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DOSIMETRY FOR FAST NEUTRON AND PROTON RADIOTHERAPY

Dan T L Jones



iThemba Laboratory for Accelerator Based Sciences
Somerset West, SOUTH AFRICA
and



International Commission on Radiation Units and
Measurements
Bethesda MD, USA



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DOSIMETRY FOR FAST NEUTRON AND PROTON RADIOTHERAPY



NEUTRON AND PROTON DOSIMETRY

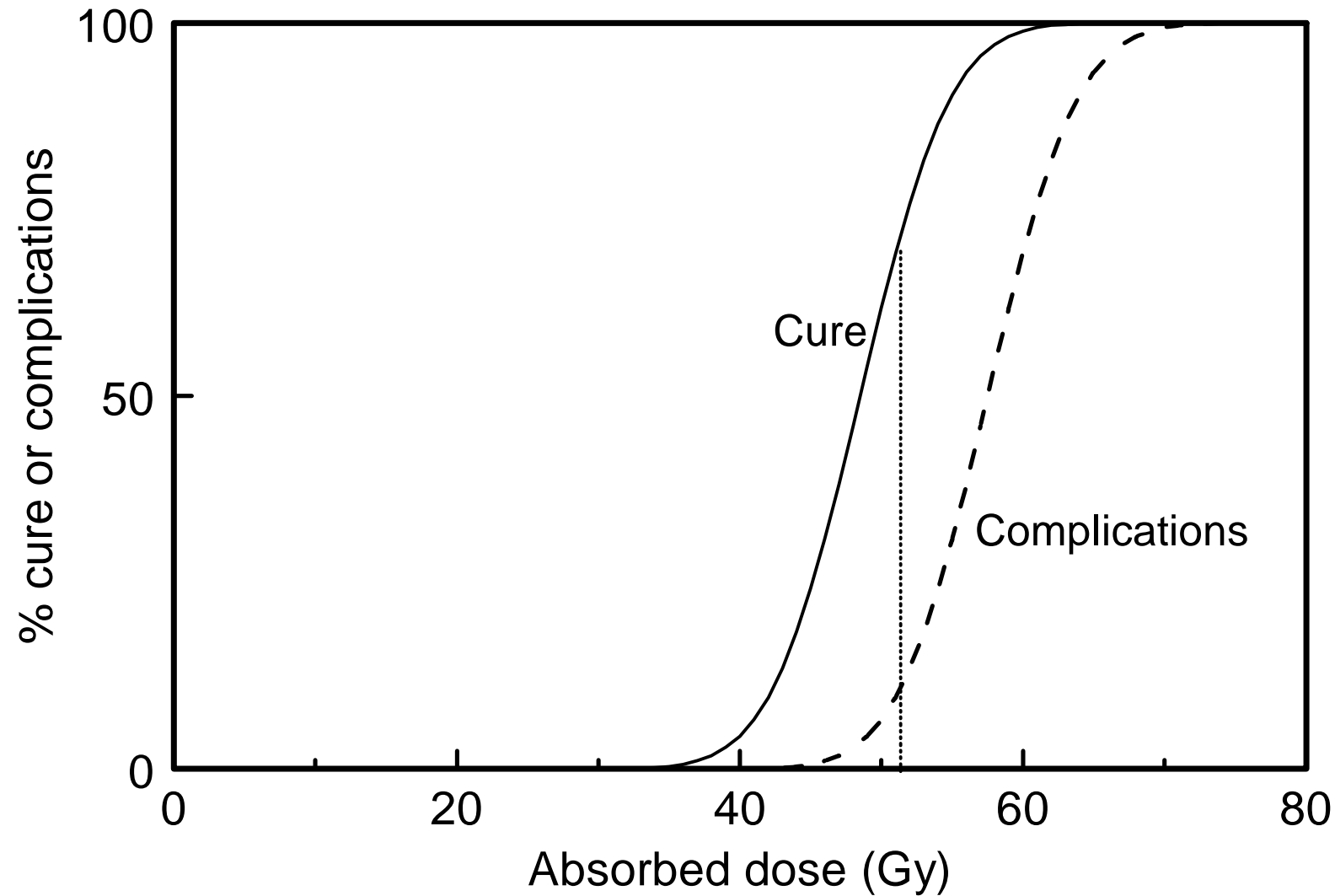
- ▶ Fast neutrons and protons undergo fundamentally different interactions in tissue
 - † neutrons interact with nuclei, while protons interact mainly with atomic electrons
- ▶ For neutrons measurement of absorbed dose to muscle tissue is required because of the element-specific nuclear interactions which neutrons undergo
 - † “tissue equivalent” dosimeter materials, which have similar neutron absorption and scattering properties, must be used
 - † specific correction factors are applied to account for the differences in composition
 - † neutrons are always accompanied by gamma rays which must be considered for accurate dosimetry
- ▶ Proton doses can be measured to materials that have similar electron density to muscle (e.g., water)
 - † proton dosimetry is inherently simpler



STANDARDISATION OF DOSIMETRY

- ▶ Tumor control and normal tissue complications are steep functions of absorbed dose
- ▶ Absorbed dose determinations at any center must be accurate and reproducible so that effects of therapy can be predicted
- ▶ Absorbed dose determinations must be consistent with those at other centres if clinical data are to be compared
- ▶ Accuracy: $\pm 3 \%$ ($\pm 5 \%$ is acceptable)
- ▶ Reproducibility: $\pm 2 \%$
- ▶ Intercomparisons between different centres play an important role in establishing uniform standards and in verifying integrity of dosimetry
- ▶ Biological weighting factors for clinical applications are fairly arbitrary
(Neutrons: 3.0, protons: 1.1)

DOSE-EFFECT CURVES



REFERENCE DOSIMETRY

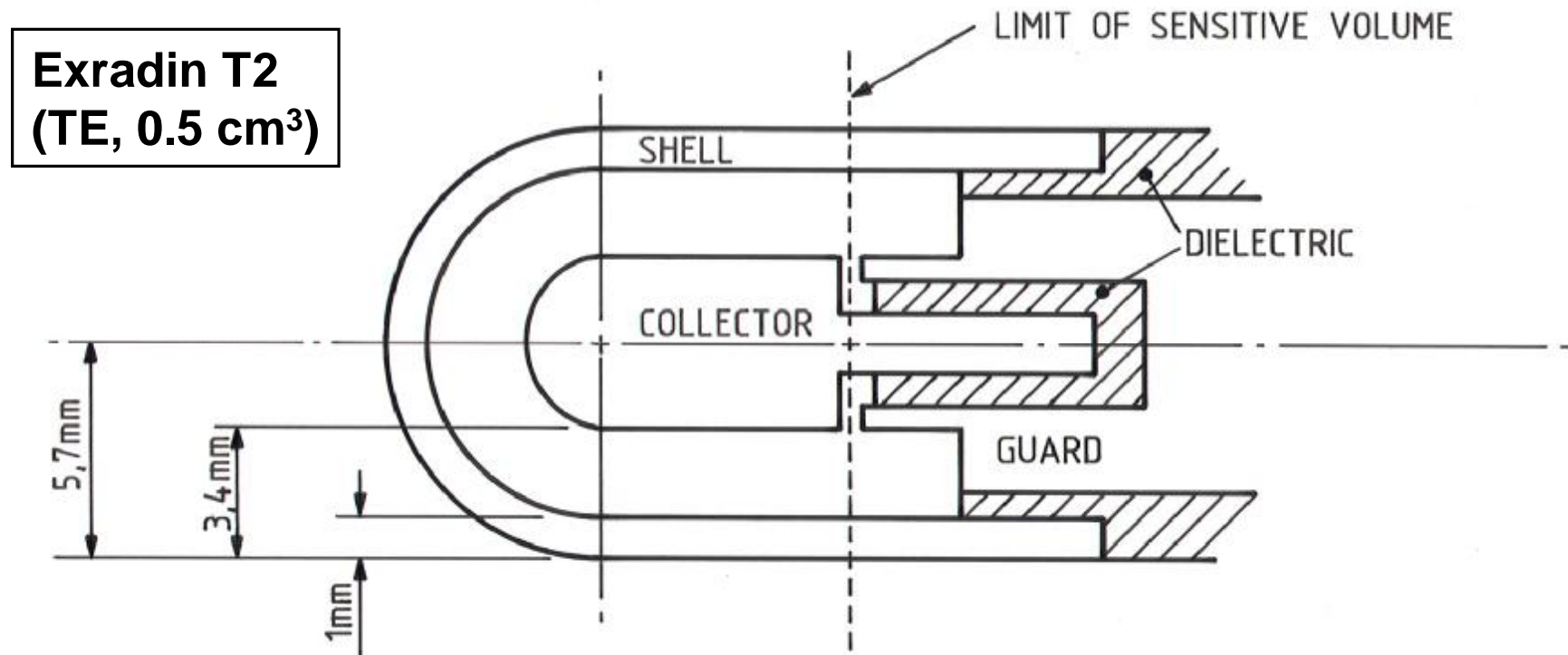
- ▶ Calorimeters are absolute dosimeters and are the instruments of choice for determining reference absorbed dose
 - † most accurate dosimeter
 - † no primary standards of neutron or proton therapy beams
 - † no radiation calibration
 - ⊙ *energy deposited determined by temperature rise*
 - † cumbersome and difficult to use in clinic
- ▶ Ionization chambers are preferred for routine use
 - † readily available and simple to use
 - † can be calibrated with a calorimeter in the user's beam
 - † calibrations are usually referred to primary ^{60}Co standards
 - ⊙ *knowledge of physical data required for determining correction factors*

BRAGG-GRAY CAVITY THEORY

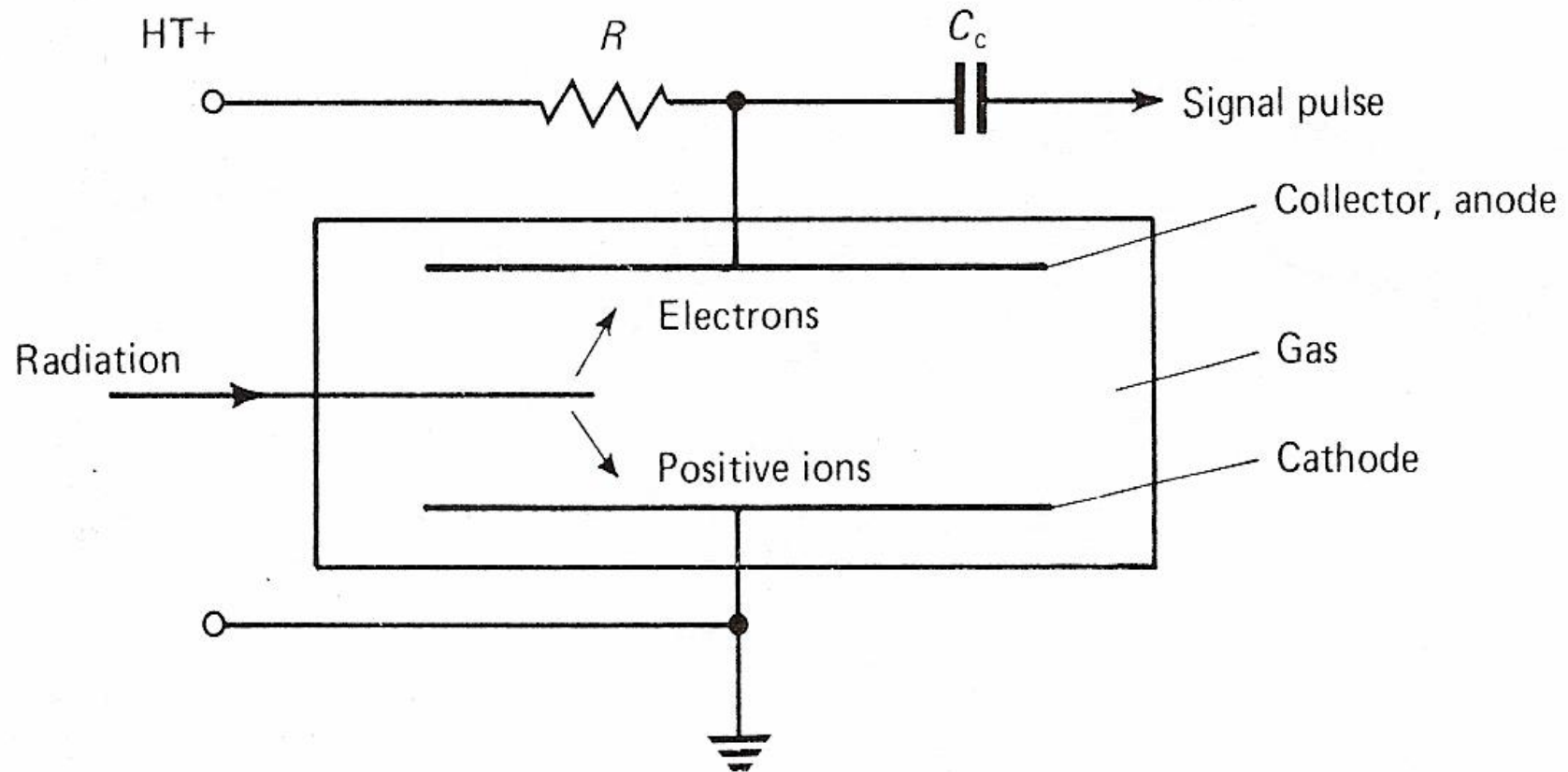
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- ▶ The Bragg-Gray theory enables calculation of the dose to a medium from ionization measurements in a gas cavity placed in the medium. The two conditions which need to be satisfied in order for the theory to hold are:
 - † a cavity in the measuring medium does not perturb the charged particle field, *i.e.* the particles lose a negligible fraction of their energy in traversing the cavity. This means that the material in the cavity should have the same absorption and scattering properties as the measuring medium. This implies the use of a small chamber or a homogeneous chamber (*i.e.* with composition of wall and gas similar to the measuring medium)
 - † the absorbed dose in the cavity is assumed to be deposited entirely by the charged particles crossing it
- ▶ Under these assumptions the ratio of the absorbed dose in the adjacent medium to the absorbed dose in the cavity is equal to the ratio of the mass collision electronic stopping powers of the respective materials

IONIZATION CHAMBER



IONIZATION CHAMBER



IONIZATION CHAMBER DOSIMETRY

The absorbed dose D_g to the mass of gas m_g in the cavity of an ionization chamber is:

$$D_g = \frac{Q}{m_g} (W_g / e) \quad (1)$$

If the ionization chamber satisfies the Bragg-Gray principle [small or homogeneous chamber, absorbed dose in cavity is deposited entirely by charged particles crossing it] then the dose to wall material D_m is:

$$D_m = D_g s_{m,g} = \frac{Q}{m_g} (W_g / e) s_{m,g} \quad (2)$$

Q	Charge produced in ionization chamber cavity gas
W_g/e	Mean energy to form an ion pair in the gas
$s_{m,g}$	Mean ratio of mass electronic stopping powers of the wall material to the gas

REFERENCE CONDITIONS FOR NEUTRON DOSIMETRY

DOSIMETER	Thimble ionization chamber
Wall material	A150 plastic
Gas filling	Dry methane-based TE gas
^{60}Co calibration factor	Air kerma (dose to air)
DOSE SPECIFICATION	Tissue
PHANTOM	Water
FIELD SIZE	10 cm x 10 cm
MEASUREMENT POINT	5 cm depth
BEAM QUALITY	Average energy / LET

RELATIVE DOSIMETRY

- ▶ Parallel plate ionization chambers are the most common and well-proven detectors for particle beam monitoring
- ▶ Ionization chambers are often the instruments of choice for dose distribution measurements
 - † simplest to use and do not require specific calibration for such relative measurements

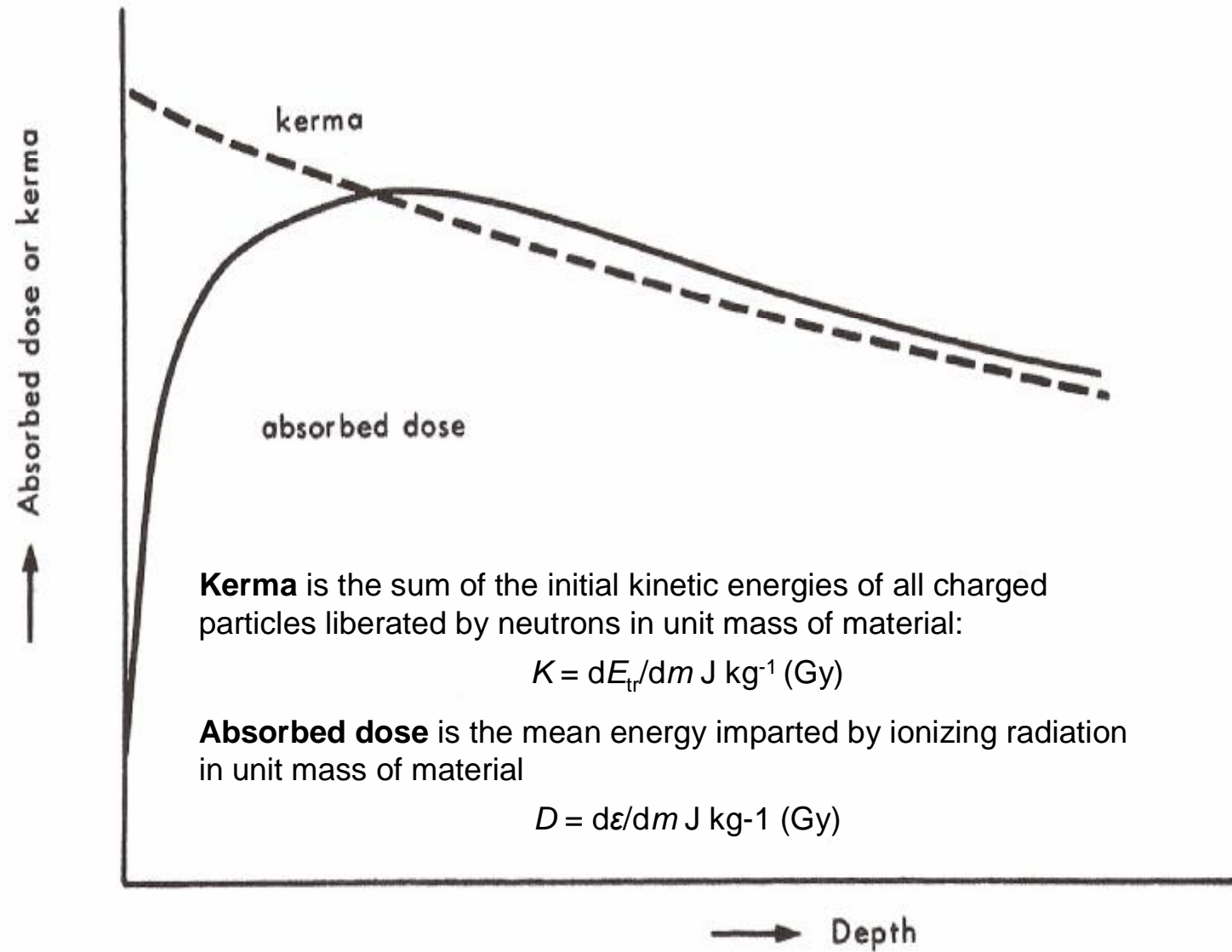


NEUTRON DOSIMETRY PROTOCOLS

- ▶ **ICRU Report 26 (1976) [ICRU, Bethesda MD]**
Neutron Dosimetry for Biology and Medicine
- ▶ **Task Group 18 (1980)**
AAPM Report No. 7 [AAPM, New York]
Protocol for neutron beam dosimetry
- ▶ **J J Broerse, B J Mijnheer, J R Williams (1981)**
British Journal of Radiology 54, 882-898
European protocol for neutron dosimetry for external beam therapy
- ▶ **B J Mijnheer, P Wootton, J R Williams, J Eenmaa, C J Parnell (1987)**
Medical Physics 14, 1020-1026
Uniformity in dosimetry protocols for therapeutic applications of fast neutron beams
- ▶ **ICRU Report 45 (1989)) [ICRU, Bethesda MD]**
Clinical Neutron Dosimetry Part 1: Determination of Absorbed Dose in a Patient Treated by External Beams of Fast Neutrons
- ▶ **D T L Jones (2001)**
Radiochim. Acta 89, 279-287
Reference dosimetry for fast neutron and proton therapy



KERMA AND ABSORBED DOSE



NEUTRON DOSIMETRY (I)

In the general case the dose to the mass of gas (m_g) in the cavity of an ionization chamber is given by:

$$D_g = \frac{Q}{m_g} (W_g/e) \quad (1)$$

Q : charge produced in the ionization chamber cavity gas

W_g/e : mean energy expended per unit charge (ion pair) in gas

The absorbed dose to the wall surrounding the gas is given by:

$$D_m = \frac{Q}{m_g} (W_g/e) s_{m,g} \quad (2)$$

$s_{m,g}$: mean ratio of the mass electronic stopping powers of the wall material to the gas

NEUTRON DOSIMETRY (II)

For neutron dosimetry with tissue-equivalent A150 plastic ionization chambers flushed with dry methane-based TE gas (the chamber is assumed to be homogeneous to satisfy the Bragg-Gray principle) equation (2) can be rewritten:

$$D_{A150} = \frac{Q}{m_{TE}} (W_{TE}/e)_n (r_{A150, TE})_n d_T \frac{1}{1+d} \quad (3)$$

$r_{A150, TE}$: A150 to TE-gas absorbed dose conversion factor. It is a corrected value of $s_{A150, TE}$ and accounts for non Bragg-Gray compliance of ionization chamber

d_T : displacement correction factor (difference in absorption and scattering when chamber is replaced by phantom material). Multiplication of charge by d_T yields the total absorbed dose at the centre of the chamber

d : correction factor to account for difference in response of chamber to neutrons and gamma rays in beam (see below)

NEUTRON DOSIMETRY (III)

The total absorbed dose to ICRU muscle tissue D_T in the mixed field is the sum of the neutron D_n and gamma D_g absorbed doses and is given by:

$$D_T = D_n + D_g = D_{A150} (K_{t, A150})_n$$

$$= \frac{Q}{m_{TE}} (W_{TE}/e)_n (r_{A150,TE})_n (K_{t, A150})_n d_T \frac{1}{1 + d} \quad (4)$$

$(K_{t,A150})_n$: ratio of kerma in ICRU muscle tissue to A150 plastic in the neutron beam

NEUTRON DOSIMETRY (IV)

It can be shown that:

$$m_{TE} = \frac{(W_{TE}/e)_c (\bar{L}/\rho)_c [(\mu_{en}/\rho)_{t,A150}]_c}{N_k (1-g) A_{wall} [(\mu_{en}/\rho)_{t,air}]_c} \quad (5)$$

Substituting (5) into (4) and using $Q = MP$:

$$D_T = M \tilde{O} N_k (1-g) A_{wall} [(\mu_{en}/\rho)_{t,air}]_c J_c d_T \frac{1}{k_t} \frac{1}{1+\delta} \quad (6)$$

$$\frac{1}{k_T} = \frac{(r_{A150,TE})_n (W_{TE}/e)_n (K_{t,A150})_n}{[(\bar{L}/\rho)_{A150,TE}]_c (W_{TE}/e)_c [(\mu_{en}/\rho)]_c}$$

- k_T : sensitivity of the TE chamber to neutrons relative to its sensitivity to the calibration of photon;
- A_{wall} : wall correction factor; (\bar{L}/ρ) : mean restricted collision mass stopping power;
- N_k : air kerma calibration factor; (m_{en}/r) : mass energy absorption coefficient;
- g : fraction of secondary electron energy converted to bremsstrahlung in air;
- M : electrometer reading
- P : chamber correction factors



NEUTRON DOSIMETRY (V)

$1/(1 + d)$ corrects for the difference in response of the TE chamber for neutrons and gammas in the neutron beam and d is given by:

$$d = \frac{D_g}{D_n + D_g} \frac{h_T^- k_T}{k_T}$$

h_T is defined similarly to k_T for the gamma component of the neutron beam:

$$\frac{1}{h_T} = \frac{[(L/r)_{A150,TE}]_g (W_{TE}/e)_g [(m_{en}/r)_{t,A150}]_g}{[(L/r)_{A150,TE}]_c (W_{TE}/e)_c [(m_{en}/r)_{t,A150}]_c}$$

h_T : sensitivity of the TE chambers to the photons in the neutron beam relative to its sensitivity to the calibration photons.

It is assumed that $h_T \sim 1$. If the gamma spectra in the ^{60}Co calibration beam and in the neutron beam are the same h_T will be exactly 1.

$$k_T = 0.95 - 1.00$$

$D_\gamma / (D_n + D_\gamma)$ is usually less than 0.2 in neutron therapy beams.

d is therefore generally less than 0.01 and is often ignored.

