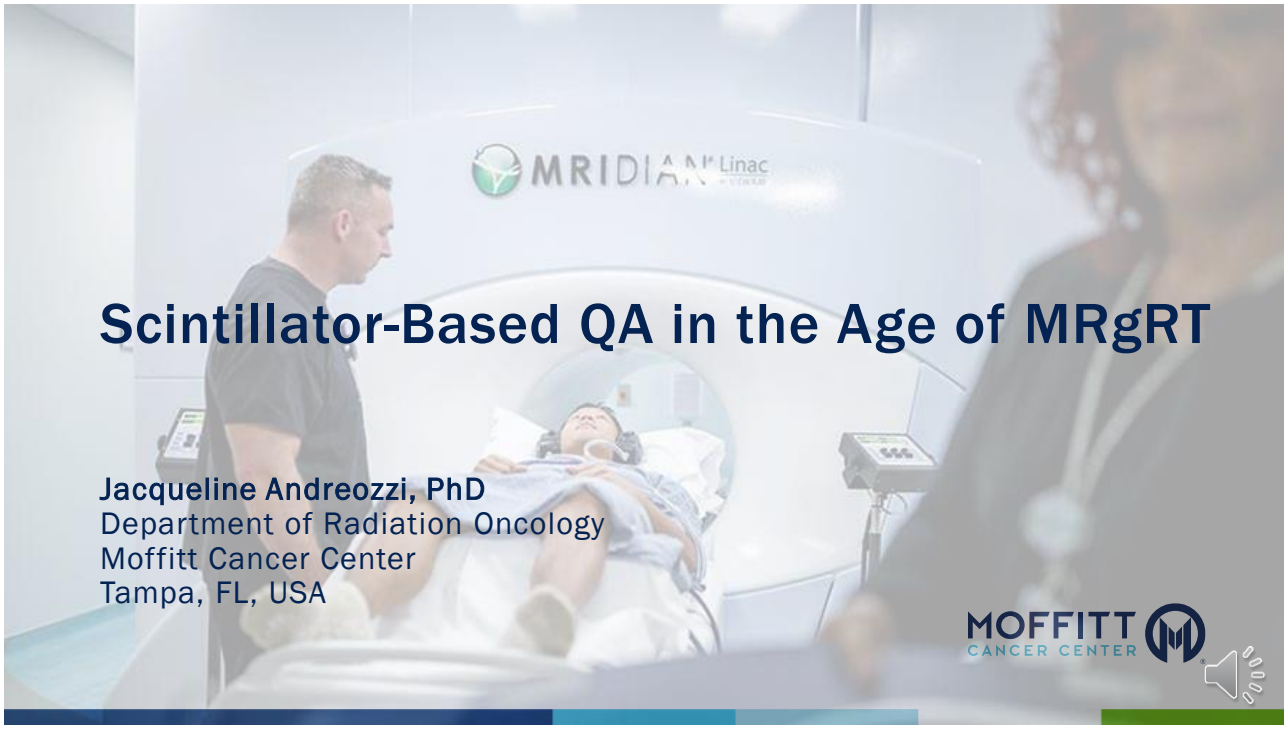


Scintillator-Based QA in the Age of MRgRT

Jacqueline Andreozzi, PhD
Department of Radiation Oncology
Moffitt Cancer Center
Tampa, FL, USA

MOFFITT CANCER CENTER

1

Disclosure

I have no actual or potential financial conflicts of interest to disclose.

2

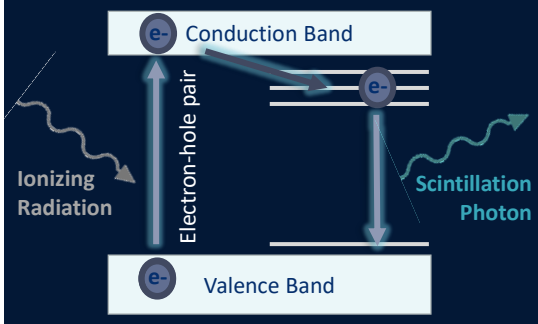
Learning Objectives

- Basics of Scintillation
- Optical Dosimetry Approaches
- Applications in MRgRT
- Future Prospects

3

Scintillation: Light Released Proportional to Dose

Mechanism



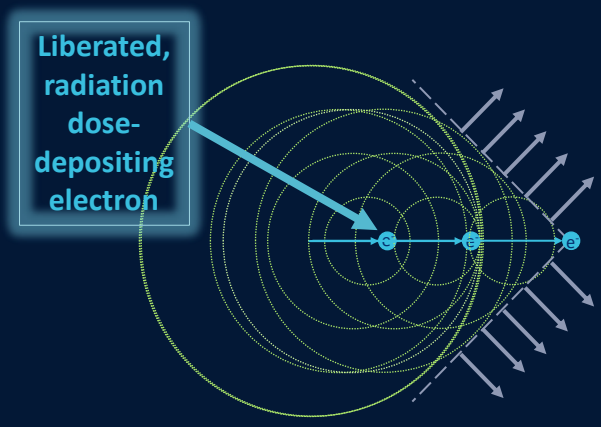
- Energy released thru scintillation is proportional to incident energy absorbed (i.e. dose)
- Emission is isotropic

POSSIBLE SCINTILLATORS:
Organic and inorganic crystals, plastics, noble gases, and silicates

