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Plastic Scintillation Detectors: Present Status and Their Application for Quality Assurance and In Vivo Dosimetry

Sam Beddar, Professor

The University of Texas MD Anderson Cancer Center &

The University of Texas Graduate School of Biomedical Sciences

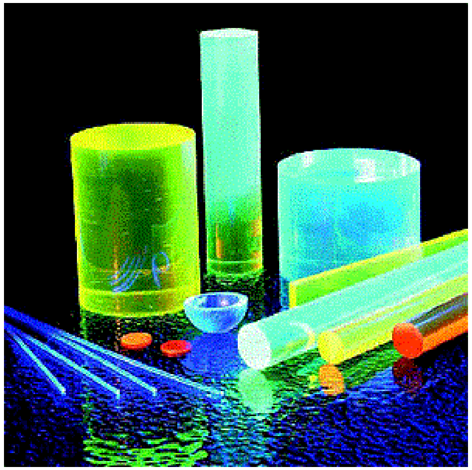
Luc Beaulieu, Professor

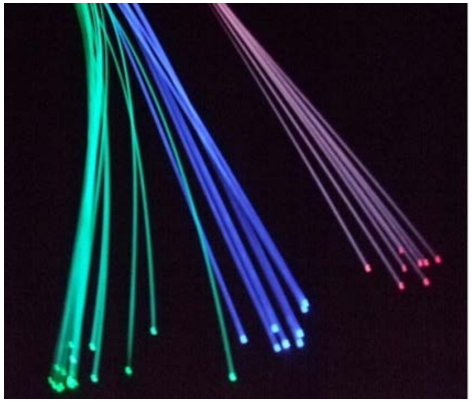
Department of Physics, Université Laval

Department of Radiation Oncology, CHU de Québec

Outline

- **Introduction**
  - Basic properties of PSDs
  - Cerenkov stem effect
- **Quality Assurance Applications**
  - Exradin W1 scintillator
  - Small field dosimetry
- ***In Vivo* Dosimetry**
  - EBRT: prostate patients
  - Other Brachytherapy Studies
- **Conclusion**





Disclosures

- The University of Texas MD Anderson Cancer Center & l'Université Laval have one license agreement with Standard Imaging.
- SB & LB had an NIH/NCI SBIR Phase I grant (1R43 CA153824-01) with Standard Imaging.
- LB & SB had Sponsored Research Agreement with Standard Imaging.
- SB had phase I, II, III Sponsored Research Agreements with Radiadyne, LLC.

- ***Scintillating Fiber Dosimetry Arrays*****.** US Patent: 8,183,534, Date Issued: May 22, 2012.
- ***Real-time in vivo Dosimetry Using Scintillation Detectors.*** US Patent: 61/143,294 filed on 01/08/2009, pending.

Lectures Series at AAPM

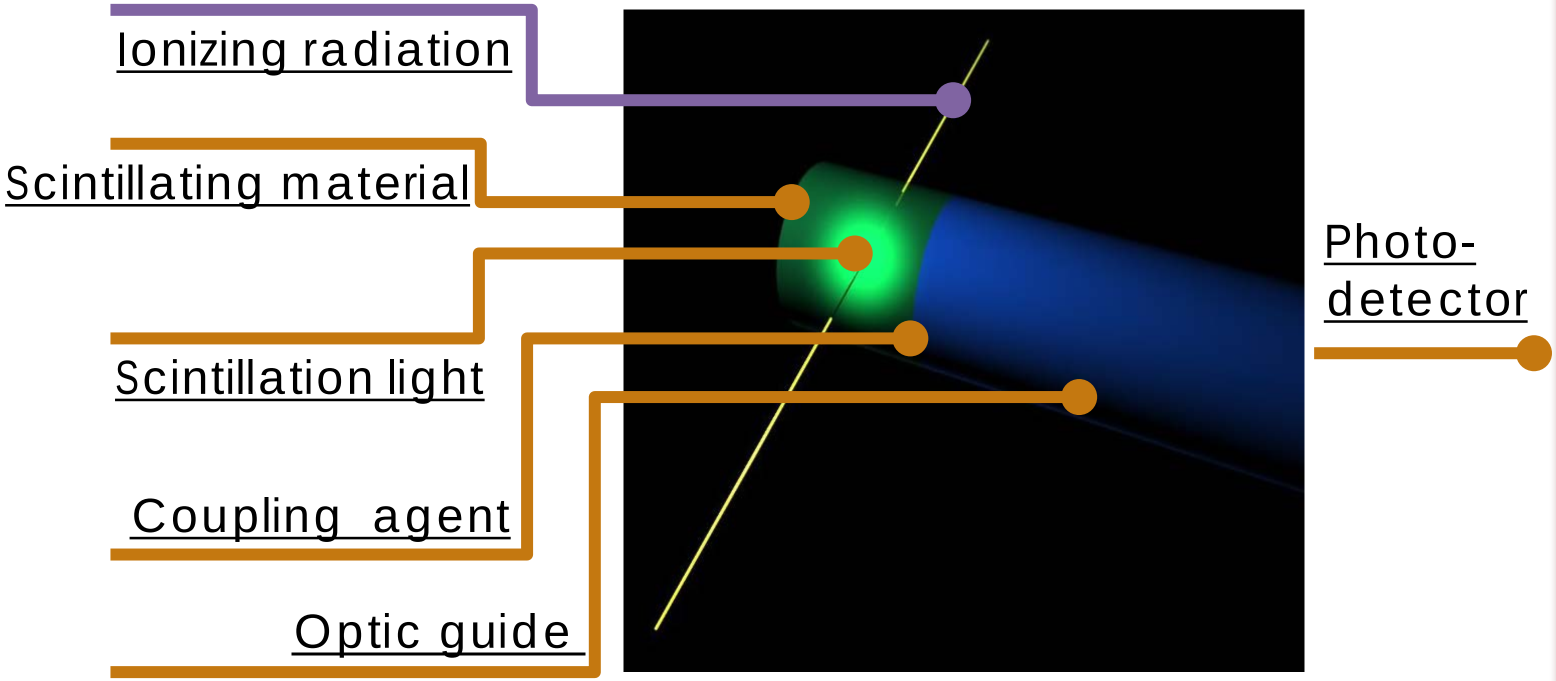
- **AAPM 2008 --- introducing PSDs, basics & properties**
  "Scintillation Dosimetry: Review, New Innovations and Applications"
- **AAPM 2010 --- further studies & validation of PSDs**
  "Scintillation Dosimetry: From Plastics to Liquids and from Photons/Electrons to Protons"
- **AAPM 2013 --- application of commercial PSDs**
  "PSDs: Present Status and their Applications for Quality Assurance and In Vivo Dosimetry"

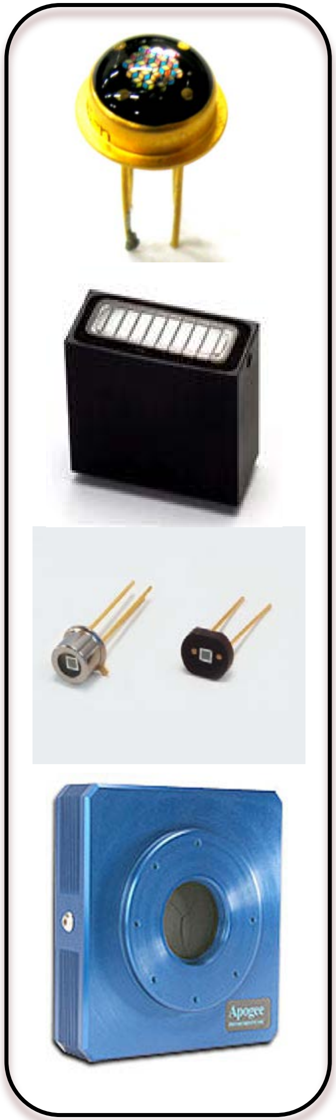
Introduction

&

Present Status

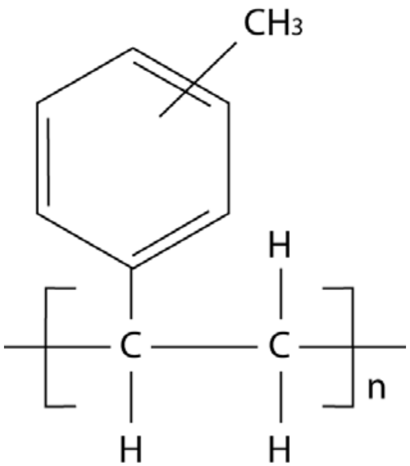
What is a PSD?

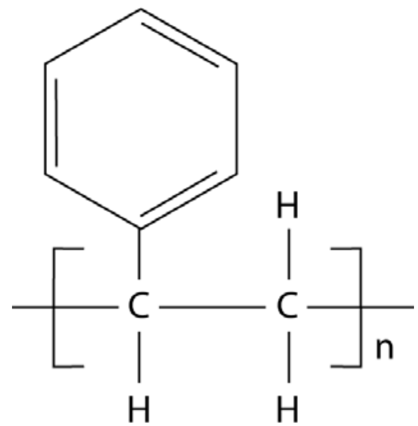

Ionizing radiation
Scintillating material
Scintillation light
Coupling agent
Optic guide
Photo-
detector


Apogee

Plastic Scintillating Materials

- Core (bulk solvent)
  - Polyvinyltoluene (*plastic scintillators*)
  - Polystyrene (*plastic scintillating fibers*)





- Cladding (scintillating fibers)
  - Polymethylacrylate (PMMA)
  - Improves transmission of light to optical fiber

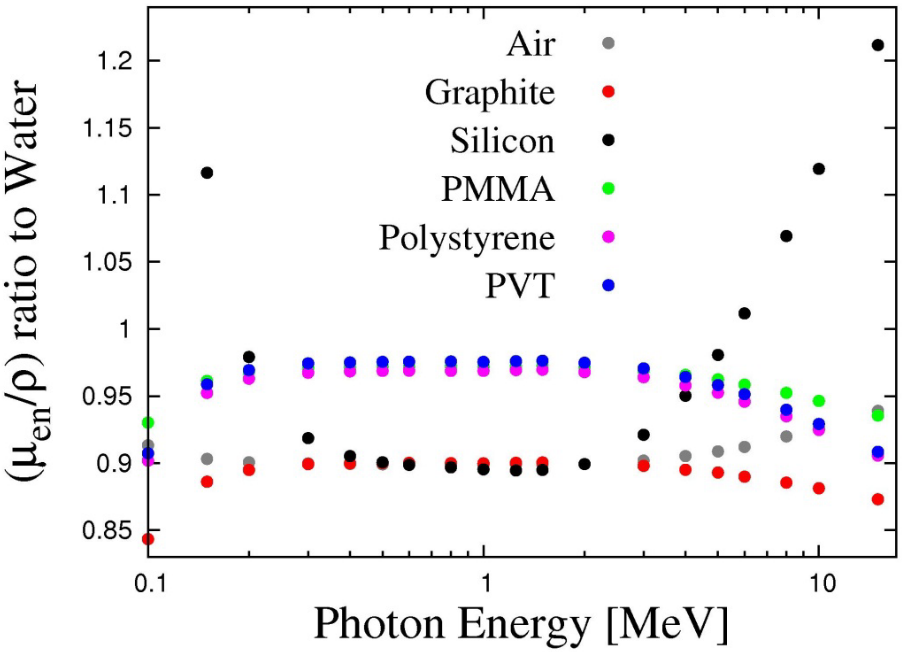
Fluors

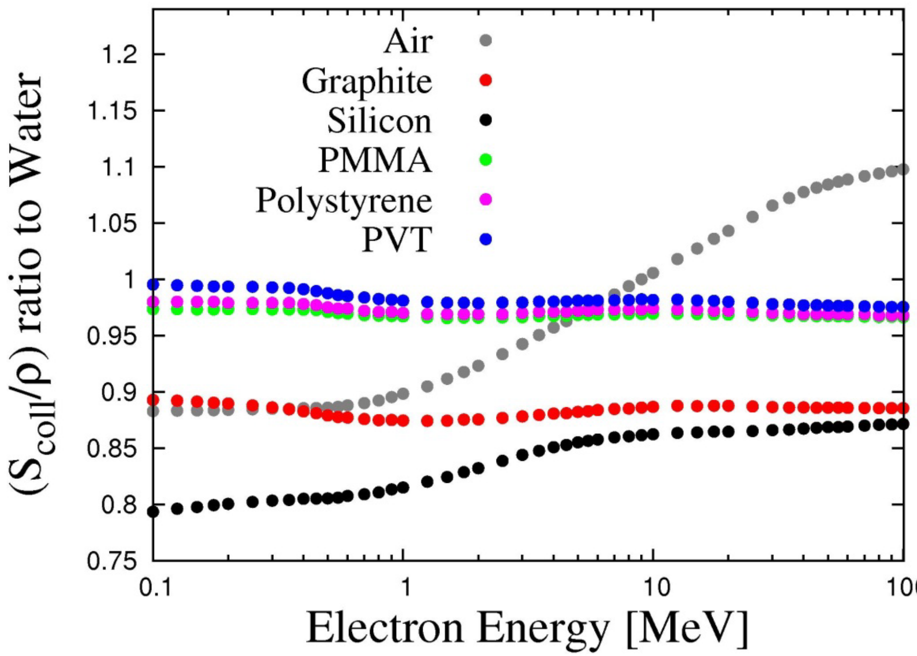
- Organic fluors (scintillating materials) are used with a bulk solvent: two components system
  - BC400: >97% PVT, < 3% organic fluors
    - e.g. p-TERPHENYL (C6H5 C6H4 C6H5).
  - Energy deposited in the solvent is transferred to the organic fluor molecules
    - Emission is typically peaked in the violet-blue region.
- "Wavelength shifters" or three components system
  - A third (organic) component can also be used to absorb the organics fluors emitted photons and re-emit at a longer wavelength
    - POPOP [1,4-bis(5-phenyloxazol-2-yl) benzene] to get scintillators emitting in the green or yellow region.

PSDs Composition

Parameter	Scintillator	Polystyrene	Water
Density (g/cm^3)	1.032	1.060	1.000
Electron density (10^{23} e^-/g)	3.272	3.238	3.343
Composition (by weight %)	H: 8.47 C: 91.53	H: 7.74 C: 92.26	H: 11.19 O: 88.81