COMPOSITION OF MATERIALS

(% by mass)

MATERIAL	H	C	N	O	OTHER
ICRU Muscle ($\rho = 1.04 \text{ g cm}^{-3}$)	10.2	12.3	3.5	72.9	1.1 (Na, Mg, P, S, K, Ca)
A150 ($\rho = 1.27 \text{ g cm}^{-3}$)	10.1	77.7	3.5	5.2	1.7 F, 1.8 Ca
TE gas ($\rho = 1.06 \times 10^{-3} \text{ g cm}^{-3}$) (64.4% CH ₄ , 32.4% CO ₂ , 3.2% N)	10.2	45.6	3.5	40.7	
Dry air ($\rho = 1.20 \times 10^{-3} \text{ g cm}^{-3}$)			75.5	23.2	1.3 Ar
Water ($\rho = 1.00 \text{ g cm}^{-3}$)	11.2			88.8	

- A150: TE for neutrons, photons (effective atomic number)
 Carbon substituted for oxygen
- stable
 - electrically conducting
 - correction for muscle absorbed dose (neutrons)

A150/TE GAS IONIZATION CHAMBERS

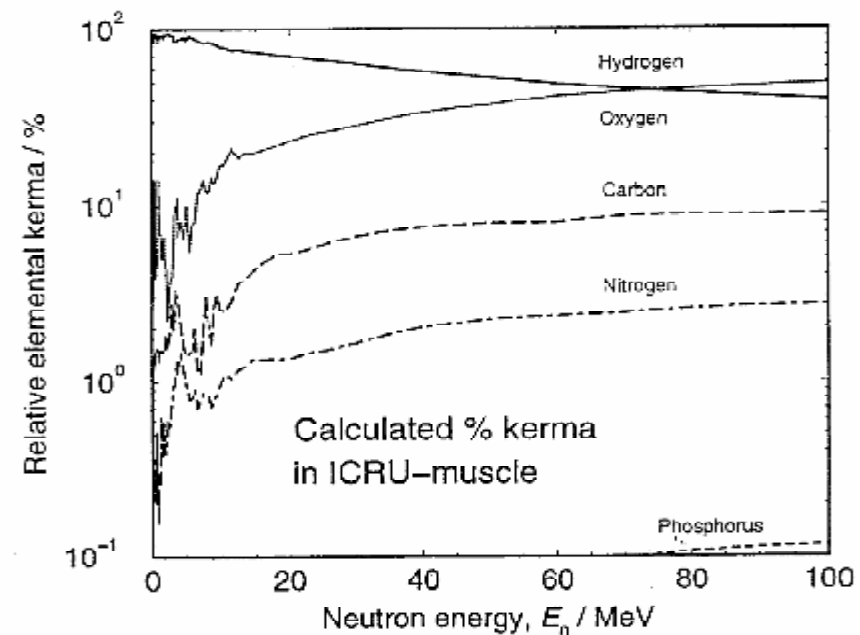
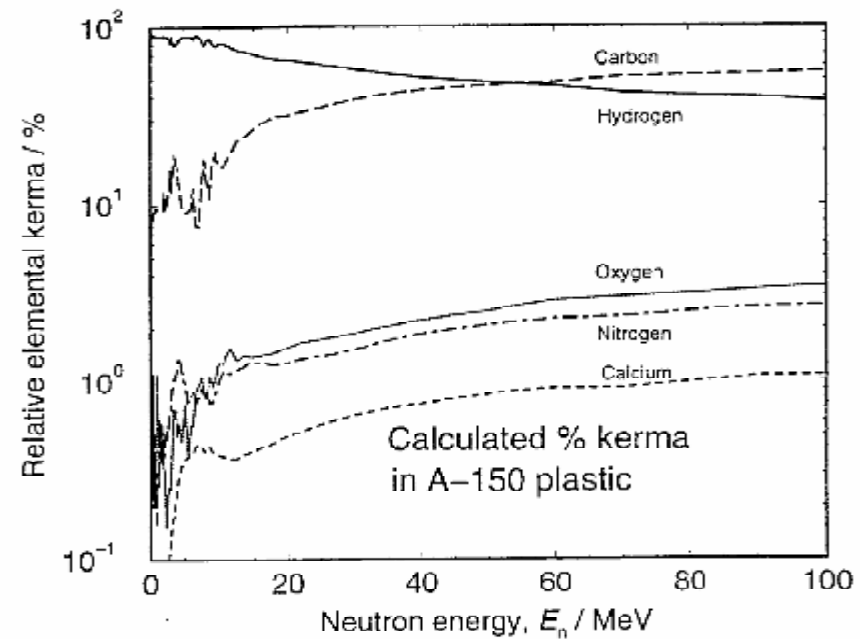
	SYMBOL	VALUE	UNCERTAINTY (%)*
Electrometer reading	M		0.1
Reading correction factors	P		0.2
Air kerma calibration factor	N_K		1.0
Absorption and scattering correction factor (A150)	A_{wall}	0.983 – 0.992 ⁺	0.2
Ratio of mean mass energy absorption coefficients in calibration beam	$[(m_{\text{en}}/r)_{\text{A150,air}}]_{\text{c}}$	1.101	0.5
Displacement correction factor	d_T	0.980 – 0.993 ⁺	0.3
Ratio of average energies required to create an ion pair in an A150/TE-gas chamber	$(W_{\text{TE}}/e)_n / (W_{\text{TE}}/e)_c$	1.06	2.0
Ratio of gas-to-wall absorbed dose conversion factor to ratio of mean restricted collision mass stopping powers	$(r_{\text{A150,TE}})_n / [(\bar{L}/r)_{\text{A150,TE}}]_{\text{c}}$	1.00	2.0
Ratio of neutron kerma	$(K_{\text{t,A150}})_n$	0.95	3.0
Overall uncertainty			4.3

*Values for different chambers are given in the original protocols

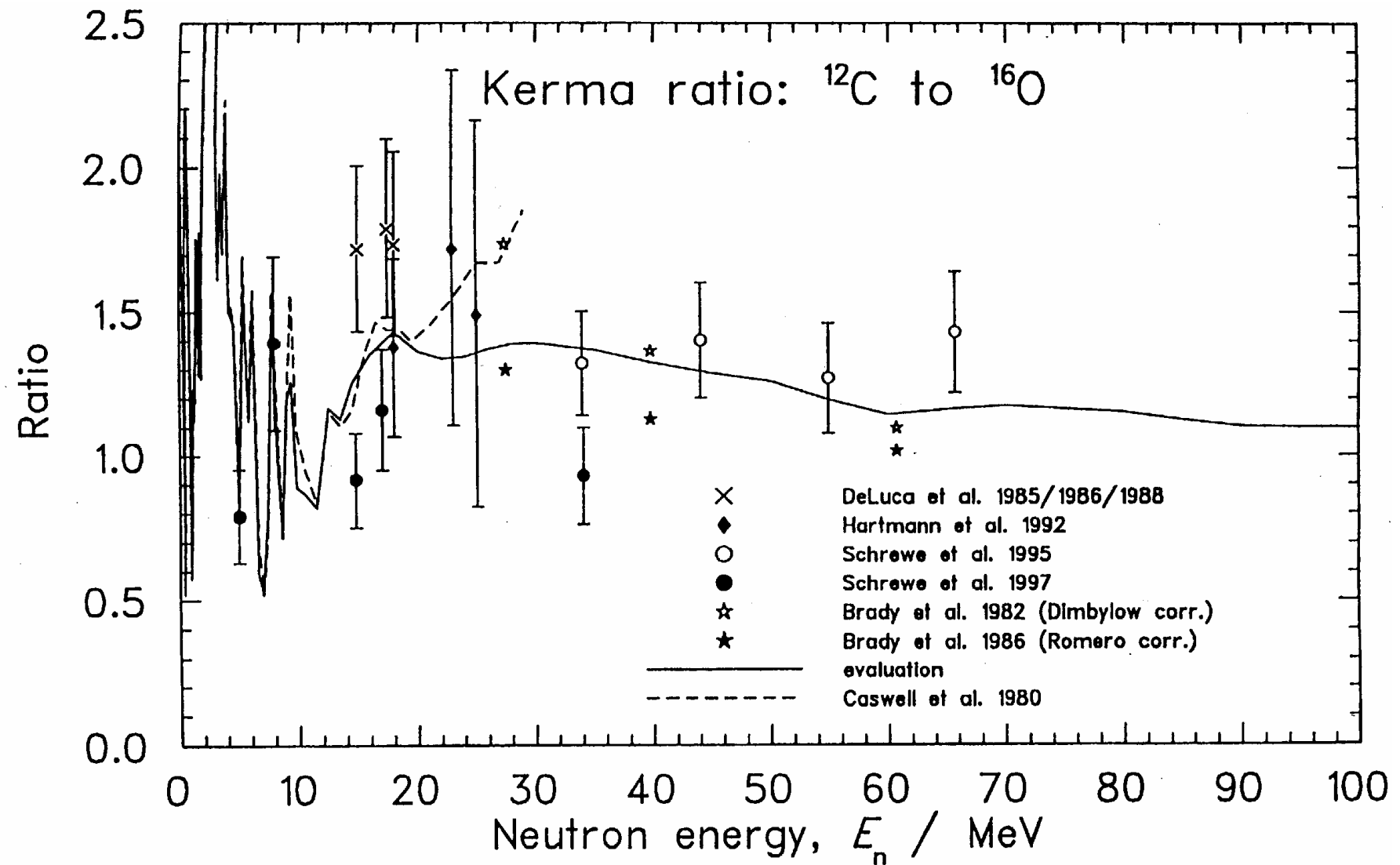
*1 standard deviation



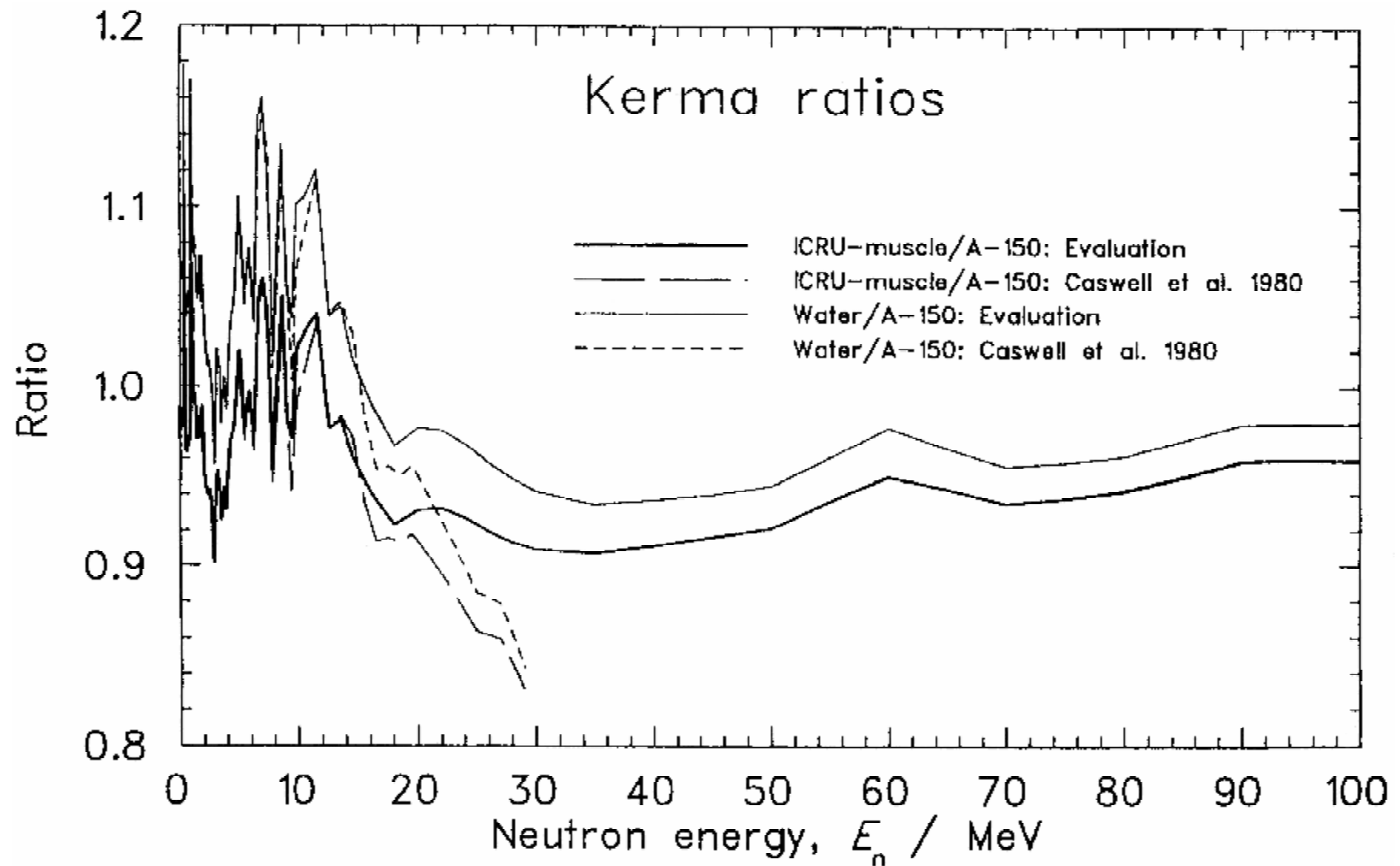
RELATIVE KERMA



KERMA RATIOS



KERMA RATIOS



FLUENCE-WEIGHTED DOSIMETRY QUANTITIES

	HARPER-B	iTL-J	iTL-R	iTL-B	FNAL-B	FNAL-A
$\bar{E}_{F,n}$ (MeV)	15.1	30.8	30.3	29.2	24.3	27.4
k_F (C)	2.137	3.453	3.373	3.272	2.801	3.063
k_F (O)	1.639	2.693	2.643	2.551	2.179	2.403
k_F (A150)	6.102	7.258	7.151	7.012	6.475	6.805
k_F (muscle)	5.798	6.779	6.692	6.559	6.087	6.393
k_F (water)	6.116	7.047	6.960	6.825	6.359	6.665
k_F (C/O)	1.304	1.282	1.276	1.282	1.285	1.275
k_{Φ}^m (C/O)	1.59 ± 0.25	1.35 ± 0.09			1.36 ± 0.19	
k_F (M/A)	0.950	0.934	0.936	0.935	0.940	0.939
k_{Φ}^m (M/A)	0.90 ± 0.03	0.92 ± 0.02			0.92 ± 0.04	
k_F (W/A)	1.002	0.971	0.973	0.973	0.982	0.979

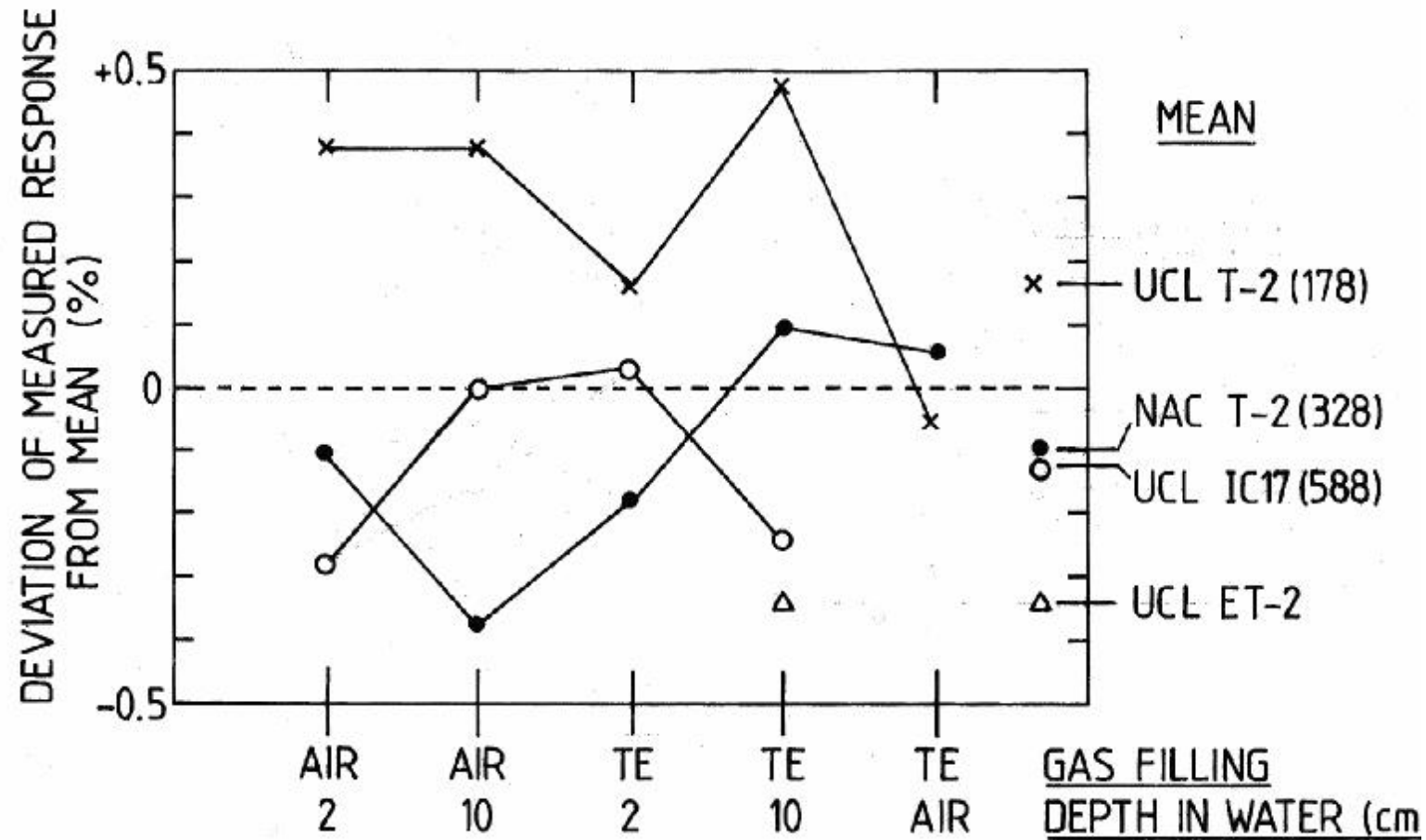
A: Awschalom et al. (1983) – inferred
B: Böhm et al. (1999) – calculated
J: Jones et al. (1992) – measured
R: Ross et al. (1992) – calculated

Harper: Harper Hospital
iTL: iThemba LABS
FNAL: Fermilab

m: measured A: A-150 M: Muscle W: Water



NEUTRON DOSIMETRY COMPARISON



NEUTRON DOSIMETRY PROCEDURES (I)

► ANNUALLY

- (1) Farmer ionization chambers (FIC) calibrated
 - ☪ National Metrology Laboratory
 - ☪ air kerma (dose to water available)
- (2) TE chambers calibrated against FIC
 - ☪ ^{60}Co calibration jig at iThemba LABS
 - ☪ in air
 - ☪ TE gas flow
- (3) Neutron beam monitors calibrated with Exradin T2 ionization chambers
 - ☪ water phantom
 - ☪ dose maximum (2 cm)
 - ☪ TE gas flow

NEUTRON DOSIMETRY PROCEDURES (II)

► **ANNUALLY** continued

(4) Constancy chamber (FWT IC17A) calibrated

- ⌚ in neutron beam
- ⌚ acrylic constancy phantom
- ⌚ 6.5 cm depth
- ⌚ ambient air

► **DAILY**

(5) Constancy check

- ⌚ FWT IC17A chamber

(6) If response differs by more than $\pm 2\%$ from calibration value

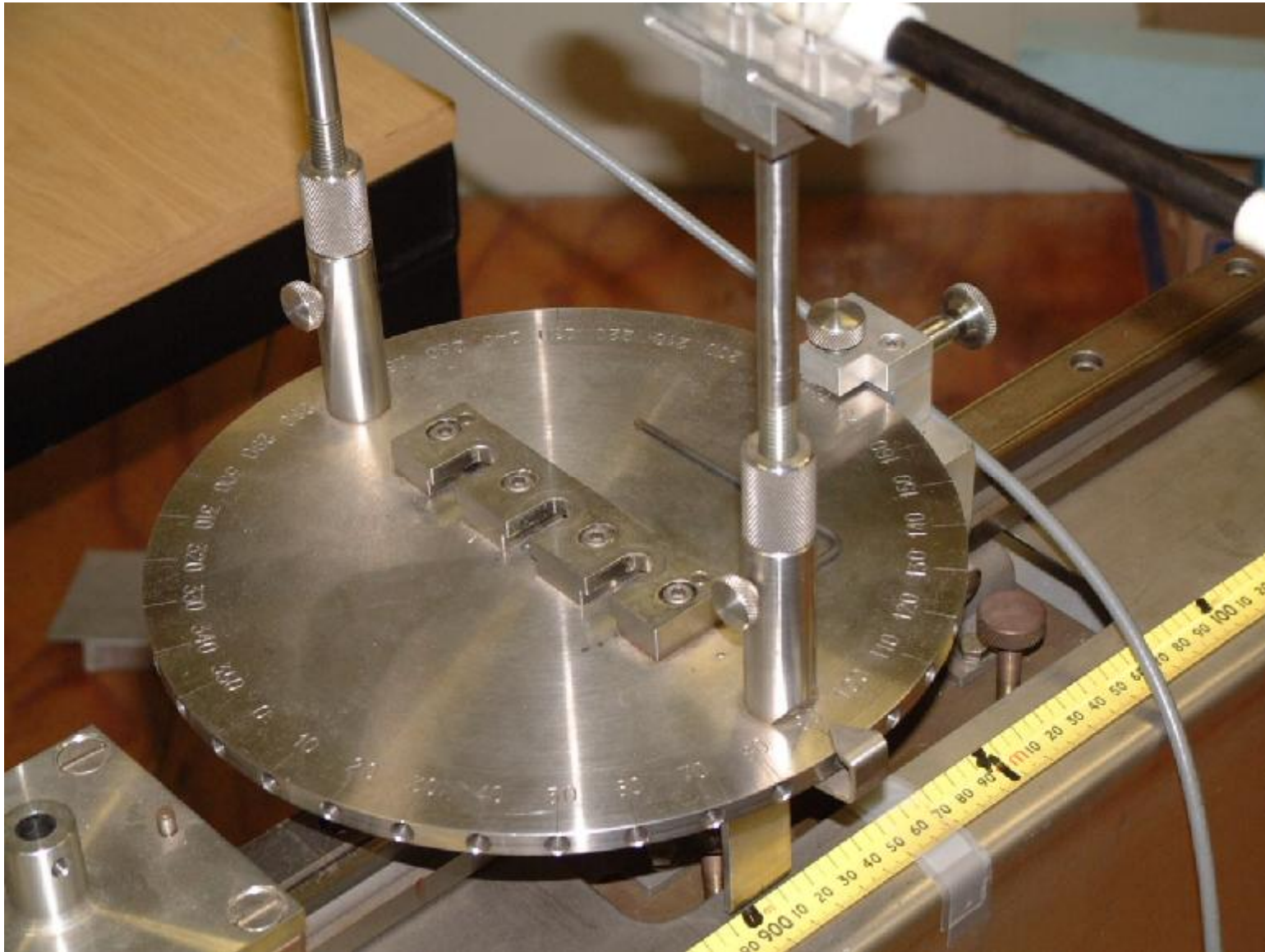
- ⌚ back to step **(3)** above

^{60}Co CALIBRATION JIG

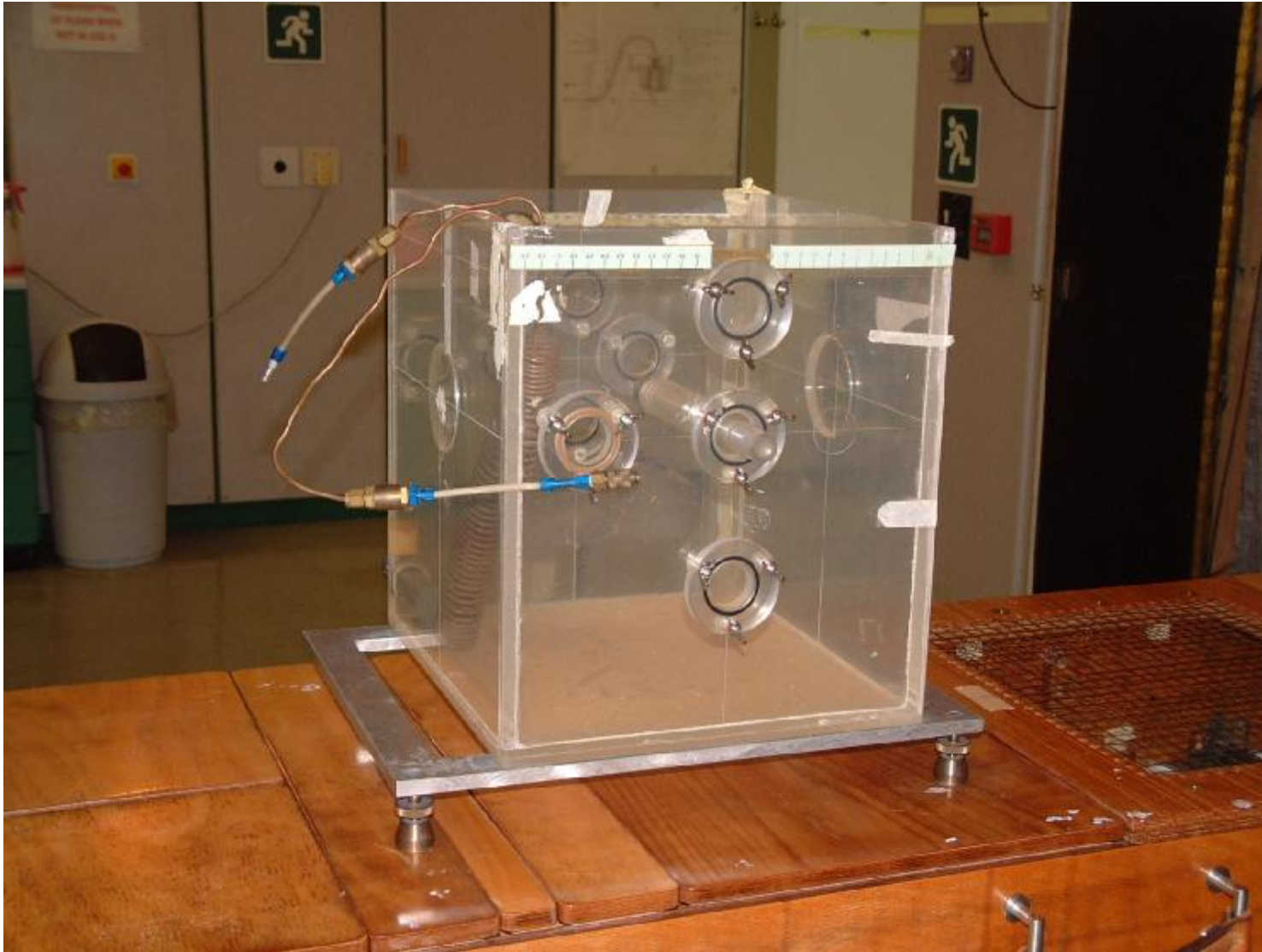
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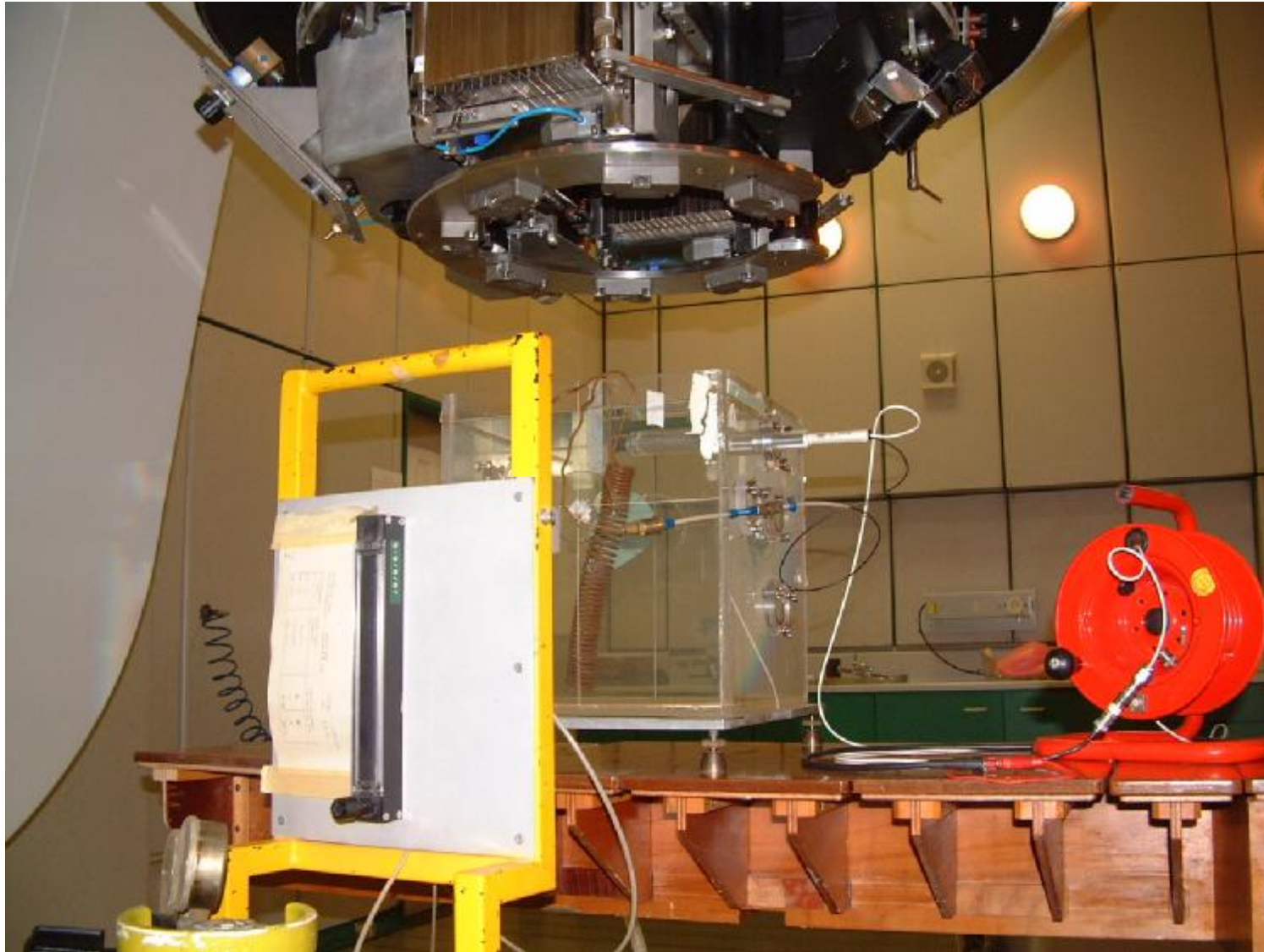
^{60}Co CALIBRATION JIG



