Accelerator-Based Standards and Applications in Industrial Dosimetry

Fred Bateman & Ronald Tosh, NIST

CIRMS 2017, 3/28/17

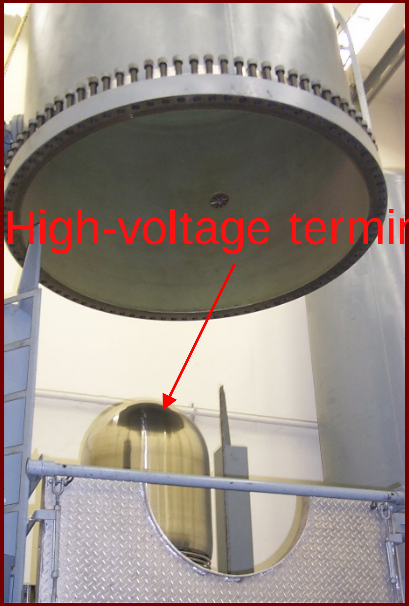
- Introduction
- Diagnostics and Quality Assurance
- Applications
- New Frontiers

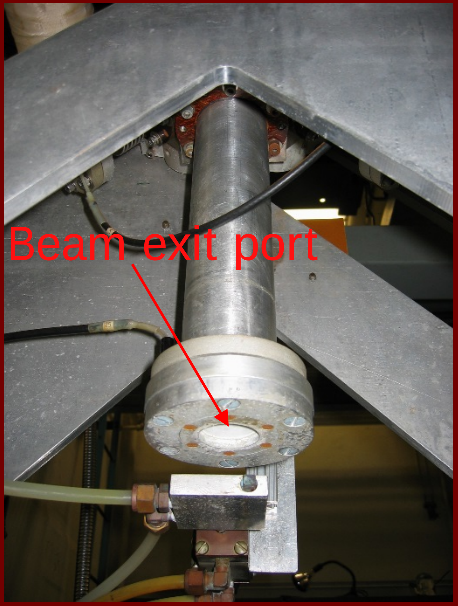
Radiation Physics Division
Electron Accelerators

- Electron Van de Graaff
  - – Direct current beams up to ~250 μA
  - – Energy range ~500 keV to 2000 keV
- MIRF Linear Accelerator
  - – Pulsed beams up to ~20 μA
  - – Energy Range ~10 to 28 MeV
- Clinac Linear Accelerator
  - – Pulsed therapy level beams
  - – 6, 18 MV photons; 6, 9, 12, 16 and 20 MeV electrons

Van de Graaff Accelerator

- Installed 1965 (52, and still going strong!)
- Applications:
  - – Radiation hardness testing
  - – Materials modification
  - – Detector calibrations





Van de Graaff Parameters

Source: hot cathode pentode

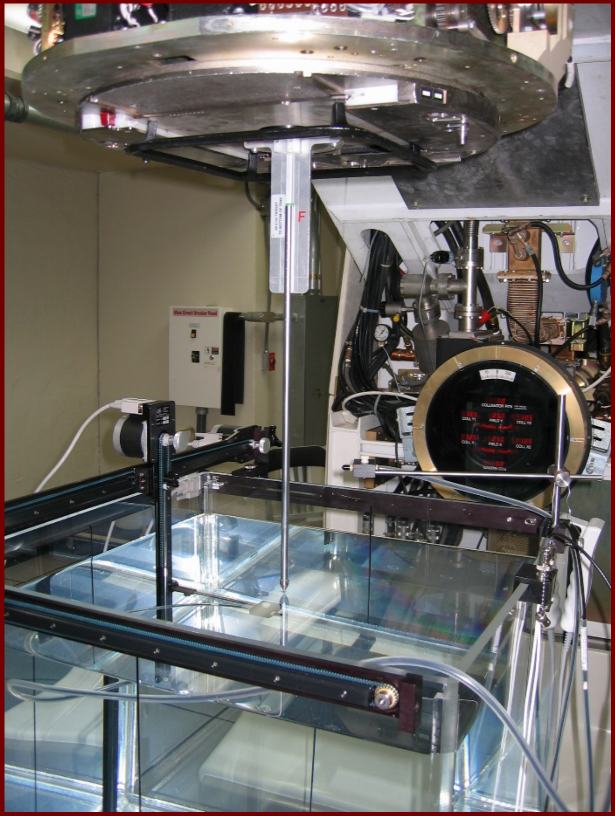
Operating mode: direct current

Duty factor: 100%

Beam current: variable up to ~0.25 mA

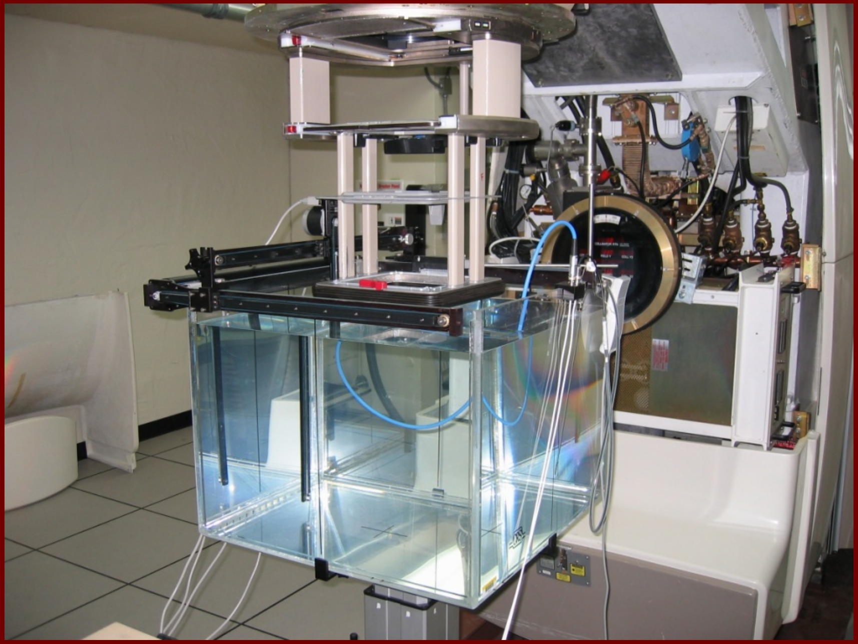
Clinac Accelerator

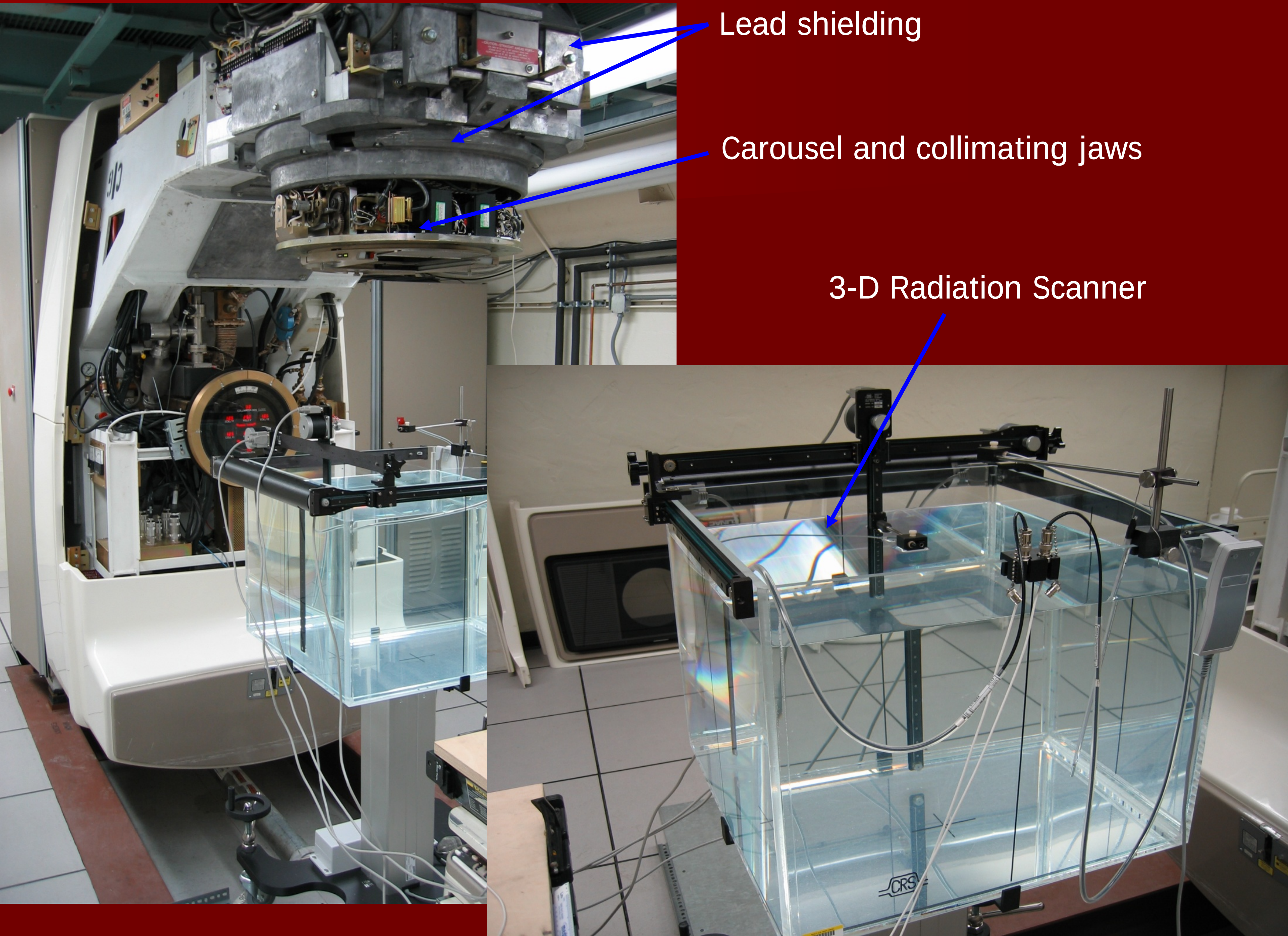
- Medical radiotherapy accelerator
- Certified “pre-owned”, installed at NIST 2004
- Applications include:
  - High-energy medical dosimetry
  - Detector calibrations



Clinac 2100C Beam Parameters

- 6 and 18 MV Photons
- 6, 9, 12, 16 and 20 MeV Electrons
- Dose Rates from 80 to 400 MU (cGy)/min
- Field Size: 0.5 x 0.5 cm to 40 x 40 cm (photon), 4 x 4 cm to 25 x 25 cm (electron)




Lead shielding
Carousel and collimating jaws
3-D Radiation Scanner

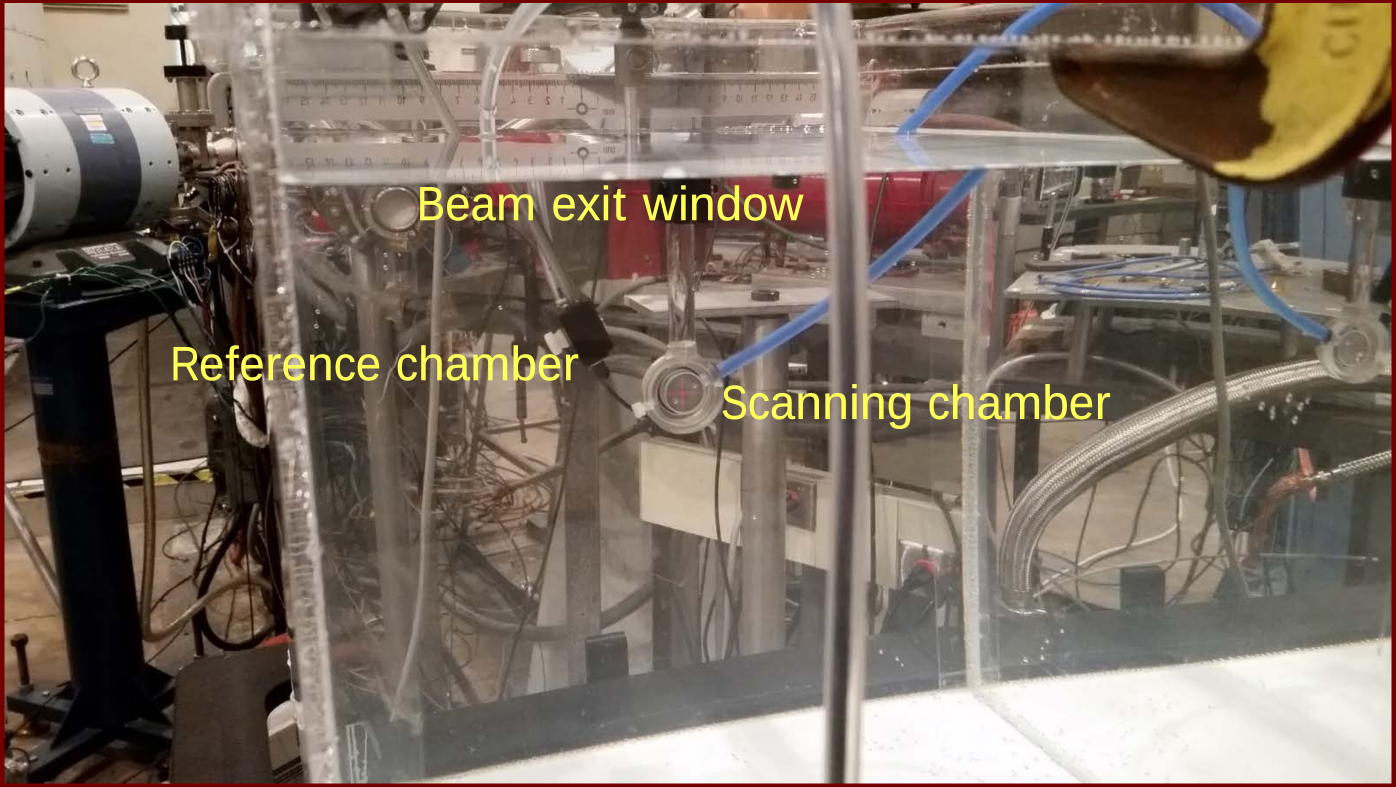
MIRF Accelerator

- Radiotherapy accelerator installed ca. 1970 at Yale New Haven hospital
- Donated to NIST in 1993
- Adapted for “industrial” and research uses
  - Radiation hardness and radiation resistance
  - Materials modification (e.g. grafting)
  - Detector calibrations and radiation shielding tests
  - Fundamental physics studies

