NIST Air-Kerma Standard for Electronic Brachytherapy Calibrations

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National Institute of Standards and Technology

Disclaimers

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Xoft, Inc. provided funding for the development of the NIST electronic brachytherapy facility and supplied systems for source control.

NIST Dosimetry Group Strategic Element

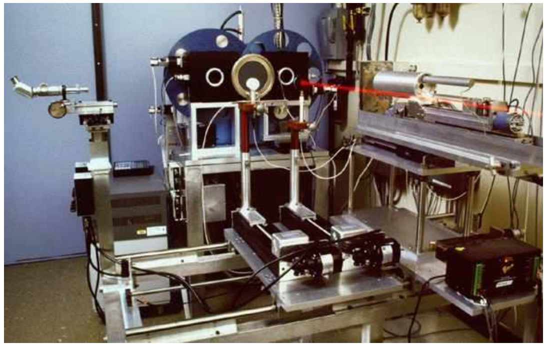
Develop dosimetric standards for x rays, gamma rays, and electrons

based on the SI unit, the gray, 1 Gy ≡ 1 J / kg

kV x rays

x-ray tube

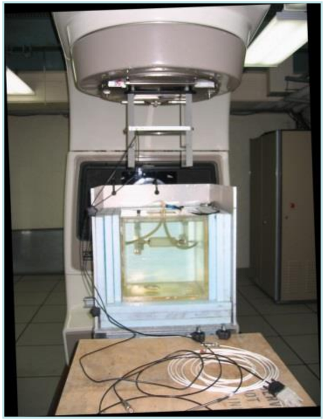
radioactive source



free-air chamber

MV x rays

linac

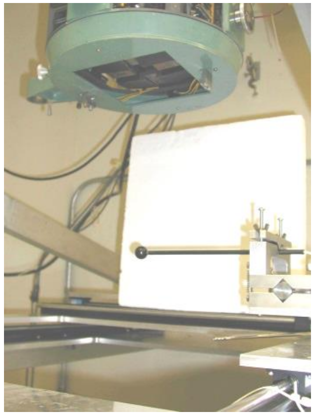


calorimetry

gamma rays

irradiator

(^{60}Co, ^{137}Cs)



cavity chamber

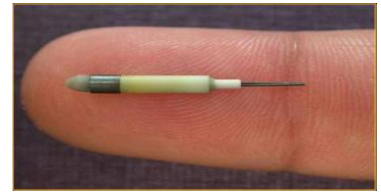
electrons

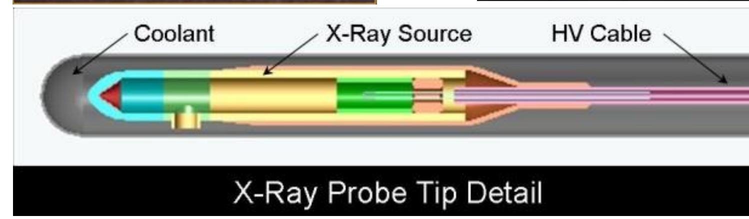
linac, Van de Graaff

radioactive source

ultrasonic/optical

NIST Standards for Radiation Therapy





- External beam (^{60}Co, orthovoltage and MV x rays, electrons, protons)
- Brachytherapy

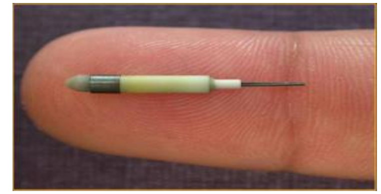
  Low-Energy, Low-Dose-Rate (^{125}I, ^{103}Pd, ^{131}Cs seeds)

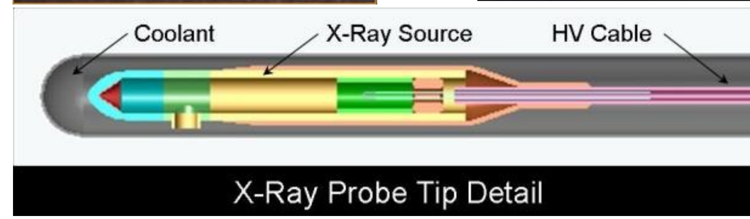
  High-Energy, Low-Dose-Rate (^{192}Ir seeds, ^{137}Cs sources)

  High-Energy, High-Dose-Rate (^{192}Ir sources)

  Low-Energy, High-Dose-Rate (miniature x-ray sources)

NIST Standards for Radiation Therapy



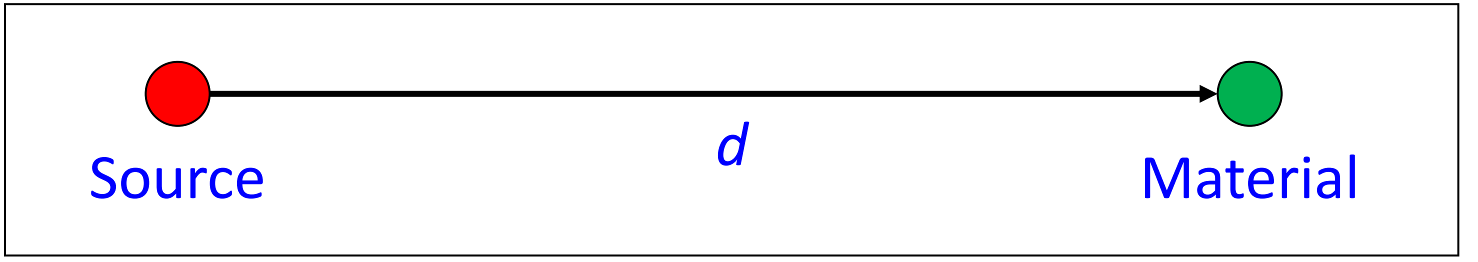


Safety and efficacy requires accurate treatment planning

↓

Dosimetry traceable to primary standards

Dosimetry of X Rays (E < 300 keV)



$$K = \frac{\mathrm{d}E_{\mathrm{tr}}}{\mathrm{d}m} = \Phi \cdot E \cdot \left(\frac{\mu_{\mathrm{tr}}}{\rho} \right)$$

KERMA = Kinetic Energy Released per unit MAss

transferred to
electrons by x rays

$$\frac{\mu_{\mathrm{tr}}}{\rho} = \frac{f_{\mathrm{pe}}\sigma_{\mathrm{pe}} + f_{\mathrm{incoh}}\sigma_{\mathrm{incoh}}}{uA}$$

photoelectric Compton

Photon and Charged-Particle Data Center

XCOM

XCOM: Photon Cross Sections Database

http://www.nist.gov/pml/data/xcom/index.cfm

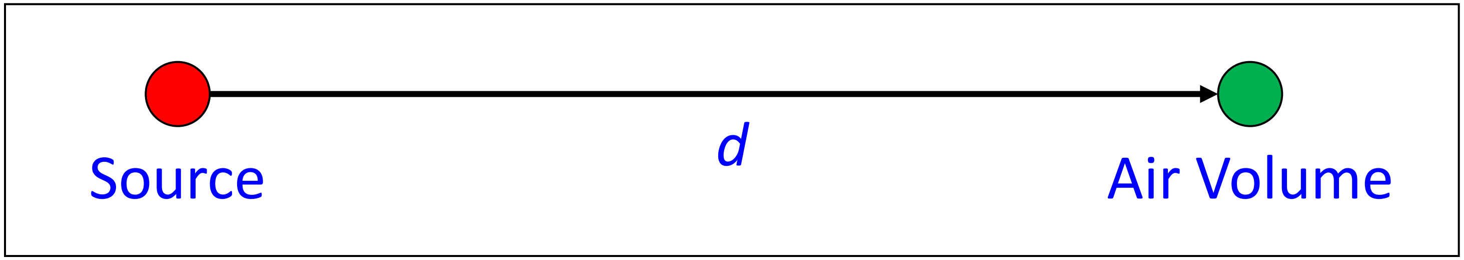
Photon Cross Sections Bibliography

http://www.nist.gov/pml/data/photon_cs/index.cfm

estar stopping-power and range tables for electrons

http://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html

Dosimetry of X Rays (E < 300 keV)



$$K_{\mathrm{air}} = Q_{\mathrm{air}} \left(\frac{\overline{W}_{\mathrm{air}}}{e} \right) \frac{1}{\rho_{\mathrm{air}} V}$$