Image: Eljen Technology Plastic Scintillators

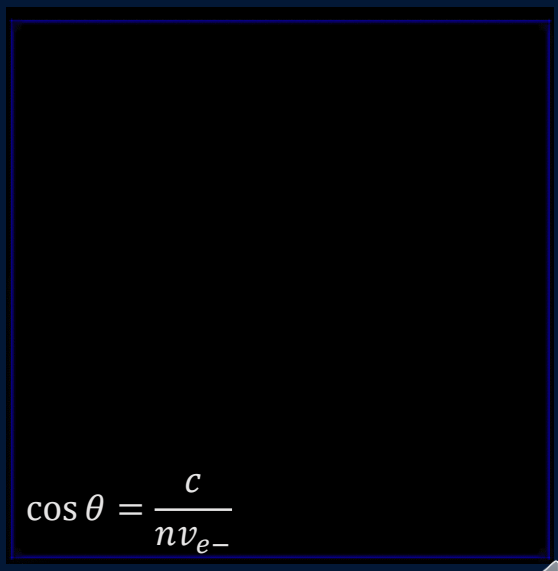
4

The Other Optical Signal: Cherenkov



$$v_{e-} = \frac{c}{n} \qquad v_{e-} > \frac{c}{n}$$

Inherent directionality in emission

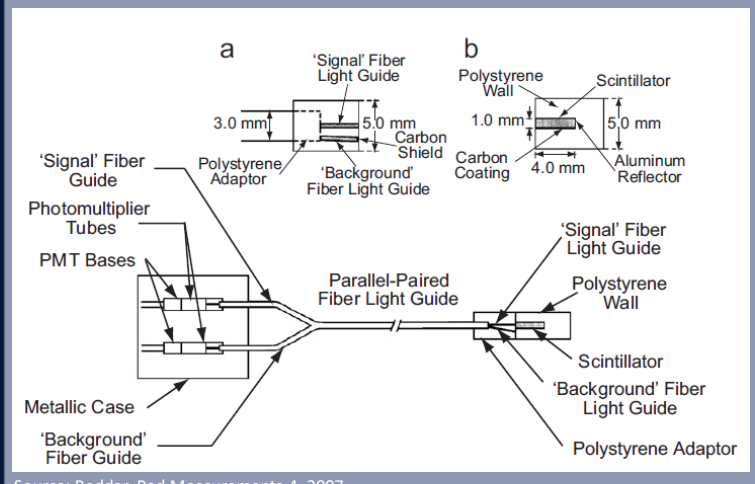


$$\cos\theta = \frac{c}{n v_{e-}}$$

Video courtesy of Adam Glaser

5

Optical Fibers Are The Traditional Signal Collectors



Source: Beddar, Rad Measurements 4, 2007

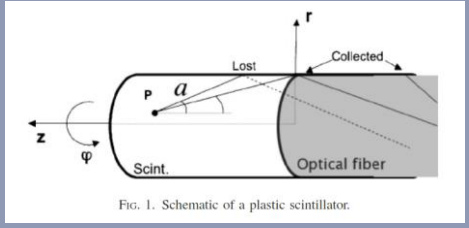


FIG. 1. Schematic of a plastic scintillator.

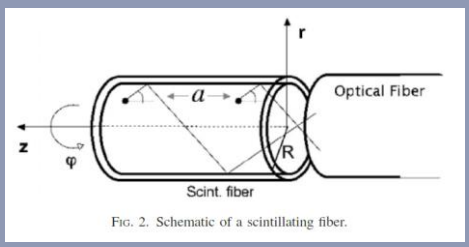


FIG. 2. Schematic of a scintillating fiber.

Source: Archambault *et al.*, Med Phys 32(7), 2005

Photomultiplier tube (PMT) or photodiode (PD) is used to convert optical signal to electrical signal read by electrometer

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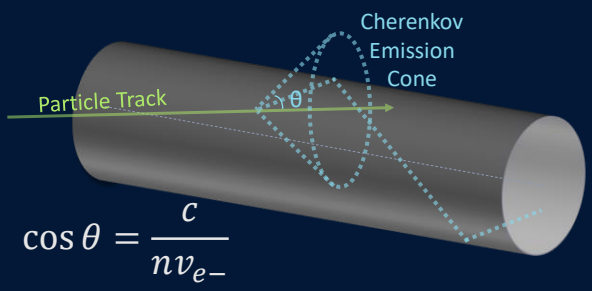
Challenge: Isolating Scintillation from Cherenkov



$$\cos\theta = \frac{c}{nv_{e-}}$$

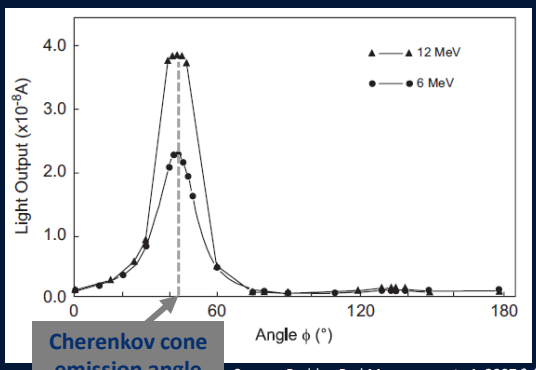
Cherenkov intensity measured is dependent on:

- Angle
- Material(s)
- Energy
- Length of cable irradiated

Cherenkov is removed from scintillation signal thru:

- Subtraction of Cherenkov in background optical cable
- Spectral methods of calibration (Guillot et al, Med Phys 38(4) 2011

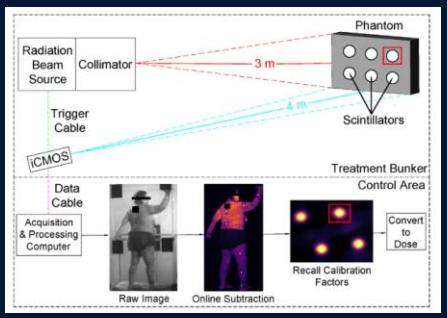
- X-rays: ~3% of the signal
- Electrons: ~12% of the signal



Source: Beddar, Rad Measurements 4, 2007

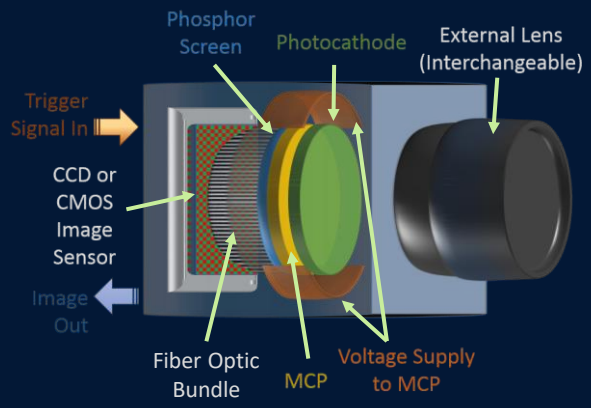
7

Cameras Make Wire-Free Measurements Possible



Source: Tendler et al., Phys Med Biol 64, 2019

Anatomy of an Intensified CMOS Camera System



Individual or binned pixel intensities (12-16 bit depth) are the quantified signal, as opposed to electrometer readings.

