Measurement of Radiation

AAPM Continuing Education Therapy Physics Review Course

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Outline

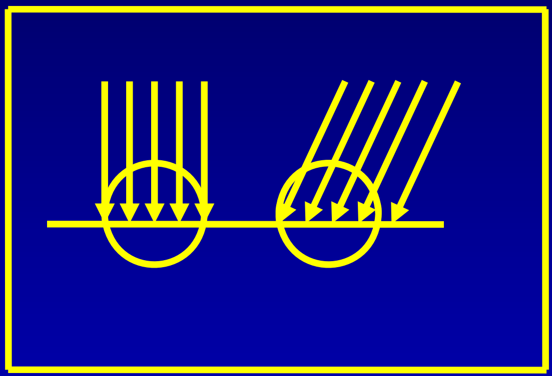
- Definition of Radiation Quantities
- Cavity Theory
- Kilovoltage X-Ray Calibration
- Megavoltage photon/electron Calibration
- Measurement of Absorbed Dose

Definition

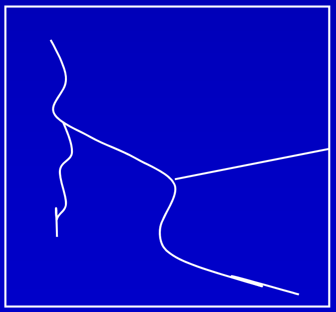
- Ionization - a process in which one or more electrons are liberated from a parent atom or molecule or other bound state
- Ionizing Radiation - Ionizing radiation consists of charged particles and/or uncharged particles capable of causing ionization by primary or secondary process
- Directly Ionizing Radiation - Charged particles deliver their energy to matter directly through many small coulomb-force interactions along the particle's track
- Indirectly Ionizing Radiation - Uncharged particles deliver their energy to matter indirectly by transferring their energy to charged particles in a relatively few large interactions. The resulting charged particles then in turn deliver the energy to the matter

Particle Fluence

$$\Phi = \frac{dN}{da}$$



$$\Phi = \frac{\Sigma(Tracklengths\ in\ volume)}{volume}$$



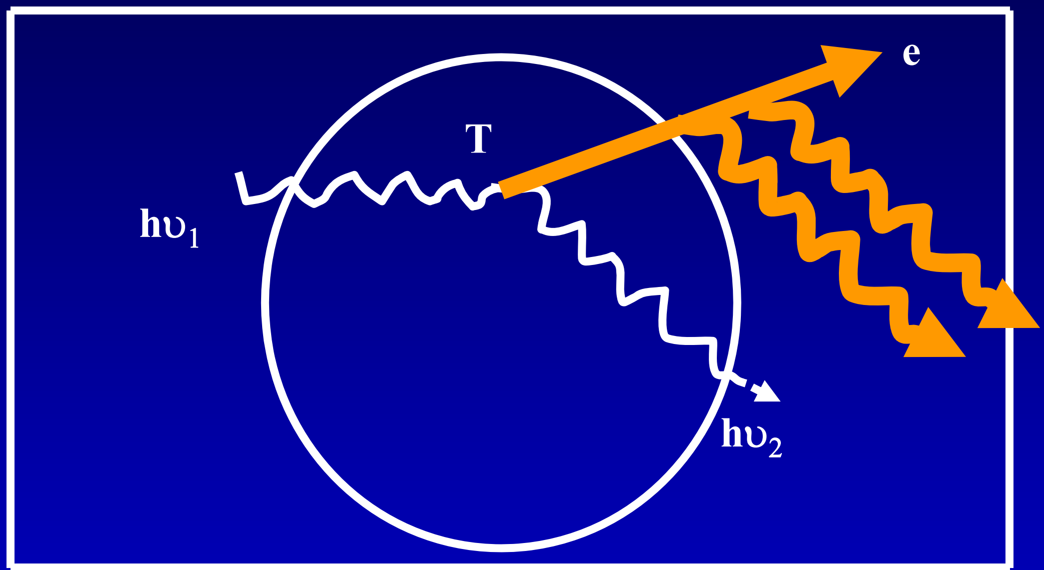
Mass Energy Transfer Coefficient

$$\frac{\mu_{\mathrm{tr}}}{\rho} = \frac{1}{\rho E N} \frac{dE_{tr}}{dl}$$

Mass Energy Absorption Coefficient

$$\frac{\mu_{\mathrm{e}n}}{\rho} = \frac{\mu_{tr}}{\rho}\left(1 - g\right)$$

Energy Transferred, E_{tr}



$$E_{tr} = (R_{in})_u - (R_{out})_u^{nonr} + \Sigma Q$$

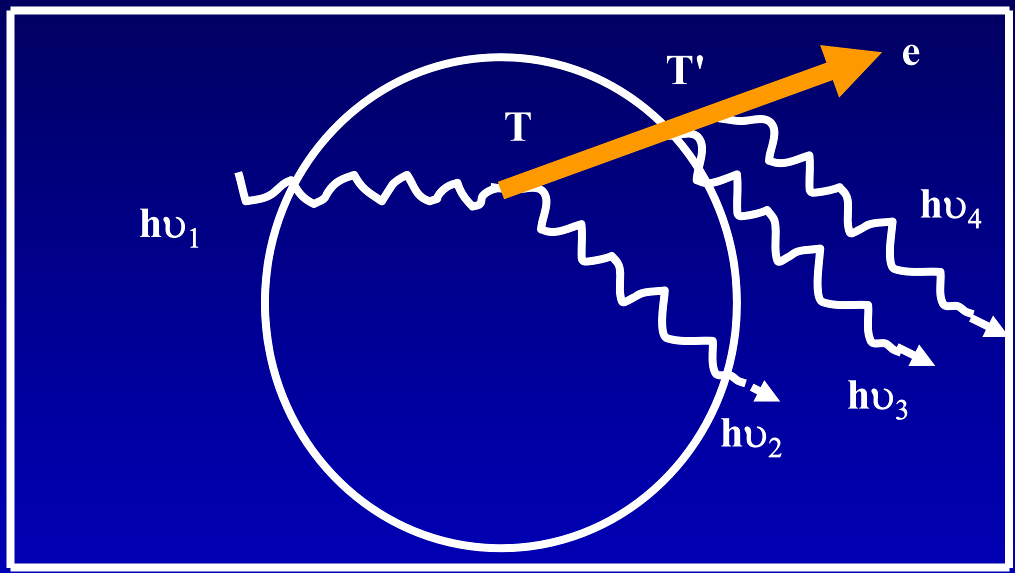
$$= hv_1 - hv_2 + 0 = T$$

Kerma

$$K = \frac{\mathrm{d}E_{tr}}{dm}$$

$$K = \Psi\left(\frac{\mu_{tr}}{\rho}\right) = \Phi\,\mathrm{E}\left(\frac{\mu_{tr}}{\rho}\right)$$

