Quantitative Dosimetry Methods for Brachytherapy

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What is "Quantitative Dosimetry?"

- Williamson's definition: absorbed dose estimation method providing
  - Accurate representation of well-defined physical quality
  - Rigorous uncertainty analysis $\Rightarrow$ <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

Outline

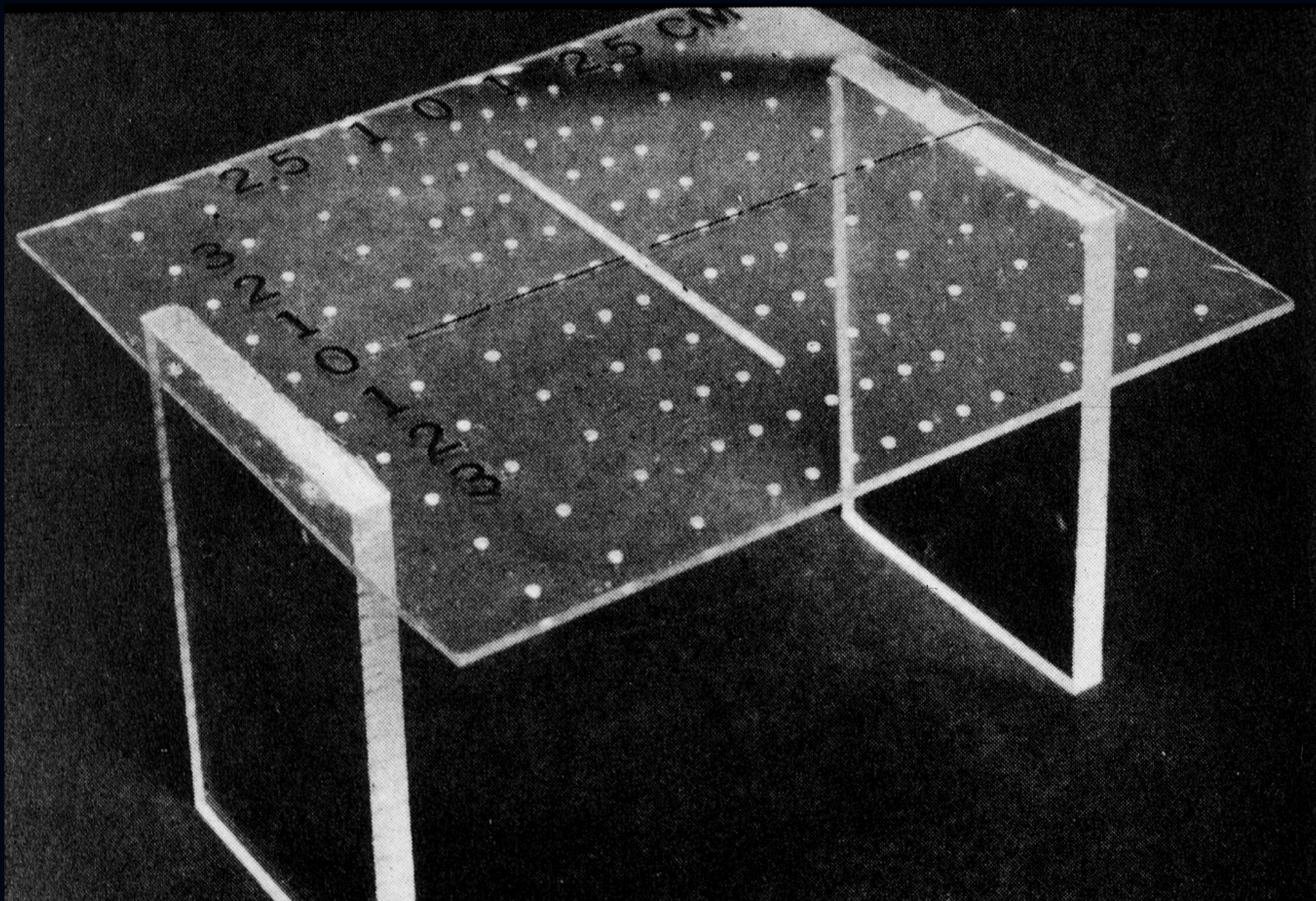
- Experimental Techniques
  - TLD dosimetry: current standard of practice
  - Emerging experimental techniques
- Monte Carlo-based dosimetry
- Results of TLD and MC dosimetry
  - Uncertainty analysis
  - Agreement

Quantitative Dosimetry Era: 1980-

- 1955 Tochlin: Film Dosimetry
- 1966 Lin & Kenny: TLD dosimetry in medium
- 1983 Ling: Diode dosimetry of I-125 seeds
- 1985 Loftus: I-125 exposure standard
- 1986 NIH ICWG contract
  - Nath, Anderson, Weaver: Validation of TLD dosimetry
- 1983 Williamson: Monte Carlo dosimetry
- 1994 Task Group 43 Report

TLD dose measurements around ^{226}Ra Needle

Lin and Cameron: Univ. of Wisconsin, 1965



Dosimetric Environment

- Large Dose Gradients
  - Wide Range of Dose Rates
  - Positioning accuracy needed for 2 % dose accuracy

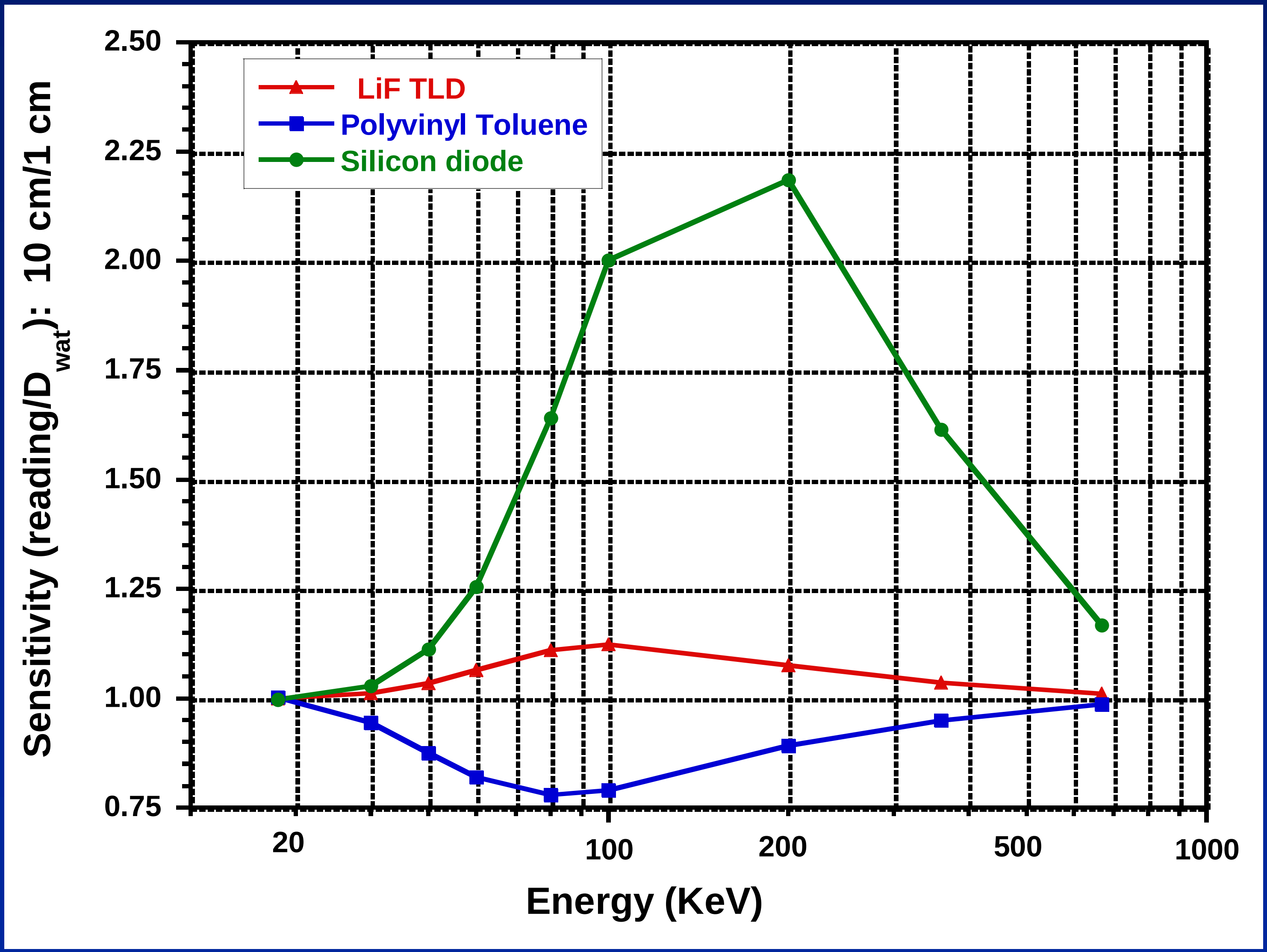
2 mm Distance	±20 μm
5 mm Distance	±50 μm
10 mm Distance	±100 μm

  - Large Number of Measurements Needed
- Low Photon Energies
- Relatively Low Dose Rates

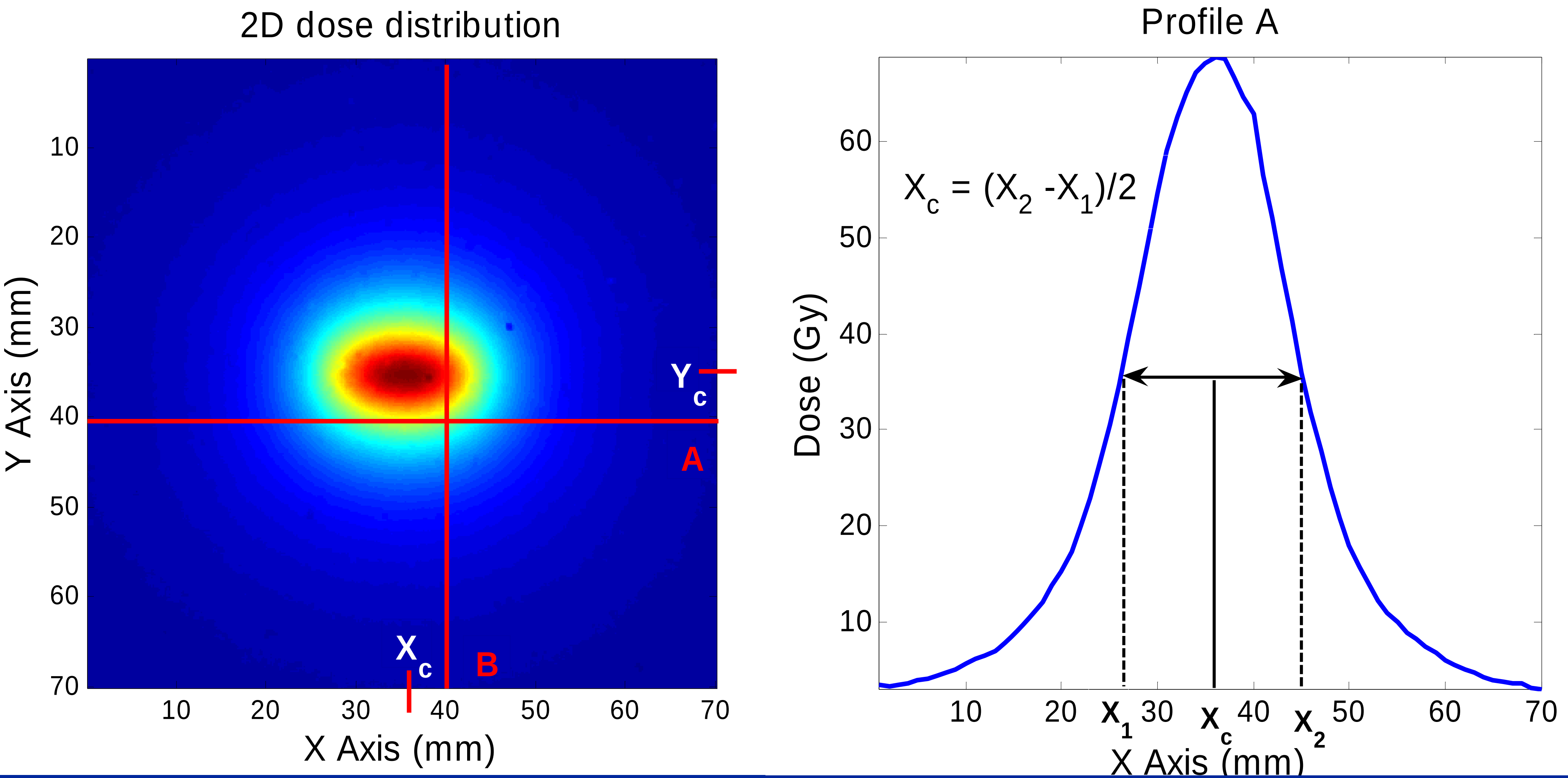
Criteria for experimental dosimeters

- Signal stability and reproducibility
  - Spatially and temporally constant Sensitivity (signal/dose)
  - Free of fading, dose-rate effects
  - Good signal-to-noise ratio (SNR)
- Small size, high sensitivity, large dynamic range
  - Small size: avoid averaging dose gradients
  - Large size: Good signal at low doses
- Good positioning accuracy
- Support measurements at many points