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A Brief History of Plastic Scintillators in RT

Fiber-based point detectors

- 1992 – Beddar *et al.,* Water-equivalent plastic scintillation detectors for high-energy beam dosimetry: 1. Physical characteristics and theoretical considerations, Phys Med Biol 37(10)
- 1999 – Letourneau *et al.,* Miniature scintillating detector for small field radiation therapy, Med Phys 26(12)
- 2011 – Guillot et al., 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(4)
- 2015 – Underwood et al., Application of the Exradin W1 scintillator to determine Ediode 60017 and microdiamond 20019 correction factors for relative dosimetry within small MV and FFF fields, Phys Med Biol 60(17)

Remote camera systems

- 2019 – Tendler *et al.,* Rapid Multisite Remote Surface Dosimetry for Total Skin Electron Therapy: Scintillator Target Imaging, Int J Radiat Oncol Biol Phys, 103(3)
- 2020 – Alexander *et al.,* Scintillation imaging as a high-resolution, remote, versatile 2D detection system for MR-linac quality assurance, Med Phys, 47(9)

10

Advantages of Plastic Scintillator Dosimeters

- Water equivalence
- Energy independe
- Angular independe
- Dose linearity
- Dose rate independence
- Near temperature independence
- Resistant to radiation damage
- <1mm spatial resolution
- Real-time (~ns temporal resolution)
- Does not perturb small field dose distributions

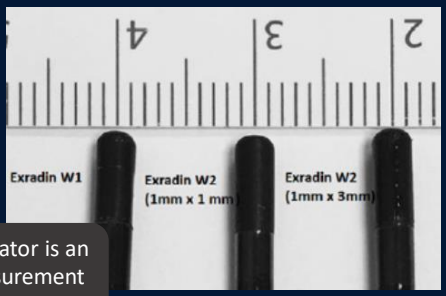
Nonmagnetic materials!

"Virtually invisible to the beam, the W2 provides less uncertainty with fewer correction factors."
- Exradin® W2 Scintillator promotional materials, *https://www.standardimaging.com/exradin-detectors/scintillators*

11

Commercially Available Systems: Exradin W1 and W2

Image source: Carrasco *et al.*, Med Phys 42(1), 2



e: Galavis *et al.*, Med Phys 46(5), 2019

Small 1mm x 1mm scintillator is an excellent choice for measurement of small fields

EXRADIN W2 SCINTILLATOR SPECIFICATIONS

SCINTILLATING FIBER COLLECTING VOLUME

W2-1x1 — 1.0 mm diameter x 1.0 mm long // **W2-1x3** — 1.0 mm diameter x 3.0 mm long
SCINTILLATOR HOUSING — 2.8 mm diameter x 42 mm long
OPTICAL FIBER — 1.0 mm diameter core x 2.2 diameter jacket x 4 m long

MATERIALS

SCINTILLATING FIBER — Polystyrene with ABS plastic enclosure and polyimide stem
OPTICAL FIBER — Acrylic (PMMA) with Polyethylene jacket
OPTICAL FIBER MINIMUM BEND RADIUS — 6 cm
SCINTILLATING FIBER PHYSICAL DENSITY — 1.05 g/cm3
RADIATION DEGRADATION — ~2% / kGy

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The Quest for Spatial Resolution: 2D Fiber Arrays



Spatial resolution for optical fiber arrays quickly becomes a logistical nightmare.

Image source: Lacroix *et al.*, Med Phys 35(8), 2008

13

Camera Systems Can Provide 1D/2D Dose Distributions

Wireless scintillation *in vivo* dosimetry during TSET with remote intensified CMOS camera system.

Source: Tendler *et al.*, Int J Radiat Oncol Biol Phys, 2019

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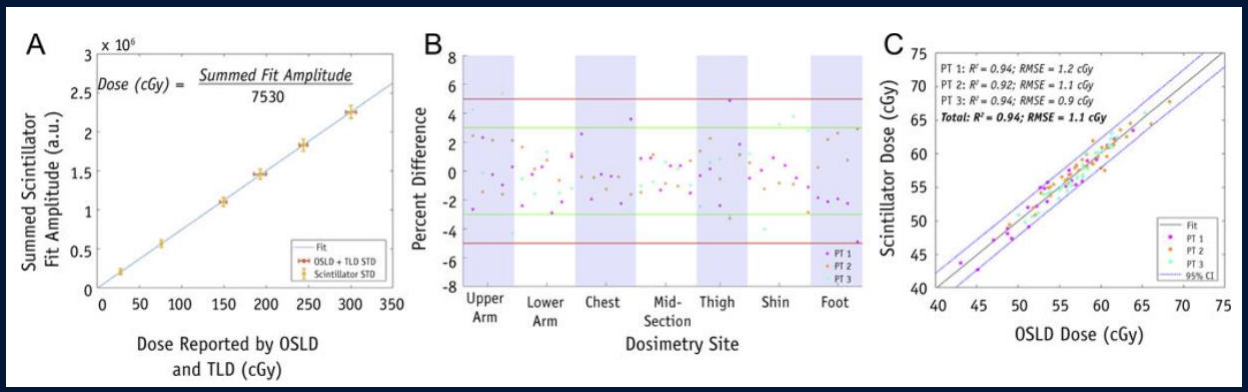
Scintillation Dosimetry during TSET



