Medical Physics

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PENN RADIATION ONCOLOGY

Penn Medicine

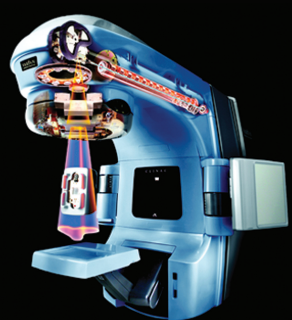
Medical Physics

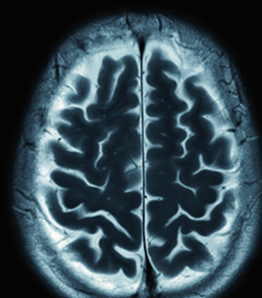
What is MEDICAL PHYSICS?

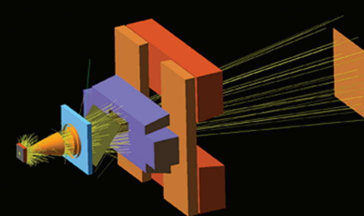
An Introduction to
the Field of Medical Physics

MEDICAL PHYSICS IS an applied branch of physics concerned with the diagnosis and treatment of human disease with applications in the following areas:

- Radiation and particle based cancer treatments
- Medical imaging modalities to identify and track diseases
- Computer simulations of disease treatment/progression and optimization of therapy
- Utilization of data analytics to improve upon current treatment outcomes







Courtesy of NPL

THERAPEUTIC MEDICAL PHYSICS	DIAGNOSTIC/IMAGING MEDICAL PHYSICS	MODELING AND OPTIMIZATION	DATA ANALYTICS AND DECISION SUPPORT

Status of Medical Physics in Africa

Introduction

Information on facilities and clinical programmes in Africa:

- 54 countries in Africa
- 1.2 billion population
- 50% of countries with RT facilities
- 20 countries with NM facilities
- ~ 1,000 MPs in region
- 10 countries with MP academic programmes
- 6 countries with MP clinical programmes

Medical Physics (MP) Workforce

The summary of the Africa's Medical Physics workforce is given as follows:

Country	No. of MPs	Country	No. of MPs
Algeria	129	Nigeria	100
Angola	4	Senegal	3
Benin	3	Sierra Leone	1
Botswana	4	South Africa	136
Burkina Faso	2	Sudan	28
Cameroon	2	Tanzania	4
Congo DR	1	Tunisia	37
Cote d'Ivoire	2	Uganda	10
Egypt	374	Zambia	6
Eritrea	2	Zimbabwe	9
Ethiopia	4	**Total**	**1,041**
Gabon	4		

The Evolution of Radiation Therapy

1895

Wilhelm Conrad Röentgen discovers x-rays

As early as 1897, it was concluded that x-rays could be used for therapeutic as well as diagnostic purposes

1911

Marie Curie published the "Theory of Radioactivity."

1920's

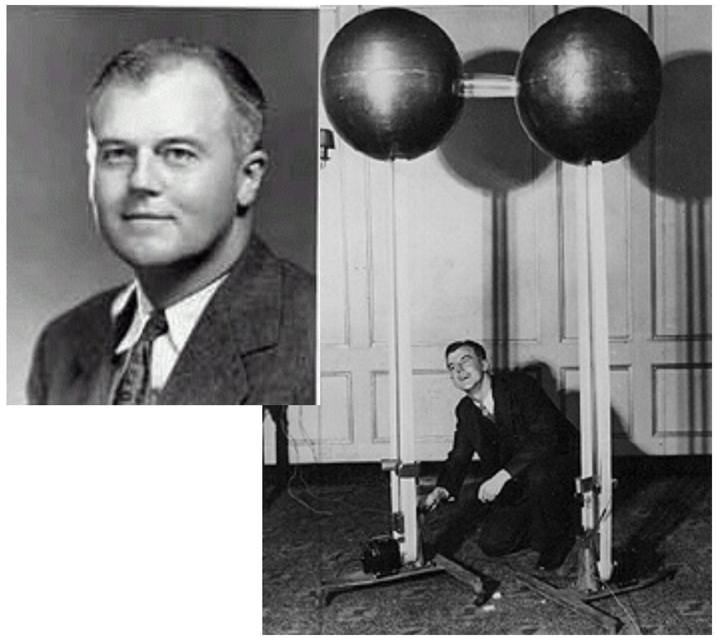
The investigation of x-ray radiation for patient therapy moved into the clinical routine in the early 1920s.

The Evolution of Radiation Therapy

1930's

Radioactive cobalt-60 was discovered by Glenn T. Seaborg and John Livingood at the University of California - Berkeley in the late 1930's.