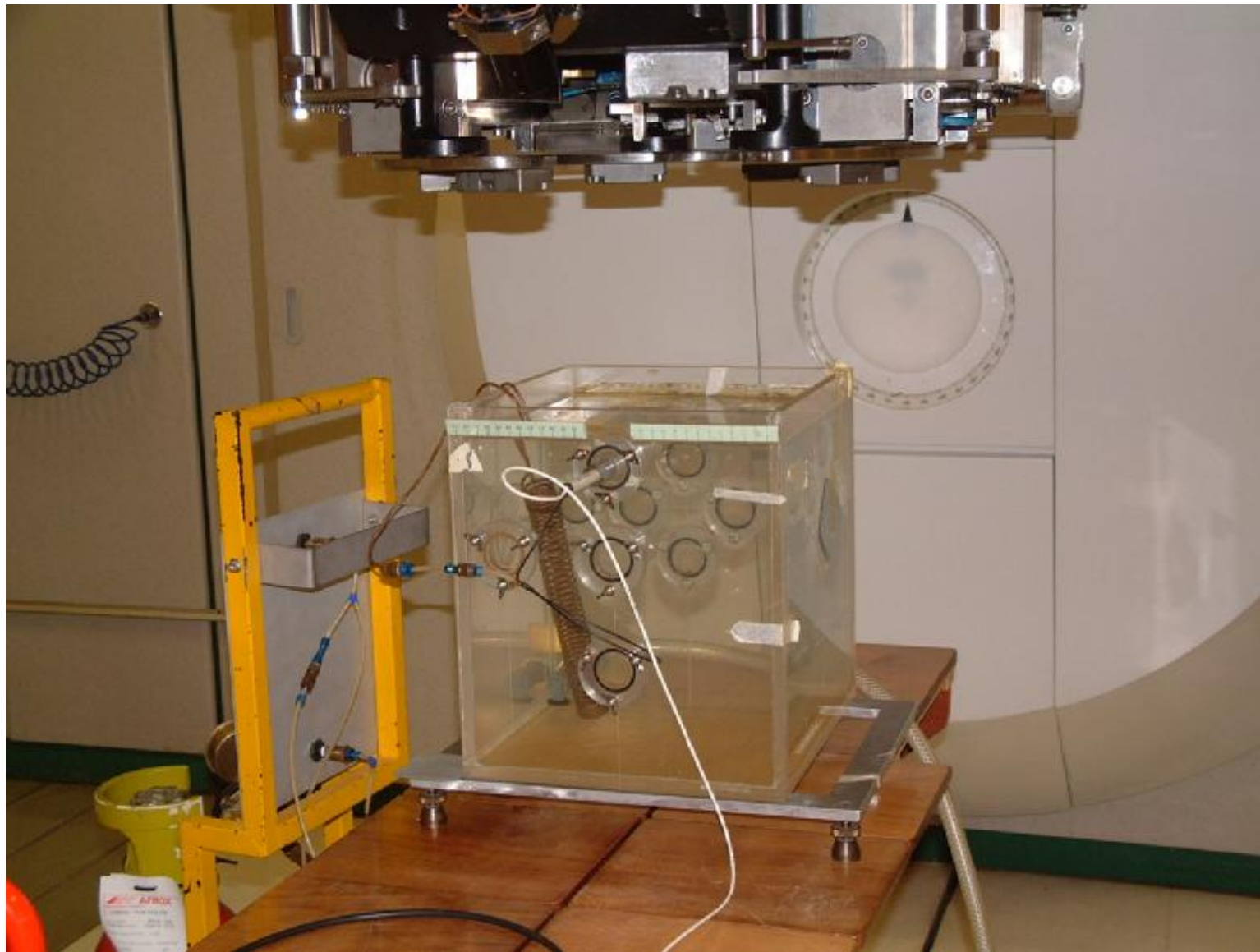
WATER PHANTOM



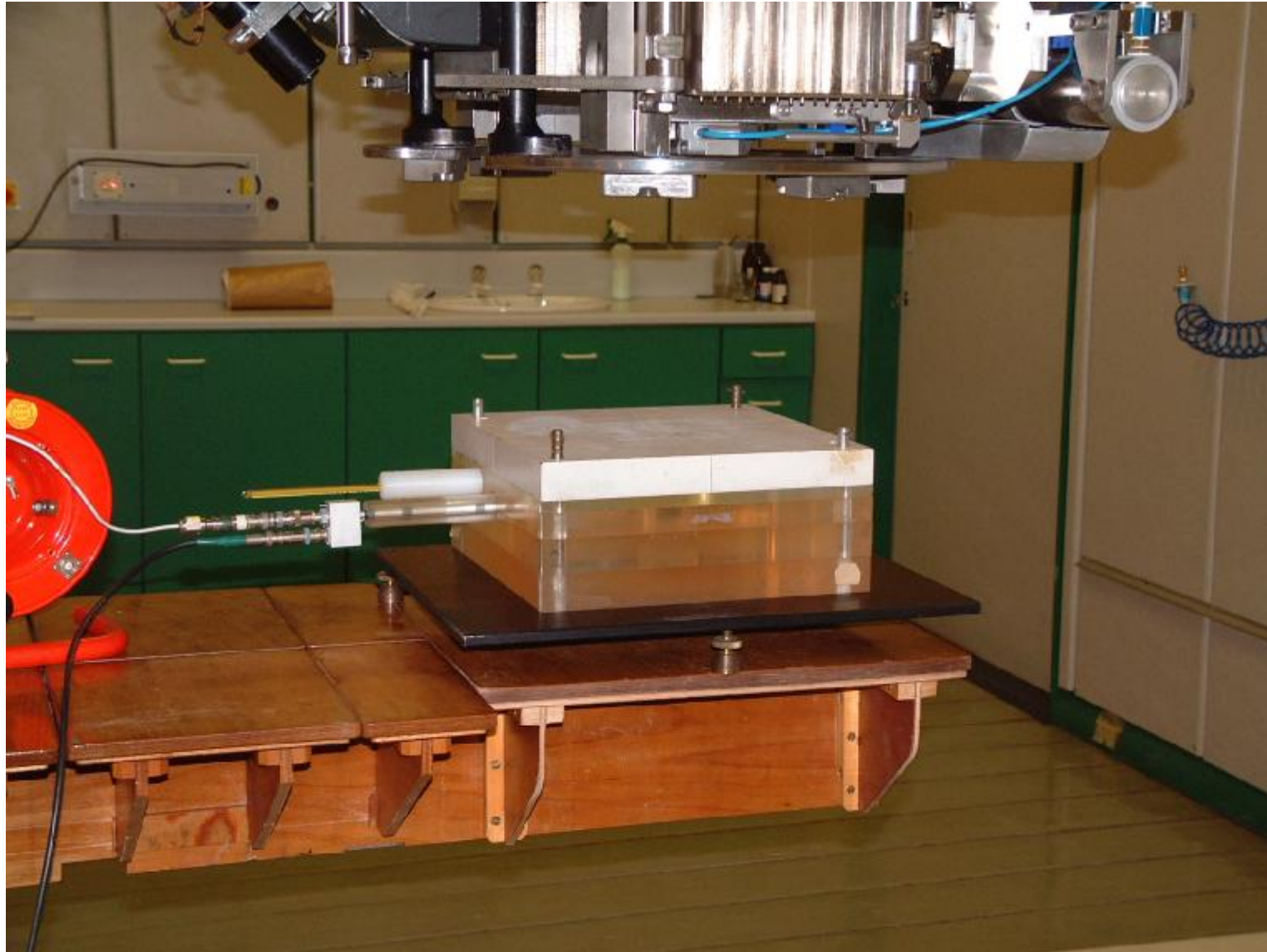
BEAM MONITOR CALIBRATION

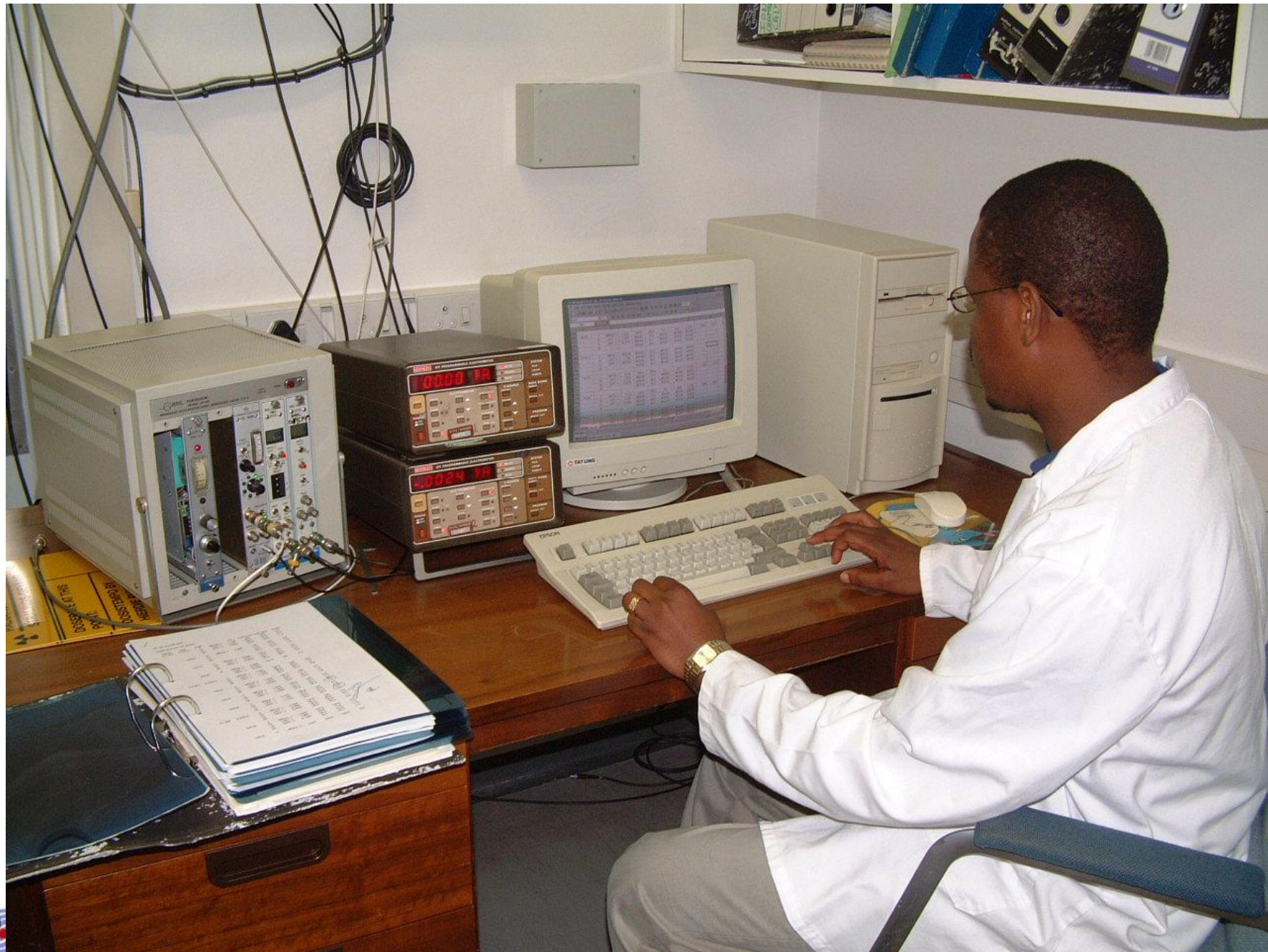


BEAM MONITOR CALIBRATION



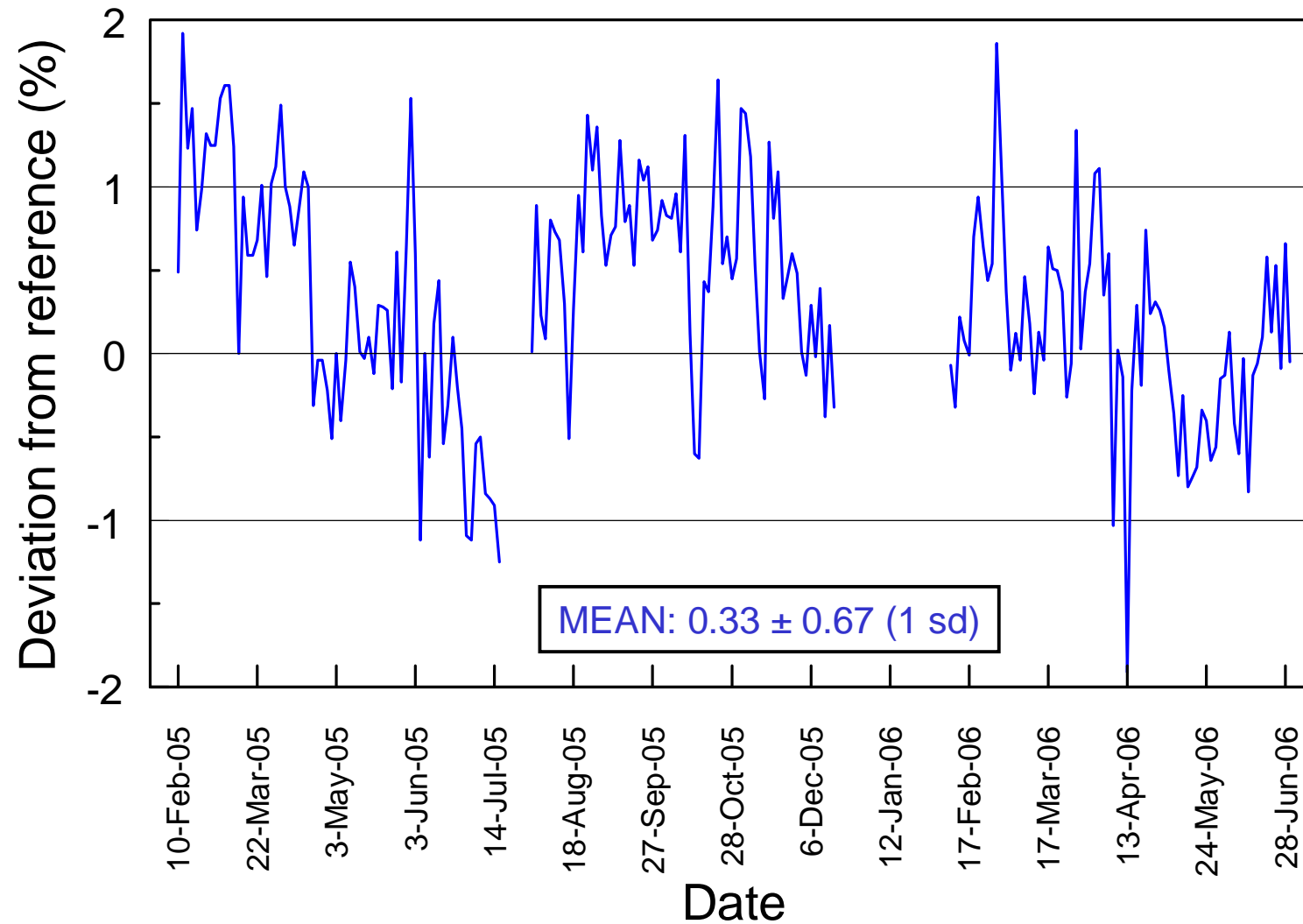
CONSTANCY CHECK



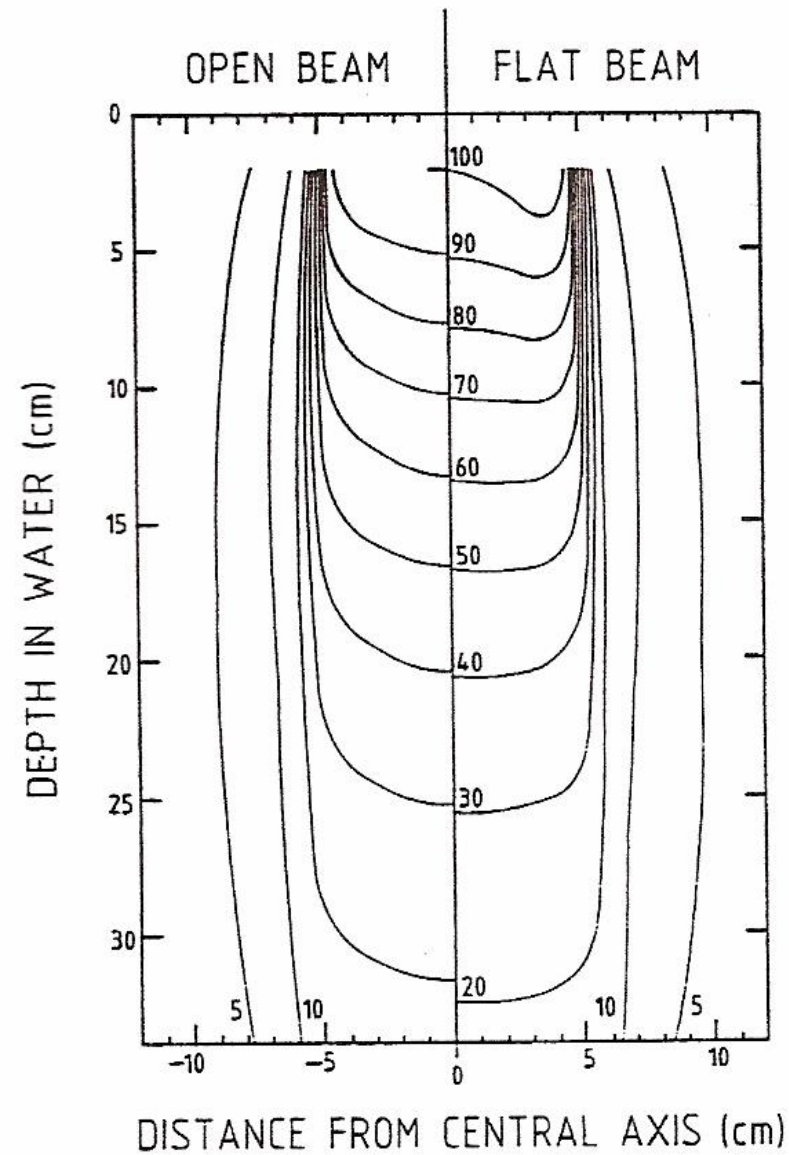




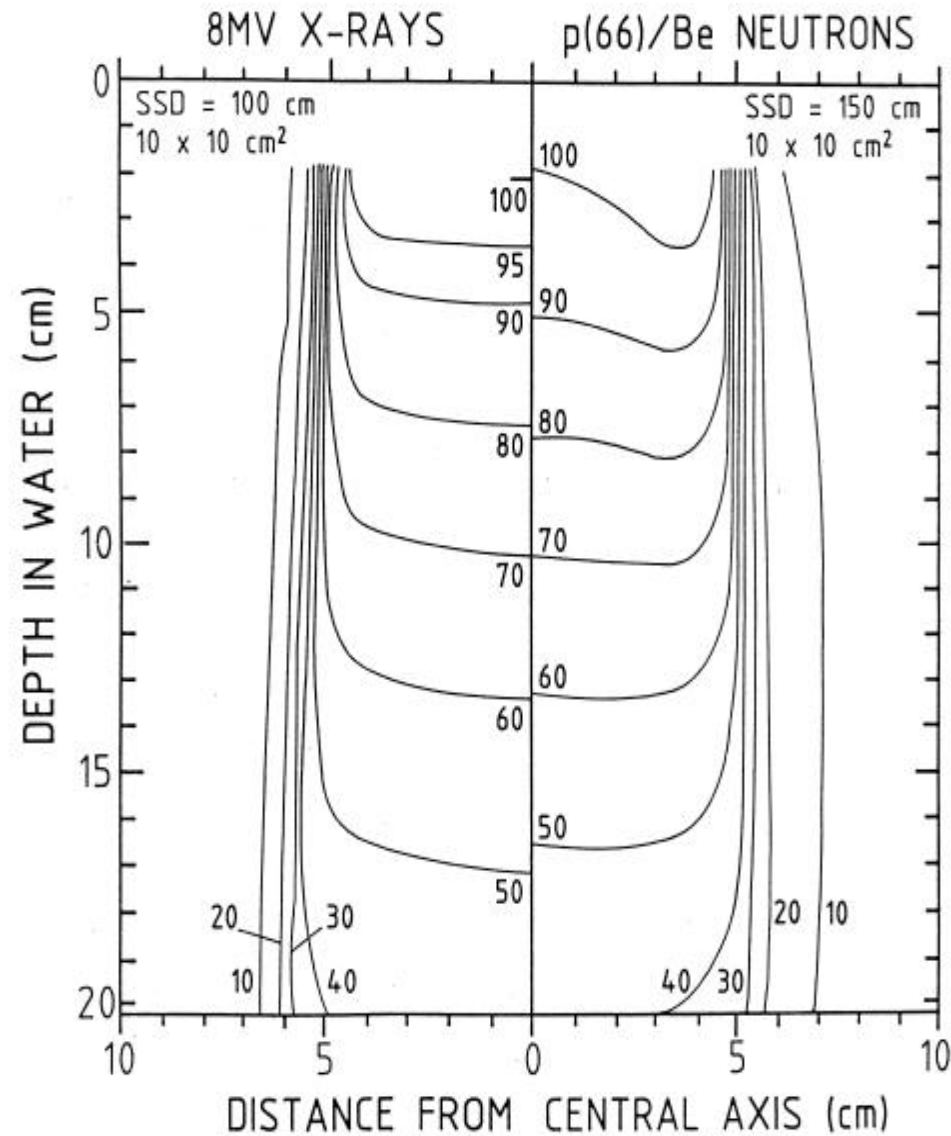
CONSTANCY CHECKS



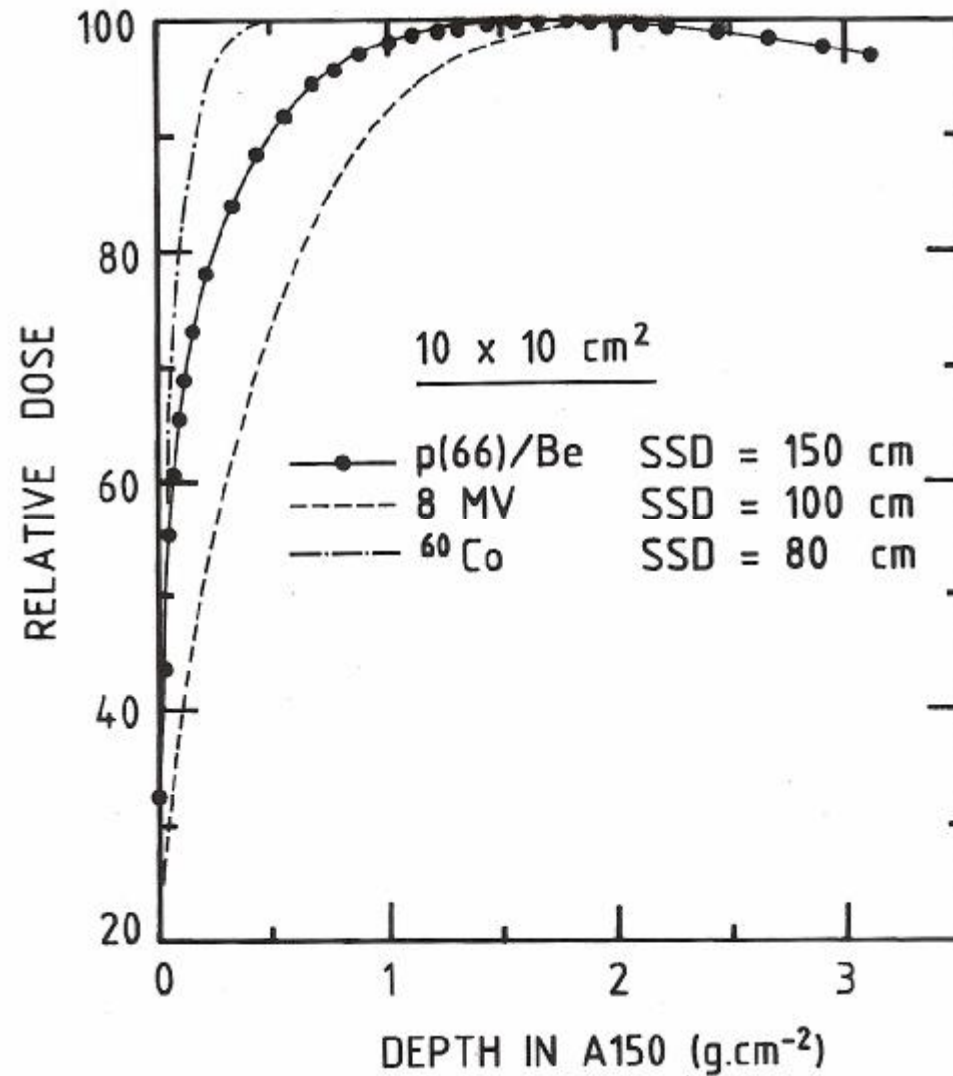
BEAM FLATTENING



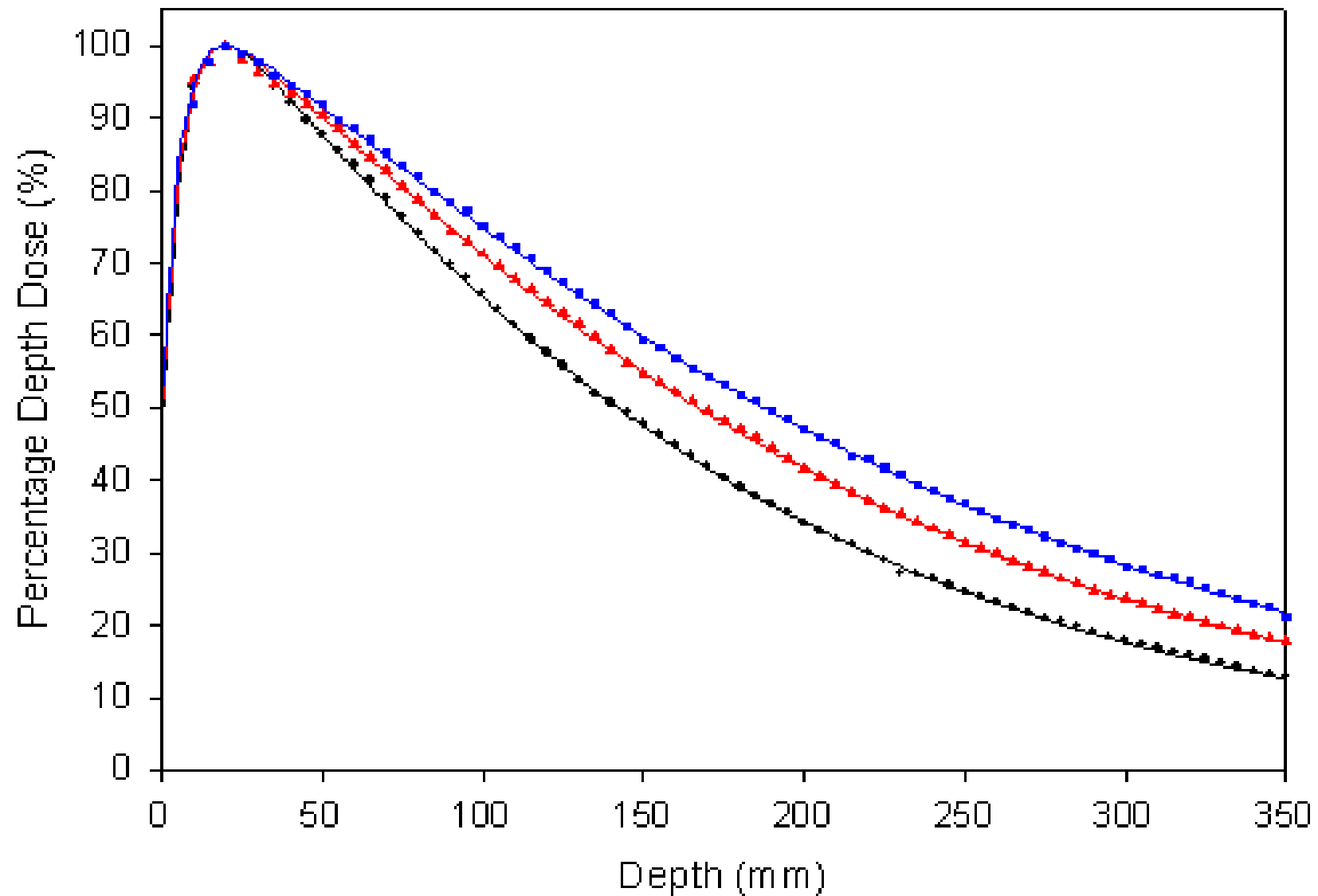
ISODOSE CURVES



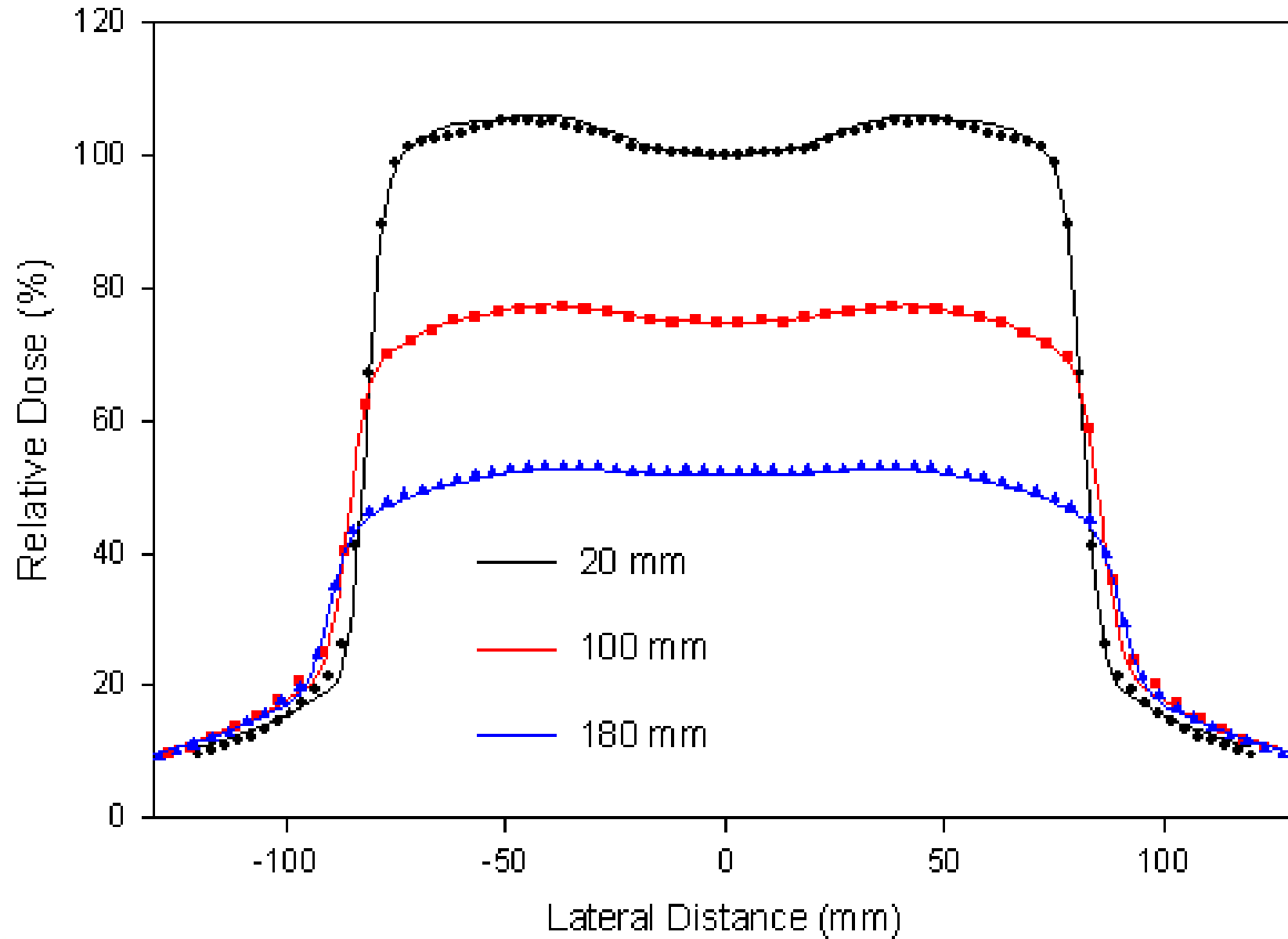
DOSE BUILD-UP



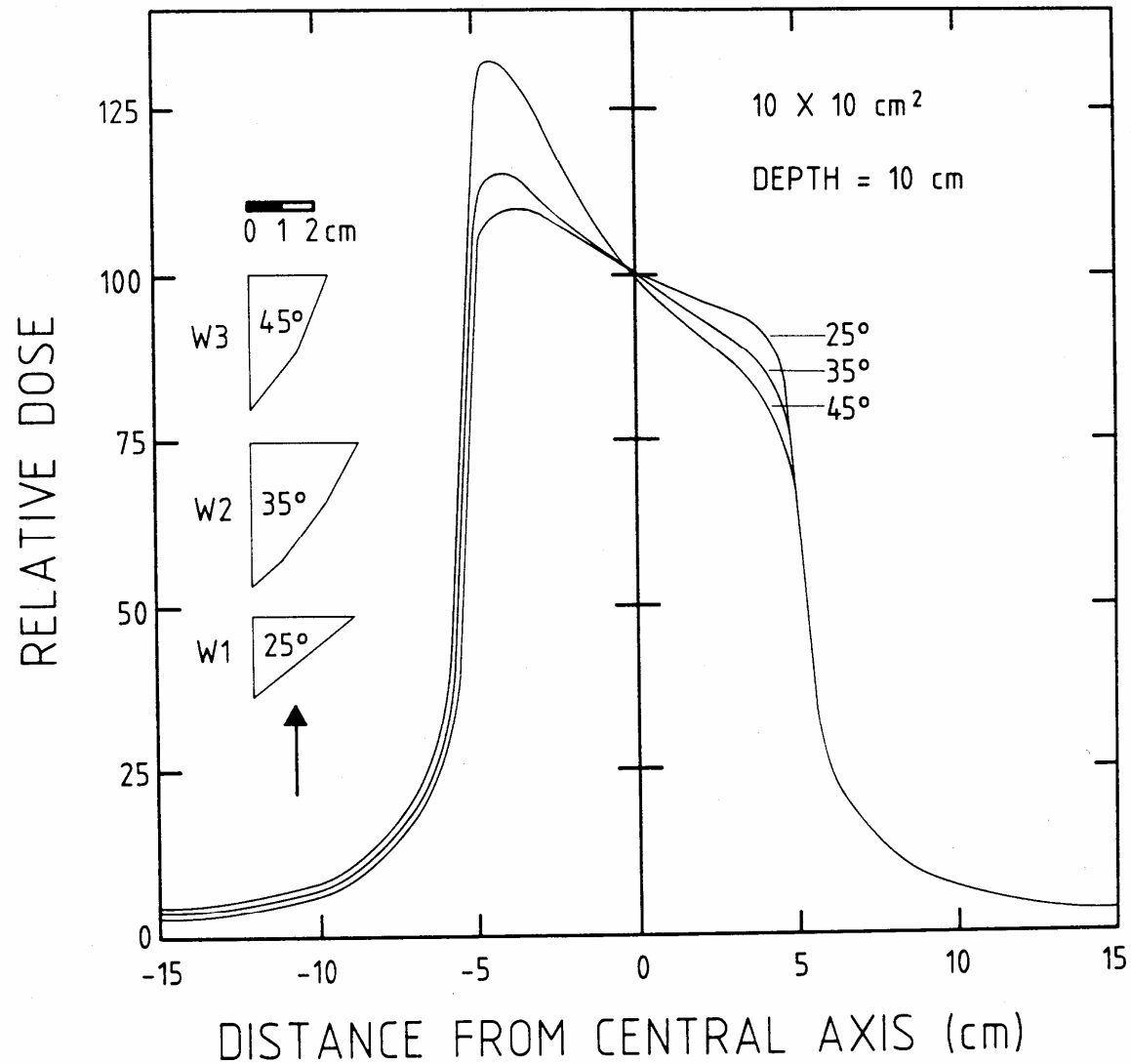
DEPTH DOSES



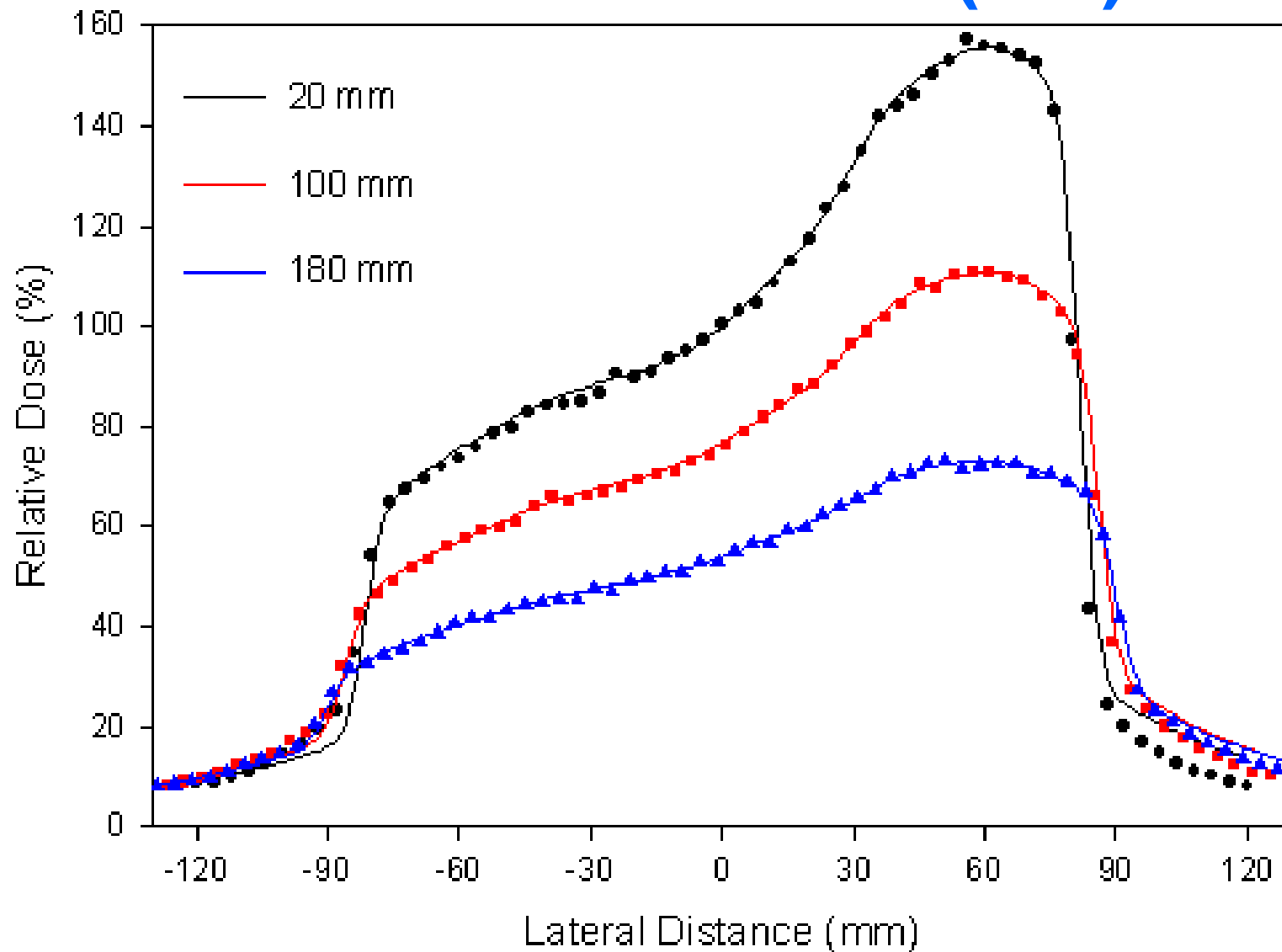
BEAM PROFILES



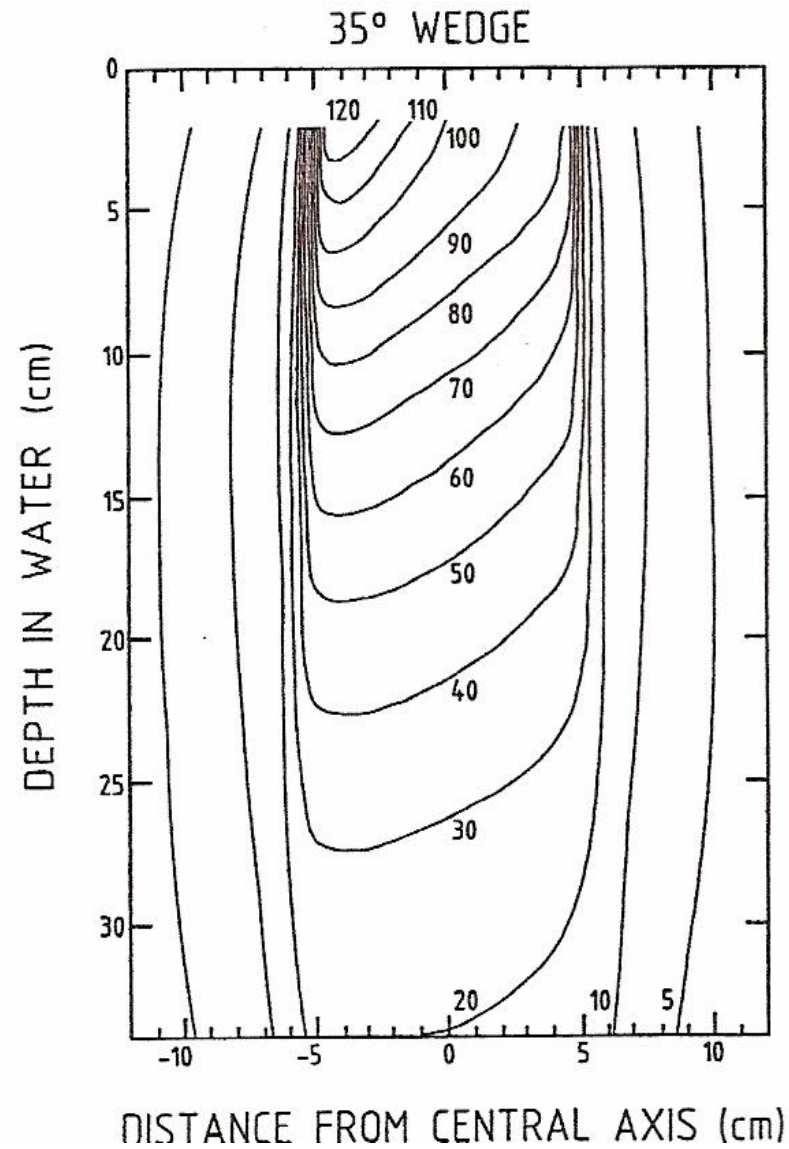
TUNGSTEN WEDGES



