams.

X ray beams with generating potential between 10 kV and 100 kV (HVL: 0.03-5 mm Al).

Medium energy X rays beams.

X ray beams with generating potential between 80 kV and 300 kV (HVL: greater than 2 mm Al).



Photon fluence and energy fluence spectra at 1 m from the target of an x-ray machine with tube potential 250 kV and added filtration of 1 mm Al and 1.8 mm Cu (target material: W; inherent filtration 2 mm Be).

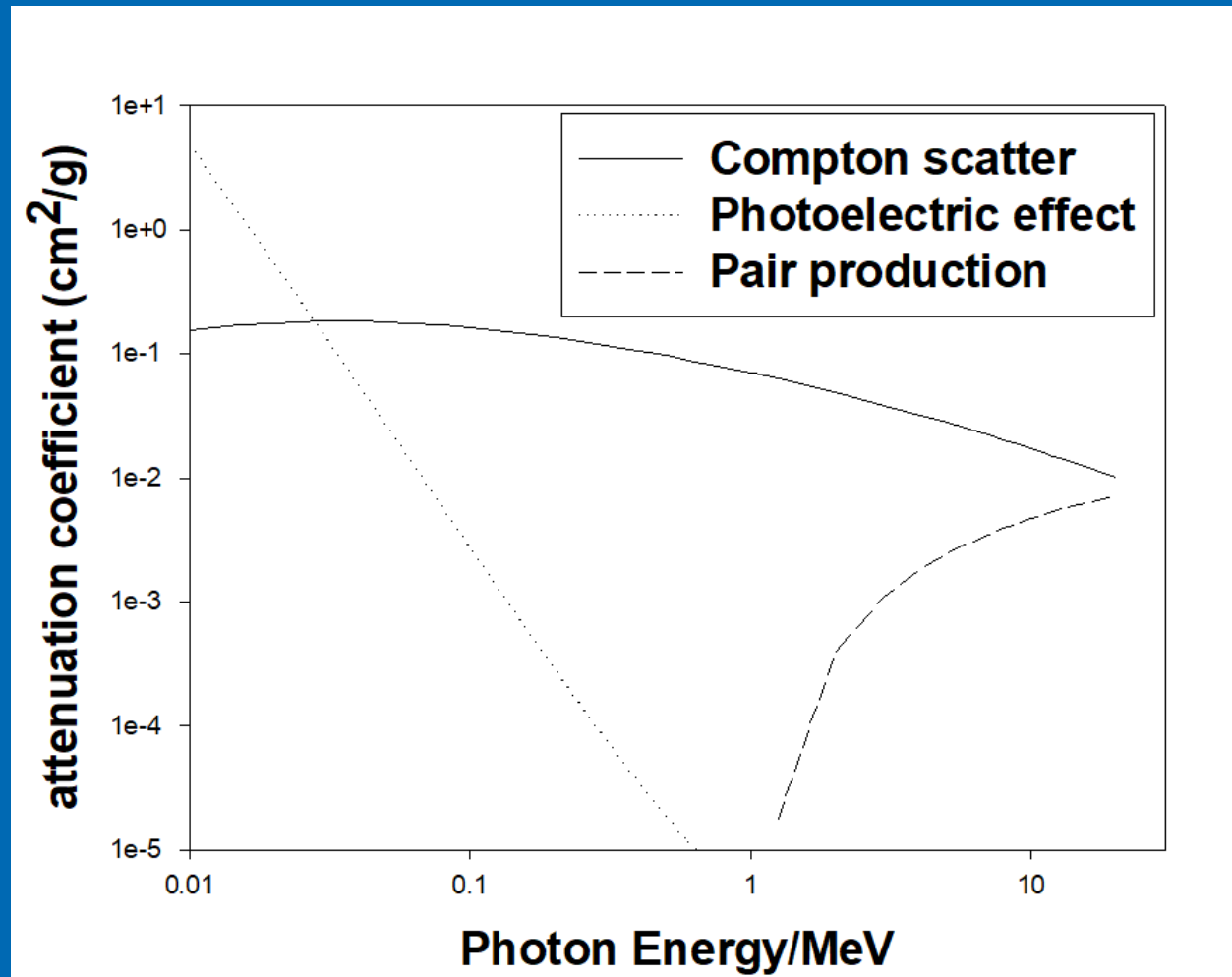
Picture of external filters



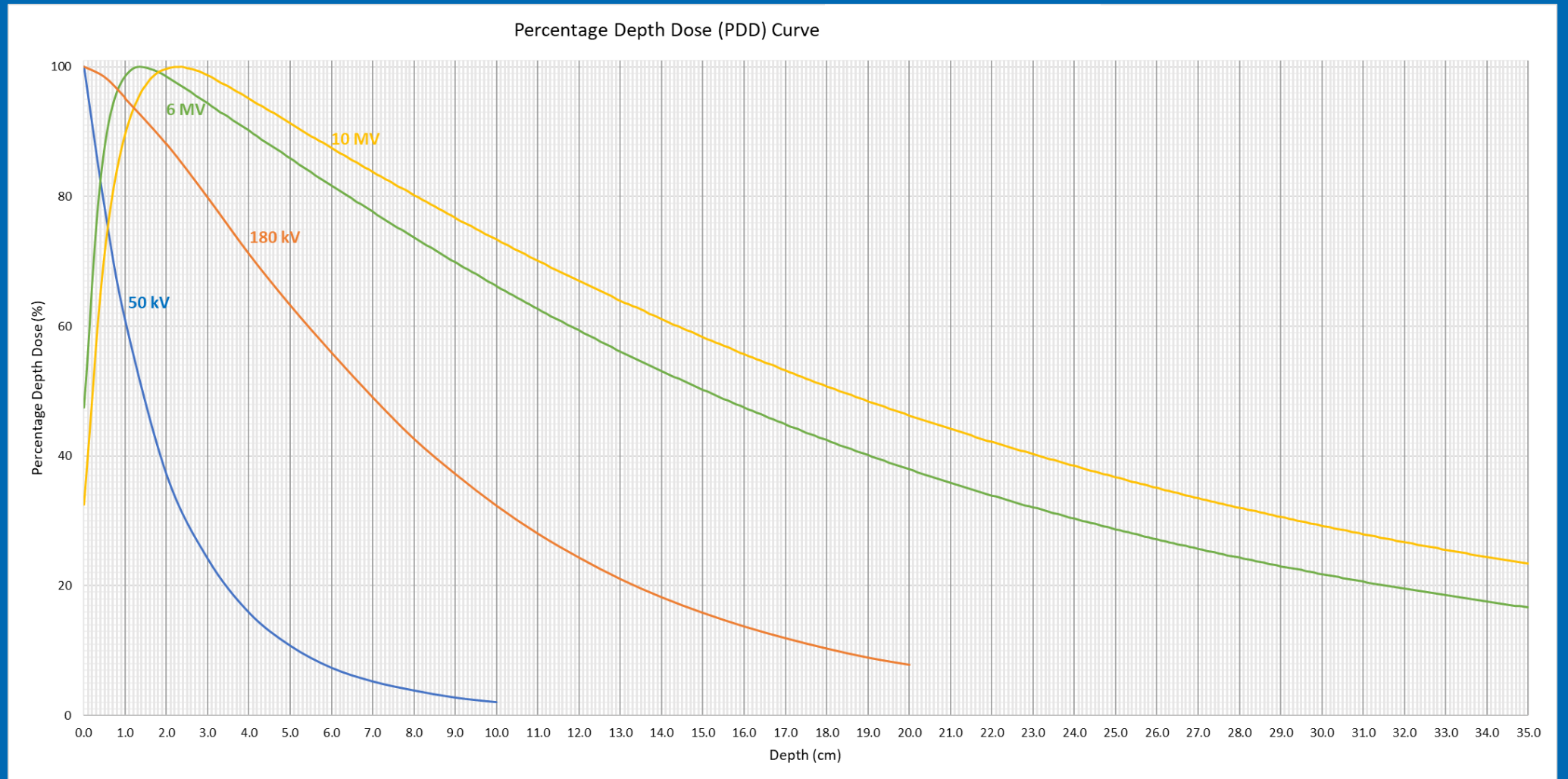
Applicators

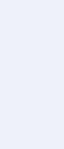


Mass attenuation coefficients for photons in water.



