TLD and Monte Carlo Techniques for Reference-Quality Brachytherapy Dosimetry

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Learning Objectives

- To review the requirements and challenges of quantitative brachytherapy dosimetry
  - Detector selection
  - Roles of experimental and computational dosimetry
- To review the formalism, techniques, and associated uncertainties of
  - current TLD dosimetry practices
  - Current Monte Carlo simulation dose-estimation practices
- To review emerging developments
  - Improved energy-response corrections for TLD-100
  - New detector systems
  - Model-based dose-calculation algorithms

(Radiumhemmet, Stockholm: 1945)

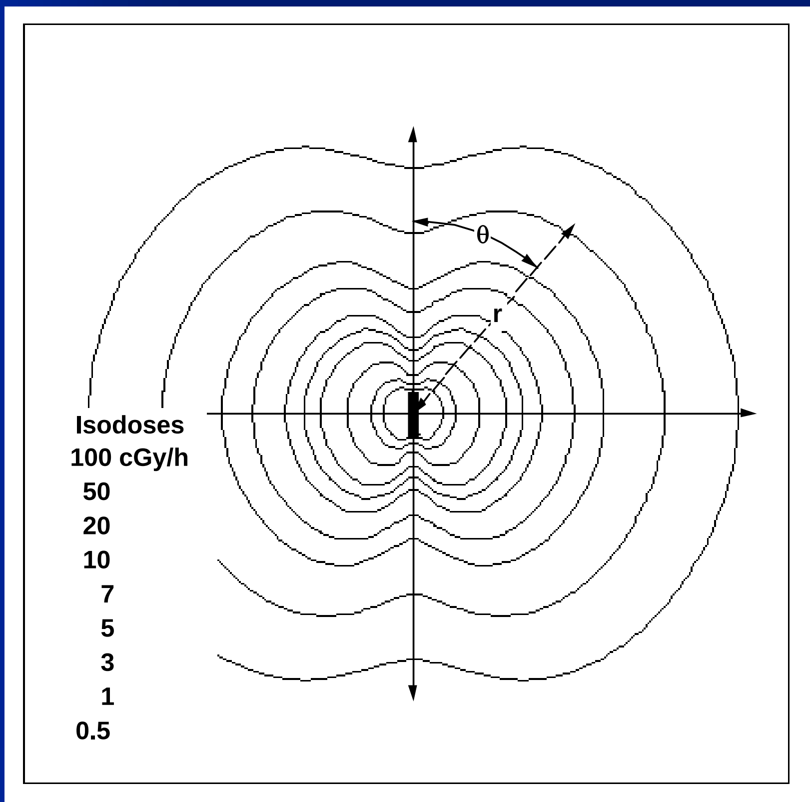
Potential COI Disclosures

- **Williamson**
  - Research grants supported by Varian and Philips
- **Rivard**
  - Research grants supported by Nucletron, Varian, and IsoRay

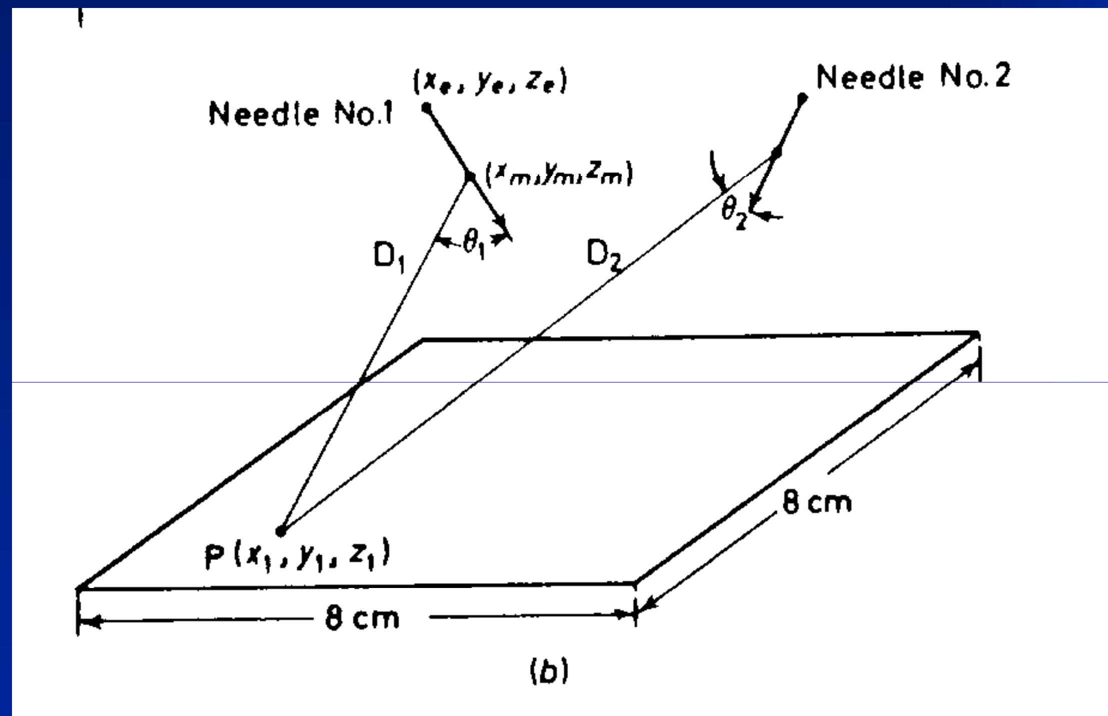
What is “Quantitative Dosimetry?”

- Williamson’s definition: absorbed dose estimation method providing
  - Accurate representation of well-defined physical quality
  - Rigorous uncertainty analysis ⇒ <10% uncertainty 0.5 to 5 cm in liquid water
  - Traceable to NIST primary standards ($S_{K,N99}$)
- Applications
  - Single-source dose-rate arrays for TG-43 parameter determination (“Reference quality” dose distributions)
  - Direct treatment planning
  - Validating semi-empirical algorithms

Single-Source Dose Distributions
Superposition Model



Single-source dose distribution
= Dosimetry

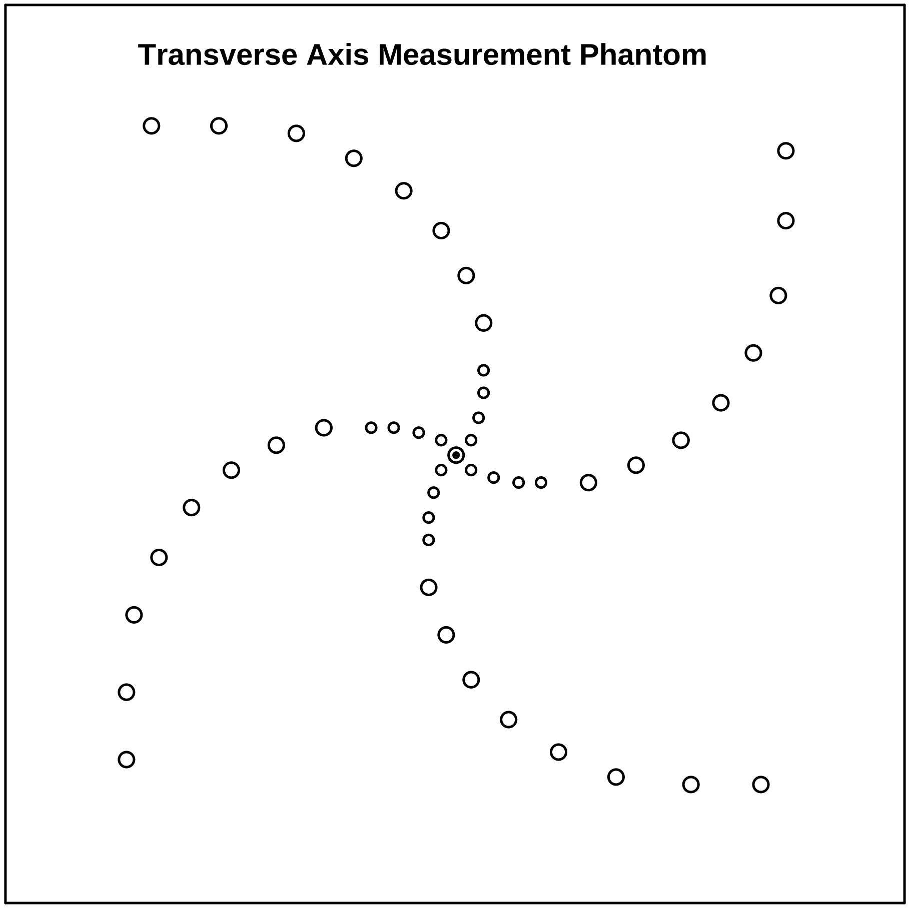


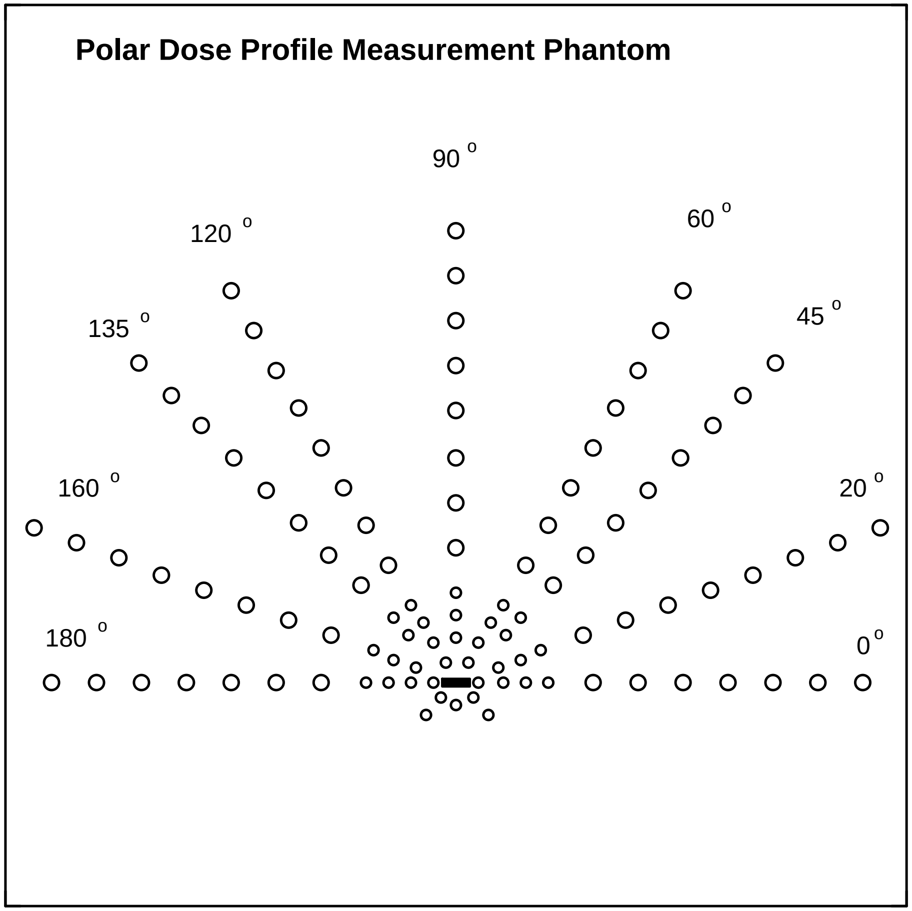
Superposition of multiple source doses
= Treatment Planning

Criteria for experimental dosimeters

- Dosimetric environment
  - Large Dose Gradients
  - Wide Range of Dose Rates
  - Low Photon Energies
- Signal stability and reproducibility
  - Spatially and temporally constant Sensitivity (signal/dose)
  - Free of fading, dose-rate effects
- Small size, high sensitivity, large dynamic range
  - Small size: avoid averaging dose gradients
  - Large size: Good signal at low doses
- ±20 μm positioning accuracy needed for 2% accuracy
- Support measurements at many points

Solid Water Phantoms for TLD Dosimetry





100-200 μm positional accuracy achievable

TLD Detectors

- Use TLD-100 LiF extruded ribbons ('chips')