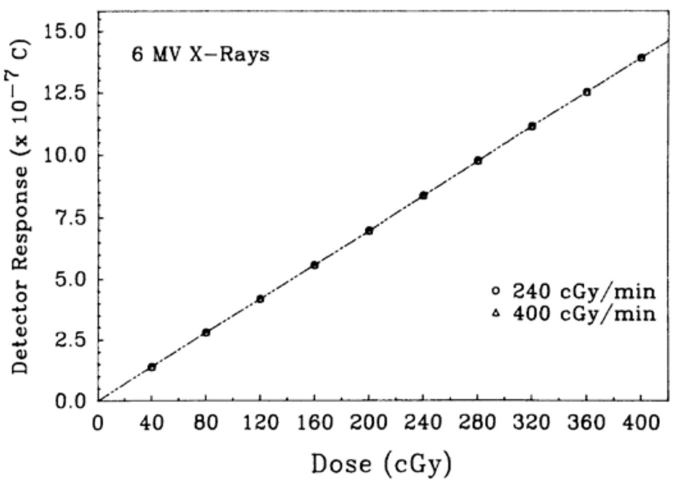
WATER EQUIVALENCE

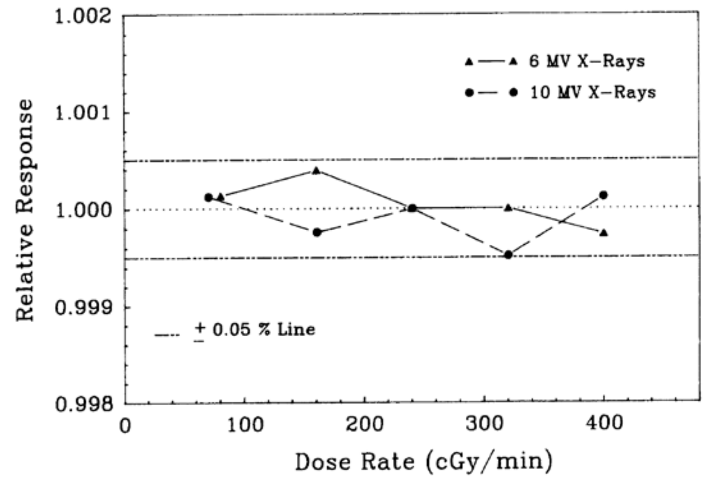


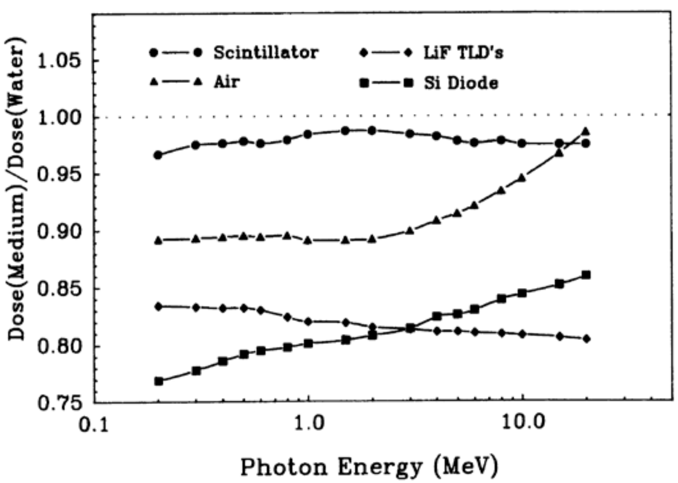


Data from NIST

Properties







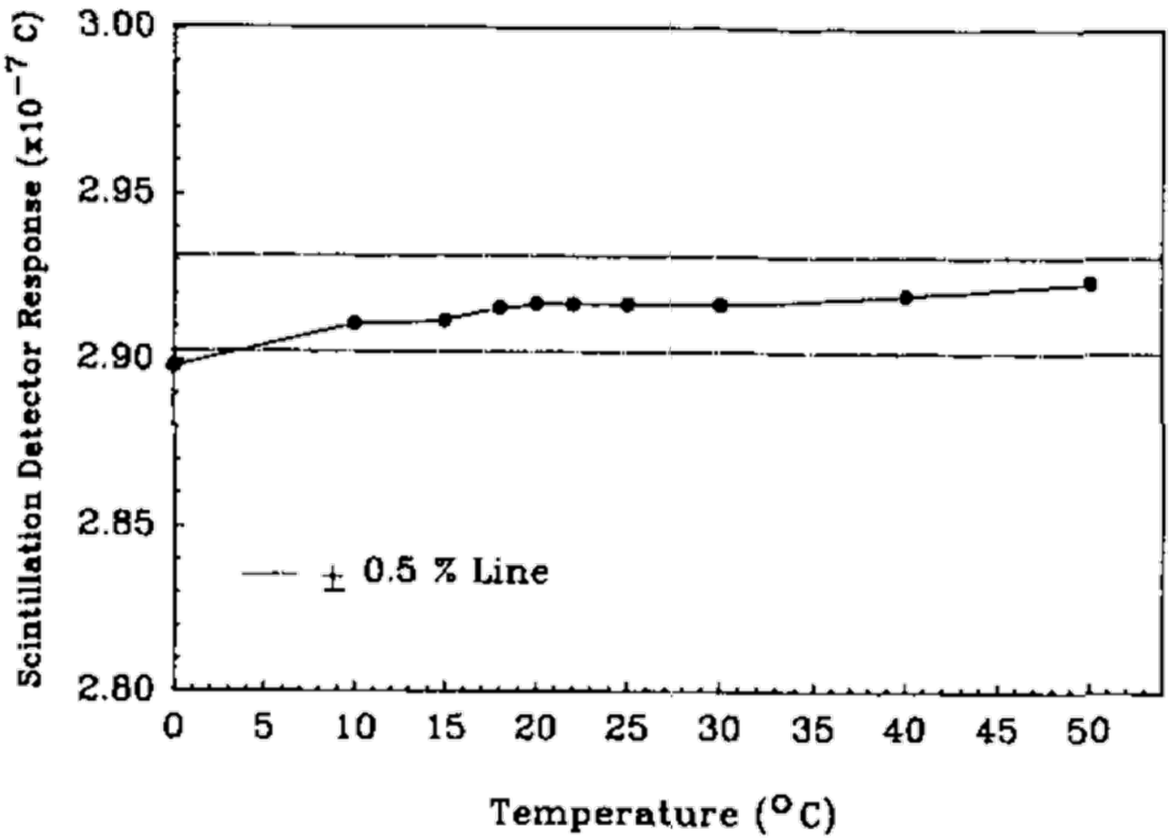
$$\frac{\overline{D}_{sci}}{\overline{D}_{med}} = 0.980 \pm 0.005$$

Beddar A S, Mackie T R, Attix F H. **Water-equivalent plastic scintillation detectors for high-energy beam dosimetry: I. Physical characteristics and theoretical considerations.** *Phys Med Biol* 37: 1883-1900, 1992.

Quenching Effect

- A decrease from the optimal scintillation efficiency, or quenching, can occur under various conditions
  - For organic scintillators, possible thermal quenching
  - Radiation damage can decrease the efficiency
    (Ionizations lead to temporary and/or permanent molecular damage)
    - Increased absorption due to defects (plastics turn yellow)
    - Need > kGy accumulated doses (10^4 to 10^5 Gy)
  - High LET: proton and ion beams
    - Overlapping excitation sites and molecule damages

Back in the Old Days… 1992



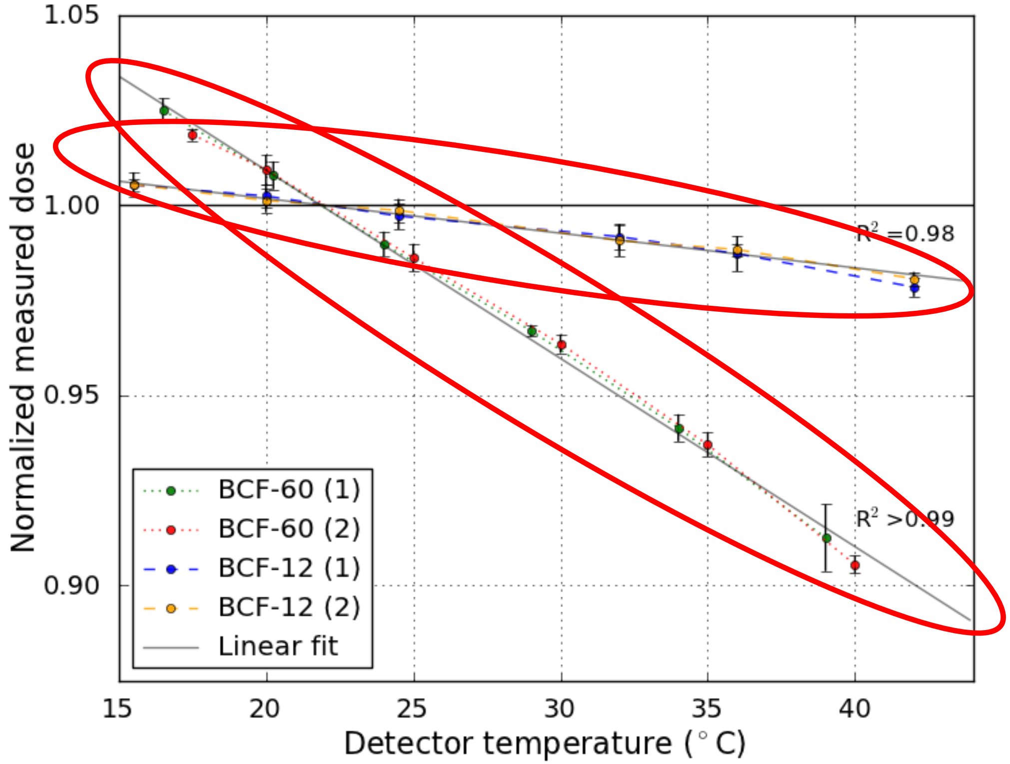
BC-408

Negligible temperature dependence reported in initial studies.

Beddar A S, Mackie T R, Attix F H. **Water-equivalent plastic scintillation detectors for high-energy beam dosimetry: I. Physical characteristics and theoretical considerations.** *Phys Med Biol* 37: 1883-1900, 1992.

Temperature Effect

- BCF-60 Exhibits Non-Negligible Temperature Dependence
  - 0.5% per °C relative to room temperature (22°C).
- BCF-12 Exhibits Smaller Temperature Dependence
  - 0.09% per °C.
- Independent detectors exhibit very similar responses.



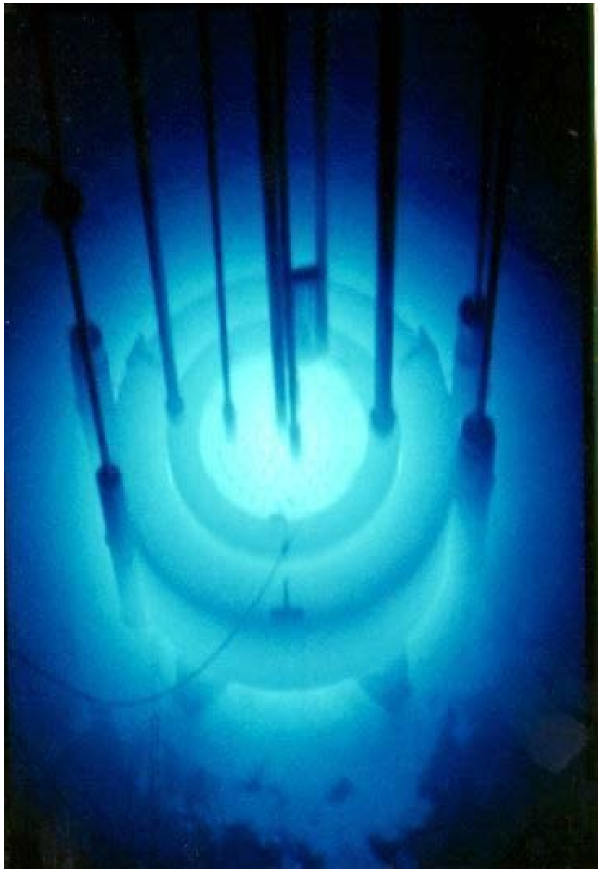
Wootton L S, Beddar A S. **Temperature dependence of BCF plastic scintillation detectors.** *Phys Med Biol* 58: 2955-67, 2013.
See also: Buranurak S, Andersen CE, Beierholm AR. **Temperature variations as a source of uncertainty in medical fiber-coupled organic plastic scintillator dosimetry**. *Radiat Meas,* 2013.

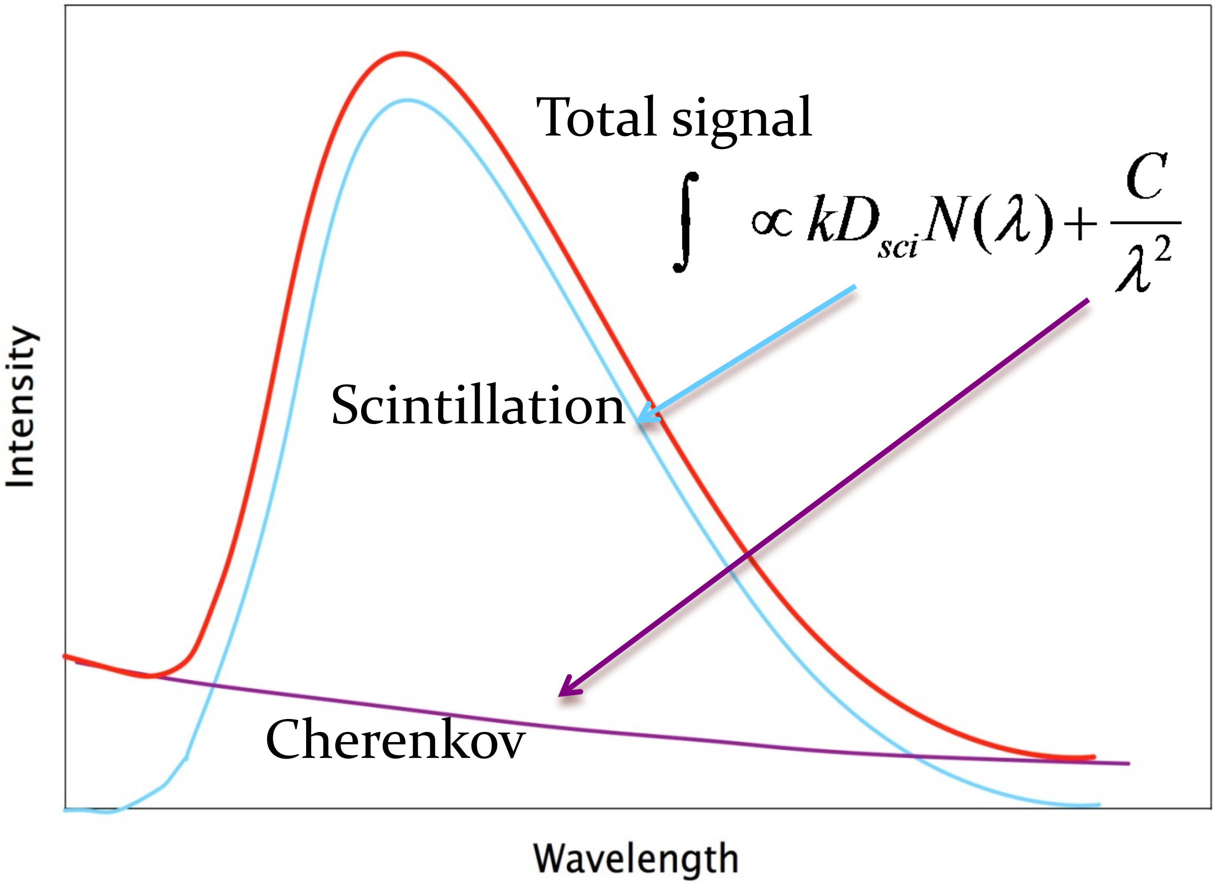
Scintillation Process : References

- *JB Birks, The Theory and Practice of Scintillation Counting, Pergamon Press Book, MacMillan, New York, 1964. [Chapters 3 and 6]*
- *GF Knoll, Radiation Detection and Measurement, 3rd Edition, John Wiley and Sons, 2000. [Chapter 8]*
- *WR Leo, Techniques for Nuclear and Particle Physics Experiments, 2nd edition, Springer-Verlag, 1992. [Chapter 7]*
- *FH Attix, Introduction to Radiological Physics and Radiation Dosimetry, John Wiley and Sons, 1986. [Chapter 15]*

