New NIST Standards for Electronic Brachytherapy

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Dosimetry Group

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Physical Measurement Laboratory

National Institute of Standards and Technology

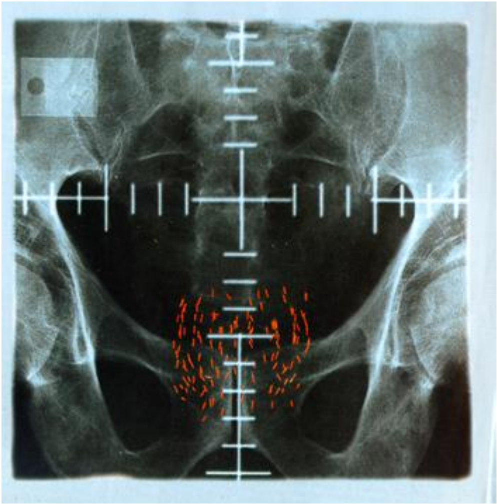
Disclaimers

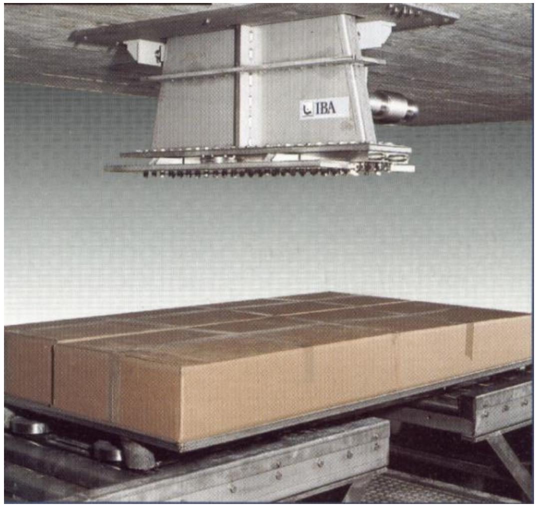
Certain commercial equipment, manufacturers, instruments, or materials are identified in this presentation in order to specify the experimental procedure adequately. Such identification is for informational purposes only and is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the manufacturer, materials, or equipment are necessarily the best available for the purpose.

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

Dosimetry Group Strategic Element

Develop dosimetric standards for x rays, gamma rays, and electrons based on the SI unit, the gray, for homeland security, medical, radiation processing, and radiation protection applications.



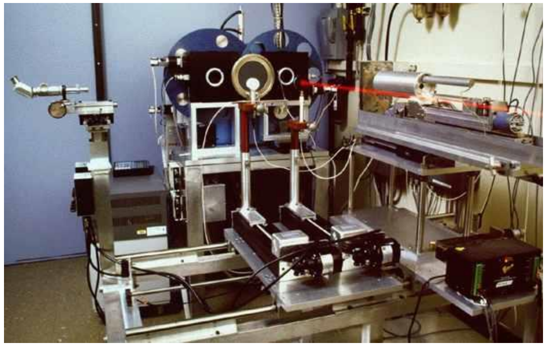


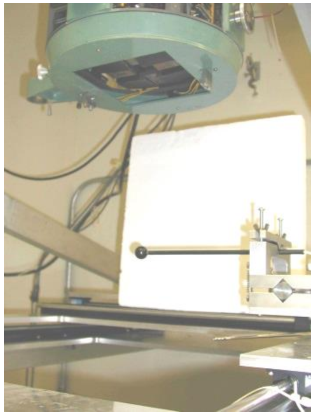
Dosimetry Group Strategic Element

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

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

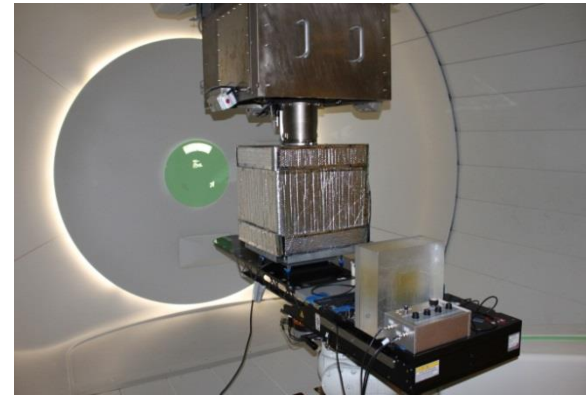
kV x rays	MV x rays	gamma rays	electrons
x-ray tube	linac	irradiator	linac, Van de Graaff
radioactive source		(^{60}Co, ^{137}Cs)	radioactive source





Radiation Therapy

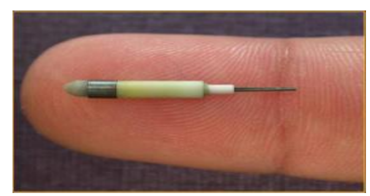
Use of ionizing radiation
to treat cancer

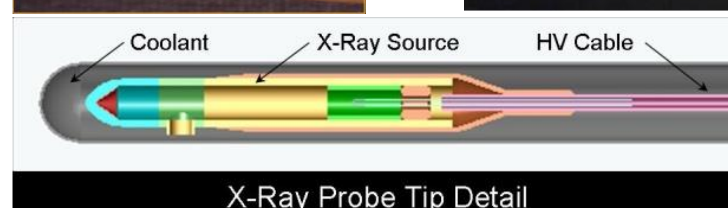


- External beam (MV x rays, electrons, protons)
- Internal administration of radionuclides (in solution)
- Brachytherapy (radiation source placed near or inside a tumor)

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

  High-Dose-Rate (HDR) Brachytherapy (^{192}Ir, miniature x-ray source)





X-Ray Probe Tip Detail

Radiation Therapy

Use of ionizing radiation
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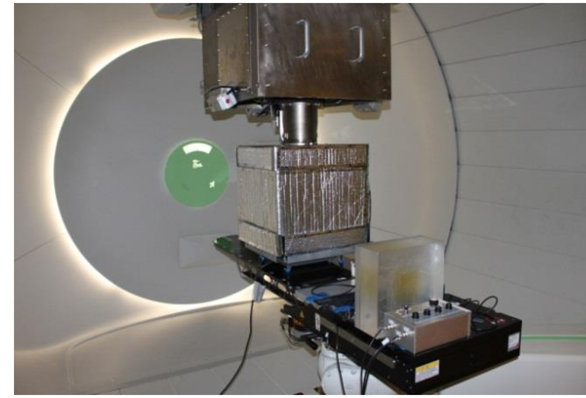

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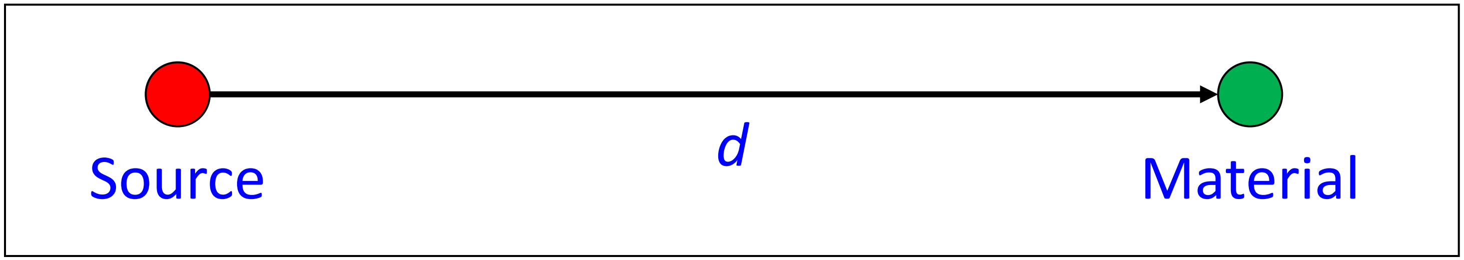
  High-Dose-Rate (HDR) Brachytherapy (^{192}Ir, miniature x-ray source)

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

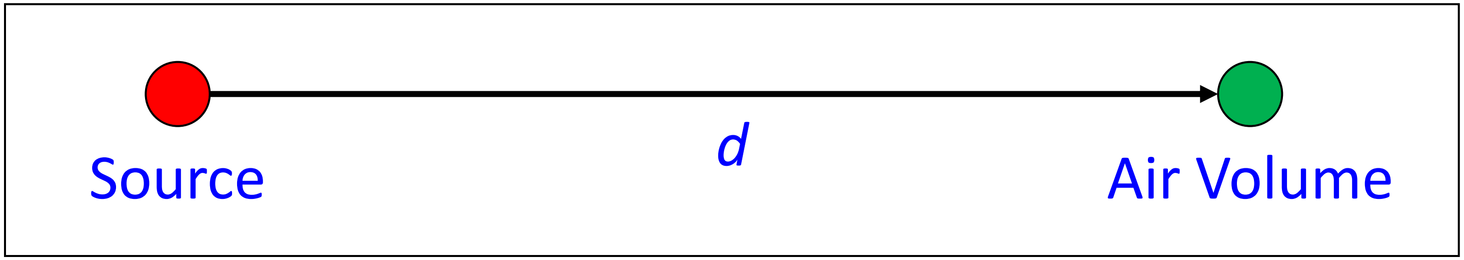
http://www.nist.gov/pml/data/photon_cs/index.cfm

estar

stopping-power
and range tables
for electrons

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

Dosimetry of X Rays (E < 300 keV)