Sensitivity (10 cm)/Sensitivity (1 cm) vs energy

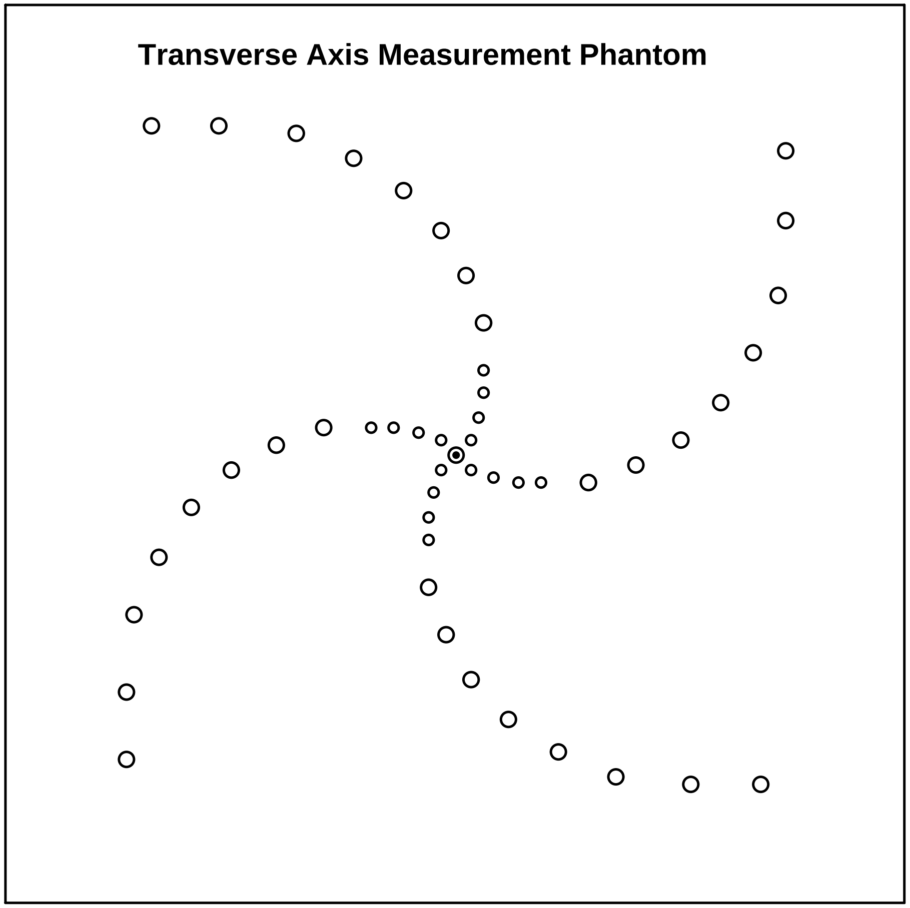


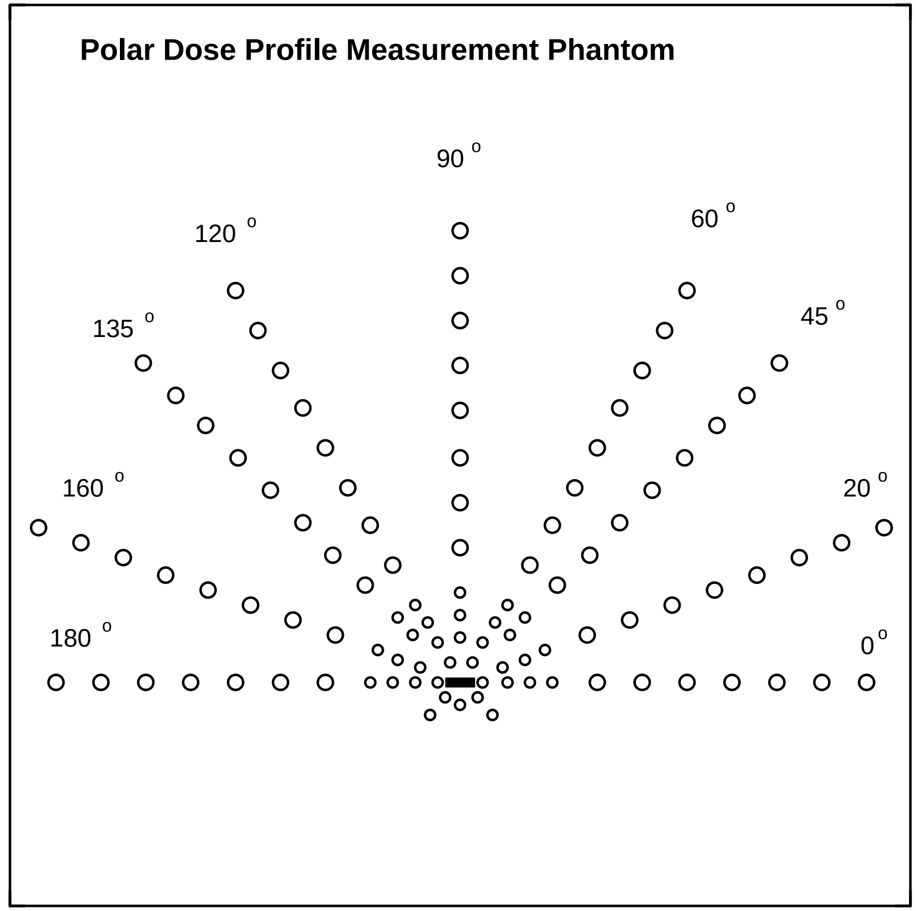
Localization via Digital Dosimeters



30-100 μm positional accuracy achievable

Solid Water Phantoms for TLD Dosimetry





100-200 μm positional accuracy achievable

TLD Detectors

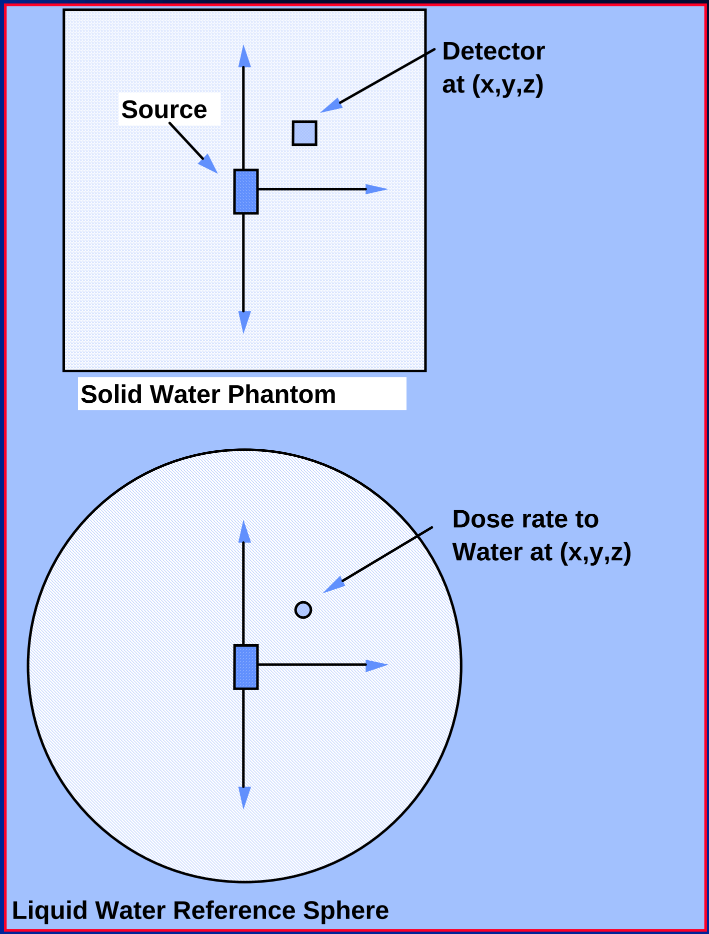
- Use TLD-100 LiF extruded ribbons (‘chips’)
  - 1 x 1 x 1 mm^3 at distances < 2 cm
  - 3 x 3 x 0.9 mm^3 at distances ≥ 2 cm
- Use RMI 453 Machined Solid Water Phantom
  - Composition ($CaCO_3$ + organic foam) not stable
  - Either perform chemical assay or use high purity PMMA
- Annealing protocol

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

  <u>OR</u>

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

Brachytherapy Dosimetry



- **Given:** $R_{det}(\vec{r})$ Relative solid state dosimeter reading (TLD or Diode)
- **Desired:** $D_{wat}(\vec{r})$ absorbed dose to water
- **Corrected for:**
  - Detector sensitivity
  - Measurement vs reference geometry
  - Radiation field Perturbation
  - Detector response artifacts

Brachytherapy Dose Measurement

$$\left[\frac{\dot{D}_{wat}(\vec{r})}{S_K}\right]_{meas}^{BRx} = \frac{R_{det}(\vec{r}) \cdot g(T)}{S_K \cdot \varepsilon_\lambda \cdot E(\vec{r})}$$

$$\varepsilon_\lambda = \left[R_{det} / D_{med}\right]_{meas}^{\lambda}$$

is measured Response in calibration beam, λ

$$E(\vec{r}) = \frac{\left[R_{det} / D_{wat}\right]_{BRx} \text{ at } \vec{r}}{\varepsilon_\lambda}$$

is relative detector response at $\vec{r}$ in Brachytherapy geometry

- S_K = Measured Air-Kerma Strength
- $g(T)$ = 1/effective exposure time (decay correction)

TLD readings

$$\langle R_{TLD}(\vec{r})\rangle = 1/n\sum_{i=1}^{n}\frac{(TL_i - TL_{bkgd})}{F_{lin}\cdot S_i}$$

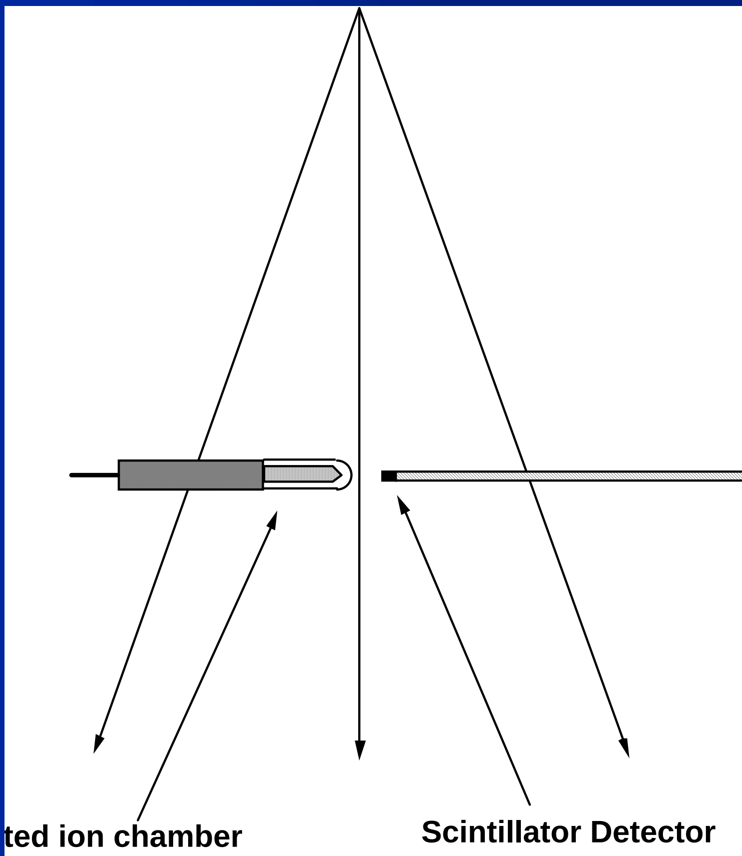
- TL_i is Measured Response of i-th detector at r
- F_{lin}(TL) is non-linearity correction for net response TL
- S_i is relative sensitivity of i-th detector derived from reading TLDs exposed to uniform doses
- TG-43 recommends n = 5-15

Relative Energy Response

$$E(\vec{r}) = \frac{\left[\langle TL(\vec{r})\rangle / D_{wat}(\vec{r})\right] \text{ for Brachy Source}}{\left[\langle TL\rangle / D_{med}\right] \text{ for Calibration Beam } \lambda}$$

$$= \frac{\varepsilon_{BRx}(TL_0, \vec{r})}{\varepsilon_{\lambda}(TL_0)} \text{ for same } TL_0$$

- E(d) obtained by
  - Measuring TLD response in free air as function of average energy in low energy x-ray beams
  - Monte Carlo calculations
  - Analytic calculations
- Generally assumed to be independent of position



