In Memoriam of Bengt Bjarngard
Small Field Dosimetry

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Challenges in Small Field Dosimetry

Small field characteristics

- Lateral electronic equilibrium
- Source occlusion

Commercial detector issues

- Characteristics
- Active vs Passive
- Correction factors

Output factors

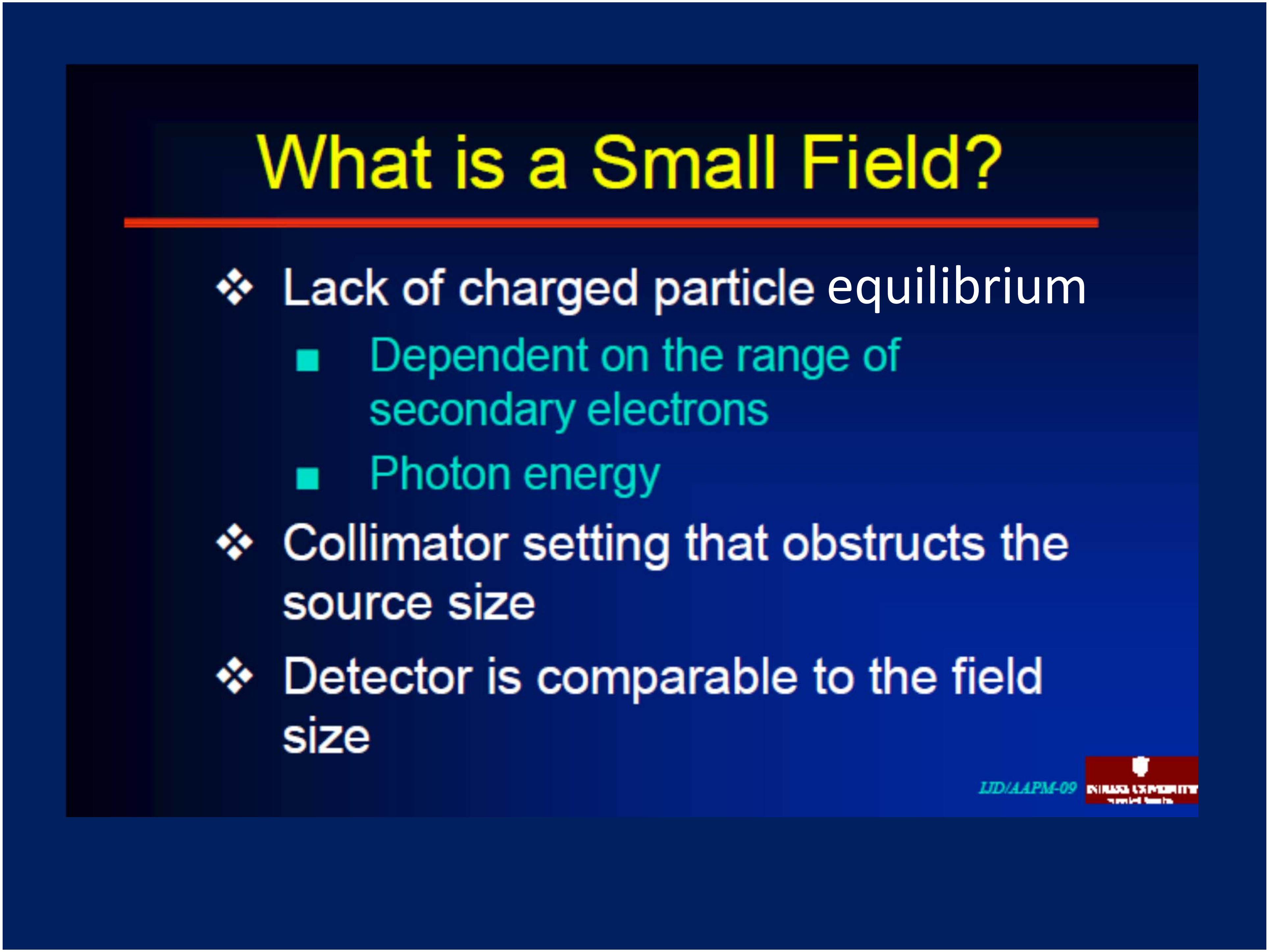
- Field size effects
- Detector examples
- Corrections

Novel detectors

- Edge
- Redesigned diode

Dosimetry

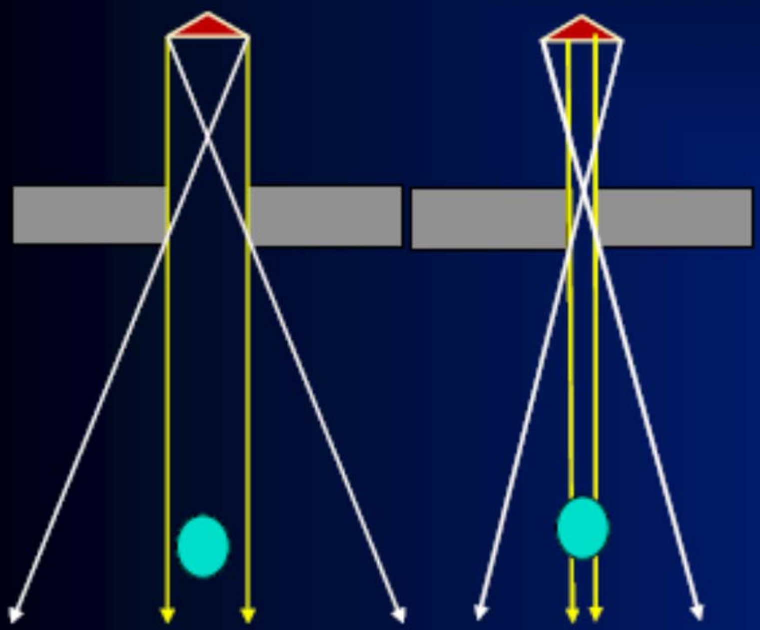
- Absolute
  - Dose
- Relative
  - Depth Dose
    - [D(r,d)/D(r,dm)]
  - TMR
  - Profiles
  - Output, S_{cp} (total scatter factor)
    - [D(r)/D(ref)]

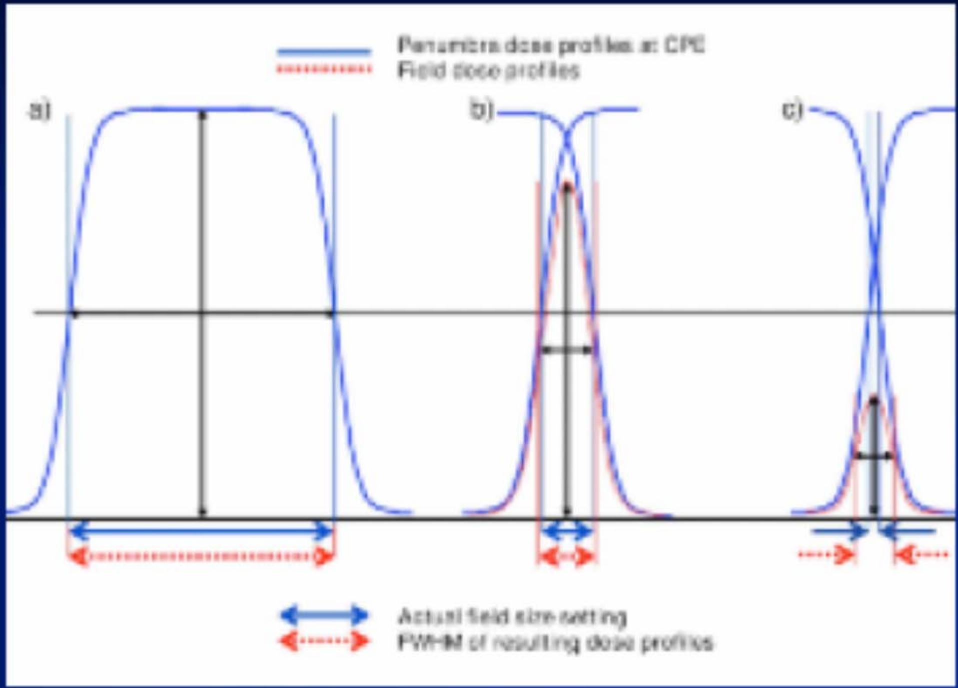

What is a Small Field?
Lack of charged particle equilibrium
Dependent on the range of secondary electrons
Photon energy
Collimator setting that obstructs the source size
Detector is comparable to the field size
LJD/AAPM-09

Values of r_{LEE} for various beams calculated with the Monte Carlo method; r_{LEE} is the minimum beam radius to achieve complete lateral electron equilibrium in water.

Beam	TPR^{20}_{10}	$\%dd(10)_x$	$r_{LEE}(g/cm^2)$
^{60}Co		57.8	0.6
6 MV	0.670	66.2	1.3
10 MV	0.732	73.5	1.7
15 MV	0.765	77.9	1.9
24 MV	0.805	83.0	2.1

Definition of Small Fields





Das et al, Med. Phys. 35, 206-215, 2008

CPE & Electron Range

- CPE, Charged Particle Equilibrium
- Electron range= d_{max} in forward direction
- Electron range in lateral direction
  - Nearly energy independent
  - Nearly equal to penumbra (8-10 mm)
- Field size needed for CPE
  - Lateral range

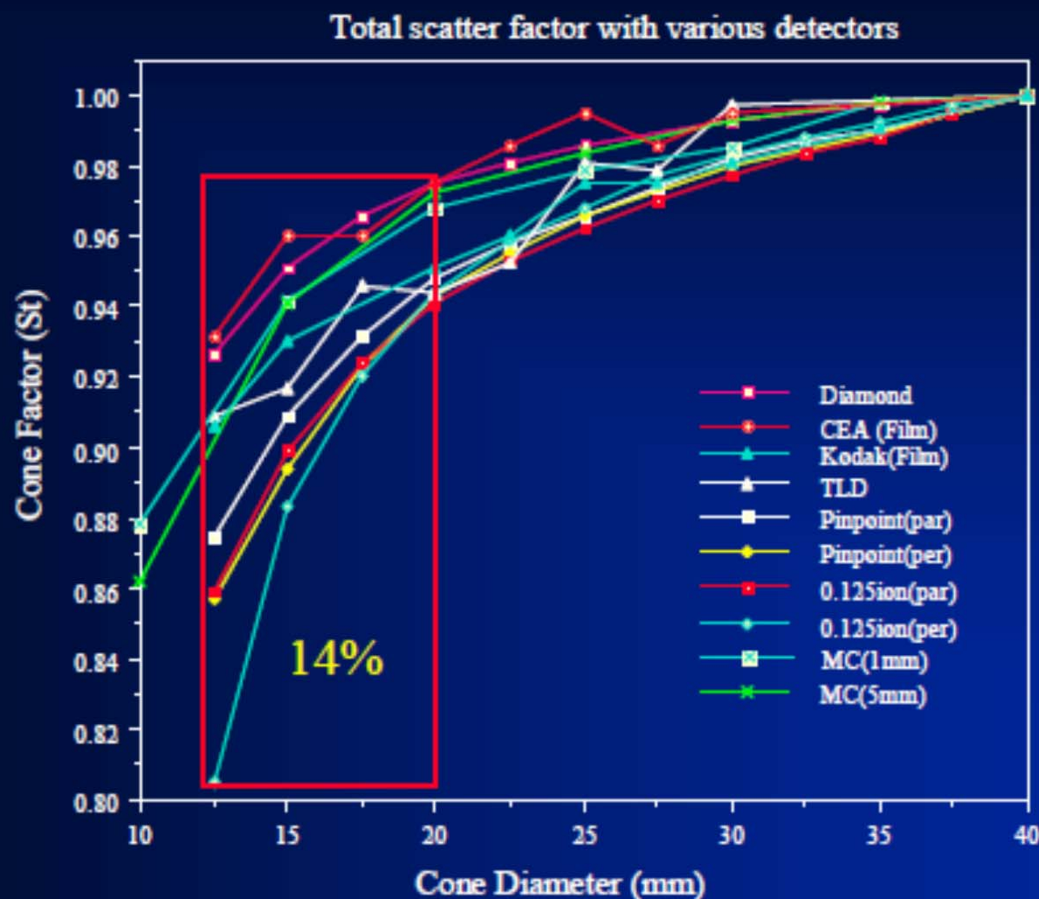
Radiation Measurements

- Charged particle equilibrium or electronic equilibrium
  - Range of secondary electrons
  - Medium (tissue, lung, bone)
- Photon energy and spectrum
  - Change in spectrum
    - Field size
    - Off axis points like beamlets in IMRT
  - Changes μ_{en}/ρ and S/ρ
- Detector size
  - Volume
  - Signal to noise ratio