1940's



Van de Graaff begins commercial Production of 2 and 2.5 MeV machines

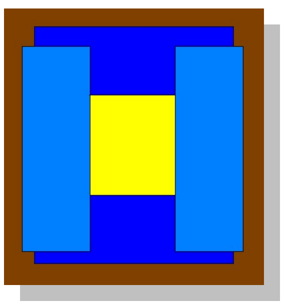
1950's

The cobalt machine was developed in Canada. It was the first available megavoltage cancer therapy machine.

The Evolution of Radiation Therapy

1960's

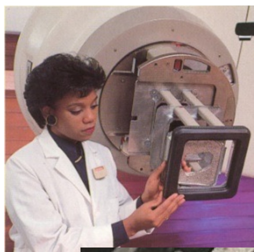
The First Clinac

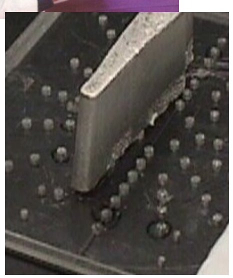


Standard Collimator

The clinac reduced complications compared to Co60

1970's

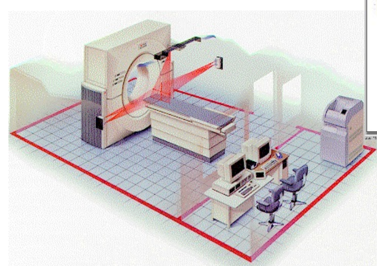


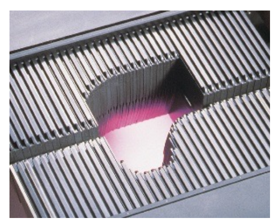


Cerrobend Blocking
Electron Blocking

Blocks were used to reduce the dose to normal tissues

1980's

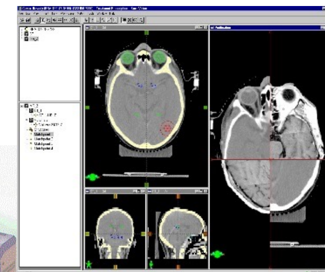


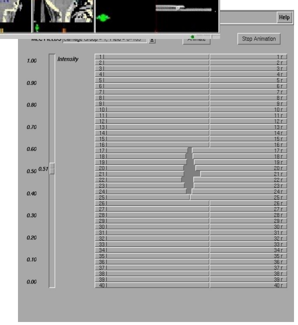


Multileaf Collimator

MLC leads to 3D conformal therapy which allows the first dose escalation trials.

Computerized 3D CT Treatment Planning

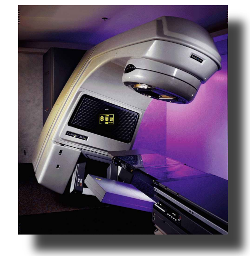




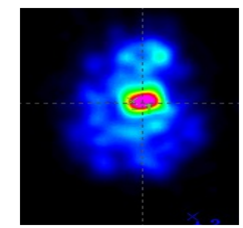
Dynamic MLC and IMRT

Computerized IMRT introduced which allowed escalation of dose and reduced compilations

1990's



2000's



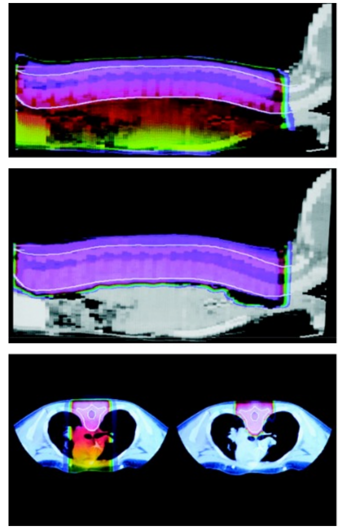
Functional Imaging

High resolution IMRT

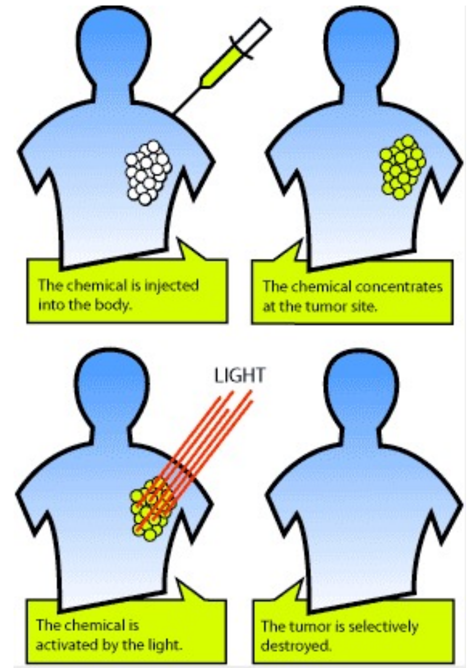
IMRT Evolution evolves to smaller and smaller subfields and high resolution IMRT along with the introduction of new imaging technologies