Percentage depth dose curve

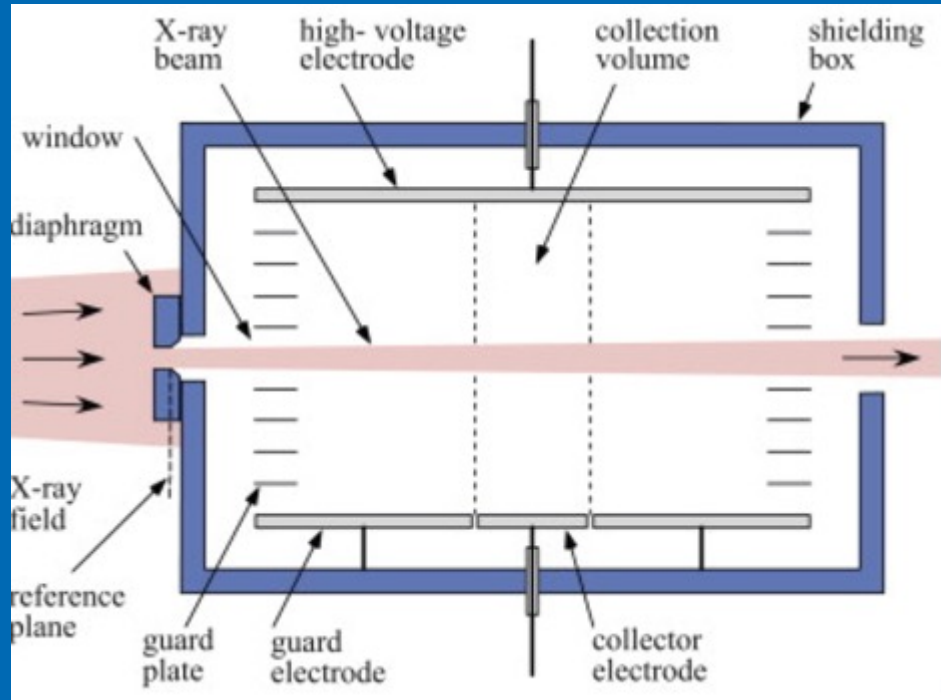




Primary standards for low and medium energy X ray dosimetry

Primary Standard of air kerma-Free air chamber

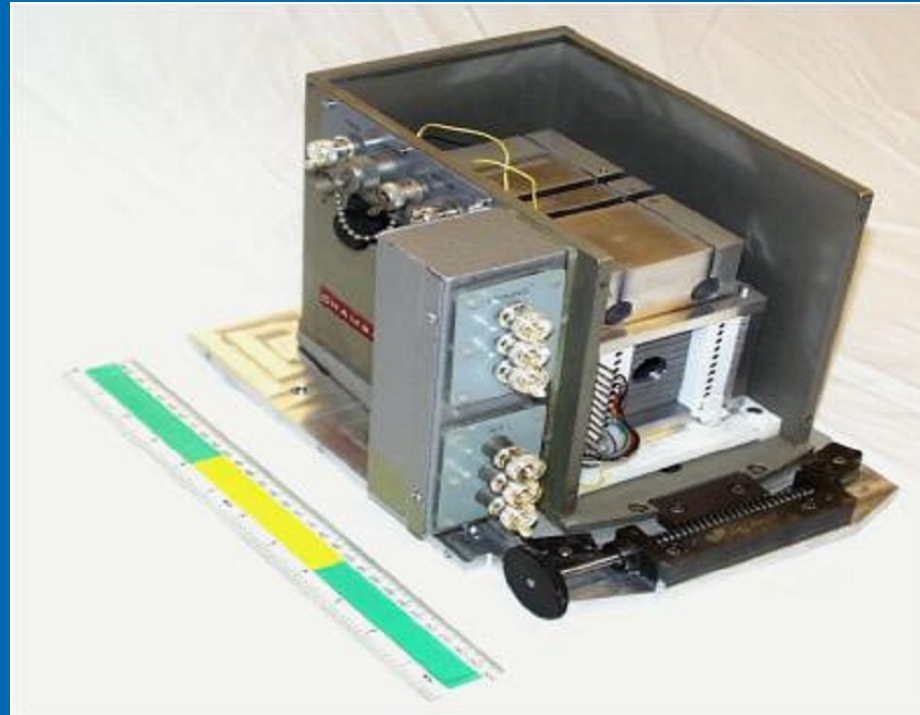
The air kerma, in terms of grays



$$M_{raw} \frac{W_{air}}{e} \frac{1}{\rho v} \frac{\pi}{(1 - g)} k_h$$

- W_{air} is the energy needed to create an ion pair in dry air
- e is the electron charge
- π are corrections (10) such as k_{pol} , k_s , field distortion.....
- g is the fraction of energy lost to bremsstrahlung
- k_h is the correction to 50% relative humidity
- ρ is the density of dry air
- V is the collecting volume of the free air chamber

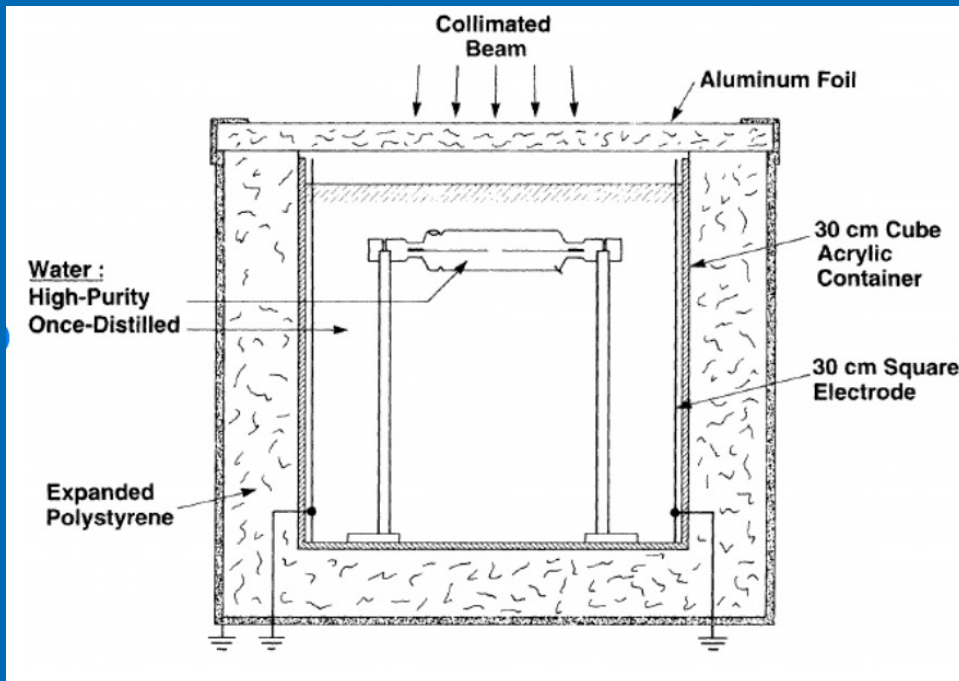
Primary Standard of air kerma-Free air chamber



FAC for X ray energies up to 50 kV

A chamber calibrated directly in terms of absorbed dose to water for medium energy X-rays.

water calorimeter



$$D_w = \frac{C_p \Delta T k}{(1 - h)}$$

C_p is the specific heat capacity of water

ΔT is the temperature rise due to the radiation

h is the heat defect

k are correction factors for perturbation, thermal conduction....

Note

For a dose of 1Gy the temperature rise is approximately 2×10^{-4} C. For medium energy X rays the dose rate is approximately 0.3 Gy/min and less for low energy X rays.

Medium energy kilovoltage X-ray beams

(80 kV to 300 kV,
with HVL greater than 2 mm Al)

Ionization chamber

An ionization chamber with a graphite wall and aluminum central electrode such as a PTW 30012, IBA FC65-G or NE 2611.

