Update on *in-vivo* Dosimetry in Real Time

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Review & update of material presented last year

Cancer Statistics

- Cancer remains the 2nd highest cause of mortality in US*

US Mortality, 2003

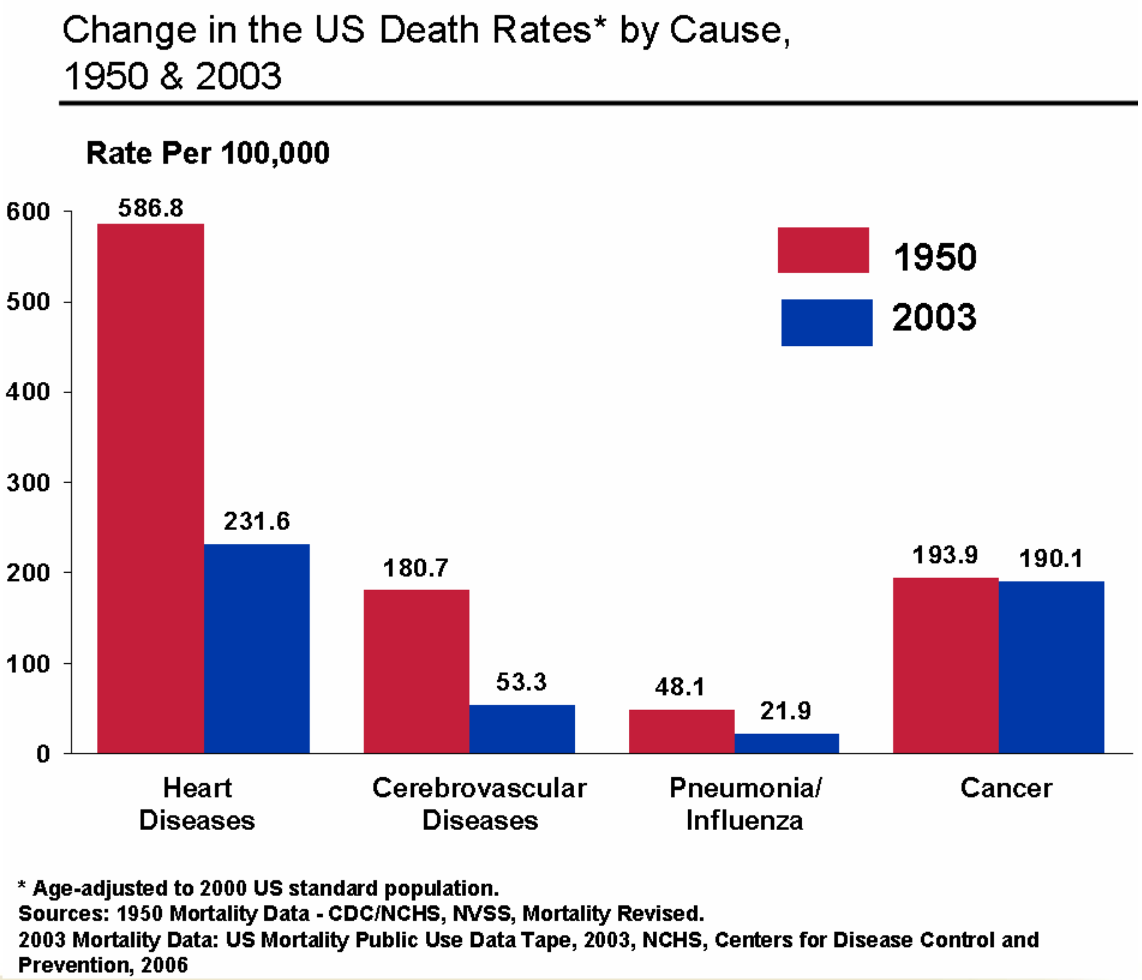
Rank	Cause of Death	No. of deaths	% of all deaths
1.	Heart Diseases	685,089	28.0
2.	**Cancer**	**556,902**	**22.7**
3.	Cerebrovascular diseases	157,689	6.4
4.	Chronic lower respiratory diseases	126,382	5.2
5.	Accidents (Unintentional injuries)	109,277	4.5
6.	Diabetes mellitus	74,219	3.0
7.	Influenza and pneumonia	65,163	2.7
8.	Alzheimer disease	63,457	2.6
9.	Nephritis	42,453	1.7
10.	Septicemia	34,069	1.4

Source: US Mortality Public Use Data Tape 2003, National Center for Health Statistics, Centers for Disease Control and Prevention, 2006.

*Cancer Statistics 2006, A Presentation From the American Cancer Society

Cancer Statistics

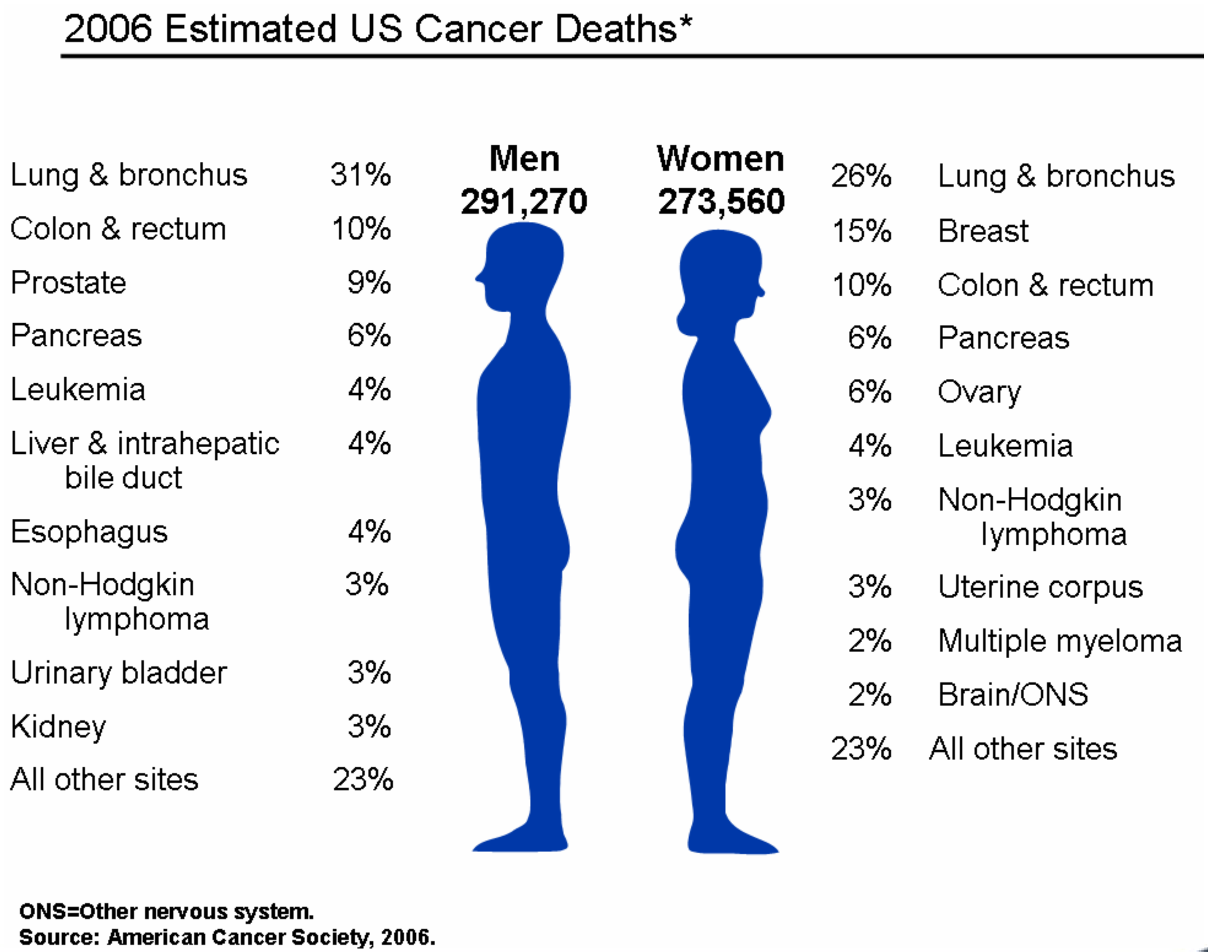
- Mortality rates due other causes decreased over the years, but the rate due to cancer remains about the same*



*Cancer Statistics 2006, A Presentation From the American Cancer Society

Cancer Statistics

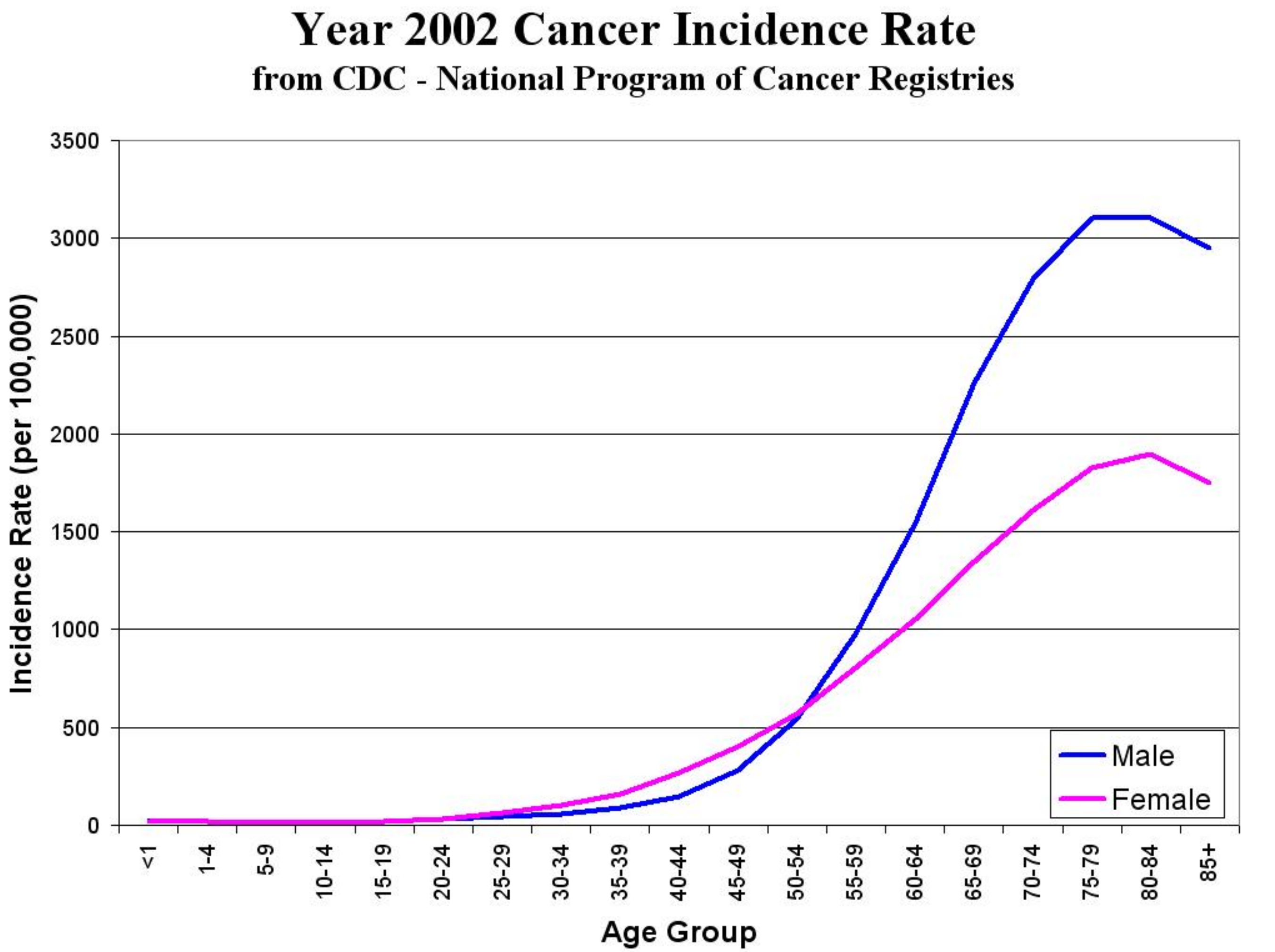
- The 3rd highest case of cancer in American male is prostate cancer*



