Scintillation dosimetry: Review, new innovations and applications

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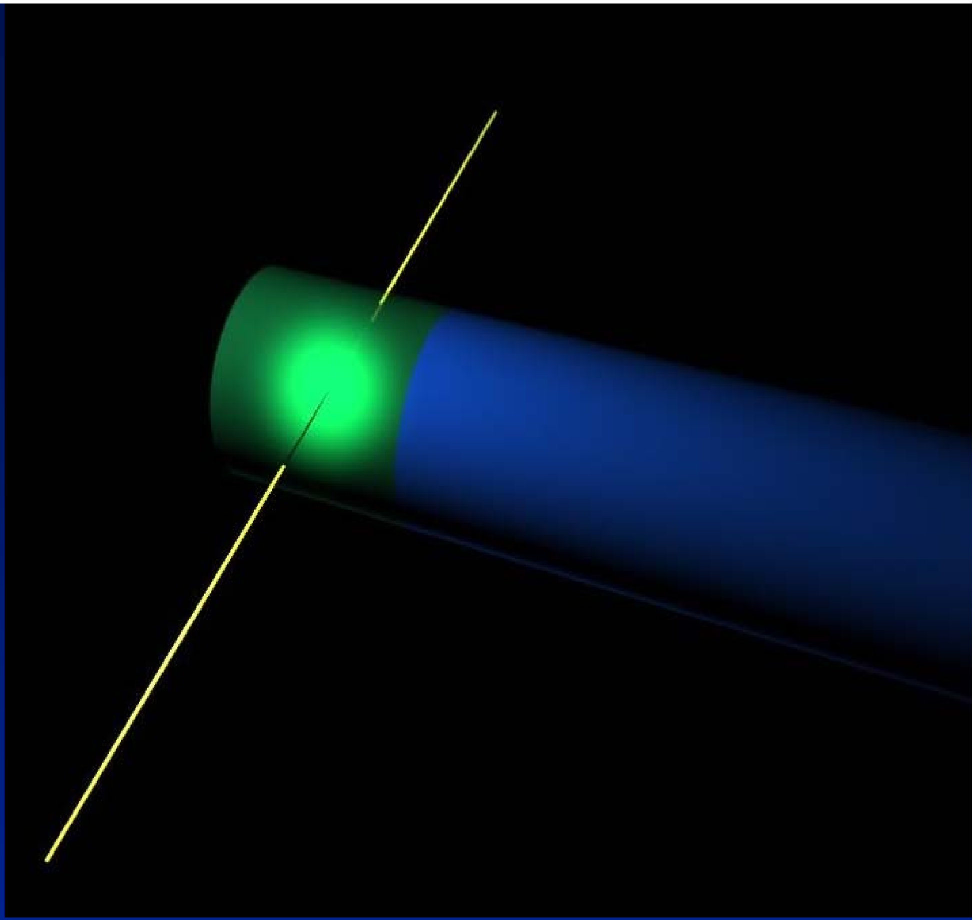
OUTLINE

- Introduction
- Properties of plastic scintillation detectors
- Applications
  - Daily QA
  - Radiosurgery
  - Clinical prototype
  - Proton therapy
  - Work in progress
- Conclusions



INTRODUCTION

- In the last 20 years, significant advances have been made in scintillation dosimetry
- They have a unique set of advantages
- With the increasing complexity of radiotherapy treatments, scintillation detectors could be used for quick and accurate dose measurements even in complex geometries

The purpose of this presentation is to show the advantages of scintillation dosimetry and to explain how it can be used in modern radiotherapy

Introduction

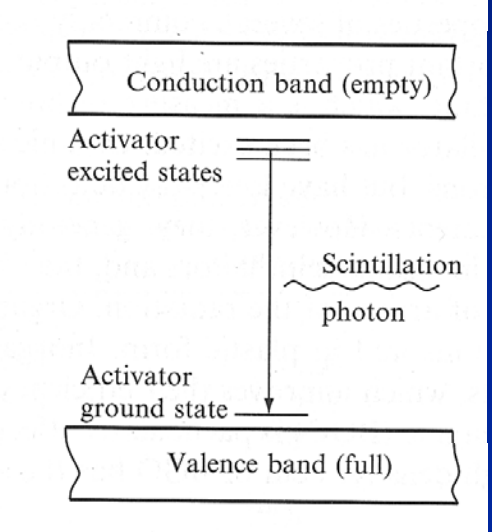
- Scintillation detectors:
  - Impinging particles or photons will excite atoms or molecules of the scintillating medium.
  - The decay of these excited states will produce photons in the visible part of the spectrum.
  - These photons are guided to a photodetector and then get converted into an electric signal.

INTRODUCTION

- Two types of scintillators:

A. Inorganic materials

- NaI, NaI(Tl), CsI, CsI(Tl), CsI(Na), CsF, BaF_2, $CdWO_4$, …
- Advantages for stopping particles: high Z and high density (up to 8-9 g/cm^3)
  - Disadvantage for dosimetry
- Need an activator: e.g. Tl (Thalium)
  - NaI: 330 nm
  - NaI(Tl): 410 nm



(b) Inorganic

INTRODUCTION

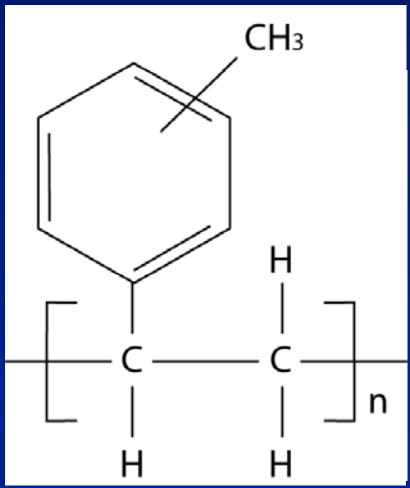
- Two types of scintillators:

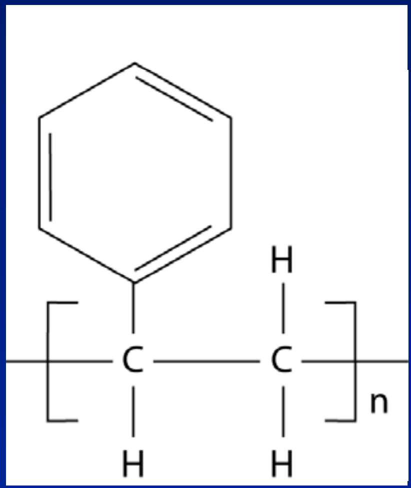
B. Organic materials (e.g. plastics)

- Lower density … and!!! nearly equivalent to water
  - Density on the order of 1.03-1.06 g/cm^3
  - (Generally) No high Z materials content.
- Excitation and emission spectra are similar in solid, liquid or vapor states

PLASTIC SCINTILLATING MATERIALS

- Core (bulk solvent)
  - Polyvinyltoluene (*plastic scintillators*)
  - Polystyrene (*plastic scintillating fibers*)





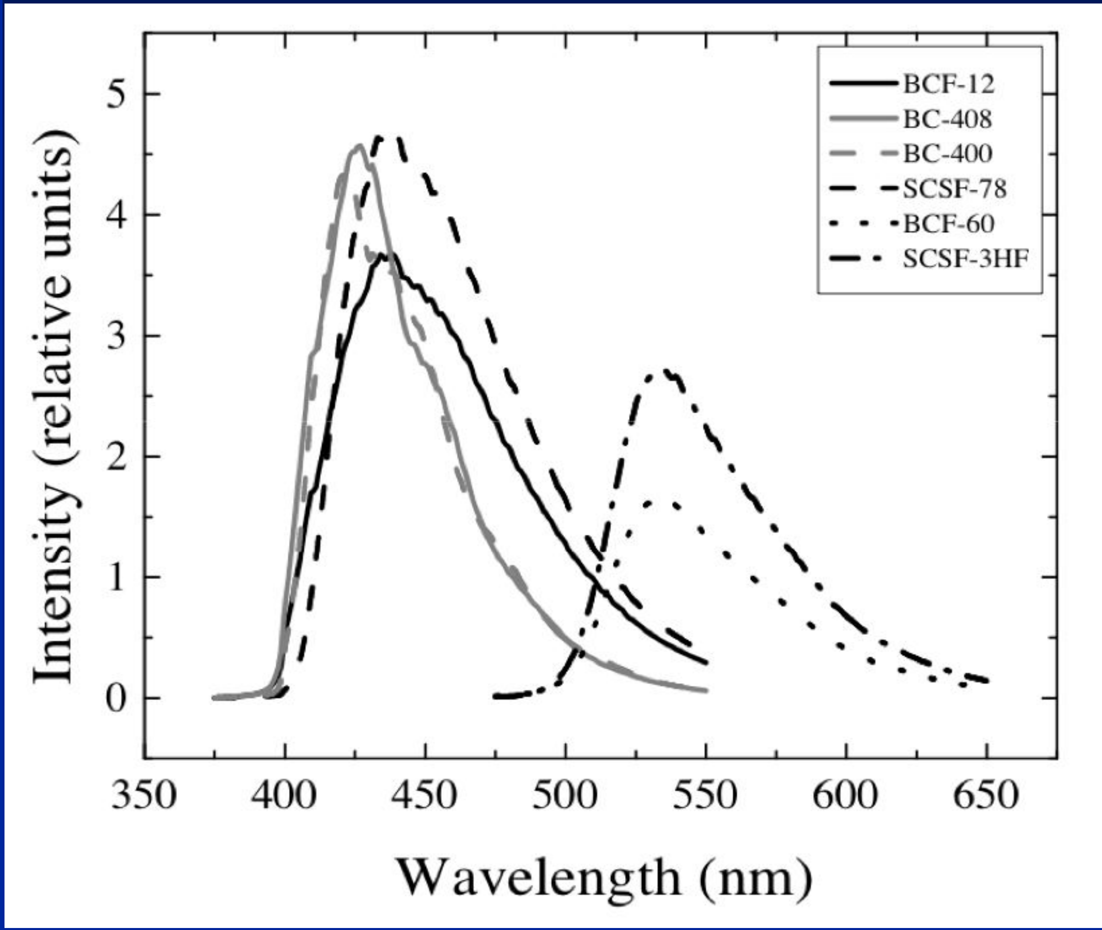
- Cladding (scintillating fibers)
  - Polymethylacrylate (PMMA)
  - Improves transmission of light to optical fiber

FLUORS

- Organic fluors (scintillating materials) are used with a bulk solvent: two components system
  - BC400: >97% PVT, < 3% organic fluors
    - » e.g. p-TERPHENYL (C6H5 C6H4 C6H5)
  - Energy deposited in the solvent is transfered to the organic fluor molecules
    - » Emission is typically peaked in the violet-blue region.
- "Wavelength shifters" or three component system
  - A third (organic) component can also be used to absorb the organics fluors emitted photons and re-emit at a longer wavelength
    - » POPOP [1,4-bis(5-phenyloxazol-2-yl) benzene] to get scintillators emitting in the green or yellow region.

SCINTILLATOR SPECTRA

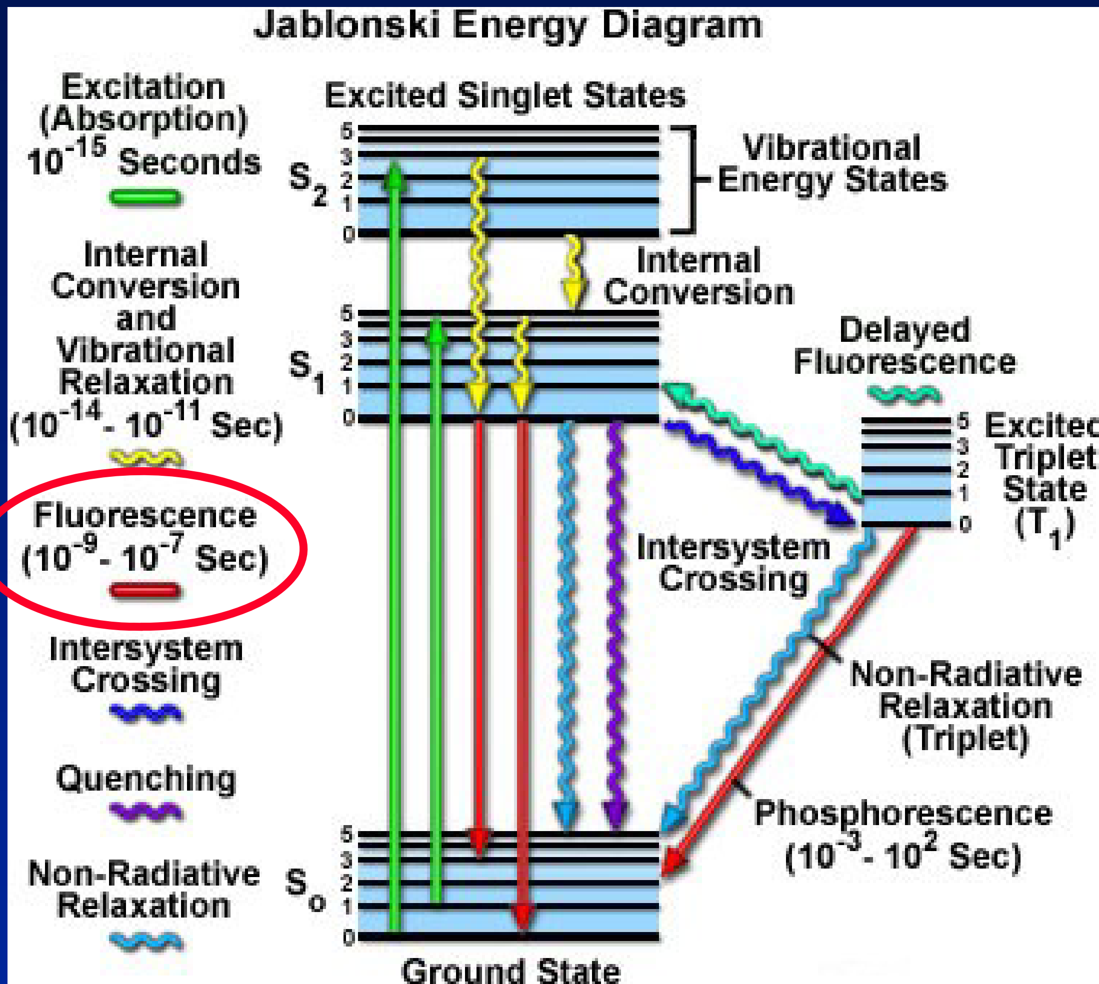
- Introduction
- Properties
- Applications
- Conclusion



Scintillators with longer wavelengths have lower light emission

Archambault L, Arsenault J, Gingras L, Beddar A S, Roy R, Beaulieu L, "Plastic scintillation dosimetry: Optimal selection of scintillating fibers and scintillators", Med. Phys 32: 2271-2278, 2005.