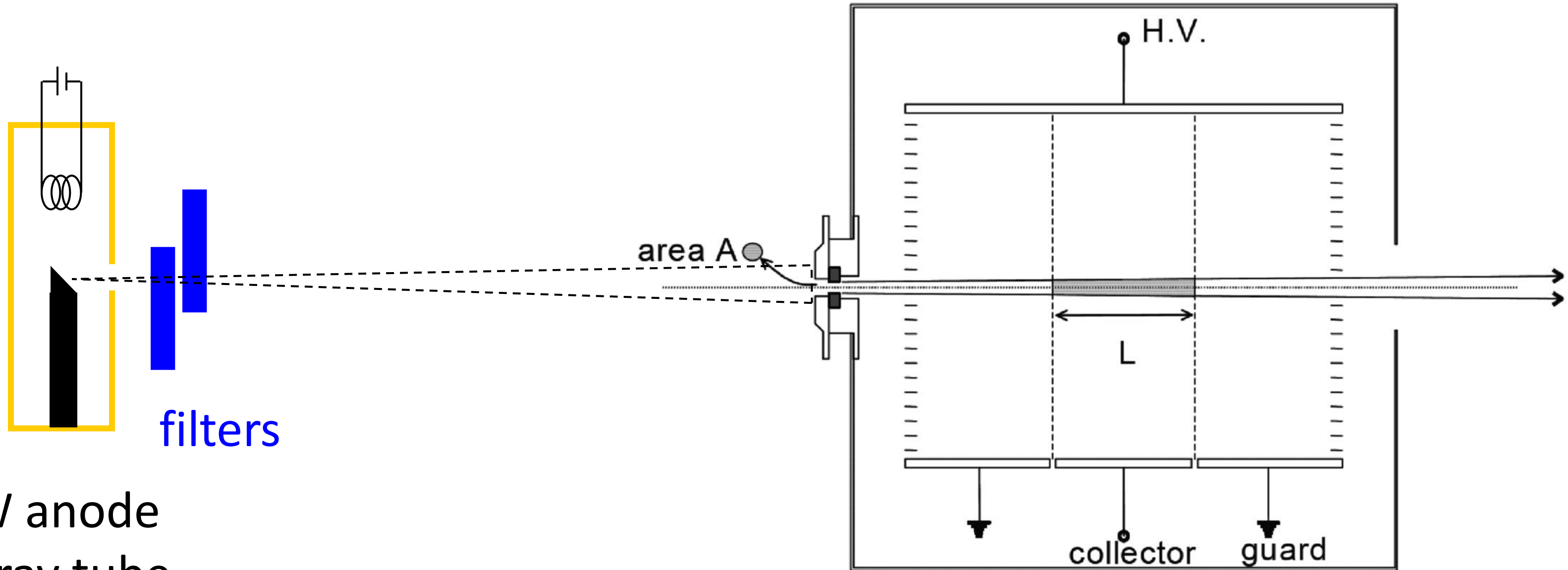
KERMA = Kinetic Energy Released per unit MAss

Secondary electrons ⟶ liberated charge in a given mass of air

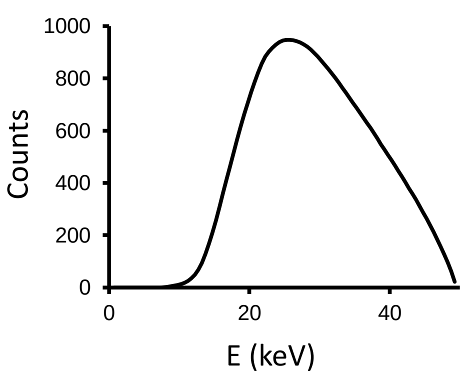
$$\mathrm{C} \cdot \left[33.97 \frac{\mathrm{J}}{\mathrm{C}} \right] \cdot \frac{1}{\mathrm{kg}} = \frac{\mathrm{J}}{\mathrm{kg}} = \mathrm{Gy}$$

Air kerma can be measured absolutely with a free-air ionization chamber

Free-Air Ionization Chamber (E < 300 keV)



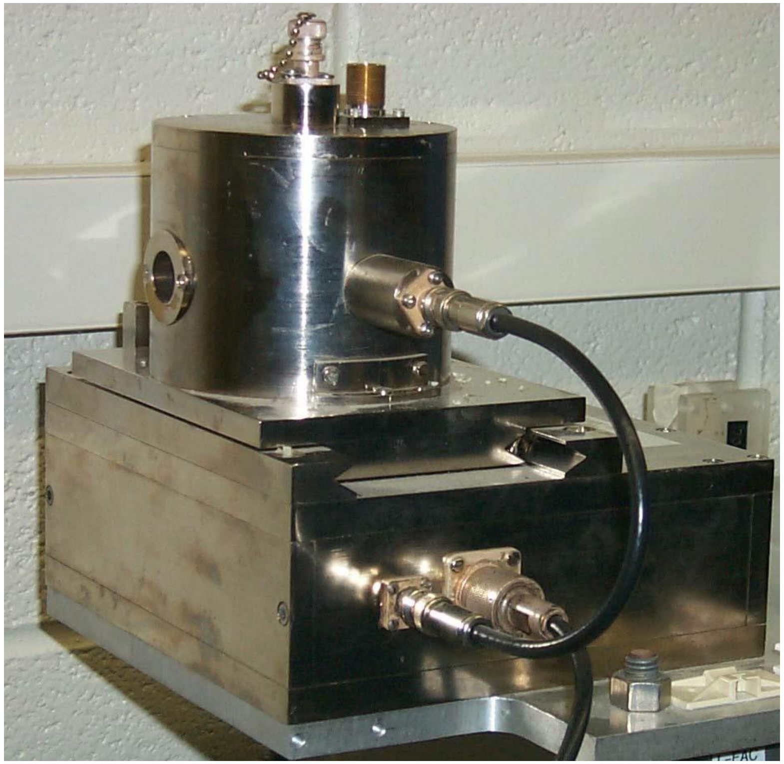
W anode
x-ray tube



Air Kerma

$$K_{\text{air}} = Q_{\text{air}} \left(\frac{\overline{W}_{\text{air}}}{e} \right) \frac{1}{\rho_{\text{air}} V} \prod_i k_i$$

NIST Free-Air Chambers

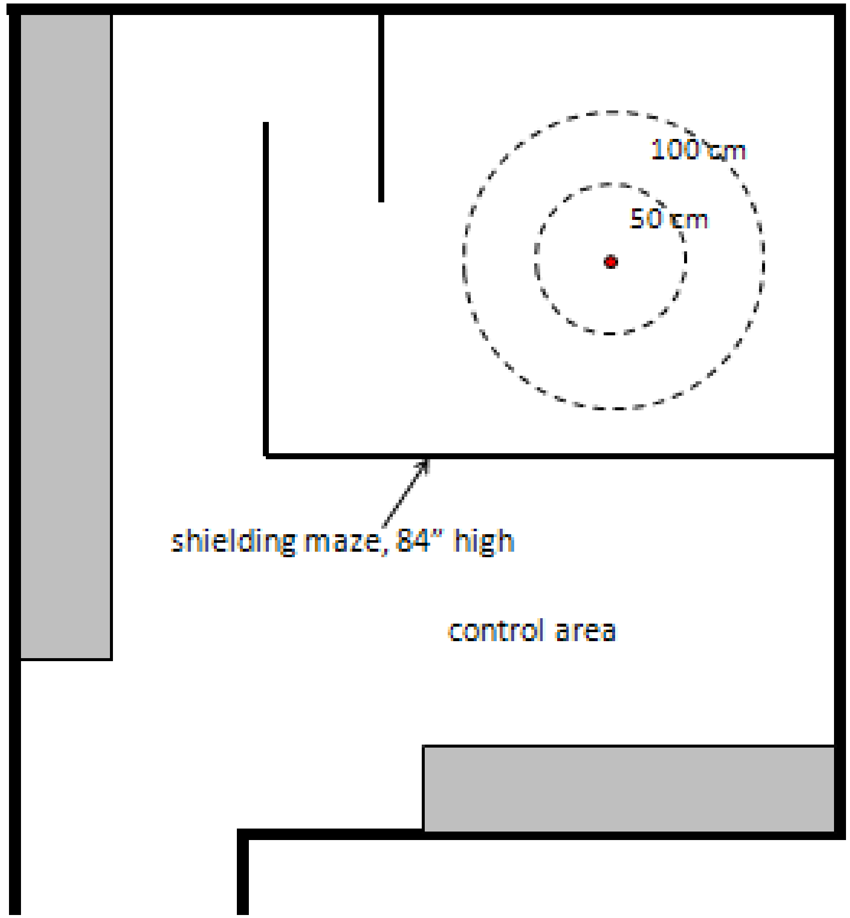


Lamperti

Ritz

Chamber	X-ray tube potential (kV)	Plate separation (mm)	Plate height (mm)	Collector length (mm)	Aperture diameter (mm)	Air absorption length (mm)	Electric field strength (V / cm)
Lamperti	10 to 60	40	50	10	5	39	750
Ritz	20 to 100	90	90	70	10	127	55

NIST Electronic Brachytherapy Calibration Facility, v. 1



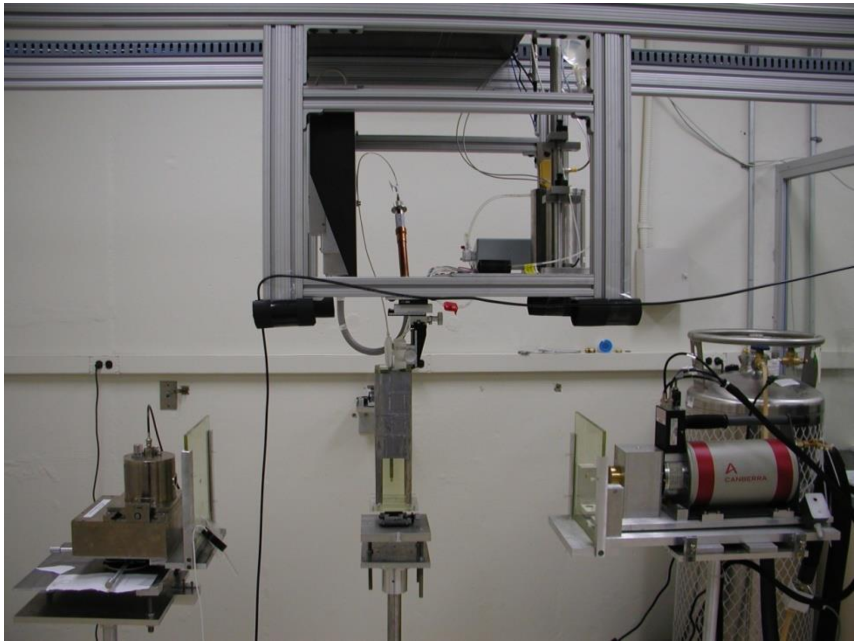
NIST Electronic Brachytherapy Calibration Facility, v. 1