The Evolution of Radiation Therapy

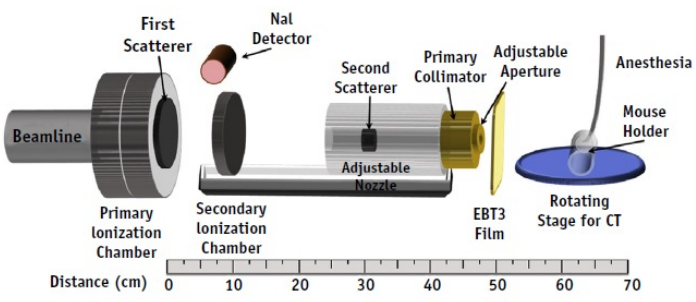
Beyond 2000's



Proton Therapy



Photodynamic Therapy



Proton FLASH
Diffenderfer, et al. Intl.Journal RadOncBioPhys, Volume 106, Issue 2
1 February 2020, Pages 440-448

Career Path in Medical Physics

- Doctor of Philosophy: ***Nuclear Physics,*** **Hampton University.**
  Thesis - Pion Electroproduction from Helium-3, Deuterium and Hydrogen
- **Instructor:** ***Radiation Oncology,*** **The University of Pennsylvania**
- **Assistant Professor,** ***Radiation Oncology,*** **The University of Pennsylvania.**
- **Associate Professor,** ***Radiation Oncology,*** **The University of Pennsylvania.**
- **Director: Medical Physics Graduate Group, The University of Pennsylvania**
- **Chair: Global Medical Physics Education and Training Committee, American Association of Physics in Medicine**
- **Research: Quality Assurance in Radiation Therapy, Global Health**

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Radiation Physics

The science of ionizing radiation and its interaction with matter, with special interest in the energy absorbed[1]

Medical physicists:* *clinician scientists who specialize in Diagnostic or Therapeutic radiation physics

- **Production of ionizing radiation for diagnostic and therapeutic means**
- **Use of radioactivity for diagnostic and therapeutic means**
- **Detection and measurement of ionizing radiation**
- **Calculation of energy deposition in matter**
- **Radiation safety and shielding**
- **Development, optimization, and quality control of diagnostic imaging and therapeutic delivery processes**

Practical, technical, and safety aspects of ensuring that all patients receive their prescribed dose of radiation to the prescribed location

[1] Andreo, P, Burns DT, Nahum AE, Seuntjens J, Attix FH. Fundamentals of Ionizing Radiation Dosimetry. 2017

Radiation Therapy for Cancer

More than 14 million new cases of cancer are diagnosed globally each year

- **Approximately 50% of all cancer patients can benefit from radiation therapy in the management of their disease**
  - Of these, approximately half present early enough to pursue ***curative*** intent
  - As opposed to ***palliative*** intent designed to relieve symptoms and improve quality of life
- ***Frequently used in combination with other treatment modalities:***
  - Surgery (pre- or post-op)
  - Systemic chemotherapy (before, during, or after radiation)
  - Most recently, immunotherapy

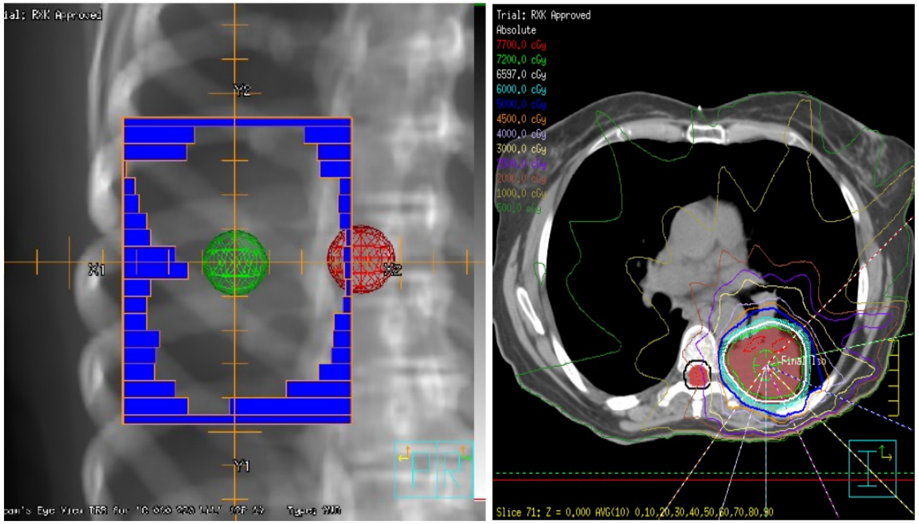
Jaffray DA, Gospodarowicz MK. Radiation Therapy for Cancer. In: Cancer: Disease Control Priorities, Third Edition (Volume 3). Washington (DC): 2015 Nov 1. Chapter 14.

