Chapter 3
Radiation Dosimeters

This set of 113 slides is based on Chapter 3 authored by
J. Izewska and G. Rajan
of the IAEA publication (ISBN 92-0-107304-6):
Radiation Oncology Physics:
A Handbook for Teachers and Students

Objective:

To familiarize students with the most important types and properties of dosimeters used in radiotherapy

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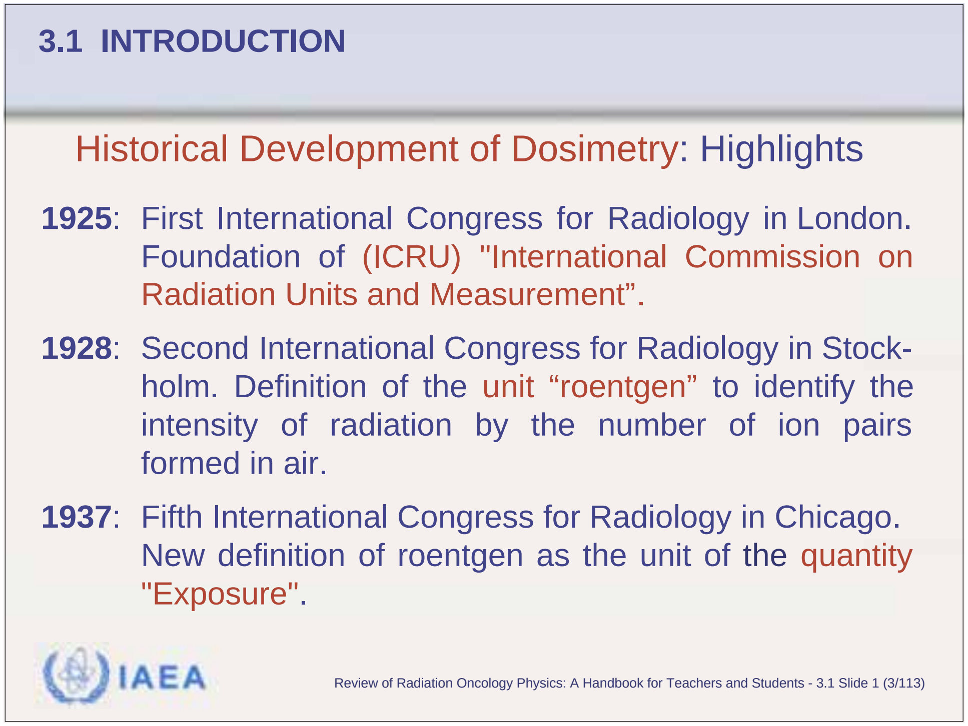


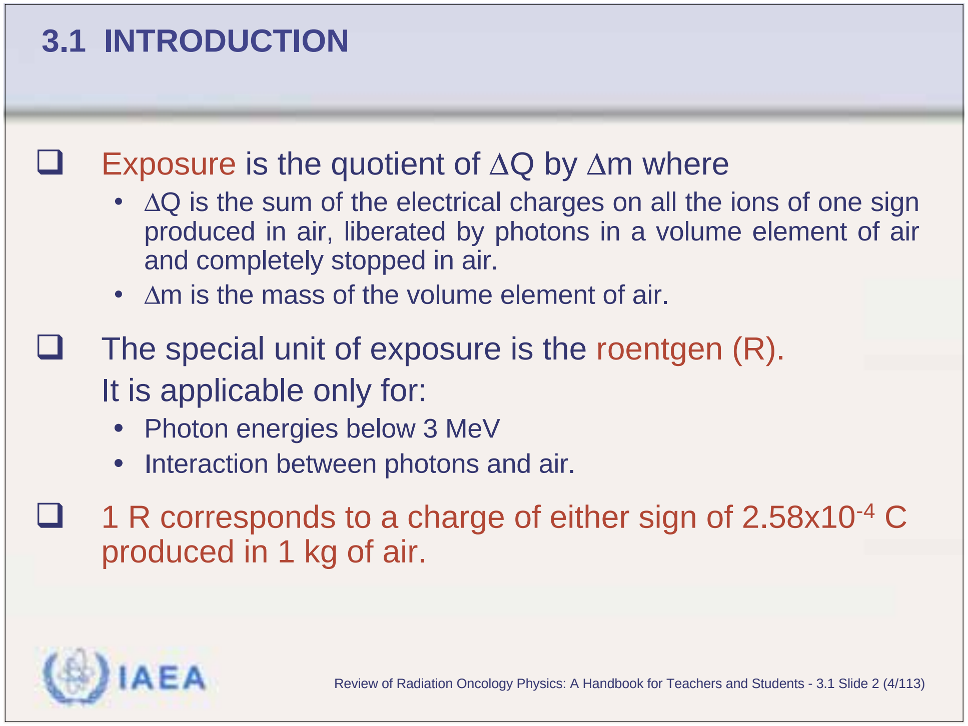
3.1 INTRODUCTION

Historical Development of Dosimetry: Highlights

1925: First International Congress for Radiology in London. Foundation of (ICRU) "International Commission on Radiation Units and Measurement”.

1928: Second International Congress for Radiology in Stockholm. Definition of the unit “roentgen” to identify the intensity of radiation by the number of ion pairs formed in air.

1937: Fifth International Congress for Radiology in Chicago. New definition of roentgen as the unit of the quantity "Exposure".



3.1 INTRODUCTION

- ☐ Exposure is the quotient of ΔQ by Δm where
  - ΔQ is the sum of the electrical charges on all the ions of one sign produced in air, liberated by photons in a volume element of air and completely stopped in air.
  - Δm is the mass of the volume element of air.
- ☐ The special unit of exposure is the roentgen (R). It is applicable only for:
  - Photon energies below 3 MeV
  - Interaction between photons and air.
- ☐ 1 R corresponds to a charge of either sign of 2.58×10^{-4} C produced in 1 kg of air.

3.1 INTRODUCTION

Historical Development of Dosimetry

1950: Definition of the dosimetric quantity absorbed dose as absorbed energy per mass.

The rad is the special unit of absorbed dose:

1 rad = 0.01 J/kg

1975: Definition of the new SI unit of dose the Gray (Gy) for the quantity absorbed dose:

1 Gy = 1 J/kg = 100 rad

3.1 INTRODUCTION

General requirements for dosimeters

- ☐ Dosimeter is a device that measures directly or indirectly
  - Exposure
  - Kerma
  - Absorbed dose
  - Equivalent dose
  - Or other related quantities.

- ☐ The dosimeter along with its reader is referred to as a dosimetry system.

3.1 INTRODUCTION

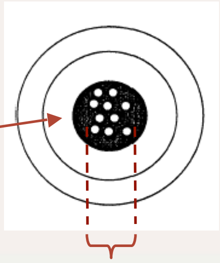
A useful dosimeter exhibits the following properties:

- High accuracy and precision
- Linearity of signal with dose over a wide range
- Small dose and dose rate dependence
- Flat Energy response
- Small directional dependence
- High spatial resolution
- Large dynamic range

3.2 PROPERTIES OF DOSIMETERS
3.2.1 Accuracy and precision

Accuracy specifies the proximity of the mean value of a measurement to the true value.

Precision specifies the degree of reproducibility of a measurement.

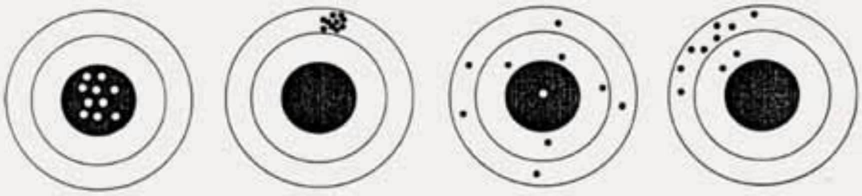


Note:
High precision
is equivalent to
small standard deviation.

3.2 PROPERTIES OF DOSIMETERS

3.2.1 Accuracy and precision

Examples for use of precision and accuracy:



High precision and High accuracy	High precision and Low accuracy	Low precision and High accuracy	Low precision and Low accuracy

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3.2 PROPERTIES OF DOSIMETERS

3.2.1 Accuracy and precision

Note: The accuracy and precision associated with a measurement is often expressed in terms of its

uncertainty.

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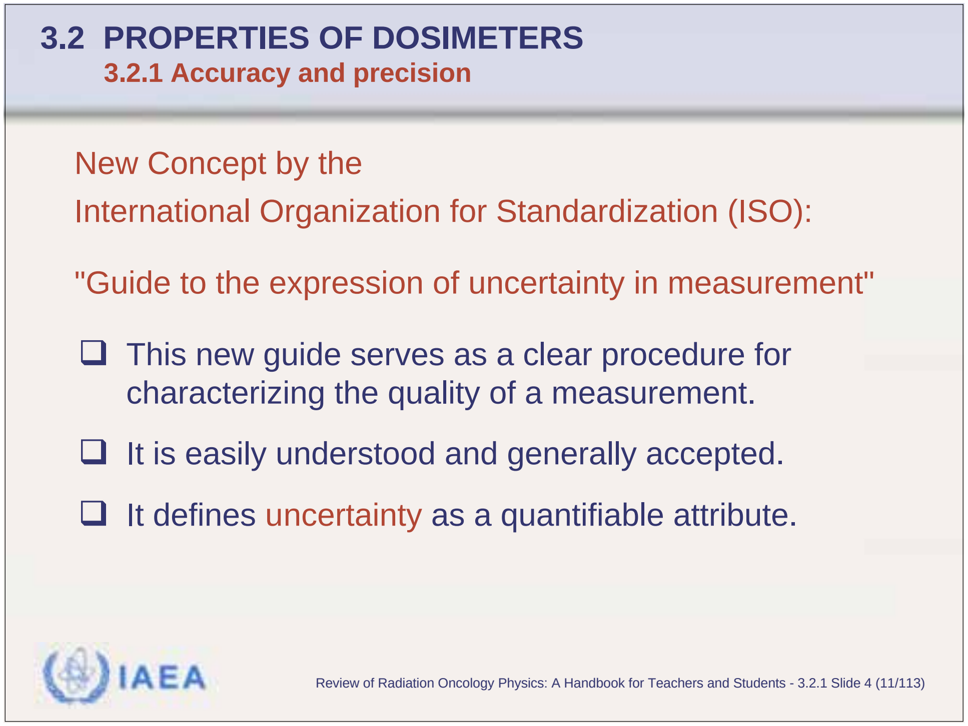


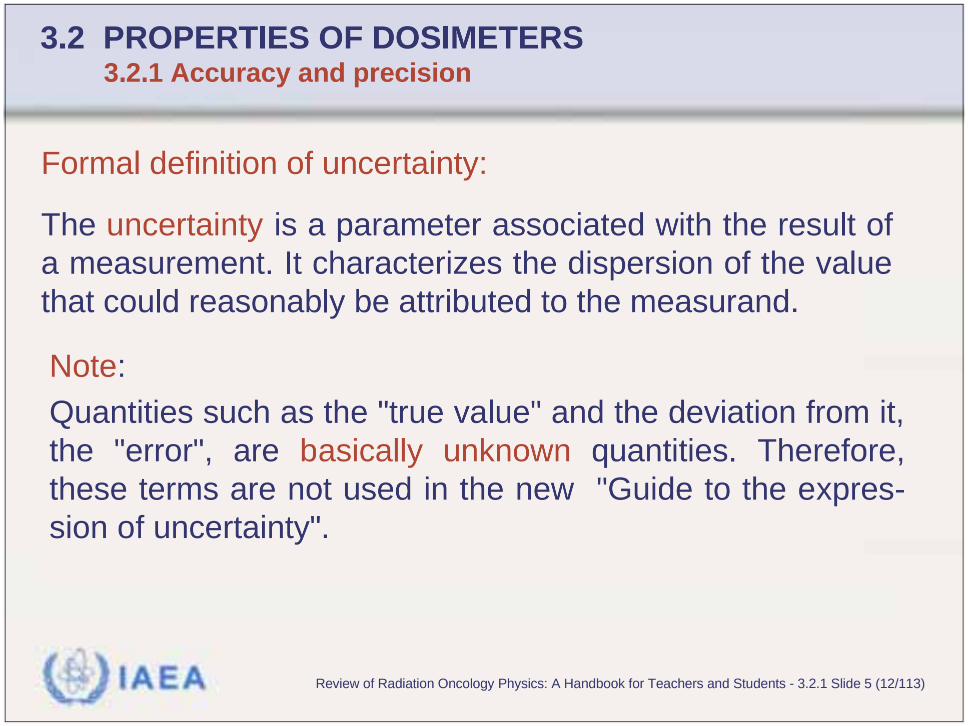
3.2 PROPERTIES OF DOSIMETERS

3.2.1 Accuracy and precision

New Concept by the
International Organization for Standardization (ISO):

"Guide to the expression of uncertainty in measurement"

- This new guide serves as a clear procedure for characterizing the quality of a measurement.
- It is easily understood and generally accepted.
- It defines uncertainty as a quantifiable attribute.



3.2 PROPERTIES OF DOSIMETERS

3.2.1 Accuracy and precision

Formal definition of uncertainty:

The uncertainty is a parameter associated with the result of a measurement. It characterizes the dispersion of the value that could reasonably be attributed to the measurand.

Note:

Quantities such as the "true value" and the deviation from it, the "error", are basically unknown quantities. Therefore, these terms are not used in the new "Guide to the expression of uncertainty".

3.2 PROPERTIES OF DOSIMETERS

3.2.1 Accuracy and precision

- ☐ Standard uncertainty:
  is the uncertainty of a result expressed as standard deviation.
- ☐ Type A standard uncertainty
  is evaluated by statistical analysis of a series of observations.
- ☐ Type B standard uncertainty
  is evaluated by means other than statistical analysis.

This classification is for convenience of discussion only.
It is not meant to indicate that there is a difference in the nature of the uncertainty such as random or systematic.