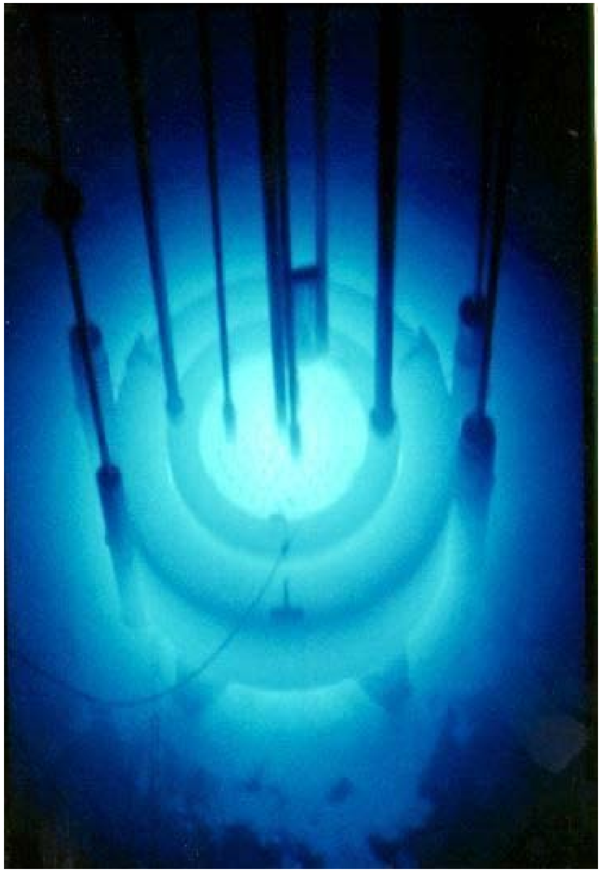
The Čerenkov Challenge

STEM EFFECT : ČERENKOV





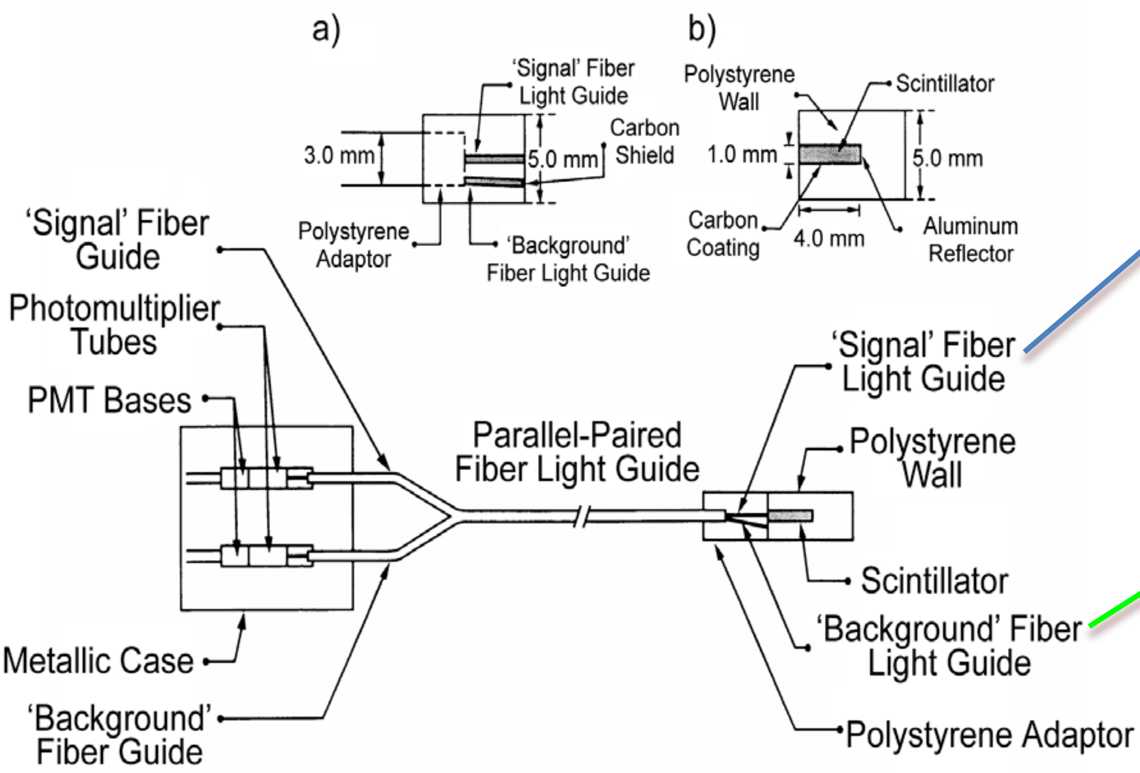
STEM EFFECT : ČERENKOV

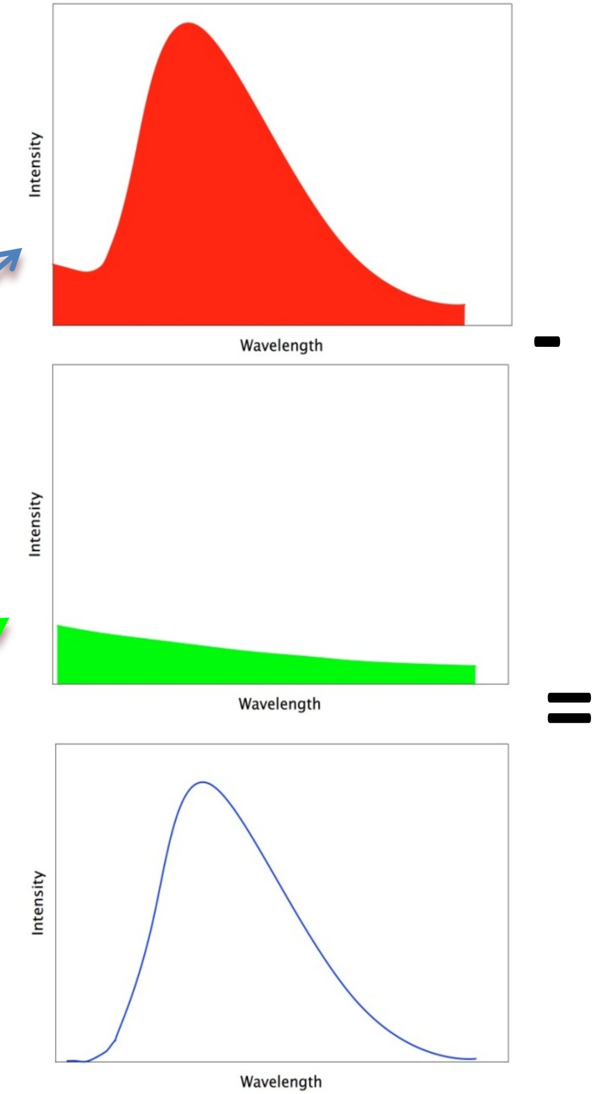


1. Background fiber substraction
2. Simple filtering
3. Timing (long decay time)
4. Chromatic removal
5. Hyperspectral decomposition
6. «Avoiding» Čerenkov generation

Beaulieu L, Goulet M, Archambault L, Beddar S. **Current status of scintillation dosimetry for megavoltage beams.** *J Phys: Conf Ser 444:* 012013, 2013.

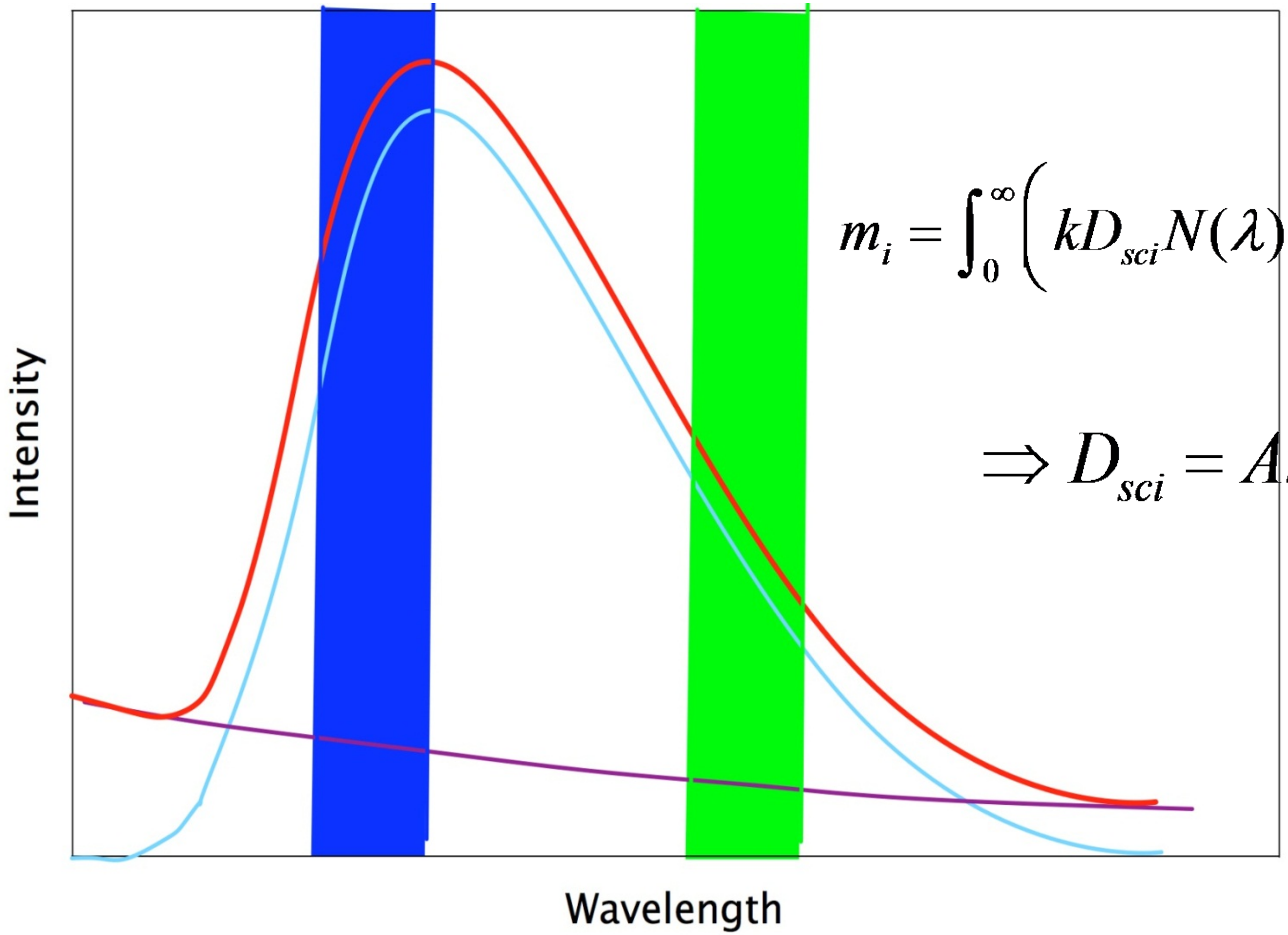
Removal : The Two Fibers Method





Beddar A S *et al*. **Water-equivalent plastic scintillation detectors for high-energy beam dosimetry: I. Physical characteristics and theoretical considerations.** *Phys Med Biol* 37: 1883-1900, 1992;
Beddar A S *et al*. **Water-equivalent plastic scintillation detectors for high-energy beam dosimetry: II. Properties and measurements.** *Phys Med Biol* 37: 1901-1913, 1992.

Removal : The Chromatic Method



$$m_i = \int_0^\infty \left(kD_{sci} N(\lambda) + \frac{C}{\lambda^2} \right) e^{-x/l(\lambda)} S_i(\lambda) d\lambda$$

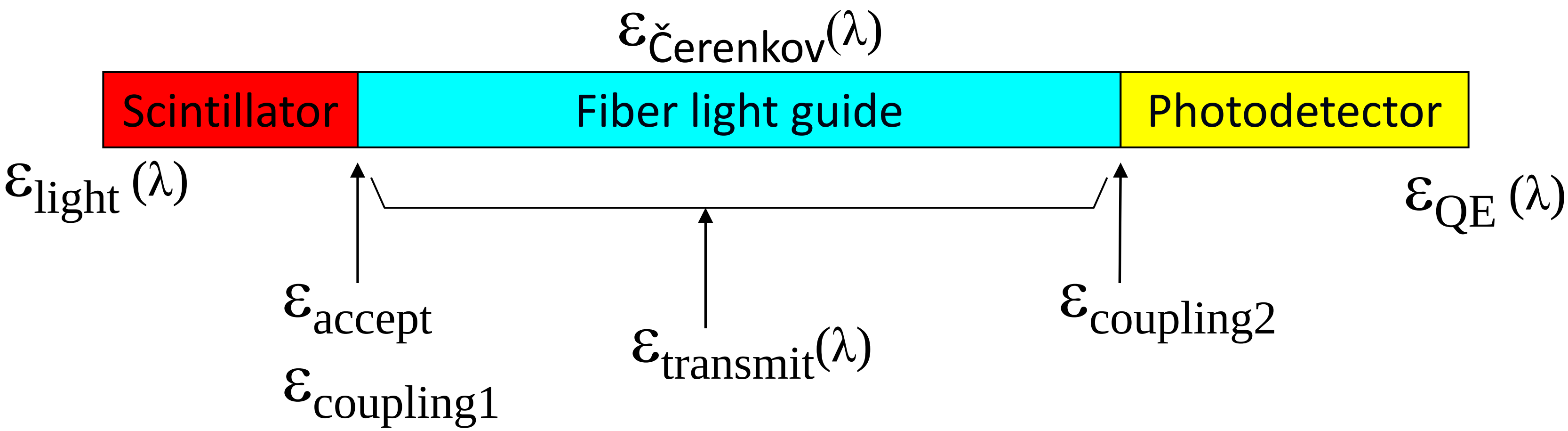
i = 1, 2

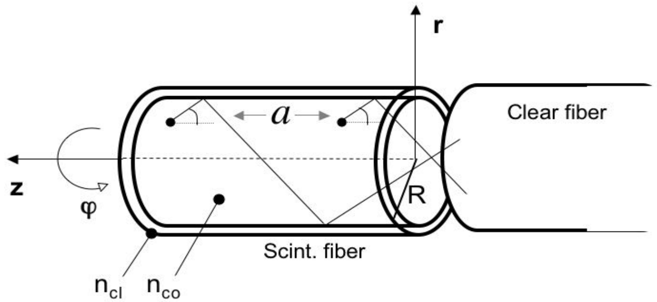
$$\Rightarrow D_{sci} = Am_1 + Bm_2$$

Fontbonne *et al*. **Scintillating fiber dosimeter for radiation therapy accelerator.** *IEEE* 49(5): 223-2227, 2002.

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: 2140-2151, 2011.

Accurate PSD = Optical Chain





Plastic scintillating fibers offer a good alternative to regular plastic scintillators:

- Increased light capture due to cladding (> internal reflection)
- The cladding is also water-equivalent/no perturbation

Advantages of Plastic Scintillators

- ✓ Linear response to dose
- ✓ Dose rate independence
- ✓ Energy independence
- ✓ Particle type independence for photons and electrons
- ✓ Insensitive to RF fields
- ✓ Real-time readout
- ✓ Spatial resolution

Quality Assurance

QA REFERENCES

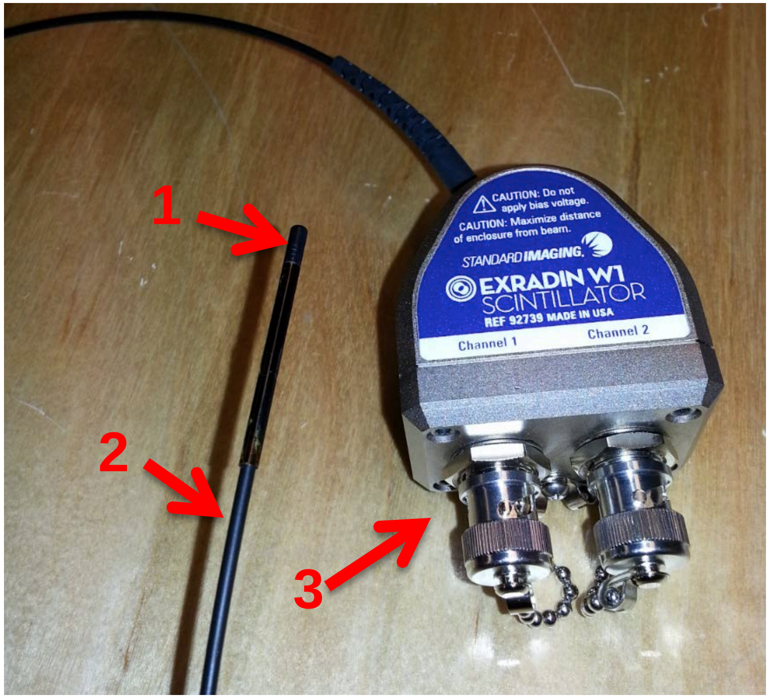
No time to go over all PSD-based devices proposed in the literature.

A recent review can be found here:

Beaulieu L, Goulet M, Archambault L, Beddar S. **Current status of scintillation dosimetry for megavoltage beams.** *J Phys : Conf Ser 444,* 012013, 2013.