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

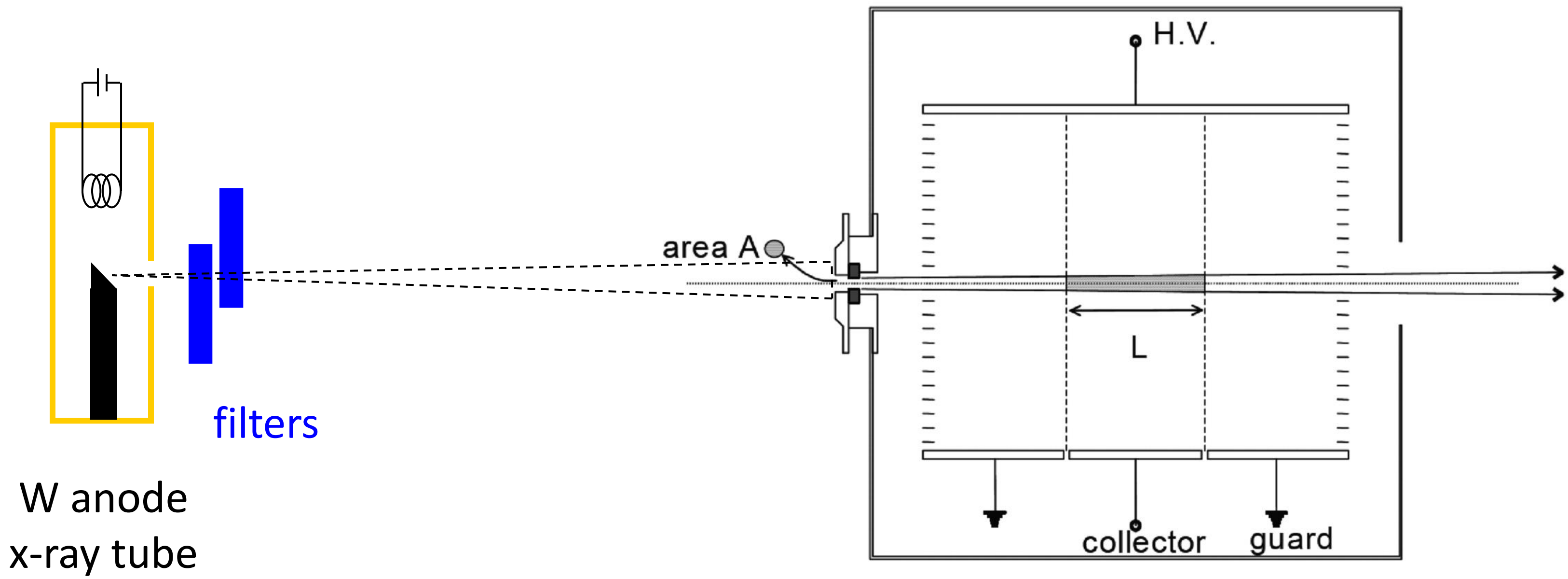
KERMA = Kinetic Energy Released per unit MAss

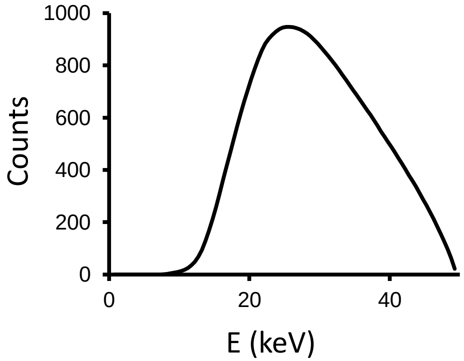
Secondary electrons ⟶ liberated charge in a given mass of air

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

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

Free-Air Ionization Chamber (E < 300 keV)

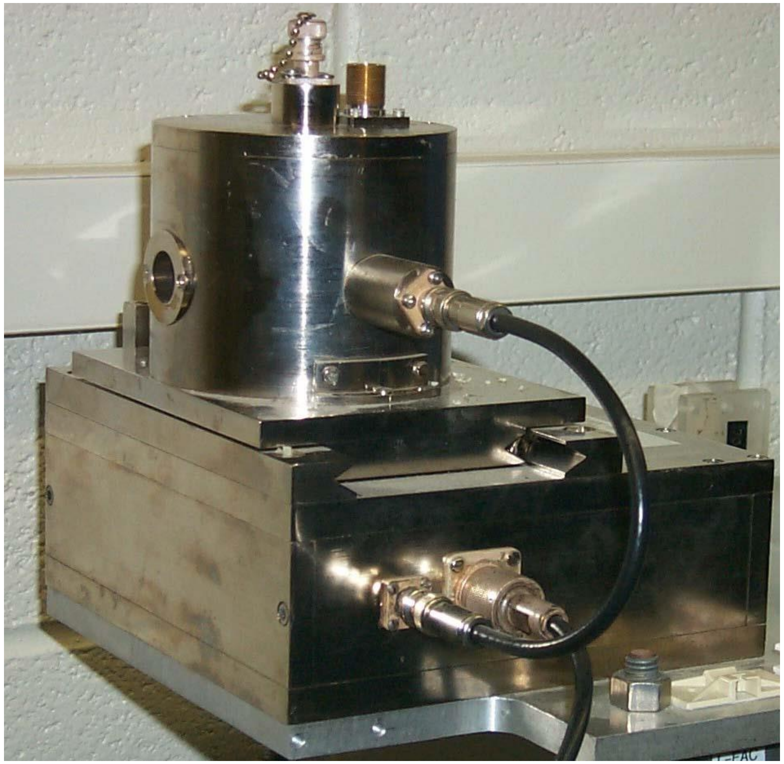




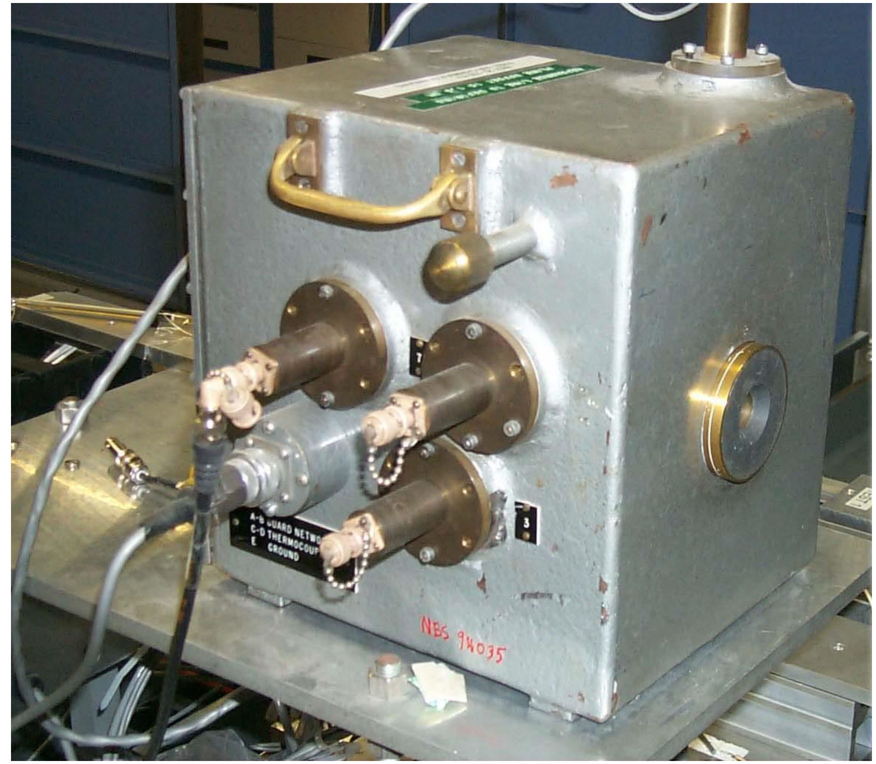
Air Kerma

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

NIST Free-Air Chambers (FACs)



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	10.146	4.994	39.02	750
Ritz	20 to 100	90	90	70.03	10.00	127.39	55

Air-Kerma Rate as Realized by Free-Air Chambers

$$\dot{K}_{\text{air}} = \frac{I}{\rho_{\text{air}} V} \frac{\overline{W}_{\text{air}}}{e} \frac{1}{1 - g_{\text{air}}} \prod_i k_i$$

$\dot{K}_{\text{air}}$ is the air-kerma rate at a given distance in air.

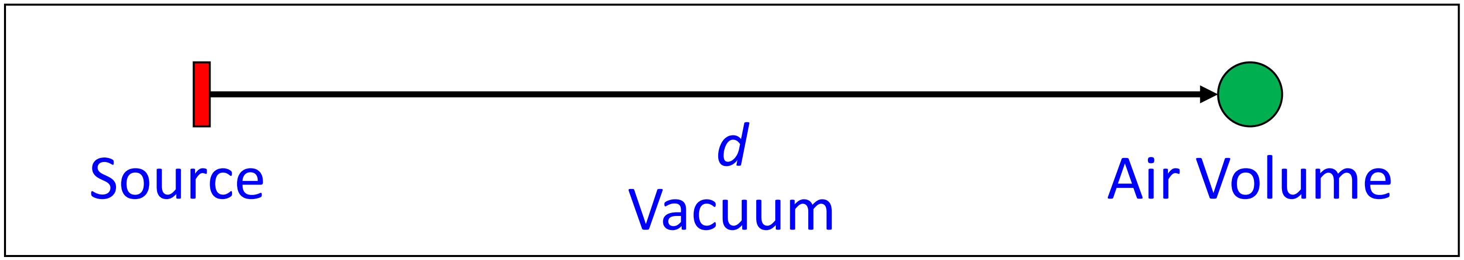
$I/(\rho_{\text{air}}V)$ is the measured ionization current divided by the mass of air in the measuring volume.

$\overline{W}_{\text{air}}$ is the mean energy expended by an electron of charge *e* to produce an ion pair in dry air. The value used at NIST is $\overline{W}_{\text{air}}/e = 33.97$ J/C.

g_{air} is the fraction of the initial kinetic energy of secondary electrons dissipated in air through radiative processes, which is 0.0 (negligible) for x rays with energies less than 300 keV.

$\Pi\, k_i$ is the product of various correction factors.

