Measurement Issues in Commissioning and Benchmarking of Monte Carlo Treatment Planning Systems

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Outline

- Dosimetric accuracy requirements in treatment planning
- Measurement dosimetry fundamentals
- Measurement issues in commissioning
- Measurement issues in verification
- Conclusions

Clinical QA

- Clinical QA protocols & guidelines
  - AAPM TG 53 (Fraass et al 1998)
  - IEC 62083 (International Electrotechnical Comission, 2000)
  - ESTRO (Mijnheer et al 2004)
  - NCS (2005)
  - etc.
- Content of clinical QA
  - **dosimetric verification and consistency**
  - many other aspects of system QA and consistency

Dosimetric accuracy

• effect of dose uncertainty on complication-free tumour control ("utility function", Schultheiss & Boyer, 1988)	1% higher accuracy --> 2% increase of cure
• ICRU Report 24 (1976)	5%
• Mijnheer et al (1987)	3.5%
• Brahme (1988)	3%

The structures these numbers are referring to are targets.
What about OAR's?

Dosimetric accuracy (cont'd)

	Present (1)	Possible (1)?
Absorbed dose at reference point in clinic	2.0	1.0
Absorbed dose at other points	1.1	0.5
Monitor stability	1.0	0.5
Beam flatness / symmetry	1.5	0.8
Patient data uncertainties	1.5	1.0
Beam and patient setup	2.5	1.6
Overall (excluding TPA)	4.1	2.4
Dose calculation (TPA)	1.0 / 3.0 / 5.0	0.5 / 2.0 / 4.0
Overall (including TPA)	4.2 / 5.1 / 6.5	2.4 / 3.1 / 4.7

TPA: treatment planning algo.

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Dosimetric and positional accuracy of TPA: acceptability criteria

	central axis	high dose region low dose gradient	large dose gradient	low dose region low dose gradient
Homogeneous water slab - simple fields	2%	3%	4 mm	3% (50% loc.dose)
Stack of tissue slabs simple fields	3%	3%	4 mm	3% (50% loc.dose)
antropomorphic phantom and/or complex beams		4%	4 mm	3% (50% loc.dose)

Van Dyk (1993)

Gamma analysis for testing the acceptability of dose distributions by comparing measurements and calculations

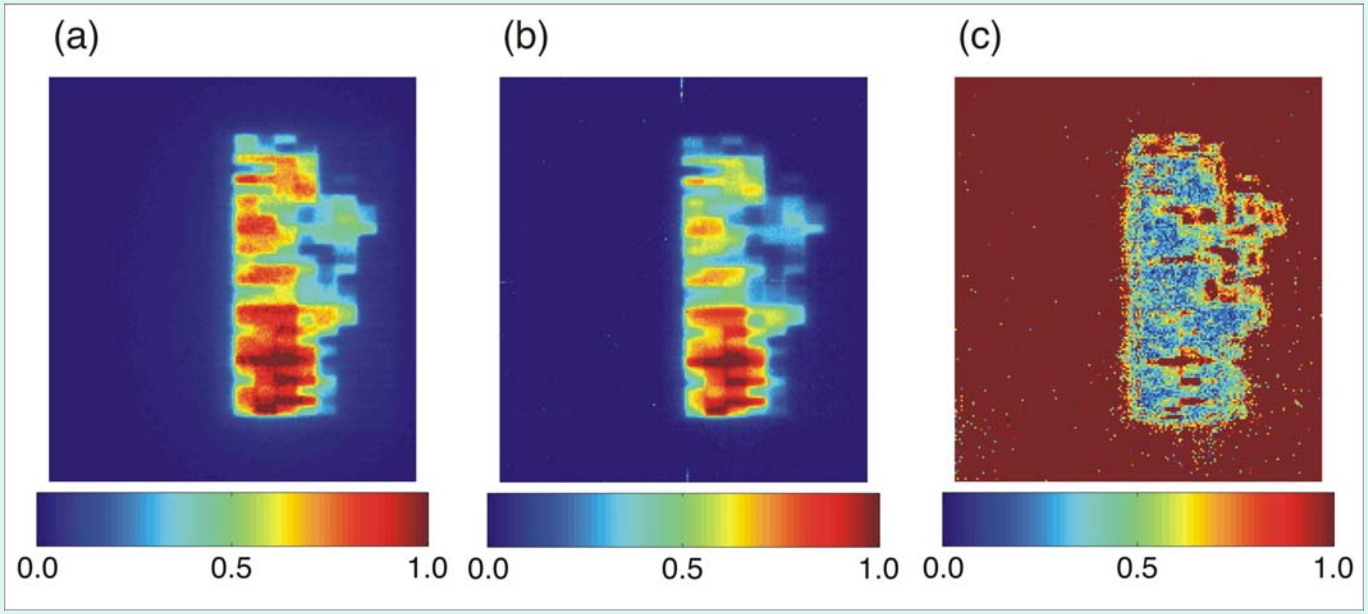


Illustration of the gamma concept (Low et al 1998) for comparison of MC calculated (a) and film measured (b) two dimensional dose maps. (c) illustrates the gamma-map for tolerance criteria of 3% (dose), 5 mm (distance).

$$\gamma(i) = \min\sqrt{\left(\frac{d(i)}{\Delta d}\right)^2 + \left(\frac{r(i)}{\Delta r}\right)^2}$$

$$d(i) = D_m(i) - D_c$$

$$r(i) = r_m(i) - r_c$$

for all points (D_c,r_c)

Clinical measurement dosimetry

Classification of dosimeters

Dosimeter	Mechanism
Gas-filled ionization chamber	Ionization in gasses
Liquid ionization chamber	Ionization in liquids
Semiconductors (diodes, diamond detectors)	Ionization in solids
TLD	Luminescence
Scintillation counters	Fluorescence
Film, gel, Fricke	Chemical reactions
Calorimetry	Heat

Measurement dosimetry in water

$$D_w(\vec{r}) = R(\vec{r})c_{\mathrm{det}}f_w(\vec{r})$$

where:

$D_w(\vec{r})$	dose to water at the point $\vec{r}$
$R(\vec{r})$	raw signal, corrected for environmental conditions as given by detector
c_{det}	detector cavity dose calibration coefficient (coupling constant)
$f_w(\vec{r})$	dose conversion coefficient converts average detector dose into dose to water at point $\vec{r}$

Dosimeter dependent coefficients & coupling constants

Factor or coefficient	Dosimetry technique		
	Calorimetry	Fricke dosimetry	Ionchamber dosimetry
R	ΔT	$\frac{\Delta OD}{\rho L}$	Q
c_{det}	c	$\frac{1}{\varepsilon(Fe^{3+})G}$	$\frac{1}{m_{gas}}\frac{W_{gas}}{e}$
f_{med}	Unity	$(D)^{med}_{Fricke}$	$s_{med,gas}p_Q$

Interpretation of a dosimeter measurement

$$D_{med} = \underbrace{N_{cav} M}_{D_{cav}} \underbrace{s_{med,cav} p_Q}_{f_{med}}$$

- N_{cav} is the cavity dose calibration factor and ties the clinical dose measurement to the chamber/detector calibration

- M is the result of a measurement corrected for "technical" influence quantities to ensure that what we actually measure a quantity proportional to the dose to the detector material

Interpretation of a dosimeter measurement (cont'd)

$$D_{med}(r) = \underbrace{N_{cav}M(r)}_{D_{cav}}\underbrace{s_{med,cav}(r)\,p_Q(r)}_{f_{med}}$$

- $s_{med,cav}$ is the stopping power ratio medium to cavity material
- p_Q is an overall perturbation correction factor that accounts for everything a cavity theory does not account for

f_{med} is the ratio of dose to medium to dose to cavity; factorization of f_{med} is questionable in regions of strong disequilibrium

Practical complications

- The outlined interpretation depends on our ability to convert cavity dose to medium dose
  - CPE or TCPE and detector is small compared to the range of secondary electrons:
    - f_{med} can be factorized in a stopping power ratio + correction factors
  - If these conditions are not fulfilled:
    - Monte Carlo calculations (within the constraints of the algorithm and basic cross-section datasets)

Why is this important for commissioning and accuracy verification of TPS?

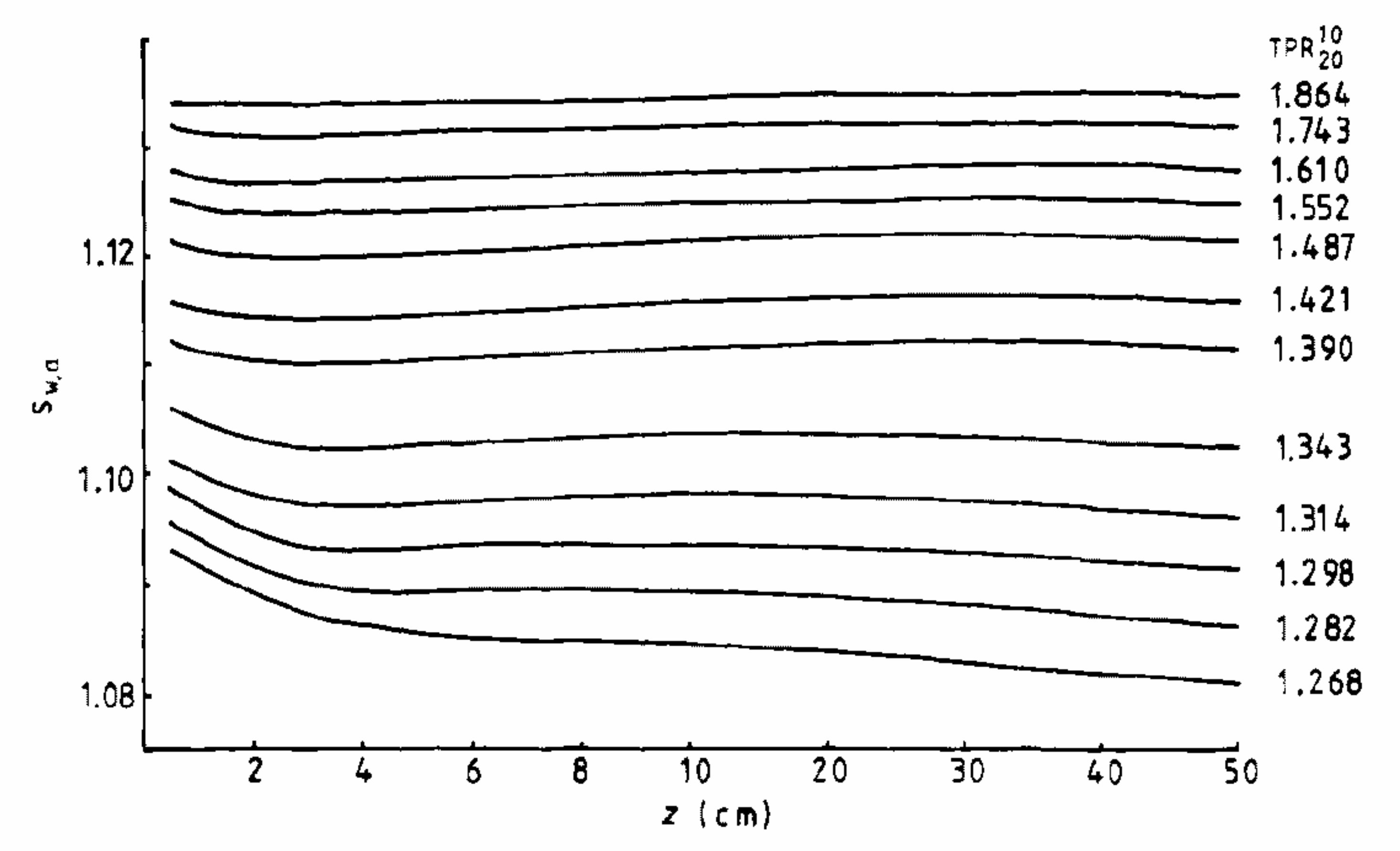
For the measurement of a dose distribution:

- In regions of CPE and TCPE: SPR corrections accurately represent detector response (and are small for air-filled chambers in photon beams)
- In regions of non-CPE: SPR corrections DO NOT accurately reflect changes in detector response and additional, sometimes large, corrections are needed
  - build-up regions in any field, interface-proximal points in heterogeneous phantoms (build-up and build-down)
  - narrow fields
  - modulated fields

Stopping power ratios (SPR's)

- SPR's are depth, field size, and radiation quality dependent
  - for reference dosimetry using ionization chambers: values based on Monte Carlo calculations and well documented
  - for relative dosimetry in TCPE: their variation relative to the reference point needs to be established

$s_{w,air}(z)$ for plane parallel bremsstrahlung spectra



^{60}Co

10 MV

20 MV

30 MV

Andreo and Brahme, PMB, 31, 839 (1986)

Perturbation correction factors: traditional factorization for ionization chambers:

$$P_Q = P_{wall} P_{gr} P_{fl} P_{cel}$$

- P_{wall}: wall perturbation
- P_{gr}: gradient effect due to displacement of phantom material by cavity
- P_{fl}: fluence perturbation
- P_{cel}: central electrode perturbation

Perturbation correction factors

- depth, field size, and radiation quality dependent
  - for reference dosimetry using ionization chambers: based on Monte Carlo calculations and relatively well documented
  - for relative dosimetry: their variation relative to the reference point is usually ignored but can be very significant

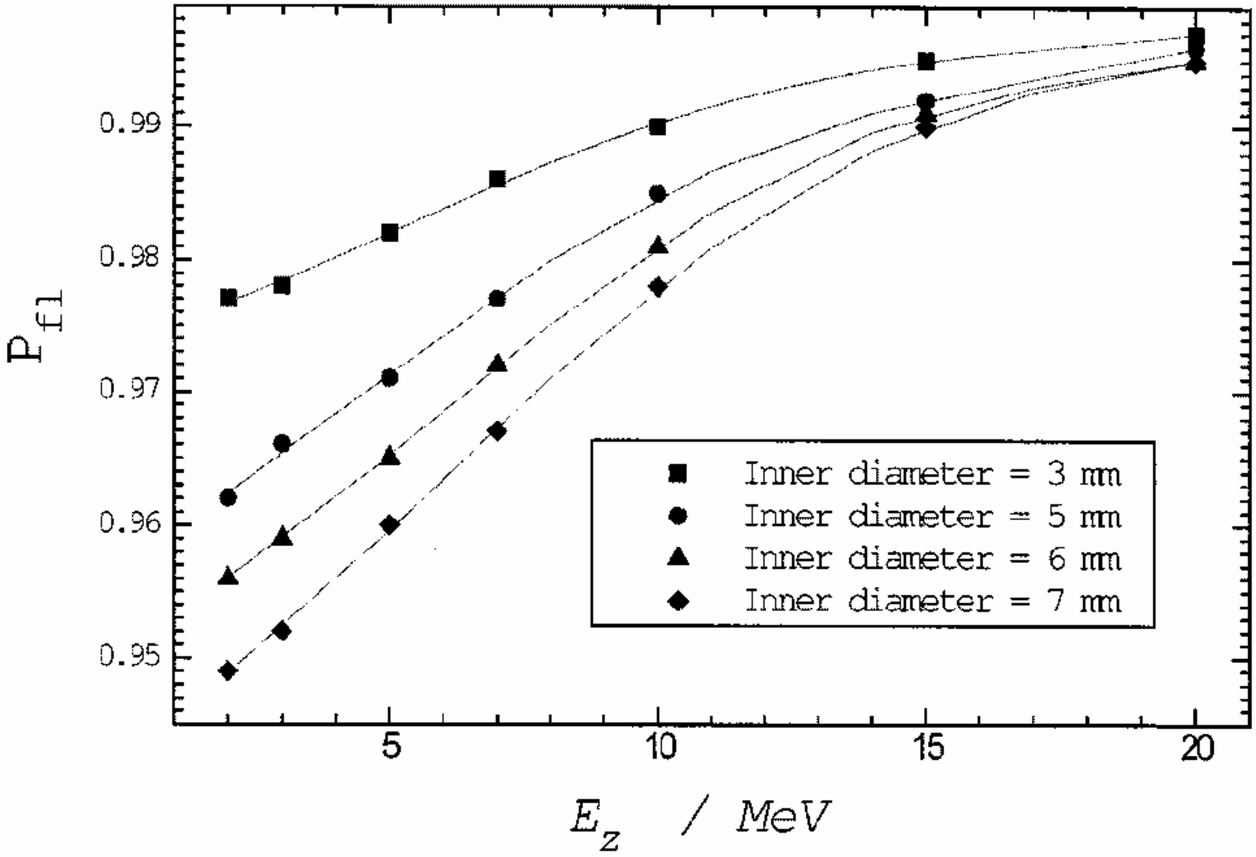
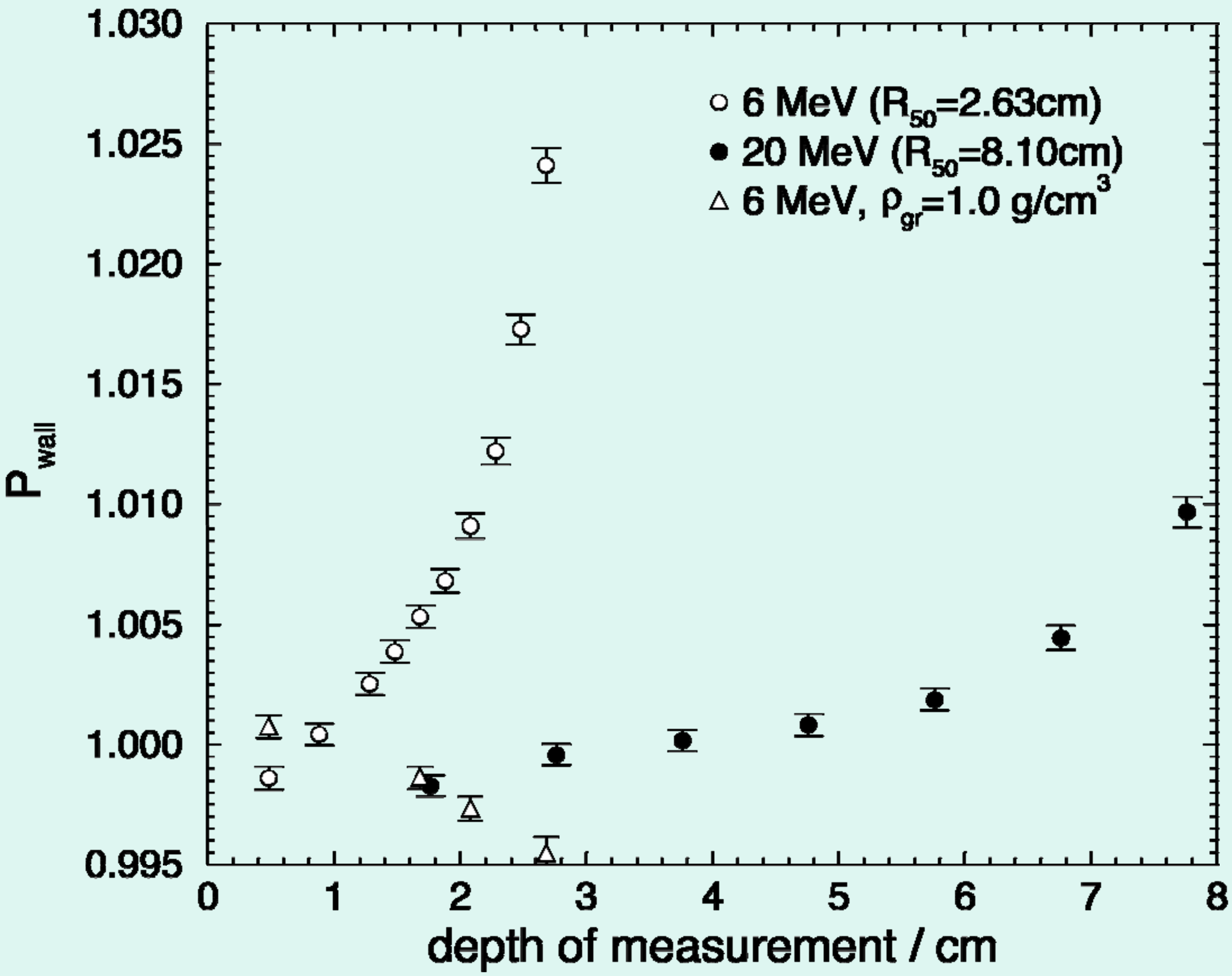
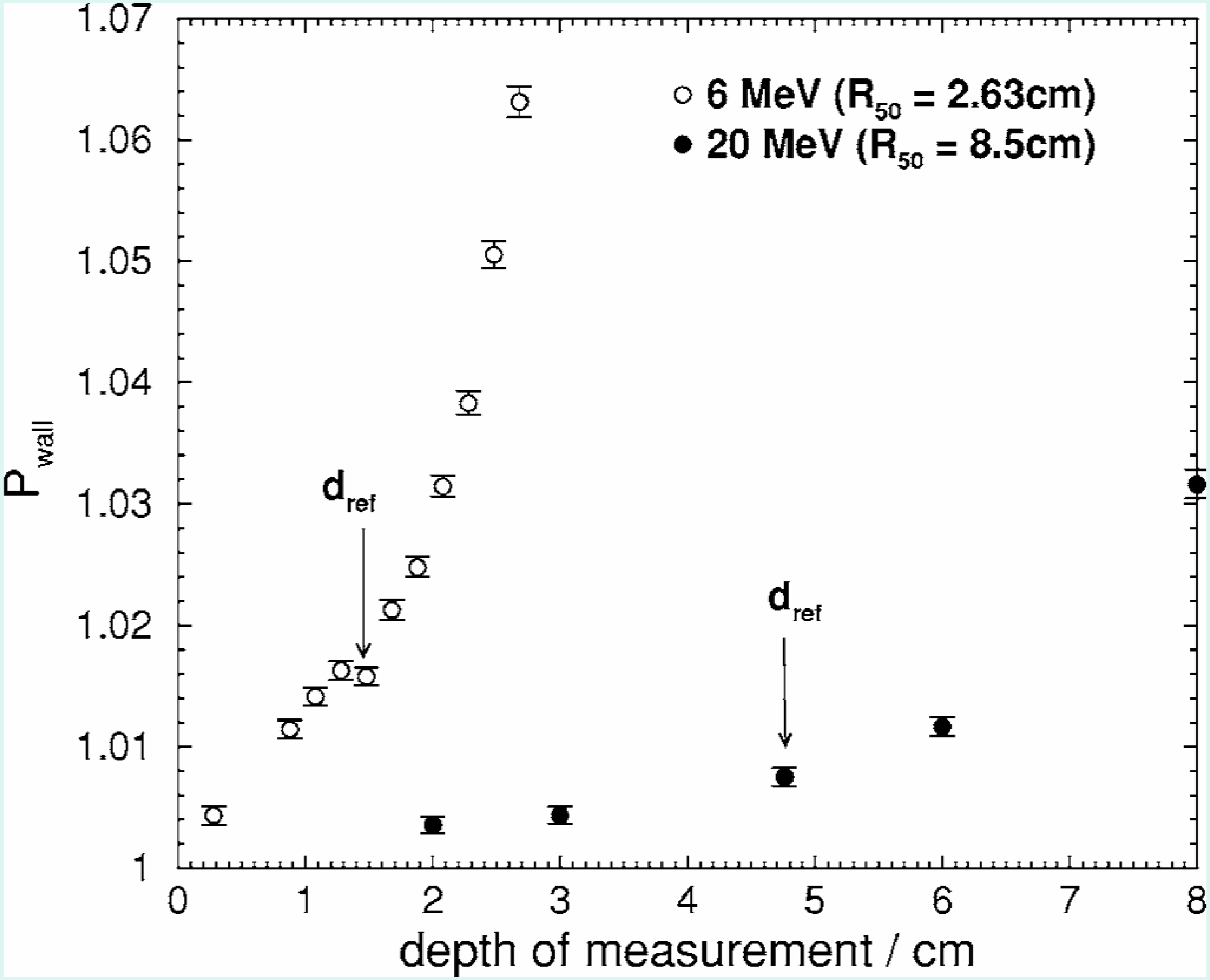


FIG. 1. Polynomial fitted curves (solid lines) of fluence correction as function of mean electron energy E_z for the AAPM TG-21 tabulated data (symbols).

