International Conference on Monte Carlo Techniques for Medical Applications (MCMA2017)

15-18 October 2017 *Napoli, Italy*
Europe/Rome timezone

A Monte Carlo perspective on small beam radiation therapy

Jan Seuntjens
Medical Physics Unit
McGill University
Canada

NSERC CRSNG

McGill

Medical Physics
RESEARCH TRAINING NETWORK

CIHR IRSC
Canadian Institutes of Health Research
Instituts de recherche en santé du Canada

DISCLOSURES and ACKNOWLEDGMENTS

- My work is supported by the Canadian Institutes of Health Research, the Natural Sciences and Engineering Research Council of Canada and the Medical Physics Research Training Network
- I am involved in commercialization projects of technology with companies Sun Nuclear Corporation and Lifeline Software
- I am involved in a research project with the company RefleXion Medical

Acknowledgements
- IAEA-TRS 483 committee (Hugo Palmans, Pedro Andreo, Saiful Huq, Karen Rosser, Ahmed Meghzifene, Jan Seuntjens)
- ICRU-91 committee (Eric Lartigau, Joost Nuyttens, Stefania Cora, George Ding, Steven Goetsch, David Roberge, Issam El Naqa, Jan Seuntjens)
- Small Field Students & colleagues
Kamen Paskalev (2002)
Hugo Bouchard (2004)
Laurent Tantot (2007)
Justin Sutherland (2009)
Eunah Chung (2011)
Pavlos Papaconstadopoulos (2013)
Lalageh Mirzakhanian (2017)

Medical Physics RESEARCH TRAINING NETWORK

McGill

NSERC CRSNG

CIHR IRSC
Canadian Institutes of Health Research
Instituts de recherche en santé du Canada

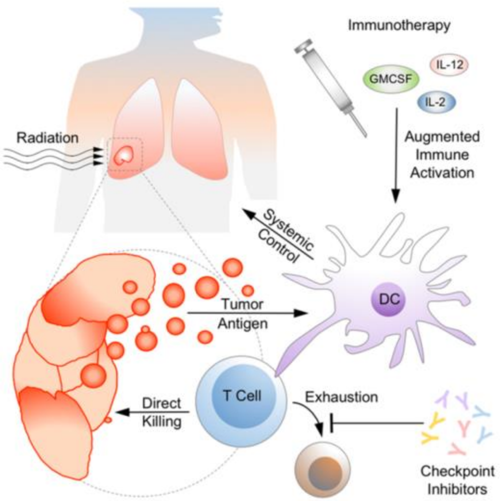
Outline

- Rationale and reminder of seminal milestone
- Small field characteristics
- Detectors and small fields
  - LCPE
  - Response decomposition
  - Detector density
  - Calibration of small fields (G-Knife, sub-LCPE fields)
- Beam model commissioning
- TPS algorithms & small fields
- Why do we care?

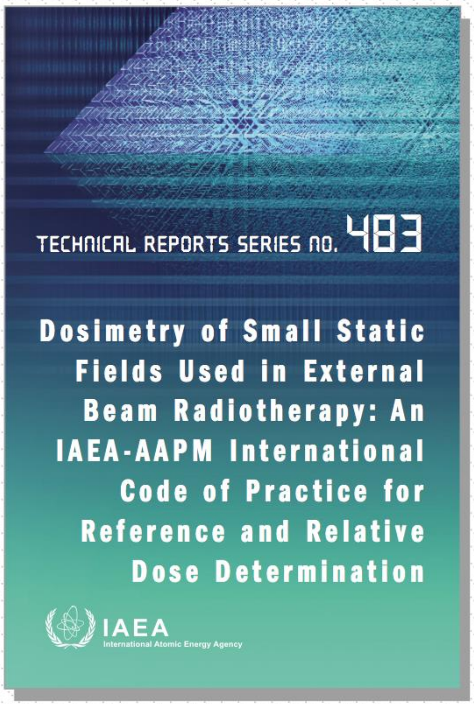
Small beam radiation therapy (SBRT)

- Biology of high dose / fraction : **BED > 100 Gy**
- Synergy of SBRT and immunotherapy
  - Melanoma
  - Renal tumours
  - Sarcomas
- Reporting of SBRT

Translational Lung Cancer Research, Vol 6, No 2 April 2017



Two important reports

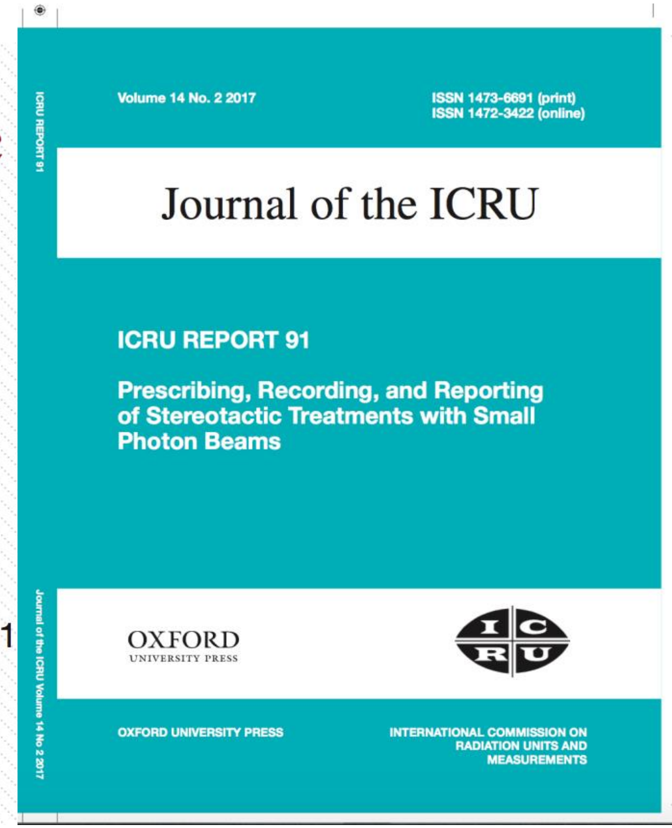


Dosimetry of Small Static Fields Used in External Beam Radiotherapy

An IAEA-AAPM International Code of Practice for Reference and Relative Dose Determination

Technical Reports Series No. 483

STI/DOC/010/483 • ISBN 978-92-0-105916-1
Price: €52.00
Language: English
Forthcoming: 2016



IAEA-TRS 483: Which problems does it solve?

- Characteristics that lead to dosimetric issues of two kinds:
  - Reference dose calibration
    - Reference fields are not 10 x 10 cm^2, SSD/SAD is not 100 cm, etc; they are called "machine-specific reference fields" (*msr*)
    - Flattening filter-free beams, beam quality specification
  - Output factors
    - Small fields
    - Detector correction factors
- Problem that was put on the backburner: calibration of composite fields

A new formalism for reference dosimetry of small and nonstandard fields

R. Alfonso
International Atomic Energy Agency, Vienna, Austria and Instituto Nacional de Oncologia y Radiobiologia, La Habana, Cuba

P. Andreo
International Atomic Energy Agency, Vienna, Austria and University of Stockholm-Karolinska Institutet, Stockholm, Sweden

R. Capote
International Atomic Energy Agency, Vienna, Austria

M. Saiful Huq
University of Pittsburgh Cancer Institute, Pittsburgh, Pennsylvania

W. Kilby
Accuray Inc., Sunnyvale, California

P. Kjäll
Elekta Instrument AB, Stockholm, Sweden

T. R. Mackie
Department of Medical Physics, University of Wisconsin, Madison, Wisconsin

H. Palmans[a)]
National Physical Laboratory, Teddington, United Kingdom and Slovensky Metrologicky Ustav, Bratislava, Slovakia

K. Rosser
Royal Marsden NHS Foundation Trust, Sutton, United Kingdom

J. Seuntjens
Medical Physics, McGill University, Montreal, Canada

W. Ullrich
BrainLAB AG, Feldkirchen, Germany

S. Vatnitsky
International Atomic Energy Agency, Vienna, Austria

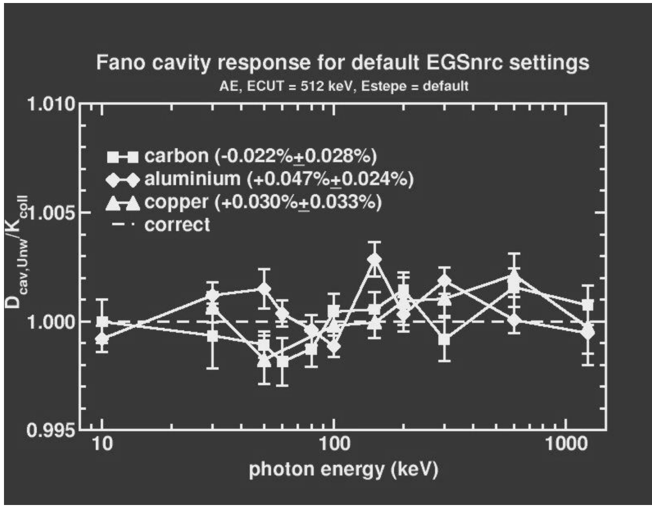
(Received 2 June 2008; revised 2 October 2008; accepted for publication 2 October 2008; published xx xx xxxx)

The "Alfonso" paper

Reminder - Seminal enabling work

Ion chamber simulation at ^{60}Co: resolution of EGS4/PRESTA artifacts

Artifact ESTEPE step control→	Aluminium 20%	Carbon 20%	Aluminium 1%	Carbon 1%
electron step	-9.0%	-5.0%	-1.4%	-0.7%
BCA	+3.4%	+2.6%	+1.5%	+0.9%
energy loss	+0.3%	+0.5%	+0.0%	+0.0%
discrete interactions	+0.7%	+0.7%	+0.7%	+0.7%
Totals	-4.6%	-1.2%	+0.8%	+0.9%



Application to kV and MV beams (Seuntjens et al 2001)

EGSnrc: Kawrakow, 2000
Penelope: Sempau & Andreo 2006
GEANT4: Poon et al 2003; Elles & Maire 2006

McGill

Small fields in stereotactic nonmalignant treatments

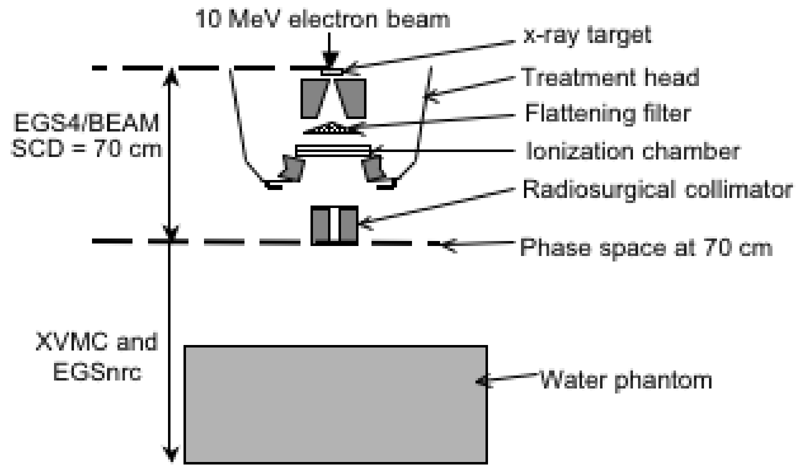


Figure 4: Schematic drawing of the geometry used for Monte Carlo simulations. The treatment head along with the collimator is simulated with BEAM/EGS4. Source-collimator distance (SCD) is 70 cm. The calculations in phantoms are performed with: (i) the EGSnrc code at source-surface distance (SSD) 100 cm for phase space validation and (ii) with the XVMC code at source-axis distance 100 cm for dose distribution calculations.

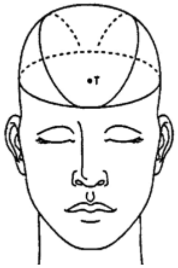


Figure 1: Beam entry trace (baseball seam) on the patient's scull for the dynamic radiosurgery technique.

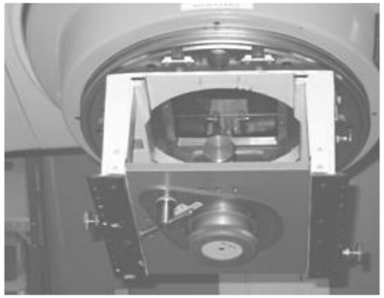
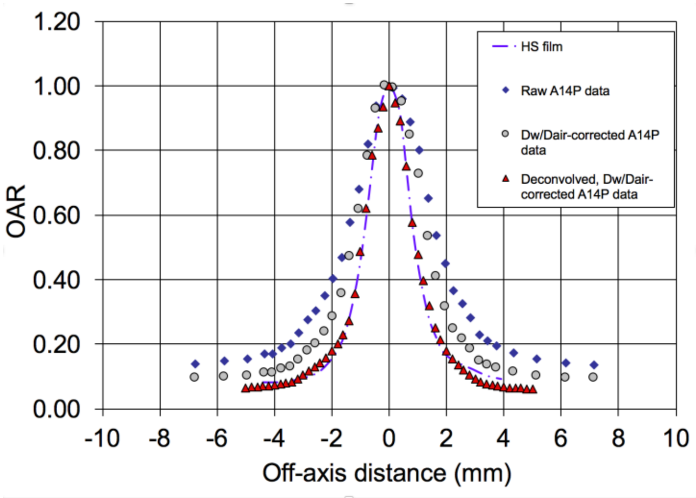
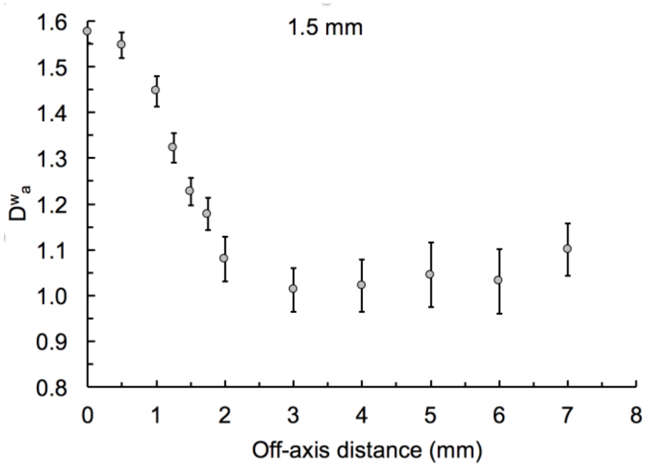


Figure 2: Radiosurgical collimator holder with a small field collimator, attached to the Clinac-18 treatment head.

McGill circa 2000 (presented at the 2001 McGill Workshop 10 days after 9/11)

Large dosimetric discrepancies!





Back in 2001 – first McGill Workshop!

Data: Paskalev et al, 2001, 2002

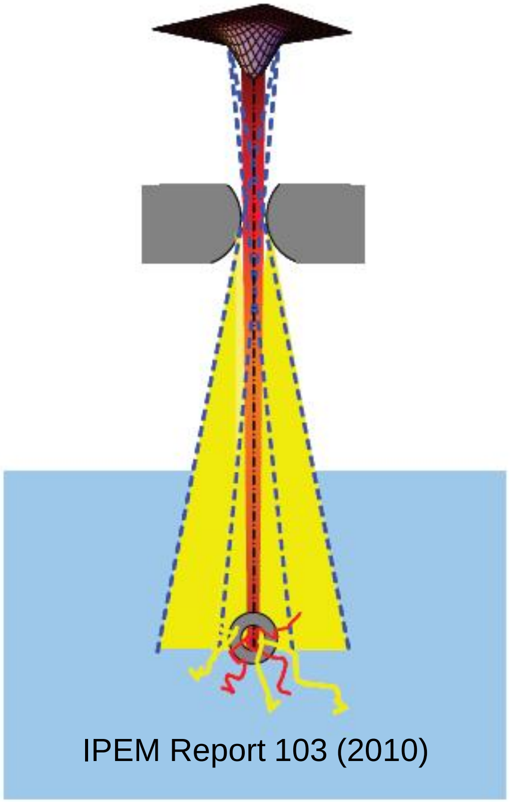
DOSRZ run on a A14P simplified model

Modeling of electric field distribution was necessary!

Separate deconvolution!