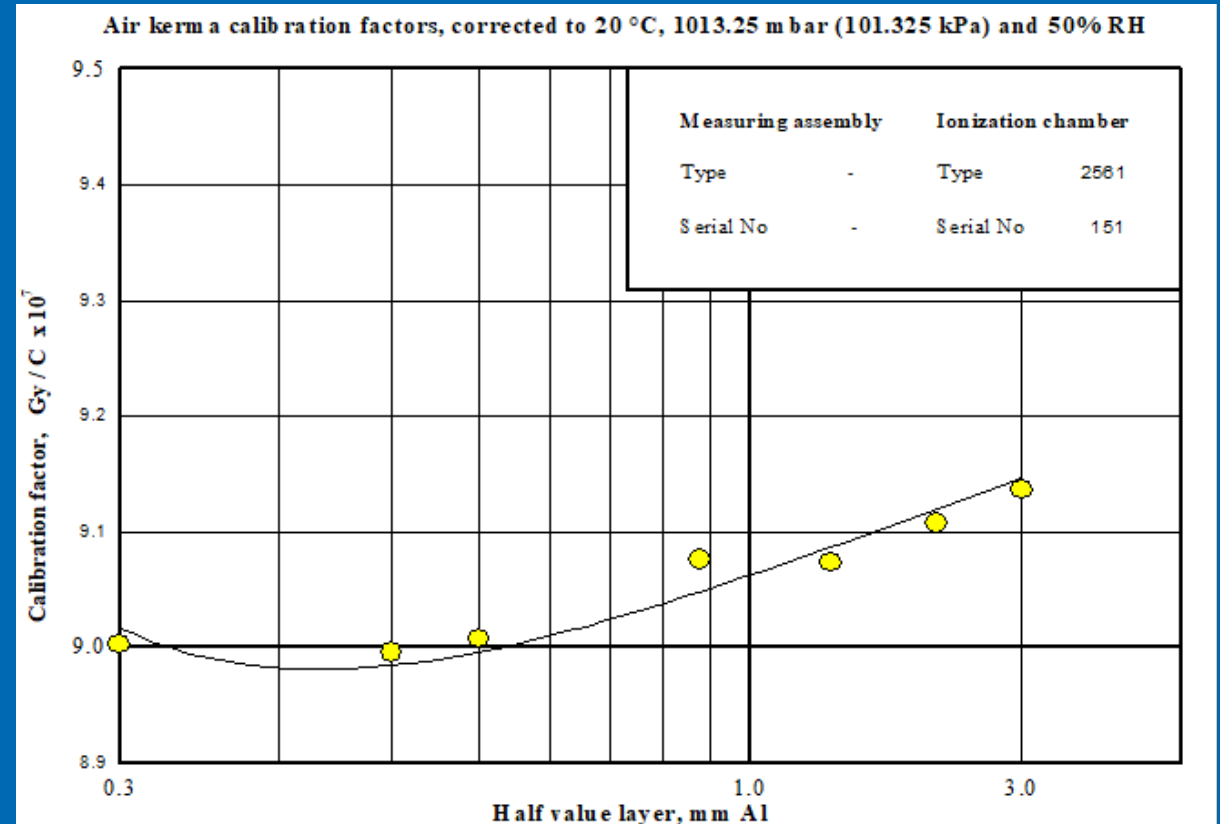


TABLE 3. SPECIFICATIONS FOR REFERENCE CLASS IONIZATION CHAMBERS FOR REFERENCE DOSIMETRY [12]

Parameter	Specification
Chamber settling	Monitoring chamber response with accumulated dose: equilibrium is reached in <5 min; the initial and equilibrium readings agree within 0.5%
Leakage	<0.1% of the chamber reading ^a
Polarity effect	Less than 0.4% of the chamber reading; the polarity energy dependence is <0.3% between the energies of the ⁶⁰ Co beam and 10 MV photon beam
Recombination correction	1. The correction is linear with the dose per pulse 2. Initial recombination (the part of the total charge recombination that is independent of the dose rate or the dose per pulse) is <0.2% at polarizing voltages of ~300 V 3. For pulsed beams, a plot of $1/M_Q$ (charge reading) versus $1/V$ is linear at least for practical values of V^b 4. For continuous beams, the plot of $1/M_Q$ versus $1/V^2$ is linear, describing the effect of general recombination; the presence of initial recombination disturbs the linearity but this is normally a small effect, which may be neglected 5. The difference in the initial recombination correction obtained with opposite polarities is <0.1% 6. If the correction exceeds 1.05, other methods have to be used [102]
Chamber stability	Change in the calibration coefficient of <0.3% over a typical recalibration period of 2 years, as well as for long term (>5 years) stability
Chamber material	Wall material not exhibiting temperature and humidity effects

^a In limited cases (e.g. small volume chambers in low dose rate beams) the leakage current may exceed this limit. In such circumstances, the leakage current has to be evaluated carefully and a correction needs to be applied to the raw ionization chamber reading.

^b V : polarizing voltage.

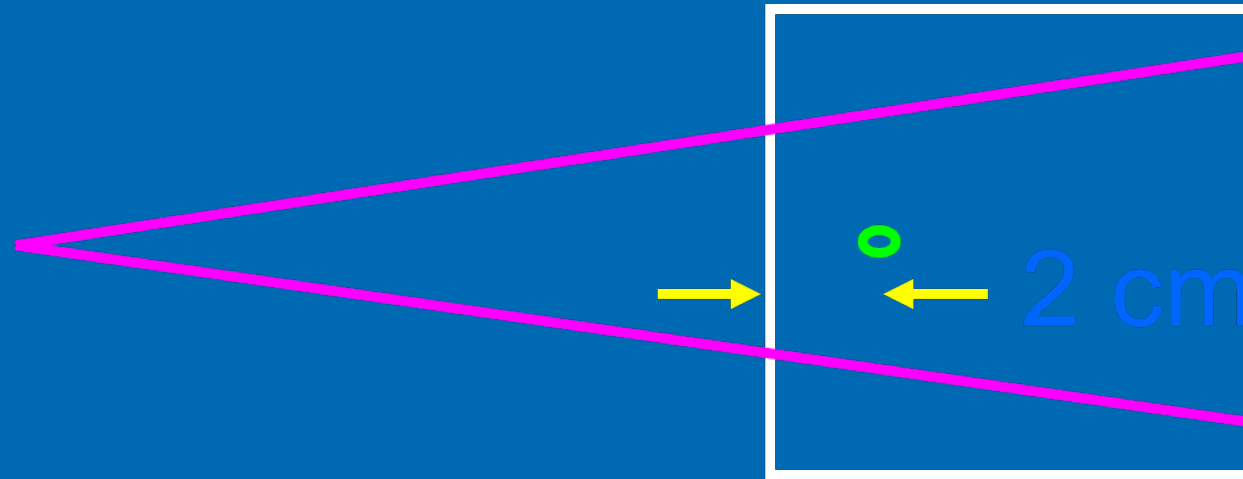
k_{ion} : continuous radiation so general recombination is dependent on dose-rate.

General recombination is negligible so only initial radiation $k_{\text{ion}} < 0.2\%$.

Reference conditions for medium energy X ray dosimetry.

Influence quantity	Reference characteristics
Phantom material	water
Measurement depth	2 g/cm ²
Reference point of the chamber	On the central axis at the centre of the cavity volume
Source to surface distance	Usual treatment distance as determined by the reference applicator
Field size	10 cm x 10 cm or a diameter of 10 cm

A chamber calibrated in terms of air kerma free in air.



Medium energy X ray dosimetry for a chamber calibrated in terms of air kerma

$$D_{w,Q}^{Z=2} = M_Q^{Z=2} N_{K,air}^{FIA} \left[\mu_{en}(Q) / \rho \right]_{w,air}^{Z=2} p_{ch}$$

$M_Q^{Z=2}$ is the reading from the chamber placed at 2 cm deep in water corrected for temperature and pressure, k_s , k_{pol}

$N_{K,air}^{FIA}$ is the air kerma calibration coefficient corrected for standard ambient conditions, for the quality of the incident beam

$\left[\mu_{en}(Q) / \rho \right]_{w,air}^{Z=2}$ is the ratio of mass energy absorption coefficients of water to air averaged over the spectrum at 2 cm deep in water,

p_{ch} is the chamber correction factor

$$p_{ch,Q} = k_{\alpha} \cdot k_{st} \cdot p_{rep} \cdot k_{sleeve}$$

k_{α} allows for the energy and angular dependence of the response of the ionization chamber in the water phantom compared with the response of the same chamber when calibrated in-air,

k_{st} accounts for the influence of the stem on the response of the ionization chamber in-water and free in-air,

p_{rep} accounts for the replacement of the phantom material by the active volume of the ionization chamber,

k_{sleeve} on accounts for the effect of the waterproof sleeve the response of the ionization chamber.

TABLE 32. RECOMMENDED VALUES OF $p_{ch,Q}$ ($f = 10$ cm, SSD = 100 cm) FOR VARIOUS CYLINDRICAL IONIZATION CHAMBERS AT A DEPTH OF 2 cm

Quality	70 kV	100 kV	120 kV	140 kV	150 kV	200 kV	250 kV	280 kV	300 kV
HVL (mm Cu)	0.108	0.192	0.303	0.477	0.838	1.581	2.498	3.384	3.592
IBA FC65-P	0.991	0.997	1.000	0.999	0.997	0.994	0.994	0.995	0.995
PTW 30013	1.001	1.008	1.014	1.016	1.016	1.011	1.008	1.006	1.006
NE 2571	0.994	1.004	1.011	1.015	1.017	1.012	1.009	1.007	1.007
Exradin A12	0.990	1.000	1.005	1.006	1.008	1.005	1.004	1.003	1.003
IBA FC65-G	0.995	1.004	1.011	1.014	1.018	1.015	1.011	1.009	1.009

Medium energy X ray dosimetry for a chamber calibrated in terms of absorbed dose to water

$$D_{w,Q}^{Z=2} = M_Q^{Z=2}(f, SSD)_{clin} N_{D,W,Q}^{Z=2}(f, SSD)_{lab} k_{g,Q}^{Z=2}(f, SSD)_{clin}$$

$N_{D,W,Q}^{Z=2}(f, SSD)_{lab}$ is the absorbed dose to water calibration coefficient at the standards laboratory field size and SSD

$k_{g,Q}^{Z=2}(f, SSD)_{clin}$ is the geometry correction factor given by the ratio of calibration coefficients in the clinic to that in the standards laboratory.