Source: Tendler *et al.,* Int J Radiat Oncol Biol Phys, 2019

15

Learning Objectives

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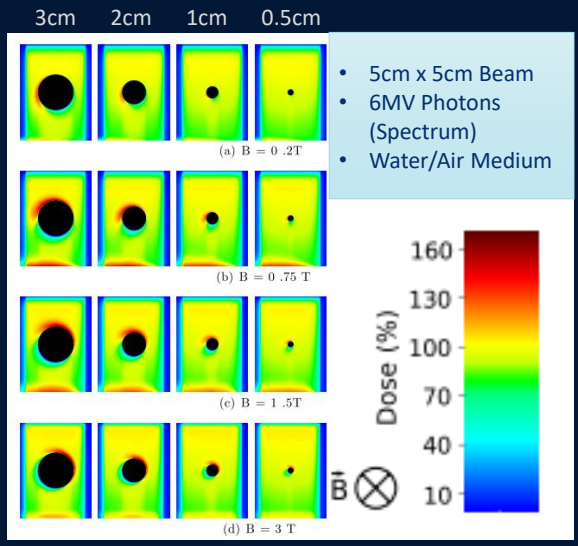
Air Cavities and Dose in a Magnetic Field



Monte Carlo simulation conducted in GEANT 4 ver. 8.1

- Effects are most pronounced at high-low density media interfaces
- Lorentz forces curl the electron paths as they are liberated from the solid medium and enter the air cavities
- Have to consider how a detector perturbs the phantom

Source: Raaijmakers *et al.,* Phys Med Biol 53, 2008

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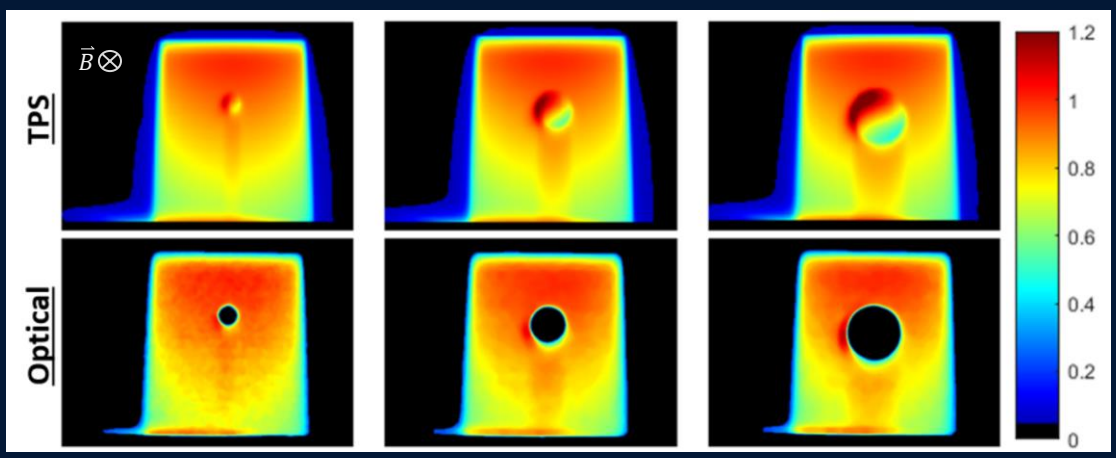
Electron Return Effect Visualized in Acrylic



Direct measurement of the Electron Return Effect on a 0.35T MR-Linac

Source: Andreozzi *et al.,* Med Phys 47(3), 2020

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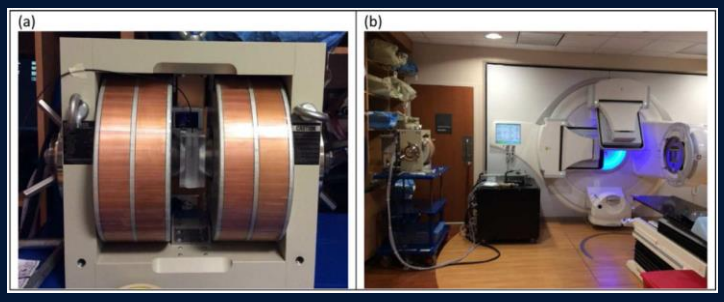
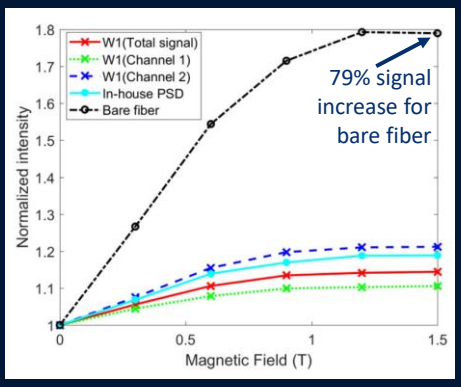
The Golden Question: How Does A Magnetic Field Affect Scintillation Signal?



Increased magnetic field from 0T to 1.5T in 0.3T increments

- Magnetic field affects trajectories of Cherenkov-inducing electrons
- Directional Cherenkov signal varies with magnetic field
- Isotropic scintillation signal should be unperturbed
- Proper Cherenkov-removal corrects for these changes
- Less dependence on magnetic field strength than ion chambers



Increase in raw light intensity measured with increase in magnetic field strength

Source: Therriault-Proulx *et al.,* Radiat Meas 116, 2018

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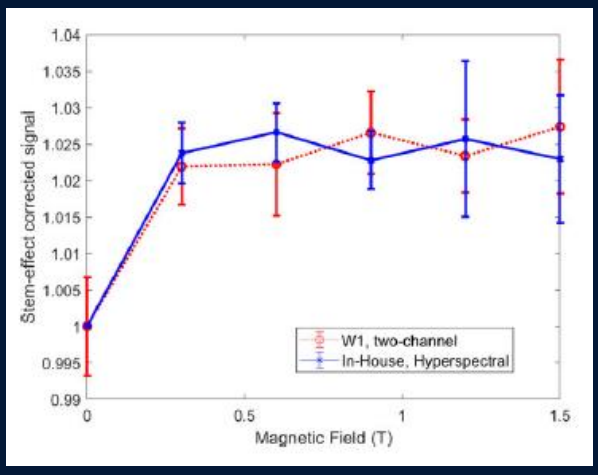
The Golden Question: How Does A Magnetic Field Affect Scintillation Signal?