Dosimetry of X-Ray-Emitting Brachytherapy Seeds

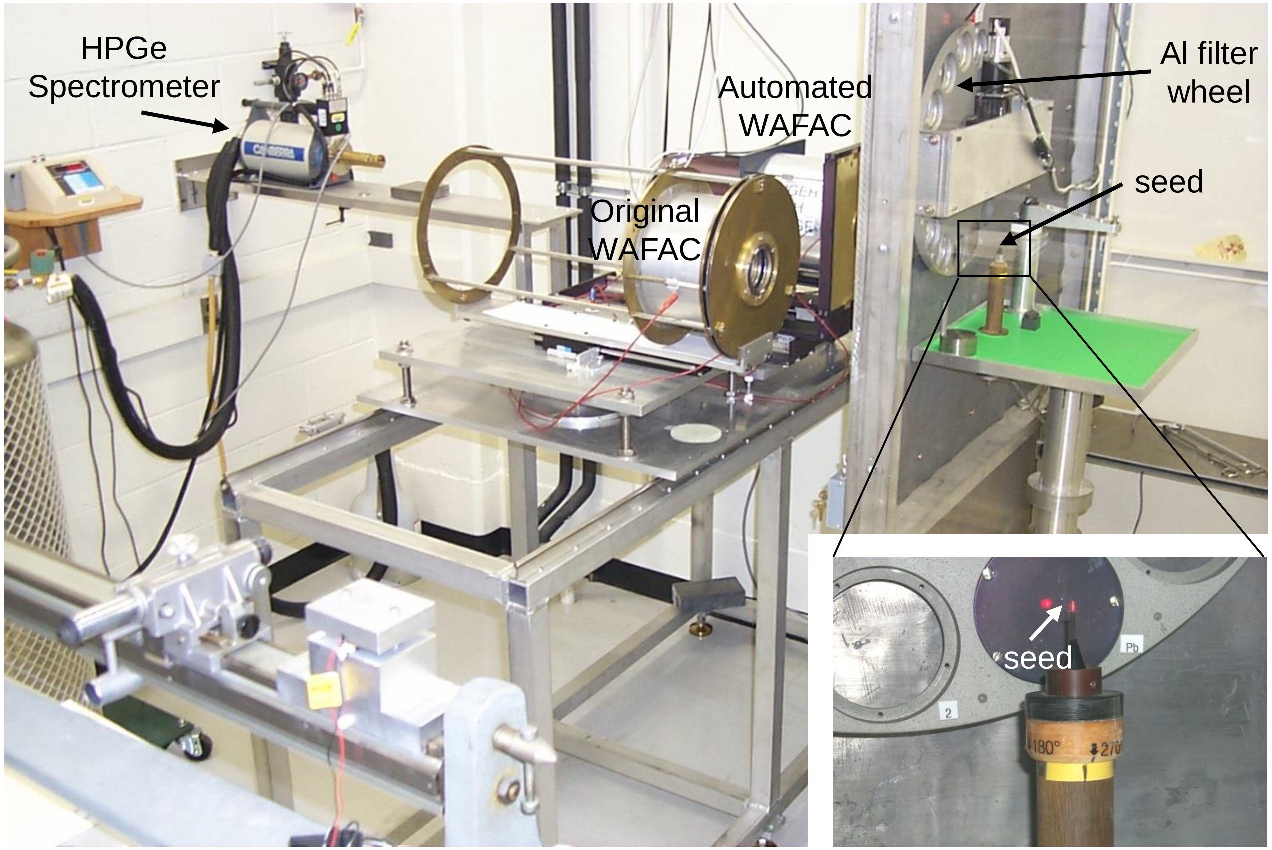


Air-kerma Strength

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

$$1\text{U} = \frac{1\,\mu\text{Gy} \cdot \text{m}^2}{\text{h}}$$

NIST Wide-Angle Free-Air Chamber (WAFAC)

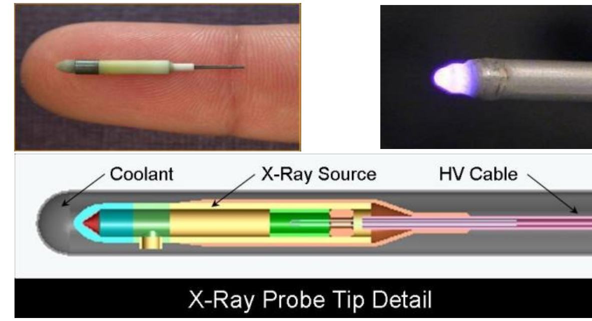


The WAFAC is the primary standard used to realize air-kerma strength of low-energy, low-dose-rate brachytherapy seeds. A seed is mounted vertically and rotated at 1 rpm during measurement to average over angular anisotropy in seed emissions. A high-purity germanium (HPGe) spectrometer is used to measure the seed spectrum.

Purpose

Design and construct a calibration facility for electronic brachytherapy

Establish a primary air-kerma standard for the Xoft miniature x-ray source



Why NIST?

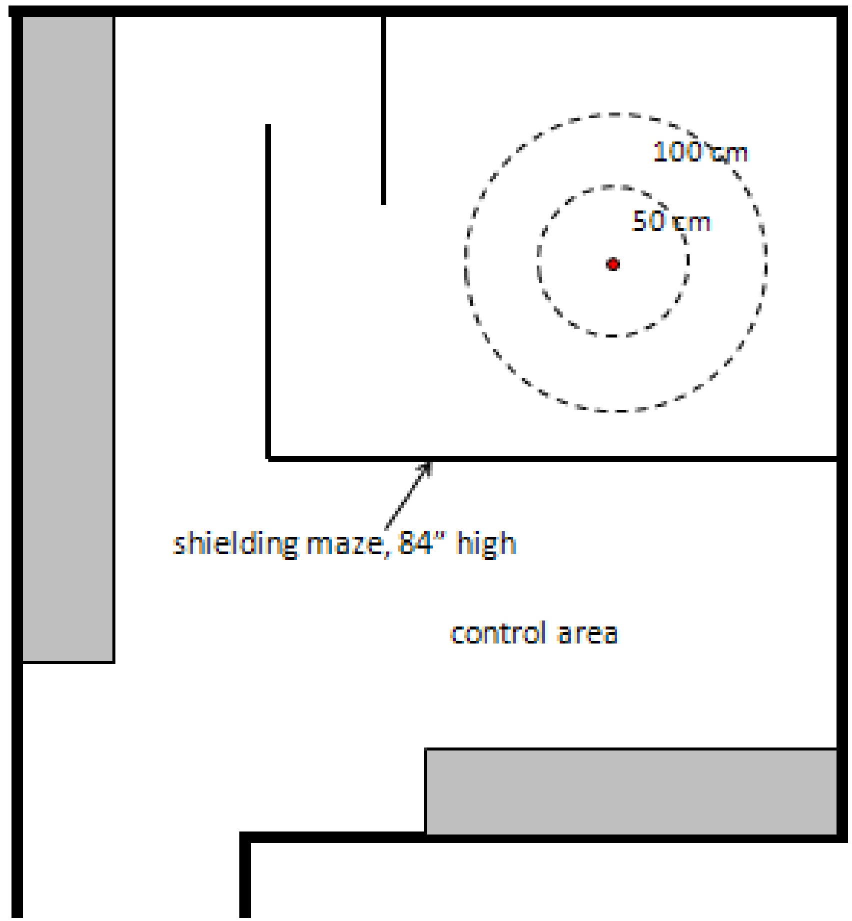
NIST provides the nation's measurement standards and has done so for conventional x-ray beams for more than 50 years

Two x-ray primary standards can be applied to the Xoft source at 50 kV:
Lamperti free-air chamber (10 kV to 60 kV)
Ritz free-air chamber (20 kV to 100 kV)

Primary calibration of the Xoft miniature x-ray source requires development of a specialized measurement apparatus, including a free-air chamber and x-ray spectrometer

X-ray spectrum can be measured in real time on the transverse axis of the source - used in the calculation of free-air-chamber correction factors

NIST Electronic Brachytherapy Calibration Facility, v. 1



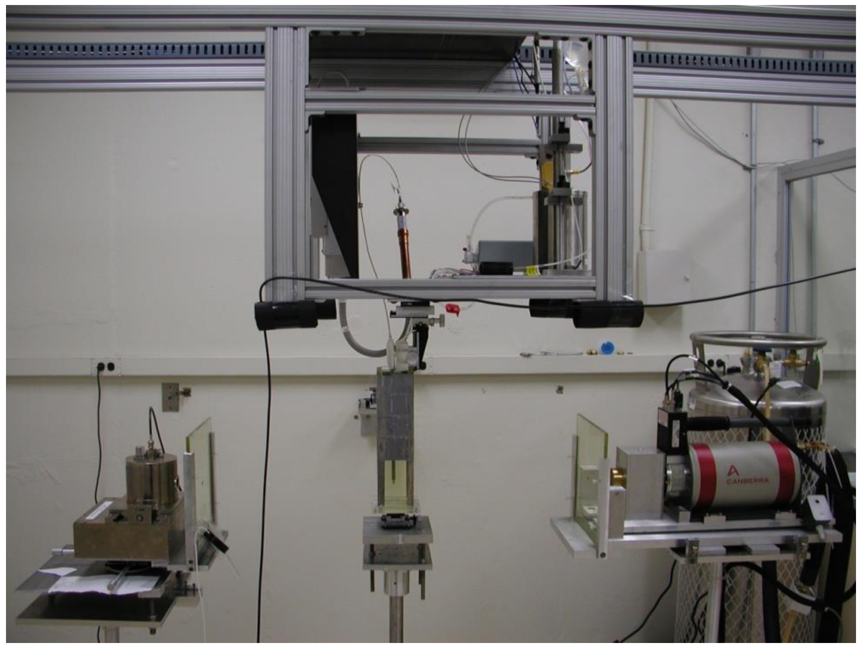
NIST Electronic Brachytherapy Calibration Facility, v. 1

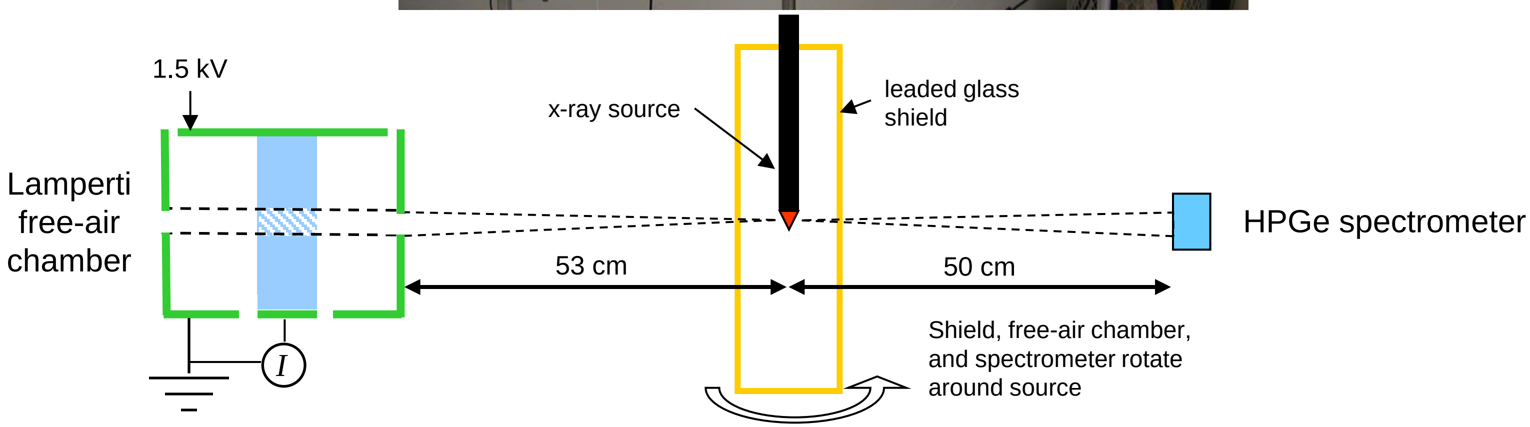
Maze entry (leaded glass)