Radiation Therapy for Cancer

Generally there are 2 primary goals to achieve maximum therapeutic effectiveness

1. ***Target dose escalation***
2. ***Normal tissue sparing***

Treatment plans are designed to *collimate* and *direct* radiation beams toward the target volume with specific intent to avoid excessive radiation to organs at risk (OARs)



Khan, F. Treatment Planning in Radiation Oncology, 3rd ed.

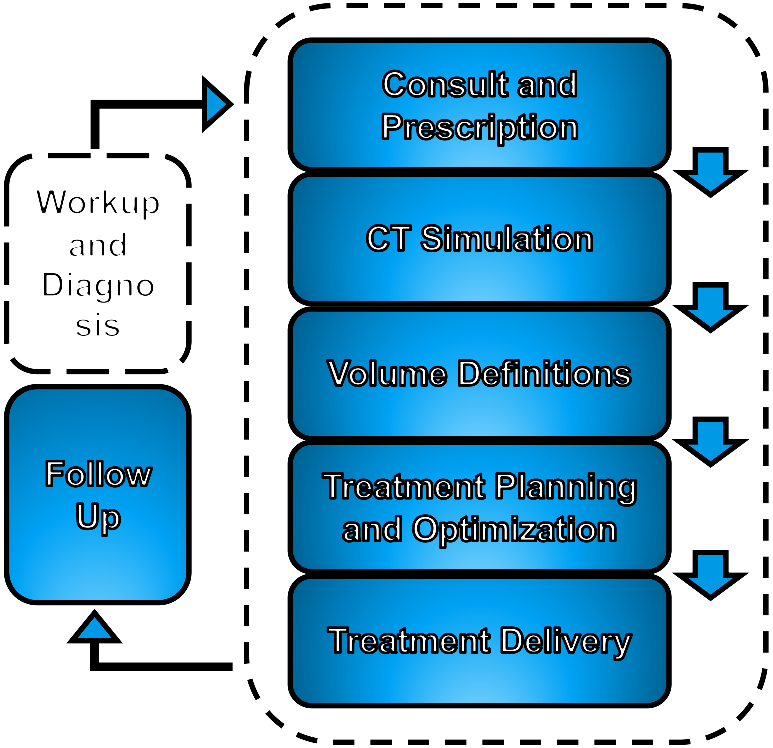
Radiation Therapy Delivery

- **External beam radiation therapy (EBRT): applied externally through directed, collimated beams of radiation**
- **Brachytherapy: insertion of radiation-emitting sources directly within the tumor or adjacent body cavity**
- **Radioisotope therapy: systemic injection of a radioisotope designed to target disease**

Radiation Therapy Workflow

Complex and carefully orchestrated sequence of events and interactions

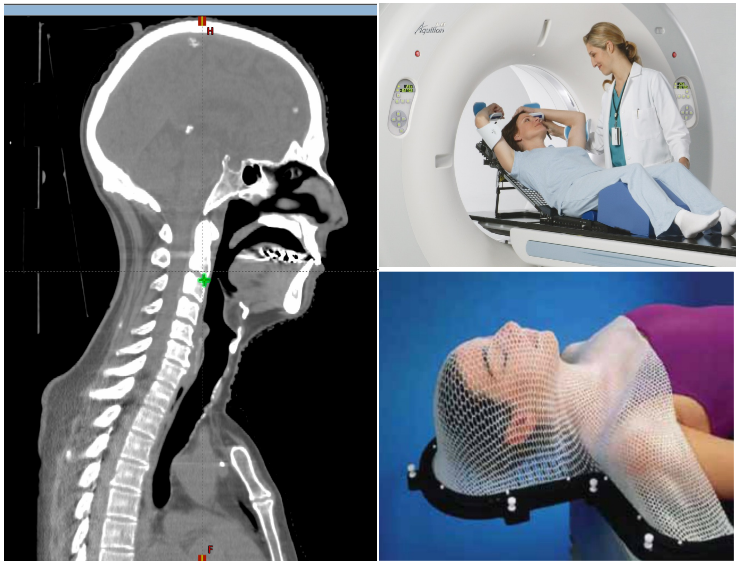
- **Requires a high level of communication and coordination of processes and systems involved**
  - *Radiation Oncologist, MD:* prescribes treatment regimen
  - *Medical physicist, MS, PhD:* all aspects of treatment
  - *Dosimetrist, CMD:* prepare treatment plan
  - *Radiation Technologist, RT:* operate the treatment units
  - *Nurse, RN:* management of patients undergoing therapy
- **Complemented by biomedical engineers, computer scientists, applied mathematicians, and information technology experts**



CT Simulation Study

***Simulation*:** **acquire volumetric image data simulating the physical and geometric aspects of treatment delivery for planning**