- Directional Cherenkov signal is affected by B field
- Isotropic scintillation signal is not
- Robust noise removal is possible

Scintillators remain an excellent choice for measurement of small fields, even in MR-linacs.

Source: Therriault-Proulx *et al.,* Radiat Meas 116, 2018

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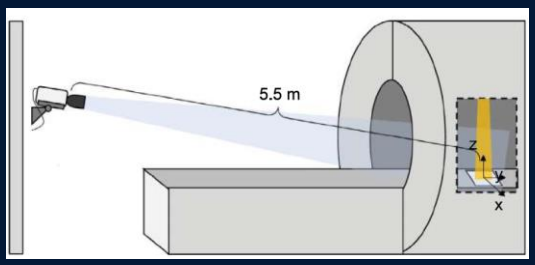
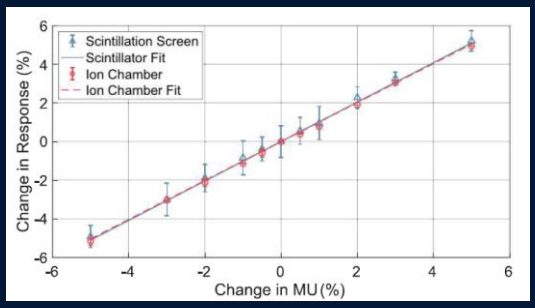
Scintillation Imaging for routine MR-Linac QA



- ICMOS camera mounted at foot of the couch
- 14” x 17” scintillation screen inside the bore in the beam path
- 10 fps readout
- 100, 200, or 500 MU per beam measured
- Sensitivity compared to calibrated A28 IC



Tests Performed:

- Field profiles (concurrent cross-plane and in-plane)
- MLC shifts
- Picket fence
- Star-shot isocenter test (scintillation screen upright, parallel to beam)

Source: Alexander *et al.,* Med Phys 47(9), 2020

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MR-Linac Field Profiles Measured on Scintillation Screen

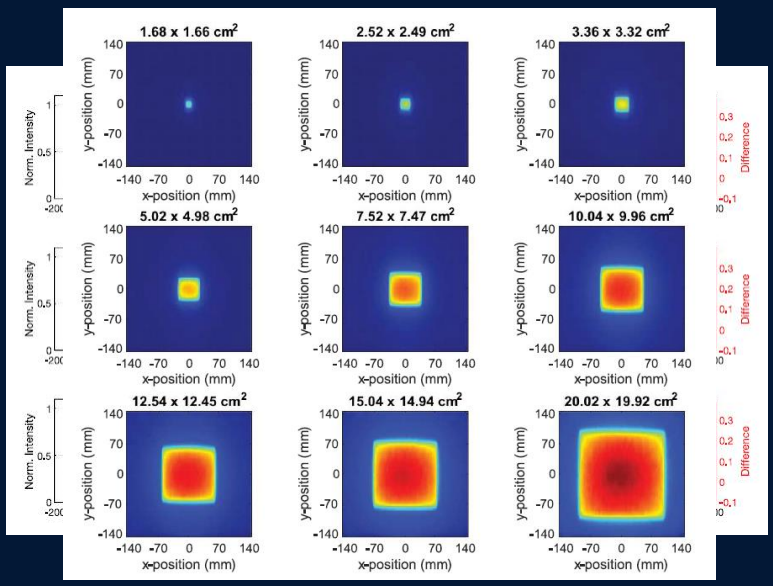

Table I. Field profiles.

Field size (cm)	Scintillator FWHM (cm)	Discrepancy mm	Discrepancy %
Cross-plane			
1.68	1.59	−0.9	−5
2.52	2.46	−0.6	−2
3.36	3.32	−0.4	−1
5.02	4.99	−0.3	−1
7.52	7.48	−0.4	−1
10.04	9.93	−1.1	−1
12.54	12.36	−1.8	−1
15.04	14.81	−2.3	−2
20.02	19.69	−3.3	−2
In-plane			
1.66	2.12	4.6	28
2.49	2.73	2.4	10
3.32	3.59	2.7	8
4.98	5.17	1.9	4
7.47	7.53	0.6	1
9.96	10.03	0.7	1
12.45	12.43	−0.2	0
14.94	14.99	0.5	0
19.92	19.71	−2.1	−1

Source: Alexander *et al.,* Med Phys 47(9), 2020

Improvements to the image transformation or imaging geometry could be necessary for in-plane small field measurements.

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MR-Linac MLC Shifts Using Scintillating Screen

TABLE II. Measured vs programmed MLC shifts.