Control area

NIST Electronic Brachytherapy Calibration Facility, v. 1

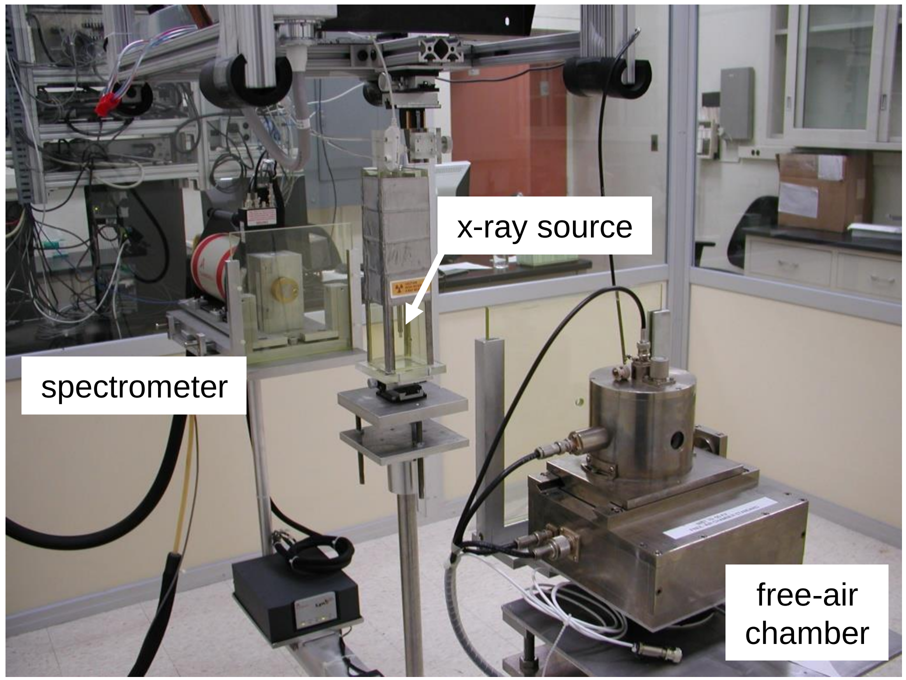
As the Xoft x-ray source can not be rotated, the Lamperti free-air chamber and HPGe spectrometer are mounted such that the **instruments rotate around the source**.





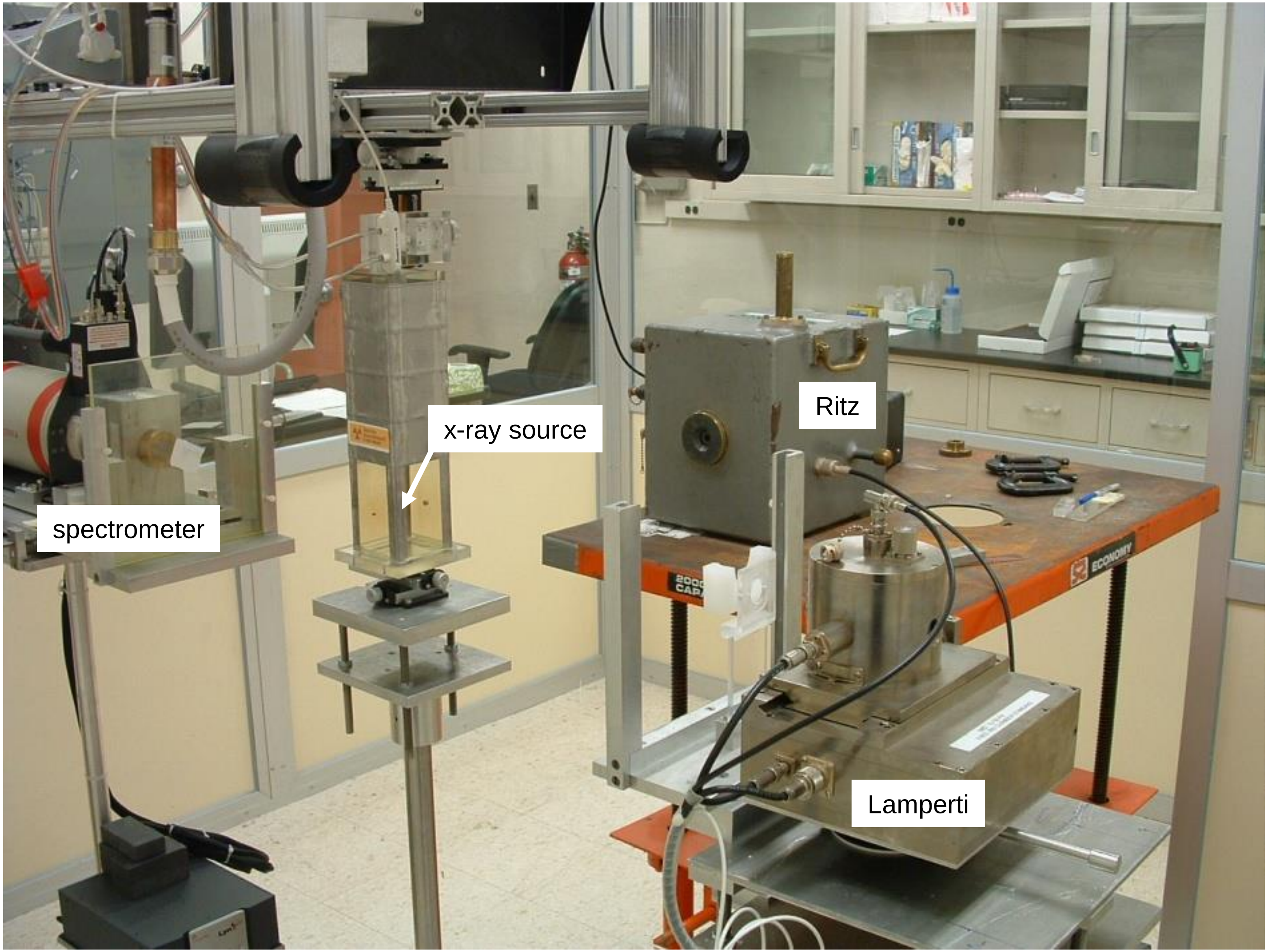
NIST Electronic Brachytherapy Calibration Facility, v. 1