3.2 PROPERTIES OF DOSIMETERS

3.2.1 Accuracy and precision

- ☐ Type A standard uncertainties:

If a measurement of a dosimetric quantity *x* is repeated *N* times, then the best estimate for *x* is the arithmetic mean of all measurements x_i

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i$$

The standard deviation σ_x is used to express the uncertainty for an individual result x_i:

$$\sigma_x = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(x_i - \bar{x}\right)^2}$$

3.2 PROPERTIES OF DOSIMETERS

3.2.1 Accuracy and precision

- The standard deviation of the mean value is used to express the uncertainty for the best estimate:

$$\sigma_{\bar{x}} = \frac{1}{\sqrt{N}}\sigma_x = \sqrt{\frac{1}{N(N-1)}\sum_{i=1}^{N}(x_i - \bar{x})^2}$$

- The standard uncertainty of type A, denoted u_A, is defined as the standard deviation of the mean value

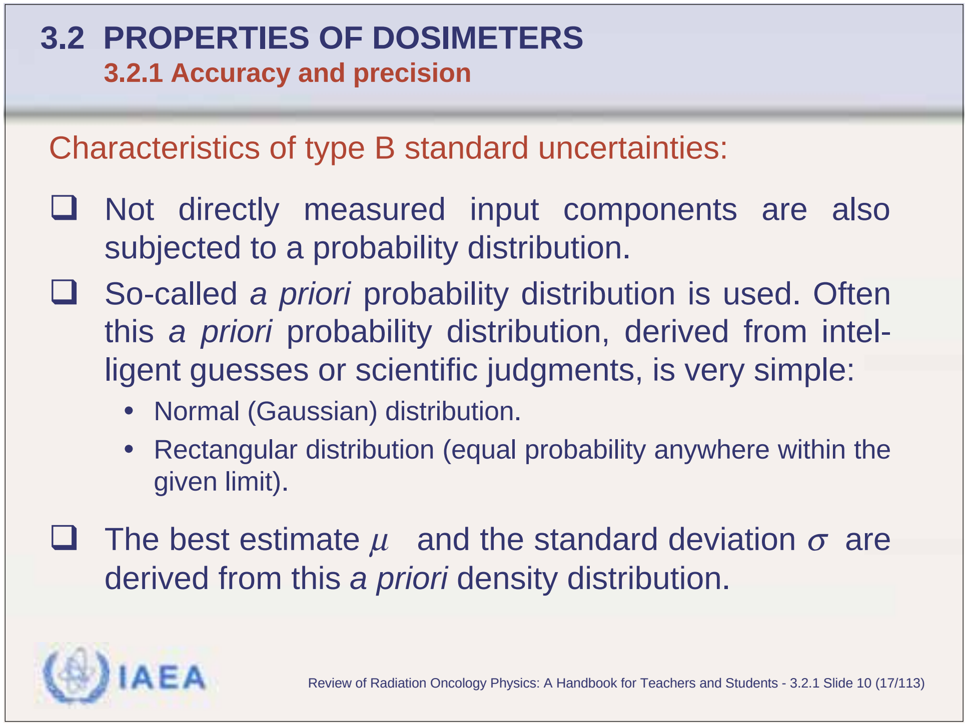
$$u_A = \sigma_{\bar{x}}$$

3.2 PROPERTIES OF DOSIMETERS

3.2.1 Accuracy and precision

Type B standard uncertainties:

- If the uncertainty of an input component cannot be estimated by repeated measurements, the determination must be based on other methods such as intelligent guesses or scientific judgments.
- Such uncertainties are called type B uncertainties and denoted as u_B.
- Type B uncertainties may be involved in:
  - Influence factors on the measuring process
  - Application of correction factors
  - Physical data taken from the literature



3.2 PROPERTIES OF DOSIMETERS

3.2.1 Accuracy and precision

Characteristics of type B standard uncertainties:

- Not directly measured input components are also subjected to a probability distribution.
- So-called *a priori* probability distribution is used. Often this *a priori* probability distribution, derived from intelligent guesses or scientific judgments, is very simple:
  - Normal (Gaussian) distribution.
  - Rectangular distribution (equal probability anywhere within the given limit).
- The best estimate μ and the standard deviation σ are derived from this *a priori* density distribution.

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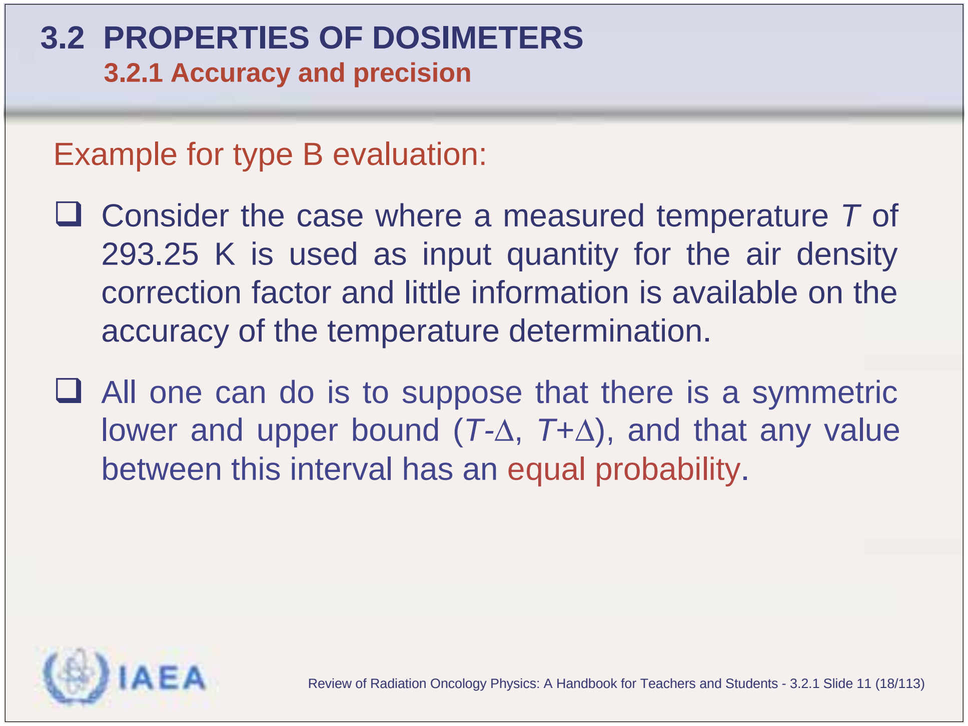

3.2 PROPERTIES OF DOSIMETERS

3.2.1 Accuracy and precision

Example for type B evaluation:

- Consider the case where a measured temperature T of 293.25 K is used as input quantity for the air density correction factor and little information is available on the accuracy of the temperature determination.
- All one can do is to suppose that there is a symmetric lower and upper bound (T-Δ, T+Δ), and that any value between this interval has an equal probability.

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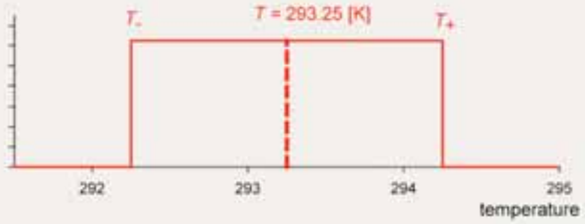
3.2 PROPERTIES OF DOSIMETERS

3.2.1 Accuracy and precision

Example (continued):

Lower bound: $T_- = T - \Delta$

Upper bound: $T_+ = T + \Delta$



3.2 PROPERTIES OF DOSIMETERS

3.2.1 Accuracy and precision

Example (continued):

Step 1: Construct the *a priority* probability density $p(x)$ for the temperature distribution:

$$p(x) = C \quad \text{for} \quad T - \Delta \le x \le T + \Delta$$
$$p(x) = 0 \quad \text{otherwise}$$

The integral $\int_{T-\Delta}^{T+\Delta} p(x)\mathrm{d}x$ must be unity.

$$\int_{T-\Delta}^{T+\Delta} p(x)\mathrm{d}x = C \cdot x\Big|_{T-\Delta}^{T+\Delta} \quad = \quad C \cdot 2\Delta$$

$$\boxed{\begin{aligned} &p(x) = 1/(2\Delta) \quad \text{for} \quad T - \Delta \le x \le T + \Delta \\ &p(x) = 0 \quad \text{otherwise} \end{aligned}}$$

3.2 PROPERTIES OF DOSIMETERS
3.2.1 Accuracy and precision

Example (continued):

Step 2: Calculate the mean (=best estimate) and the variance *v* of the temperature using that *p*(T)

$$\bar{x} = \int_{-\infty}^{+\infty} x \cdot p(x)\,\mathrm{d}x = \frac{1}{2\Delta}\int_{T-\Delta}^{T+\Delta} x\,\mathrm{d}x \quad = \quad T$$

$$v = \int_{-\infty}^{+\infty} (x-\bar{x})^2\, p(x)\,\mathrm{d}x = \frac{1}{2\Delta}\int_{T-\Delta}^{T+\Delta} (x-T)^2\,\mathrm{d}x = \frac{1}{3}\Delta^2$$

⇨ $$u_B = \sqrt{v} = \Delta / \sqrt{3}$$

3.2 PROPERTIES OF DOSIMETERS
3.2.1 Accuracy and precision

Combined uncertainties:

The determination of the final result is normally based on several components.

Example: Determination of the water absorbed dose $D_{w,Q}$ in a radiation beam of quality Q by use of an ionization chamber

$$D_{w,Q} = M_Q\, N_{D,w,Q_o}\, k_Q$$

where M_Q is the measured charge

$N_{D,w}$ is the calibration factor

k_Q is the beam quality correction factor

3.2 PROPERTIES OF DOSIMETERS

3.2.1 Accuracy and precision

Combined uncertainties (example cont):

The uncertainty of the charge M_Q can be assessed by statistical analysis of a series of observations ⇒ the uncertainty of M_Q is of type A

The uncertainties of $N_{D,w}$ and k_Q will be of type B

The combined uncertainty, u_C, of the absorbed dose $D_{w,Q}$ is the quadratic addition of type A and type B uncertainties:

$$u_C\left(D_{w,Q}\right) = \sqrt{u_A^2\left(M_Q\right) + u_B^2\left(N_{D,w,Q_o}\right) + u_B^2\left(k_Q\right)}$$

3.2 PROPERTIES OF DOSIMETERS

3.2.1 Accuracy and precision

☐ Expanded uncertainties

- The combined uncertainty is assumed to exhibit a normal distribution.
- The combined standard uncertainty u_C corresponds to a confidence level of 67% .
- A higher confidence level is obtained by multiplying u_C with a coverage factor denoted by k:

$$U = k \cdot u_C$$

- U is called the expanded uncertainty. For k = 2, the expanded uncertainty corresponds to the 95% confidence level.

3.2 PROPERTIES OF DOSIMETERS

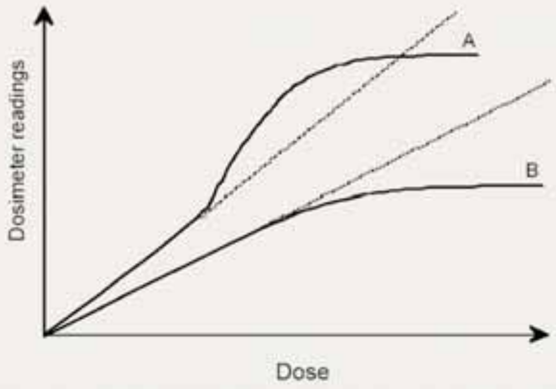
3.2.2 Linearity

- The dosimeter reading should be linearly proportional to the dosimetric quantity.
- Beyond a certain range, usually a non-linearity sets in.
- This effect depends on the type of dosimeter.

3.2 PROPERTIES OF DOSIMETERS

3.2.2 Linearity

Two possible cases



Case A:

- linearity
- supralinearity
- saturation

Case B:

- linearity
- saturation

3.2 PROPERTIES OF DOSIMETERS

3.2.3 Dose rate dependence

- ☐ *M/D* may be called the response of a dosimeter system
- ☐ When an integrated response $M = \int (M/D)(\mathrm{d}D/\mathrm{d}t)\,\mathrm{d}t$

  is measured, the dosimetric quantity should be independent of the dose rate d*D*/d*t* of the quantity.
- ☐ Other formulation:
  The response *M/D* should be constant for different dose rates $(\mathrm{d}D/\mathrm{d}t)_1$ and $(\mathrm{d}D/\mathrm{d}t)_2$.

$$M = (M/D)\int (\mathrm{d}D/\mathrm{d}t)\,\mathrm{d}t$$

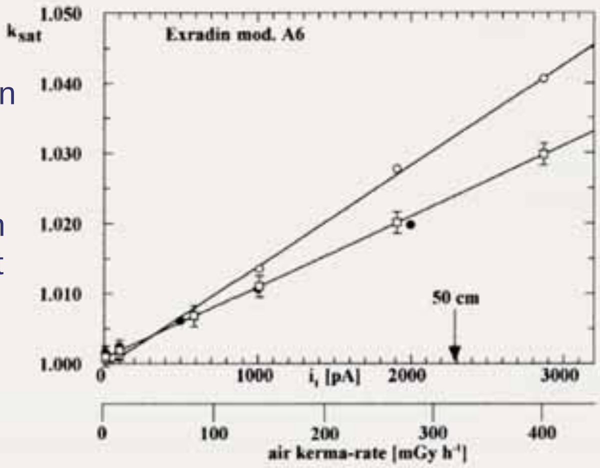
3.2 PROPERTIES OF DOSIMETERS

3.2.3 Dose rate dependence

Example:

The ion recombination effect is dose rate dependent.

This dependence can be taken into account by a correction factor that is a function of dose rate.



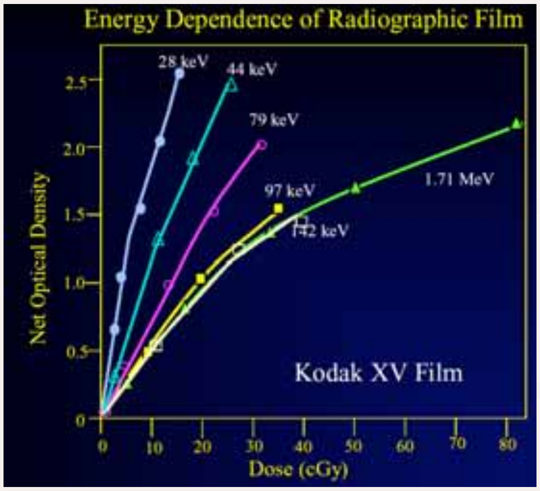
3.2 PROPERTIES OF DOSIMETERS

3.2.4 Energy dependence

The response of a dosimetric system is generally a function of the radiation energy.

Example 1:

Energy dependence of film dosimetry



3.2 PROPERTIES OF DOSIMETERS

3.2.4 Energy dependence

- ❑ The term "radiation quality" is often used to express a specific distribution of the energy of radiation.
- ❑ Therefore, a dependence on energy can also be called a dependence on radiation quality.
- ❑ Since calibration is done at a specified beam quality, a reading should generally be corrected if the user's beam quality is not identical to the calibration beam quality.

3.2 PROPERTIES OF DOSIMETERS

3.2.4 Energy dependence

- ❑ Example 2:
  - A well known example of energy dependence is the determination of absorbed dose by an ionization chamber calibrated in terms of absorbed dose to water in a calibration radiation quality (usually ^{60}Co beam)
  - The determination of absorbed dose in a user's beam which is different from a ^{60}Co beam requires a quality correction factor.

$$D_{w,Q} = M_Q \; N_{D,w,Q_o} \; k_Q$$

quality correction factor

3.2 PROPERTIES OF DOSIMETERS

3.2.5 Directional dependence

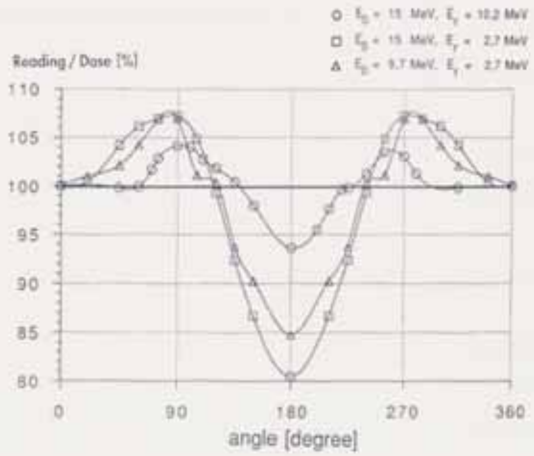
- ❑ The variation in response as a function of the angle of the incidence of the radiation is called the directional dependence of a dosimeter.
- ❑ Due to construction details and physical size, dosimeters usually exhibit a certain directional dependence.