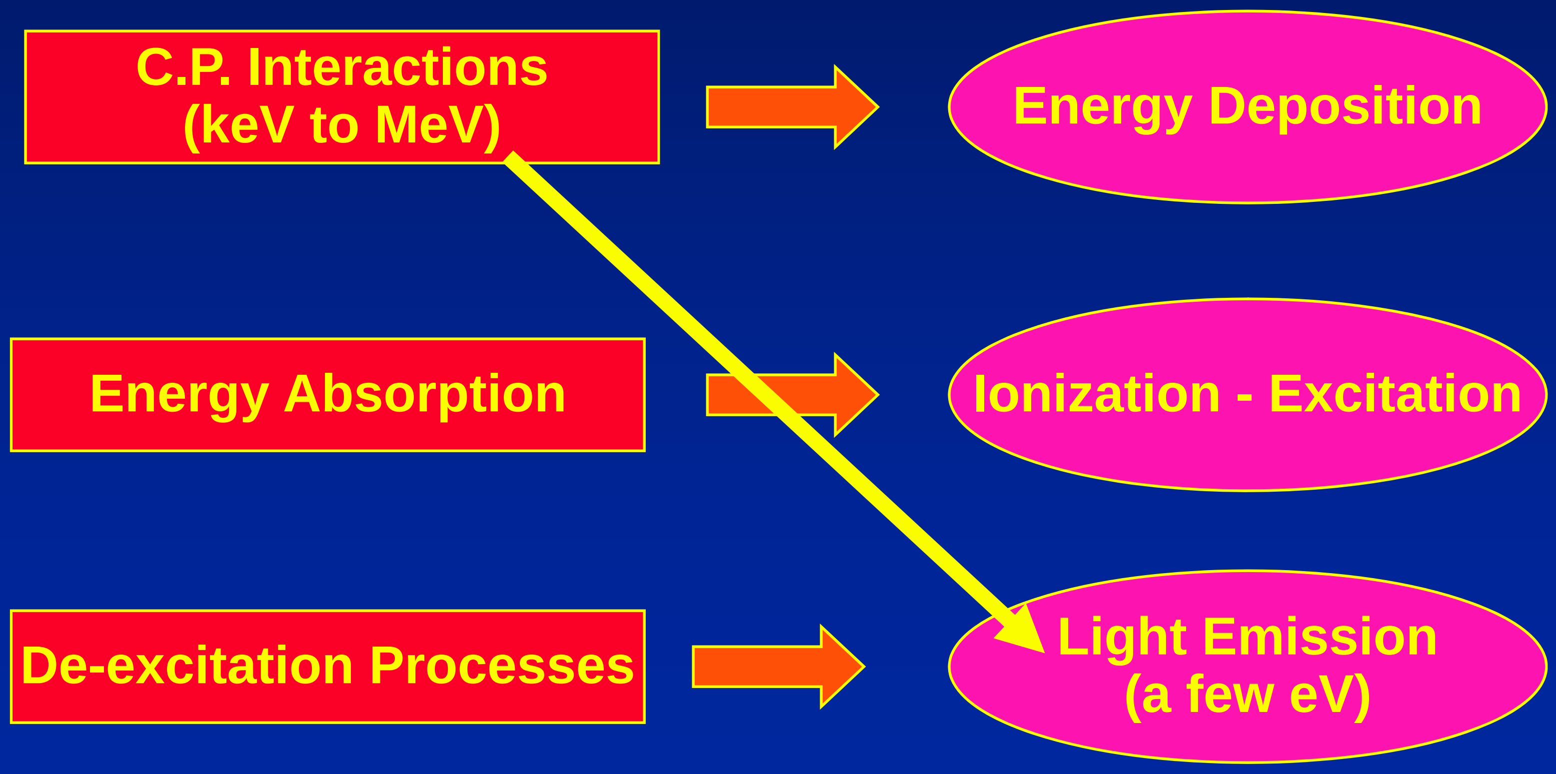
SCINTILLATION PROCESS



- Prompt fluorescence following excitation (10^{-9} – 10^{-7} s) important for radiation detection

SCINTILLATION PROCESS

Dose deposition and scintillation



SCINTILLATION EFFICIENCY

- Only a small portion of the incident kinetic energy lost is converted in fluorescent energy
  - For plastic scintillating fibers like BCF-12 about 8000 photons/MeV
    - This means about 125 eV / scintillation photon.
    - The total energy of visible light produced (at 430 nm or ~ 2.9 eV) represents an efficiency of 2.4% (97.6% goes in phonons!)
  - The light output depends on the LET (i.e. CP type)

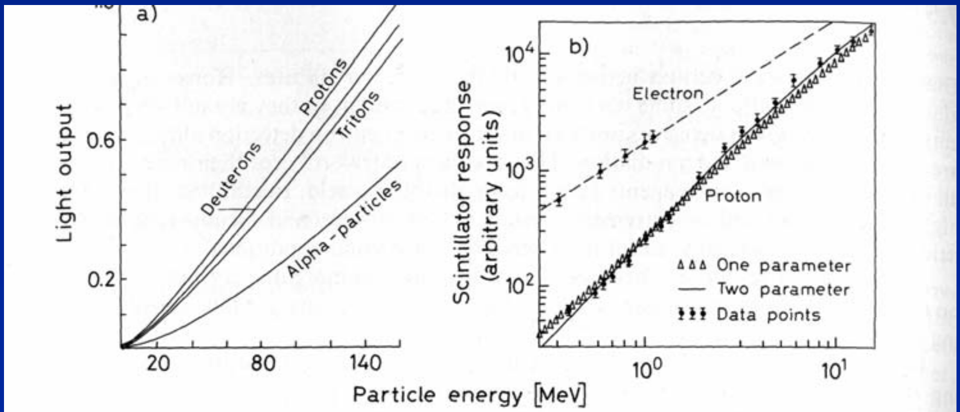
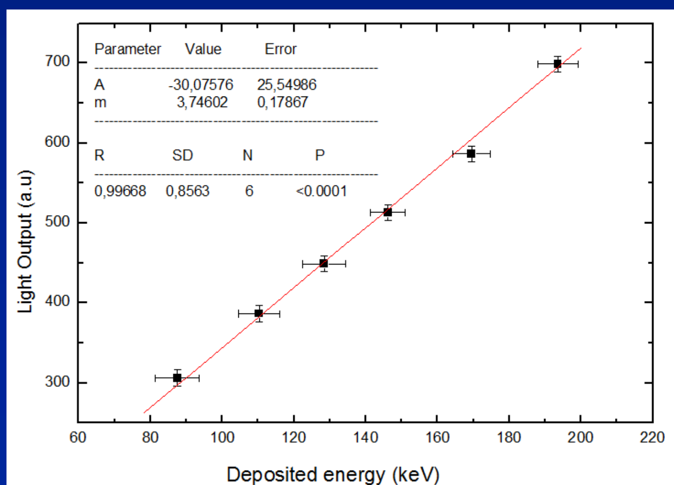


Fig. 7.8a, b. Response of NE102 plastic scintillator to different particles ((**a**) from *Gooding* and *Pugh* [7.6]; (**b**) from *Craun* and *Smith* [7.7])

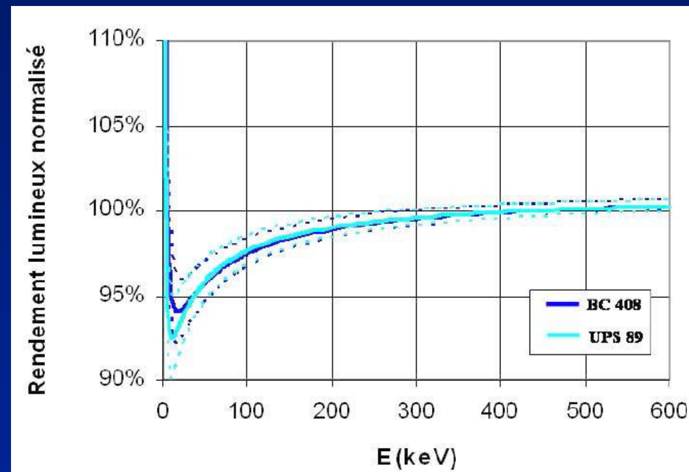
SCINTILLATION PROCESS: LINEARITY

- Measurements for low energy electrons from Compton scatter experiments:

A.M. Frelin, PhD thesis,Caen, France.



BCF-12 from our group



	dL/dE cst à 1%	L(E) cst à 2.5%	L(hν) cst à 5%
BC408	140 keV	100 keV	230 keV
BC428	130 keV	100 keV	260 keV
BC430	190 keV	160 keV	410 keV
UPS89	120 keV	94 keV	230 keV
UPS974	130 keV	110 keV	260 keV
UPS974R	77 keV	41 keV	56 keV

Tableau III.6 : Limite inférieure de linéarité du rendement lumineux et des quantités de scintillation produites pour des électrons et des photons.

SCINTILLATION PROCESS: SUMMARY

- Organic (plastic) scintillators are:
  - Made of low Z materials.
  - Light output is directly proportional to the exciting energy.
    - » Linear with deposited energy for e^-,γ.
    - » …for electron above 100-125 keV.
  - (Mostly) Transparent to its emitted photons.
  - The gap is wide enough to be insensitive to a wide range of temperatures.
  - Fast time response (physics of orbital transitions).

SCINTILLATION PROCESS: SUMMARY

- Scintillation efficiency is not the collection efficiency.
  - » These photons must be detected.
  - » Linearity must be preserved throughout the complete detection chain
  - » Light must be calibrated to Dose.

Scintillation Process: References

- *JB Birks, The Theory and Practice of Scintillation Counting, Pergamon Press Book, MacMillan, New York, 1964. [Chapters 3 and 6]*
- *GF Knoll, Radiation Detection and Measurement, 3rd Edition, John Wiley and Sons, 2000. [Chapter 8]*
- *WR Leo, Techniques for Nuclear and Particle Physics Experiments, 2nd edition, Springer-Verlag, 1992. [Chapter 7]*
- *FH Attix, Introduction to Radiological Physics and Radiation Dosimetry, John Wiley and Sons, 1986. [Chapter 15]*

ADVANTAGES OF PLASTIC SCINTILLATORS

- **Linear response to dose**
- **Dose rate independence**
- **Energy independence**
- **Temperature independence**
- **Spatial resolution**

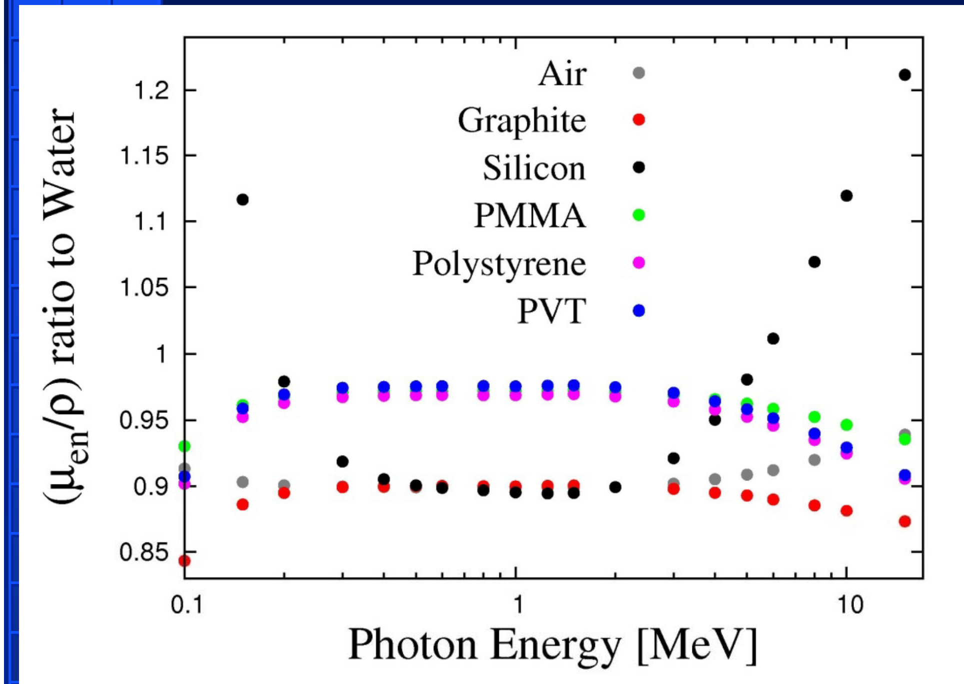
Water Equivalence

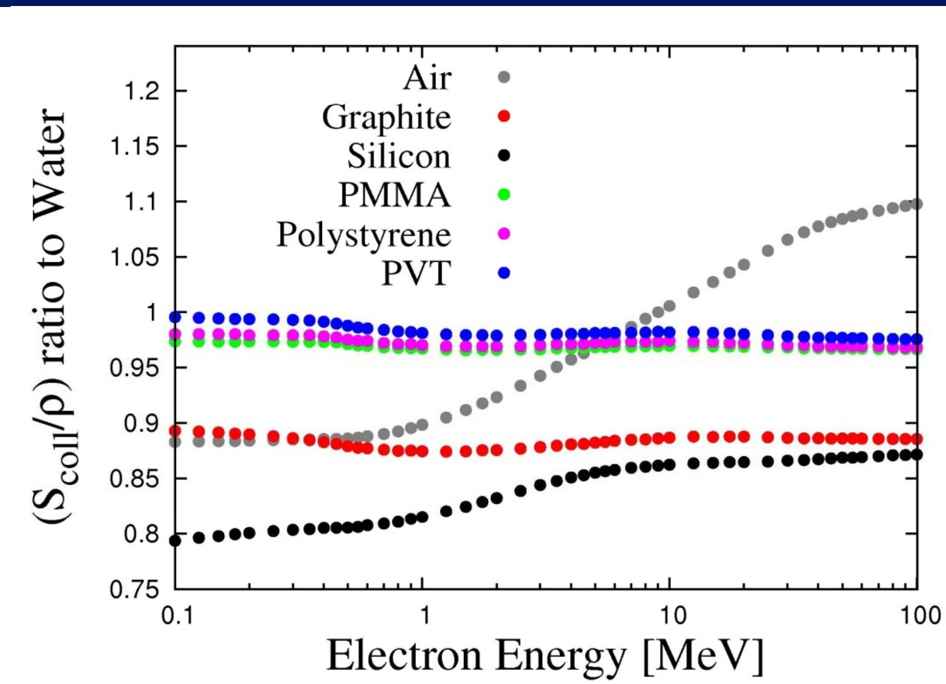
- W-E is achieved by:
  - Media-matching (walls and sensitive volume)
  - Density state of the sensitive volume (gaseous vs. condensed)
- W-E depends on:
  - Mass energy-absorption coefficients
  - Mass collision stopping powers