source in
water cooling
catheter



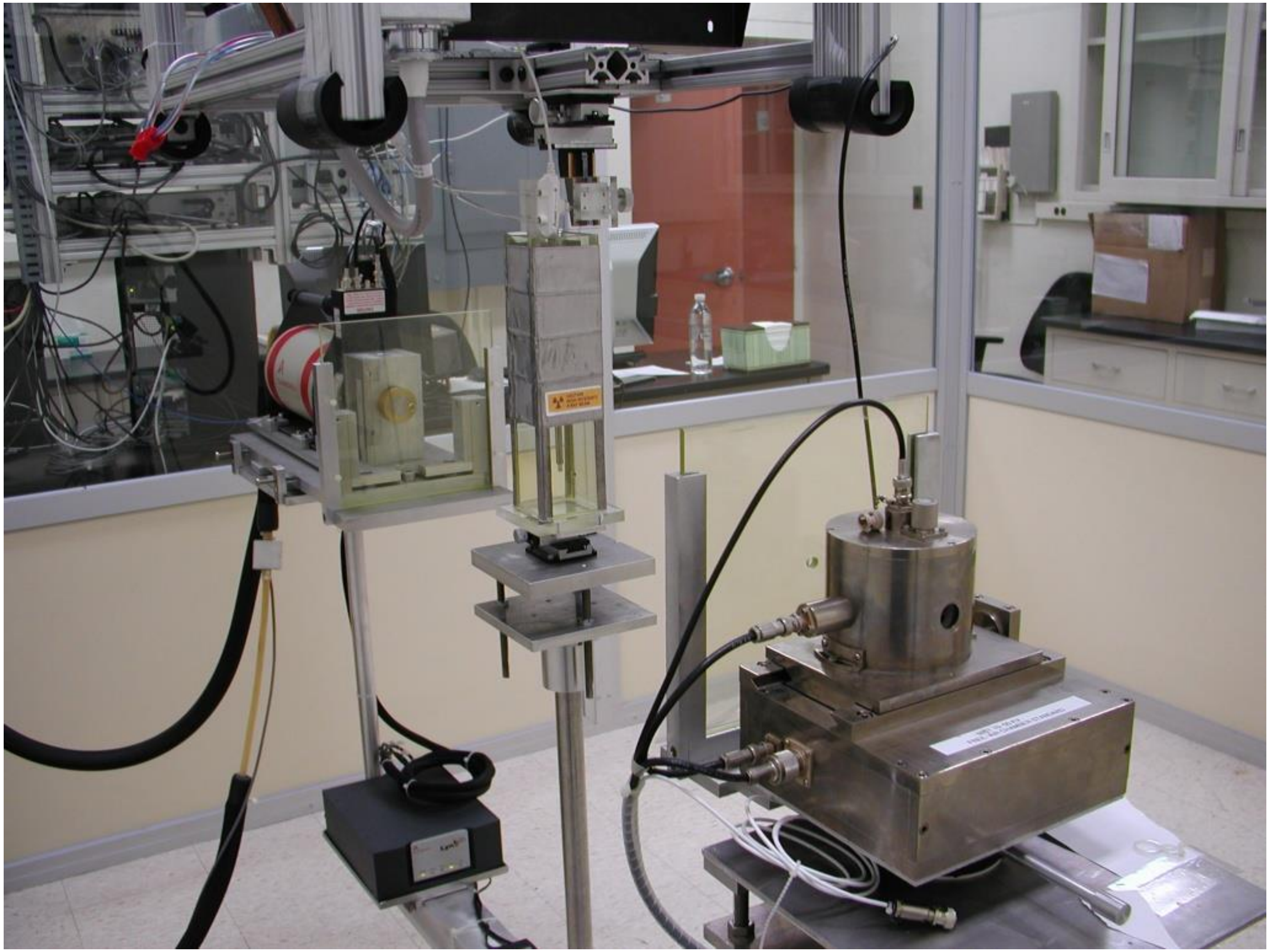
leaded glass
shield

Comparison of Lamperti and Ritz Free-Air Chambers



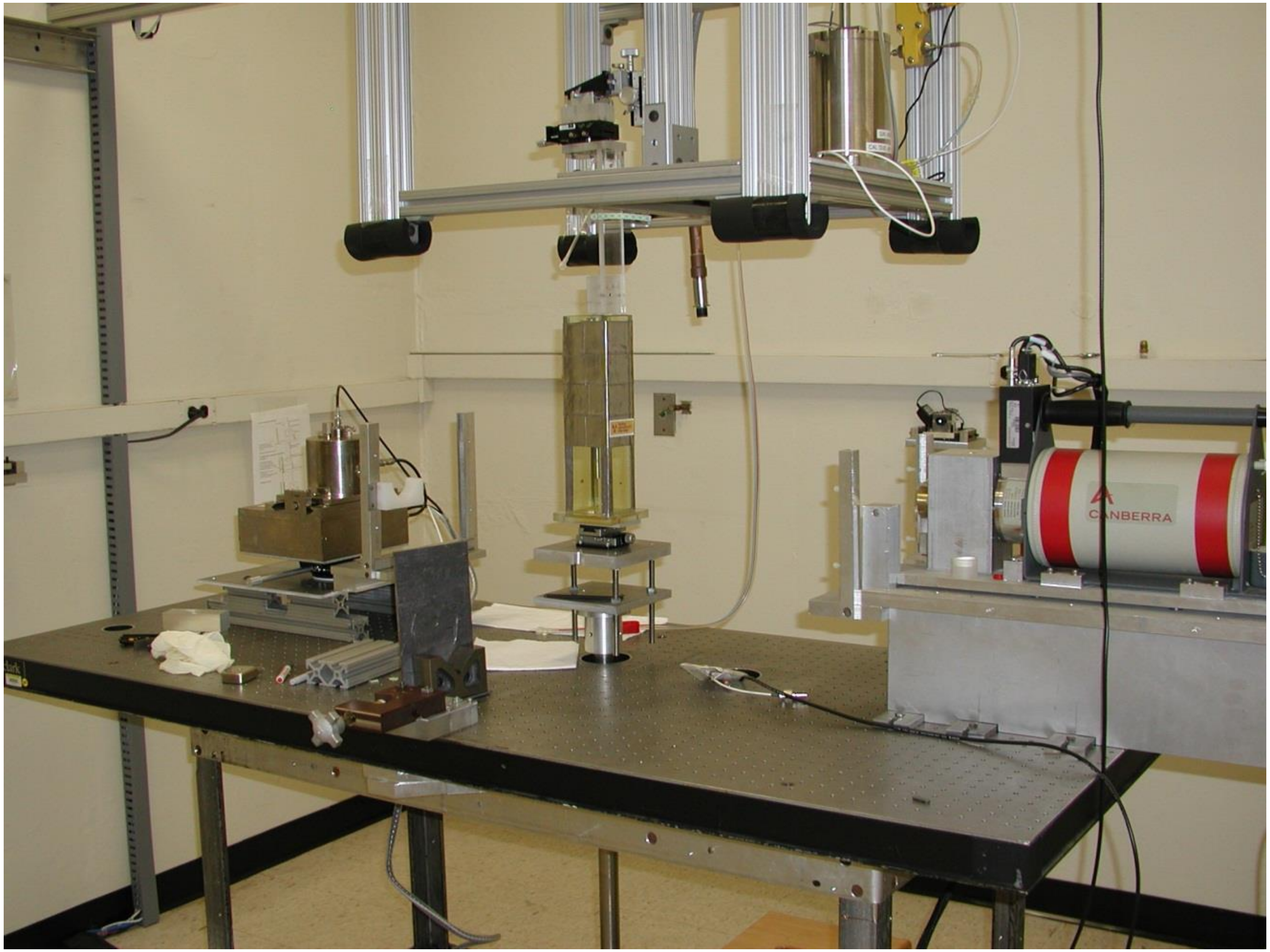
NIST Electronic Brachytherapy Calibration Facility, v. 1

PROBLEM – Alignment not reproducible



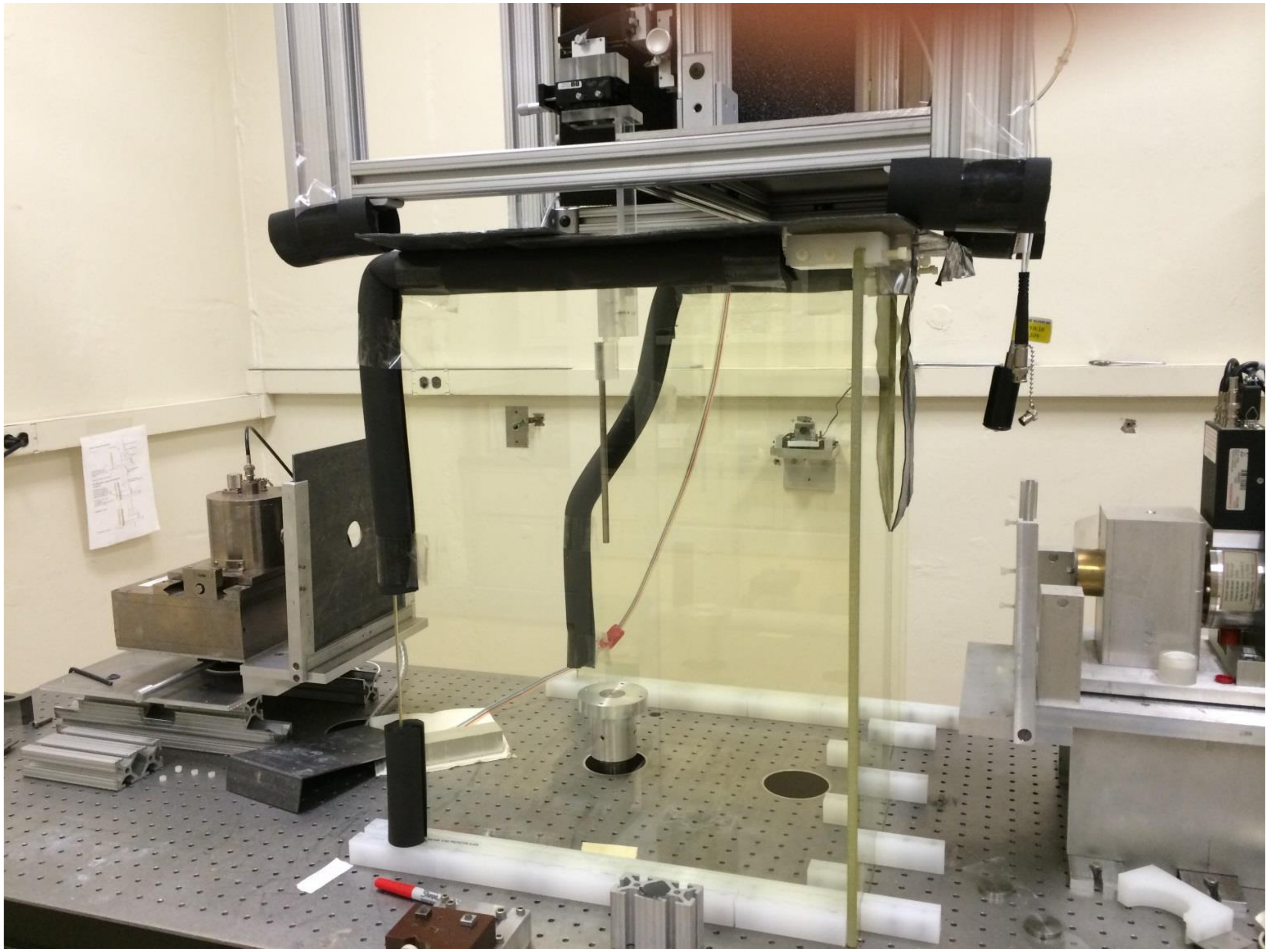
NIST Electronic Brachytherapy Calibration Facility, v. 2