Net Energy Transferred, E_{tr}^{n}



$$E_{tr}^{n} = (R_{in})_u - (R_{out})_u^{nonr} - R_u^r + \Sigma Q$$

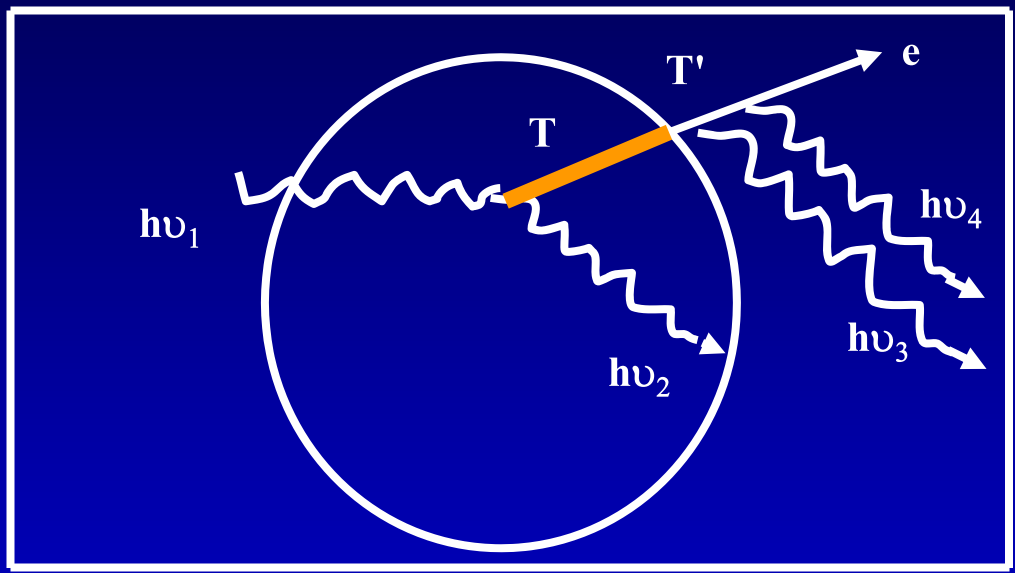
$$= h\nu_1 - h\nu_2 - (h\nu_3 + h\nu_4) + 0$$

Collision Kerma

$$K_c = \frac{dE_{tr}^{n}}{dm}$$

$$K_c = \Psi \left(\frac{\mu_{en}}{\rho} \right) = \Phi E \left(\frac{\mu_{en}}{\rho} \right)$$

Energy Imparted, *E*



$$E = (R_{in})_u - (R_{out})_u + (R_{in})_c - (R_{out})_c + \Sigma Q$$

$$= h\nu_1 - h\nu_2 - (h\nu_3 + h\nu_4 + T') + 0$$

Absorbed Dose - the expectation value of the energy imparted to matter per unit mass at a point

$$D = \frac{dE}{dm}$$

To what materials???

Exposure, X

$$X = \frac{dQ}{dm} \quad (C/kg)$$

where dQ is the absolute value of the total charge of the ions of one sign produced in (dry) air when all the electrons liberated by photons in air of mass dm are completely stopped in air

$$\left(\frac{W}{e}\right)_{air} = 33.97\,(J/C)$$

$(W/e)_{air}$ is the mean energy expended in air per ion pair formed. It gives the number of joules of energy deposited in the air per coulomb of charge released

Collision Air Kerma and Exposure

$$(K_c)_{air} = X\left(\frac{W}{e}\right)_{air}$$

$$\Psi\left(\frac{\mu_{en}}{\rho}\right)_{air} = X\left(\frac{W}{e}\right)_{air}$$

Air Kerma and Exposure

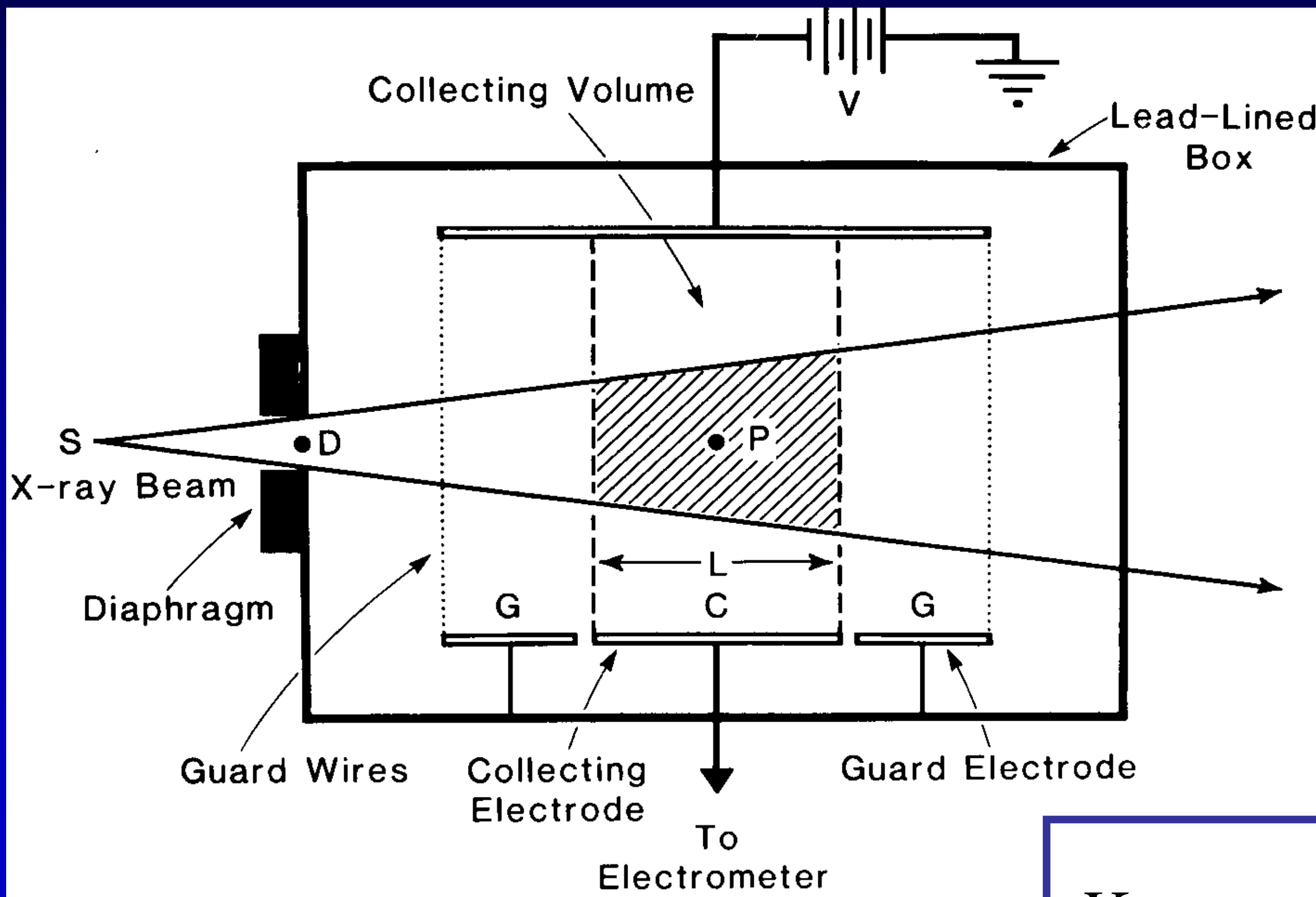
g is the fractional radiative energy loss

$$(1 - g) K_{air} = \frac{\overline{w}}{e} X$$

For kV x-rays: K_{air} (Gy) = 8.76×10^{-3} X (R)

For Co-60: K_{air} (Gy) = 8.79×10^{-3} X (R)

Measurement of Exposure

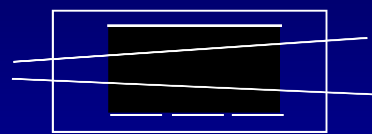


Free Air Chamber

$$X_D = \frac{Q}{\rho A_D L}$$

Cavity Chamber

The basis of an air-wall chamber is that the air surrounding the active volume can be "condensed" into a "solid air" wall



The definition of an air-wall chamber is a chamber whose walls interact with radiation in the same manner as air interacts

For a non-air-wall chamber:

Gas to wall conversion

$$D_{air} = J_g \left(\frac{\overline{W}}{\overline{e}} \right) \left(\frac{S}{\rho} \right)_g^w \left(\frac{\mu_{en}}{\rho} \right)_w^{air}$$