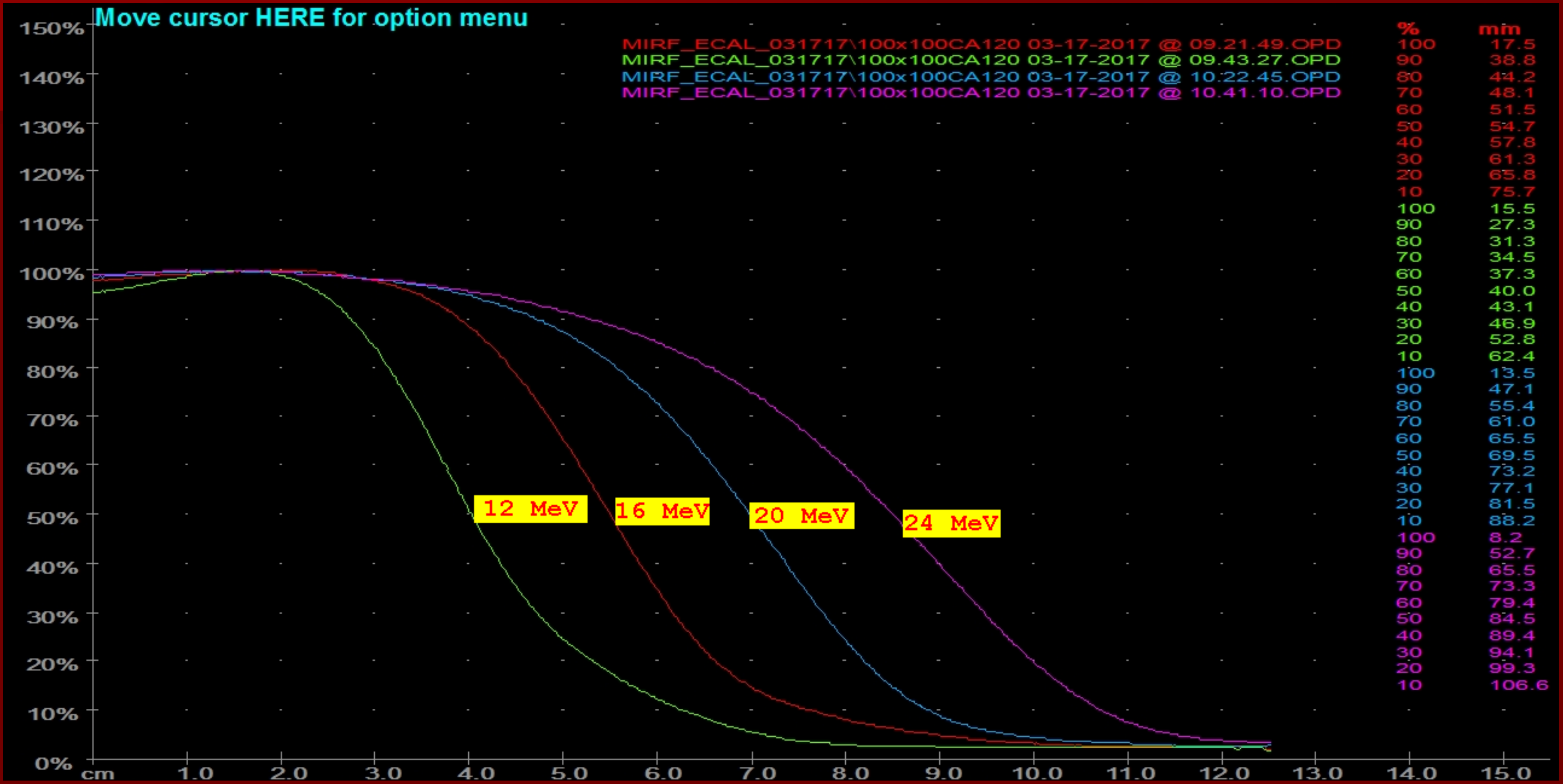
Dosimetry for Quality Assurance

MIRF Beam Energy Validation

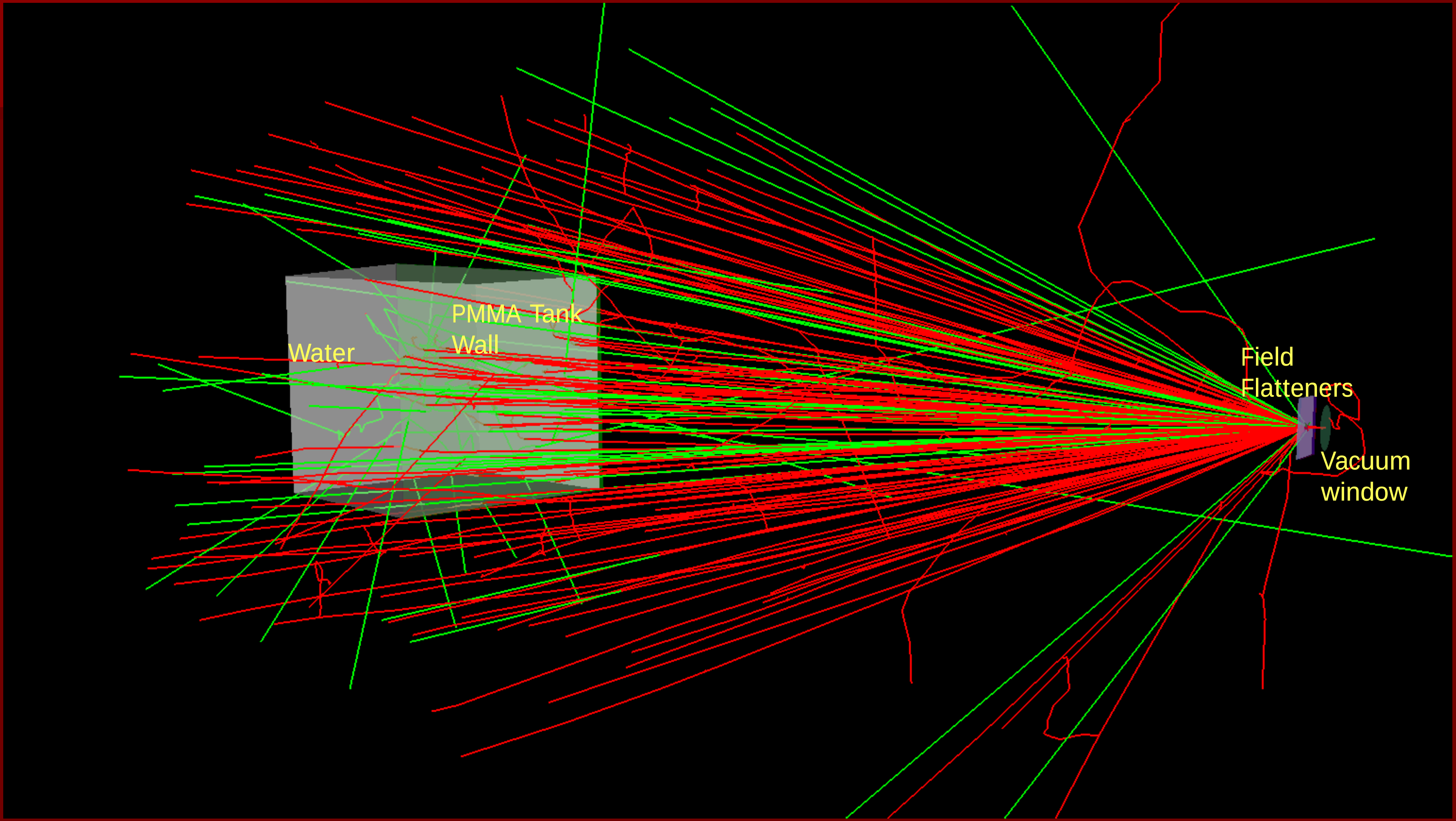
- Measure depth-dose curves in a water phantom with ion chamber
- Use dosimetry protocols (ICRU, AAPM) to determine energy at phantom surface