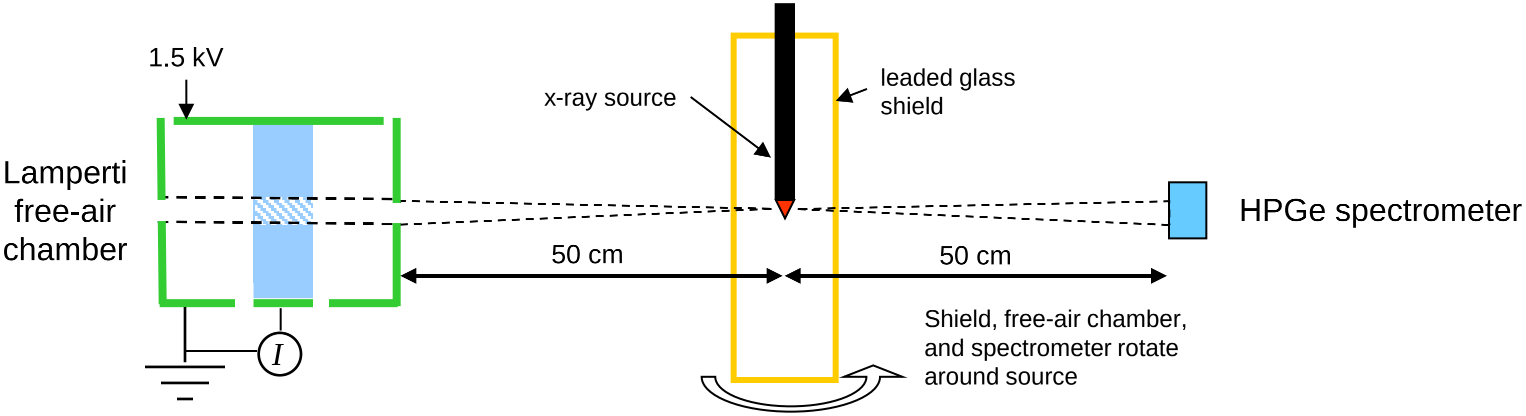
Maze entry (leaded glass)

Control area

NIST Electronic Brachytherapy Calibration Facility, v. 1

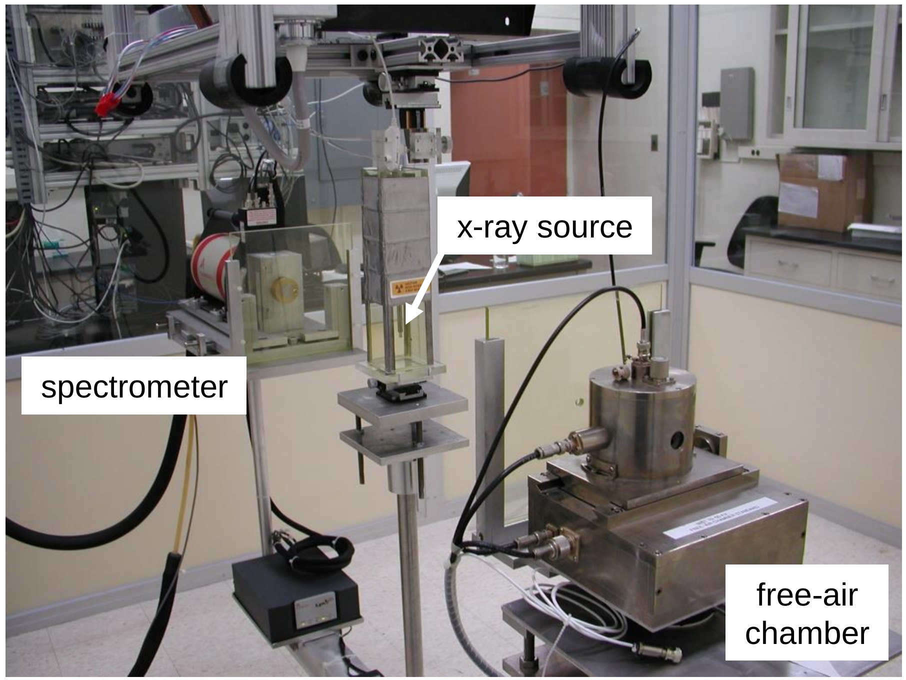
- The Xoft x-ray source can not be continuously rotated (like a brachytherapy seed)
- Lamperti free-air chamber and HPGe spectrometer **rotate around the source**





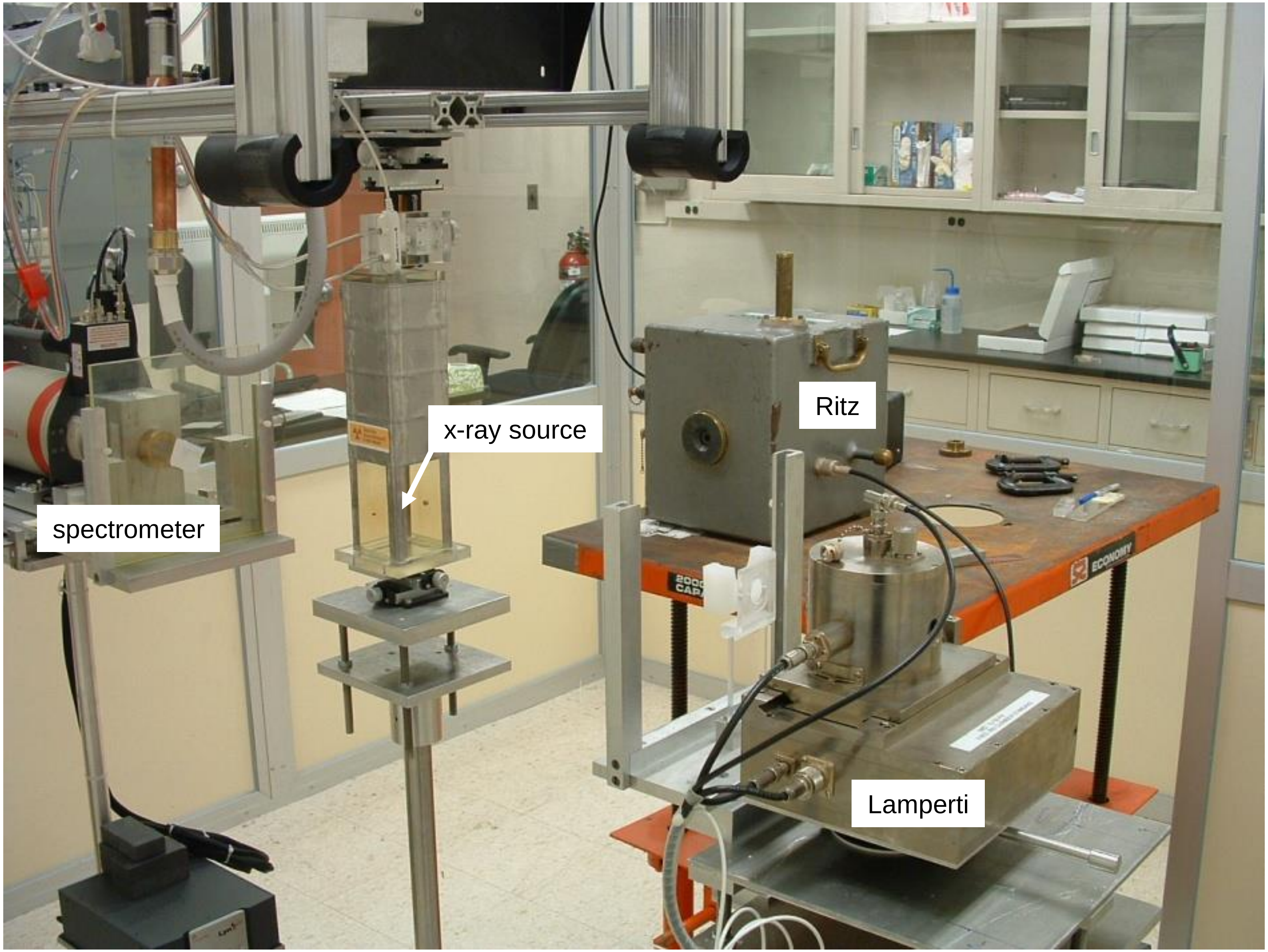
NIST Electronic Brachytherapy Calibration Facility, v. 1