Ding and Wu, Med. Phys. 28, 298 (2001)



Buckley and Rogers, Med. Phys. 33 455 (2006)



Buckley and Rogers, Med. Phys. 33 1788 (2006)

Commissioning measurements

- beam model verification
  - in-air measurements
  - in-water measurements
- in-phantom verification
  - heterogeneous measurements
- reference dose measurements / system calibration

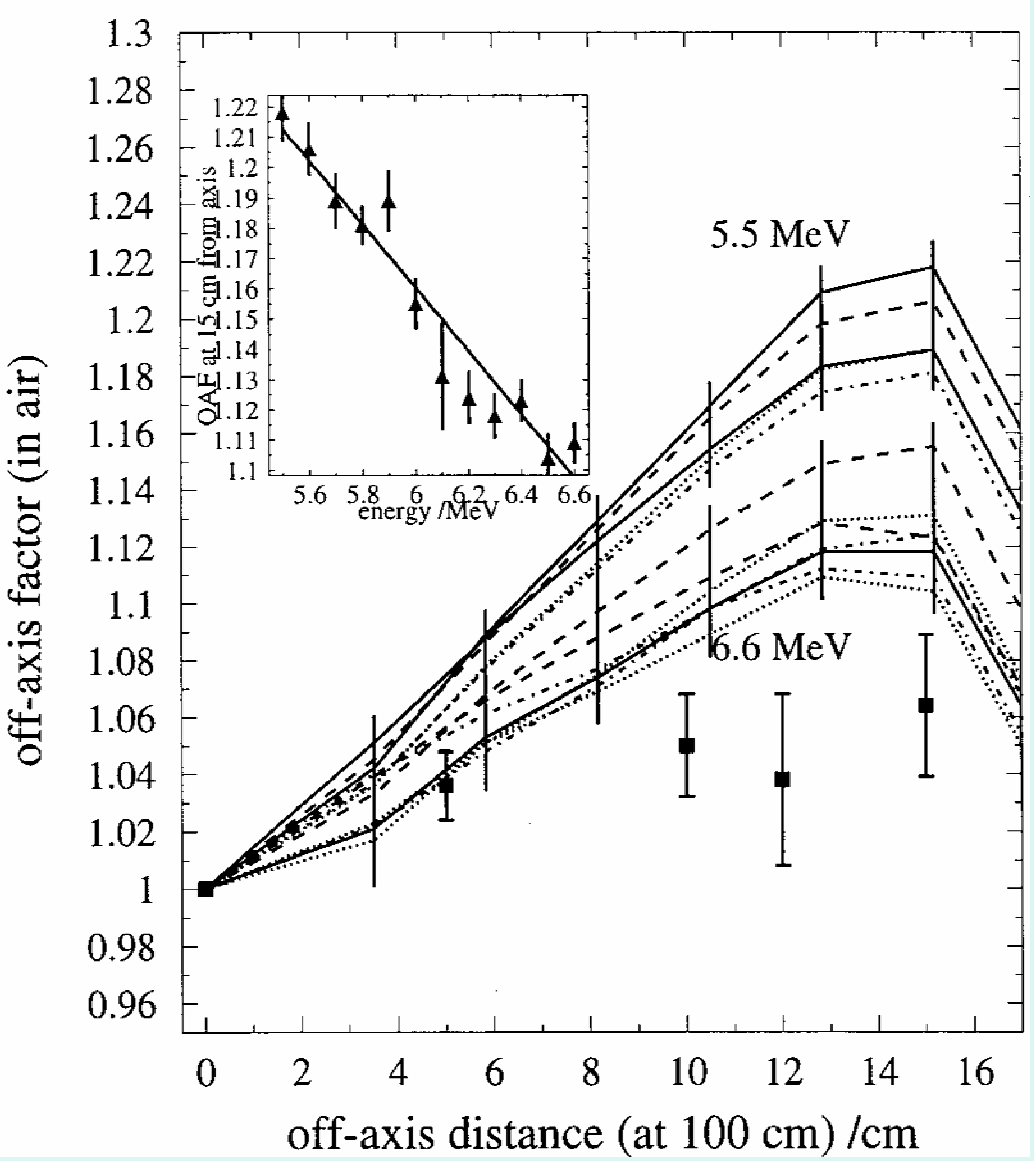
In-air measurements

- Parameters of primary source determined
  - mean energy of electrons exiting the vacuum window
  - FWHM of intensity distribution of electron beam exiting the vacuum window
- Measurement issues?
  - detector response can change as a function of off axis distance

Off axis profiles are sensitive to the energy of the primary electron source.

Off axis profiles are collision kerma (to water or air) profiles.

Sheikh-Bagheri & Rogers (2002) Med. Phys. 29, 379 - 390.

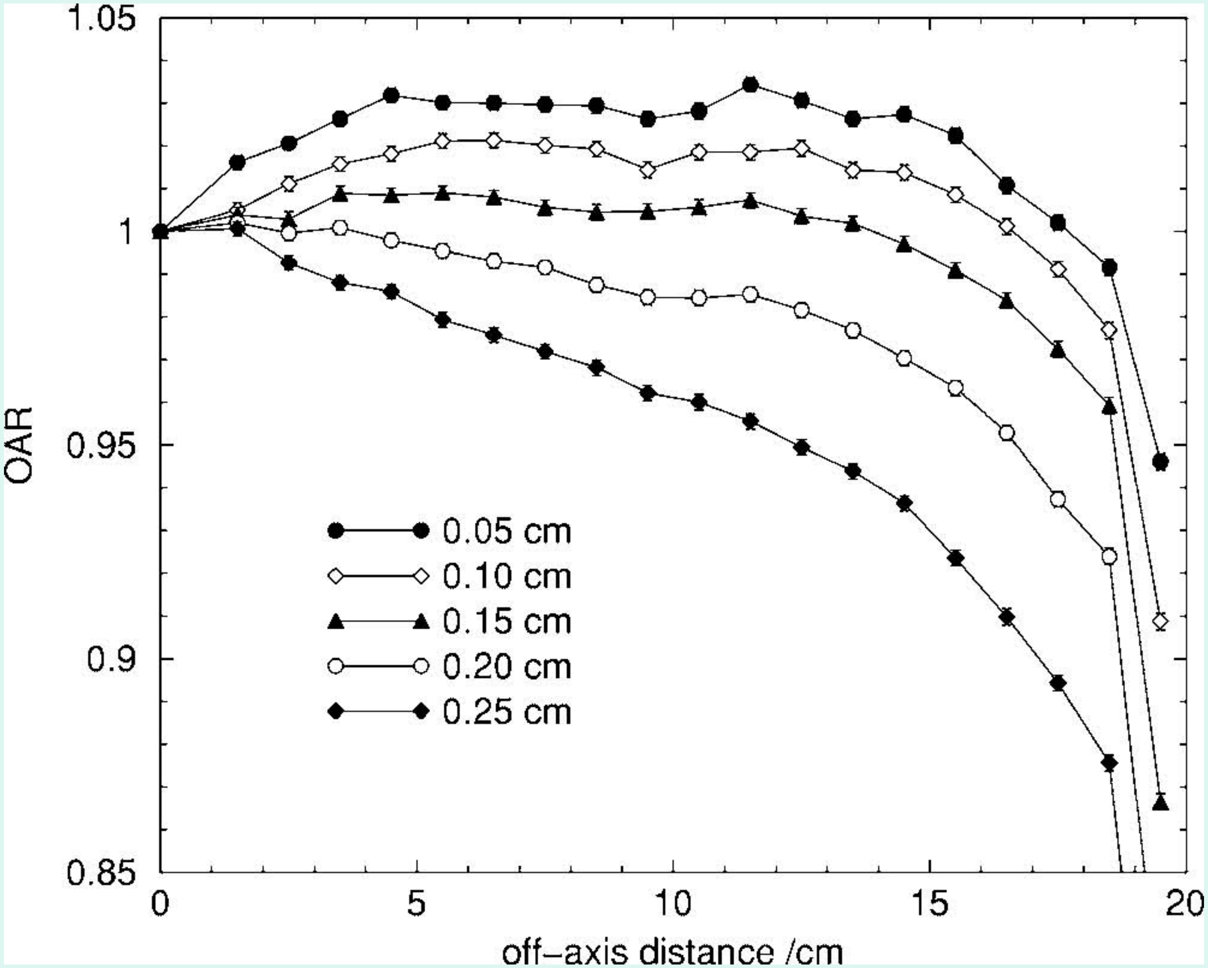


AAPM Summer School, 2006

Off axis profiles are sensitive to the radius of the primary electron source.

Build-up cap:

“hevimet”

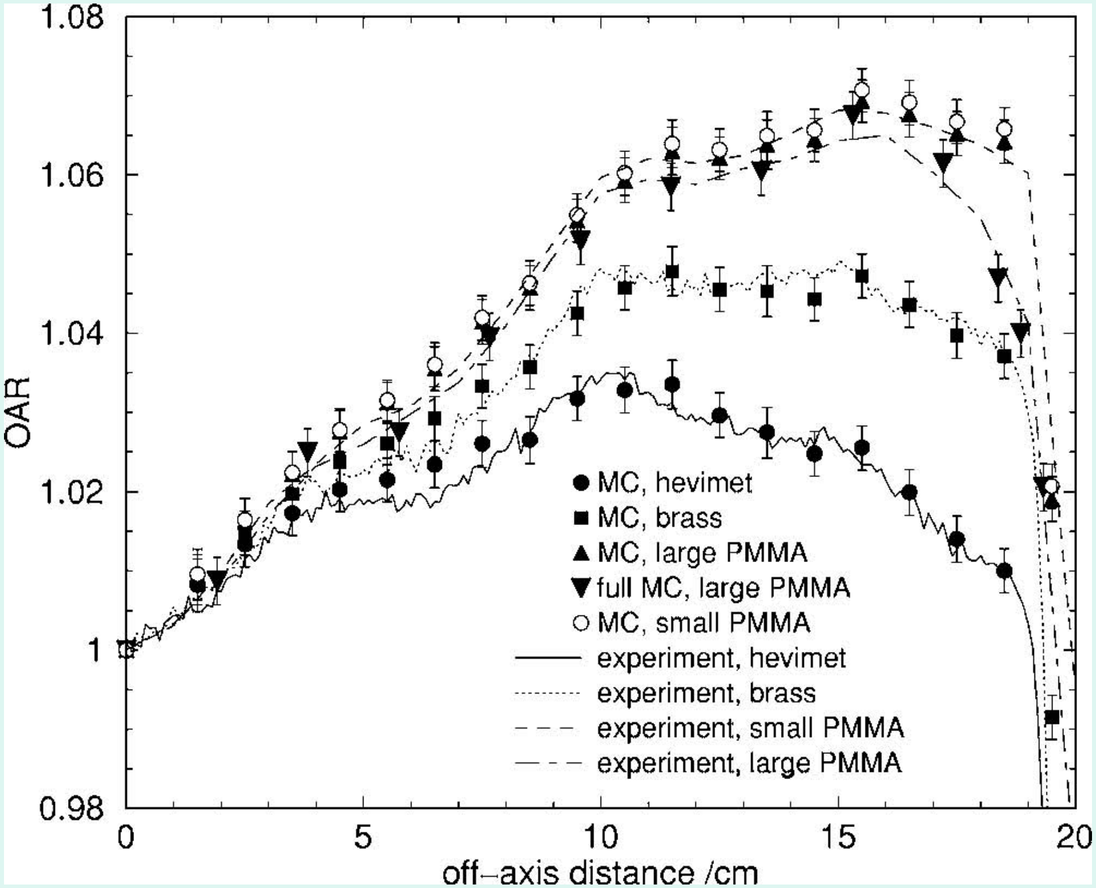


Tonkopi et al (2005) Med Phys 32, 2918 - 2927

In-air measurements:

Which build-up cap should be used?

Experimental validation of different types of b.u. caps.



Tonkopi et al (2005) Med Phys 32, 2918 - 2927

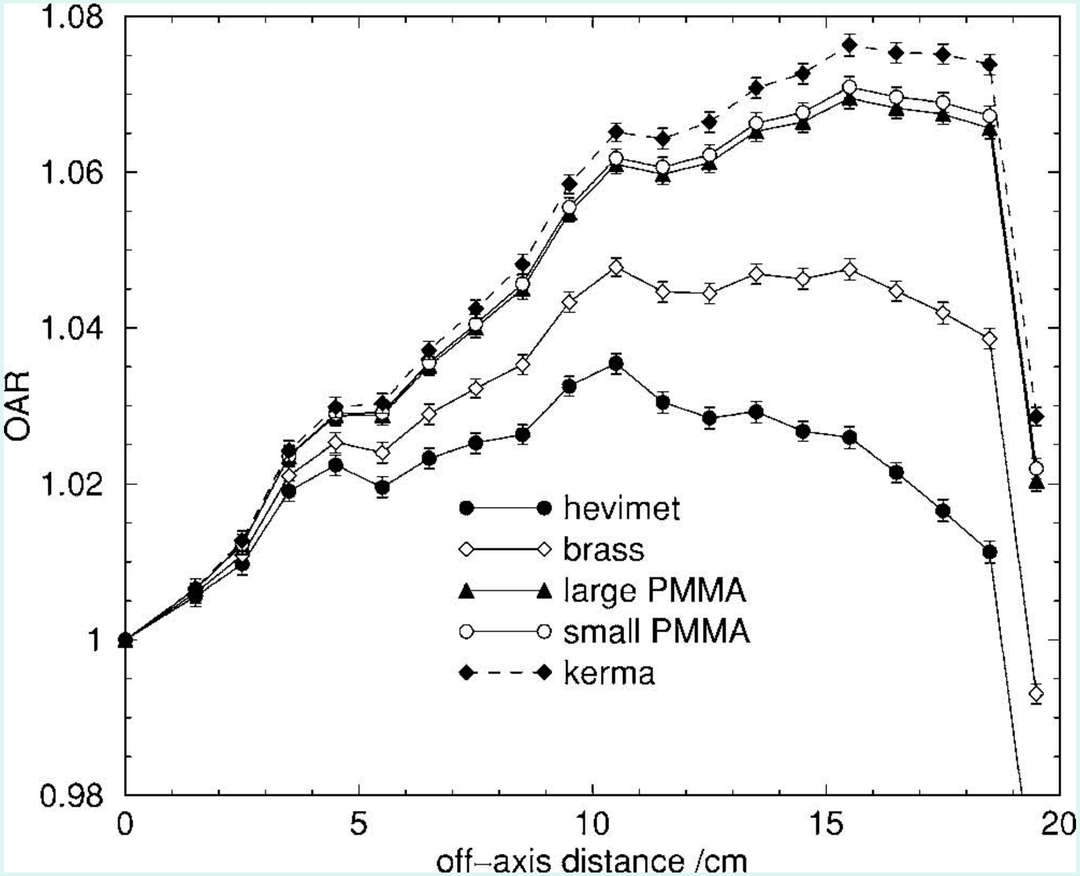
In-air measurements:

Which build-up cap should be used?

Cap that approximates collision air kerma the best?

Note:

1. small difference between two cap sizes
2. -> resolution does not significantly decrease with large cap size.



Tonkopi et al (2005) Med Phys 32, 2918 - 2927

In-air measurements, wide beam profiles for electrons

- in-air wide-field open beam profiles uncover details about
    - electron source parameters
    - scattering foils
    - filters in the beam

Wide beam profile measurements for Total Skin Electron Therapy

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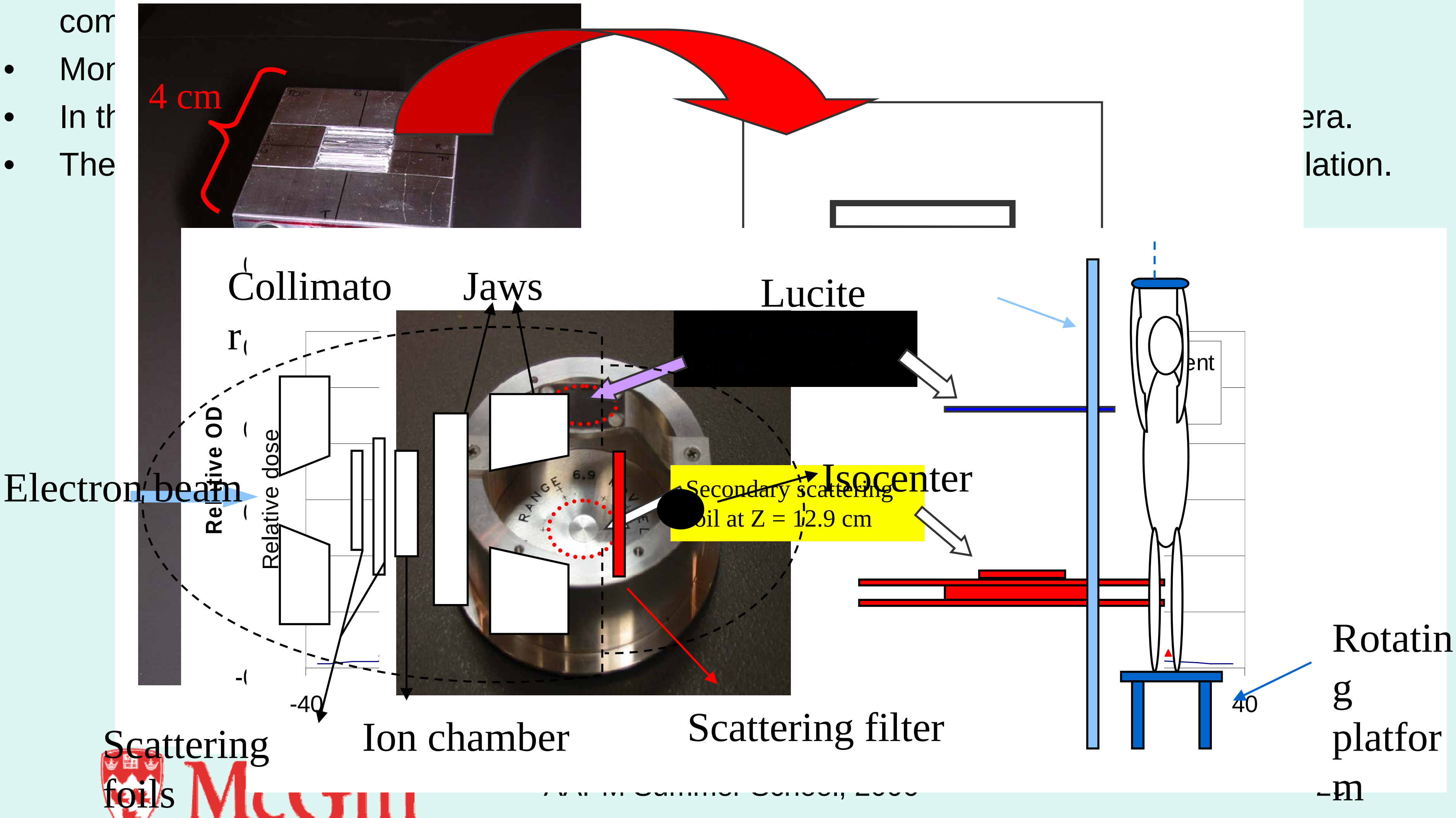
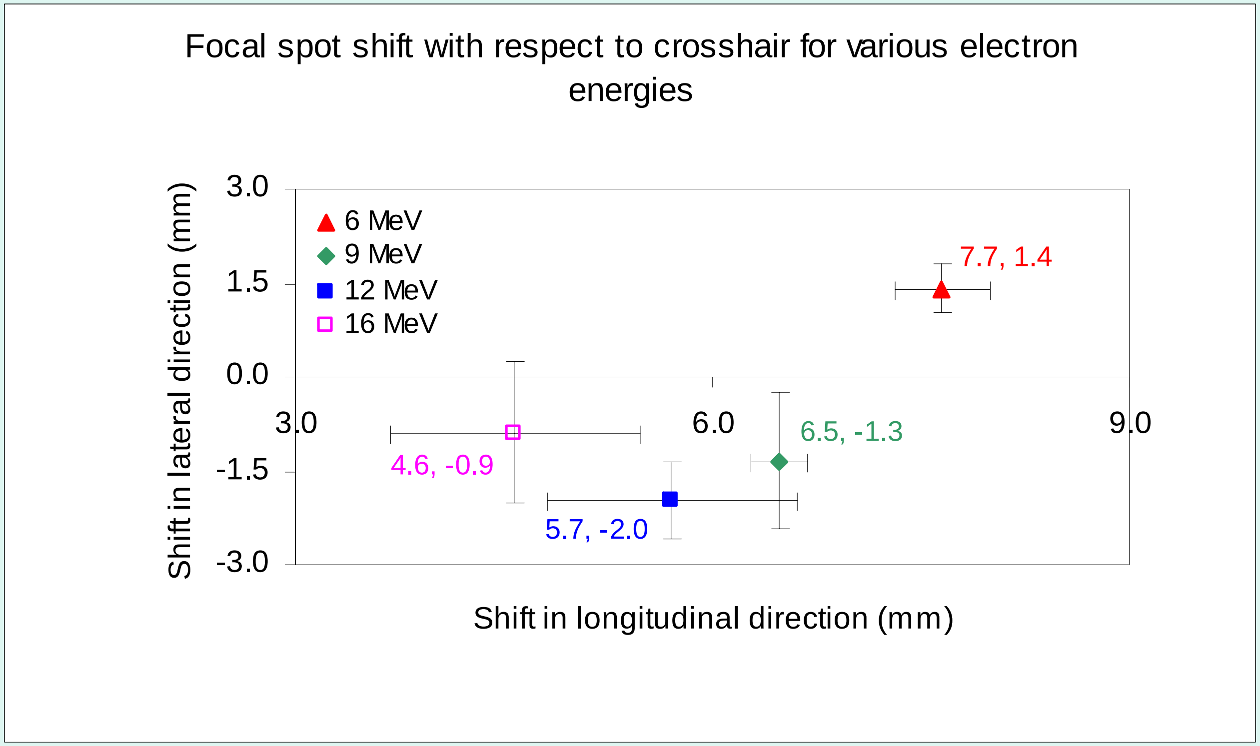


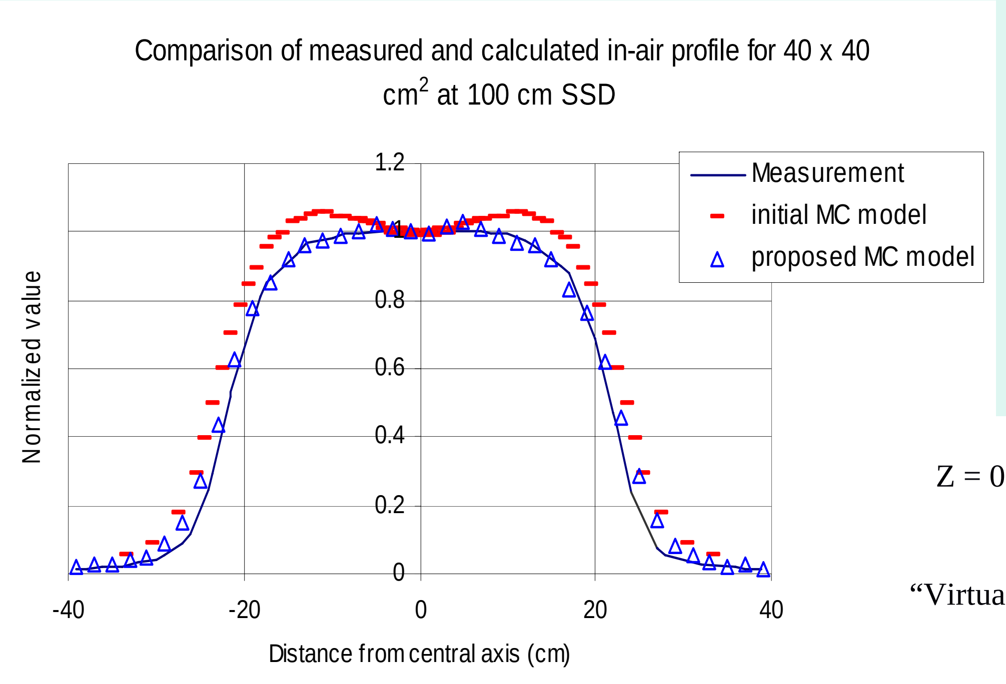
Source description optimization



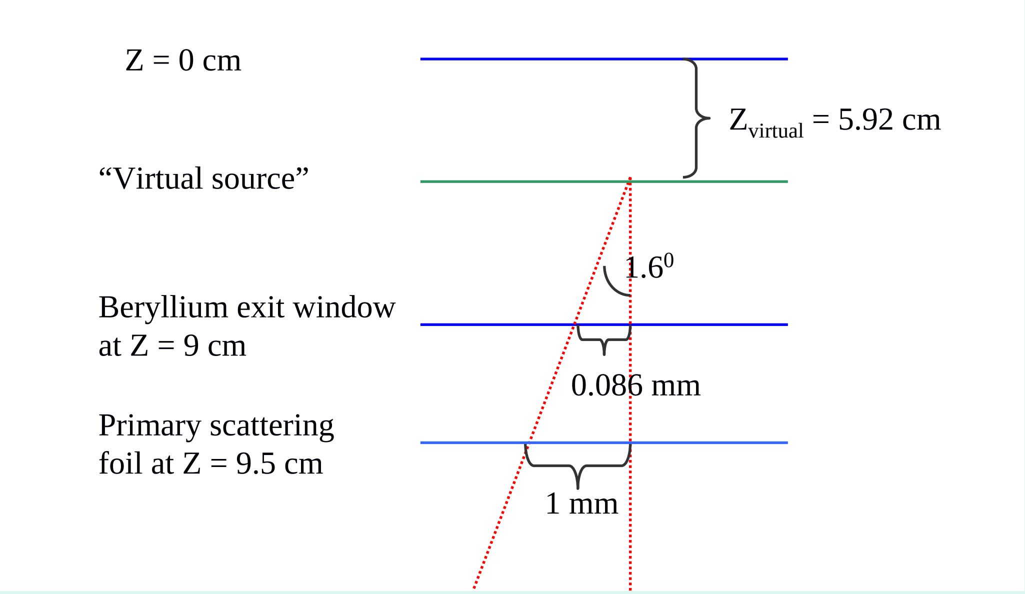
Focal spot is elliptical and has a Gaussian distribution.

Lateral and longitudinal shifts with respect to the crosshair is also observed for all measurements.

Source description optimization



Proposed divergent beam model shows improved result for 40 x 40 cm^2 in-air profile.