Dose to gas

Wall to air conversion

Absorbed Dose and Exposure

$$D_{med} = 0.876 \left(\frac{\mu_{en}}{\rho} \right)_{air}^{med} X \qquad (cGy / R)$$

The *f* factor

$$D_{med} = 33.97 \left(\frac{\mu_{en}}{\rho} \right)_{air}^{med} X \qquad (Gy / C / kg)$$

under the condition of CPE

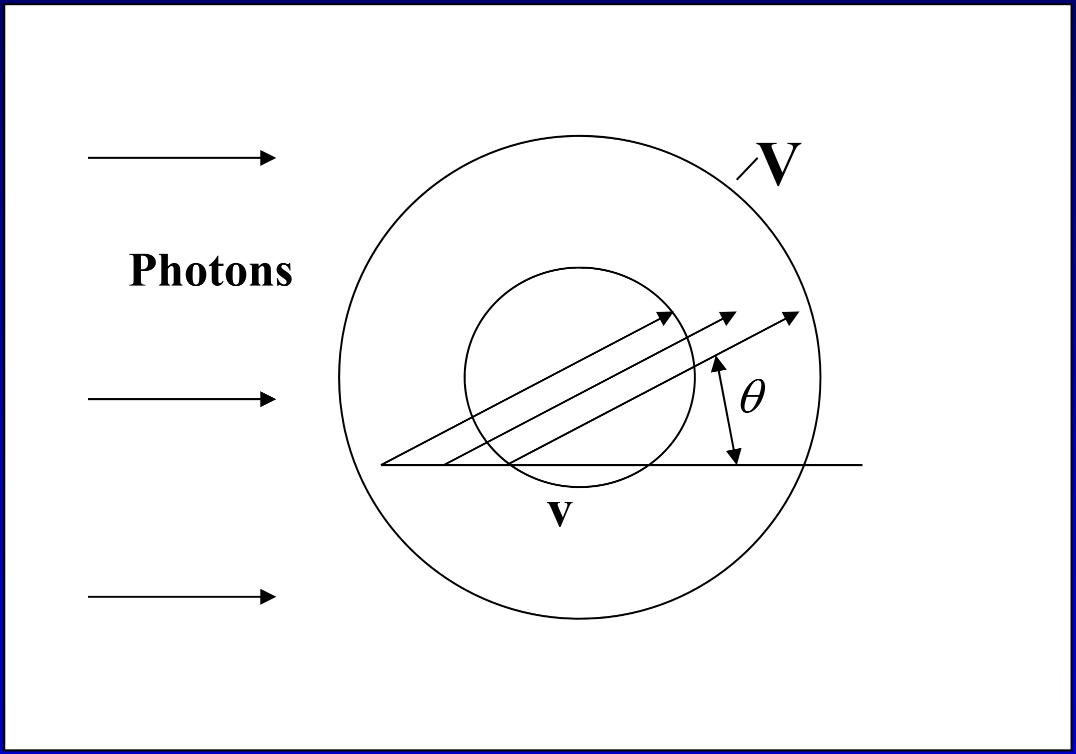
Charged Particle Equilibrium

Charged Particle Equilibrium (CPE) exists for a volume v if each charged particle of a given type and energy leaving v is replaced by an identical particle entering.

$$(Rin)_c = (Rout)_c$$

i.e., energy carried in and out by charged particles is equal

Charged Particle Equilibrium(CPE)



Homogeneous phantom

Uniform photon field

No heterogeneous E/B field

Dose and Collision Kerma
(under the condition of CPE)

$$D = K_c = \Psi \left(\frac{\mu_{en}}{\rho} \right)$$

$$\frac{D_A}{D_B} = \frac{(K_c)_A}{(K_c)_B} = \frac{\left(\frac{\overline{\mu}_{en}}{\rho} \right)_A}{\left(\frac{\overline{\mu}_{en}}{\rho} \right)_B} = \left(\frac{\overline{\mu}_{en}}{\rho} \right)_B^A$$

Large cavity theory

Break Down of CPE
(CPE does not exit in many situations)

For high-energy photon beams: the attenuation of the photon beam is significant for a full electron buildup, it is impossible for CPE to occur.

For example, a 10 MeV photon beam is attenuated 7% in the maximum range of its secondary electrons.

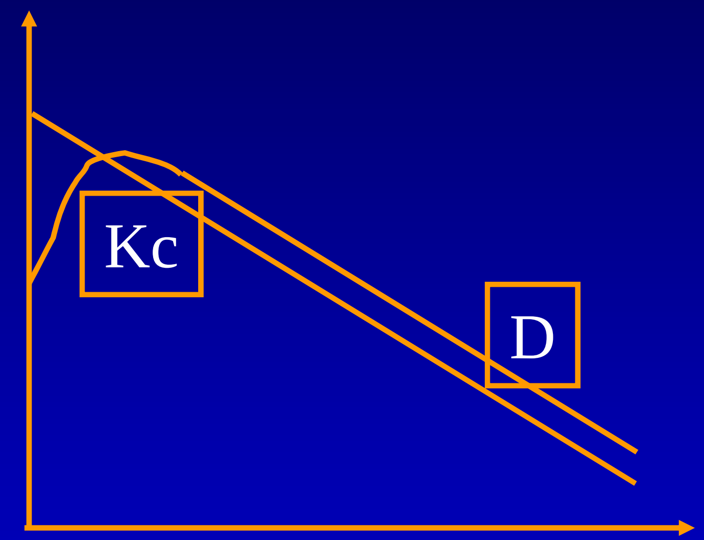
Transient Charged Particle Equilibrium (TCPE)

(D is proportional to Kc)

$$D \overset{TCPE}{=\!=} K_c e^{\mu' \overline{x}}$$

$$= K_c \beta$$

$$\overset{TCPE}{=\!=} K_c \left(1 + \mu' \overline{x}\right)$$



Cavity Theory

(to convert dose from one material to another)

Large cavity theory (for "photon detectors"): If the detector size is much greater than the mean electron range in a phantom irradiated by a photon beam, then

$$\frac{D_{med}}{D_{\det}} = \left(\frac{\overline{\mu}_{en}}{\rho} \right)_{med,\det}$$

Dose to medium

Dose to detector

Conversion factor

Cavity Theory (cont.)

Small (Bragg-Gray) cavity theory (for "electron detectors"): if the detector size is much smaller than the mean electron range in a phantom irradiated by a photon beam, then

$$\frac{D_{med}}{D_{\text{det}}} = s_{med,\text{det}}$$

Dose to medium

Dose to detector

Conversion factor

Cavity Theory (Cont.)

Burlin cavity theory: for intermediate sized detectors

$$\frac{D_{med}}{D_{\det}} = \alpha \left(\frac{\overline{\mu}_{en}}{\rho} \right)_{med,\det} + (1-\alpha) s_{med,\det}$$

$(1-\alpha) = \beta$

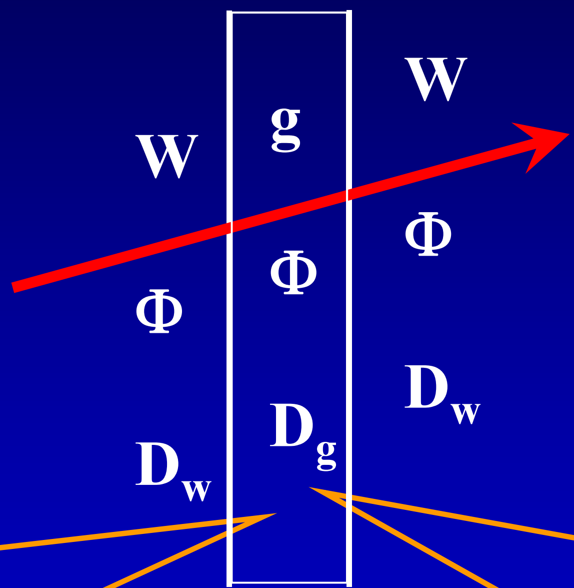
Dose to medium

Dose to detector

Conversion factor

$\alpha + \beta \neq 1$; see Ma and Nahum PMB 38:93-114 (1993)