Parameter	Scintillator	Polystyrene	Water
Density (g/cm^3)	1.032	1.060	1.000
Electron density (10^{23} e$^-$/g)	3.272	3.238	3.343
Composition (by weight %)	H: 8.47 C: 91.53	H: 7.74 C: 92.26	H: 11.19 O: 88.81

WATER EQUIVALENCE

- Introduction
- Properties
- Applications
- Conclusion





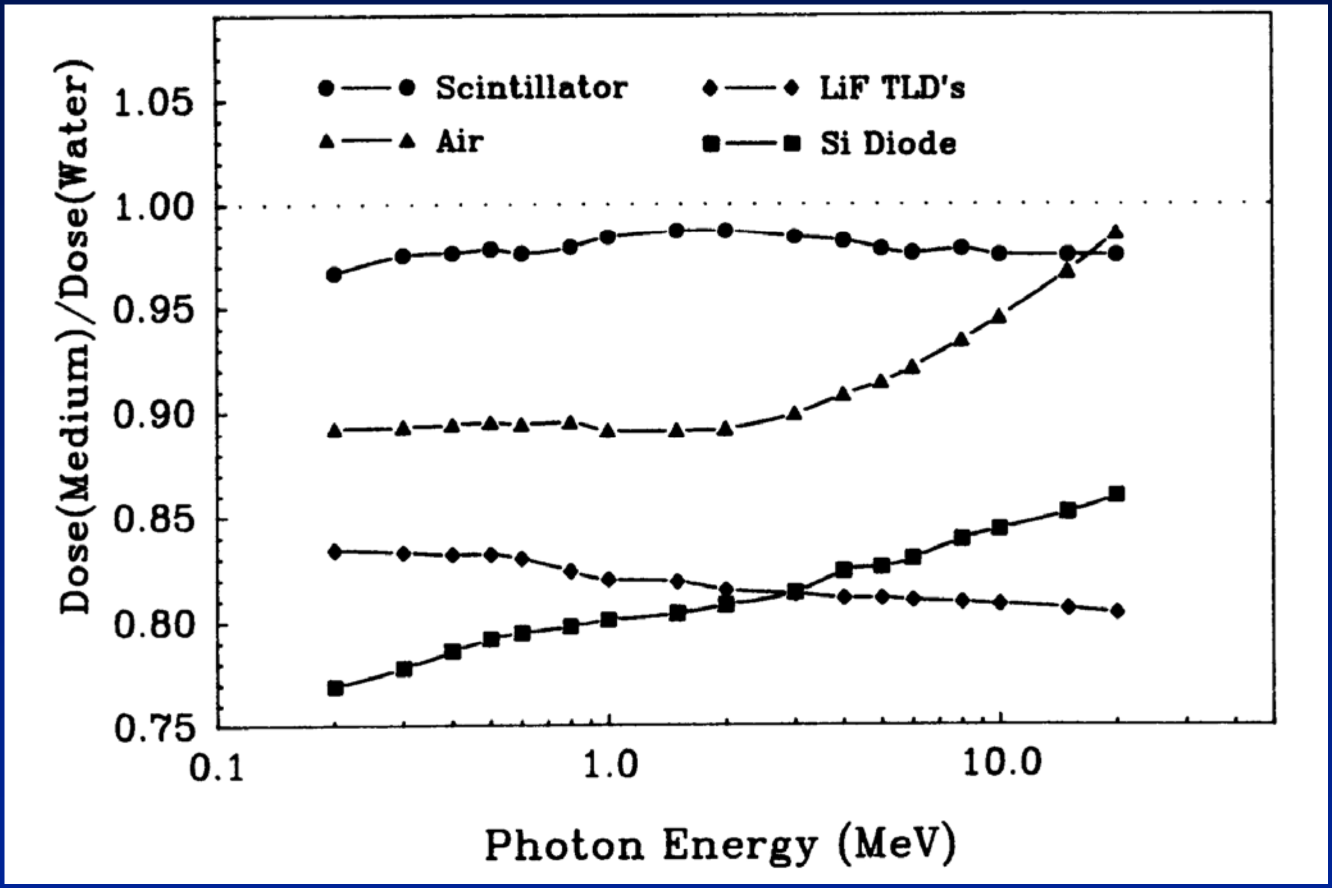
According to Burlin cavity theory, above 125 keV:

$$\frac{\overline{D}_{sci}}{\overline{D}_{med}} = 0.980 \pm 0.005$$

Beddar A S, Mackie T R, Attix F H, "Water-equivalent plastic scintillation detectors for high-energy beam dosimetry: I. Physical characteristics and theoretical considerations", Phys. Med. Biol. 37: 1883-1900, 1992.

ENERGY DEPENDENCE

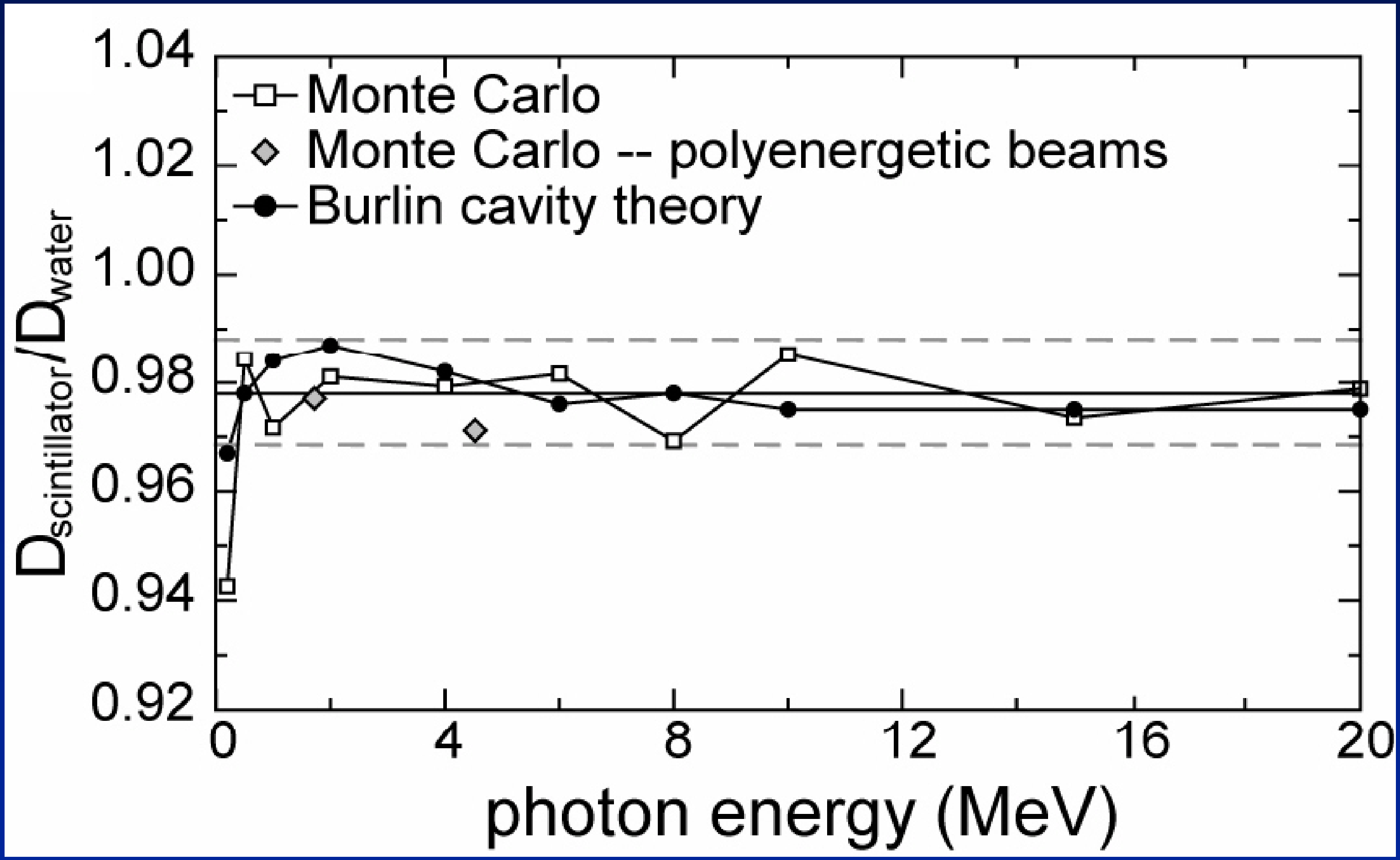
- Introduction
- Properties
- Applications
- Conclusion



- Detecting volumes: intermediate cavities
- Best energy dependence relative to other dosimeters used in radiotherapy

Beddar A S, Mackie T R, Attix F H, "Water-equivalent plastic scintillation detectors for high-energy beam dosimetry: I. Physical characteristics and theoretical considerations“, Phys. Med. Biol. 37: 1883-1900, 1992.

Energy Dependence



Beddar A S, Briere TM, Mourtada FA, Vassiliev O, Liu HH, Mohan R, "Monte Carle calculations of the absorbed dose and energy dependence of plastic scintillators", Med. Phys. 32: 1265-1269, 2005.

Detector Configuration

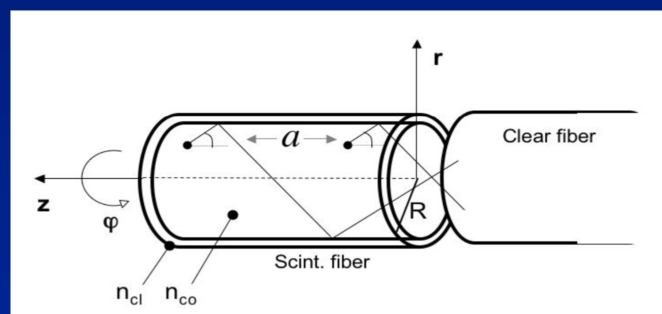
Scintillator | Fiber light guide | Photodetector

ε_{accept}

$\varepsilon_{couple1}$

$\varepsilon_{transmit}$

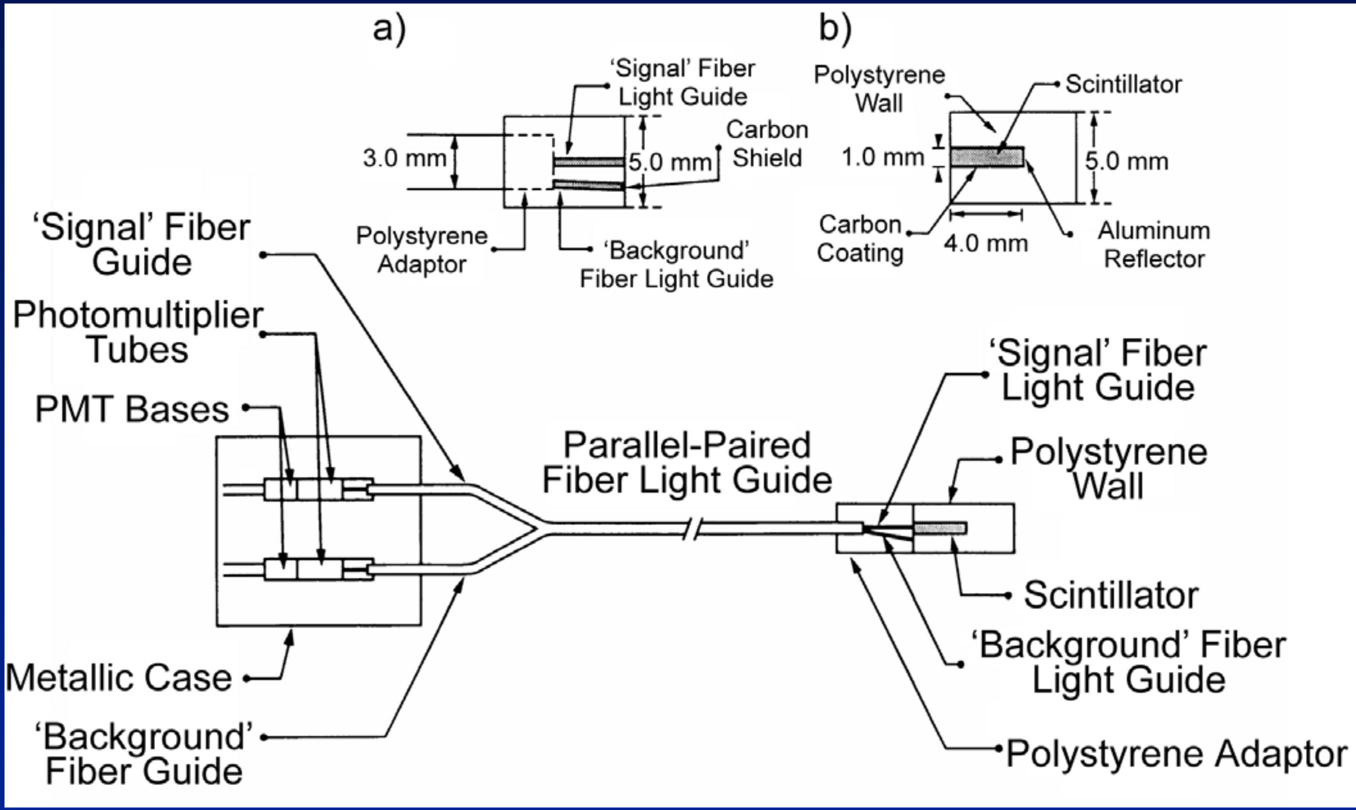
$\varepsilon_{couple2}$



Plastic scintillating fibers offer a good alternative to regular plastic scintillators:

- Increased light capture due to cladding (>internal reflection)
- The cladding is also water-equivalent/ no perturbation

ORIGINAL PROTOTYPE

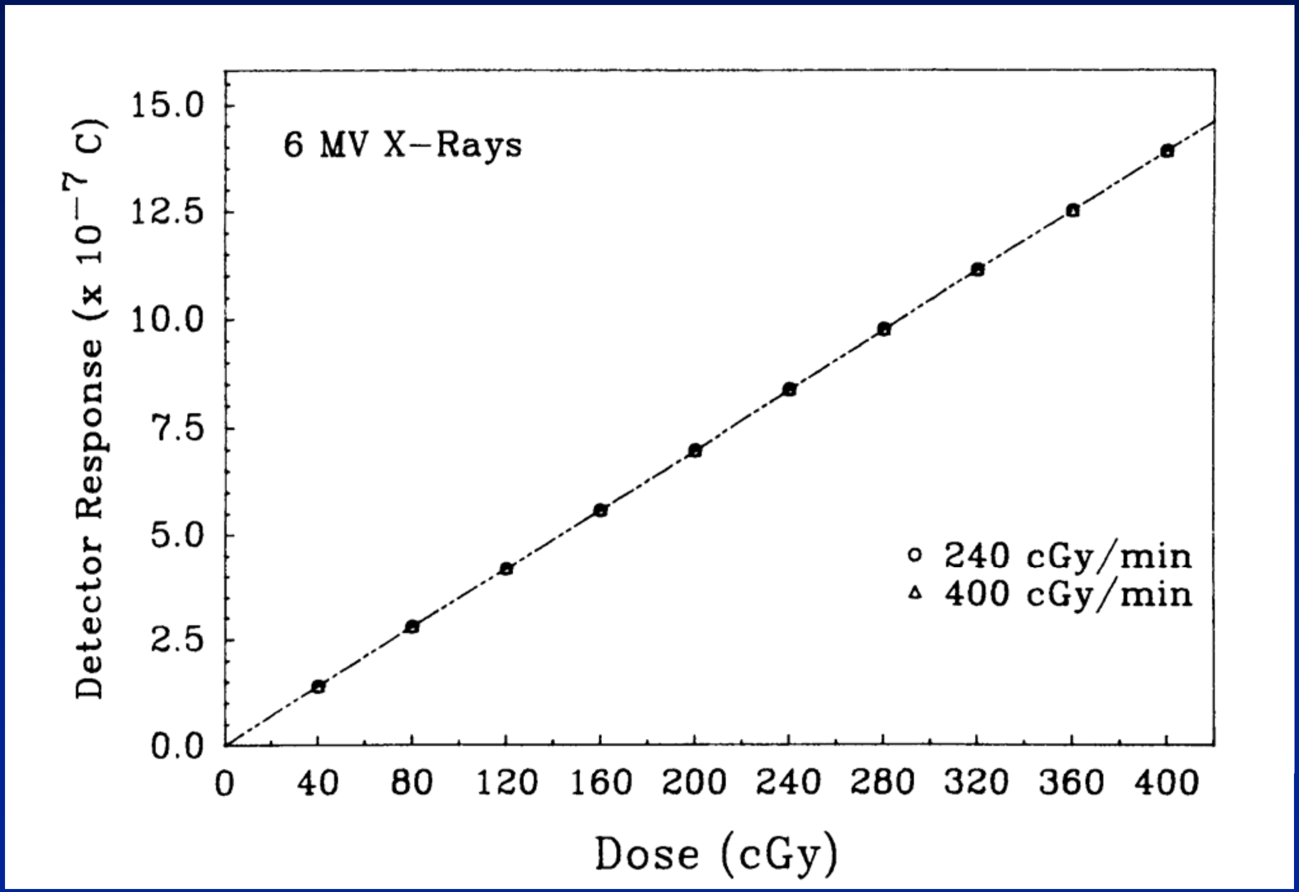


- High sensitivity (PMT)
- Remove Cerenkov with background subtraction

Beddar, A S, Mackie, T R, and Attix, F H, "Water-equivalent plastic scintillation detectors for high-energy beam dosimetry: I. Physical characteristics and theoretical considerations," Phys. Med. Biol. 37: 1883-1900, 1992.

LINEARITY

- Introduction
- Properties
- Applications
- Conclusion



Light production is proportional to the dose deposited

DOSE RATE INDEPENDENCE

- Introduction
- Properties
- Applications
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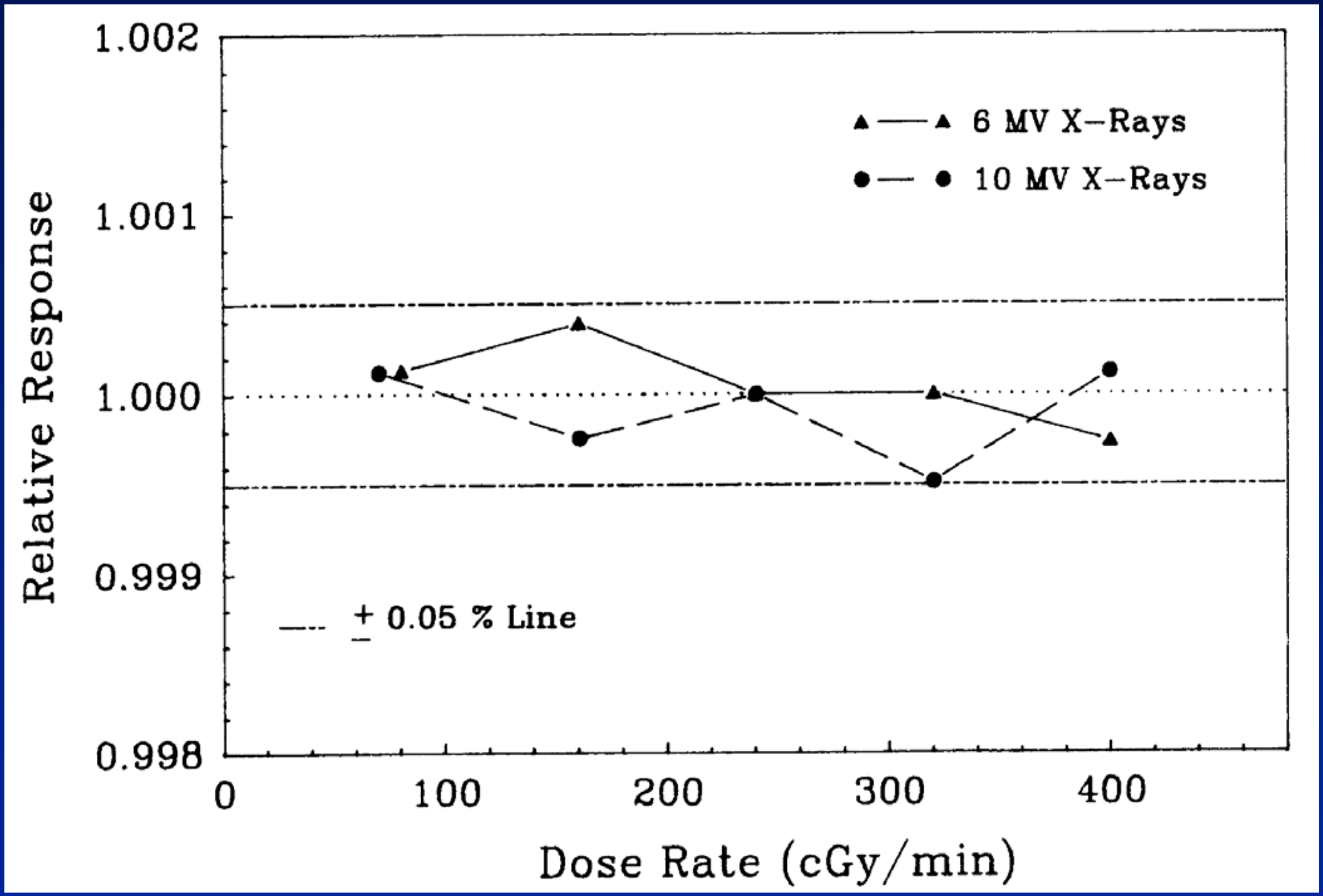
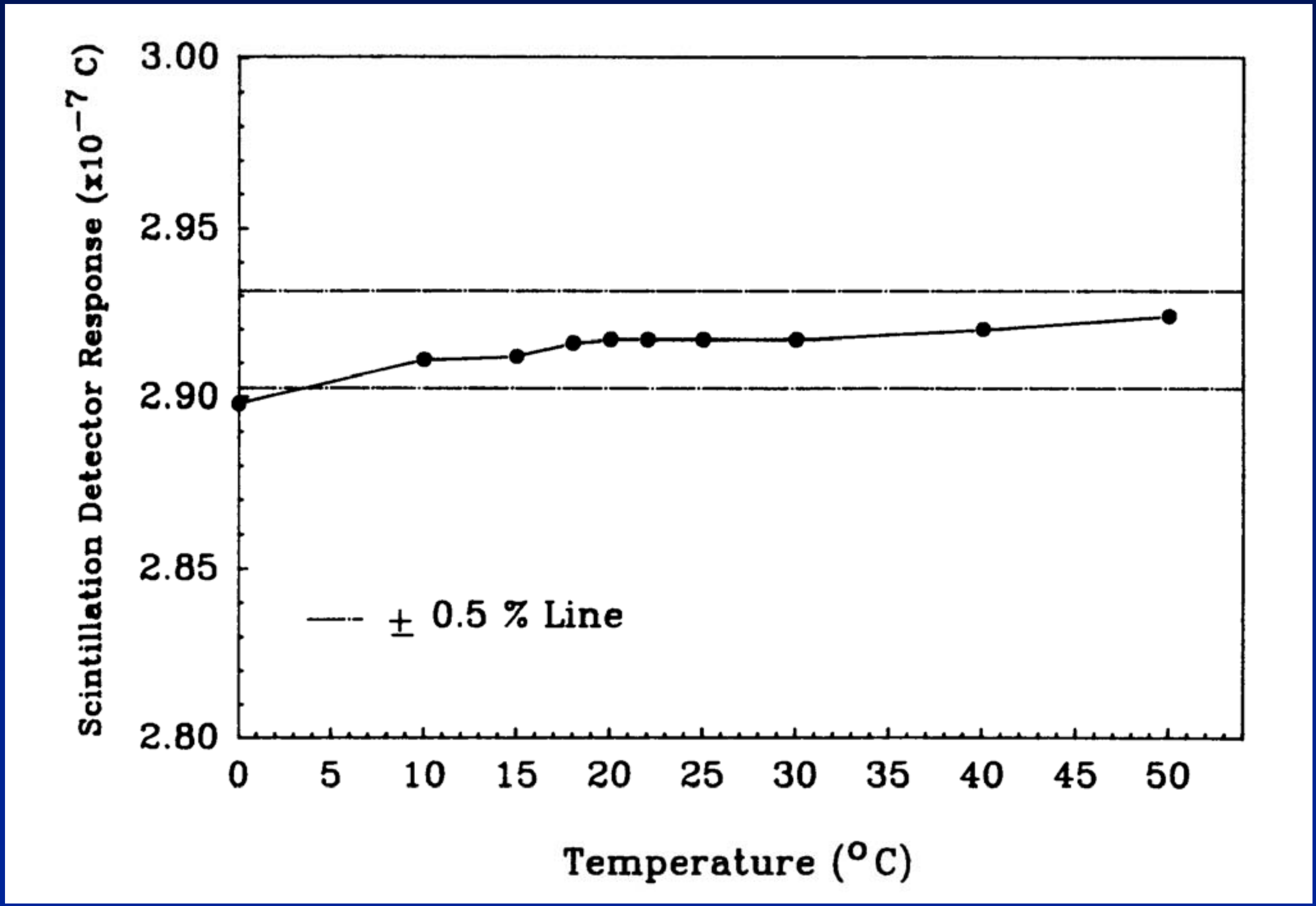


Not affected by dose rate variations

TEMPERATURE

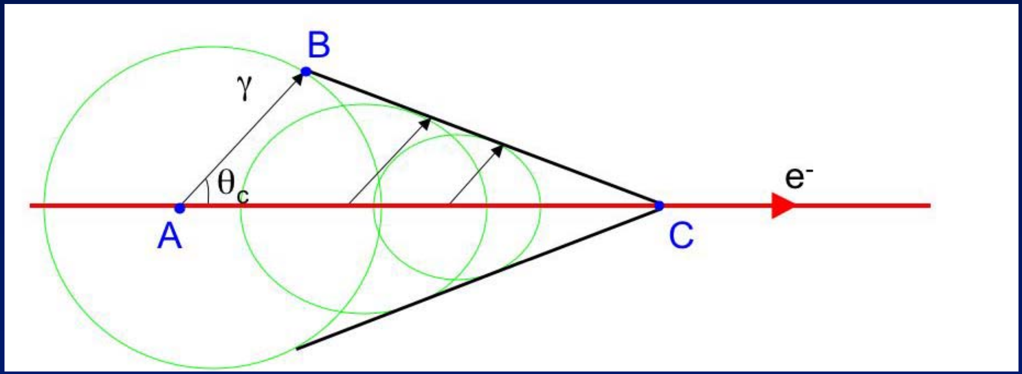
- Introduction
- Properties
- Applications
- Conclusion



No temperature dependence between 18ºC and 30ºC

Cerenkov Emission

- Introduction
- Properties
- Applications
- Conclusion



- In plastics like polystyrene, electrons with energies 146 keV and higher produce a blue light due to Cerenkov emission
- This light is superposed on the scintillation signal
- If a large amount of clear optical fiber is in the radiation field, Cerenkov emission can be significant (>15 %)

Although the light spectrum due to Cerenkov emission is different from the scintillation spectrum, de Boer et al have shown that spectral filtration is not sufficient to remove completely the Cerenkov light.

de Boer S F, Beddar A S Rawlinson J F "Optical filtering and spectral measurement of radiation-induced light in plastic scintillator dosimetry", Phys Med Biol 38: 945-958, 1993.