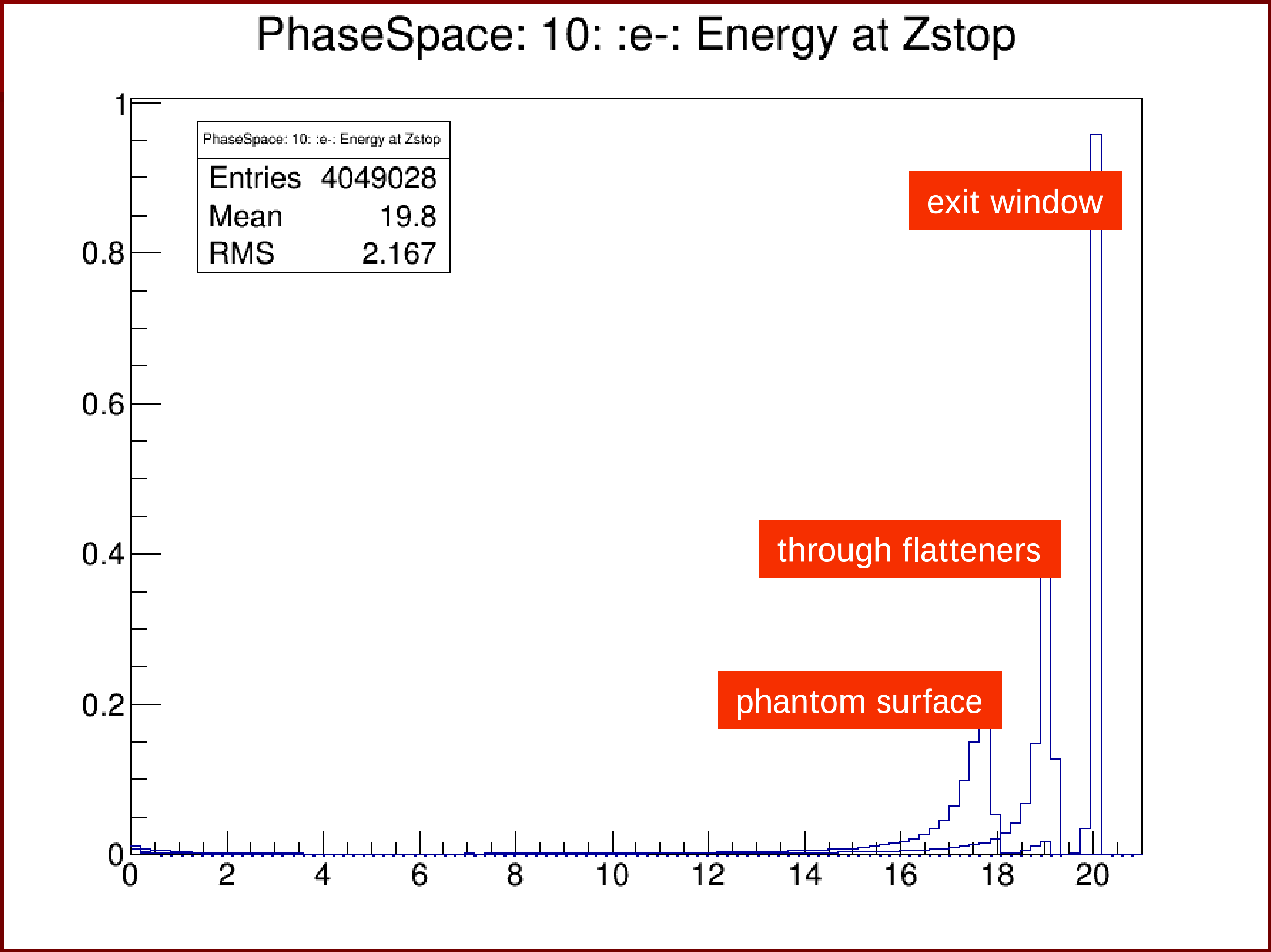
Measured Depth-Dose Curves in Water



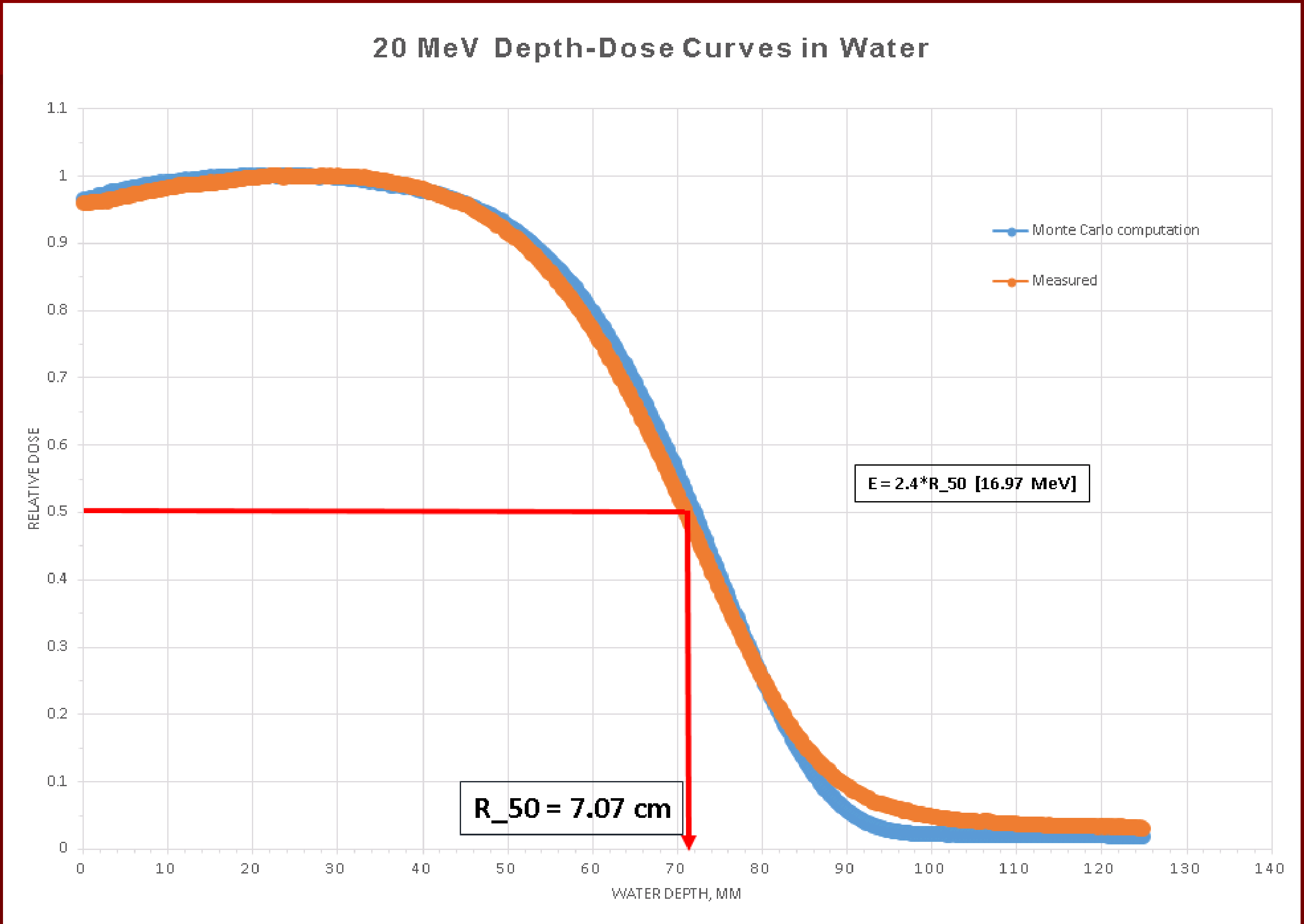
MIRF Monte Carlo modeling



20 MeV Computed Energy Spectra



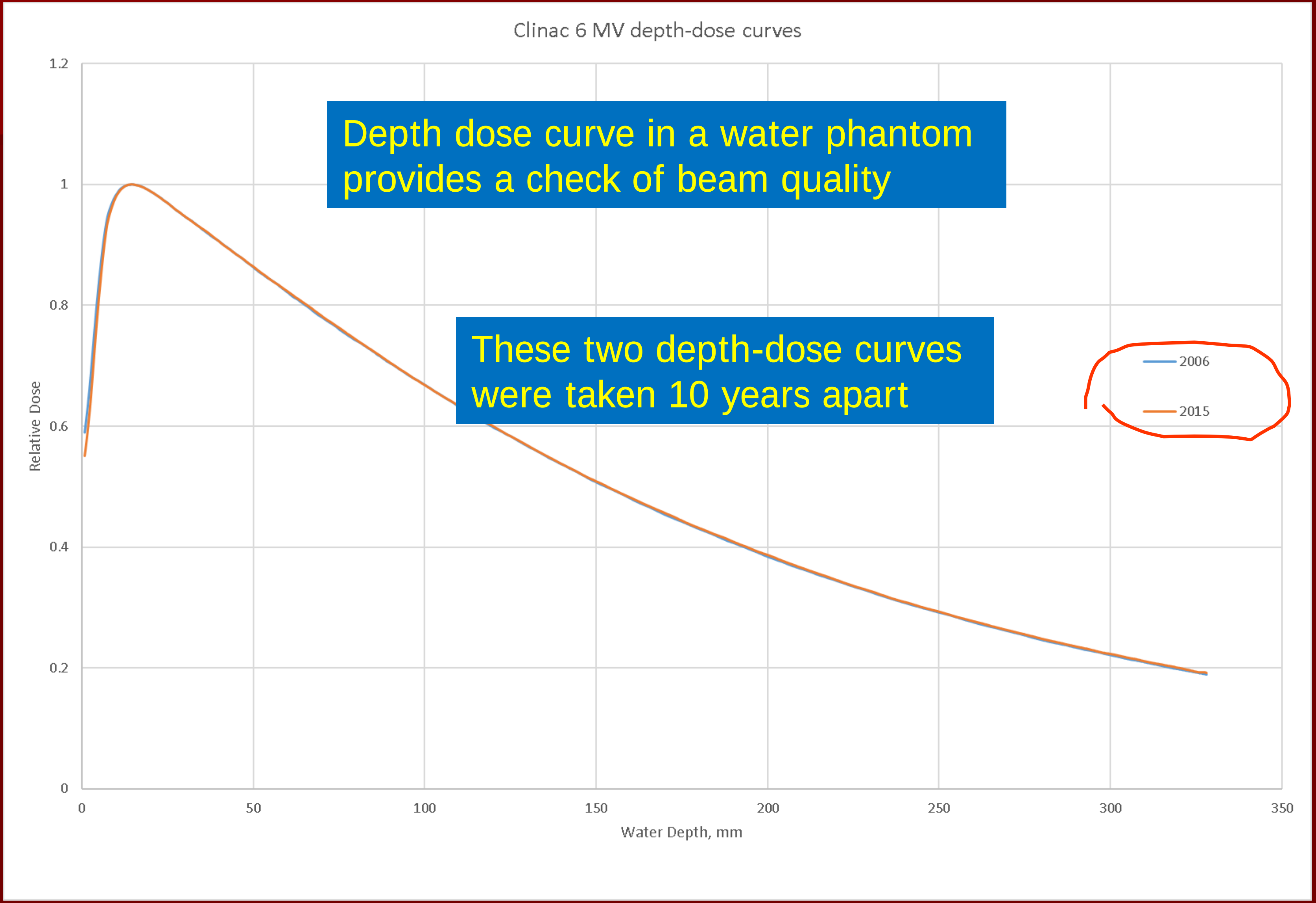
Measured vs. Computed Depth-Dose Curves



MIRF Energy Calibration Results

Nominal E0 [MeV]	Energy at phantom surface	Meas R50 [cm]	Meas Energy [MeV]	% difference
12	9.52	3.98	9.55	0.31
16	13.26	5.47	13.13	-0.98
20	17.11	7.07	16.97	-0.82
24	20.92	8.53	20.47	-2.2

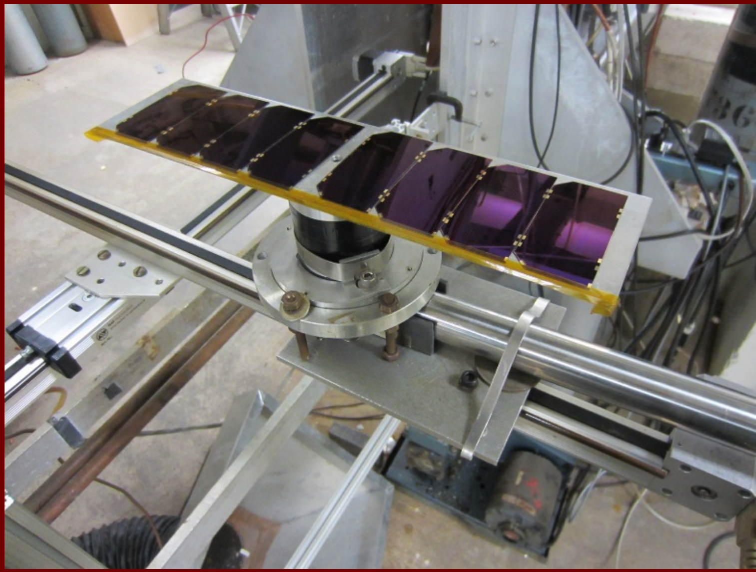
Clinac Accelerator QA

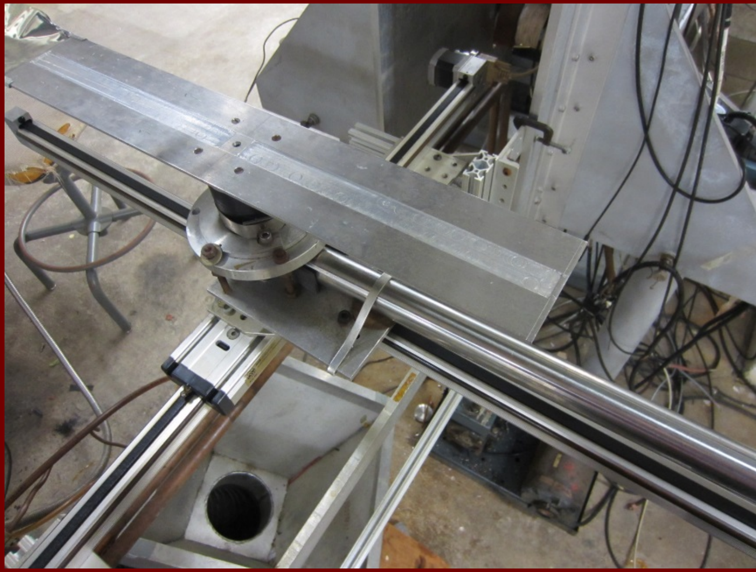


Dosimetry Applications

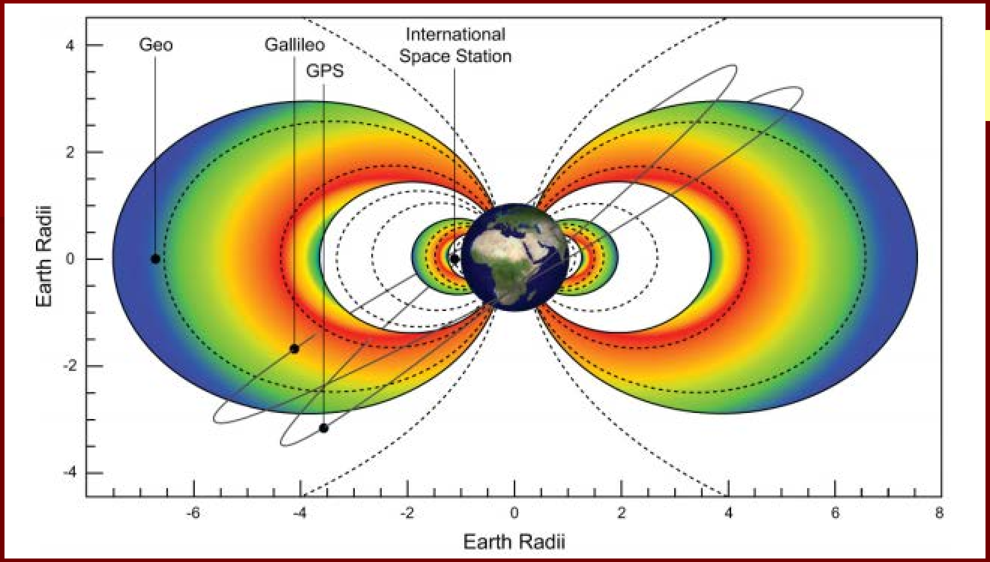
Solar Cell Radiation Testing

- Accelerated radiation damage studies with electron beam
- Study radiation hardness
- Performance assessment leads to improved cell design
- Relevant quantity is the **electron fluence**
- Main radiation effects are total ionizing dose (TID) and displacement damage dose (DDD); lattice defects

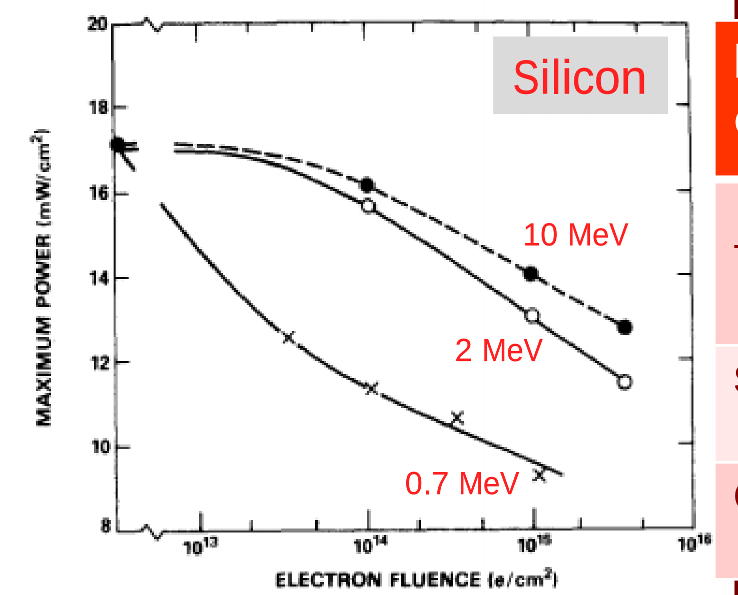




Electron Radiation Effects



R.B. Horne et al., Space Weather 11, 169-186 (2013).



D. Walker, R.Statler, Solar Cells 22, 69-77 (1987).

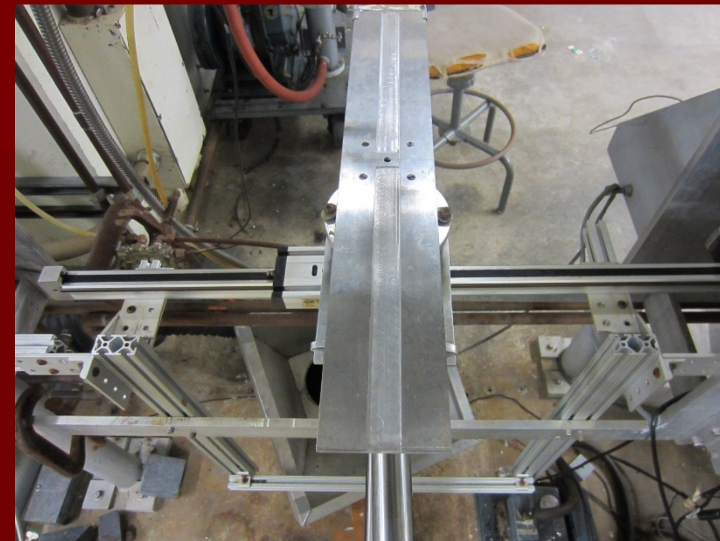
Electron degradation of solar cells in circular orbit at 20,000 km

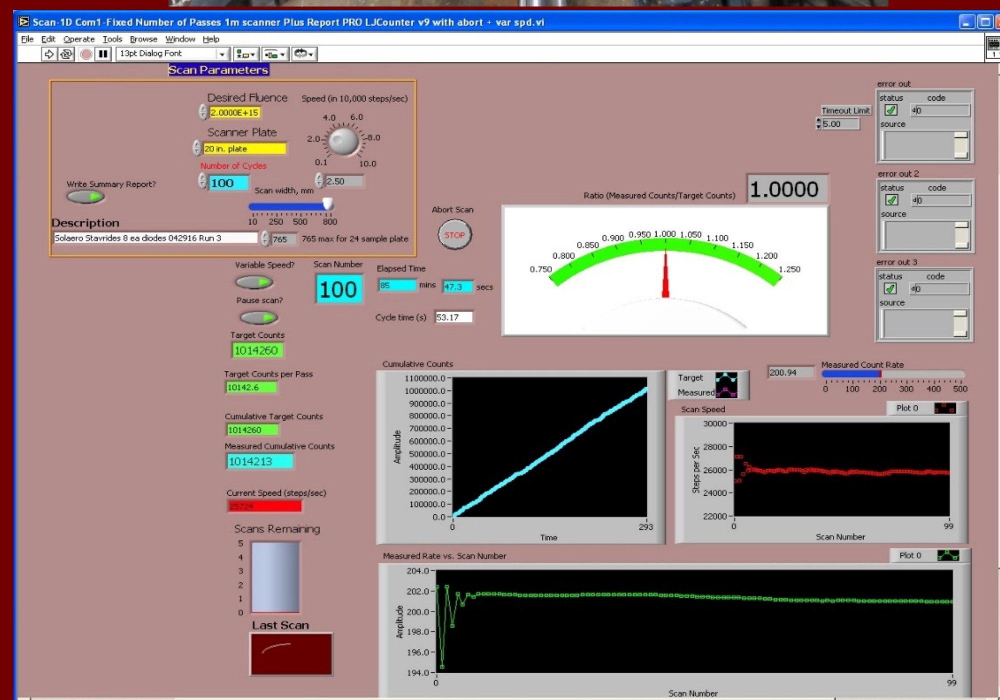
Type	Electron Fluence E>0.4 MeV ($e^-/cm^2/yr$)	1-MeV electron equiv. fluence ($e^-/cm^2/yr$)	Power Loss (5 yr)
Silicon	1.4E14	5.3E13	12 %
GaAs	1.4E14	1.1E13	4 %

Typical 1E14 1 MeV session gives equivalent of 10(Si) 50(GaAs) years of exposure in about 5 mins!