Programmed shift (mm)	Measured shift (mm)	Discrepancy mm	Discrepancy %
Scintillation Screen			
0.50	0.44	−0.06	−12
1.00	0.92	−0.08	−8
2.00	2.02	0.02	1
3.00	3.02	0.02	1
IC profiler-MR			
0.50	0.71	0.21	42
1.00	1.20	0.20	20
2.00	2.03	0.03	1
3.00	2.69	−0.31	−10

- MLC shifts 0.5mm-3mm
- Scintillator sensitive to shifts ≥ 0.5mm
- Scintillator average discrepancy: 0.04mm
- IC Profiler-MR average discrepancy: 0.19mm
- IC Profiler-MR limited by detector array resolution

Source: Alexander *et al.,* Med Phys 47(9), 2020

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MR-Linac Scintillation Screen Picket Fence Test

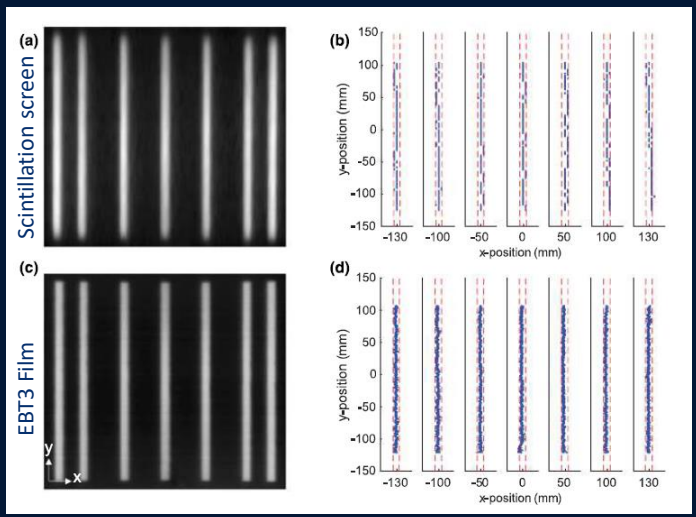

TABLE III. Picket fence test results.

MLC position (mm)	Measured position (mm) Scintillation screen	Film
−130.00	−130.3 ± 0.4	−130.1 ± 0.3
−100.00	−100.2 ± 0.4	−100.2 ± 0.3
−50.00	−49.8 ± 0.4	−50.1 ± 0.2
0.00	0.2 ± 0.4	−0.3 ± 0.3
50.00	50.4 ± 0.4	49.6 ± 0.2
100.00	100.4 ± 0.4	99.7 ± 0.2
130.00	130.3 ± 0.6	129.9 ± 0.2

- Both scintillation and EBT3 film results agree within 1mm tolerance

Source: Alexander *et al.,* Med Phys 47(9), 2020

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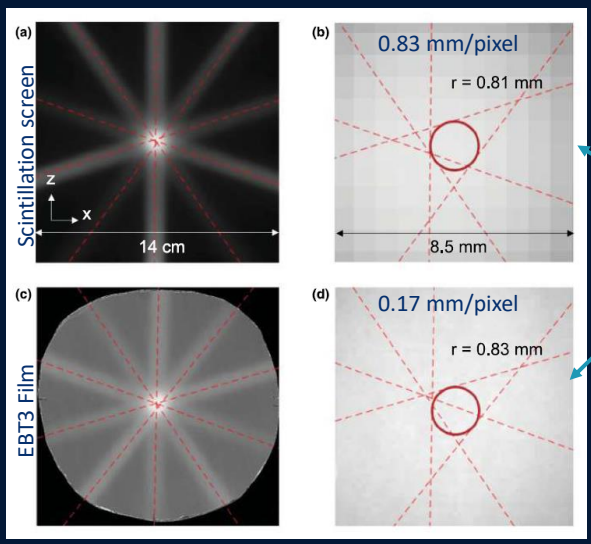
MR-Linac Star Shot Using Scintillating Screen



2% difference in measured isocenter radius

Source: Alexander *et al.,* Med Phys 47(9), 2020

25

Concurrent Approach to Verifying RT, MRI, and Laser Isos

Source: Andreozzi *et al.,* AAPM Annual Meeting 2018

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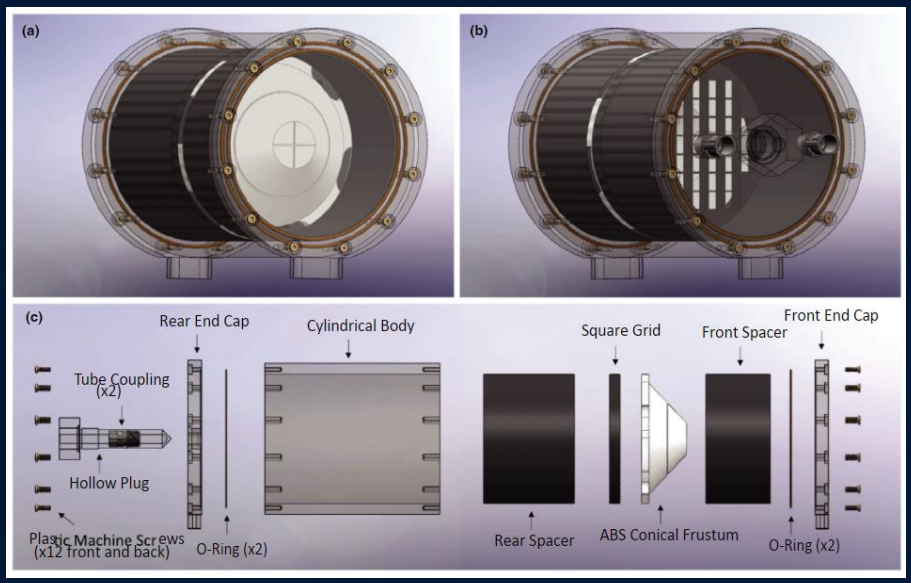
Visual Isocenter Position Enhanced Review (VIPER)



Source: Alexander *et al.*, Med Phys (Accepted, 2021)