source in
water cooling
catheter



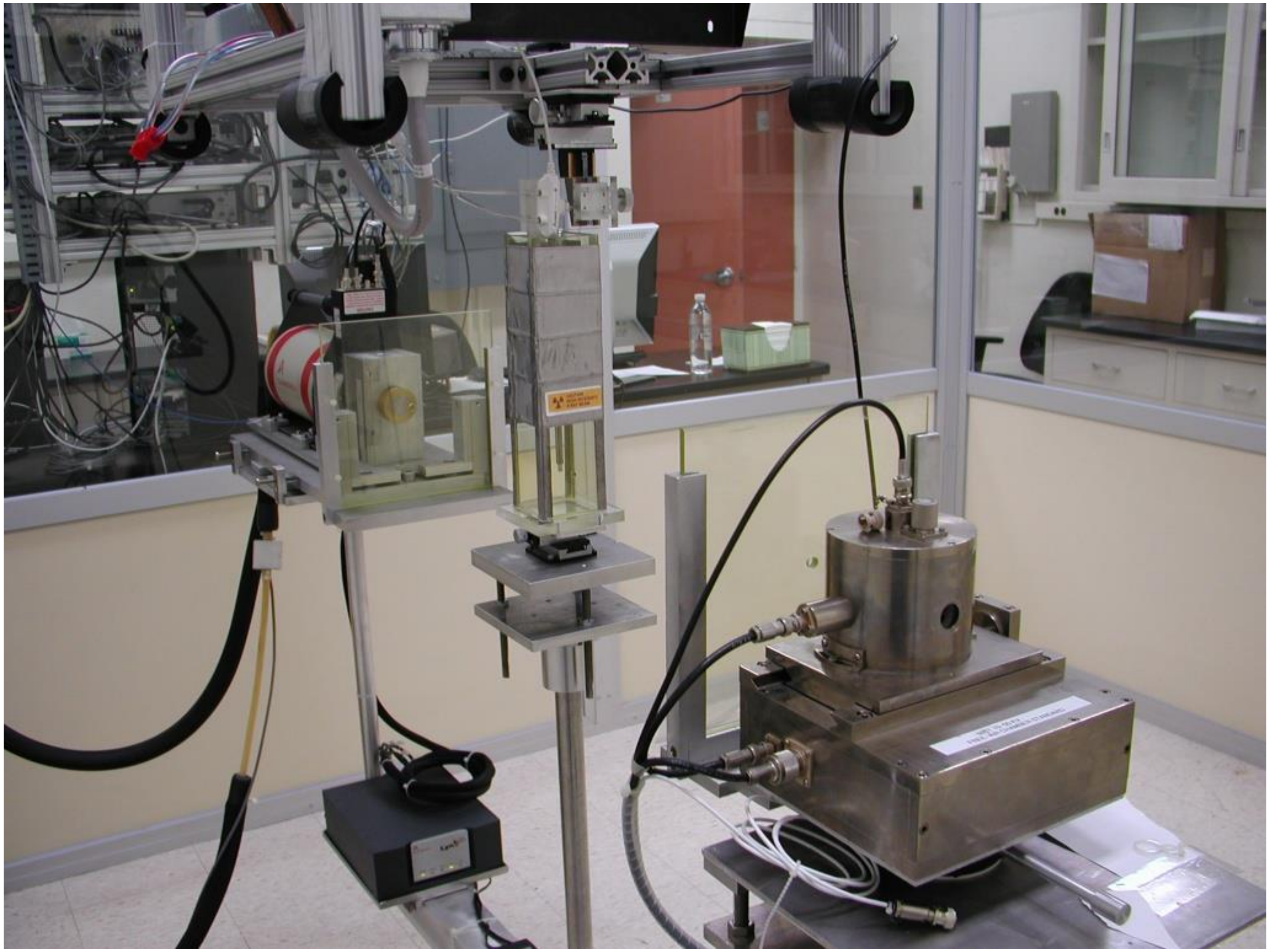
leaded glass
shield

Comparison of Lamperti and Ritz Free-Air Chambers



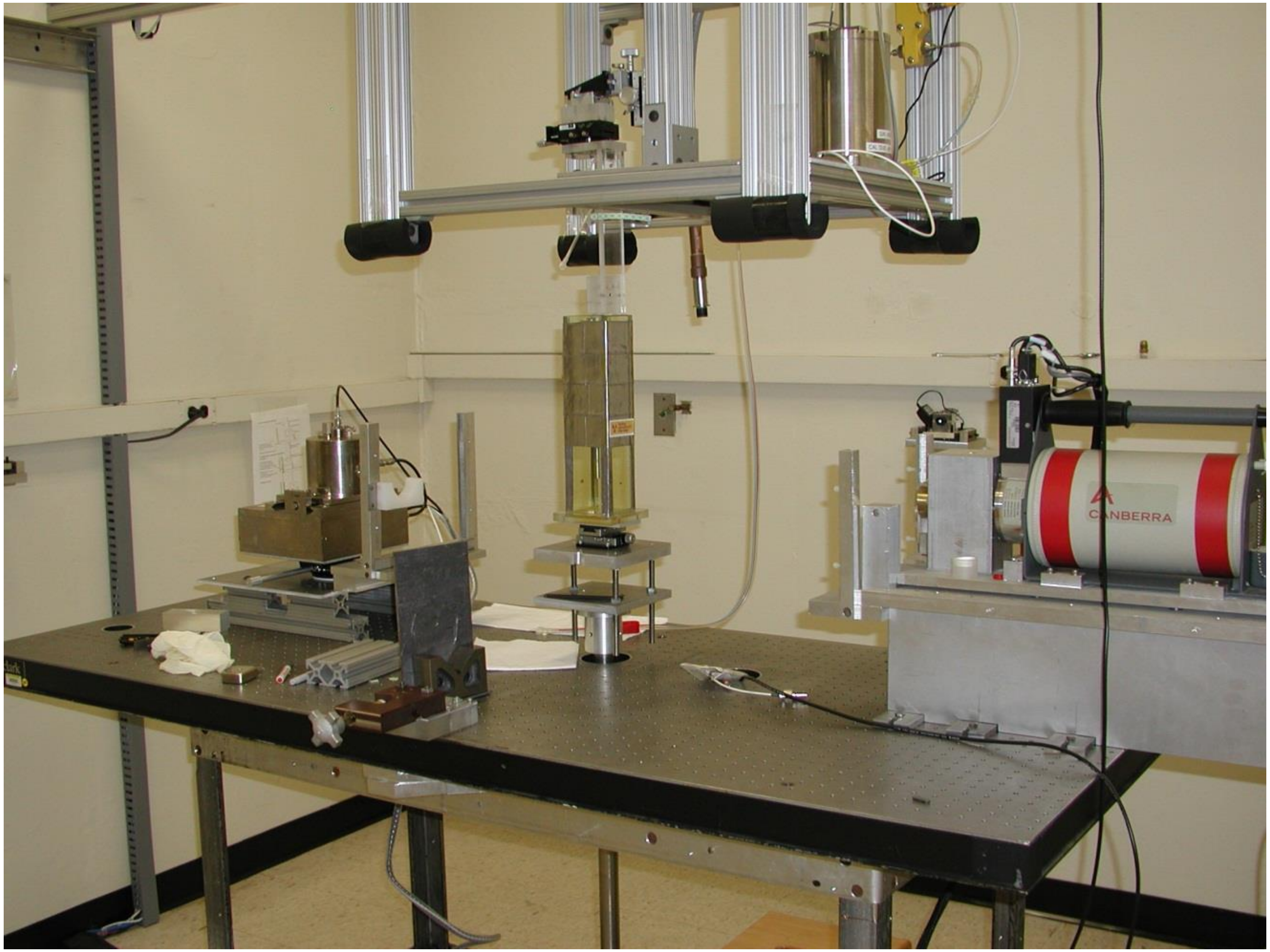
NIST Electronic Brachytherapy Calibration Facility, v. 1

PROBLEM – Alignment not reproducible



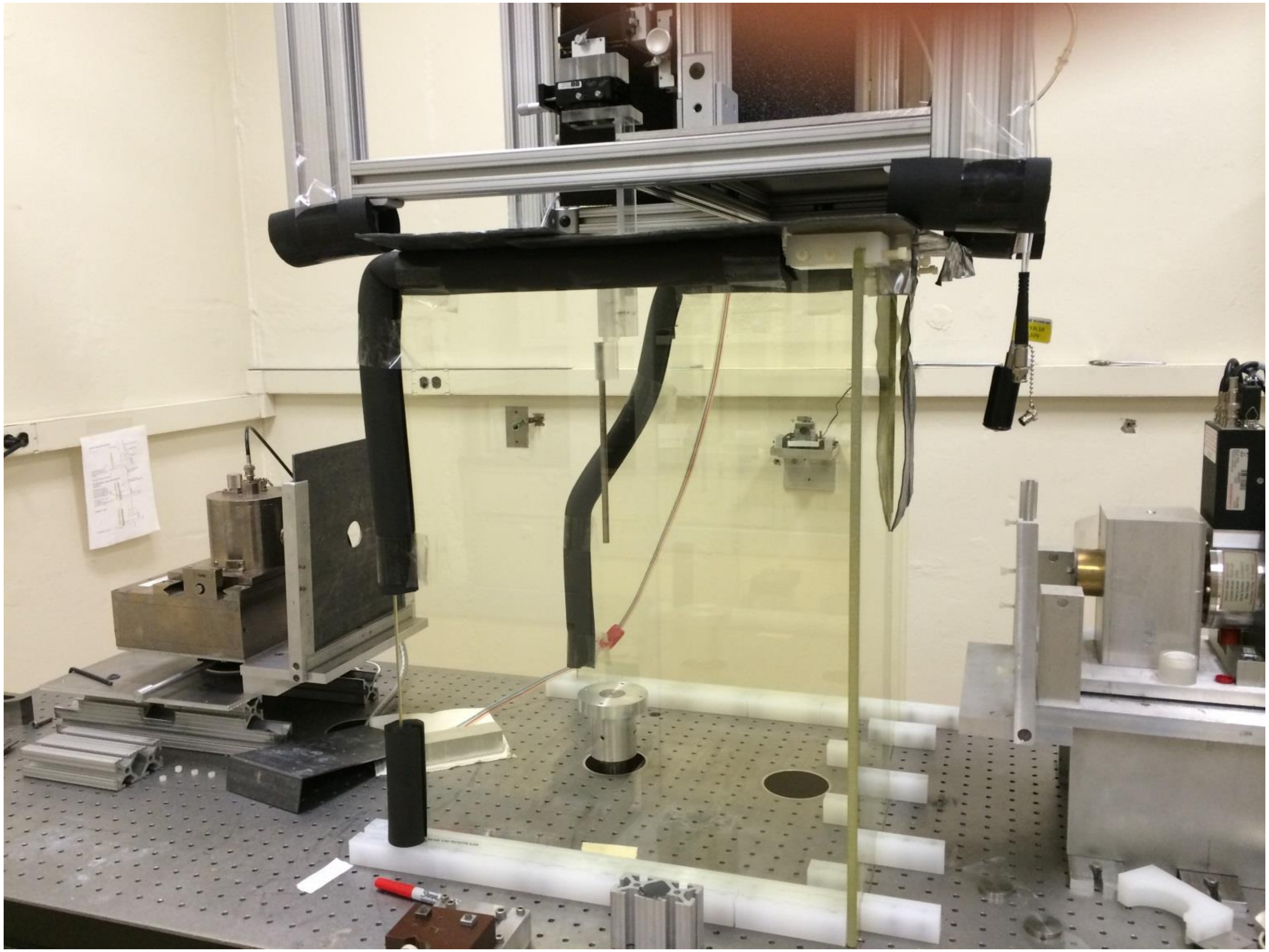
NIST Electronic Brachytherapy Calibration Facility, v. 2