Bragg-Gary Cavity Theory



1st condition: cavity does not perturb electron fluence

2nd condition: dose deposited by electrons crossing it

Bragg-Gary Cavity Theory

Primary only

$$\frac{D_w}{D_g} = \frac{\left(\frac{\overline{S}}{\rho}\right)_w \Phi}{\left(\frac{\overline{S}}{\rho}\right)_g \Phi} = \left(\frac{\overline{S}}{\rho}\right)_g^w$$

Unrestricted
stopping power
for primary electrons

CPE exists
for knock-on electrons

Spencer-Attix Cavity Theory

Spencer-Attix theory explicitly takes into account all knock-on electrons above some energy threshold (traditionally called Δ)

Primary & secondary

$$\frac{D_m}{D_g} = \frac{\int_{\Delta}^{E_{\max}} \Phi \left(\frac{L(\Delta)}{\rho} \right)_m d\mathrm{E} + \mathrm{TE}_m}{\int_{\Delta}^{E_{\max}} \Phi \left(\frac{L(\Delta)}{\rho} \right)_g d\mathrm{E} + \mathrm{TE}_g} = \left(\frac{\overline{L}}{\rho} \right)_g^m$$

Restricted stopping power

Track-end effect

Spencer-Attix vs. Bragg-Gray

(S-A is more accurate than B-G)

Water to air stopping power ratios at 0.65 of csda range (Nahum1978).

Incident Energy (MeV)	Stopping power ratio for water to air			
	Spencer-Attix Δ(MeV)			Bragg-Gray
	0.001	0.01	0.1	
5	1.146	1.131	1.124	1.121
10	1.116	1.102	1.096	1.091
20	1.076	1.064	1.058	1.053

Q: What's the difference between S-A and B-G?

Kilovoltage X-Ray Beam Calibration (The AAPM TG-61 Protocol)

- Use both the in-air and in-phantom methods for tube potentials 100 - 300 kV
- More complete data (for water, tissue & bone)
- Recommendations for relative measurements
- Recommendations for QA and consistency check

Q: What’s new in TG-61?

The physics of kV x-ray dosimetry

- Very short electron ranges (< 0.5 mm water)
- Large scatter contributions and SSD, field size, beam quality dependent
- Bragg-Gray cavity conditions very difficult to fulfil - even for air-filled ion chambers
- Kerma = dose (also K_{col} = K as negl. Brem.)
- Ion chambers calibrated as "exposure meters" and used as "photon detectors"

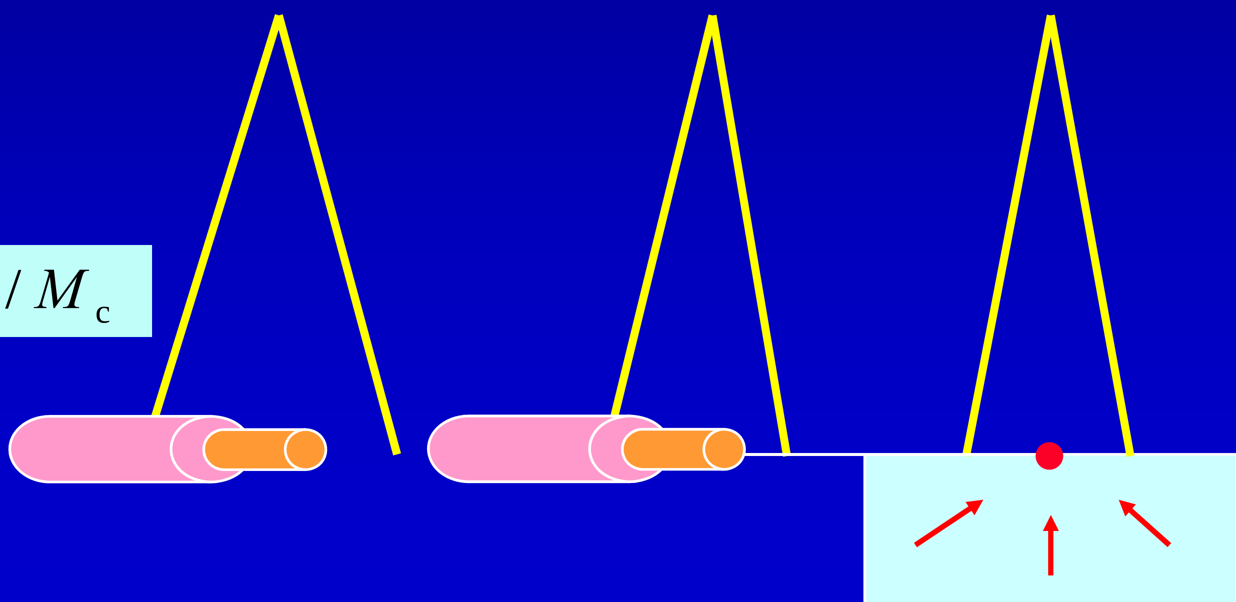
Q: What's the difference between kV & MV x-ray dosimetry?