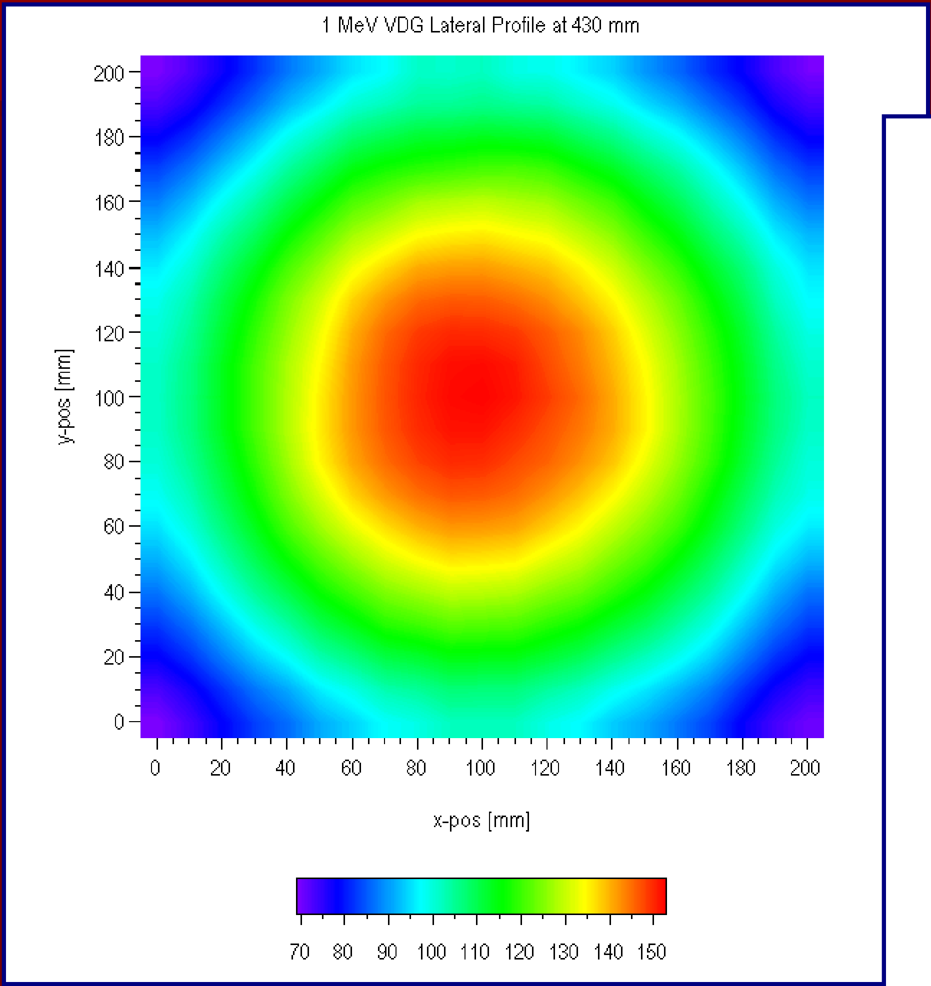
2D Radiation Scanner

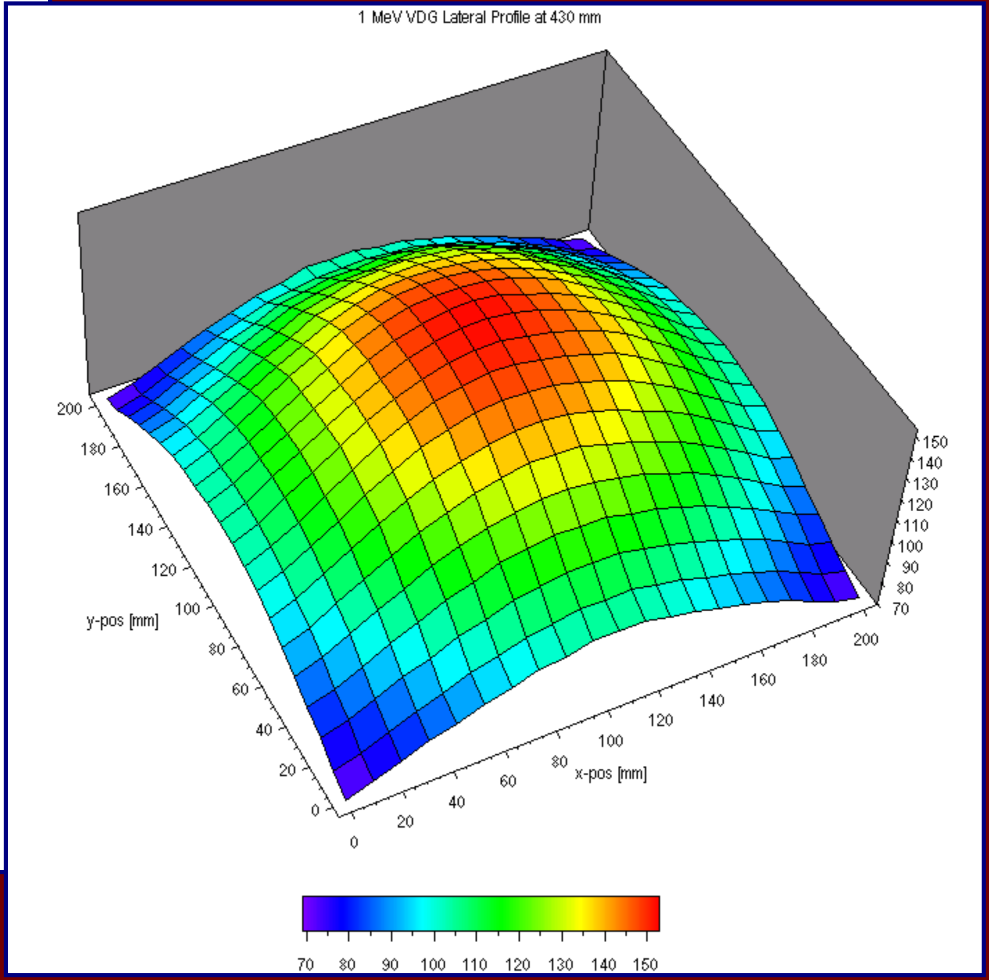
- Performs 2D scans
- Faraday cup and samples cycle in and out of beam
- Faraday cup records electron fluence seen by samples
- Computer-controlled via LabView interface
- Also used for field mapping





Van de Graaff Measured Beam Profiles

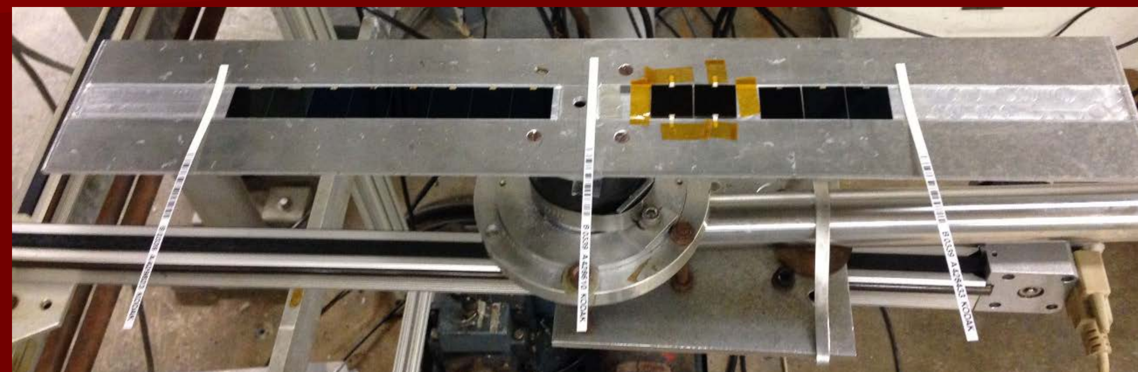




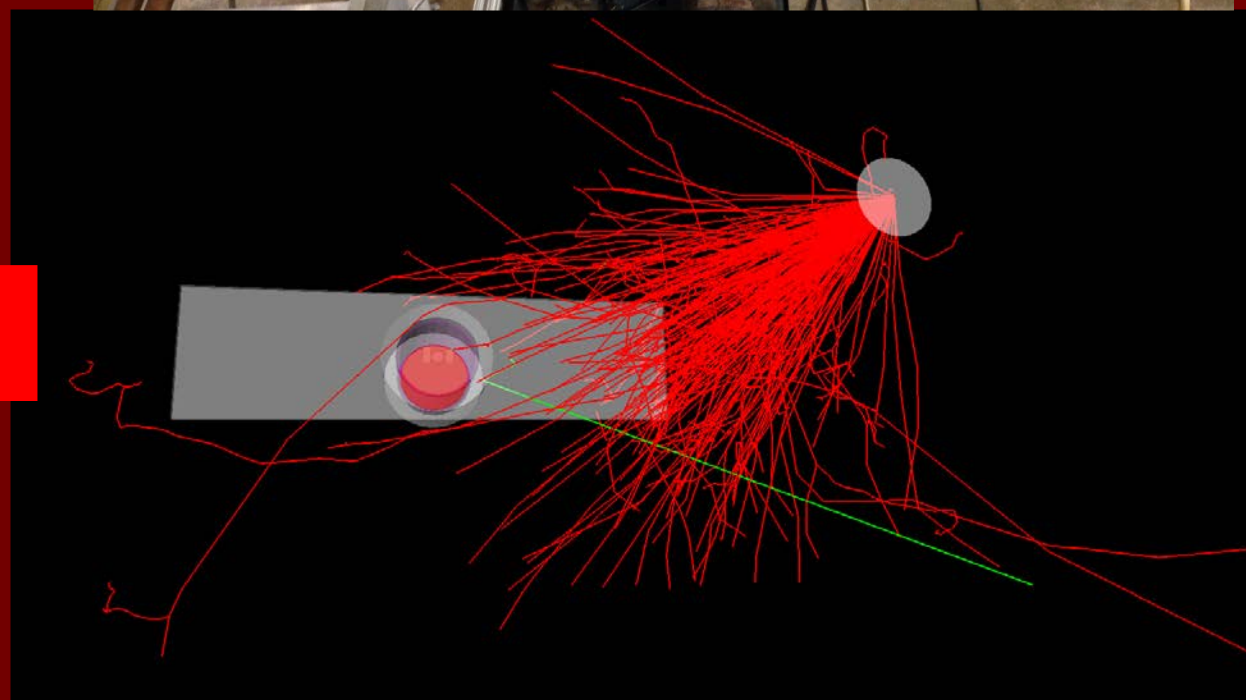
Irradiation of solar cells & electron fluence calibration

- Study to relate dose measured with alanine films to incident electron fluence

Dosimetry calibration and cell irradiation geometry



Full Monte Carlo simulation, including scanner movement



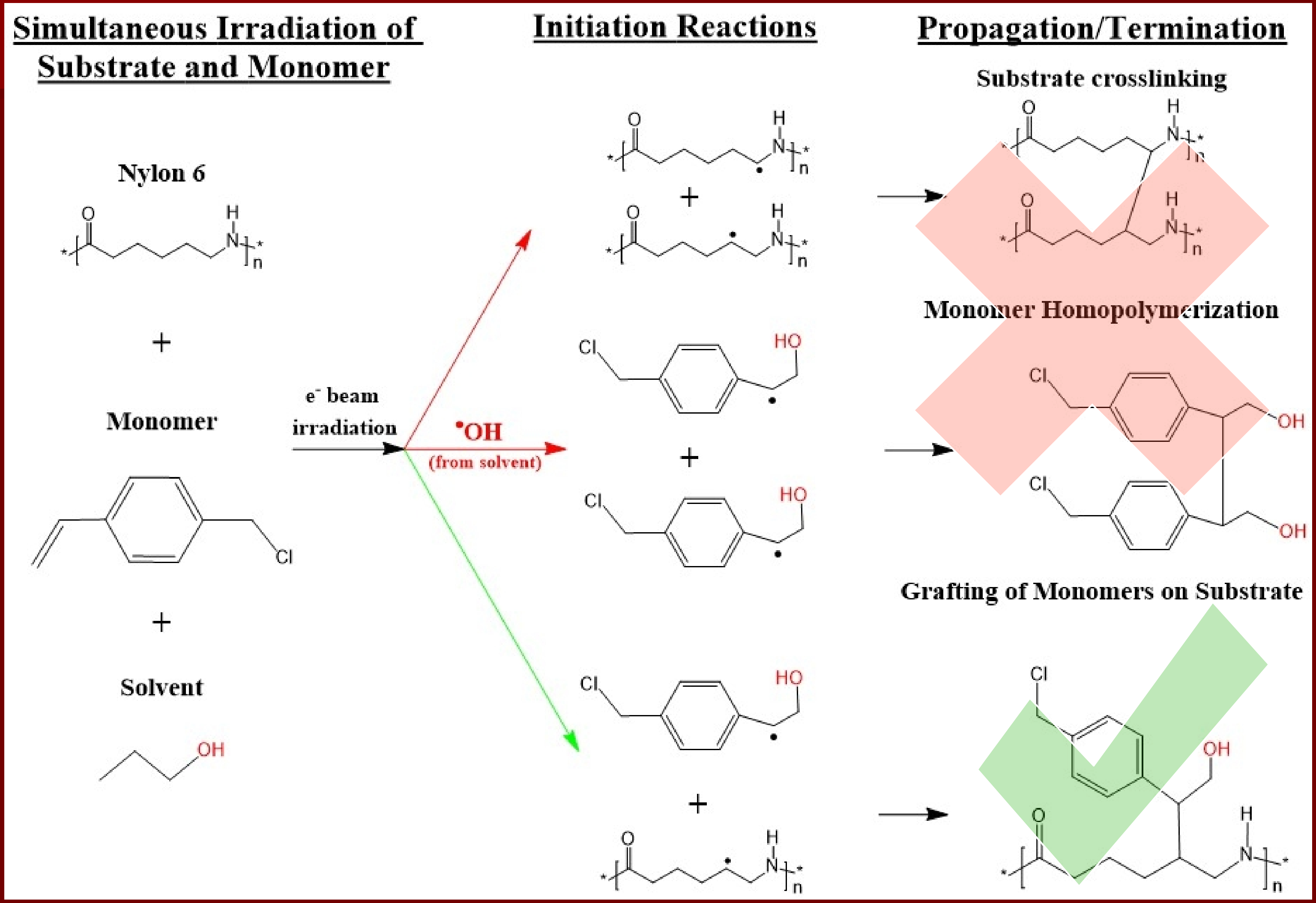
Measured and computed dose-to-fluence ratios