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

$\mathrm{TL} =$ TLD mean net reading

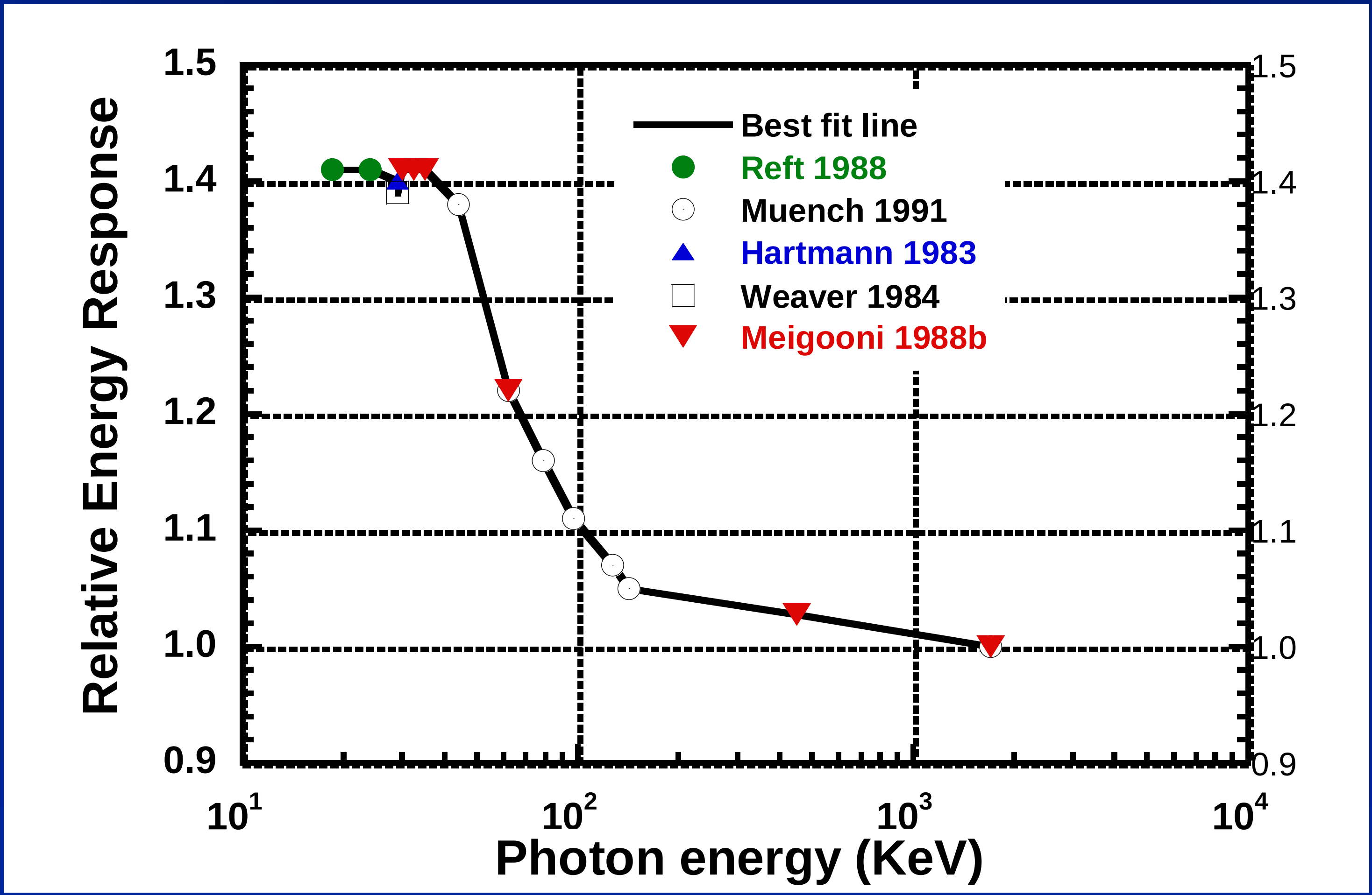
$K_{air}^{FS} =$ measured air kerma

$$E(r) = \left(\frac{\mathrm{TL}}{K_{air}^{FS}}\right)_{Meas}^{h\nu} \cdot \frac{\left(K_{air} / D_{wat}\right)_{MC}^{h\nu}}{c_{repl} \cdot c_{disp}(r) \cdot \varepsilon_{\lambda}}$$

$$c_{repl} = \frac{D_{wat} \text{ in medium}}{K_{wat}^{FS} \text{ in cavity}} \approx 0.97$$

$$c_{disp}(r) = D_{wat}(\vec{r}) \text{ at point} \Big/ \left[\frac{1}{V(\vec{r})} \int_{V(\vec{r})} D_{wat}(\vec{r}\,')dV'\right] \in (0.80 - 1.00)$$

Measured E factors



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

Monte Carlo Evaluation of E(d)

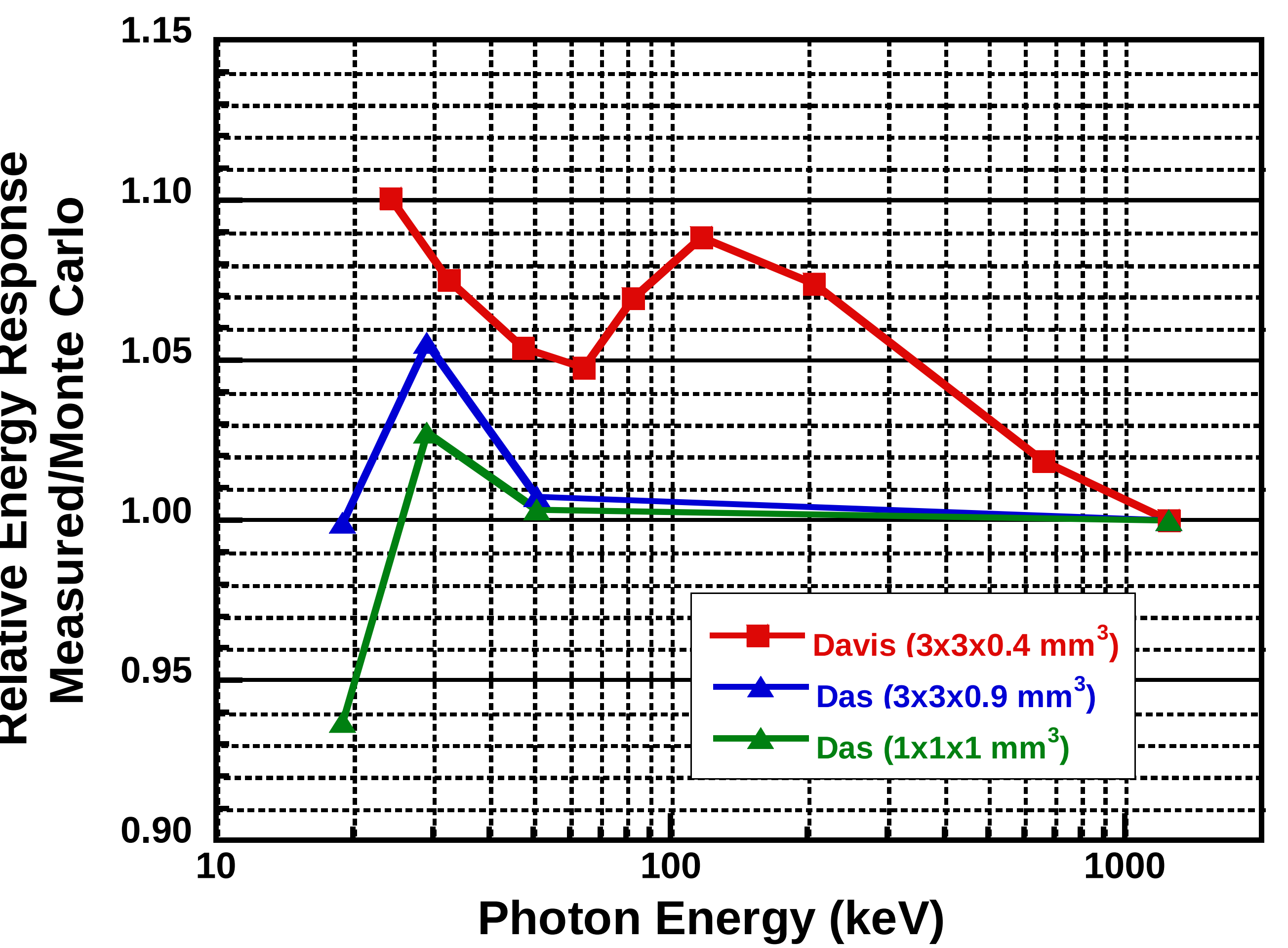
- E(d) Corrects for
  - Measurement medium and geometry vs water
  - Calibration medium vs. water
  - Detector artifacts: Energy response, volume averaging, angular anisotropy, self attenuation
- Assume: Detector response ✪ energy imparted to active volume for beam qualities λ

$$\text{If} \qquad R_{det}^{\lambda} = \alpha \cdot D_{det}^{\lambda}$$

$$\text{Then} \qquad E(\vec{r}) = \frac{\left[\Delta D_{det}(\vec{r}) / \Delta D_{wat}(\vec{r})\right]_{BRx}^{MC}}{\left[\Delta D_{det} / \Delta D_{med}\right]_{\lambda}^{MC}}$$

Measured vs. Calculated E(d)

Davis 2003 and Das 1995



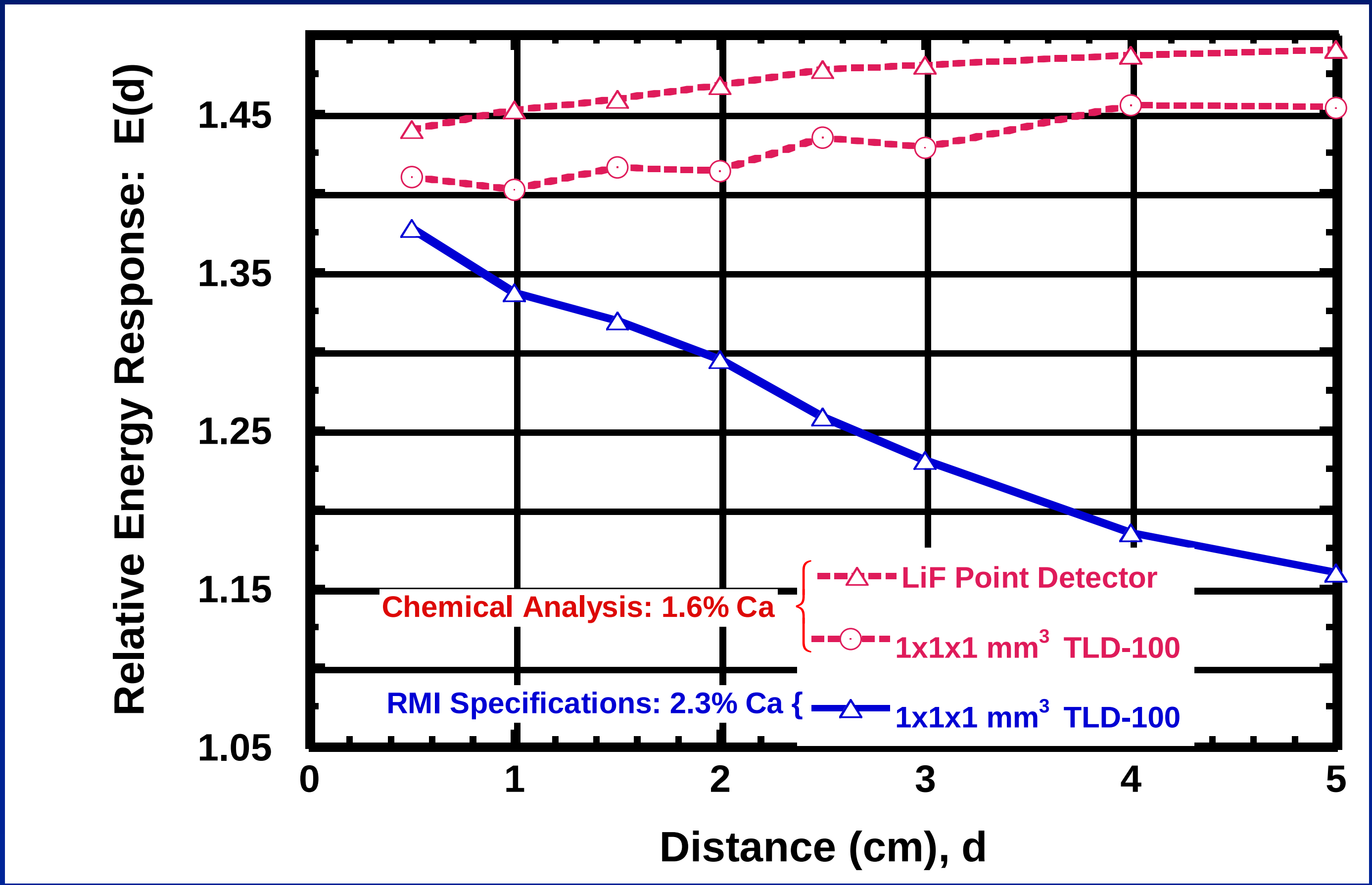
R_λ = TL at energy λ

K_{air}^{λ} = measured air kerma

$$\alpha_\lambda = \frac{\left(TL / K_{air}\right)_{Meas}^{\lambda}}{\left(D_{TLD} / K_{air}\right)_{MC}^{\lambda}}$$

Energy linearity of TLD is controversial

I-125 Seed E(d) in Solid Water



- Solid-to-Liquid Water correction: 4%-15% at 1-5 cm
- 10-30% variations in SW composition reported: 5%-20% dosimetric errors