CERENKOV EMISSION

- Introduction
- Properties
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Techniques to remove the Cerenkov effect:

Background subtraction

$$D_{sci} \propto M - M_{crkv}$$

Note: requires 2 optical fibers

Simple filtering

Find the optimal *$S(\lambda)$* that max. *$N(\lambda)$* and min. *$1/\lambda^2$*

Chromatic filtration

With 2 different wavelength filter *$S_1(\lambda)$* and *$S_2(\lambda)$*,

$$m_i = \int_0^\infty \left(kD_{sci}N(\lambda) + \frac{C}{\lambda^2} \right) e^{-x/l(\lambda)} S_i(\lambda) d\lambda \qquad i = 1,2$$

$$\Rightarrow D_{sci} = Am_1 + Bm_2$$

Where *A* and *B* are fixed by calibration under 2 different conditions

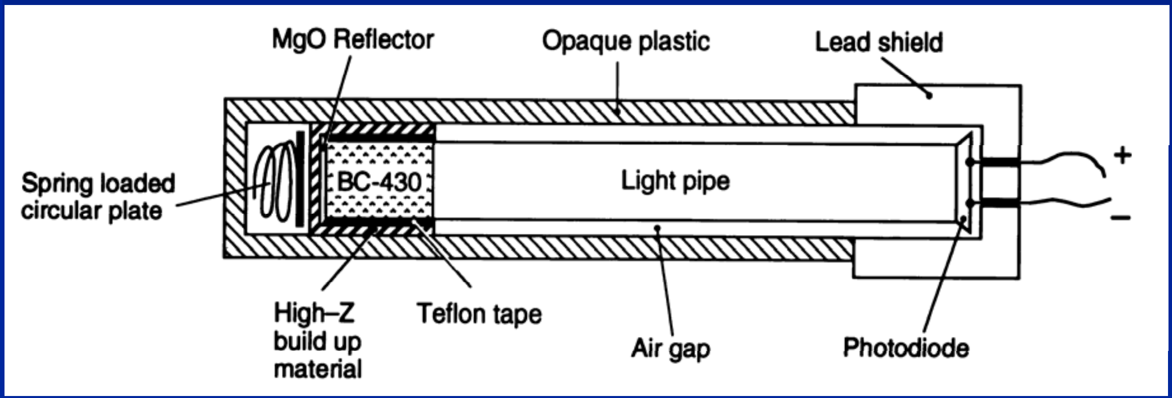
Fontbonne J M, Iltis G, Ban G, Battala A, Vernhes J C, Tillier J, Bellaize N, le Brun C, Tamain B, Mercier K, Motin J C, "Scintillating fiber dosimeter for radiation therapy acclerator“, IEEE Trans. Nucl. Sci. 49: 2223-2227, 2002.

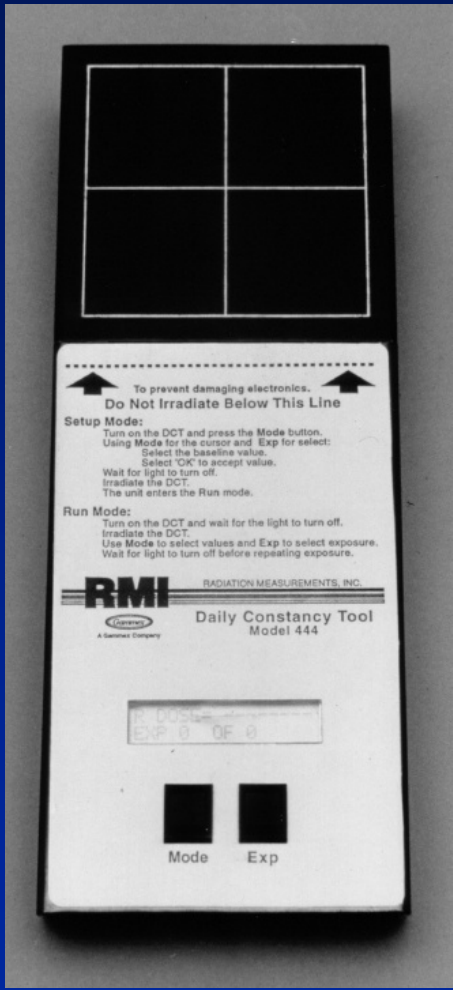
Applications of Plastic Scintillators

- **Daily QA**
- **EBRT: Basics measurements**
  - **Depth dose**
  - **Dose profiles**
- **Radiosurgery**
- **IMRT: Clinical prototype**
- **Proton dosimetry**
- **Other clinical innovations**

A DAILY QA DETECTOR SYSTEM

- Commercialized product
- Rugged and simple to construct
- Good stability and reproducibility
- Independent of temperature and pressure
- No high-voltage bias
- Remote operation and reset
- Easily used by trained technical staff
- Cost effective





Beddar S, "A new scintillator detector system for the quality assurance of ^{60}Co and high-energy therapy machines". Phys Med Biol 39: 253–263, 1994.

A DAILY QA DETECTOR SYSTEM

- Introduction
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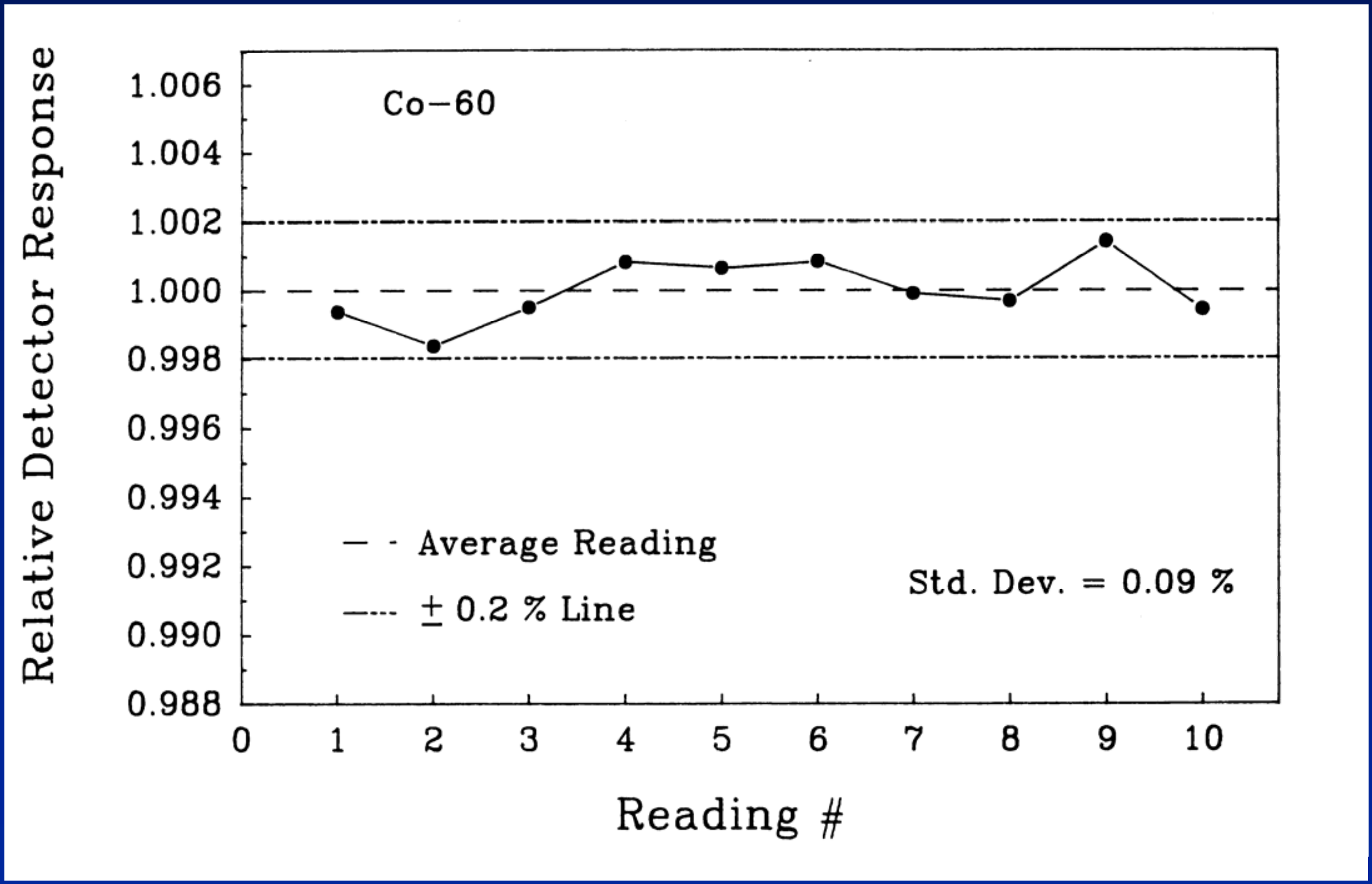
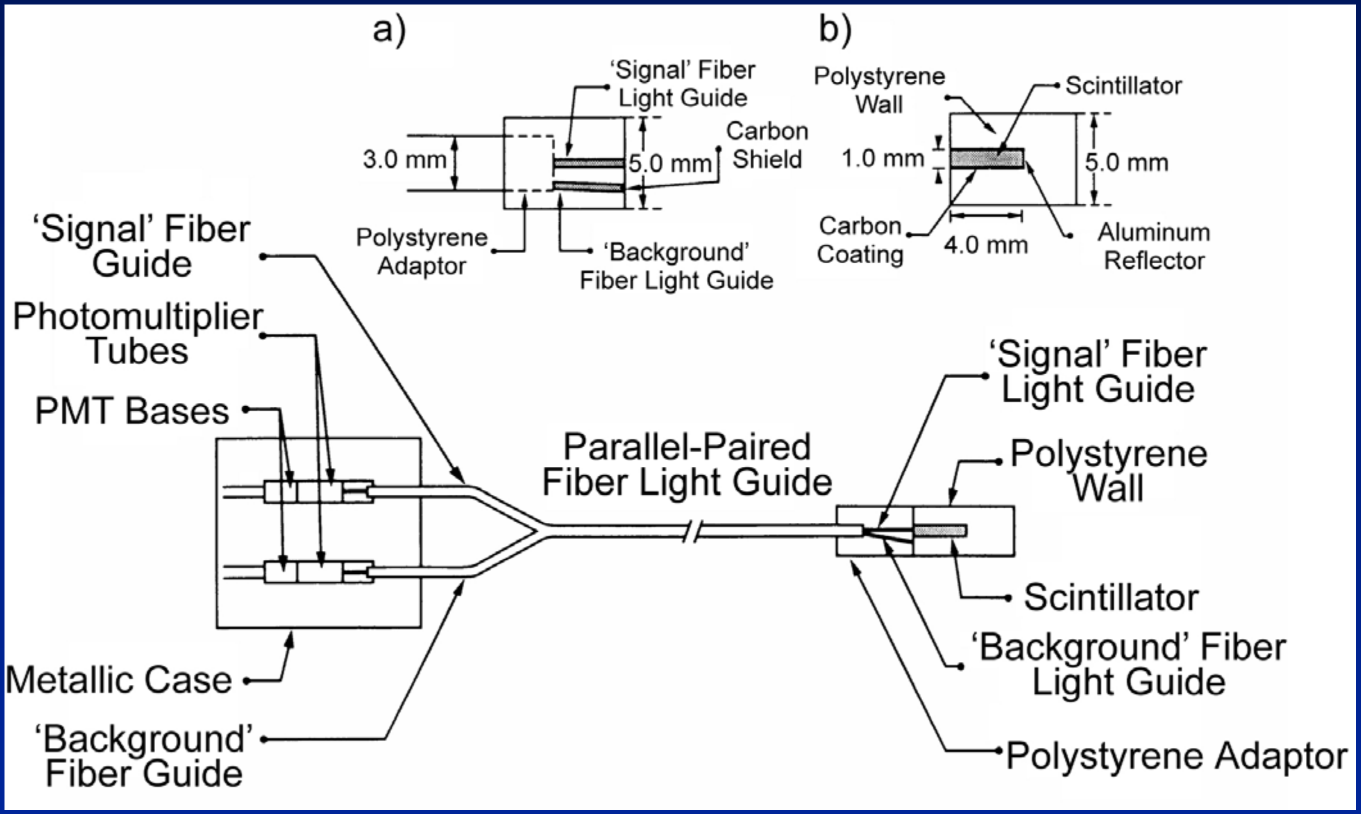
Stability of the QA device over time



Beddar A S, "A new scintillator detector system for the quality assurance of 60Co and high-energy therapy machines", Phys Med Biol 39: 253–263, 1994.

ORIGINAL PROTOTYPE



EBRT

- Introduction
- Properties
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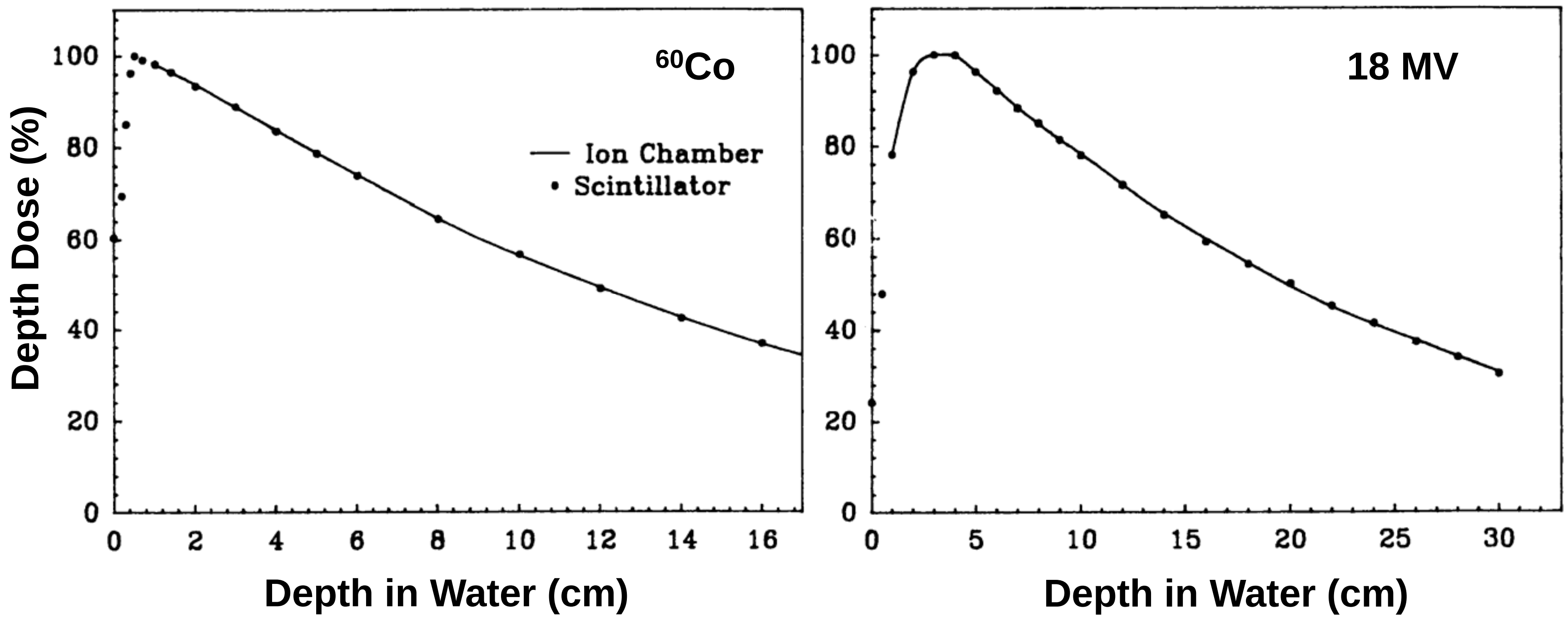
Accurate for photon measurements