Parameters Characterizing Radiation Detectors

- Energy dependence
- Dose response
- Accuracy and precision
- Sensitivity
- Stability
- Fading
- Spatial resolution Extra cameral signal
- Traceability

Dosimetric Variation with Detectors



Das et al, J Radiosurgery, 3, 177-186, 2000

IJD/AAPM-09

Summary of small field output factor (S_{cp}) measurements with different passive detectors

Detector	Energy							
	6 MV				18 MV			
	.5x.5	1x1	2x2	3x3	.5x.5	1x1	2x2	3x3
DOT-micro	0.54	0.73	0.84	0.88	0.31	0.56	0.79	0.88
TLD	0.48	0.73	0.83	0.87	0.29	0.58	0.78	0.88
MOSFET	0.57	0.76	0.83	0.87	0.41	0.62	0.80	0.87

1 mm diameter - Dot-micro uncertainty: (+/-) 4%
3mm x 3mm - TLD uncertainty: (+/-) 2%
MOSFET uncertainty: (+/-) 3%

Detector characteristic to consider in small field dosimetry

1. Spatial resolution – output measurements & scans
2. Dimensions
3. Sensitivity – signal/noise
4. Density
5. Angular dependence
6. Energy dependence
7. Water-equivalence
8. Dose linearity or known dose dependence

Active	Vendor	Type	Sensitive Area (mm^2)	Detector thickness (mm)	Density (g/cm^3)	Water-proof
Ion chamber	PTW	Pin-point 3104	5.0	0.6	1.19	Yes
		3105	14	0.6	same	
	PTW	Markus 23343	23	2.0	0.92	Yes
		Advanced Markus	20	1.0	same	
	Exradin	MicroChamber A16	6.0	2.4	1.10	Yes
	Exradin	MicroChamber T14	2	1.0	same	Yes
	PTW	microLion (LIC)[1]	4.9	0.35	≈ 0.67	
Solid State	Scanditronix Diode	Electron	3.14	≈0.06	2.33	Yes
		Stereo	0.6	same	same	Yes
		Shielded[#]	3.14	same	same	Yes
	Sun Nuclear Diode	Edge	0.64	same	same	Yes
	PTW	Diamond	≈ 7.1	0.26	3.5	Yes

	Vendor	Type	Sensitive Area (mm^2)	Detector Thickness (mm)	Density (mm^3)	Water-proof
Passive	TLD	Microcubes	1.0	1.0	2.64	No
	Thermo-Fisher	Ribbons Rods	10.1 1.0	0.89-0.15 1.0	Same Same	No No
	Asahi techno glass Corp	RPL GRD[2]	0.28	1.5	2.61	No
	Landauer	OSL(Dots)[3]	0.78	0.2	3.97	Yes
	Film Kodak	Radiographic EDW	Limited by readout	0.2	1.34	No
	International Speciality Product	Radiochromic		0.23	1.34	Yes
	3 D Dosimeters (MGS Research)	Gel-dosimeters (polymer/ radiochromic)[4]	0.25-1mm Limited by readout	0.25-1mm Limited by readout	1.02	NA
		Radiochromic plastic Presage[4]			1.05-1.067	NA

Output Factor = OF

$$OF = D(d_0,r) / D(d_0,r_0) = [M(d_0,r_0)/M(d_0,r_0)]\ L/\rho(w,det)_{r,ro}\ CF$$

d_0 = 5 or 10 cm

r_0 = 10x10 or 5x5 cm^2

For field sizes > 3x3 cm^2 :

CF = 1.00 &

$(L/\rho)^{wat}_{det}(r,r_o) = 1.00$

$k^{f_{clin}, f_{msr}}_{Q_{clin}, Q_{msr}}$ $k^{f_{clin}, f_{msr}}_{Q_{clin}, Q_{msr}}$

The field factor defined as $\Omega^{f_{clin}, f_{msr}}_{Q_{clin}, Q_{msr}}$

Conventionally referred as field output factor

Converts absorbed dose to water (D_w) per MU at a reference point in a phantom for the machine-specific reference field (f_{msr}) of beam quality Q_{msr}, to that of the clinical field of interest (f_{clin}) of beam quality Q_{clin}

$$\Omega_{Q_{\mathrm{clin}},Q_{\mathrm{msr}}}^{f_{\mathrm{clin}},f_{\mathrm{msr}}} = \frac{M_{Q_{\mathrm{clin}}}^{f_{\mathrm{clin}}}}{M_{Q_{\mathrm{msr}}}^{f_{\mathrm{msr}}}} \cdot k_{Q_{\mathrm{clin}},Q_{\mathrm{msr}}}^{f_{\mathrm{clin}},f_{\mathrm{msr}}} = s_{c,p} \cdot k_{Q_{\mathrm{clin}},Q_{\mathrm{msr}}}^{f_{\mathrm{clin}},f_{\mathrm{msr}}},$$

$$k_{Q_{\mathrm{msr}},Q}^{f_{\mathrm{msr}},f_{\mathrm{ref}}}$$

↓

accounts for the difference between the detector response in the field f_{msr} and f_{clin} in the medium

Field size dependent sensitivity

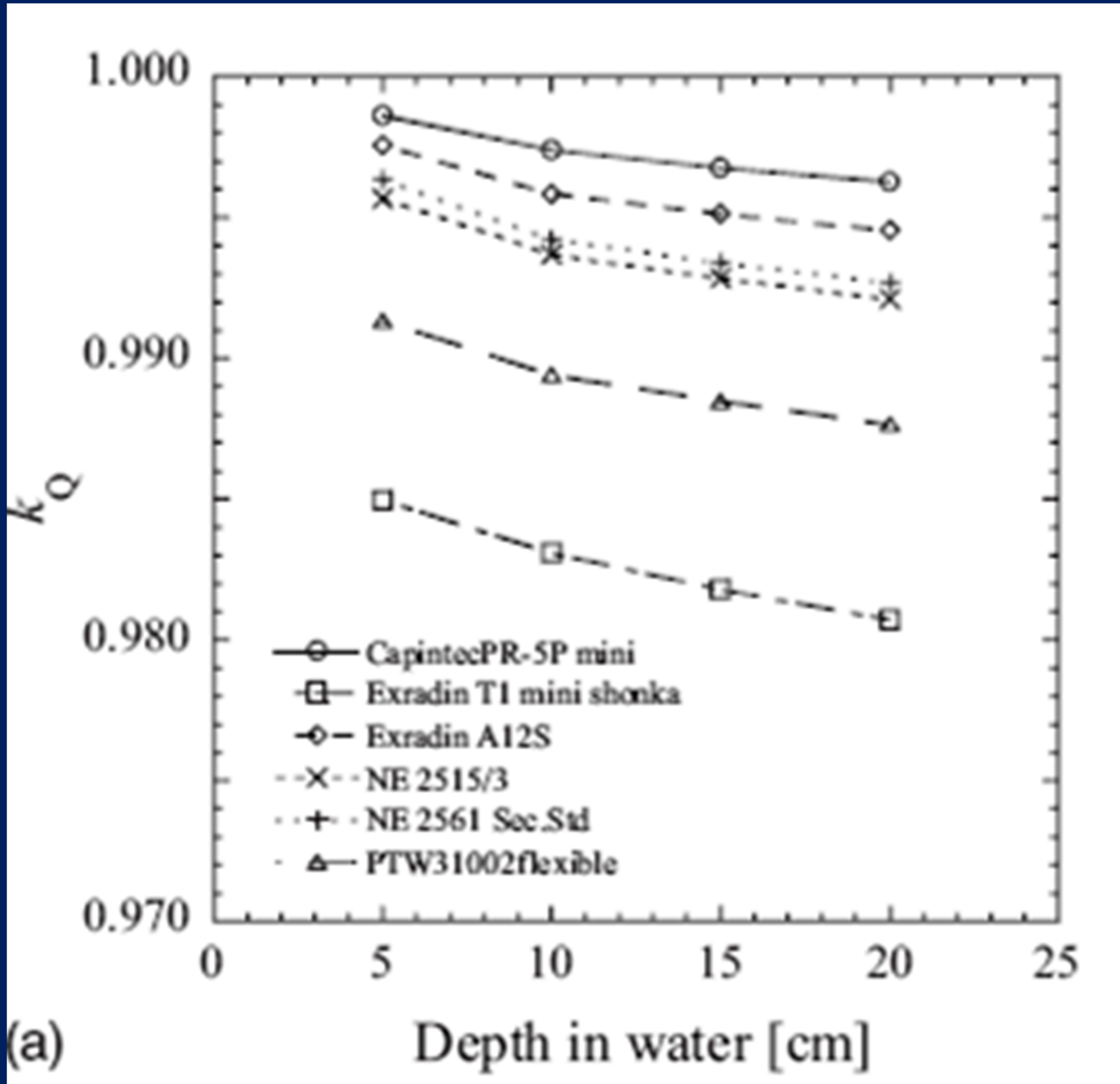
Definition of k^{fcl}_{Qcl} Defined in IAEA/AAPM

(ionization chamber)

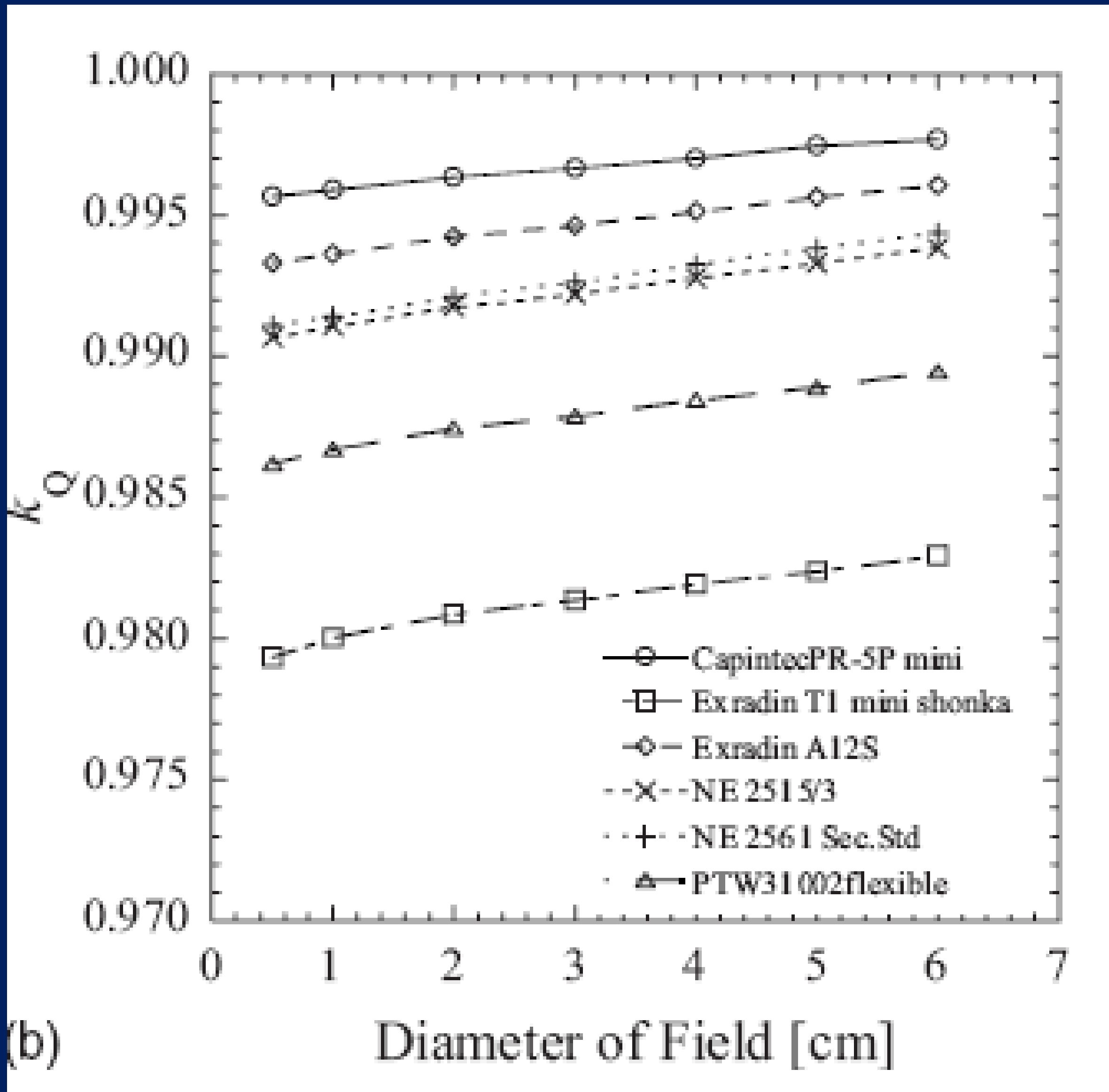
$$k^{f_{clin},f_{msr}}_{Q_{clin},Q_{msr}} = \frac{\left[\left(\frac{\bar{L}}{\rho}\right)^{w}_{air} \cdot P_{fl} \cdot P_{grad} \cdot P_{stem} \cdot P_{cell} \cdot P_{wall}\right]_{f_{clin}}}{\left[\left(\frac{\bar{L}}{\rho}\right)^{w}_{air} \cdot P_{fl} \cdot P_{grad} \cdot P_{stem} \cdot P_{cell} \cdot P_{wall}\right]_{f_{msr}}}$$