The geometry correction factor for medium energy X rays.

$$k_{g,Q}^{z=2}(f, SSD)_{clin} = \frac{N_{D,w,Q}^{z=2}(f, SSD)_{clin}}{N_{D,w,Q}^{z=2}(f, SSD)_{lab}}$$

$$= \frac{N_{K,air,Q}^{FIA}(f, SSD)_{clin}}{N_{K,air,Q}^{FIA}(f, SSD)_{lab}} \frac{\left[\frac{\mu_{en}(Q, f, SSD)_{clin}}{\rho} \right]_{w,air}^{z=2}}{\left[\frac{\mu_{en}(Q, f, SSD)_{lab}}{\rho} \right]_{w,air}^{z=2}} \frac{p_{ch,Q}(f, SSD)_{clin}}{p_{ch,Q}(f, SSD)_{lab}}$$

TABLE 33. ESTIMATED RELATIVE STANDARD UNCERTAINTY^a OF $D_{w,Q}$ AT THE REFERENCE DEPTH IN WATER FOR A MEDIUM ENERGY X RAY BEAM

Physical quantity or procedure	Relative standard uncertainty (%)	
	$N_{D,w}$ based	N_K based
Step 1: standards laboratory		
Calibration of secondary standard (N_D or N_K) at PSDL	1.0	0.5
Long term stability of secondary standard	0.1	0.1
Calibration of the user dosimeter at the standards laboratory	0.5	0.5
Combined uncertainty in step 1	1.1	0.7
Step 2: User X ray beam		
Procedure to obtain the calibration coefficient in the user beam	0.5	0.5
Chamber perturbation correction		1.0
Field size dependence of the chamber perturbation factor		0.5
Ratio of the mean mass energy absorption coefficient water to air		0.5
Geometry correction factor	0.2	
Long term stability of the user dosimeter	0.3	0.3
Dosimeter reading M_Q relative to timer or beam monitor	0.1	0.1
Establishment of reference conditions	1.0	1.0
Correction for influence quantities k_i	0.8	0.8
Combined uncertainty in step 2	1.4	1.9
Combined standard uncertainty of $D_{w,Q}$ (steps 1 and 2)	1.8 (1.7) ^b	2.0 (1.9) ^b

b combined standard uncertainty with the user dosimeter calibrated directly at the PSDL.

95% confidence level (k=2)

Field output factor for medium energy X rays

$$\Omega = \frac{D_{w,Q}(f, SSD)_{clin}}{D_{w,Q}(f, SSD)_{ref}}$$

$$\approx \frac{M_Q^{Z=2}(f, SSD)_{clin} \left[\mu_{en}(Q) / \rho \right]_{w,air}^{z=2} (f, SSD)_{clin}}{M_Q^{Z=2}(f, SSD)_{ref} \left[\mu_{en}(Q) / \rho \right]_{w,air}^{z=2} (f, SSD)_{ref}}$$



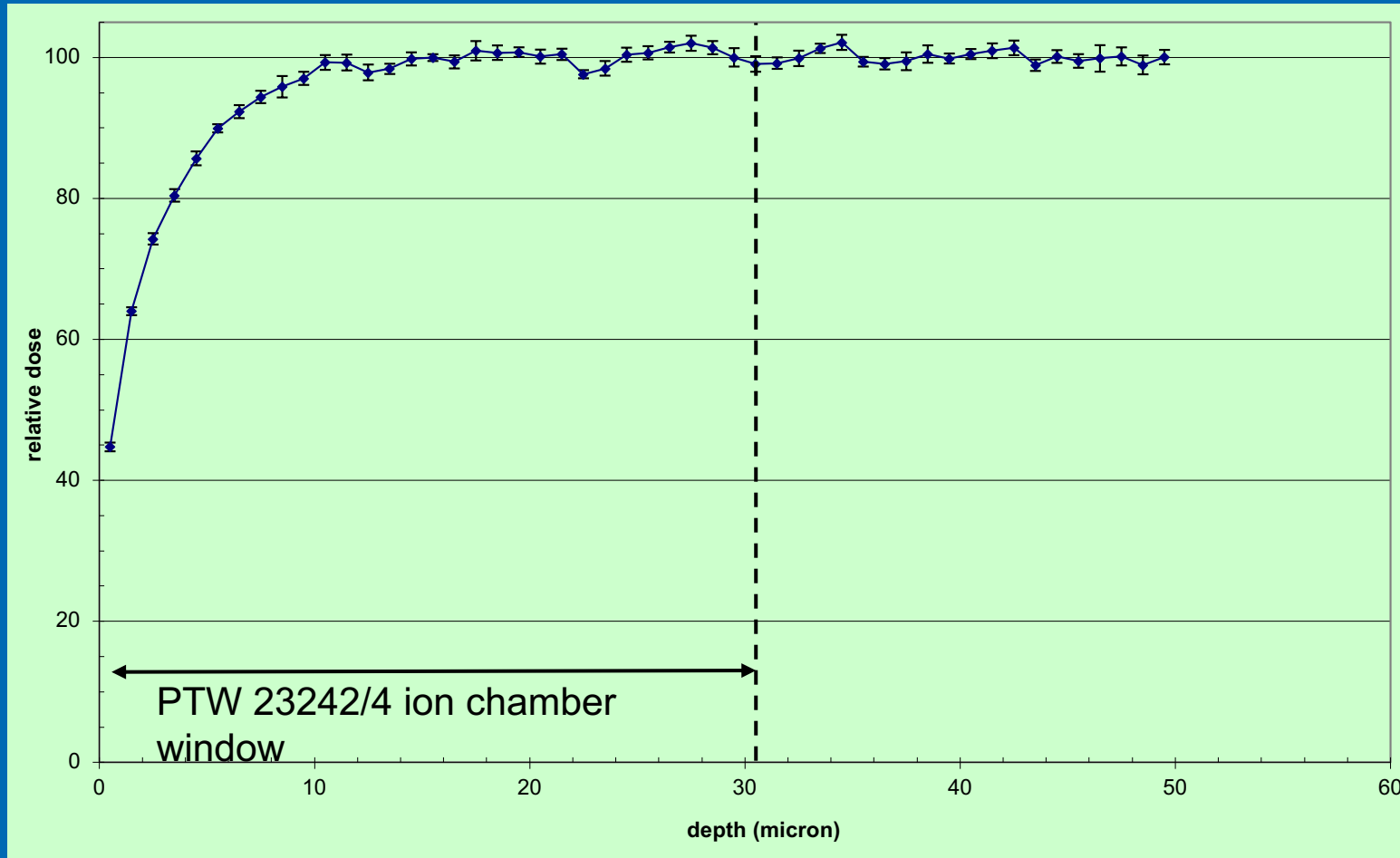
Low energy kilovoltage X-ray beams
(10 kV to 100kV, HVL: 0.03 to 5 mm Al)

Equipment used for low energy kV X-ray dosimetry.



Chambers: PTW 23344 –volume 0.2cc, PTW 23342-volume 0.02 cc,
Above 70 kV, Farmer type chamber with graphite wall and
Al central electrode.

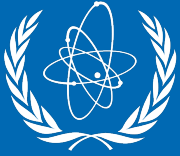
Build up for PTW 23344 and 23342 chambers



When used above 40 kV, need an addition 0.2 mm of build-up (PMMA, polyethylene or mylar foils).

Low energy kV X-ray energy

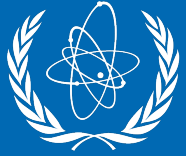
1. PTW 23342 or PTW 23344 chamber **calibrated free in air in terms of air kerma.**
2. Above 70 kV a Farmer type chamber with an aluminum central electrode and graphite wall is **calibrated free in air in terms of air kerma.**
3. PTW 23342 or PTW 23344 chamber calibrated in PMMA phantom directly in terms of **absorbed dose to water.**



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Influence quantity	Reference characteristics
Measurement point	Free in air at the end of the applicator
Reference point of the chamber	Plane parallel chamber: at the centre of the chamber outside surface of the chamber window (or foil if used). Cylindrical chamber: on the chamber axis at the centre of the cavity volume.
Source to surface distance	Usual treatment distance as determined by the reference applicator
Field size	10 cm x 10 cm or a diameter of 10 cm

Reference conditions for the determination of absorbed dose to water in low energy X ray beams using in-air method.