SOLUTION – Optical table for rigid mounting of instruments

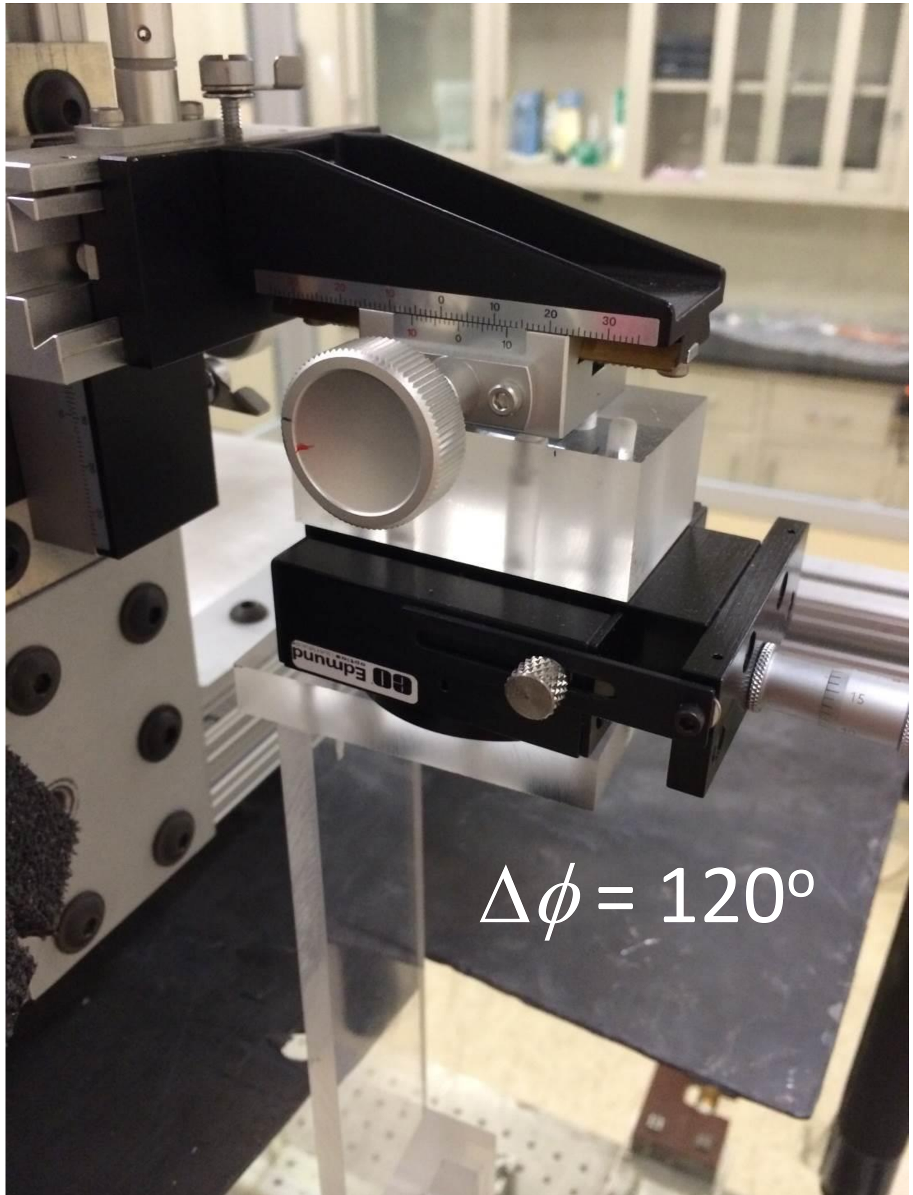


NIST Electronic Brachytherapy Calibration Facility, v. 2

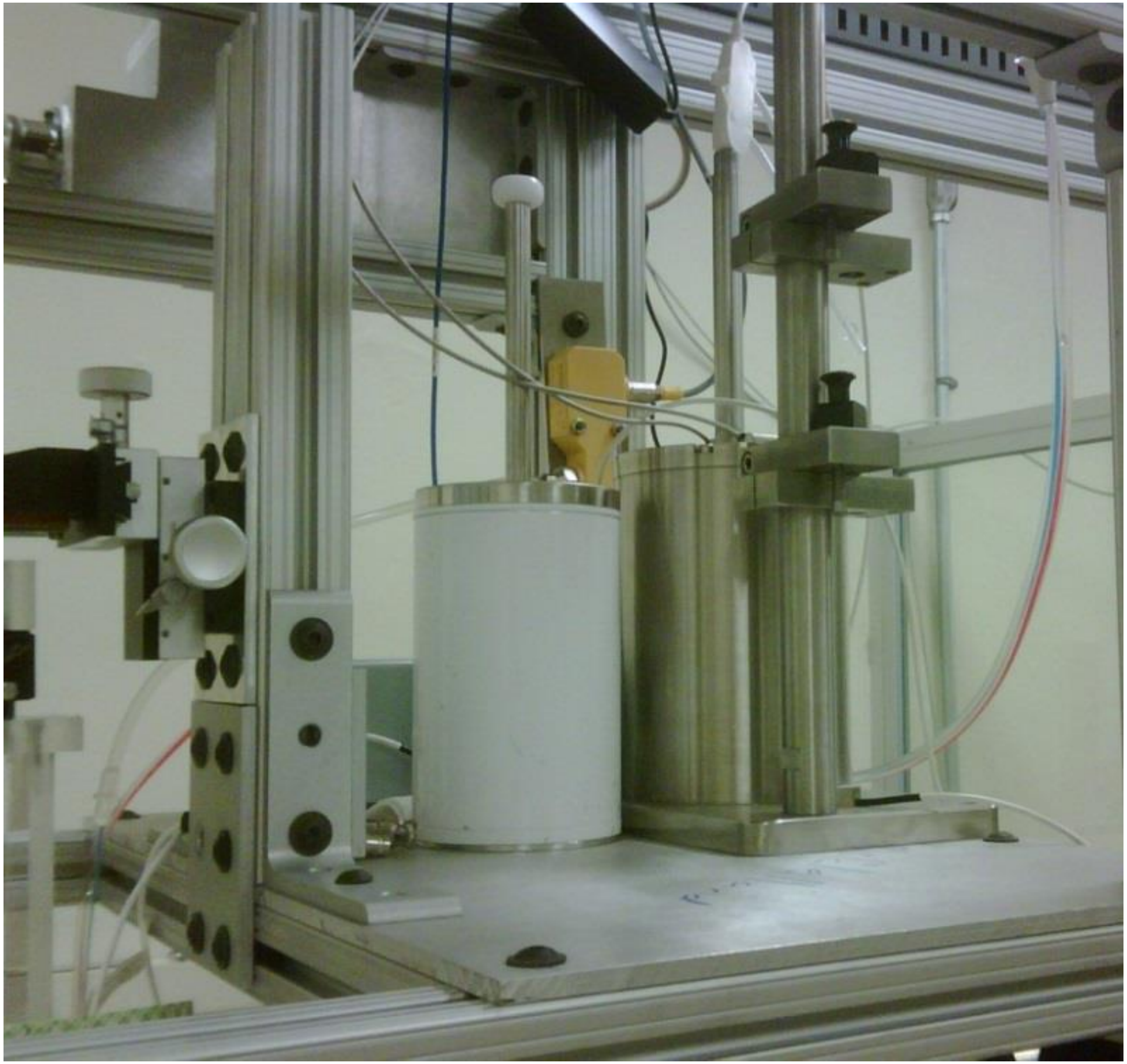
SOLUTION – Larger lead-glass surround



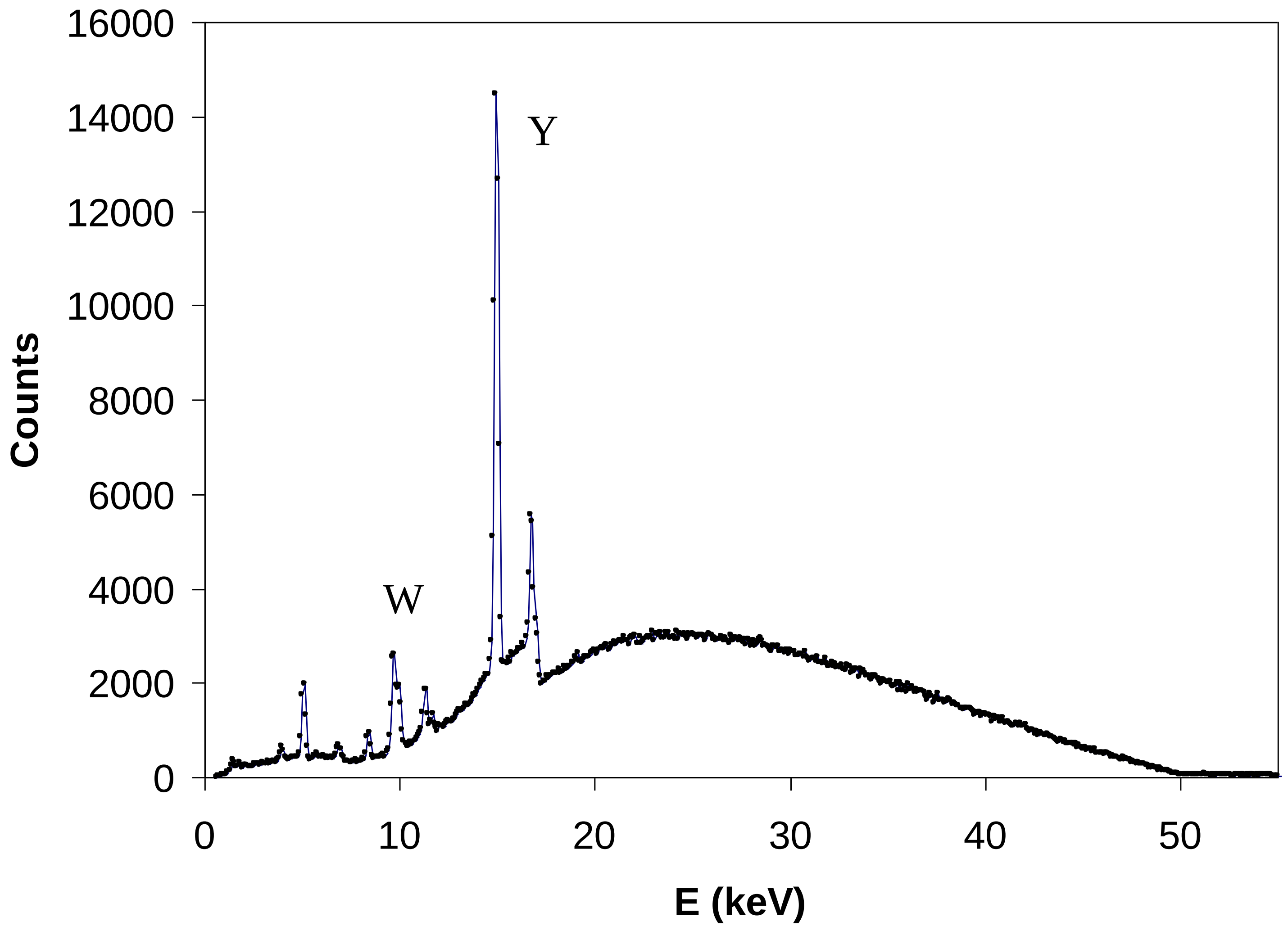
NIST Electronic Brachytherapy Calibration Facility, v. 2



NIST Electronic Brachytherapy Calibration Facility, v. 2



Pulse Height Distribution - Xoft Source at 50 kV



Fluorescence peaks at 14.9 keV and 16.7 keV are from Y

Peaks from 8 keV to 12 keV are from the W anode

Spectrometry of X-Ray Sources

For a photon detector, the measured pulse-height distribution, $H(h)$, is given by

$$H(h) = \int S(E)R(E,h)\,\mathrm{d}E$$

$S(E)$ is the incident photon spectrum

$R(E,h)$, the *response function*, is the probability per pulse height that a photon incident with energy E will produce a pulse of height h

Spectrometry of X-Ray Sources