k_Q varies with Field Size and Depth

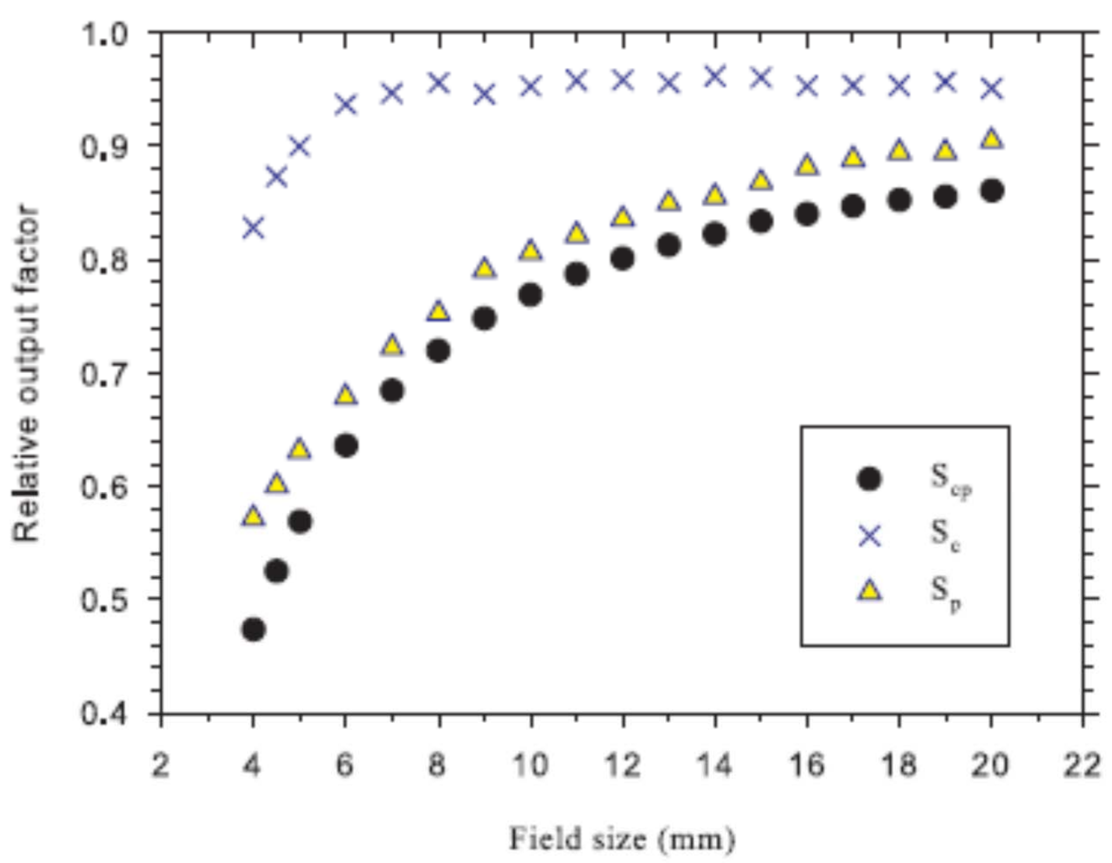
k_Q is related to $k_{Q_{msr},Q}^{f_{msr},f_{ref}}$



Kawachi et al, Med Phys, 35, 4591-4598, 2008



Kawachi et al, Med Phys, 35, 4591-4598, 2008



MC calculations for S_c, S_p, and S_{cp} for 6 MV normalized to 10x10 cm^2

S_c = collimator factor
S_p = phantom scatter
S_{cp} = total scatter factor

A practical and theoretical definition of very small field size for radiotherapy output factors P.H. Charles et al.

Medical Physics, Vol. 41, No. 4, April 2014

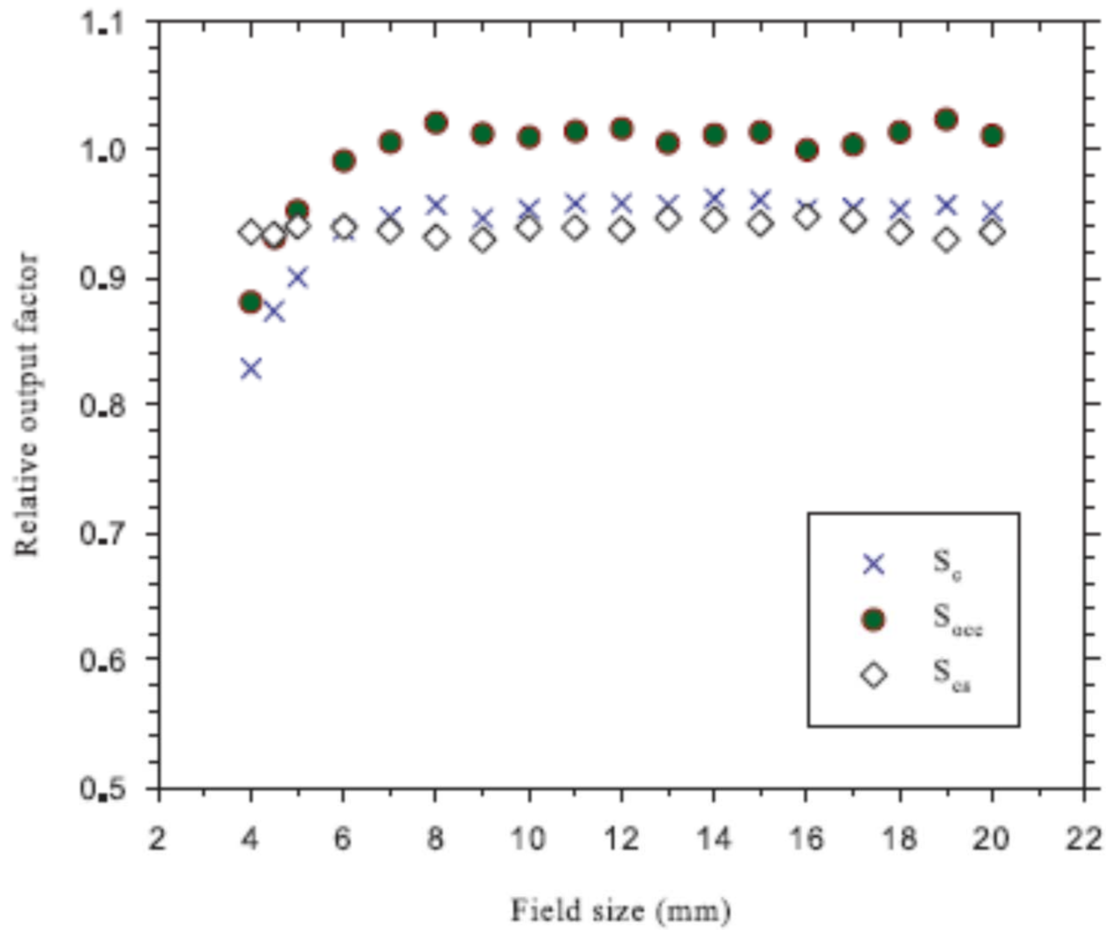


FIG. 5. S_c, S_{occ}, and S_{cs} as a function of field size. All factors are normalized to a field size of 100 mm. The Monte Carlo statistical uncertainty is 0.5% (approximately equal to the marker size).

$S_c = S_{cs}S_{occ}$

- **S_c = total collimator scatter**
- **S_{occ} = source occlusion**
- **S_{cs} = collimator scatter**