Formalism for kV x-ray dosimetry

- The backscatter method

$$D_w = M N_K (\mu_{en} / \rho)^{\mathrm{w}}_{\mathrm{air}} P_{stem,air} B_w$$

$$N_K = K_c / M_{\mathrm{c}}$$

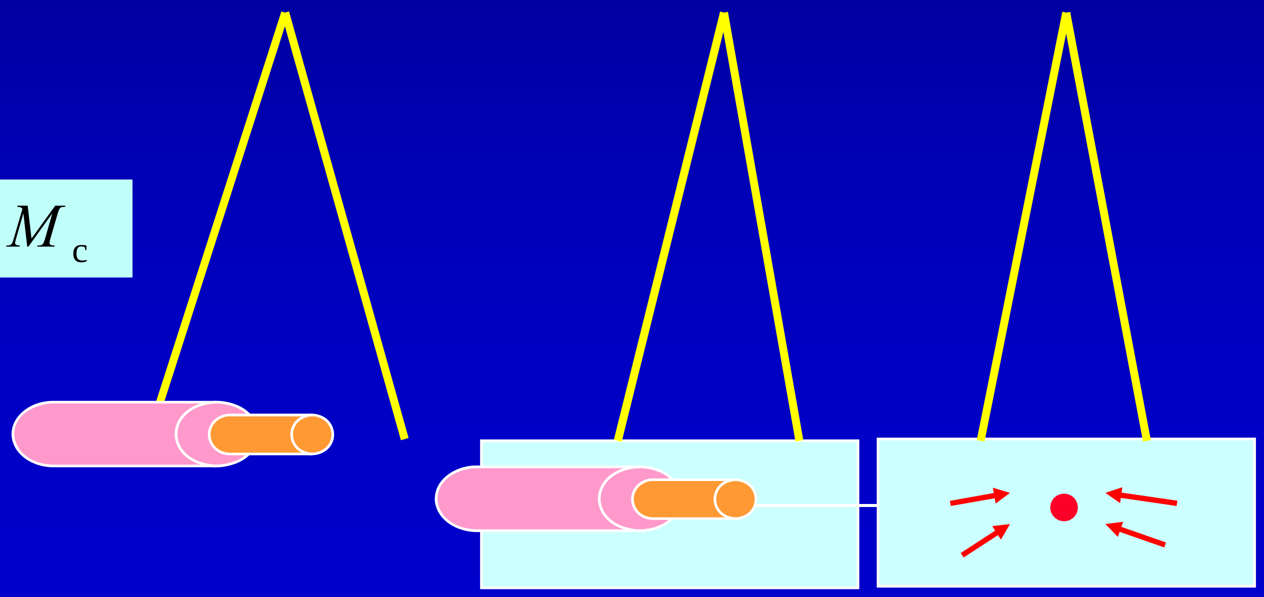


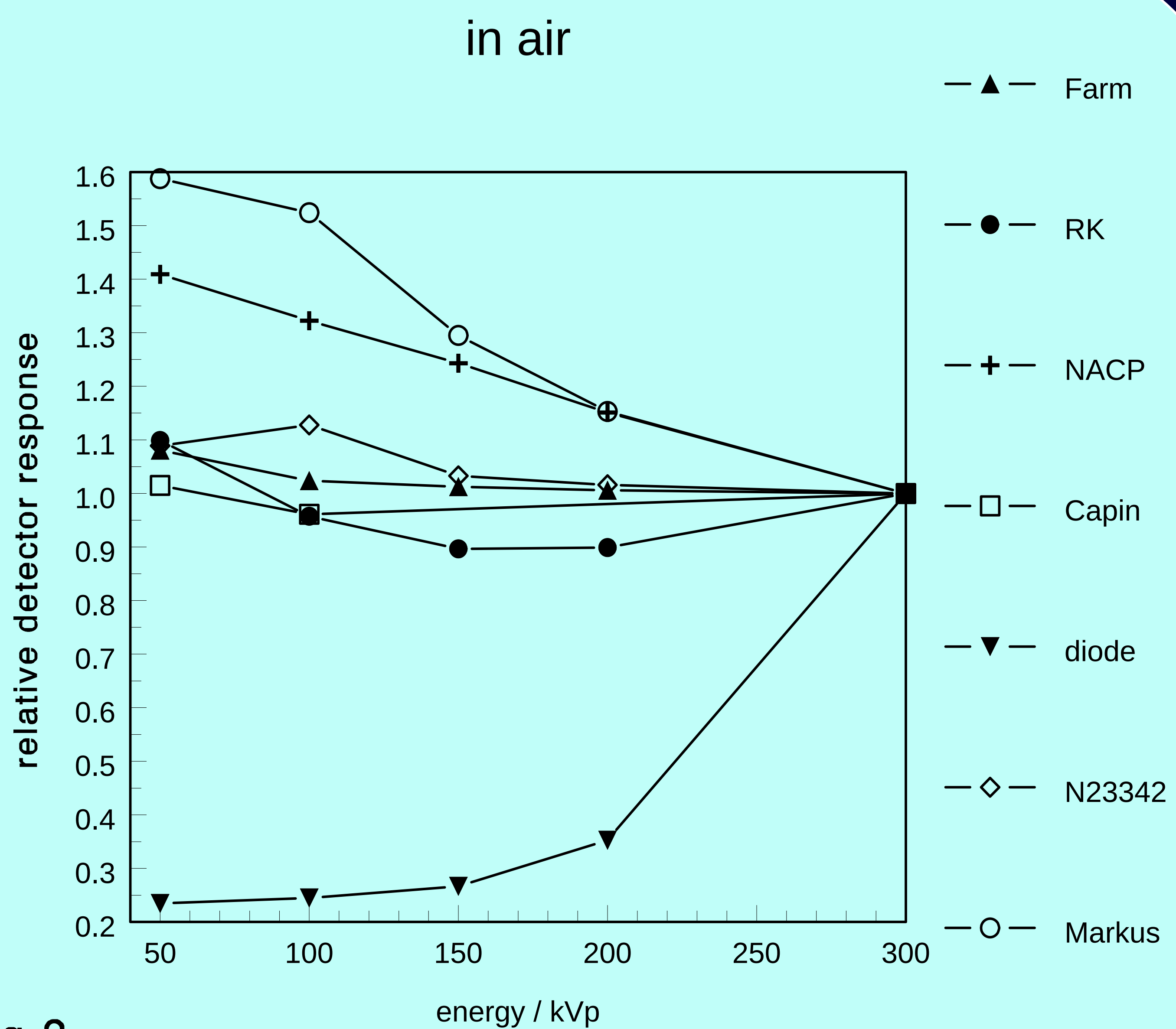
Formalism for kV x-ray dosimetry

- The in-phantom method

$$D_w = M N_K (\mu_{en}/\rho)^{\mathrm{w}}_{\mathrm{air}} P_{\mathrm{sheath}} P_{\mathrm{Q,cham}}$$

$$N_K = K_c / M_{\mathrm{c}}$$





in air
relative detector response
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
50
100
150
200
250
300
energy / kVp
Farm
RK
NACP
Capin
diode
N23342
Markus