SOLUTION – Optical table for rigid mounting of instruments

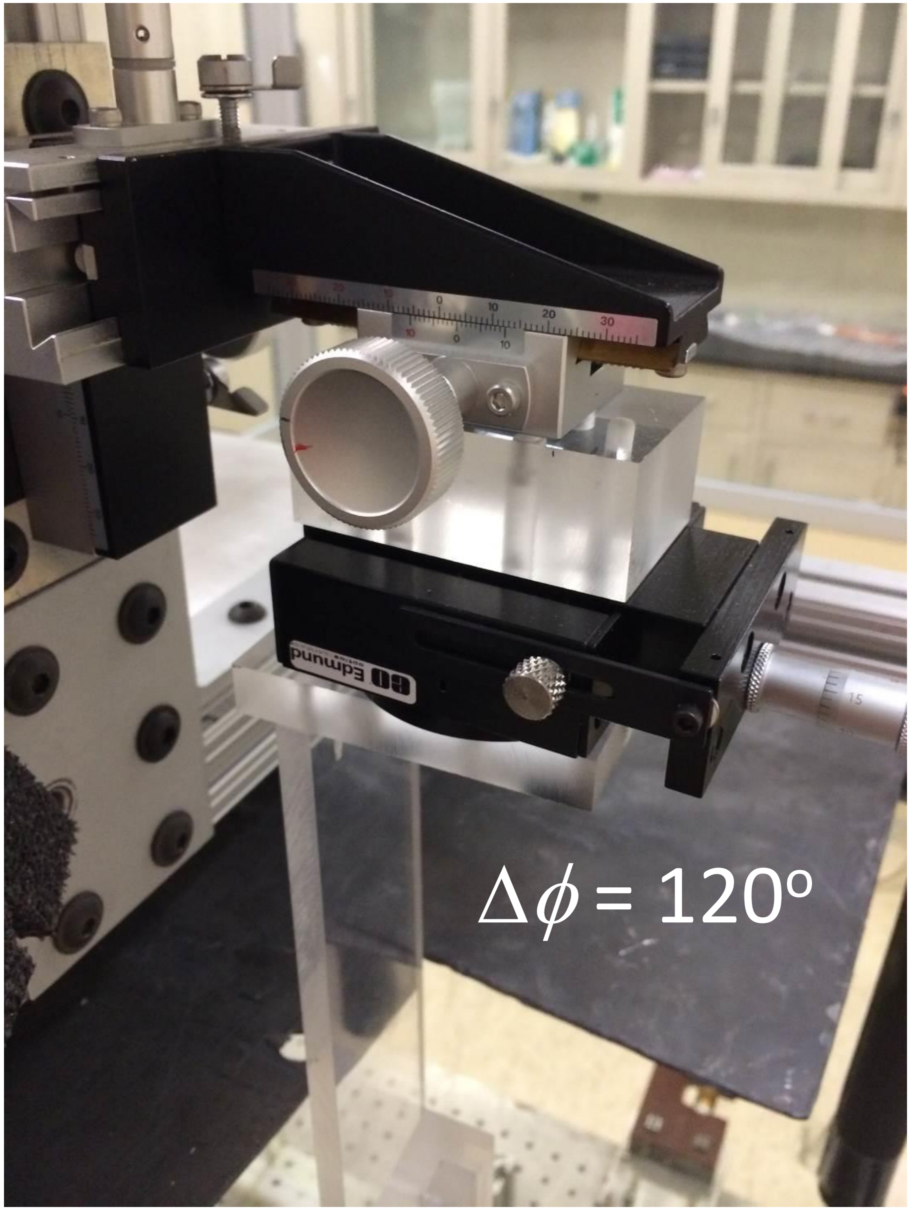


NIST Electronic Brachytherapy Calibration Facility, v. 2

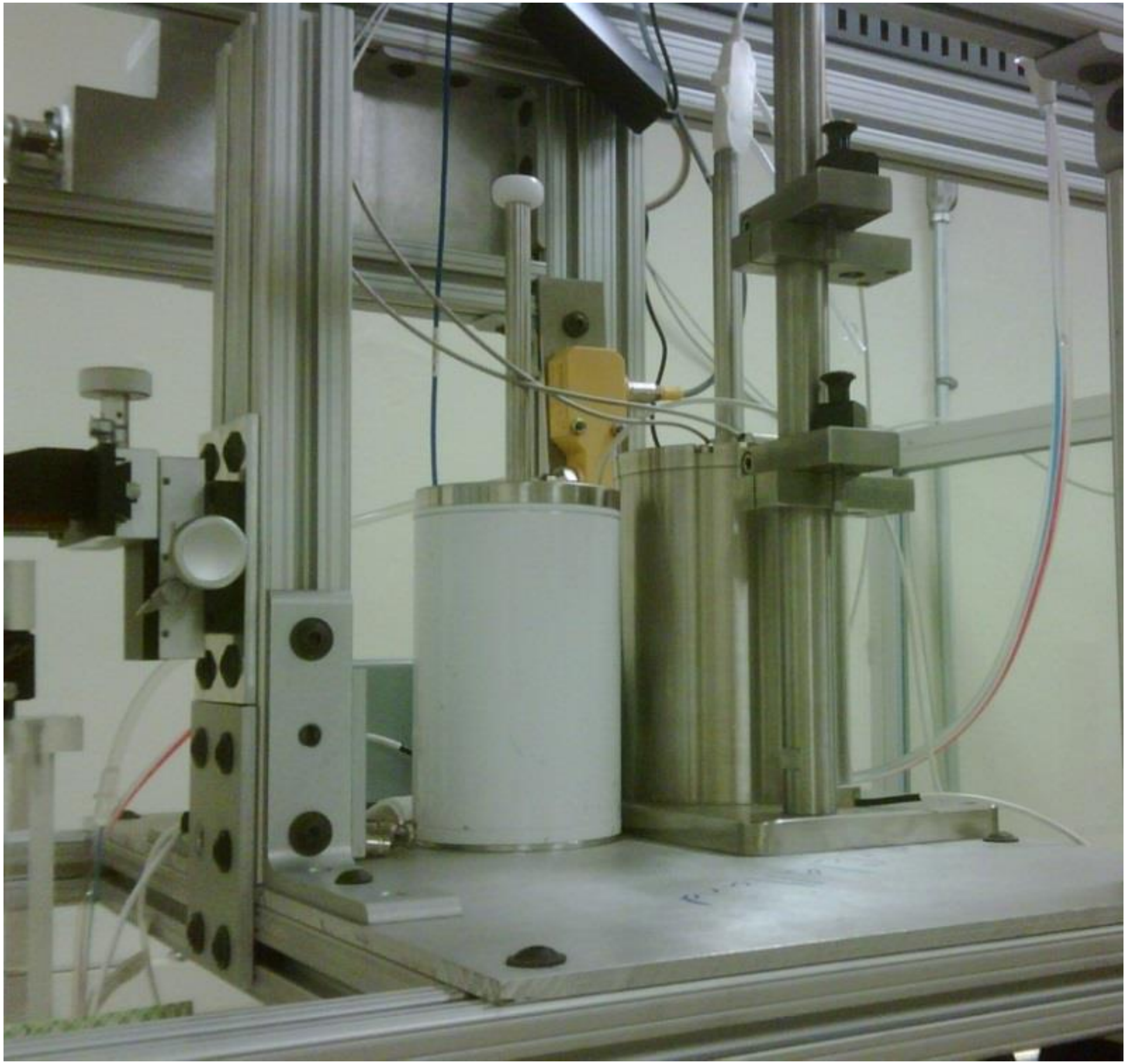
SOLUTION – Larger lead-glass surround



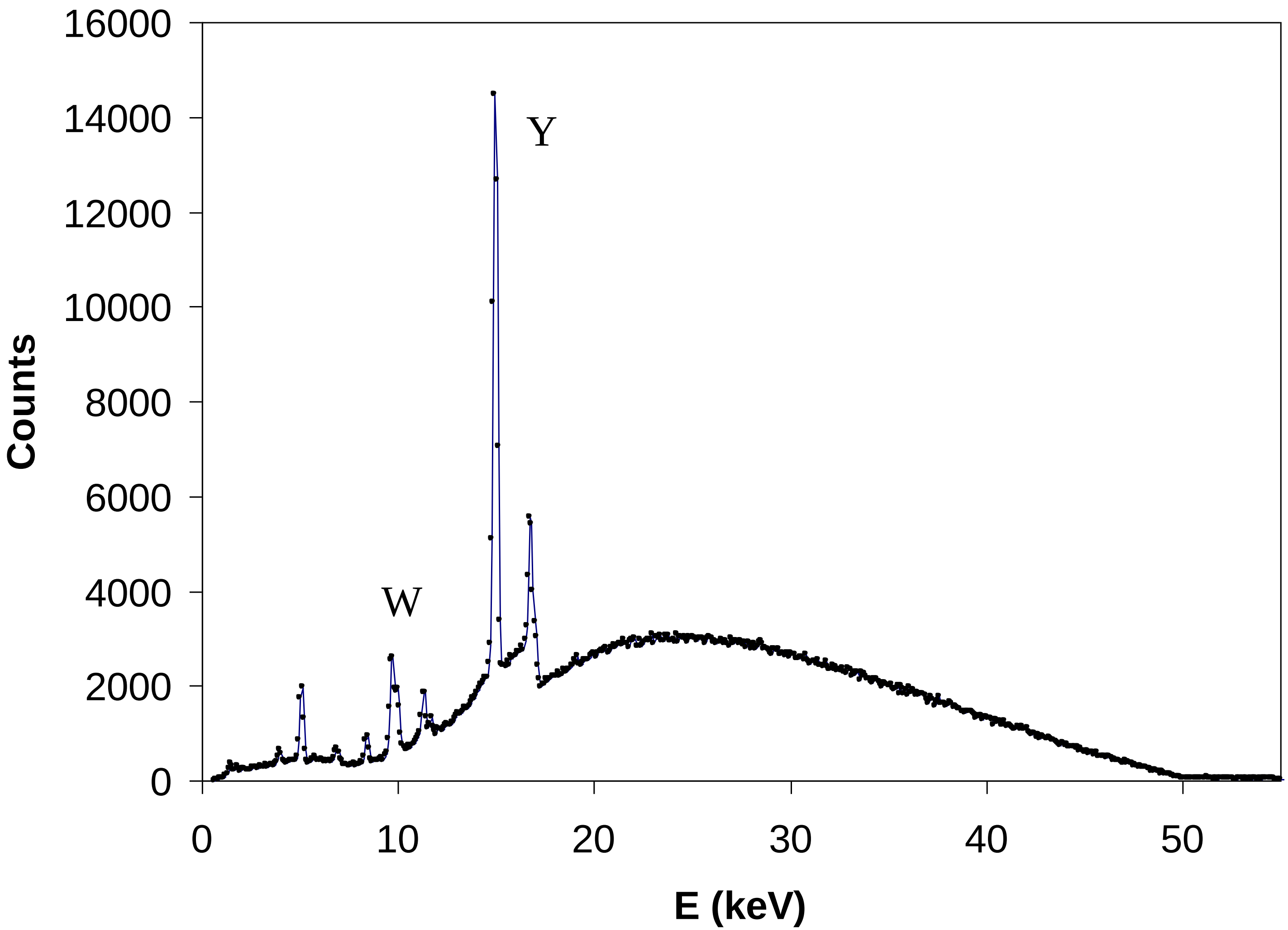
NIST Electronic Brachytherapy Calibration Facility, v. 2



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

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

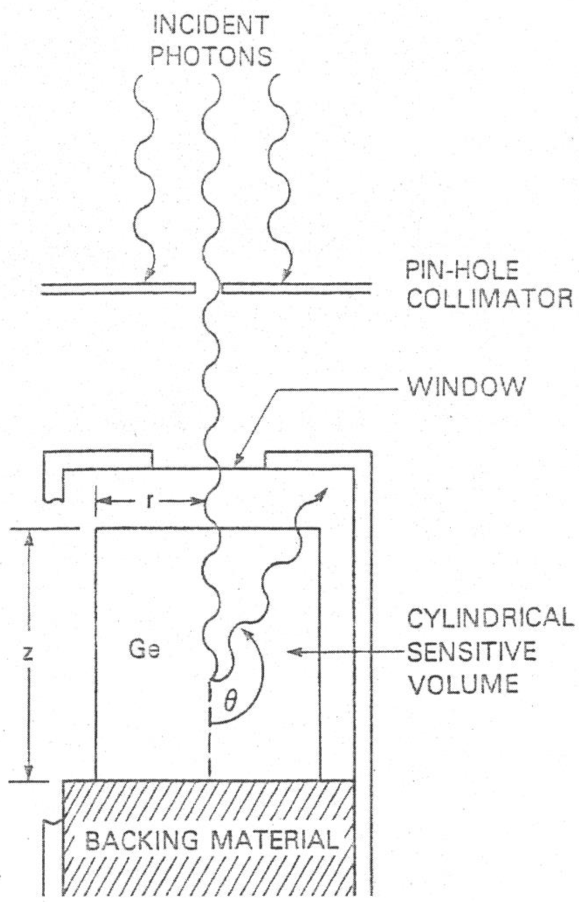
T(*E*) is the *window-attenuation factor*.