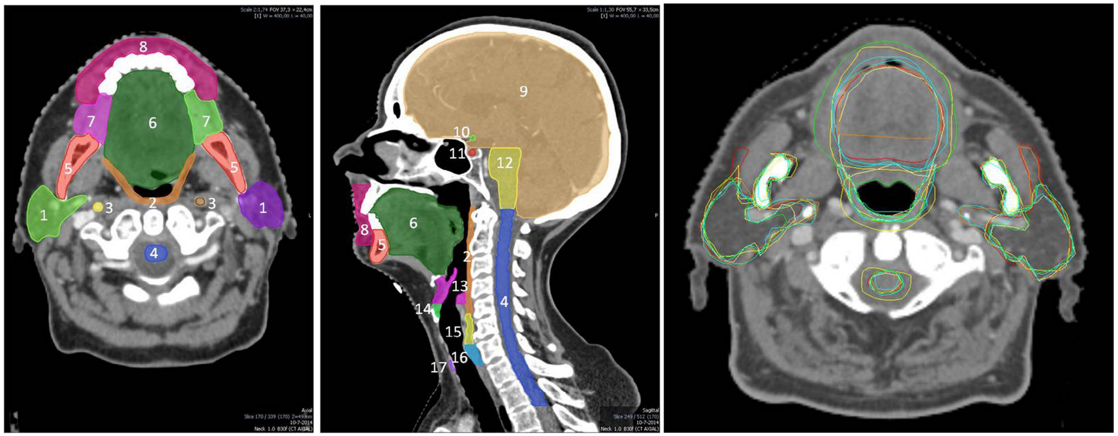
- **Patient model describing geometric relationship between radiation beam and patient anatomy**
- **Accurate dose calculation is only possible when sufficiently accurate data are available**
- ***Specially adapted CT scanner, patient setup and immobilization simulating treatment***



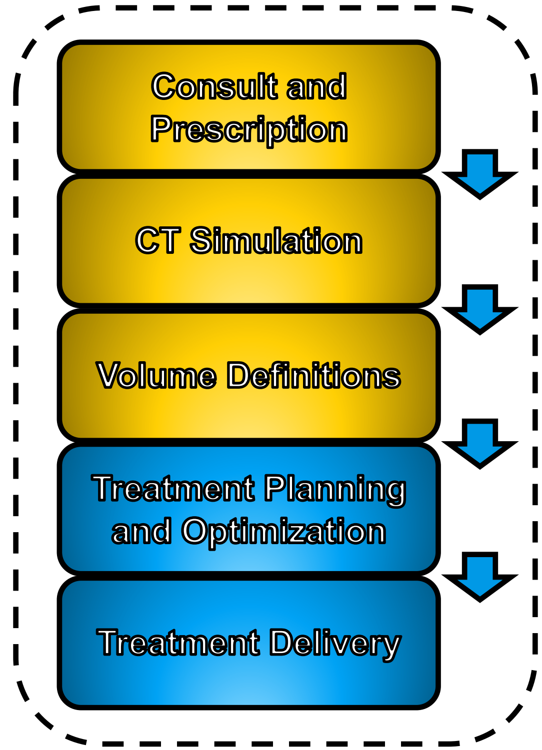
Khan, F. Treatment Planning in Radiation Oncology, 3rd ed.
Bushberg, J. The Essential Physics of Medical Imaging, 3rd ed.

Image Segmentation

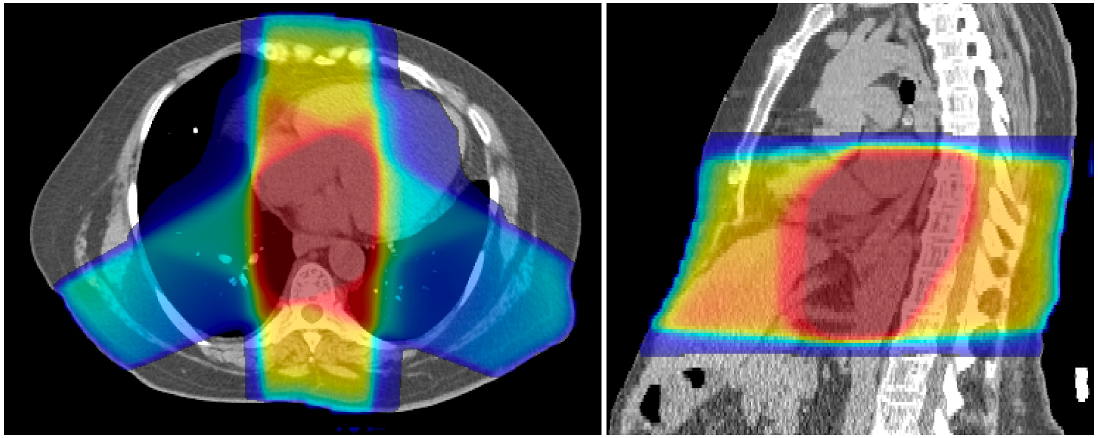
Radiotherapy and Oncology 117 (2015) 83-90