EXRADIN W1 SCINTILLATOR

- Detector:
  - < 2.3 mm^3 sensitive volume (1)
  - Clear optical fiber for transport (2)
- Photodetector (3)
  - Two channels
    - Chromatic stem effect removal
  - Stay in the vault, but shielded
- Two channels electrometer with dedicated software (4)

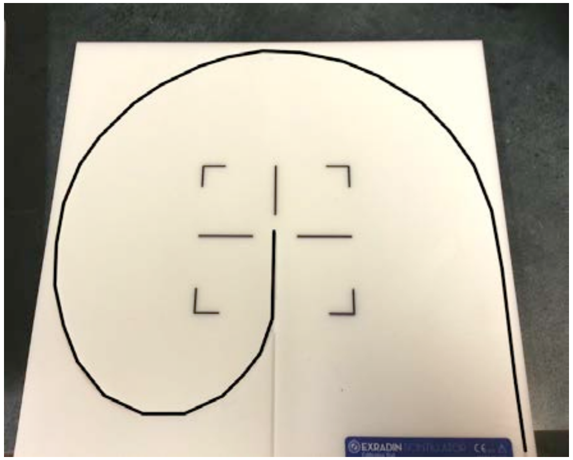


Calibration Process

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

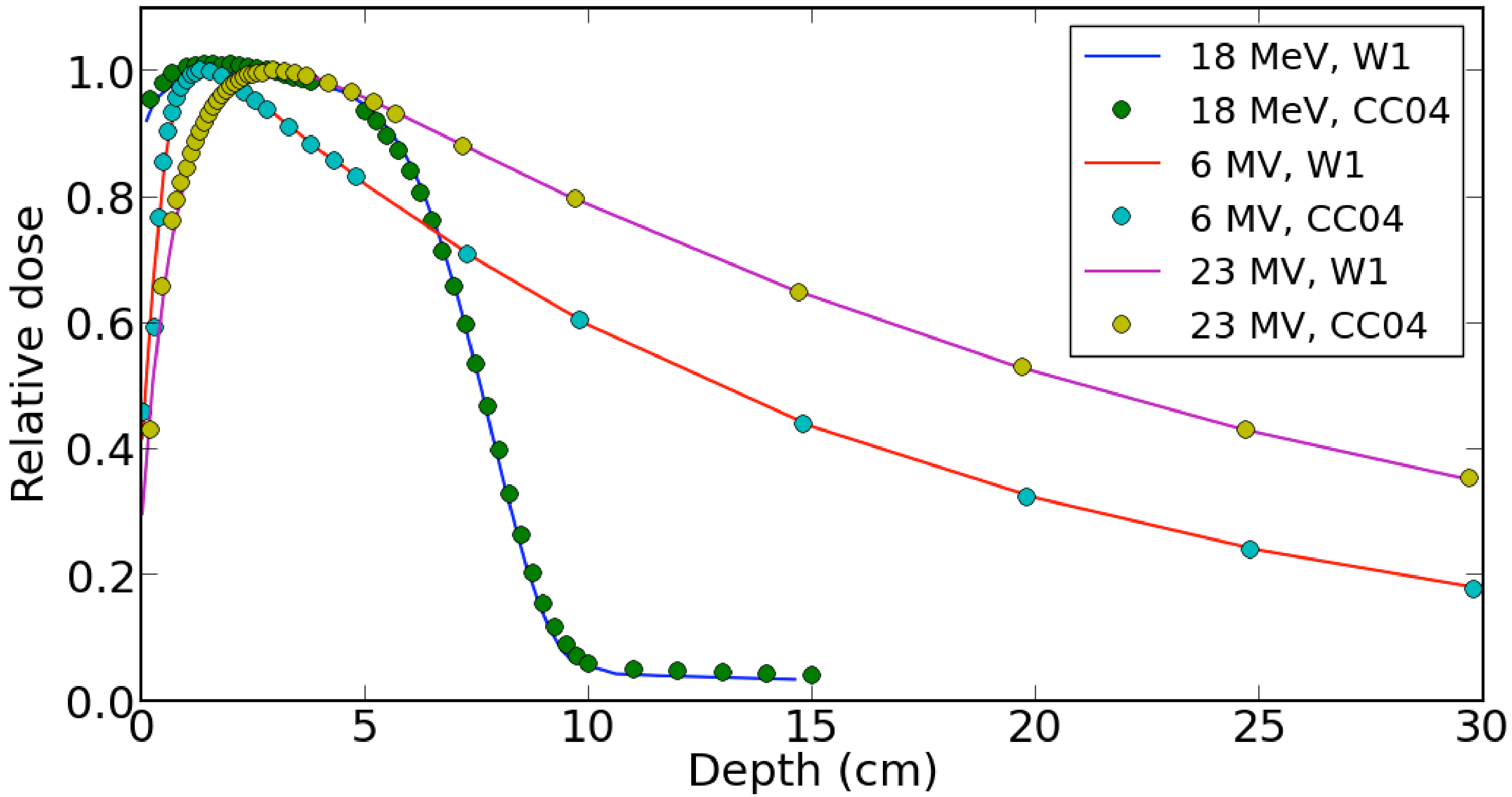
Fiber in minimum position

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.

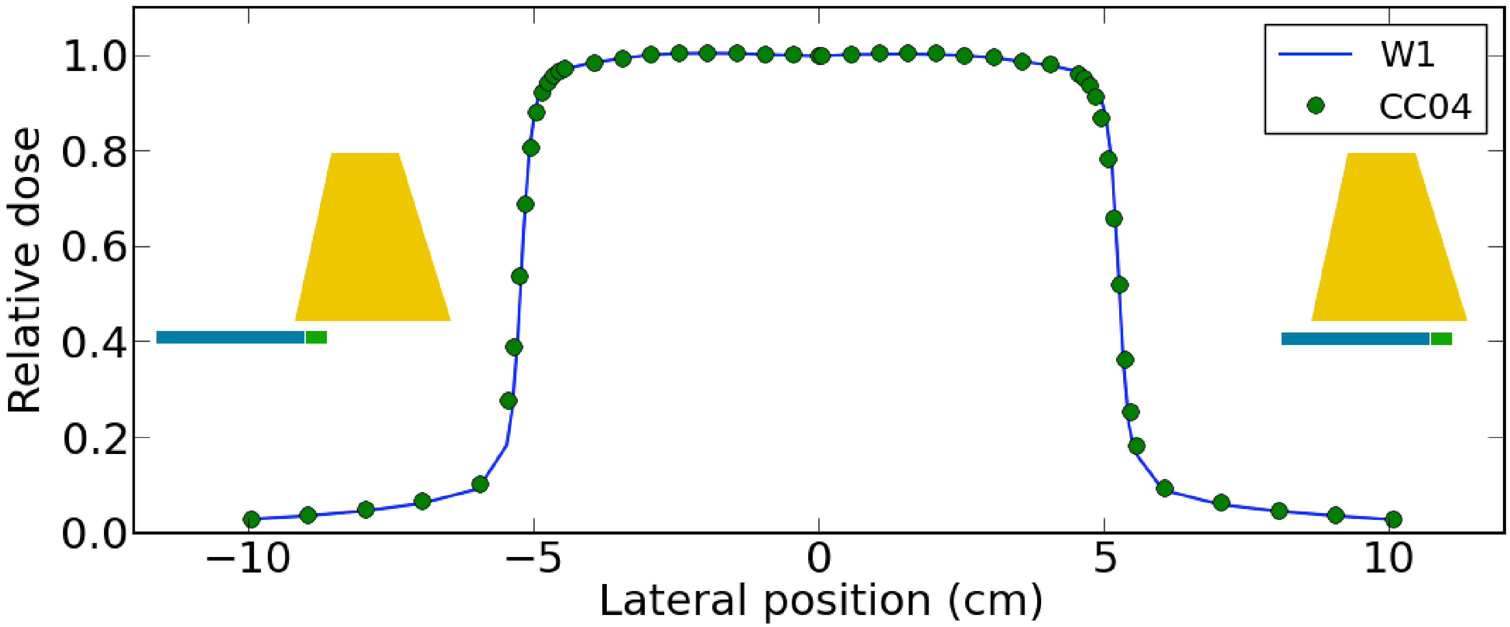
BASIC MEASUREMENTS : γ & e- PDDS



Lacroix F, Guillot M, McEwen M, Cojocaru C, Gingras L, Beddar AS, Beaulieu L. **Extraction of depth-dependent perturbation factors for parallel-plate chambers in elecron beams using plastic scintillation detector**. *Med Phys* 37(8):4331-4342, 2010

Basic Measurements : Profiles

- No residual stem effect



Small Field Dosimetry

Small Fields and Radiosurgery

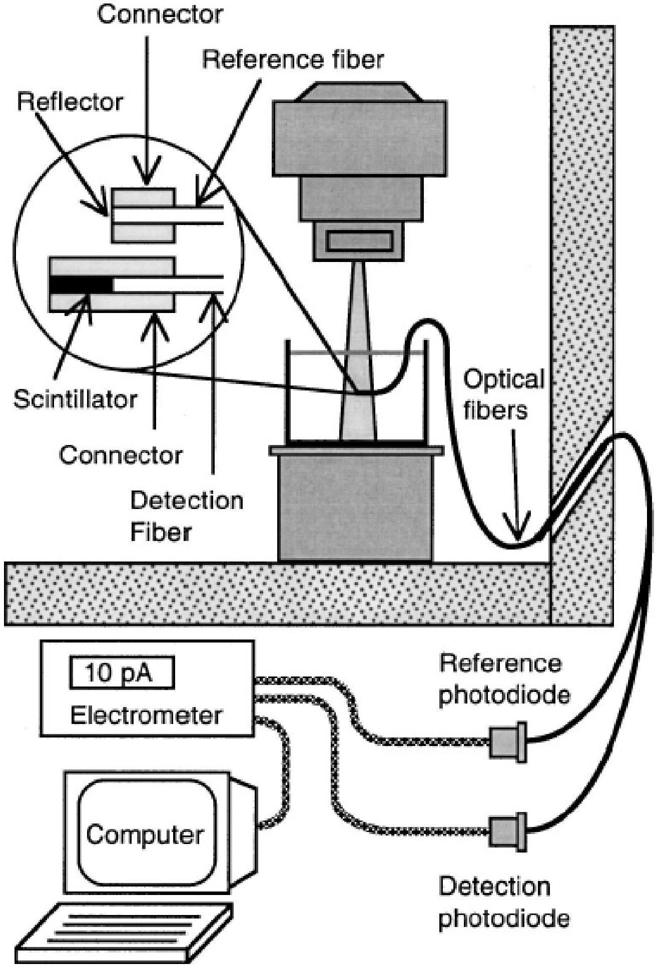


FIG. 1. The miniature scintillating detector in a treatment room.

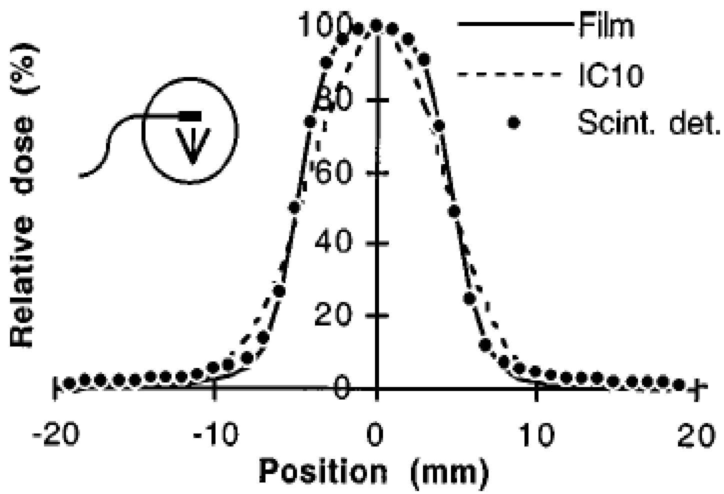
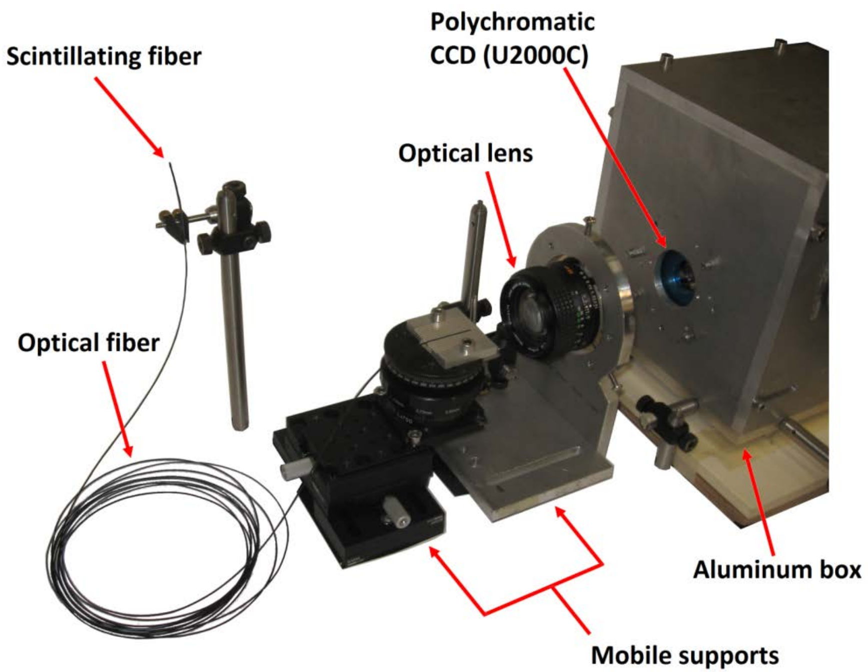


FIG. 9. Axial profiles of a 1 cm diam 6 MV photon beam measured with a ion chamber IC10, a film, and the scintillating detector.

Letourneau *et al*. **Miniature scintillating detector for small field radiation therapy.** *Med Phys* 26: 2555-2561, 1999.