	Measurements				**Monte Carlo Results (per source particle)**		
Film #	Measured Dose [kGy]	Fluence Run 1	Fluence/Dose		Films (dose-to-water)	Faraday Cup Fluence	Fluence/Dose
1	39.57	9.76397E+13	2.46752E+09				
2	39.13	9.76397E+13	2.49526E+09				
3	38.13	9.76397E+13	2.56070E+09				
1b	37.57	1.00868E+14	2.68479E+09				
2b	39.13	1.00868E+14	2.57776E+09				
3b	38.86	1.00868E+14	2.59567E+09				
Averages →	38.7317	9.92536E+13	2.56362E+09		9.7778E-13	0.00252813	2.5856E+09
	Measurement/MC						
	0.9915						

Radiation Grafting Applications on MIRF

- Synthesis of Polymer Electrolyte Membranes (PEM) for hydrogen fuel cells
  - Involves grafting of proton-conducting functionalized-monomers onto fluorocarbon substrates
- Synthesis of membranes for extraction of uranium from seawater
  - grafting of vinylbenzyl chloride to nylon fabrics attaches chemical groups that can extract uranium from seawater

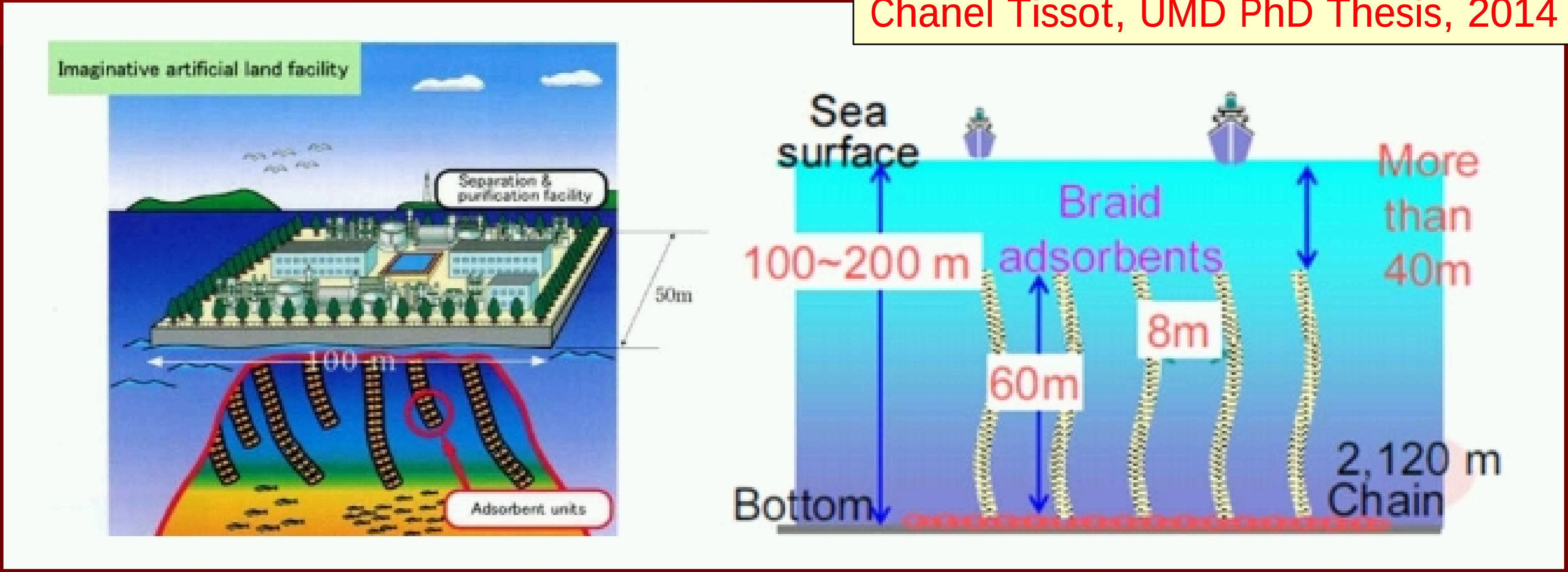
Radiation Grafting Process



Electron Beam Grafting Set-Up

Uranium Extraction Concept

Chanel Tissot, UMD PhD Thesis, 2014



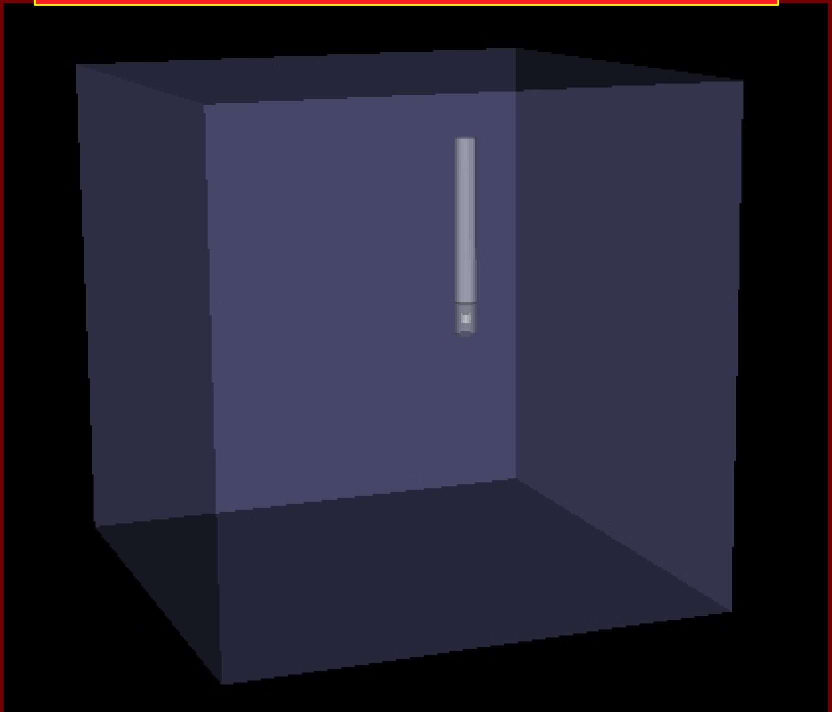
Uranium has to be harvested from winged-nylon braids.

Seawater contains very little uranium, ~ 3 ppb, but there is a lot of it! There is a total of about 4.5 billion tons of uranium trapped in seawater.

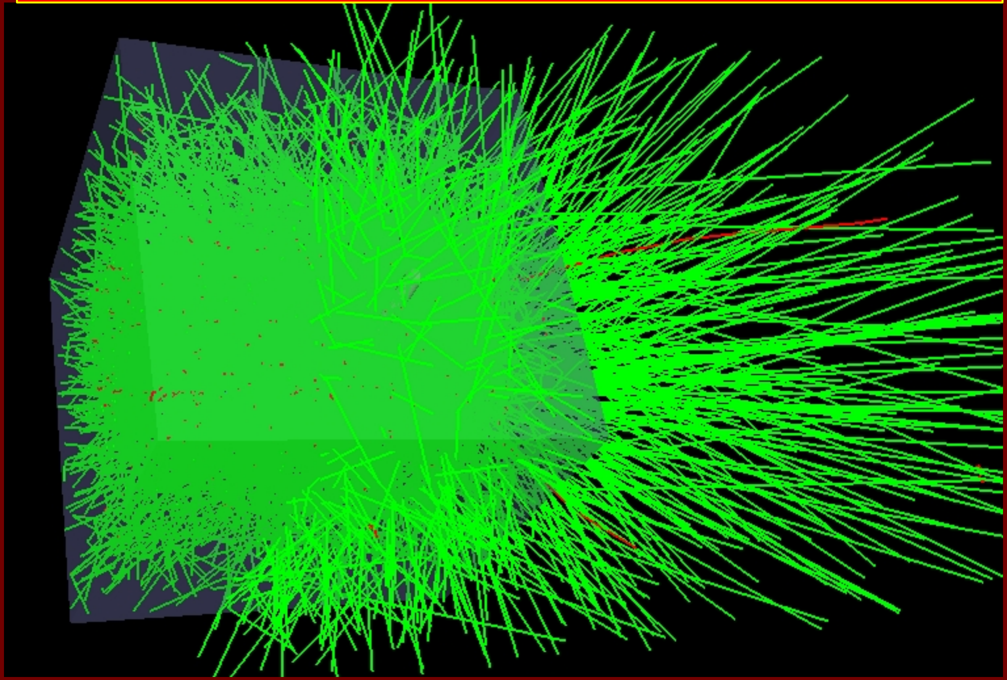
Modeling of Polystyrene Calorimeter in Clinac 6 MV Beam in Water Phantom

- Compare with dose-to-water measured with calibrated ionization chamber at same location
- Modeling agrees with measured ratio to about 1 %

Water Phantom with polystyrene calorimeter probe at 10 cm depth

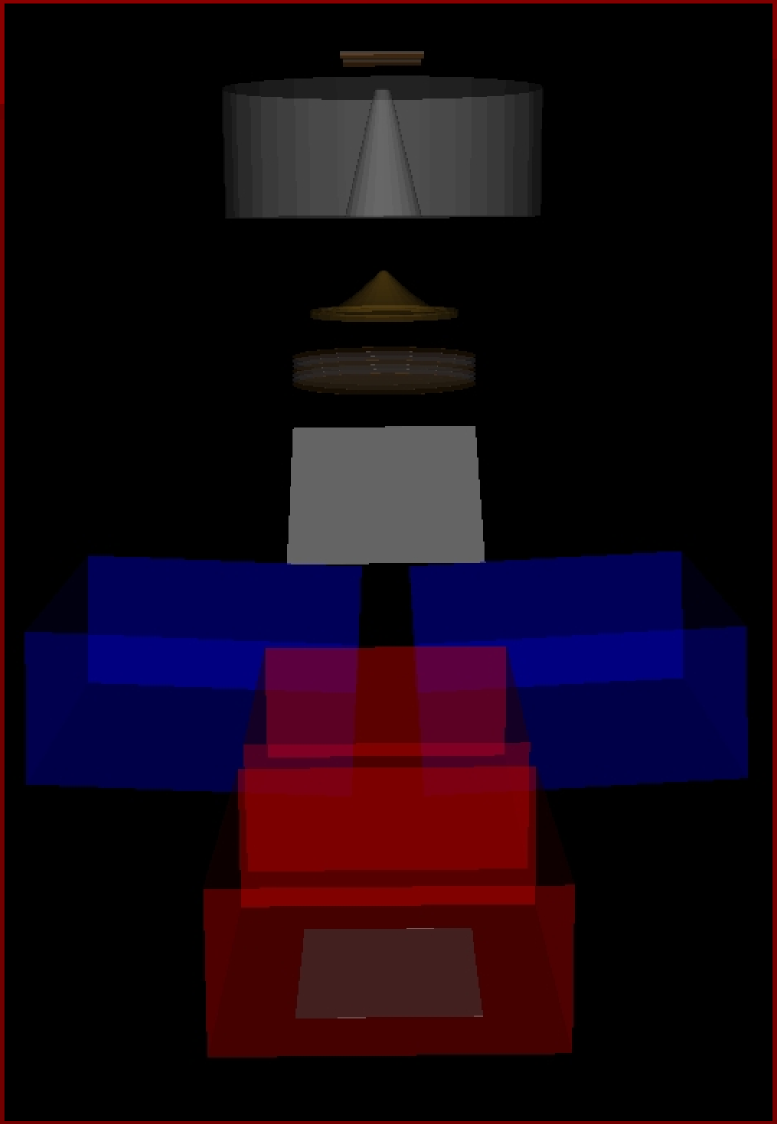


Clinac 6 MV photons incident from left– uses previously-generated phase space file