  1 x 1 x 1 mm^3 at distances $<$ 2 cm

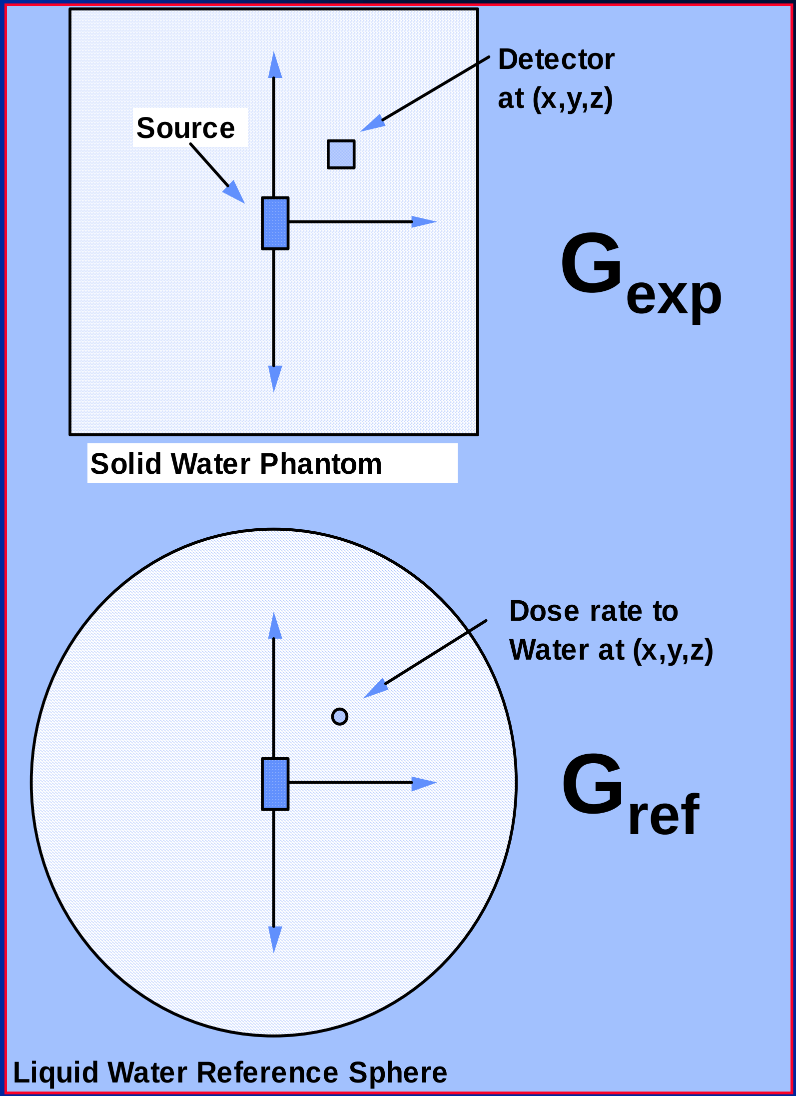
  3 x 3 x 0.9 mm^3 at distances $\geq$ 2 cm
- Use RMI 453 Machined Solid Water Phantom
  - Composition ($CaCO_3$ + organic foam) not stable
  - Either perform chemical assay or use high purity PMMA
- Annealing protocol

  1 hour 400° C followed by 24 hours of 80° C pre-irradiation

  OR

  1 hour 400° C pre-irradiation followed by 10 minutes at 100° C Post-irradiation

Brachytherapy Dosimetry



- **Given:** M(r) = dosimeter (TLD or Diode) reading in geometry G_{exp}
- **Desired:** $\left(\dot{D}_{med}(r)/S_K\right)$ = absorbed dose rate to water in reference geometry, G_{ref}
- **Many Corrections**
  - Detector sensitivity
  - Phantom vs reference geometry
  - Radiation field Perturbation
  - Detector response artifacts

Experimental Dose Measurement-I

$$\left[\frac{\dot{D}_{med}(r)}{S_K}\right] = \frac{M \cdot k_l(M) \cdot g(\Delta T) \cdot p_{phant}(r)}{S_K \cdot S_{AD}(M_0) \cdot S_{AD}^{rel}(r)}$$

$$\frac{M(r) \cdot k_l(M \rightarrow M_0) \cdot g(\Delta T) \cdot p_{phant}(Q_{exp}, G_{exp} \rightarrow Q_{ref}, G_{ref}; r)}{S_K \cdot S_{AD}(M_0, Q_0, G_0) \cdot S_{AD}^{rel}(Q_0, G_0 \rightarrow Q_{exp}, G_{exp}, r)}$$

- M = reading at position r in geometry G_{exp} and spectrum Q_{exp}
- S_K = Measured Air-Kerma Strength
- g(T) = decay correction over integration interval, $\vec{r}$ ΔT
- $K_l(M)$ = linearity correction relative to reference level, M_0
- $S_{AD} = M_0/D_{med0}$ = absorbed dose sensitivity in calibration beam with geometry G_0 and spectrum, Q_0

Experimental Dose Measurement-II

$$\left[\frac{\dot{D}_{med}(r)}{S_K}\right] = \frac{M \cdot k_l(M) \cdot g(\Delta T) \cdot p_{phant}(r)}{S_K \cdot S_{AD}(M_0) \cdot S_{AD}^{rel}(r)}$$

- **Relative absorbed dose sensitivity: corrects for impact of G_0/Q_0 vs. G_{exp}/Q_{exp} differences on dosimeter response**

$$S_{AD}^{rel}(Q_0, G_0 \rightarrow Q_{exp}, G_{exp}, r) = \frac{S_{AD,wat}(r, M_0, Q_{exp}, G_{exp})}{S_{AD,med_0}(M_0, Q_0, G_0)}$$

- **Phantom correction factor: impact of G_{exp}/Q_{exp} vs. G_{ref}/Q_{ref} differences on dosimeter response**

$$p_{phant,wat}(Q_{exp}, G_{exp} \rightarrow Q_{ref}, G_{ref}; r) = \frac{D_{wat}(r, Q_{ref}, G_{ref})}{D_{wat}(r, Q_{exp}, G_{exp})}$$

TLD readings

$$M(r) = 1/n \sum_{i=1}^{n} \frac{(TL_i - TL_{bkgd})}{S_i}$$

- TL_i is Measured Response of i-th detector at r
- S_i is relative sensitivity of i-th detector derived from reading TLDs exposed to uniform doses
- TG-43 recommends n = 5-15

Relative Energy Response

$$E(Q_0,G_0 \rightarrow Q_{ref},G_{ref},r;G_{exp}) = \frac{S_{AD}^{rel}(Q_0,G_0 \rightarrow Q_{exp},G_{exp},r)}{p_{phant,wat}(Q_{exp},G_{exp} \rightarrow Q_{ref},G_{ref};r)}$$

$$= \frac{k_{bq}^{rel}(Q_0 \rightarrow Q_{exp};M_0)\cdot f^{rel}(Q_0,G_0 \rightarrow Q_{exp},G_{exp},r)}{p_{phant}(Q_{exp},G_{exp} \rightarrow Q_{ref},G_{ref};r)}$$

- **Absorbed dose energy dependence**

$$f^{rel}(Q_0,G_0 \rightarrow Q_{exp},G_{exp},r) \equiv \frac{f(r,Q_0,G_0)}{f(r,Q_{exp},G_{exp})} = \frac{\left(\bar{D}_{det}/D_{wat}\right)(r,Q_{exp},G_{exp})}{\left(\bar{D}_{det}/D_{med_0}\right)(Q_0,G_0)}$$

- **Relative intrinsic energy dependence**

$$k_{bq}^{rel}(Q_0 \rightarrow Q_{exp};M_0) \equiv \frac{k_{bq}(M_0,Q_0)}{k_{bq}(M_0,Q_{exp})} = \frac{\left(M_0/\bar{D}_{det}\right)(r,Q_{exp},G_{exp})}{\left(M_0/\bar{D}_{det}\right)(Q_0,G_0)}$$

Estimation of Energy-Response Corrections

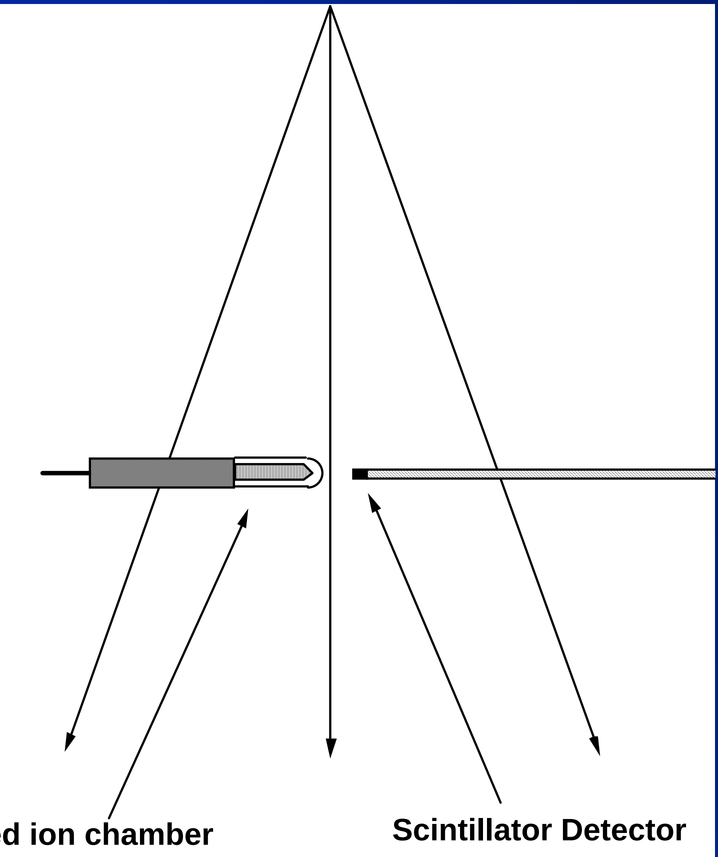
- Theoretical Approximation

$$E_{Thy}(r;G_{exp}) \approx \frac{f^{rel}(Q_0, G_0 \rightarrow Q_{exp}, G_{exp}, r)}{p_{phant}(Q_{exp}, G_{exp} \rightarrow Q_{ref}, G_{ref}; r)}$$

assuming $k_{bq}^{rel}(Q_0 \rightarrow Q_{exp}; M_0) \approx 1$

- Direct measurement: x-ray beam with spectrum $Q_{FS} \approx Q_{exp}$

$$E_{meas}(r;G_{exp}) = \frac{S_{K,air}(M_0, Q_{exp}, G_{FS})}{S_{AD,med_0}(M_0, Q_0, G_0)} \times \frac{\left(K_{air} / D_{wat}\right)(Q_{FS}, G_{FS})}{p_{disp}(r, G_{exp}) \cdot p_{VolAvg}(r, G_{exp}) \cdot p_{phant,wat}(G_{exp} \rightarrow G_{ref}; Q_{exp}, r)}$$



Compare detector to "matched" X-ray Beam calibration in Free-Air $Q_{FS} = 40\text{-}120$ kVp

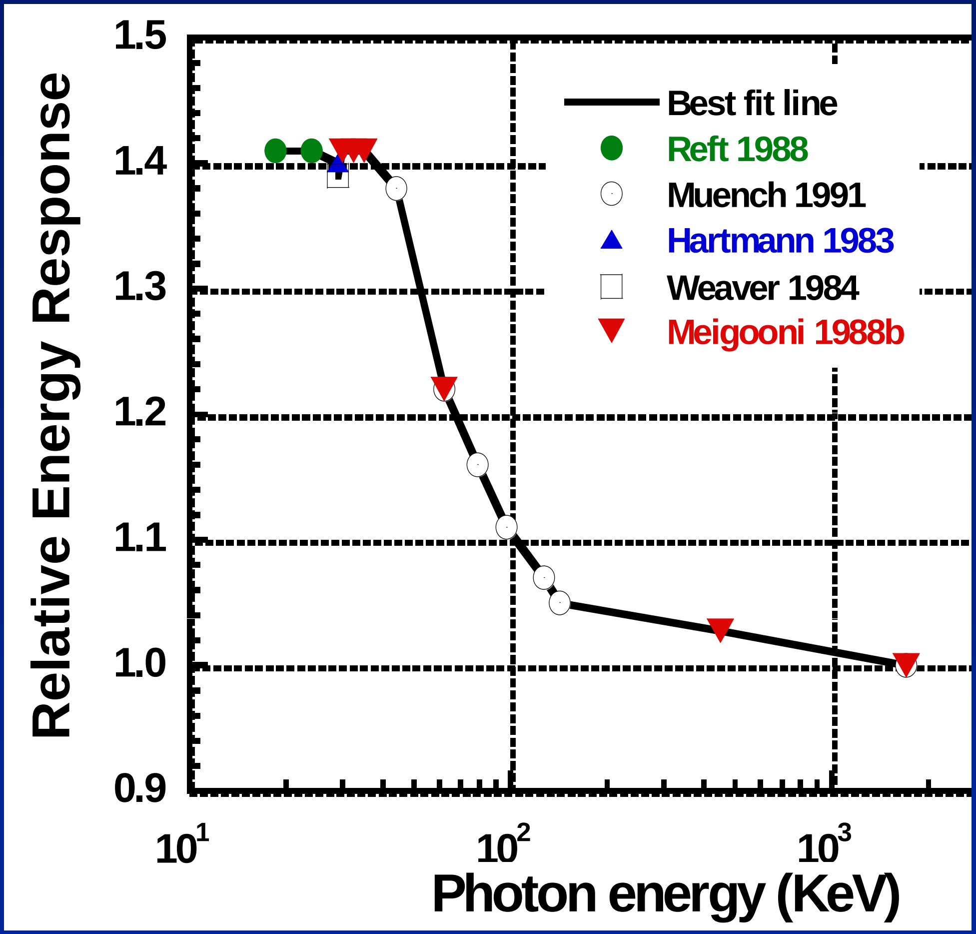
$$S_{K,air}(Q_{FS}) = M(Q_{FS}, G_{FS}) / K_{air}^{FS}$$

$$E(r) = \left(\frac{S_{K,air}(Q_{FS})}{S_{AD}(Q_0)} \right) \cdot \frac{\left(\overline{\mu_{en}/\rho}\right)_{wat}^{air}(Q_{FS})}{p_{VolAvg} \cdot p_{disp}(r) \cdot p_{disp}}$$

$$p_{disp}(G_{FS} \rightarrow G_{exp}) = \frac{D_{wat} \text{ in medium}}{K_{wat}^{FS} \text{ in cavity}} \approx 0.97$$

$$p_{VolAvg}(Q_{exp}, G_{exp}) = \frac{D_{wat}(r)}{\overline{D}_{wat}(r)} = \left. \frac{D_{wat}(r) \text{ at point } r}{V^{-1} \int_{V(r)} D_{wat}(r')dV'} \right\} \in (0.80 - 1.00)$$