*Cancer Statistics 2006, A Presentation From the American Cancer Society

Cancer Statistics

- Cancer Incidence by Age Group



Cancer Treatment

- Over 200,000 new cases of prostate cancer diagnosed per year in US

- Unless dramatic change is made in treatment of prostate cancer, radiotherapy is likely to remain treatment of choice in foreseeable future

Need for Real-Time Dosimetry

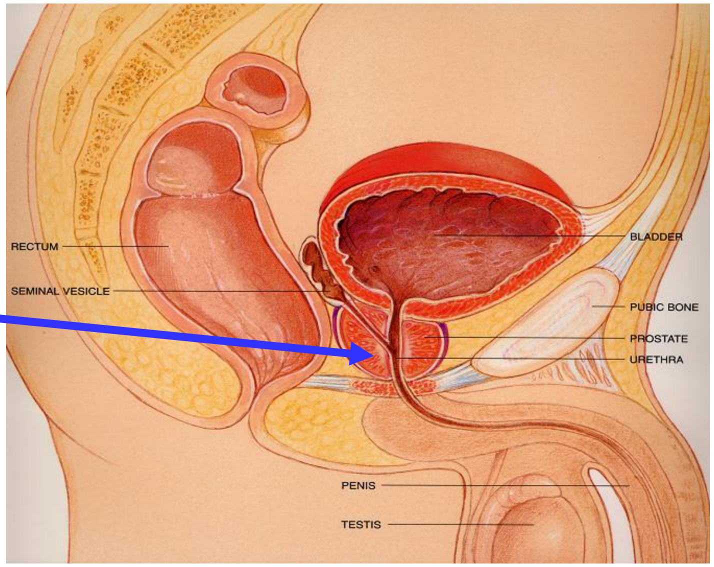
- Accurately assessing the dose to target organs and surrounding tissues in radiation therapy is paramount to achieving maximum treatment efficacy

- The goal of radiation therapy is to:
  - deliver an optimum dose of ionizing radiation to the target area
  - minimizing the dose to the surrounding tissues

Need for Real-Time Dosimetry

- Frequently the target tissue is:
  - spatially dynamic
  - in close proximity to other tissues whose radiation dose should be minimized to avoid damage

Example: prostate



Need for Real-Time Dosimetry

- Skin Dose
  - There also is a need to accurately assess skin dose in real-time during fluoroscopically-guided interventional procedures to minimize skin damage
  - This has become a concern to the extent that FDA proposed regulations for monitoring radiation doses delivered by fluoroscopy machines[1]

[1] Federal Register 2002; Vol.67, No.237, pp. 76055-76094, Dec 10, 2002

Need for Real-Time Dosimetry

- A highly spatially resolved real-time patient dosimetry system
  - Instantaneous verification of radiation dose

- Real-time radiation dose
  - Allow balancing the clinical benefit of enhanced visualization versus radiation risks associated with long interventional procedures

Current State of Real-Time Dosimetry

- MOSFET:
  - Semiconductor detector
  - Radiation damage to semiconductor causes shift in threshold voltage
  - Threshold shift is proportional to absorbed dose
  - Threshold voltage shift is measured after irradiation, i.e., not true real-time dosimeter

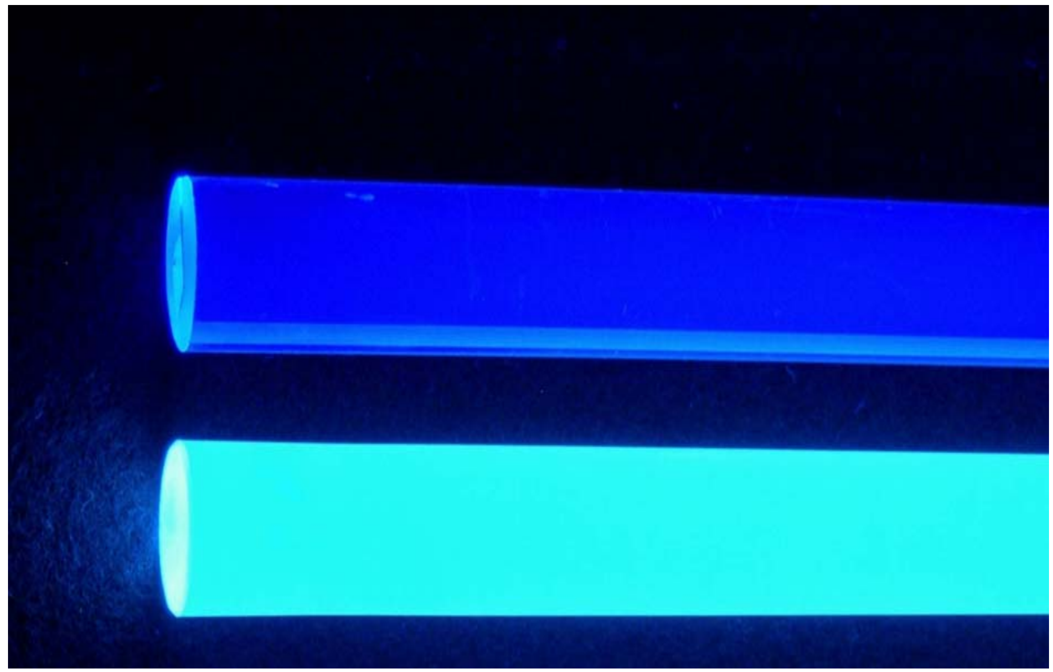
Current State of Real-Time Dosimetry

- Diode:
  - Semiconductor detector
  - Ionizing radiation produces free electrons and holes
  - The number of electron-hole pairs depends on the energy transmitted by the radiation to the semiconductor
  - Real-time dosimeter
  - Relatively large

Development of Real-Time Dosimeter

- Global Dosimetry Solutions is endeavoring to develop real-time dosimeter

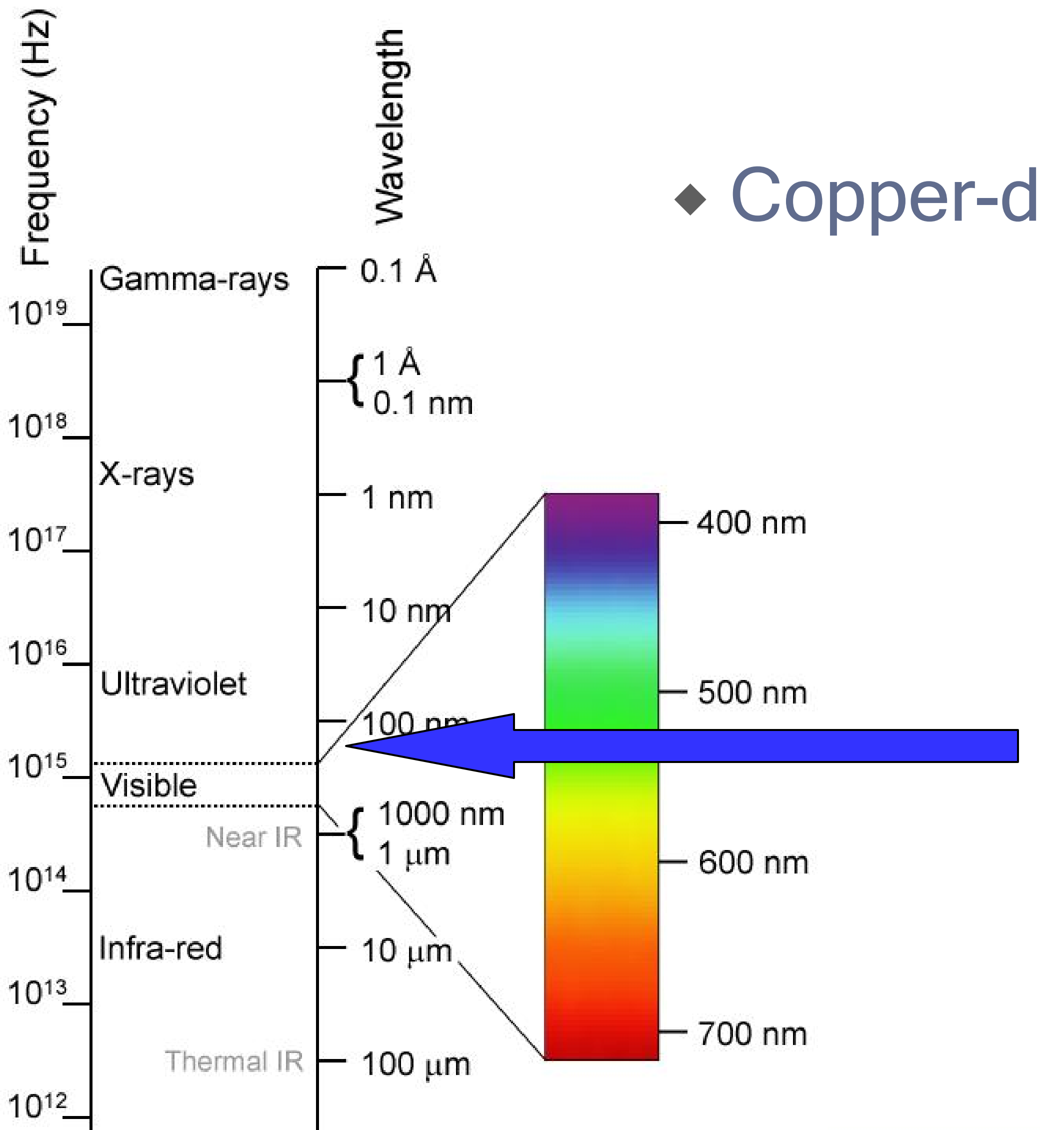
The core technology was developed at the US Naval Research Laboratory by Drs. Brian Justus and Alan Huston



Blue-green photoluminescence of Cu-doped quartz rod, excited by 254 nm (short) UV light. For comparison, a similar quartz rod that has not been doped with copper ions is also shown