The response function can be written

$$R(E,h) = T(E)\int D(E,\varepsilon)\, G(\varepsilon,h)\,\mathrm{d}\varepsilon$$

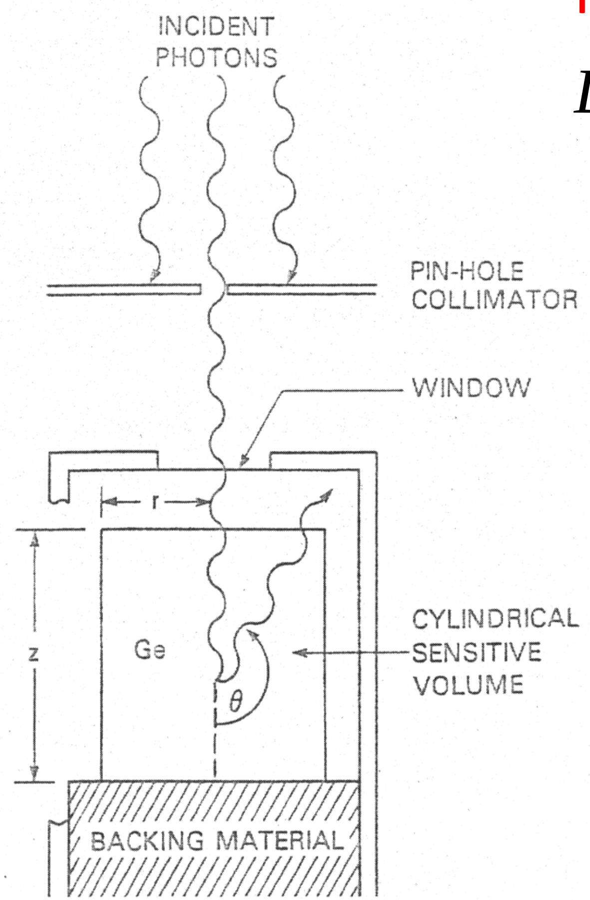
$T(E)$ is the *window-attenuation factor*

$D(E,\varepsilon)$, the *energy-deposition spectrum*, is the probability per deposited energy that a photon incident with energy E deposits an energy ε in the detector

$G(\varepsilon,h)$, the *intrinsic resolution function*, is the probability per pulse height that the deposition of energy ε will give rise to a pulse of height h

Spectrometry of X-Ray Sources

The *energy-deposition spectrum* $D(E,\varepsilon)$ depends on the detector dimensions: cylinder of radius *r* and height *z*



For E < 300 keV:

$$D(E,\varepsilon) = P_0(E,\varepsilon)\,\delta(\varepsilon - E)$$

Photopeak (complete absorption)

$$+ P_{x\alpha}(E,\varepsilon)\,\delta(\varepsilon - E + E_\alpha) + P_{x\beta}(E,\varepsilon)\,\delta(\varepsilon - E + E_\beta)$$