Fig.2

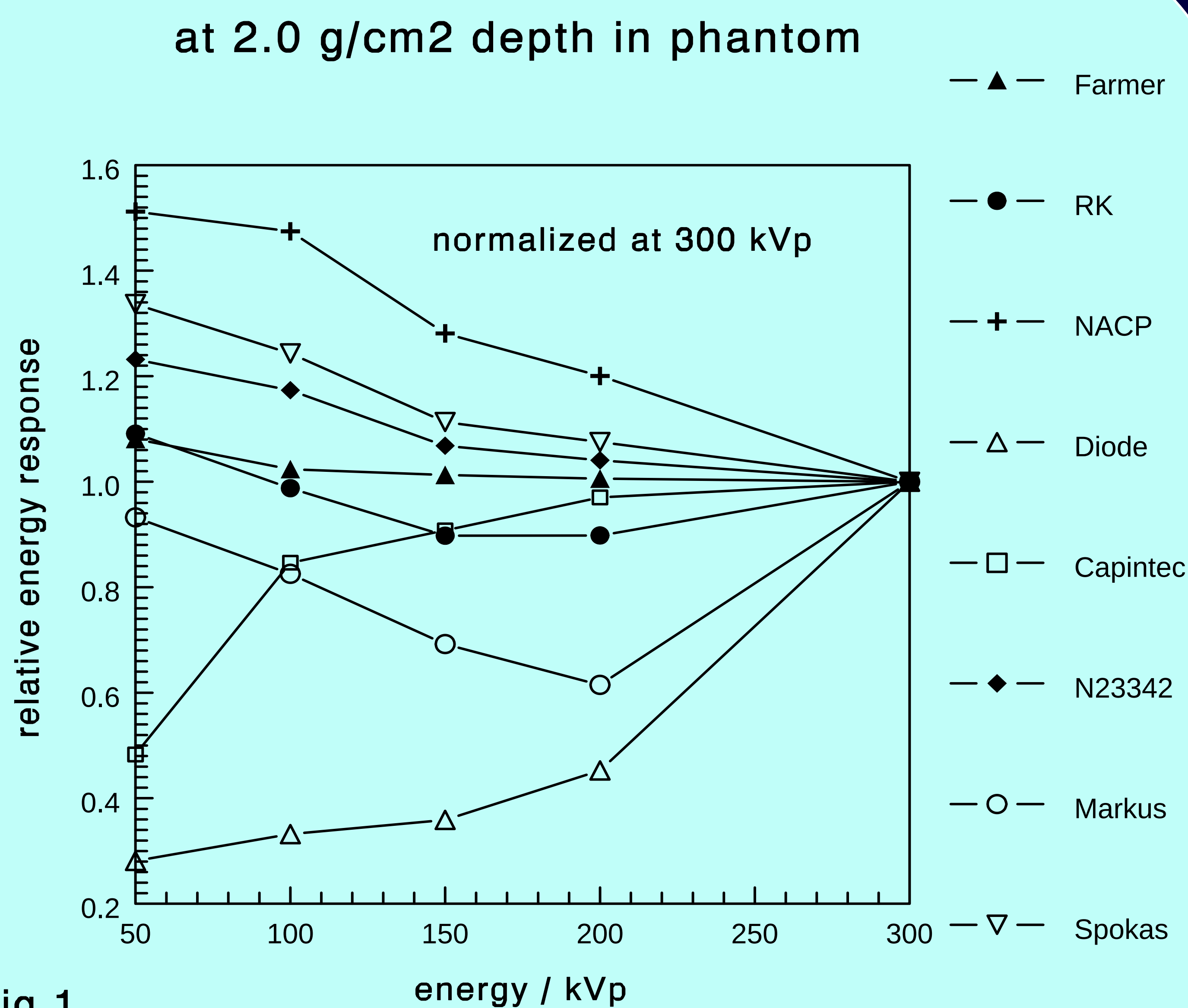
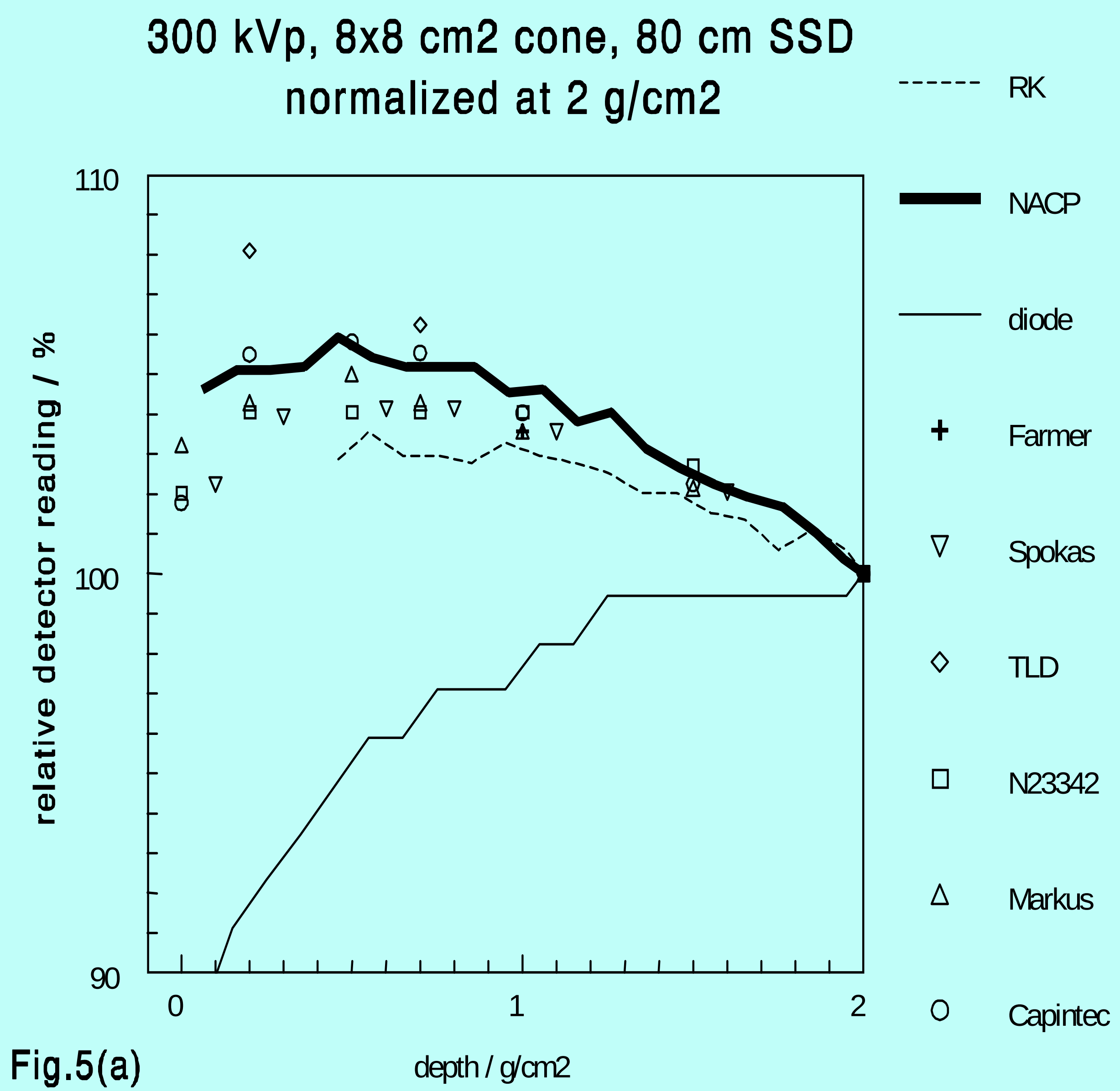
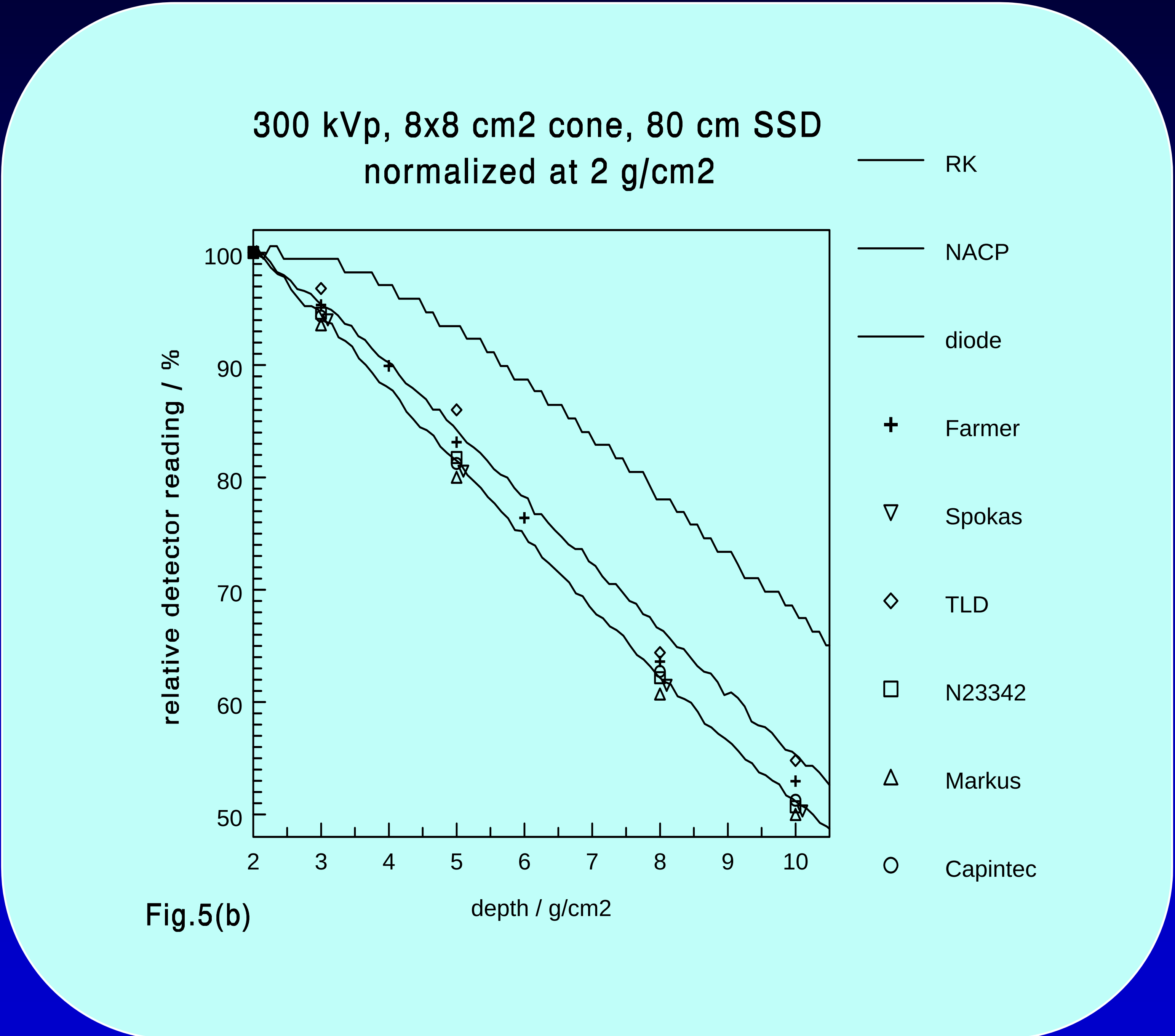

at 2.0 g/cm2 depth in phantom
normalized at 300 kVp
relative energy response
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
50
100
150
200
250
300
energy / kVp
Farmer
RK
NACP
Diode
Capintec
N23342
Markus
Spokas