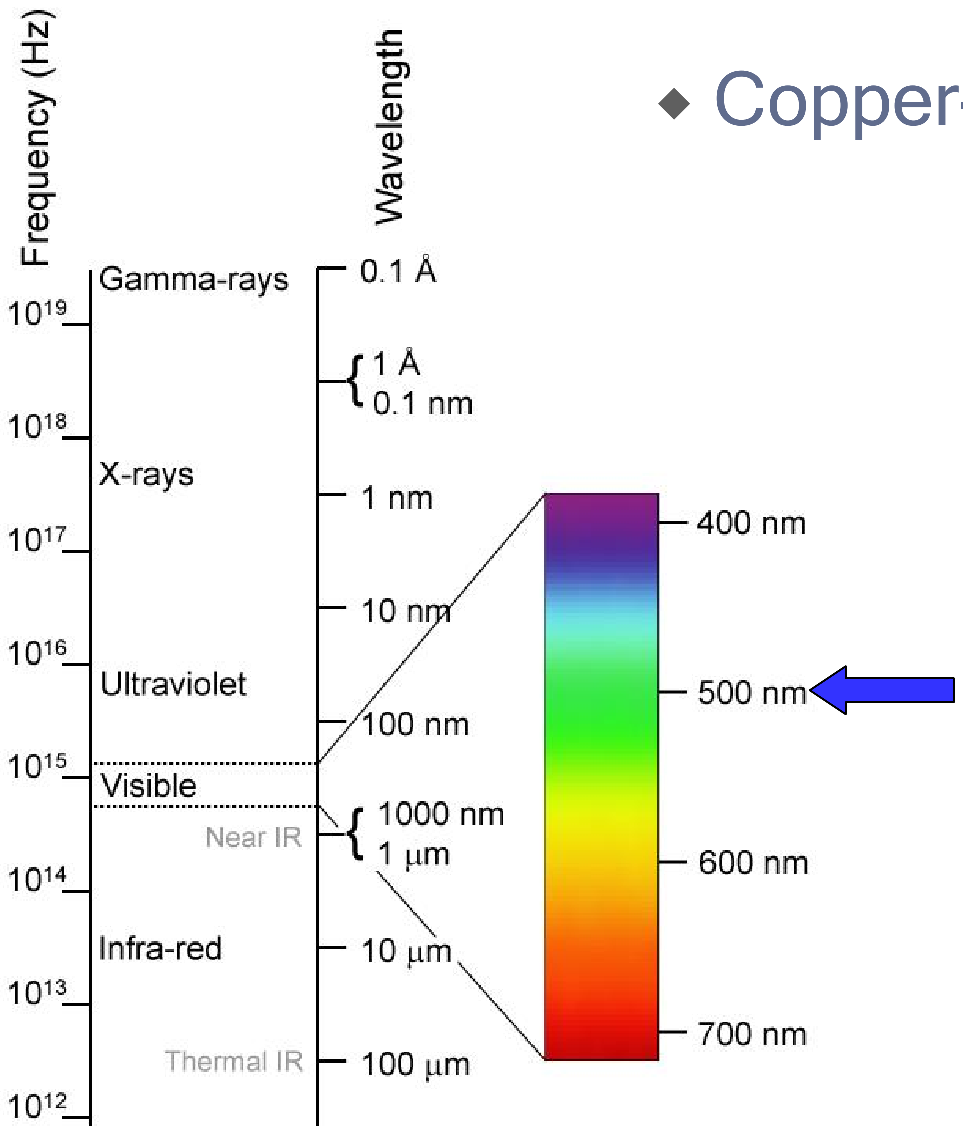
Development of Real-Time Dosimeter

- Copper-doped quartz scintillator



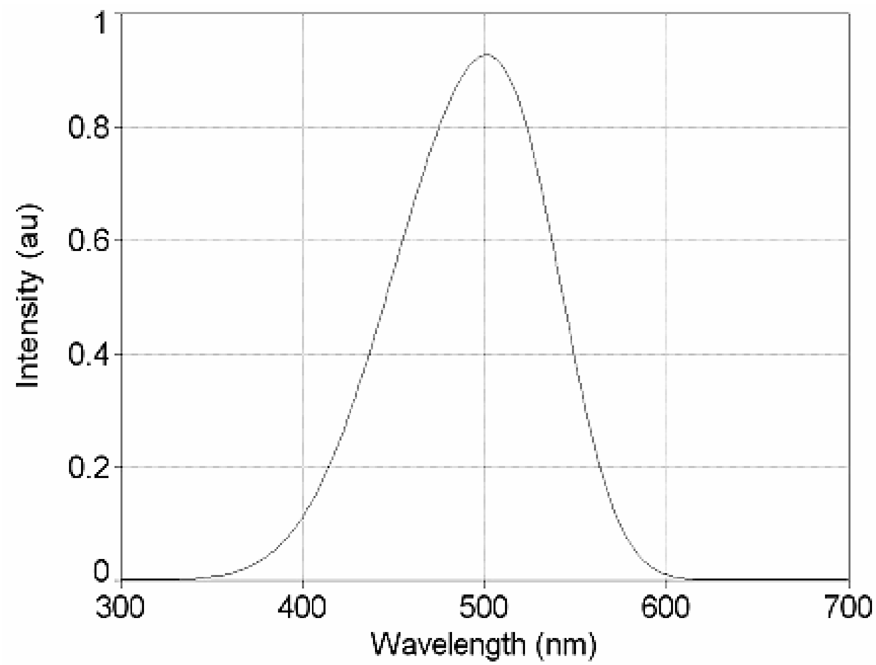
Broad absorption
with peak at 260 nm
(~4.78 eV)

Development of Real-Time Dosimeter



- Copper-doped quartz scintillator

Luminescence peak is at ~500 nm (~2.48 eV)



Development of Real-Time Dosimeter

- Cu-doped quartz dosimeter can operate in several modes:
  - Optically-stimulated luminescence
  - Thermoluminescence
  - CW scintillation
  - Time-gated scintillation

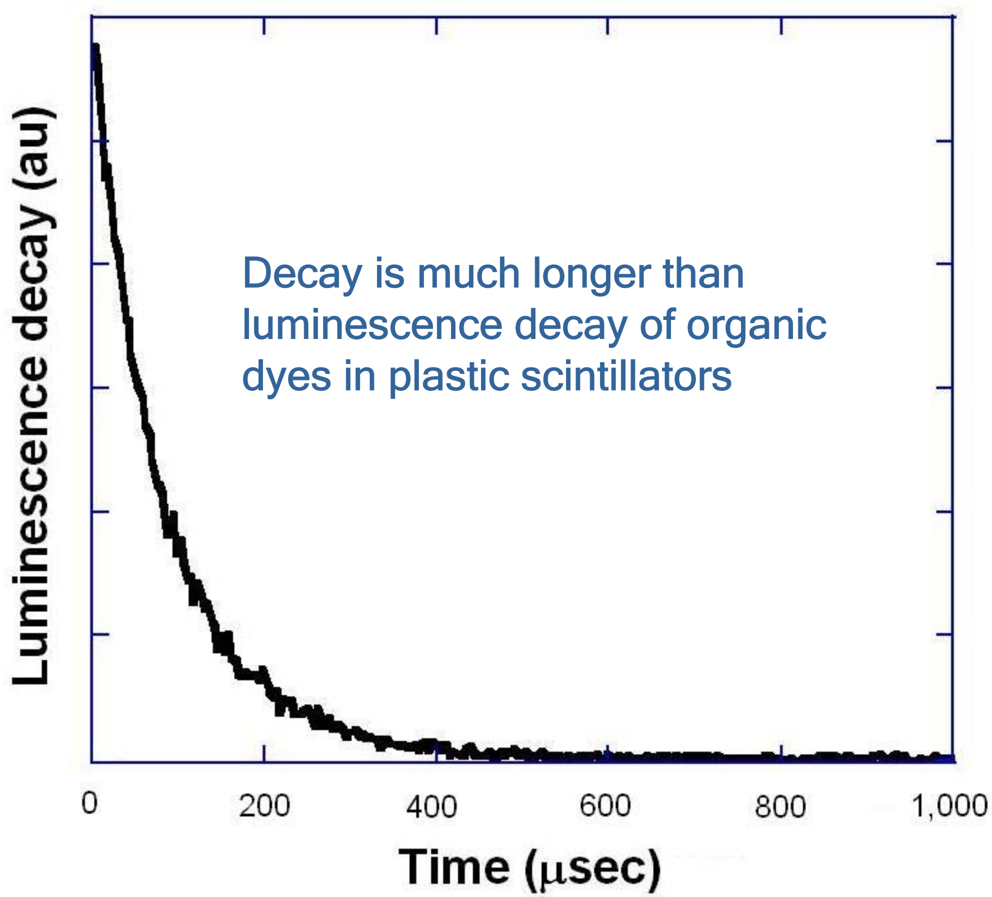
Development of Real-Time Dosimeter

- Luminescence from Cu-doped quartz

  - expose to radiation:
    scintillation
  - turn radiation off:
    long-lived luminescence

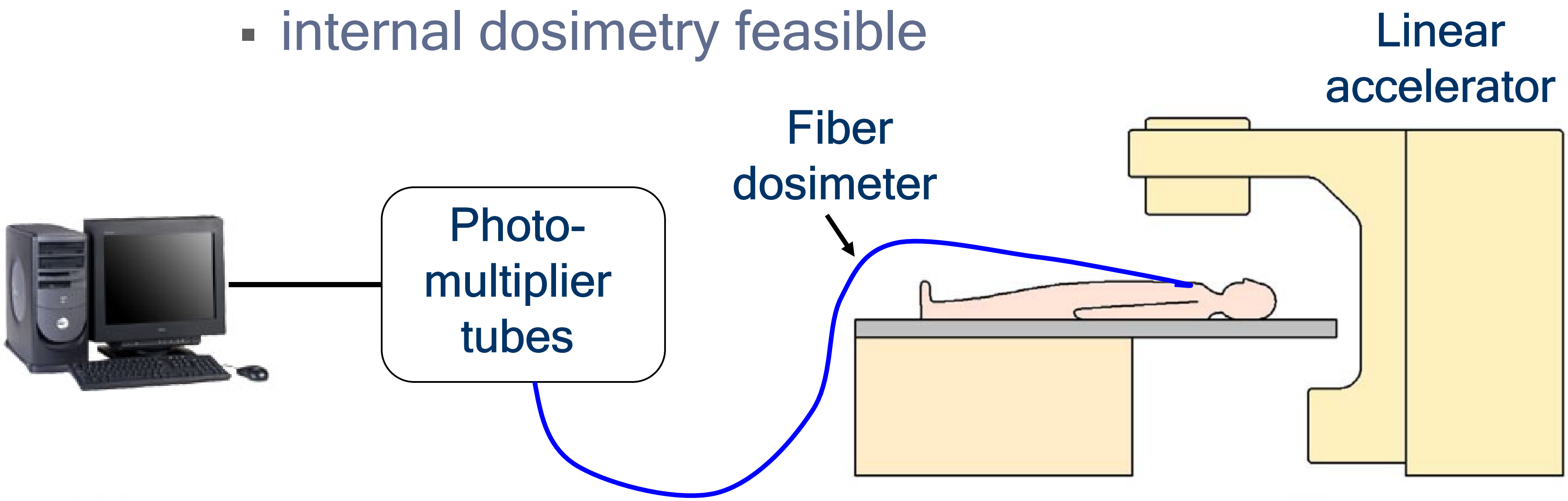
Biexponential decay of luminescence:
$\tau_1 = 51\ \mu\text{sec}$
$\tau_2 = 104\ \mu\text{sec}$

Signal decays to zero in ~0.5 msec.