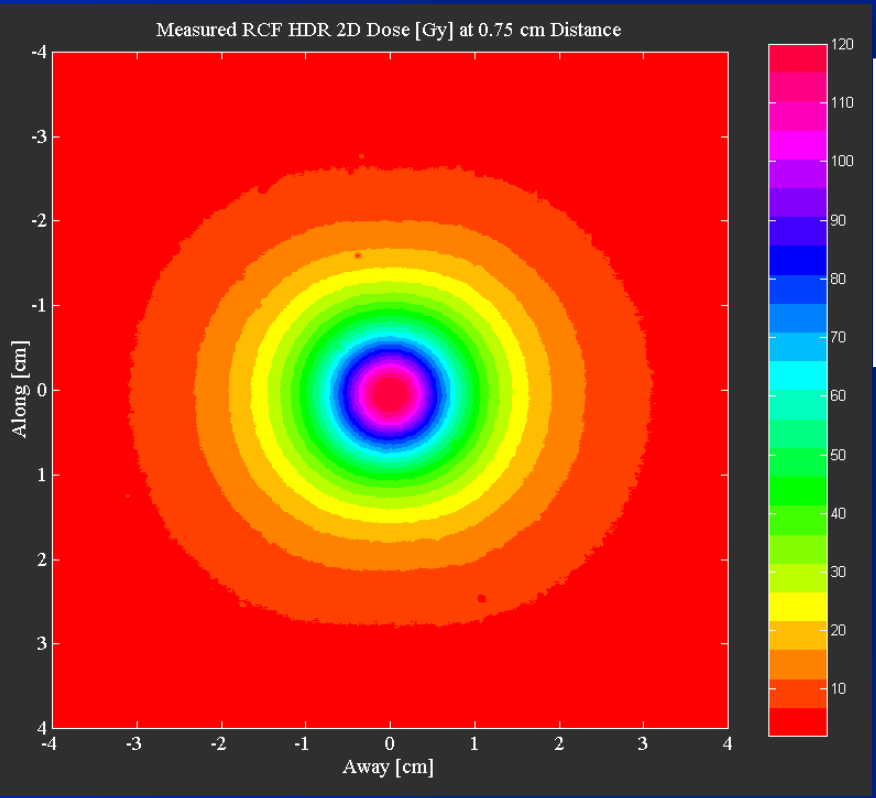
Summary: TLD phantom dosimetry

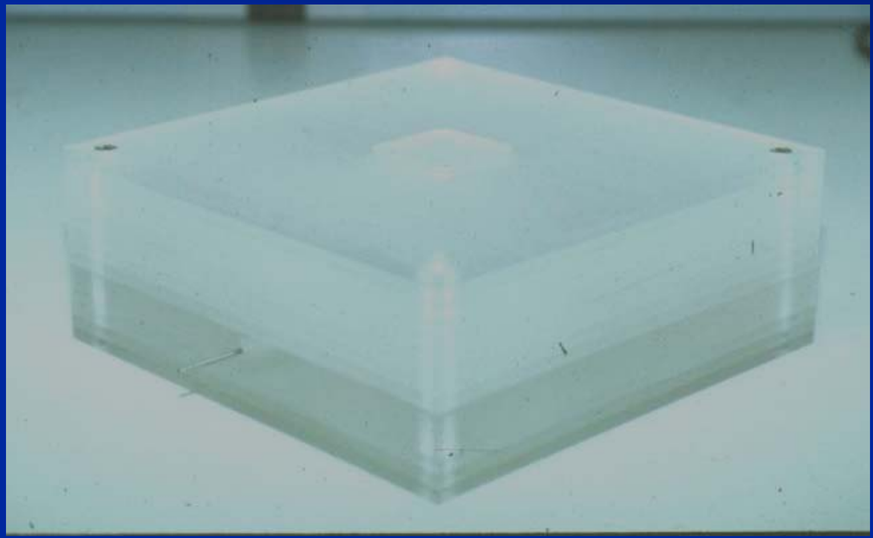
- 1-3 mm size $\Rightarrow$ precision: 2-5% above 1 cGy
- Energy response corrections
  - Distance independent, excluding phantom corrections
  - Energy linearity is controversial (<10%)
  - Many corrections routinely ignored
- Widely-used SW phantom has uncertain composition
  - High-purity industrial plastics recommended
- Extensive benchmarking of TLD vs Monte Carlo
  - 3-10% agreement for Pd-103 and I-125 sources
  - 7%-10% absolute dose measurement uncertainty

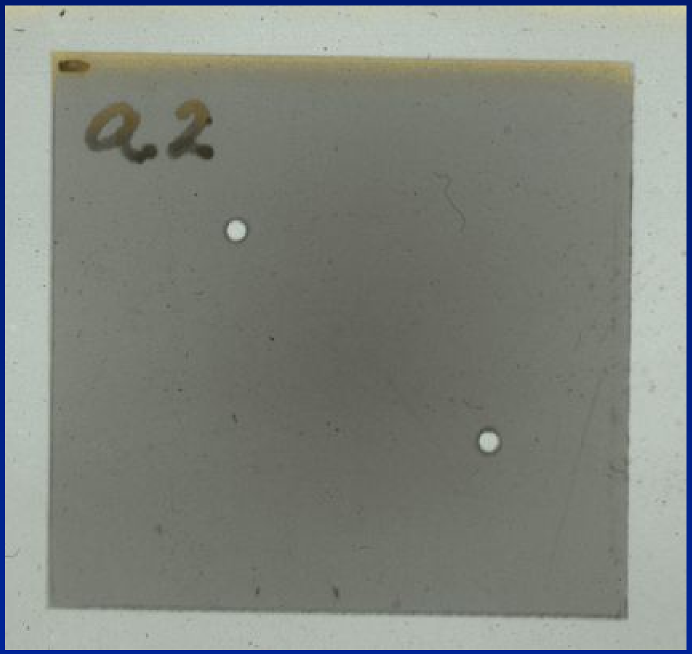
Other dosimetry systems

- Plastic scintillator (PS) and diode probes
  - High sensitivity, small size, good SNR, and waterproof
  - Single element detectors requiring water scanning system
- PS: established as transfer/relative dosimeter 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
  - Well established as relative dosimeter