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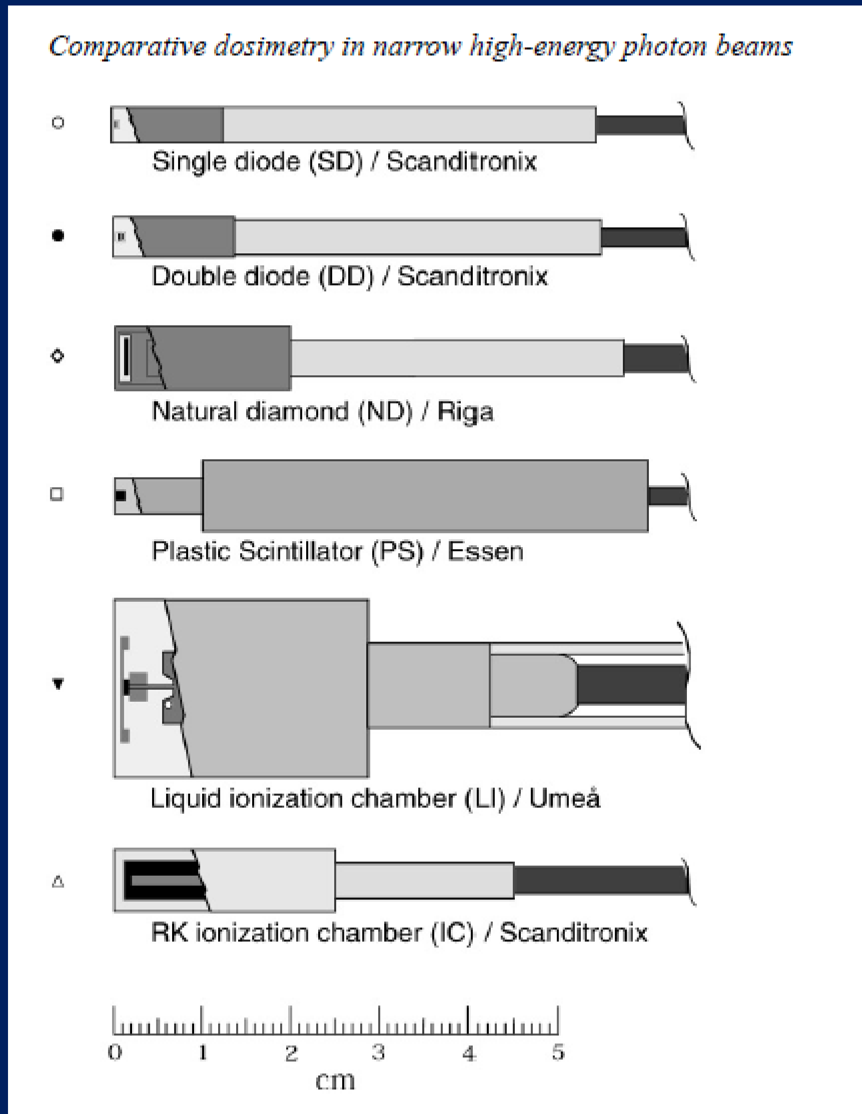
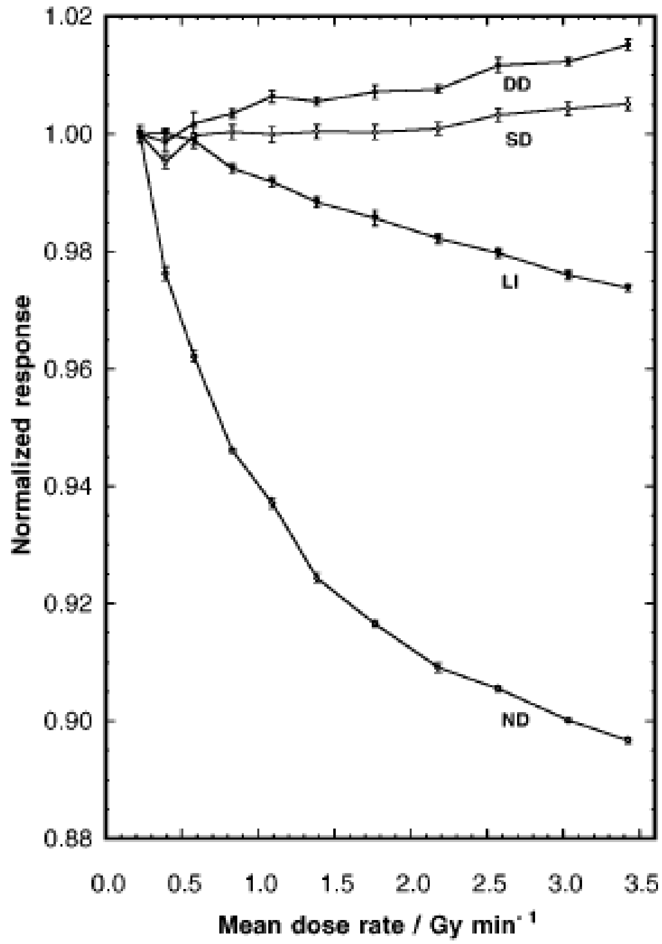
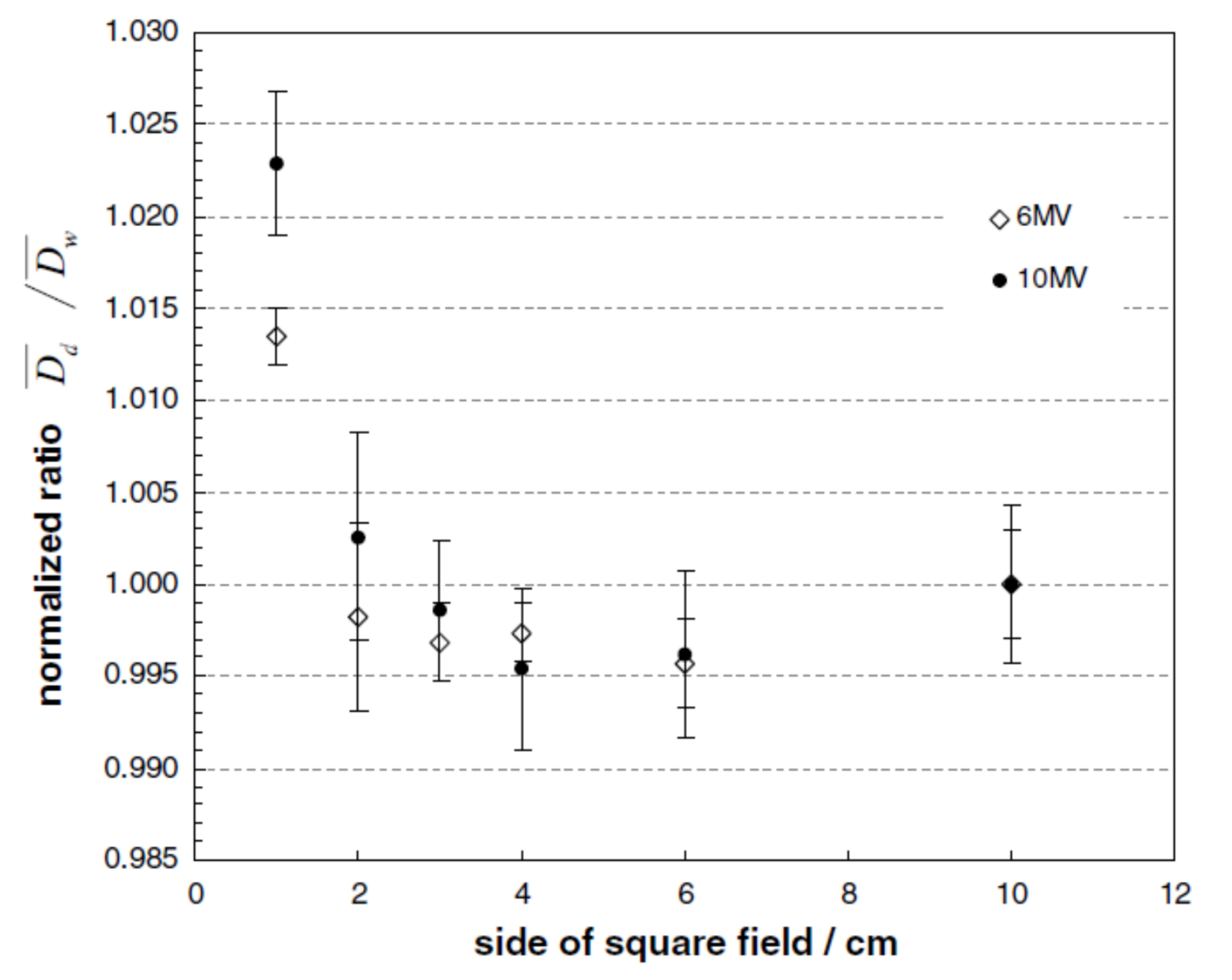


Westermark, M., Arndt, J., Nilsson, B., and Brahme, A. PMB 45 (2000)



Dose rate dependence for various detectors for 6 MV irradiations – data normalized to Farmer chamber

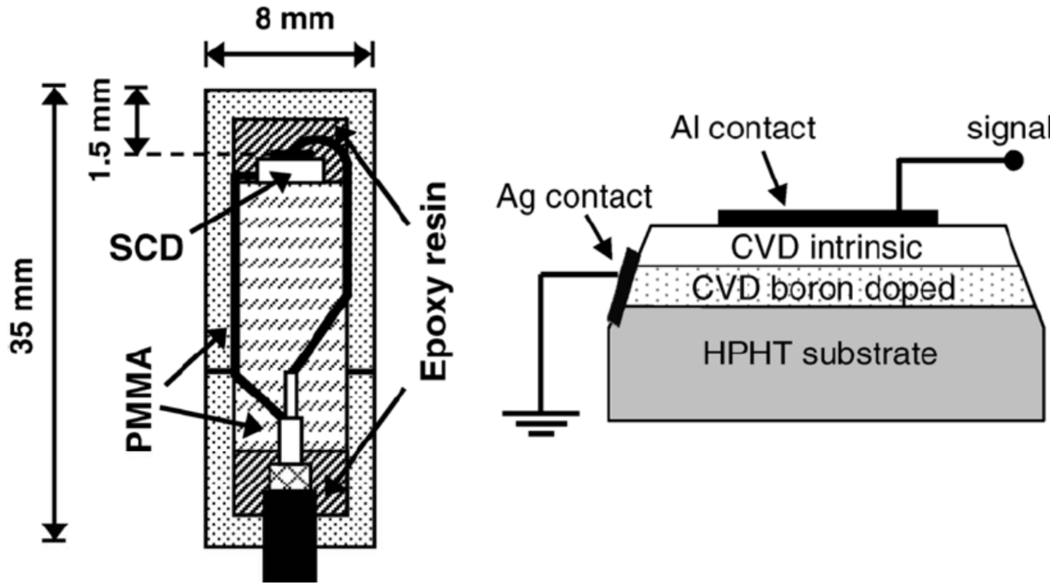
Westermark, M., Arndt, J., Nilsson, B., and Brahme, A.
PMB 45 (2000)



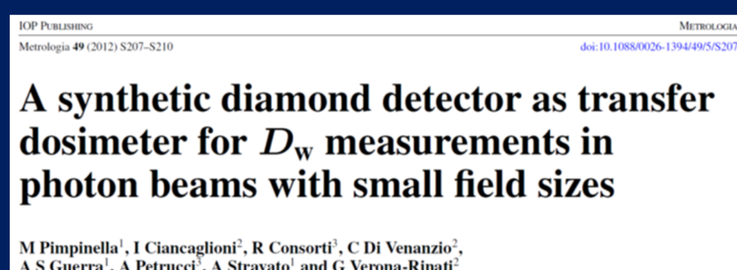
MC calculations of the field size dependence of the output factor for a diamond detector for 6 and 10 MV

M. Pimpinella et al.
Metrologia 49 (2012) S207-210

M Pimpinella *et al* **Metrologia 49 (2012)**



Schematic diagram of the SCD dosimeter showing longitudinal cross-section (left) and details of connections (right)



IOP Publishing Metrologia
Metrologia **49** (2012) S207–S210 doi:10.1088/0026-1394/49/5/S207

A synthetic diamond detector as transfer dosimeter for D_w measurements in photon beams with small field sizes

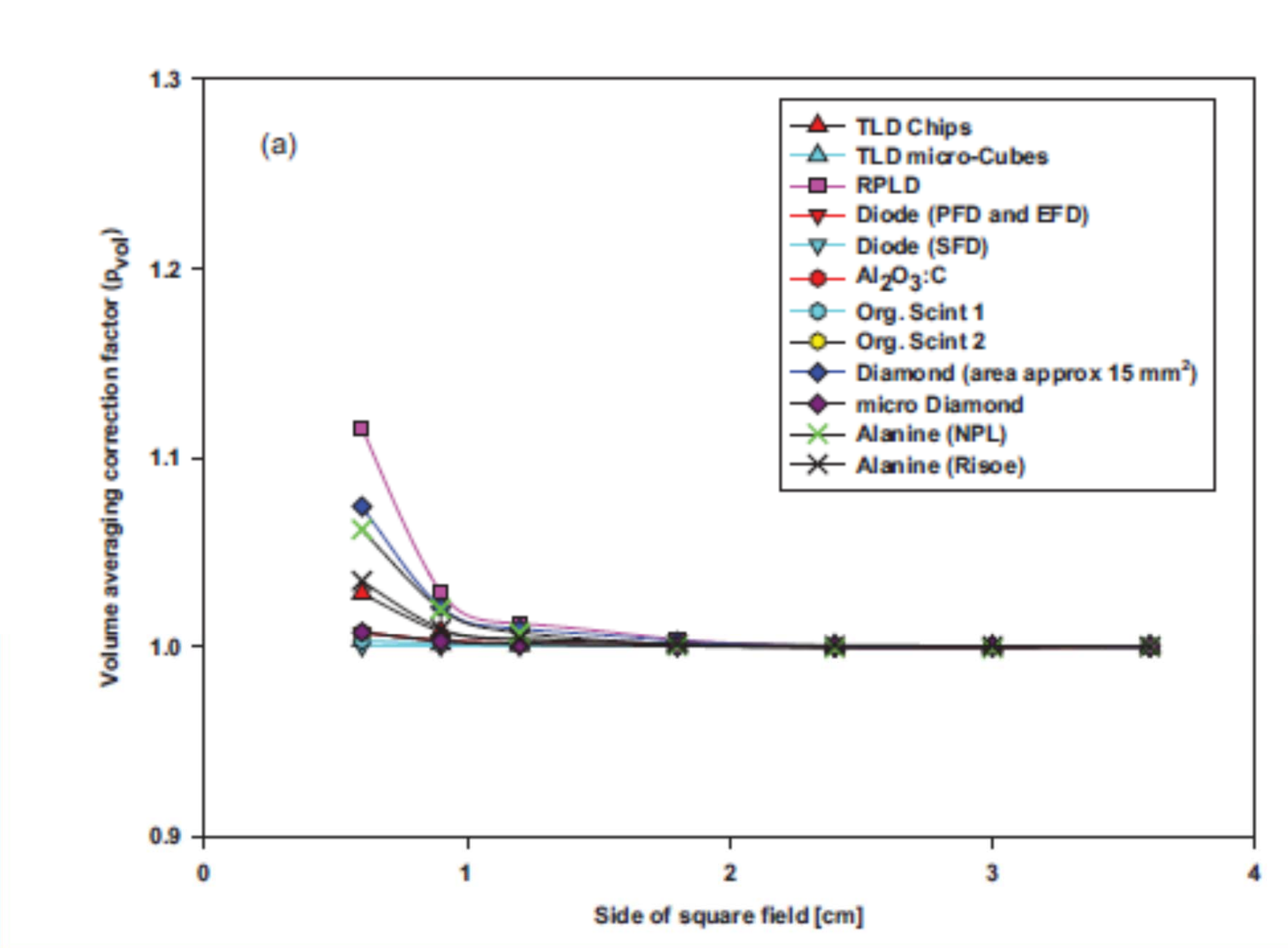
M Pimpinella[1], I Ciancaglioni[2], R Consorti[3], C Di Venanzio[2], A S Guerra[1], A Petrucci[3], A Stravato[1] and G Verona-Rinati[2]

TABLE II. Calculated volume-averaging correction factors [$1/F_{average}$ in Eq. (3)] for each detector.