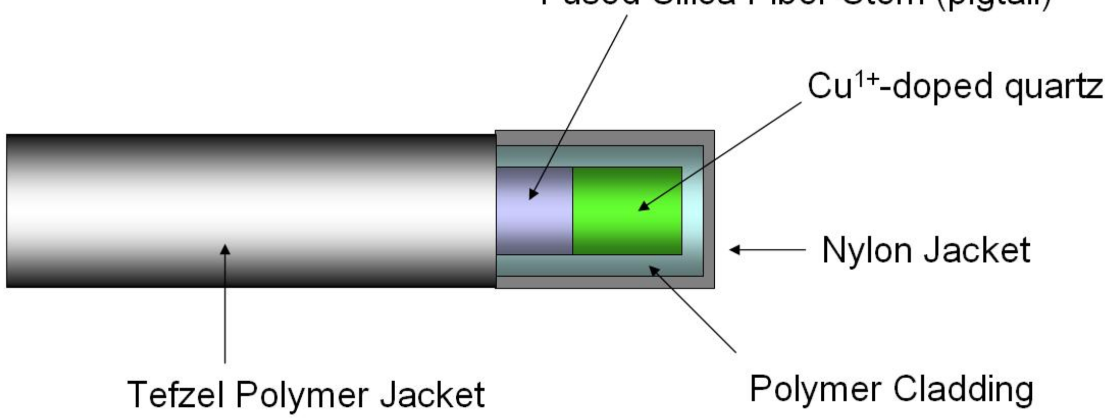
Development of Real-Time Dosimeter

- Objective: Thin, fiber dosimeter
  - Patient dose verification during external beam radiotherapy treatment
    - real-time dose information
    - point detection with sub-mm resolution
    - internal dosimetry feasible



Development of Real-Time Dosimeter

- Objective: Thin, fiber dosimeter
  - Fiber dosimeter construction
    - Cu-doped quartz rod drawn into 400 micron diameter fiber
    - Quartz fiber fusion-spliced onto standard multi-mode optical glass fiber and terminated

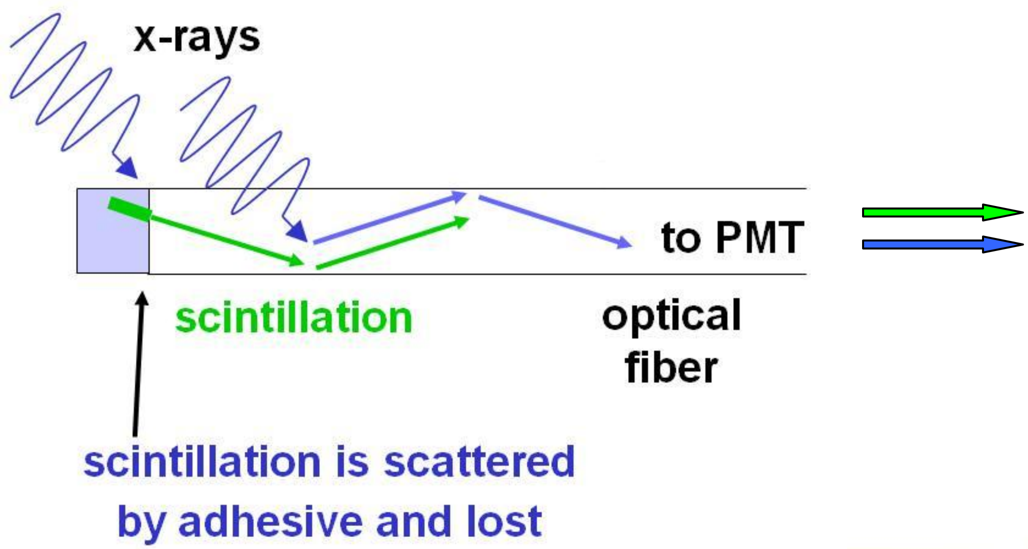


Development of Real-Time Dosimeter

- Objective: Thin, fiber dosimeter
  - Cu-doped quartz fiber
    - Fully compatible with fiber optic transmission of signal
    - Can be fused directly to the optic fiber without a visible boundary in radiographs
    - Thin enough to be inserted into the target tissue of a patient through a FDA-approved catheter

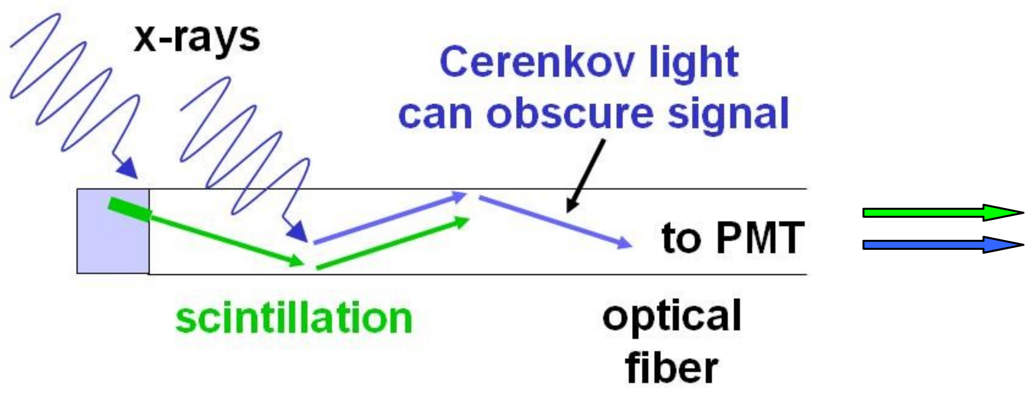
Development of Real-Time Dosimeter

- Some workers have used adhesive to attach scintillator to fibers
  - Bubbles in adhesive scatter light
  - Fusion-splicing of quartz fiber to glass fiber eliminates that source of error



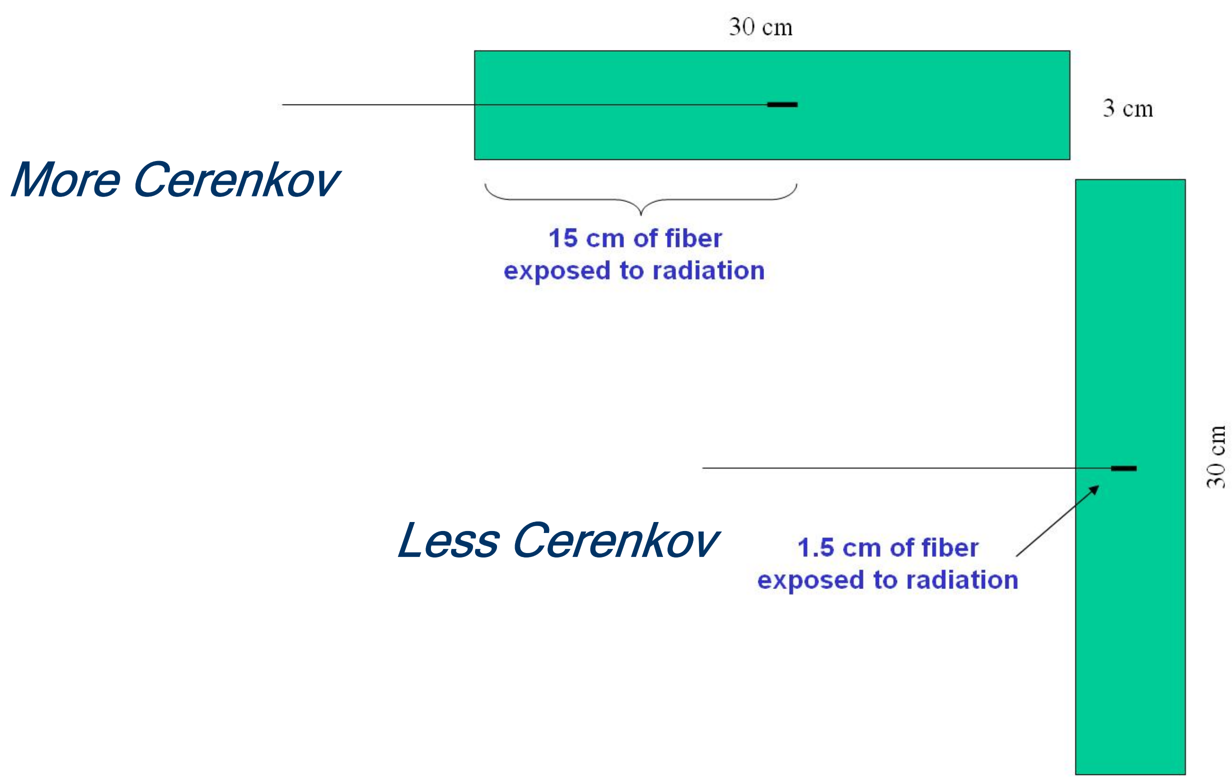
Development of Real-Time Dosimeter

- Upon exposure to high energy radiation
  - Luminescence from Cu-doped quartz
  - Cerenkov radiation from optical fiber
  - Cerenkov radiation interferes with measurement



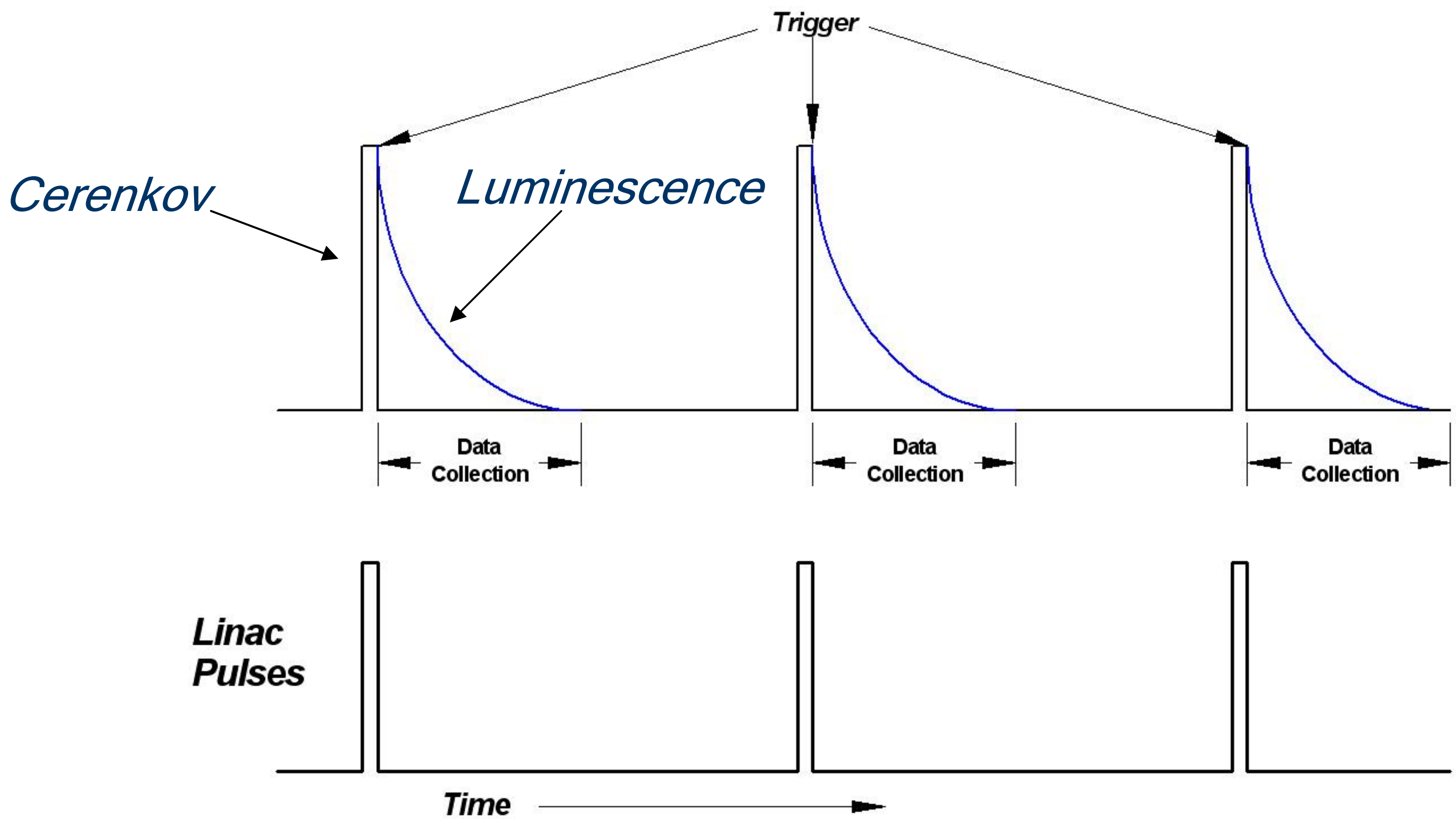
Development of Real-Time Dosimeter

- Amount of Cerenkov radiation is affected by:
  - How much optical fiber is exposed to radiation