3.2 PROPERTIES OF DOSIMETERS

3.2.5 Directional dependence

Example:

Directional dependence
of a plane-parallel
ionization chamber



3.2 PROPERTIES OF DOSIMETERS

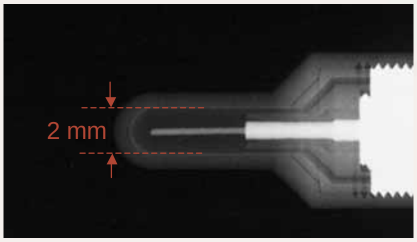
3.2.6 Spatial resolution and physical size

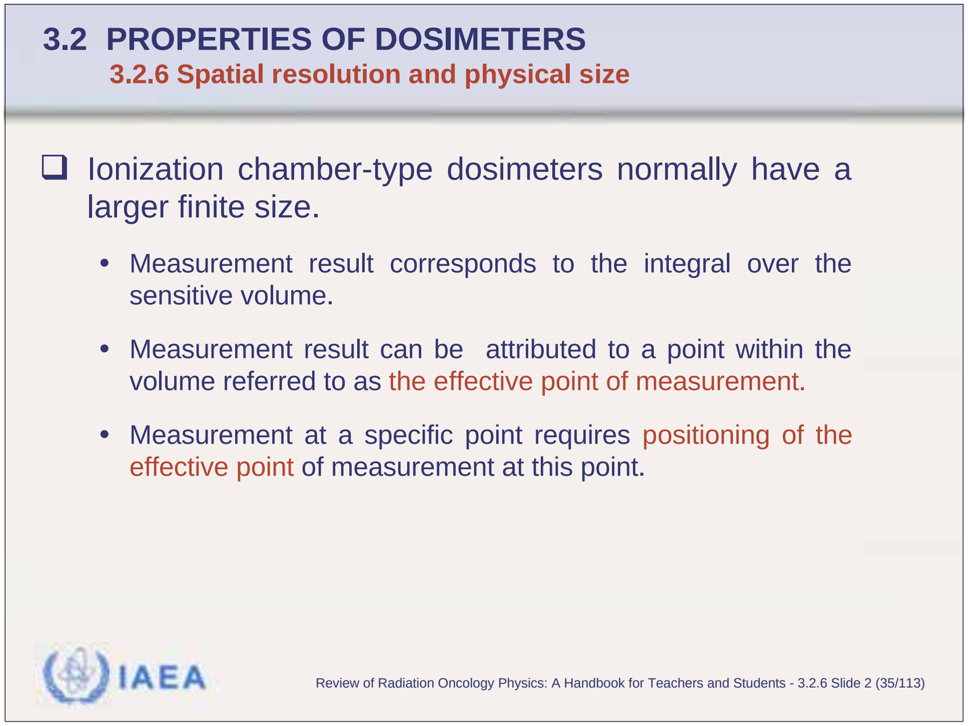
☐ The quantity absorbed dose is a point quantity

☐ Ideal measurement requires a point-like detector

☐ Examples that approximate a ‘point’ measurement are:

- TLD
- Film, gel, where the ‘point’ is defined by the resolution of the read-out system)
- Pin-point micro-chamber →



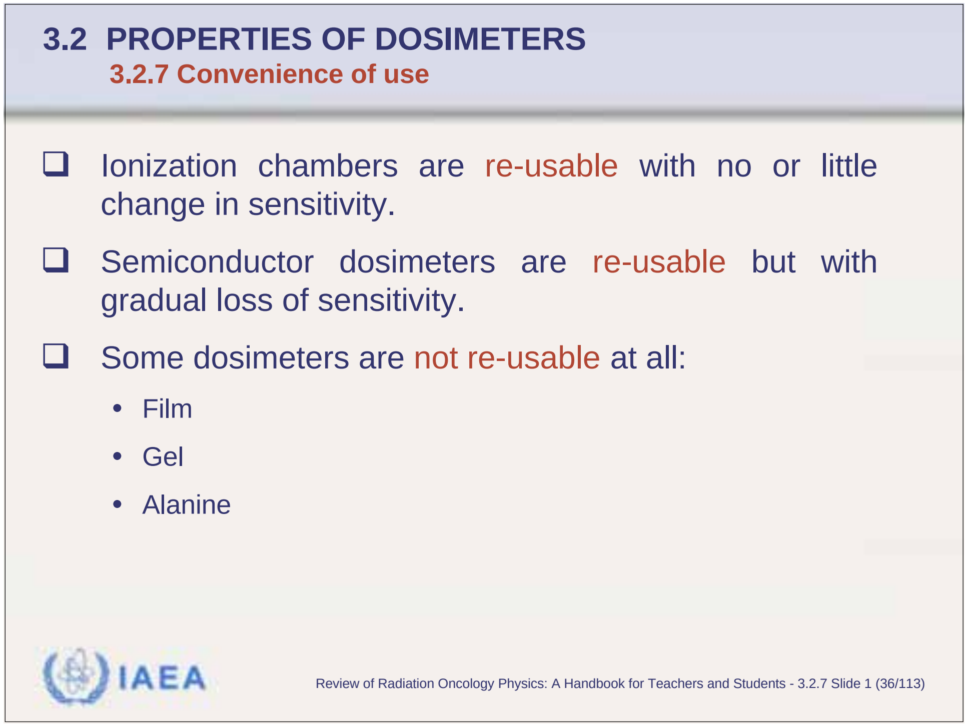


3.2 PROPERTIES OF DOSIMETERS

3.2.6 Spatial resolution and physical size

❑ Ionization chamber-type dosimeters normally have a larger finite size.

- Measurement result corresponds to the integral over the sensitive volume.
- Measurement result can be attributed to a point within the volume referred to as the effective point of measurement.
- Measurement at a specific point requires positioning of the effective point of measurement at this point.



3.2 PROPERTIES OF DOSIMETERS

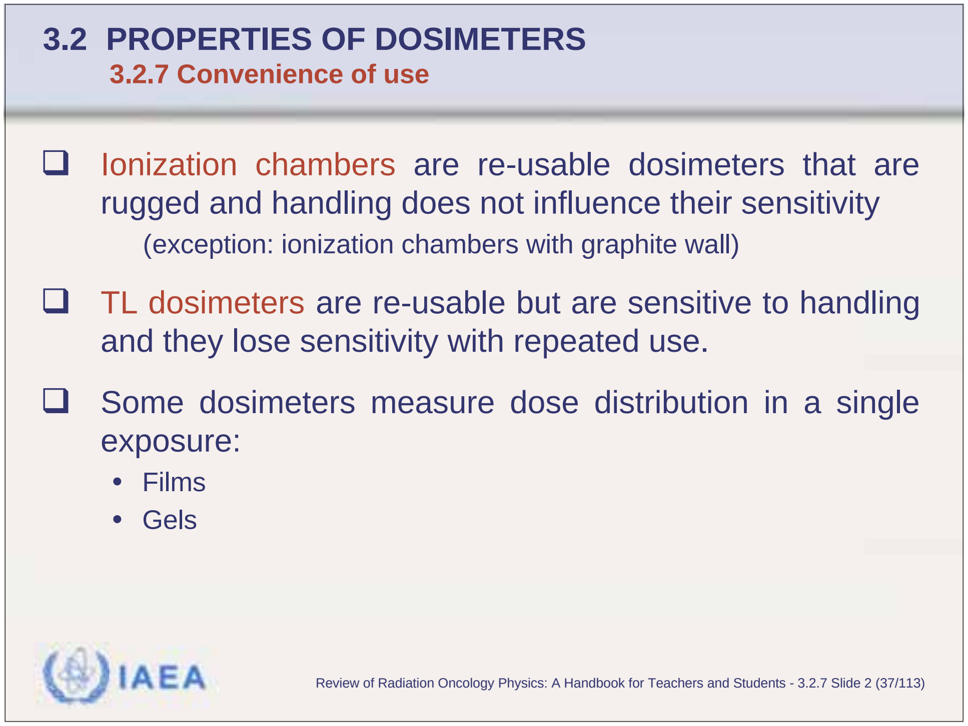
3.2.7 Convenience of use

❑ Ionization chambers are re-usable with no or little change in sensitivity.

❑ Semiconductor dosimeters are re-usable but with gradual loss of sensitivity.

❑ Some dosimeters are not re-usable at all:

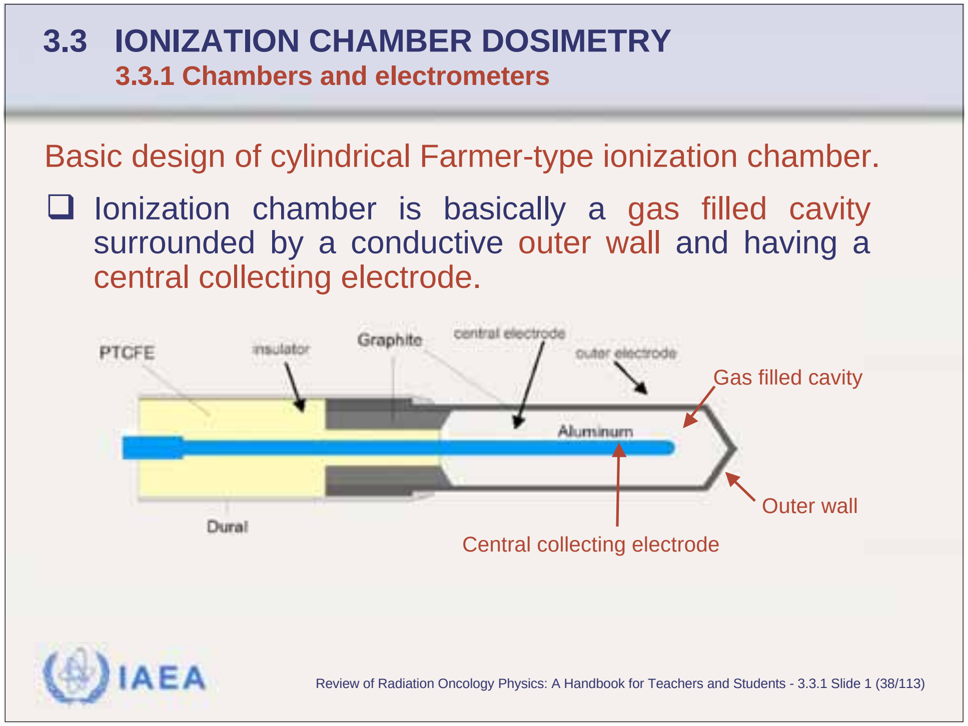
- Film
- Gel
- Alanine



3.2 PROPERTIES OF DOSIMETERS

3.2.7 Convenience of use

- ❑ Ionization chambers are re-usable dosimeters that are rugged and handling does not influence their sensitivity
  (exception: ionization chambers with graphite wall)
- ❑ TL dosimeters are re-usable but are sensitive to handling and they lose sensitivity with repeated use.
- ❑ Some dosimeters measure dose distribution in a single exposure:
  - Films
  - Gels



3.3 IONIZATION CHAMBER DOSIMETRY

3.3.1 Chambers and electrometers

Basic design of cylindrical Farmer-type ionization chamber.

- ❑ Ionization chamber is basically a gas filled cavity surrounded by a conductive outer wall and having a central collecting electrode.

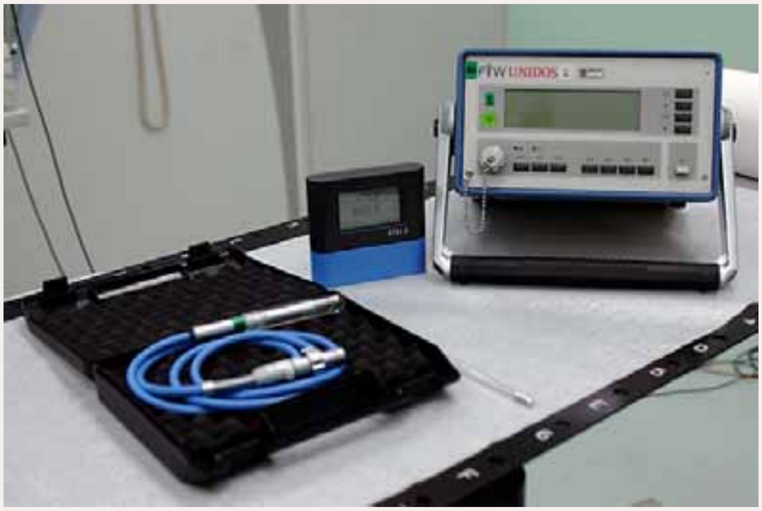
3.3 IONIZATION CHAMBER DOSIMETRY

3.3.1 Chambers and electrometers

- The wall and the collecting electrode are separated with a high quality insulator to reduce the leakage current when a polarizing voltage is applied to the chamber.
- A guard electrode is usually provided in the chamber to further reduce chamber leakage.
- The guard electrode intercepts the leakage current and allows it to flow to ground directly, bypassing the collecting electrode.
- The guard electrode ensures improved field uniformity in the active or sensitive volume of the chamber
(for better charge collection).