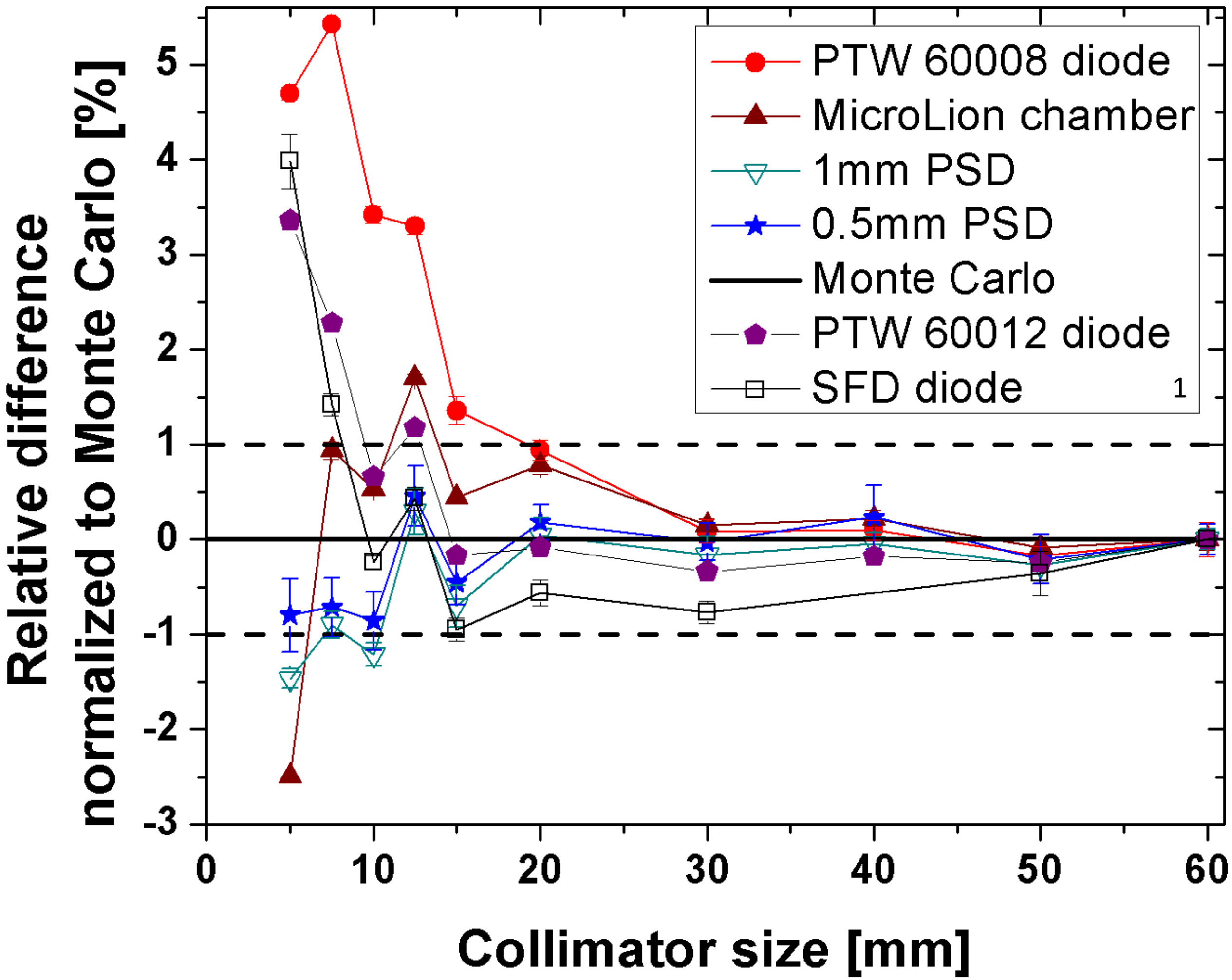
Small Field : Lab PSD System



– Collimator used: 5, 7.5, 10, 12.5, 15, 20, 30, 40, 50, 60 mm

– Stem parallel to the beam axis with all detectors

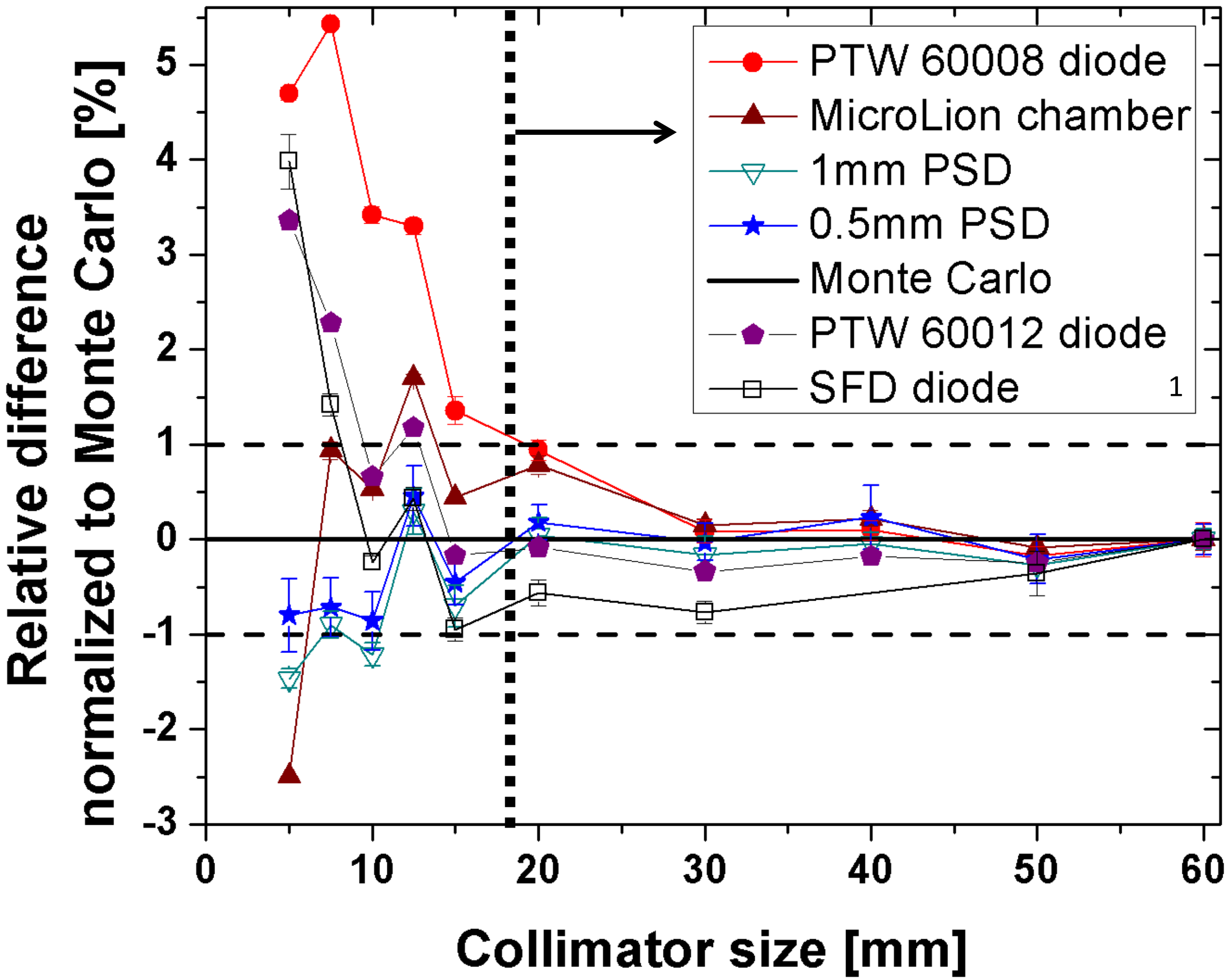
Total Scatter Factors



[1] Araki, Med. Phys. **33** (2006)

Morin J, Beliveau-Nadeau D, Chung E, Seuntjens J, Theriault D, Archambault L, Beddar S, Beaulieu L. **A comparative study of small field total scatter factors and dose profiles using plastic scintillation detectors and other stereotactic dosimeters: the case of the Cyberknife**. *Med Phys* 40(1): 011719, 2013.

Total Scatter Factors



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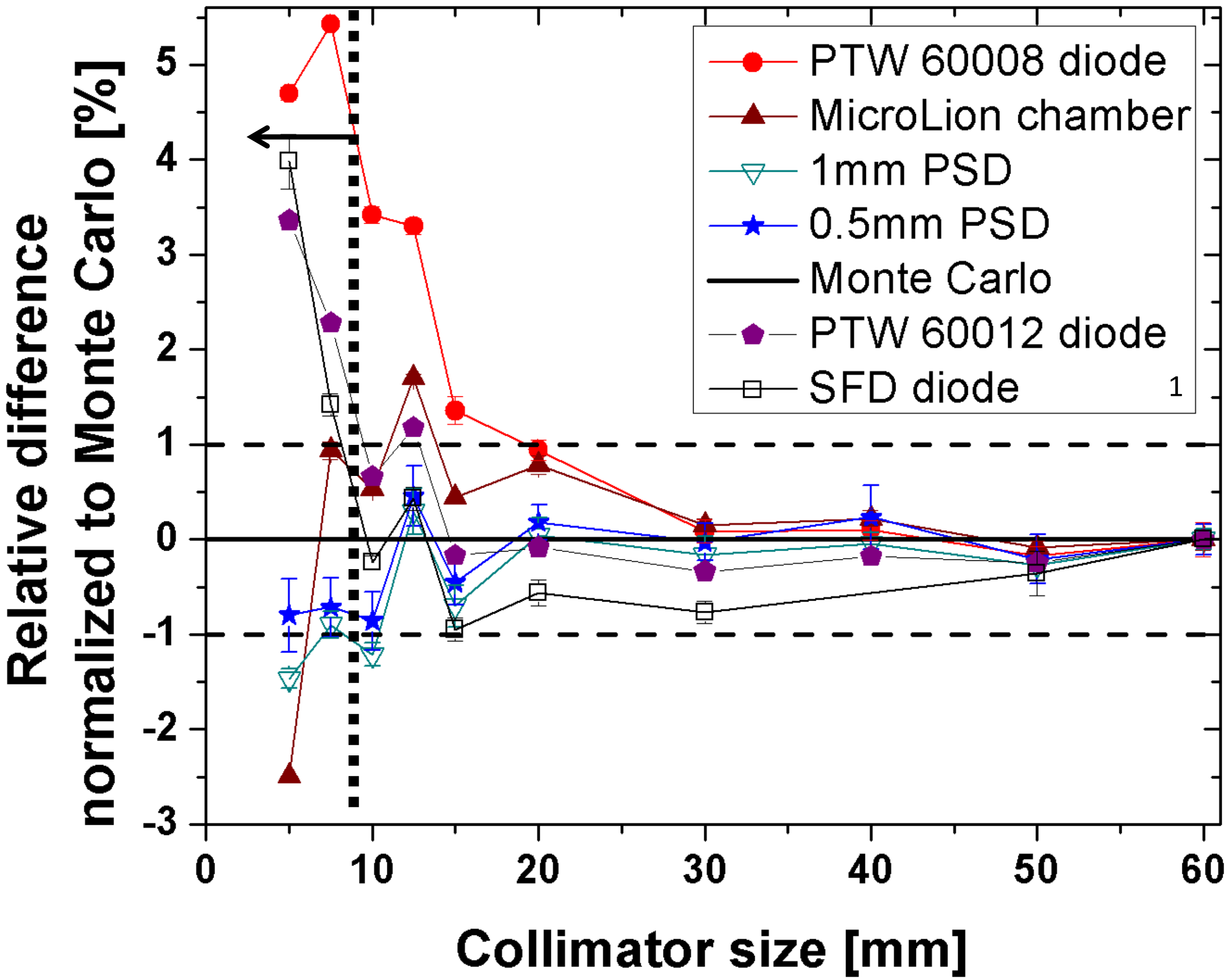
Total Scatter Factors



[1] Araki, Med. Phys. **33** (2006)

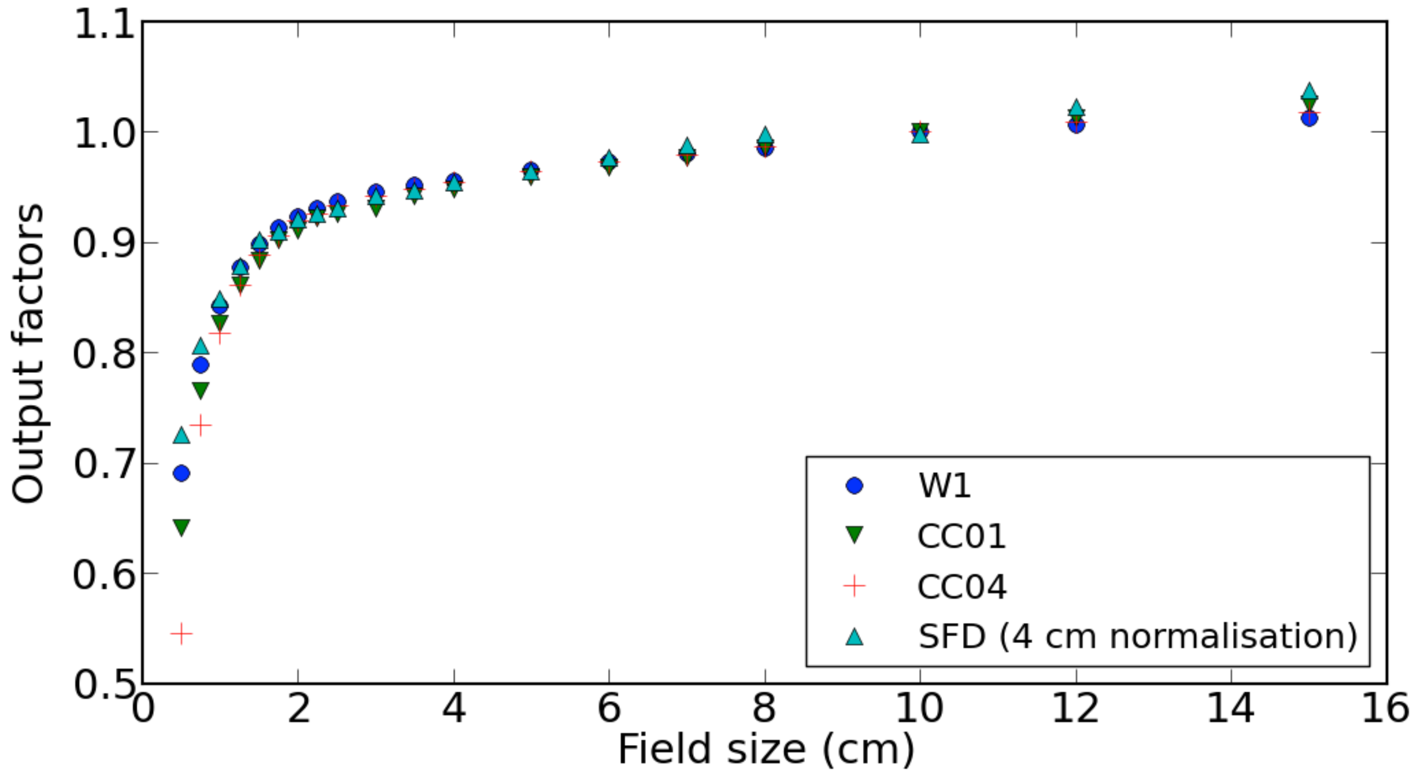
Morin J, Beliveau-Nadeau D, Chung E, Seuntjens J, Theriault D, Archambault L, Beddar S, Beaulieu L. **A comparative study of small field total scatter factors and dose profiles using plastic scintillation detectors and other stereotactic dosimeters: the case of the Cyberknife**. *Med Phys* 40(1): 011719, 2013.

Total Scatter Factors

Detectors	Collimator diameter [mm]	Correction factors	Literature	Difference [%]
PTW 60008 diode	5	0.950	0.944[1]	0.6
	7.5	0.942	0.951[1]	0.9
PTW 60012 diode	5	0.963	0.957[2]	-0.6
	7.5	0.971	0.967[2]	-0.4
SFD diode	5	0.957	0.952[3]	-0.5
	7.5	0.980	0.976[3]	-0.4
MicroLion chamber	5	1.020	1.023[4]	0.3
	7.5	0.984	0.997[4]	1.3

[1]Francescon *et al*. J Appl *Clin Med Phys* **10** (2009)
[2]Francescon *et al. Med Phys* **35** (2008)
[3]Araki. *Med Phys* **33** (2006)
[4]Francescon *et al. Med Phys* **38** (2011)

SBRT Commissioning : Exradin W1

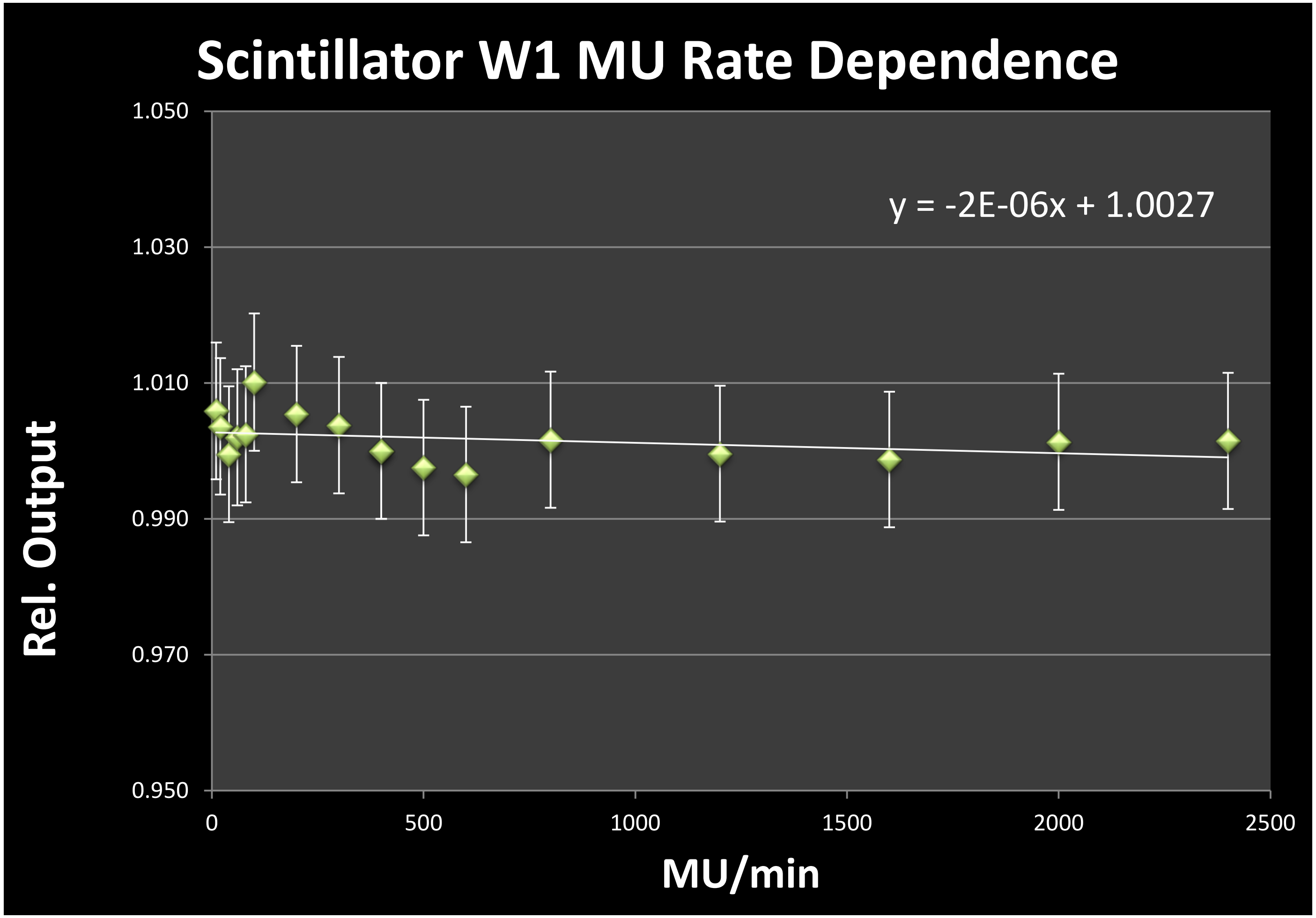


– Same conclusion as with the laboratory system!

Dose Rate Independence

- High dose rate delivery: > 2000 MU/min ?
- How do Ion Chambers fit in?
  - P_{ion} is affected by dose rate
- Comparison to the Exradin W1 PSD

Dose Rate Independence : FFF Beams



THE UNIVERSITY OF CHICAGO MEDICINE

Kamil M. Yenice, Ph.D.

Dose Rate Independence

- Calibrate and measure at different dose rates
  - High dose rate: 6MV, SRS mode, short (60 cm) SSD
    ≈ 2700 MU/min

Detectors	Dose ratio (% diff)	Corrected dose ratio
A12 / W1	0.989 (1.1%)	0.998 (0.2%)
CC13 / W1	0.991 (0.9%)	1.005 (0.5%)
IBA SFD / W1	0.943 (5.7%)	N/A

  - Even worse in electrons : 6.3% correction needed!

Measurements planned and performed by Dany Therriault, Luc Gingras and Louis Archambault.

Dose Rate Independence

- Ion chambers affected by changes in P_{ion}
  - Fully corrected by measuring P_{ion} at a given dose rate
  - W1 PSD is independent of dose rate at least up to 2700MU/min (max. tested!)

Measurements planned and performed by Dany Therriault, Luc Gingras and Louis Archambault.