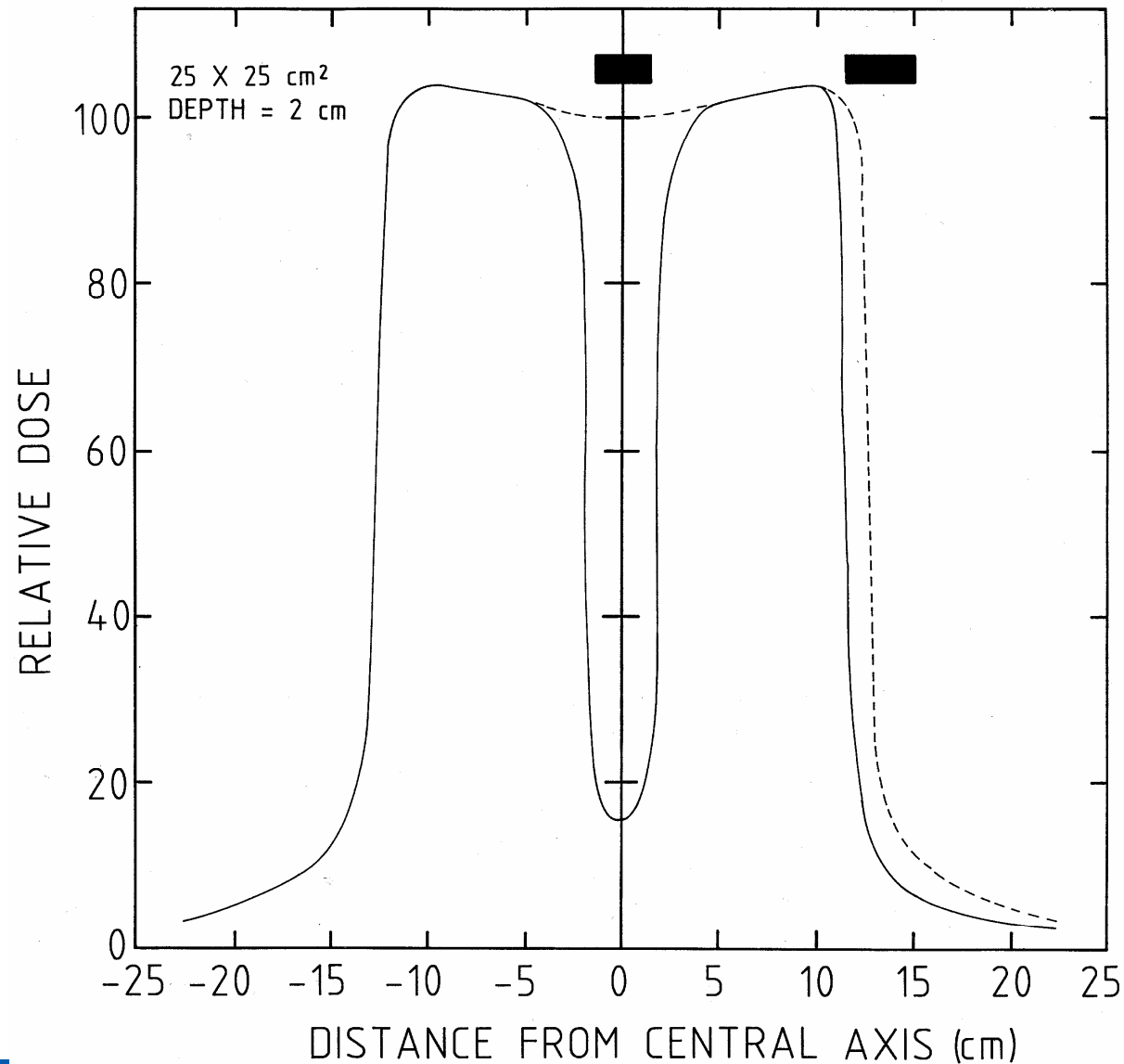
TUNGSTEN WEDGE (25°)



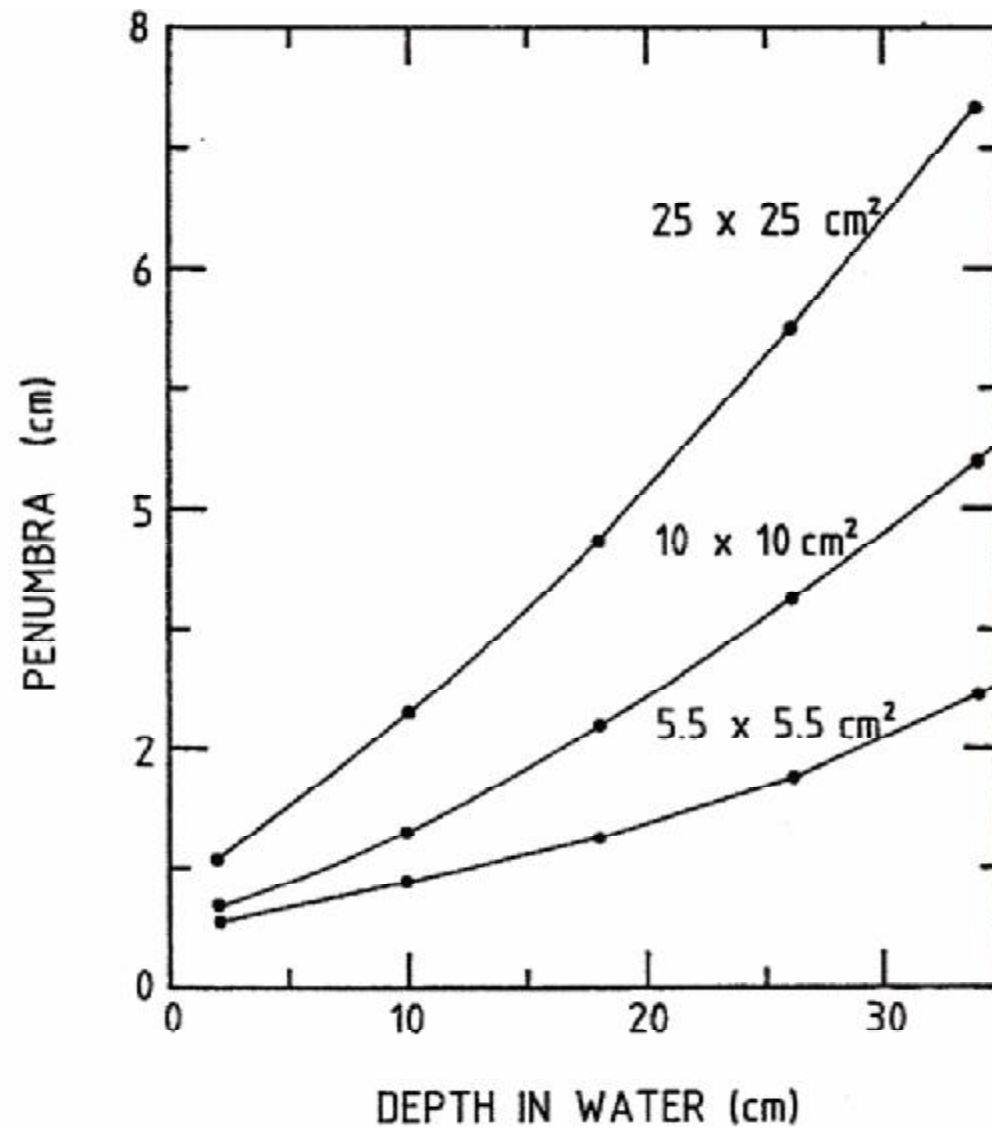
WEDGED FIELD



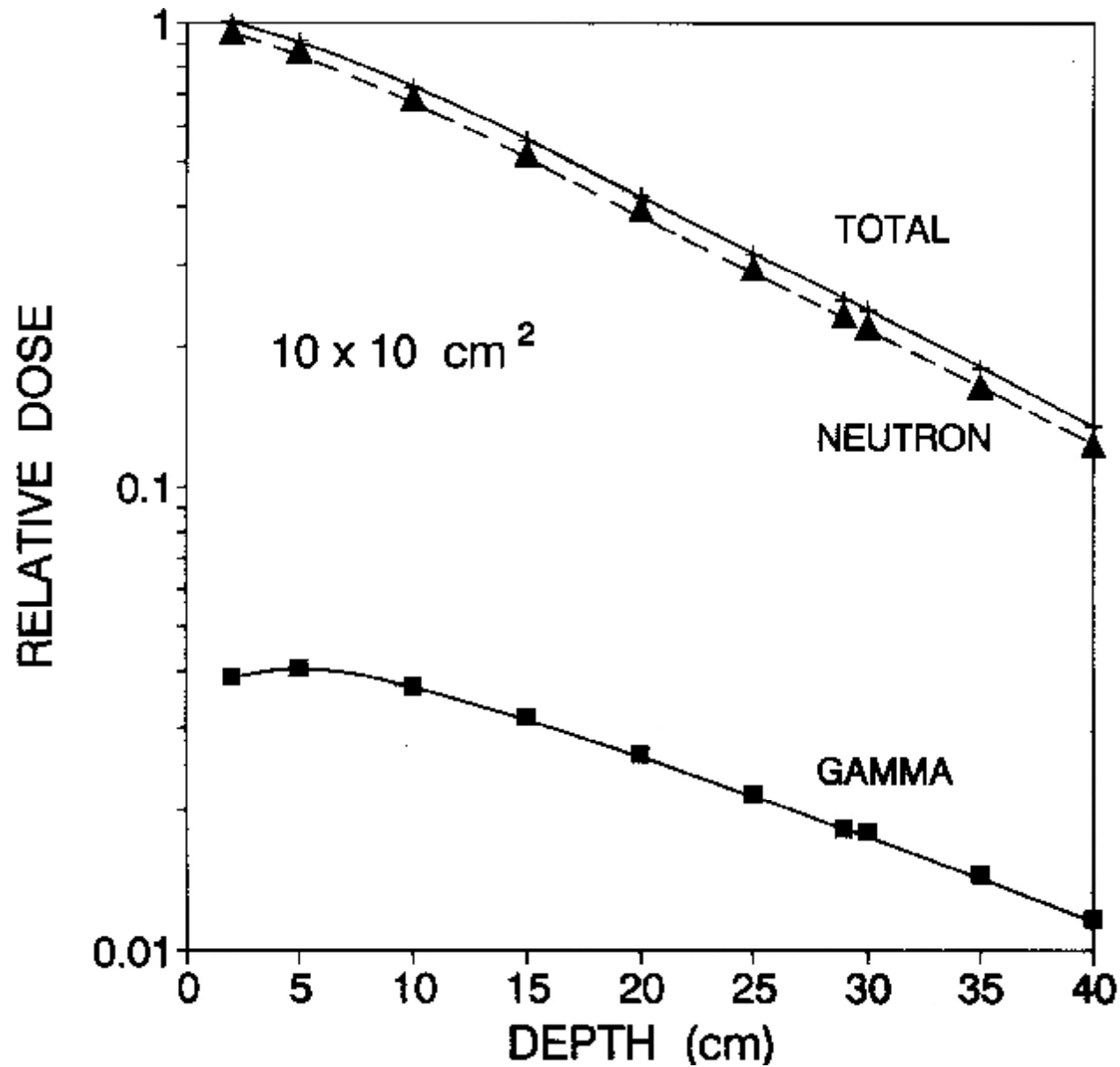
TUNGSTEN BEAM BLOCKS



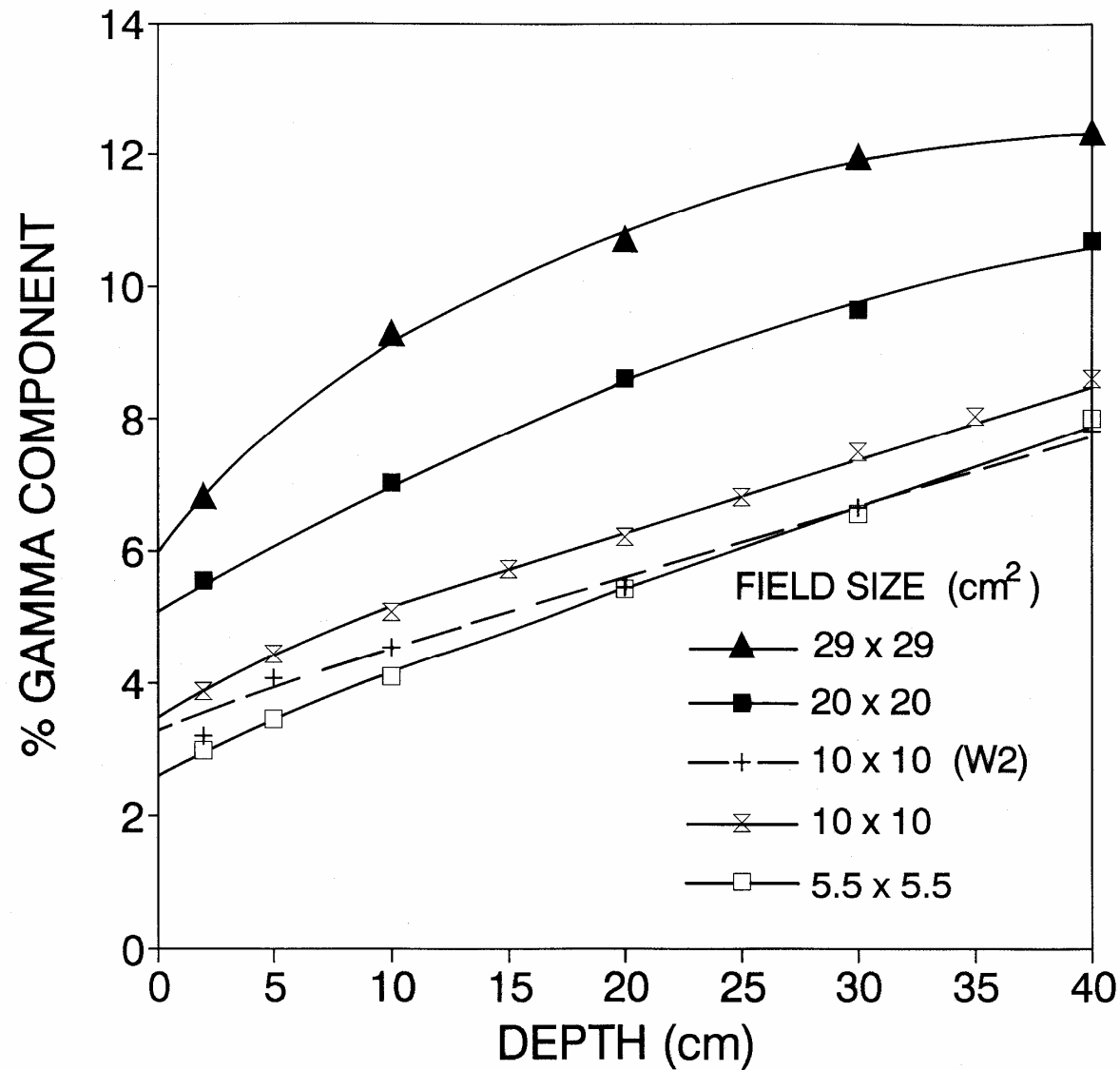
PENUMBRAE



GAMMA DOSE



GAMMA COMPONENT



PROTON DOSIMETRY

- ▶ Much simpler than neutron dosimetry
- ▶ Match electron density of materials and tissue
- ▶ Water is reference material (consistent with conventional therapy protocols)
- ▶ Ionization chambers
 - † ambient air gas filling
 - † correction factors well known
 - † w-value problematic [energy to create ion pair in air]
- ▶ Calorimetry
- ▶ Faraday cup
- ▶ ^{12}C activation: $[^{12}\text{C}(\text{p}, \text{pn})^{11}\text{C}]$