Beddar, A. S., Mackie, T. R., and Attix, F. H., "Water-equivalent plastic scintillation detectors for high-energy beam dosimetry: II. Properties and measurements," Phys. Med. Biol. 37, 1901-1913 (1992)

EBRT

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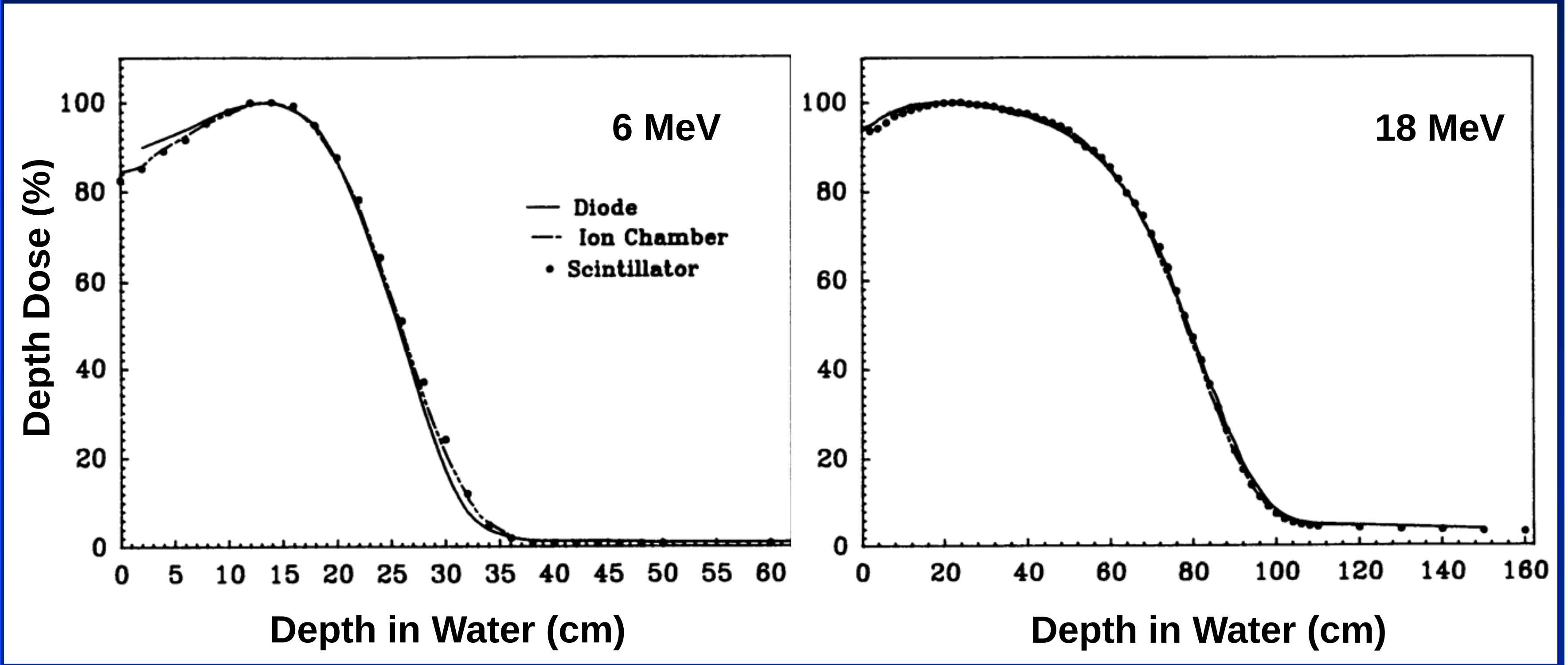
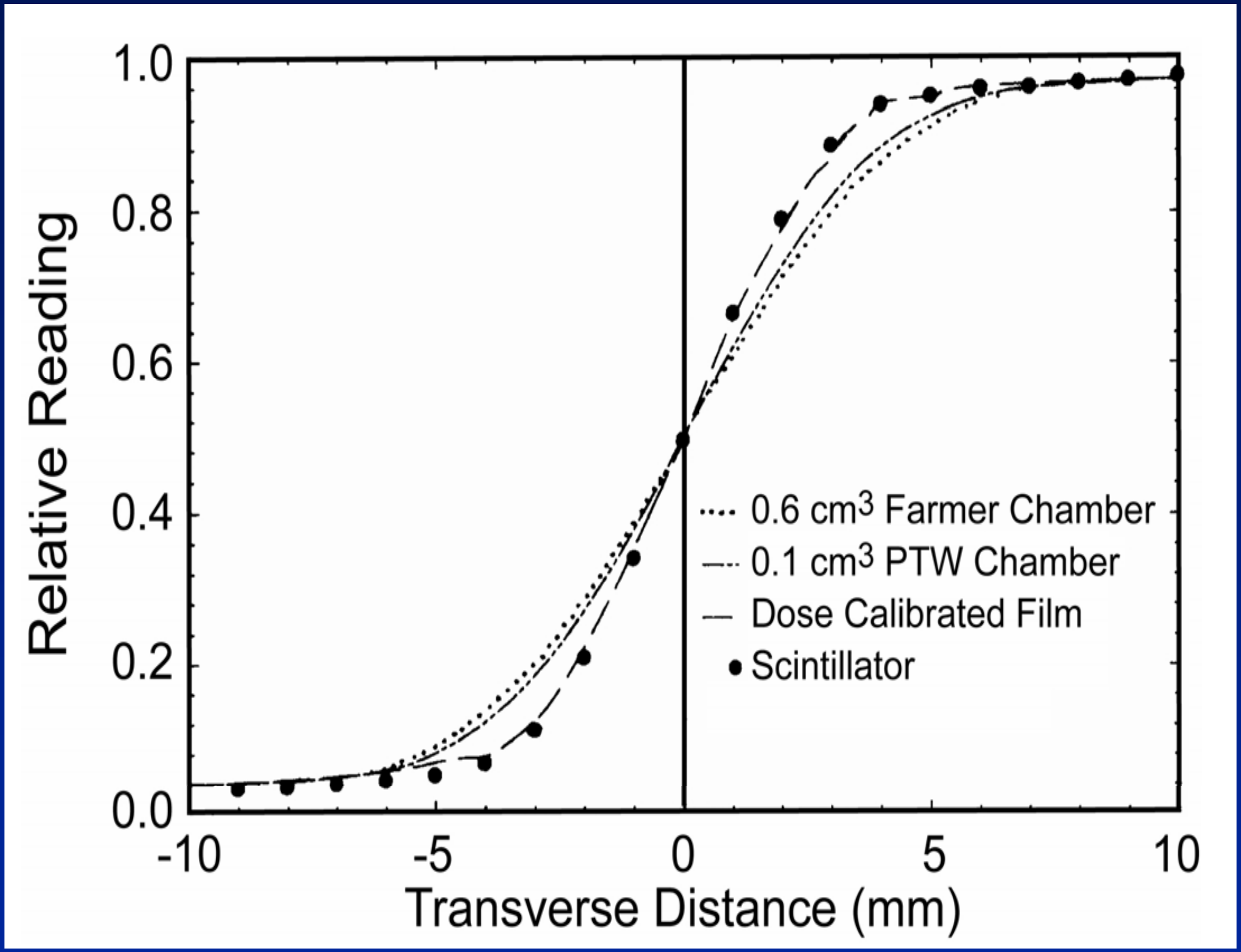
Accurate for electron measurements:



Beddar, A. S., Mackie, T. R., and Attix, F. H., "Water-equivalent plastic scintillation detectors for high-energy beam dosimetry: II. Properties and measurements," Phys. Med. Biol. 37, 1901-1913 (1992) c

Spatial Resolution

- Introduction
- Properties
- Applications
- Conclusion



Beddar, A. S., Mackie, T. R., and Attix, F. H., "Water-equivalent plastic scintillation detectors for high-energy beam dosimetry: II. Properties and measurements," Phys. Med. Biol. 37, 1901-1913 (1992) c

Spatial Resolution

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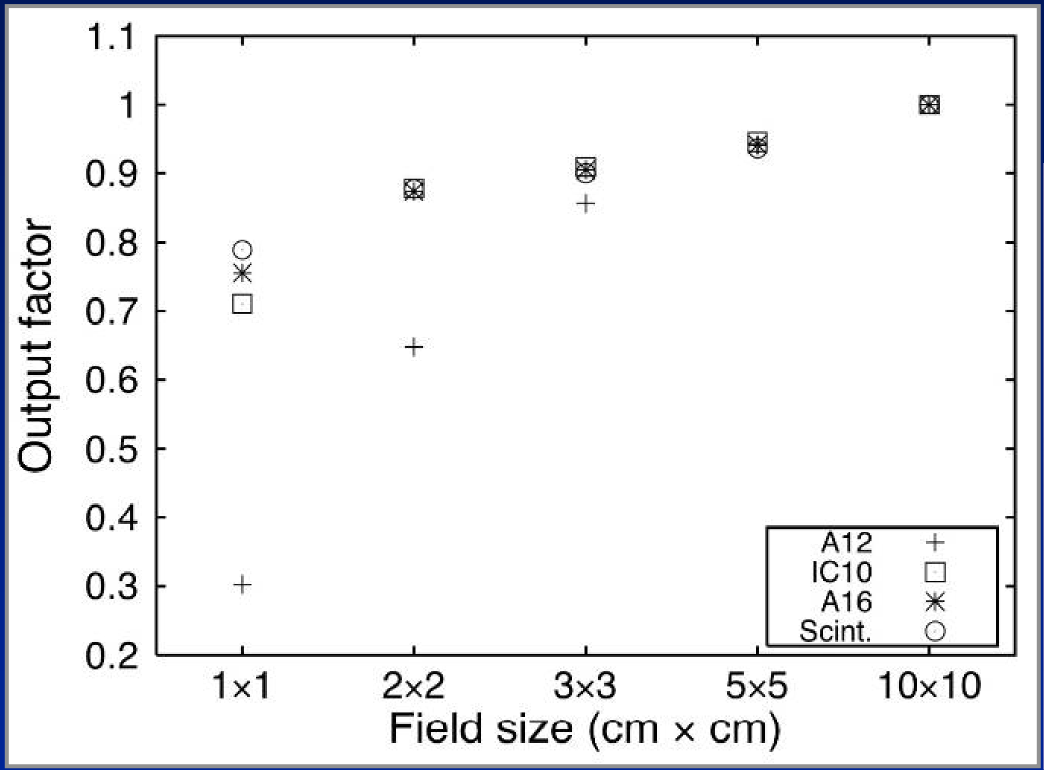
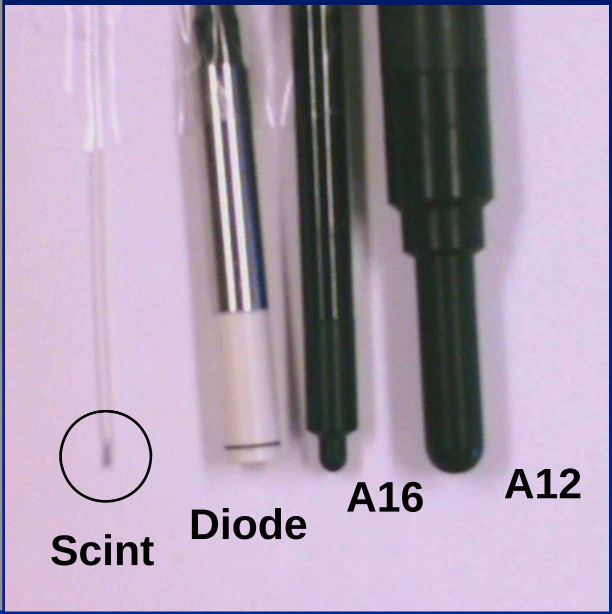
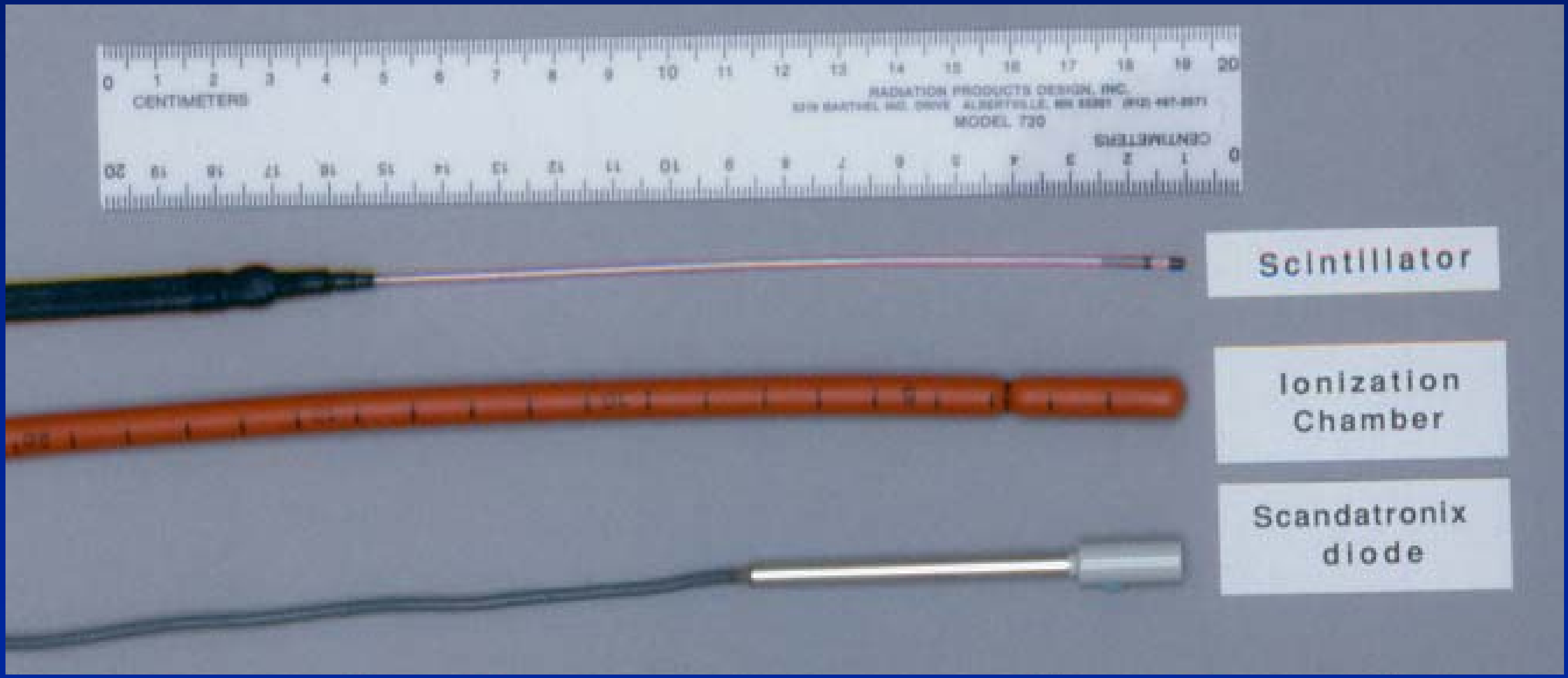