Emerging Dosimetry Systems 2D RadioChromic Film Ir-192 HDR Source

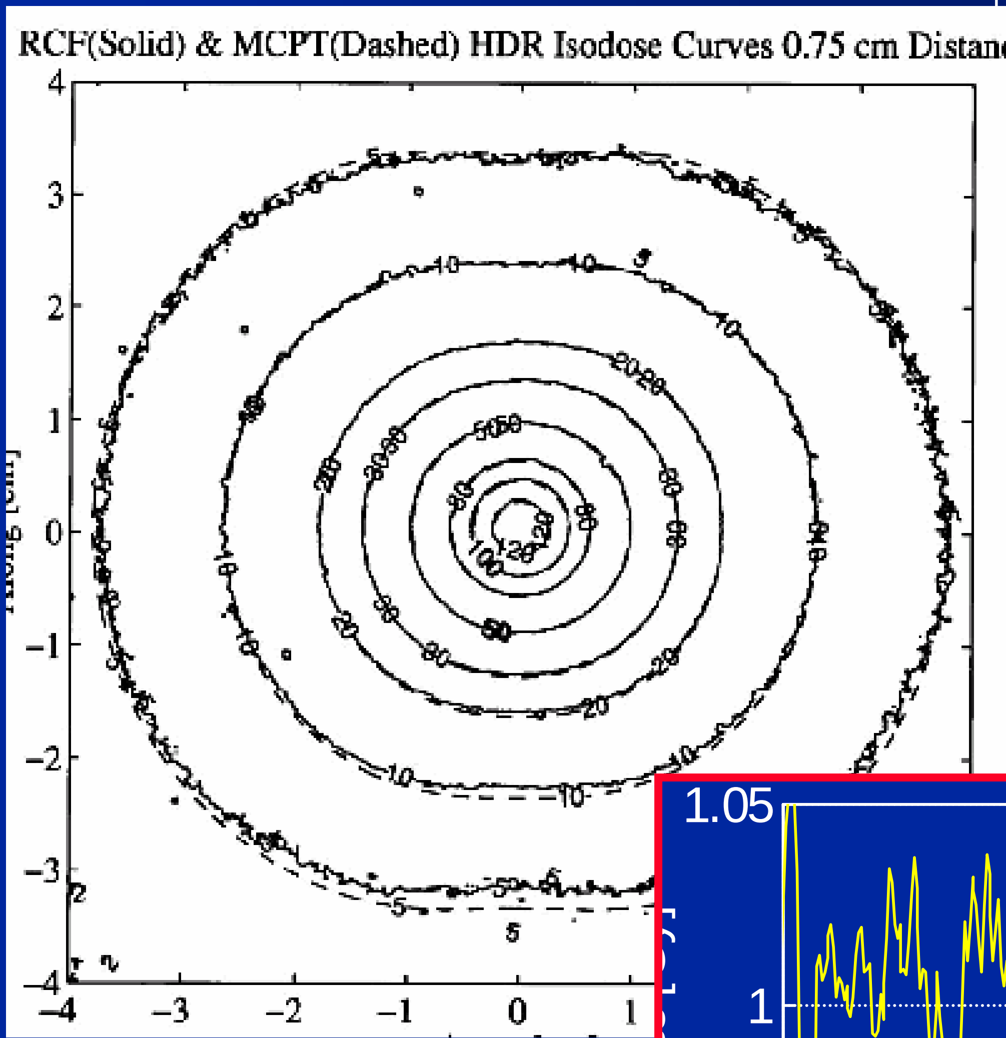


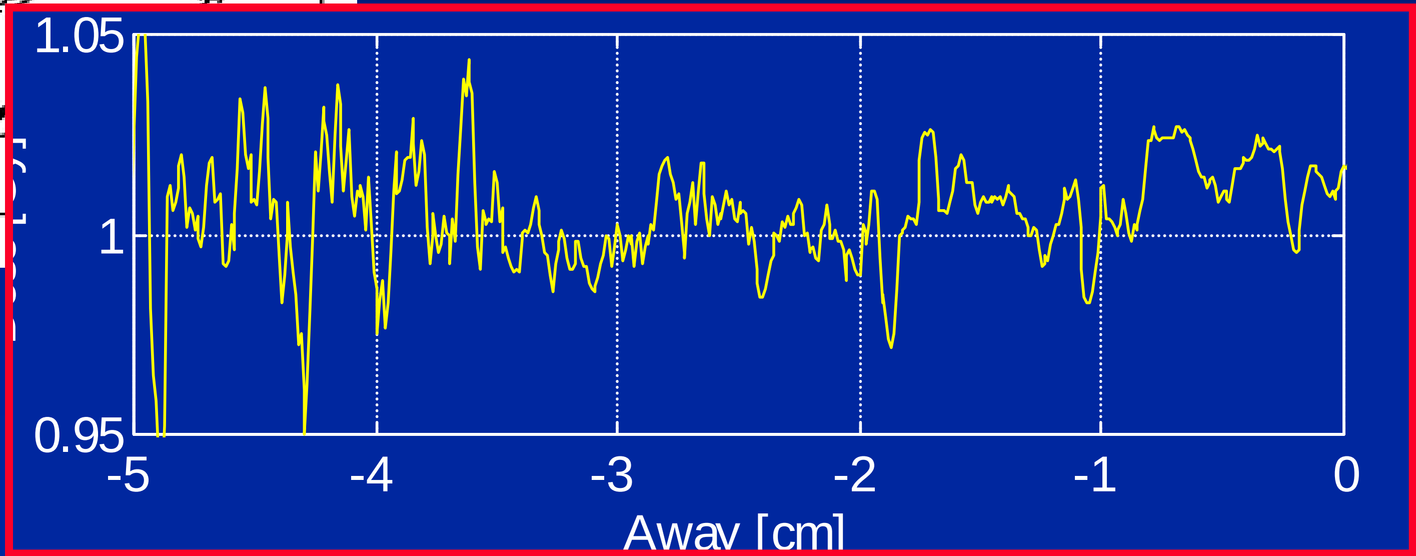




Absolute RCF Dose Measurement vs Monte Carlo HDR ^{192}Ir Source

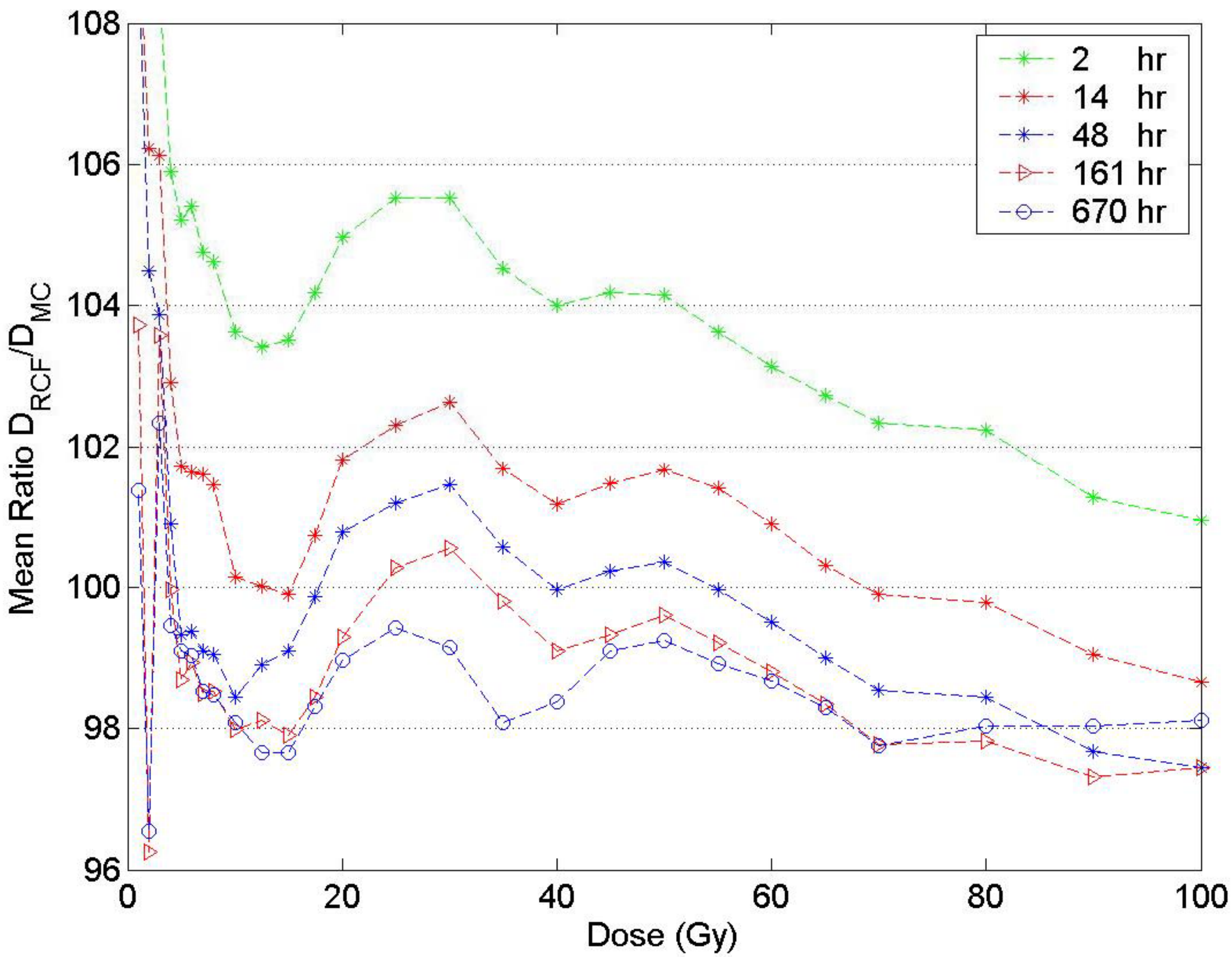
RCF 2σ uncertainty: 4.6%





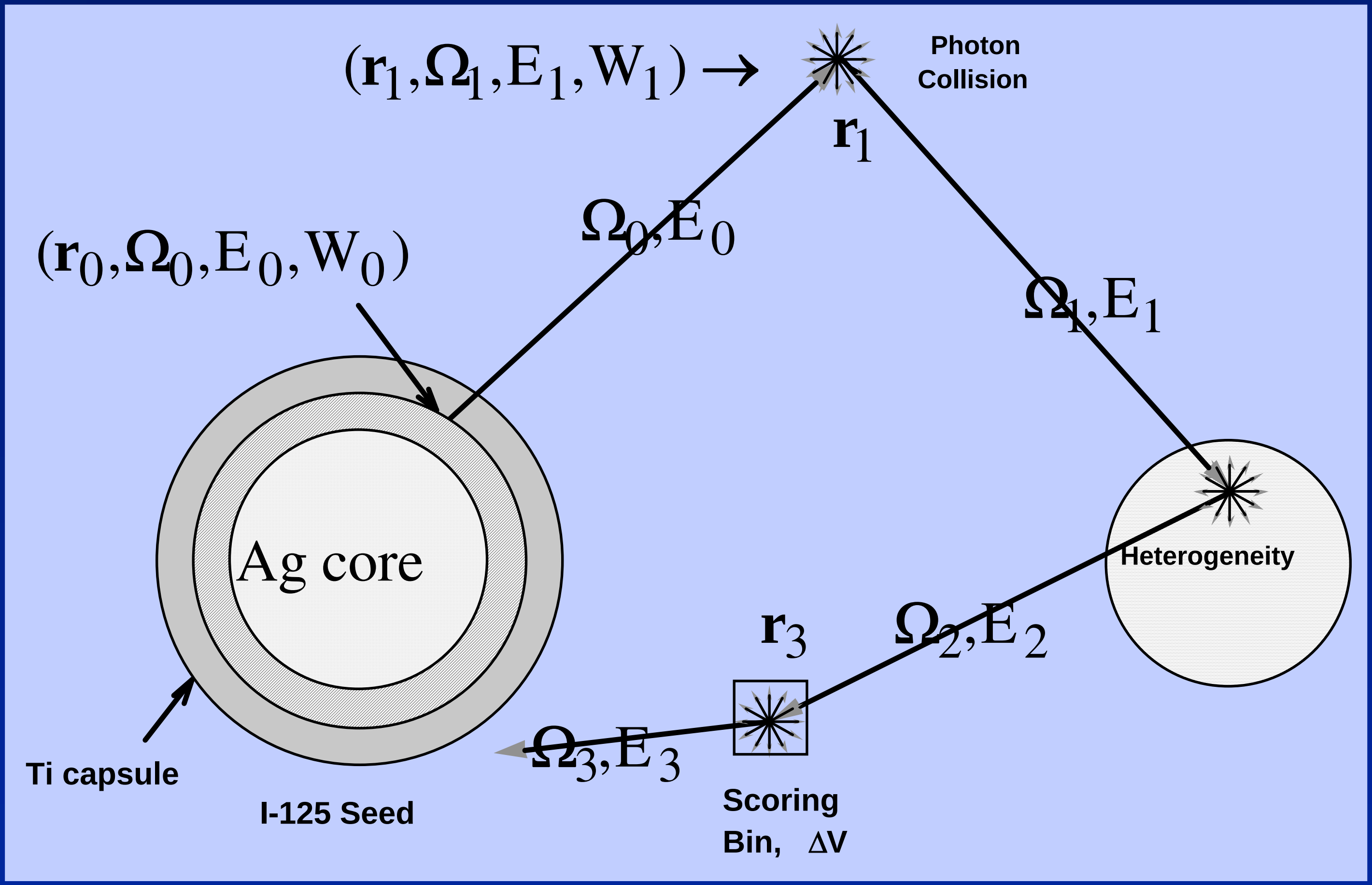
Absolute RCF dosimetry for LDR Sources

Cs-137: RCF/MC vs. Exposure-to-densitometry time interval



- Mean error vs dose
- 6 day exposure
- Very high 100 μm spatial resolution
- Fading artifacts not significant
- Energy linearity within 5%

Monte Carlo Simulation
Typical Trajectory



Monte Carlo Technical Issues

Particle Collision Dynamics

Total and differential cross sections for all collision processes and media

Geometric Model

Size, location, shape, composition and topology of each material object

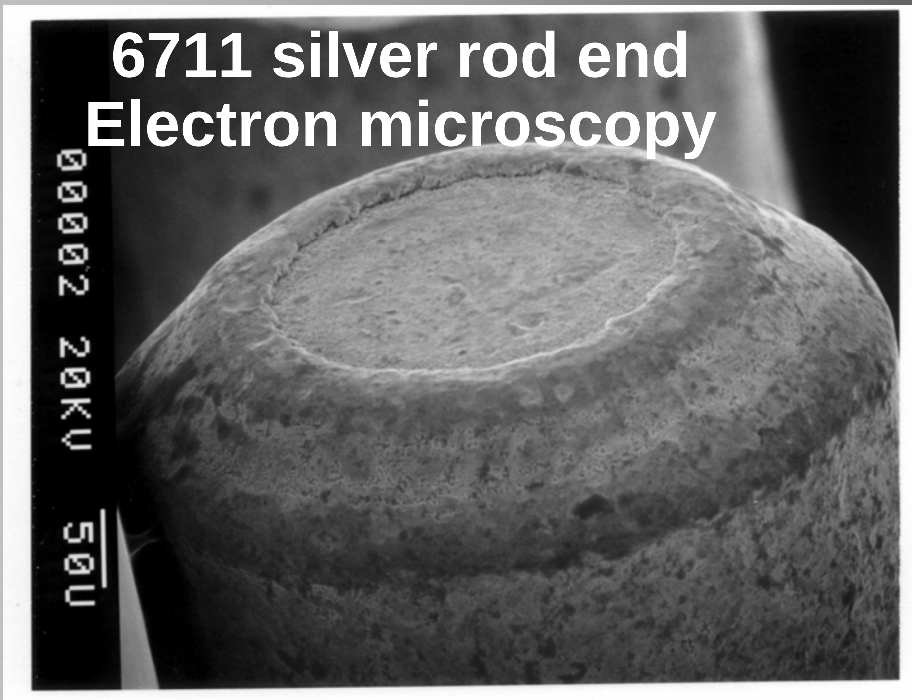
Detector Model

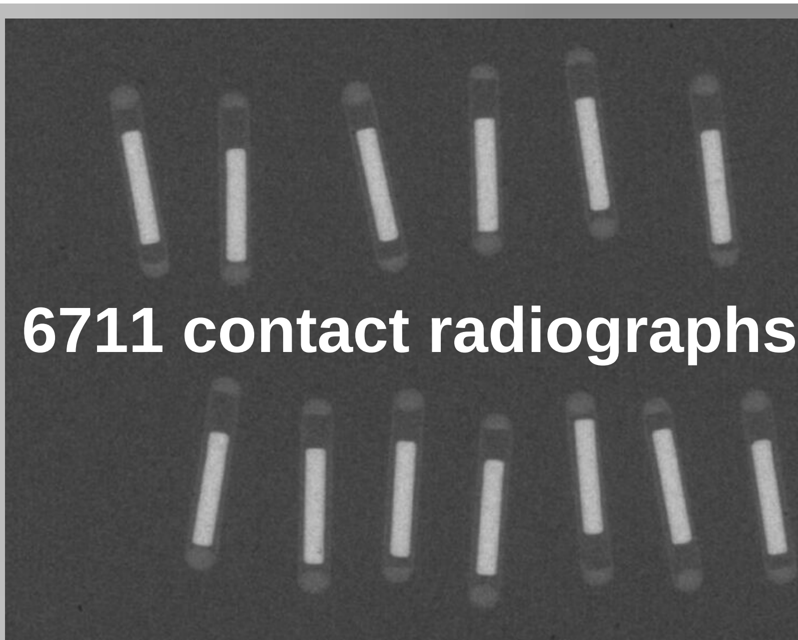
relationship between dose and collision density

Collisional Physics Requirements for Low-Energy Brachytherapy

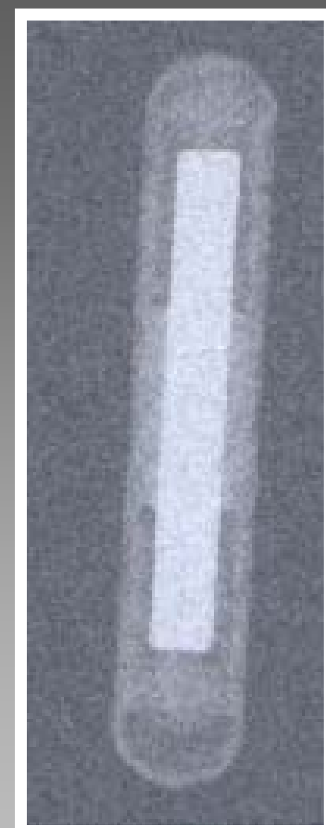
- Only photon transport needed
  - Secondary CPE obtains (Dose ≈ Kerma)
  - Neutral-particle variance reduction techniques useful
- Comprehensive model of photon collisions
  - NIST EXCOM or EPDL97 Cross sections are essential!!
  - Coherent scattering and electron binding corrections
    - » Use molecular/condensed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