In-water beam model verification measurements

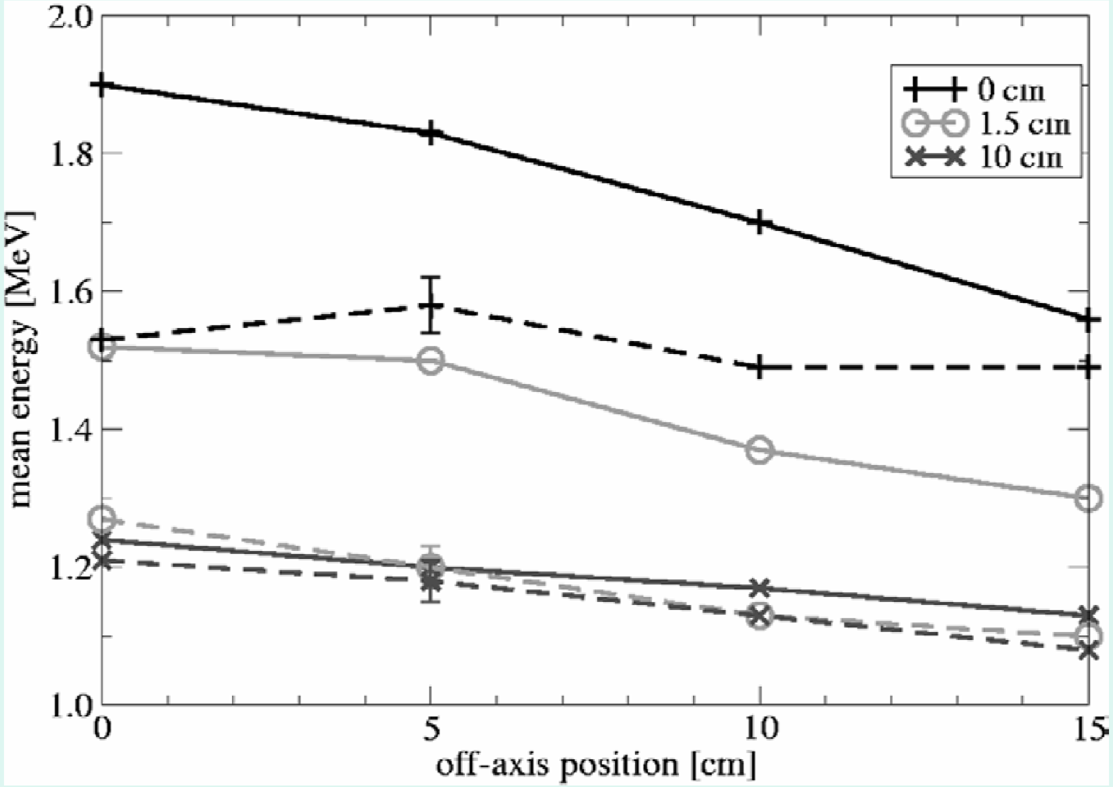
- In-water measurements are frequently used for beam model optimization since:
  - these measurements are performed as part of a standard commissioning.
  - reproduction of these measurements by the MC planning system forms a core consistency test of the system's commissioning.
  - reference dosimetry is carried out in water (e.g., TG-51 or IAEA TRS-398) and thus allows to link the output measured to the source's energy and fluence parameters.

Different measurement issues in open photon fields in water

- in-field, CPE or TCPE
  - standard measurement, SPR is nearly constant and represents detector response well; detector perturbations are small (point-of-measurement shift is $0.6 * r_{inner}$ upstream)
- in-field, non-CPE (build-up)
  - non standard measurement, SPR varies modestly but does not represent variation in detector response well; detector perturbations are large, detector dependent.
- penumbra (non-CPE)
  - detector size must be small relative to field-size and penumbra width, SPR does not represent detector response well, lateral fluence perturbations, detector dependent.
- out-of-field (CPE or TCPE)
  - detector size must be sufficiently large to collect sufficiently large signal. SPE represents detector response well.

In-water off-axis measurements:

Behaviour of avg. photon and avg. electron energy



full lines: photons

dashed lines: electrons

-> stopping power ratio w/air is position independent

However: wall correction changes by about 2% since contributions to ionization change for modest changes in avg. photon energy.

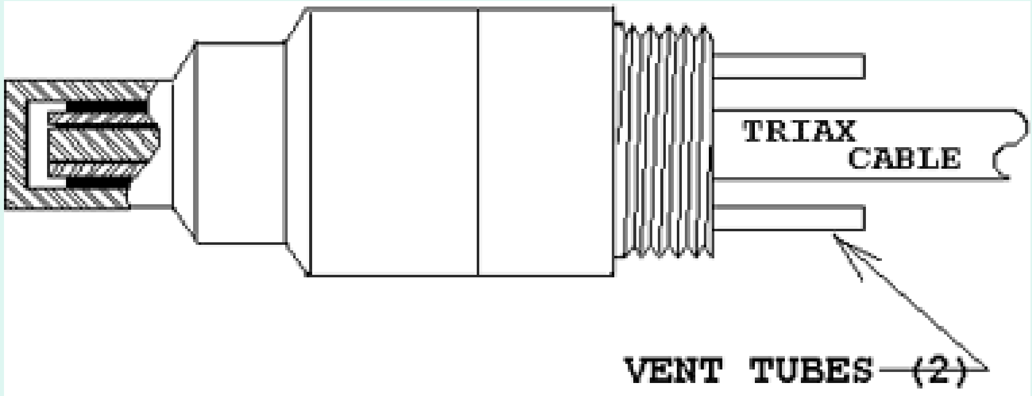
Dohm et al (2005) Phys Med Biol 50: 1449 - 1457

A14P ExRadin ionization chamber

Geometry of the measuring volume

Collecting electrode diameter: 1.5 mm

Separation: 1 mm

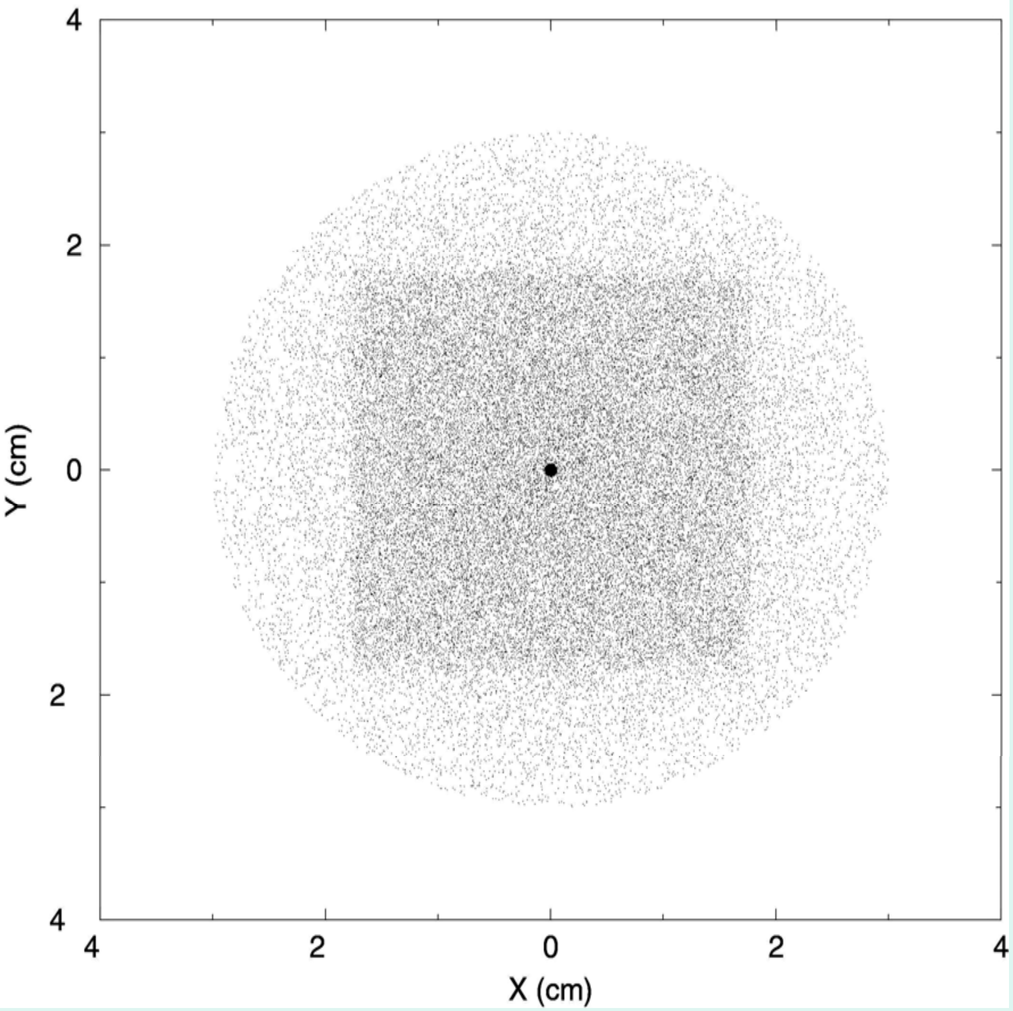


Effective volume of the chamber determined by electric field in chamber.

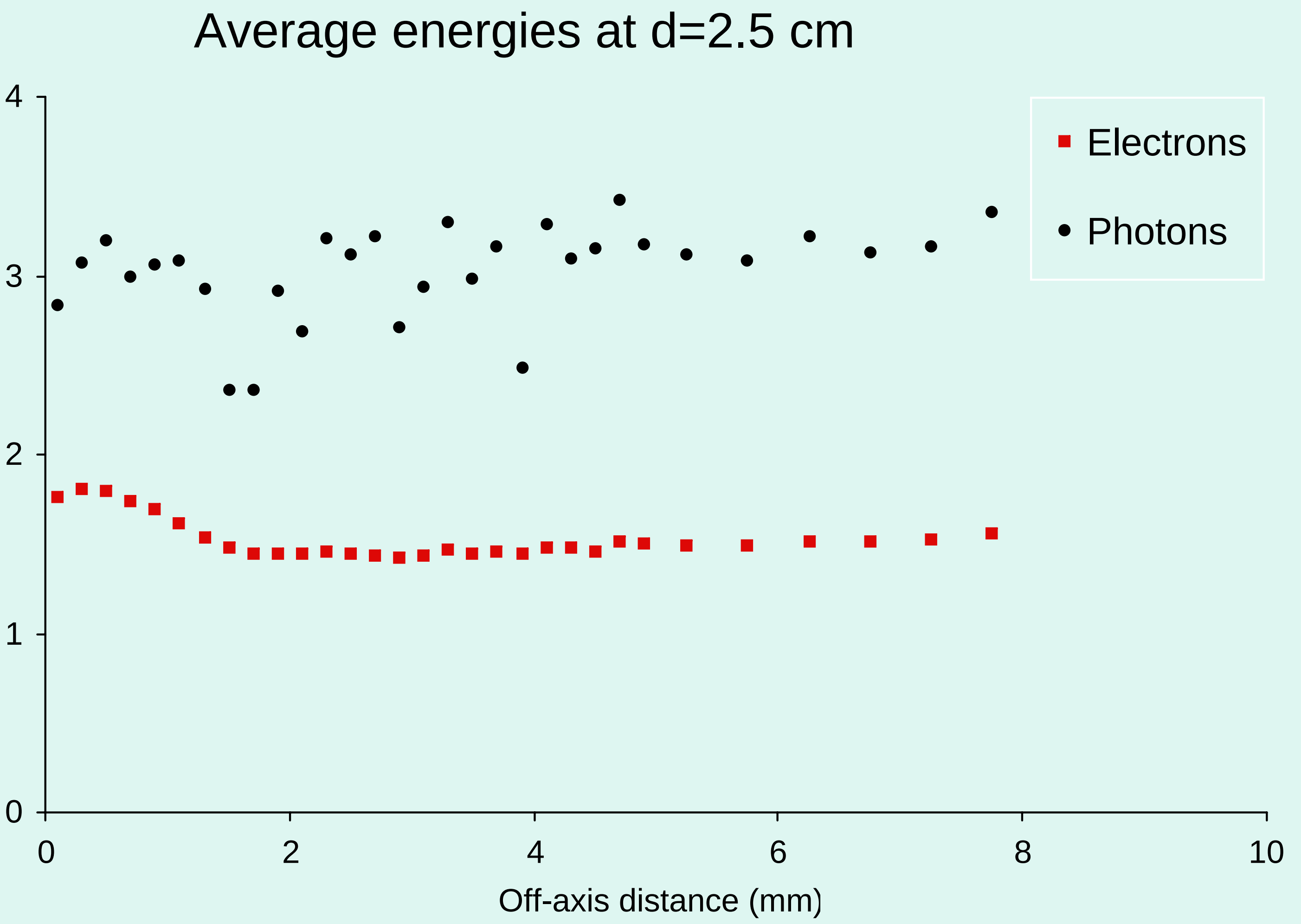
Laplace equation: $\nabla^2 U = 0$
Boundary condition: Surface potential