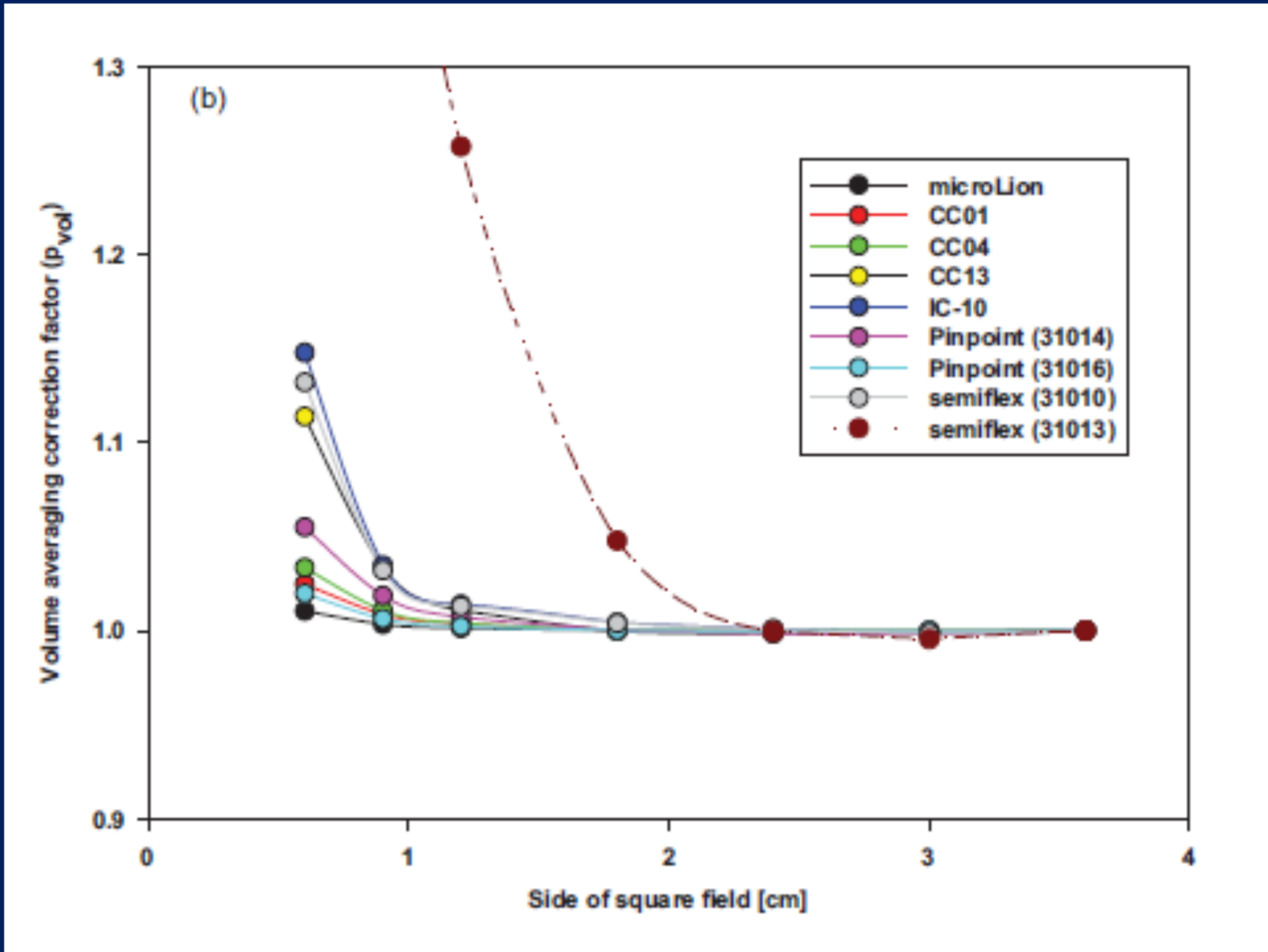
Detector	5-mm cone diameter	7.5-mm cone diameter	10-mm cone diameter
0.5-mm PSD	1.003	1.001	1.000
1.0-mm PSD	1.011	1.002	1.001
PTW 60008	1.014	1.003	1.001
PTW 60012	1.014	1.003	1.001
MicroLion chamber	1.068	1.016	1.007
SFD diode	1.004	1.001	1.000

$$F_{average} = \frac{\int_0^{2\pi} \int_0^{d/2} D(r,\theta)\, r\, dr\, d\theta}{\pi d^2/4}. \quad (3)$$

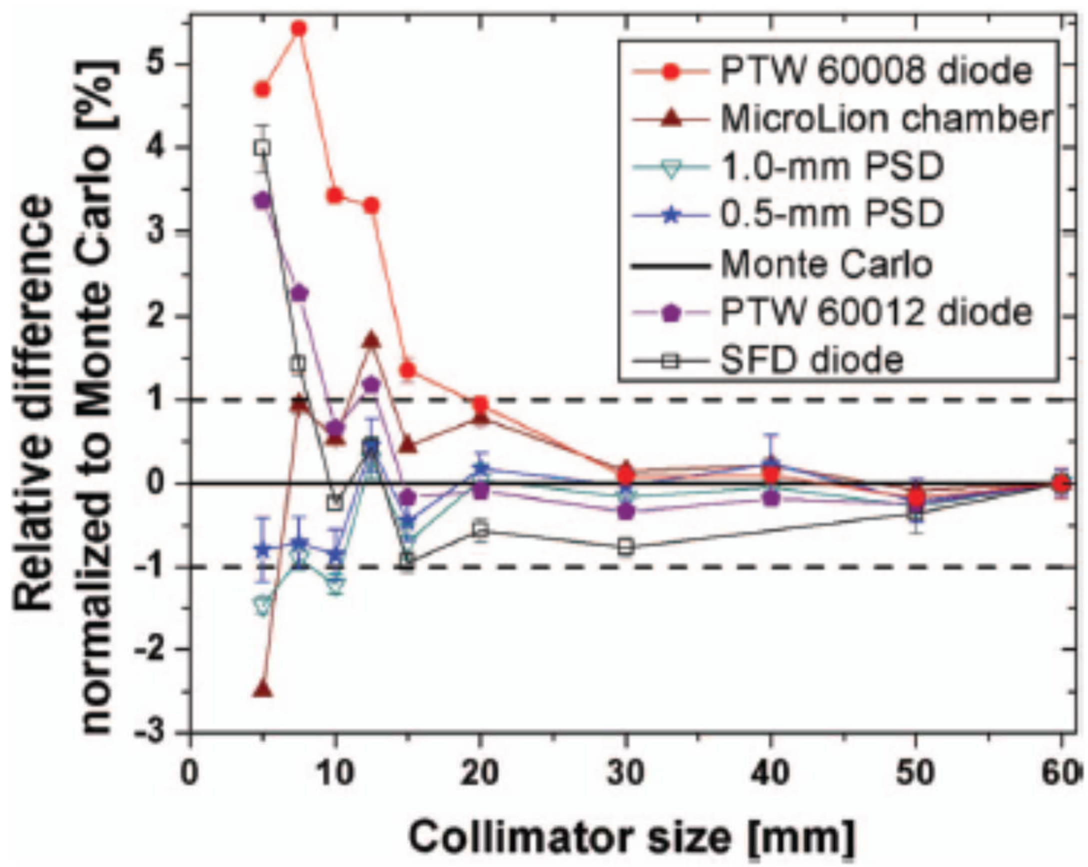
Morin, J., Beliveau-Nadeau, D., Chung, E., Seuntjens, J., Theriault, D., Archambault, L., Bedder, S. and Beaulieu, L.Med. Phys. 40 (2013)



Azangwe et al., Detector specific correction factors for small radiotherapy fields, Med. Phys. 41 (2014) 072103-1



Azangwe et al., Detector specific correction factors for small radiotherapy fields, Med. Phys. 41 (2014) 072103-1



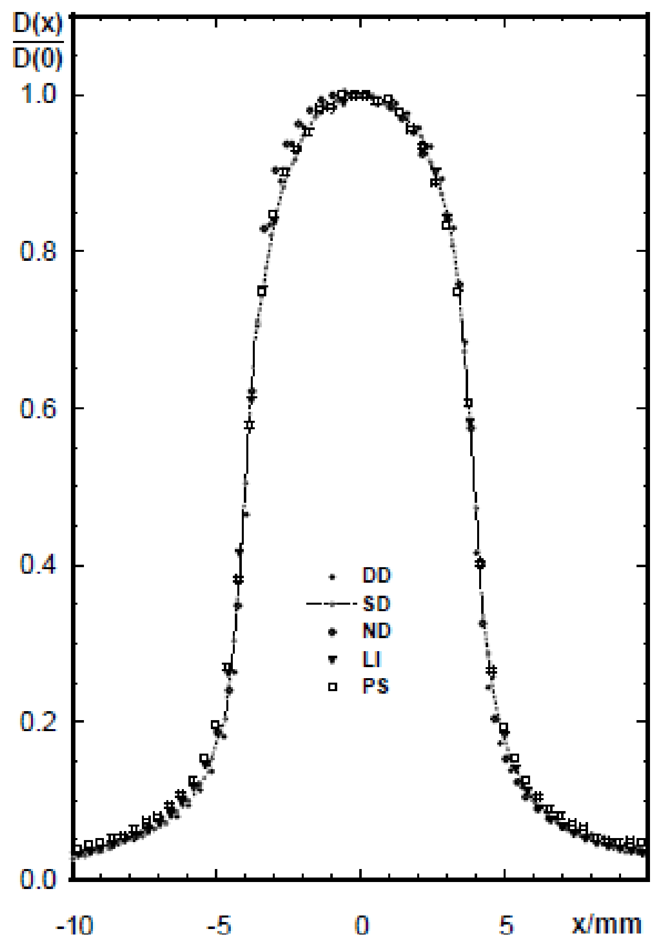
Relative total scatter factors normalized to MC calculations (solid black line) for various detectors

Morin, J., Beliveau-Nadeau, D., Chung, E., Seuntjens, J., Theriault, D., Archambault, L., Bedder, S. and Beaulieu, L.Med. Phys. 40 (2013)

TABLE III. Correction factors $k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$ for the PTW 60008 diode, the PTW 60012 diode, the SFD, and the microlion obtained using the 0.5-mm PSD as a reference dosimeter. The reference detector was corrected for the volume-averaging effect by using the calculated correction factors (Table II).