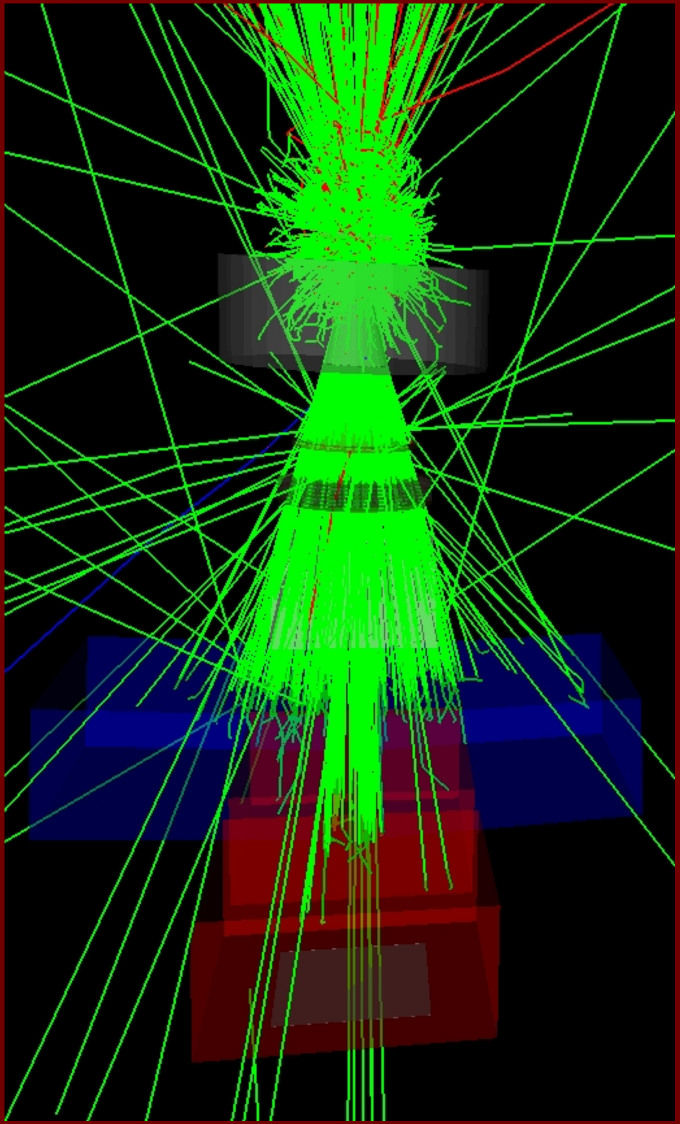


Clinac Modeling

Clinac Accelerator Components

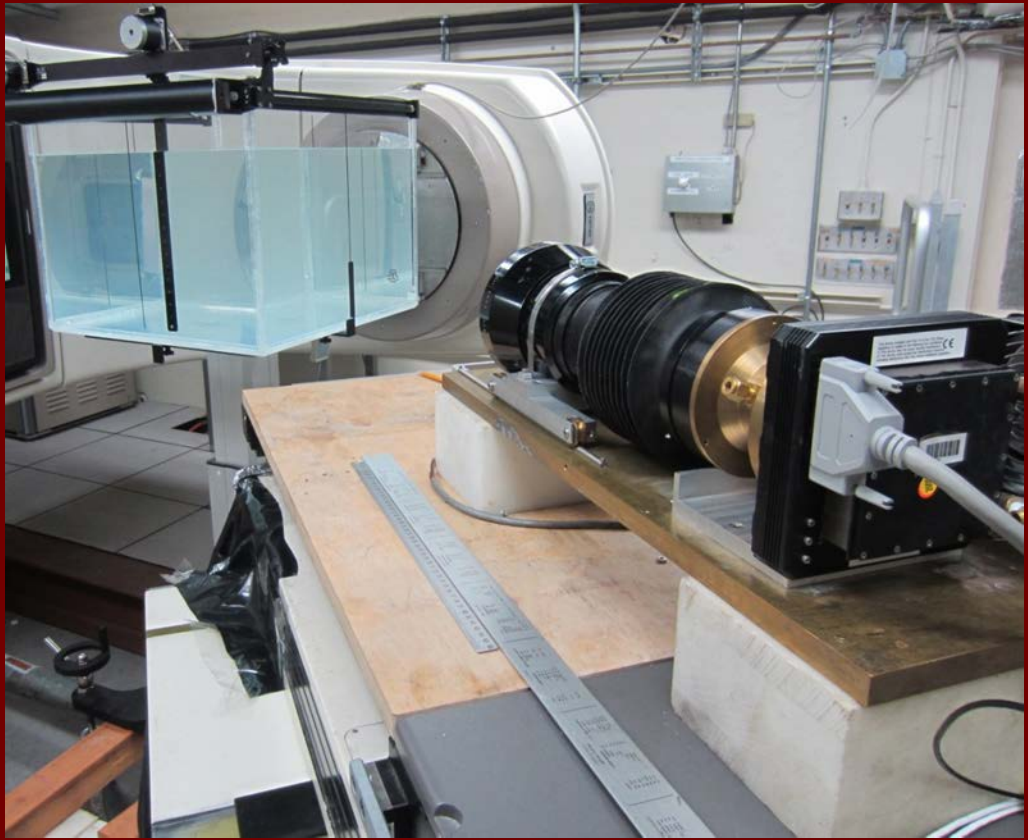


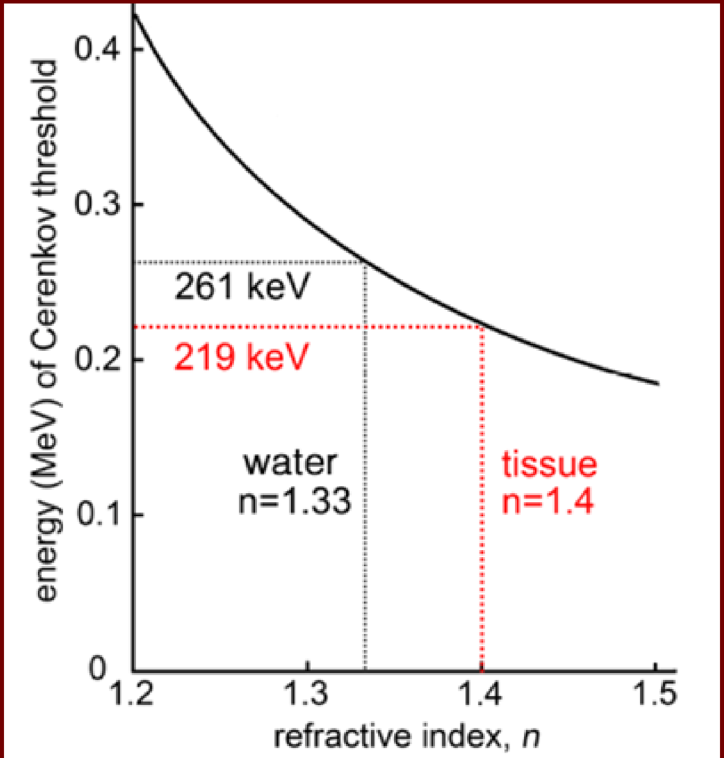
6 MV Photon Trajectories



New Frontiers

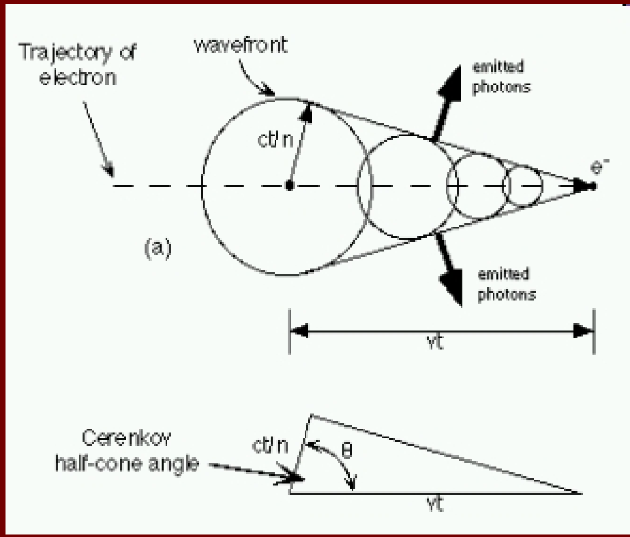
Cherenkov Imaging of Radiotherapy Beams in a Water Phantom





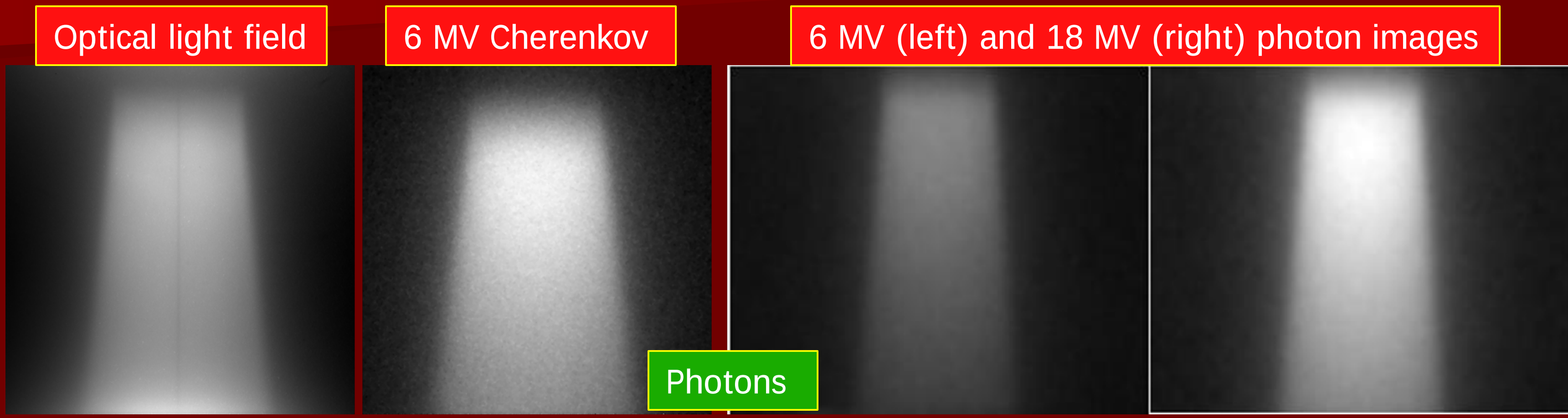
Cherenkov Effect

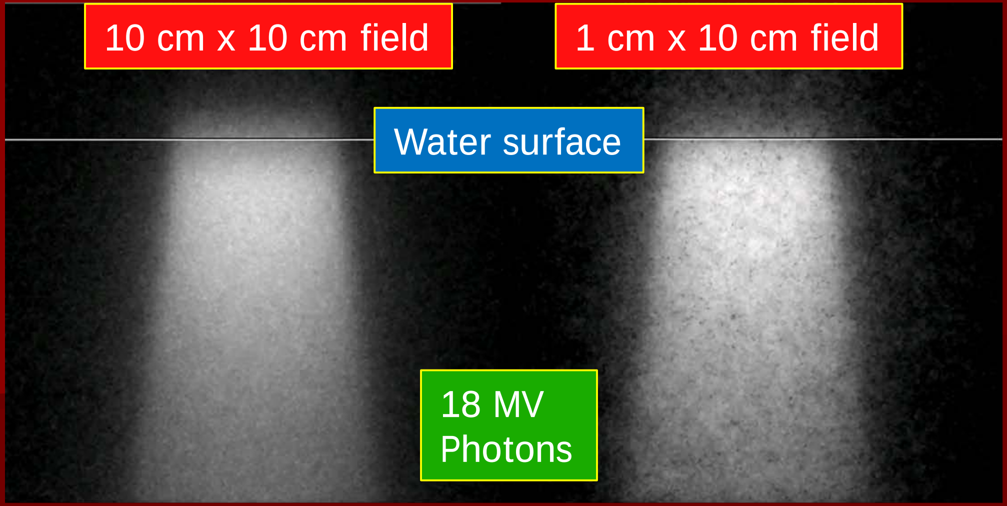
- Equivalent to sonic boom for light
- Critical angle for Čerenkov emission:
  $\theta_c = \arccos(1/\beta n)$
- The number of Čerenkov photons per unit path per wavelength $\propto 1/\lambda^2$



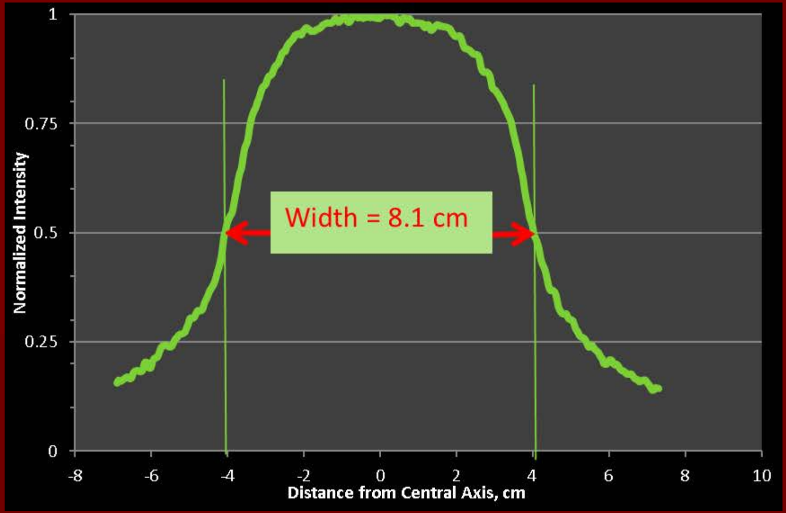
- The number of emitted photons per cm $\approx 750\ sin^2\theta_c$
  – typical photon energy is around 3 eV.
- Čerenkov yield is only about 160 photons per cm for ultra-relativistic electrons in water
- Light output is VERY SMALL, but it's "free"!