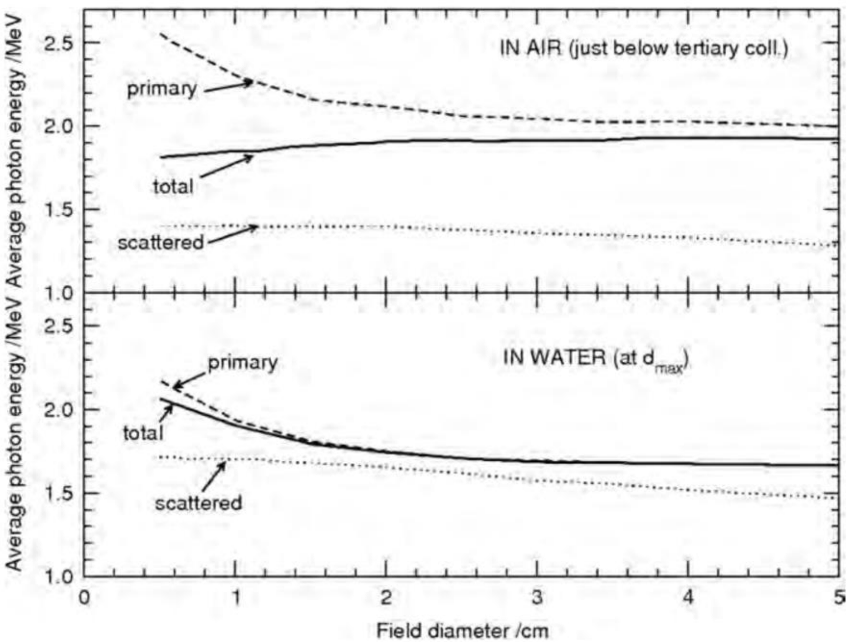
Small photon field conditions IAEA TRS 483 – ICRU 91

- Beam-related small-field conditions
  - the existence of lateral charged particle disequilibrium
  - change in photon fluence spectrum -> beam quality
  - partial geometrical shielding of the primary photon source as seen from the point of measurement
- Detector-related small-field condition
  - detector size compared to field size

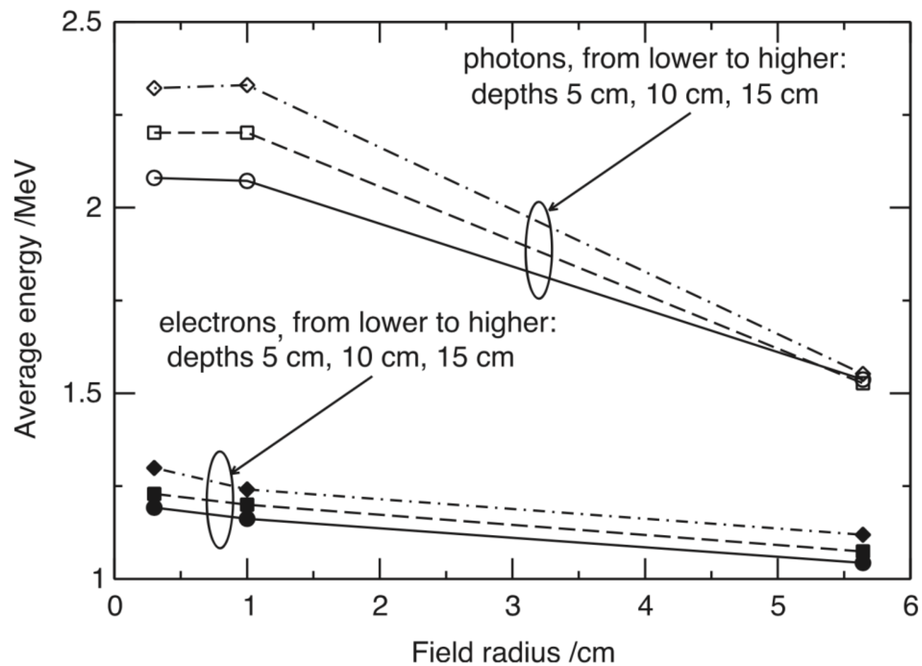


Small beams

Data from Verhaegen et al 1998

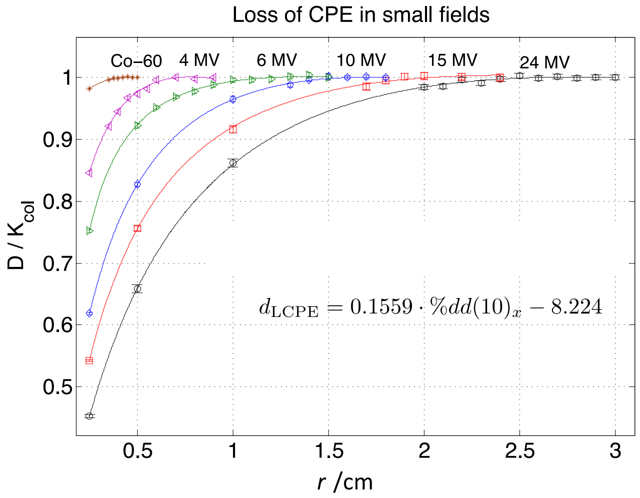


Data from Sanchez-Doblado, et al 2003

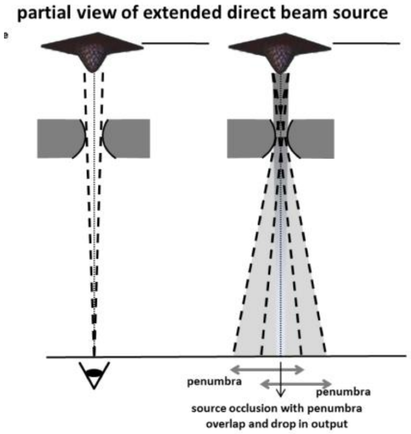


McGill

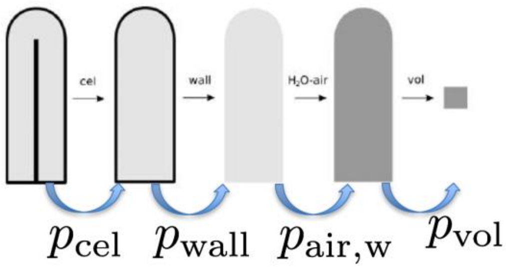
Textbook characterization of small beams



Radiation disequilibrium

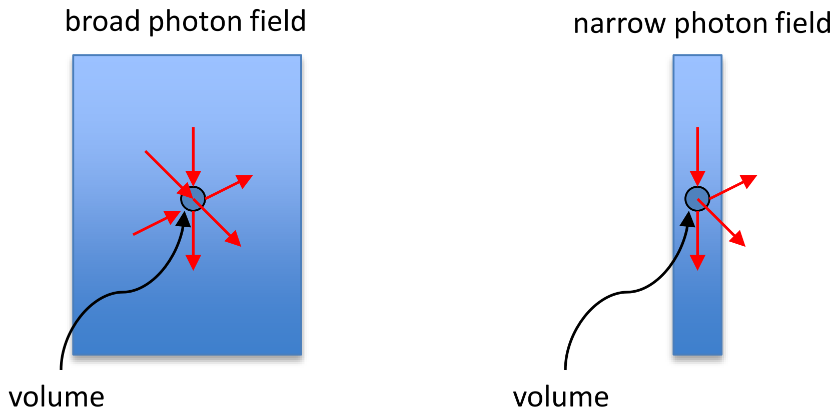


Source occlusion



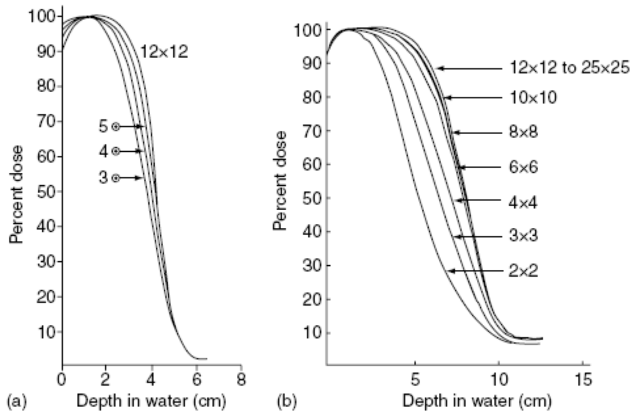
Detector correction factors

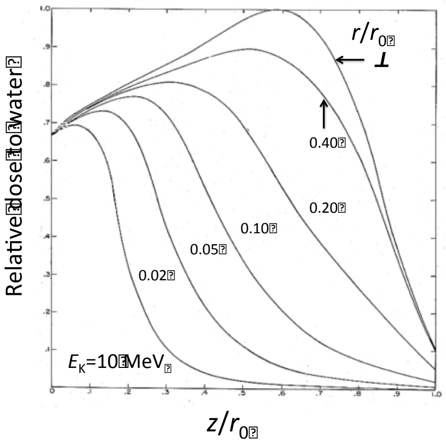
Lateral charged particle loss



A small field can be defined as a field with size smaller than the "lateral range" of charged particles

Lateral charged particle loss



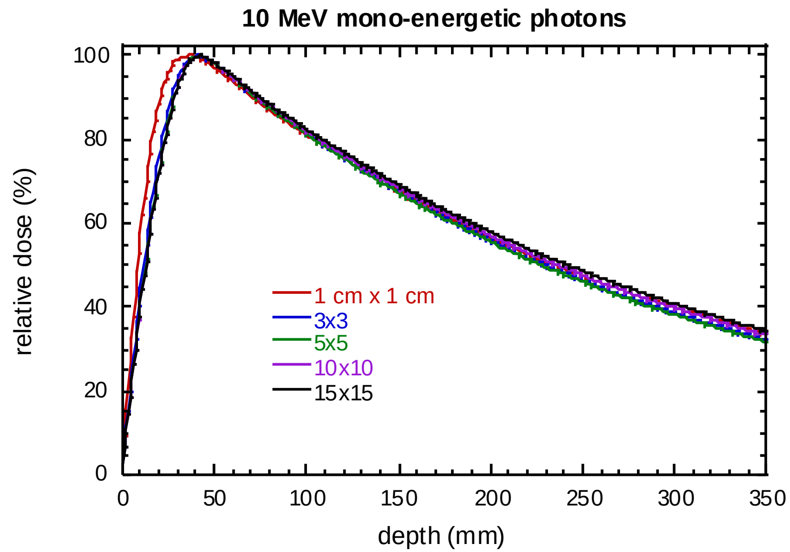


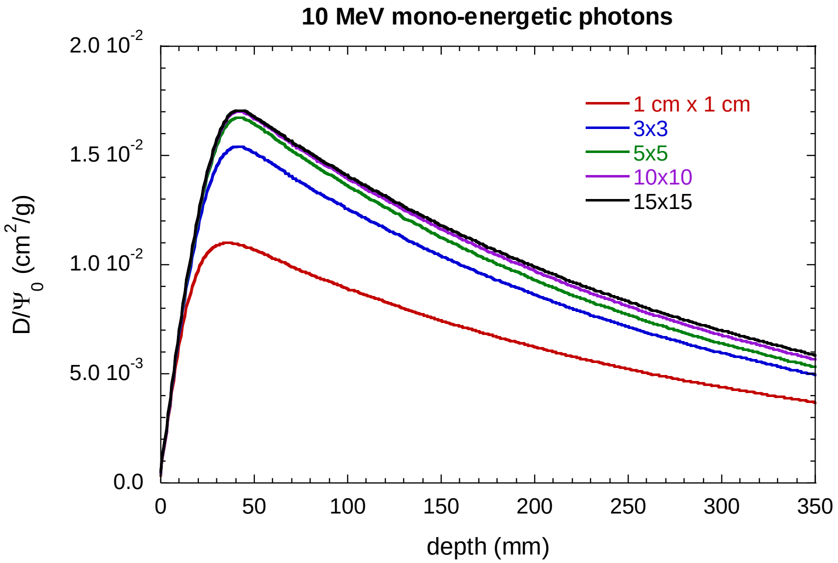
Berger and Seltzer (1982)

An electron beam can considered "wide" when its PDD is independent of the size of the field.
The transition to non-equilibrium conditions occurs at $r \approx r_0$ the CSDA range

Slide courtesy: P. Andreo

Lateral charged particle loss



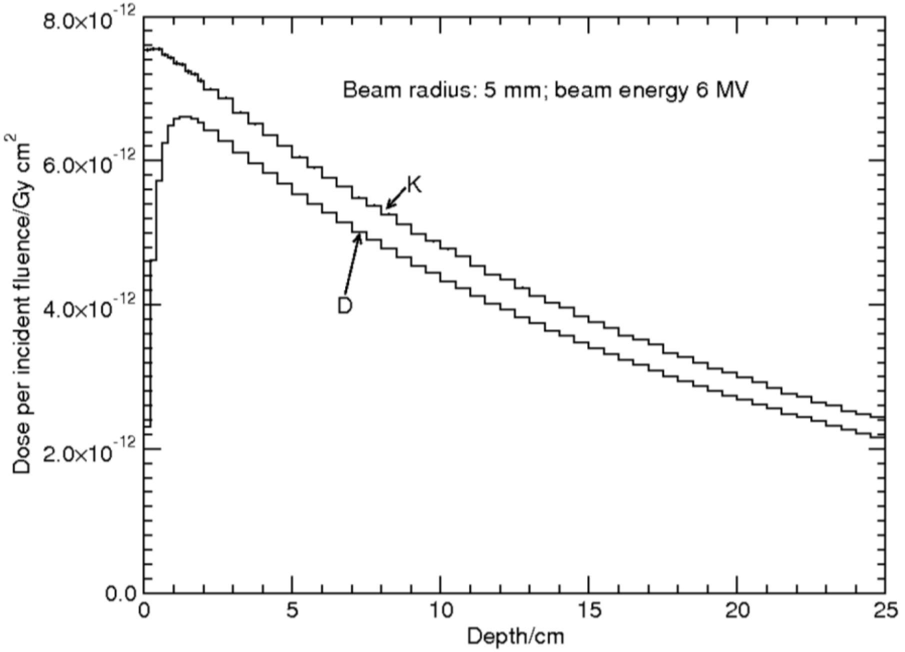


In photon beams the transition from TCPE to non-equilibrium a a function of field size is less abrupt.

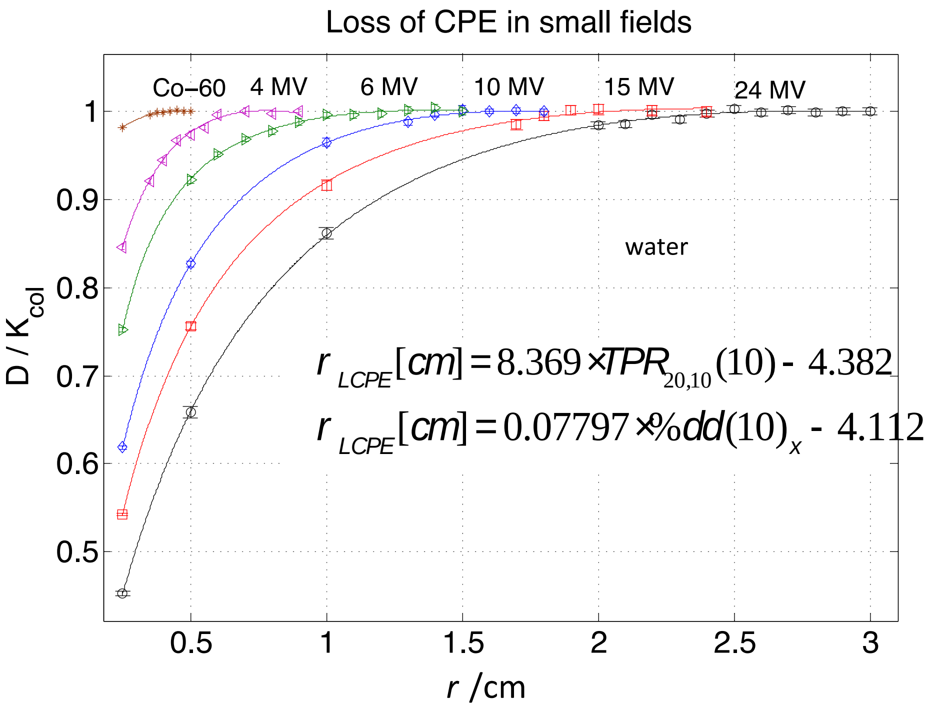
Slide courtesy: P. Andreo

McGill

Lateral charged particle loss



In small fields there is **no depth** at which D > K_{col}

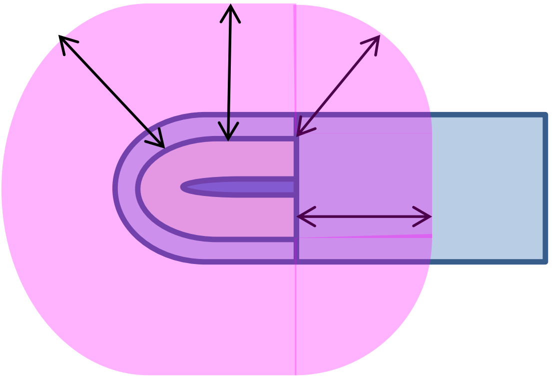


msr field versus small field

- *msr*: Largest possible reference field less than or equal to 10 x 10 cm² that can be realized on a machine and that is used for calibration $f_{\mathrm{msr}} \geq 2r_{\mathrm{LCPE}} + \Delta$
- Small field: one of the edges of the detector is less then a lateral charged particle equilibrium range (r_{LCPE}) away from the edge of the field