Measured TLD-100 relative Energy Response



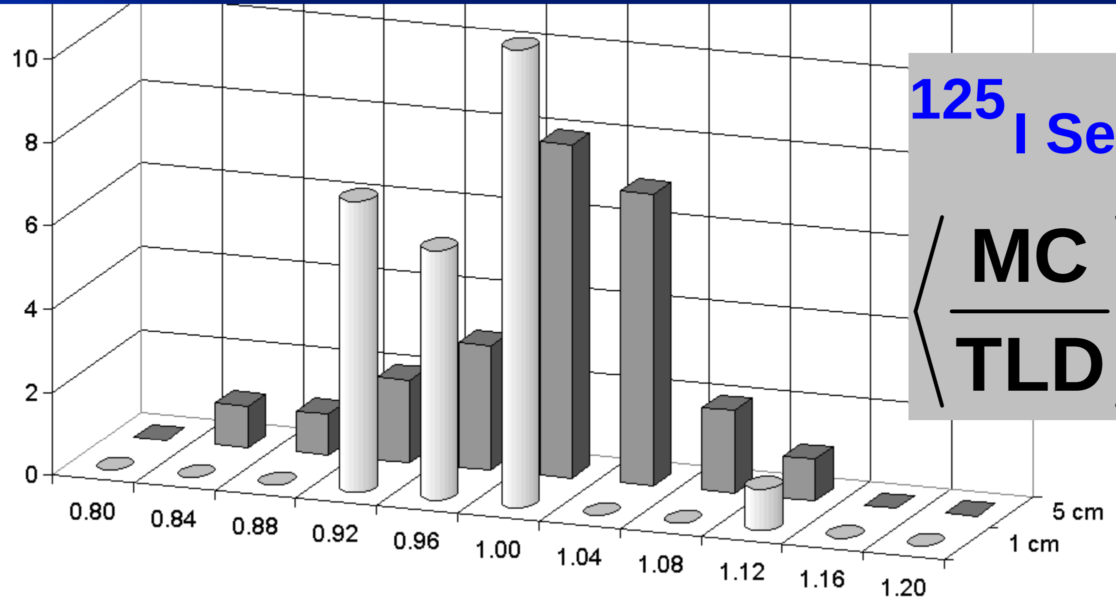
- E_{thy}(1 cm) = 1.42
  - Dolan (2006) in water medium
  - 6711 ^{125}I
- E_{meas} = 1.39-1.44 for ^{125}I
  - 1980-1990 in-air measurements
- Conclusion:

$$E_{Thy} \approx E_{meas}$$

$$\Rightarrow k_{bq}^{rel}(4\ \mathrm{MV} \rightarrow {}^{125}\mathrm{I}) \approx 1$$

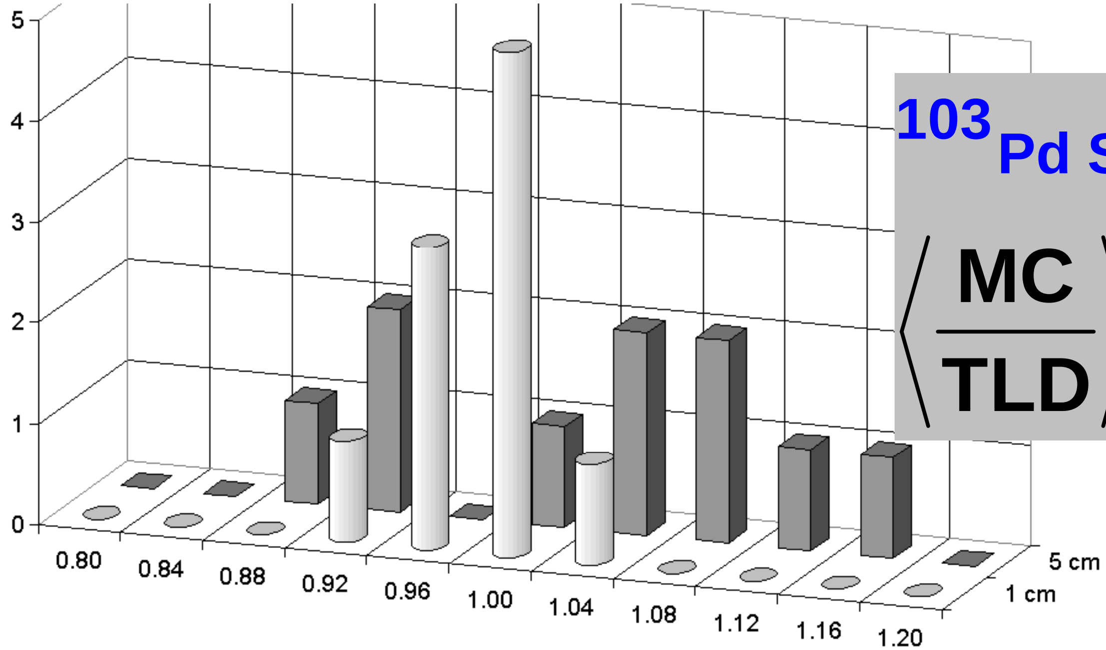
- Conventional choice: E =1.4 w/o regard to details
- 2004 TG-43 U1 has assigned 5% uncertainty to E

Monte Carlo vs. TLD Dose Rates



^{125}I Seeds: 14 Models and 25 comparisons

$$\left\langle \frac{MC}{TLD} \right\rangle = \begin{cases} 0.979 \pm 0.045 \text{ (1 cm)} \\ 1.002 \pm 0.066 \text{ (5 cm)} \end{cases}$$

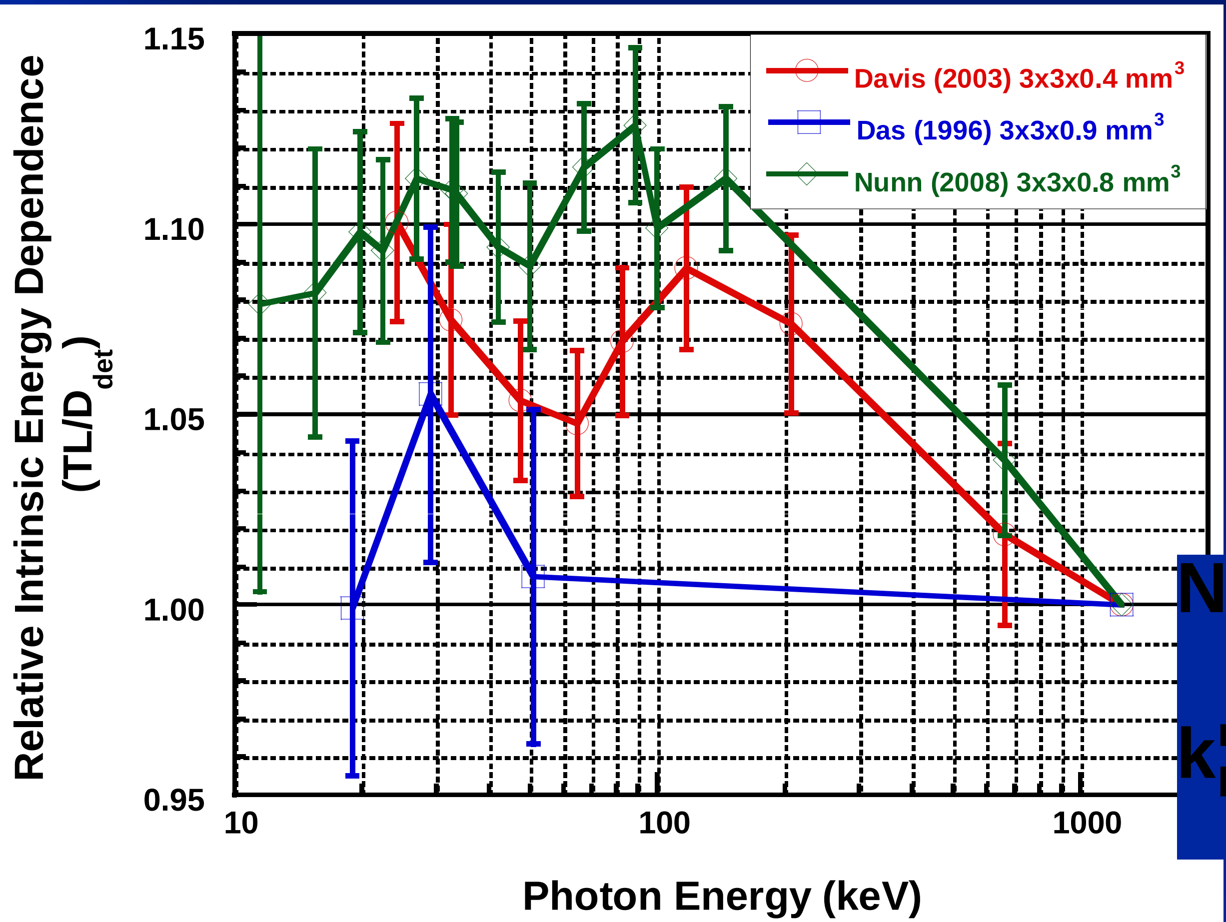


^{103}Pd Seeds: 5 Models and 10 comparisons

$$\left\langle \frac{MC}{TLD} \right\rangle = \begin{cases} 0.982 \pm 0.028 \text{ (1 cm)} \\ 1.045 \pm 0.106 \text{ (5 cm)} \end{cases}$$

Modern Measurements: $k_{bg} \neq 1$

Nunn 2008, Davis 2003, and Das 1995



$$k_{bq}^{rel}(Q_0 \rightarrow Q) = \frac{S_{K,air}^{rel}(Q_0, G_{fs} \rightarrow Q, G_{fs})}{f_K^{rel}(Q_0, G_{fs} \rightarrow Q, G_{fs})}$$

Nunn-Davis Results

$$k_{bq}^{rel} = \begin{cases} 1.09\text{-}1.10 \pm 2\% \text{ 23 keV} \\ 1.08\text{-}1.11 \pm 2\% \text{ 32 keV} \end{cases}$$

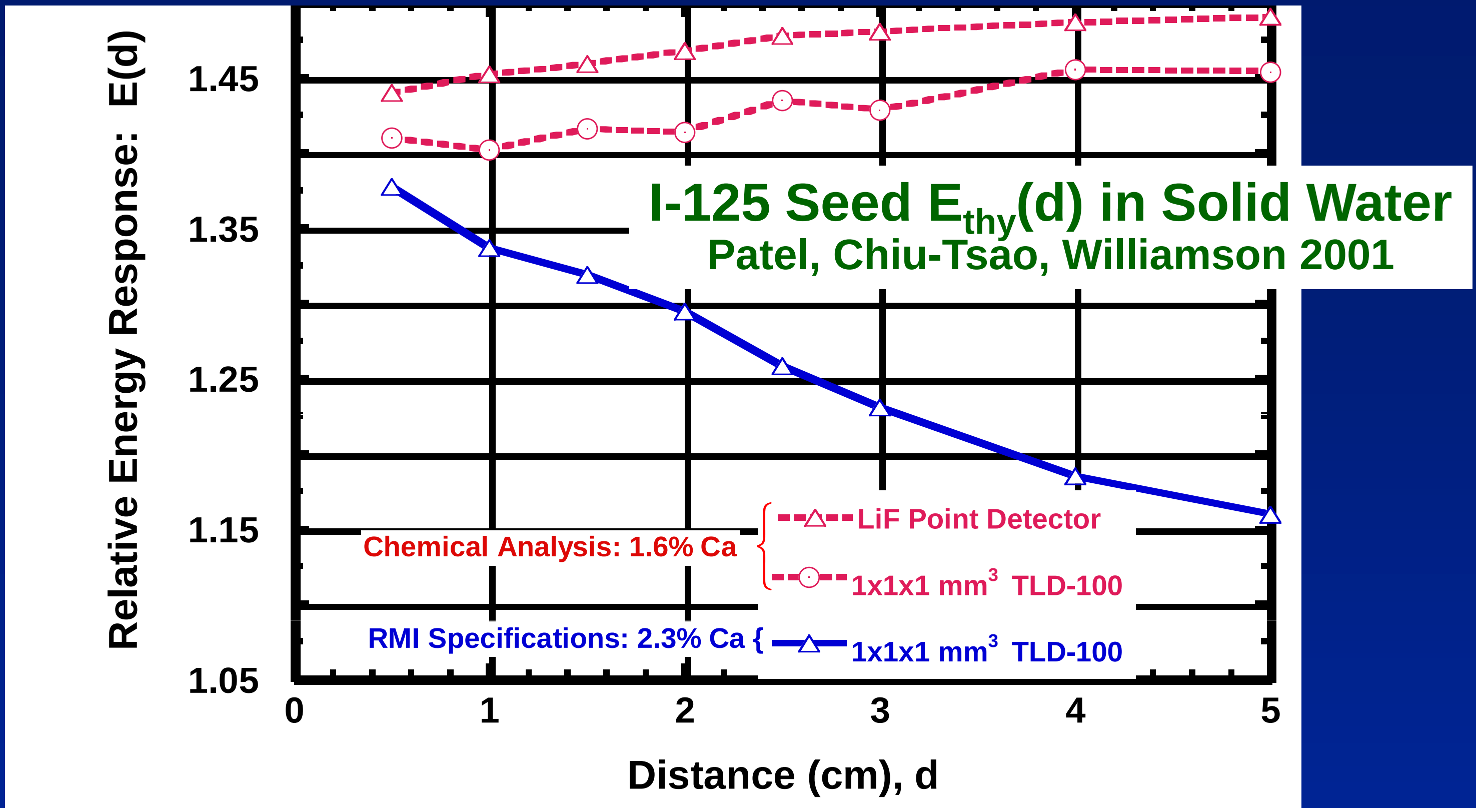
Energy linearity of TLD is controversial