Cherenkov light images in a water phantom

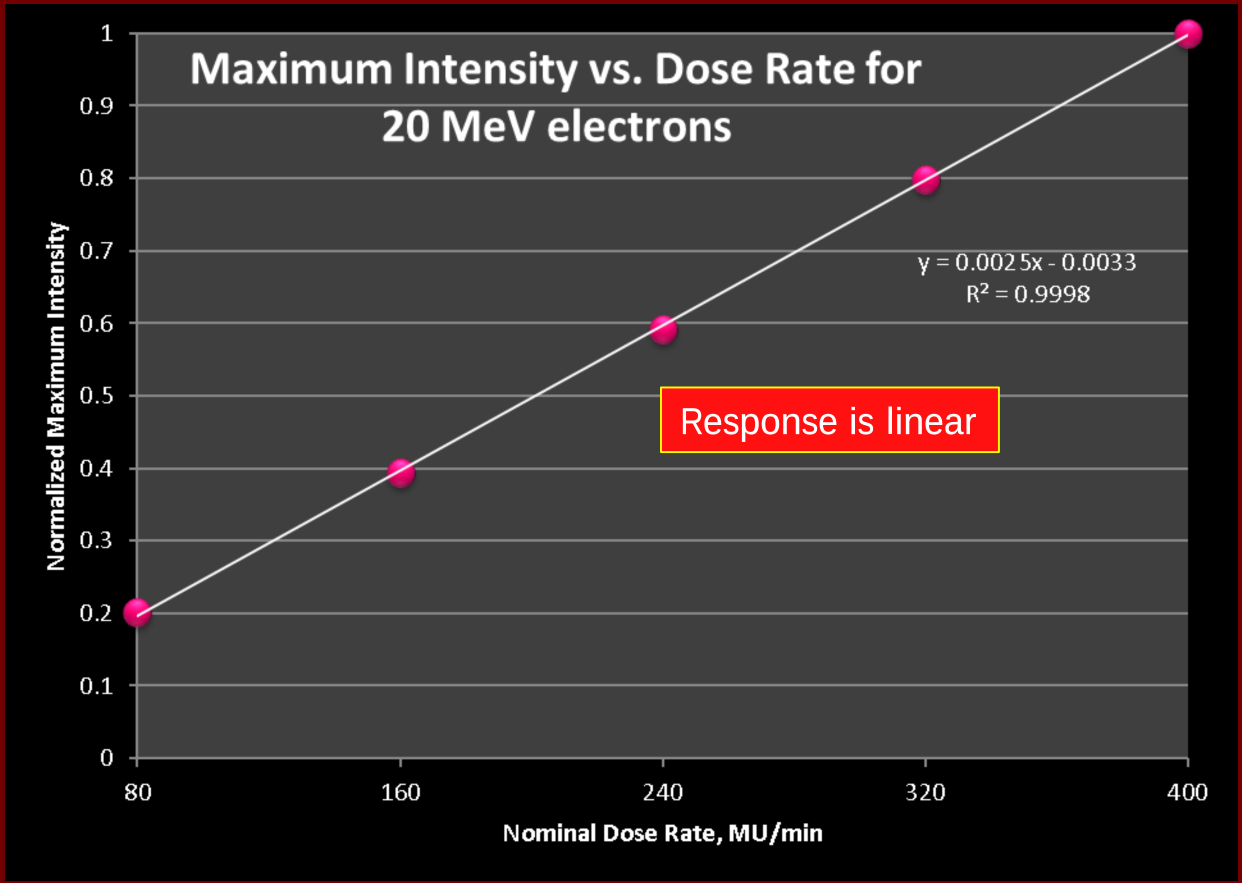




10 cm x 10 cm field
1 cm x 10 cm field
Water surface
18 MV Photons

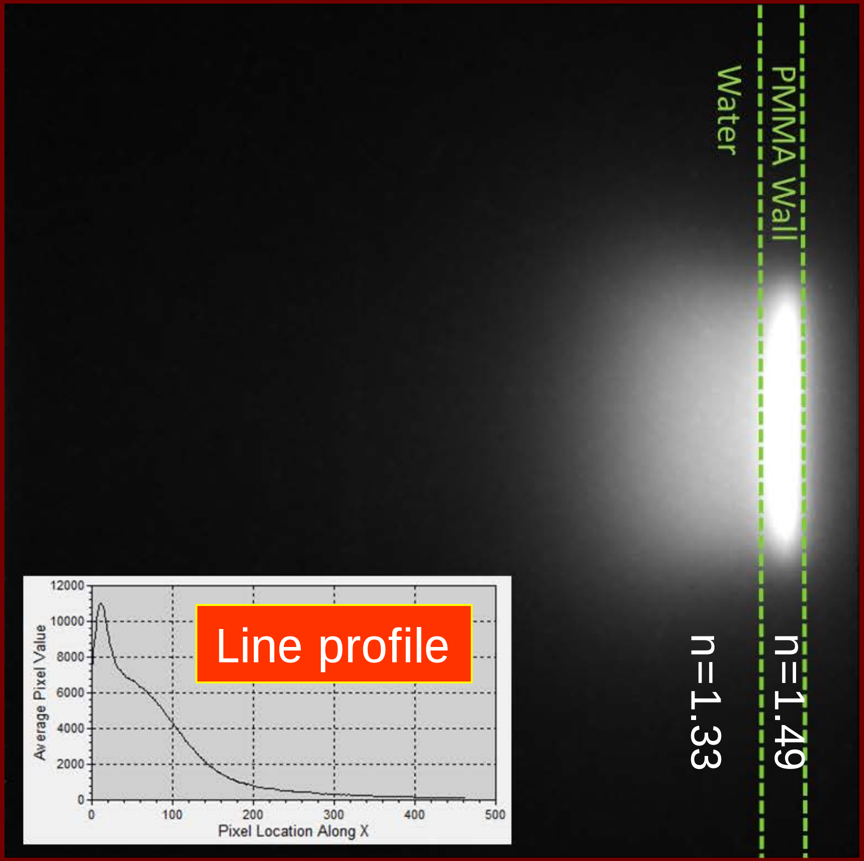


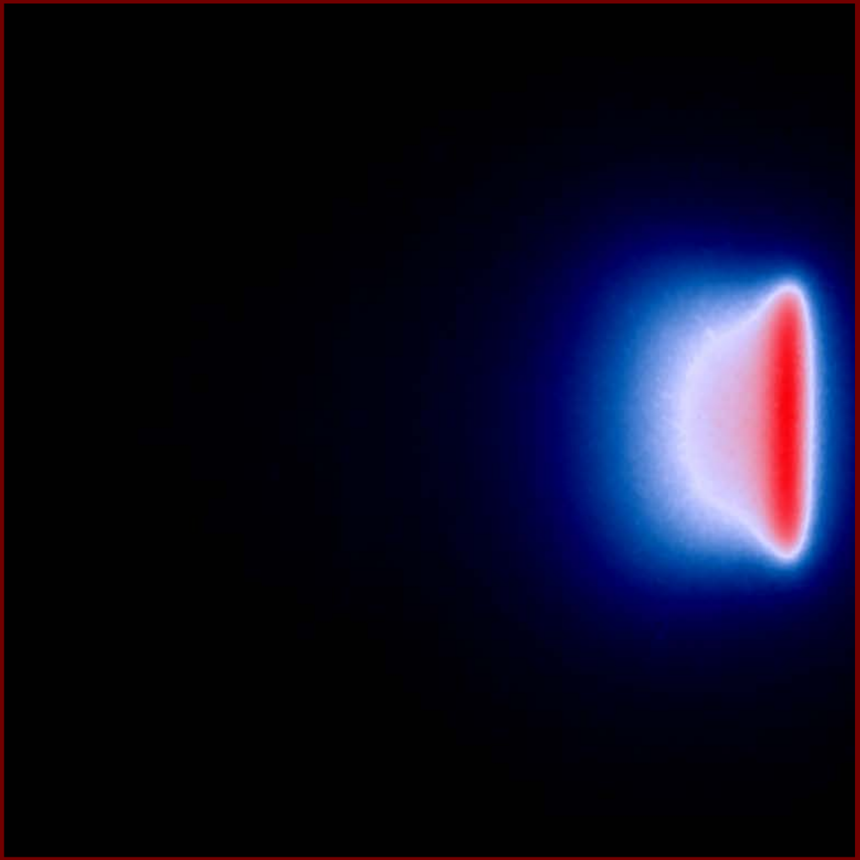
Width = 8.1 cm
Normalized Intensity
Distance from Central Axis, cm



Maximum Intensity vs. Dose Rate for 20 MeV electrons
y = 0.0025x - 0.0033
R² = 0.9998
Response is linear
Normalized Maximum Intensity
Nominal Dose Rate, MU/min

Cherenkov Light Output from Different Materials

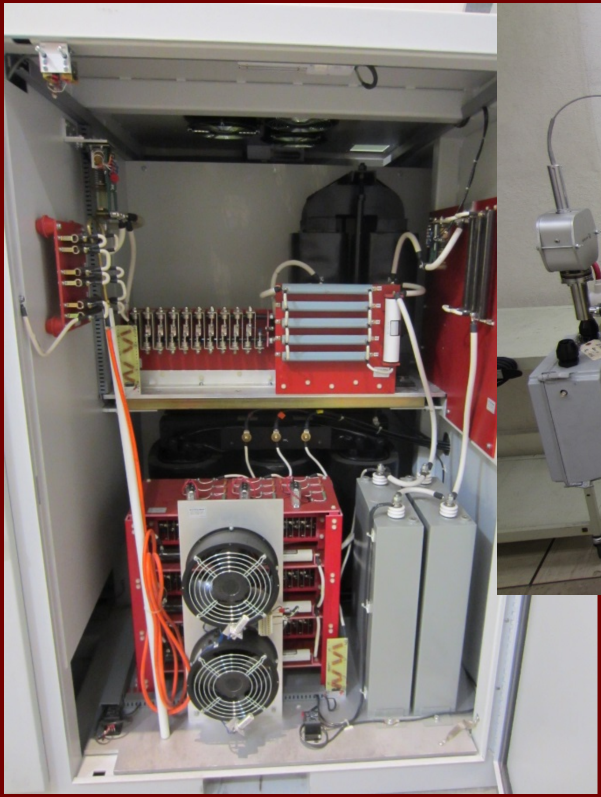


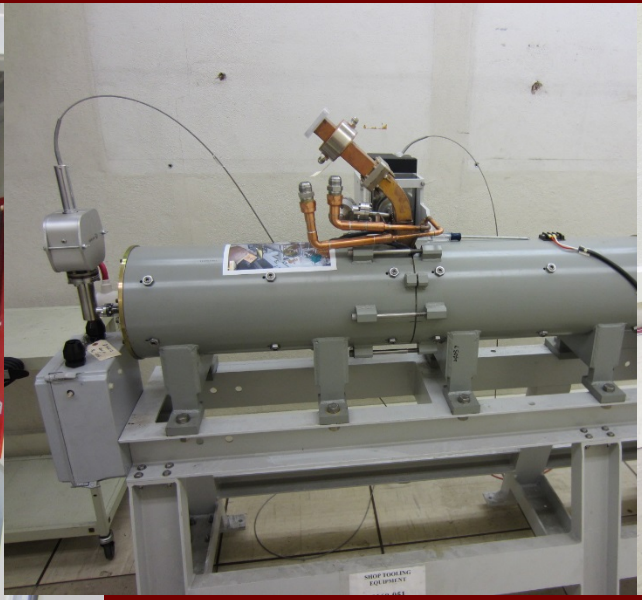


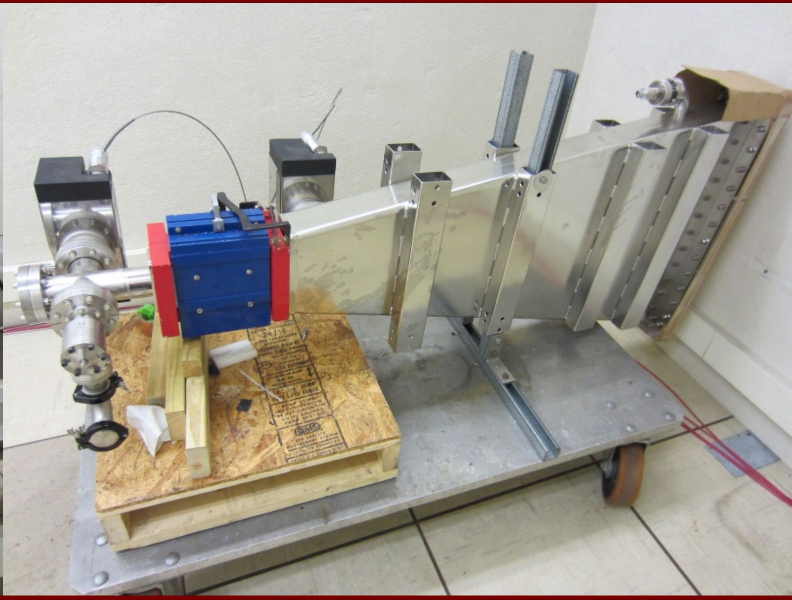
20 MeV electrons incident from side of PMMA water tank

Titan Accelerator (AIMS Facility)

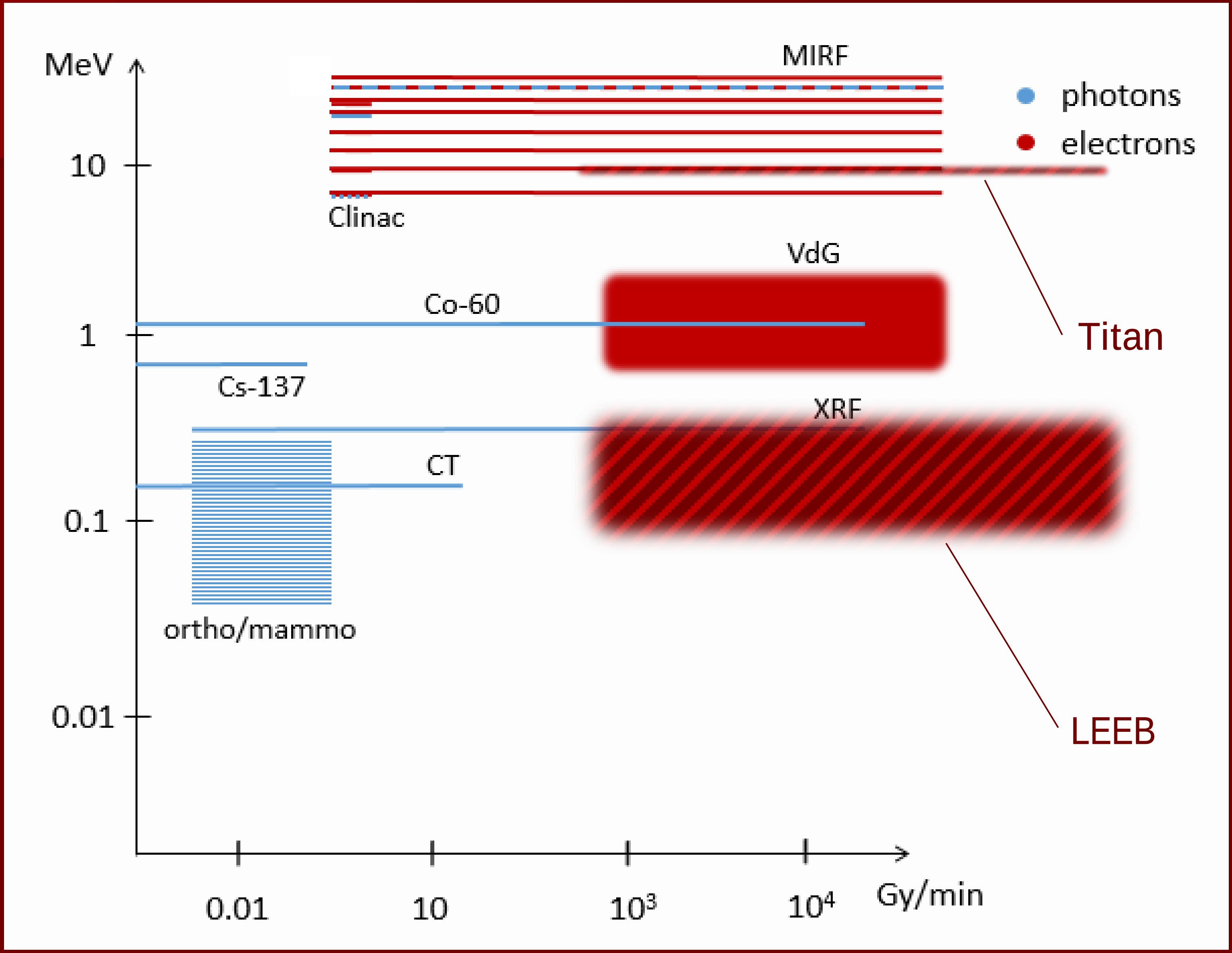
- Industrial 10 MeV, 17 kW e-beam accelerator
- Installation has begun
- Irradiation conditions will match those of industry
- High-dose dosimetry, sterilization applications etc.