In Vivo Dosimetry

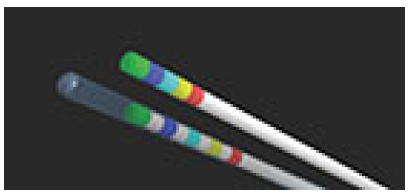
In-Vivo Dosimetry

- Advantages of internal *in-vivo* dosimetry:
  - Point of measurement can be placed directly adjacent to organ at risk or within treatment volume.
- Direct verification of treatment.
- Detect adverse events or treatment variances, potentially stop treatment and re-assess.
- Clinical validation to monitor patient treatment delivery is underway.

In-Vivo Dosimetry

- 2 recent Vision 20/20 papers in Medical Physics

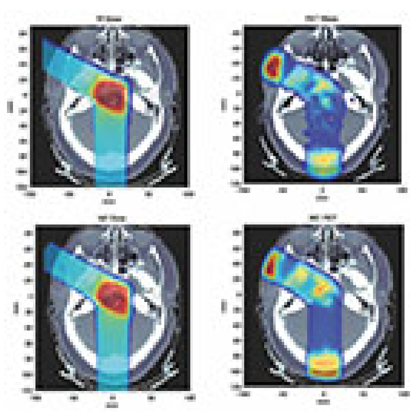
Editor's Picks



***In vivo* dosimetry in brachytherapy**

Kari Tanderup, Sam Beddar, Claus E. Andersen, Gustavo Kertzscher, and Joanna E. Cygler

Med. Phys. 40, 070902 (2013)



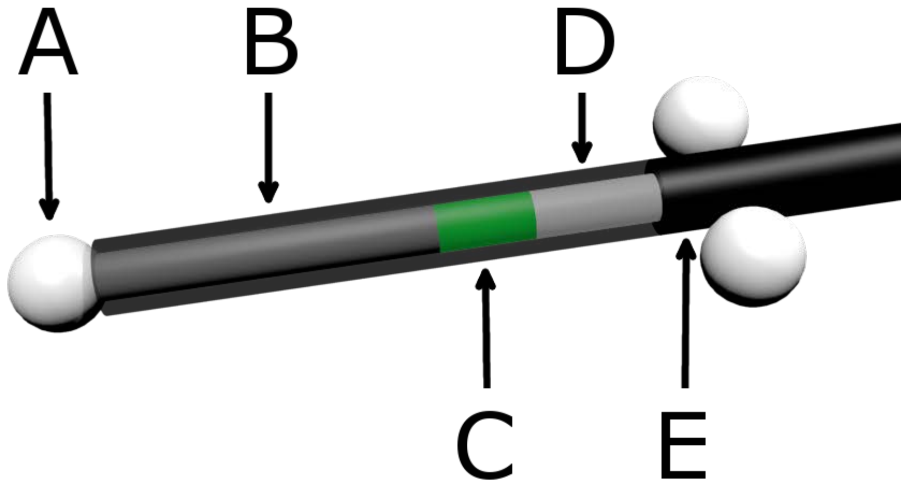
***In vivo* dosimetry in external beam radiotherapy**

Ben Mijnheer, Sam Beddar, Joanna Izewska, and Chester Reft

Med. Phys. 40, 070903 (2013)

System Design

- BCF-60 Scintillating Fiber optically coupled to clear plastic optical fiber with cyanoacrylate.
- Fiducials used as surrogate to localize scintillating fiber.
  - All fibers are water-equivalent
- Light transmitted by clear optical fiber and captured by a CCD camera.



A – Ceramic fiducials

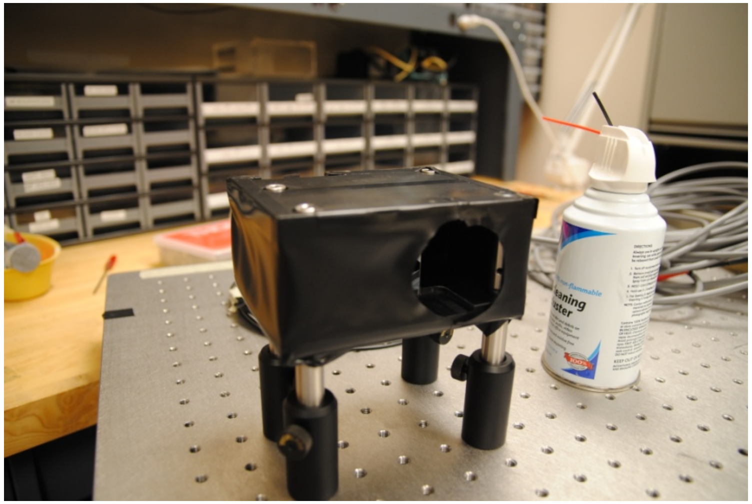
B – Carbon spacer

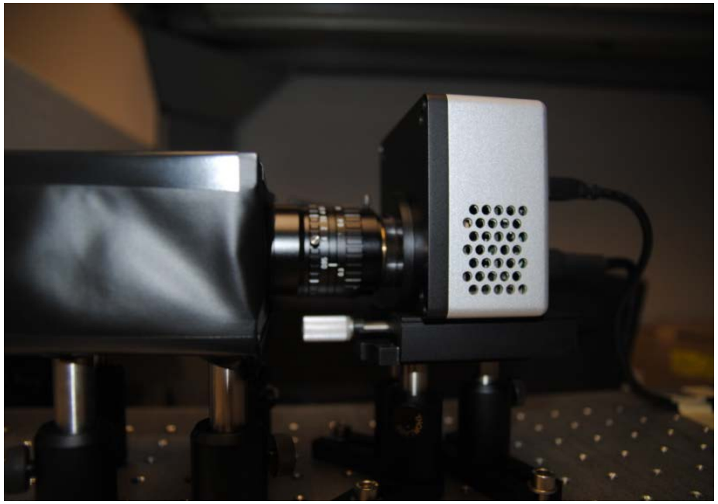
C – Scintillating fiber

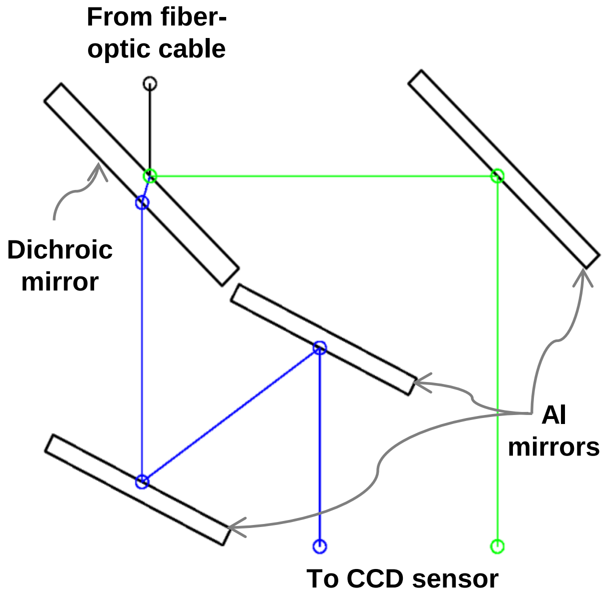
D – Optical fiber

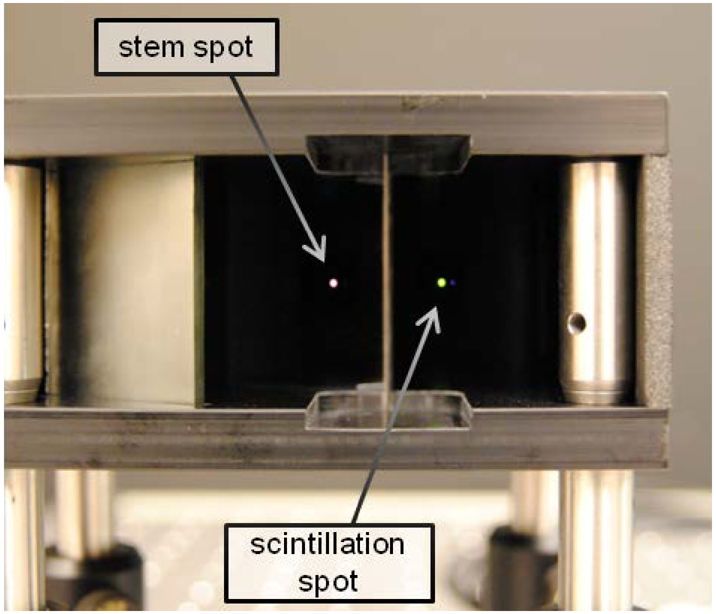
E – Polyethylene jacketing

System Design – Dichroic Mirror



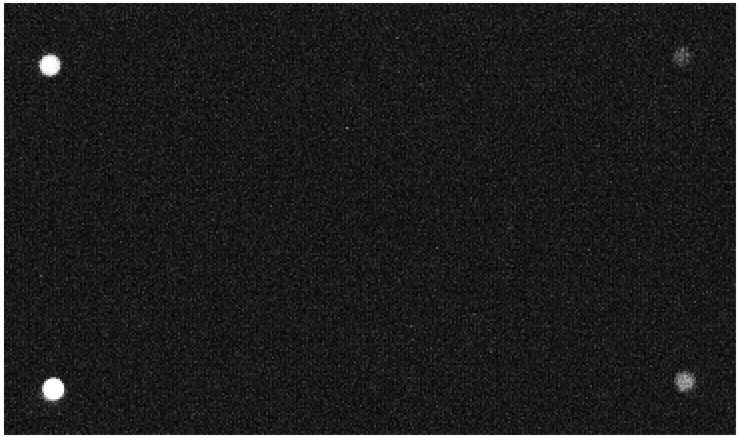






System Design – Photodetector

- Andor Luca S CCD Camera
  - Captures light output from scintillator.
  - Intensity measured by summing pixel values in region of interest (ROI).
  - Black box shields from the ambient light.



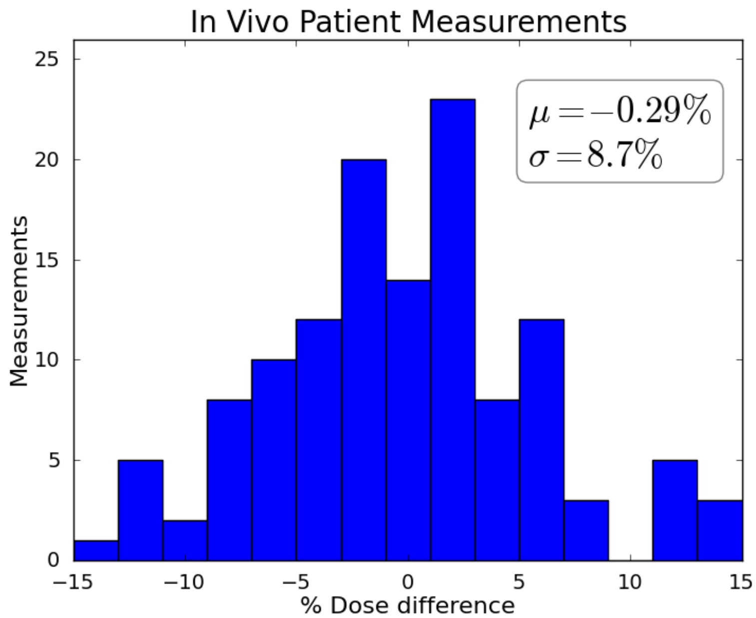
Protocol Design

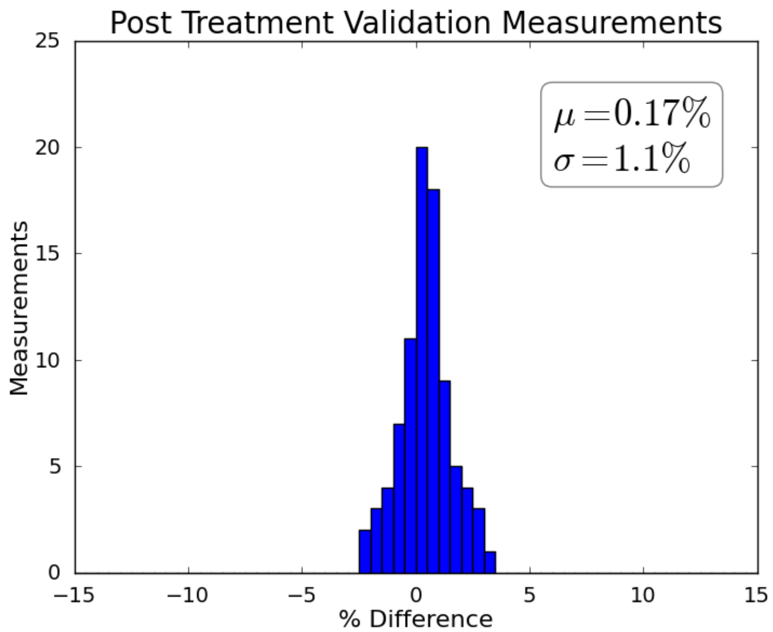
- IRB approved protocol for Prostate cancer patients
  - PSDs can be attached to rectal balloon used for immobilization
- *In-vivo* measurements during two fractions each week (Tue, Thu)
- Set of PSDs fabricated for each patient
  - Latex sheath insulated PSDs to facilitate re-use for same patient

Protocol Design

- Daily CT for *in-vivo* fractions
  - Necessary to localize detectors
- Simple validation of PSDs performed after each treatment
  - 200 cGy delivered in simple, static, fixed geometry
  - Deviations > 2% are considered indicative of loss of proper function
  - Non-functioning detectors re-calibrated or discarded and re-fabrication of new detectors
- 5 Patients enrolled (142 total measurements).
  - Only 5 thrown out due to problems with software (2) or detectors' malfunction (3).

Measurement Results





- Histogram of differences between measured and calculated doses.
- Differences centered around zero: no systematic error.

Measurement Results

Patient	Measurements	Average Difference [95% Confidence Interval]*	Standard Deviation	Validation
1	30	-2.6% [-4.7%, -0.4%]	5.5%	-0.1%
2	28	-1.1% [-3.8%, +1.6%]	7.0%	0.5%
3	30	1.5% [-1.0%, +4.0%]	6.6%	0.3%
4	28	3.2% [-2.2%, 8.6%]	13.9%	0.5%
5	21	-3.3% [-6.3%, -0.3%]	6.5%	-0.5%

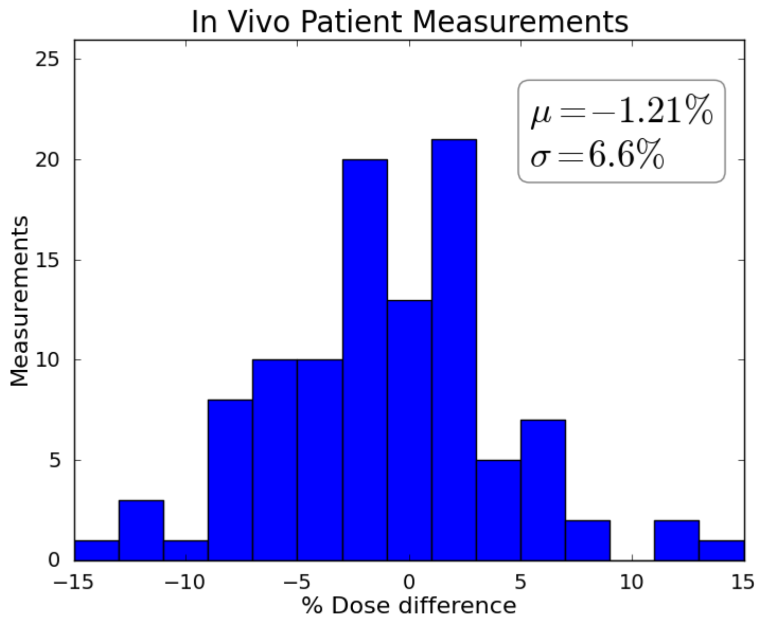
Metric	Aggregate Analysis
Average of Means	-0.5% [-4.0%, +3.0%]
Standard Deviation of Means	2.8%
Measurements within ± 10%	82% (90% w/out Pt. 4)

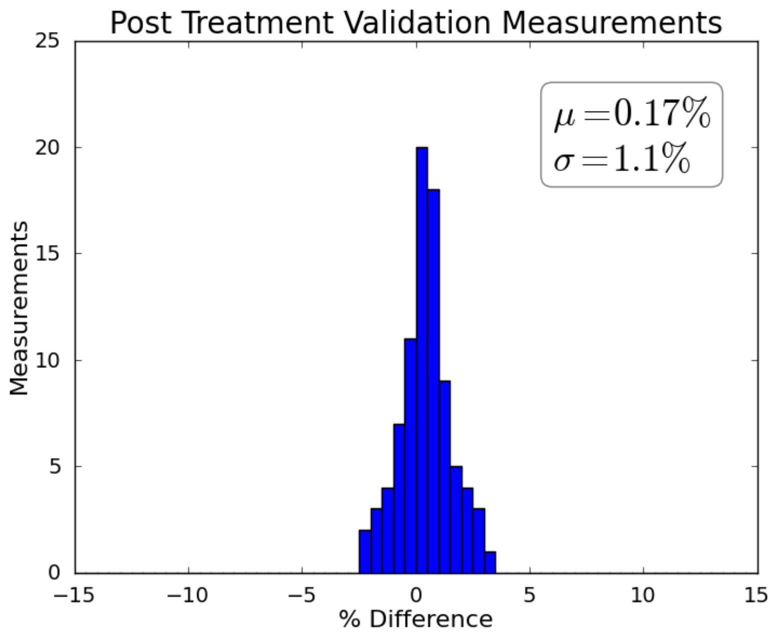
1Sigma: $\sqrt{\left(\frac{1}{N-1}\sum(x-\bar{x})^2\right)}$

Confidence Interval of the Mean: $\bar{x} \pm \frac{1.96\sigma}{\sqrt{N}}$

*Calculated using student t distribution with N-1 degrees of freedom.