Impact of k^{rel} Revisions on MC-TLD Agreement

- Rivard comparisons of TLD and MC at 1 cm and 5 cm for ^{125}I and ^{103}Pd sources
- Revised k_{rel} > 1.05 will significantly worsen agreement

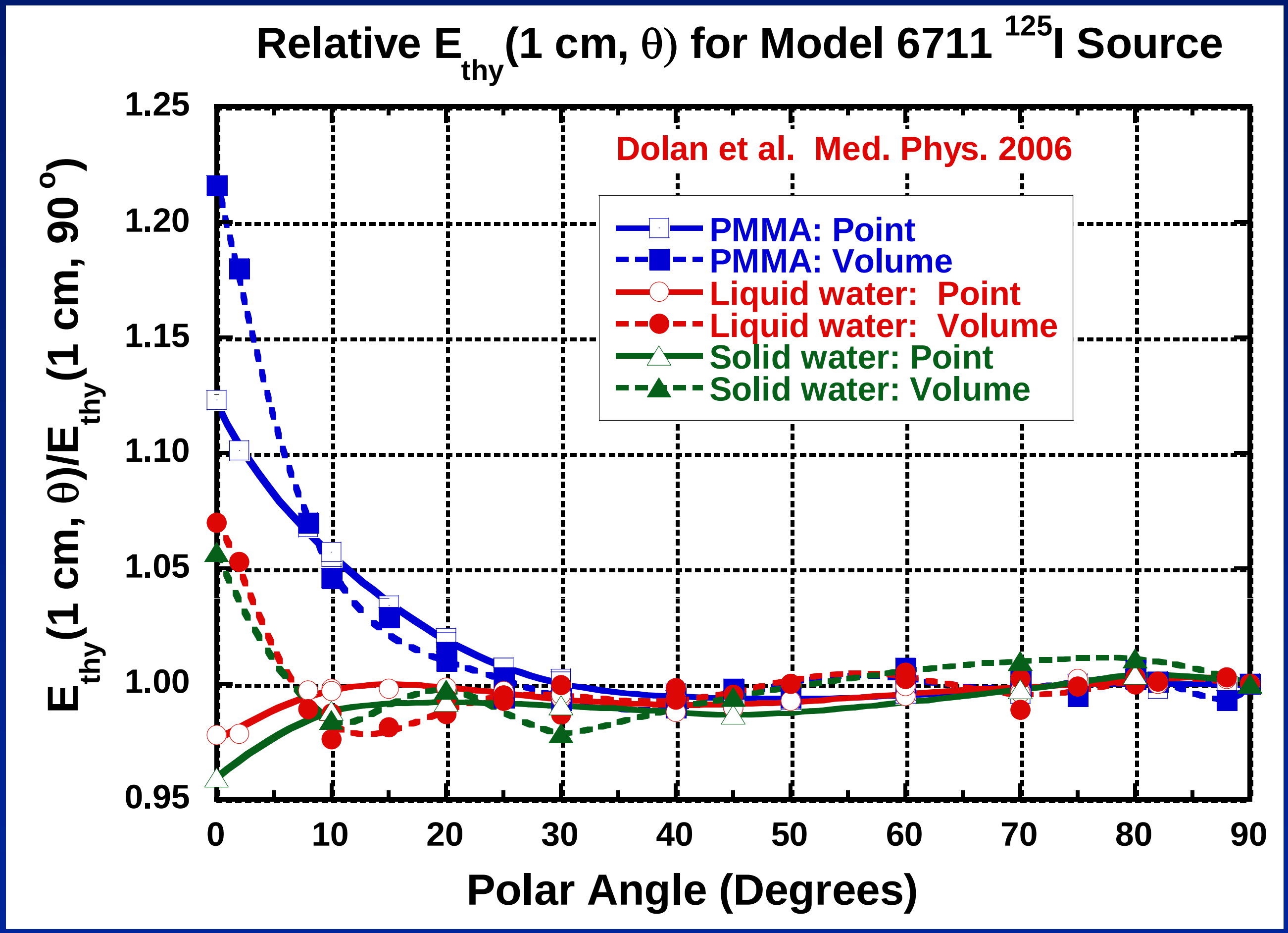
Source	Distance	Monte Carlo/TLD dose rate			
		$K_{bq}^{rel} = 1.00$	$K_{bq}^{rel} = 1.05$	$K_{bq}^{rel} = 1.075$	$K_{bq}^{rel} = 1.10$
^{125}I	1 cm	0.979 ± 0.045	1.028	1.052	1.077
	5 cm	1.002 ± 0.066	1.052	1.077	1.102
^{103}Pd	1 cm	0.982 ± 0.028	1.031	1.056	1.080
	5 cm	1.045 ± 0.106	1.097	1.123	1.150

Absorbed Dose Energy Response Correction



- E_{thy} is not a constant
  - 4% variation with distance even in water
  - Displacement correction ≈ 4% for 1 mm mini-cubes
- Solid-to-Liquid Water correction: 4%-15% at 1-5 cm
  - 10-30% variations in SW [Ca] reported ⇒ 5%-20% dosimetric errors

Absorbed Dose Energy Response Correction



- Up to 22% variation in $E(r,\theta)$ with polar angle

TLD uncertainties: $\dot{D}_{wat}(r)/S_K$ for Model 6711 ^{125}I in PMMA				
Component	1 cm distance		5 cm distance	
	$\%\sigma_{x_i}$	Type	$\%\sigma_{x_i}$	Type
TLD reading statistics	1.3%	A	2.2%	A
TLD calibration (including Linac calibration)	1.8%	A+B	1.8%	A+B
$f^{rel}(Q_0 \rightarrow Q_{exp}, r)$ and $p_{phant}(G_{exp} \rightarrow G_{ref}, r)$	0.7%	B	1%	B
Seed/TLD positioning (Δd = 100 μm)	1.2%	B	0.2%	B
$k_{bq}^{rel}(Q_0 \rightarrow Q_{exp})$	5%	B	5%	B
NIST S_K + one local transfer	1%	B	1%	B
Combined std. uncertainty (*k* = 1)	5.7%		5.9%	

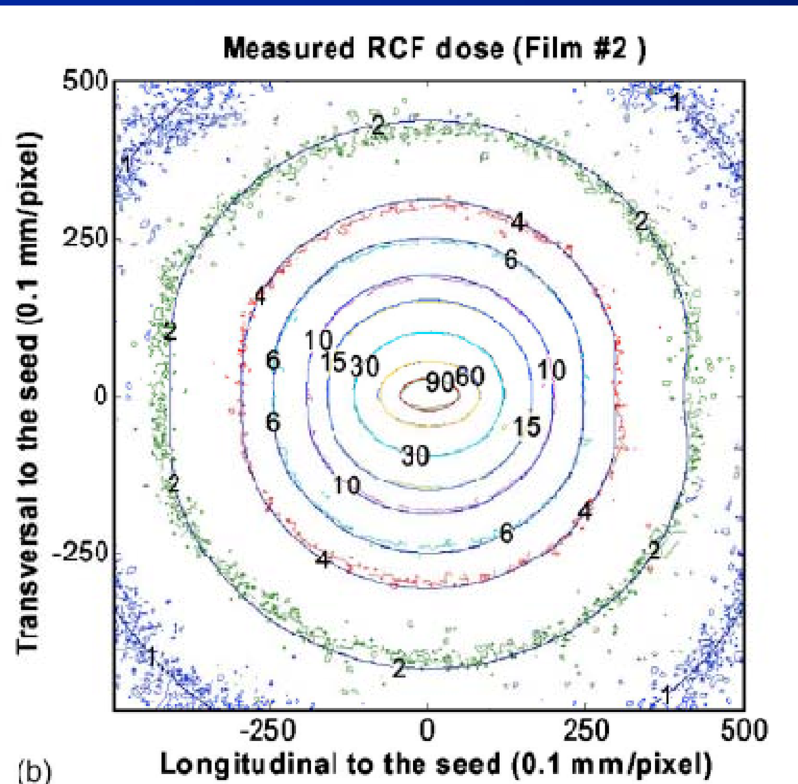
Monte Carlo uncertainties: Model 6711 seed in liquid water			
Distance	1 cm	5 cm	10 cm
Statistics	0.2%	0.3%	0.7%
Photon cross-sections	0.7%	2.4%	4.1%
Seed geometry	1.1%	0.9%	0.8%
Source energy spectrum	0.2%	0.3%	0.5%
Combined std. uncertainty (*k* =1)	1.3%	2.6%	4.3%

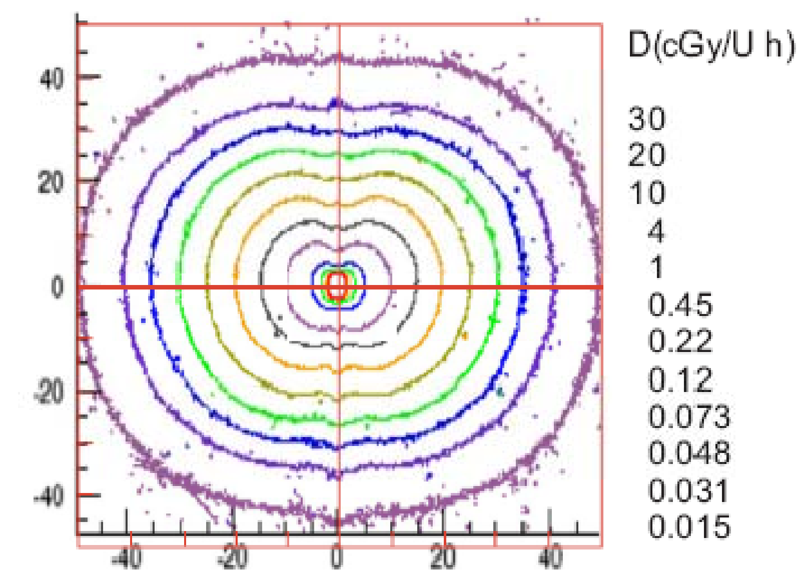
Adapted from Dolan et al. Med Phys 2006

Other dosimetry systems

- Single element detectors
  - High sensitivity, small size, good SNR, and waterproof
  - Plastic scintillator
    - » Used as transfer/relative dosimeters for beta sources
    - » Large (30%) energy nonlinearity
  - Diode: underutilized in presenter's opinion
    - » Energy linearity well established
    - » Large E(d) variation for medium energy sources
    - » Established as relative dosimeter for low-energy
- 2D/3D dosimetry media
  - Radiochromic film and polymer gels
  - Improved positional accuracy and spatial resolution

Radiochromic Film





- **Le and Williamson 2006**
  - **MD-55-2 RCF with LDR ^{137}Cs source**
  - **6 day exposure**
  - **Uncertainty (k = 1) < 3.4% for D>5 Gy, 0.1 mm spatial resolution, double-exposure technique**
  - **Agreement with MC ≈ 3%**
- **Chiu-Tsao 2008**
  - **EBT RCF with Model 3500 ^{125}I seed**
  - **0.6 to 279 h exposures**
  - **Relative dose mapping (k=1) uncertainty ≈ 4% at 0.2 mm spatial resolution**
  - **Good agreement with TG-43**

Summary: TLD phantom dosimetry

- 1-3 mm size $\Rightarrow$ precision: 2-5% above 1 cGy
- Energy response corrections
  - Distance independent, excluding phantom corrections
  - Value of k_{bq} is controversial (<10%)
  - Highly approximate f_{rel} values are routinely used
- Widely-used SW phantom has uncertain composition
  - High-purity industrial plastics recommended
- Extensive benchmarking of TLD vs Monte Carlo
  - 2-10% agreement for Pd-103 and I-125 sources
  - 6%-10% absolute dose measurement uncertainty