REFERENCE PROTON DOSIMETRY

- ▶ Calorimeters are the instruments of choice for determining reference absorbed dose
- ▶ Practical instruments are ionization chambers with traceable ^{60}Co calibration coefficients
 - † two proton dosimetry protocols are in current use:
ICRU Report 59 (ICRU, 1998)
IAEA TRS-398 (IAEA, 2000)
- ▶ Similar techniques are used for reference dosimetry for passively modified beams and for scanned beams
- ▶ Other methods for reference dosimetry include fluence determinations using
 - † Faraday cups
 - † ^{12}C activation
 - ⌘ converted to dose using appropriate stopping powers in water

PROTON DOSIMETRY PROTOCOLS (I)

- ▶ J T Lyman, M Awshalcom, H Bichsel, G T Y Chen, J Dicello, P Fessenden, M Goitein, G Lam, J C McDonald, A R Smith, R TenHaken, L Verhey, S Zink

PROTOCOL FOR HEAVY CHARGED-PARTICLE THERAPY BEAM DOSIMETRY

AAPM REPORT NO. 16, 1986

(American Association of Physicists in Medicine)

- ▶ S Vynckier, D E Bonnett and D T L Jones

CODE OF PRACTICE FOR CLINICAL PROTON DOSIMETRY

Radiother. Oncol. 20 (1991) 53-63

- ▶ S Vynckier, D E Bonnett and D T L Jones

SUPPLEMENT TO CODE OF PRACTICE FOR CLINICAL PROTON DOSIMETRY

Radiother. Oncol. 32 (1994) 174-179



PROTON DOSIMETRY PROTOCOLS (II)⁵²

- ▶ L Verhey, H Blattmann, P M DeLuca, D Miller, P Andreo, H Bichsel, D T L Jones and S Vynckier

CLINICAL PROTON DOSIMETRY PART I: BEAM PRODUCTION, BEAM DELIVERY AND MEASUREMENT OF ABSORBED DOSE

ICRU Report 59, 1998

(International Commission on Radiation Units and Measurements)

- ▶ P Andreo, D T Burns, K Hohlfeld, M S Huq, T Kanai, F Laitano, V G Smythe and S Vynckier

ABSORBED DOSE DETERMINATION IN EXTERNAL BEAM RADIOTHERAPY: AN INTERNATIONAL CODE OF PRACTICE BASED ON STANDARDS OF ABSORBED DOSE TO WATER

Technical Reports Series No. 398, 2000

(International Atomic Energy Agency)

- ▶ D T L Jones

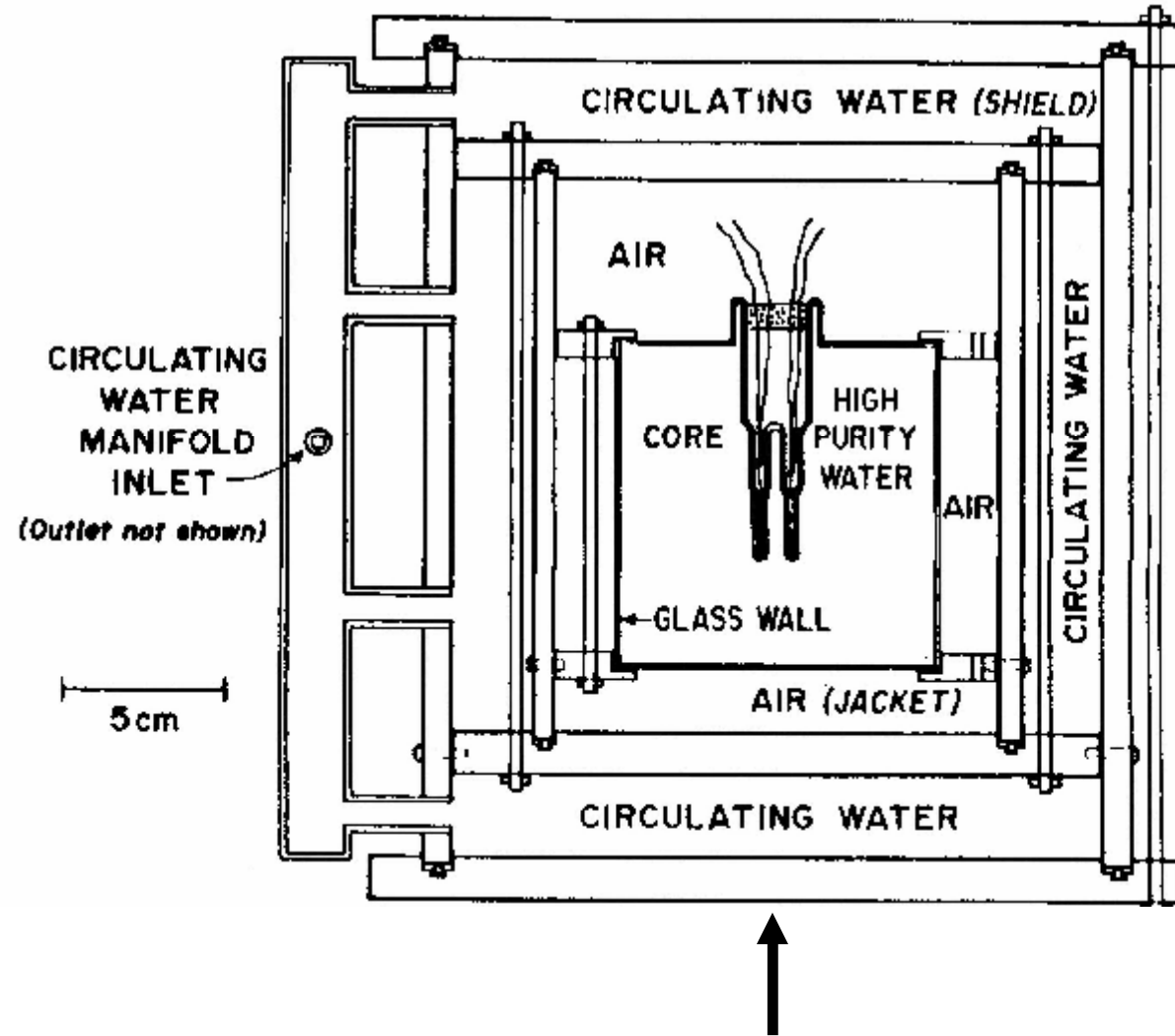
REFERENCE DOSIMETRY FOR FAST NEUTRON AND PROTON THERAPY

Radiochim. Acta 89 (2001) 279-287

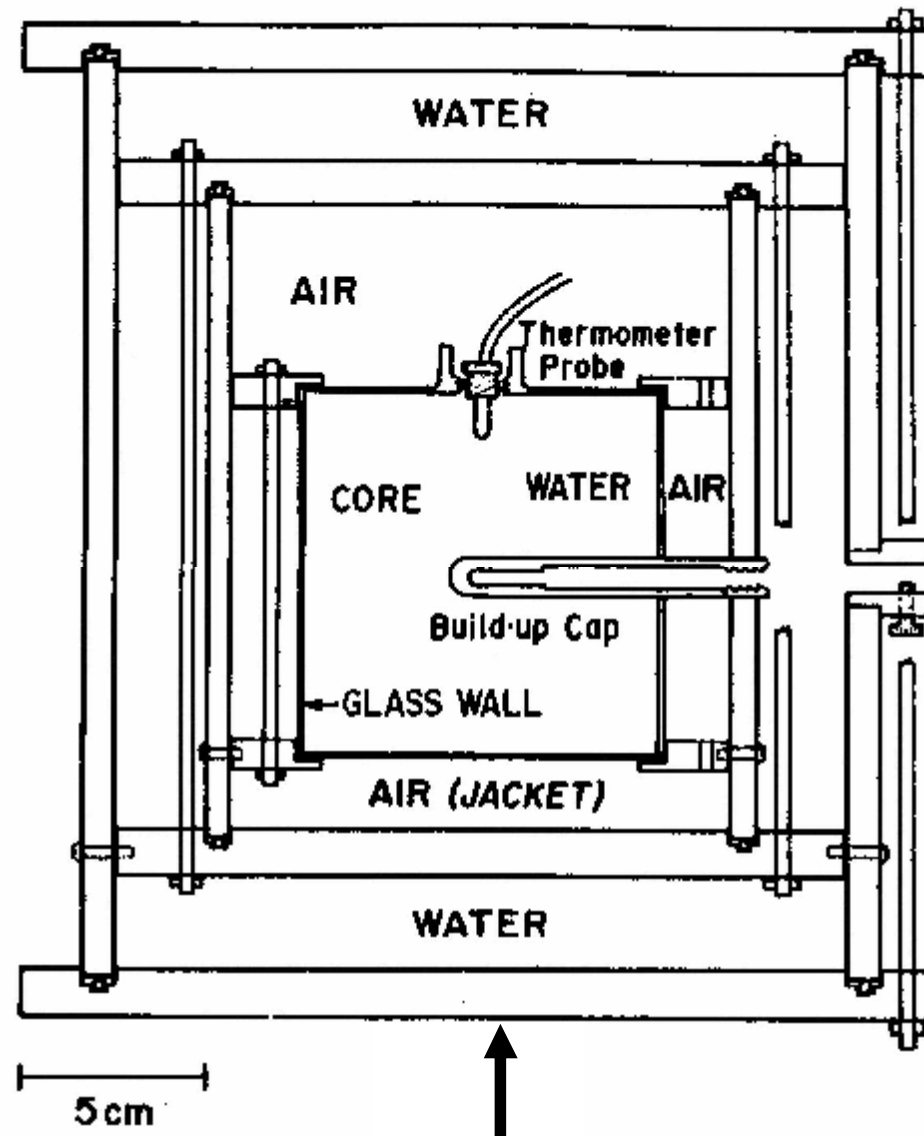


WATER CALORIMETER

$$D_w = \Delta T \ k \ (1+T_D) \ s_{w,cal}$$



DUMMY CALORIMETER



FARADAY CUP

$$D_w = (n/a) s_w (1.602 \times 10^{-10})$$

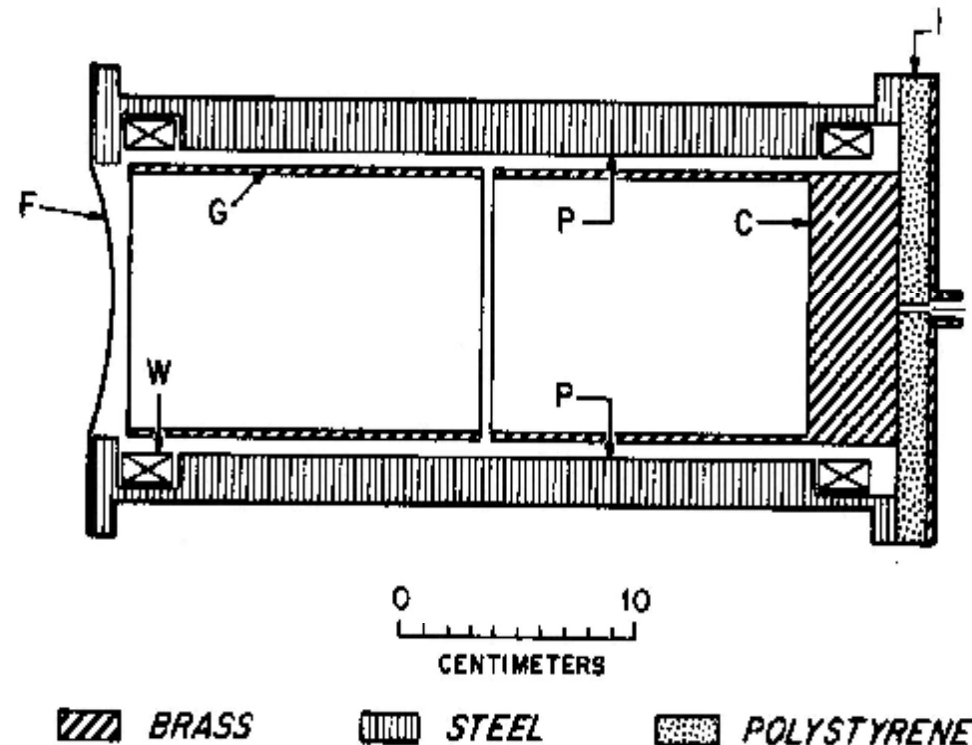


FIG. 2. Schematic of Faraday cup. C is the collecting cup, F is the entrance window, G is a guard ring for electric field application, W are windings for magnetic field application, P is the steel casing, I is a polystyrene insulator.

CARBON ACTIVATION

$^{12}\text{C}(p,pn)^{11}\text{C}$ (20.5 min)

$$D_w = \frac{A_0}{\sigma(E) N \lambda} (1 - e^{-\lambda t})^{-1} e^{-\lambda t} s_w (1.602 \times 10^{-10})$$

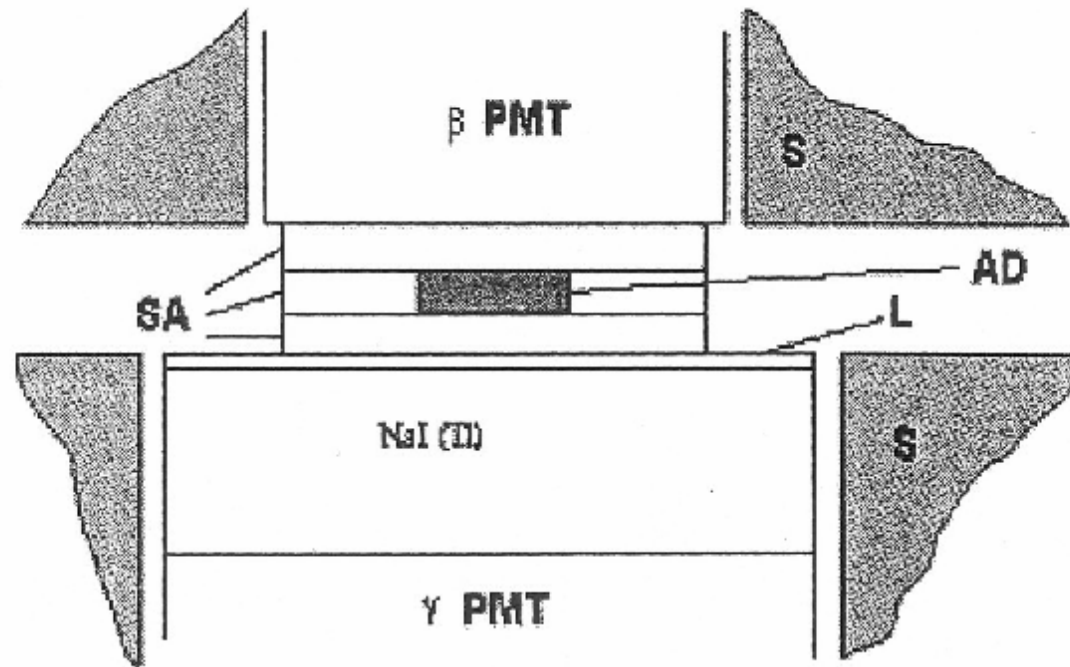


FIG. 4. Schematic diagram of the counting unit's scintillator assembly. SA—scintillator assembly; AD—activated detector; L—thin aluminum lid for alpha- and beta-particle protection; NaI(Tl)—NaI(Tl) crystal; β PMT and γ PMT—photomultipliers in the β and γ counting channels, respectively; S—radiation and light shielding.

IONIZATION CHAMBER DOSIMETRY

The absorbed dose D_g to the mass of gas m_g in the cavity of an ionization chamber is:

$$D_g = \frac{Q}{m_g} (W_g / e) \quad (1)$$

If the ionization chamber satisfies the Bragg-Gray principle [small or homogeneous chamber, absorbed dose in cavity is deposited entirely by charged particles crossing it] then the dose to wall material D_m is:

$$D_m = D_g s_{m,g} = \frac{Q}{m_g} (W_g / e) s_{m,g} \quad (2)$$

Q	Charge produced in ionization chamber cavity gas
W_g/e	Mean energy to form an ion pair in the gas
$s_{m,g}$	Mean ratio of mass electronic stopping powers of the wall material to the gas

ICRU REPORT 59 (1998)

Clinical Proton Dosimetry Part I:
Beam Production, Beam Delivery and
Measurement of Absorbed Dose

► Also includes information on

- † rationale for proton therapy
- † history of proton therapy
- † dosimetric quantities and units
- † beam production
- † beam modification
- † beam monitoring
- † relative dosimetry

PROTON DOSIMETRY- ICRU 59 (I)

Dose to water in the proton beam:

$$D_{w,p} = M_p^{\text{corr}} N_{D,\text{air}} C_p$$

M_p^{corr} chamber electrometer reading corrected for ion recombination, temperature and pressure and other response modifying quantities

$N_{D,\text{air}}$ absorbed dose calibration factor

C_p chamber factor

PROTON DOSIMETRY - ICRU 59 (II)

60

$$= N_{D,air} \frac{N_k (1 - g) A_{wall} A_{ion}}{S_{wall,air} (\mu_{en}/\rho)_{air,wall} K_{hum}}$$

N_k	air kerma calibration factor
g	fraction of initial secondary electron energy expended in radiative interactions (bremsstrahlung) in air (= 0.003 for ^{60}Co)
A_{wall}	correction for attenuation and scatter in the wall and build-up
A_{ion}	correction for ion recombination in the gas of the ionization chamber when exposed in air in the calibration ^{60}Co beam.
$S_{wall,air}$	mean ratio of restricted mass stopping powers of wall material to gas for secondary electrons for ^{60}Co gamma rays
$(\mu_{en}/\rho)_{air,wall}$	mass energy absorption coefficient for the calibration ^{60}Co gamma rays
K_{hum}	correction factor to account for the difference in response between ambient air and dry air

PROTON DOSIMETRY-ICRU 59 (III)

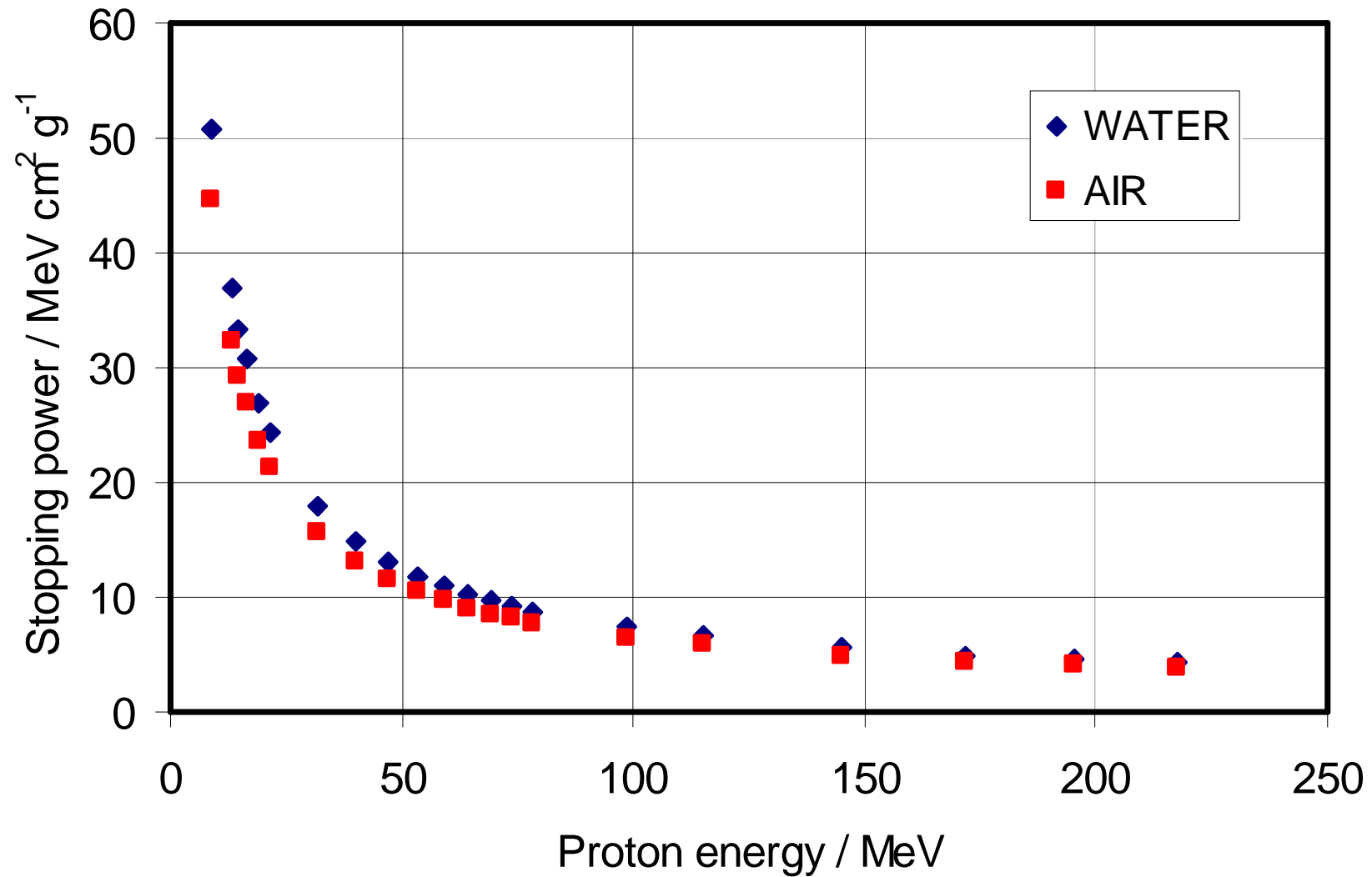
$$C_p = (S_{w,air})_p \frac{(W_{air}/e)_p}{(W_{air}/e)_c}$$

$(S_{w,air})_p$ water to air mass electronic stopping power ratio in the proton beam

$(W_{air}/e)_p$ mean energy to form an ion pair in the ionization chamber air filling for protons

$(W_{air}/e)_c$ mean energy to form an ion pair in the ionization chamber air filling for the calibration beam (^{60}Co)

ICRU 59 STOPPING POWERS



IAEA TRS 398 (2000)

Absorbed Dose Determination in External Beam Radiotherapy:
An International Code of Practice for Dosimetry Based on
Standards of Absorbed Dose to Water

- ▶ Co-60 GAMMA RAY BEAMS
- ▶ HIGH ENERGY PHOTON BEAMS (1-50 MeV)
- ▶ HIGH ENERGY ELECTRON BEAMS (3-50 MeV)
- ▶ LOW ENERGY KILOVOLTAGE X RAY BEAMS (≤ 100 kV)
- ▶ MEDIUM ENERGY KILOVOLTAGE X RAY BEAMS (≥ 80 kV)
- ▶ PROTON BEAMS (50-250 MeV)
- ▶ HEAVY ION BEAMS (He-Ar, ranges: 2-30 cm in water)

PROTON DOSIMETRY-TRS 398 (I)

Dose to water D_{w,Q_0} in ^{60}Co calibration beam (quality Q_0):

$$D_{w,Q_0} = M_{Q_0} N_{D,w,Q_0}$$

Dose to water $D_{w,Q}$ in proton beam (quality Q):

$$D_{w,Q} = M_Q N_{D,w,Q}$$

M chamber electrometer reading corrected for ion recombination, temperature and pressure and other response modifying quantities

N_{D,w,Q_0} calibration factor in terms of absorbed dose to water in ^{60}Co (quality Q_0)

$N_{D,w,Q}$ calibration factor in terms of absorbed dose to water in the proton beam (quality Q)



PROTON DOSIMETRY-TRS 398 (II)

Since no primary dose standards for proton beams are available $D_{w,Q}$ has to be calculated:

$$D_{w,Q} = M_Q N_{D,w,Q_0} k_{Q,Q_0}$$

$$k_{Q,Q_0} = \frac{(s_{w,air})_Q}{(s_{w,air})_{Q_0}} \frac{(w_{air}/e)_Q}{(w_{air}/e)_{Q_0}} \frac{p_Q}{p_{Q_0}}$$

k_{Q,Q_0} chamber specific factor which corrects for differences between ^{60}Co beam quality (Q_0) and proton beam quality (Q) [calculated]

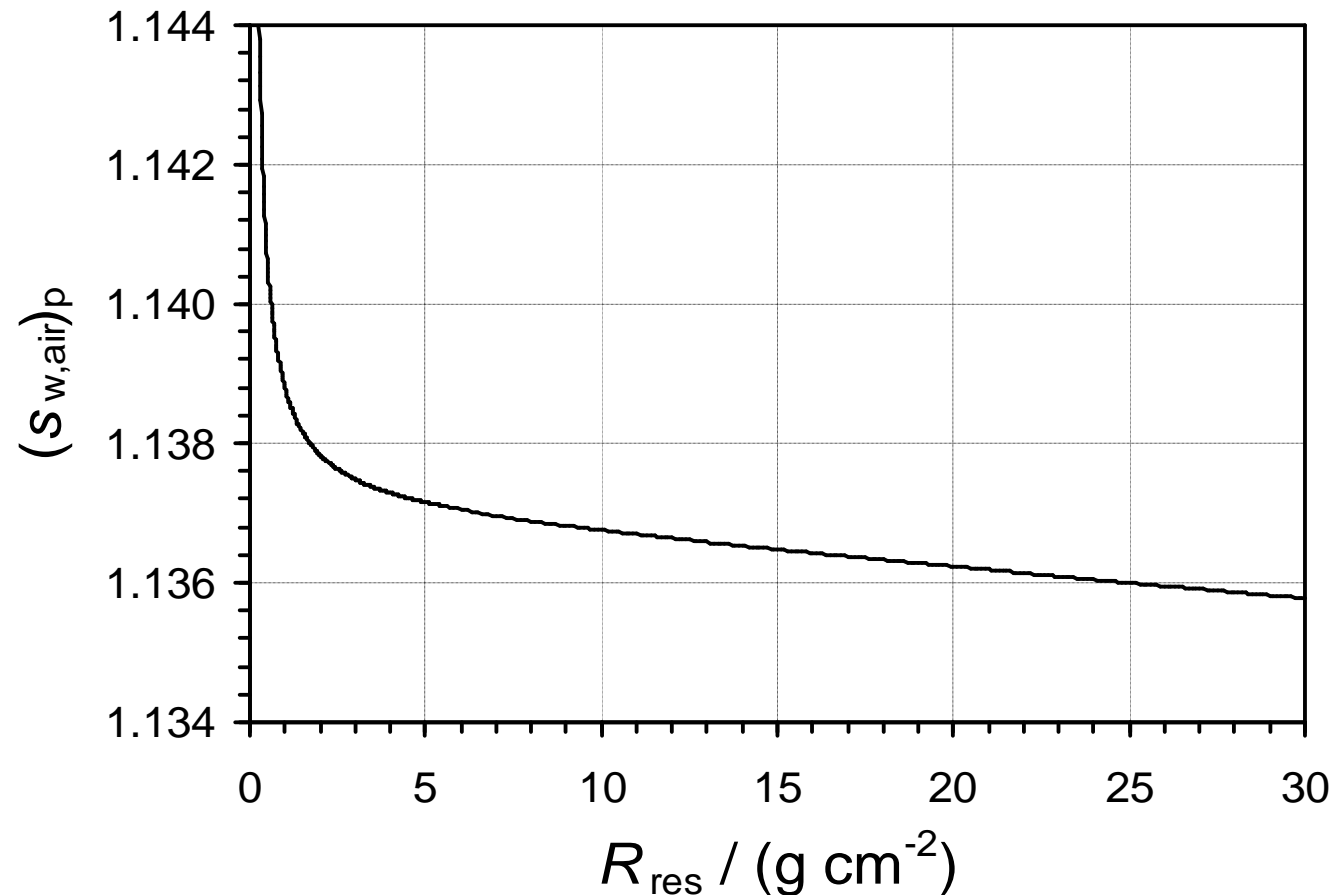
$s_{w,air}$ mean water to air mass stopping power ratio

$(w)W_{air}/e$ mean energy to form ion pair in ionization chamber air filling

p product of chamber perturbation factors [p_{wall} , p_{cav} , p_{cel} , p_{disp} ...]