Measurement Results





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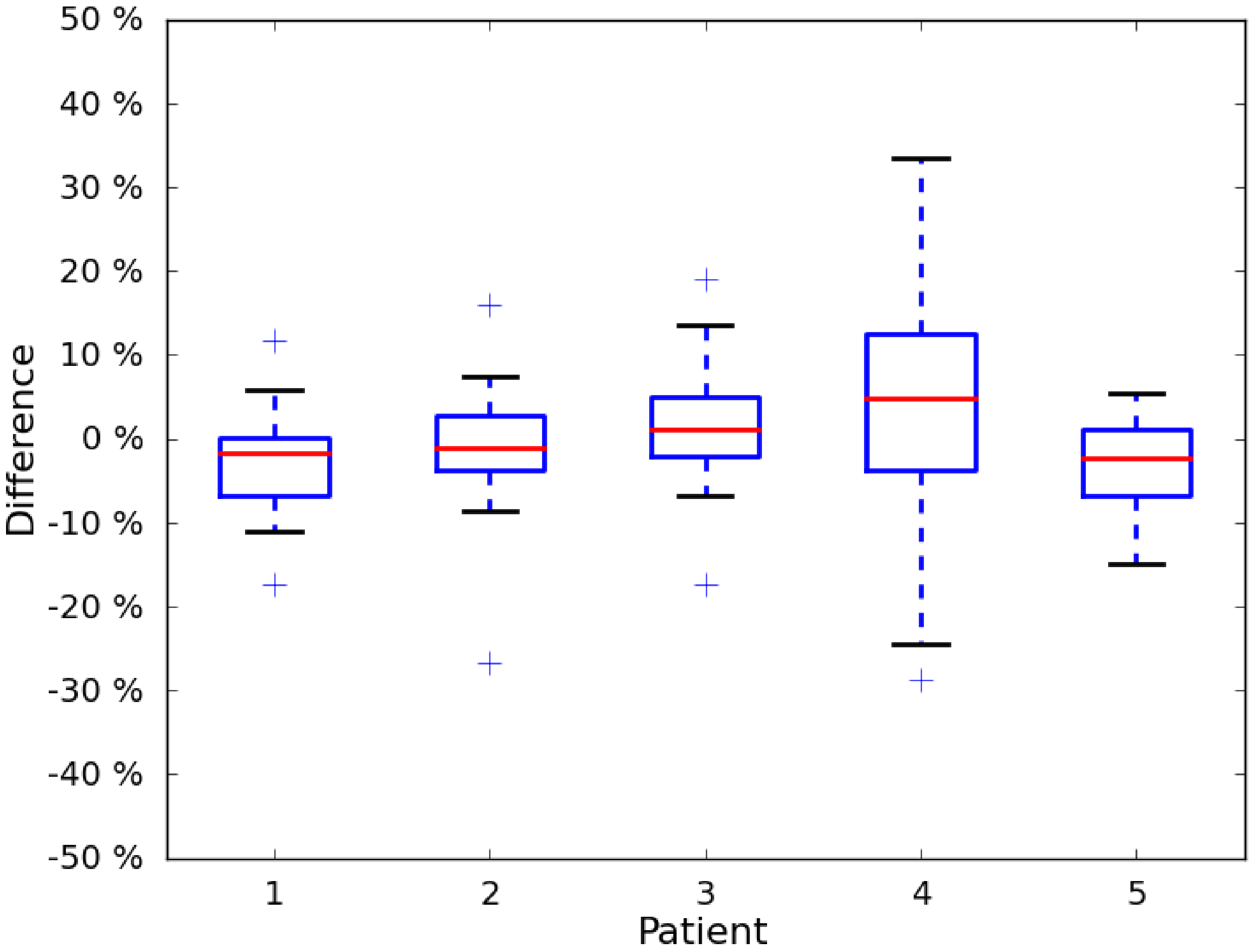
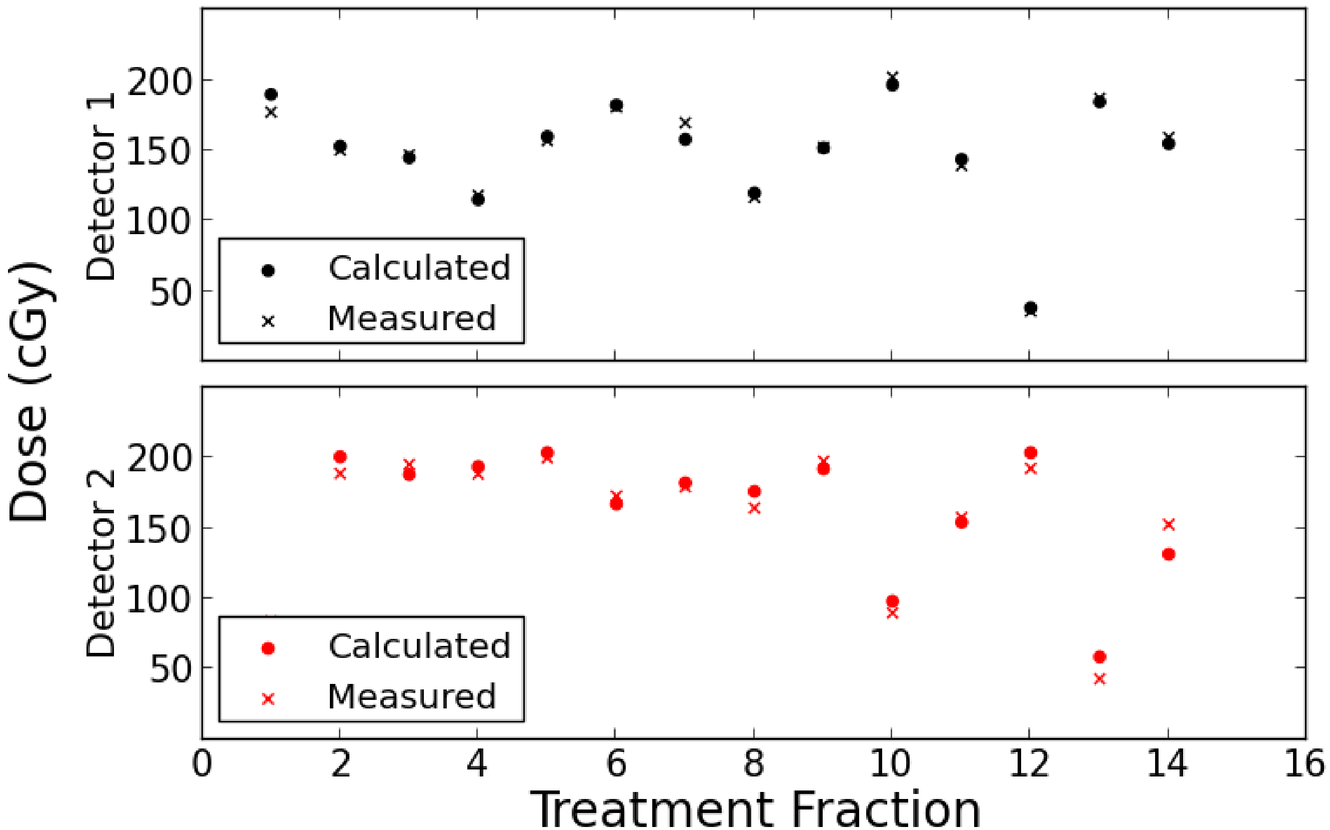
Measurement Results



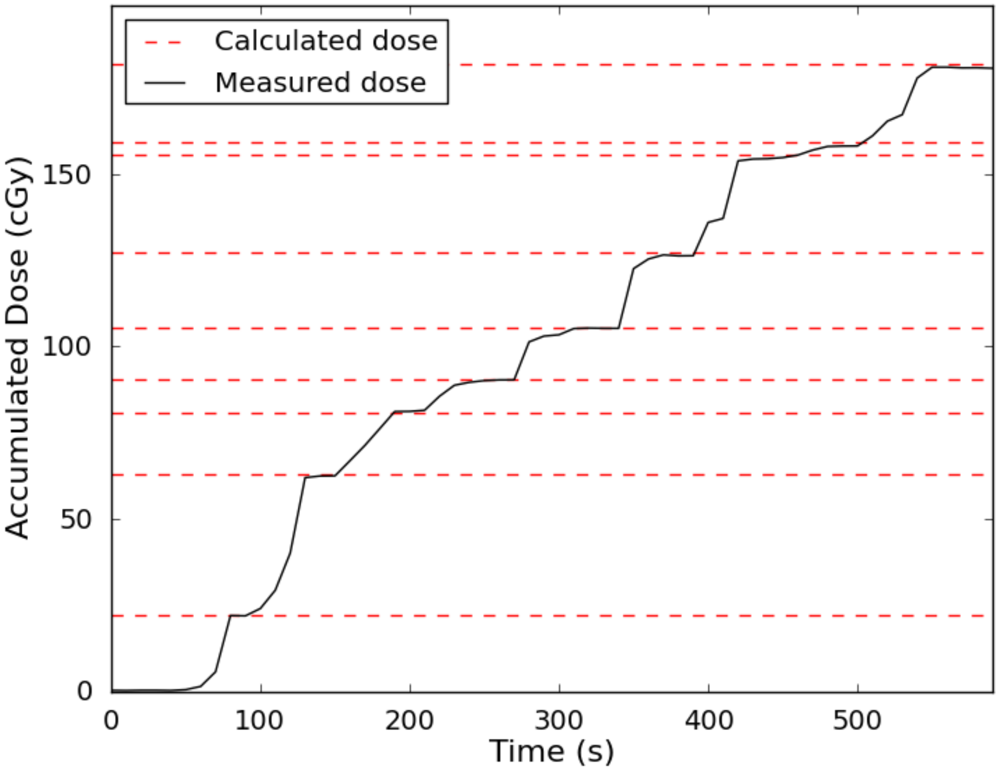
Measurement Results



Day to day agreement between detectors and TPS throughout a sample patient treatment (patient #2, σ = 7%).

Measurement Results

- Demonstration of achievable real-time accuracy.
- Solid line: measured dose in real-time.
- Dashed lines: indicate the cumulative dose calculated after each beam/segments delivery by the TPS.
- Plateaus the in measured dose indicate beam-off. (Should coincide with the dashed lines)



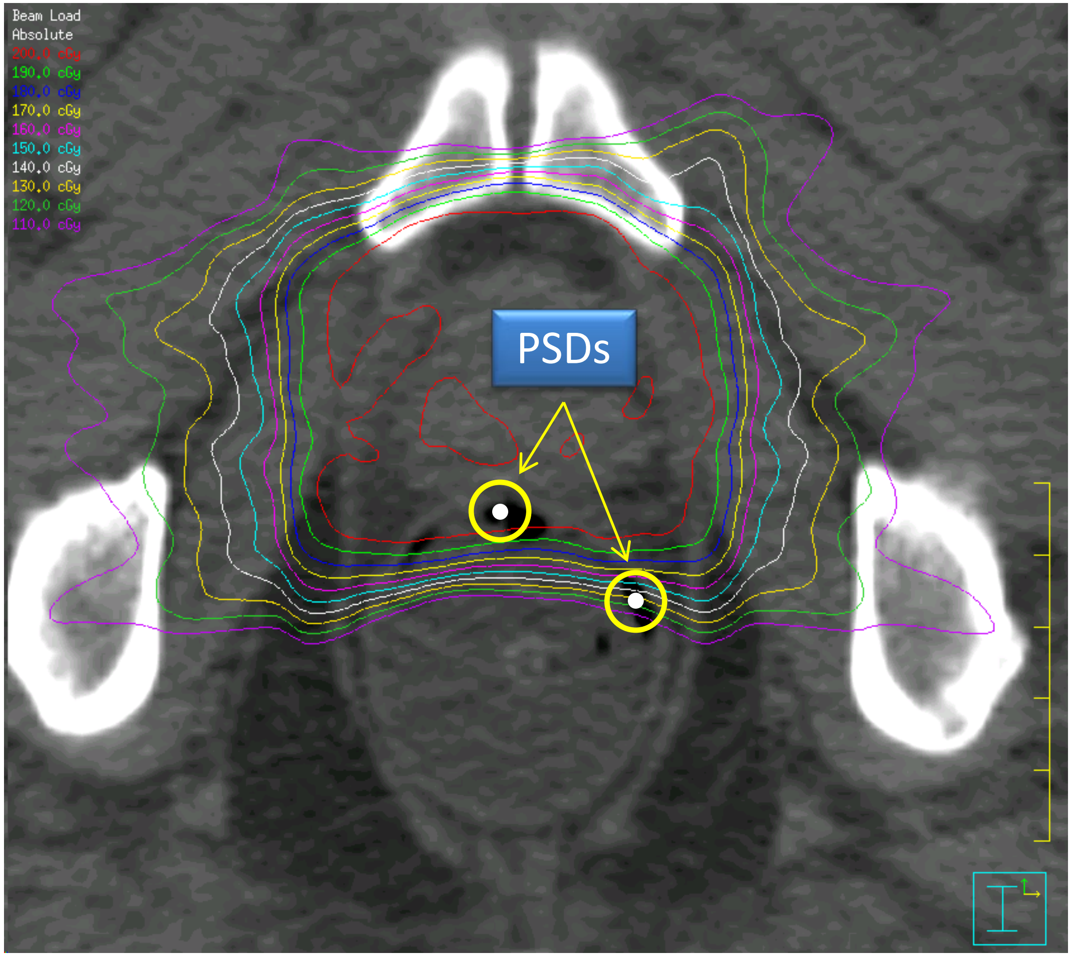
Measurement Results

- Additionally, detectors were well tolerated by patients.
  - 4/5 did not notice a difference between balloons with and without detectors.
  - 1 could tell a difference but said it was tolerable.

- Treatment workflow was not compromised by the adaptation of the in-vivo dosimetry system and the detector placement within the patient.
  - Clinical implementation is feasible and should be non-disruptive to the daily treatment workflow.

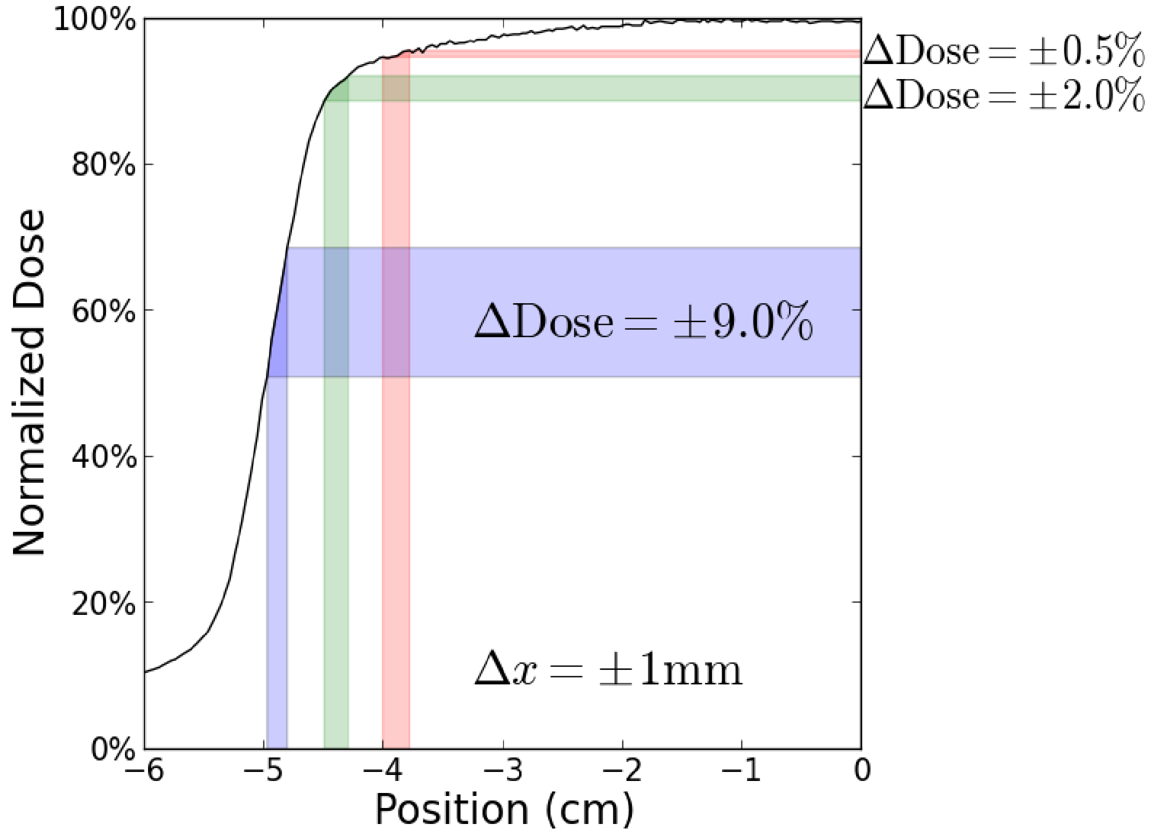
Discussion

- Ideally detectors are positioned anteriorly.
  - Homogeneous and larger doses.
- Balloon is occasionally rotated, positioning detectors laterally in rectum.
  - High dose gradient.
  - Smaller doses.