3.3 IONIZATION CHAMBER DOSIMETRY

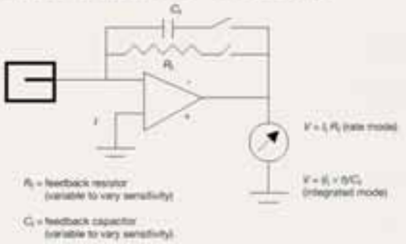
3.3.1 Chambers and electrometers



3.3 IONIZATION CHAMBER DOSIMETRY

3.3.1 Chambers and electrometers

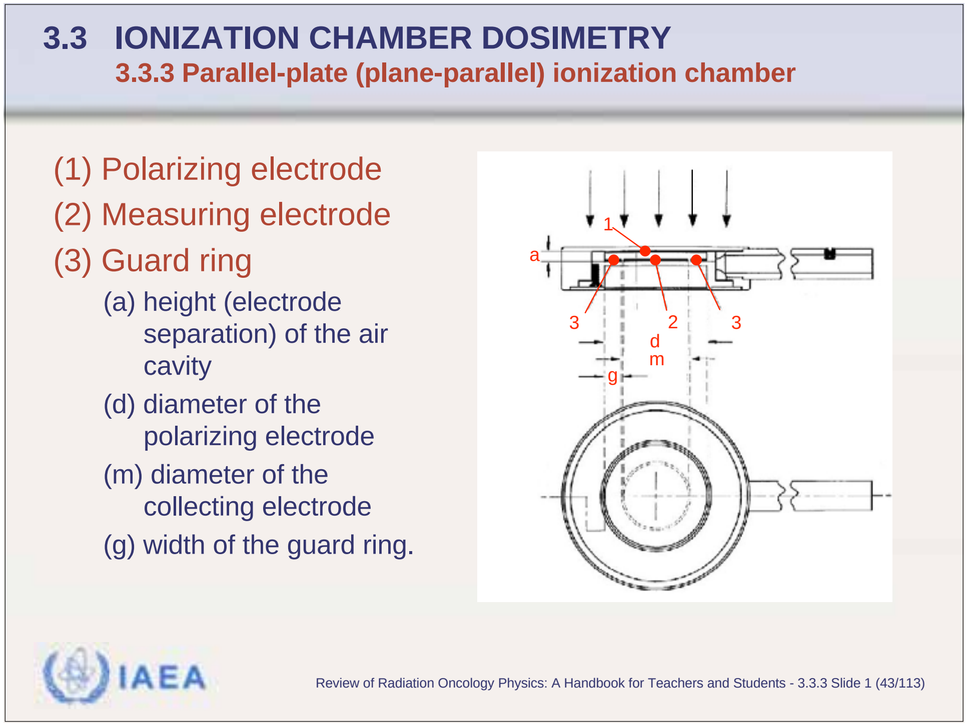
- An electrometer is a high gain, negative feedback, operational amplifier with a standard resistor or a standard capacitor in the feedback path to measure the chamber current and charge, respectively, collected over a fixed time interval.



3.3 IONIZATION CHAMBER DOSIMETRY

3.3.2 Cylindrical (thimble type) ionization chamber

- Cylindrical (thimble) ionization chamber
  - Most popular design
  - Independent of radial beam direction
  - Typical volume between 0.05 -1.00 cm^3
  - Typical radius ~2-7 mm
  - Length~ 4-25 mm
  - Thin walls: ~0.1 g/cm^2
  - Used for:
    electron, photon, proton,
    or ion beams.



3.3 IONIZATION CHAMBER DOSIMETRY

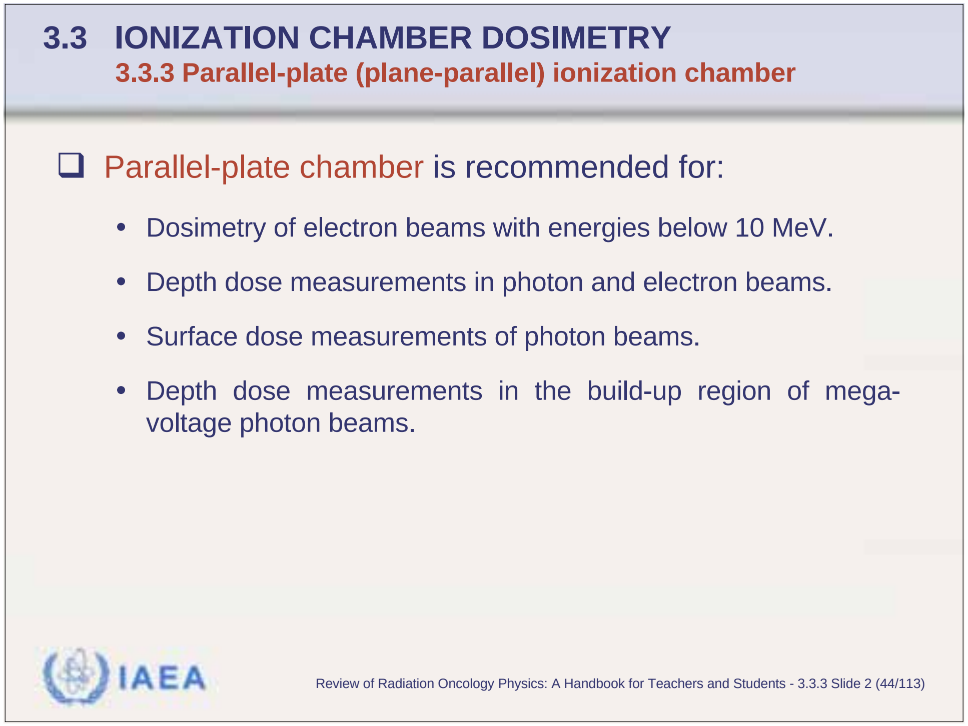
3.3.3 Parallel-plate (plane-parallel) ionization chamber

(1) Polarizing electrode

(2) Measuring electrode

(3) Guard ring

- (a) height (electrode separation) of the air cavity
- (d) diameter of the polarizing electrode
- (m) diameter of the collecting electrode
- (g) width of the guard ring.



3.3 IONIZATION CHAMBER DOSIMETRY

3.3.3 Parallel-plate (plane-parallel) ionization chamber

☐ Parallel-plate chamber is recommended for:

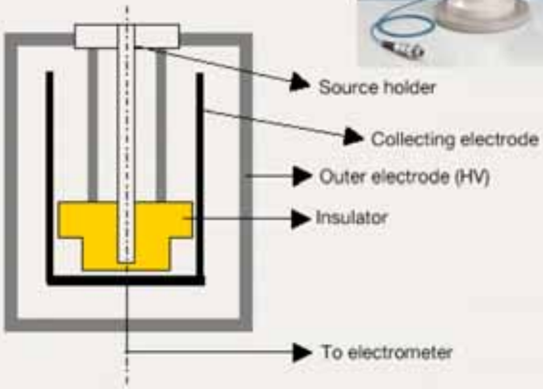
- Dosimetry of electron beams with energies below 10 MeV.
- Depth dose measurements in photon and electron beams.
- Surface dose measurements of photon beams.
- Depth dose measurements in the build-up region of mega-voltage photon beams.

3.3 IONIZATION CHAMBER DOSIMETRY

3.3.4 Brachytherapy chamber

- ❑ High sensitivity (useful for low rate sources as used in brachytherapy)
- ❑ Large volumes (about 250 cm^3)
- ❑ Can be designed to accommodate various sources sizes
- ❑ Usually calibrated in terms of the reference air kerma rate

Well type chamber



3.3 IONIZATION CHAMBER DOSIMETRY

3.3.5 Extrapolation chambers

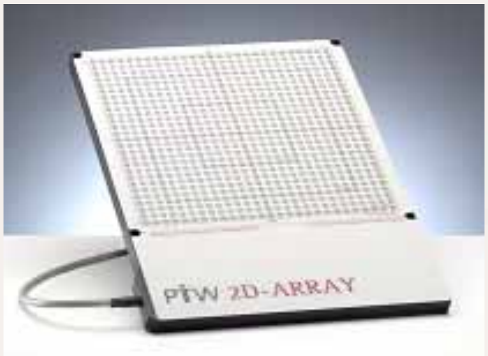
- ❑ Extrapolation chambers are parallel-plate chambers with a variable electrode separation.
- ❑ They can be used in absolute radiation dosimetry (when embedded into a tissue equivalent phantom).
- ❑ Cavity perturbation for electrons can be eliminated by:
  - Making measurements as a function of the cavity thickness
  - Extrapolating electrode separation to zero.
- ❑ Using this chamber, the cavity perturbation for parallel-plate chambers of finite thickness can be estimated.

3.3 IONIZATION CHAMBER DOSIMETRY

3.3.6 Segmented chamber

Segmented chamber (example)

- 729 ionization chambers
- Volume of each: 5 mm x 5 mm x 4 mm
- Calibrated in terms of absorbed dose
- Commercialized software available



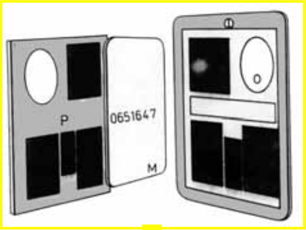
3.4 FILM DOSIMETRY

3.4.1 Radiographic film

Radiographic X-ray film performs important functions, e.g. in:

Radiotherapy

Radiation Protection



Diagnostic radiology

3.4 FILM DOSIMETRY

3.4.1 Radiographic film

Typical applications of a radiographic film in radiotherapy:

- ❑ Qualitative and quantitative dose measurements (including electron beam dosimetry)
- ❑ Quality control of radiotherapy machines
  - congruence of light and radiation fields
  - determination of the position of a collimator axis
  - dose profile at depth in phantom
  - the so called star-test
- ❑ Verification of treatment techniques in various phantoms
- ❑ Portal imaging.

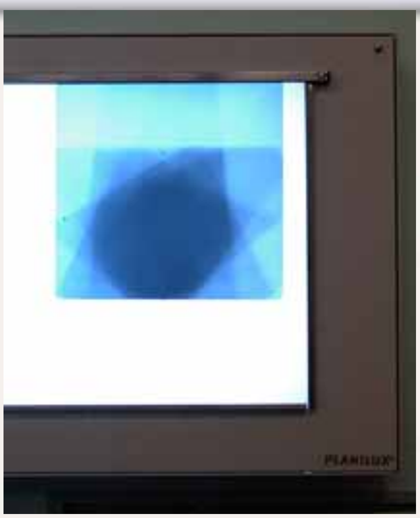
Important aspect:
Film has also an archival property

3.4 FILM DOSIMETRY

3.4.1 Radiographic film

Typical applications of a radiographic film in radiotherapy:

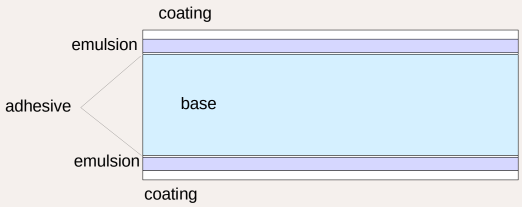
Verification of treatment techniques in various phantoms.

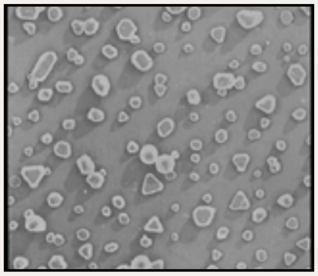


3.4 FILM DOSIMETRY
3.4.1 Radiographic film

Principle:

- ☐ A thin plastic base layer (200 μm) is covered with a sensitive emulsion of AgBr crystals in gelatine (10-20 μm).





Electron micrograph of AgBr grains in gelatine with size of 0.1-3 μm

---

3.4 FILM DOSIMETRY
3.4.1 Radiographic film

Principle (cont.):

- ☐ During irradiation, the following reaction is caused (simplified):
  - Ag Br is ionized
  - Ag^+ ions are reduced to Ag: $Ag^+ + e^- \rightarrow Ag$
  - The elemental silver is black and produces a so-called latent image.
- ☐ During the development, other silver ions (yet not reduced) are now also reduced in the presence of silver atoms.
- ☐ This means: If one silver atom in a silver bromide crystal is reduced, all silver atoms in this crystal will be reduced during development.
- ☐ The rest of the silver bromide (in undeveloped grains) is washed away from the film during the fixation process.

3.4 FILM DOSIMETRY

3.4.1 Radiographic film

- ☐ Light transmission is a function of the film opacity and can be measured in terms of optical density (OD) with devices called densitometers.
- ☐ The OD is defined as $OD = \log_{10}\left(\frac{I_0}{I}\right)$ and is a function of dose, where

  I_0 is the initial light intensity, and
  I is the intensity transmitted through the film.
- ☐ Film gives excellent 2-D spatial resolution and, in a single exposure, provides information about the spatial distribution of radiation in the area of interest or the attenuation of radiation by intervening objects.

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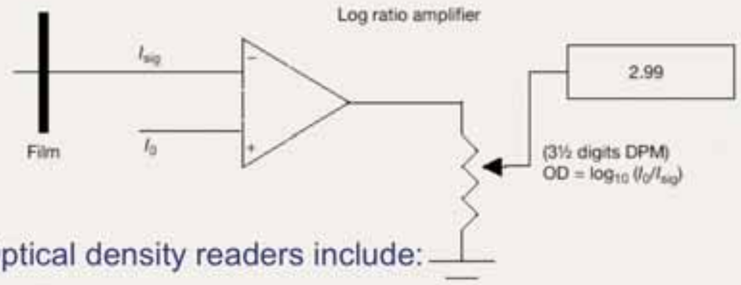
3.4 FILM DOSIMETRY

3.4.1 Radiographic film

Principle of operation of a simple film densitometer



Optical density readers include:

Film densitometers
Laser densitometers
Automatic film scanners.

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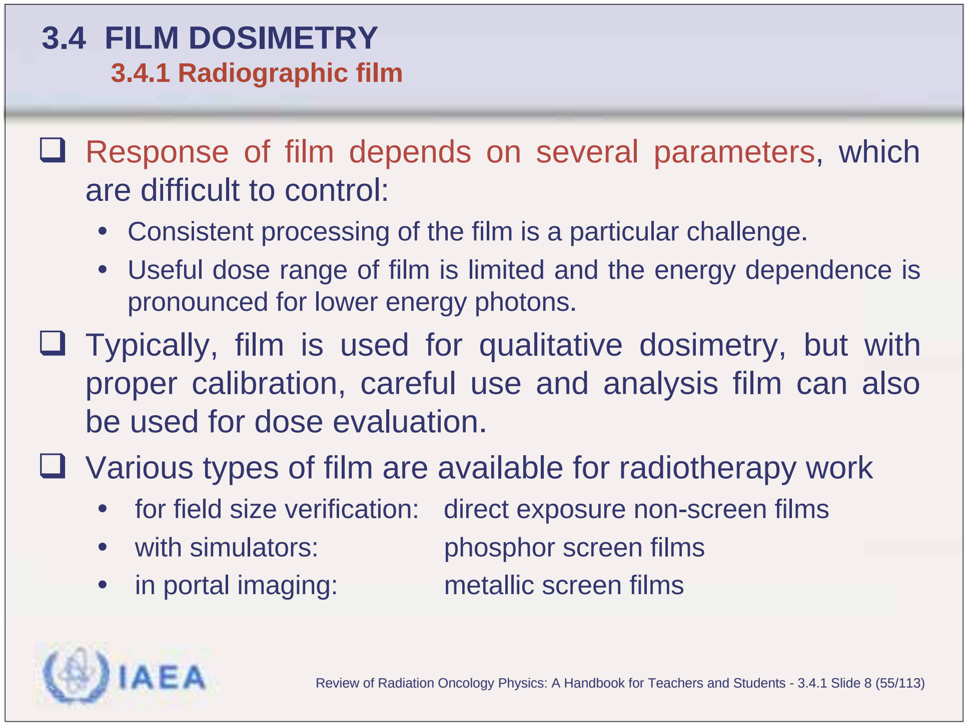
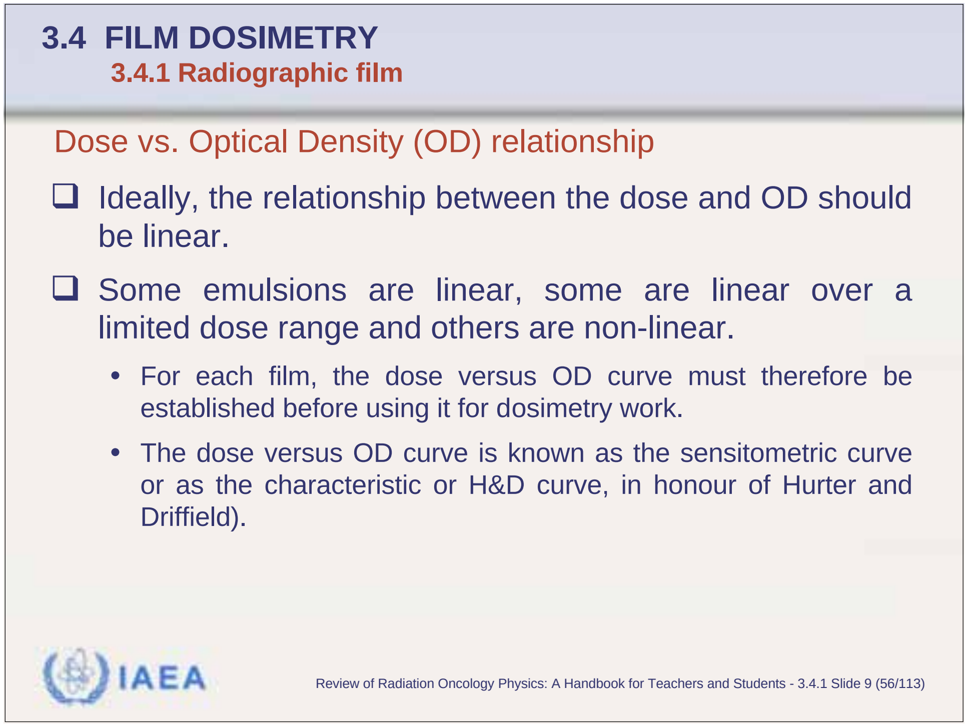