$(s_{w,air})_p = 1.137 - (4.3 \times 10^{-5}) R_{res} + (1.84 \times 10^{-3})/R_{res}$ [R_{res} : residual range]

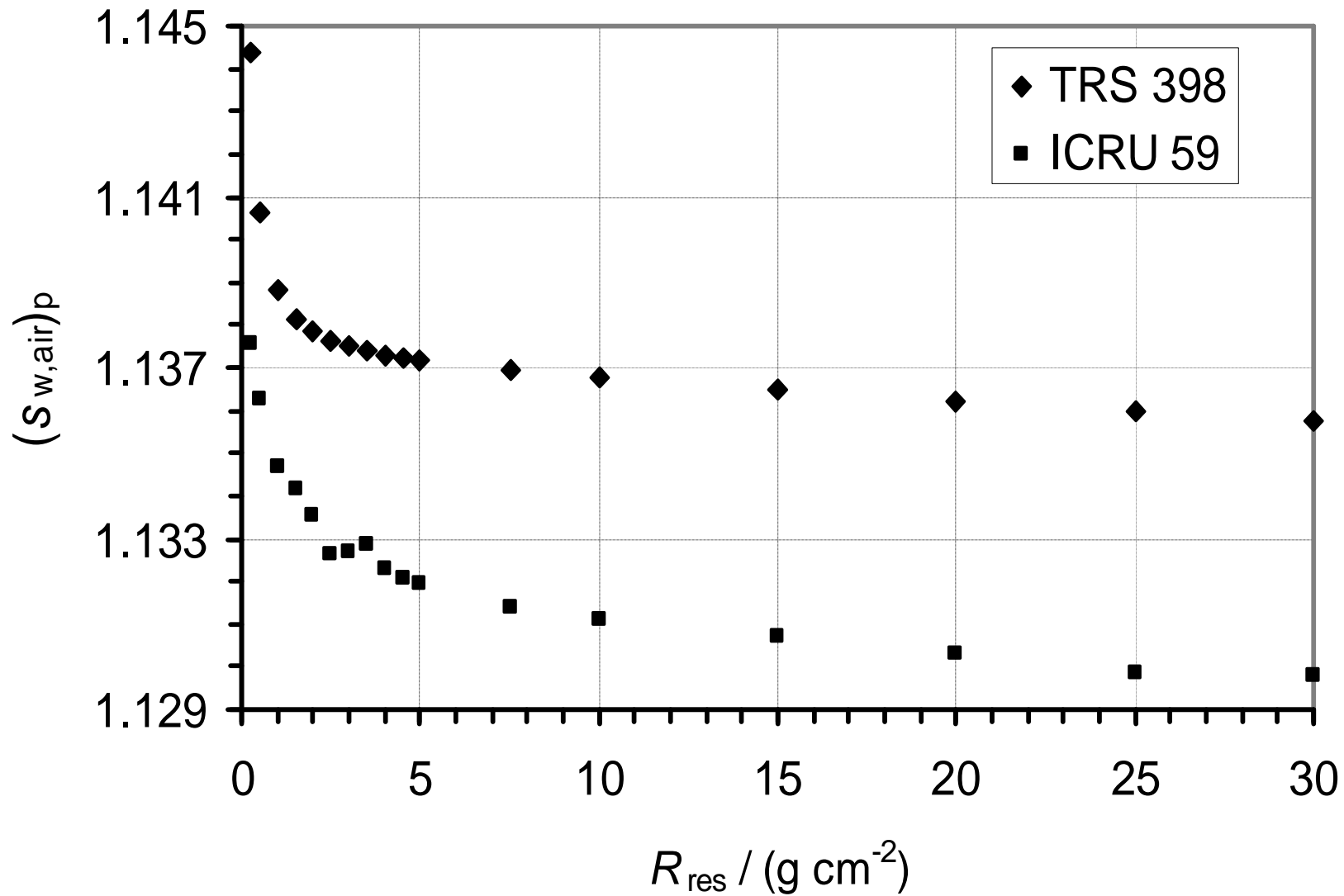
TRS 398 STOPPING POWER RATIOS



ICRU 59 AND TRS 398: DIFFERENCES

	ICRU 59	TRS 398
$(w_{\text{air}})_p$ [J C ⁻¹]	34.8 ± 4.0 % (humid air)	34.23 ± 0.4 % (dry air)
$(W_{\text{air}})_c$ [J C ⁻¹]	33.77 ± 0.15 % (humid air)	33.97 ± 0.2 % (dry air)
$(s_{w,\text{air}})_p$	ICRU 49 (Tables)	ICRU 49 + secondary electrons + nuclear interactions
Chamber perturbation factors (p)	No	Yes (= 1.00)
Chamber perturbation factors (c)	No	Yes
Calibration coefficient	N_K (N_X , $N_{D,w}$ allowed)	$N_{D,w}$ only
Overall uncertainty	± 2.6 %	± 2.0 %

STOPPING POWER RATIOS



W/w-VALUE

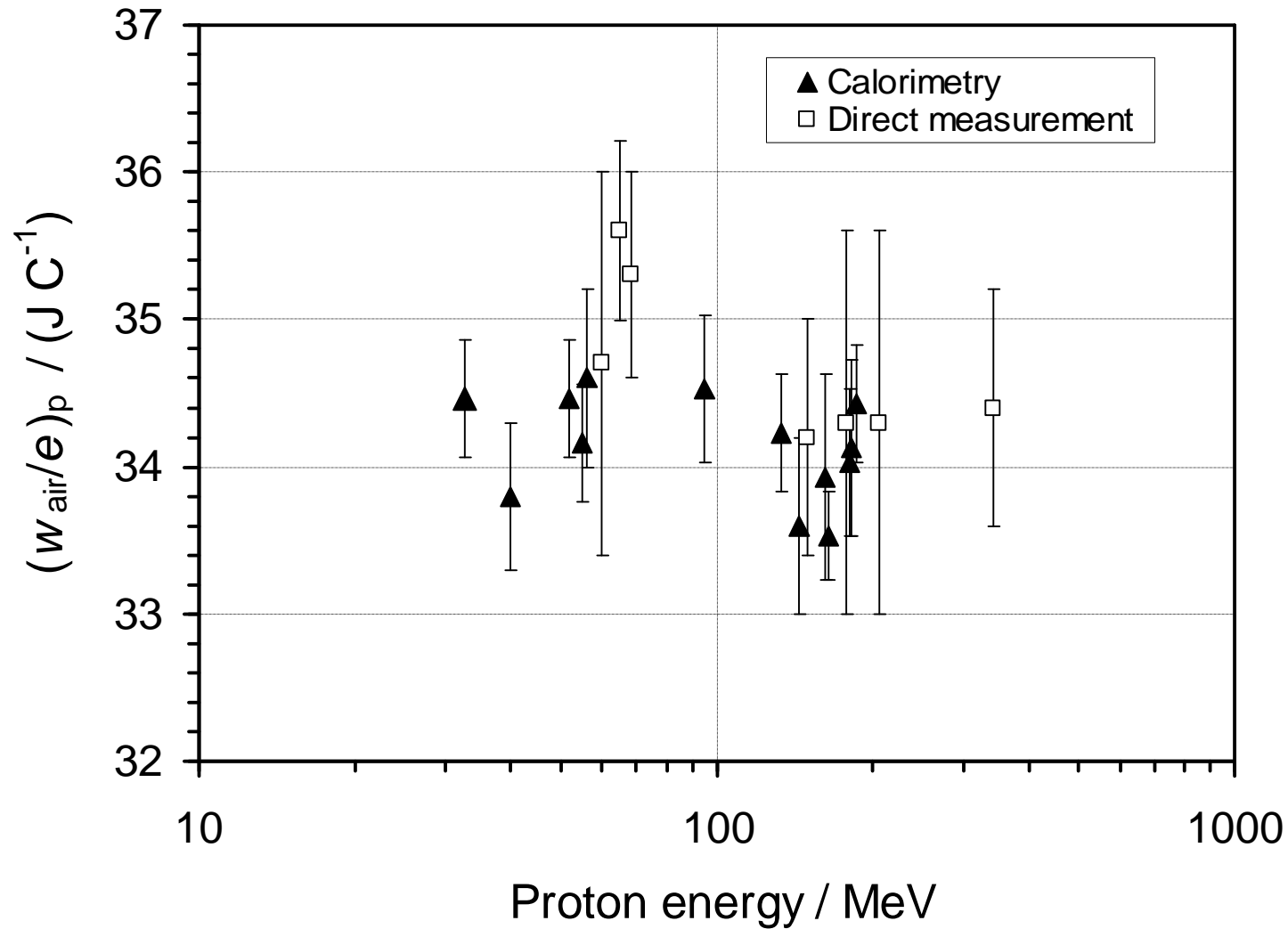
- ▶ Mean energy required to create an electron-ion pair by an ionizing particle which imparts all (W) or some (w) of its energy to the gas is a significant factor in proton dose determinations with ionization chambers
- ▶ **ICRU 59**
 - † indirect measurements $\bar{O} \ 34.2 \text{ J C}^{-1}$
 - † direct measurements $\bar{O} \ 35.2 \text{ J C}^{-1}$
 - † compromise: $\bar{O} \ 34.8 \pm 2.0 \% \text{ J C}^{-1}$
- ▶ **TRS 398**
 - † weighted median method $\bar{O} \ 34.23 \pm 0.4 \% \text{ J C}^{-1}$
- ▶ A thorough evaluation revealed a best value of $34.2 \pm 0.4 \% \text{ J C}^{-1}$ which is consistent with the TRS-398 value

DOSIMETRY PROTOCOLS: w -VALUES

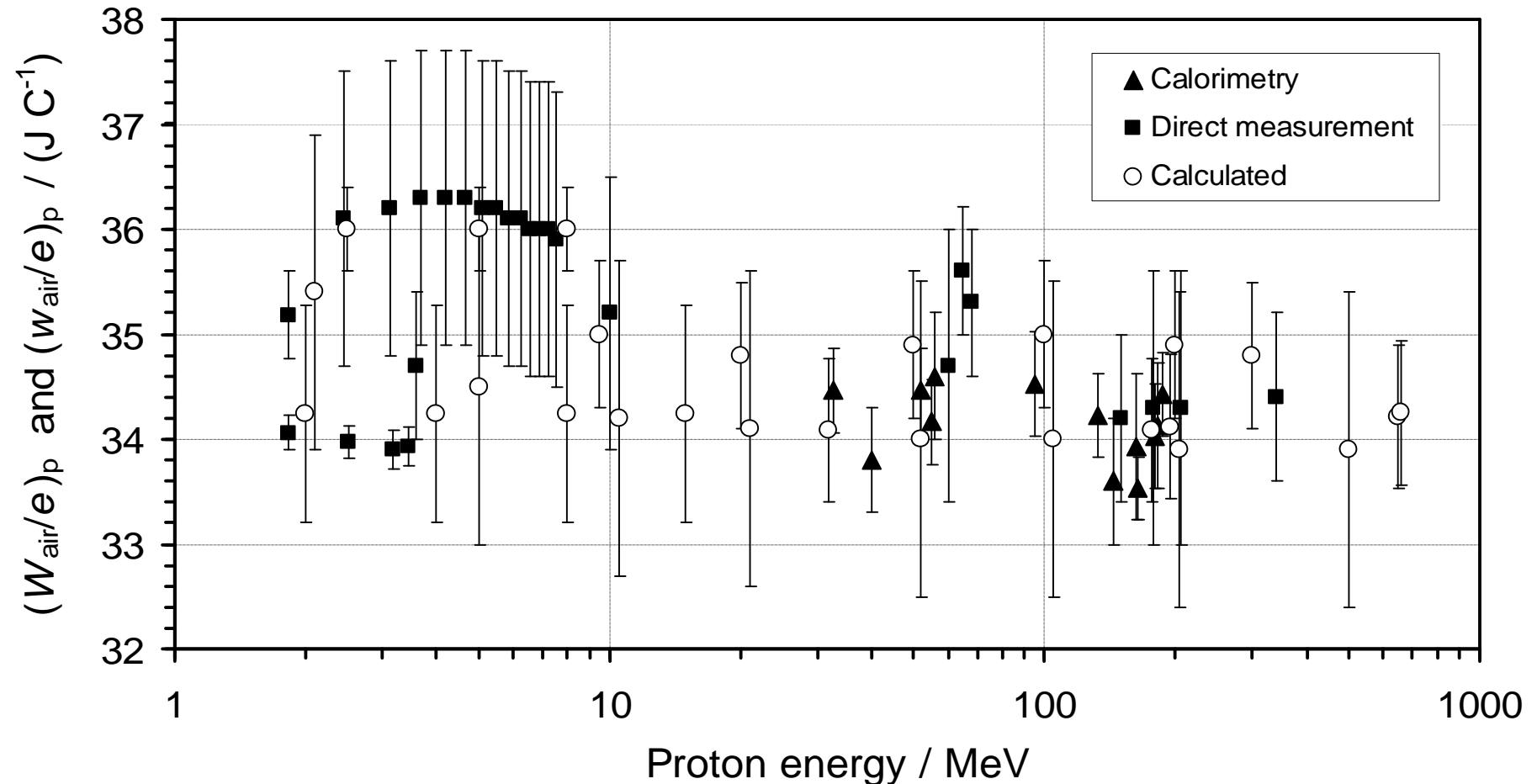
Protocol	$w_p (W_c)$ $J C^{-1}$	Source of w_p	Reference
AAPM	$34.3 \pm 4.0 \%$ ($33.73 \pm 1.2 \%$) [humid air]	<i>Measured value</i> (Verhey <i>et al.</i> , 1979)	AAPM, 1986
ECHED	$35.2 \pm 4.0 \%$ ($33.97 \pm 0.2 \%$) [dry air]	<i>Measured value</i> (ICRU, 1979)	Vynckier <i>et al.</i> , 1991; 1994
ICRU 59	$34.8 \pm 2.0 \%$ ($33.77 \pm 0.15 \%$) [humid air]	<i>Compromise between values measured directly and those inferred from comparisons with calorimetry</i>	ICRU, 1998
IAEA TRS 398	$34.23 \pm 0.4 \%$ ($33.97 \pm 0.2 \%$) [dry air]	<i>Statistical analysis using weighted medians</i> (Muller, 2000a)	IAEA, 2000

PROTON w_{air} -VALUES

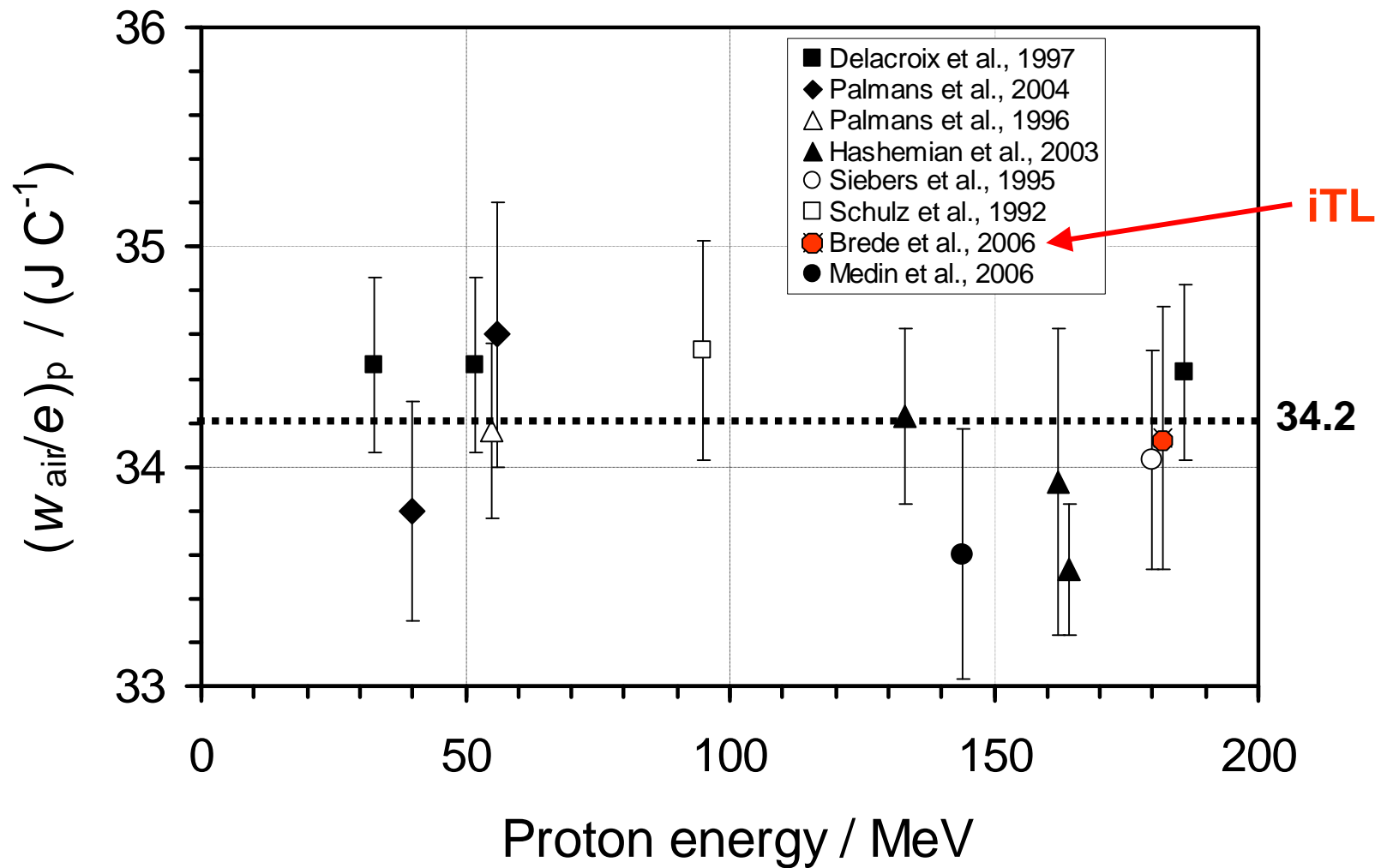
Measured > 20 MeV



PROTON $(W/w)_{\text{air}}$ -VALUES 1940 – 2006



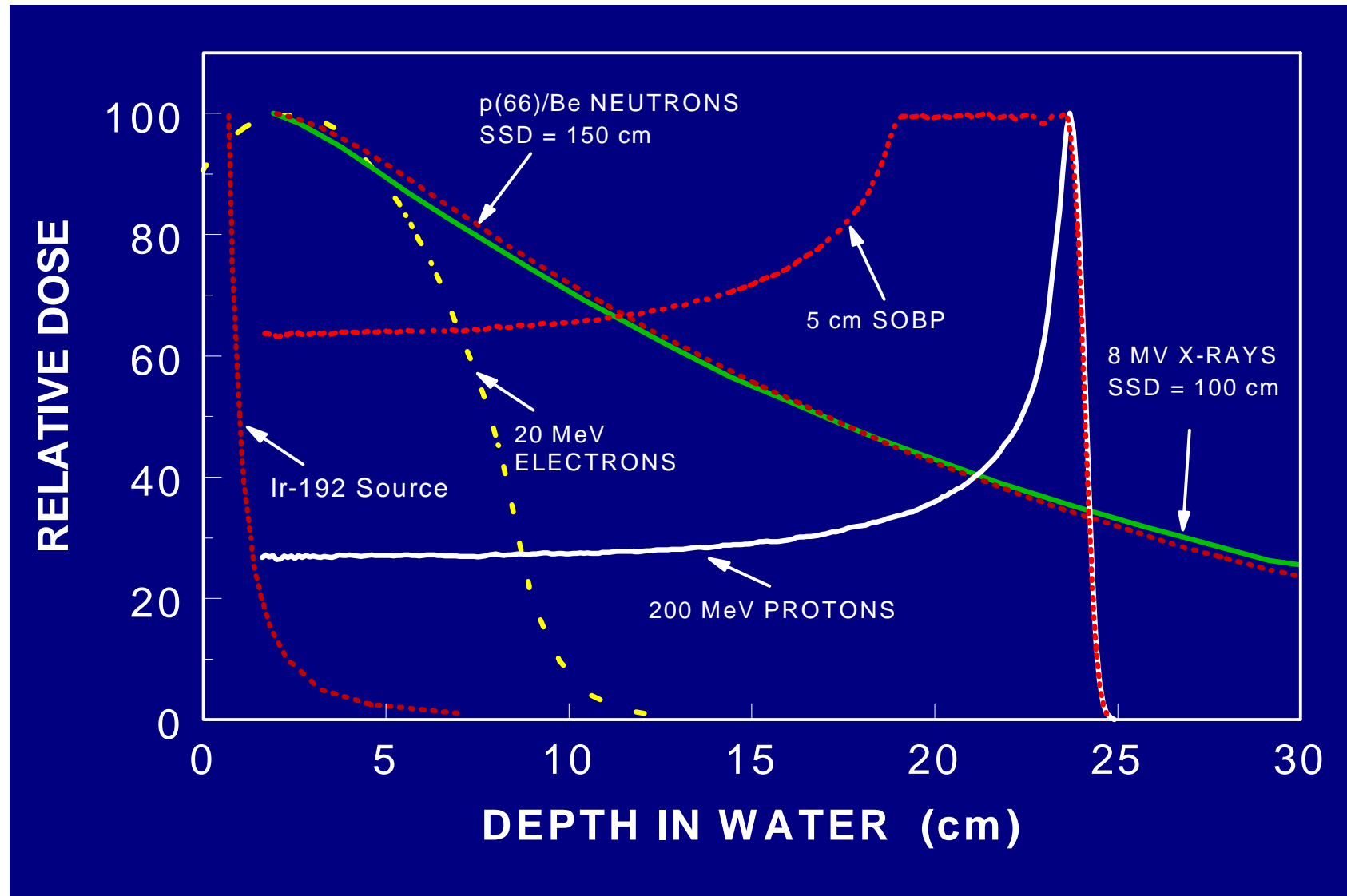
PROTON w_{air} -VALUES Calorimetry



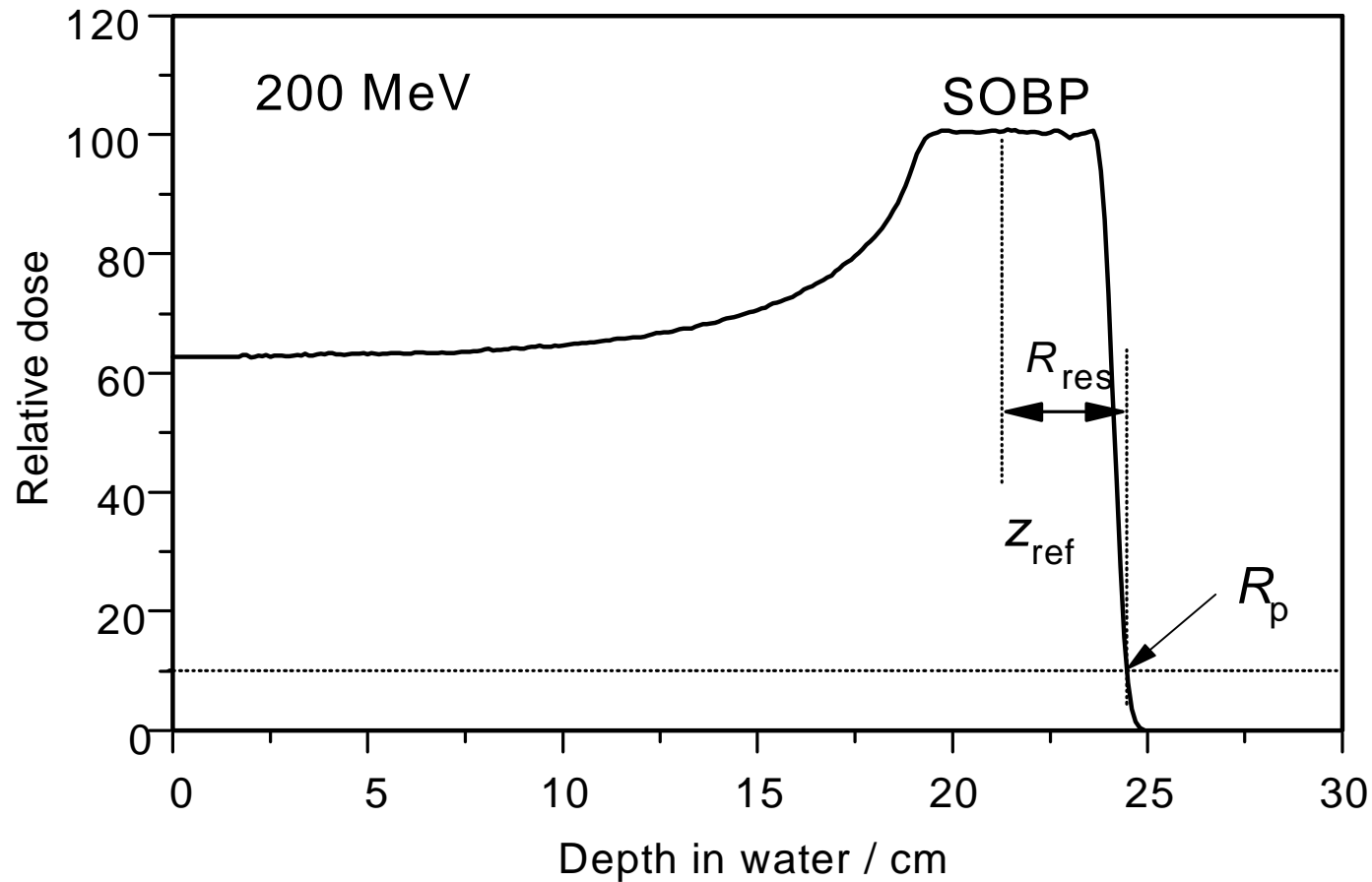
PROTON DOSIMETRY: Recommendations

- ▶ TRS 398 should be adopted as the standard proton dosimetry protocol
 - † it is simple to use (tables and formulae provided)
 - † it harmonizes with the protocols for standard radiotherapy beams (also given in TRS 398) which are being universally adopted
 - † more recent and accurate physical data and constants are used
 - † the formalism and calculations are more robust and rigorous than that of ICRU 59
- ▶ Differences of $\pm 3\%$ are observed between proton absorbed doses measured with different ionization chambers using ICRU 59 and TRS 398 – not clinically significant

DEPTH DOSE CURVES



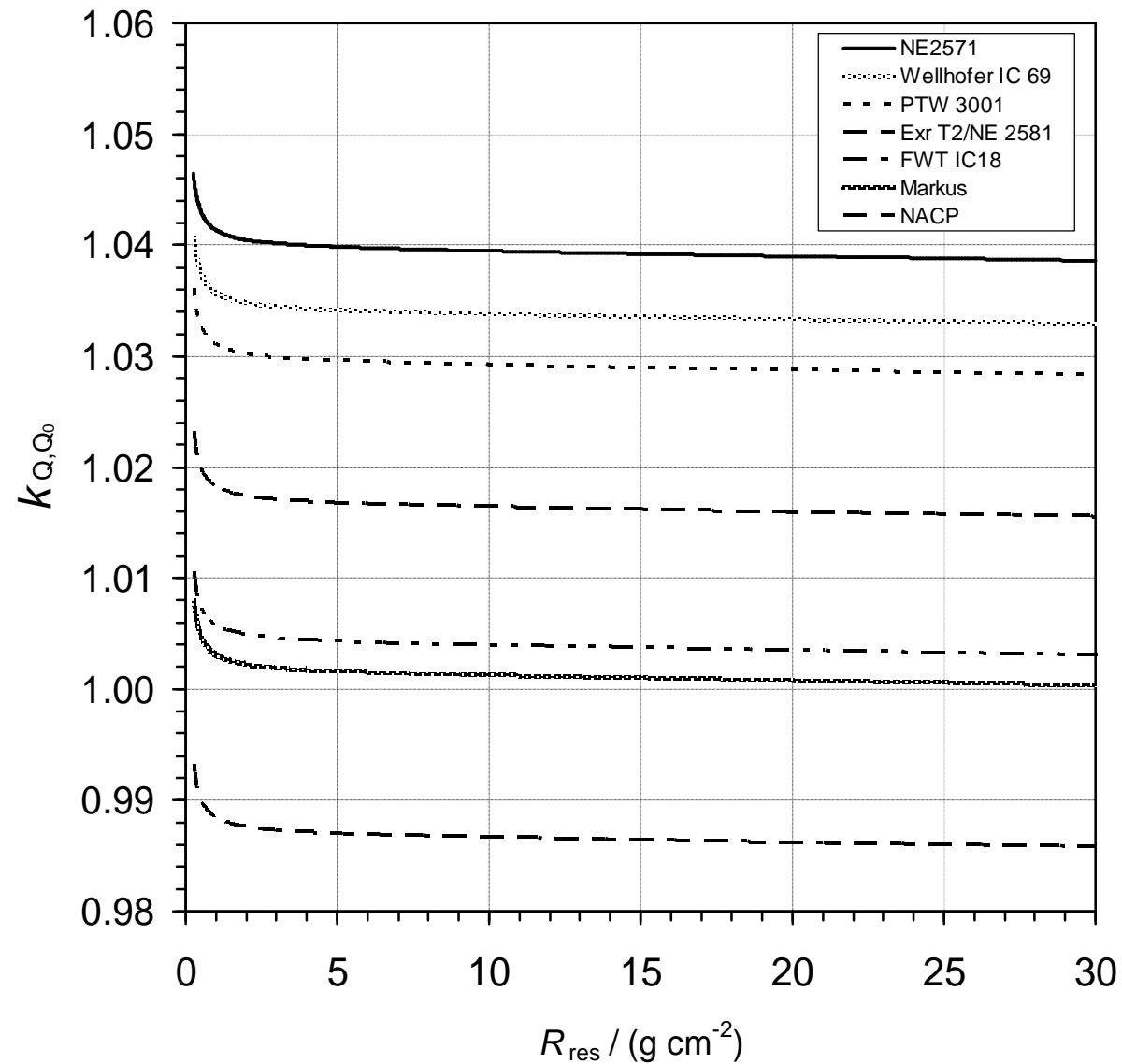
TRS 398 QUALITY INDEX: RESIDUAL RANGE



REFERENCE CONDITIONS FOR PROTON DOSIMETRY

DOSIMETER	Thimble ionization chamber
Wall material	A150 plastic / graphite
Gas filling	Ambient air
^{60}Co calibration factor	Air kerma / <u>Dose to water</u>
DOSE SPECIFICATION	Water
PHANTOM	Water
FIELD SIZE	10 cm x 10 cm
MEASUREMENT POINT	Middle of SOBP 3 cm depth (plateau)
BEAM QUALITY	Residual range