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Free in air measurement using a Farmer type chamber

Low energy X ray dosimetry for a chamber calibrated in terms of air kerma

$$D_{w,Q}^{surface} = M_Q^{FIA} N_{K,air}^{FIA} \left[\mu_{en}(Q) / \rho \right]_{w,air}^{FIA} B_{w,Q}(f, SSD)_{clin}$$

M_Q^{FIA} is the reading on the chamber Free In Air corrected for temperature and pressure, k_s , k_{pol}

$N_{K,air}^{FIA}$ is the air kerma calibration coefficient corrected for standard ambient conditions, for the quality of the incident beam

$\left[\mu_{en}(Q) / \rho \right]_{w,air}^{FIA}$ is the ratio of mass energy absorption coefficients of water to air averaged over the spectrum Free In Air,

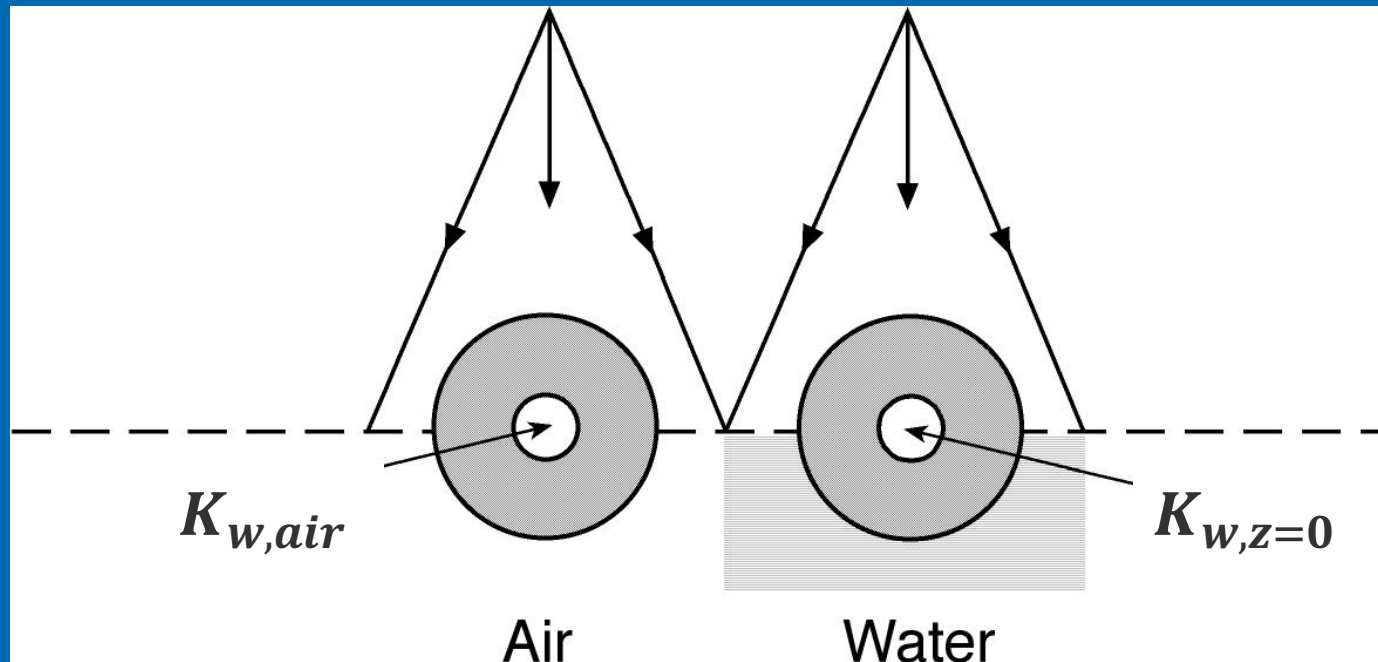
$B_{w,Q}(f, SSD)_{clin}$ is the backscatter factor

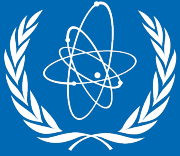


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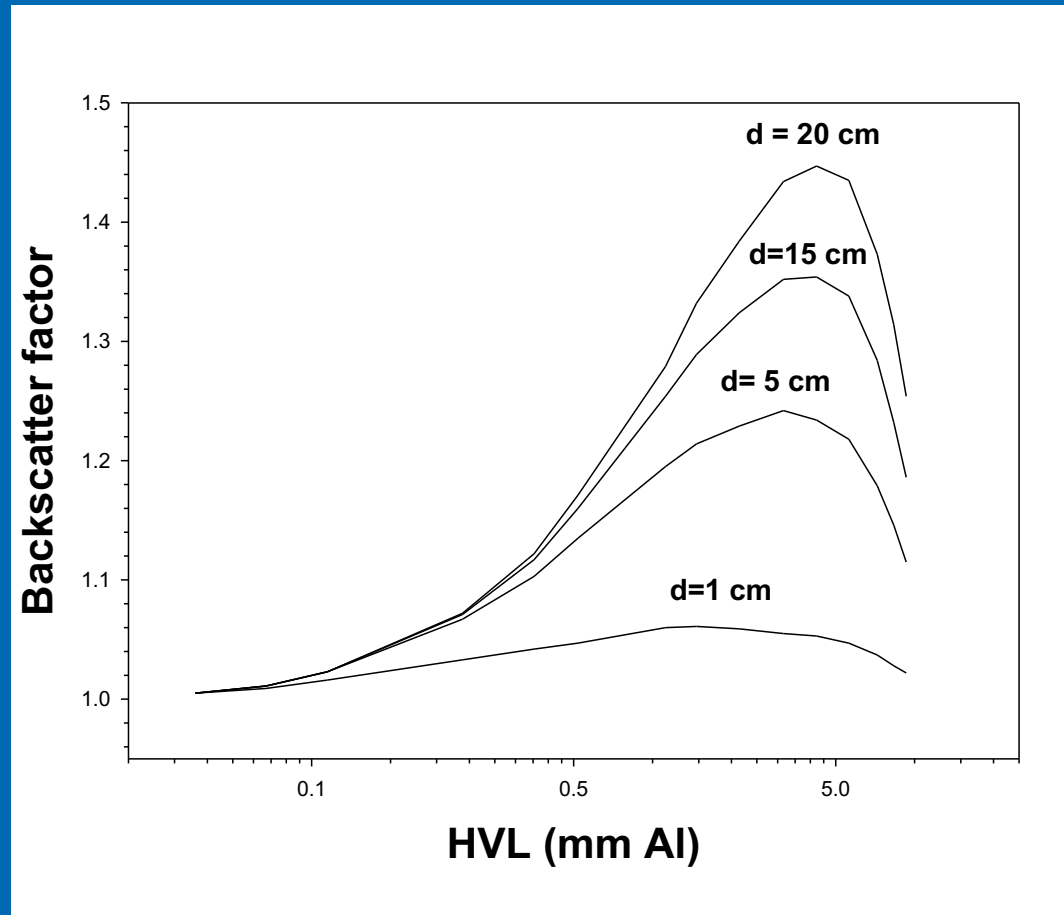
Backscatter factor

$$B_{w,Q} = \frac{K_{w,z=0}}{K_{w,air}}$$





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Variation of the backscatter factor with HVL for different beam diameters (d) , source to surface distance = 20 cm

Low energy X ray dosimetry for a chamber calibrated in terms of absorbed dose to water

TABLE 27. REFERENCE CONDITIONS FOR THE DETERMINATION OF ABSORBED DOSE IN LOW ENERGY X RAY BEAMS USING THE IN-PHANTOM METHOD

Influence quantity	Reference value or reference characteristic
Phantom material	Water equivalent plastic or PMMA
Chamber type	Plane parallel for low energy X rays (up to 100 kV)
Measurement depth	Phantom surface
Reference point of the chamber	At the centre of the outside surface of the chamber window (or foil, if used)
Source–surface distance	Defined by the end of the reference applicator
Field size	Same field size as that used for the calibration at the standards laboratory



$$D_{w,Q}^{surface}(f, SSD) = M_Q^{PMMA}(f, SSD)_{clin} N_{D,W,Q}^{PMMA}(f, SSD)_{lab} k_{g,Q}^{PMMA}(f, SSD)_{clin}$$

$$N_{D,W,Q}^{Z=2}(f, SSD)_{lab}$$

is the absorbed dose to water calibration coefficient at the standards laboratory field size and SSD.

$$k_{g,Q}^{Z=2}(f, SSD)_{clin}$$

is the geometry correction factor given by the ratio of calibration coefficients in the clinic to that in the standards laboratory.

TABLE 29. GEOMETRY CORRECTION FACTORS FOR THE CHAMBER TYPE PTW 23344 AT DIFFERENT FIELD SIZES FOR THE PTB TW SERIES [190], NORMALIZED TO THE REFERENCE CONDITIONS $Q_0 = 30$ kV, 0.36 mm Al AND $f = 3$ cm

f (cm)	Geometry correction factor						
	10 kV	20 kV	30 kV	40 kV	50 kV	70 kV	100 kV
2	1.00	1.00	1.01	1.02	1.02	1.03	1.04
3	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5	1.00	1.00	0.99	0.98	0.98	0.96	0.96
6	1.00	1.00	0.99	0.98	0.97	0.95	0.95

The geometry correction factor for low energy X rays.

$$k_{g,Q}^{PMMA}(f, SSD)_{clin} = \frac{N_{D,w,Q}^{PMMA}(f, SSD)_{clin}}{N_{D,w,Q}^{PMMA}(f, SSD)_{lab}}$$

$$= \frac{N_{K,air,Q}^{PMMA}(f, SSD)_{clin}}{N_{K,air,Q}^{PMMA}(f, SSD)_{lab}} \frac{\left[\frac{\mu_{en}(Q, f, SSD)_{clin}}{\rho} \right]_{w,air}^{PMMA}}{\left[\frac{\mu_{en}(Q, f, SSD)_{lab}}{\rho} \right]_{w,air}^{PMMA}} \frac{B_{w,Q}(f, SSD)_{clin}}{B_{w,Q}(f, SSD)_{lab}}$$