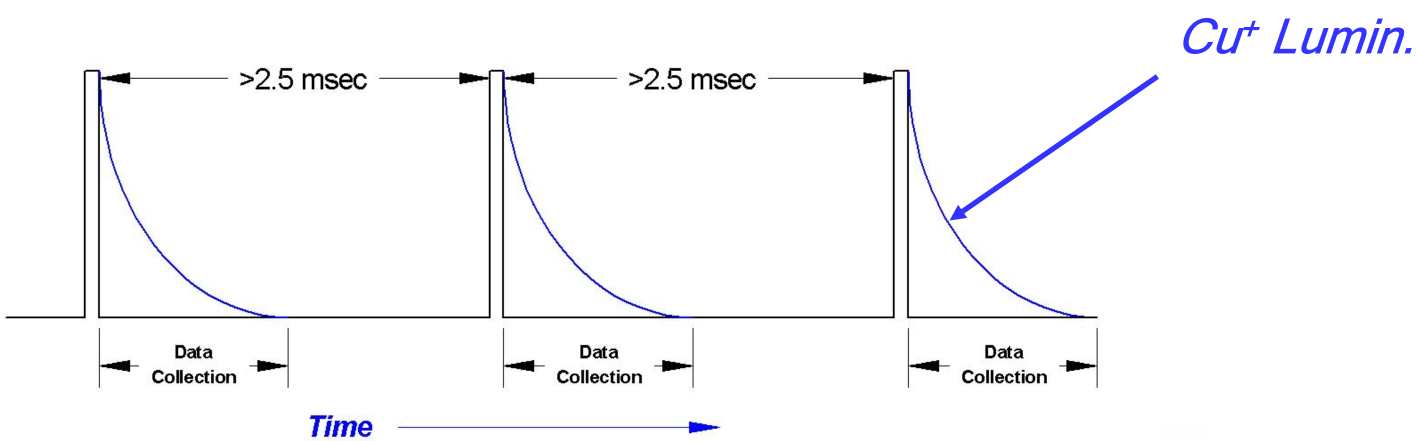
Development of Real-Time Dosimeter

- The effect of Cerenkov radiation is eliminated by gating data collection



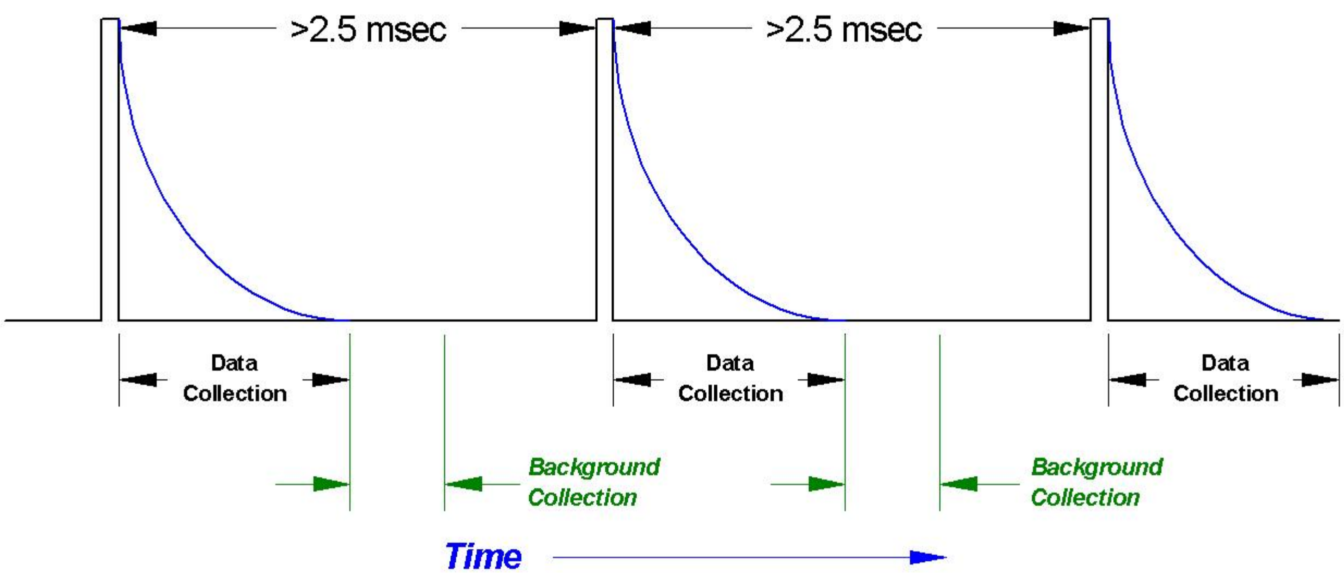
Development of Real-Time Dosimeter

- Cu-doped quartz gated data collection
  - The minimum time between linac pulses:
    - Varian = ~2.9 msec
    - Elekta = ~2.5 msec
  - Luminescence persists for ~0.5 msec after end of linac pulse, permitting detection of signal *without Cerenkov interference*



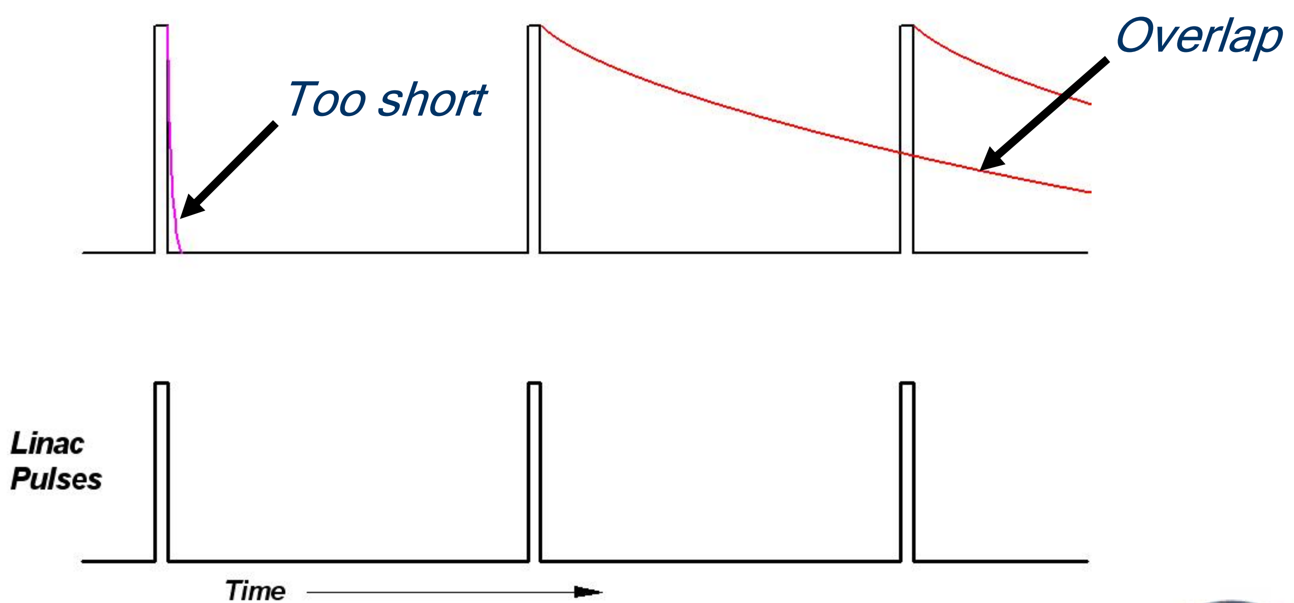
Development of Real-Time Dosimeter

- Cu-doped quartz gated data collection
  - Background signal is collected during 0.5 msec window *after* the luminescence signal is measured, and is subtracted from the signal (performed for each pulse)



Development of Real-Time Dosimeter

- Cu-doped quartz is ideally suited for gated data collection
  - Luminescence from other scintillators either fades too quickly for adequate data collection, or is too long and overlaps subsequent pulses



Development of Real-Time Dosimeter

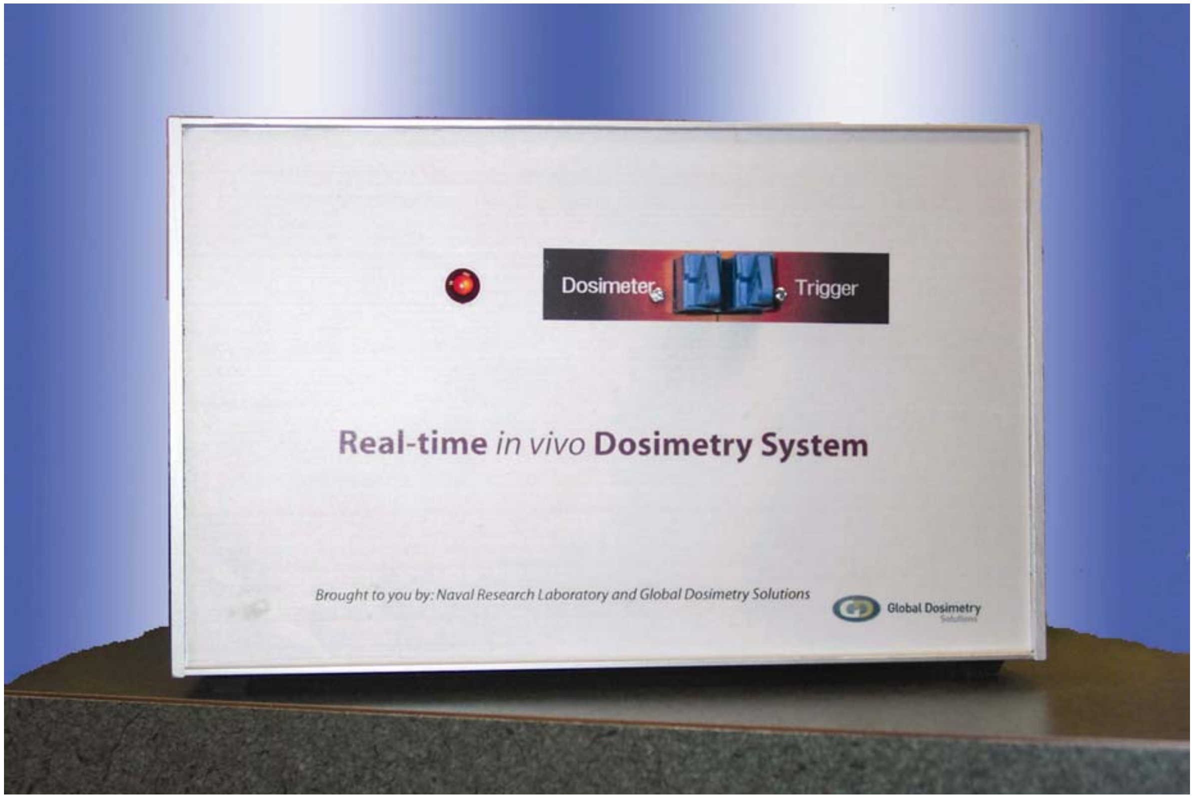
- Detector Comparison*

	Fiber Cu^{1+} silica	Diode	Diamond
Z	10.8	14	6
Density (g/cm^3)	2.2	2.33	2.62
Sens Area (mm^2)	0.13	5.0	4.3
Diameter (mm)	0.4	2.4	2.5
Sens Vol th (mm)	1.0	0.45	0.33
Sensitivity ^{60}Co	$5x10^5$ cts/Gy	$3.3x10^{10}$ e^-/Gy	$3.6x10^{10}$ e^-/Gy

*Chester Reft PhD, University of Chicago Hospitals, "*Radiation Characteristics of a Gated Fiber-Optic-Coupled Detector*," 2006 AAPM Presentation