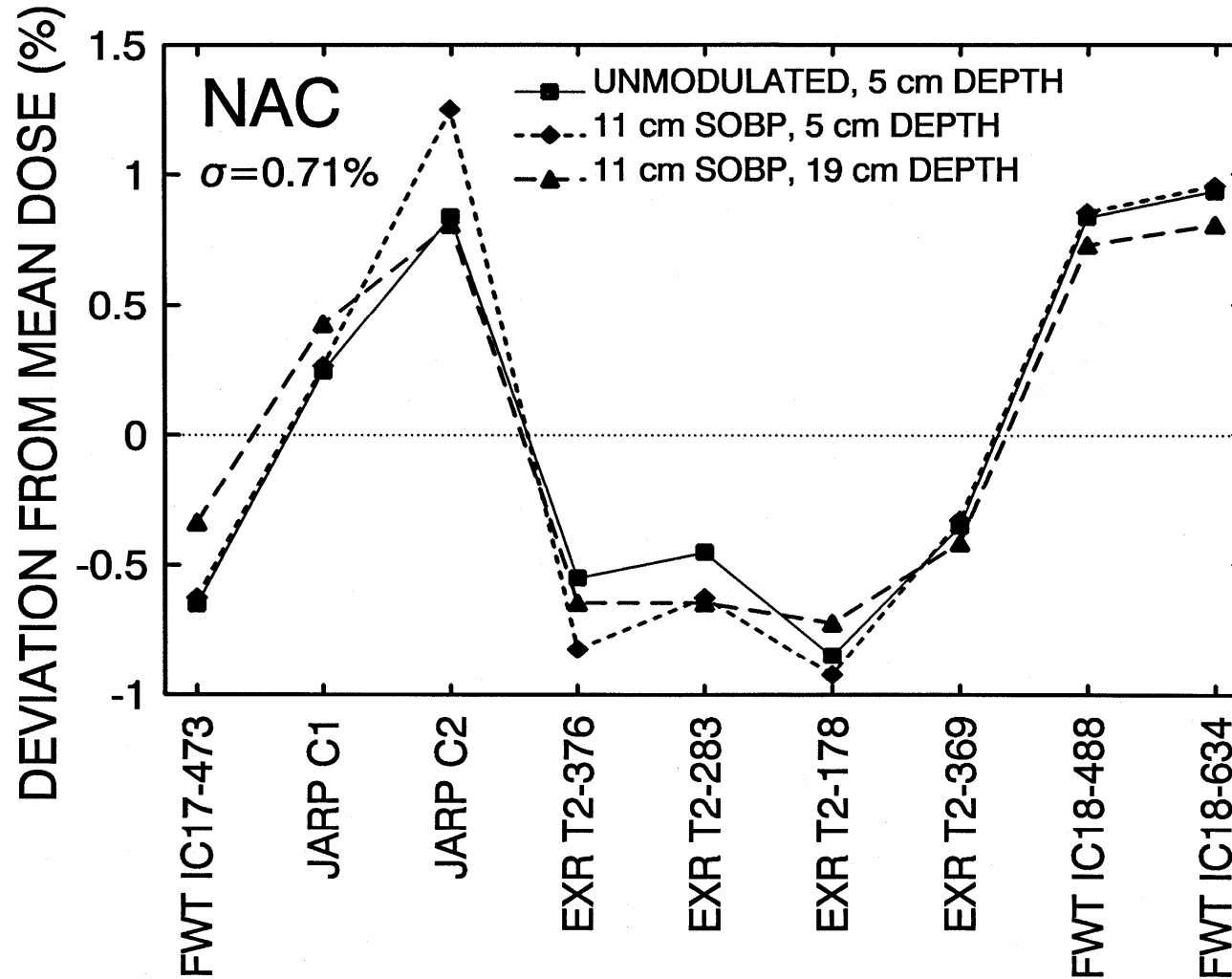
TRS 398 QUALITY FACTORS



PROTON DOSIMETRY COMPARISONS

REFERENCE	PROTOCOL	NUMBER OF CHAMBERS	BEAM ENERGY (MeV)	MAXIMUM DIFFERENCE (%)
Kacperek <i>et al.</i> (1991)	ECHED	8	60	4.5
Jones <i>et al.</i> (1992)	ECHED	7	60 – 80	2.5
Jones <i>et al.</i> (1994a)	ECHED	7	200	1.8
Schreuder <i>et al.</i> (1994)	AAPM/ECHED	7	135-185	1.4
Medin <i>et al.</i> (1995)	TRS 277	7	170	1.5
Jones (1996)	ECHED	6	58-168	2.3
Palmans <i>et al.</i> (1996)	ECHED	10	85	1.2
Vatnitsky <i>et al.</i> (1996b)	AAPM/ECHED	23	100-250	5.8
Hiroaka <i>et al.</i> (1997)	-	5	70	0.8
Cuttone <i>et al.</i> (1999)	ECHED	3	28-62	2.1
Vatnitsky <i>et al.</i> (1999b)	ICRU 59	11	155	2.9
Nohtomi <i>et al.</i> (2001)	ICRU 59	5	250	1.5
Palmans <i>et al.</i> (2001)	TRS 398	17	75	1.5
Fukumura <i>et al.</i> (2002)	TRS 398	8	150	0.9
Kacperek <i>et al.</i> (2002)	ICRU 59	10	63	3.2
Vatnitsky <i>et al.</i> (2002)	ICRU 59/TRS 398	6	100-155	3.1

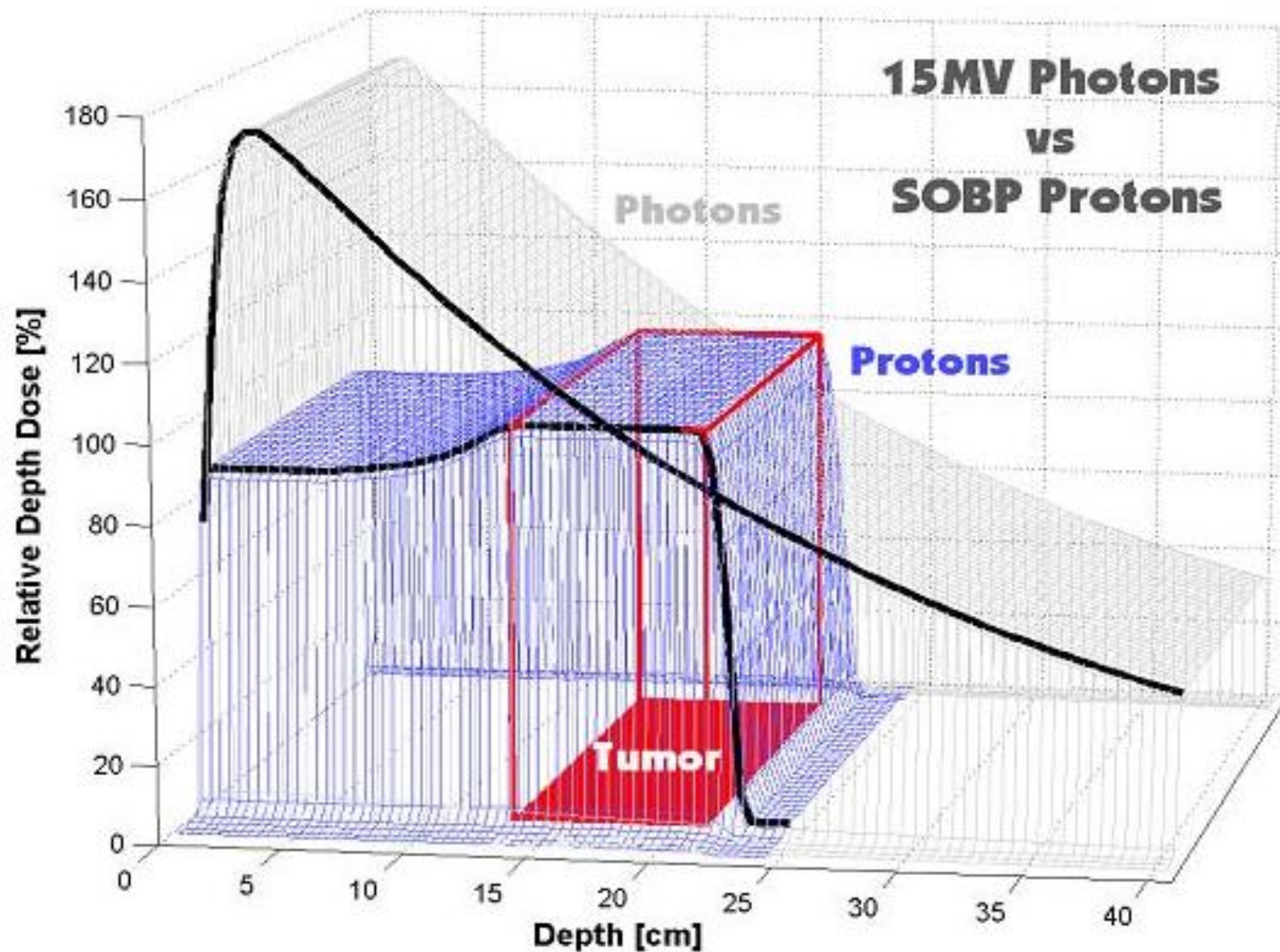
PROTON DOSIMETRY COMPARISON



RELATIVE DOSIMETRY

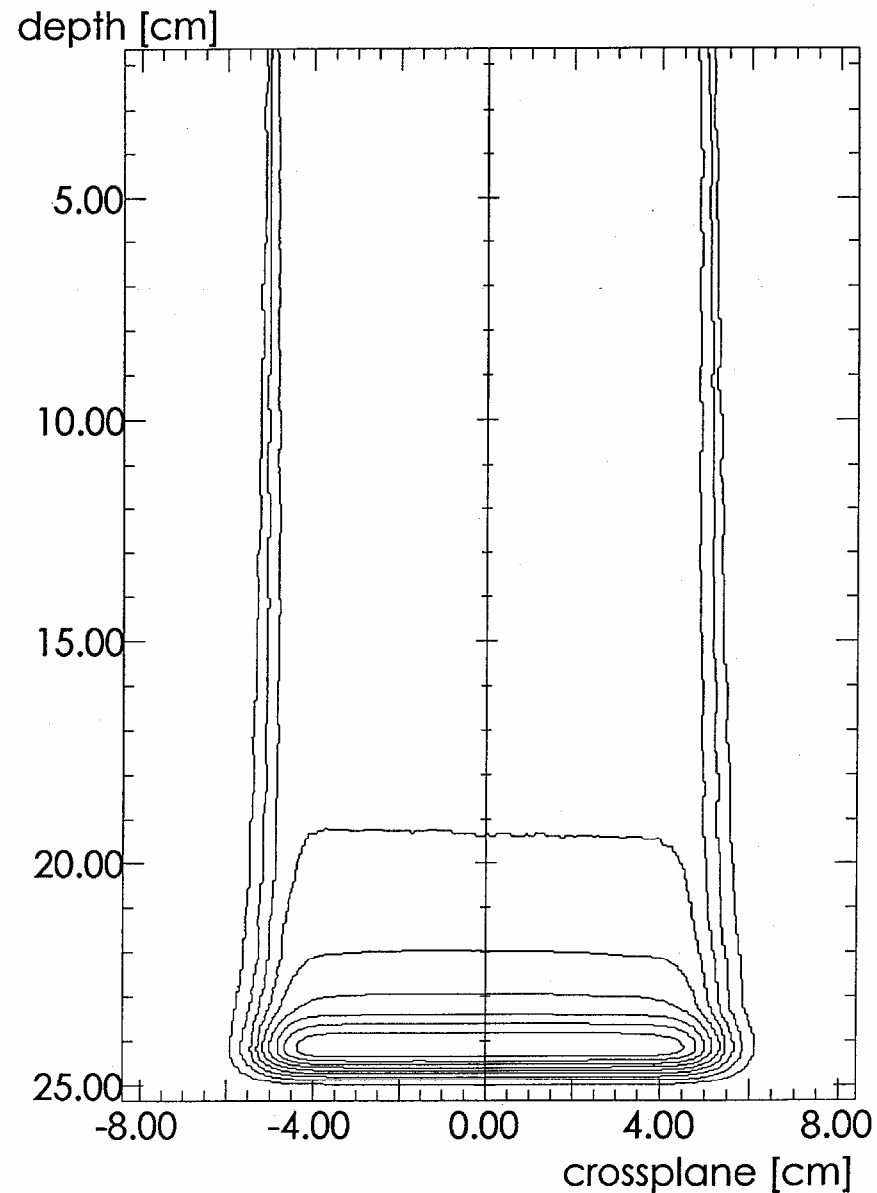
- ▶ There is little difference between reference dosimetry for passively modified beams and for scanned beams.
- ▶ Parallel plate ionization chambers are the most common and well-proven detectors for proton beam monitoring.
 - † for scanning beams MWICs or pixel ionization chamber arrays are used for monitoring the beam position.
- ▶ Ionization chambers are often the instruments of choice for dose distribution measurements
 - † simplest to use and do not require specific calibration for such relative measurements
 - † diodes and diamond detectors are also used
 - † radiographic films, scintillator screens or 2-D pixel detectors can be used to measure the dose distributions of scanned beams.

DOSE DISTRIBUTIONS

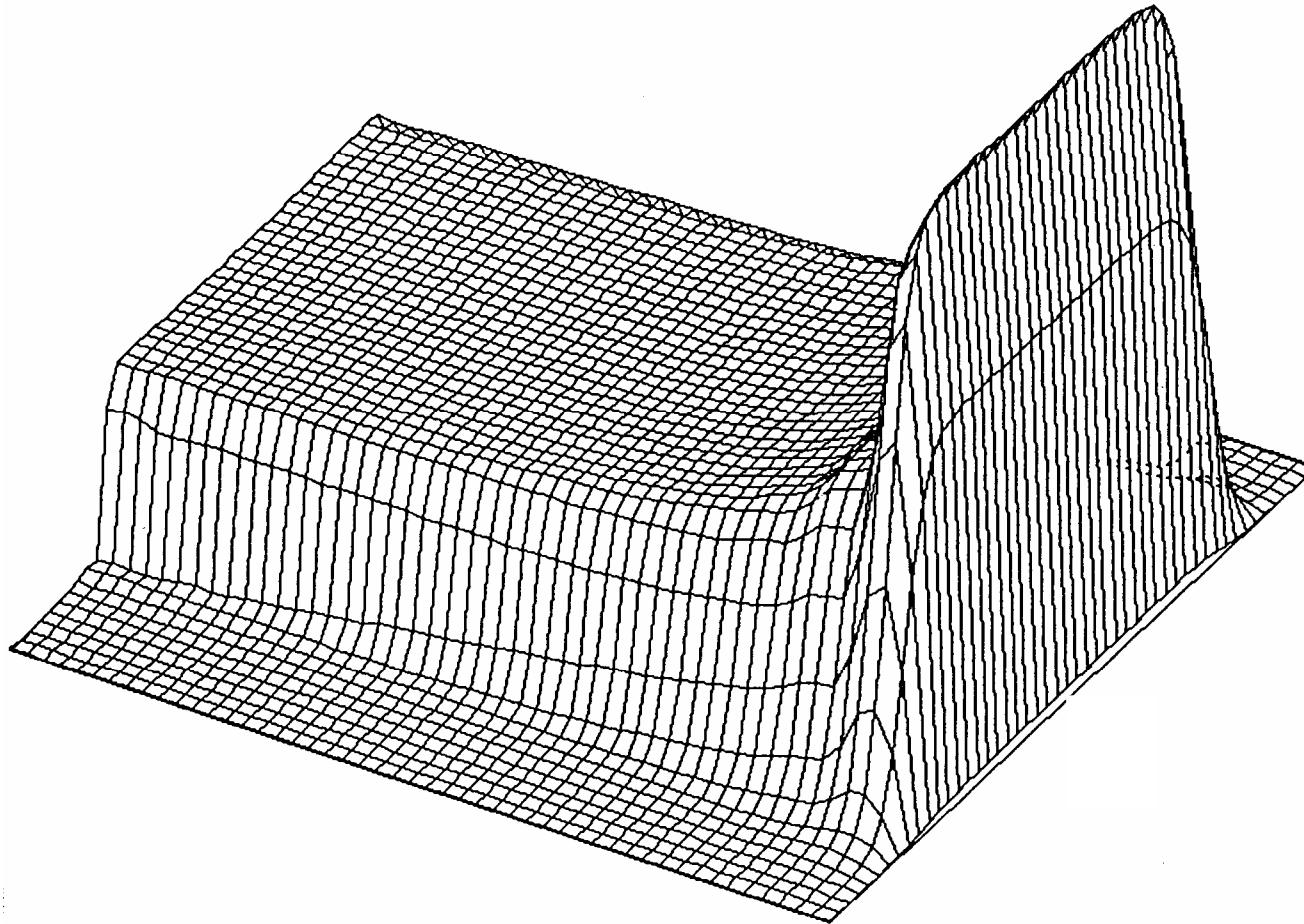


ISODOSE DISTRIBUTIONS (191 MeV)