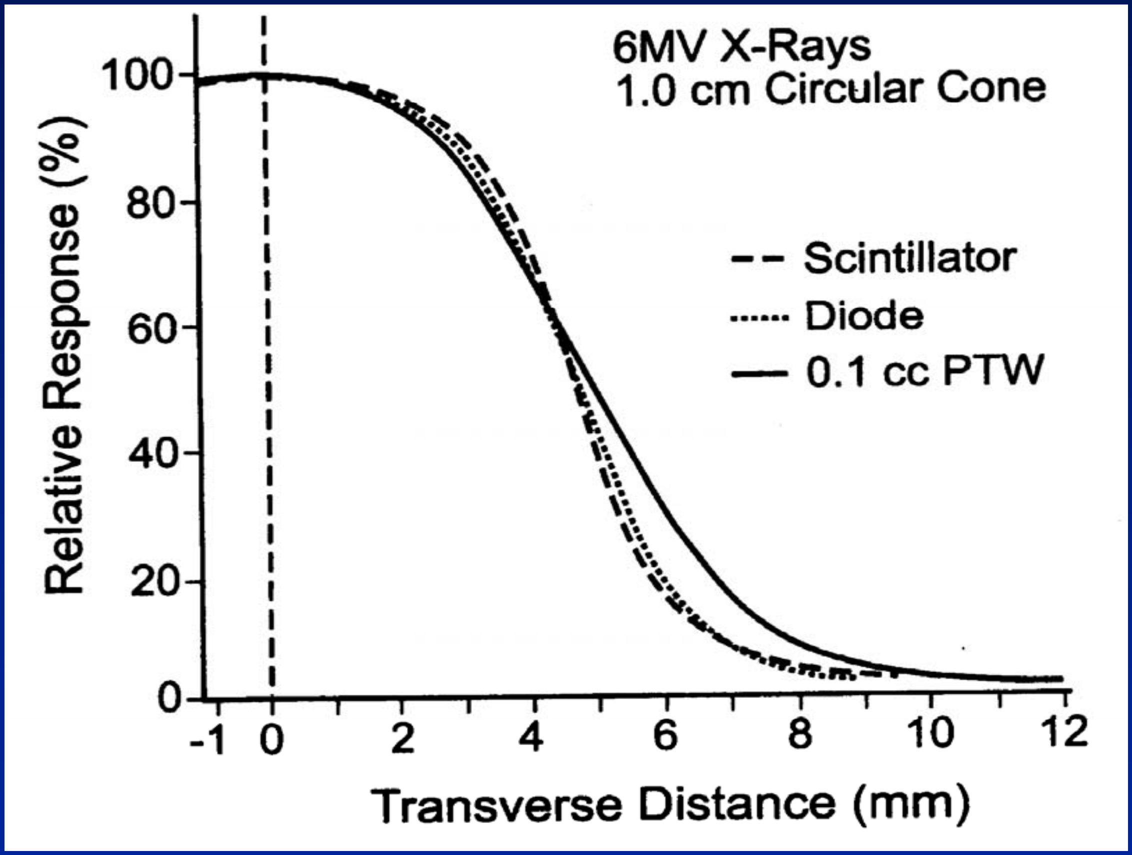
Archambault L, Beddar S, Gingras L, Lacroix F, Roy R, Beaulieu L, "Water-equivalent dosimeter array for small-field external beam radiotherapy", Med Phys 34: 1583–1592, 2007.

DOSIMETRY FOR STEREOTACTIC RADIOSURGERY

- Introduction
- Properties
- Applications
- Conclusion

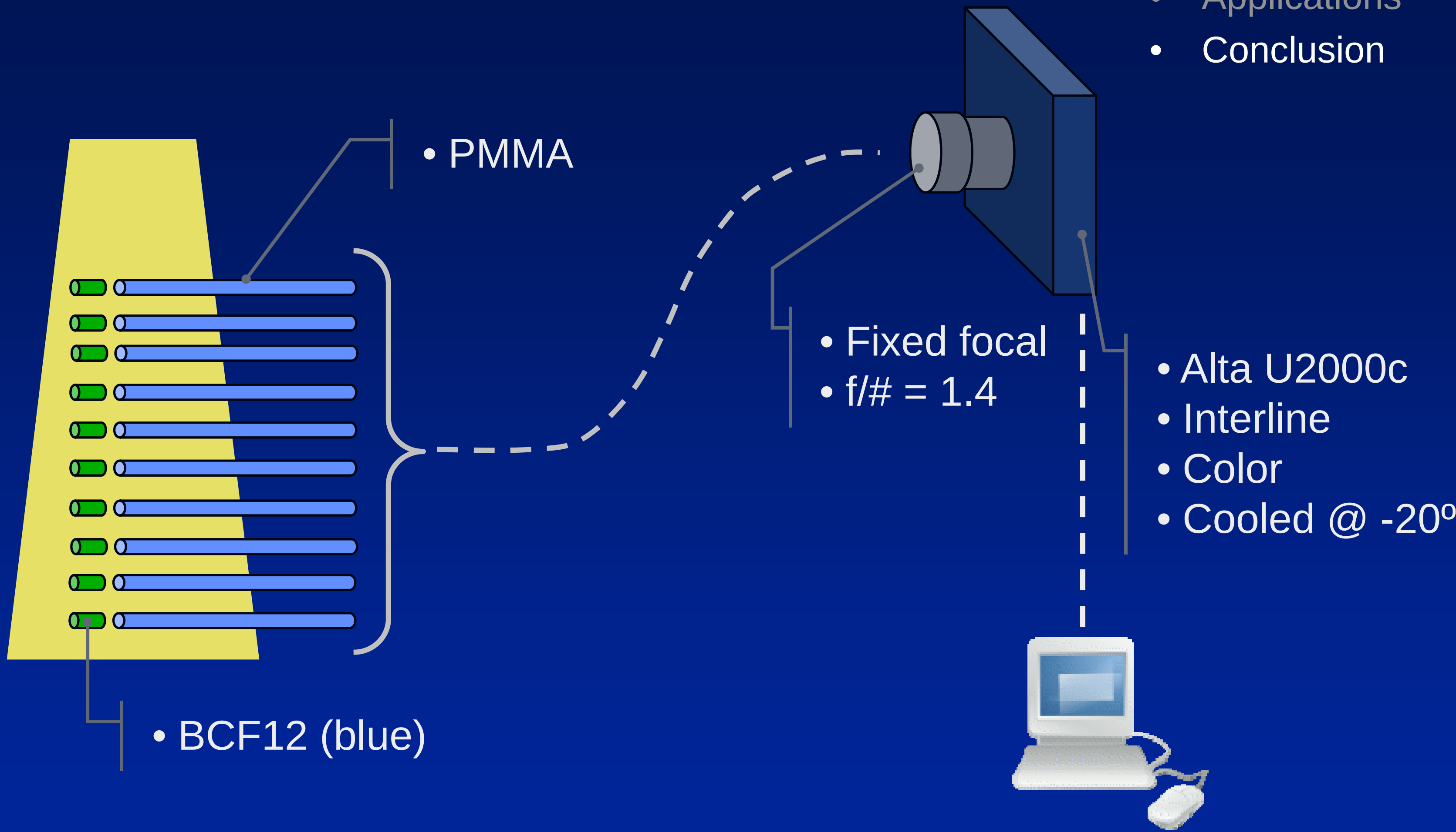


DOSIMETRY FOR STEREOTACTIC RADIOSURGERY



Beddar S, Kinsella T J, Ikhlef A, Sibata C H, "Miniature 'Scintillator-Fiberoptic-PMT' detector system for the dosimetry of small fields in stereotactic radiosurgery", IEEE Trans. Nucl. Sci. 48: 924-928, 2001.

SCINTILLATION FIBER ARRAY PROTOTYPE



- Subtract Cerenkov contamination with chromatic removal

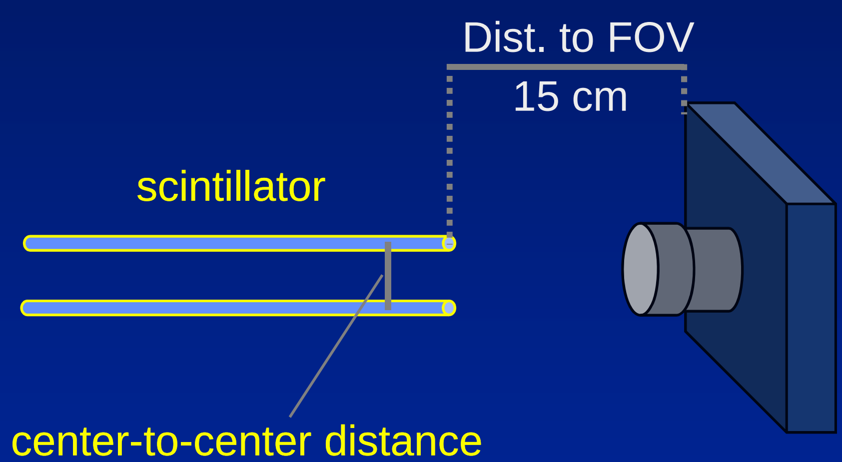
Archambault L, Beddar S, Gingras L, Roy R, Beaulieu L, "Measurement accuracy and Cerenkov removal for high performance, high spatial resolution scintillation dosimetry", Med. Phys. 33: 128-135, 2006.

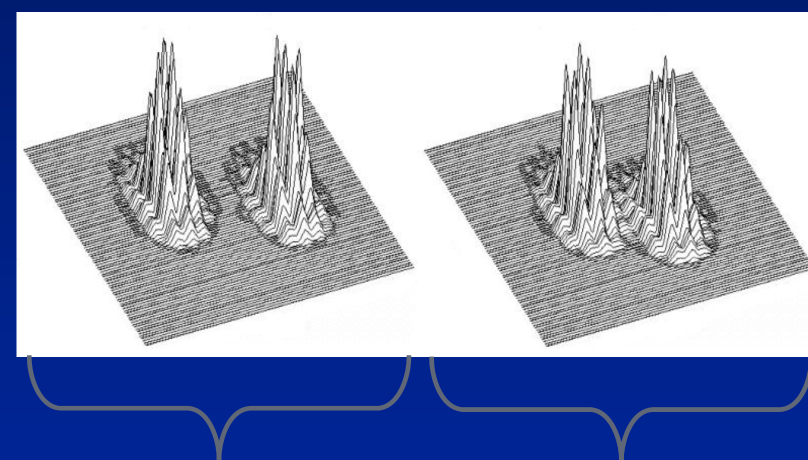
Scintillation Fiber Array Detector for QA

- Introduction
- Properties
- Applications
- Conclusion

Lacroix F, Archambault L, Gingras L, Beddar AS, and Beaulieu L. Clinical prototype of a plastic water-equivalent scintillating fiber dosimeter matrix for IMRT QA applications, Med Phys 35 (2008) 3682-3690.