Detectors	Collimator diameter (mm)	Experimental correction factors	Literature	Difference (%)
PTW 60008 diode	5	0.950	0.944 (Ref. 36), 0.945 (Ref. 38)	−0.6, −0.5
	7.5	0.942	0.951 (Ref. 36), 0.960 (Ref. 38)	0.9, 1.8
	10	0.959	0.965 (Ref. 36), 0.974 (Ref. 38)	0.6, 1.5
PTW 60012 diode	5	0.963	0.957 (Ref. 5), 0.963 (Ref. 38)	−0.6, 0
	7.5	0.971	0.967 (Ref. 5), 0.975 (Ref. 38)	−0.4, 0.4
	10	0.985	0.978 (Ref. 5), 0.983 (Ref. 38)	−0.7, −0.2
SFD	5	0.957	0.952 (Ref. 8)	−0.5
	7.5	0.980	0.976 (Ref. 8)	−0.4
	10	0.994	–	–
MicroLion chamber	5	1.020	1.025 (Ref. 38)	0.5
	7.5	0.984	0.998 (Ref. 38)	1.4
	10	0.986	0.995 (Ref. 38)	0.9

Morin, J., Beliveau-Nadeau, D., Chung, E., Seuntjens, J., Theriault, D., Archambault, L., Bedder, S. and Beaulieu, L.Med. Phys. 40 (2013)



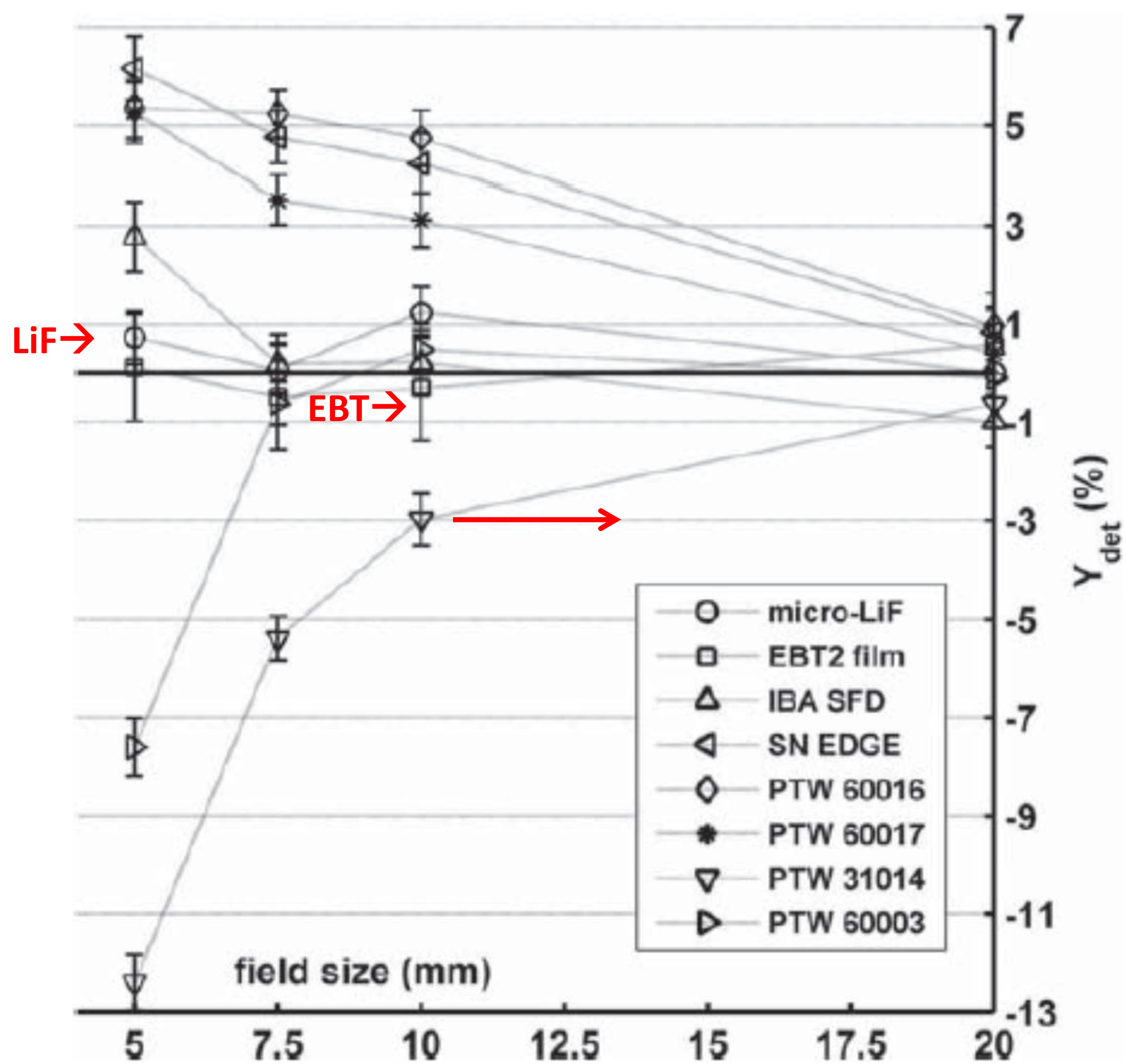
Detectors:
- Double diode
- Single diode
- Diamond (natural)
- Liquid ion chamber
- Plastic scintillator

Beam profiles for 8 mm diameter collimator for 6 MV photons measured with detectors at 10 cm depth

Westermark, M., Arndt, J., Nilsson, B., and Brahme, A.PMB 45 (2000)

What about passive detectors?

Difference between MC and measurements



Difference (%) between measurements & MC calculations for various detectors

C. Moignier et al, Med. Phys., 41 (2014) 071702-2

TABLE V. Detector correction factors $(p_{fl})_{Q_{\text{int}}}^{Q_{\text{clin}}}(p_{\text{spec}})_{Q_{\text{int}}}^{Q_{\text{clin}}}$. Factors shown are ratios of detector ratios relative to the dose ratios determined t measurement for each field size $\left(\frac{D_{w,Q_{\text{clin}}}^{f_{\text{clin}}}}{D_{w,Q_{\text{int}}}^{f_{\text{int}}}}\right)/\left(\frac{M_{Q_{\text{clin}}}^{f_{\text{clin}}}}{M_{Q_{\text{int}}}^{f_{\text{int}}}} \times (p_{\text{vol}})_{Q_{\text{int}}}^{Q_{\text{clin}}}\right)$.

FS [cm]	0.6	0.9	1.2	1.8	2.4	3.0	4.2
TLD chips	★ 1.000	...	1.003	1.008	1.004	1.000	1.005
TLD micro-cubes	★ 0.998	...	1.000	1.001	1.009	1.000	1.001
IBA SFD diode	★ 0.995	...	0.998	1.002	1.006	1.000	0.990
IBA PFD diode	0.936	...	0.962	0.985	0.999	1.000	1.000
IBA EFD diode	0.961	...	0.983	0.992	1.002	1.000	0.997
PTW 60003Diamond (Sensitive area ~ 15 mm^2)	0.995	...	0.983	0.992	1.002	1.000	0.996
PTW 60019 microDiamond	0.961	...	0.980	0.990	1.001	1.000	0.999
RPLD (GDM-302M)	...	...	...	0.993	0.998	1.000	0.994
Al_2O_3:C	0.980	0.982	0.985	0.991	0.999	1.000	...
Scintillator 1	1.022	1.009	1.000	0.996	1.001	1.000	...
Scintillator 2	1.028	1.015	1.006	1.000	1.004	1.000	...
PTW 31018microLion	★ 0.970	...	0.980	0.990	1.000	1.000	0.999
IBA CC01	1.000	...	0.993	0.993	1.000	1.000	0.997
IBA CC04	1.096	...	1.007	0.998	1.003	1.000	0.997
IBA CC13[b]	...	...	1.033	1.008	1.005	1.000	0.996
Wellhöfer IC10[b]	...	...	1.030	1.005	1.005	1.000	0.996
PTW 31014 PinPoint	1.034	...	1.007	1.002	1.000	1.000	0.998
PTW 31016 PinPoint 3D	1.078	...	1.013	1.000	1.001	1.000	0.998
PTW 31010 Semiflex[b]	...	...	1.027	1.002	1.004	1.000	0.996
PTW 31013 Semiflex[a,b]	...	...	...	...	1.013	1.000	0.992

Azangwe et al., Detector specific correction factors for small radiotherapy fields, Med. Phys. 41 (2014) 072103-1

Corrections for Cerenkov Radiation

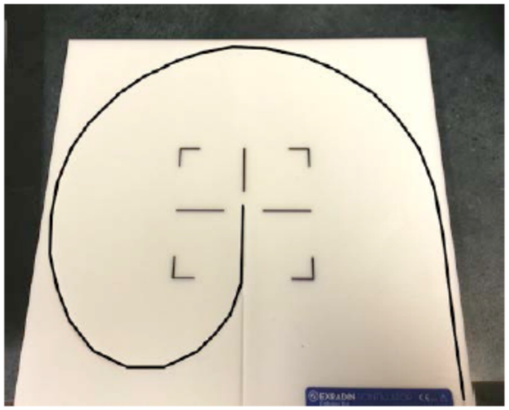
1. Background fiber subtraction
2. Simple filter to separate signals
3. Chromatic removal

Spectral Method for correcting for Cerenkov light

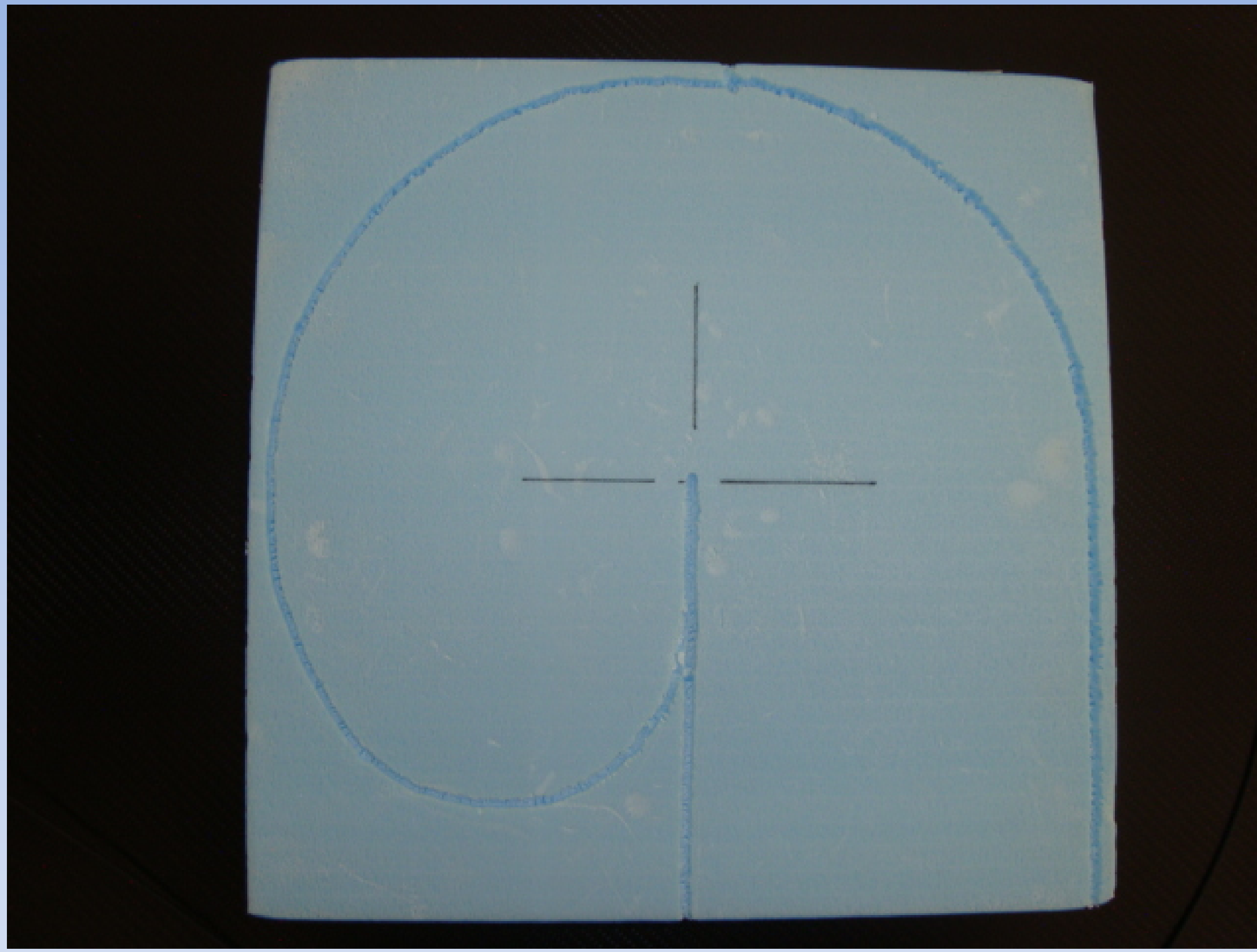
- Irradiation by a known dose
- Vary the amount optical fiber