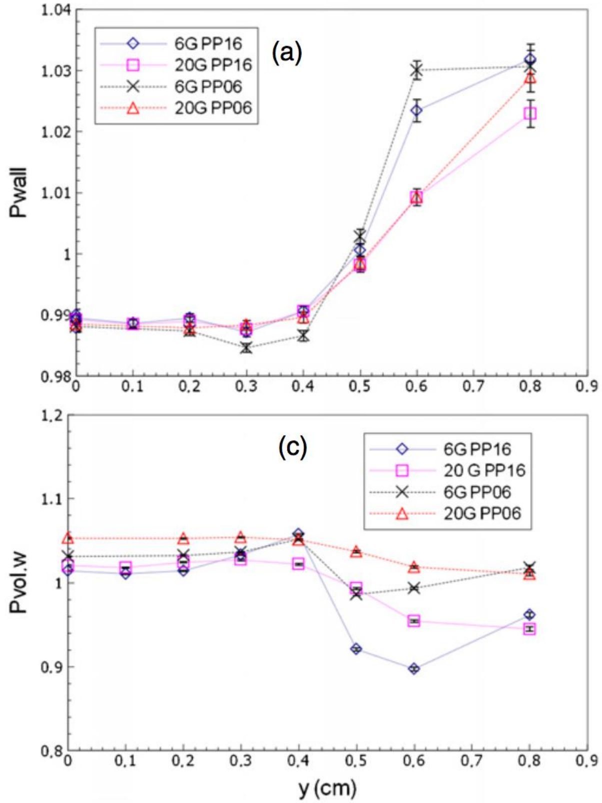
$$r_{LCPE}[cm] = 8.369 \times TPR_{20,10}(10) - 4.382$$

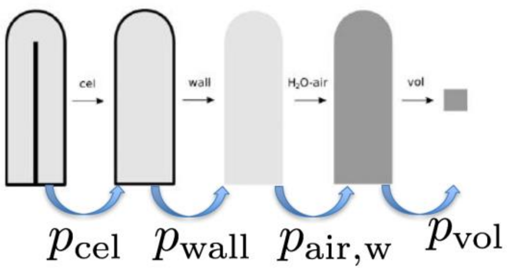
$$r_{LCPE}[cm] = 0.07797 \times \%dd(10)_x - 4.112$$



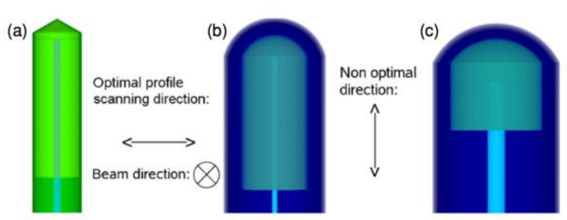
McGill

Detector response





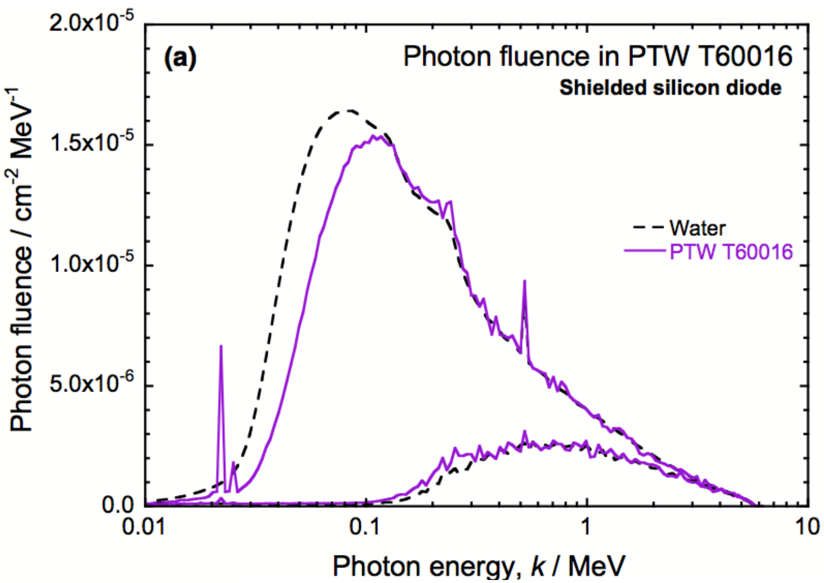
PP16 = 31016
PP06 = 31006

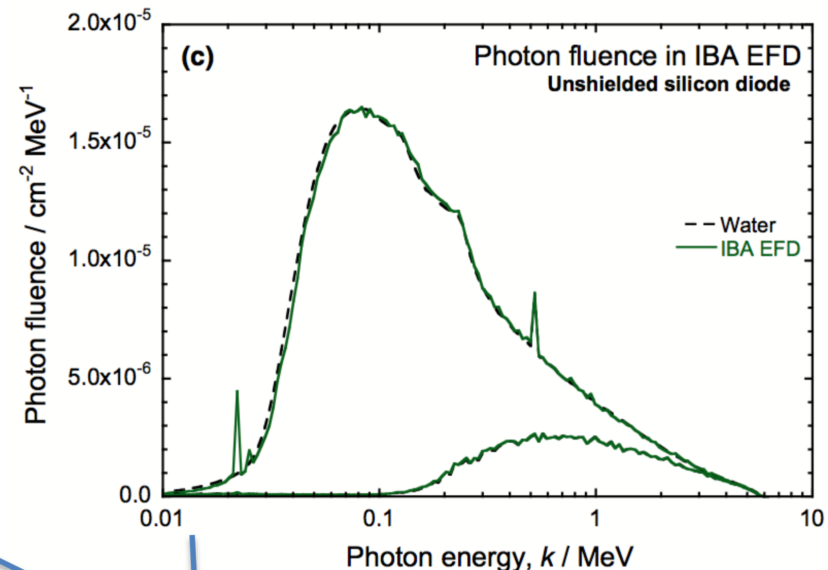


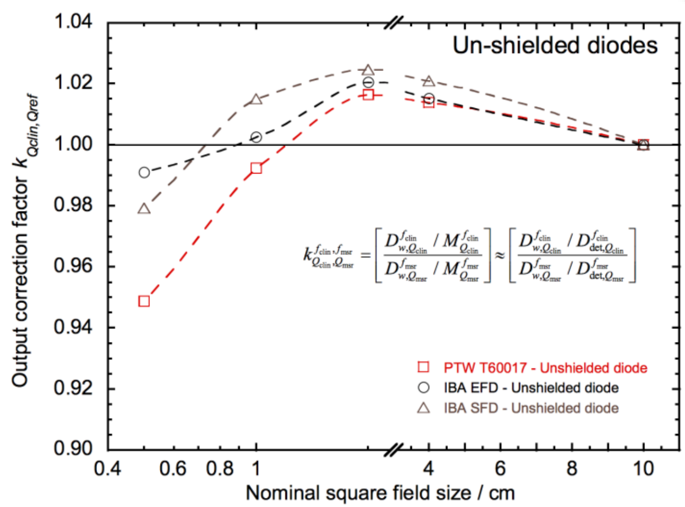
Crop et al 2009

McGill

Spectra inside detectors & response





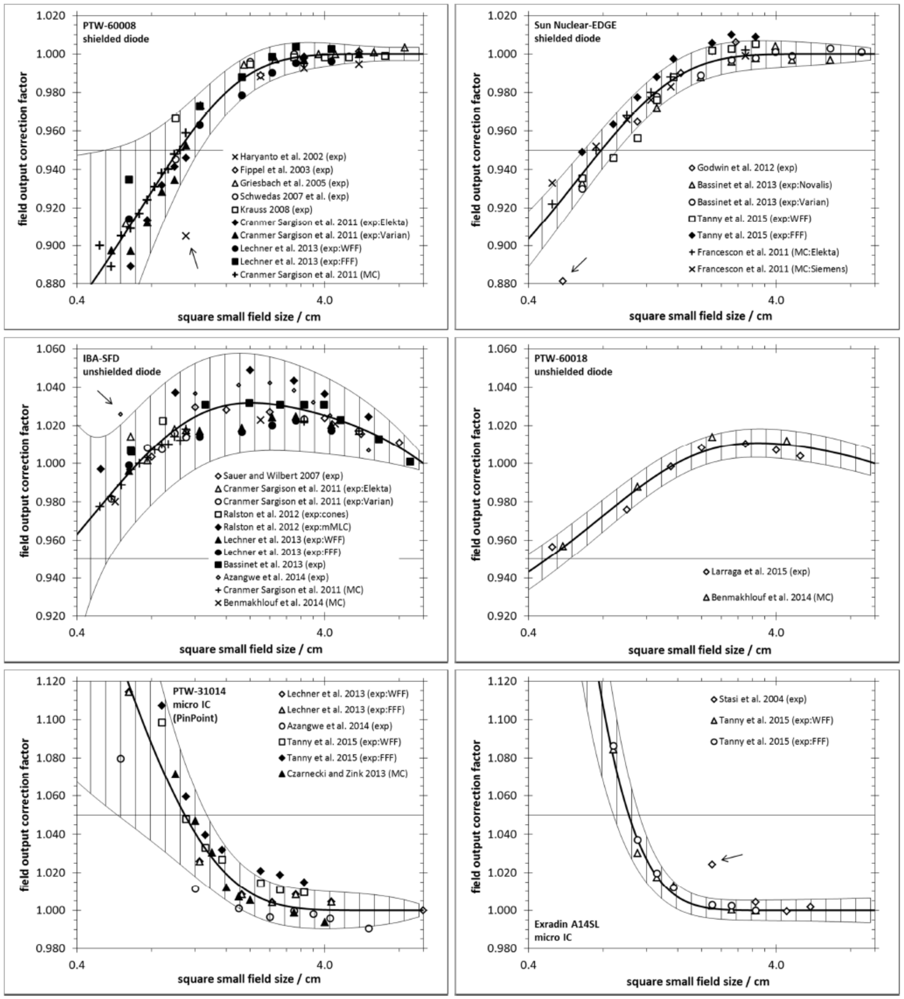


Benmakhlouf and Andreo, 2017

Benmakhlouf and Andreo, 2013

McGill

TRS 483 Small field output correction factors



Field size specification using FWHM inplane and crossplane!

ICRU Report 91 follows the TRS 483 recommendations for the measurement of output factors for small fields

Remarks:

1. Uncertainties are k=2
2. Corrections > 5% are not recommended

McGill

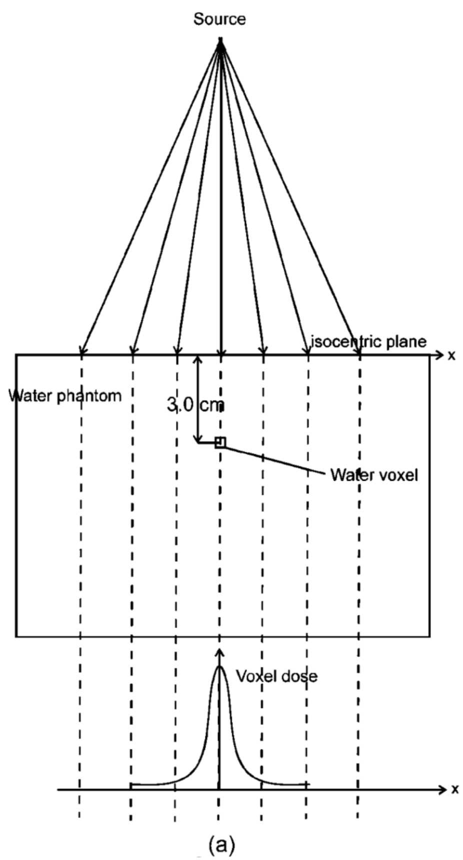
Questions post TRS-483 small field report

- More data is needed (phantoms, GammaKnife)
- Do we still need a calibration solution for modulated fields?
- Intermediate field calibration for machines that do not fulfill *msr* calibration conditions.

Related question

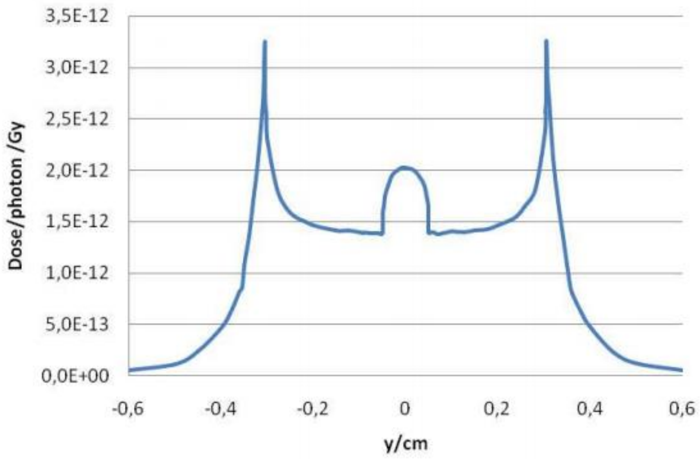
- Do we need alternative techniques to determine relative output?
- Do we need alternative techniques to calibration “sub-*msr*” fields?

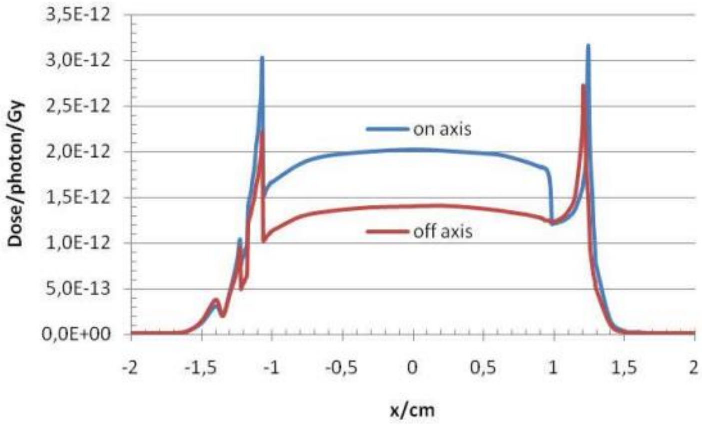
Insights gained using MC: Decomposing the detector response