1.5 mm field

- special collimator
- Diameter of the field: 1 mm at 70 cm from the source



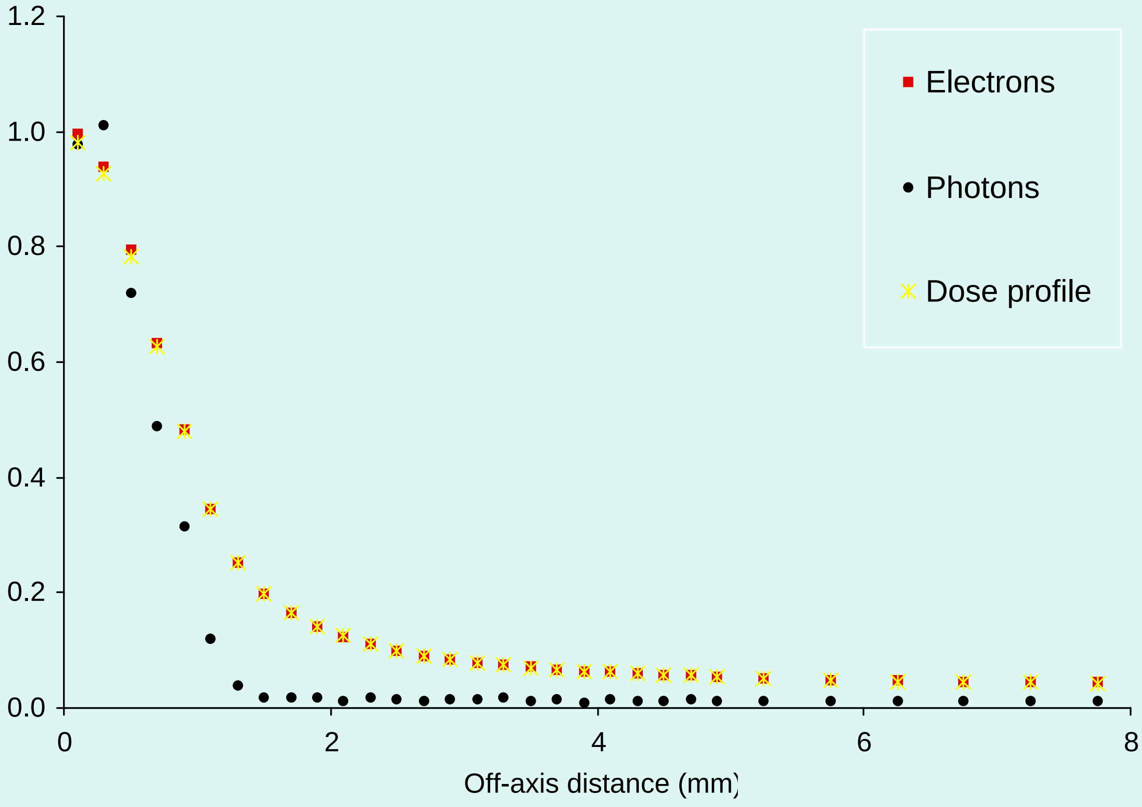
Narrow 1.5 mm field



Narrow 1.5 mm field

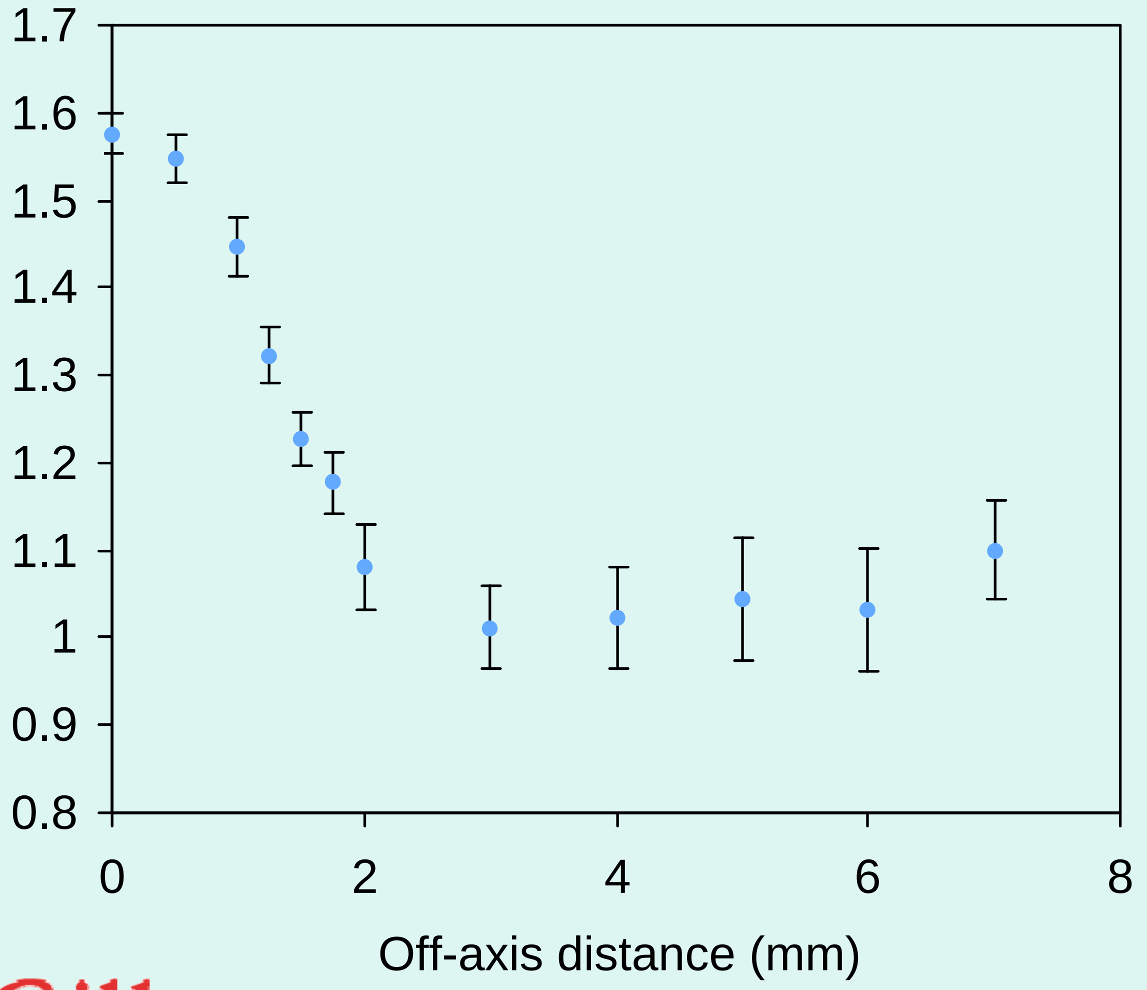
Fluence at d= 2.5 cm

normalized to the central axis value

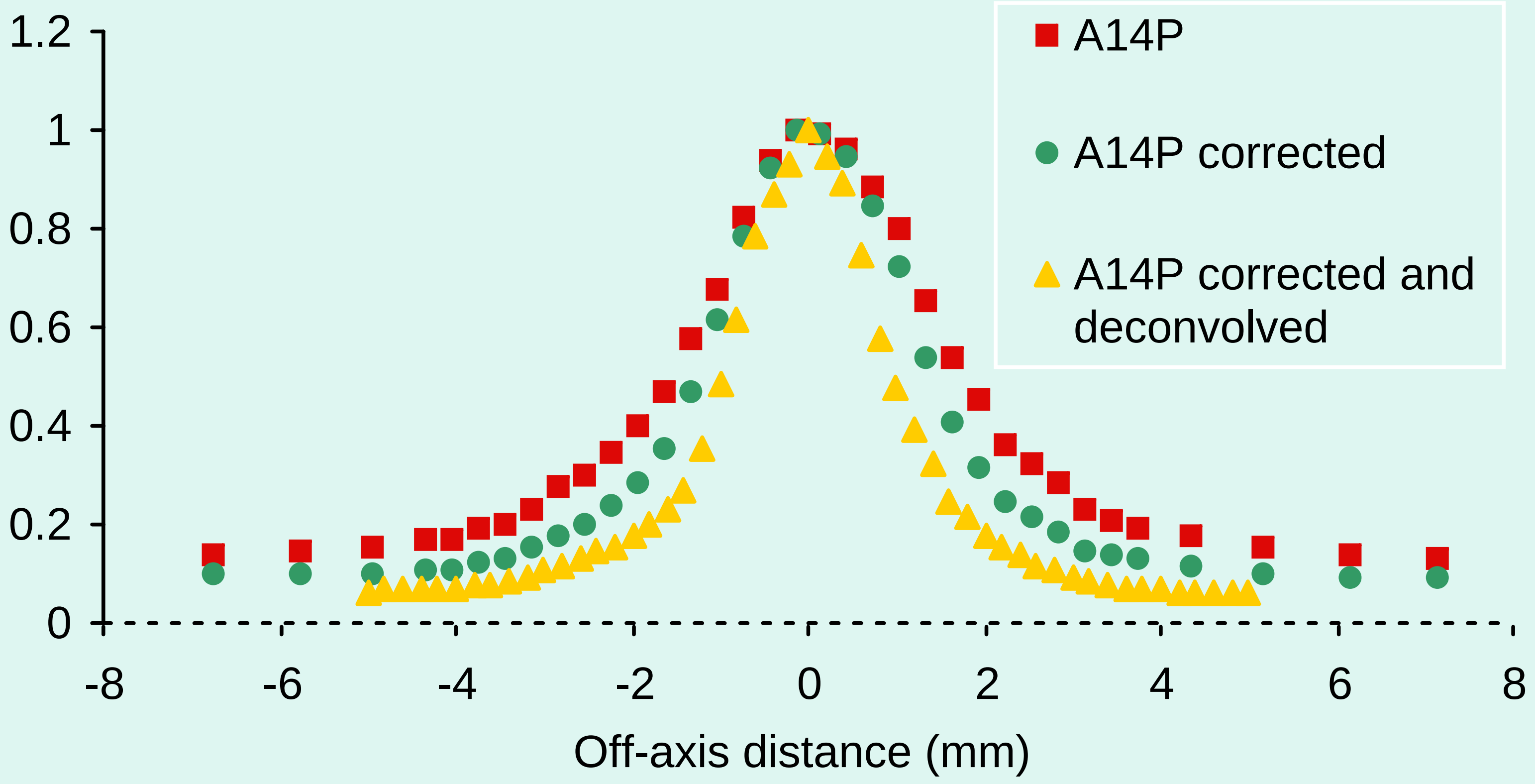


Narrow 1.5 mm field

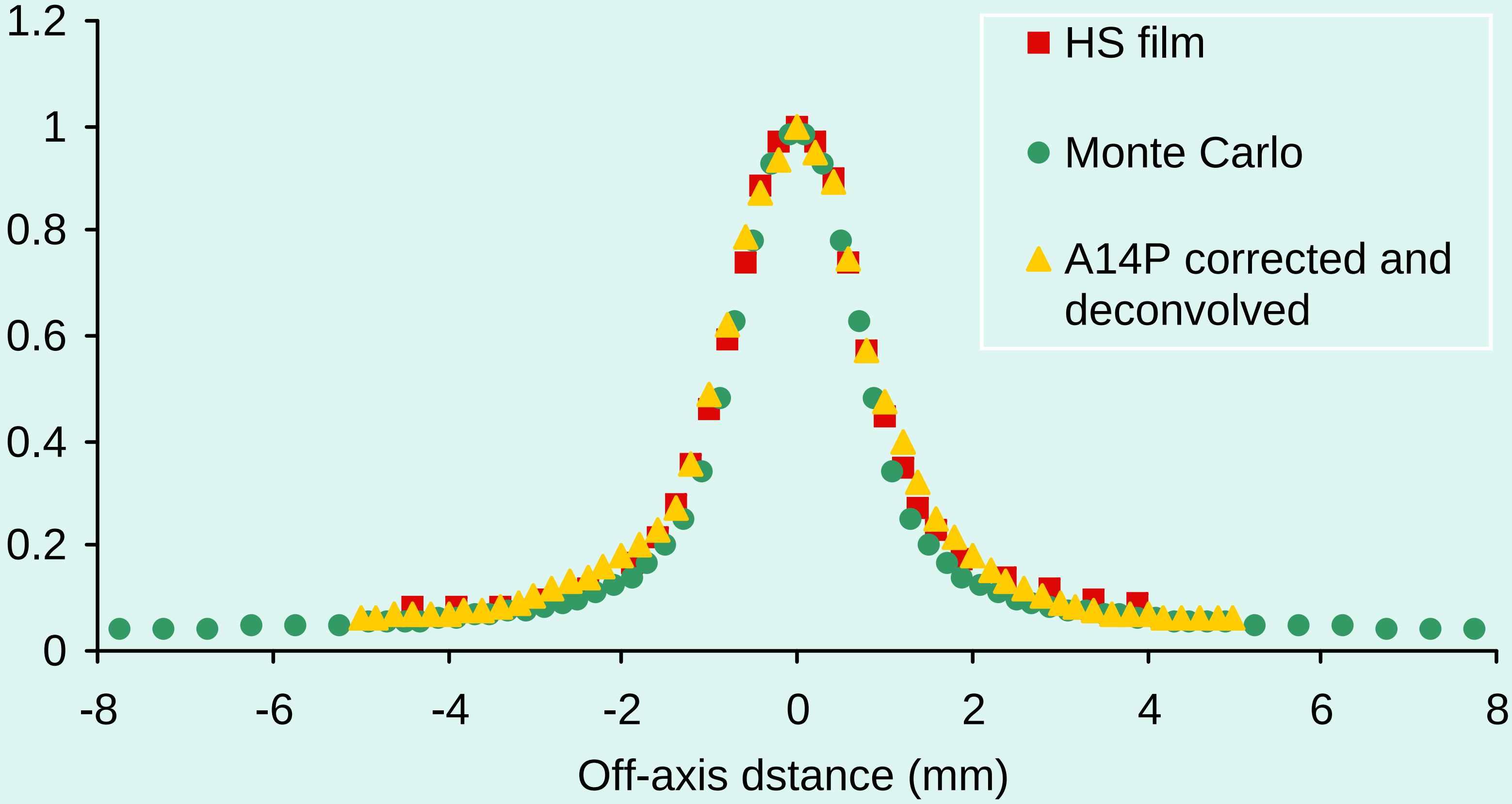
Dose water-to-air ratio



Narrow 1.5 mm field
OAR at d = 2.5 cm measured with A14P



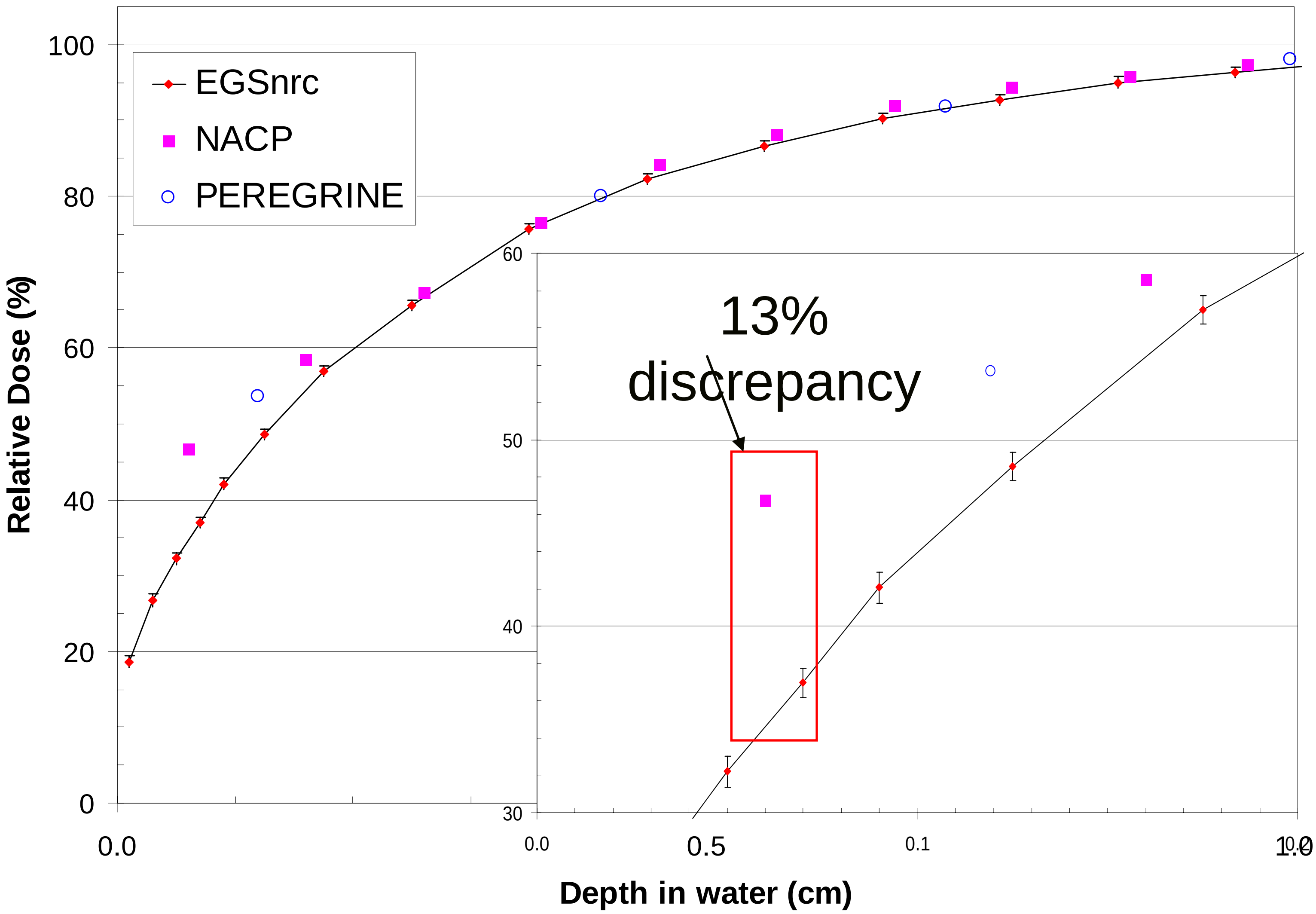
Narrow 1.5 mm field OAR at d=2.5 cm



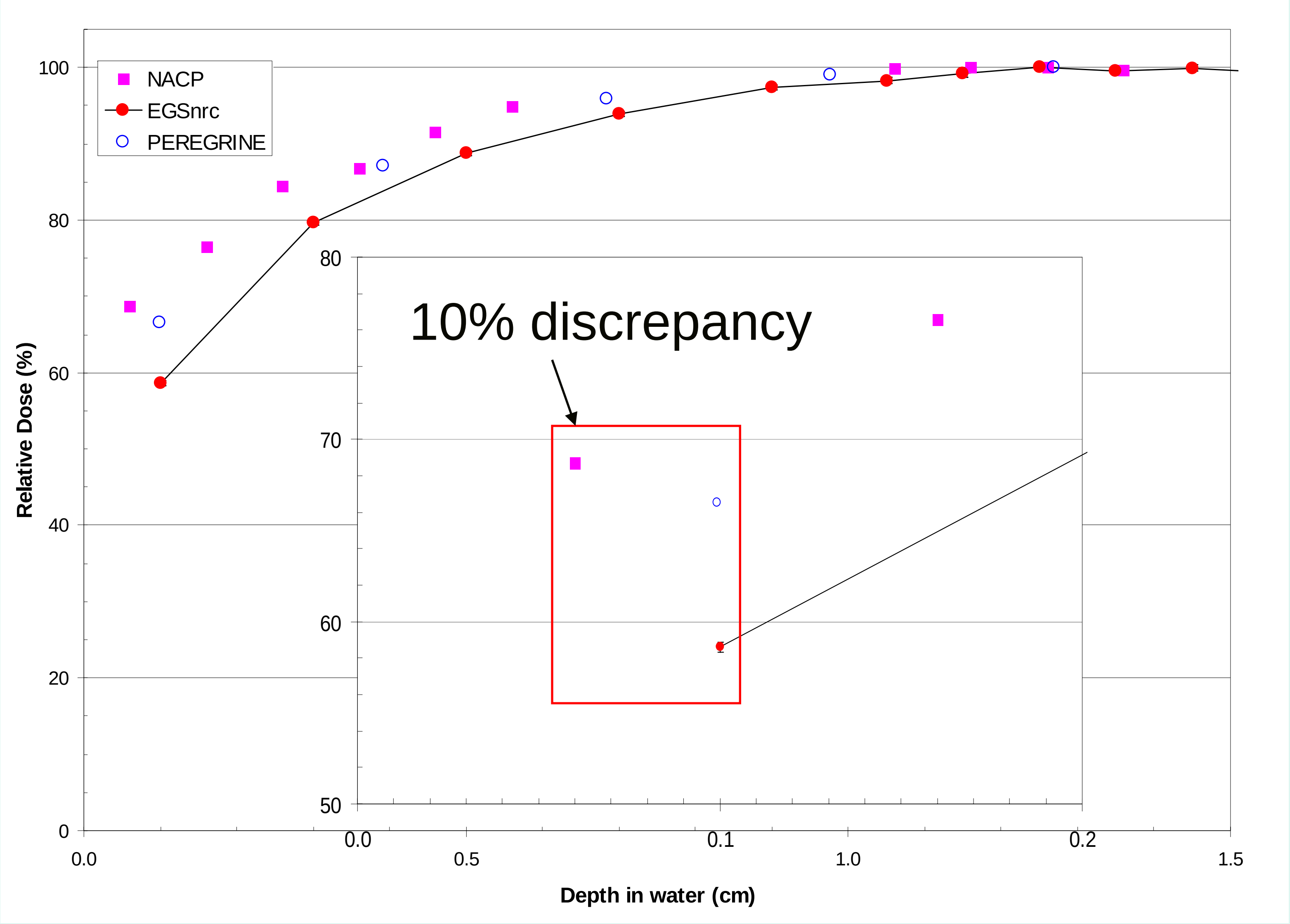
Build-up dose measurements

- Build-up dose calculations are challenging but may be clinically important for DVH's of superficial structures. However:
  - Discrepancies have been reported between measured and calculated build-up doses at high photon energies.
  - Benchmark measurements are needed to ensure the system accurately calculates dose in the build-up region.
  - Benchmark measurements are prone to uncertainties ranging up to 50% of the local dose.

Buildup region – 6 MV - 10x10 cm^2



Buildup region – 6 MV- 40x40 cm^2



NACP chamber response in buildup region

$$D_{cav} = \left(\frac{Q}{m_{air}}\right)\left(\frac{W}{e}\right)_{air}$$

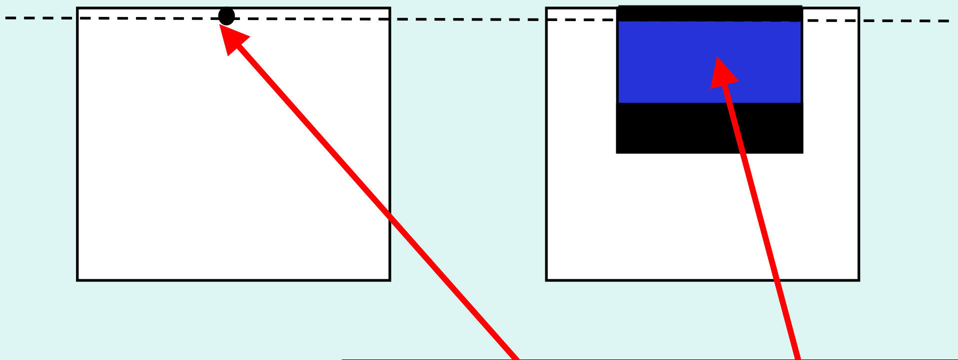
$$\frac{D_{cav}(d)}{D_{cav}(d_{max})} = \frac{Q(d)}{Q(d_{max})}$$

DOSRZnrc cavity simulations

NACP measurement

Field size (cm^2)	Calculated relative surface cavity dose	Measured relative surface ionization
10x10	45 ± 1 %	47 ± 2 %
40x40	67 ± 2 %	69.0 ± 0.3 %

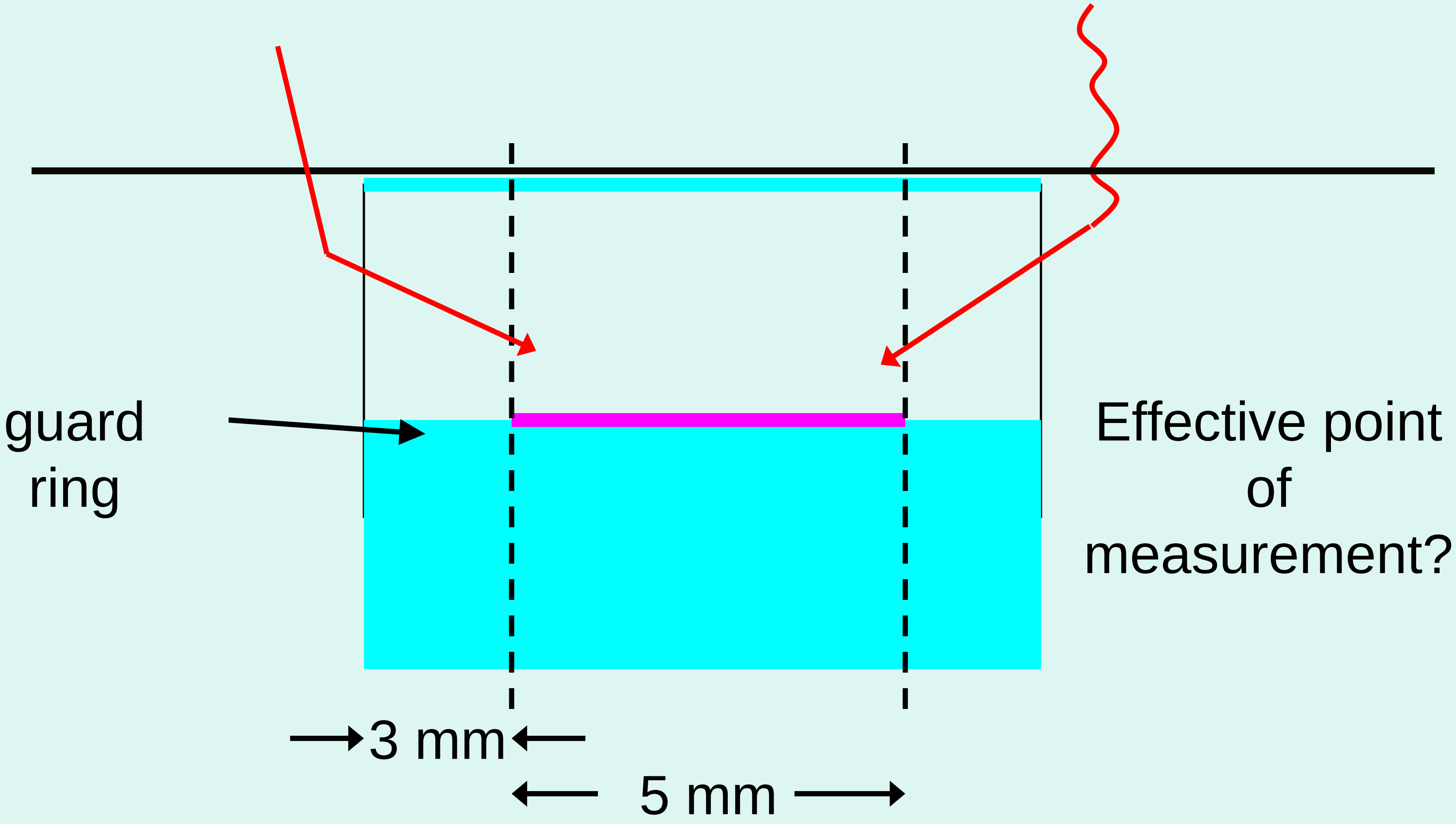
Perturbation correction factors – 10x10 cm^2



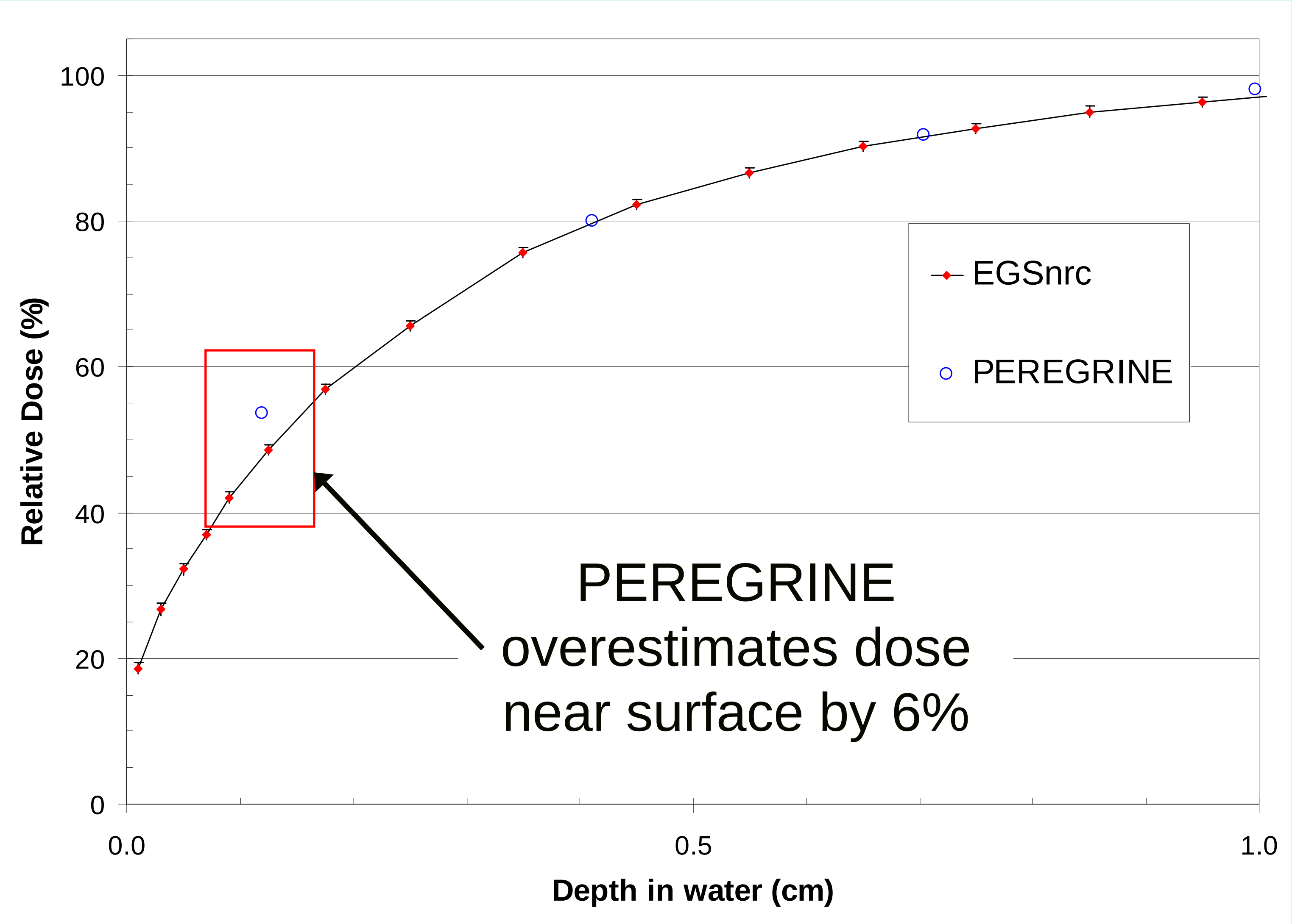
$$D_{water}(d)=D_{cav}(d)\left(\bar{L}(d)\big/\rho\right)_{air}^{water}\boxed{\Phi_{air}^{water}(d)}$$

Depth (cm)	Perturbation correction
0.0	0.78 ± 0.02
1.5	0.99 ± 0.008

Sources of chamber perturbation



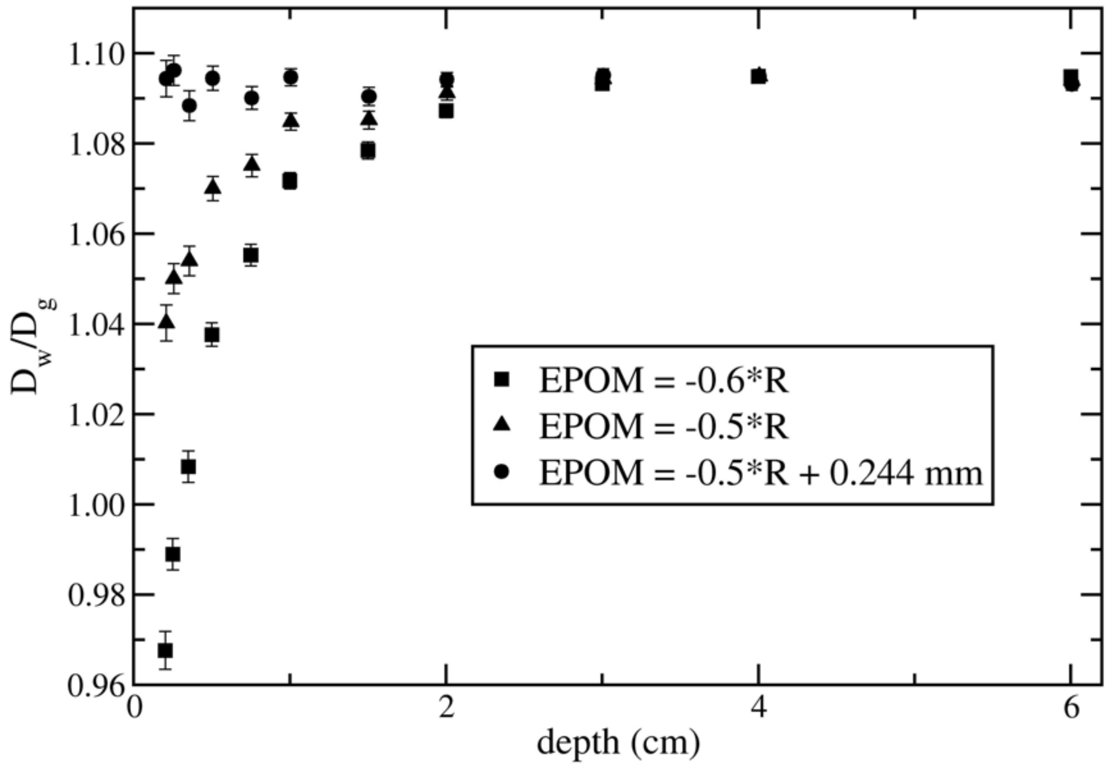
Buildup region – 10x10 cm^2



PEREGRINE overestimates dose near surface by 6%

Reconciling measurements and calculations in the build-up region by adjusting EPOM

->simple if it works; but is chamber dependent!

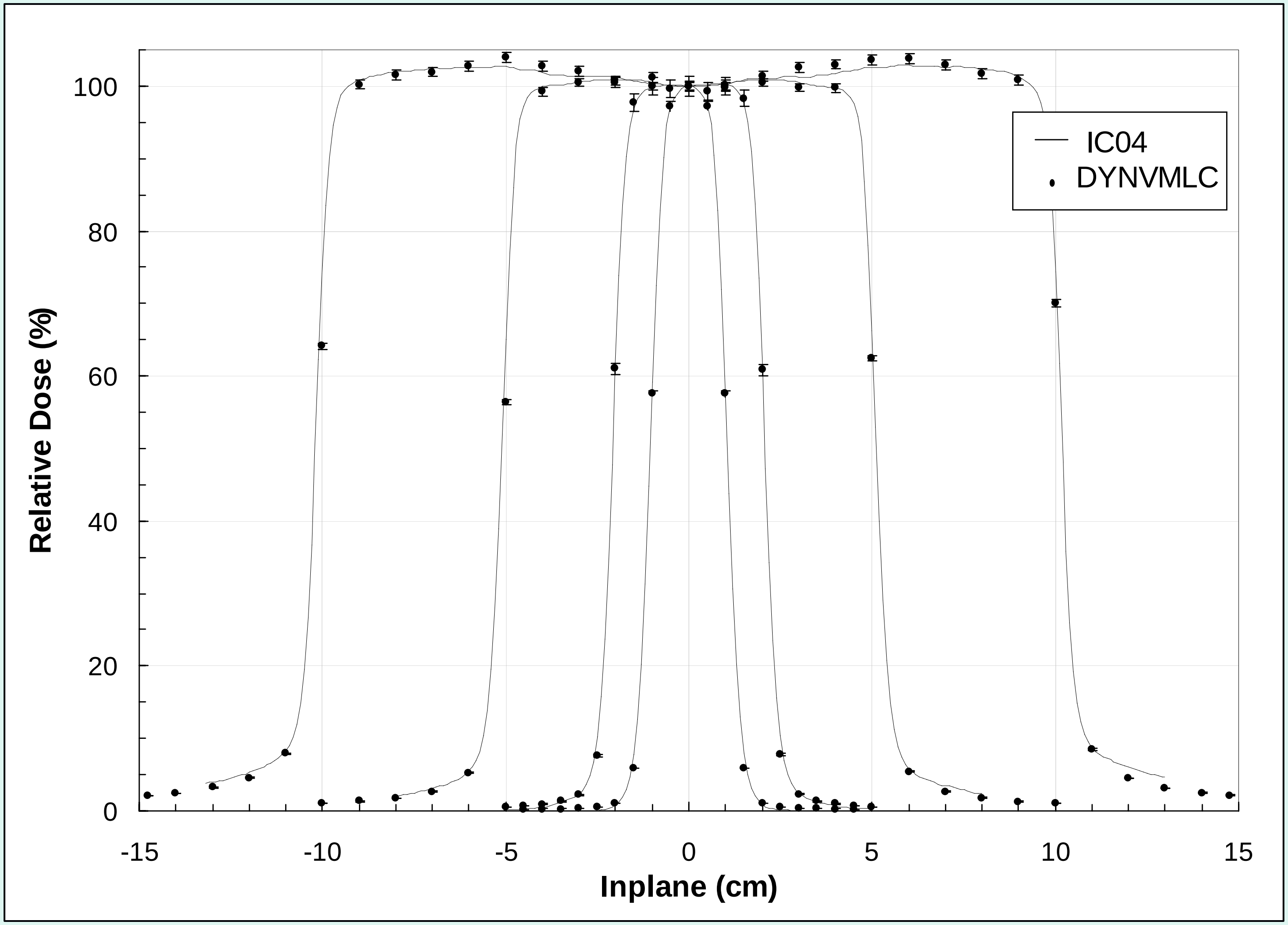


Kawrakow (2006) Med. Phys. **33**, 1829

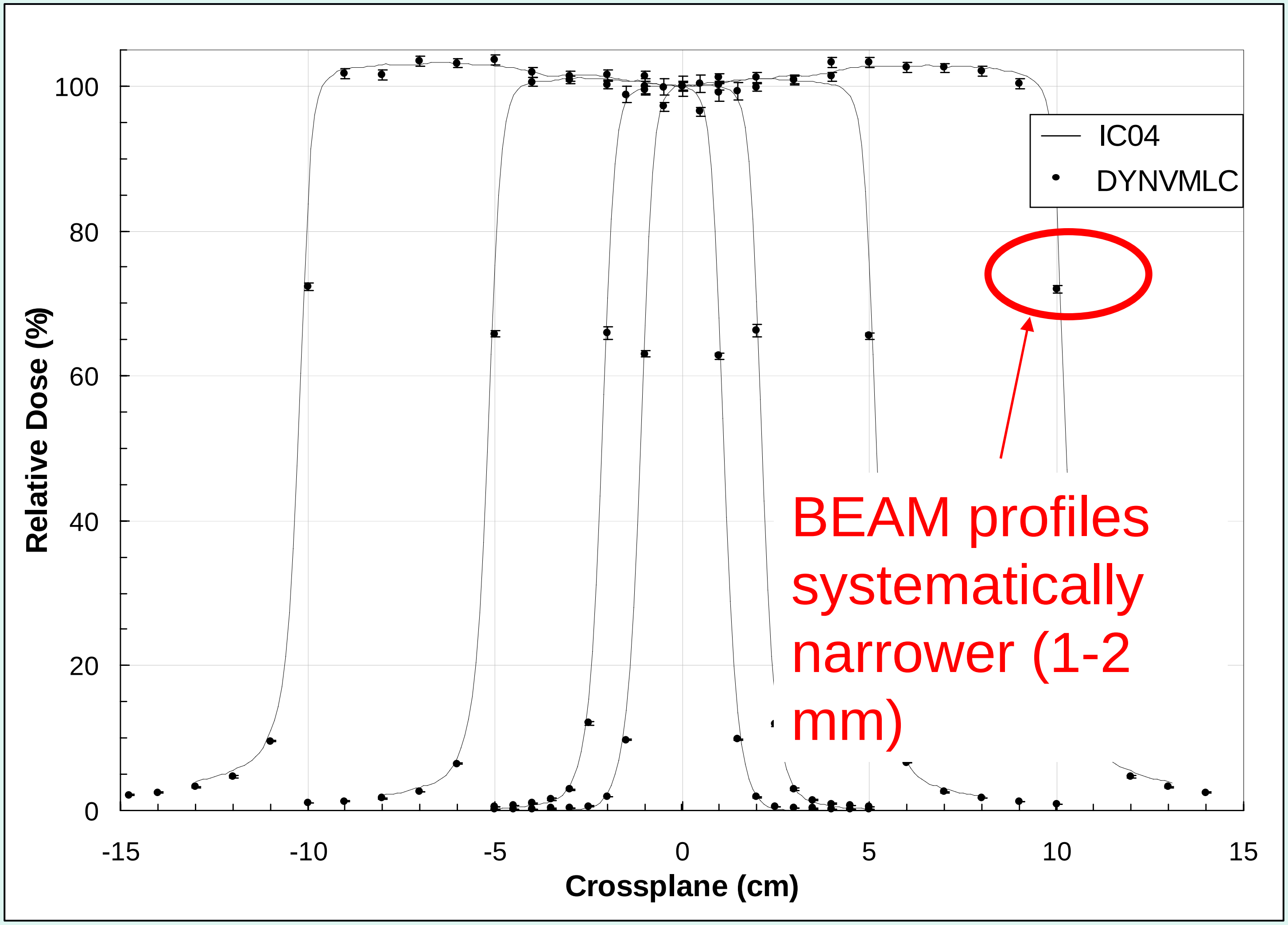
Measurements in the presence of beam modifiers - MLC's