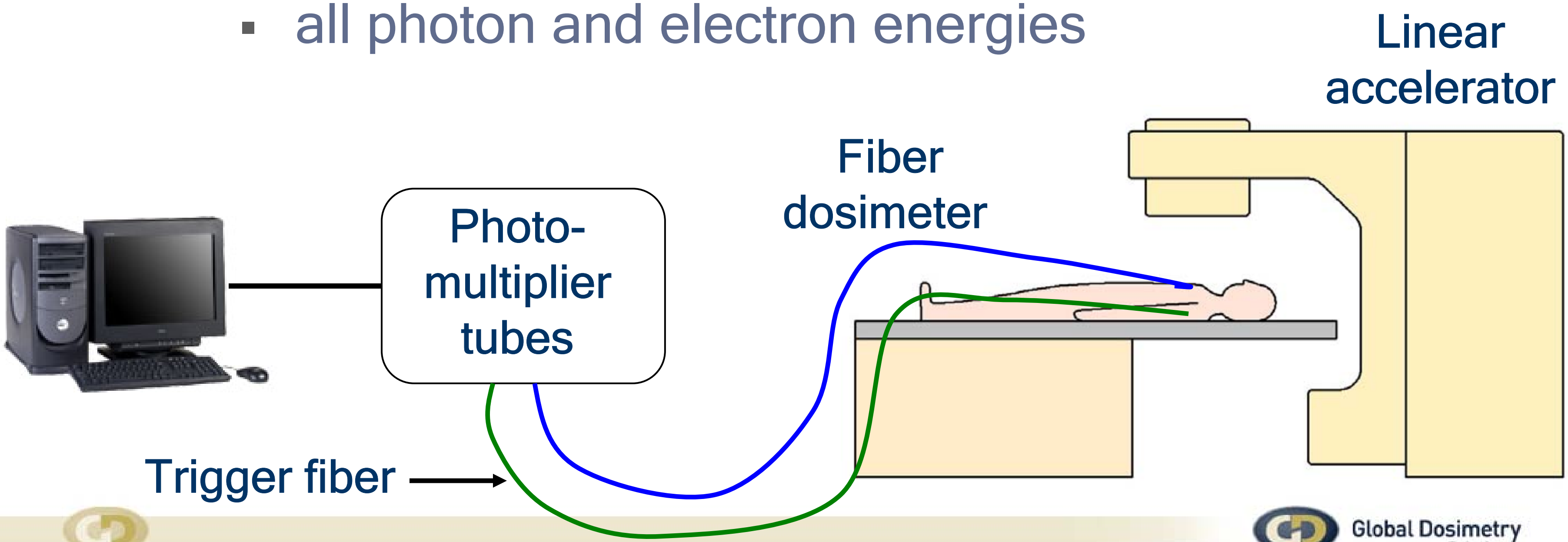
Test Results with Pulsed Radiation

- GDS-NRL Single-channel Prototype
  Real-time *in vivo* Dosimetry System



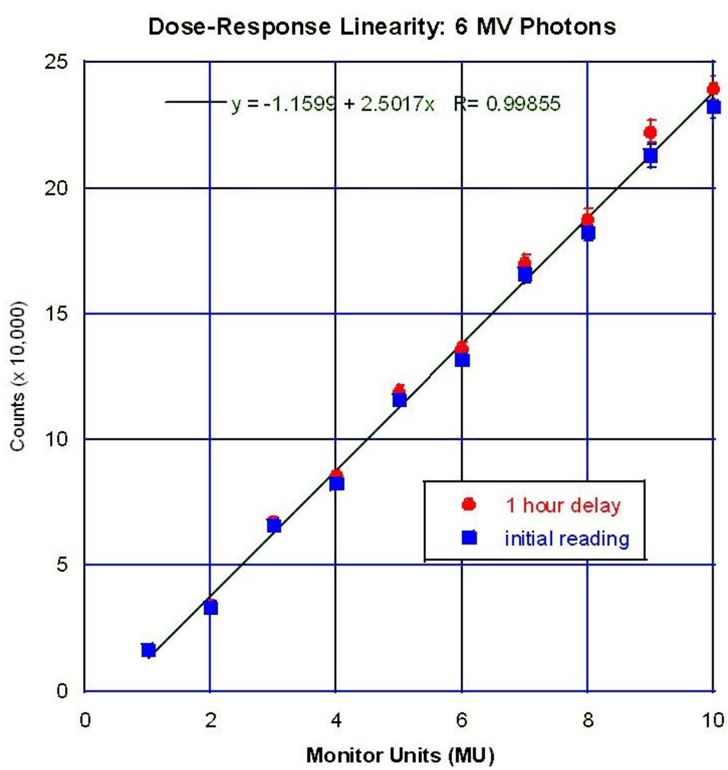
Development of Real-Time Dosimeter

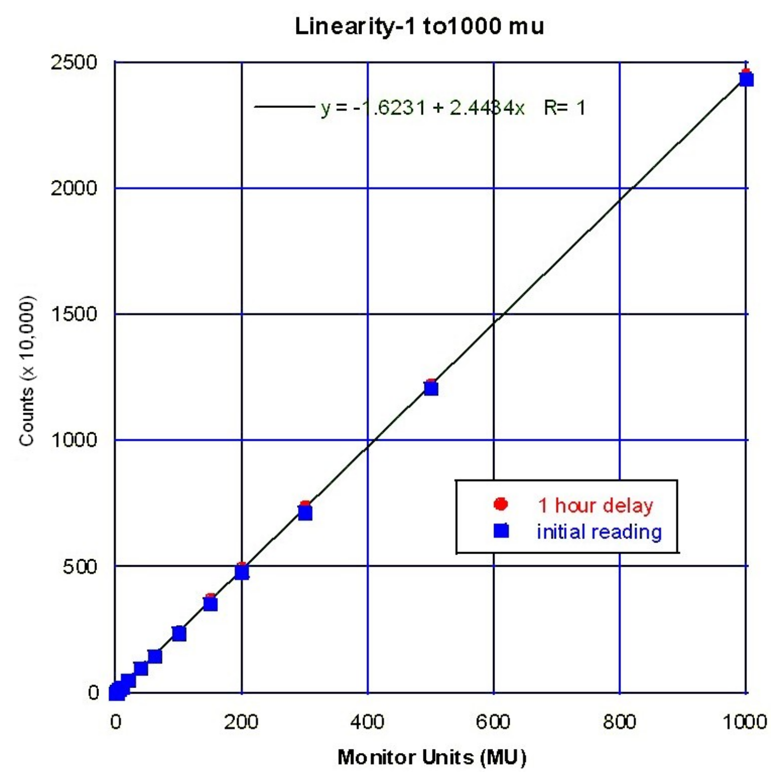
- Gated data collection
  - Trigger fiber was used to detect linac pulse optically
  - Eliminates need for electrical interface with linac power supply.
  - Optical trigger works with all linear accelerators
    - all manufacturers
    - all photon and electron energies



Test Results with Pulsed Radiation

- Linearity data from NCI - Dose response to photons is linear over 3 orders of magnitude with R value of 0.999

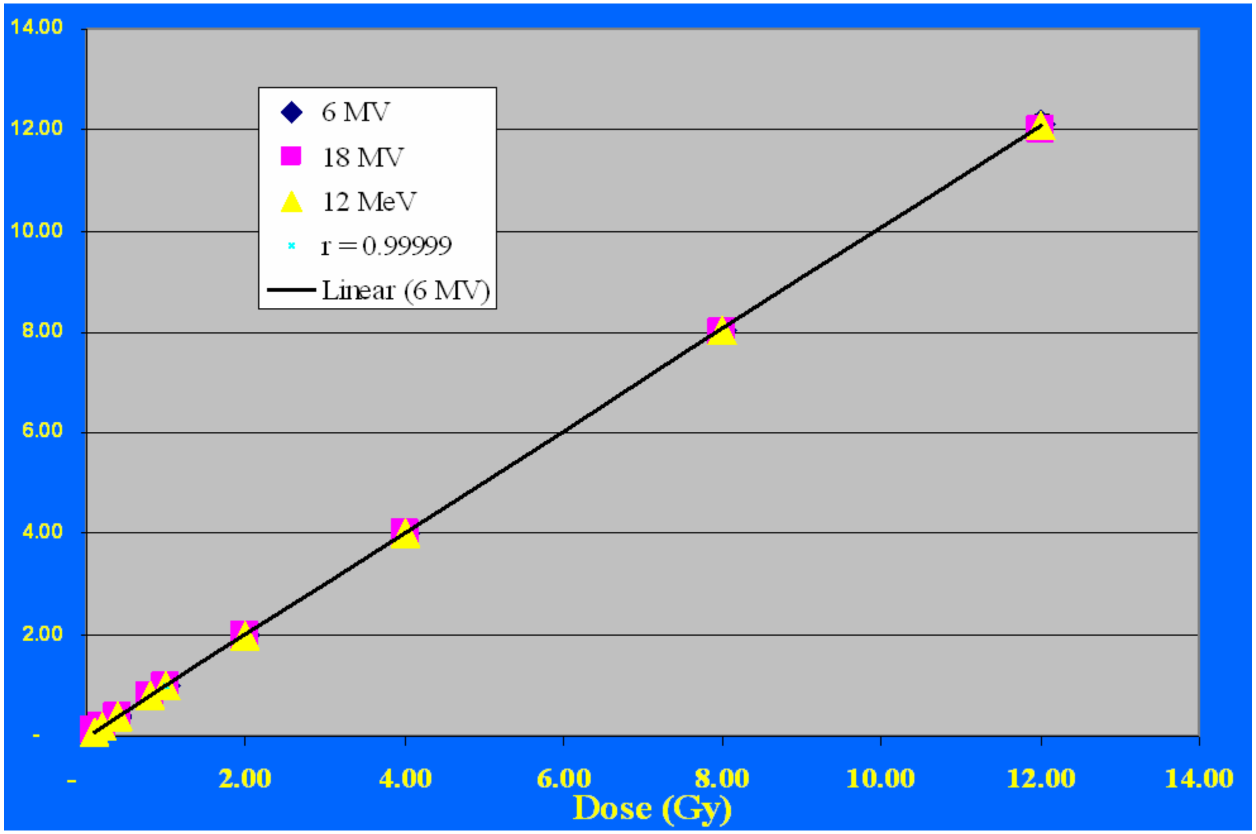




A monitor unit (MU) is a measure of machine output of a linear accelerator in radiation therapy. 1 MU gives an absorbed dose of 1 cGy (or rad) at a depth of Dmax for a field size of 10x10 cm for a source-to-axis distance of 100 cm [Wikipedia].