TABLE 30. ESTIMATED RELATIVE STANDARD UNCERTAINTY^a OF $D_{w,Q}$ AT THE REFERENCE DEPTH IN WATER FOR A LOW ENERGY X RAY BEAM

Physical quantity or procedure	Relative standard uncertainty (%)	
	$N_{D,w}$ based	N_K based
Step 1: standards laboratory	SSDL	SSDL
Calibration of secondary standard (N_D or N_K) at PSDL	1.4	0.5
Long term stability of secondary standard	0.1	0.1
Calibration of the user dosimeter at the standards laboratory	0.5	0.5
Combined uncertainty in step 1	1.5	0.7
Step 2: user X ray beam		
Interpolation of the calibration coefficient to the user beam	0.5	0.5
Ratio of the mean mass energy absorption coefficient water to air		0.5
Backscatter factor		1.0
Geometry correction factor	1.0	
Long term stability of the user dosimeter	0.3	0.3
Dosimeter reading M_Q relative to timer or beam monitor	0.1	0.1
Establishment of reference conditions ^b	1.0	1.0
Correction for influence quantities k_i	0.8	0.8
Combined uncertainty in step 2	1.7	1.8
Combined standard uncertainty of $D_{w,Q}$ (steps 1 and 2)	2.3 (2.2) ^c	1.9 (1.9) ^c

c combined standard uncertainty with the user dosimeter calibrated directly at the PSDL.

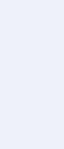
95% confidence level (k=2)

Field output factor for low energy X rays

$$\Omega = \frac{D_{w,Q}(f, SSD)_{clin}}{D_{w,Q}(f, SSD)_{ref}}$$

$$\approx \frac{M_Q^{FIA}(f, SSD)_{clin} B_{w,Q}(f, SSD)_{clin}}{M_Q^{FIA}(f, SSD)_{ref} B_{w,Q}(f, SSD)_{ref}}$$





Beam Quality Index: Half Value Layer

Definition of HVL

The thickness of a specified absorber which reduces the beam intensity to half its original value.

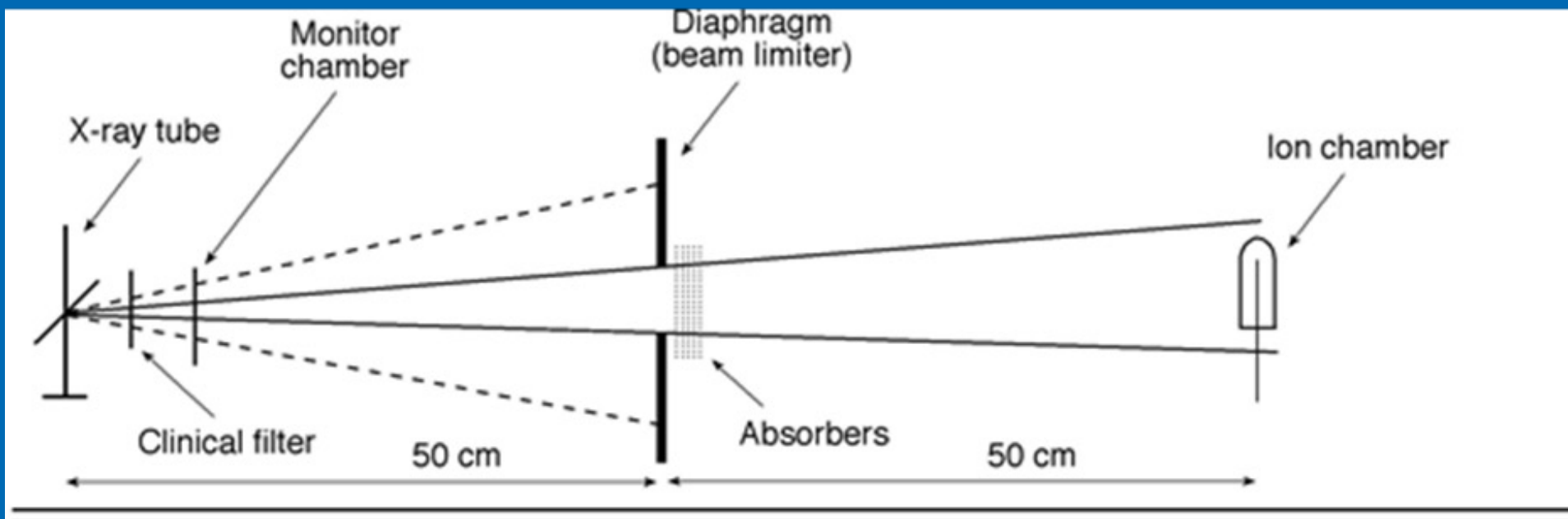
Low energy X rays

Specified in mm Al (0.03-5 mm Al)

Medium energy X rays

Specified in mm Cu (greater than 2 mm Al)