- Leakage and Transmission
  - contributes >10% of open field dose in IMRT
  - spectrum (beam hardening)
  - contribution to organs at risk
  - widening of penumbra (rounded leaf ends)
- Tongue and groove effect
  - 10-15% under-dosing for static fields
  - no detailed study for IMRT

Across leaf bank

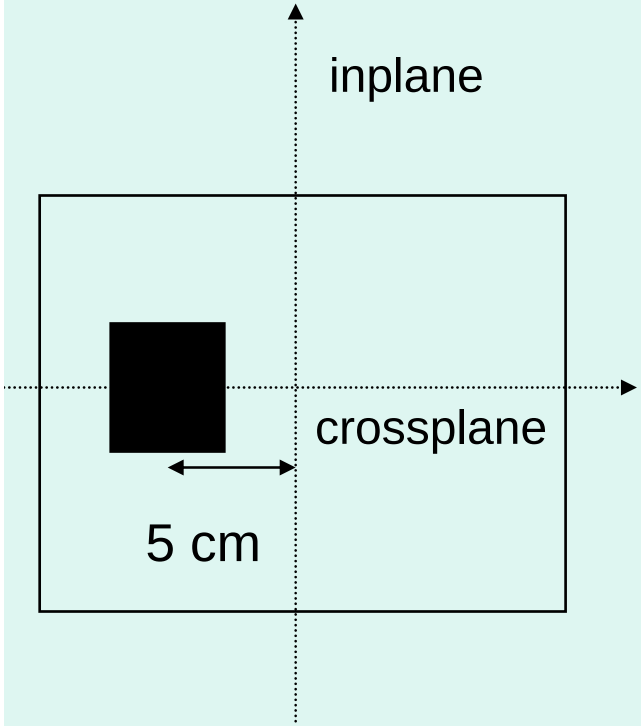


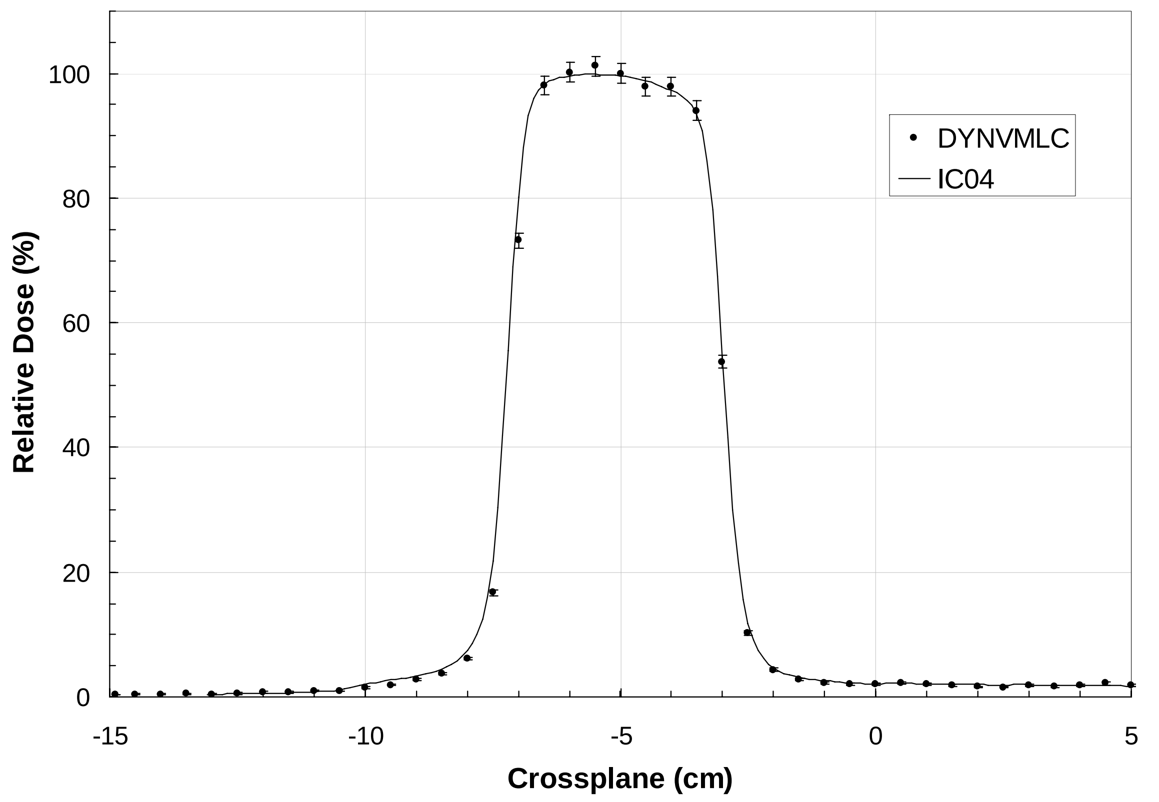
Along direction of leaf motion



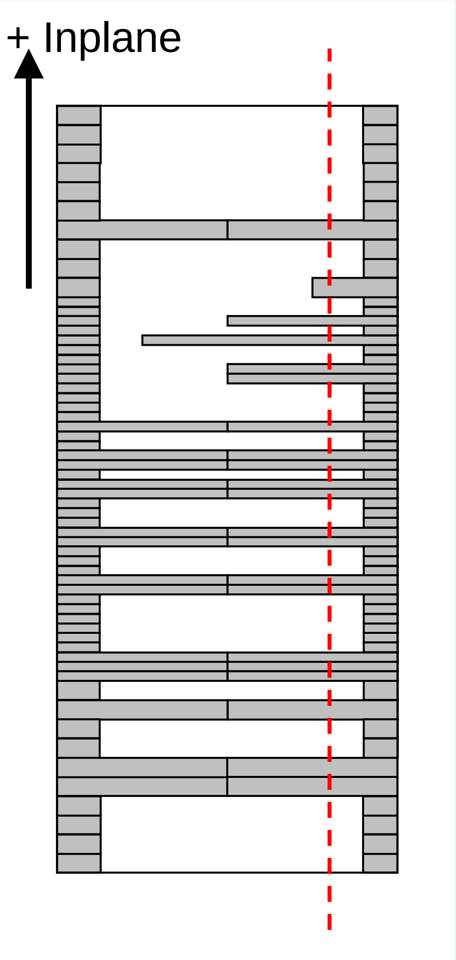
BEAM profiles systematically narrower (1-2 mm)