Fig.1



300 kVp, 8x8 cm2 cone, 80 cm SSD
normalized at 2 g/cm2
110
100
90
relative detector reading / %
0
1
2
depth / g/cm2
RK
NACP
diode
Farmer
Spokas
TLD
N23342
Markus
Capintec

Fig.5(a)



300 kVp, 8x8 cm2 cone, 80 cm SSD
normalized at 2 g/cm2
relative detector reading / %
100
90
80
70
60
50
2
3
4
5
6
7
8
9
10
depth / g/cm2
RK
NACP
diode
Farmer
Spokas
TLD
N23342
Markus
Capintec

Fig.5(b)

Megavoltage Photon & Electron Calibration (The AAPM TG-51 Protocol)

- TG-51 applies to clinical reference dosimetry for external beam radiation therapy using ion chambers.
- Beam quality range: ^{60}Co - 50 MV for photons; 4 - 50 MeV for electrons

Beam quality range:	60Co - 50	MV for photons
	4 - 50	MeV for electrons

- A water phantom (at least 30cm x 30cm x 30cm) for clinical reference dosimetry, other phantom materials for routine checks and relative dosimetry measurements.
- A 1-mm (±20%) lead foil for photon beams

Megavoltage Photon & Electron Calibration (The AAPM TG-51 Protocol)

- Simplification compared to TG-21 (less tabulated data).

TG-21:

$$D_w = \overline{M} P_{ion} C_{cap} \left(\overline{L} / \rho\right)_{air}^{w} P_{wall} P_{repl} N_{gas}$$

TG-51:

$$D_w^Q = M k_Q N_{D,w}^{^{60}Co}$$

for photons:

$$D_w^Q = M_{raw} P_{ion} P_{TP} P_{elec} P_{pol} k_Q N_{D,w}^{^{60}Co}$$

for electrons:

$$D_w^Q = M_{raw} P_{TP} P_{pol} P_{ion} P_{elec} k_{R_{50}}^{'} k_{ecal} P_{gr}^Q N_{D,w}^{^{60}Co}$$

Beam Specification

Photon beam specification: %dd(10)x

%dd(10) : measured PDD at 10 cm depth in water for a 10cm x 10cm field at 100cm SSD

%dd(10)x : the photon component of the PDD at 10 cm depth in water for a 10cm x 10cm field at 100cm SSD

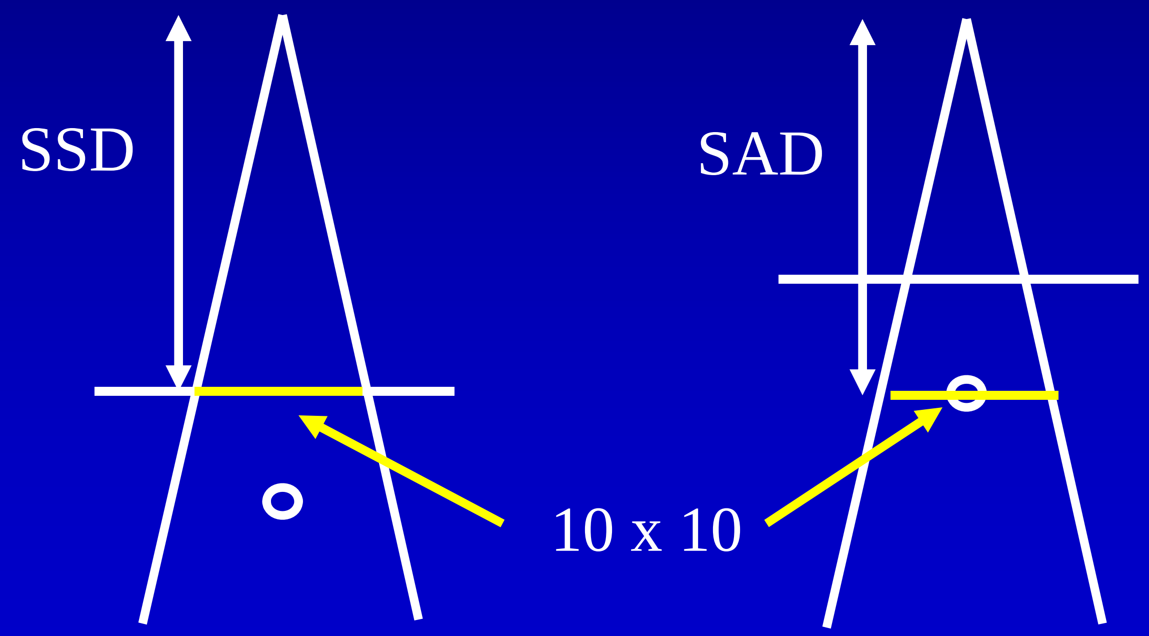
%dd(10)pb : the PDD at 10 cm depth in water for a 10cm x 10cm field at 100cm SSD with a 1 mm lead foil at about 50 cm from the phantom surface (or 30cm if 50cm clearance is not available)

Q: How to derive %dd(10)x?

Reference Conditions

Photon beam measurements:

The reference depth: $\mathbf{d}_{ref}$ = 10 cm depth in water for a 10cm x 10cm field at 100cm SSD or SAD.



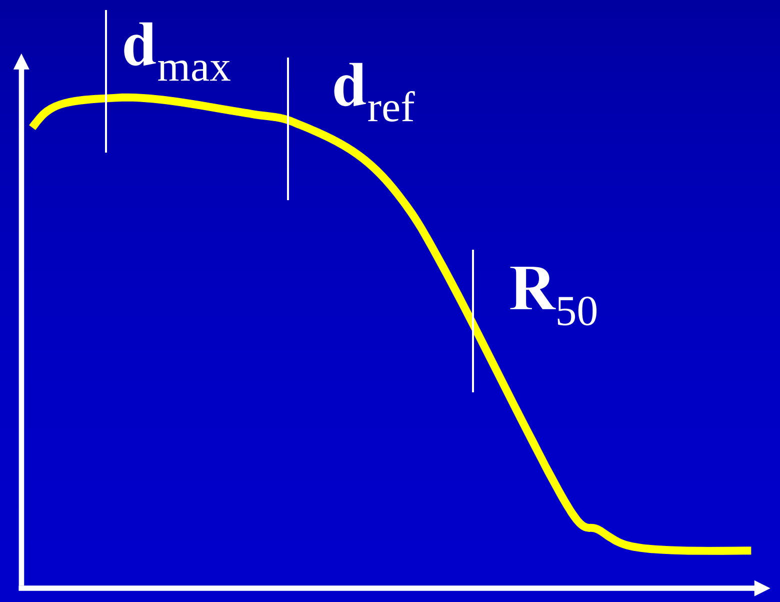
Reference Conditions

Electron beam measurements:

The reference depth: $\mathbf{d}_{ref} = 0.6\ \mathbf{R}_{50} - 0.1$ cm depth in water

The field size is 10x10 for E ≤ 20 MeV or 20x20 for E > 20 MeV

SSD = 90-110cm are allowed



Electron beam specification: R_{50}

R_{50}: the depth in water at which the absorbed dose falls to 50% of the maximum dose

I_{50}: the depth in water at which the measured ionization falls to 50% of the maximum ionization

$$R_{50} = 1.029 I_{50} - 0.06 \text{ (cm)}$$
$$\text{for } 2\text{cm} \leq I_{50} \leq 10\text{cm}$$

or

$$R_{50} = 1.059 I_{50} - 0.37 \text{ (cm)}$$
$$\text{for } I_{50} > 10\text{cm}$$

Questions:

- Can you describe the equipment need for MV photon and electron reference dosimetry?
- Can you describe the step-by-step procedure to Determine D_w in a photon beam?
- Can you describe the step-by-step procedure to Determine D_w in an electron beam?