Fiber Spatial Discrimination





two fibers
3 mm c-to-c

two fibers
2 mm c-to-c

DEPTH DOSE

- Introduction
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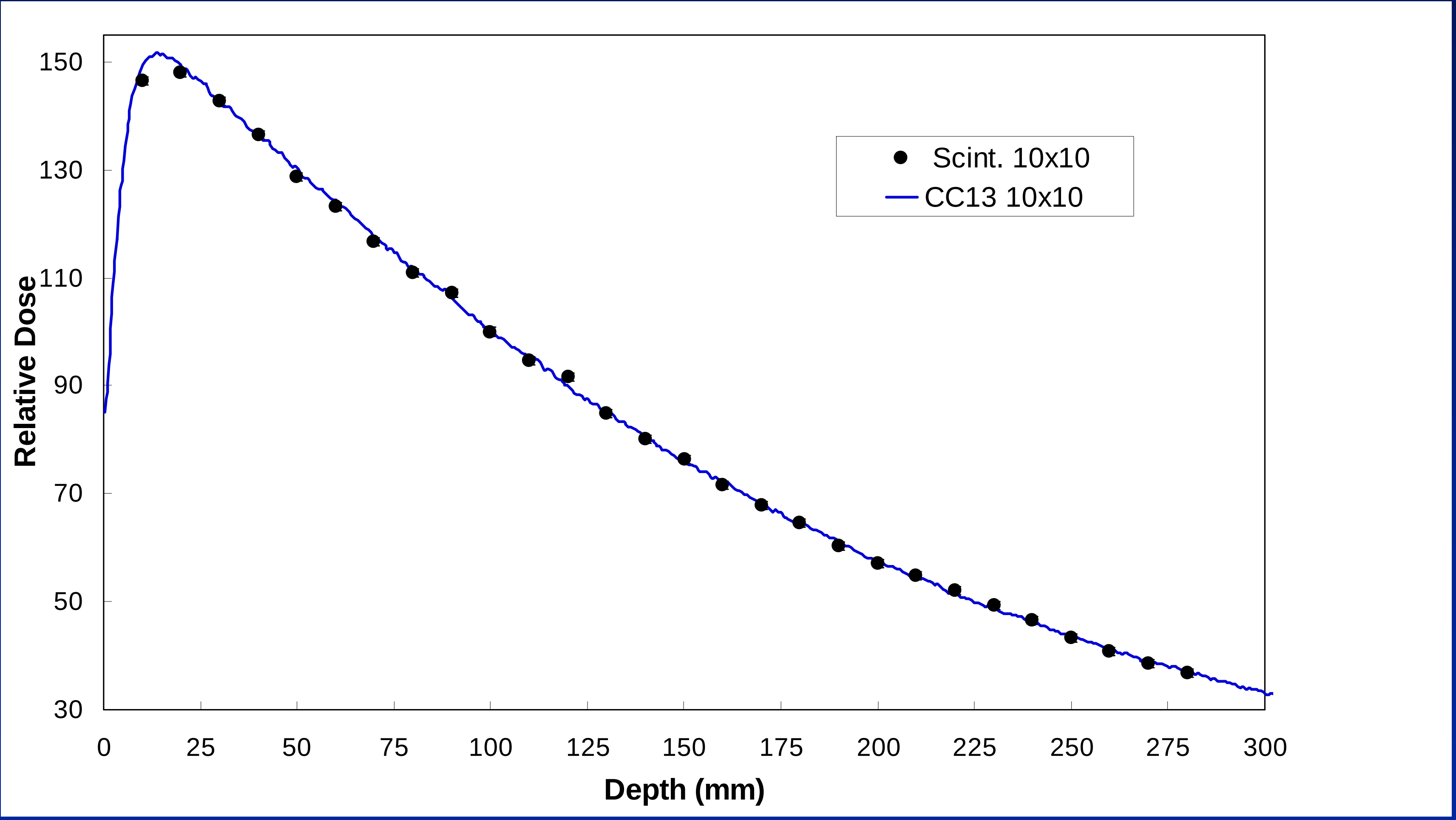

Lacroix F, Archambault L, Gingras L, Beddar AS, and Beaulieu L. Clinical prototype of a plastic water-equivalent scintillating fiber dosimeter matrix for IMRT QA applications, Med Phys 35 (2008) 3682-3690.

Beam Profile

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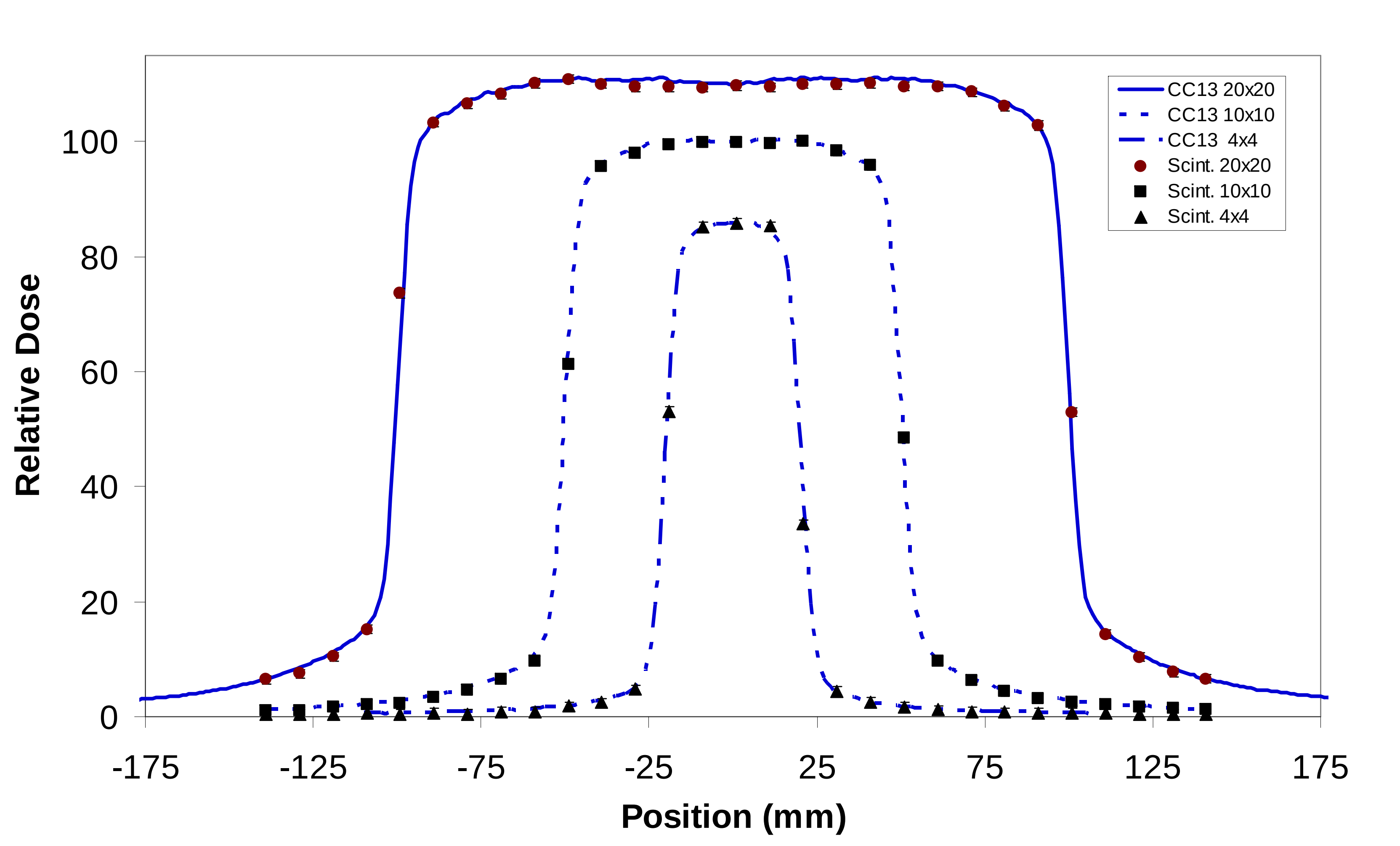
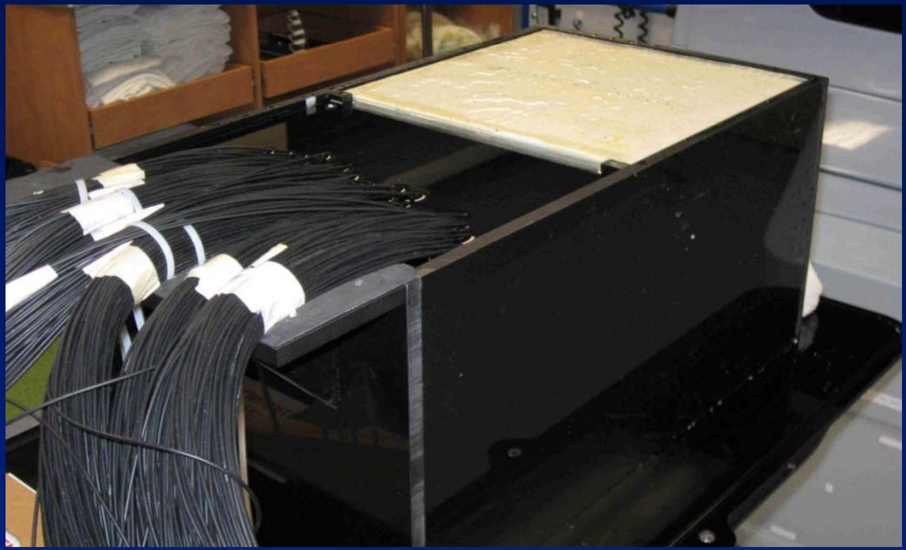


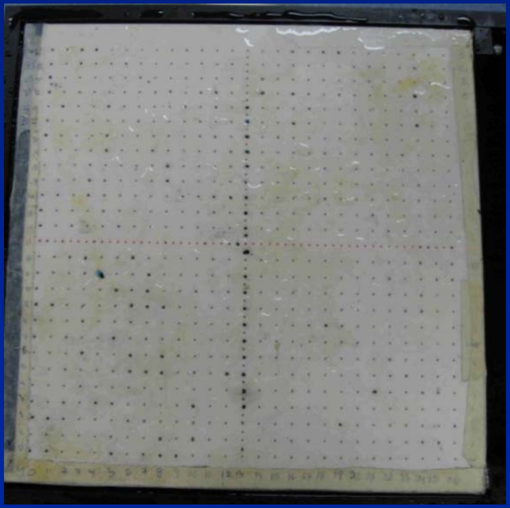
Lacroix F, Archambault L, Gingras L, Beddar AS, and Beaulieu L. Clinical prototype of a plastic water-equivalent scintillating fiber dosimeter matrix for IMRT QA applications, Med Phys 35 (2008) 3682-3690.

Planar Array

- Introduction
- Properties
- Applications
- Conclusion

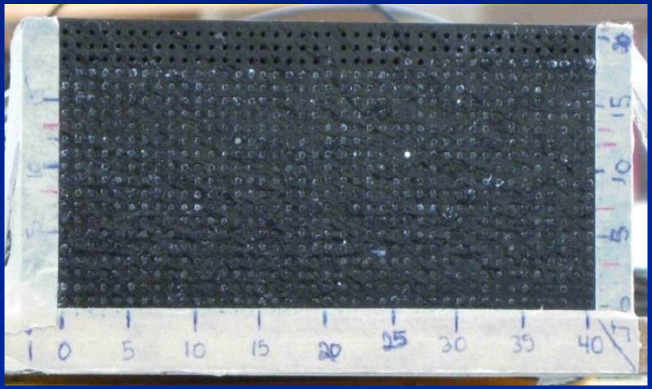


781 detector-elements



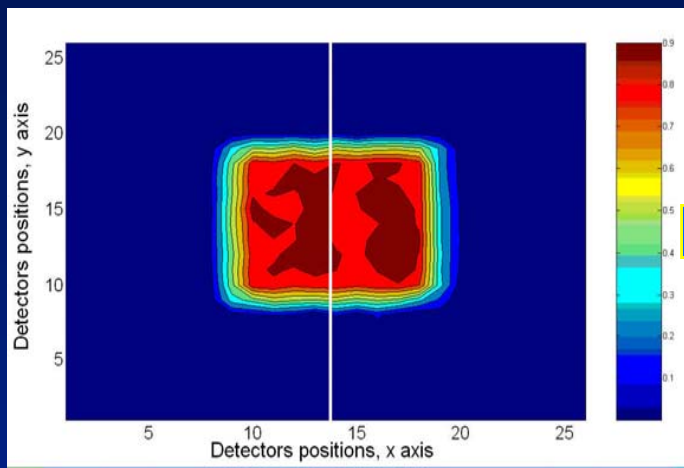
Detector plane 28×27

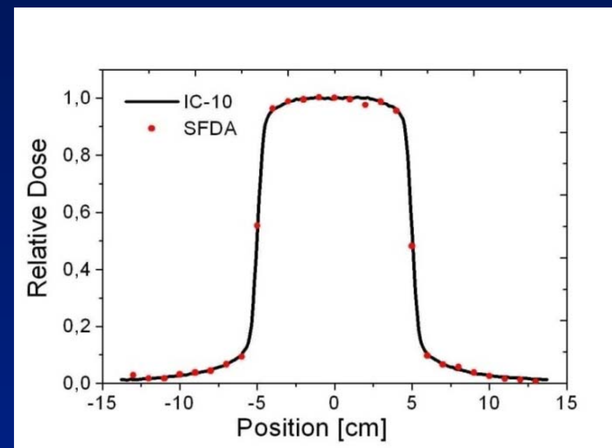
CCD side

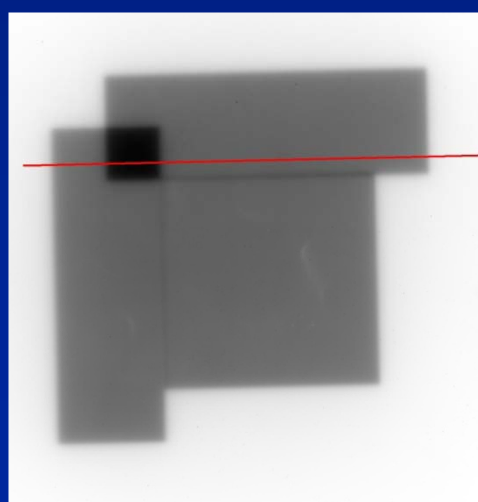


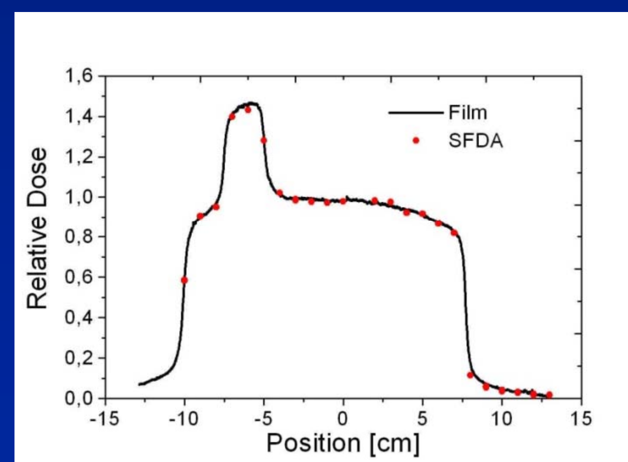
Connector 11.5x5.5 cm^2

PLANAR ARRAY









SUMMARY

- Scintillation dosimeters possess a unique set of advantages
  – Water equivalence, linear dose response, energy and temperature independence, spatial resolution, etc…
- Several types of scintillation detectors have been developed in the last 15 years
- Main applications:
  – Conventional EBRT (photons and electrons)
  – Quality assurance device (daily and IMRT)
  – Radiosurgery
  – Protons
  – Brachytherapy

CONCLUSIONS

- Scintillation dosimetry will be increasingly used in radiotherapy.
- Their advantages make them ideal for measuring complex dose distributions such as those produced by IMRT.
- They can compete with other dosimeters in terms of measurement accuracy, convenience and can be economical.

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