Ge K_α and K_β fluorescence x-ray escape

$$+ C(E,\varepsilon)$$

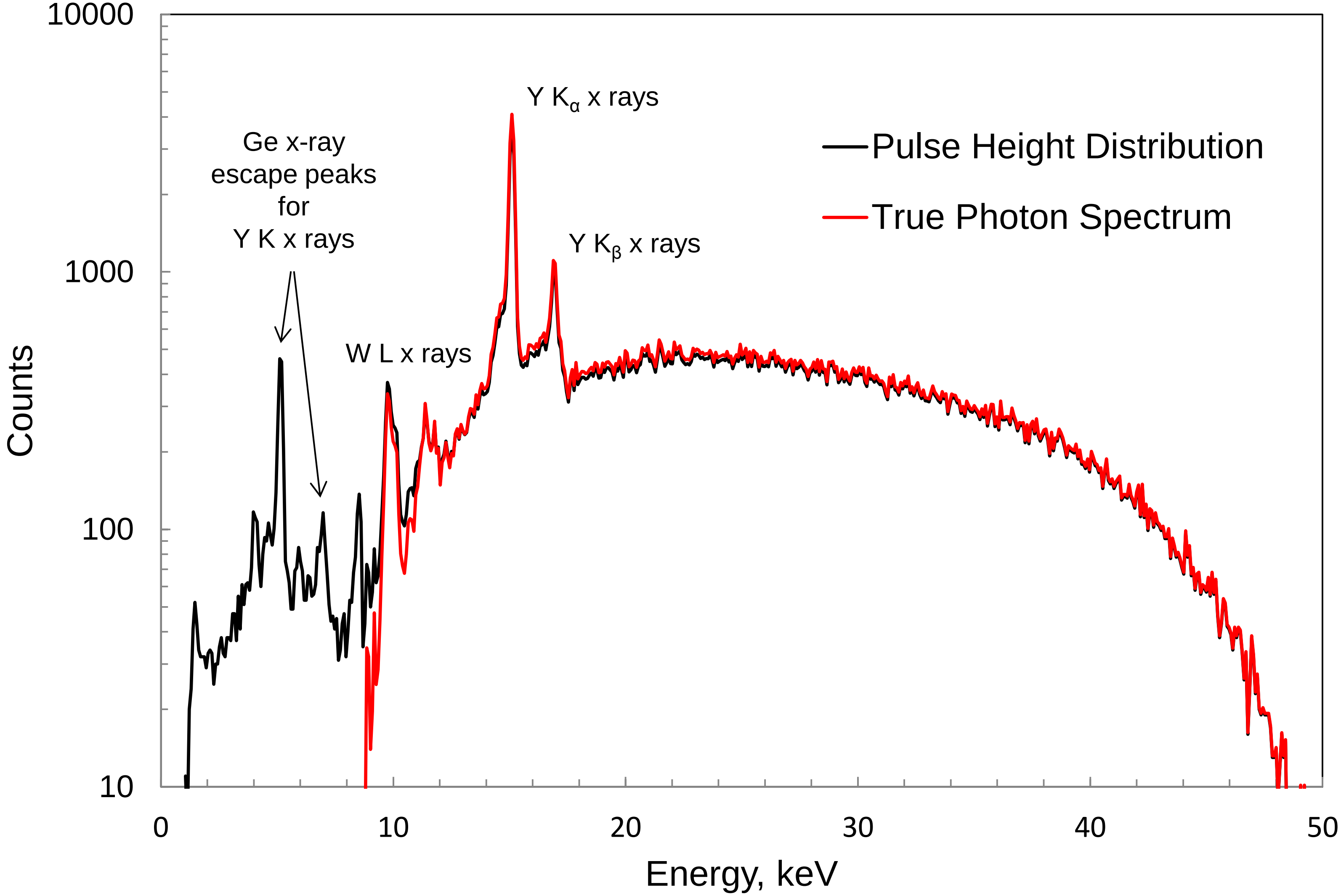
Compton continuum

Accurately calculated by Monte Carlo

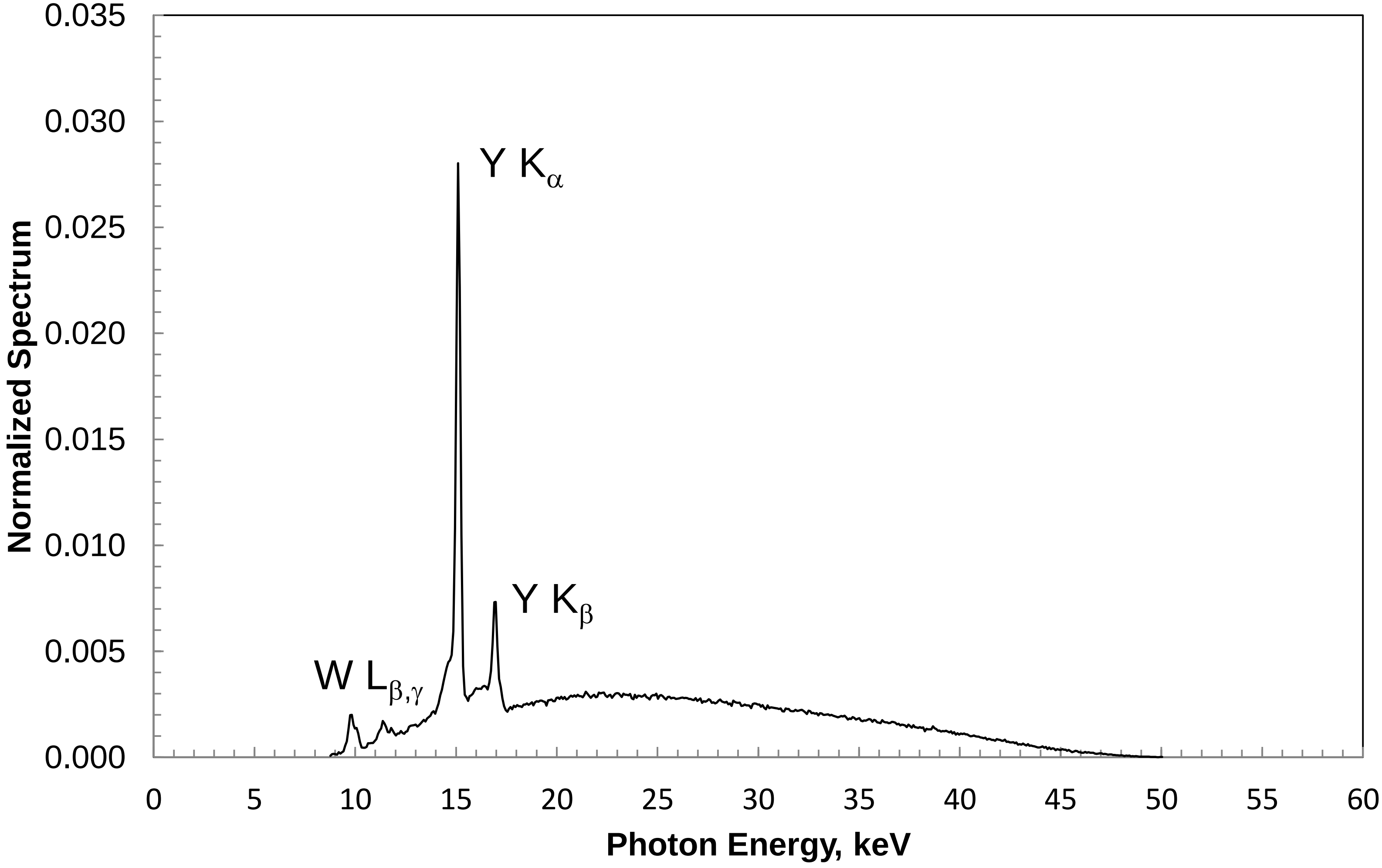
Seltzer, S.M., "Calculated response of intrinsic germanium detectors to narrow x-ray beams with energies up to 300 keV," *Nucl. Instr. Meth*. **188**, 133-151 (1981).

Unfolded Spectrum: Xoft source at 50 kV

$$\boxed{H(h)} = \int \boxed{S(E)} R(E,h)\,\mathrm{d}E$$



Spectrum of Xoft Source at 50 kV



Free-Air Chamber Correction Factors for Xoft Source at 50 kV

$$\dot{K}_{\text{air}} = I_{\text{air}} \left(\frac{\overline{W}_{\text{air}}}{e} \right) \frac{1}{\rho_{\text{air}} V} \prod_i k_i$$

Air-kerma rate at 50 cm

Factor	For:	Lamperti	Ritz
1 k_{ion}	ion recombination	≈1.0000	≈1.0000
2 $k_{humidity}$	humidity of air	0.998	0.998
3 k_{att}	attenuation	1.0087	1.0283
4 k_{el}	electron loss	1.0008	1.0000
5 k_{sc}	photon scatter	0.9987	0.9970
6 k_{fl}	fluorescence reabsorption	0.9979	0.9969
7 $k_{br}/(1\text{-}g)$	effects of bremsstrahlung	1.0	1.0
8 k_{ii}	initial ion	1.0	1.0
9 k_{dia}	diaphragm scatter	1.0	1.0
Π $k_{1\text{-}9}$		**1.0041**	**1.0200**

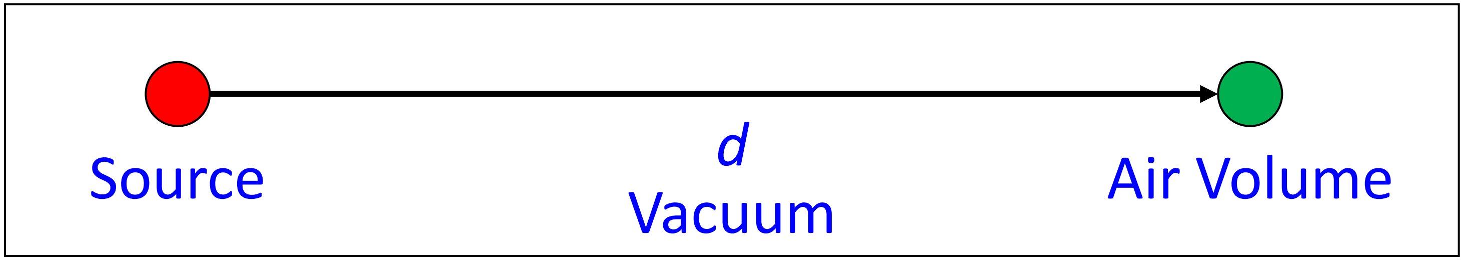
Uncertainty Budget for Xoft Source at 50 kV

Component	For:	Relative standard uncertainty, %	
		Type A	Type B
Q_{net}, I_{net}	net charge or current	s_Q[a], s_I[a]	0.06
	typical value	0.14[b]	
W/e	mean energy per ion pair	-	0.15
ρ_0	air density	0.01	0.07
V_{eff}	effective volume	0.04	0.01
k_{ion}	ion recombination	0.03	
$k_{humidity}$	humidity of air		0.04
k_{att}	attenuation	-	0.11
k_{el}	electron loss	-	0.06
k_{sc}	photon scatter	-	0.03
k_{fl}	fluorescence reabsorption	-	0.05
$k_{br}/(1-g)$	effects of bremsstrahlung	-	0.02
k_{ii}	initial ion	-	0.04
k_{dia}	diaphragm scatter	-	0.10
k_d	electric field distortion	-	0.20
	polarity difference	0.02	
Combined	**air kerma**	**0.15**	**0.321**

$U = 0.71\ \%$ $(k = 2)$

[a] Determined as the standard deviation of the mean of the measurement.
[b] Typical value for sources measured in 2013/2014