HVL measurement set-up

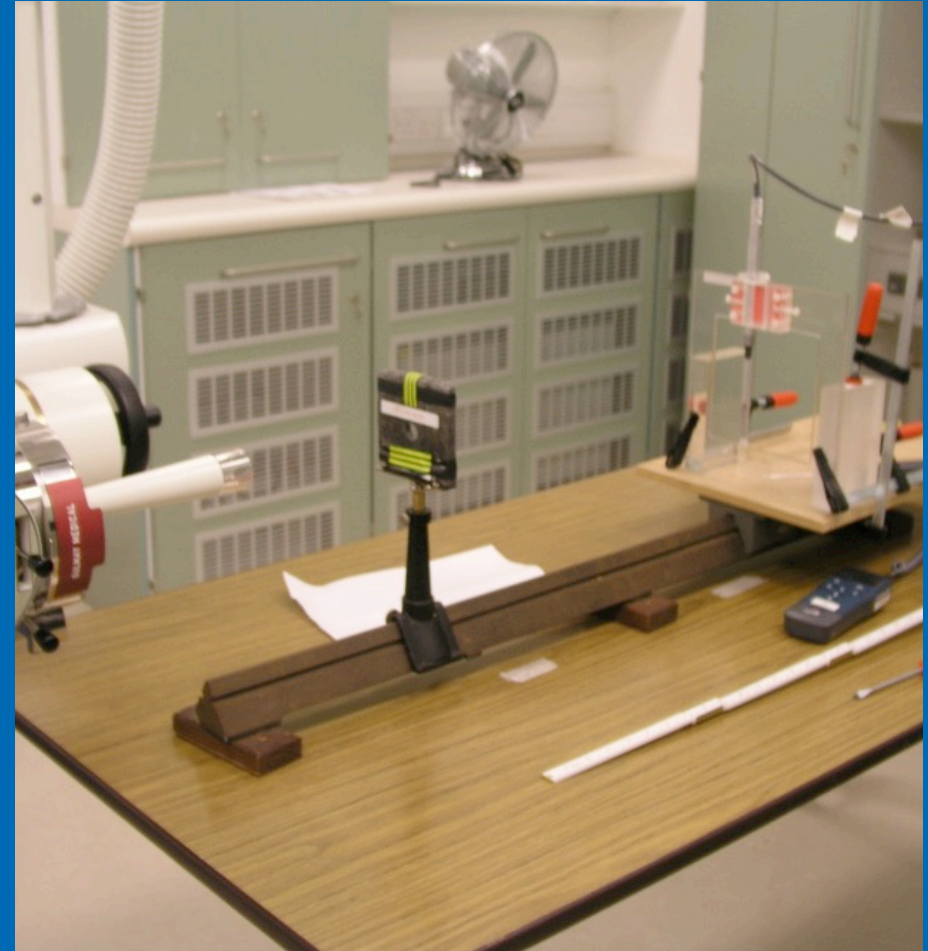


Requirement of HVL measurement

1. Scatter free conditions

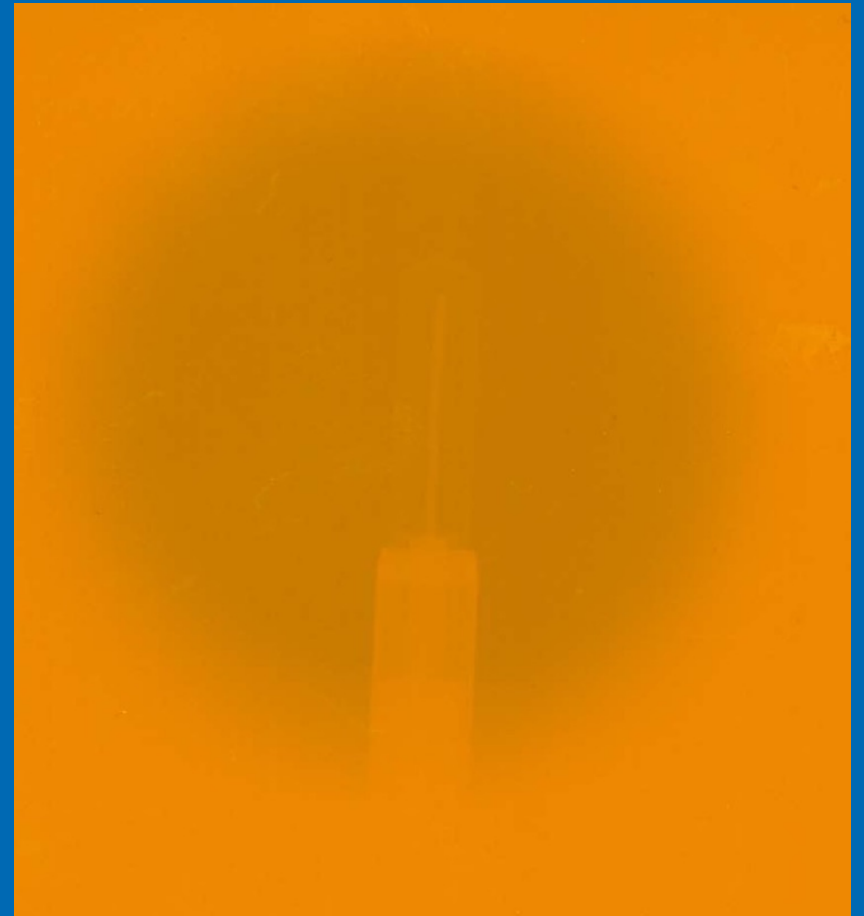
- detector placed at least 50 cm from the attenuating material and diaphragm.
- absorber placed mid-way between X-ray tube and detector
- place chamber at least 40 cm away from any scattering material.

2. Ionisation chamber should have a limited beam quality dependence (if energy response varies by more than 2 % over the quality range then each measurement should be converted to air kerma)



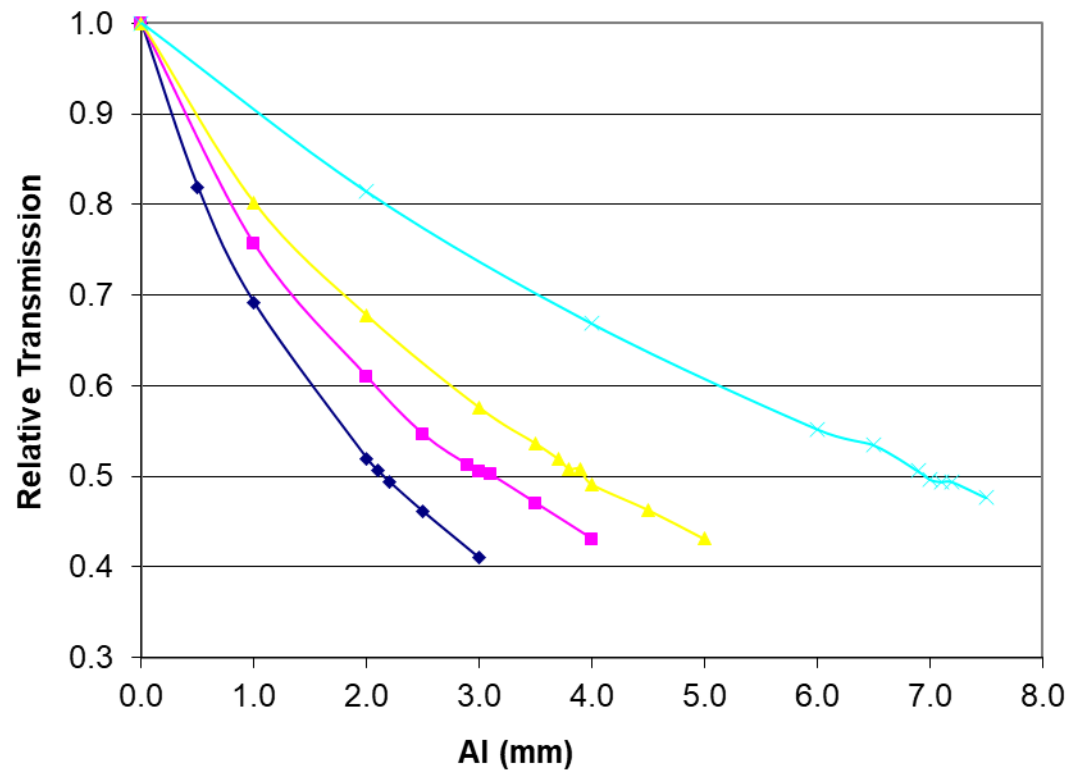
Requirement of HVL measurement

3. Absorber should be of high purity material (99.9% pure).
4. Thickness of the absorber should be measured to an accuracy of 0.05 mm.
5. Thickness of the diaphragm must be thick enough to attenuate the primary beam to 0.1%
6. The beam diameter defined by the diaphragm should ensure that the sensitive volume of the chamber is fully envelope the beam.