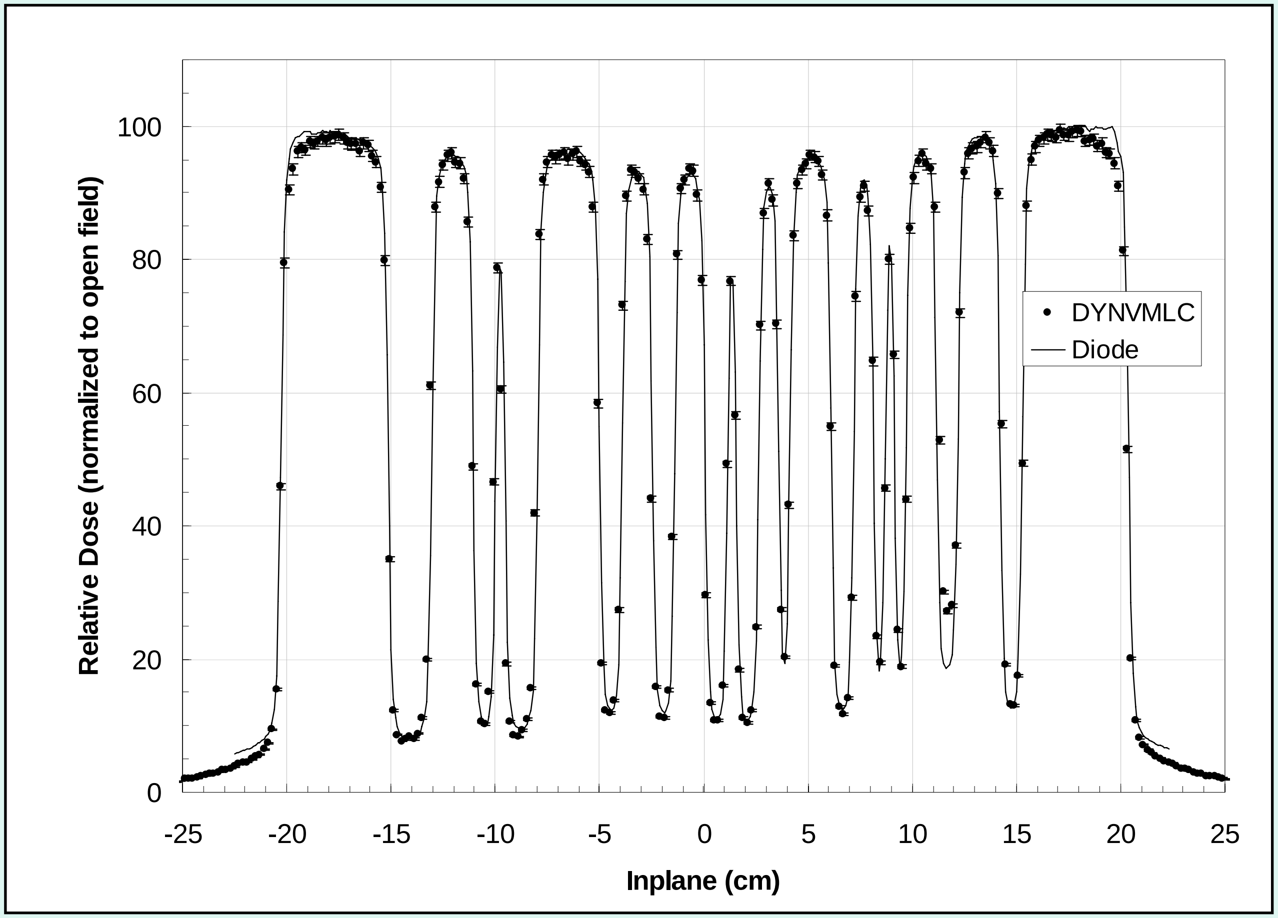
Validation – 5 cm offset

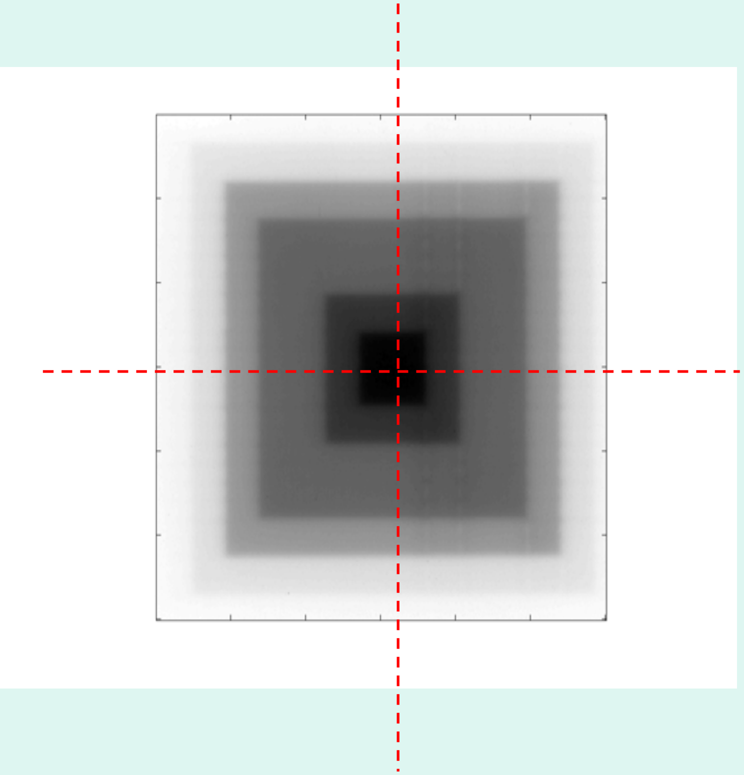




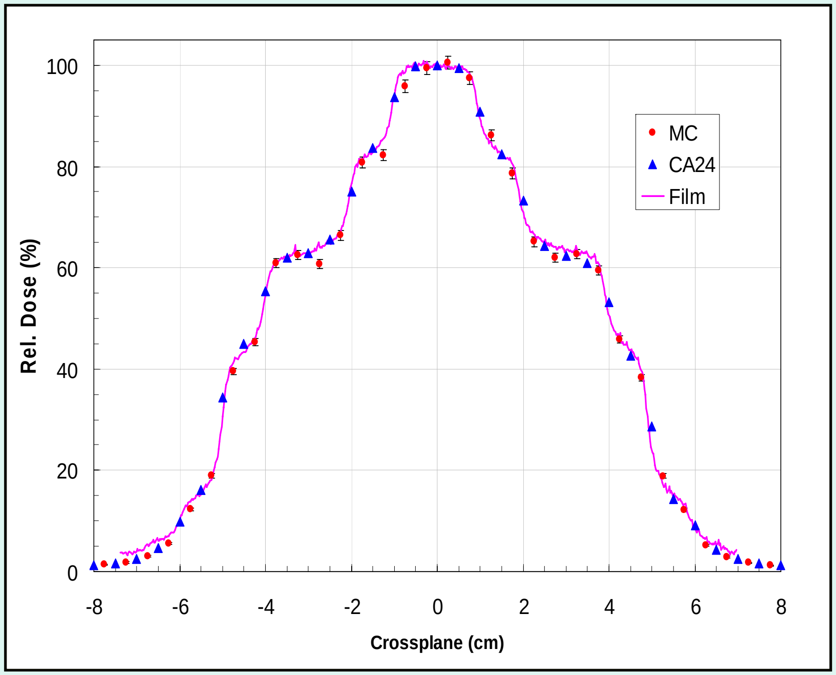
MLC bar pattern

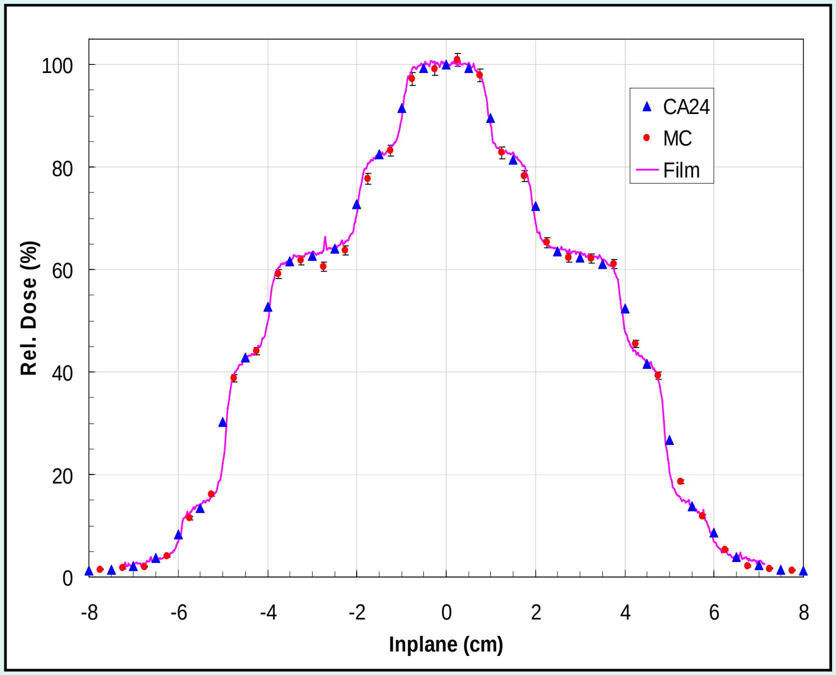




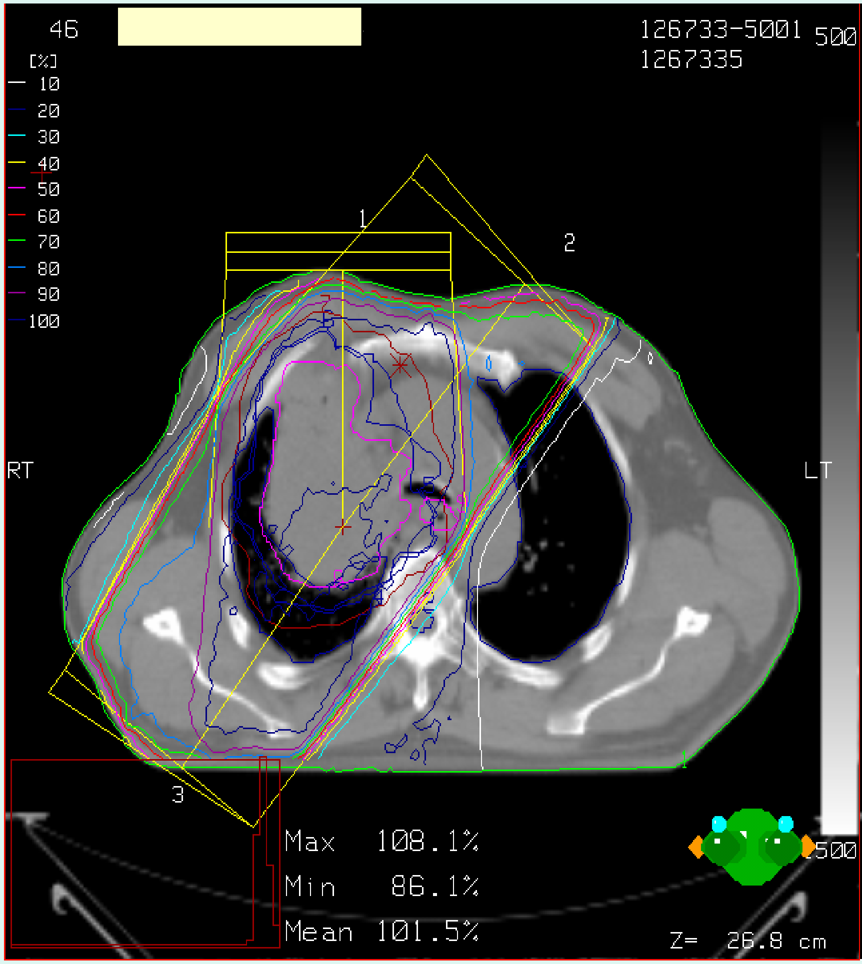


Static Delivery

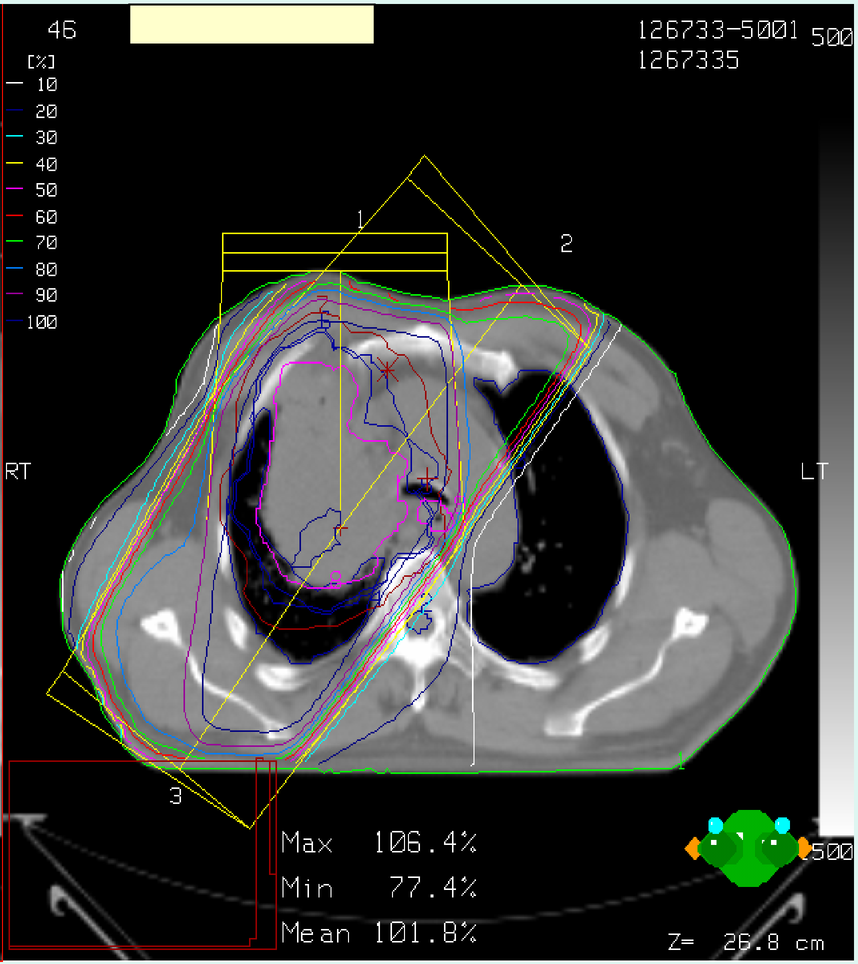




Importance of beam modeling for 3D-CRT

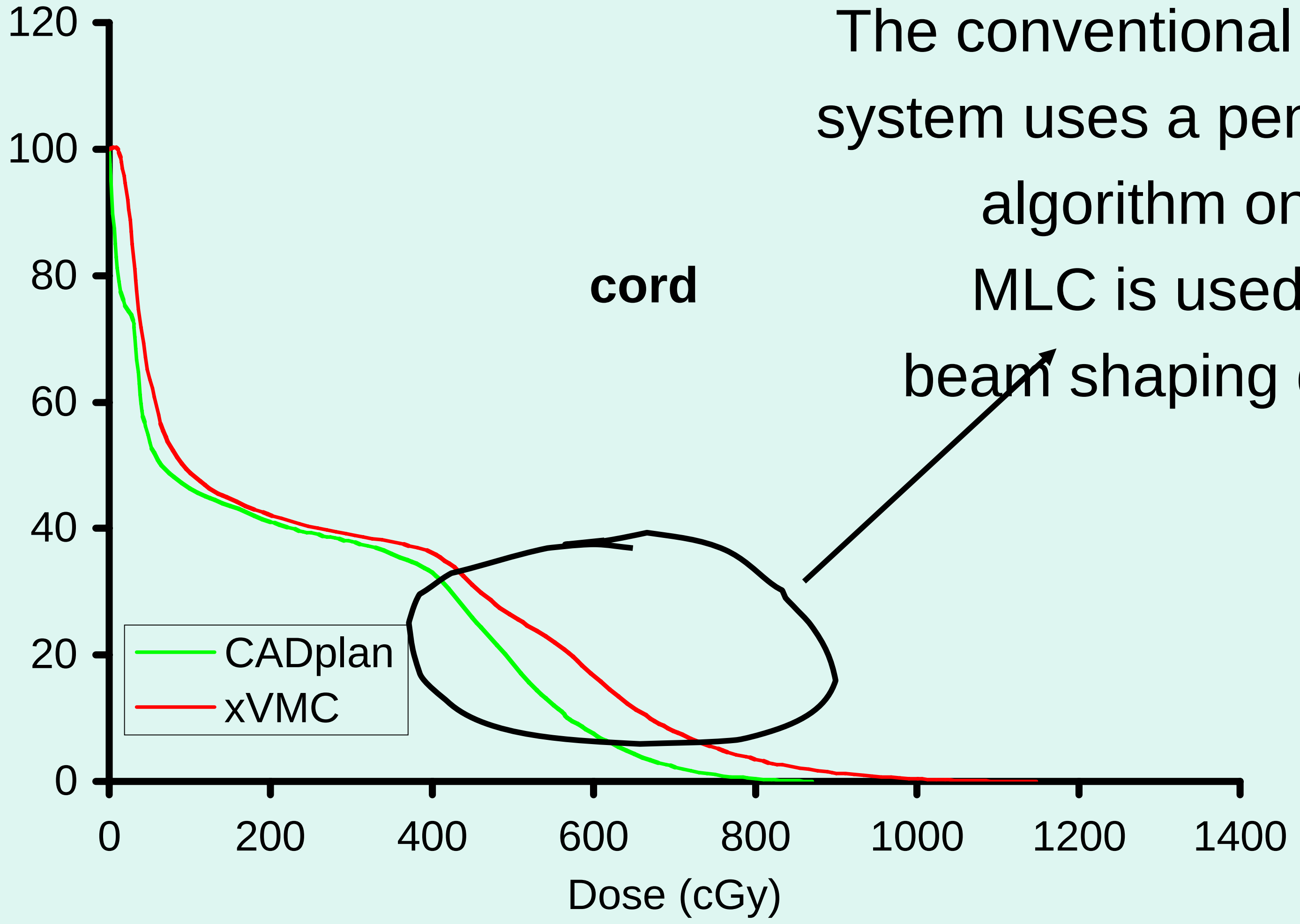


Monte Carlo – all tissues to water



CADplan

All tissues to water, plan 2

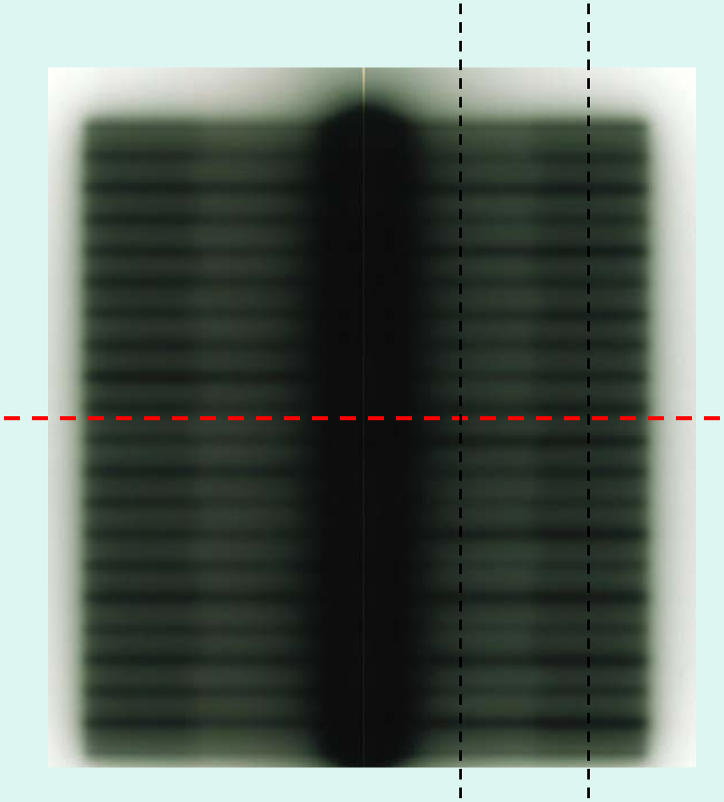


The conventional planning system uses a pencil beam algorithm once
MLC is used as beam shaping device

Validation – MLC leakage

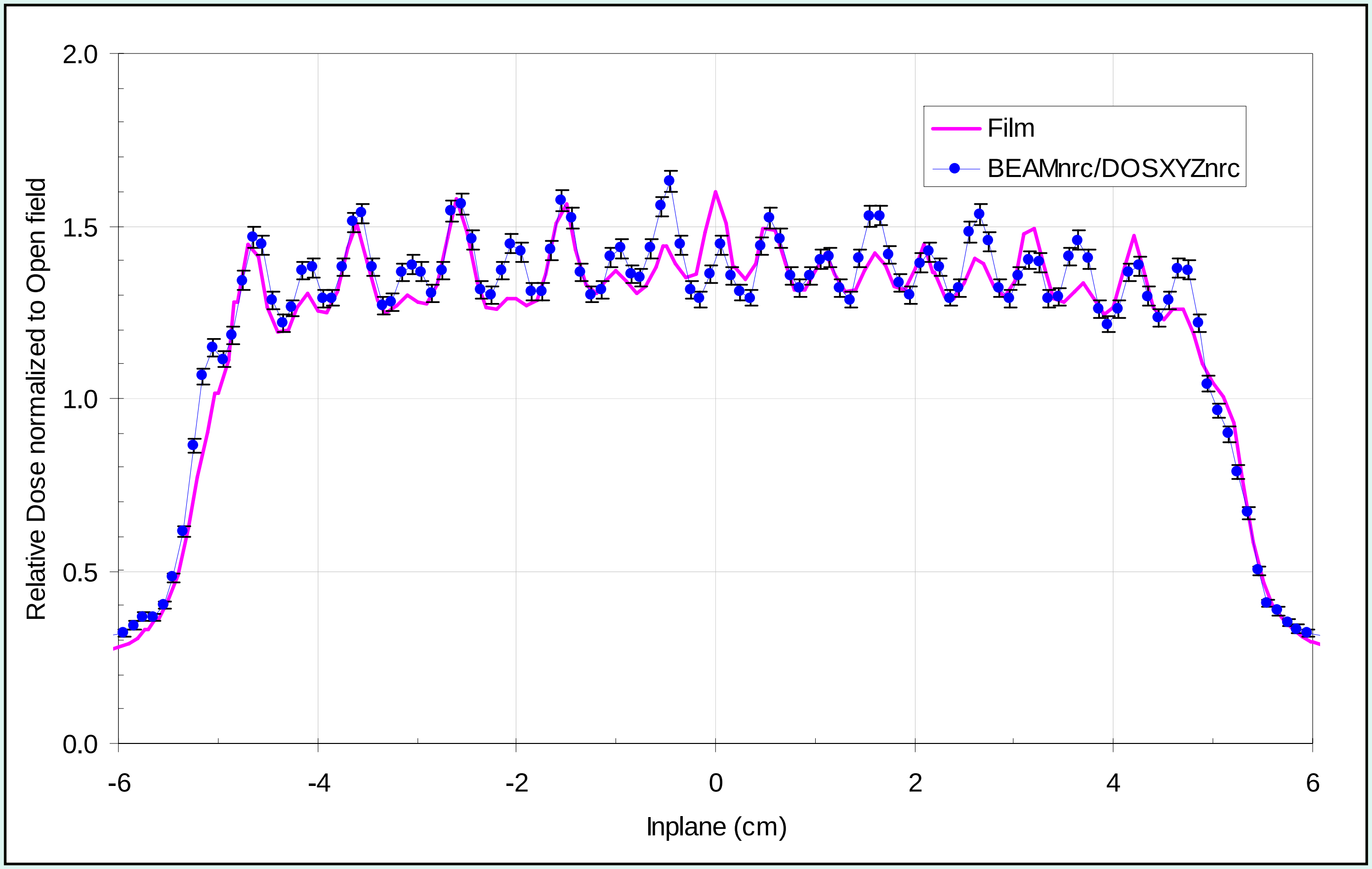
Leaf material density and abutting leaf air gap were chosen to match simulated MLC leakage profiles with film measurements

- leaf gaps measured physically
- measured leakage is sensitive to measurement configuration
- simulation should match measurement geometry



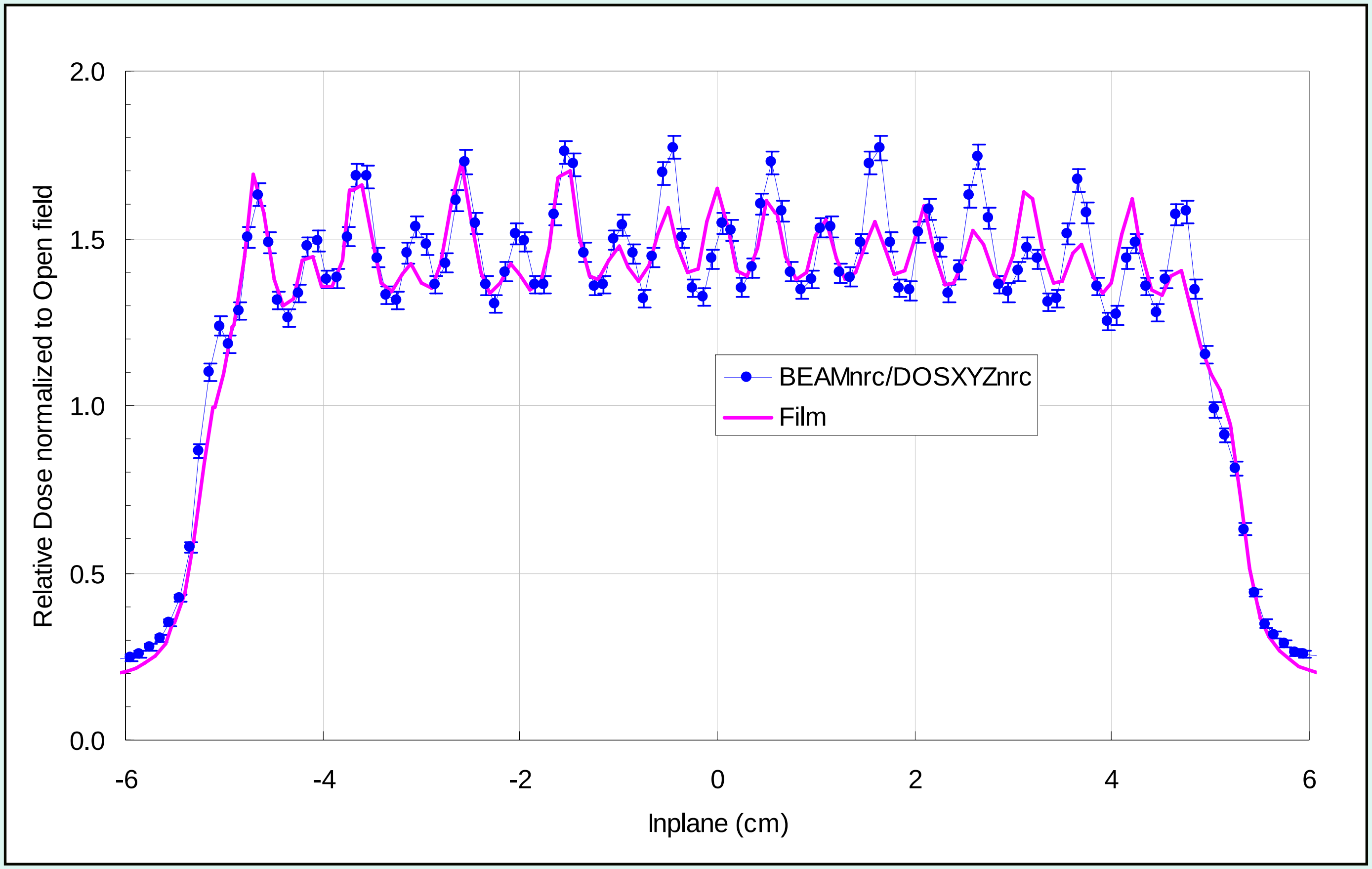
Interleaf leakage at 2 cm offset

- density = 17.7 g/cm^3
- interleaf air gap = 0.0057 cm



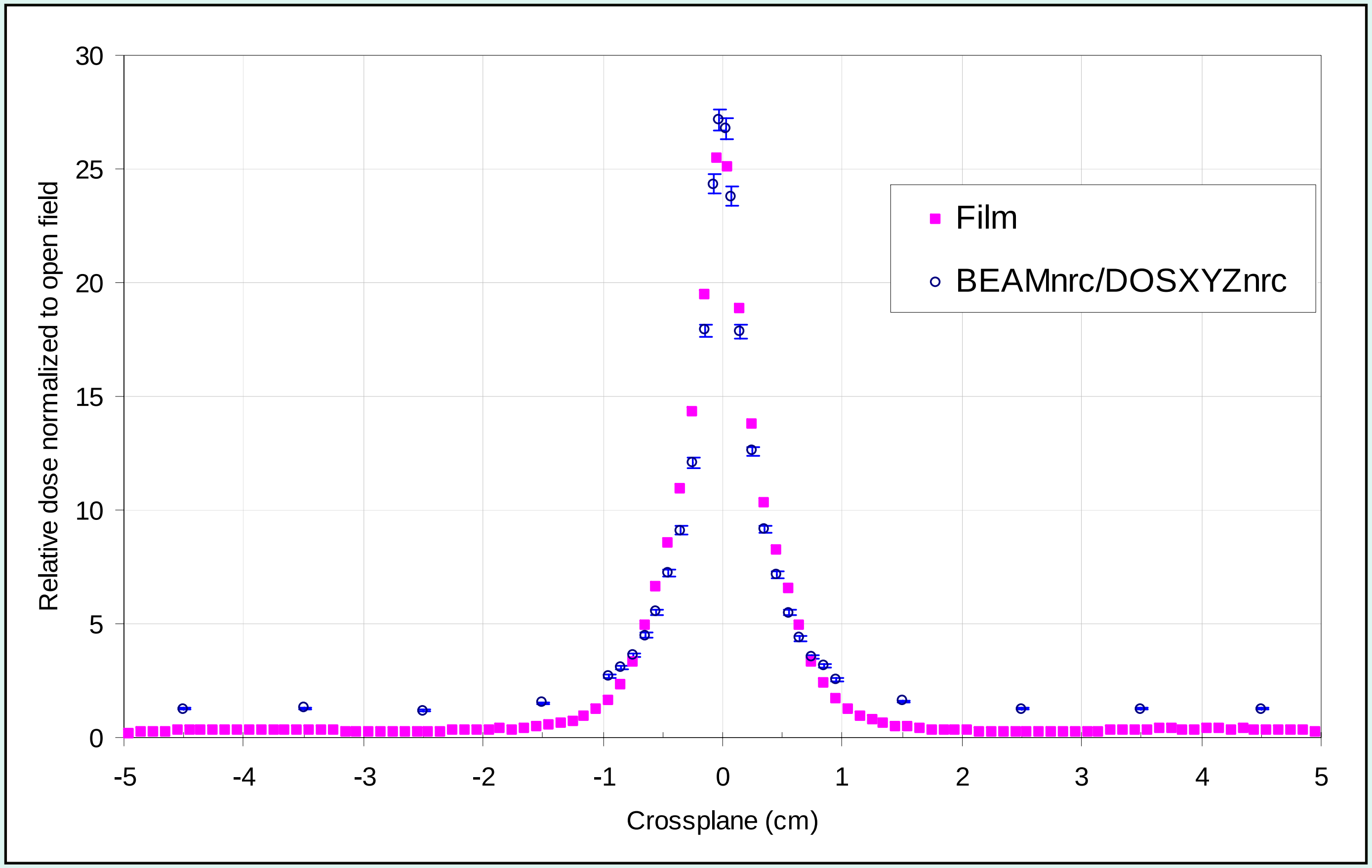
Interleaf leakage at 4 cm offset

- 0.2- 0.3 % increase in transmission due to leaf driving screw hole

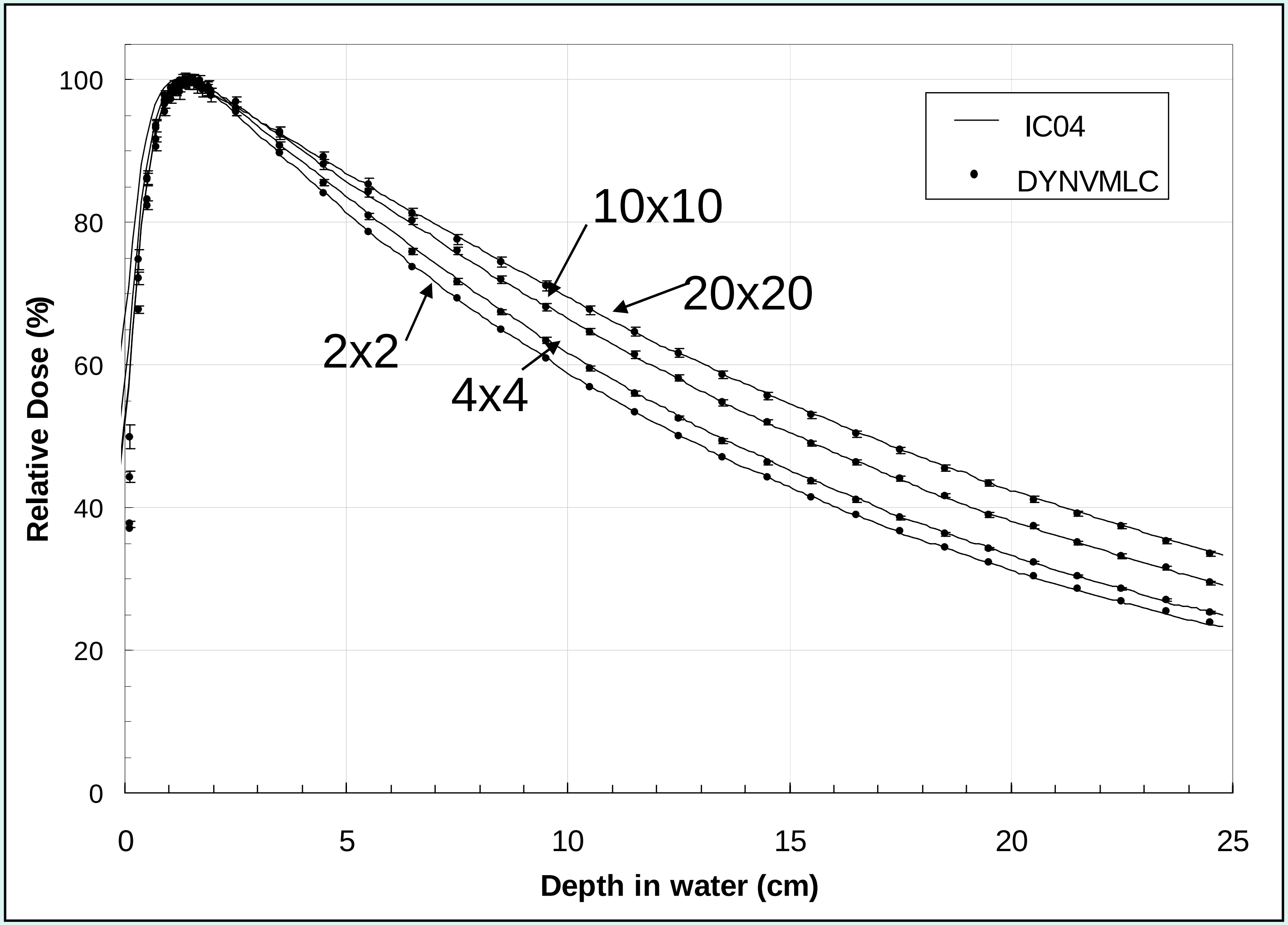


Leakage between abutting leaves

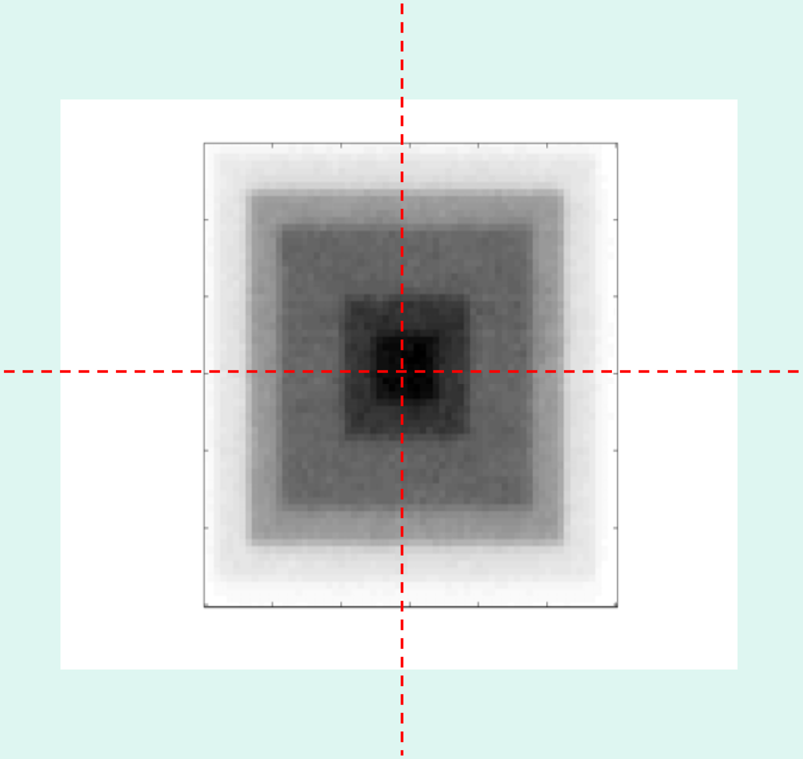
- abutting leaf gap = 0.004 cm

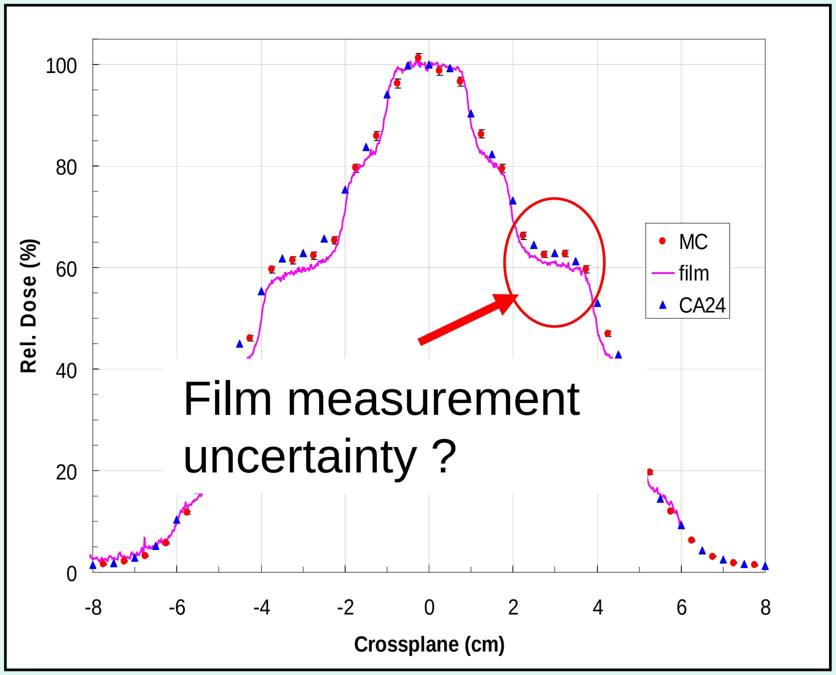


Depth dose profiles

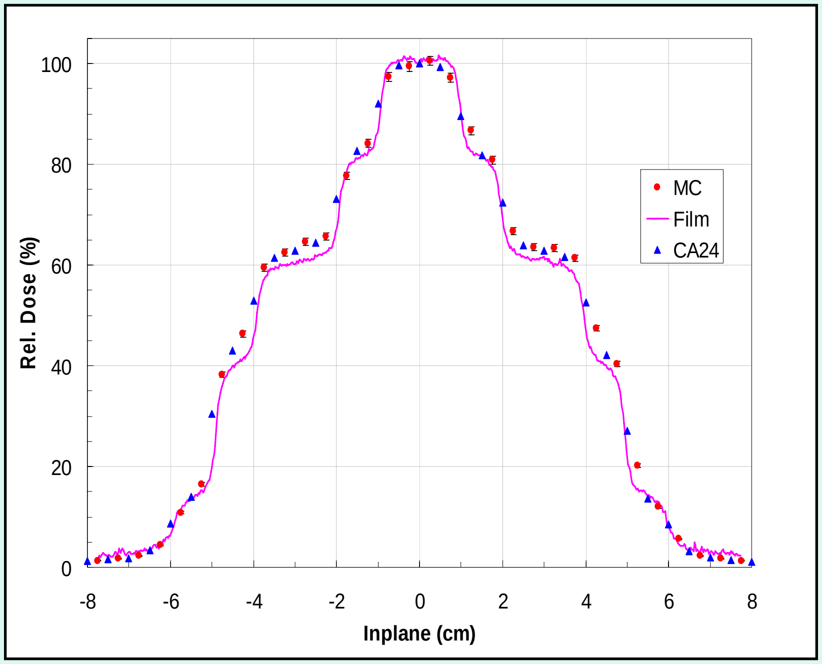


Dynamic Delivery

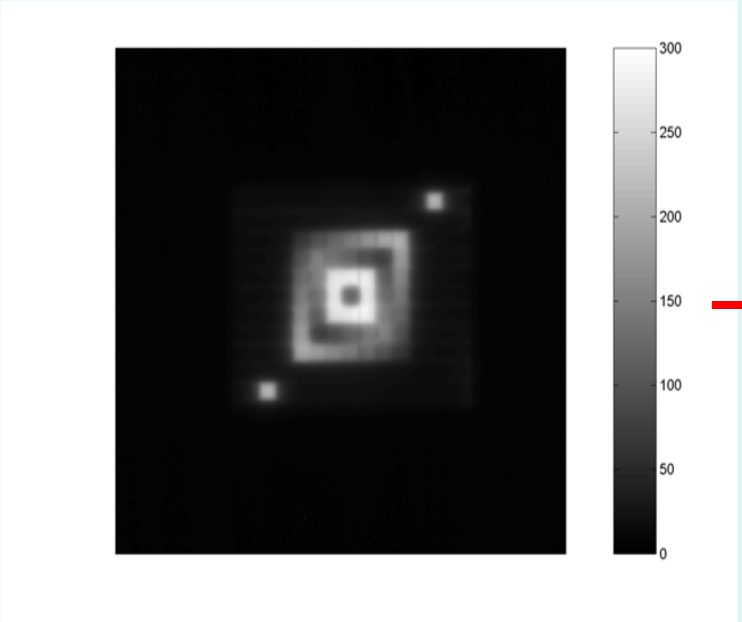




Film measurement uncertainty ?