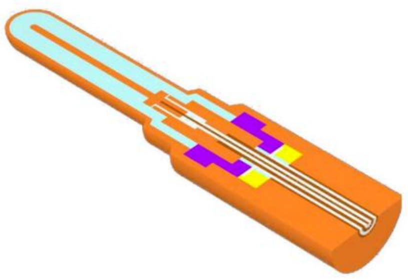


Bouchard and Seuntjens, 2004

Decomposing detector response





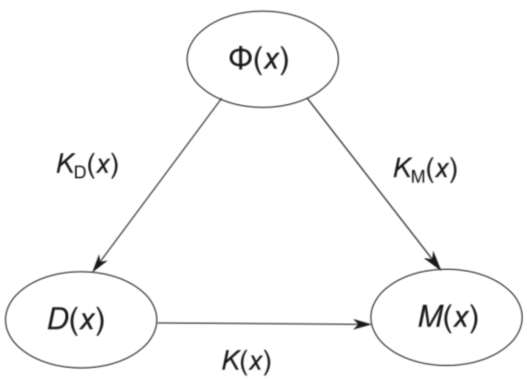


The “batman” mask

Tantot and Seuntjens, 2008

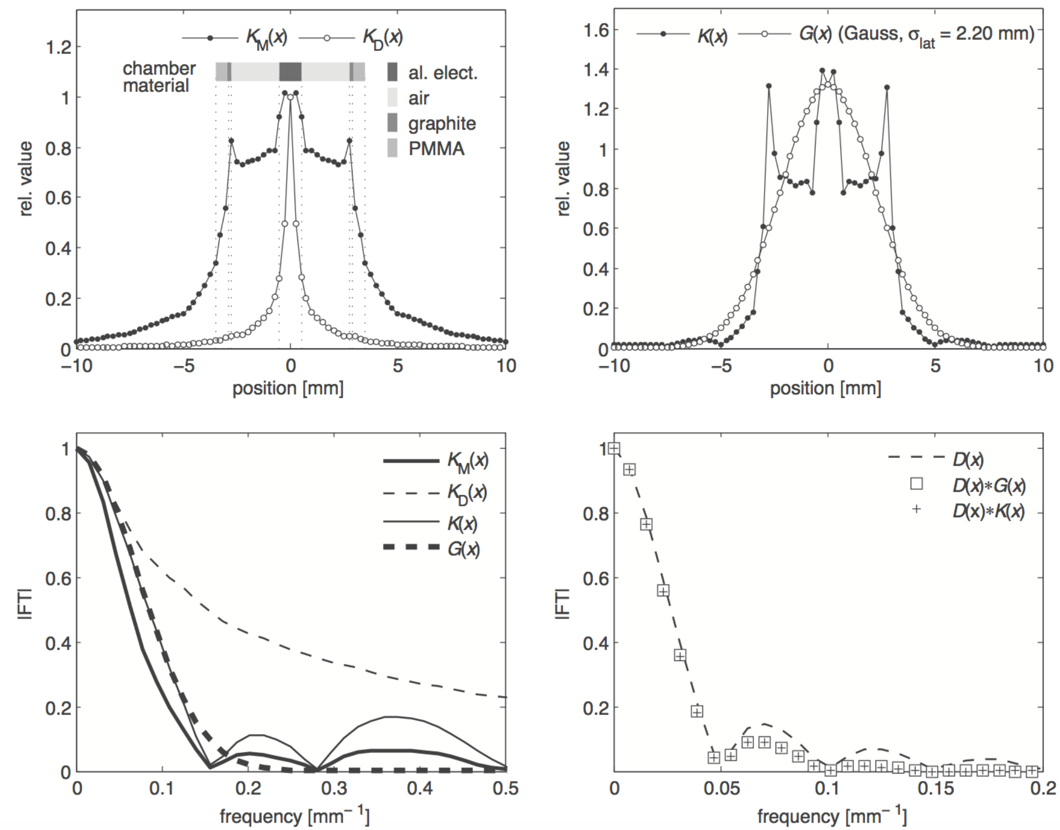
McGill

Decomposing the detector response

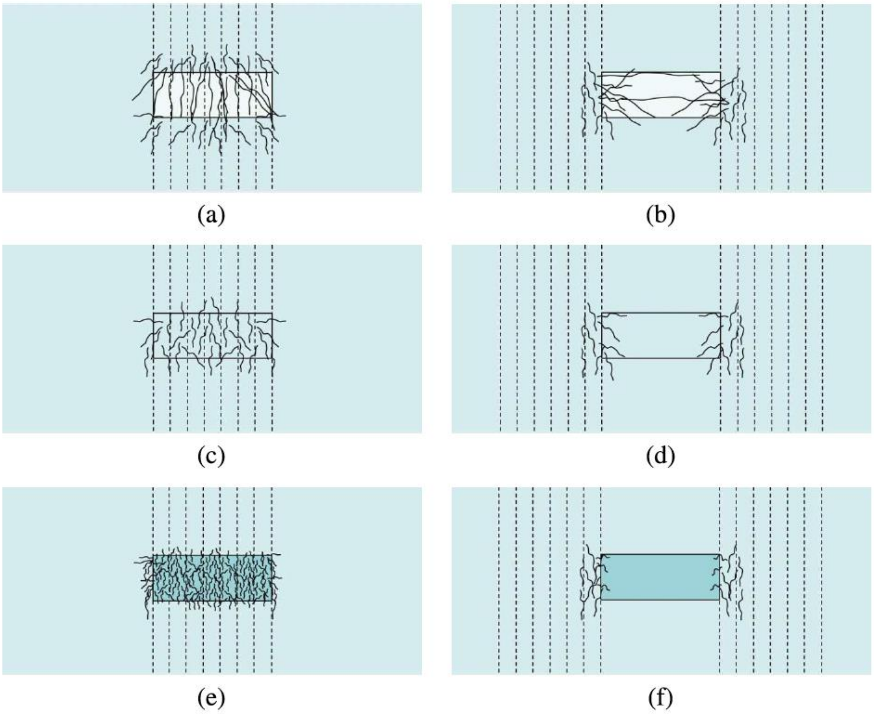


Looe et al, 2012

Gaussian kernels are a first order approximation



$$D_{\text{in}} \qquad\qquad D_{\text{out}}$$



Water vapour

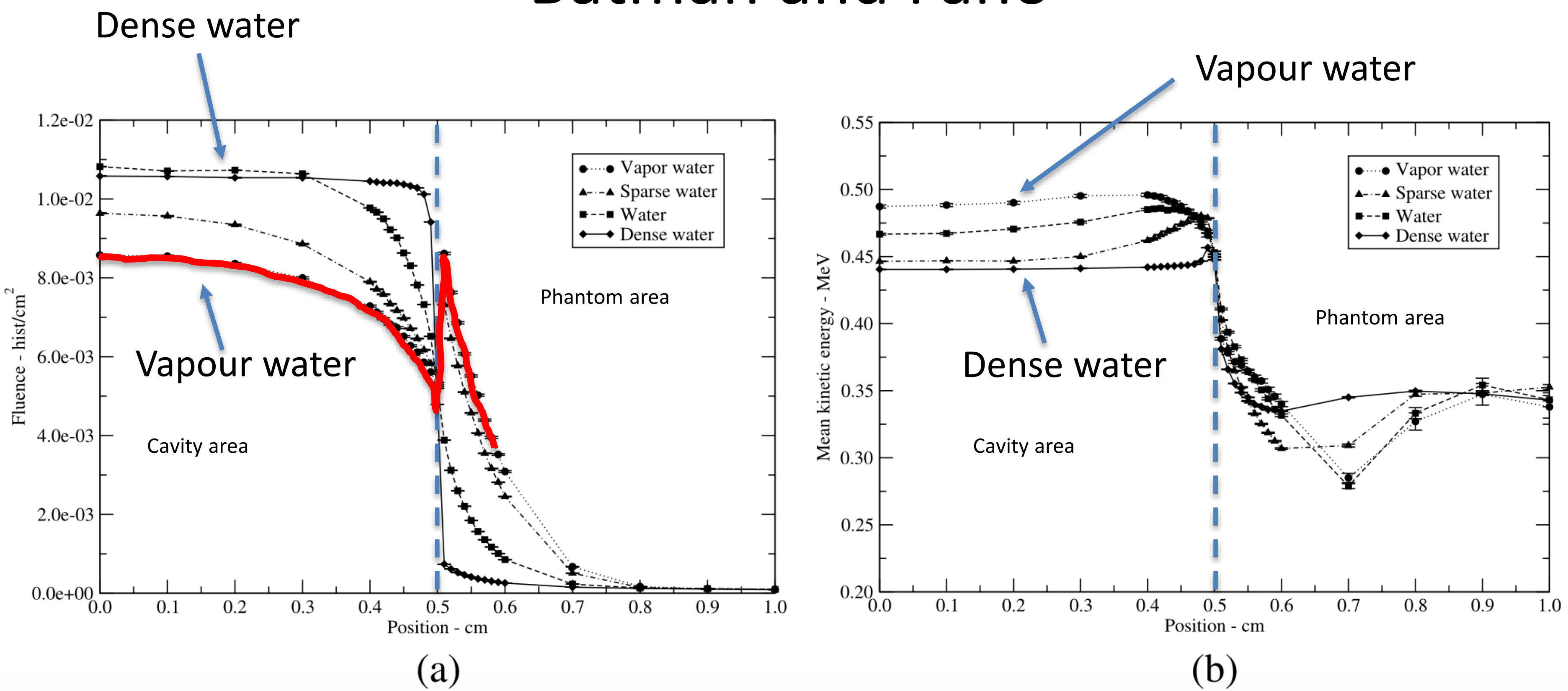
Liquid water

Dense water

$$\begin{aligned} D_{\text{cav}}^{\text{small field}} &= w_1 D_{\text{in}} + w_2 D_{\text{out}} \\ &= (w_1 - w_2) D_{\text{in}}(\rho) + w_2 D_{\text{Fano}} \end{aligned}$$

Bouchard et al 2015AB

Batman and Fano



Fluence function and mean kinetic energy in a 5 mm radius cavity filled with different densities under Fano conditions

E=1.25 MeV

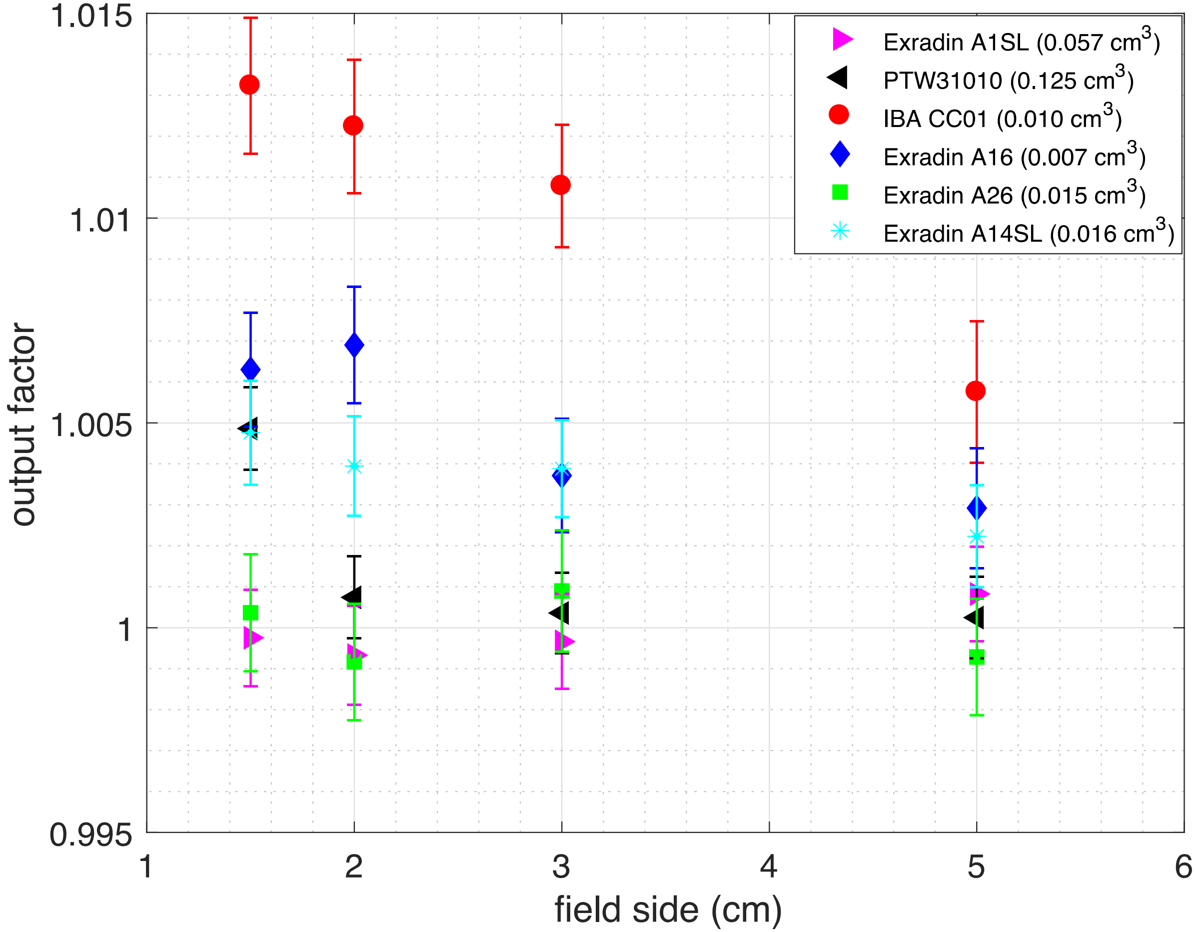
Bouchard et al 2015AB

Field sizes between *msr* and small

- The LCPE criterion is violated for field sizes below

$$2r_{\mathrm{LCPE}} + \Delta$$

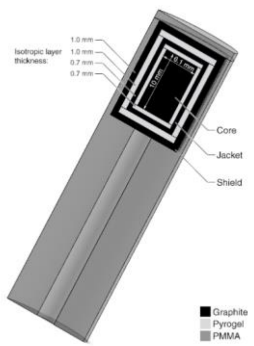
- For 6 MV and reference class chambers this limits the smallest *msr* field to be larger than ~ 4 cm
- New upcoming radiation equipment may/will not have calibration fields this large
- To what extent can we live with correction factors that start to contain some more significant perturbation effects?

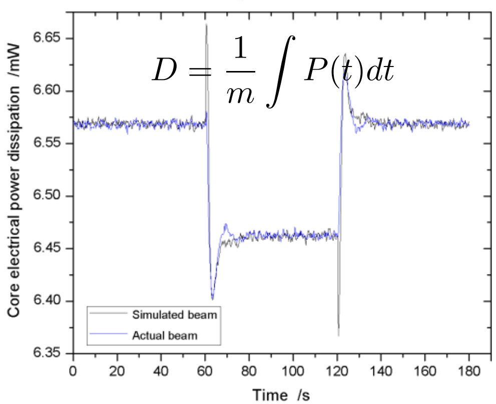


Preliminary Mirzakhanian et al, 2017

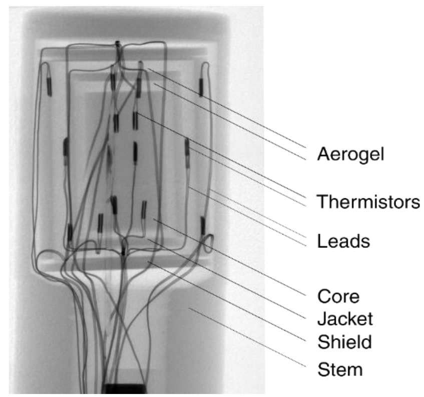
McGill

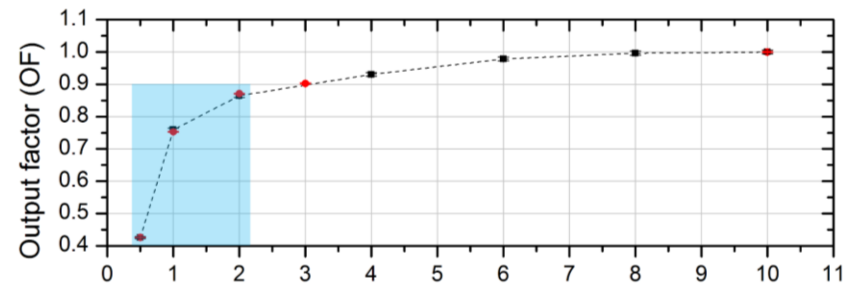
More advantageous reference detector?

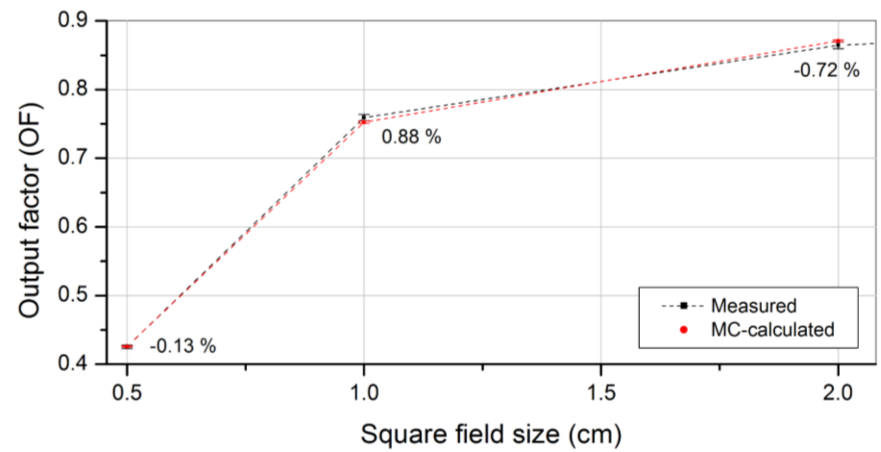




self-calibrate & self-check



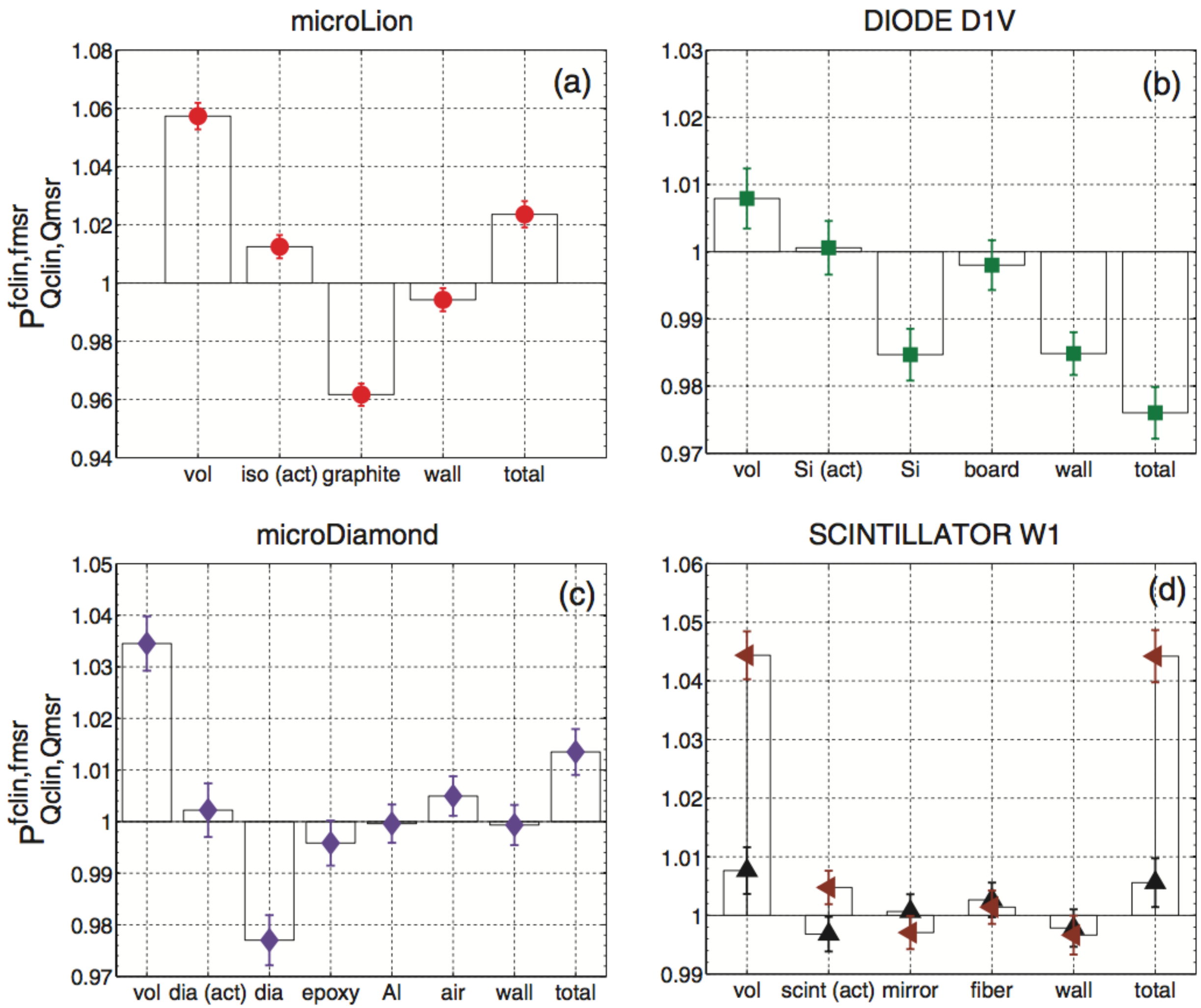




J. Renaud et al, 2017

McGill

Playing with compensated detector designs



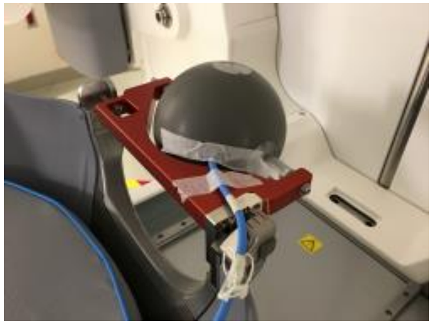
Other authors: Underwood et al and others