Test Results with Pulsed Radiation

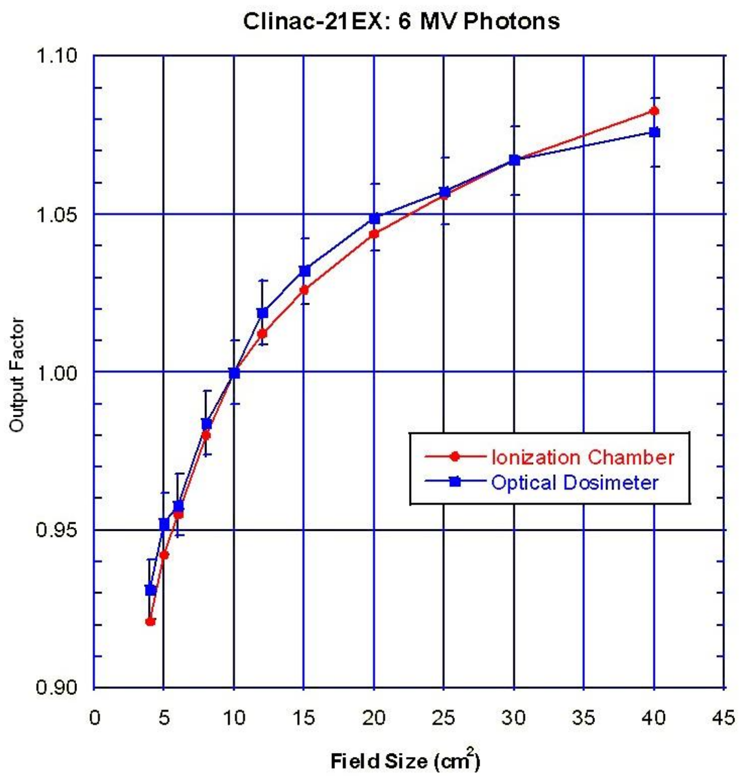
- Linearity data reported in 2006*

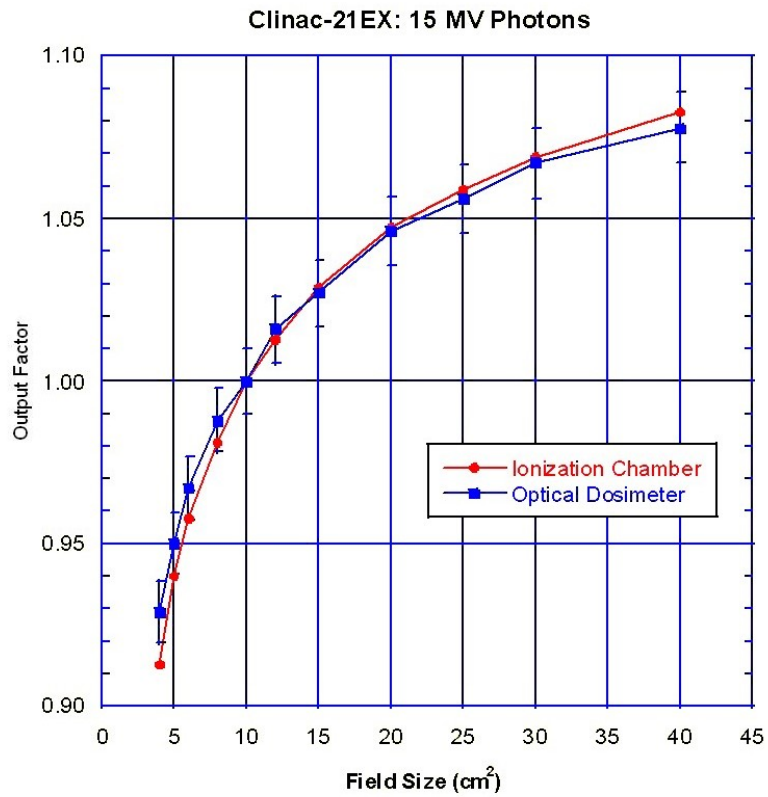


*Chester Reft PhD, University of Chicago Hospitals, “*Radiation Characteristics of a Gated Fiber-Optic-Coupled Detector*,” 2006 AAPM Presentation

Test Results with Pulsed Radiation

- Field Size - Dose response is independent of beam field size and photon energy



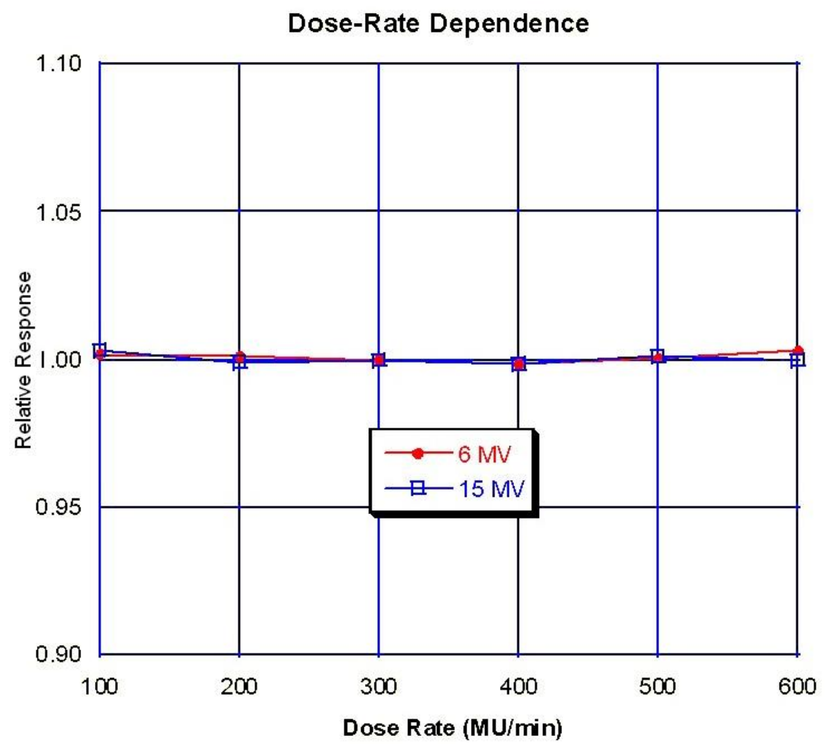


Global Dosimetry Solutions

Test Results with Pulsed Radiation

- Dose Rate - Dose response is independent of dose rate

NCI Result for photons



Test Results with Pulsed Radiation

- Energy Response – Energy response is independent of photon energy, some energy dependence for electrons

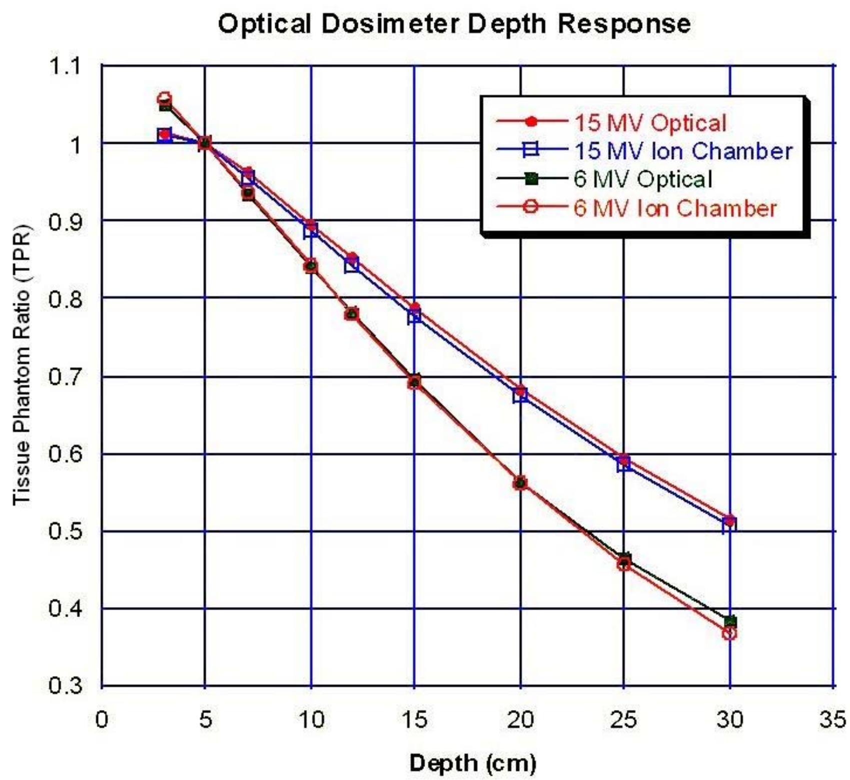
Detector energy response
normalized to 6 MV photons*

Energy	Q(Energy)/Q(6 MV)	
6 MV	1.000	Photons
18 MV	0.993	Photons
6 MeV	0.950	Electrons
9 MeV	0.976	Electrons
12 MeV	0.998	Electrons
16 MeV	1.006	Electrons
20 MeV	1.020	Electrons

*Chester Reft PhD, University of Chicago Hospitals, "*Radiation Characteristics of a Gated Fiber-Optic-Coupled Detector*," 2006 AAPM Presentation