3.4 FILM DOSIMETRY

3.4.1 Radiographic film

- ❑ Response of film depends on several parameters, which are difficult to control:
  - Consistent processing of the film is a particular challenge.
  - Useful dose range of film is limited and the energy dependence is pronounced for lower energy photons.
- ❑ Typically, film is used for qualitative dosimetry, but with proper calibration, careful use and analysis film can also be used for dose evaluation.
- ❑ Various types of film are available for radiotherapy work

• for field size verification:	direct exposure non-screen films
• with simulators:	phosphor screen films
• in portal imaging:	metallic screen films



3.4 FILM DOSIMETRY

3.4.1 Radiographic film

Dose vs. Optical Density (OD) relationship

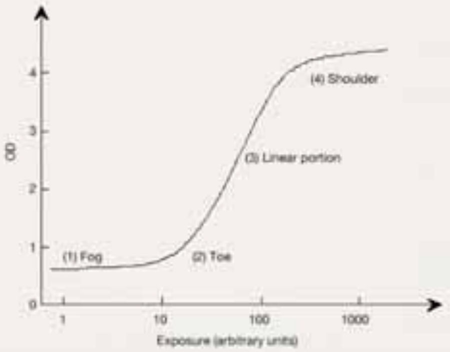
- ❑ Ideally, the relationship between the dose and OD should be linear.
- ❑ Some emulsions are linear, some are linear over a limited dose range and others are non-linear.
  - For each film, the dose versus OD curve must therefore be established before using it for dosimetry work.
  - The dose versus OD curve is known as the sensitometric curve or as the characteristic or H&D curve, in honour of Hurter and Driffield).

3.4 FILM DOSIMETRY

3.4.1 Radiographic film

Parameters of radiographic films based on H&D curve

- ❑ Gamma: slope of the linear part
- ❑ Latitude: range of exposures that fall in the linear part
- ❑ Speed: exposure required to produce an OD >1 over the fog
- ❑ Fog: OD of unexposed film



3.4 FILM DOSIMETRY

3.4.2 Radiochromic film

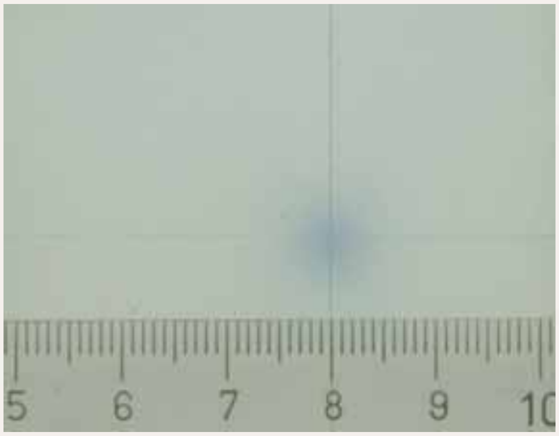
- ❑ Radiochromic film is a new type of film well suited for radiotherapy dosimetry.
- ❑ This film type is self-developing, requiring
  - Neither a developer
  - Nor a fixer.
- ❑ Principle: Radiochromic film contains a special dye that is polymerized and develops a blue color upon exposure to radiation.
- ❑ Similarly to radiographic film, the radiochromic film dose response is determined with a suitable densitometer.

3.4 FILM DOSIMETRY

3.4.2 Radiochromic film

Example (QA Test of target positioning at a Gamma Knife):

Blue color produced by the focused radiation in a Gamma Knife.



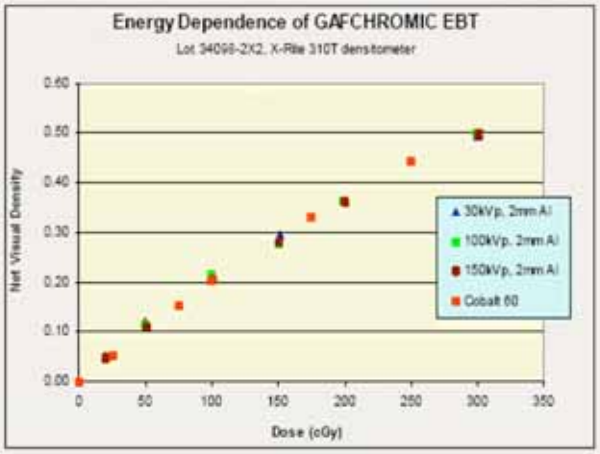
3.4 FILM DOSIMETRY

3.4.2 Radiochromic film

- ☐ The most commonly used radiochromic film type is the GafChromic film. It is a colourless film with a nearly tissue equivalent composition (9.0% hydrogen, 60.6% carbon, 11.2% nitrogen and 19.2% oxygen).
    - Data on various characteristics of GafChromic radiochromic films (e.g., sensitivity, linearity, uniformity, reproducibility, post-irradiation stability, etc.) are available in the literature (see also AAPM Task Group 55).
    - It is expected that the radiochromic film will play an increasingly important role film dosimetry

3.4 FILM DOSIMETRY

3.4.2 Radiochromic film



3.4 FILM DOSIMETRY

3.4.2 Radiochromic film

Advantages

- ❑ No quality control on film processing needed.
- ❑ Radiochromic film is grainless
  ⇒ very high resolution
- ❑ Useful in high dose gradient regions for dosimetry such as in:
  - Stereotactic fields
  - Vicinity of brachytherapy sources
- ❑ Dose rate independence
- ❑ Better energy characteristics except for low energy x rays (25 kV)

Disadvantages

- ❑ GafChromic films are generally less sensitive than radiographic films

3.5 LUMINESCENCE DOSIMETRY

- Upon absorption of radiation, some materials retain part of the absorbed energy in metastable states.
- When this energy is subsequently released in the form of ultraviolet, visible or infrared light, this phenomenon is called

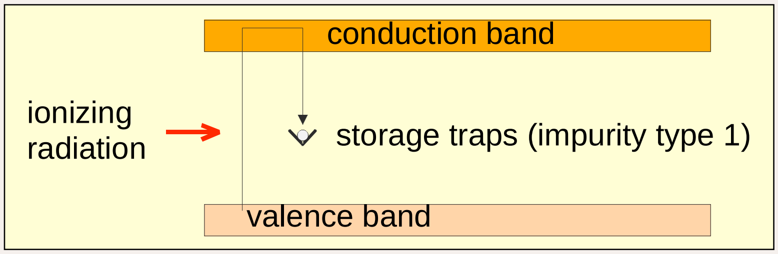
Luminescence

3.5 LUMINESCENCE DOSIMETRY

- There are two types of luminescence:
  - Fluorescence
  - Phosphorescence
- The difference depends on the time delay between the stimulation and the emission of light:
  - Fluorescence has a time delay between 10^{-10} to 10^{-8} s.
  - Phosphorescence has a time delay exceeding 10^{-8} s.

3.5 LUMINESCENCE DOSIMETRY

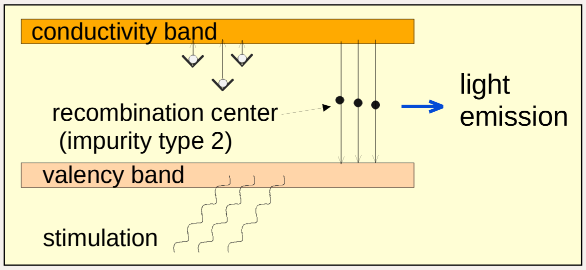
Principle**:**



- ❑ Upon radiation, free electrons and holes are produced
- ❑ In a luminescence material, there are so-called storage traps
- ❑ Free electrons and holes will either recombine immediately or become trapped (at any energy between valence and conduction band)

3.5 LUMINESCENCE DOSIMETRY

Principle (cont.):



- ❑ Upon stimulation, the probability increases for the electrons to be raised to the conduction band ….
- ❑ and to release energy (light) when they combine with a positive hole (needs an impurity of type 2)

3.5 LUMINESCENCE DOSIMETRY

- The process of luminescence can be accelerated with a suitable excitation in the form of heat or light.
- If the exciting agent is heat, the phenomenon is known as thermoluminescence
- When used for purposes of dosimetry, the material is called
  - Thermoluminescent (TL) material

  or
  - Thermoluminescent dosimeter (TLD).

3.5 LUMINESCENCE DOSIMETRY

- The process of luminescence can be accelerated with a suitable excitation in the form of heat or light.
- If the exciting agent is light, the phenomenon is referred to as optically stimulated luminescence (OSL)

3.5 LUMINESCENCE DOSIMETRY

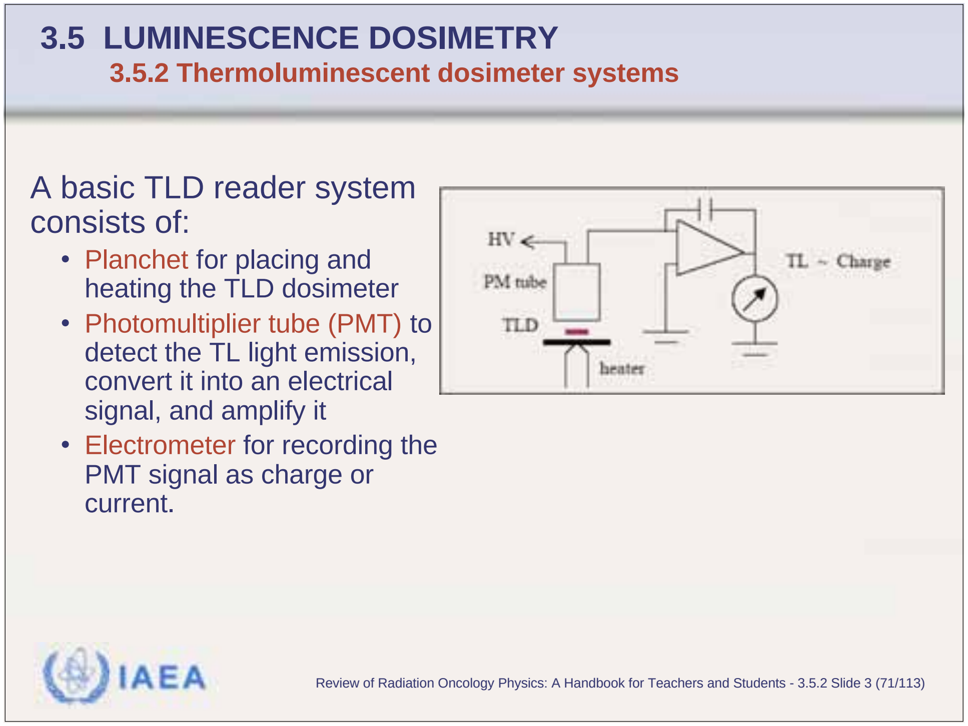
3.5.1 Thermoluminescence

- Thermoluminescence (TL) is thermally activated phosphorescence
- Its practical applications range from radiation dosimetry to archeological pottery dating (natural impurities in fired clay and storage process by natural irradiation which starts just after firing).
- Useful literature (from 1968):
  CAMERON JR, SUNTHARALINGAM N, KENNEY GK:
  “Thermoluminescent dosimetry”
  University of Wisconsin Press, Madison, Wisconsin

3.5 LUMINESCENCE DOSIMETRY

3.5.2 Thermoluminescent dosimeter systems

- TL dosimeters most commonly used in medical applications are (because of their tissue equivalence):
  - LiF:Mg,Ti
  - LiF:Mg,Cu,P
  - $Li_2B_4O_7$:Mn
- Other TLDs are (because of their high sensitivity):
  - $CaSO_4$:Dy
  - Al_2O_3:C
  - CaF_2:Mn
- TLDs are available in various forms (e.g., powder, chip, rod, ribbon, etc.).
- Before use TLDs have to be annealed to erase any residual signal.

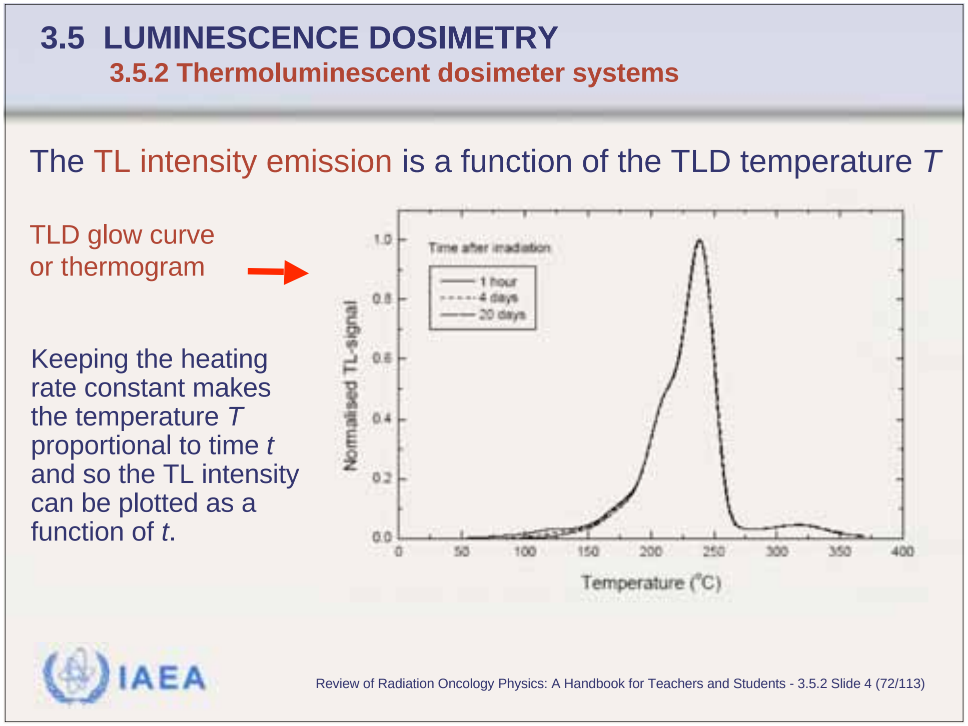


3.5 LUMINESCENCE DOSIMETRY

3.5.2 Thermoluminescent dosimeter systems

A basic TLD reader system consists of:

- Planchet for placing and heating the TLD dosimeter
- Photomultiplier tube (PMT) to detect the TL light emission, convert it into an electrical signal, and amplify it
- Electrometer for recording the PMT signal as charge or current.