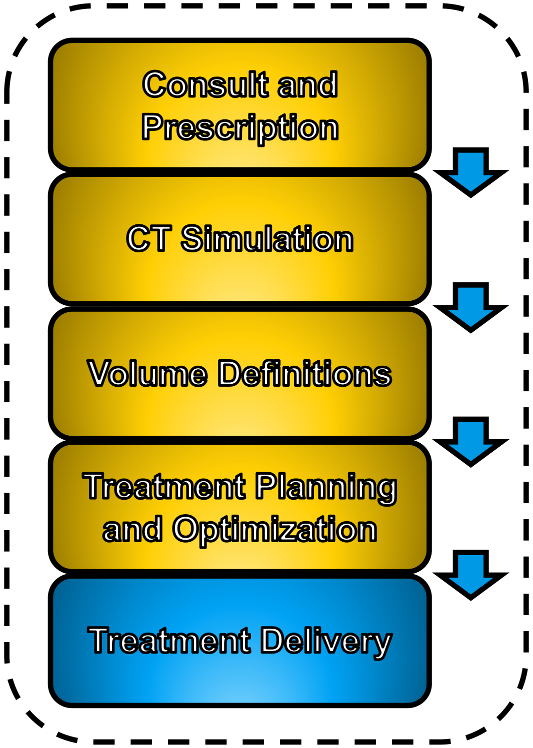


- ***Delineation in 3D is necessary to optimize the spatial dose patterns that best match the target shape and avoid normal tissue (<u>digitally defined!</u>)***
  - **Planning objectives and overall plan quality are processed according to dose deposition within delineated regions of interest (ROIs)**



Radiation Treatment Planning





Special planning software allows to model beam placement as well as dose contributed by each beam

- ***Inverse Planning:*** *What pattern of incident energy fluence will result in the desired distribution of energy absorbed within the patient?*
- *Start by quantifying the desired distribution*

Radiation Treatment Planning

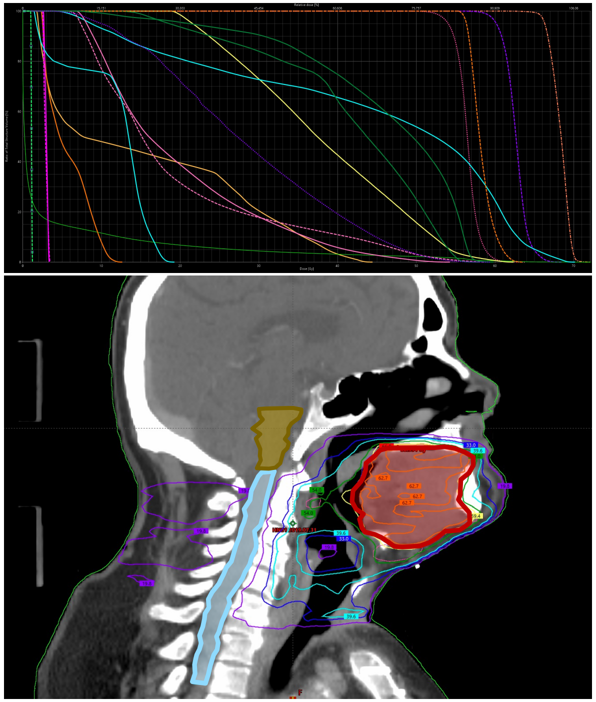
Dose distribution criteria specified as a combination of constraints and priority factors:

$$F_{obj}(j) = \sum_{i=1}^{N} (d_i - c)^2 \cdot \varepsilon\omega$$

- j: contoured planning structure (Target, OAR, optimization)
- d_i: dose at a single sample point for iteration i
- c: constraint for the structure (max, min, mean, DVH)
- ω: priority constraint
- ε: flag for meeting constraint

Overall score given by the sum of individual objective functions:

$$F_{obj} = \sum_{PTV} F_{PTV} + \sum_{OARs} F_{OARs}$$



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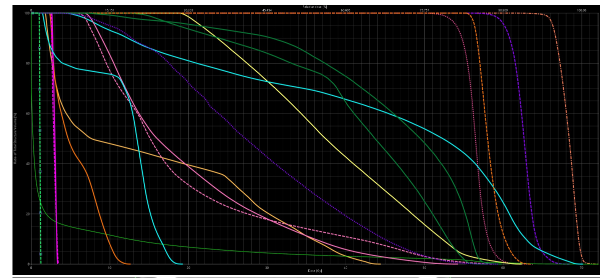
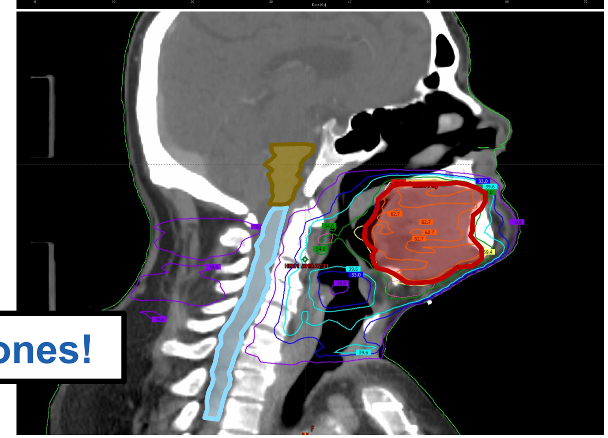
Overall score given by the sum of individual objective functions:

Constraints define acceptable solutions, *not* optimal ones!

$$F_{obj} = \sum_{PTV} F_{PTV} + \sum_{OARs} F_{OARs}$$



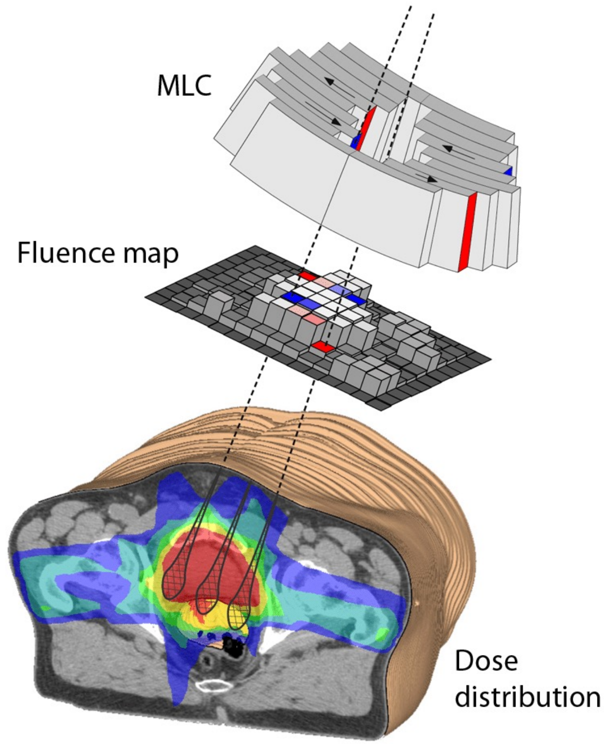


Radiation Treatment Planning

<u>Intensity-Modulated Radiation Therapy (IMRT)</u>: delivery of nonuniform fluence to generate an optimized composite dose distribution

- Dose distribution criteria specified in TPS
- Each field divided into discrete beamlets
- Beamlet weights within each field are optimized to meet the specified criteria
- Optimized fluence converted into deliverable leaf collimator sequences

- ***Photon energies, number of beams, arc start/stop angles, table rotations, gantry rotation speed***



Hårdemark et al. (2003, RaySearch white paper), RaySearch Laboratories AB, Copyright c 2003

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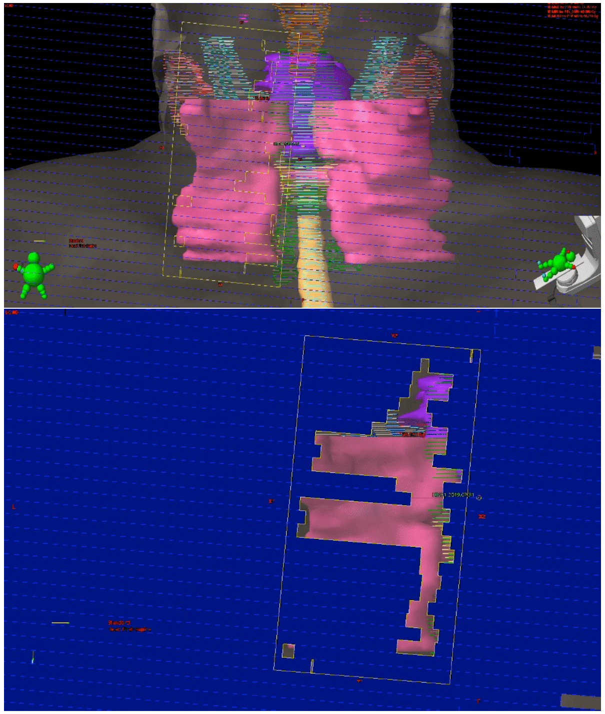
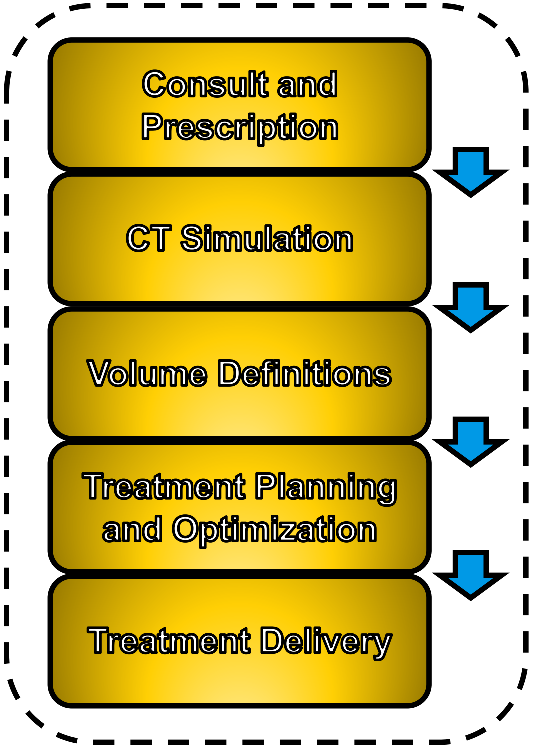