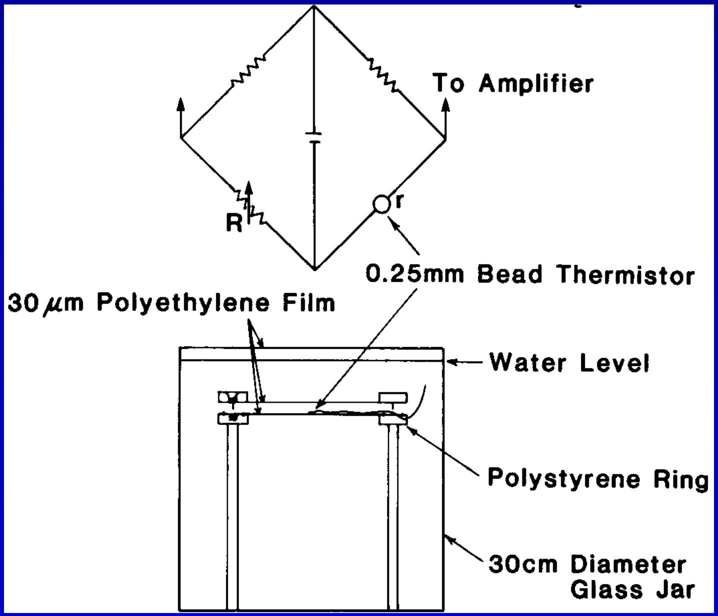
Q: Could you explain the physical meaning of the k_Q factor?

Measurement of Absorbed Dose

The specific heat of water is 1 cal/g/°C and 1 cal = 4.185 J.

The rise in temperature, ΔT produced by 1 Gy is

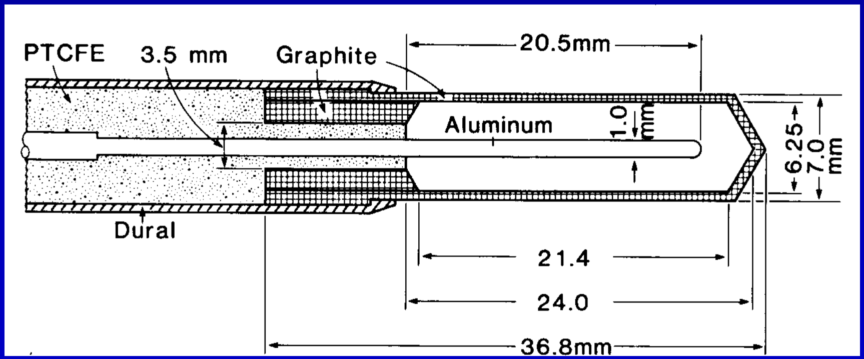
$$\Delta T = \frac{1}{4.185}\left(cal / kg^{-1}\right)\times\frac{1}{10^{3}}\left(cal^{-1} kg\,°C\right) = 2.389\times10^{-4}°C$$

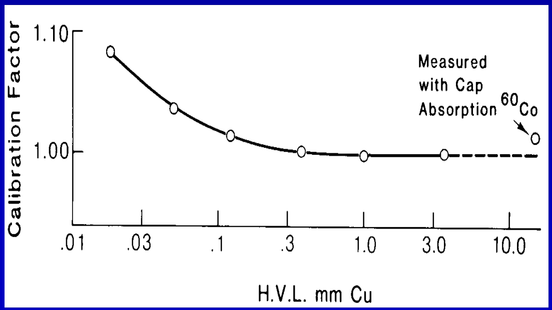


Steve Domen's water calorimeter

Ionization Chamber Dosimetry

Farmer chamber: the thimble wall is made of graphite and the central electrode is made of aluminum. The collecting volume of the chamber is nominally 0.6 cm^3.



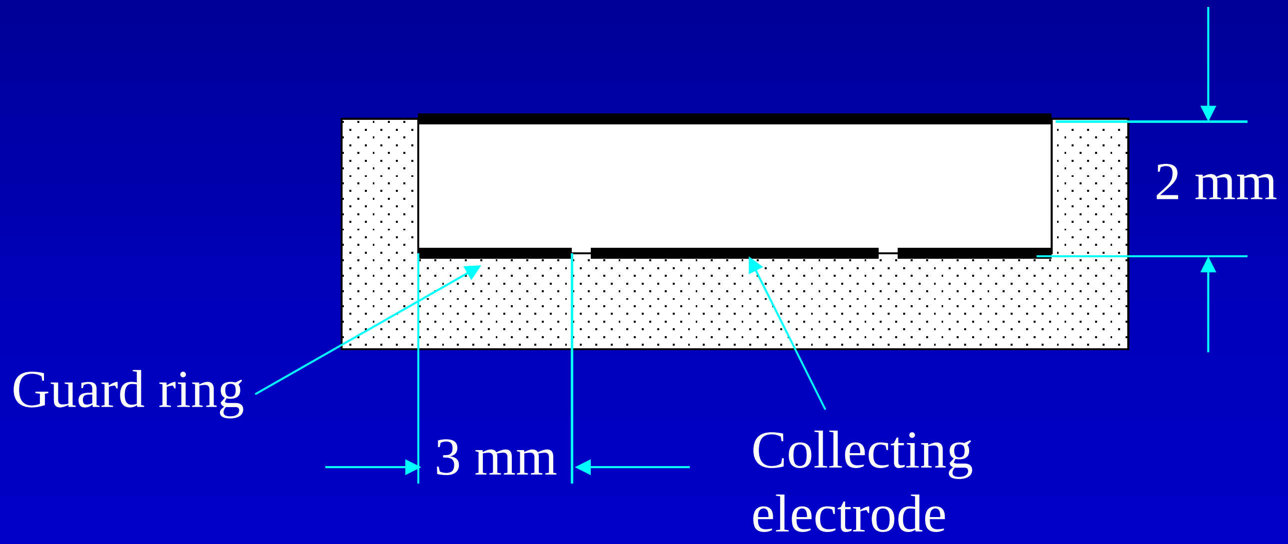


Energy response of a Farmer chamber

Can you describe the geometry and wire connection?

Ionization Chamber Dosimetry

Parallel-plate chamber: a parallel-plate chamber usually has a thin front wall (window) and a small electrode spacing.



What's the function of the 3 mm guard ring?

Charge Measurement

According to AAPM TG-51:

$$M = P_{ion} P_{TP} P_{elec} P_{pol} M_{raw}$$

Can you explain these P factors?

Questions:

- What’s chemical dosimetry? Can you describe Fricke dosimetry?
- What kind of solid detectors are commonly used for radiotherapy dosimetry?
- Can you describe how film, diode and TLD work, and their accuracy ?


I remember I read it
somewhere!!!

Acknowledgments

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