3.5 LUMINESCENCE DOSIMETRY

3.5.2 Thermoluminescent dosimeter systems

The TL intensity emission is a function of the TLD temperature *T*

TLD glow curve or thermogram →

Keeping the heating rate constant makes the temperature *T* proportional to time *t* and so the TL intensity can be plotted as a function of *t*.

3.5 LUMINESCENCE DOSIMETRY

3.5.2 Thermoluminescent dosimeter systems

- ☐ The main dosimetric peak of the LiF:Mg,Ti glow curve is between 180° and 260°C; this peak is used for dosimetry.
- ☐ TL dose response is linear over a wide range of doses used in radiotherapy, however:
  - In higher dose region it increases exhibiting supralinear behaviour
  - at even higher doses it saturates
- ☐ To derive the absorbed dose from the TL-reading after calibration, correction factors have to be applied:
  - Energy correction
  - Fading
  - Dose-response non-linearity corrections

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3.5 LUMINESCENCE DOSIMETRY

3.5.2 Thermoluminescent dosimeter systems

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3.5 LUMINESCENCE DOSIMETRY

3.5.3 Optically stimulated luminescence systems

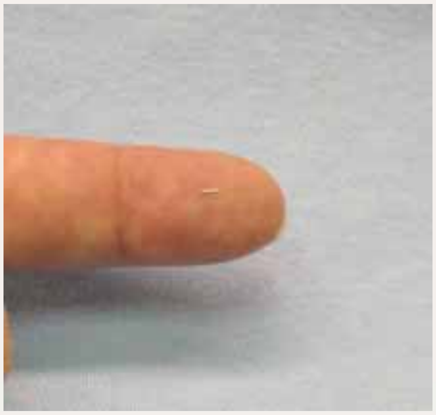
☐ Optically-stimulated luminescence (OSL) is based on a principle similar to that of the TLD. Instead of heat, light (from a laser) is used to release the trapped energy in the form of luminescence.

- OSL is a novel technique offering a potential for *in vivo* dosimetry in radiotherapy.
- A further novel development is based on the excitation by a pulsed laser (POSL)
- The most promising material is Al_2O_3:C
- To produce OSL, the chip is excited with a laser light through an optical fiber and the resulting luminescence (blue light) is carried back in the same fiber, reflected through a 90° by a beam-splitter and measured in a photomultiplier tube.

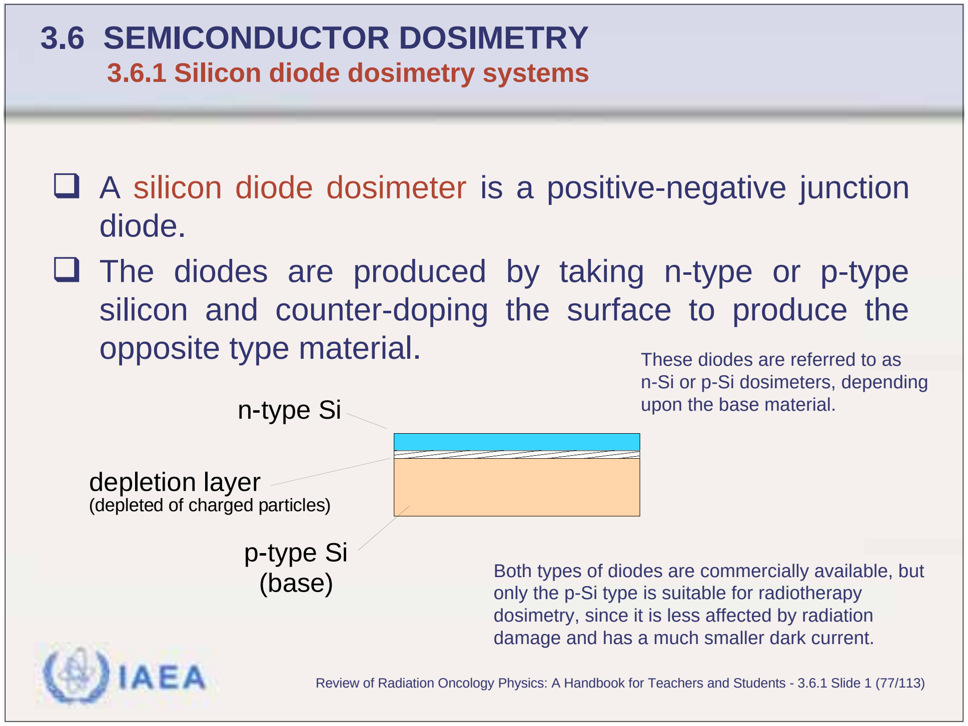
3.5 LUMINESCENCE DOSIMETRY

3.5.3 Optically stimulated luminescence systems

Crystal: 0.4 mm x 3 mm



Optical fiber read out



3.6 SEMICONDUCTOR DOSIMETRY
3.6.1 Silicon diode dosimetry systems

- ☐ A silicon diode dosimeter is a positive-negative junction diode.
- ☐ The diodes are produced by taking n-type or p-type silicon and counter-doping the surface to produce the opposite type material.

These diodes are referred to as n-Si or p-Si dosimeters, depending upon the base material.

n-type Si

depletion layer
(depleted of charged particles)

p-type Si
(base)

Both types of diodes are commercially available, but only the p-Si type is suitable for radiotherapy dosimetry, since it is less affected by radiation damage and has a much smaller dark current.

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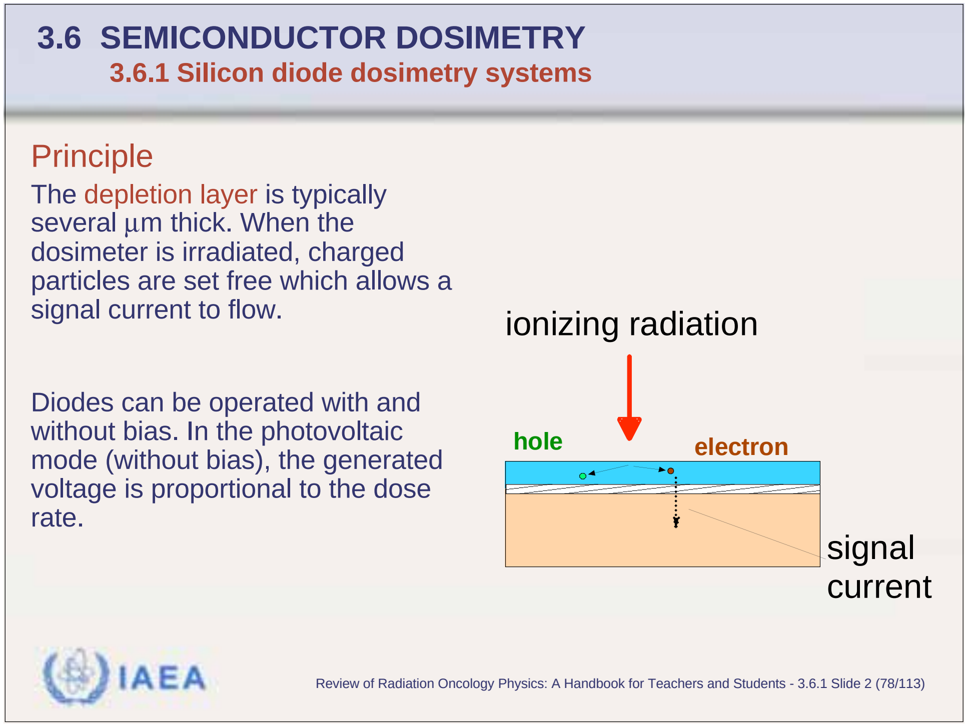

3.6 SEMICONDUCTOR DOSIMETRY
3.6.1 Silicon diode dosimetry systems

Principle

The depletion layer is typically several μm thick. When the dosimeter is irradiated, charged particles are set free which allows a signal current to flow.

Diodes can be operated with and without bias. In the photovoltaic mode (without bias), the generated voltage is proportional to the dose rate.

ionizing radiation

hole

electron

signal
current

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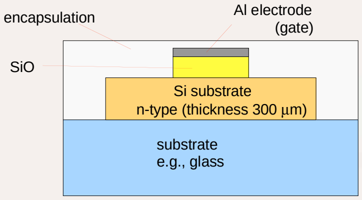
3.6 SEMICONDUCTOR DOSIMETRY

3.6.1 Silicon diode dosimetry systems

3.6 SEMICONDUCTOR DOSIMETRY

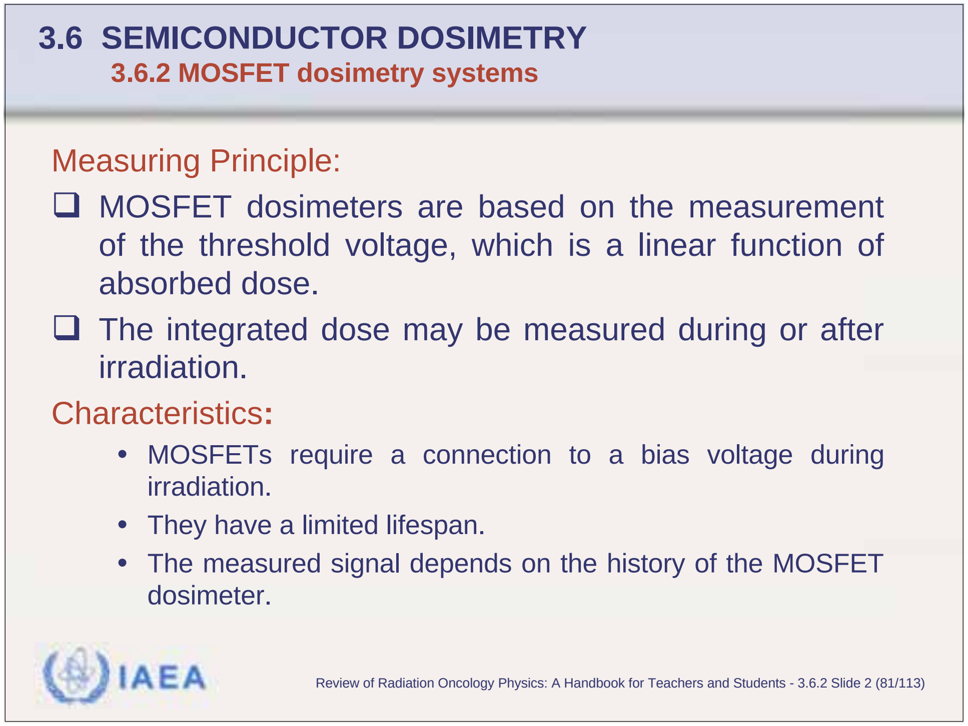
3.6.2 MOSFET dosimetry systems

❑ A MOSFET dosimeter is a Metal-Oxide Semiconductor Field Effect Transistor.



Physical principle:

- Ionizing radiation generates charge carriers in the Si oxide.
- The charge carries moves towards the silicon substrate where they are trapped.
- This leads to a charge buildup causing a change in threshold voltage between the gate and the silicon substrate.



3.6 SEMICONDUCTOR DOSIMETRY

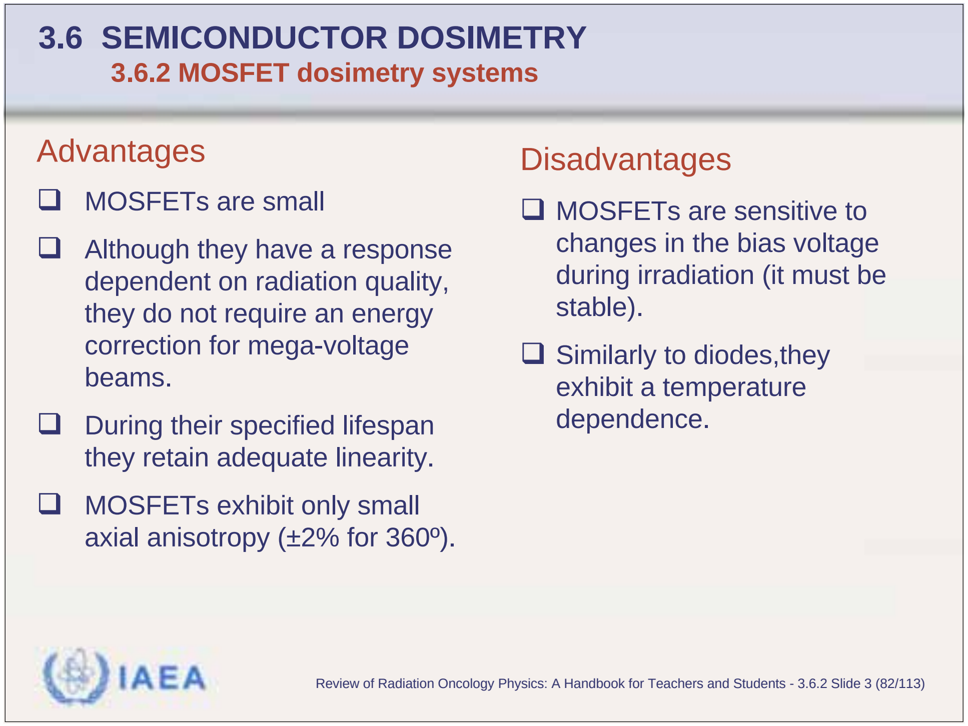
3.6.2 MOSFET dosimetry systems

Measuring Principle:

- MOSFET dosimeters are based on the measurement of the threshold voltage, which is a linear function of absorbed dose.
- The integrated dose may be measured during or after irradiation.

Characteristics**:**

- MOSFETs require a connection to a bias voltage during irradiation.
- They have a limited lifespan.
- The measured signal depends on the history of the MOSFET dosimeter.



3.6 SEMICONDUCTOR DOSIMETRY

3.6.2 MOSFET dosimetry systems

Advantages

- MOSFETs are small
- Although they have a response dependent on radiation quality, they do not require an energy correction for mega-voltage beams.
- During their specified lifespan they retain adequate linearity.
- MOSFETs exhibit only small axial anisotropy (±2% for 360º).