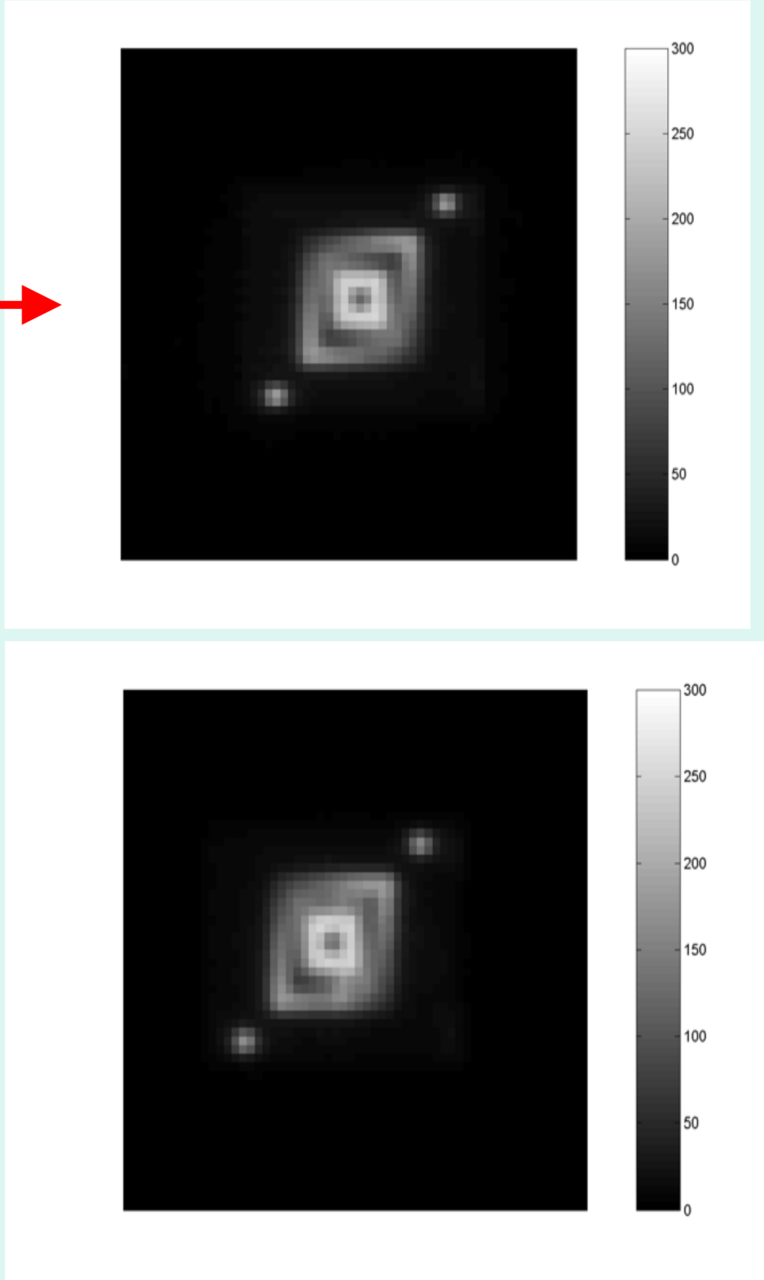


IMRT pattern



EDR2 d=1.5 cm ~200 cGy

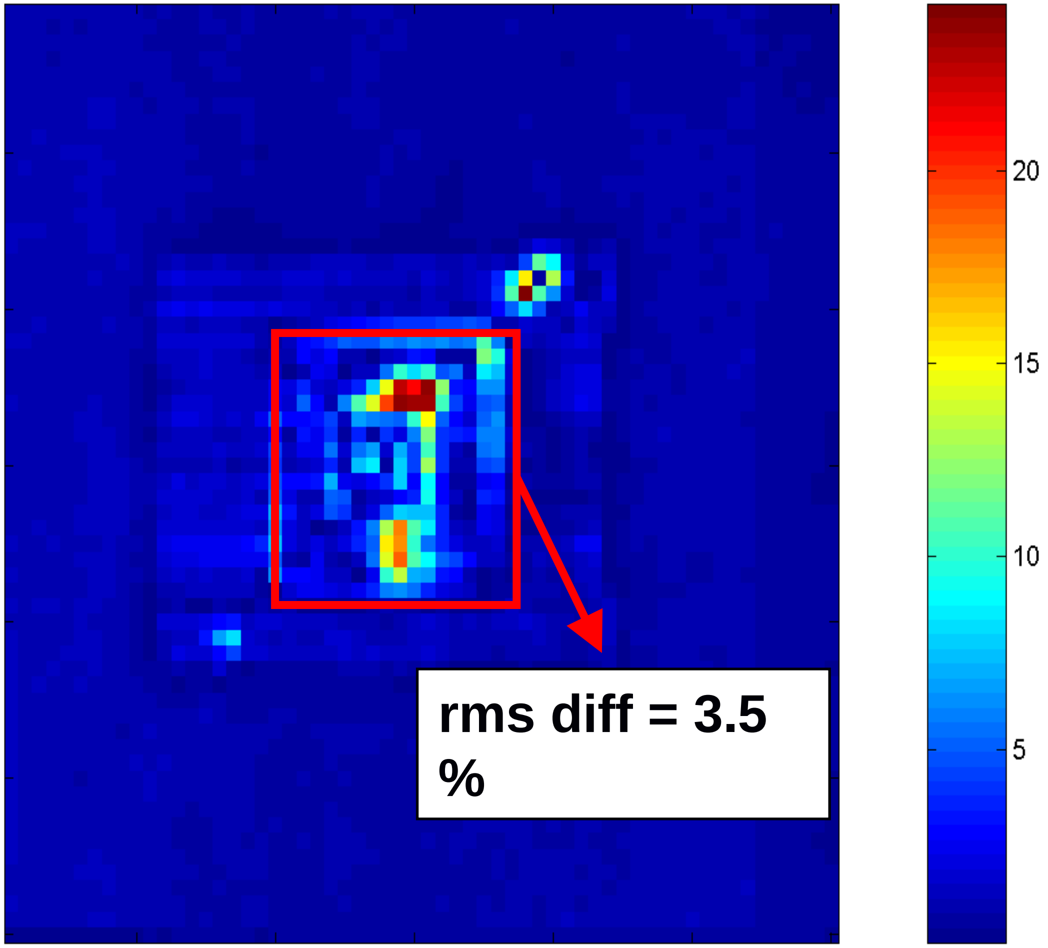
(0.022 x 0.022 cm^2 pixels)



BEAMnrc/DOSXYZnrc

(0.22 x 0.22 x 1 cm^3 voxels)

IMRT pattern



rms diff = 3.5 %

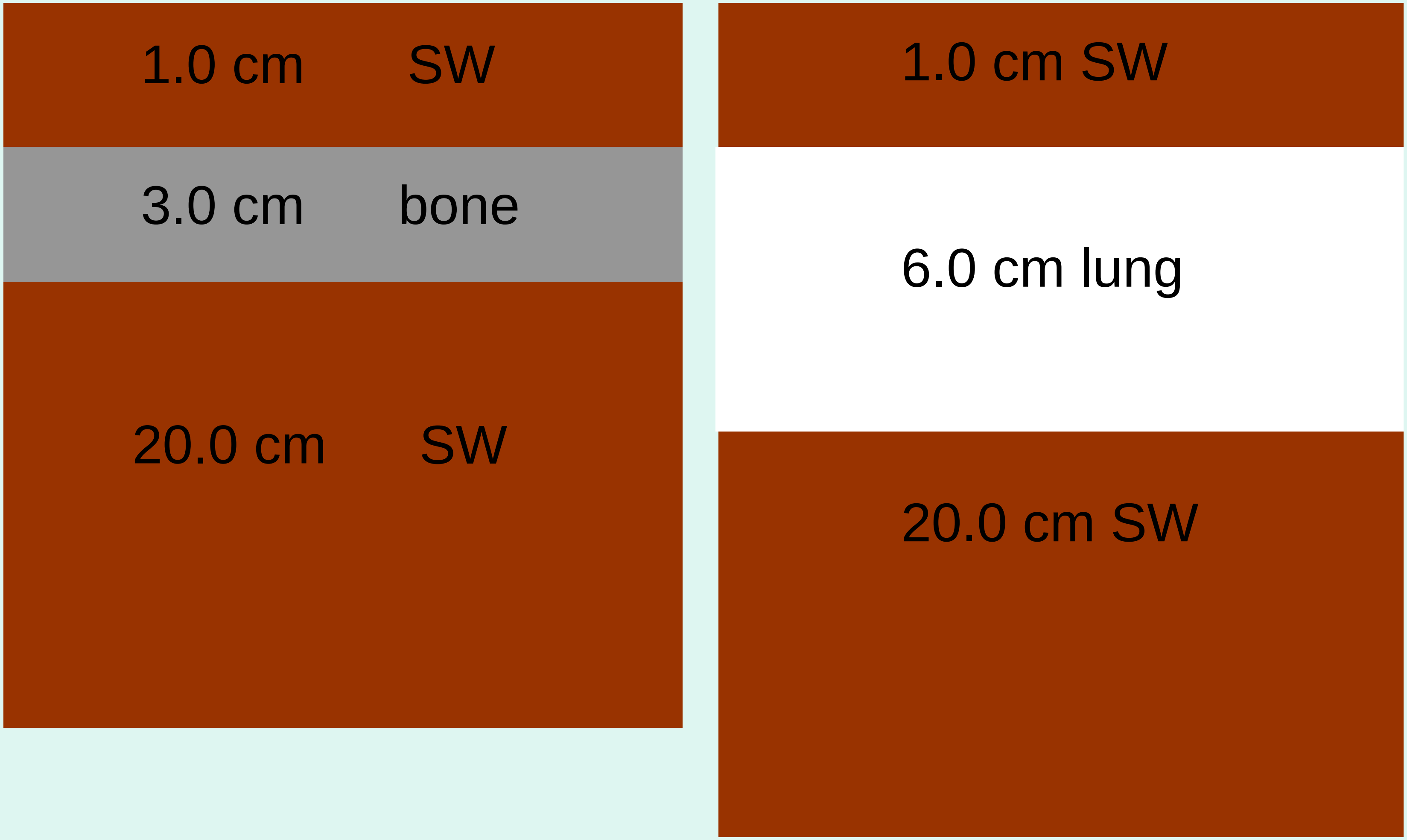
Some conclusions on “Measurements in the presence of beam modifiers”

- Use suitable detectors: photon diode, small volume ionization chamber, diamond detector, radiochromic film (EBT - humidity effects!)
- MLC leakage, transmission and field definition calculations need to agree with measurements - <u>think about dose calculations to organs at risk!!</u>
  - measurements are used to optimize dimensions and properties in calculation model
  - the beam model must be realistic to ensure proper OAR dose calculations ALSO for non-IMRT planning
  - therefore: contact manufacturer if you are sure of your measurements and agreement is not obtained

In-phantom measurements to verify dose calculation accuracy

- Assuming beam models have been verified and found accurate, inherent dose calculation accuracy in patient or phantom may be compromised by implementation issues such as:
  - voxel-to-region alignment, voxel sizes
  - CT - interaction coefficient conversion
  - runtime limitations, smoothing options
- Verification is needed in heterogeneous phantoms
  - simple, slab-based phantoms
  - more complex heterogeneous phantoms

Slab Phantoms, photon beam, 6 MV
(Gammex -RMI, tissue equivalent materials):



1.0 cm SW

3.0 cm bone

20.0 cm SW

1.0 cm SW

6.0 cm lung

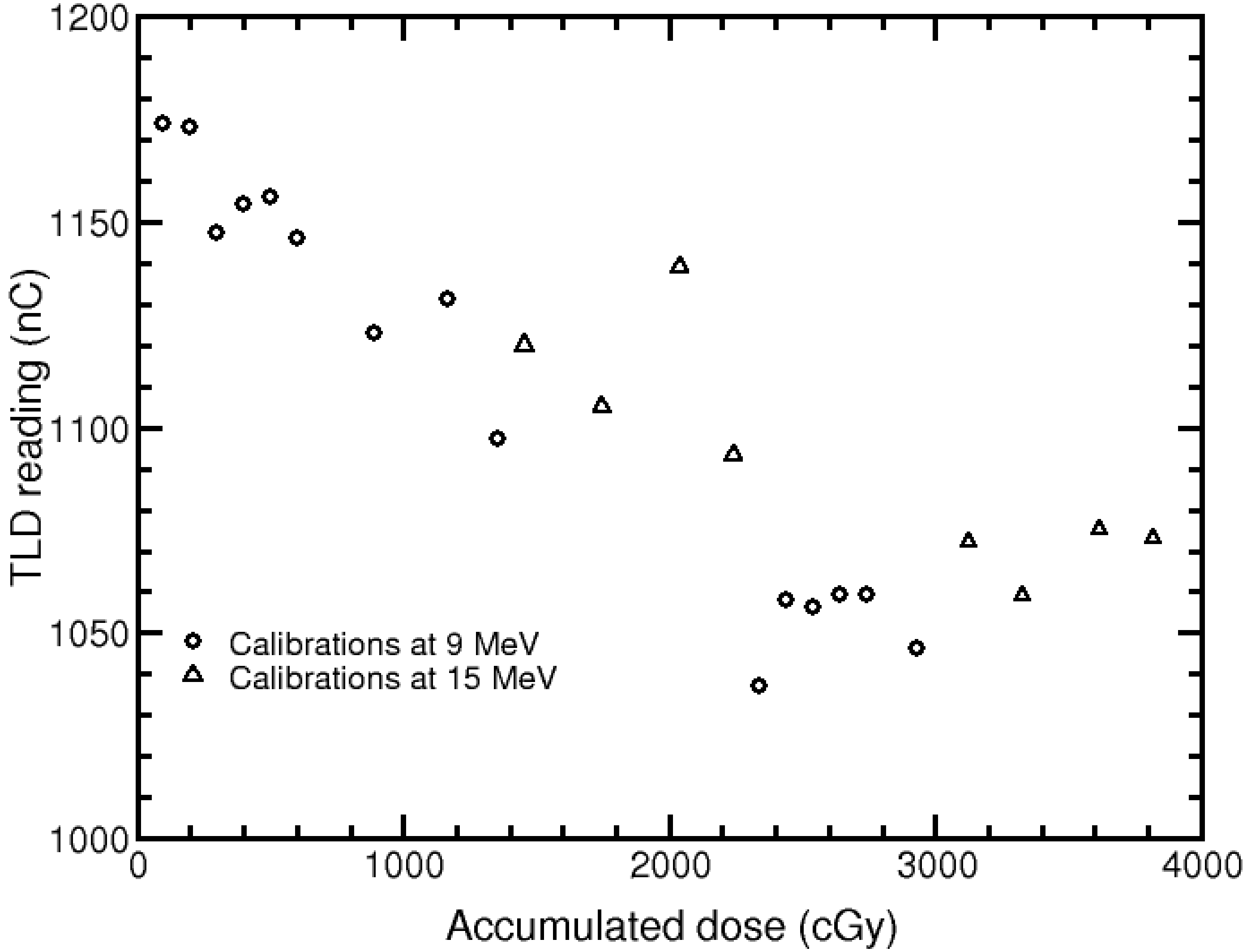
20.0 cm SW

fluence
perturbation
of TLD in
narrow field?

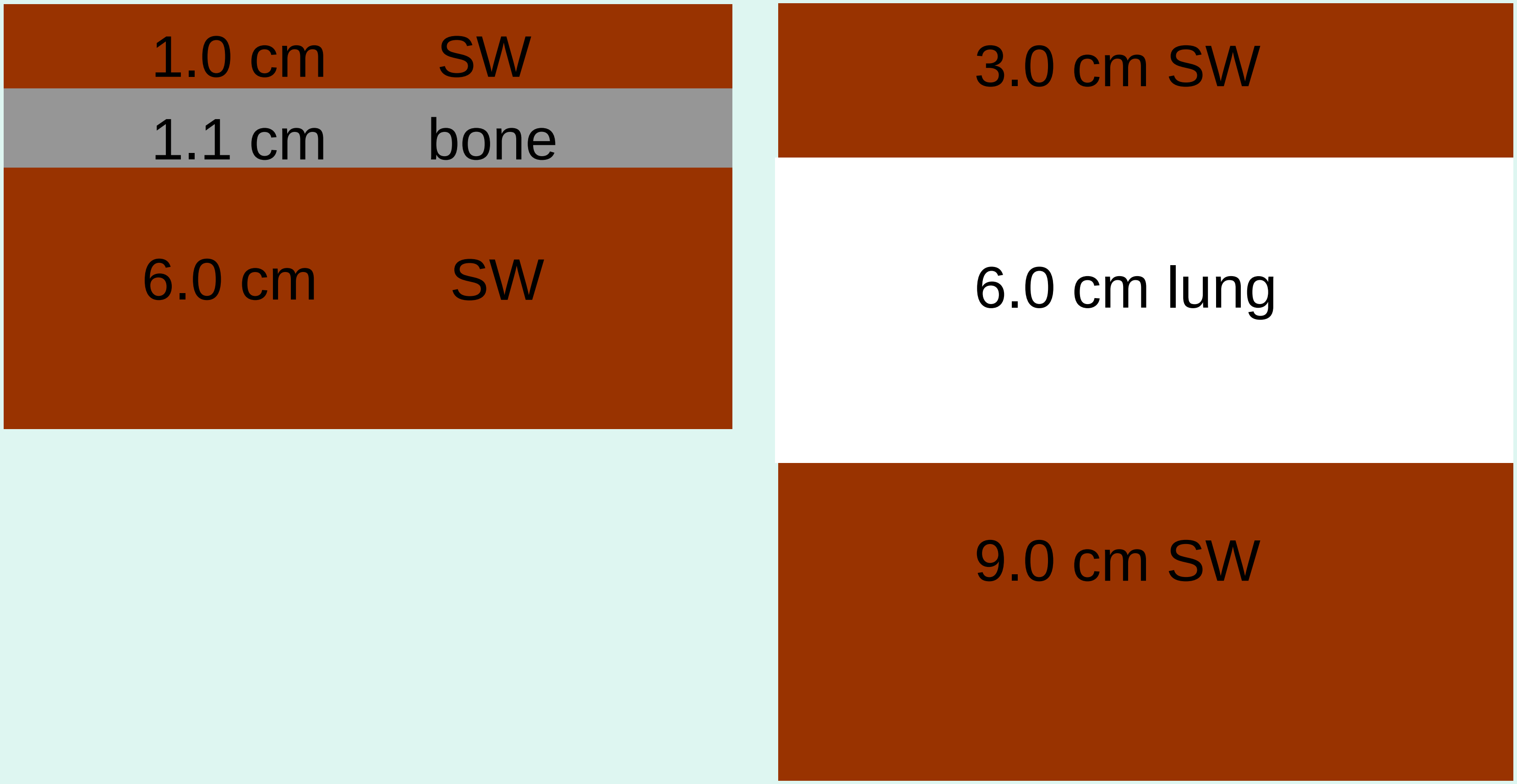
Heath et al 2004

Heath et al 2004

TLD-700 response as a function of accumulated dose…



Slab Phantoms, electron beams
(Gammex -RMI, tissue equivalent materials):