D(*E,ε*), 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(*ε,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* depends on the detector dimensions: cylinder of radius *r* and height *z*



Accurately calculated by Monte Carlo code

Spectrometry of X-Ray Sources

Energy-deposition spectrum: E < 300 keV

$$D(E,\varepsilon) = P_0(E,\varepsilon)\,\delta(\varepsilon - E) + P_{x\alpha}(E,\varepsilon)\,\delta(\varepsilon - E + E_\alpha) + P_{x\beta}(E,\varepsilon)\,\delta(\varepsilon - E + E_\beta) + C(E,\varepsilon)$$

$P_0(E)$ = probability that incident energy E is completely absorbed

$P_{x\alpha}(E)$ = probability that incident energy E is completely absorbed except for escape of the Ge K_α fluorescence x-ray energy (9.876 keV)

$P_{x\beta}(E)$ = probability that incident energy E is completely absorbed except for escape of the Ge K_β fluorescence x-ray energy (10.986 keV)

$C(E,\varepsilon)$ = Compton continuum

Spectrometry of X-Ray Sources

With $D(E,\varepsilon)$ normalized to one incident photon, the *detection efficiency* is

$$\eta(E) = \int D(E,\varepsilon)\,\mathrm{d}\varepsilon = P_0(E) + P_{\mathrm{x}\alpha}(E) + P_{\mathrm{x}\beta}(E) + \int C(E,\varepsilon)\,\mathrm{d}\varepsilon = 1 - \exp\left[-\mu(E)z\right]$$

and we get the last remaining and important quantity in the description.

photopeak efficiency

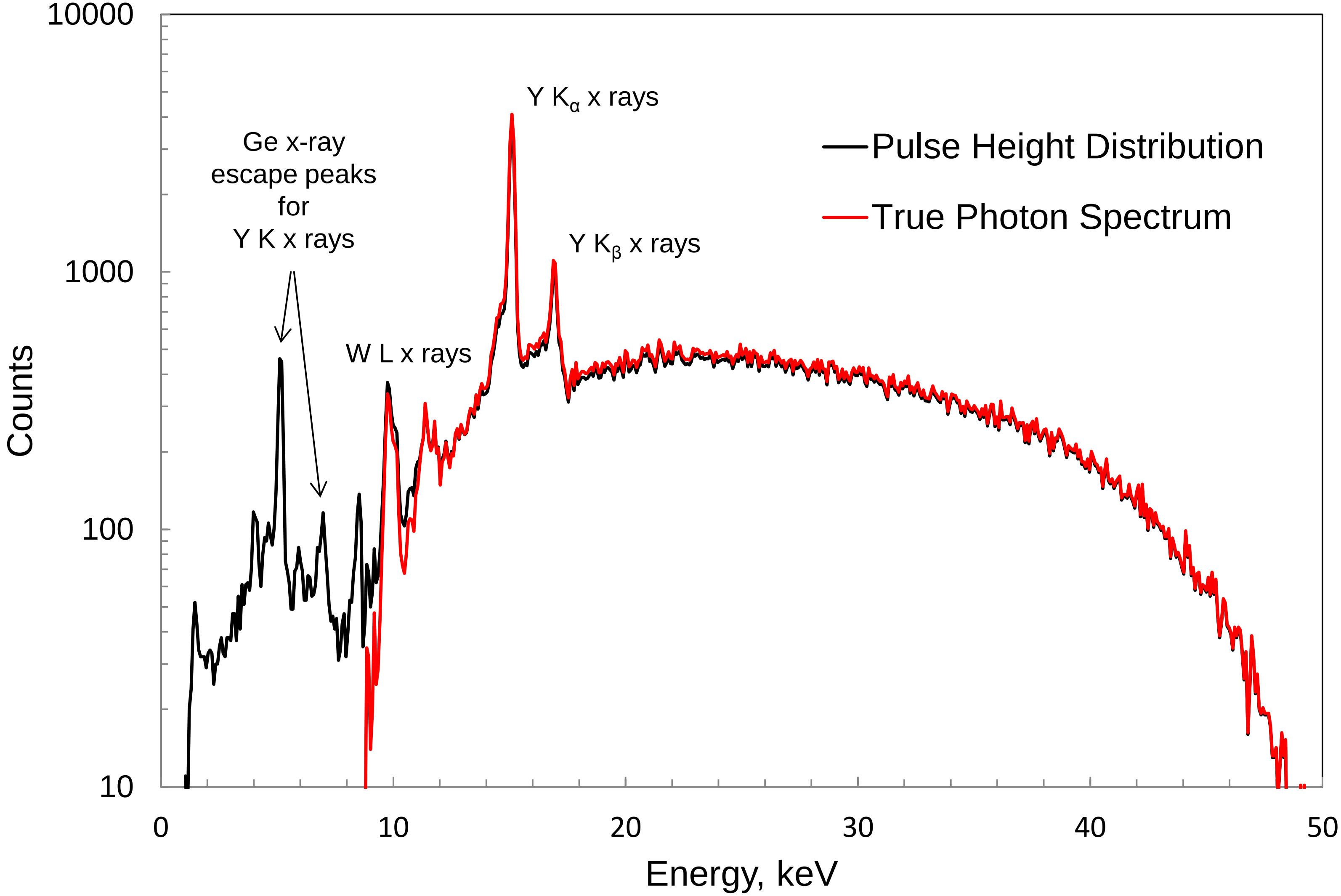
Note that the *photofraction* = $P_0(E)/\eta(E)$

Data on energy-deposition spectra, $D(E,\varepsilon)$, for our HPGe detector of
r = 5.642 mm and z = 10 mm (window is 0.025 mm Be) is from the methods of:

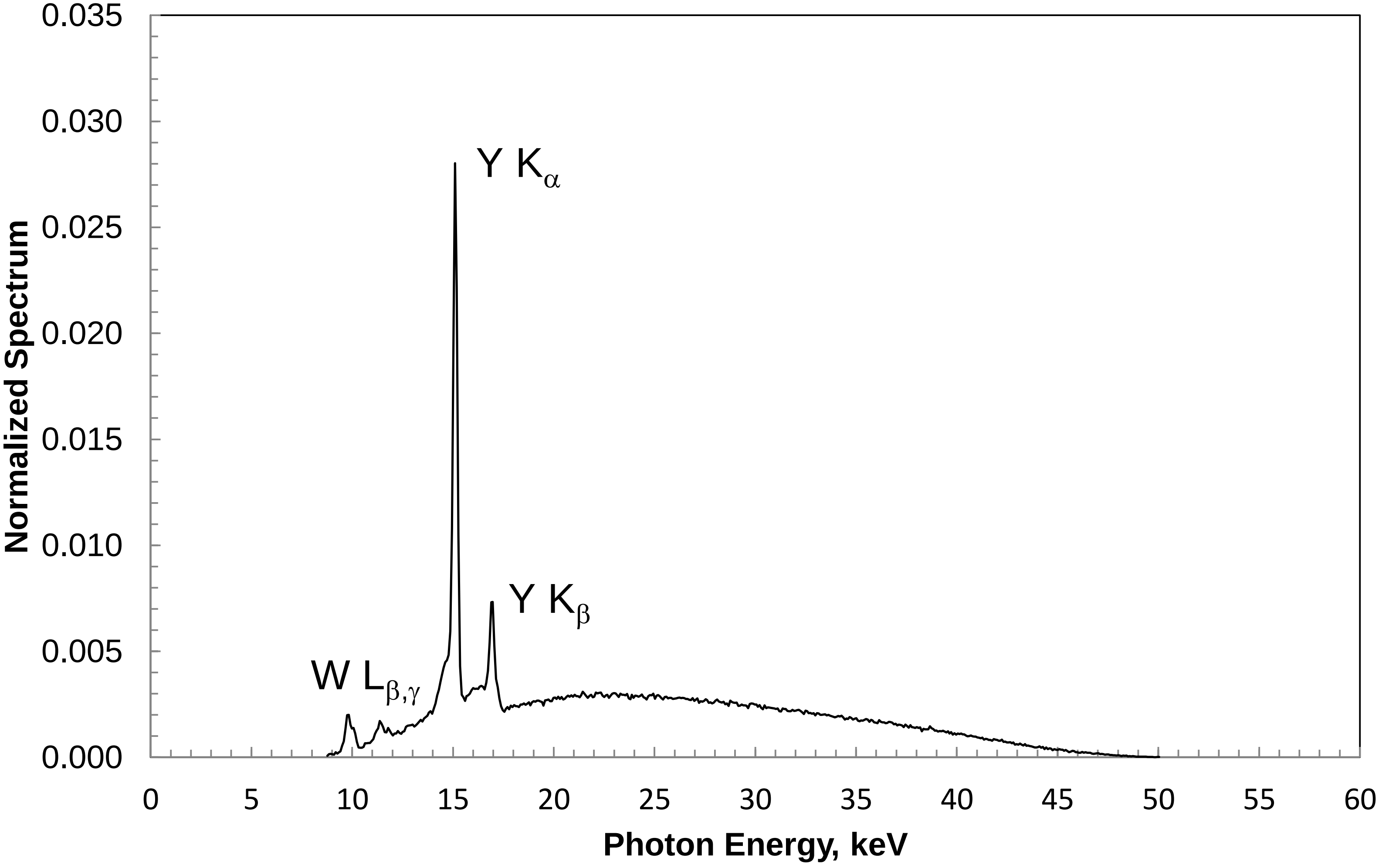
Seltzer, S.M., “Calculated response of intrinsic germanium detectors to narrow x-ray beams with energies up to 300 keV,” *Nucl. Instr. Meth*. **188**, 133-151 (1981).

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

$$\dot{K}_{\mathrm{air}} = \frac{I}{\rho_{\mathrm{air}} V} \frac{\overline{W}_{\mathrm{air}}}{e} \frac{1}{1-g_{\mathrm{air}}} \prod_i k_i$$

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 $k_{br}/(1-g)$	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
K_{vac}/K_{air}	conversion to air-kerma strength	1.12	1.12