Papaconstadopoulos et al, 2014

GammaKnife calibration

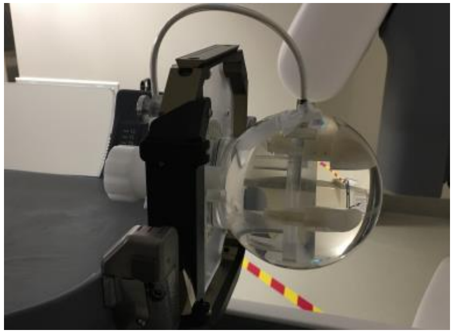
ABS parallel

ABS perpendicular

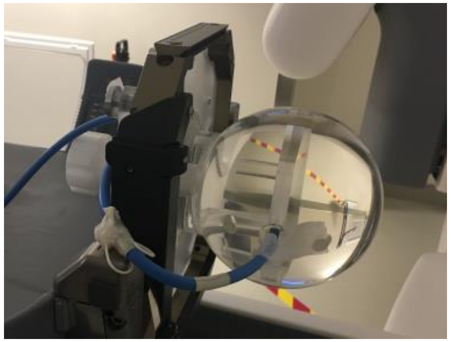


ABS 45^o

Solid Water



Lucy 0^o



Lucy 270^o

McGill

GammaKnife *msr* correction factors

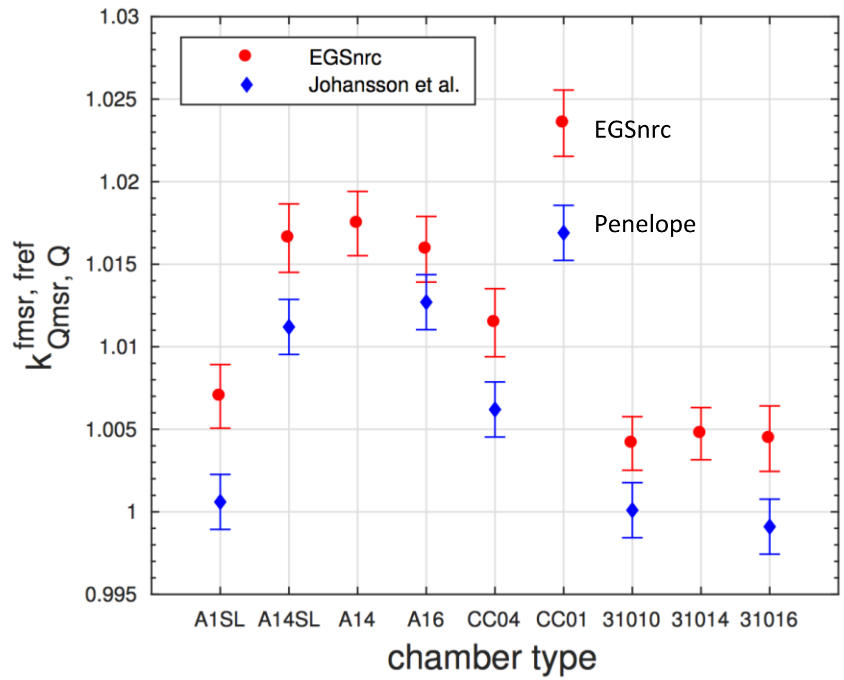
TABLE I. Chambers specifications used in this study.

chamber type	sensitive volume (cm^3)	cavity length (mm)	cavity radius (mm)	electrode material
Exradin A1SL[a]	0.057	5.7	2.1	C-552
Exradin A14SL[a]	0.016	2.1	2.1	C-552
Exradin A14[a]	0.016	2.0	2.0	C-552
Exradin A16[a]	0.007	1.7	1.2	C-552
IBA CC04[a]	0.040	3.6	2.0	C-552
IBA CC01[b]	0.010	3.6	1.0	Steel
PTW 31010[b]	0.125	6.5	2.8	Aluminium
PTW 31014[b]	0.015	5.0	1.0	Aluminium
PTW 31016[b]	0.016	2.9	1.45	Aluminium

[a] Chambers modeled in both codes: EGSnrc and PENELOPE

[b] Chambers modeled in EGSnrc

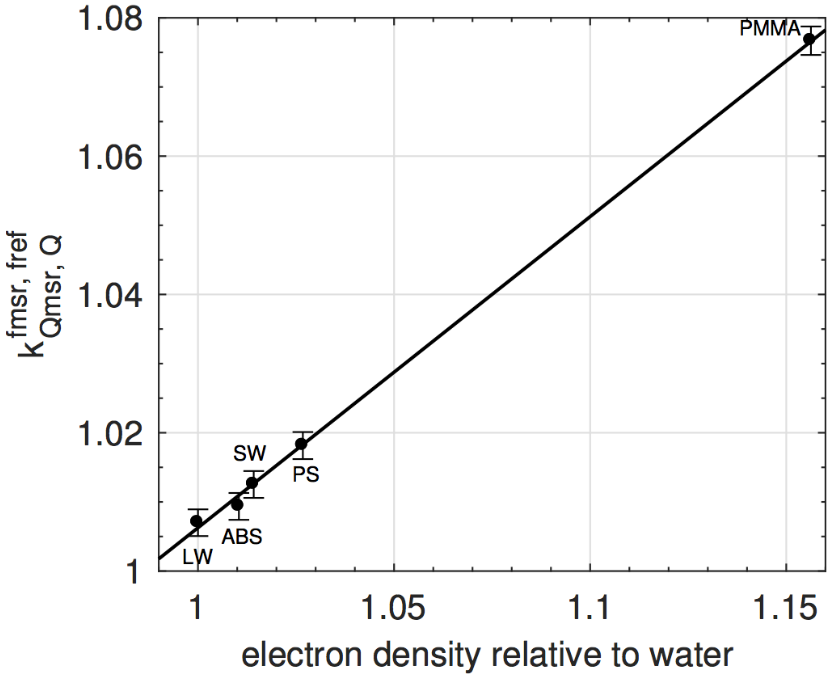
r_{LCPE} ~ 4 mm, for a 16 mm field we are close to *msr* limit for the largest chambers.



$$D^{f_{msr}}_{w,Q_{msr}} = M^{f_{msr}}_{Q_{msr}} \cdot N^{f_{ref}}_{D,w,Q_0} \cdot k^{f_{msr},f_{ref}}_{Q_{msr},Q_0}$$

Mirzakhanian et al, 2017

Phantoms of different plastics



chamber type	parallel $k'^{f_{msr},f_{ref}}_{Q_{msr},Q_0}$	parallel a	perpendicular $k'^{f_{msr},f_{ref}}_{Q_{msr},Q_0}$	perpendicular a
Exradin A1SL	1.0070	0.4499	1.0070	0.4234
Exradin A14SL	1.0166	0.4487	1.0105	0.4299
Exradin A14	1.0175	0.4599	1.0148	0.4259
Exradin A16	1.0159	0.4248	1.0174	0.4352
IBA CC04	1.0115	0.4316	1.0112	0.4263
IBA CC01	1.0235	0.4445	1.0354	0.4329
PTW 31010	0.9976	0.4082	1.0307	0.4421
PTW 31014	0.9986	0.4280	1.0169	0.4327
PTW 31016	1.0044	0.4340	1.0072	0.4387

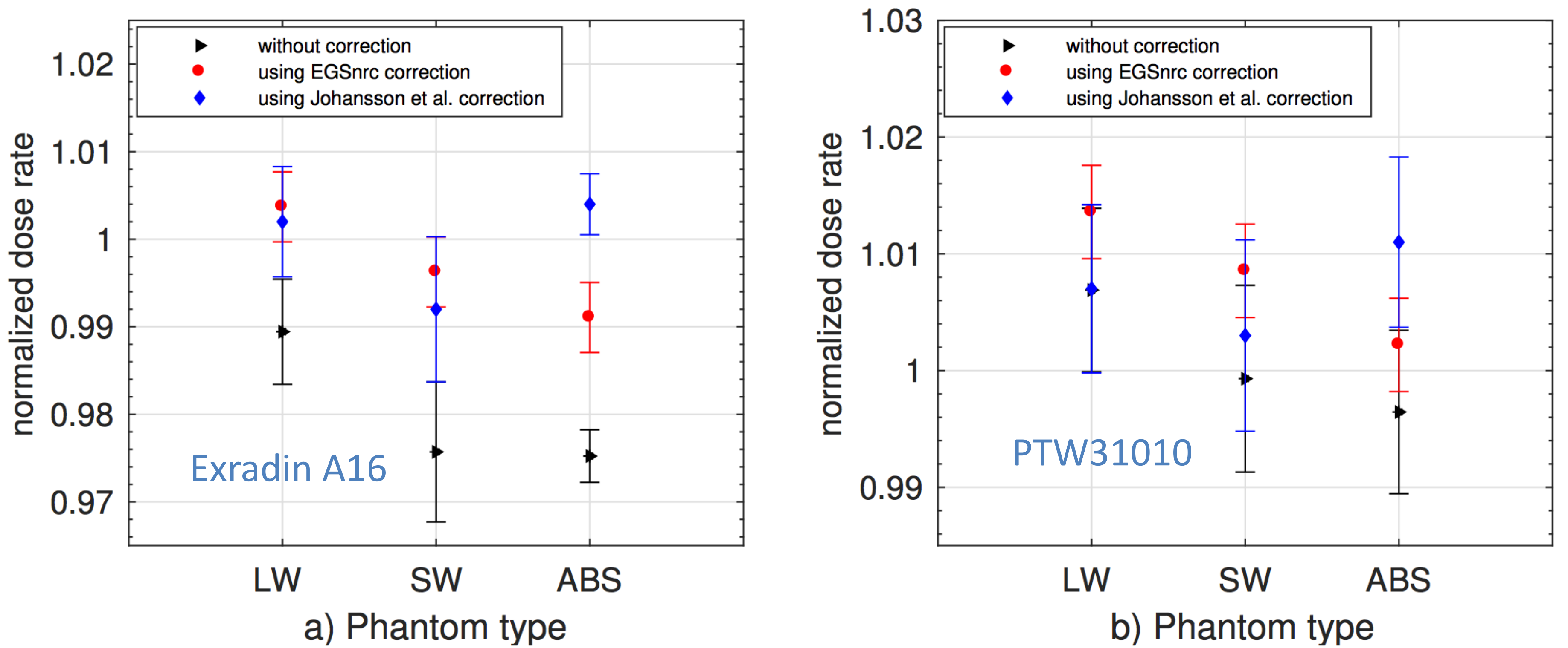
$$k^{f_{msr},f_{ref}}_{Q_{msr},Q_0} = (\rho_e^{rel} - 1)a_{ch} + k'^{f_{msr},f_{ref}}_{Q_{msr},Q_0}$$

Single global fit to all phantom e-density dependence, *b*=0.4285±2.5%

$$k^{f_{msr},f_{ref}}_{Q_{msr},Q_0} = k'^{f_{msr},f_{ref}}_{Q_{msr},Q_0} k^{w,\mathrm{plastic}}_{Q_{msr}} = k'^{f_{msr},f_{ref}}_{Q_{msr},Q_0}[(\rho_e^{rel} - 1)b + 1]$$