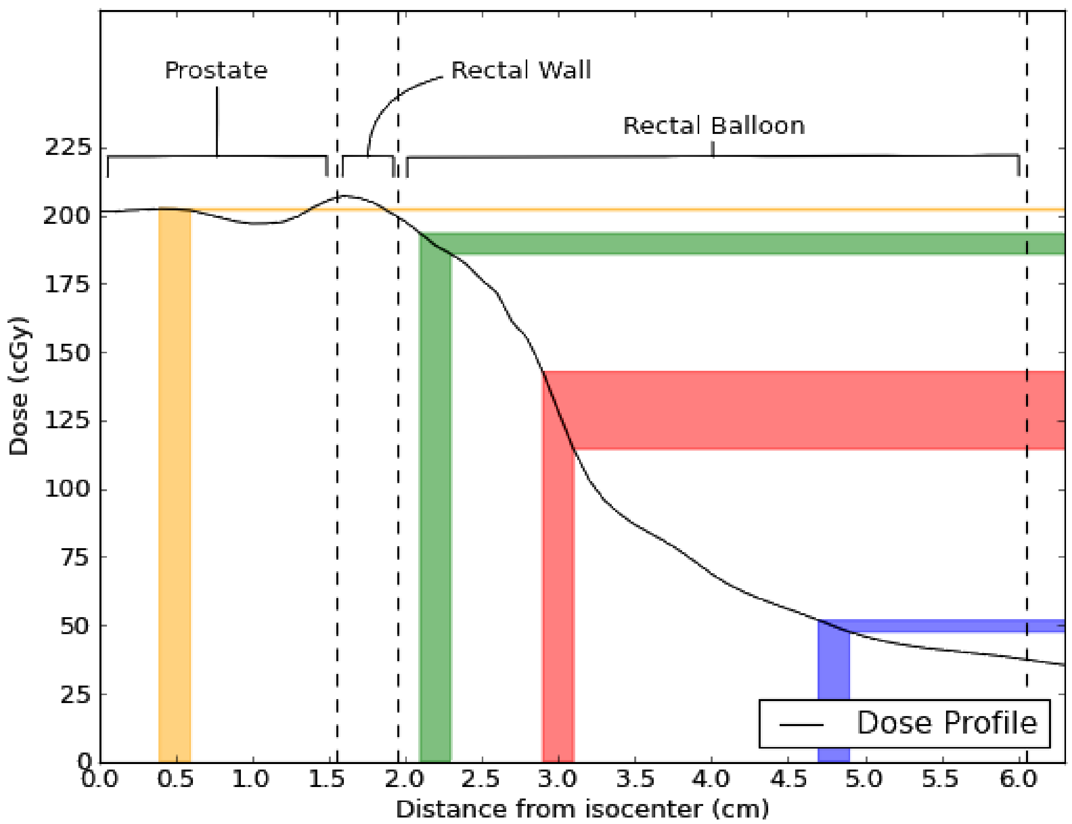
Discussion

- The effect of positional uncertainty on expected dose uncertainty depends greatly on magnitude of the dose gradient.
- Shallow gradient diminishes the effect of positional uncertainty.
- Steep high dose gradient exacerbates the effect of positional uncertainty.



DISCUSSION

Patient dose profile taken from isocenter to posterior rectum.



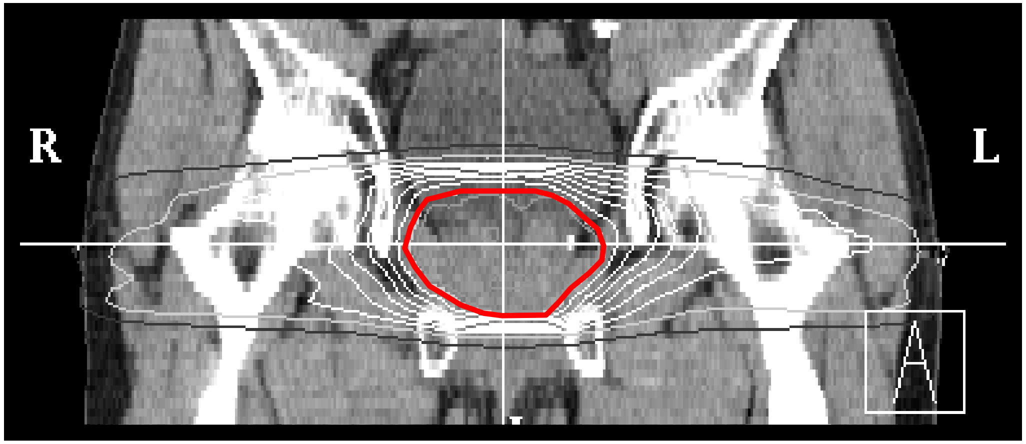
Lateral rectum exhibits the steepest dose gradient: Lower absolute dose inflates % difference.

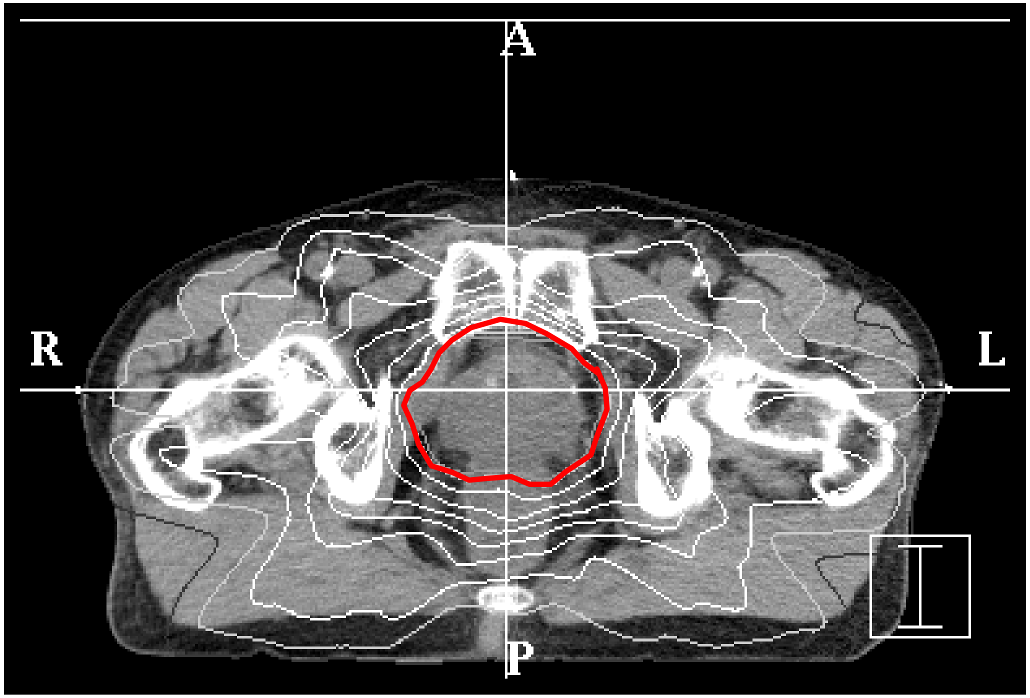
Discussion

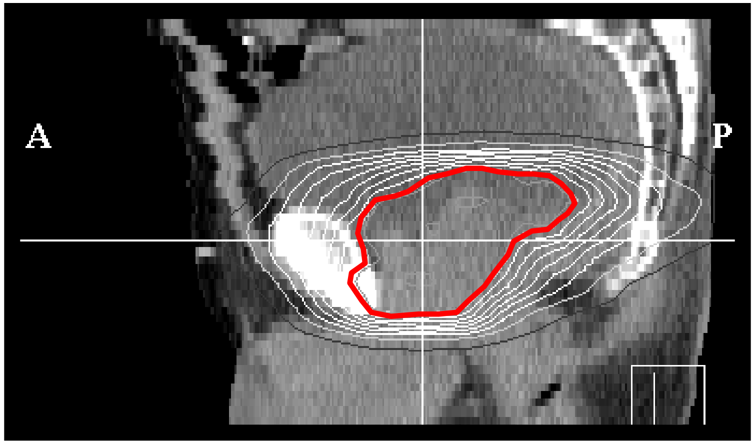
- Measurements with calculated doses > 170 cGy (corresponding to an anteriorly positioned detector) exhibit -1.4% ± 4.7%* average agreement.
- Measurements with calculated doses < 170 cGy (corresponding to laterally/posteriorly positioned detectors) exhibit 0.7% ± 11.1%* average agreement.
- Anterior dose measurements are more consistent.

*Mean and standard deviation of 65 and 72 measurements respectively, considered in aggregate regardless of patient of origin.

Discussion : Prostate Motion ???

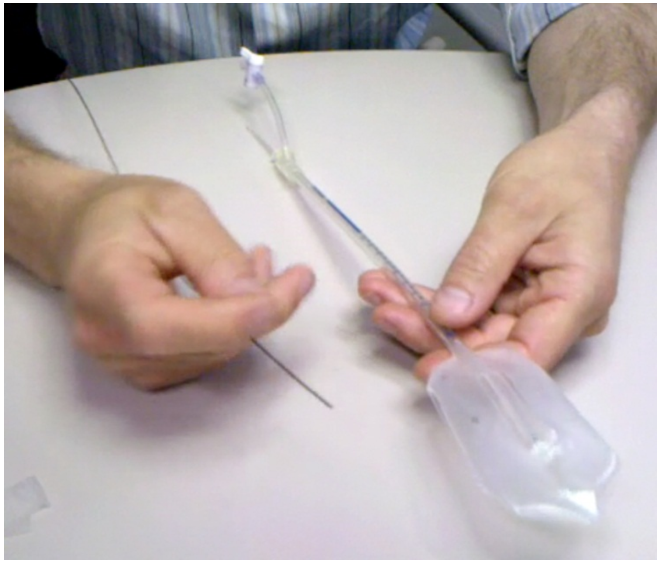


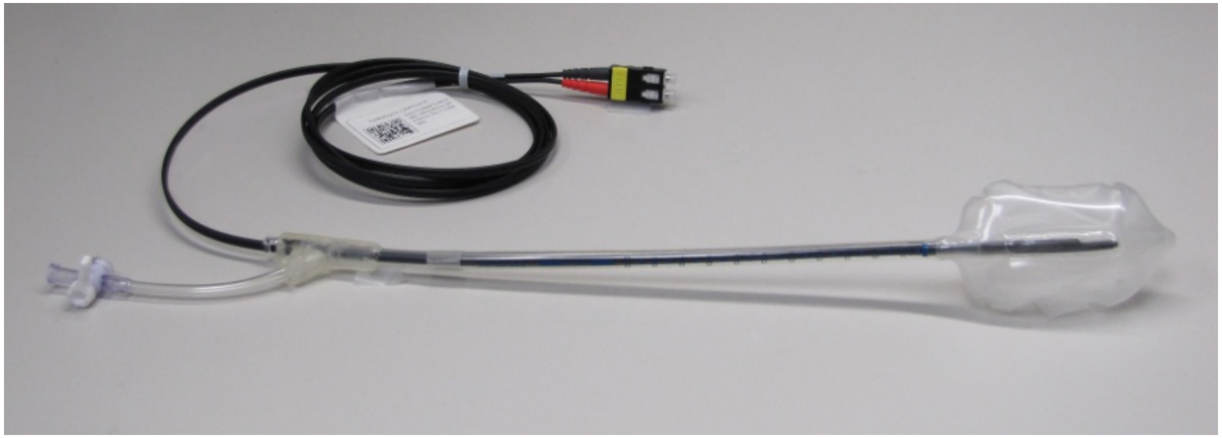




25 treatment CTs acquired during a course of 42 Txs

Lei Dong (MDACC), 2002





Courtesy of John Isham, CEO, RadiaDyne

OTHER RELEVANT STUDIES USING PSDs FOR *IN VIVO* DOSIMETRY (*IN PHANTOM OR IN PATIENTS*)

Lambert J, Nakano T, Law S, Elsey J, McKenzie DR, Suchowerska N. ***In vivo* dosimeters for HDR brachytherapy: a comparison of a diamond detector, MOSFET, TLD, and scintillation detector.** *Med Phys* 34(5): 1759-65, 2007.

Beierholm A, Andersen CE, Lindvold L, Kjær-Kristoffersen F, Medin J. **A comparison of BCF-12 organic scintillators and Al2O3:C crystals for real-time medical dosimetry.** *Radiat Meas* 43(2-6): 898-903, 2008.

Cartwright LE, Suchowerska N, Yin YB, Lambert J, Haque M, and McKenzie DR. **Dose mapping of the rectal wall during brachytherapy with an array of scintillation dosimeters.** *Med Phys* 37: 2247–2255, 2009.

Archambault L, Briere TM, Poenisch F, Beaulieu L, Kuban DA, Lee A, Beddar S. **Toward a real-time in vivo dosimetry system using plastic scintillation detectors.** *Int J Radiat Oncol Biol Phys* 78(1): 280-287, 2010.

Suchowerska N, Jackson M, Lambert J, Yin YB, Hruby G, McKenzie DR. **Clinical trials of a urethral dose measurement system in brachytherapy using scintillation detectors.** *Int J Radiat Oncol Biol Phys* 79(2): 609-15, 2011.

OTHER RELEVANT STUDIES USING PSDs FOR *IN VIVO* DOSIMETRY (*IN PHANTOM OR IN PATIENTS*)

Therriault-Proulx F, Briere TM, Mourtada F, Aubin S, Beddar S, Beaulieu L. **A phantom study of an in vivo dosimetry system using plastic scintillation detectors for real-time verification of 192Ir HDR brachytherapy.** *Med Phys* 38(5): 2542-51, 2011.

Therriault-Proulx F, Archambault L, Beaulieu L, Beddar S. **Development of a novel multi-point plastic scintillation detector with a single optical transmission line for radiation dose measurement.** *Phys Med Biol* 57(21): 7147-7159, 2012.

Klein D, Briere TM, Kudchadker R, Archambault L, Beaulieu L, Lee A, Beddar S. **In-phantom dose verification of prostate IMRT and VMAT deliveries using plastic scintillation detectors.** *Radiat Meas* 47(10): 921-929, 2012.

Therriault-Proulx F, Beddar S, Beaulieu L. **On the use of a single-fiber multipoint plastic scintillation detector for (192)Ir high-dose-rate brachytherapy.** *Med Phys* 40(6): 062101, 2013.

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Co-authors

F.H. Attix
S. Aubin
S.F. de Boer
J. Boivin
A. Bourgoin
T.M. Briere
P. Després
J.C. Gagnon
M.T. Gillin
L. Gingras
M. Goulet
M. Guillemette
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A. Ikhlef
S. Klawikowski
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… and all others who have contributed to the field of scintillation dosimetry.

What is so Special About the 3 Colors ?

- **AAPM 2008 --- introducing PSDs, basics & properties**
  "Scintillation Dosimetry: Review, New Innovations and Applications"
- **AAPM 2010 --- further studies & validation of PSDs**
  "Scintillation Dosimetry: From Plastics to Liquids and from Photons/Electrons to Protons"
- **AAPM 2013 --- application of commercial PSDs**
  "PSDs: Present Status and their Applications for Quality Assurance and In Vivo Dosimetry"

The 3 colors of scintillators R-G-B