Basic Discrete Event Monte Carlo Algorithm

Randomly select Location, direction & energy of primary photon

→ select distance to next collision

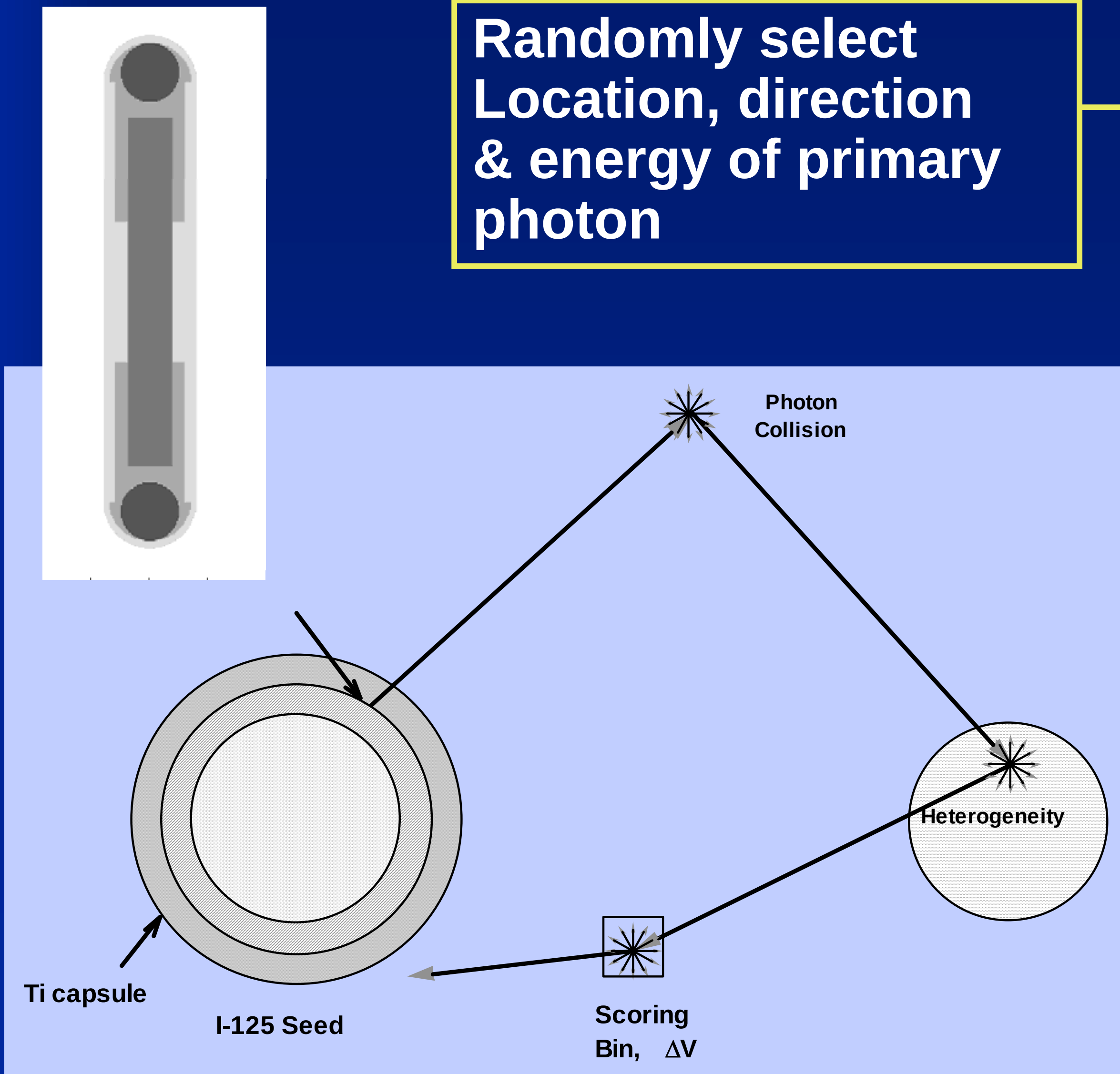
→ Select type of collision

→ Select type of collision

→ Select Energy and angle of photon leaving collision

→ Score collision's dose contribution

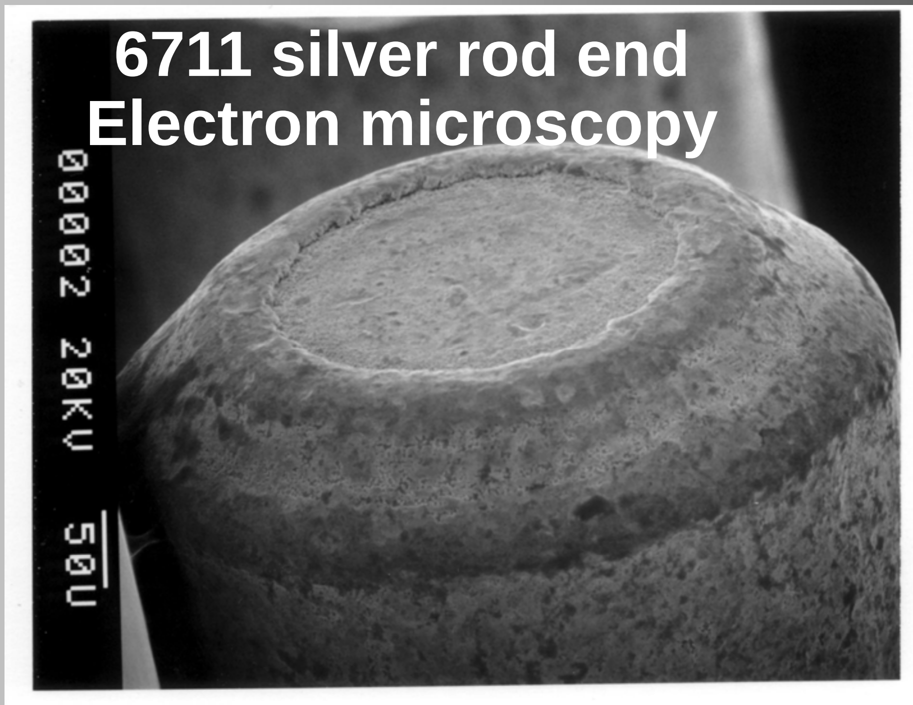
(loop back to: select distance to next collision)

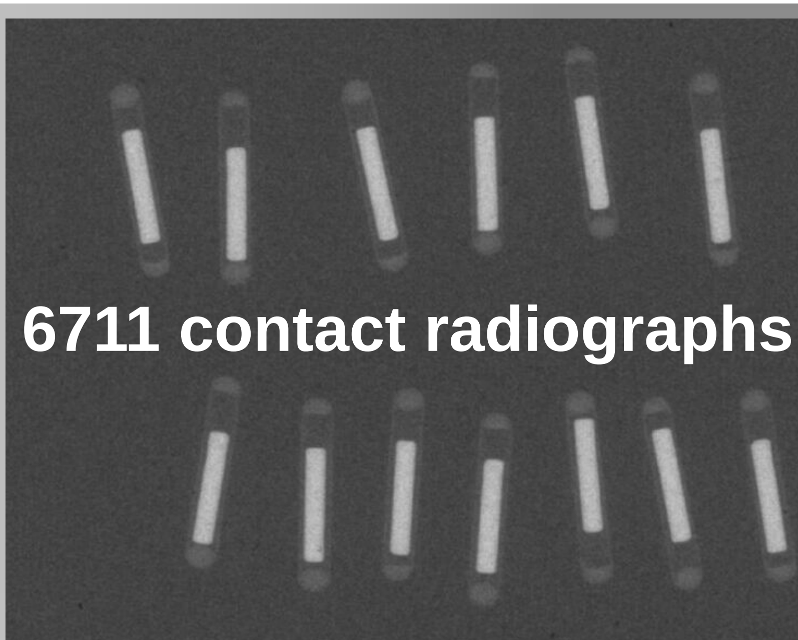


Collisional Physics Requirements for Low-Energy Brachytherapy

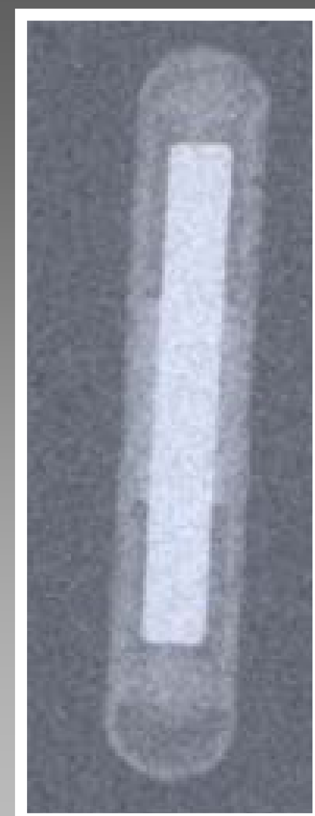
- Only photon transport needed
  - Secondary CPE obtains (Dose ≈ Kerma)
  - Neutral-particle variance reduction techniques useful
- Comprehensive model of photon collisions
  - NIST EXCOM or EPDL97 Cross sections are essential!!
  - Coherent scattering and electron binding corrections
    - » Use molecular/condensed medium form factors
  - Characteristic x-ray emission from photo effect
- Options: MCNP, EGSnrc, VCU's PTRAN_CCG, GEANT, Penelope

Geometric Model Validation

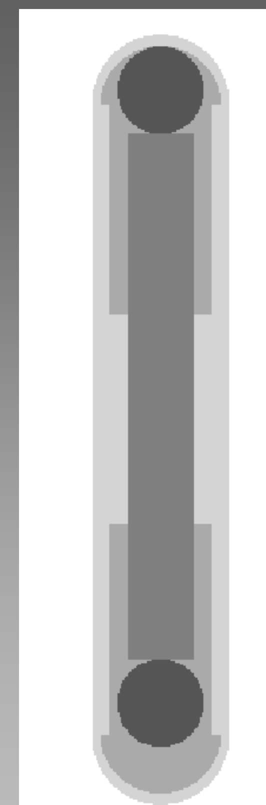




DraxImage I-125 Seed



Contact Radiograph



Final Model

Calculation of TG-43 Parameters by MCPT

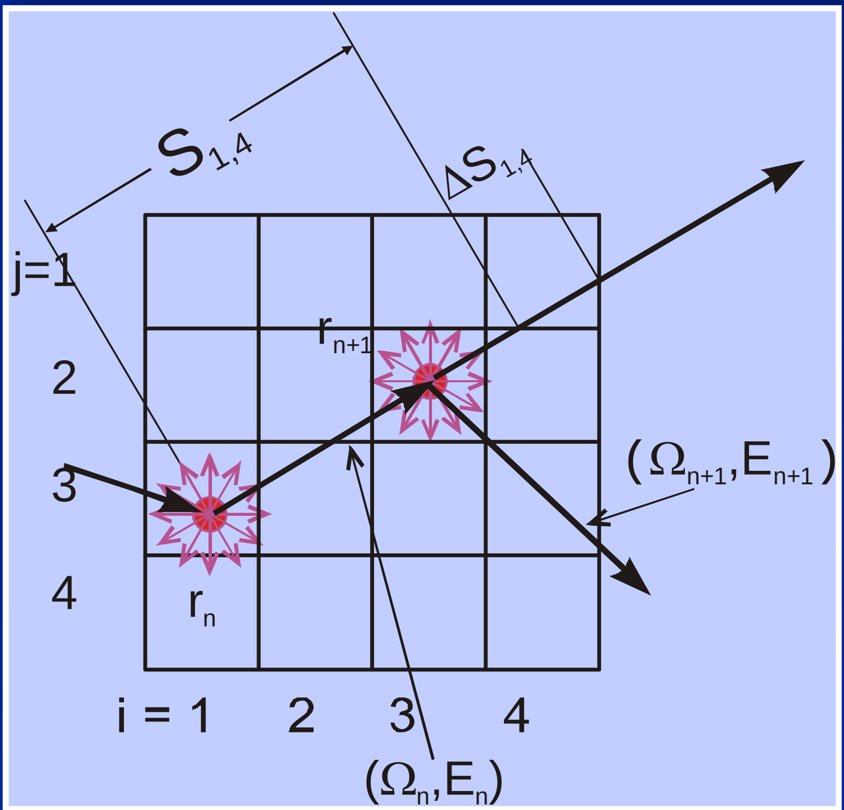
MCPT calculates per disintegration within source:

- Dose to medium, $\Delta D_{med}(r)$, near source in phantom geometry: usually 30 cm liquid water sphere
- Air-kerma strength, ΔS_K, in free-air geometry usually 5 m air sphere or detailed model of calibration vault

$$\Lambda = \frac{\Delta D_{wat}(r = 1\,cm, \theta = \pi/2)}{\Delta S_K}$$

$$g(r) = \frac{\Delta D_{wat}(r, \pi/2) \cdot G(1\,cm, \pi/2)}{\Delta D_{wat}(1\,cm, \pi/2) \cdot G(r, \pi/2)}$$

Analog and Tracklength Dose Estimation



Need cubic array of voxels:

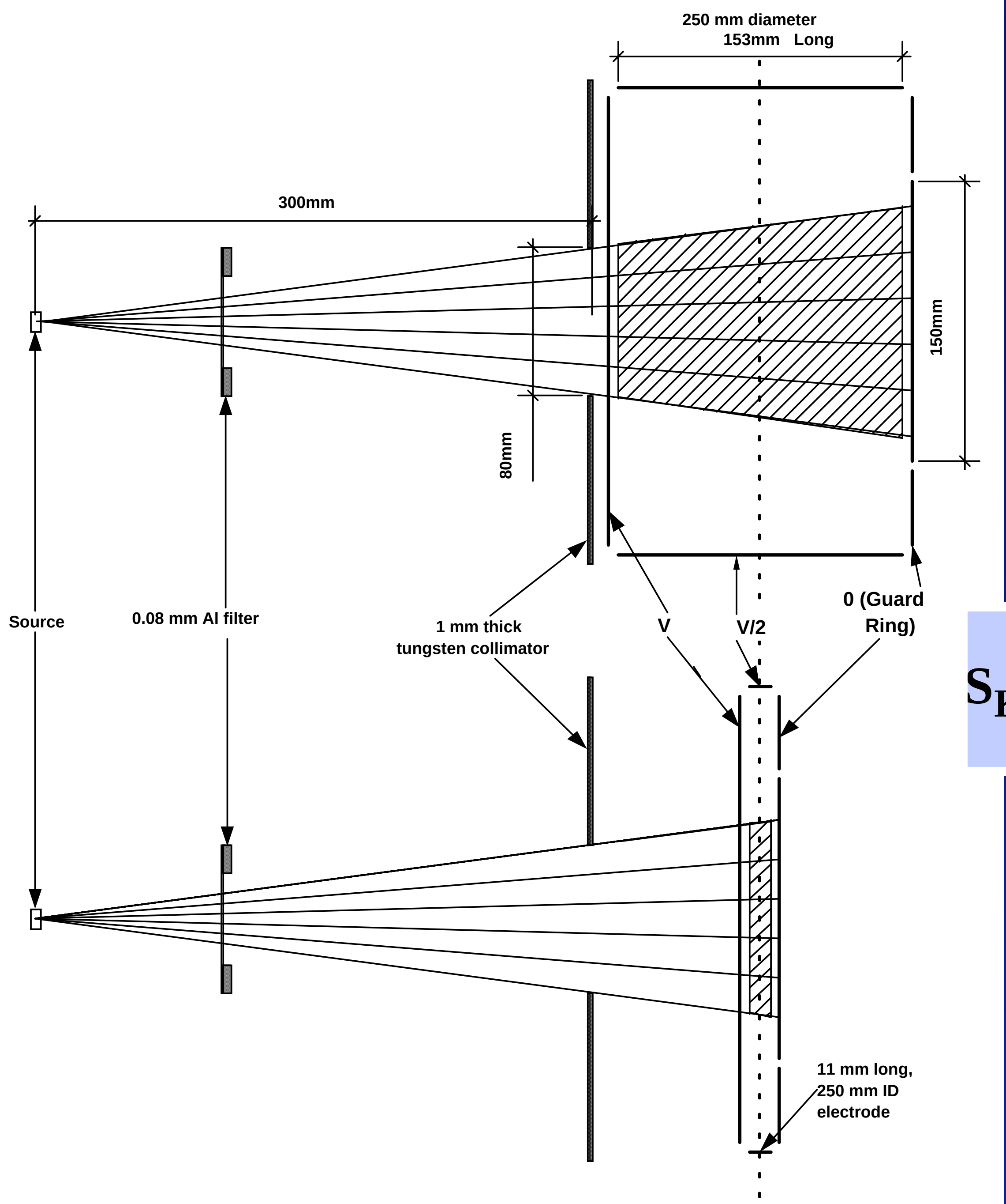
1x1x1 mm^3 to 2x2x2 mm^3

Analogue Estimator (EGS method)

$$D_{2,3} \text{ from } n+1 = \frac{\text{Energy in - Energy out}}{\text{voxel mass}}$$

Expected Value Tracklength Estimator

$$D_{1,4} \text{ from } n \propto E_n \cdot \frac{\Delta s_{1,4}}{\text{voxel volume}} \cdot (\mu_{en}/\rho)$$

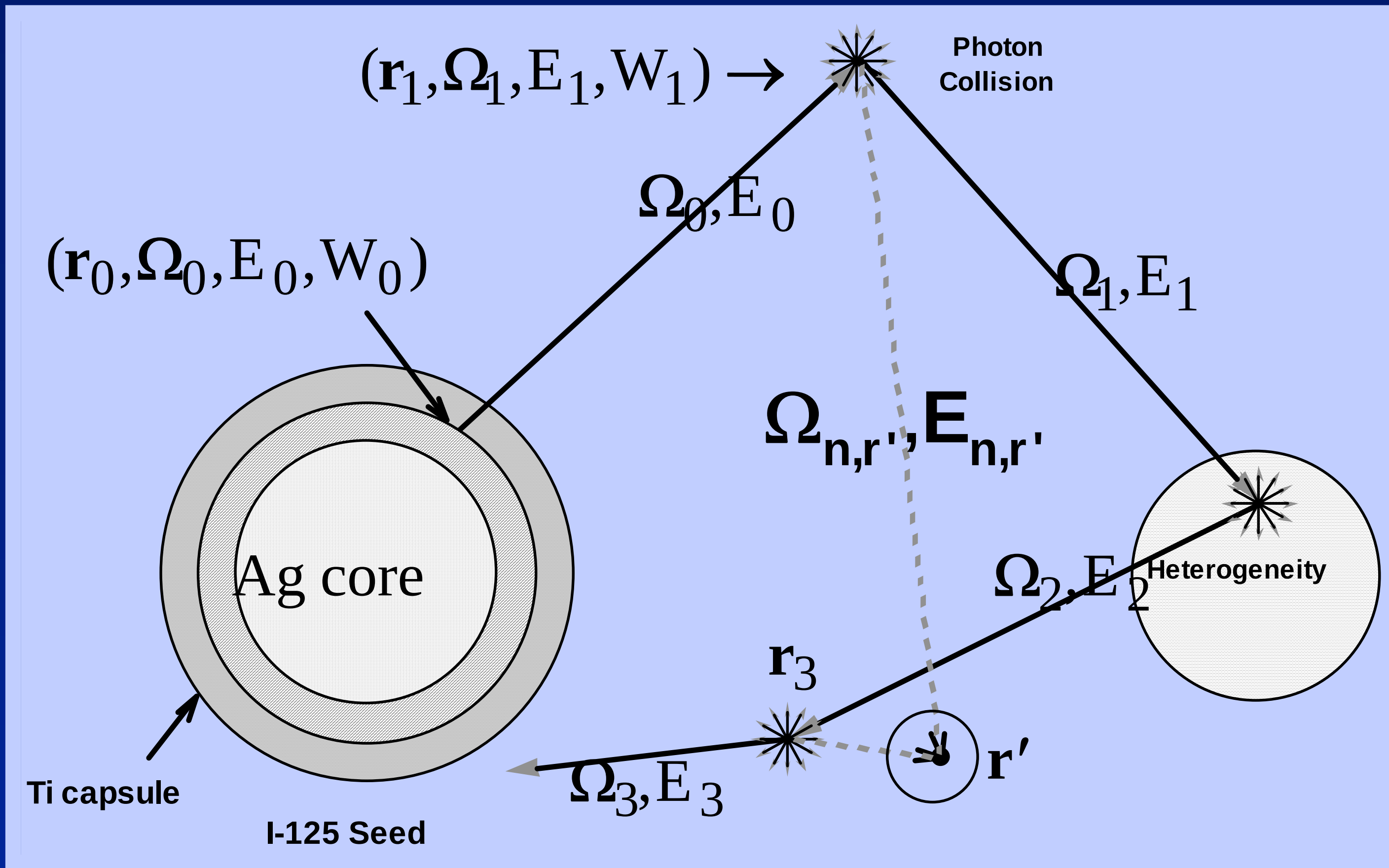


Wide-angle Free Air Chamber

NIST Primary Standard
interstitial sources
photons < 50 keV

$$S_{K,99N} = \frac{(I_{153} - I_{11})d^2}{\rho_{air}(V_{153} - V_{11})}(W/e)\prod_i k_i$$

Kerma at a Point: Next Flight Estimator



$$\Delta D(r')\ \text{from}\ n \propto p\left(\Omega_{n,r'}\right)\cdot E_{n,r'}\cdot(\mu_{en}/\rho)\cdot\frac{e^{-\mu\cdot|r'-r_n|}}{|r-r_n|^2}$$

Calculation of ΔS_K
Extrapolated Point-Kerma method

- Place sealed source model at center of large air sphere
- Calculate air-kerma/disintegration, $\Delta K_{air}(d)$, as function transverse axis distance, d
- Extrapolate to free-space geometry by curve fitting

$$\Delta \dot{K}_{air}(d) \cdot d^2 = \Delta S_K \cdot (1 + \alpha d) \cdot e^{-\mu d}$$

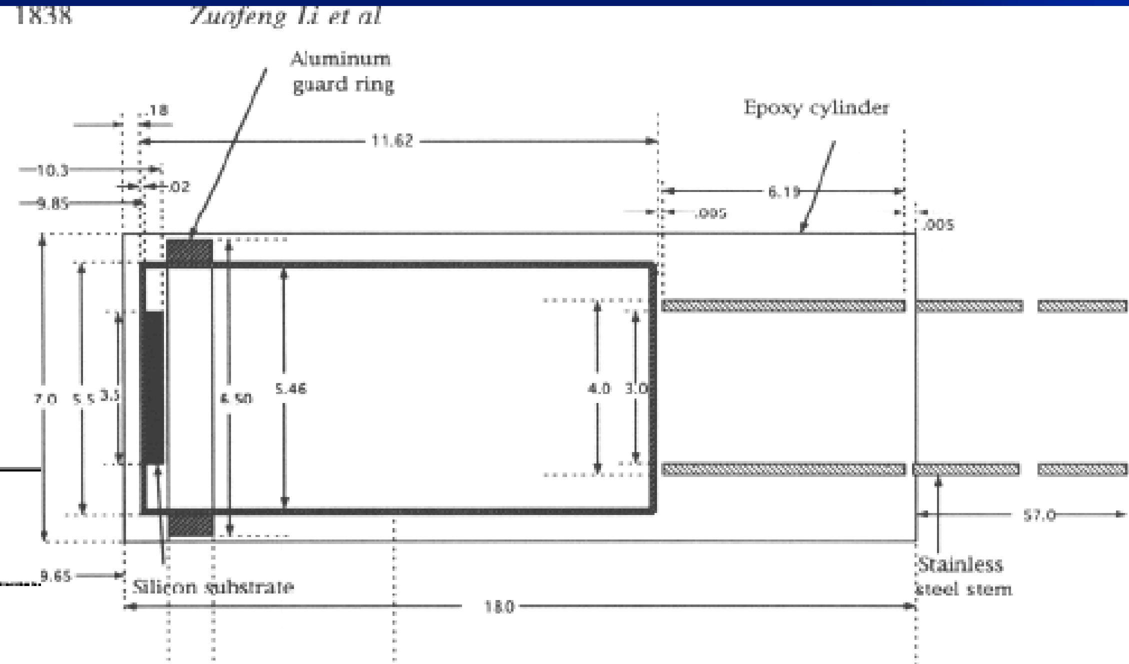
Where ΔS_K and α are unknowns

$(1 + \alpha d)$ - SPR accounts for scatter buildup

μ = primary photon attenuation coefficient

Next-Flight Estimator Application

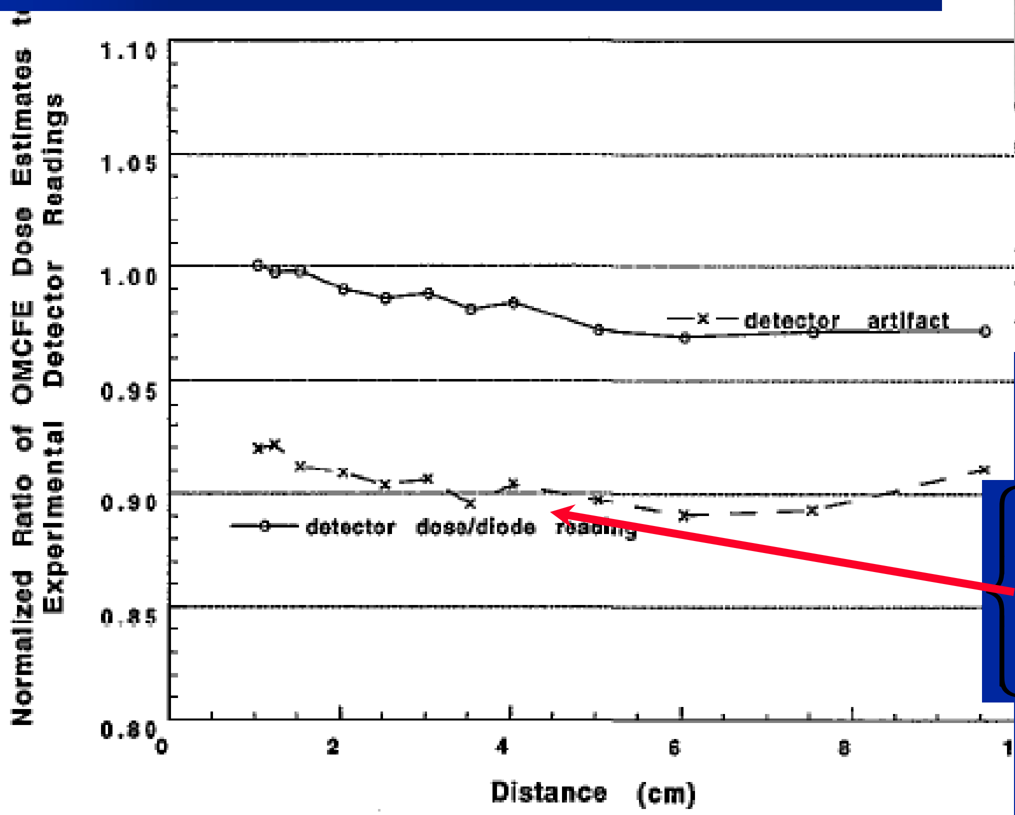
Use point dose at center of 60 μm x 3 mm Si active volume to approximate $\bar{D}$