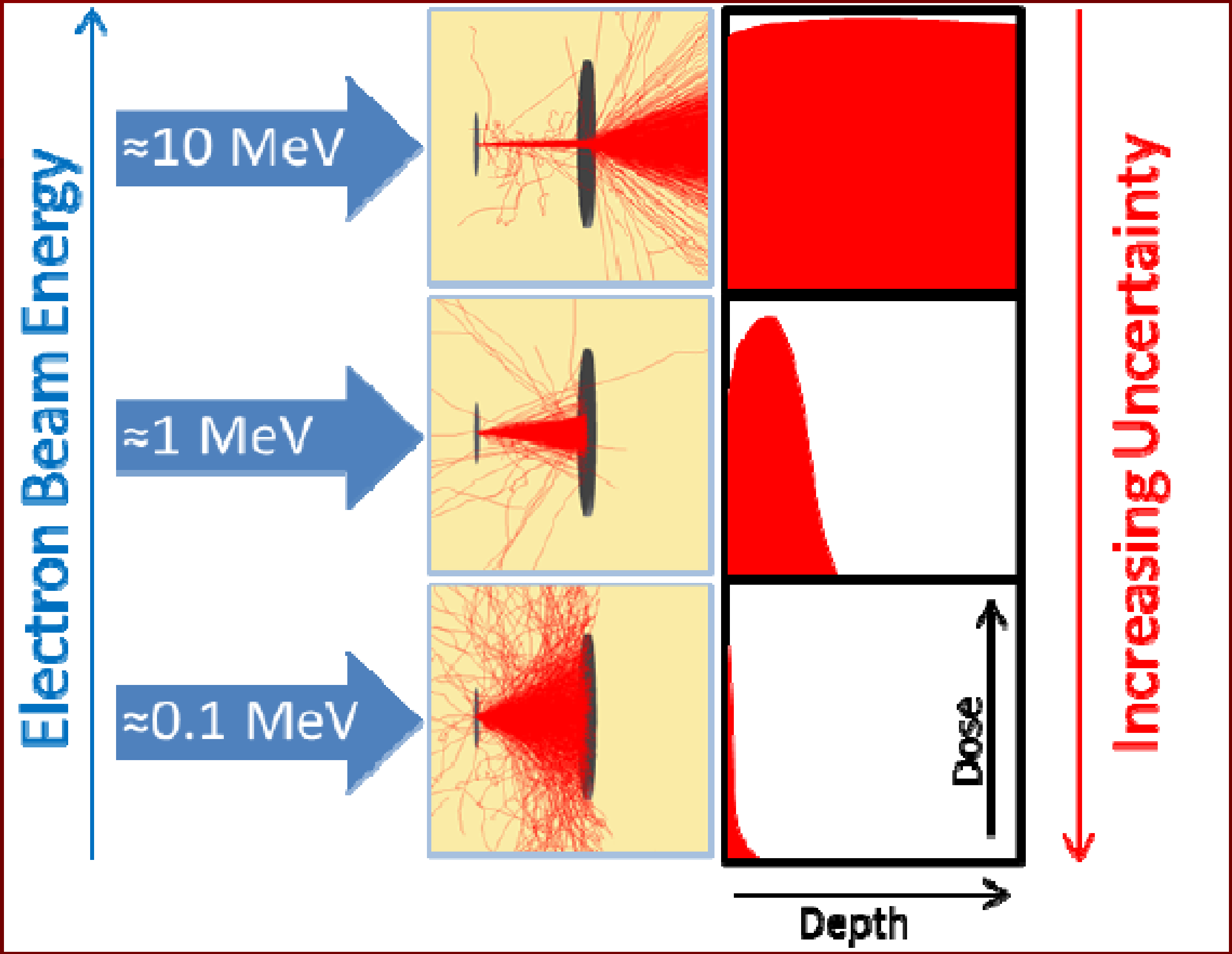
NIST Facilities Summary



Traceability for LEEB?

- Helt-Hansen et al. in Rad Phys Chem
  - "Calorimetry for dose measurement at electron accelerators in the 80-120 keV energy range" 74 (2005) 354-371
  - "Dμ – a new concept in industrial low-energy electron dosimetry" 79 (2010) 66-74
  - ~10% uncertainty
- Galer et al., IMRP 2016 (Vancouver)
  - "A primary standard calorimeter for low energy electron beams"
  - "...it is hoped to reduce the uncertainty ... to ~5% (k=2)"
  - https://imrp.guide/lectures/view/92

Prospects for LEEB absolute dosimetry



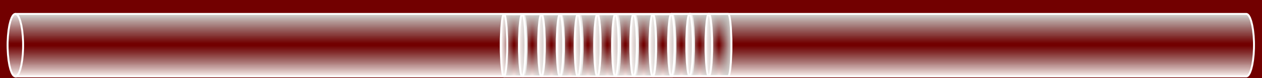
Monte Carlo simulations of electron beams on 2 mm graphite wafer
NIST internal, Fred Bateman

Photonic thermometers

- Fiber Bragg Grating (FBG)

Resolution

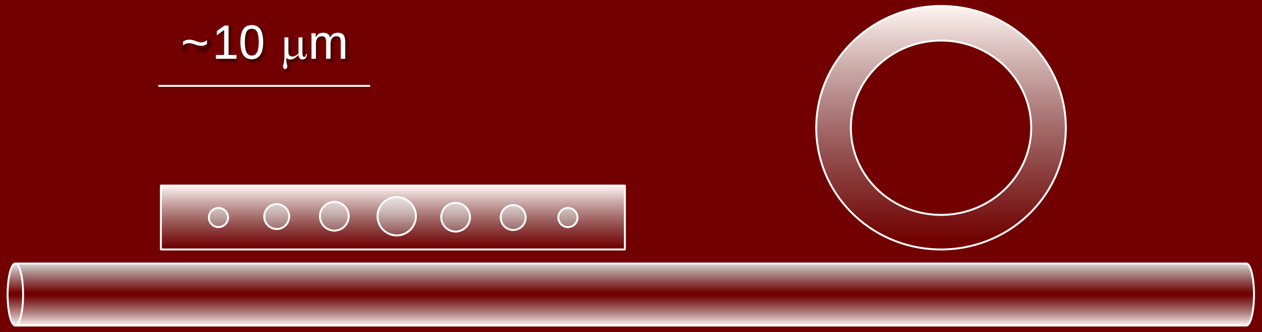
~10 mm



~100 mK

- Nanofabricated devices

~10 μm



~1 mK[1]

Photonic crystal cavity

Micro-loop

[1]Z. Ahmed et al., DOI 10.1081/E-ENN3-120054060

Photonic thermometers - NOAC

NOAC – NIST on a Chip, 2017

“Photonic Dosimeter”

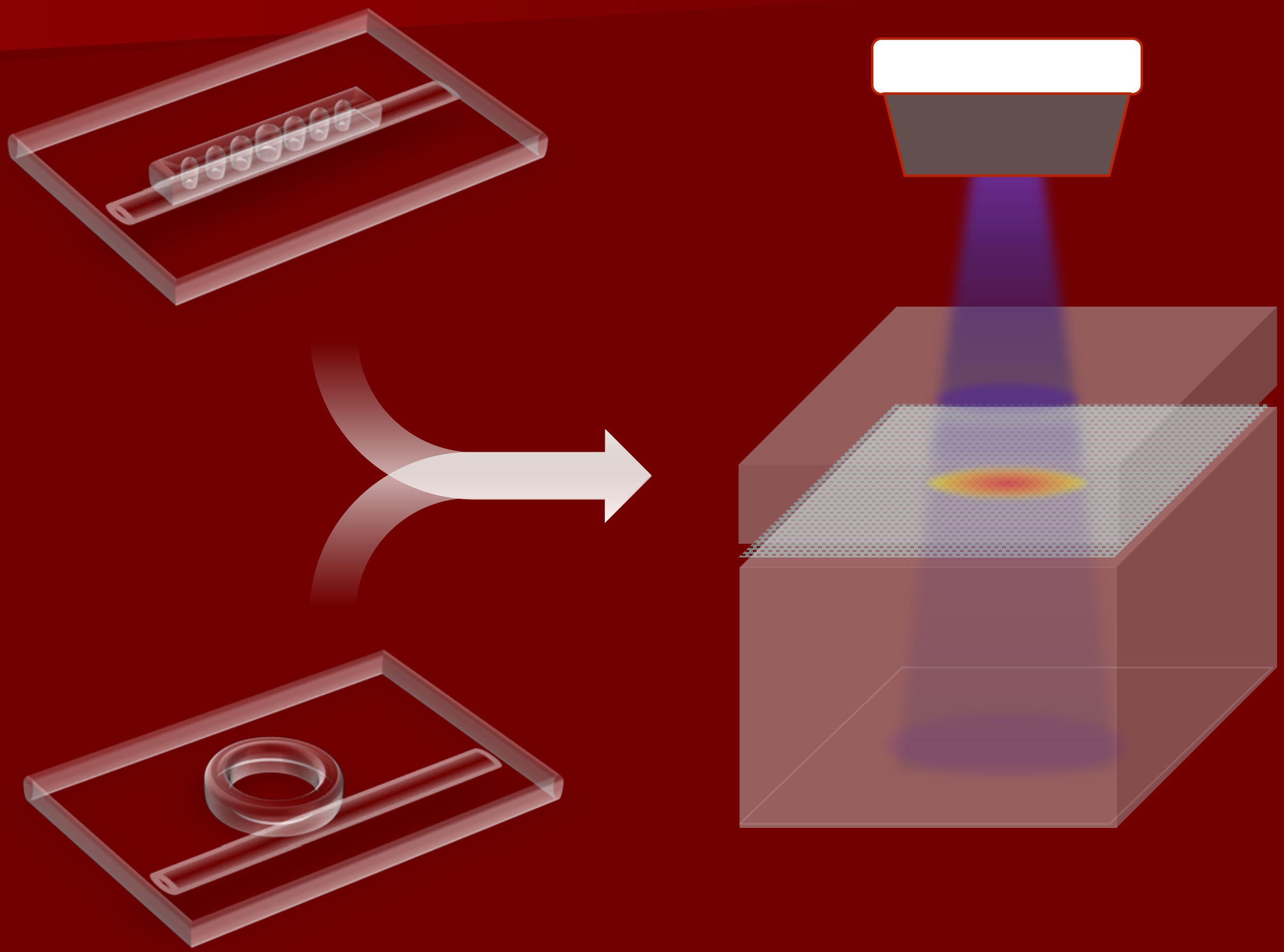
R. Fitzgerald, R. Tosh – Radiation Physics Division (NIST)

Z. Ahmed, N. Klimov – Sensor Science Division (NIST)

Objectives

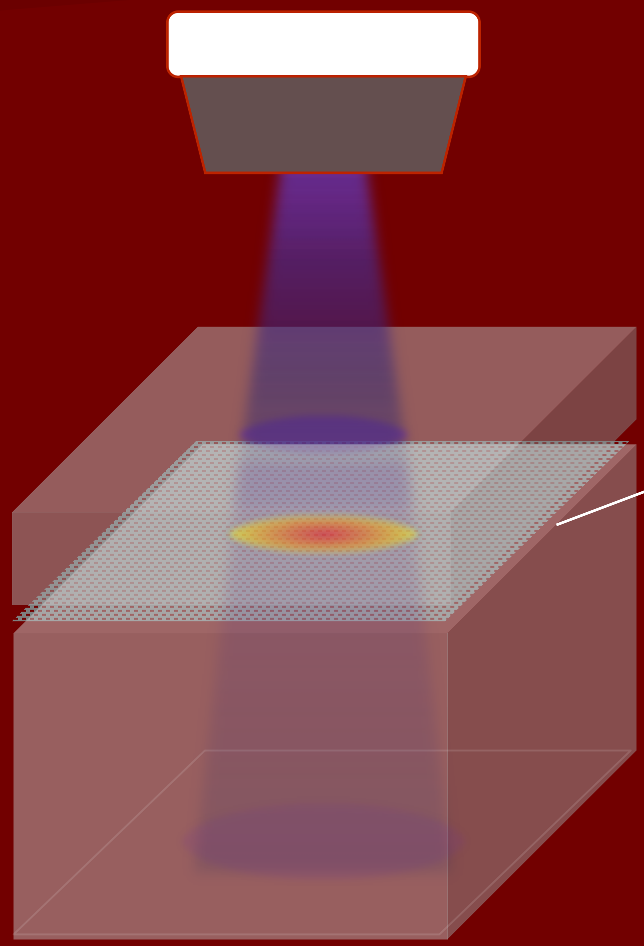
- Assess radiation response – photons, electrons, ...
- Optimize for calorimetry and for dosimetry
- Devise calibration methodology
- ?
- Produce field-deployable sensors on a chip

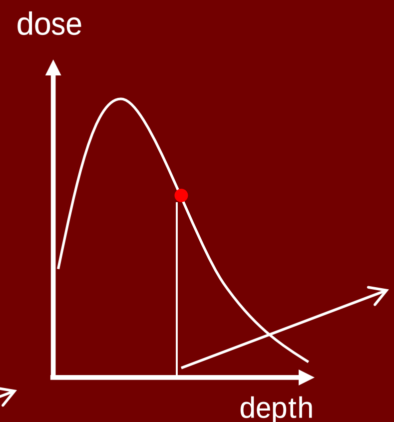
Sensor arrays for calorimetry?



The Electronic Gray (e-Gy)

Marc Desrosiers, 24th CIRMS, http://www.cirms.org/pdf/cirms2016/CIRMS-2016-Desrosiers.pdf





~cm, 10 MeV

~mm, 1 MeV

~μm, 0.1 MeV

More details:

“Chip-scale calorimetry for industrial dosimetry”
Ileana Pazos, NIST
25th CIRMS Meeting, 9:45 a.m., March 29, 2017