Geometric Model Validation

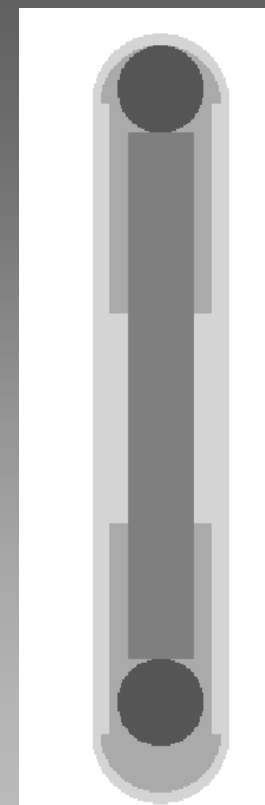




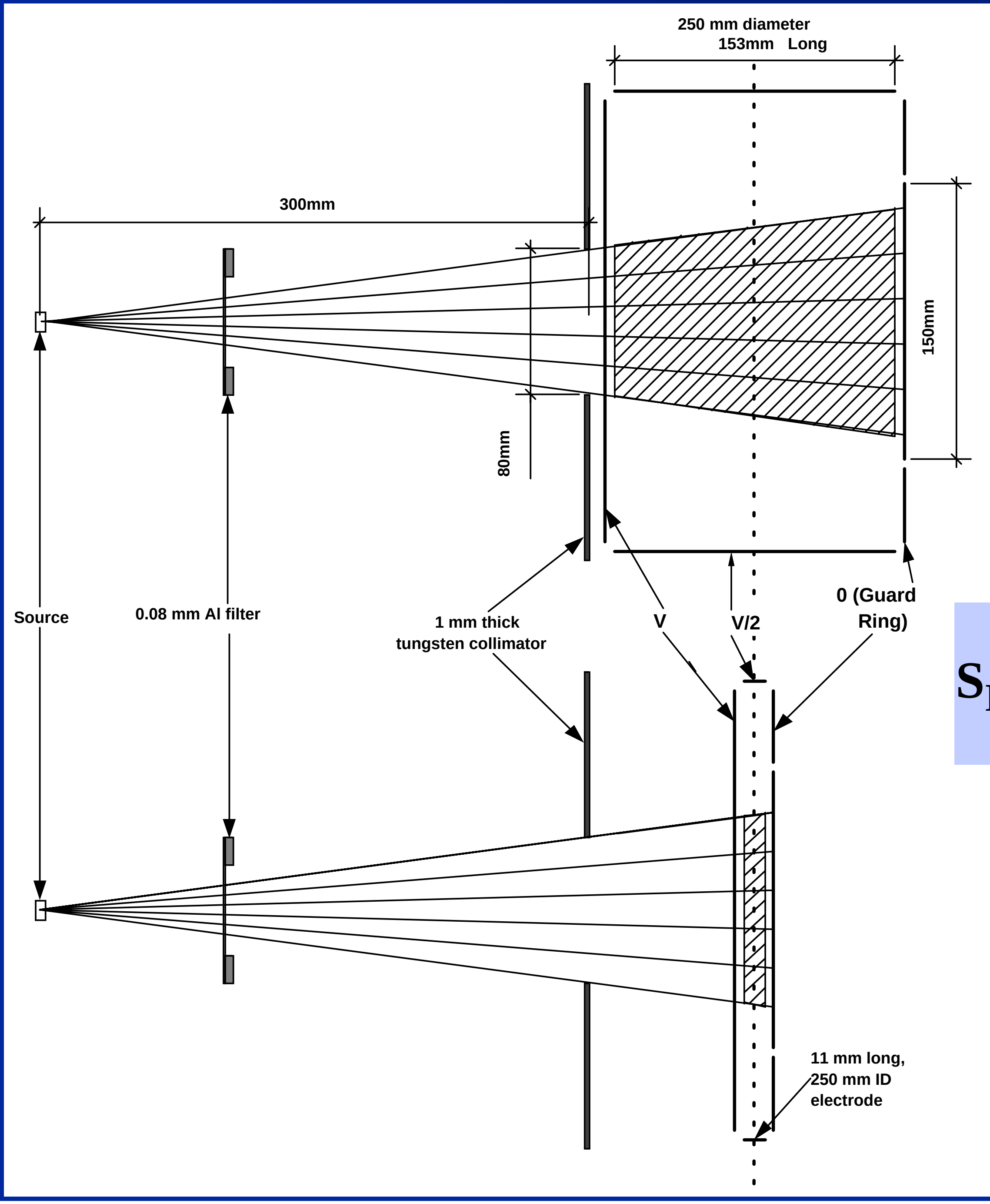
DraxImage I-125 Seed



Contact Radiograph



Final Model

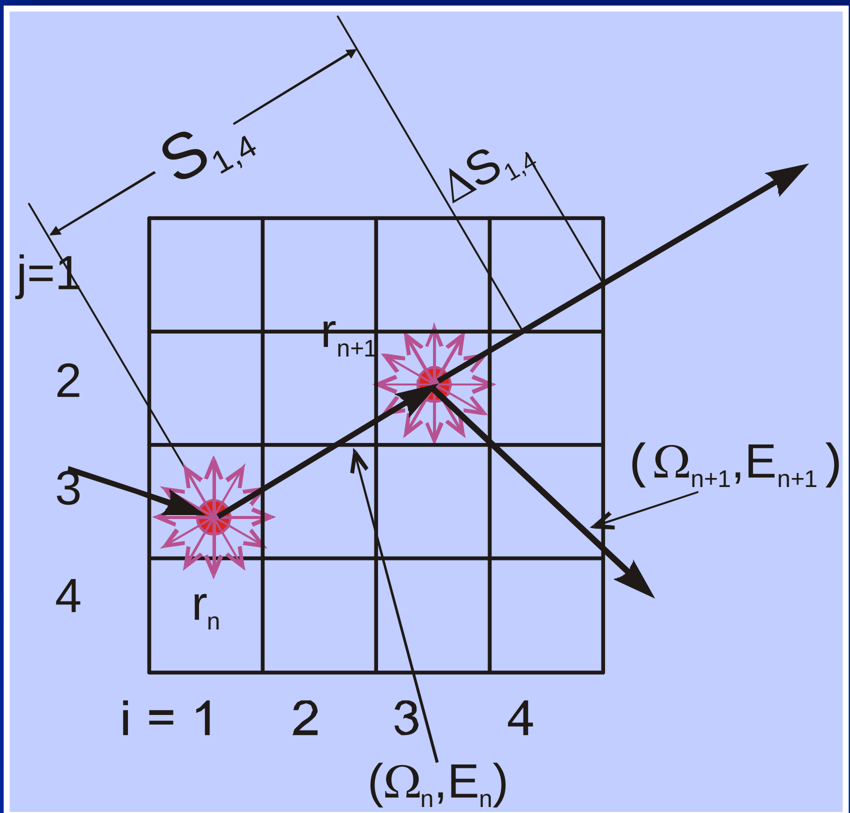


Wide-angle Free Air Chamber

NIST Primary Standard interstitial sources photons < 50 keV

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

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

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

Estimator Use

- Tracklength estimators
  - 20-50X more efficient than analog
  - Models volume averaging and medium replacement by extended detectors
  - 3D patient (voxel array) calculations
- Next flight estimators: dose-at-a-point
  - Condensed-medium dose calculations at least 1-2 mm from interfaces
  - Dilute-medium (air) kerma calculations
  - 0.1% - 2% statistical precision for I-125 dosimetry
- Kalli/Cashwell “Once-more-collided Flux”
  - Point doses near media interfaces
  - Energy imparted to small detectors

Monte Carlo quantities for typical seed study

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

Bounded next-flight estimator for most distances

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

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

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

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

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

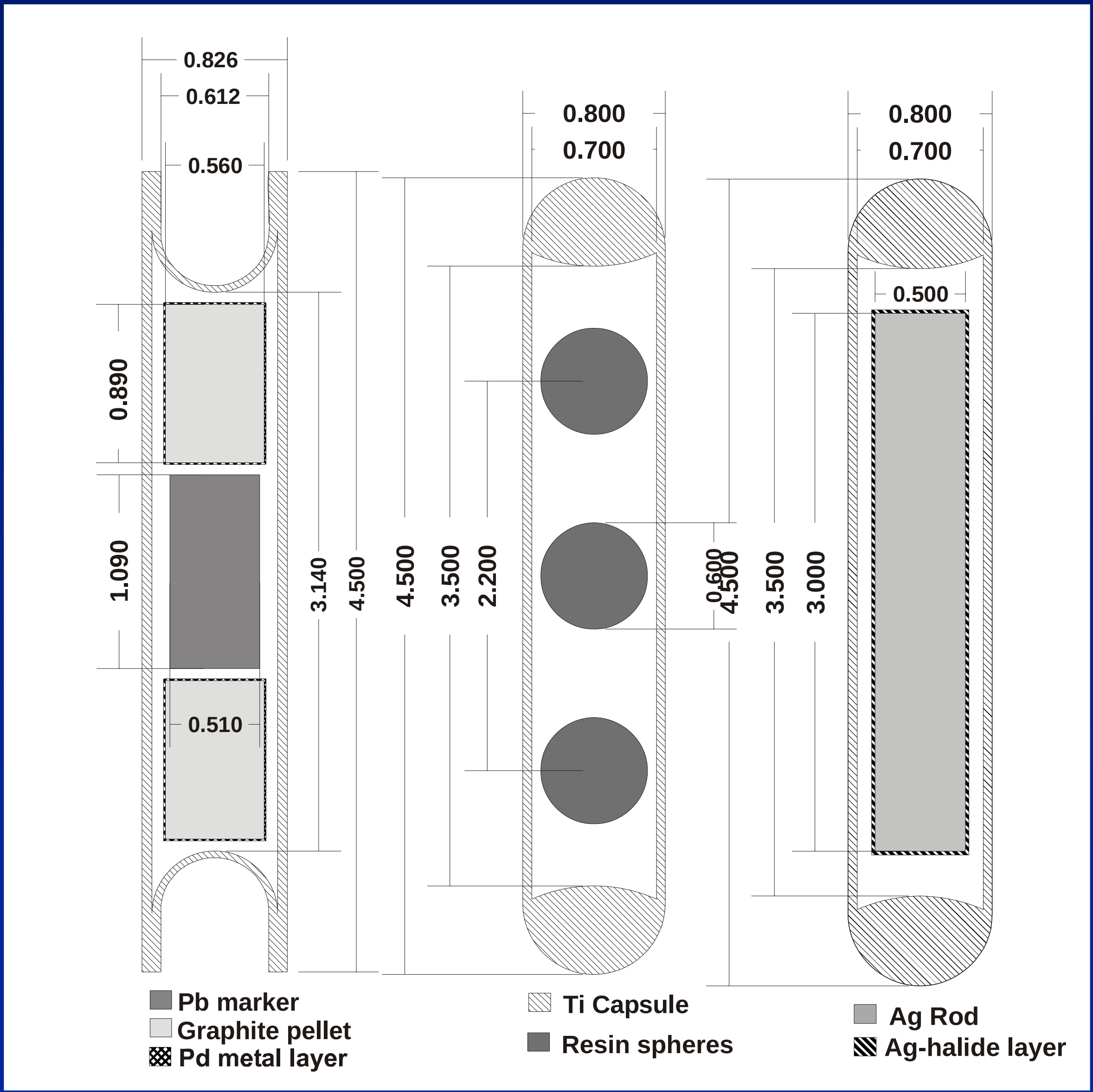
$$\Delta \dot{K}_{air}(d) \cdot d^2 = \Delta S_K \cdot (1 + \alpha d) \cdot e^{-\mu d}$$

Where ΔS_K and α are unknowns

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

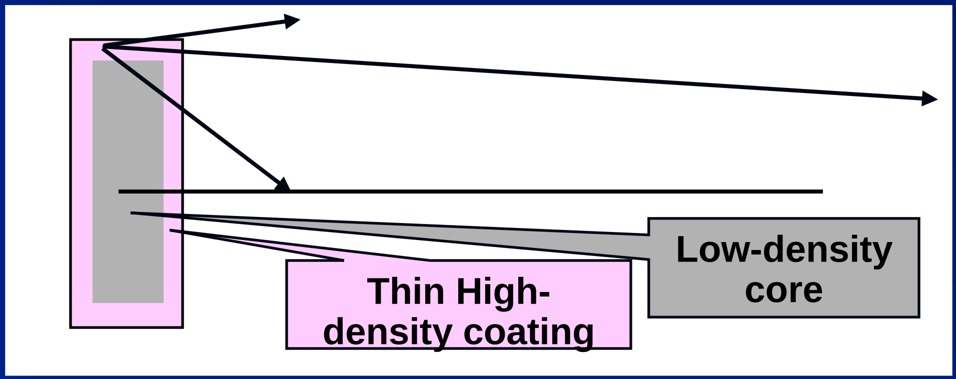
μ = primary photon attenuation coefficient

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

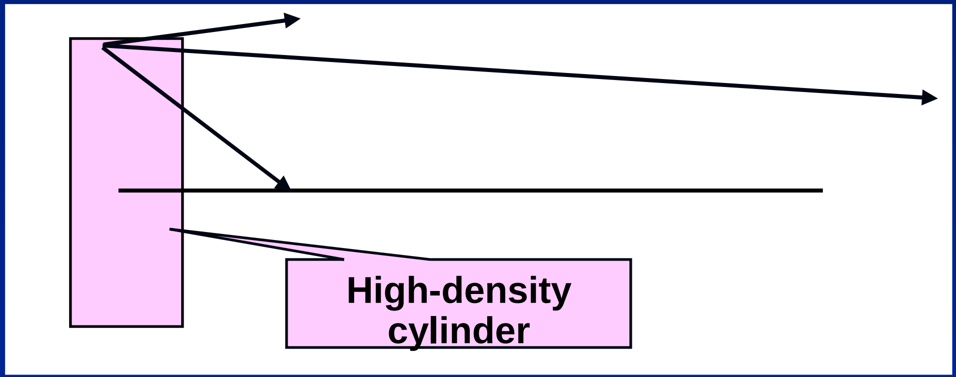


- Model 200
  - ^{103}Pd distributed in thin (2-25 μm) Pd metal coating of right circular graphite cylinder
- Model 6702
  - ^{125}I distributed on surface of radio transparent resin spheres
- Model 6711
  - ^{125}I distributed in thin (≈3 μm) silver-halide coating of right circular Ag cylinder

Sharp corners and opaque coatings



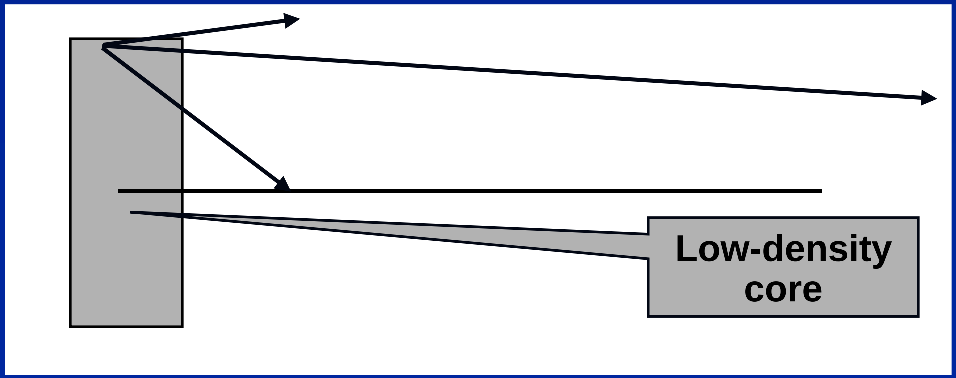
Near transverse-axis:
- Anisotropic at long distances
- Isotropic at short distances
- Inverse square-law deviations