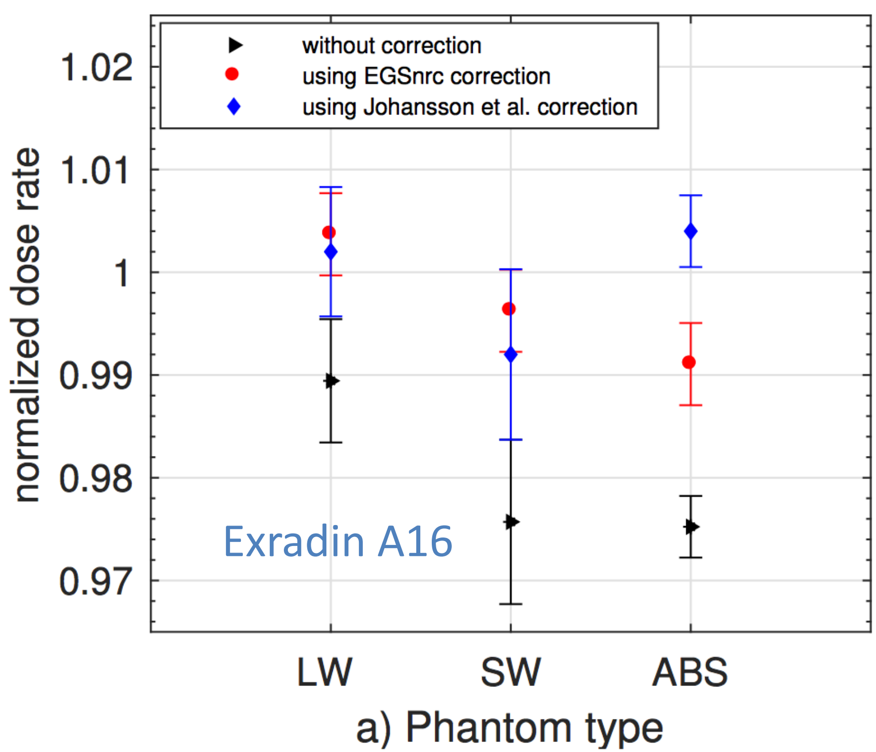
Mirzakhanian et al, 2017

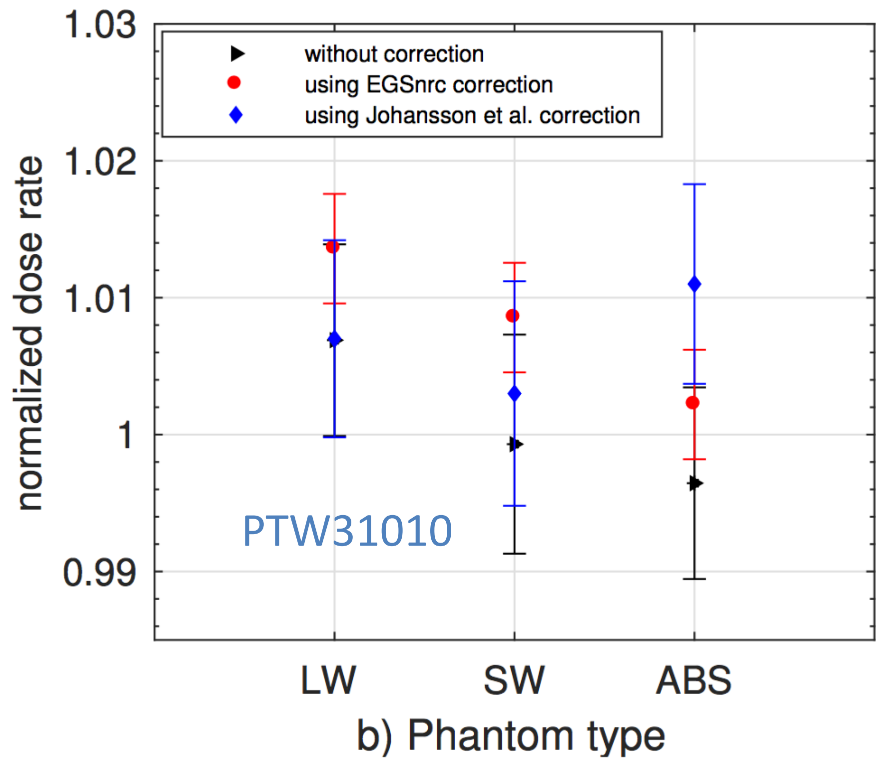
McGill



Consistency of intercomparison improves from 1.29% to 0.59%

Mirzakhanian et al, 2017

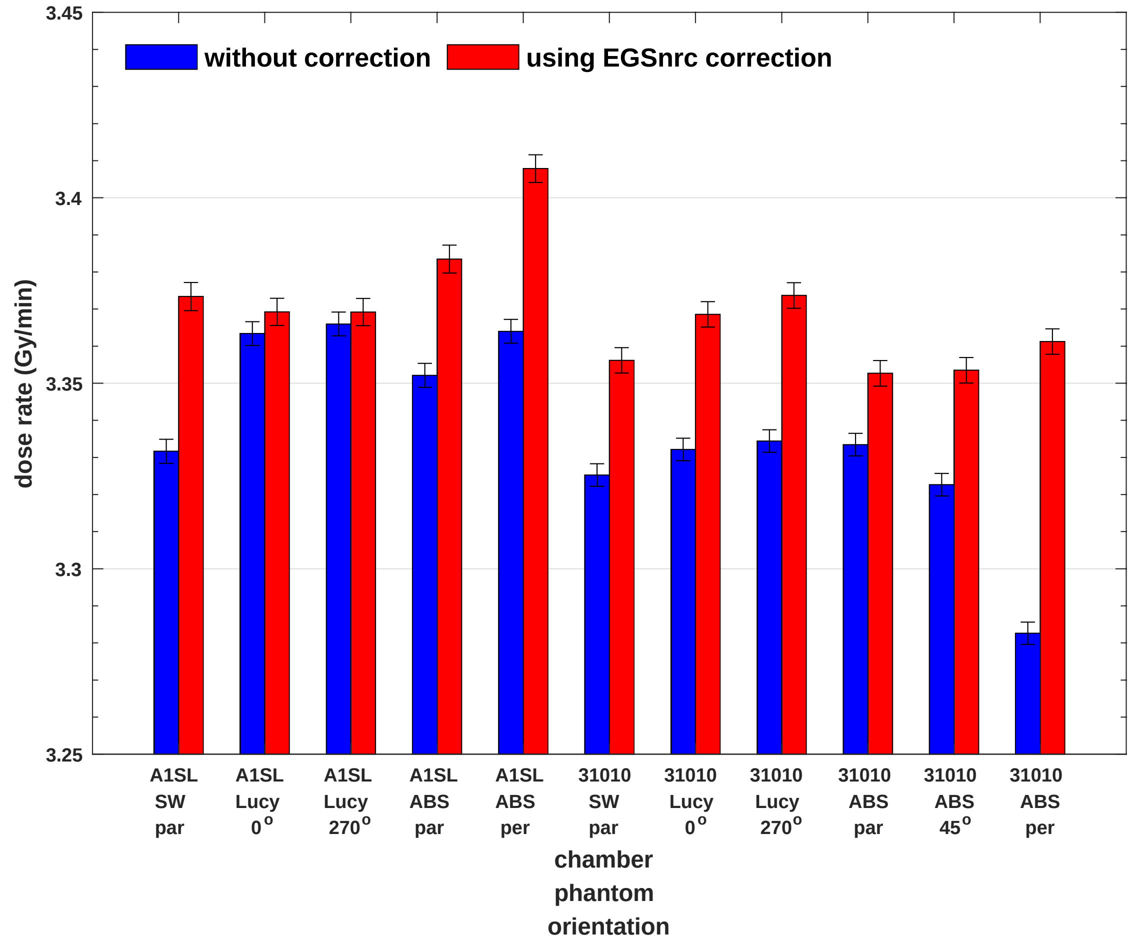




Consistency of intercomparison improves from 1.29% to 0.59%

Mirzakhanian et al, 2017

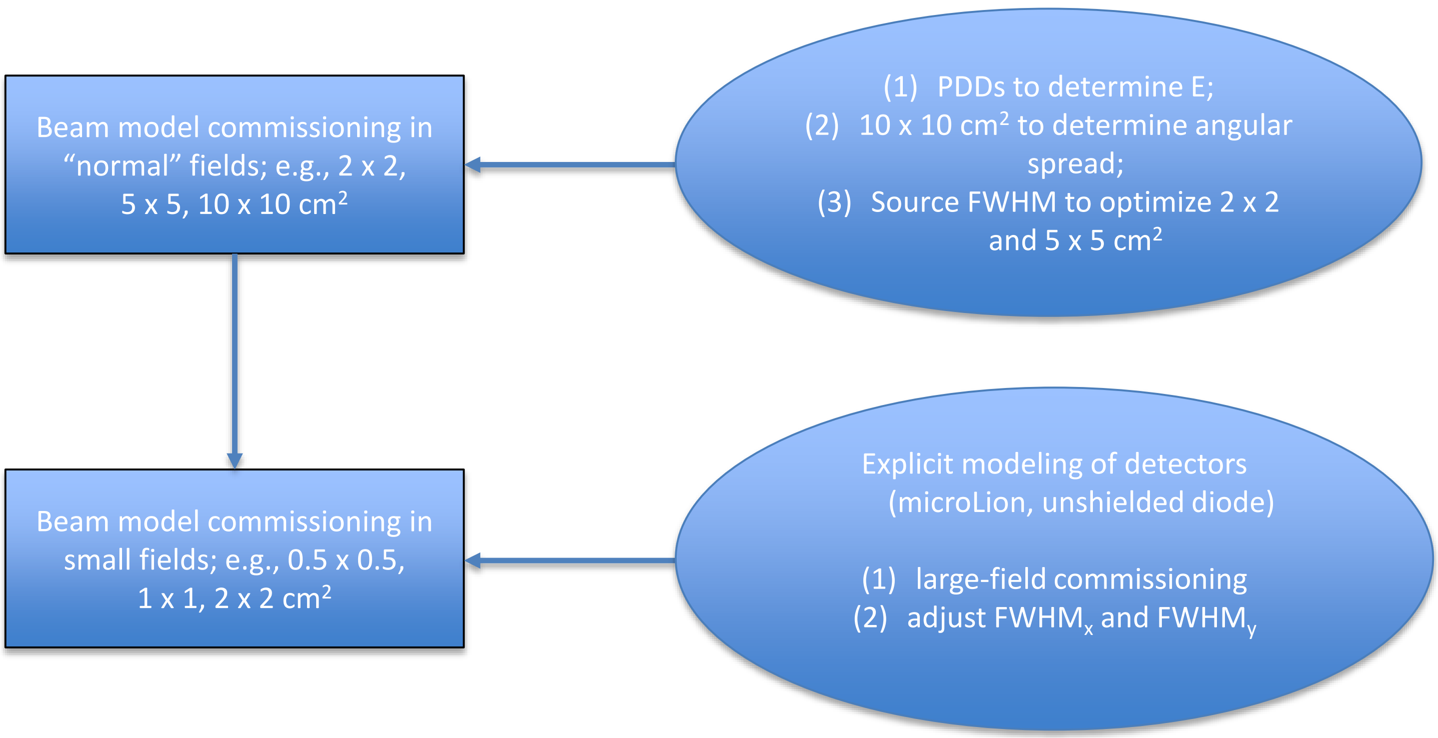
GammaKnife correction factors



Measurements at the Sunnybrook ICON system

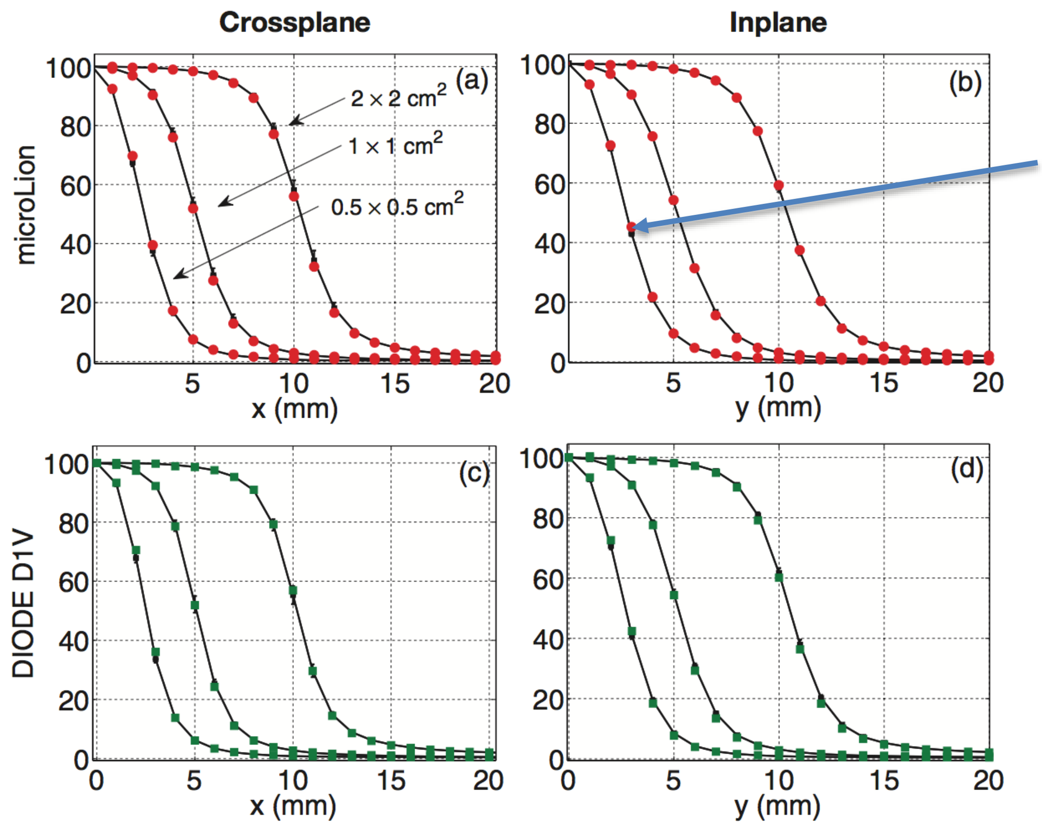
Mirzakhanian et al, 2018

MC beam model commissioning small fields



There is a strong coupling between detector used and optimized MC model parameters

Beam model commissioning small fields

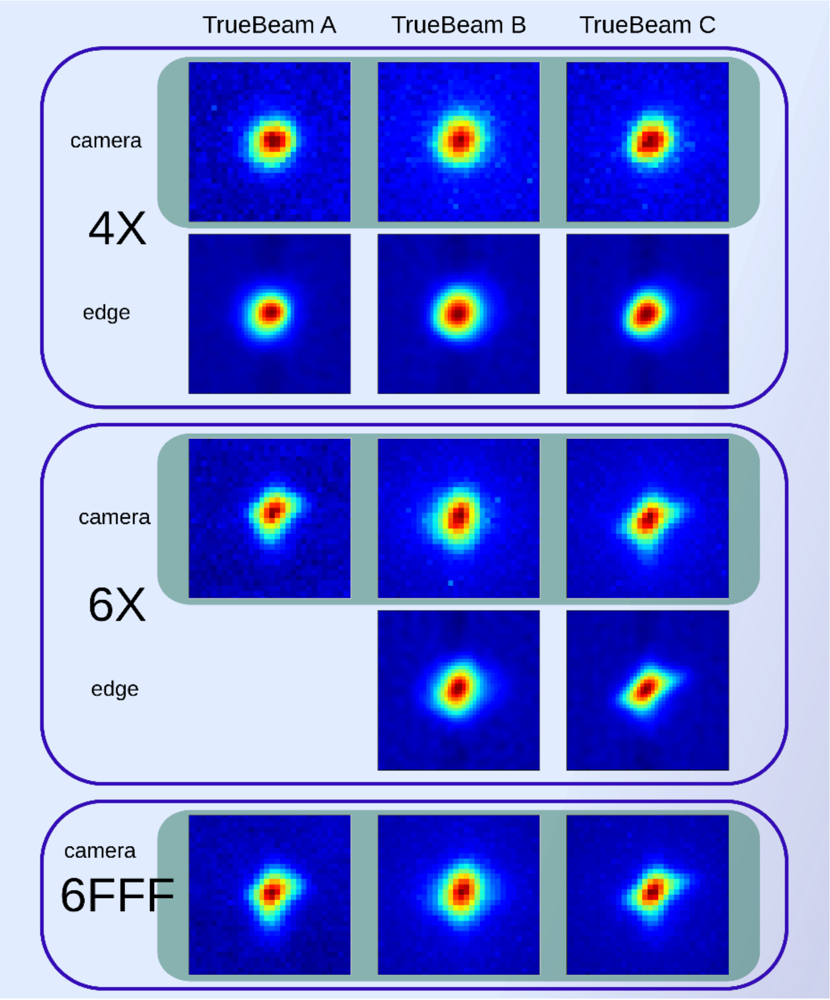


Multiple measurements, multiple collimation setting

Papaconstadopoulos et al 2015

McGill

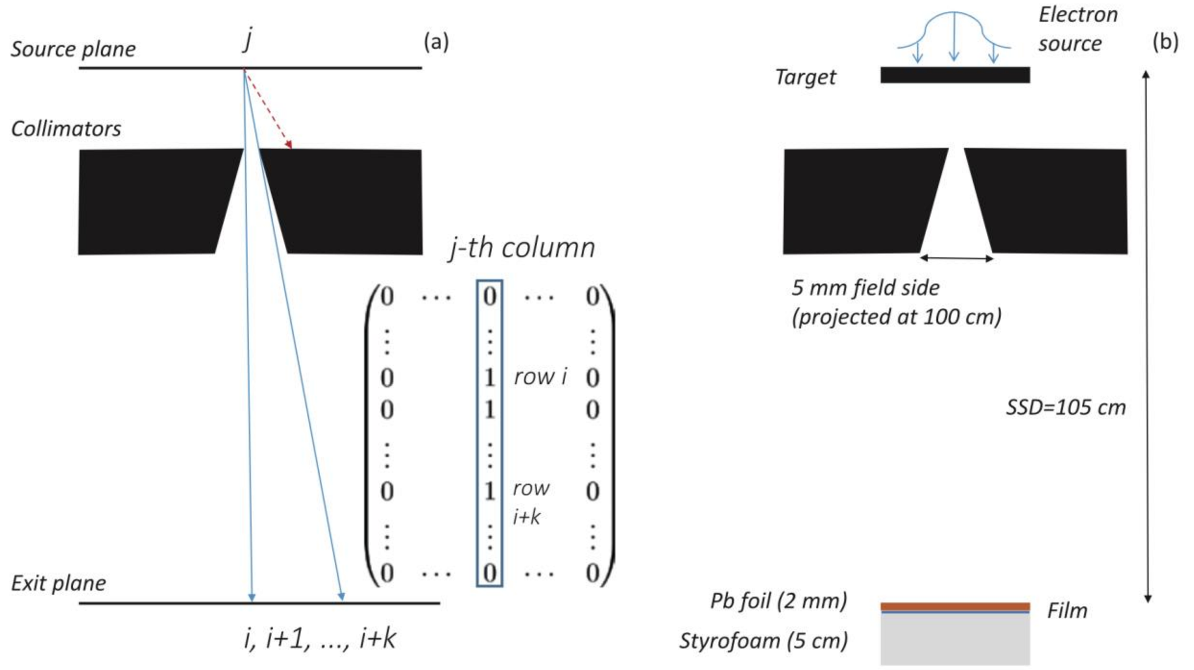
Beam models suitable for SRT planning algorithms are accelerator spot size dependent



Variability in source intensity distribution. Spot sizes range between 2.5 mm and 4.6 mm and the typical spot size is also not perfectly circular