Scanditronix Electron Field Diode

Monte Carlo Model

Li & Williamson, PMB 1993



$$\frac{1}{k_{bg}(d)} = \left[\frac{\bar{D}(d)}{M(d)}\right]_{MC} \approx \left[\frac{D_{NF}(d)}{M(d)}\right]_{MC}$$

Monte Carlo quantities and estimators for typical seed study

ΔD_{wat} (cGy/simulated photon): { Transverse axis / angular dose profiles

Next-flight estimator for all distances

Track-length estimator for RTP voxel grid

ΔE_{ab} Energy imparted to WAFAC volume/simulated photon

Track-length estimator when fluence varies over detector

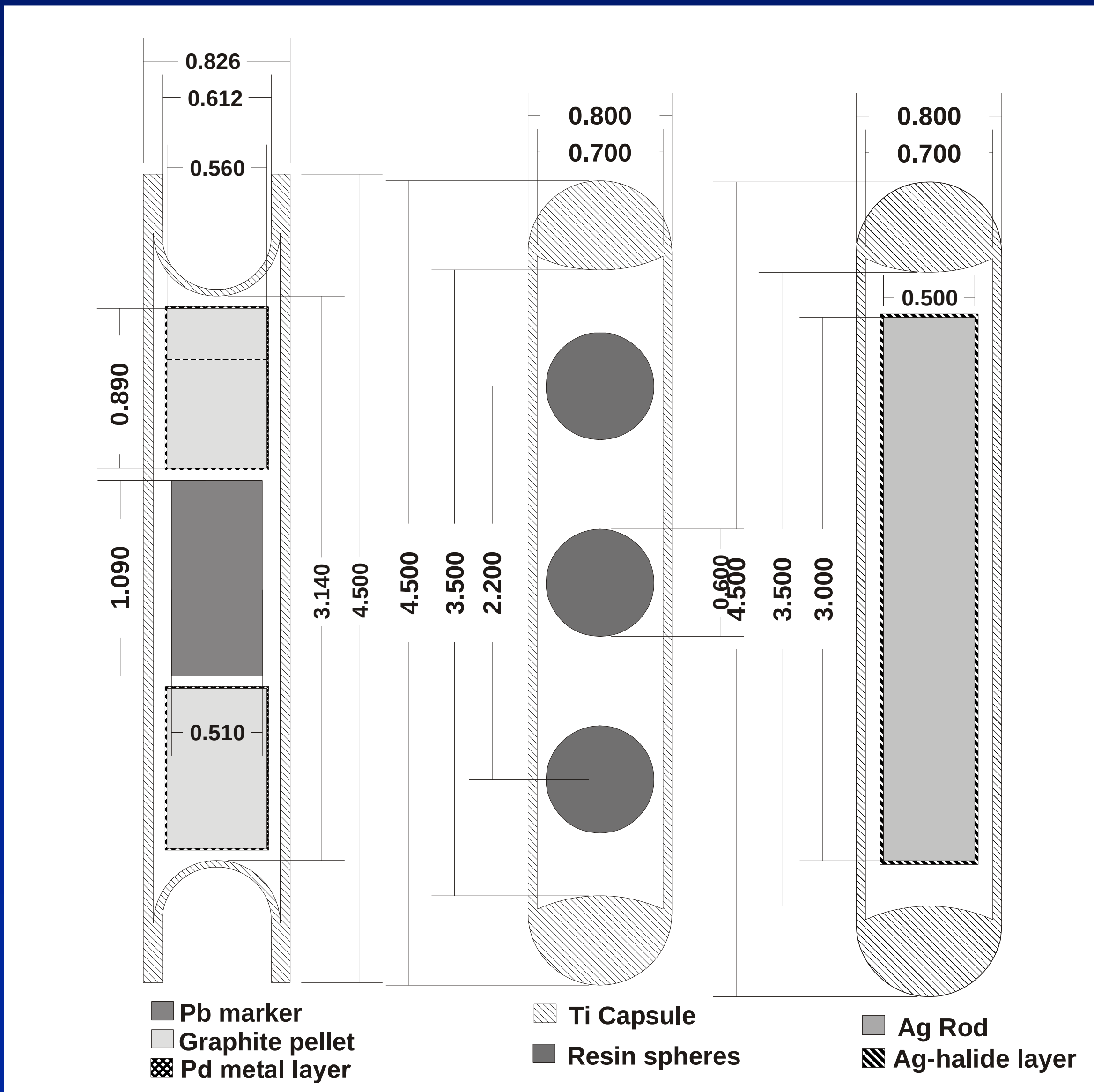
Next-flight point dose estimator for TLD/diode detectors > 2 cm from source

ΔK_{air} at geometric points in free air { Transverse-axis / angular fluence profile (30 cm)

Track length for WAFAC

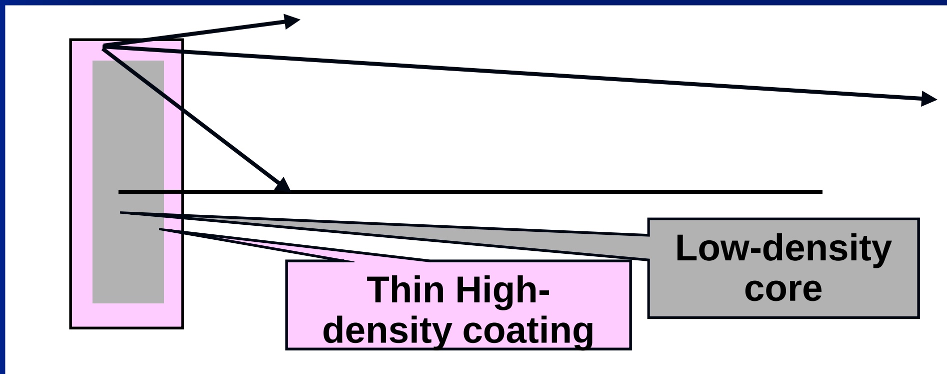
Next-flight for transverse axis distribution

Models 200 (^{103}Pd), 6702 (^{125}I) and 6711 (^{125}I) Seeds

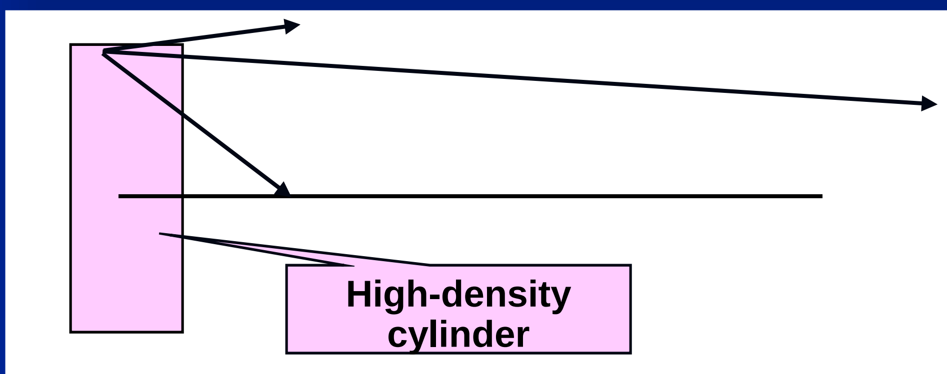


- Model 200
  - ^{103}Pd distributed in thin (2-25 μm) Pd metal coating of right circular graphite cylinder
- Model 6702
  - ^{125}I distributed on surface of radio transparent resin spheres
- Model 6711
  - ^{125}I distributed in thin ($\approx$3 μm) silver-halide coating of right circular Ag cylinder

Sharp corners and opaque coatings



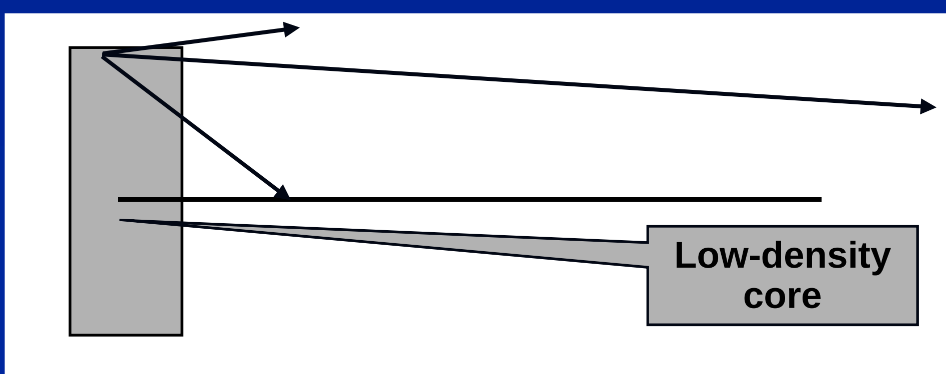
Near transverse-axis:
- Anisotropic at long distances
- Isotropic at short distances
- Inverse square-law deviations



Anisotropic at long and short distances

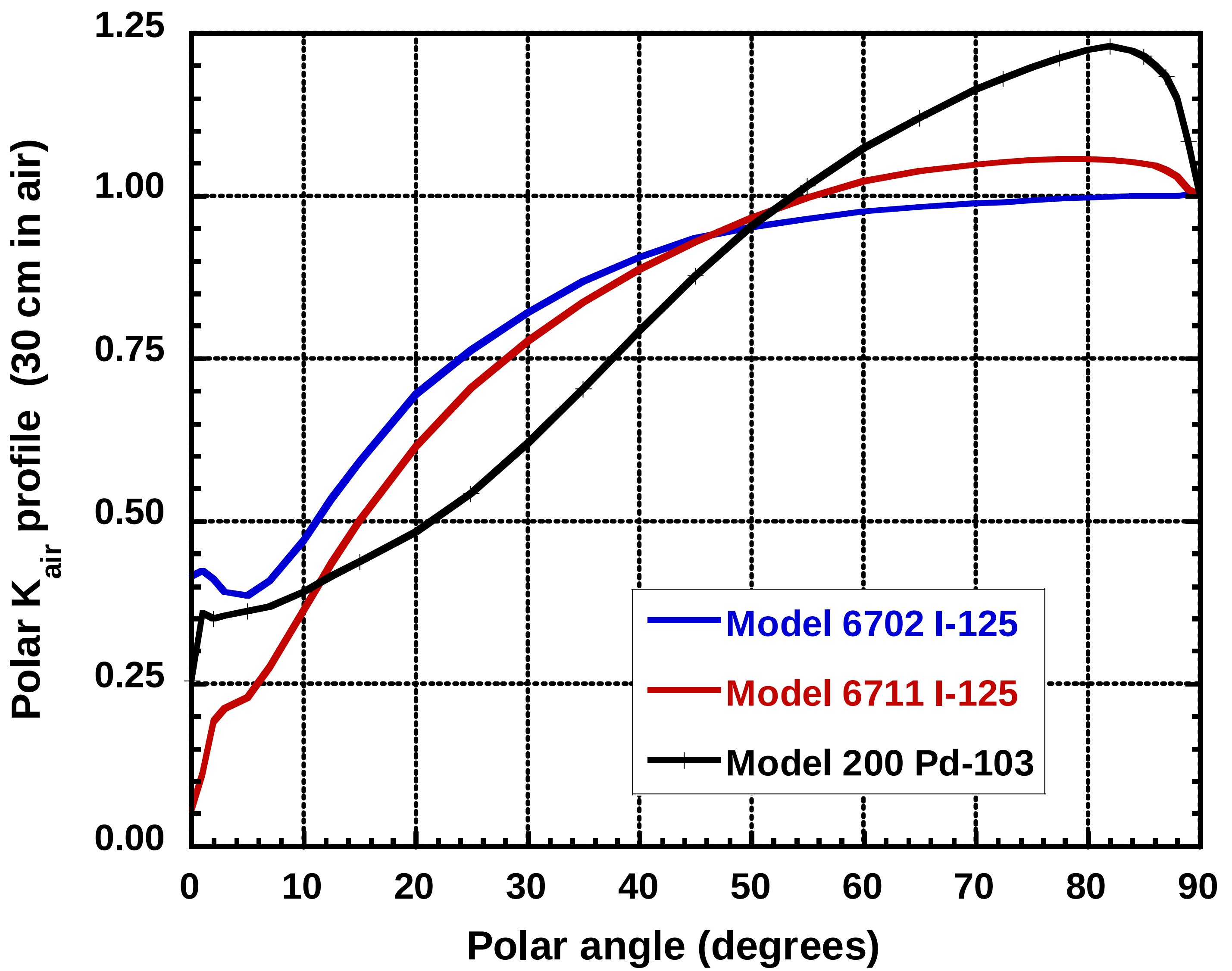
Circular ends contribute at

$$\theta = \tan^{-1}\left[\frac{L}{2\times d}\right] = \begin{cases} 8^\circ & d = 1\ \text{cm} \\ 0.3^\circ & d = 30\ \text{cm} \end{cases}$$