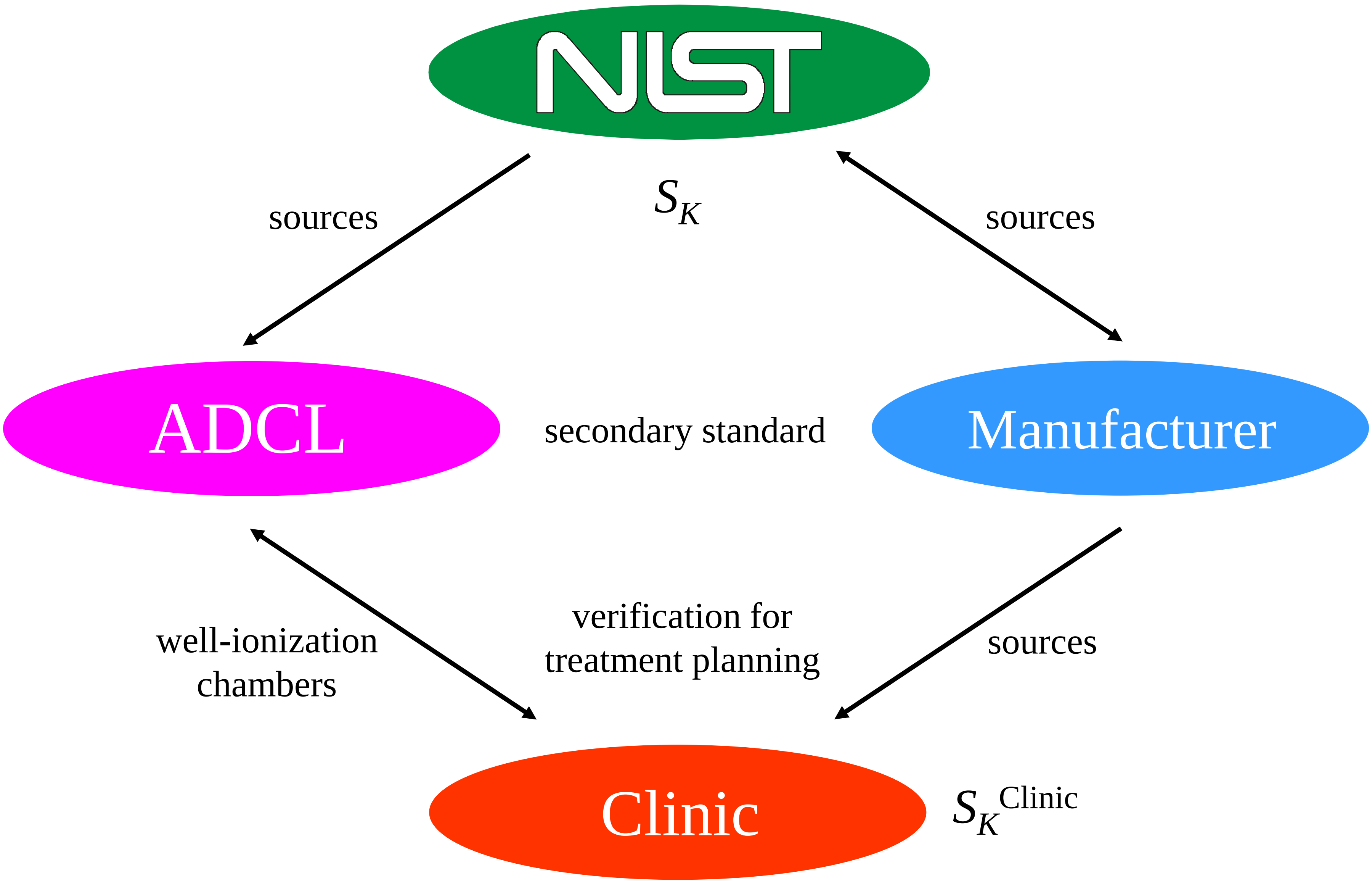
Uncertainty Budget for Xoft Source at 50 kV

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
	aperture penetration	negligible	
	chamber face penetration	negligible	
	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

Measurement Traceability for Brachytherapy Sources



Clinical Brachytherapy Source Measurements

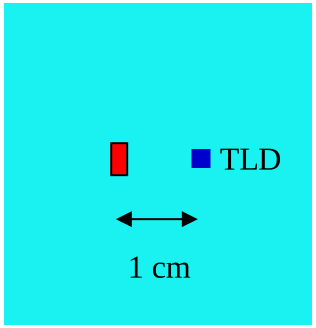
Well-ionization chambers, calibrated by an ADCL

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

Brachytherapy Dose-Rate Measurements (LDR seeds)

Dose rate is typically measured using thermoluminescent dosimeters (TLDs) placed in solid, water-equivalent phantoms at various distances from a seed

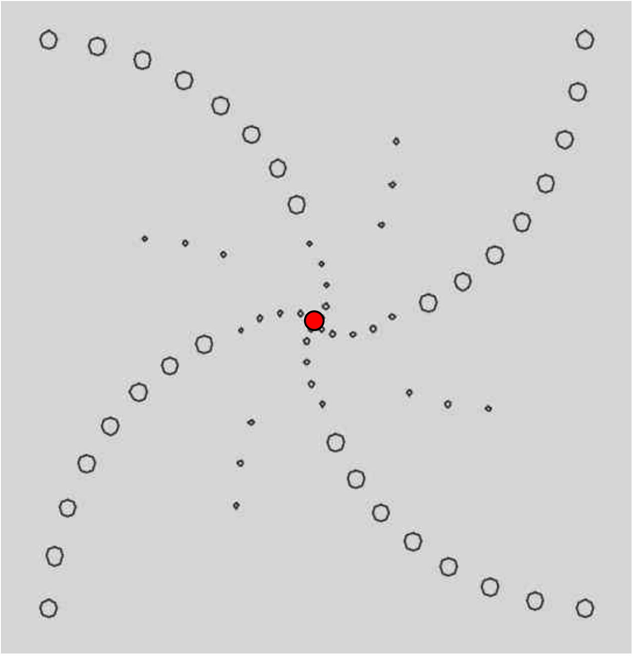
$\dot{D}(r_0, \theta_0)$ measurement

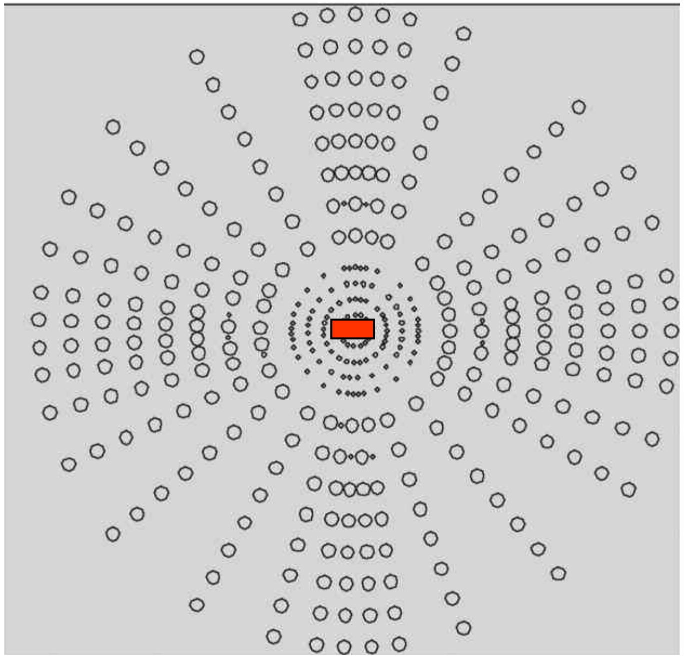


$$\Lambda = \frac{\dot{D}(r_0, \theta_0)}{S_K}$$

Dose Rate Constant

$\dot{D}(r, \theta)$ measurements

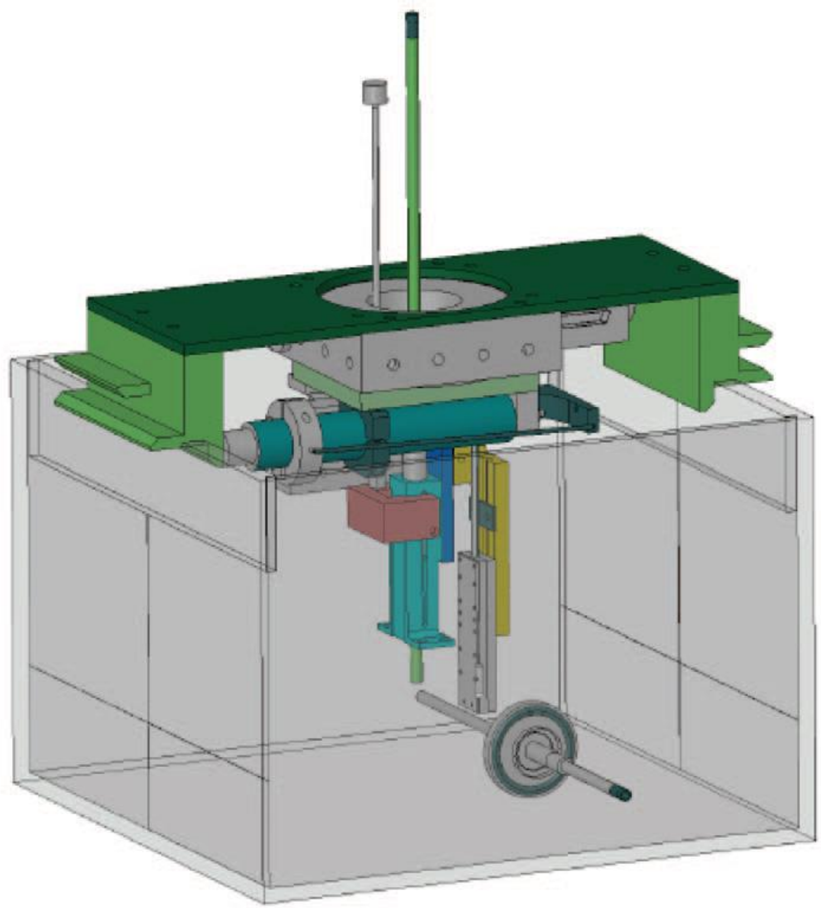




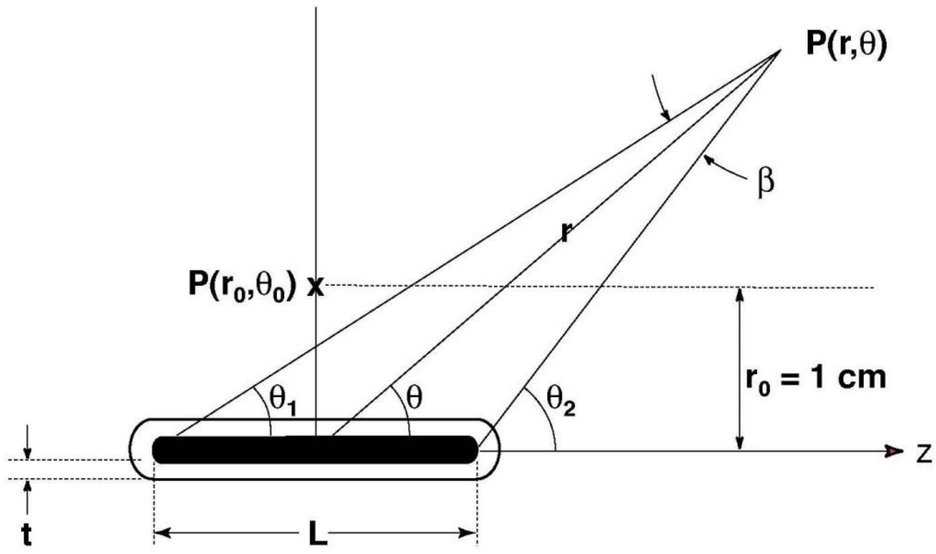
Brachytherapy Dose-Rate Measurements (Xoft source)

Dose rate was measured in water using a parallel-plate ionization chamber

Rivard, Davis, DeWerd, Rusch, and Axelrod, *Med. Phys.* 33, 4020 (2006)



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

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

Dose Rate Constant (NIST-traceable S_K)

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

r_0 = 1 cm

θ_0 = π / 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* (in press 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

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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

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- Jason Walia – spectrometer calibration