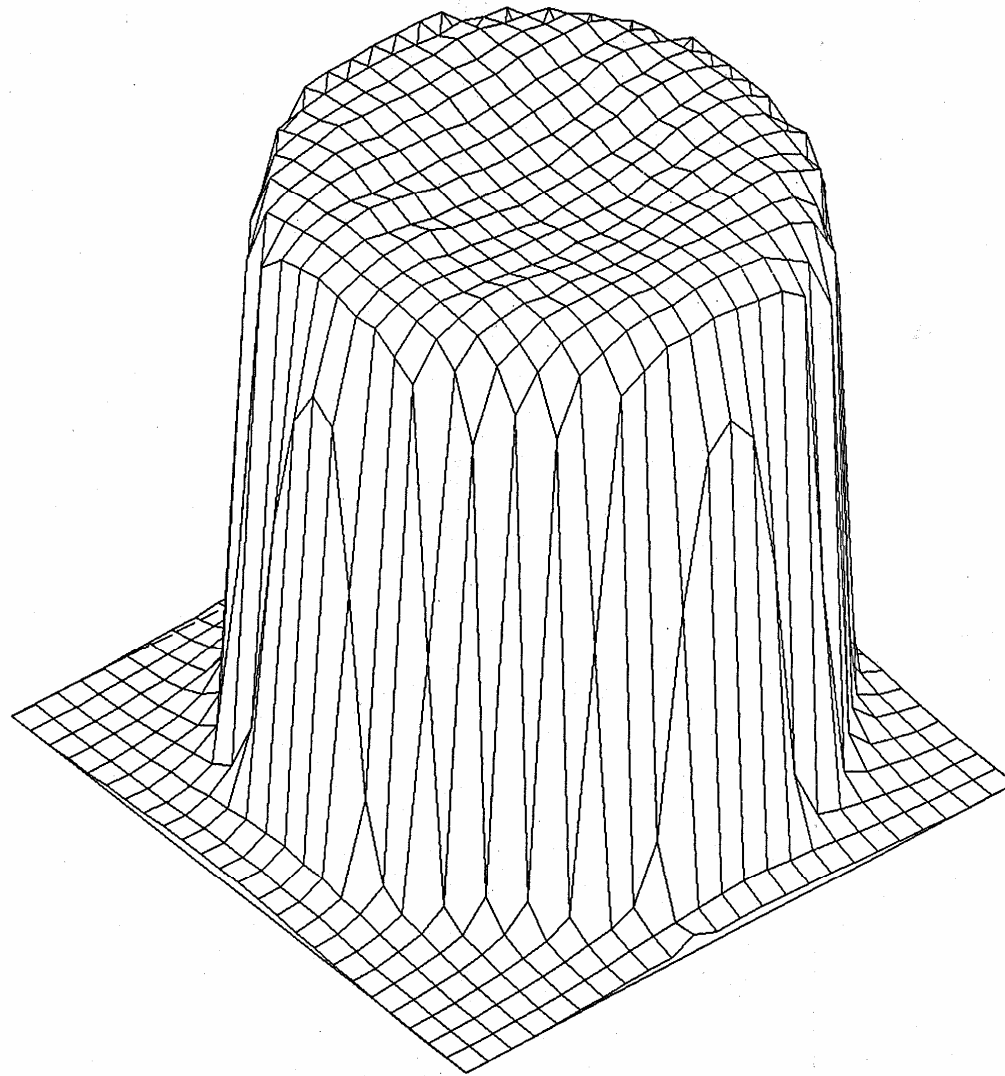
83



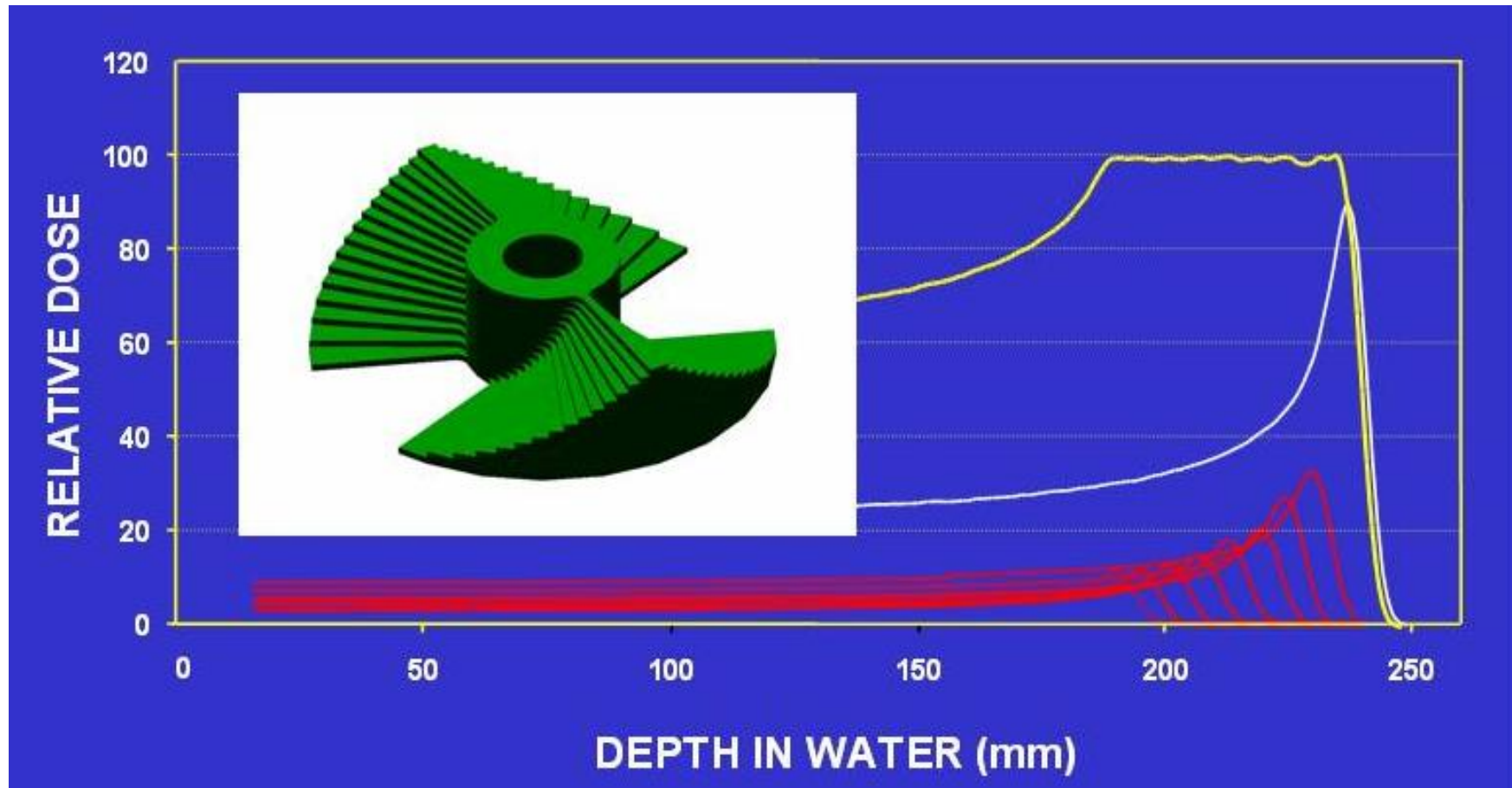
DEPTH DOSE DISTRIBUTION



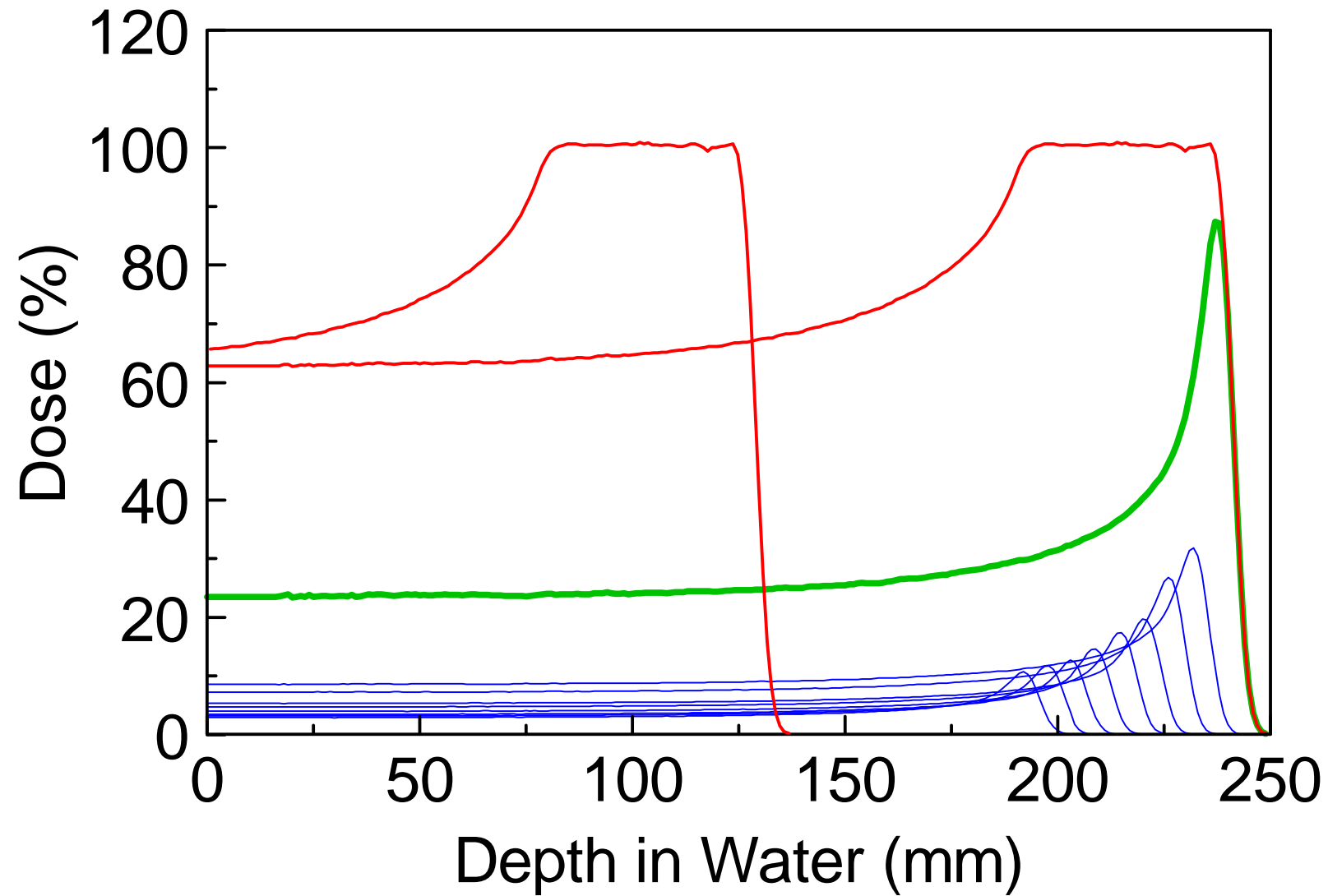
LATERAL DOSE DISTRIBUTION



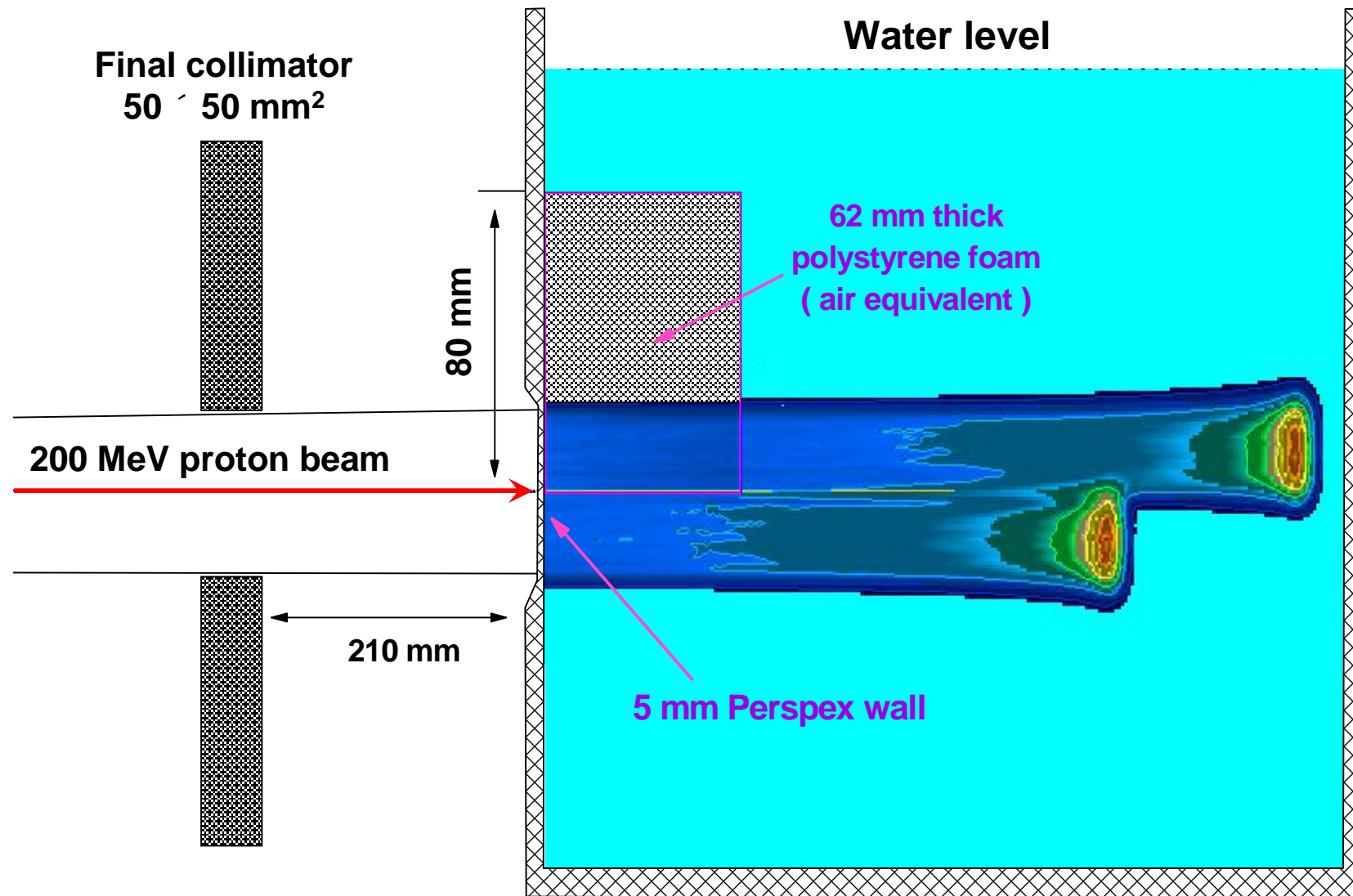
SPREAD-OUT BRAGG PEAK (SOBP)



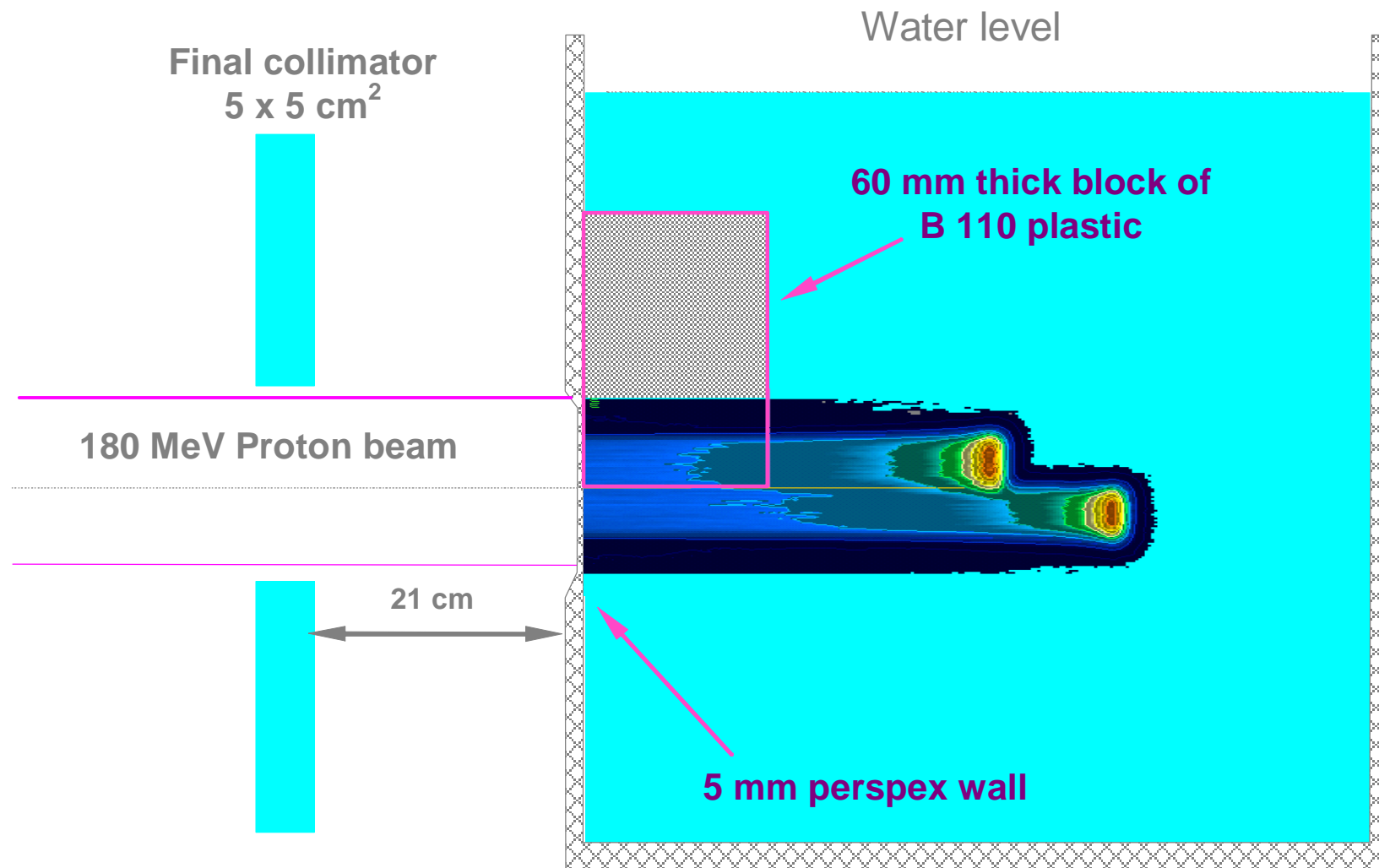
SPREAD OUT BRAGG PEAK + RANGE SHIFT



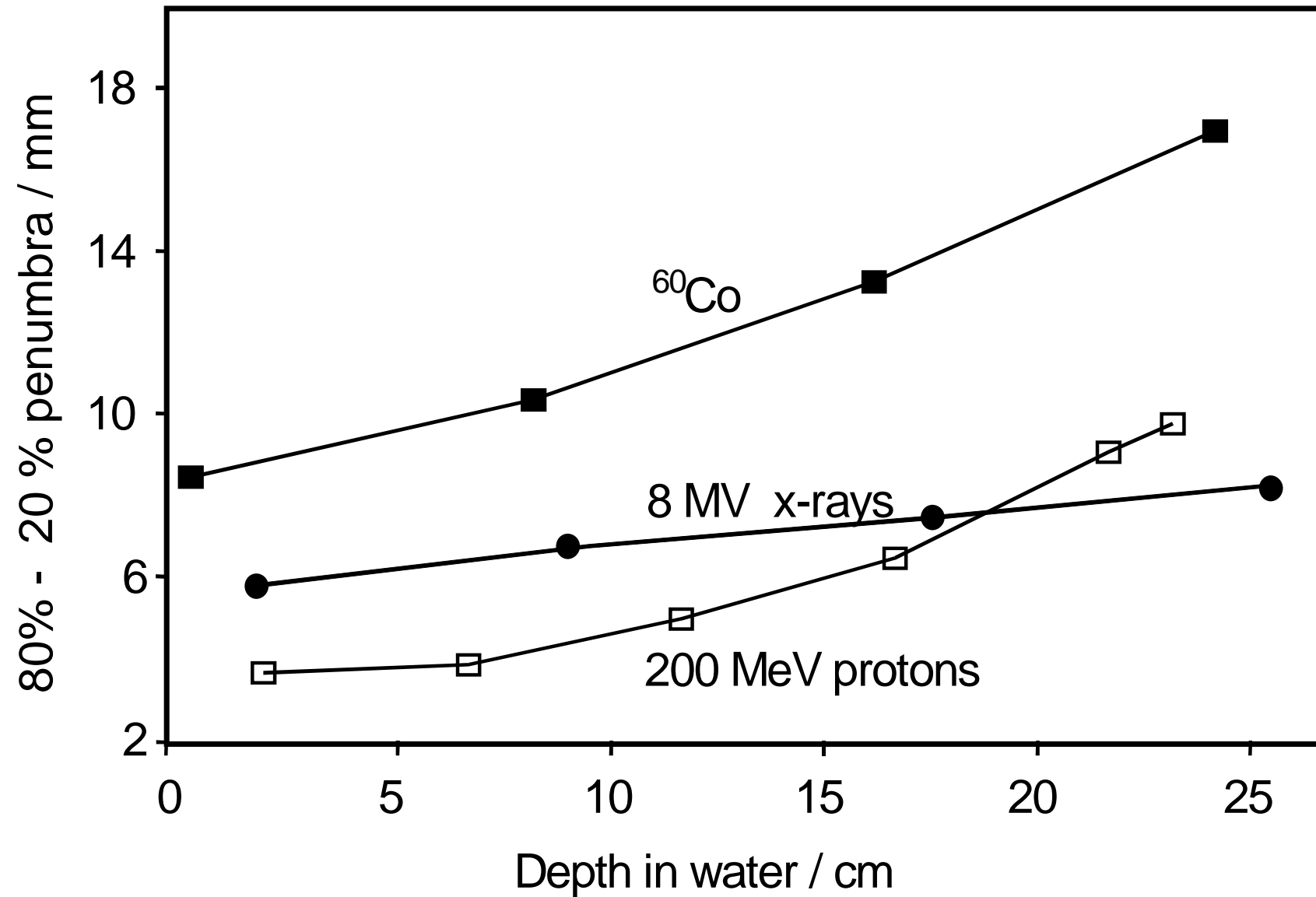
EFFECT OF INHOMOGENEITY (I)



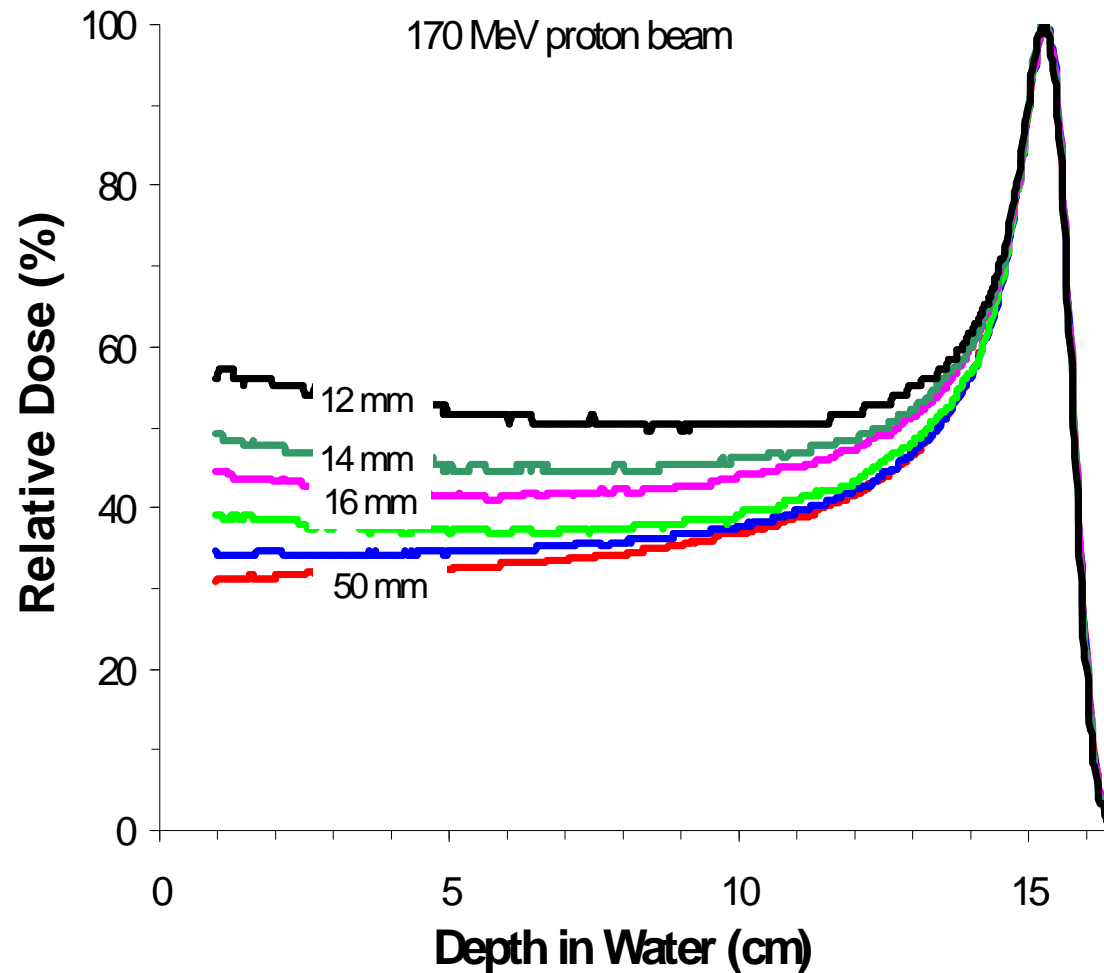
EFFECT OF INHOMOGENEITY (II)



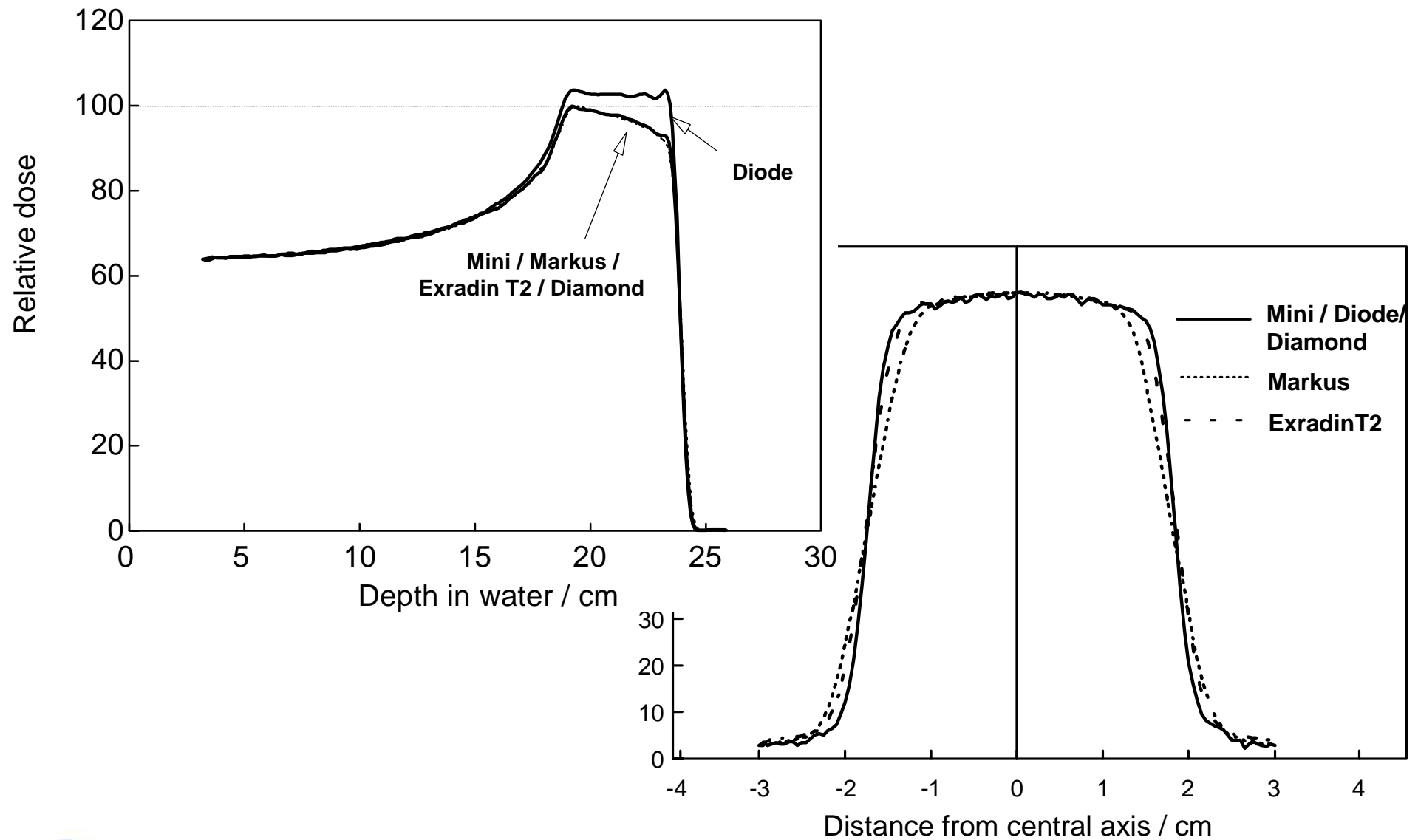
BEAM PENUMBRAE



FIELD DIAMETER EFFECT

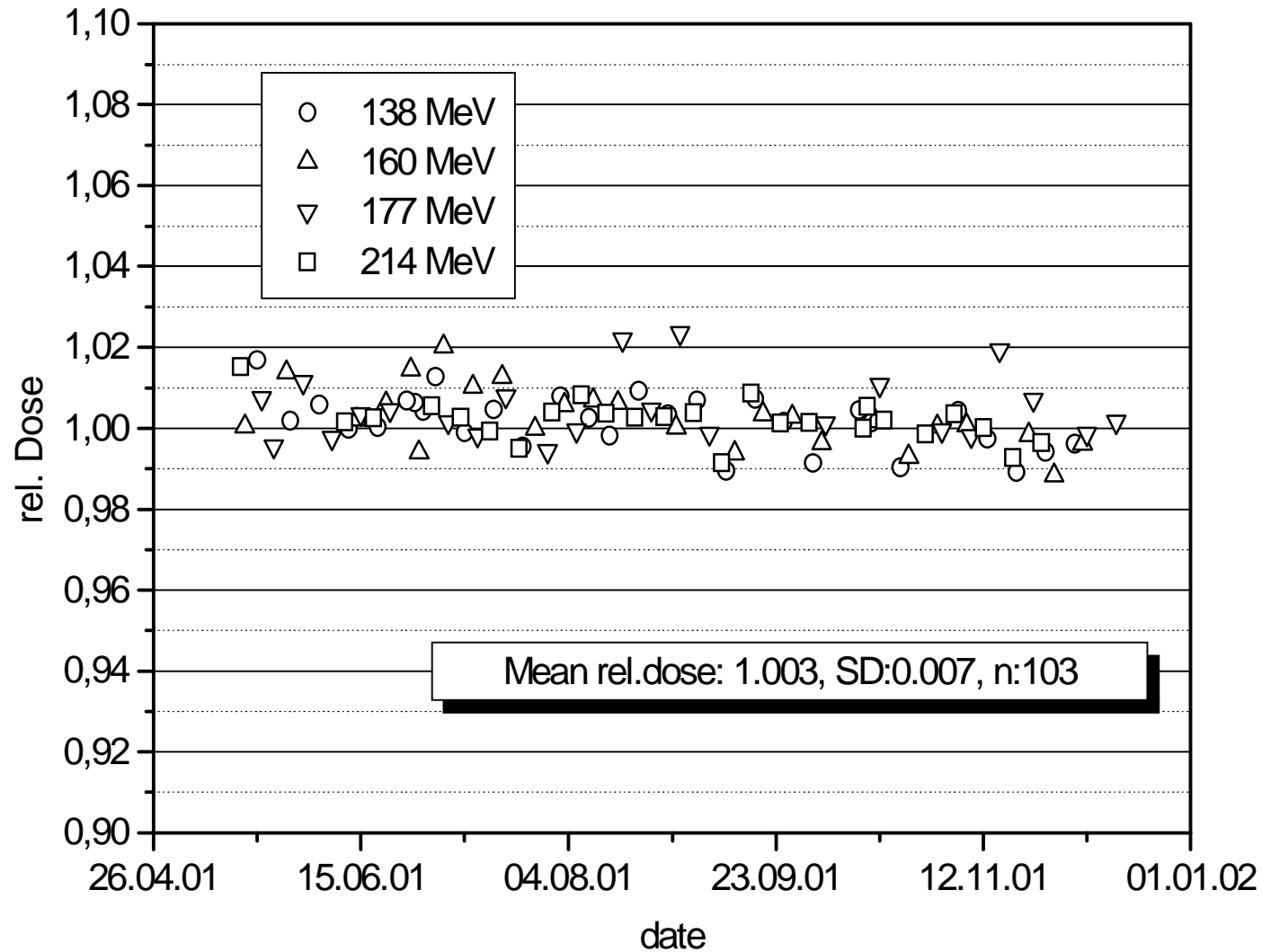


DOSE DISTRIBUTIONS



DOSE UNIFORMITY

Scanned beams



PROCEDURES FOR BEAM CALIBRATION

Dose to water

At National Metrology Laboratory:

Annually

1. Calibration of secondary standard ionization chamber (Farmer type) in ^{60}Co

At Therapy Facility:

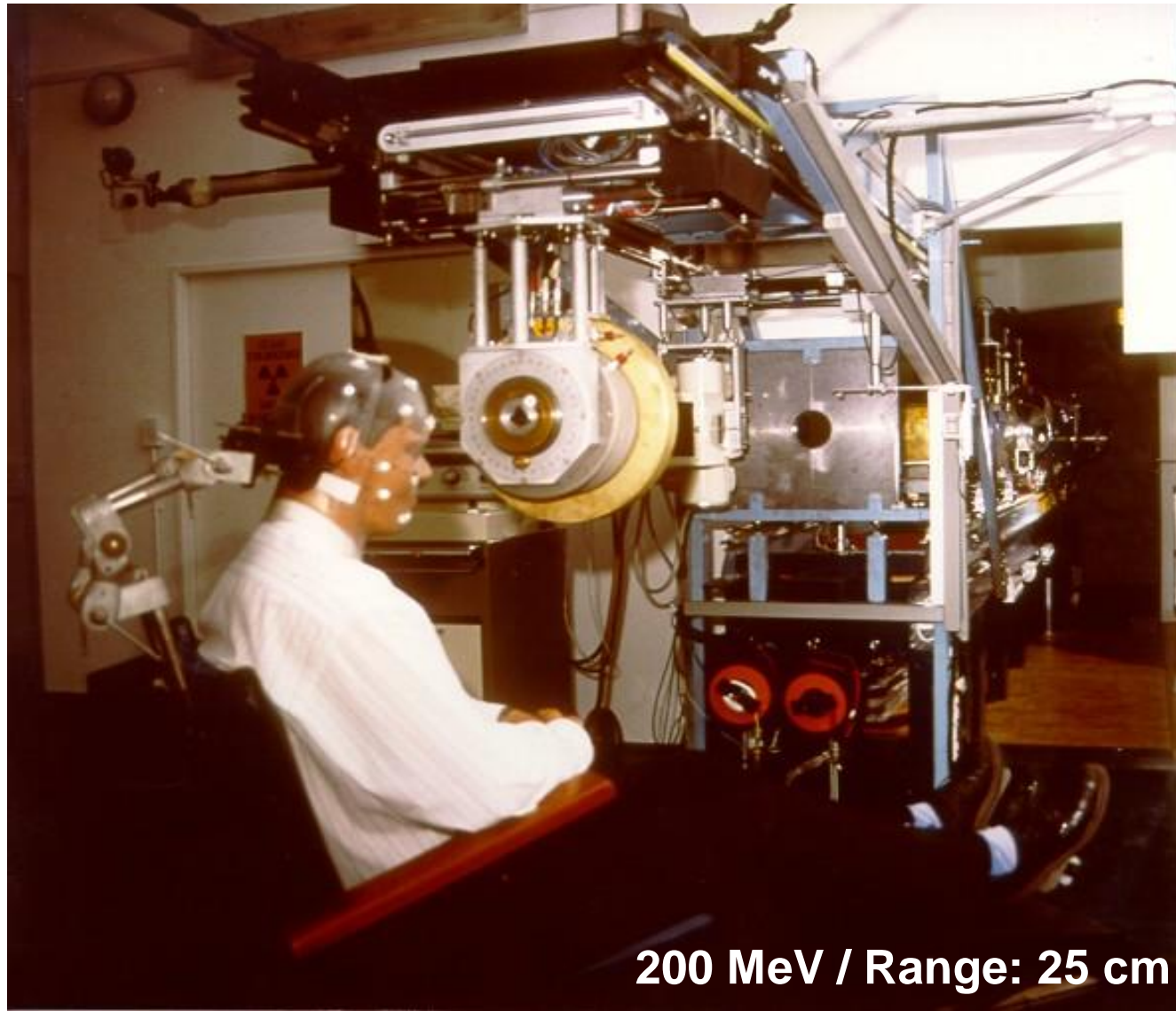
Annually

2. Calibration of reference ionization chambers against secondary standard in ^{60}Co
3. Calibration of beam monitor with reference chambers under reference conditions (water)
4. Calibration of constancy chamber (solid phantom)

Daily

5. Dose constancy checks
6. Field-specific calibrations

iTL PROTON THERAPY BEAM LINE



200 MeV / Range: 25 cm

CONSTANCY CALIBRATION/CHECK