Anisotropic at long and short distances

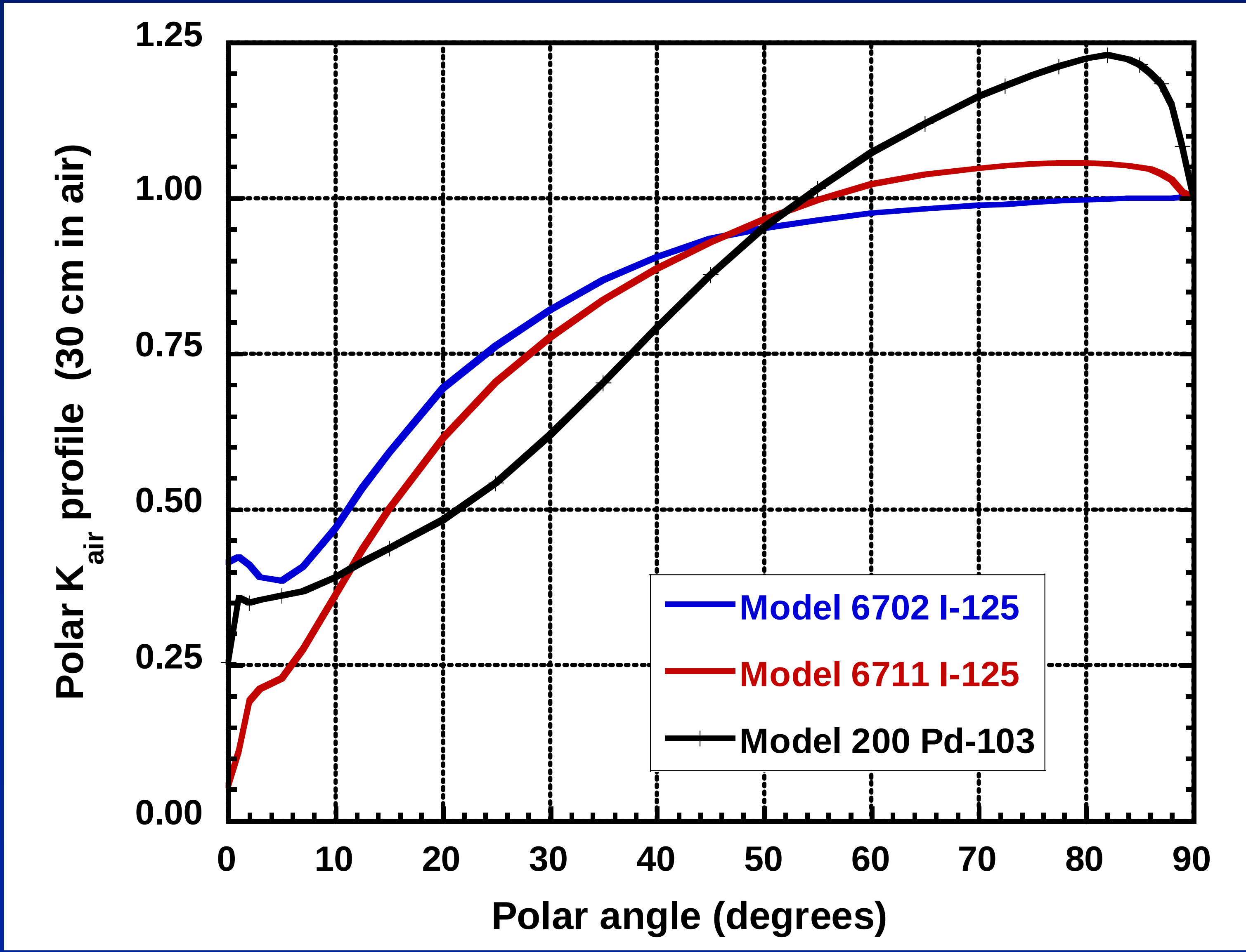
Circular ends contribute at

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

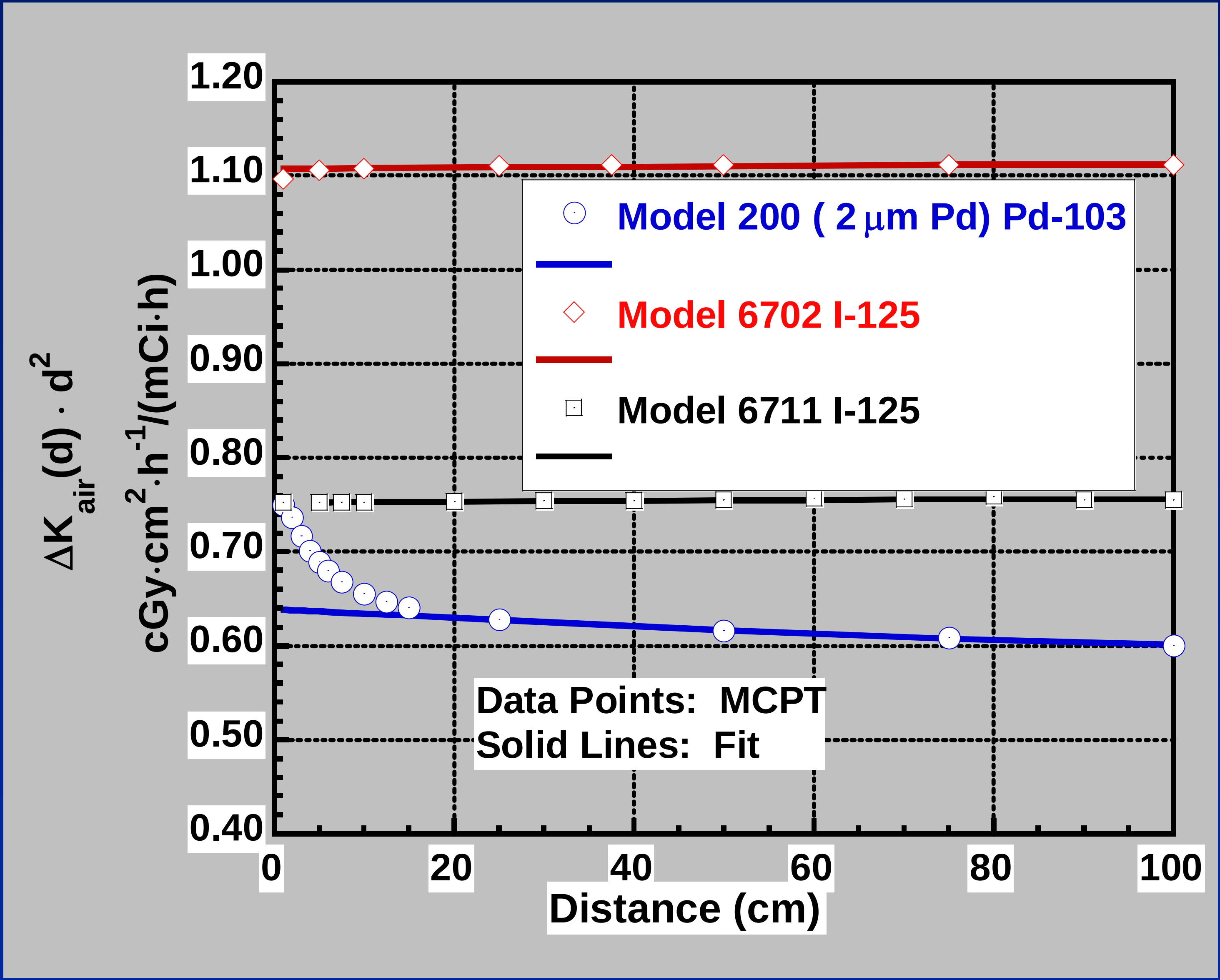


Isotropic at both long and short distances

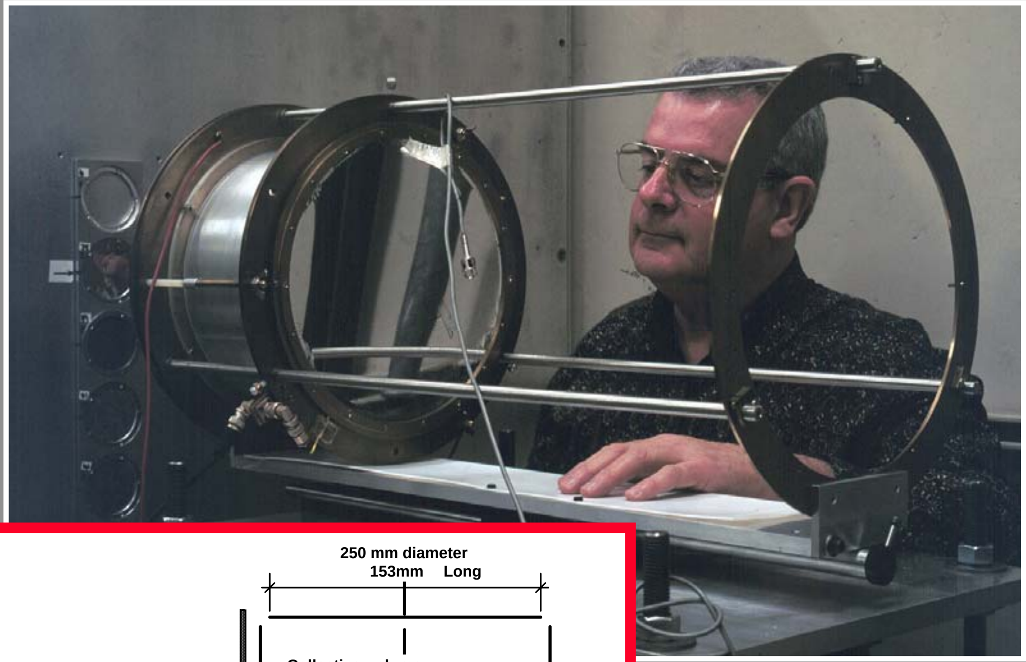
Polar Anisotropy in Air (30 cm)