Disadvantages

- MOSFETs are sensitive to changes in the bias voltage during irradiation (it must be stable).
- Similarly to diodes,they exhibit a temperature dependence.

3.7 OTHER DOSIMETRY SYSTEMS

3.7.1 Alanine/electron paramagnetic resonance dos. systems

- An alanine dosimeter is an amino acid, pressed in the form of rods or pellets with an inert binding material.
- The dosimeter can be used at a level of about 10 Gy or more with sufficient precision for radiotherapy dosimetry.

3.7 OTHER DOSIMETRY SYSTEMS

3.7.1 Alanine/electron paramagnetic resonance dos. systems

Principle**:**

- The radiation interaction results in the formation of alanine radicals
- The concentration of the radicals can be measured using an electron paramagnetic resonance (known also as electron spin resonance) spectrometer.
- The intensity is measured as the peak to peak height of the central line in the spectrum.
- The readout is non-destructive.

3.7 OTHER DOSIMETRY SYSTEMS

3.7.1 Alanine/electron paramagnetic resonance dos. systems

Advantages

- Alanine is tissue equivalent.
- It requires no energy correction within the quality range of typical therapeutic beams.
- It exhibits very little fading for many months after irradiation.

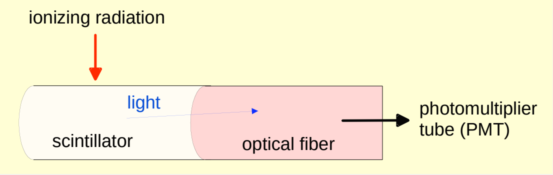
Disadvantages

- The response depends on environmental conditions during irradiation (temperature) and storage (humidity).
- Alanine has a low sensitivity.

3.7 OTHER DOSIMETRY SYSTEMS

3.7.2 Plastic scintillator dosimetry system

- Plastic scintillators are also a new development in radiotherapy dosimetry.



- The light generated in the scintillator is carried away by an optical fibre to a PMT (outside the irradiation room).
- Requires two sets of optical fibres, which are coupled to two different PMTs, allowing subtraction of the background Cerenkov radiation from the measured signal.

3.7 OTHER DOSIMETRY SYSTEMS

3.7.2 Plastic scintillator dosimetry system

Advantages

- The response is linear in the therapeutic dose range.
- Plastic scintillators are almost water equivalent.
- They can be made very small (about 1 mm^3 or less)
- They can be used in cases where high spatial resolution is required:
  - High dose gradient regions
  - Buildup regions
  - Interface regions
  - Small field dosimetry
  - Regions very close to brachytherapy sources.

3.7 OTHER DOSIMETRY SYSTEMS

3.7.2 Plastic scintillator dosimetry system

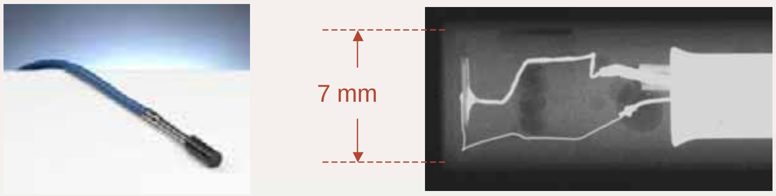
Advantages (cont.)

- Due to flat energy dependence and small size, they are ideal dosimeters for brachytherapy applications.
- Dosimetry based on plastic scintillators is characterized by good reproducibility and long term stability.
- They are independent of dose rate and can be used from 10 mGy/min (ophthalmic plaque dosimetry) to about 10 Gy/min (external beam dosimetry).
- They have no significant directional dependence and need no ambient temperature or pressure corrections.

3.7 OTHER DOSIMETRY SYSTEMS

3.7.3 Diamond dosimeters

- ☐ Diamonds change their resistance upon radiation exposure. Under a biasing potential, the resulting current is proportional to the dose rate of radiation.
- ☐ The dosimeter is based on a natural diamond crystal sealed in a polystyrene housing with a bias applied through thin golden contacts.



3.7 OTHER DOSIMETRY SYSTEMS

3.7.3 Diamond dosimeters

Advantages

- ☐ Diamond dosimeters are waterproof and can be used for measurements in a water phantom.
- ☐ They are tissue equivalent and require nearly no energy correction.
- ☐ They are well suited for use in high dose gradient regions, (e.g., stereotactic radiosurgery).

3.7 OTHER DOSIMETRY SYSTEMS

3.7.3 Diamond dosimeters

Disadvantages

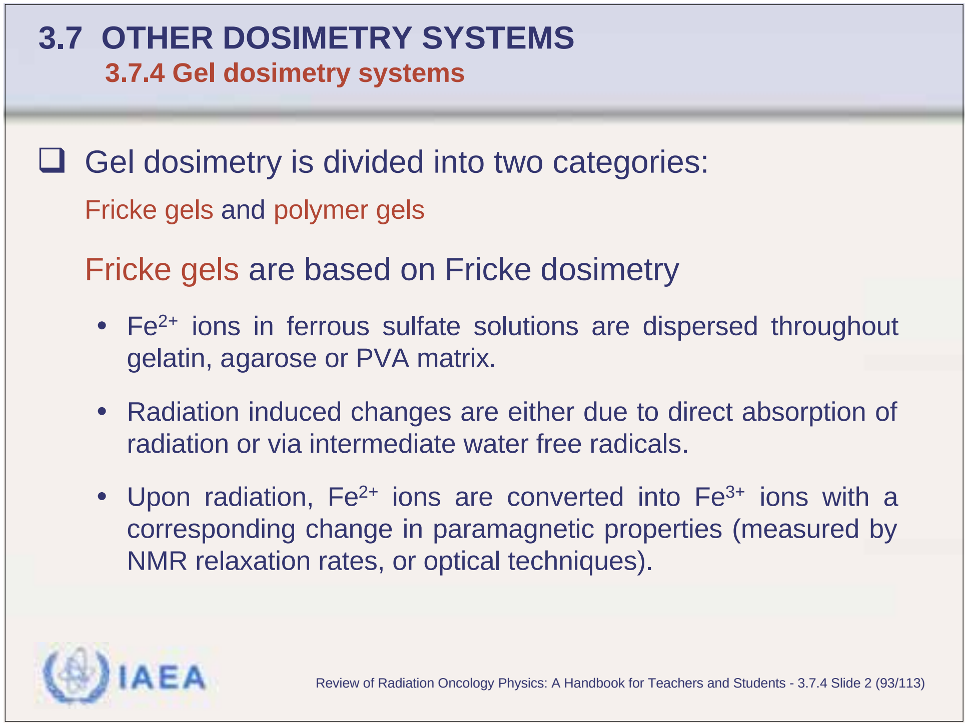
- In order to stabilize their dose response (to reduce the polarization effect) diamonds should (must) be irradiated prior to each use.
- They exhibit a small dependence on dose rate, which has to be corrected for when measuring:
  - Depth dose
  - Absolute dose
- Applying a higher voltage than specified can immediately destroy the diamond detector.

3.7 OTHER DOSIMETRY SYSTEMS

3.7.4 Gel dosimetry systems

Gel dosimetry systems are true 3-D dosimeters.

- The gel dosimeter is a phantom that can measure absorbed dose distribution in a full 3-D geometry.
- Gels are nearly tissue equivalent and can be molded to any desired shape or form.



3.7 OTHER DOSIMETRY SYSTEMS

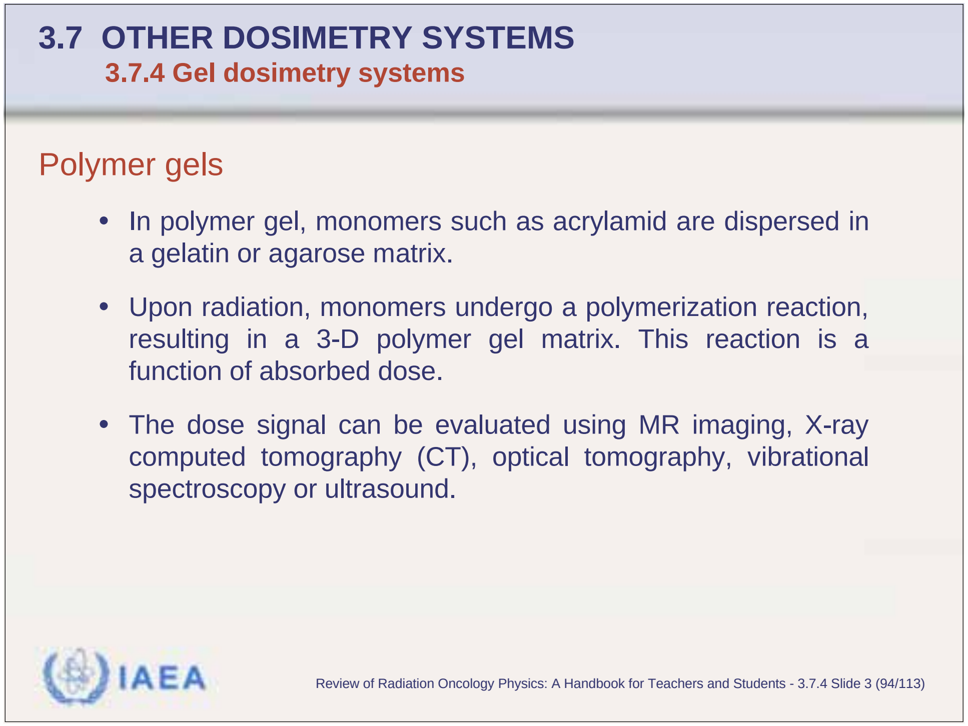
3.7.4 Gel dosimetry systems

❑ Gel dosimetry is divided into two categories:

Fricke gels and polymer gels

Fricke gels are based on Fricke dosimetry

- Fe^{2+} ions in ferrous sulfate solutions are dispersed throughout gelatin, agarose or PVA matrix.
- Radiation induced changes are either due to direct absorption of radiation or via intermediate water free radicals.
- Upon radiation, Fe^{2+} ions are converted into Fe^{3+} ions with a corresponding change in paramagnetic properties (measured by NMR relaxation rates, or optical techniques).



3.7 OTHER DOSIMETRY SYSTEMS

3.7.4 Gel dosimetry systems

Polymer gels

- In polymer gel, monomers such as acrylamid are dispersed in a gelatin or agarose matrix.
- Upon radiation, monomers undergo a polymerization reaction, resulting in a 3-D polymer gel matrix. This reaction is a function of absorbed dose.
- The dose signal can be evaluated using MR imaging, X-ray computed tomography (CT), optical tomography, vibrational spectroscopy or ultrasound.

3.7 OTHER DOSIMETRY SYSTEMS

3.7.4 Gel dosimetry systems

Advantages

- A number of polymer gel formulations are commercially available.
- There is a semilinear relationship between the NMR relaxation rate and the absorbed dose at a point in the gel dosimeter.
- Due to the large proportion of water, polymer gels are nearly water equivalent and no energy corrections are required for photon and electron beams used in radiotherapy.
- Polymer gels are well suited for use in high dose gradient regions, (e.g., stereotactic radiosurgery).

3.7 OTHER DOSIMETRY SYSTEMS

3.7.4 Gel dosimetry systems

Disadvantages

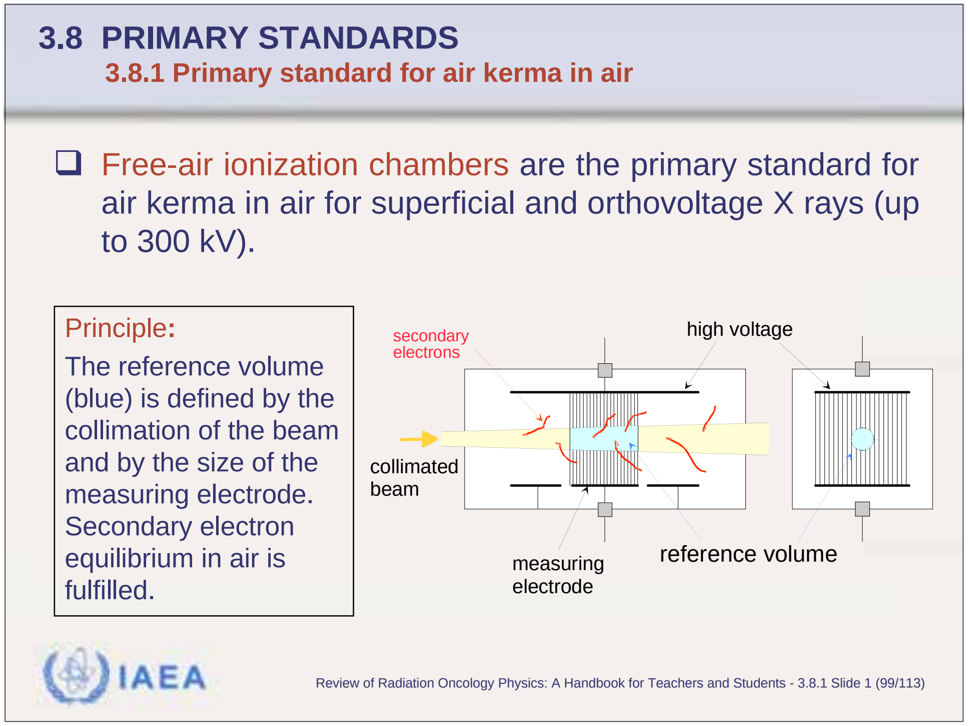
- Method usually needs access to an MRI machine.
- A major limitation of Fricke gel systems is the continual post-irradiation diffusion of ions, resulting in a blurred dose distribution.
- Post-irradiation effects can lead to image distortion.
- Possible post-irradiation effects:
  - Continual polymerization.
  - Gelation and strengthening of the gel matrix.

3.8 PRIMARY STANDARDS

- Primary standards are instruments of the highest metrological quality that permit determination of the unit of a quantity from its definition, the accuracy of which has been verified by comparison with standards of other institutions of the same level.
  - Primary standards are supported by primary standards dosimetry laboratories (PSDLs) in about 20 countries worldwide.
  - Regular international comparisons between the PSDLs, and with the Bureau International des Poids et Mesures (BIPM), ensure international consistency of the dosimetry standards.

3.8 PRIMARY STANDARDS

- Ionization chambers used in hospitals for calibration of radiotherapy beams must have a calibration coefficient traceable (directly or indirectly) to a primary standard.
  - Primary standards are not used for routine calibrations, since they represent the unit for the quantity at all times.
  - Instead, the PSDLs calibrate secondary standard dosi-meters for secondary standards dosimetry laboratories (SSDLs) that in turn are used for calibrating the reference instruments of users, such as therapy level ionization chambers used in hospitals.