Air-Kerma Rate vs. Air-Kerma Strength

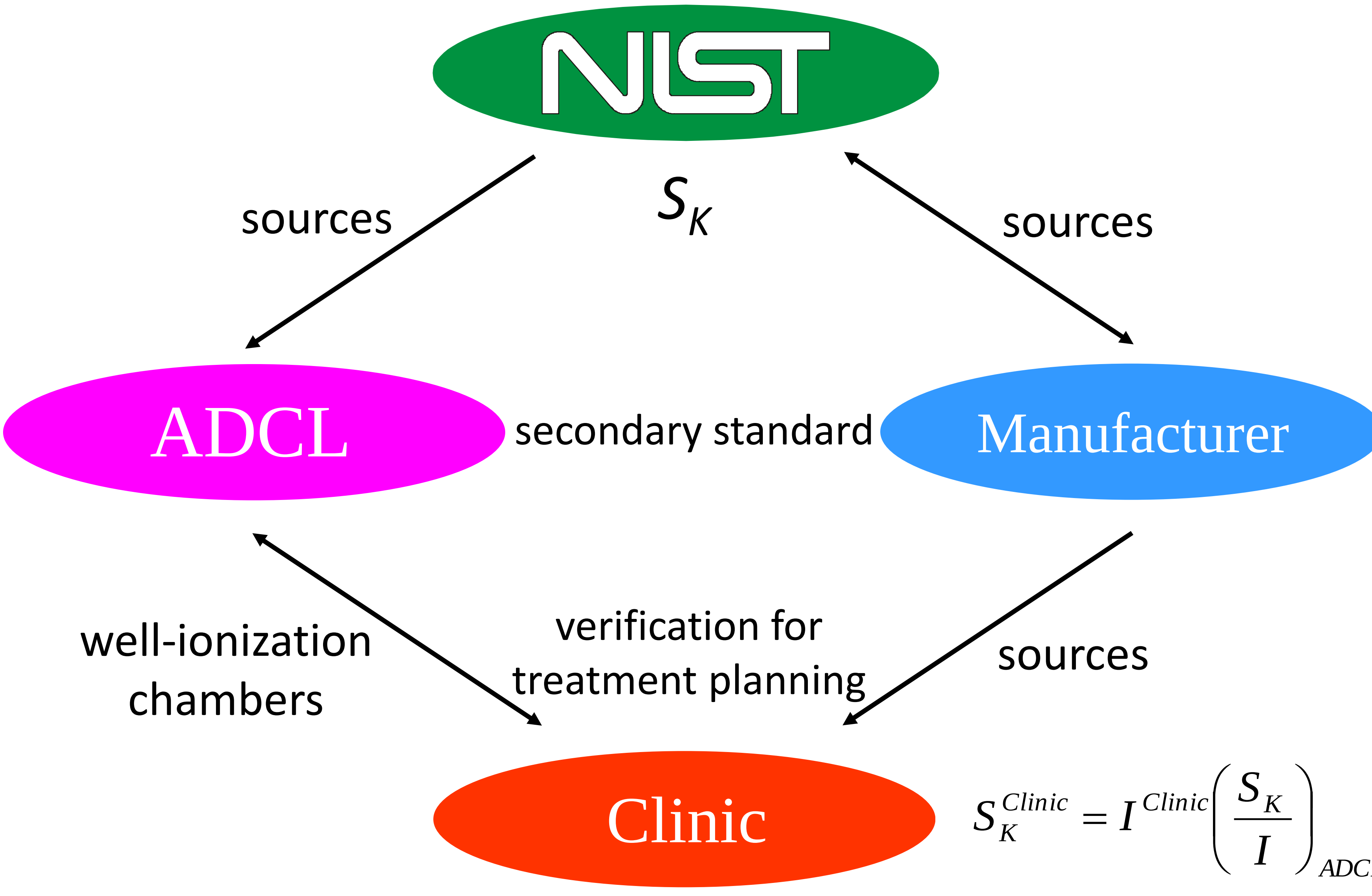


$$S_K = \dot{K}_{\text{air}}(d) \cdot d^2 = I_{\text{air}} \left(\frac{\overline{W}_{\text{air}}}{e} \right) \frac{1}{\rho_{\text{air}} V} \prod_i k_i \cdot d^2$$

Air-kerma strength

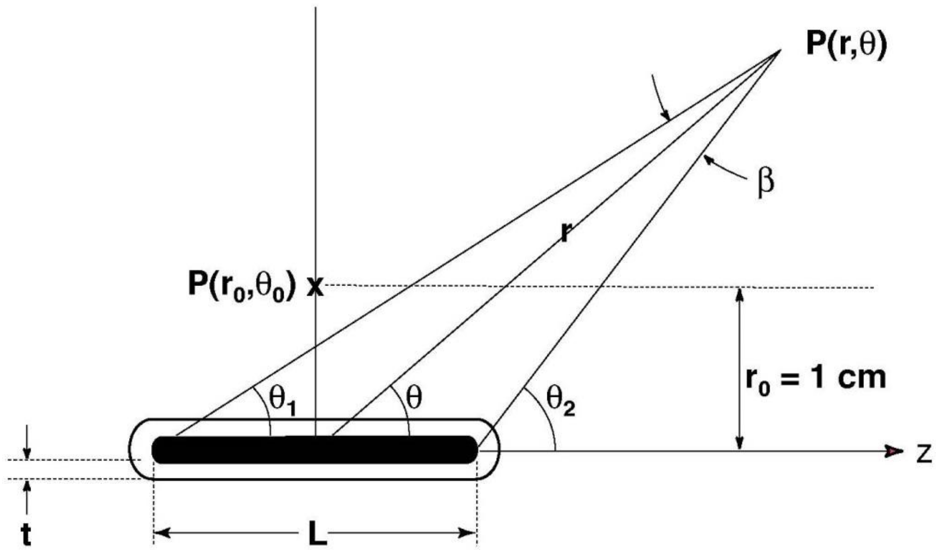
Factor		Lamperti
$\Pi\ k_{1\text{-}9}$		1.0041
K_{vac}/K_{air}	conversion to air-kerma strength	**1.12**

Measurement Traceability for Brachytherapy Sources



$$S_K^{Clinic} = I^{Clinic}\left(\frac{S_K}{I}\right)_{ADCL}$$

AAPM TG-43 Formalism for Brachytherapy Dose Calculations



Dose rate in water

$$\dot{D}(r,\theta) = S_K \cdot \Lambda \cdot \frac{G_L(r,\theta)}{G_L(r_0,\theta_0)} \cdot g_L(r) \cdot F(r,\theta)$$

Geometry Function

$$G_L(r,\theta) = \frac{\beta}{Lr\sin\theta} \qquad G_L(r,0) = (r^2 - L^2/4)^{-1}$$

Dose Rate Constant (NIST-traceable S_K)

$$\Lambda = \frac{\dot{D}(r_0,\theta_0)}{S_K}$$

r_0 = 1 cm

$\theta_0 = \pi / 2$

Radial Dose Function

$$g_X(r) = \frac{\dot{D}(r,\theta_0)}{\dot{D}(r_0,\theta_0)} \frac{G_X(r_0,\theta_0)}{G_X(r,\theta_0)}$$

2D Anisotropy Function

$$F(r,\theta) = \frac{\dot{D}(r,\theta)}{\dot{D}(r,\theta_0)} \frac{G_L(r,\theta_0)}{G_L(r,\theta)}$$

Modified Formalism for Electronic Brachytherapy Sources

Dose-rate conversion coefficient χ

DeWerd, Culberson, Micka, and Simiele, *Brachytherapy* (2015)

- TG-43 point-source approximation
- 2D Anisotropy Function applicable due to polar anisotropy
- *i* subscript denotes applicator

Dose rate in water

$$\dot{D}_i(r,\theta) = \dot{K}_{50cm} \cdot \chi_i(r_0,\theta_0) \cdot G_P(r,\theta) \cdot g_i(r) \cdot F_i(r,\theta)$$

Geometry Function

$$G_P(r,\theta) = \frac{1}{r^2}$$

Dose Rate Conversion Coefficient
(NIST-traceable $\dot{K}_{50cm}$)

$$\chi_i = \frac{\dot{D}_i(r_0,\theta_0)}{\dot{K}_{50cm}}$$

r_0 = 1 cm
$\theta_0 = \pi / 2$

Radial Dose Function

$$g_i(r) = \frac{\dot{D}_i(r,\theta_0)}{\dot{D}_i(r_0,\theta_0)} \frac{G_P(r_0,\theta_0)}{G_P(r,\theta_0)}$$

2D Anisotropy Function

$$F_i(r,\theta) = \frac{\dot{D}_i(r,\theta)}{\dot{D}_i(r,\theta_0)}$$

AAPM Dosimetric Prerequisites

LDR Brachytherapy

- Air-kerma strength calibrations traceable to NIST

- TG-43 parameters published (experimental and Monte Carlo)

- NIST standard transferred to the ADCLs

- Annual comparisons between NIST and ADCLs

AAPM Dosimetric Prerequisites

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Electronic Brachytherapy

- AAPM Task Group proposed

Summary

- NIST air-kerma standard for electronic brachytherapy realized
- Standard transferred to AAPM ADCL using a well chamber
- Proficiency test with AAPM ADCL completed
- New calibration service pending: "Well Ionization Chamber Calibration with Electronic Brachytherapy Sources"
- Clinical implementation of new standard in progress

Acknowledgements

- Xoft, Inc. – funding for the development of the NIST electronic brachytherapy facility; sources and associated equipment
- Mel McClelland and Dave Eardley – design, fabrication, and installation of mechanical, electrical, and electronic systems
- Ron Tosh – computer control code
- Jason Walia – spectrometer calibration