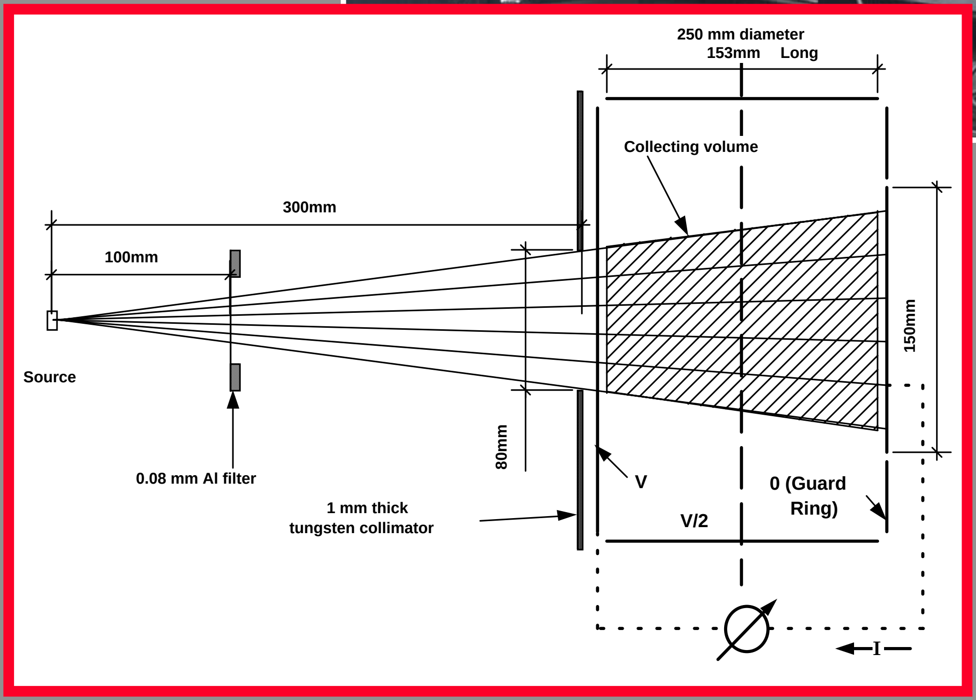


ΔS_K: Point-Extrapolation Method



‘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

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

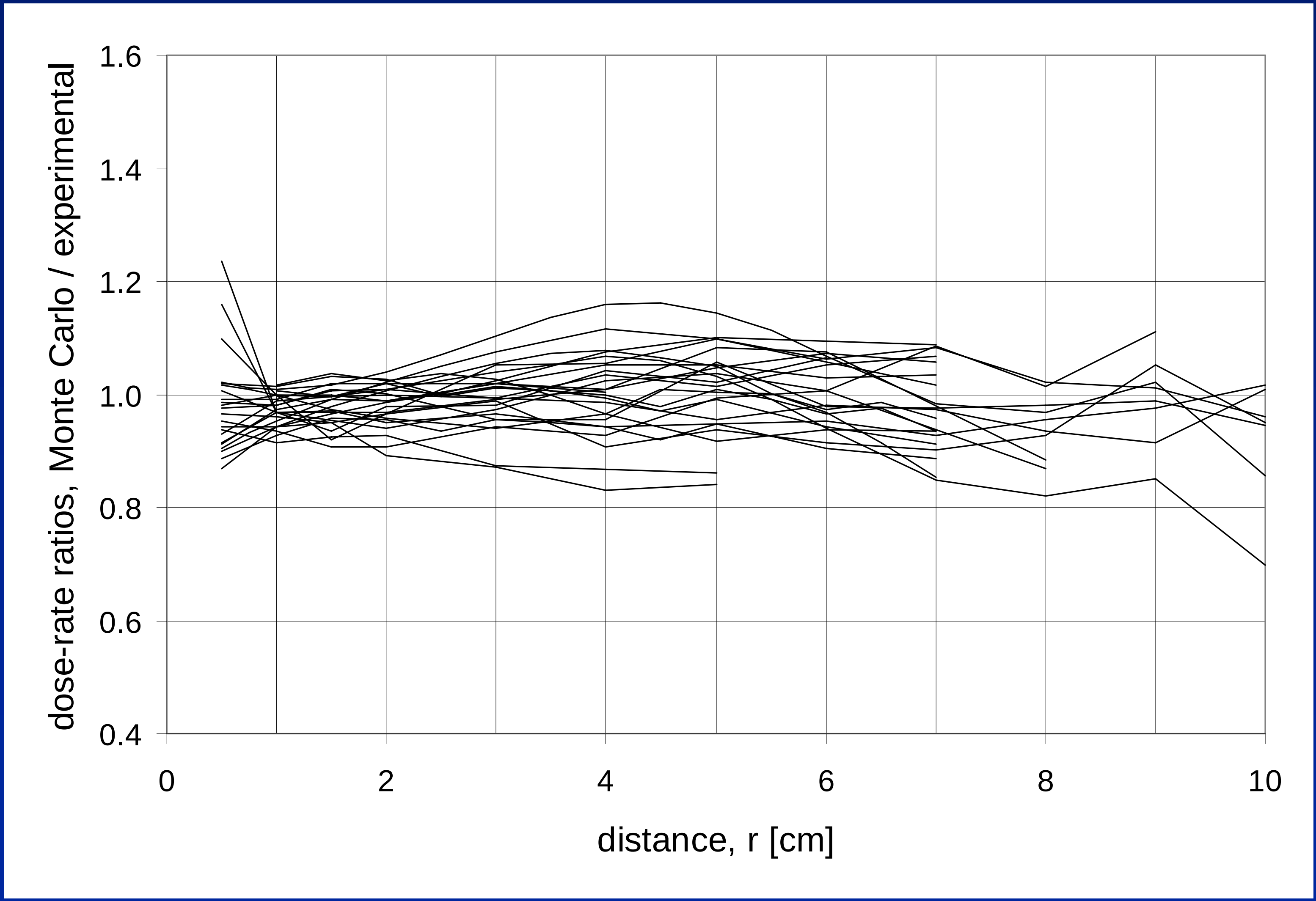
$$k_{inv} = \text{inverse-square correction} = \frac{\int_A \Phi(\ell) \cdot dA}{\Phi(d) \cdot A} = 1.0089$$

Pd-103 Dose-Rate Constants

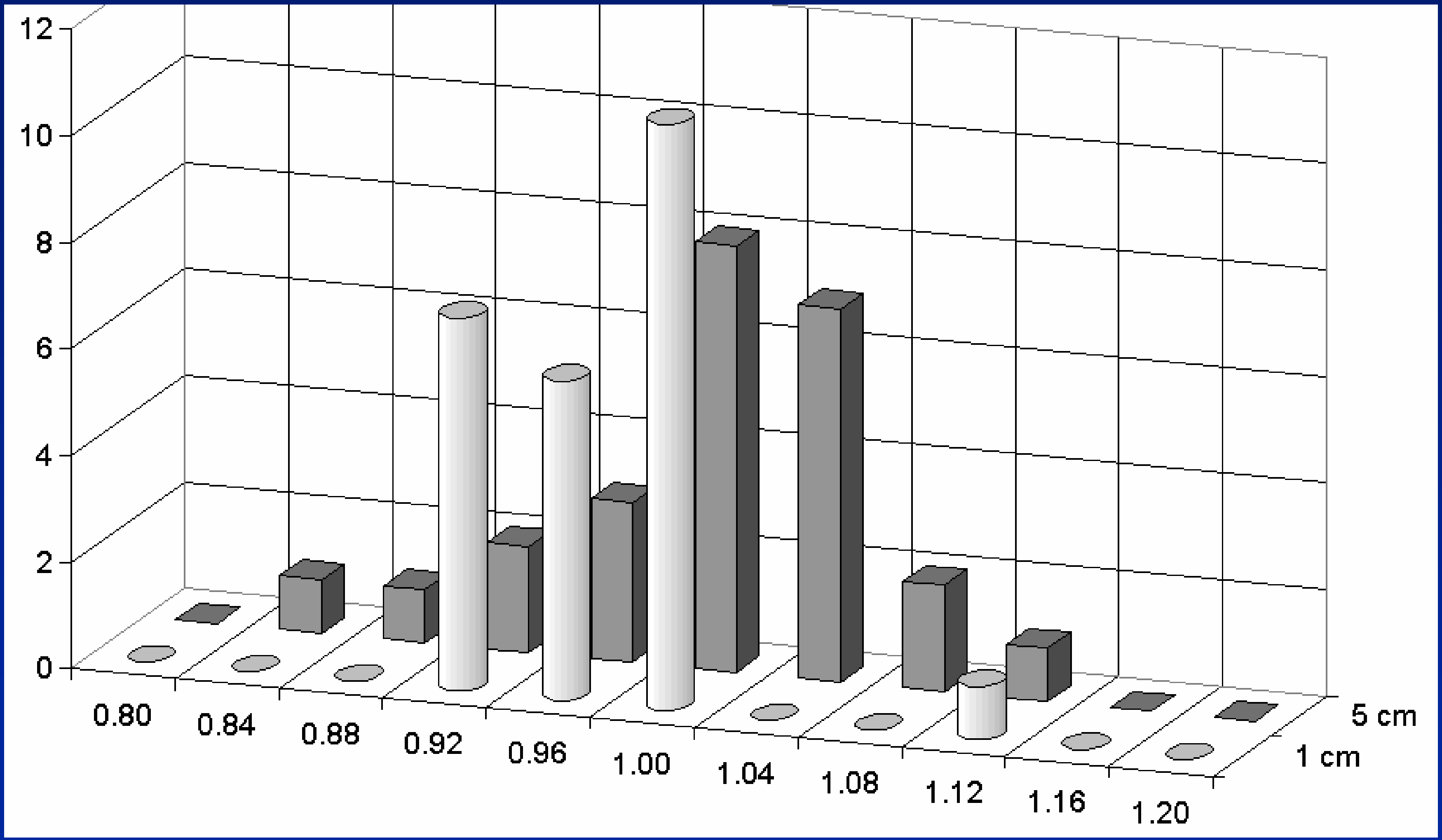
Source	Investigator	$\Lambda_{xxD,N99S}$		
		TLD	MC Extrap.	MC WAFAC
Point	This work	___	0.683	0.683
Model 200 (light)	This work Nath 2000 ICWG 1989	--- 0.684 0.65	0.797	0.691
Model 200 (heavy)	This work ICWG 1989	----- 0.65	0.744	0.694
NAS MED 3633	Li Wallace 1998	0.693 0.68	0.677	---

Monte Carlo vs. TLD: ^{125}I Seeds

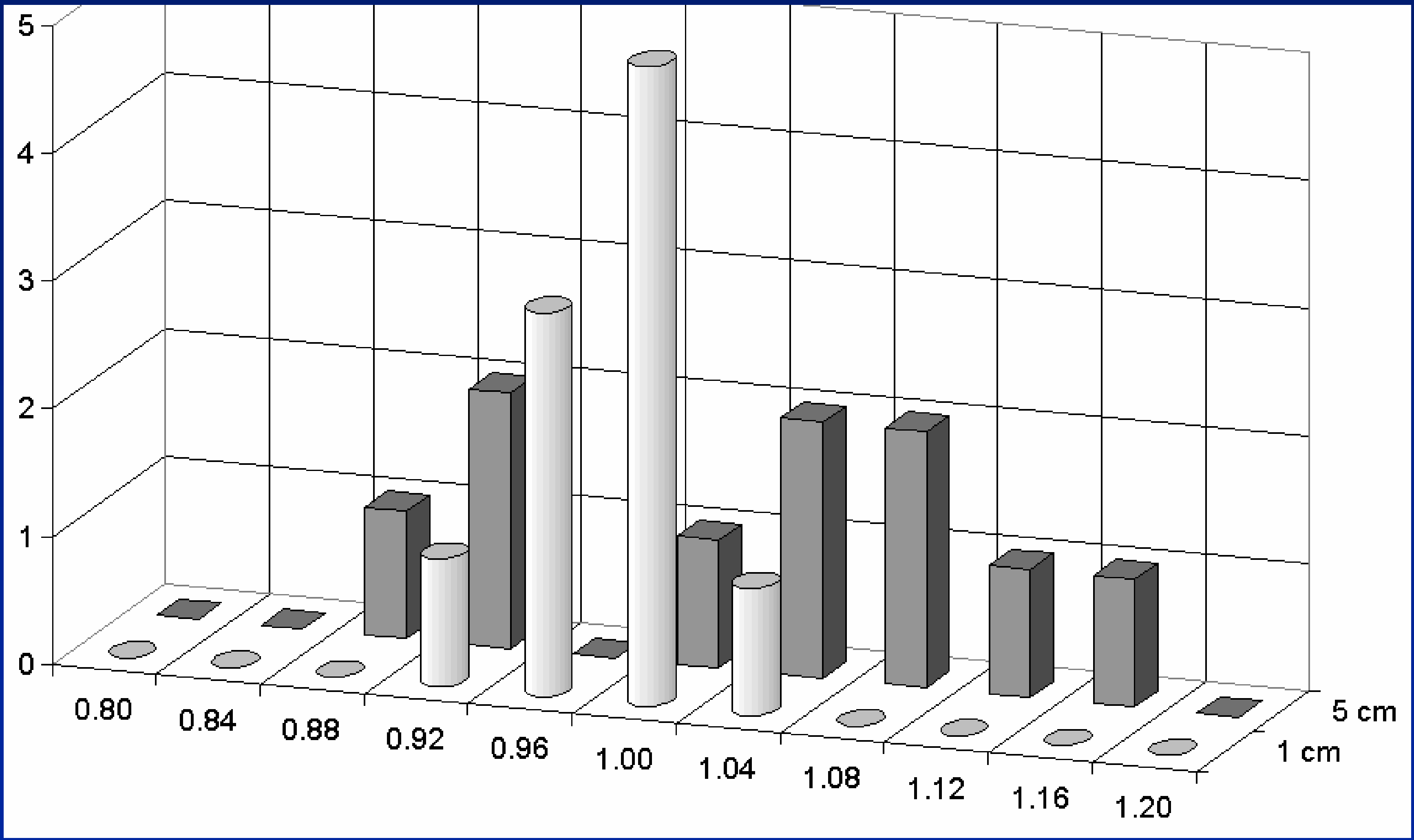
- **14 Seed models, 38 Candidate datasets**



Monte Carlo/TLD Dose Rates: ^{125}I Seeds



Monte Carlo/TLD Dose Rates: ^{125}I Seeds



TLD and Monte Carlo Uncertainty Analysis

Table 2: Uncertainties for ^{125}I transverse-axis TLD and Monte Carlo dose estimation

TLD uncertainties in measurement of $\dot{D}_{wat}(\vec{r})/S_K$ for ^{125}I in Solid Water				
Component	1 cm distance		5 cm distance	
	$\%\sigma_{x_i}$	Type	$\%\sigma_{x_i}$	Type
Repetitive TLD measurements	**4%**	**A**	**4%**	**A**
TLD calibration (including Linac calibration)	**3%**	**A+B**	**3%**	**A+B**
Solid-to-liquid water conversion	**2%**	**B**	**6%**	**B**
Seed and TLD positioning errors ($\Delta d = 100\ \mu m$)	**2%**	**B**	**1%**	**B**
Energy-response correction	**5%**	**B**	**5%**	**B**
ADCL S_K measurement + transfer	**2%**	**B**	**2%**	**B**
Total combined uncertainty	7.9%		9.5%	

Uncertainties for Monte Carlo estimates $\dot{D}_{wat}(\vec{r})/S_K$ for ^{125}I in liquid water		
Statistics	**0.3%**	**1.0%**
Photo ionization cross-sections ($\Delta\sigma_{PE} = 2.3\%$)	**1.5%**	**4.5%**
Seed geometry	**2%**	**2%**
Source energy spectrum	**0.1%**	**0.3%**
Total combined uncertainty	**2.5%**	**5.0%**

Monte Carlo vs TLD

- Measurement Pros and Cons
  - Large uncertainties and many artifacts
  - Tests conjunction of all a priori assumptions: seed geometry, detector response corrections, etc
- Monte Carlo Pros and Cons
  - Artifact free and low uncertainty
  - Garbage in-Garbage out
    - » Seed geometry errors
    - » Will not anticipate contaminant radionuclides etc., S_K errors
  - Does not model detector signal formation

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
  - Measurement: Confirm assumptions underlying Monte Carlo model
- Major needs: more accurate and efficient dose-measurement systems for low energy sources
  - Test source-to-source variations during manufacturing process