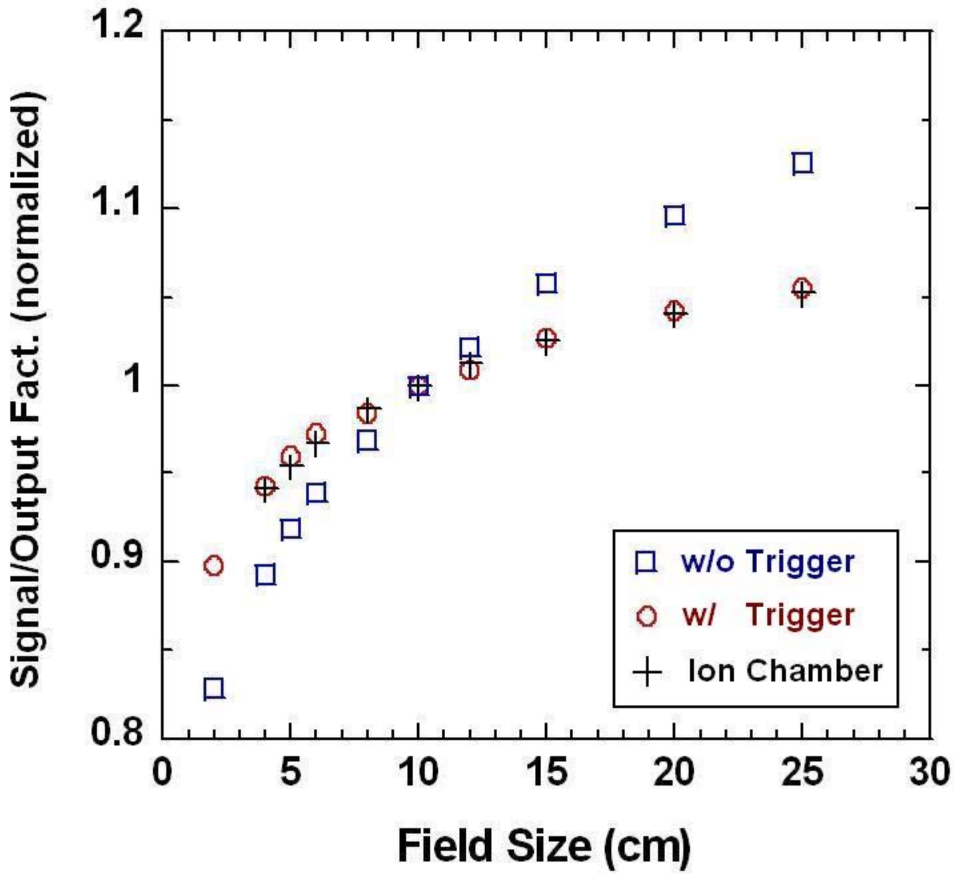
Test Results with Pulsed Radiation

- Depth dose response in good agreement with ion chamber measurements



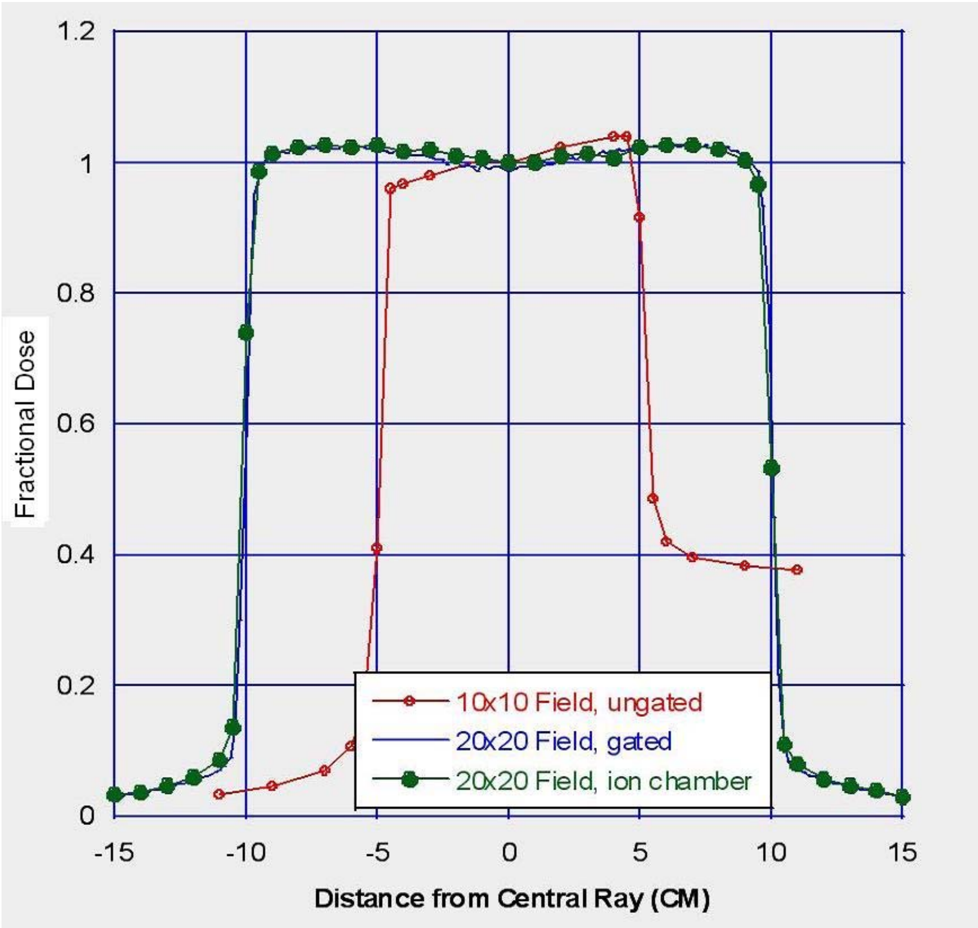
Test Results with Pulsed Radiation

- Dose Response Comparison, *with* and *without* Trigger
  - Excellent agreement with Ion Chamber when Trigger enabled
  - Fiber dosimeter able to measure smaller field than Ion Chamber



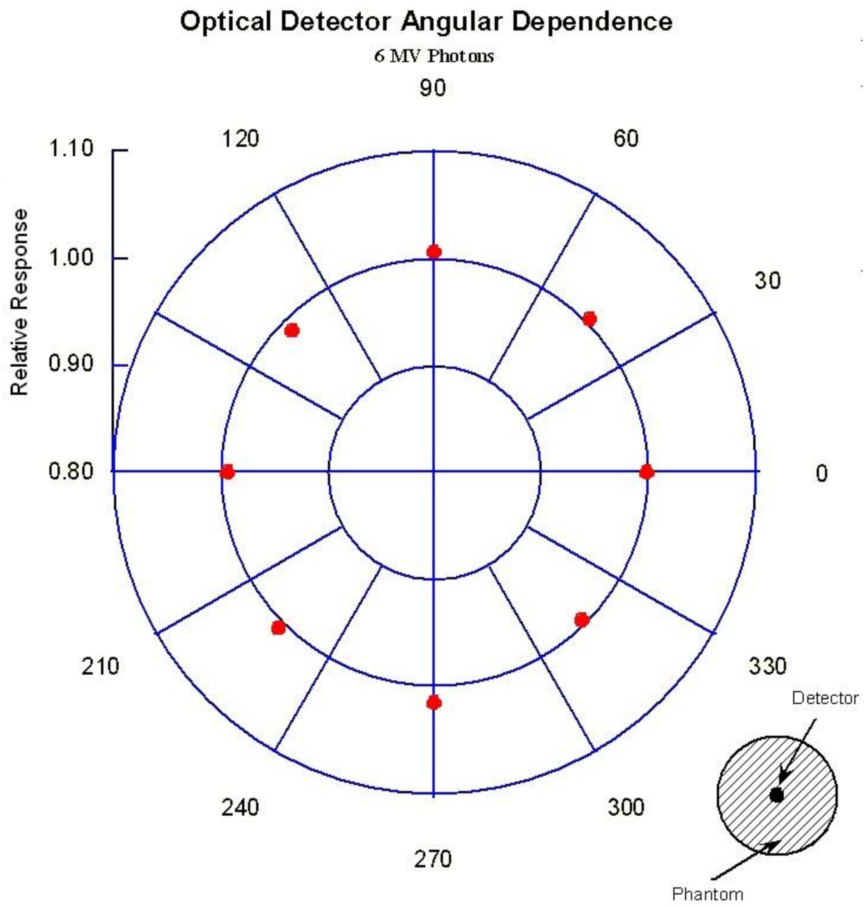
Test Results with Pulsed Radiation

- Dose Response Comparison, *with* and *without* Trigger



Test Results with Pulsed Radiation

- Angularity – Directional response is uniform to ±1%



Test Results with Pulsed Radiation

- Summary:
  - Output factor for both 6 MV and 15 MV photon showed good agreement with ion chamber measurements
  - Photon energy response is not energy dependent
  - Some energy dependence for electrons
  - Depth dose response also showed good agreement with ion chamber for both 6 MV and 15 MV
  - Detector response shown to be independent of dose rate
  - Directional response was shown to be highly uniform
  - Capable of measuring field smaller than ion chamber

Continuous-Wave Mode

- For lower energy photons where Cerenkov radiation is not a problem, the dosimeter can be operated in continuous-wave (CW) mode
  - Trigger is not required
- Applicable in
  - Fluoroscopy
  - Mammography

Continuous-Wave Mode

- Mammography
  - Typical Mammography X-ray Tube Potential
    23 kVp – 35 kVp

Continuous-Wave Mode

- Mammography Dosimeter Comparison*

	MOSFET**	Cu-doped Fiber Dosimeter**
Angular Response	Reduced signal @120°-150°, and @190° - 220°	No significant anisotropy
Unexpected, Random Failure	Yes	No
Energy Dependence	9.25 ±8.28%	4.62 ±2.10%
Overall Reproducibility	25.95 ±8.28%	1.07 ±0.68%
Reusable	No	Yes

* *"Breast Dosimetry in Clinical Mammography,"* Luis Alberto Do Rego Benevides, PhD Dissertation, University of Florida 2005

** Average of all detectors studied

Possible Future Improvements

- Eliminate Trigger Fiber for Pulse-Mode
- Multi-channel Device (24 – 36)
- Reduce fiber dosimeter diameter from ~0.4 mm to 0.1 - 0.2 mm

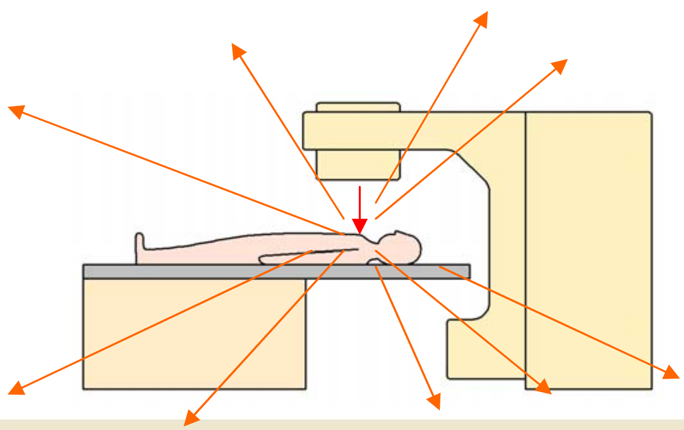
This is where we left off last year

Trigger Fiber

- It must always be in the beam
- Limited application in IMRT
- Various ways to eliminate the trigger fiber was considered
  - Simplest way turned out to be the most effective

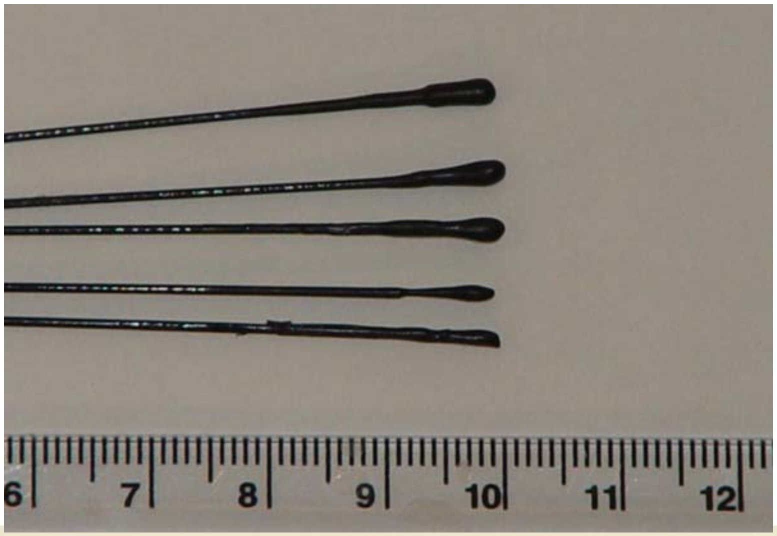
Scattered-Photon Trigger (*Patent Pending*)

- A moment of "*Epiphany*"
  - Actually, it was more of "*duh*" moment
  - A realization that whenever there is a linac pulse, the therapy room is filled with scattered photons



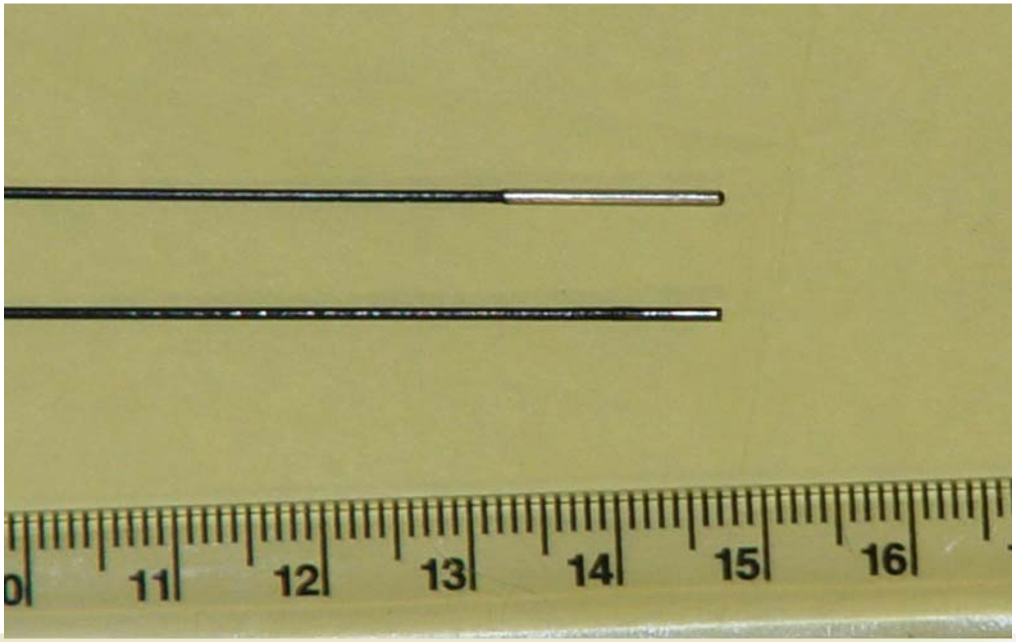
Fiber Detector Construction

- Up to now, the fiber detector was terminated with rubberizing compound
  - Light leakage
  - Inconsistent size & shape
  - Time-consuming to manufacture



Fiber Detector Construction

- New termination uses epoxy
  - No light leakage
  - Consistent size & shape (< 1 mm diameter)
  - Simple & quick to manufacture



Thank You!

Questions?