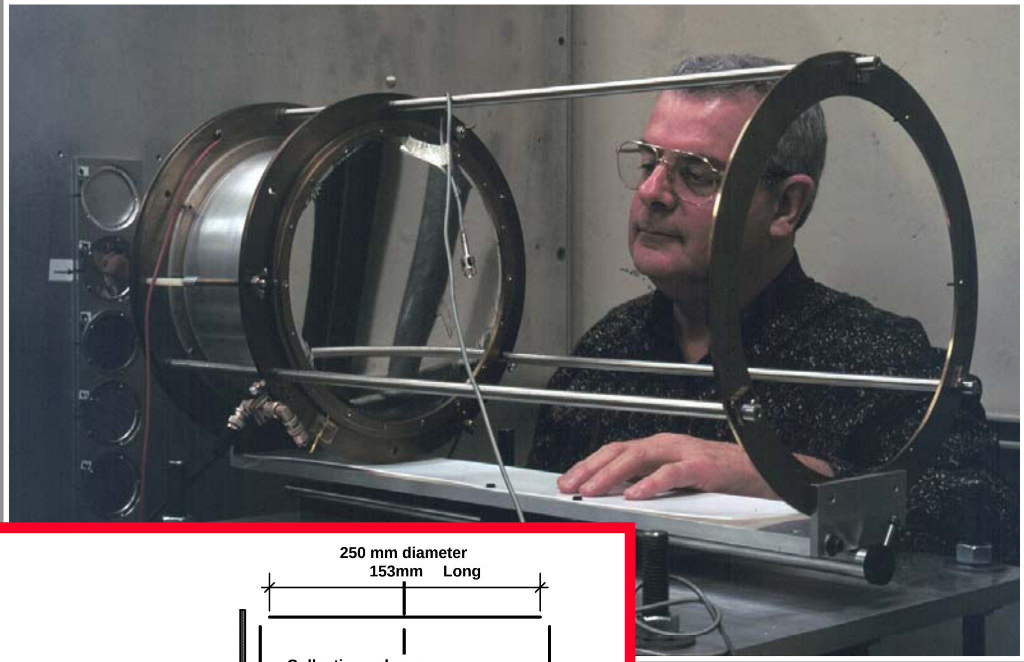


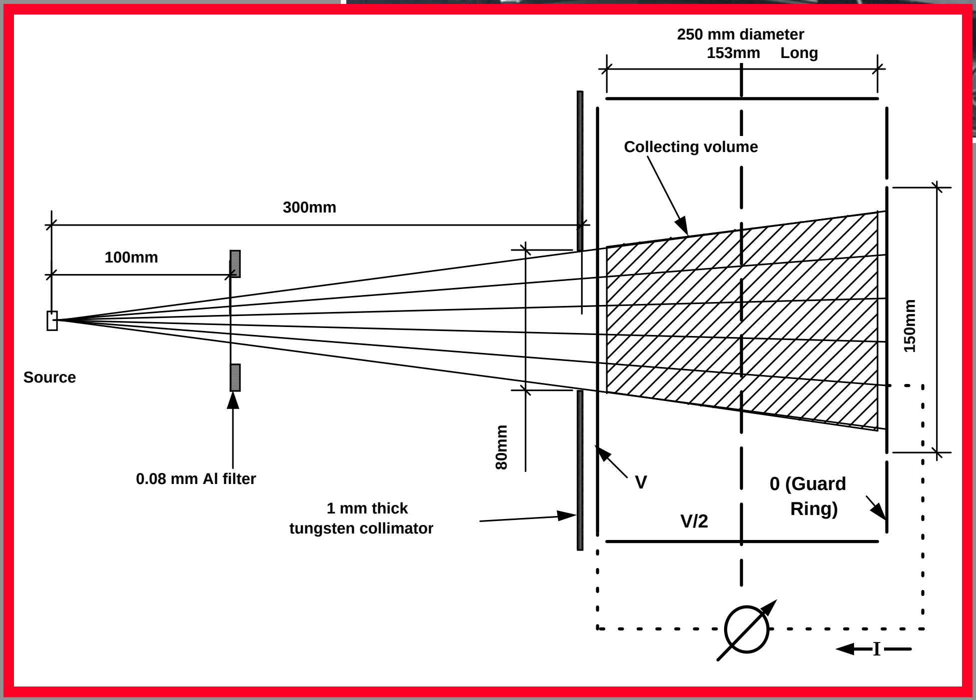
Isotropic at both long and short distances

Polar Anisotropy in Air (30 cm)



‘WAFAC:’ Wide Angle Free-Air Chamber





Rotating Seed Holder

WAFAC Simulation Method

$$\Delta S_K = \frac{(\Delta E_{ab}^{153} - \Delta E_{ab}^{11}) \cdot d^2}{\rho_{air} \cdot (V_{153} - V_{11})} \cdot k_{inv} \cdot k_{att}$$

where ΔE_{ab}^{x} = Energy absorbed/disintegration in WAFAC volume of length x

d = 38 cm = seed-to-WAFAC volume center

$$k_{att} = \left.\frac{(\Delta S_K)_{extr}}{k_{inv} \cdot \left(\Delta K \cdot d^2\right)_{WFC}}\right\} \text{for a point source} = \begin{cases} 1.025 & \text{Pd-103} \\ 1.013 & \text{I-125} \end{cases}$$

$$k_{inv} = \text{inverse–square correction} = \frac{\int_A \Phi(\ell) \cdot dA}{\Phi(d) \cdot A} = 1.0089$$

Pd-103 Dose-Rate Constants

Source	Investigator	$\Lambda_{xxD,N99S}$		
		TLD	MC Extrap.	MC WAFAC
Point	Monroe 2002	____	0.683	0.683
Model 200 (light)	Monroe 2002 Nath 2000	--- 0.684	0.797	0.691
Model 200 (heavy)	Monroe 2002 ICWG 1989	----- 0.65	0.744	0.694
NAS MED 3633	Li Wallace 1998	0.693 0.68	0.677	---

TLD uncertainties: $\dot{D}_{wat}(r)/S_K$ for Model 6711 ^{125}I in PMMA

Component	1 cm distance		5 cm distance	
	$\%\sigma_{x_i}$	Type	$\%\sigma_{x_i}$	Type
TLD reading statistics	1.3%	A	2.2%	A
TLD calibration (including Linac calibration)	1.8%	A+B	1.8%	A+B
$f^{rel}(Q_0 \rightarrow Q_{exp}, r)$ and $p_{phant}(G_{exp} \rightarrow G_{ref}, r)$	0.7%	B	1%	B
Seed/TLD positioning (Δd = 100 μm)	1.2%	B	0.2%	B
$k_{bq}^{rel}(Q_0 \rightarrow Q_{exp})$	5%	B	5%	B
NIST S_K + one local transfer	1%	B	1%	B
Combined std. uncertainty (k = 1)	5.7%		5.9%	

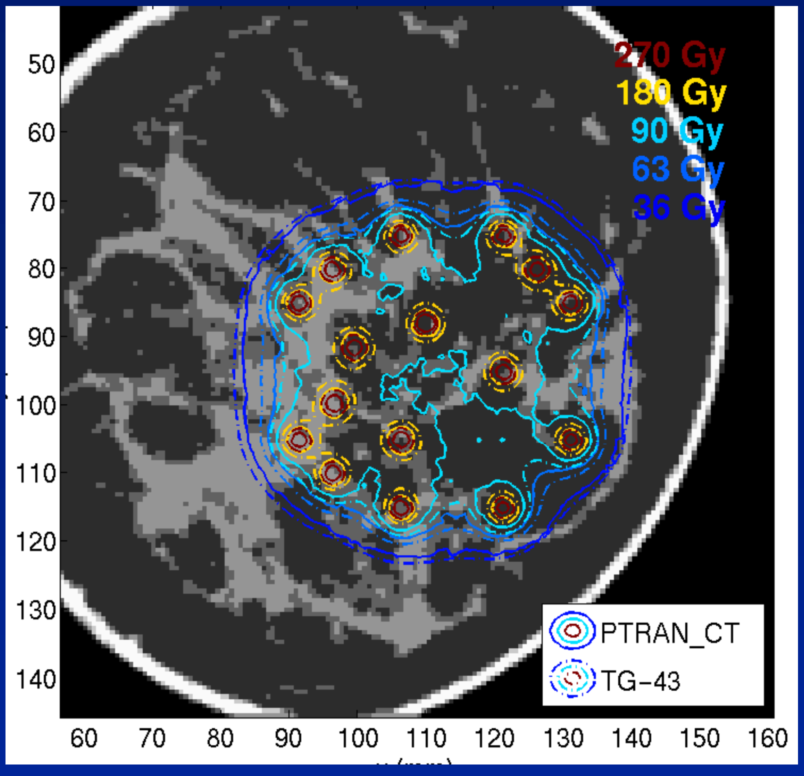
Monte Carlo uncertainties: Model 6711 seed in liquid water

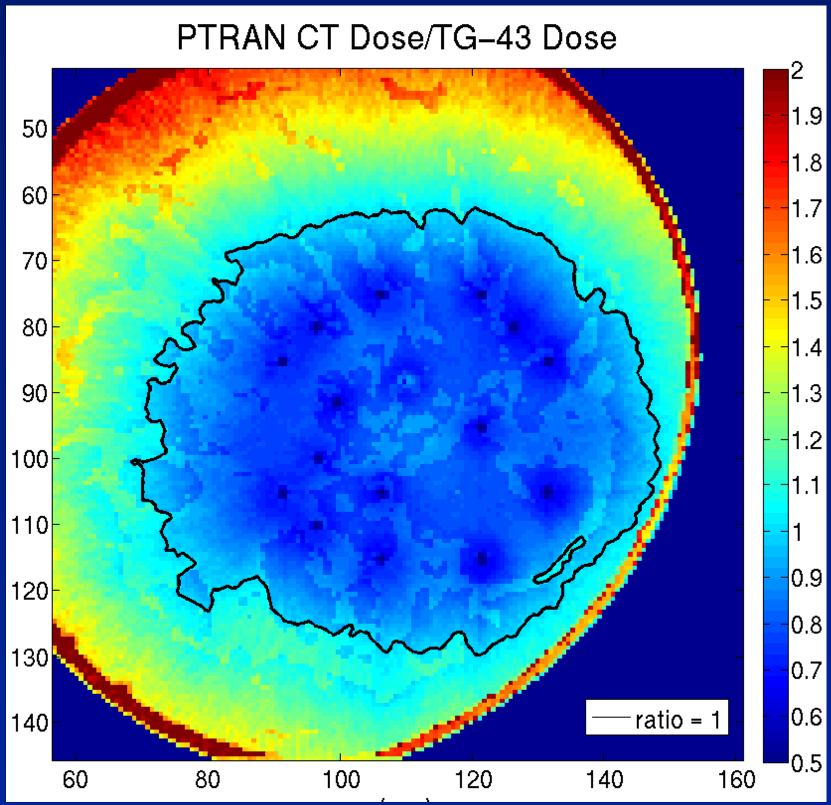
Distance	1 cm	5 cm	10 cm
Statistics	0.2%	0.3%	0.7%
Photon cross-sections	0.7%	2.4%	4.1%
Seed geometry	1.1%	0.9%	0.8%
Source energy spectrum	0.2%	0.3%	0.5%
Combined std. uncertainty (k =1)	1.3%	2.6%	4.3%

Adapted from Dolan et al. Med Phys 2006

Monte Carlo-based Treatment planning

Consolidating Dosimetry and treatment planning into a single process





- Permanent seed APBI: 70 ^{125}I seeds, D_{90} = 115 Gy
- 0.7 mm voxels, average SD = 1.2%, single-processor CPU time = 30 min

Monte Carlo vs TLD

- Measurement Pros and Cons
  - Large uncertainties and many artifacts
  - Tests conjunction of all a priori assumptions: geometry, detector response corrections, calibration etc
- Monte Carlo Pros and Cons
  - Artifact-free, low uncertainty, and unlimited spatial resolution
  - Garbage in-Garbage out
    - » Seed geometry errors
    - » Will not anticipate contaminant radionuclides etc., S_K errors
  - Does not model detector signal formation process
- Hence: TG-43 continues to require both measured and Monte Carlo single-seed dose distributions

Dosimetry: Conclusions

- Low energy brachytherapy: main catalyst for improving dosimetry and source standardization for 30 years
  - Single-source dose distributions have 5% uncertainty
  - Both MC and measurement have important roles
- Current Role
  - Monte Carlo: primary source of dosimetric data
    - Soon: MC dosimetry and planning will be a single process
  - Measurement: Confirm Monte Carlo assumptions
- Major needs: more accurate and efficient dose-measurement systems for low energy sources
  - Test batch-to-batch and/or source-to-source variations during manufacturing process