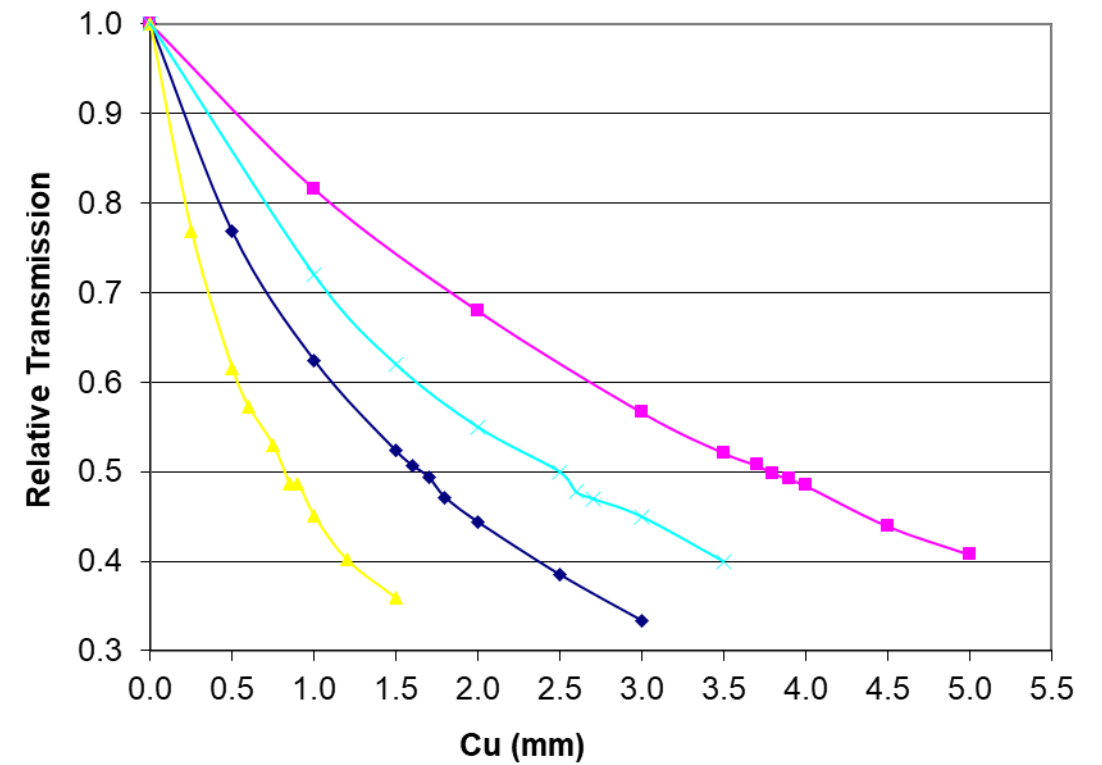


Examples of HVL measurements

HVL measurements for different low kV beam energies

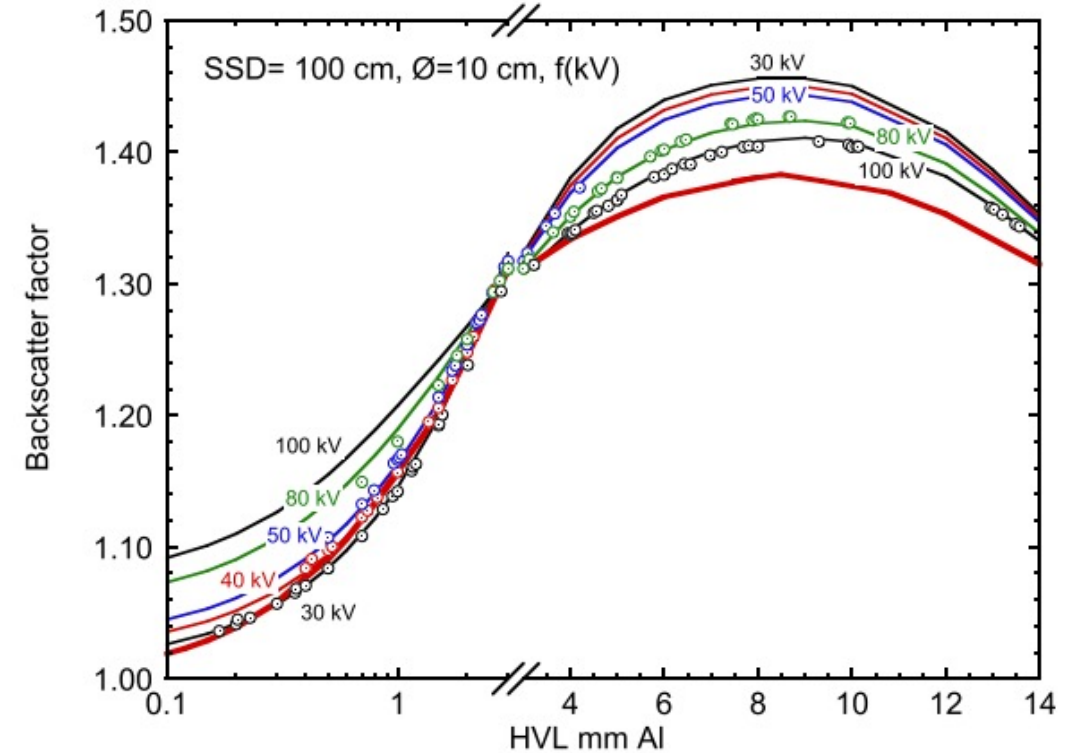
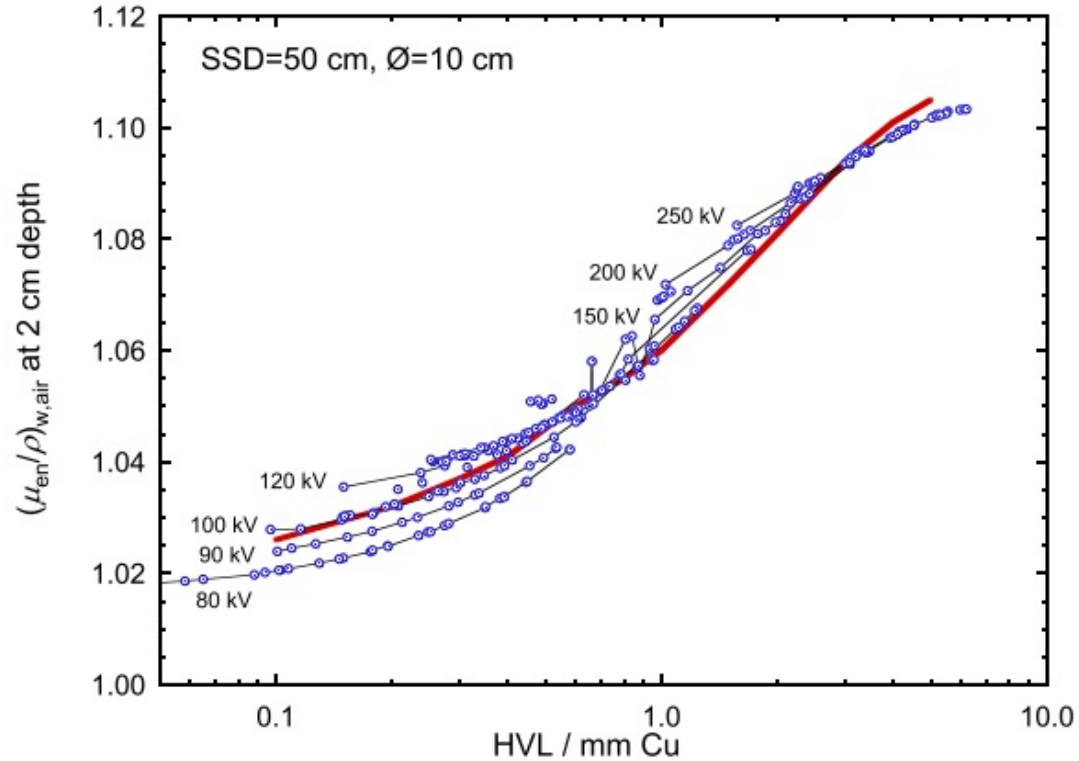


HVL measurements for different medium energy kV beams

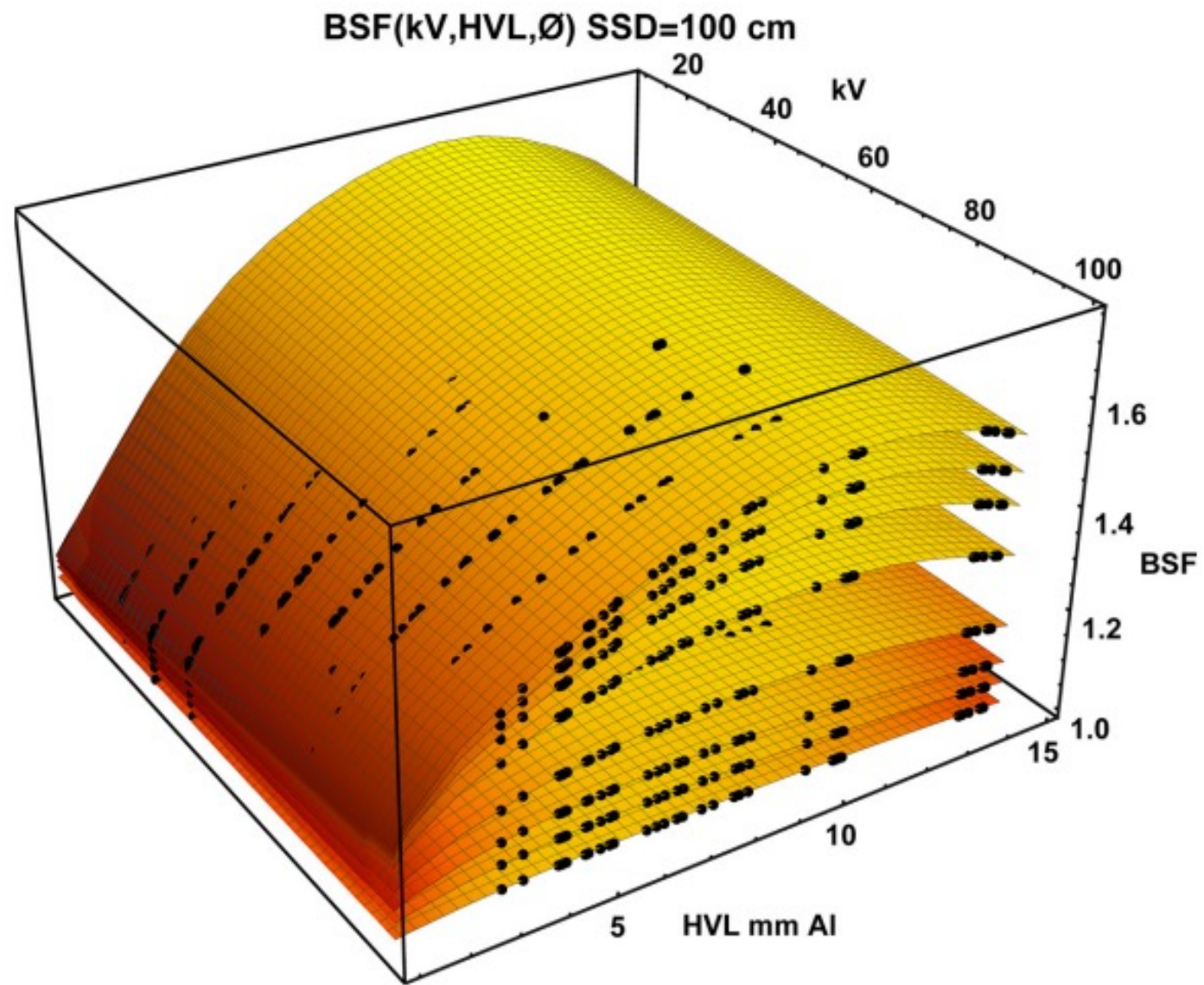




BUT



Taken from Andreo P, Data for the dosimetry of low- and medium-energy kV x rays, Phys. Med. Biol. 64 (2019) 205019 (19pp)



GUI: <http://kvx-rays.iaea.org/>

Tube Voltage [10 - 150 kV]

Current kV: 30



Half Value Layer (HVL) [0.01 - 10 mm Al]

Current HVL: 5.01



Source-to-Skin Distance (SSD) [10 - 100 cm]

Current SSD: 30



Field Diameter (f) [1 - 30 cm]

Current Diameter: 15



Calculate

Results

Tube Voltage [kV]: 30.0

HVL [mm Al]: 5.01

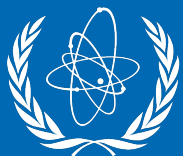
SSD [cm]: 30.0

f [cm]: 15.0

$B_w(Q, f, SSD)$: 1.4610

$[\mu_{\text{en}}(Q)/\rho]_{\text{w,air}}^{\text{FIA}}$: 1.0330

Product $B_w(Q, f, SSD) \times [\mu_{\text{en}}(Q)/\rho]_{\text{w,air}}^{\text{FIA}}$: 1.5092



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