Sawkey et al, 2012

Linac source size and occlusion

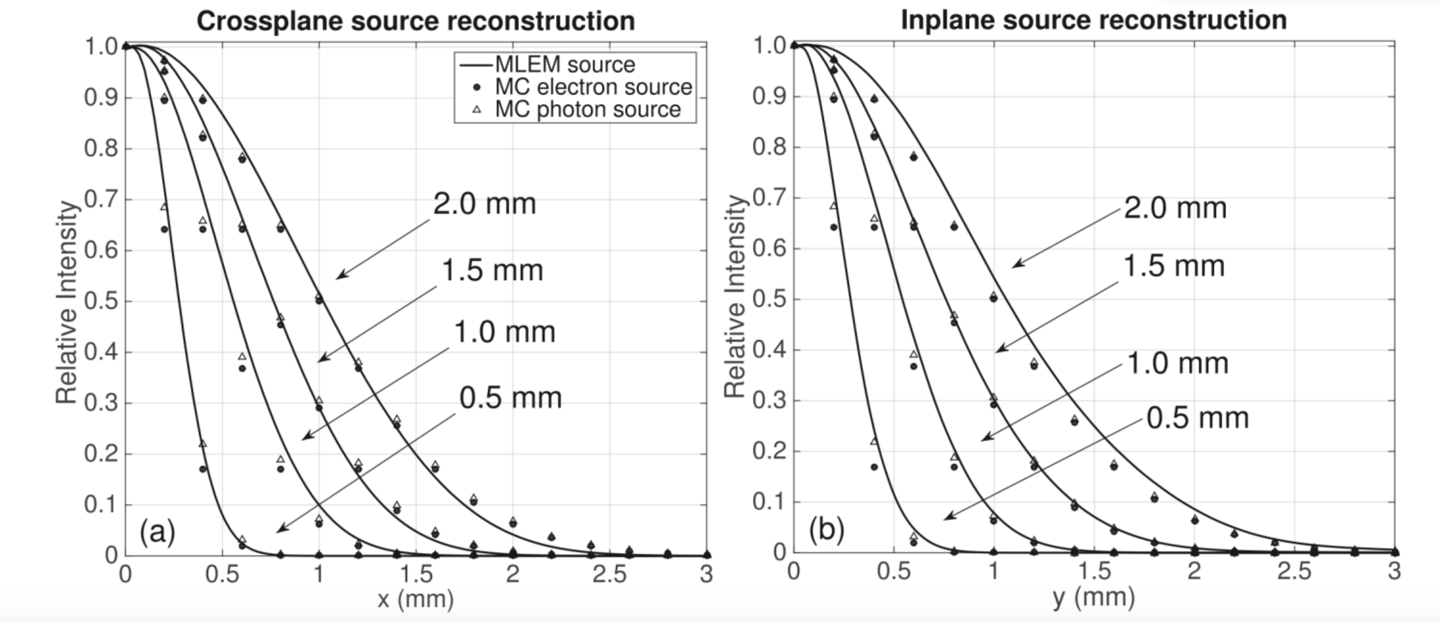


maximum-likelihood expectation-maximization algorithm

$$\varphi^{\mathrm{new}} = \frac{\varphi}{\mathbf{A}^T \mathbf{1}} \mathbf{A}^T \frac{\mathbf{m}}{\mathbf{A}\varphi},$$

Papaconstadopoulos et al 2016

Internal consistency- MLEM vs. MC



Papaconstadopoulos et al 2016

MC versus MLEM on Novalis Tx

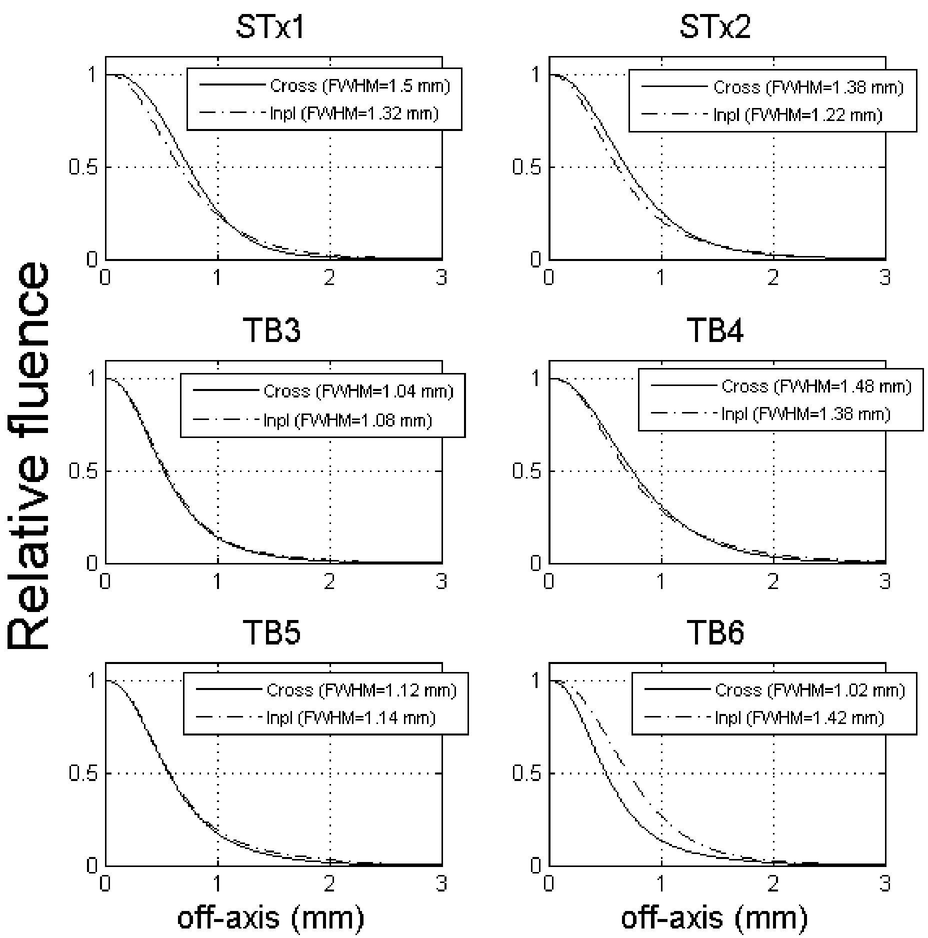
Table 3. FWHM and FWTM values of the reconstructed source using the film profile measurements, the MC electron source (incident on the target) and the photon source (at 0.2 mm depth in the target) as determined during model commissioning.

		$FWHM_x$ (mm)	$FWTM_x$ (mm)	$FWHM_y$ (mm)	$FWTM_y$ (mm)
Detailed MC commissioning	e^- source	1.25	2.26	1.10	2.00
	γ source	1.28	2.32	1.13	2.04
MLEM	rec source	1.22	2.29	1.21	2.32
	σ_{total} (rec source)	0.12	0.27	0.11	0.20
	σ_{jaw} (rec source)	0.11	0.21	0.10	0.15
	σ_{exp} (rec source)	0.03	0.12	0.04	0.11
	σ_{psf} (rec source)	0.04	0.16	0.01	0.07

Note: The total and component uncertainties of the reconstruction are presented at the 1 σ level.

Papaconstadopoulos et al 2016

Linac source size variation

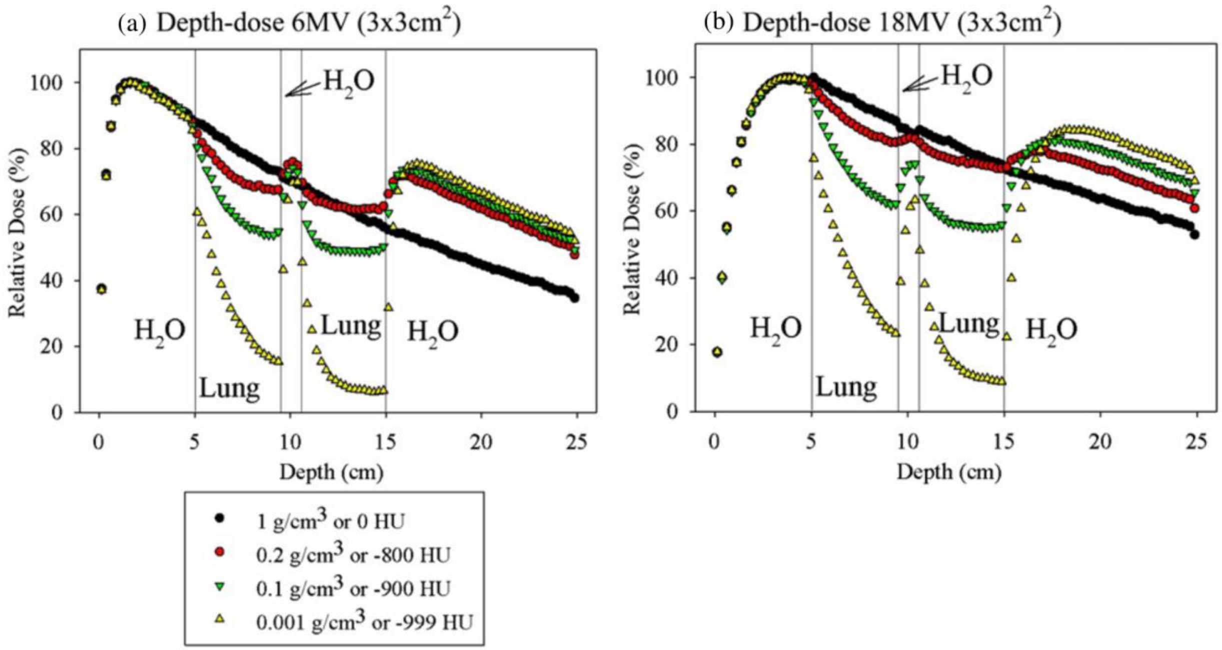


- Source size measurements with simple methods
- Measurement-less small-field output factor prediction
- Variations from accelerator to accelerator

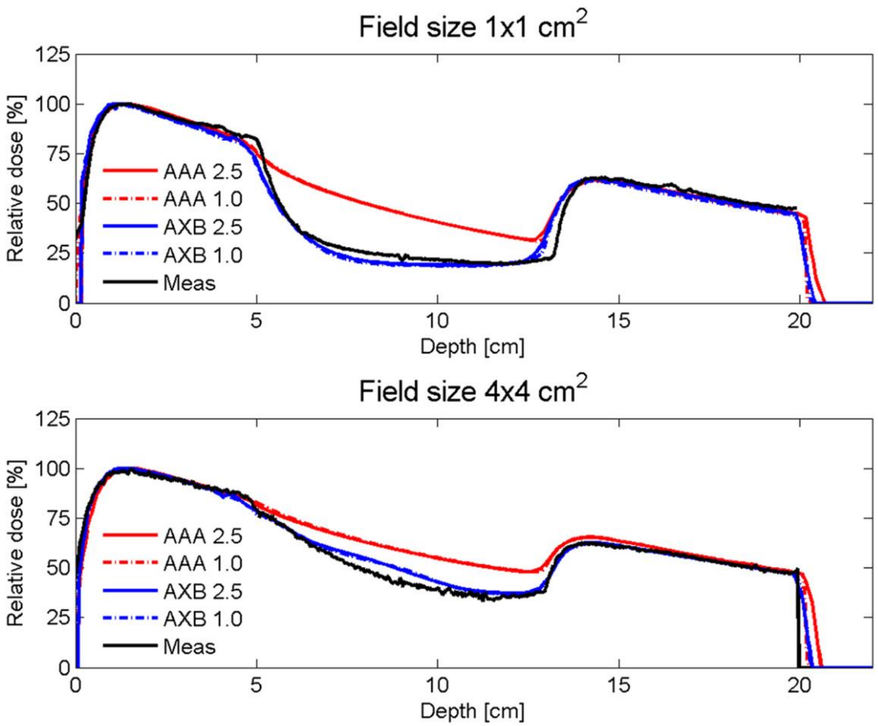
Papaconstadopoulos et al 2018

Treatment Planning Algorithms – small fields

- Factor based
  - Successfully used in cranial SRS
- Model based
  - Beam model
    - coupled angular - energy distribution of a representative set of particles in the beam (photons and contamination particles)
    - Source parameters - TPS parameterizes the source size – impact on dose calculation accuracy
    - Collimation system - Backup collimation, alignment of different collimation systems
  - Patient model
    - Type a (or category 1)
      - equivalent path-length scaling for inhomogeneity corrections
    - Type b (or category 2)
      - changes in lateral electron transport are considered in some fashion
      - Advanced type-b: MC or deterministic transport algorithms

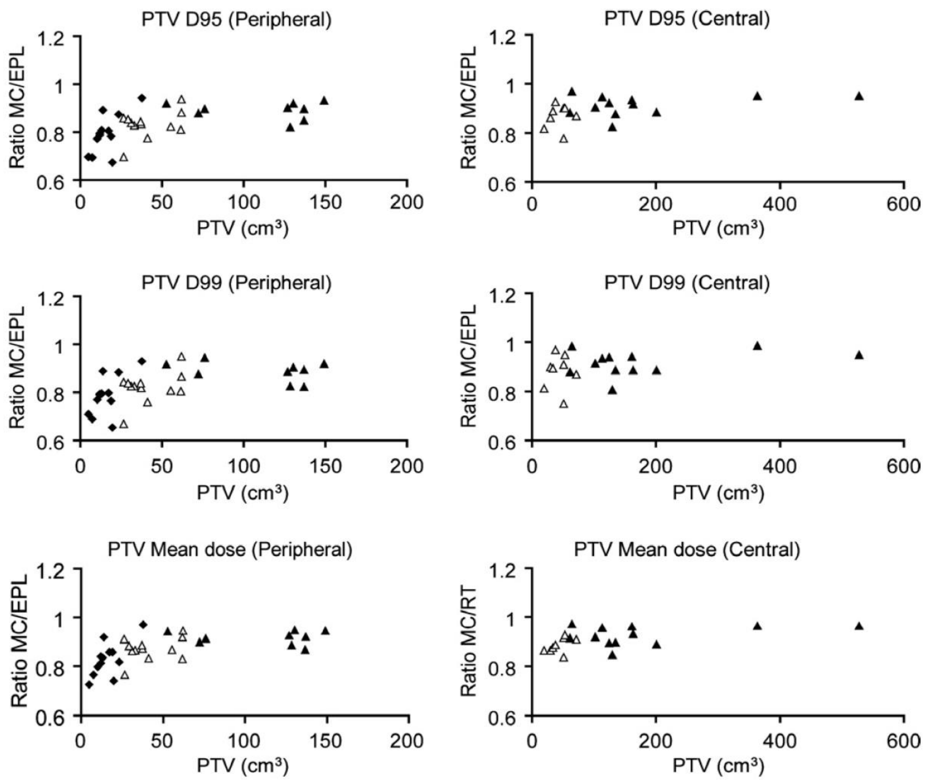


Monte Carlo-calculated central-axis depth-dose profiles for a lung slab phantom geometry irradiated by a 6 MV and a 18 MV beam (3 x 3 cm^2 field size) with a 1 × 1 × 1 cm^3 tumour embedded in the lung, with decreasing lung slab density. Disher, *et al.*, 2012

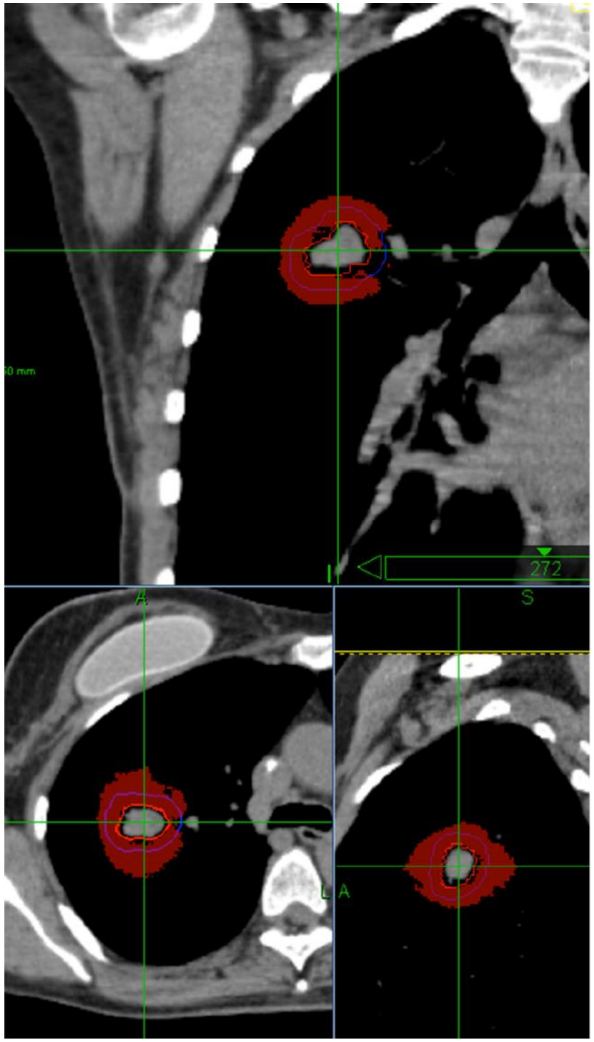


Comparison of category 2 algorithms AAA and Acuros XB (AXB, Varian) calculated with measured percentage depth doses for field sizes of 1 x 1 cm^2 and 4 x 4 cm^2. The phantom consists of foam, with a low-density $\rho = 0.03$ g cm^{-3} and a thickness of 8 cm sandwiched between two layers of polystyrene with a density of $\rho = 1.05$ g cm^{-3}. Kroon, *et al.*, 2013