Fiber in minimum position

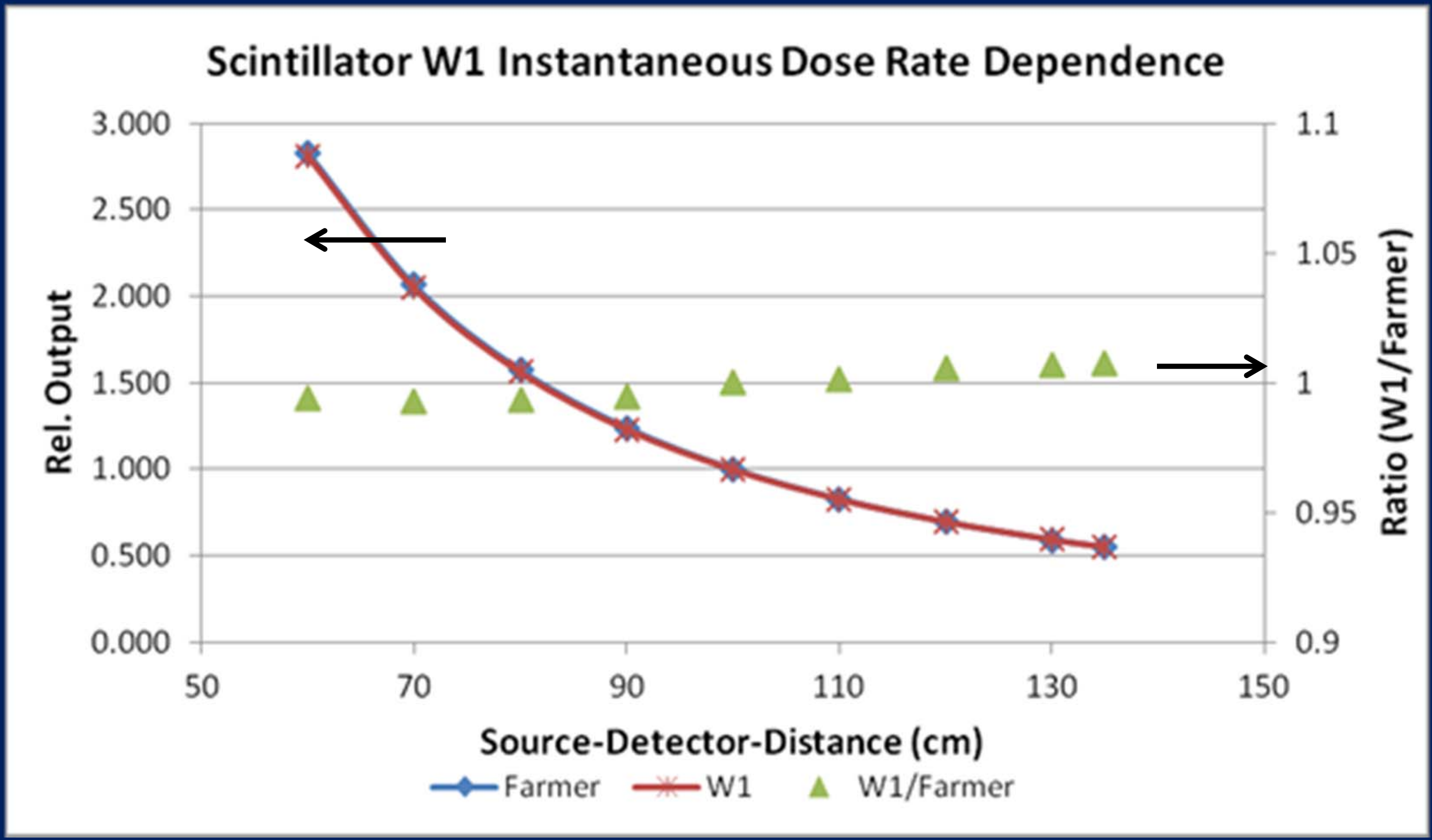
Fiber in maximum position



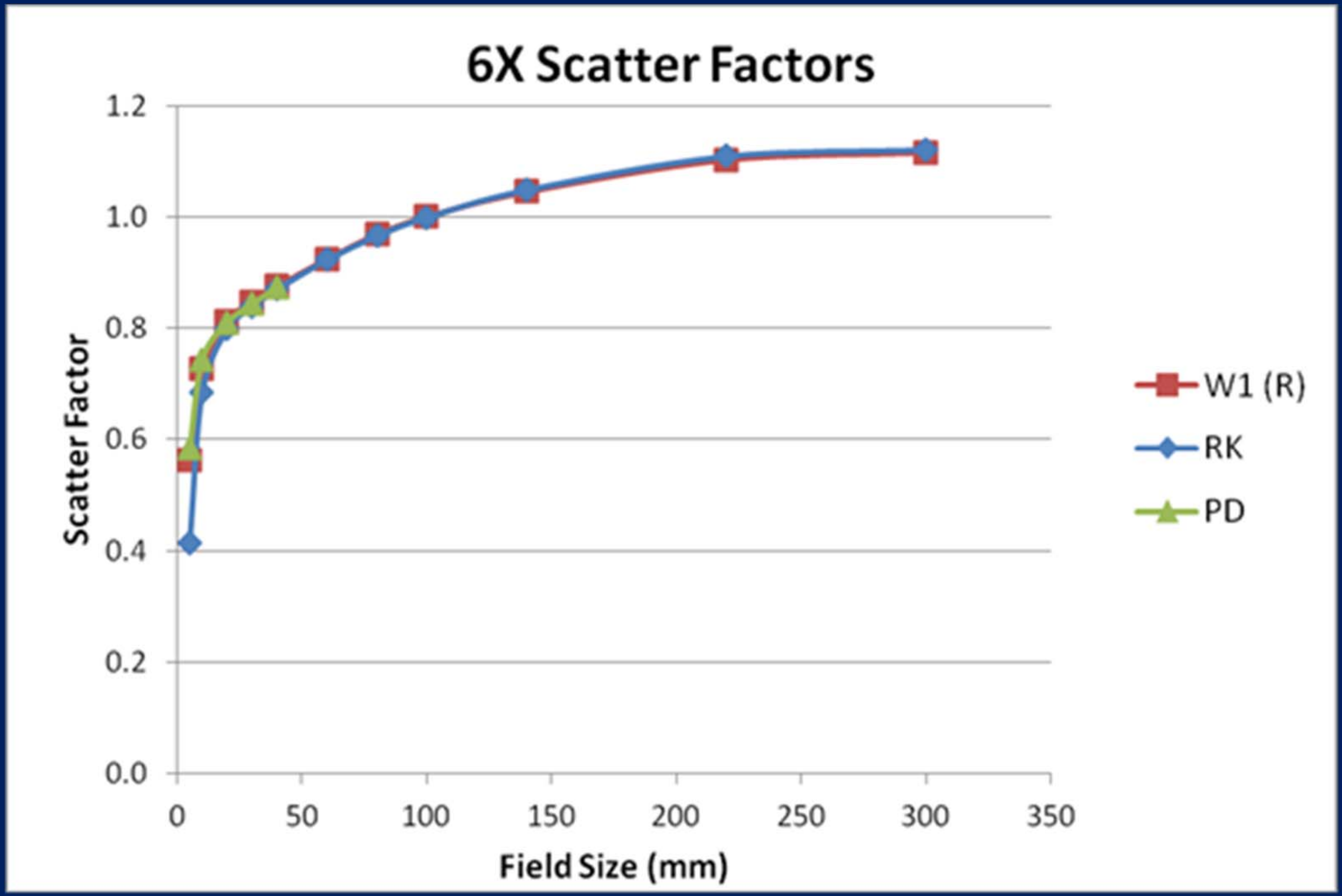
Guillot M, Gingras L, Archambault L, Beddar S, Beaulieu L. Spectral method for the correction of the Cerenkov light effect in plastic scintillation detectors: A comparison study of calibration procedures and validation in Cerenkov light-dominated situations. *Med Phys* 38: 2140–2150, 2011.



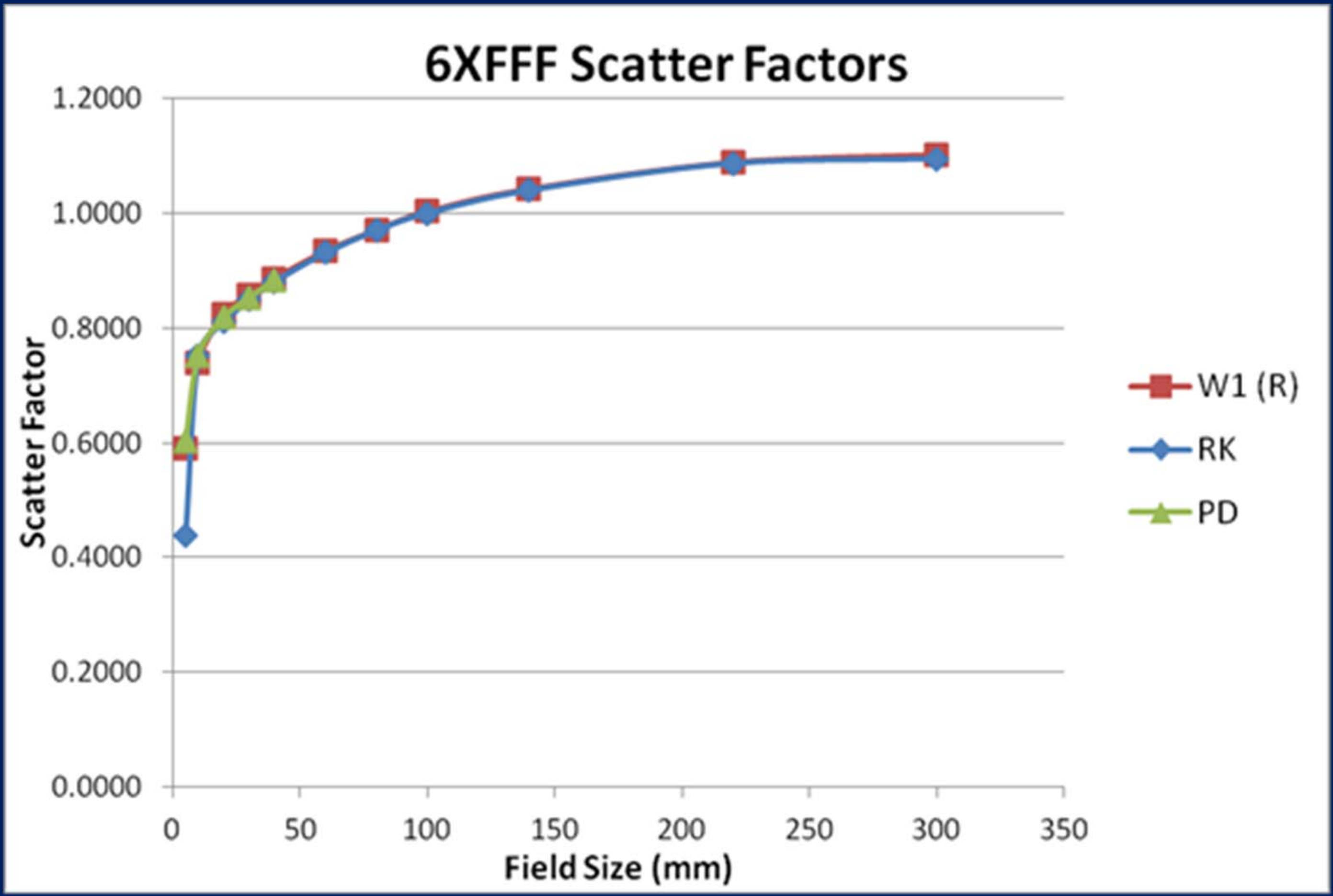
Custom in-air calibration phantom for the W1 scintillator. The pattern on the vendor-supplied calibration phantom was transferred to a piece of Styrofoam and traced out with a drill bit.



A Farmer ionization chamber which is known to have little instantaneous dose rate dependence was used as reference. For both detectors, the output was normalized to that of 100 cm SDD.