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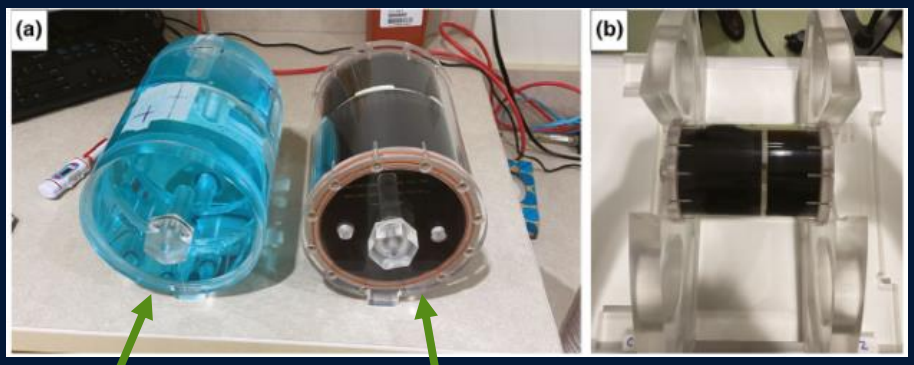
Visual Isocenter Position Enhanced Review (VIPER)



Manufacturer daily QA phantom

Prototype daily QA phantom

Prototype daily QA phantom in manufacturer jig

Source: Alexander *et al.*, Med Phys (Accepted, 2021)

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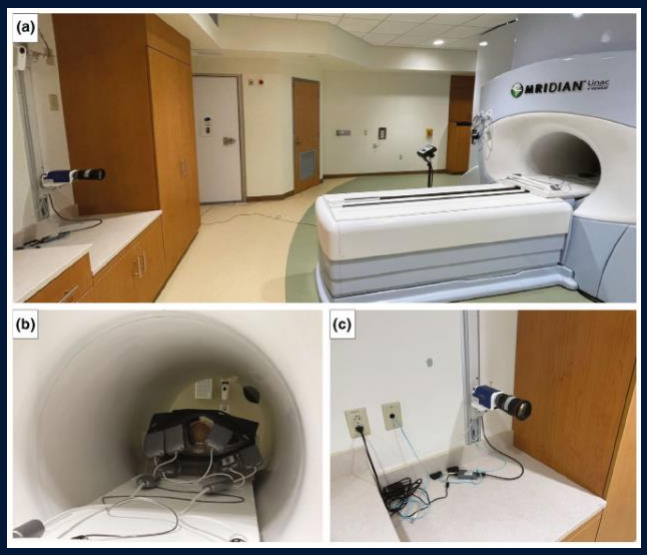
Visual Isocenter Position Enhanced Review (VIPER)



iCMOS camera system mounted on wall at foot of the couch

Source: Alexander *et al.*, Med Phys (Accepted, 2021)

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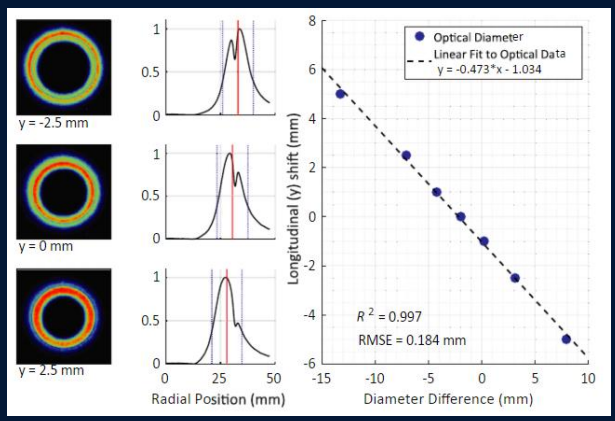
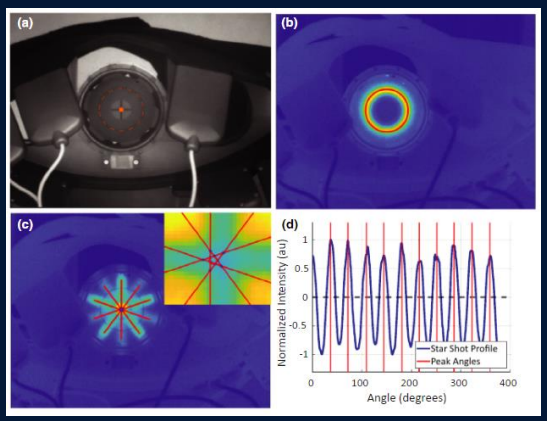
Visual Isocenter Position Enhanced Review (VIPER)



Ring diameter correlates to RT isocenter in-out of bore (y axis)



Star-shot correlates to RT x-z isocenter alignment

Source: Alexander *et al.*, Med Phys (Accepted, 2021)

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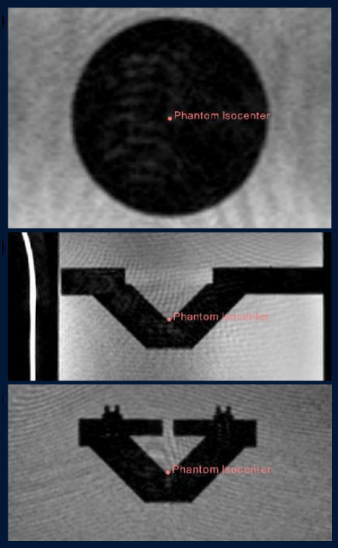
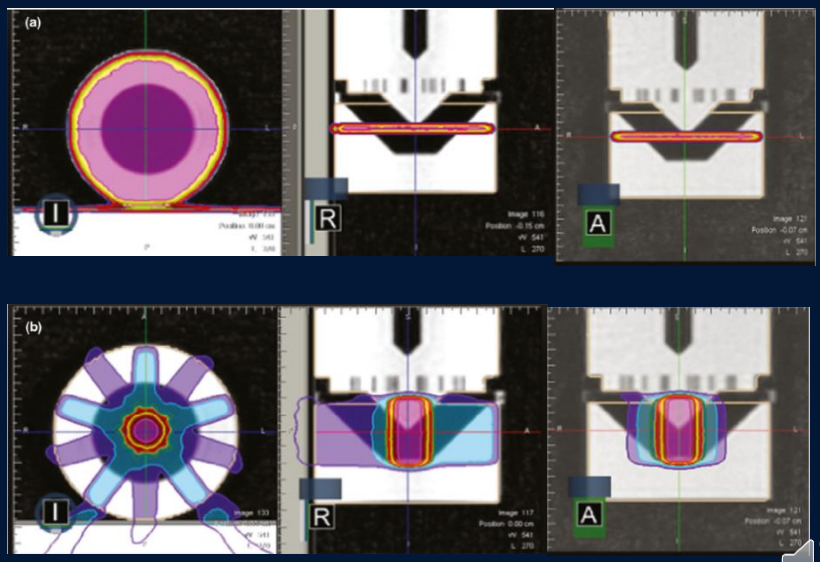
MRI Isocenter Extracted from Phantom Features