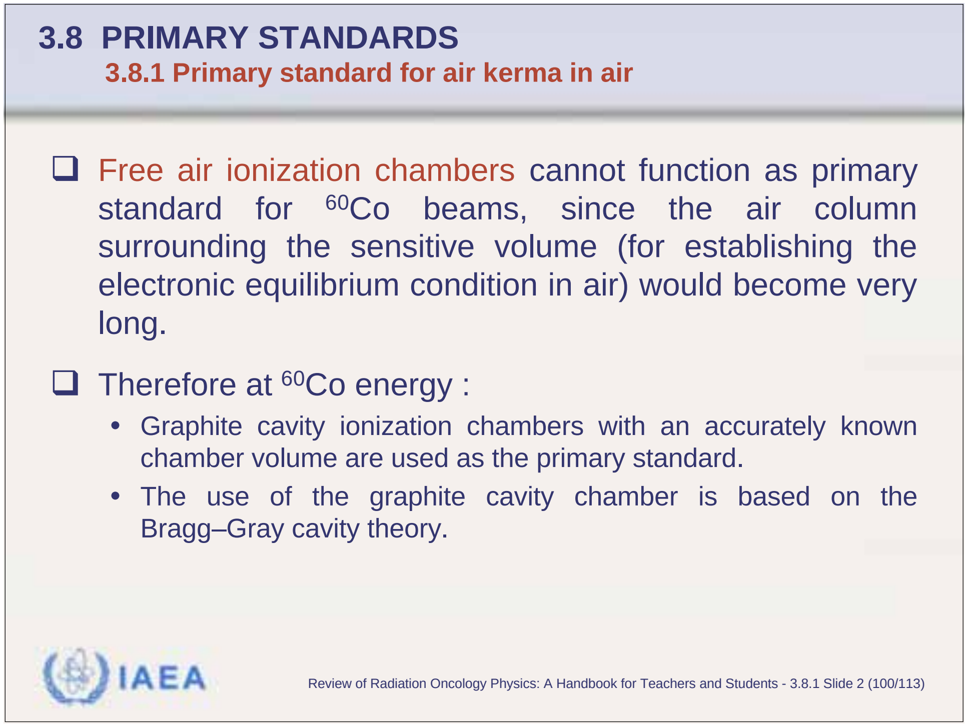


3.8 PRIMARY STANDARDS

3.8.1 Primary standard for air kerma in air

- ❑ Free-air ionization chambers are the primary standard for air kerma in air for superficial and orthovoltage X rays (up to 300 kV).

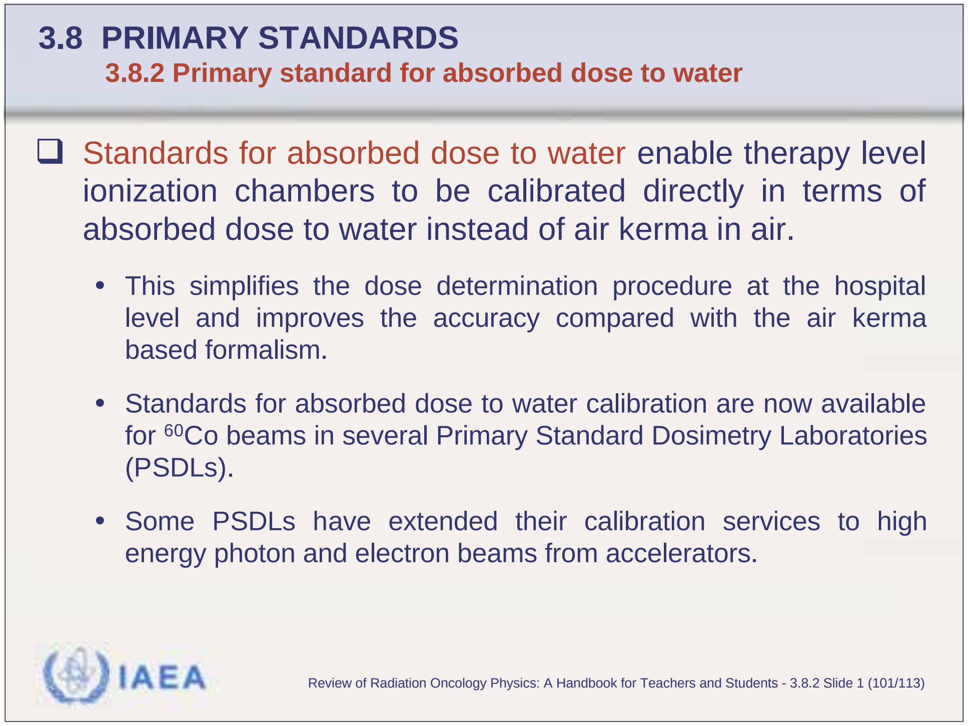
Principle:
The reference volume (blue) is defined by the collimation of the beam and by the size of the measuring electrode. Secondary electron equilibrium in air is fulfilled.



3.8 PRIMARY STANDARDS

3.8.1 Primary standard for air kerma in air

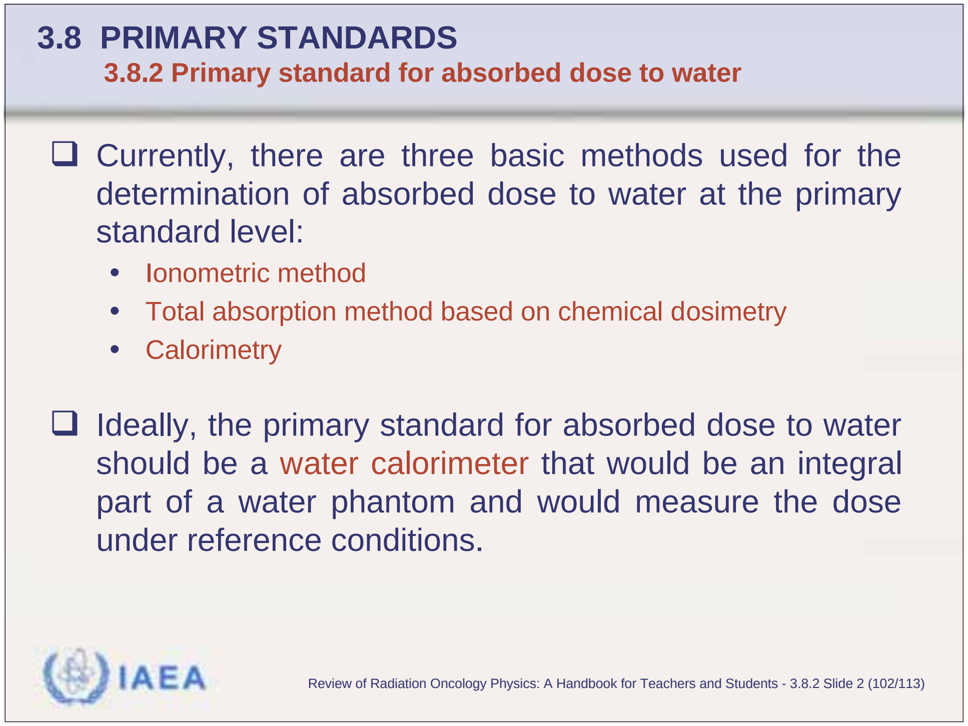
- ❑ Free air ionization chambers cannot function as primary standard for ^{60}Co beams, since the air column surrounding the sensitive volume (for establishing the electronic equilibrium condition in air) would become very long.
- ❑ Therefore at ^{60}Co energy :
  - Graphite cavity ionization chambers with an accurately known chamber volume are used as the primary standard.
  - The use of the graphite cavity chamber is based on the Bragg–Gray cavity theory.



3.8 PRIMARY STANDARDS

3.8.2 Primary standard for absorbed dose to water

- Standards for absorbed dose to water enable therapy level ionization chambers to be calibrated directly in terms of absorbed dose to water instead of air kerma in air.
    - This simplifies the dose determination procedure at the hospital level and improves the accuracy compared with the air kerma based formalism.
    - Standards for absorbed dose to water calibration are now available for ^{60}Co beams in several Primary Standard Dosimetry Laboratories (PSDLs).
    - Some PSDLs have extended their calibration services to high energy photon and electron beams from accelerators.



3.8 PRIMARY STANDARDS

3.8.2 Primary standard for absorbed dose to water

- Currently, there are three basic methods used for the determination of absorbed dose to water at the primary standard level:
    - Ionometric method
    - Total absorption method based on chemical dosimetry
    - Calorimetry
- Ideally, the primary standard for absorbed dose to water should be a water calorimeter that would be an integral part of a water phantom and would measure the dose under reference conditions.

3.8 PRIMARY STANDARDS

3.8.3 Ionometric standard for absorbed dose to water

- A graphite cavity ionization chamber with accurately known active volume, constructed as a close approximation to a Bragg–Gray cavity, is used in a water phantom at a reference depth.
  - Absorbed dose to water at the reference point is derived from the cavity theory using the mean specific energy imparted to the air in the cavity and the restricted stopping power ratio of the wall material to the cavity gas.
  - The BIPM maintains an ionometric standard of absorbed dose to water.

3.8 PRIMARY STANDARDS

3.8.4 Chemical dosimetry standard for absorbed dose to water

- In chemical dosimetry systems the dose is determined by measuring the chemical change produced by radiation in the sensitive volume of the dosimeter.
- The most widely used chemical dosimetry standard is the Fricke dosimeter.

3.8 PRIMARY STANDARDS

3.8.4 Chemical dosimetry standard for absorbed dose to water

Fricke dosimeter

☐ The Fricke dosimeter is a solution of the following composition in water:

- 1 mM $FeSO_4$ [or $Fe(NH_4)_2(SO_4)_2$]
- plus 0.8 N H_2SO_4 , air saturated
- plus 1 mM NaCl
- Irradiation of a Fricke solution oxidizes ferrous ions Fe^{2+} into ferric ions Fe^{3+}.
- Ferric ions Fe^{3+} exhibit a strong absorption peak at a wavelength of 304 nm, whereas ferrous ions Fe^{2+} do not show any absorption at this wavelength.

3.8 PRIMARY STANDARDS

3.8.4 Chemical dosimetry standard for absorbed dose to water

Fricke dosimeter

☐ The Fricke dosimeter response is expressed in terms of its sensitivity, known as the radiation chemical yield or G value.

- The G value is defined as the number of moles of ferric ions produced per joule of the energy absorbed in the solution.
- The chemical dosimetry standard is realized by the calibration of a transfer dosimeter in a total absorption experiment and the subsequent application of the transfer dosimeter in a water phantom, in reference conditions.

3.8 PRIMARY STANDARDS

3.8.5 Calorimetric standard for absorbed dose to water

- ❑ Calorimetry is the most fundamental method of realizing the primary standard for absorbed dose, since temperature rise is the most direct consequence of energy absorption in a medium.
  - Graphite is in general an ideal material for calorimetry, since it is of low atomic number Z and all the absorbed energy reappears as heat, without any loss of heat in other mechanisms (such as the heat defect).
  - The graphite calorimeter is used by several PSDLs to determine the absorbed dose to graphite in a graphite phantom.

3.8 PRIMARY STANDARDS

3.8.5 Calorimetric standard for absorbed dose to water

- ❑ The conversion to absorbed dose to water at the reference point in a water phantom may be performed by an application of the photon fluence scaling theorem or by measurements based on cavity ionization theory.

3.9 SUMMARY OF COMMONLY USED DOSIMETRIC SYSTEMS

The four most commonly used radiation dosimeters:

- ☐ Ionization chambers
- ☐ Radiographic films
- ☐ TLDs
- ☐ Diodes

3.9 SUMMARY OF COMMONLY USED DOSIMETRIC SYSTEMS: IONIZATION CHAMBERS

Advantage	Disadvantage
☐ Accurate and precise	☐ Connecting cables required
☐ Recommended for beam calibration	☐ High voltage supply required
☐ Necessary corrections well understood	☐ Many corrections required
☐ Instant readout	

3.9 SUMMARY OF COMMONLY USED DOSIMETRIC SYSTEMS: FILM

Advantage

- 2-D spatial resolution
- Very thin: does not perturb the beam

Disadvantage

- Darkroom and processing facilities required
- Processing difficult to control
- Variation between films & batches
- Needs proper calibration against ionization chambers
- Energy dependence problems
- Cannot be used for beam calibration

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3.9 SUMMARY OF COMMONLY USED DOSIMETRIC SYSTEMS: TLD

Advantage

- Small in size: point dose measurements possible
- Many TLDs can be exposed in a single exposure
- Available in various forms
- Some are reasonably tissue equivalent
- Not expensive

Disadvantage

- Signal erased during readout
- Easy to lose reading
- No instant readout
- Accurate results require care
- Readout and calibration time consuming
- Not recommended for beam calibration

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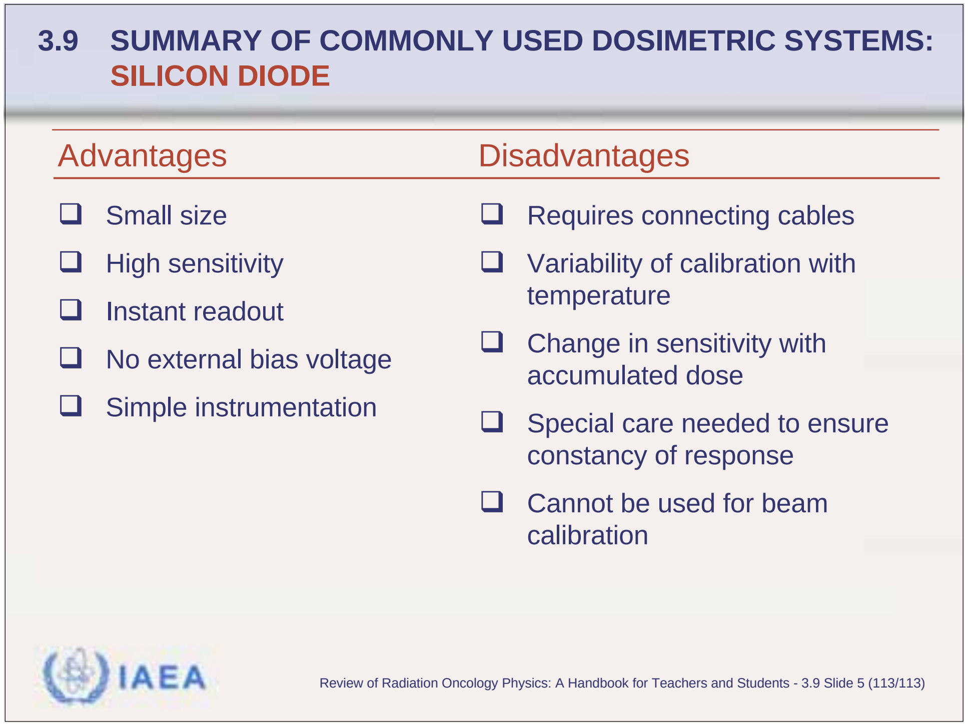

3.9 SUMMARY OF COMMONLY USED DOSIMETRIC SYSTEMS: SILICON DIODE

Advantages

- Small size
- High sensitivity
- Instant readout
- No external bias voltage
- Simple instrumentation

Disadvantages

- Requires connecting cables
- Variability of calibration with temperature
- Change in sensitivity with accumulated dose
- Special care needed to ensure constancy of response
- Cannot be used for beam calibration

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