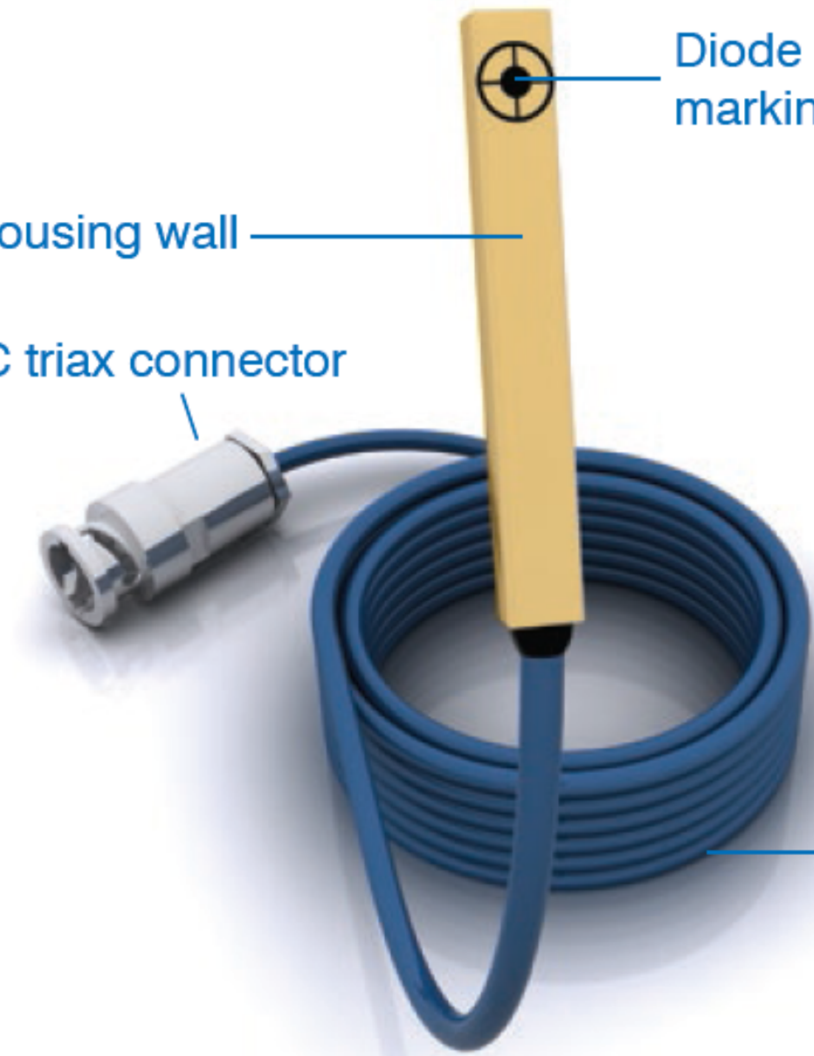
Scatter factors (Scp) for the 6X photon beam measured with the W1 scintillator, RK ionization chamber (RK) and electron diode



Scatter factors (Scp) for the 6XFFF photon beam measured with the W1 scintillator, RK ionization chamber (RK) and electron diode.

SUN NUCLEAR corporation

Detector EDGE™



EDGE Detector Specifications

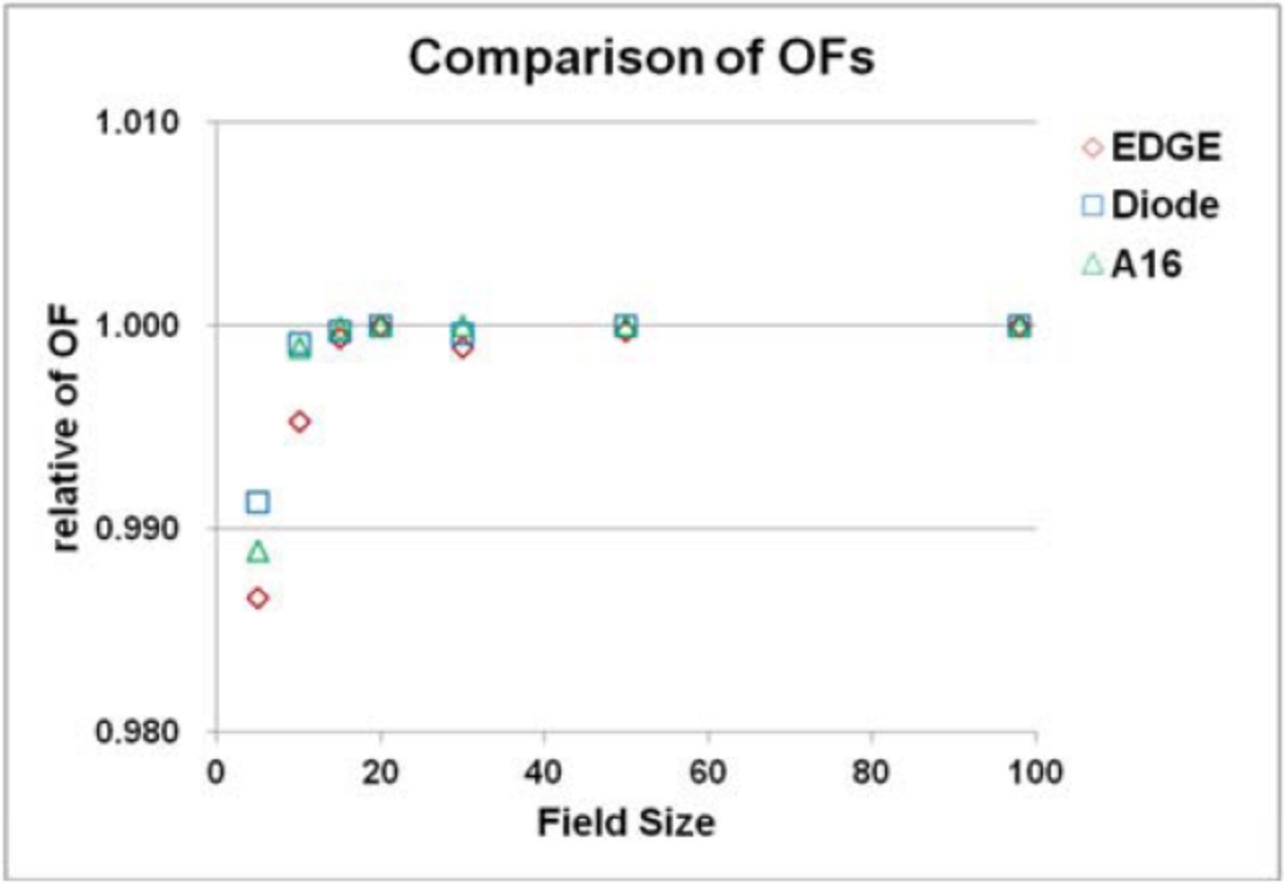
Active detection area (mm):	0.8 x 0.8
Diode die location (mm):	0.3 from top 4.7 from end 2.7 from side Location is indicated by a target on top of housing
Water depth equivalent (mm):	0.5
Housing wall thickness (mm):	0.13, brass
External dimensions (mm):	3.8 x 5.5 x 38
Sensitivity (nC/Gy):	32.0
Impedance (Mohm):	>200 at 10mV reverse bias
Output polarity:	Negative
Cable:	3.4mm dia. x 1.8m long, triax
Cable connector:	BNC or TNC triax, or adapters upon request

Evaluation of the EDGE Detector in Small-field Dosimetry

Hun-Joo SHIN, Myong-Ho KIM and Ihl-Bohng CHOI

Journal of the Korean Physical Society, Vol. 63, No. 1, July 2013, pp. 128~134

Field Sizes (mm^2)	D_{max} (mm) EDGE	Diode	A16	MC
5 × 5	8.5 ★	7.5	10.5	9.0 ★
10 × 10	12.0	9.5	13.0	13.0
15 × 15	13.0	10.0	13.5	13.0
20 × 20	13.5	10.0	14.0	13.0
30 × 30	12.5	10.5	14.0	13.0
50 × 50	14.0	10.0	14.0	15.0
98 × 98	13.5	10.0	14.0	14.0
average	12.4 ★	9.6	13.3	12.9 ★
min	8.5	7.5	10.5	9.0
max	14.0	10.5	14.0	15.0
median	13.0	10.0	14.0	13.0



Measured relative output factors for 6 MV photons for various field sizes for the Edge, diode, and A16 detectors

Relative sensitivity of diode increase with decreasing field size

Include a perturbation to compensate for over-response

Redesign diode by including an air gap → independent of field size

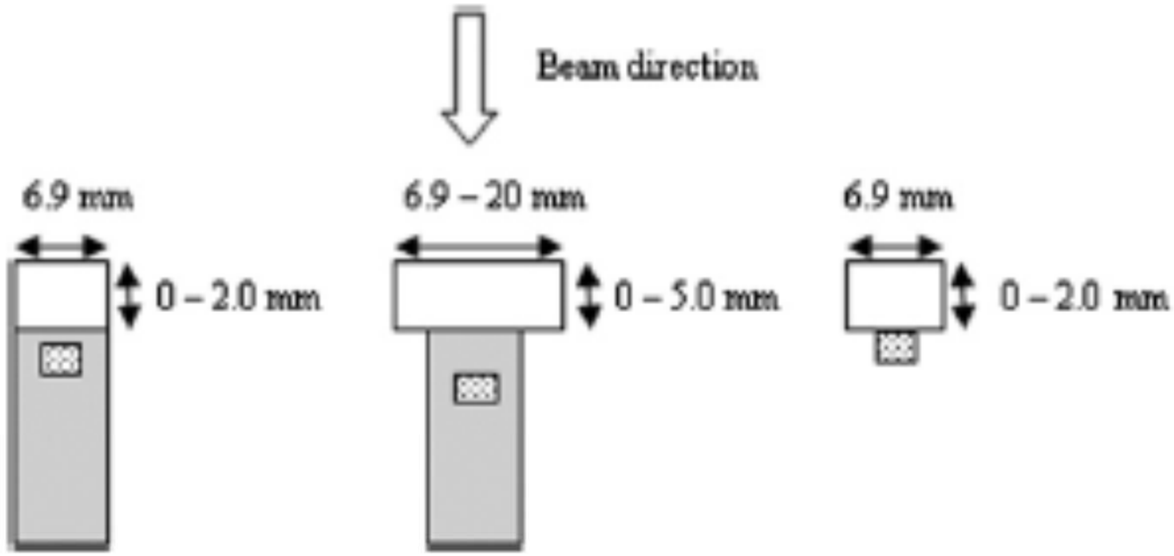


Figure 1. Schematic of the placement of the air gap proximal to the diode detector. The grey represents the body of the detector, the dotted area is the silicon chip, and the white is the air gap. From left to right are schematics of the PTW60017 diode, PTW60016 diode and the unenclosed silicon chip respectively. The geometry of both the air gap and the detector is cylindrical in the perpendicular to beam direction. The diagram is not to scale.

Monte Carlo-based diode design for correction-less small field dosimetry

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Table 2. $k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}$ for the three diodes simulated in this study as a function of square field size. These values are normalized to the field size of 50 mm. Shown is the unmodified detector design (without the air gap) as well as the modified detector design which includes the air gap. Note that the Monte Carlo statistical uncertainty in each value is approximately 0.5%.

	PTW 60016		PTW 60017		Unenclosed silicon chip	
Field size (mm)	No air	Air	No air	Air	No air	Air
5	0.900	0.995	0.922	1.001	0.975	1.004
6	0.911	0.997	0.938	1.004	0.985	1.004
7	0.921	0.999	0.944	1.000	0.984	1.000
8	0.931	1.005	0.957	1.001	0.995	0.999
9	0.945	1.004	0.966	0.997	0.989	1.003
10	0.948	0.999	0.969	0.998	0.996	0.995
12	0.966	1.000	0.983	0.995	0.995	0.998
18	0.991	0.995	0.997	1.000	1.004	1.005
30	0.995	0.995	1.000	0.999	0.997	1.001
50	1.000	1.000	1.000	1.000	1.000	1.000

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Conclusions

1. Small field considerations
- Lateral electronic equilibrium
- Source Occulsion

2. Detector considerations
- Dimensions/Sensitive area
- Density
- Angular dependence
- Energy dependence

3. k_Q correction is field size and depth dependent

Conclusions Continued

4. No one ideal detector

- Use at least two different acceptable detectors
- Plastic scintillator may be an ideal small field detector?
- Unshielded diode good for fields > $1x1\ cm^2$
- Stereotactic field diode good for fields → $0.6x0.6\ cm^2$
- Passive detectors such as TLDs and radiochromic film good for point dose measurements → $0.6x0.6\ cm^2$

Thank you for your attention

Questions ???