Source: Andreozzi *et al.,* AAPM Annual Meeting 2018



Source: Alexander *et al.,* Med Phys (Accepted, 2021)

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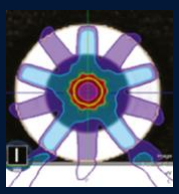
Summary: Scintillation Approaches to MR-Linac QA

- Fiber-based scintillation detectors have been shown to perform well in magnetic fields
  - Good choice for small-field measurements on MR-Linac
  - Commercial products available
- Remote camera acquisition of scintillation has been used for *in vivo* wireless dosimetry in TSET
- Remote camera acquisition of scintillation has been implemented in MR-Linac QA tasks



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Patient QA Needs In Adaptive Radiotherapy

- Current practice:
  - ArcCheck-MR measurement for every initial patient plan
  - Secondary dose calculation comparison for each adaptive plan (with patient on the table)
- Ask ourselves, is it *really* necessary to implement more extensive patient QA?
- Opinion: It is more prudent to focus on rigorous commissioning, and efficient, regular, machine QA tasks
- Scintillation-based dosimetry is a promising tool that could be developed to streamline machine QA

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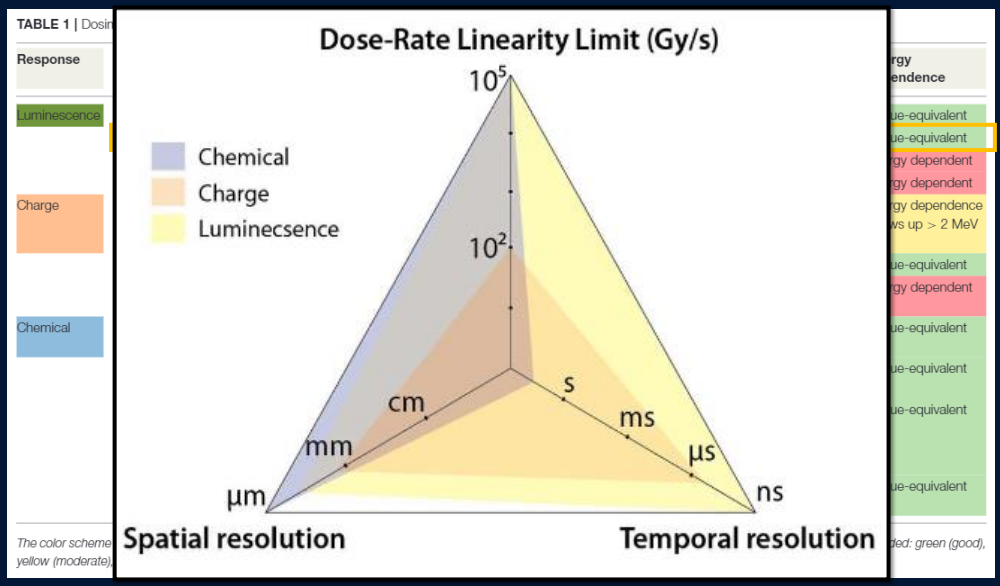
Promising Scintillator Prospects in FLASH



Source: Ashraf et al., Frontiers in Physics, 8(328), 2020

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Acknowledgements

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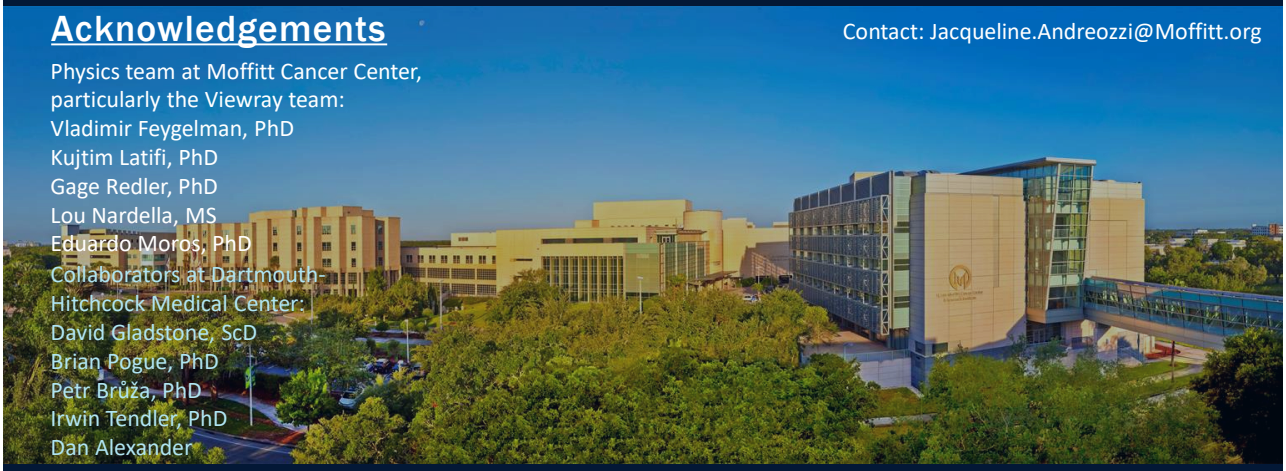
David Gladstone, ScD
Brian Pogue, PhD
Petr Brůža, PhD
Irwin Tendler, PhD
Dan Alexander

Contact: Jacqueline.Andreozzi@Moffitt.org



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