Considerations for Clinical Prescription Using Category 2 Dose Calculation Algorithms in Small Fields



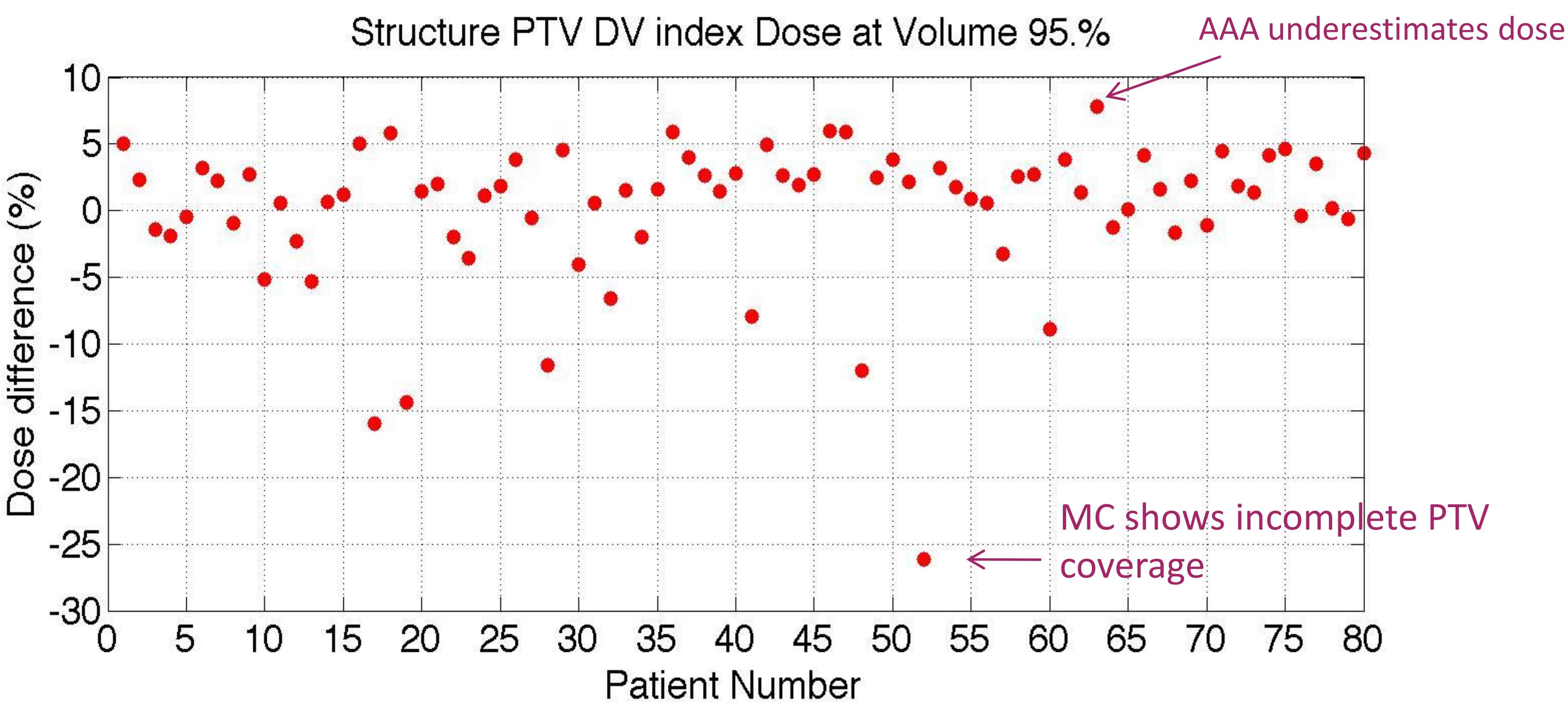
Ratio of MC and EPL calculated PTV $D_{95\,\%}$, $D_{99\,\%}$ and mean dose for peripheral and central pulmonary tumors. Bold diamonds represent tumors <3 cm, open triangles represent tumors of 3–5 cm and bold triangles represent tumors >5 cm. Data is for the CyberKnife 6 MV beam. [van der Voort van Zyp, *et al.*, 2010]).



Region of dose difference exceeding 15 Gy outside the GTV, between equivalent path length correction (EPL) and Monte Carlo for CyberKnife (6 MV) treatments of a tumor with size 3.6 cm^3. Dose prescribed 60 Gy. (Lacornerie, *et al.*, 2014)

--> ICRU Report 91 mandates the use of advanced type b model-based dose calculation algorithms (Monte Carlo, etc)

Large scale lung SBRT dose calculations



- Positive results indicate the dose is underestimated by AAA
- Negative results indicate the PTV coverage is overestimated by AAA
- Range: +8% to -26%

E. Soisson et al 2012

Why do we care?

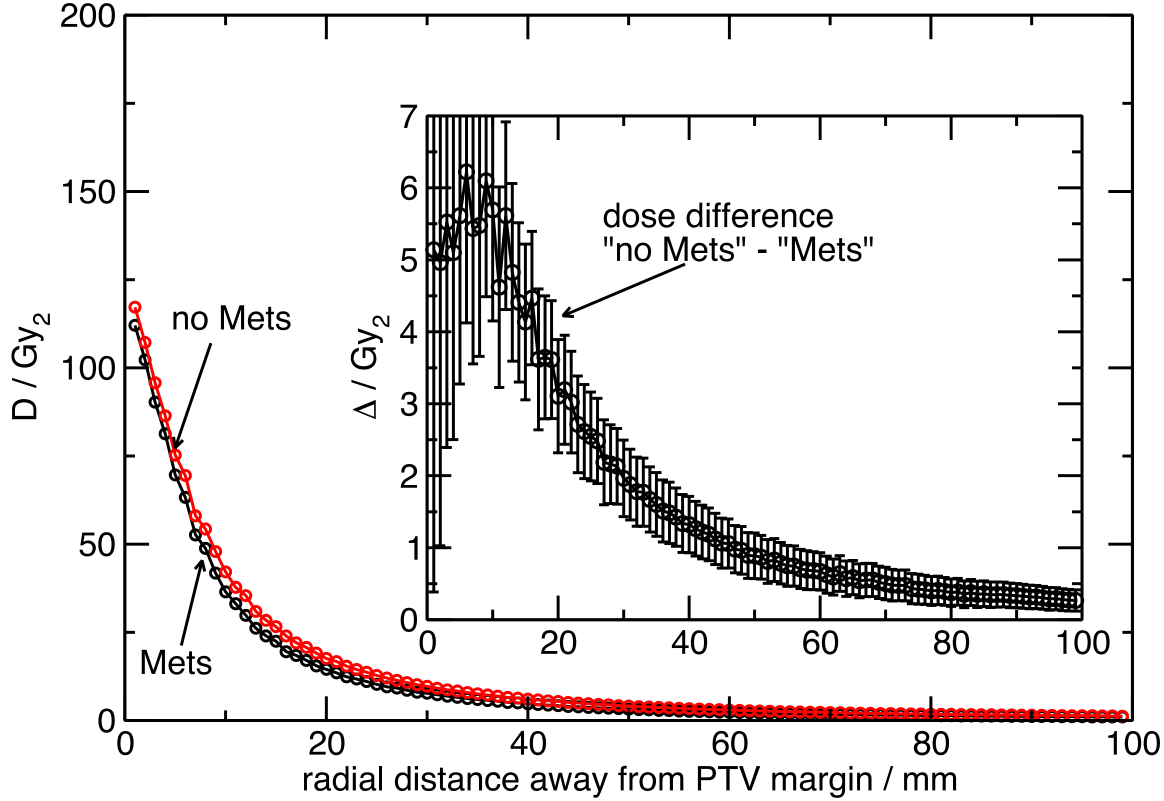
- 217 primary stage I non-small cell lung cancer (NSCLC) treated using SBRT between 2011 and 2015
- 37 pts developed distant metastases; median follow-up time 24 months
- 2 institutions

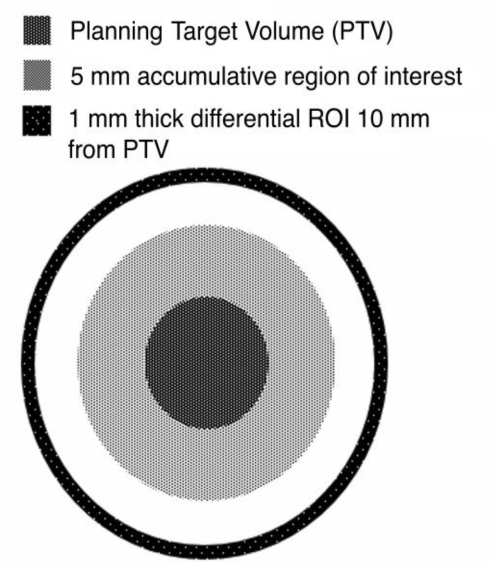
Radify (M.A. Renaud)→

AAA versus MC

Poster session #56 (Boustead et al, 2017)

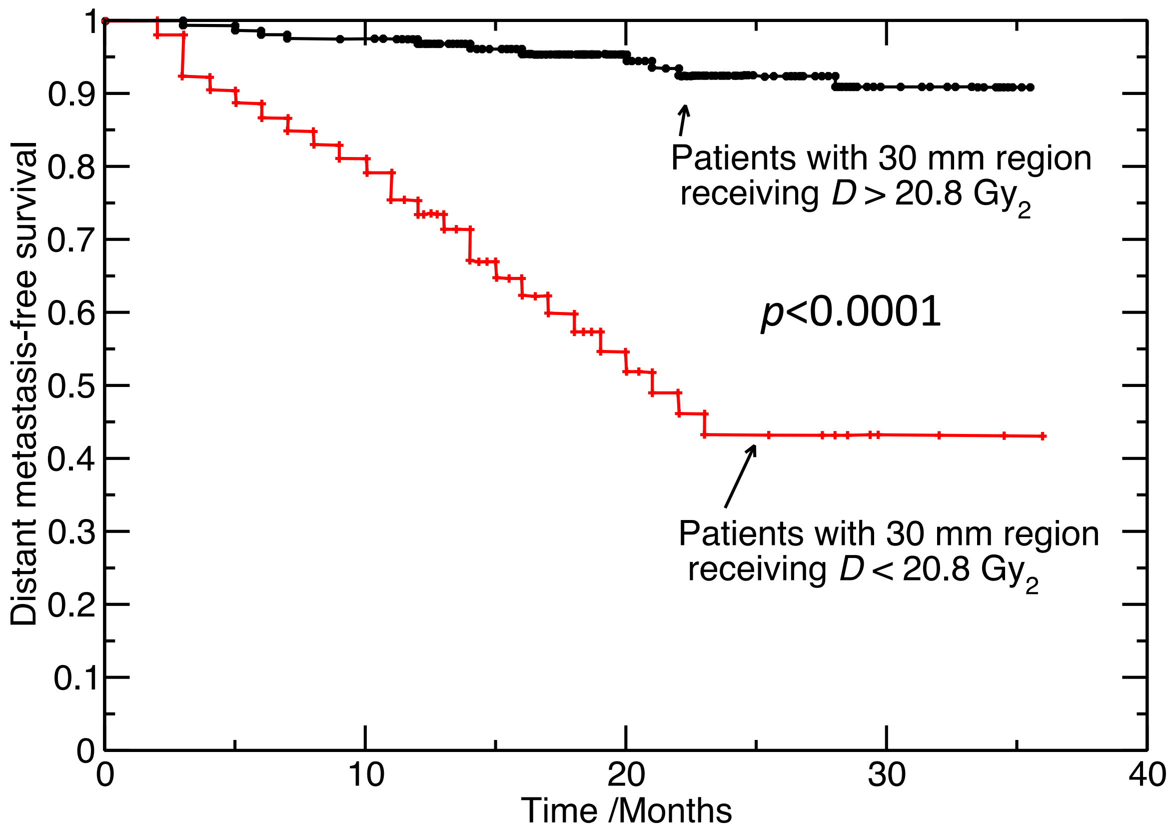
Dose difference → different outcome in terms of distant metastasis probability

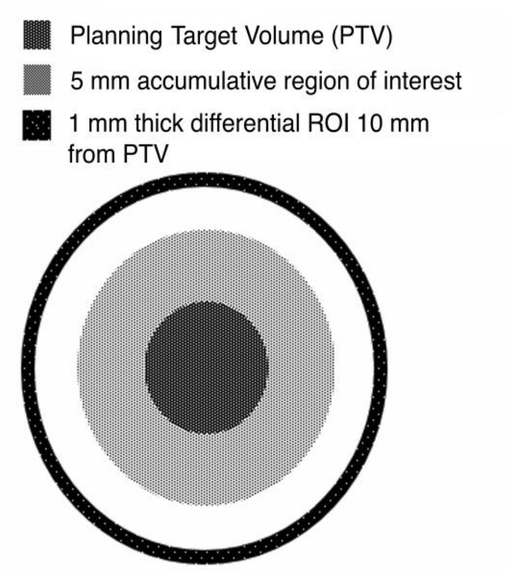




A. Boustead et al; preliminary

Same data: Distant metastasis-free survival



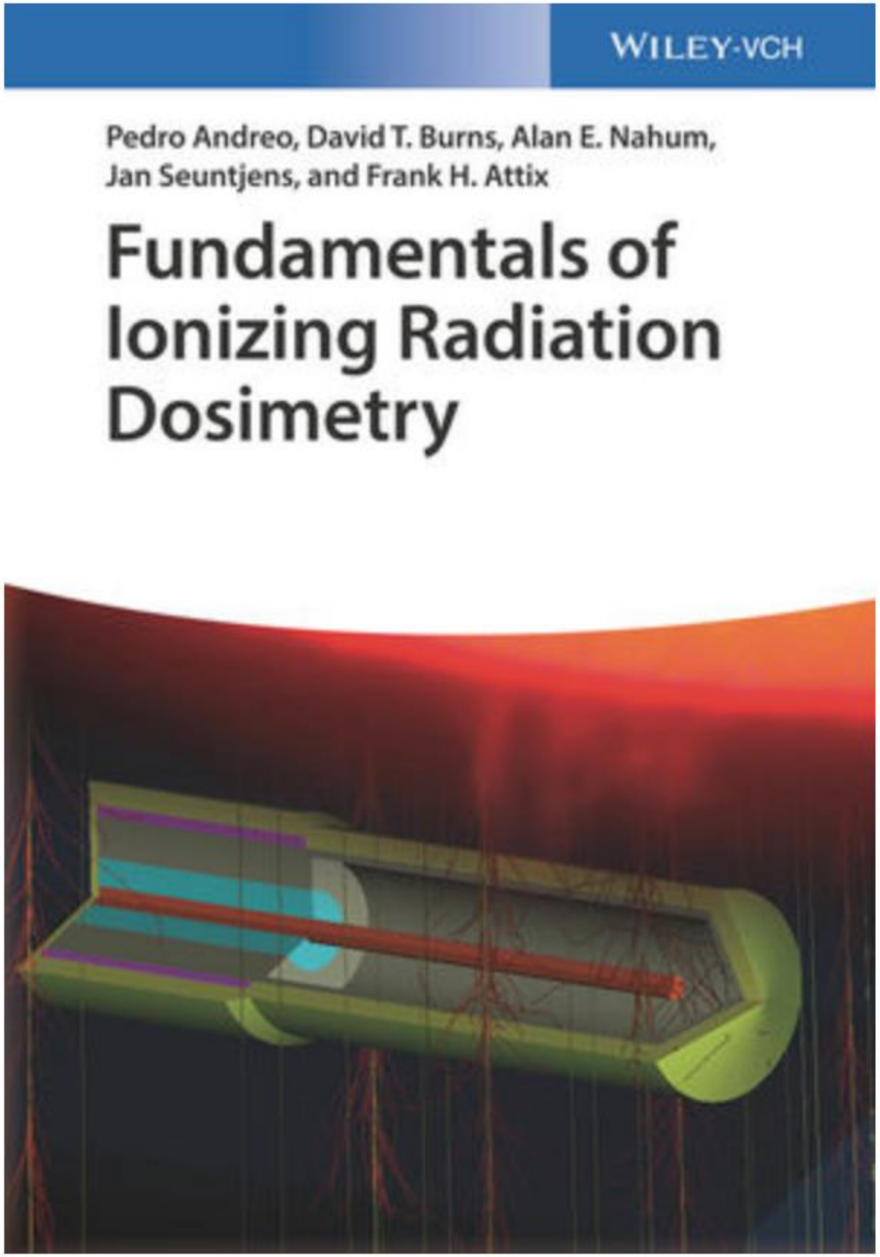


A. Boustead et al; preliminary

Conclusions

- Small photon beams are tricky
- Successful SRT hinges on accurate small field dosimetry
- In the past two decades our understanding and formalization of small field dosimetry has significantly improved
  - Calibration
  - Detectors and correction factors
  - Dose calculation algorithms
- Monte Carlo techniques have played and continue to play a core role in our understanding of radiation dosimetry of these fields

FIORD is here!
The new Attix book



Thank you!

McGill