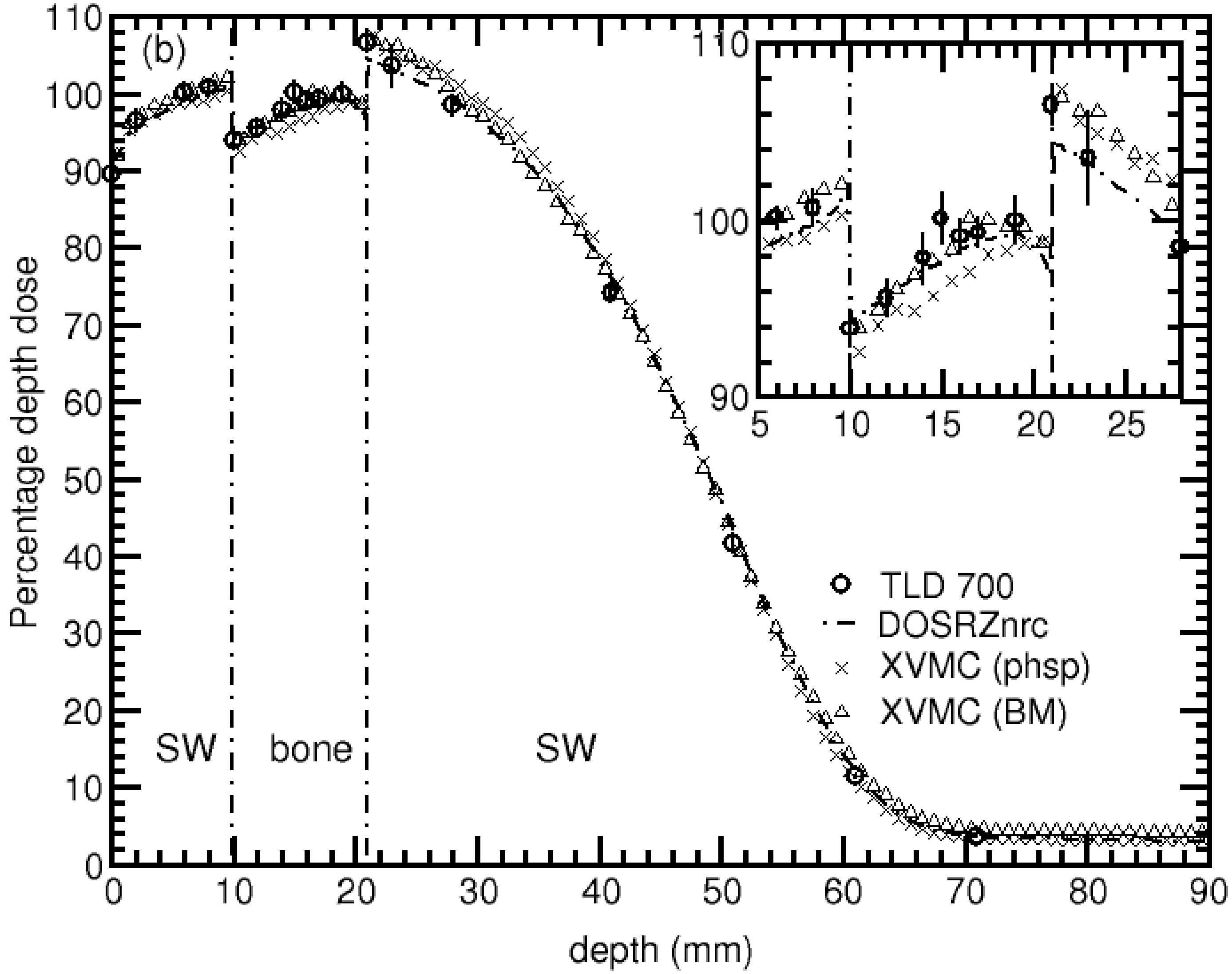


1.0 cm SW
1.1 cm bone
6.0 cm SW

3.0 cm SW
6.0 cm lung
9.0 cm SW

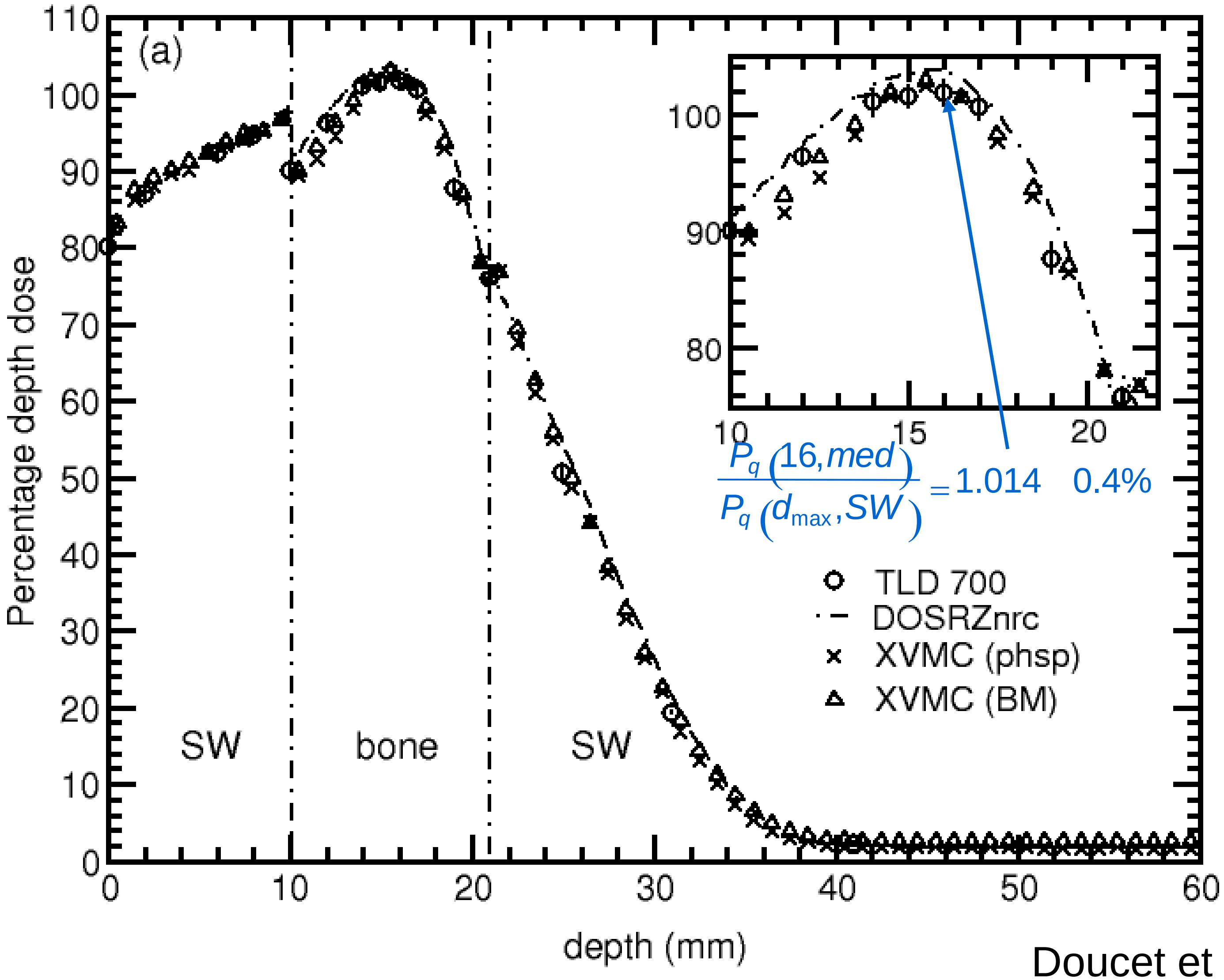
Doucet et al 2003

15 MeV electrons



Doucet et al 2003

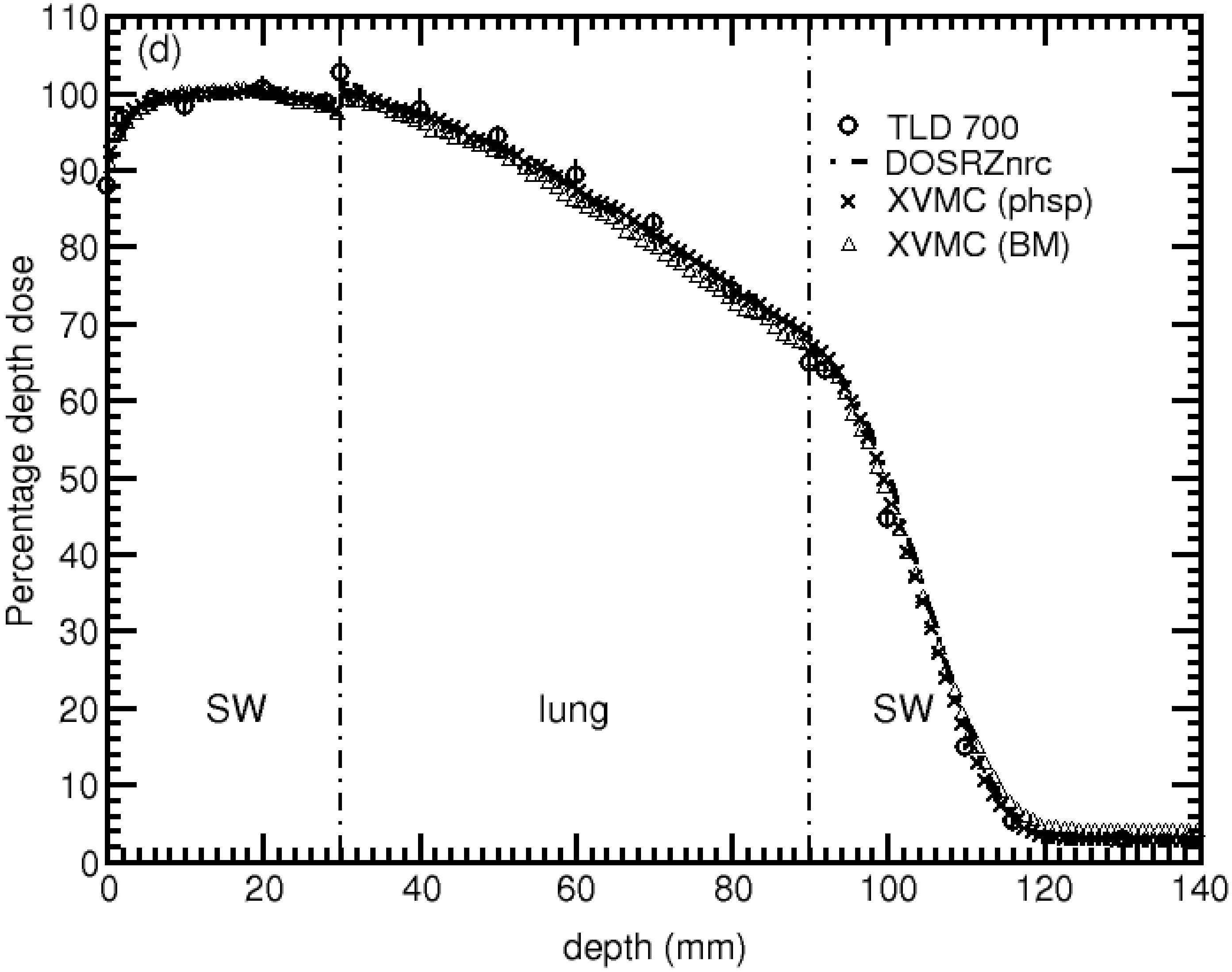
9 MeV electrons



$$\frac{P_q\left(16, med\right)}{P_q\left(d_{\max}, SW\right)} = 1.014 \quad 0.4\%$$

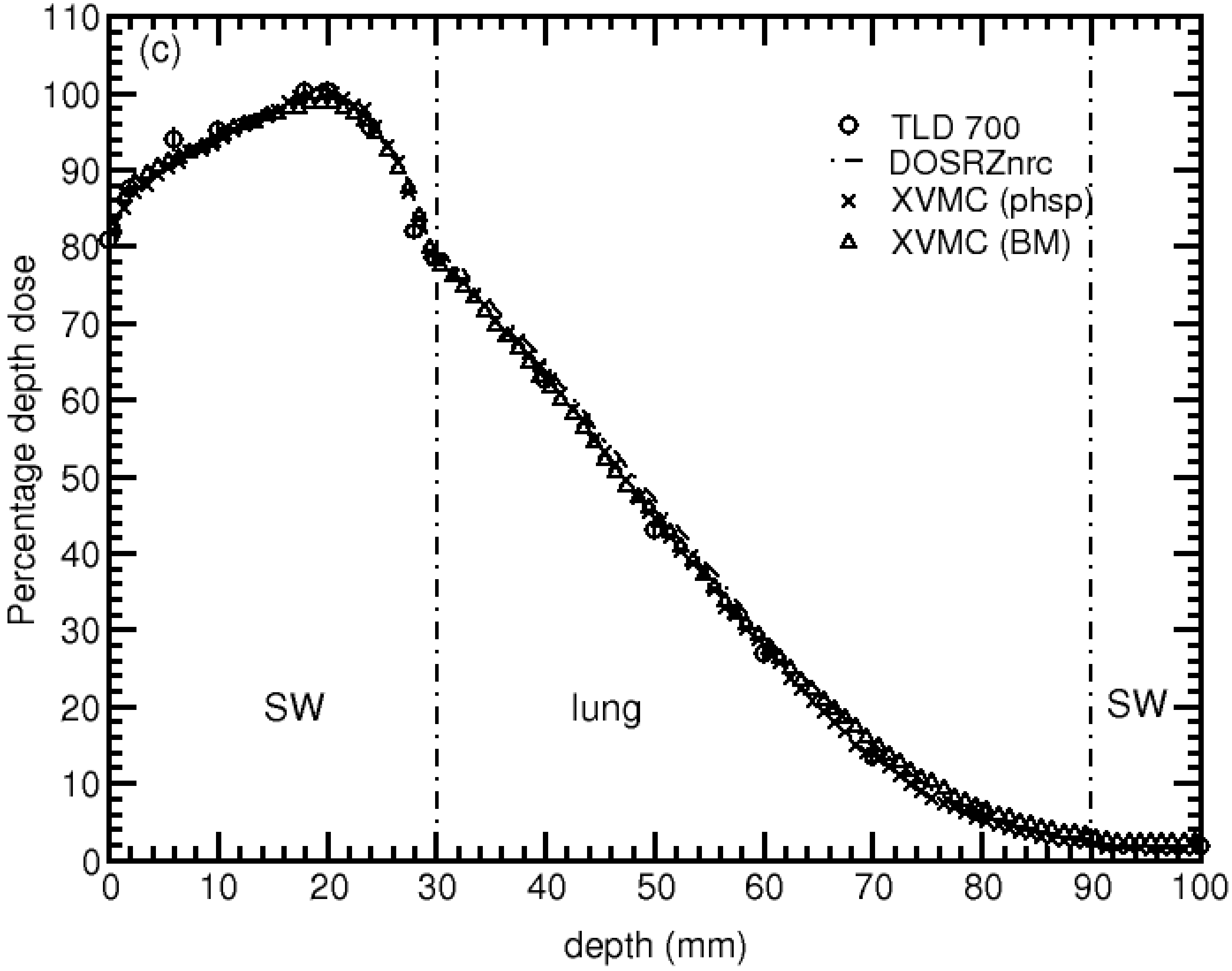
Doucet et al 2003

15 MeV electrons



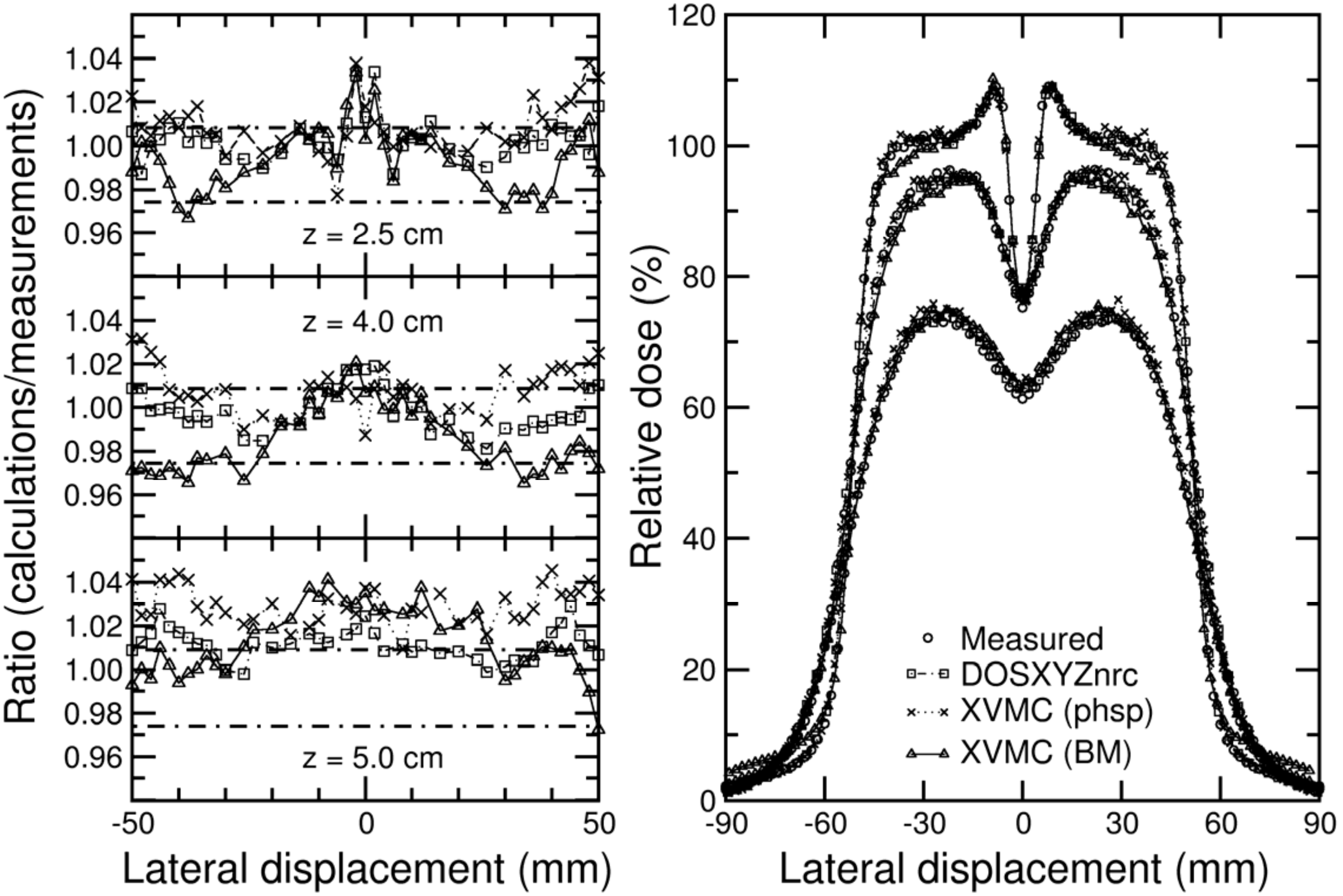
Doucet et al 2003

9 MeV electrons

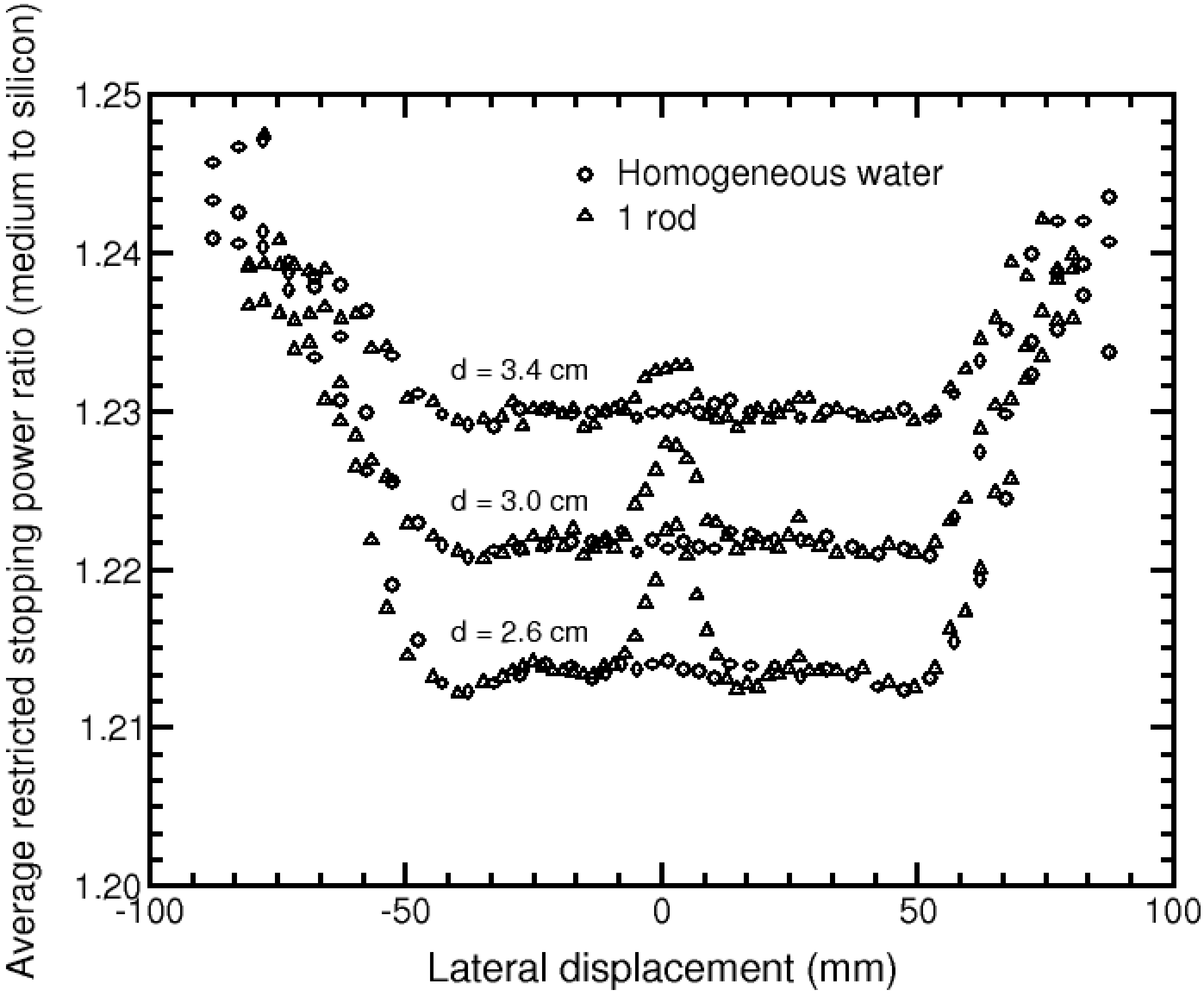


Doucet et al 2003

Water phantom, Al rod on central axis, 15 MeV

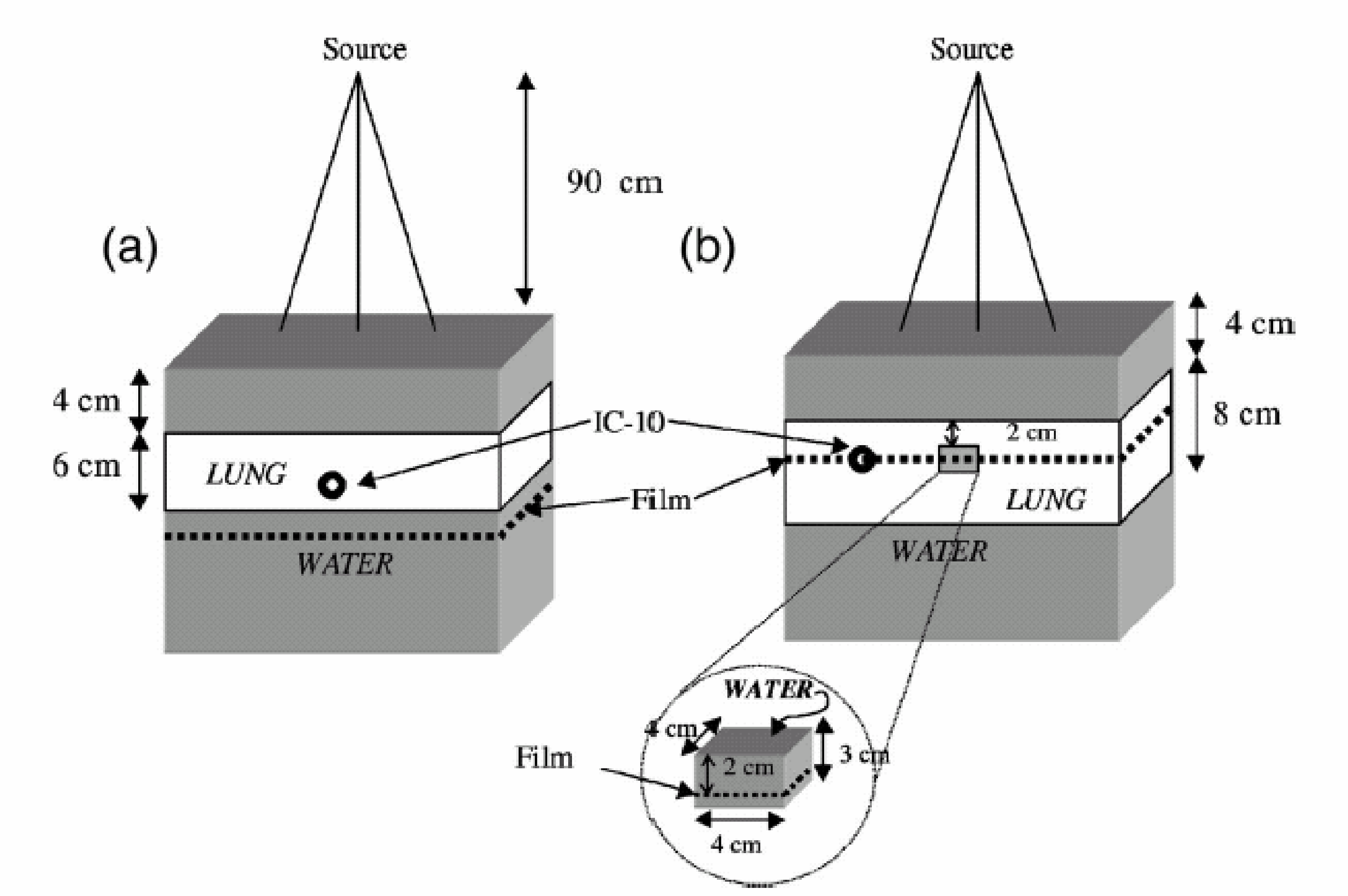


Doucet et al 2003



Doucet et al 2003

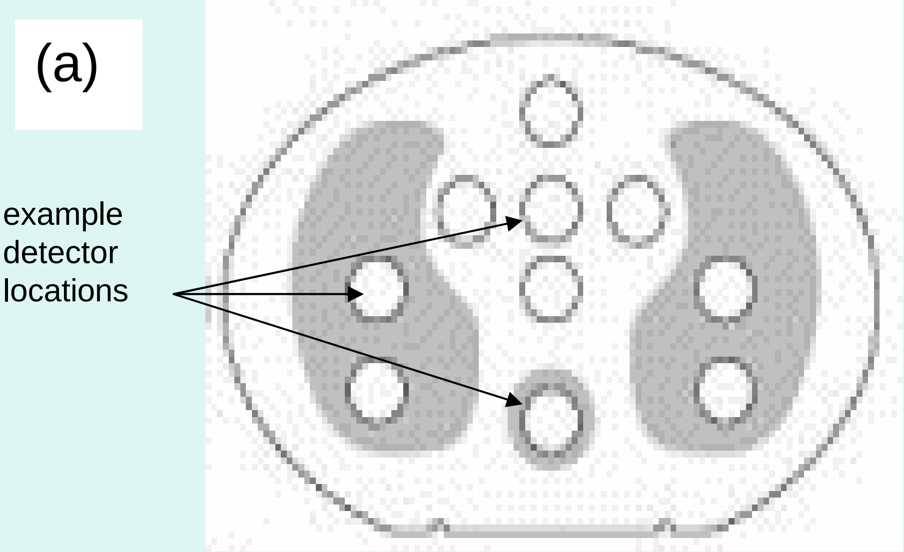
More complex, realistic heterogeneous phantoms …



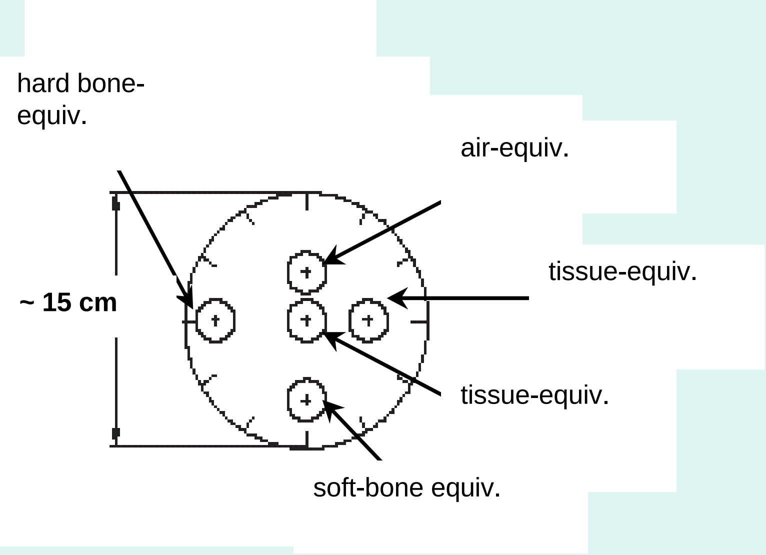
Layered lung-equivalent phantom (a) full slab and (b), tumor geometry used in the measurement of dose. (Charland et al 2003)

Direct verification of treatment plans, realistic phantoms

(a)



(b)



(a) sample detector locations within an anthropomorphic lung phantom;

(b) phantom with interchangeable air, bone, and tissue equivalent rods at illustrated locations, mimicking head/neck tissues.

Conclusions

- Measurement issues are an important component of commissioning and verification of a MC TP system.
- The user of an MC-based TP system must be aware of complications in measurements in non-equilibrium situations.
- Suitability of detectors for a given purpose must be assessed when planning system accuracy in these regions is at stake.
- MC planning has the potential to be dosimetrically superior to conventional planning systems especially in dose estimations for OAR's -> BUT: to this end, extra validation is needed.
- Commissioning and verification should also carefully deal with the other components of the implementation such as CT to interaction coefficient conversion procedure, voxel statistics, smoothing functions, etc all of which are specific to MC planning systems.

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