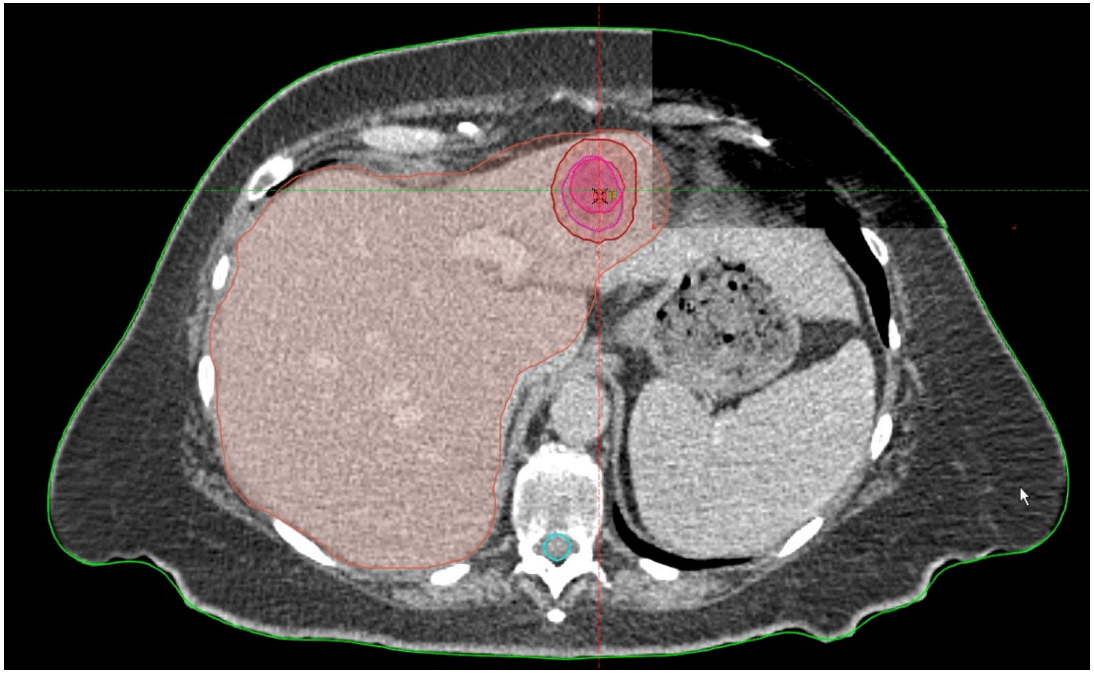
Radiation Therapy Delivery

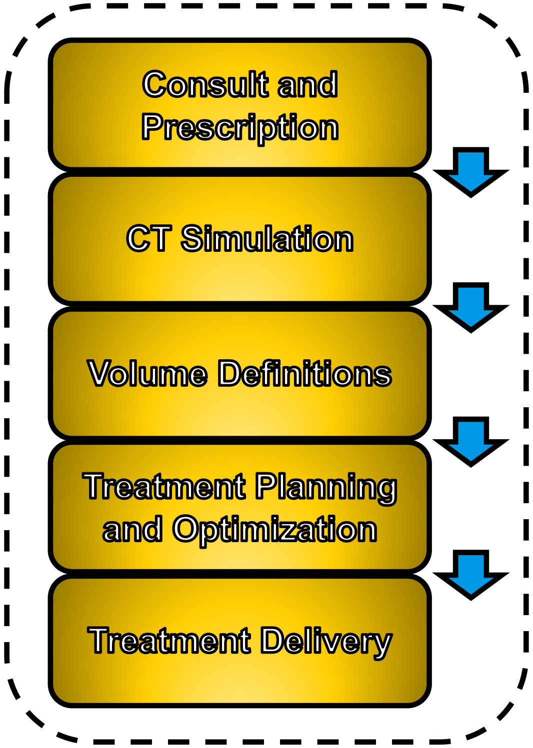
Delivery of the planned dose distribution requires reproducible setup geometry consistent with the simulation study

- **Standard treatment planning assumes a fixed relationship between patient anatomy and dose distribution**
- **Image guidance to compare treatment geometry with planning reference**
- **Depends on real-time image registration to quantify rotation and translational adjustments prior to beam on**

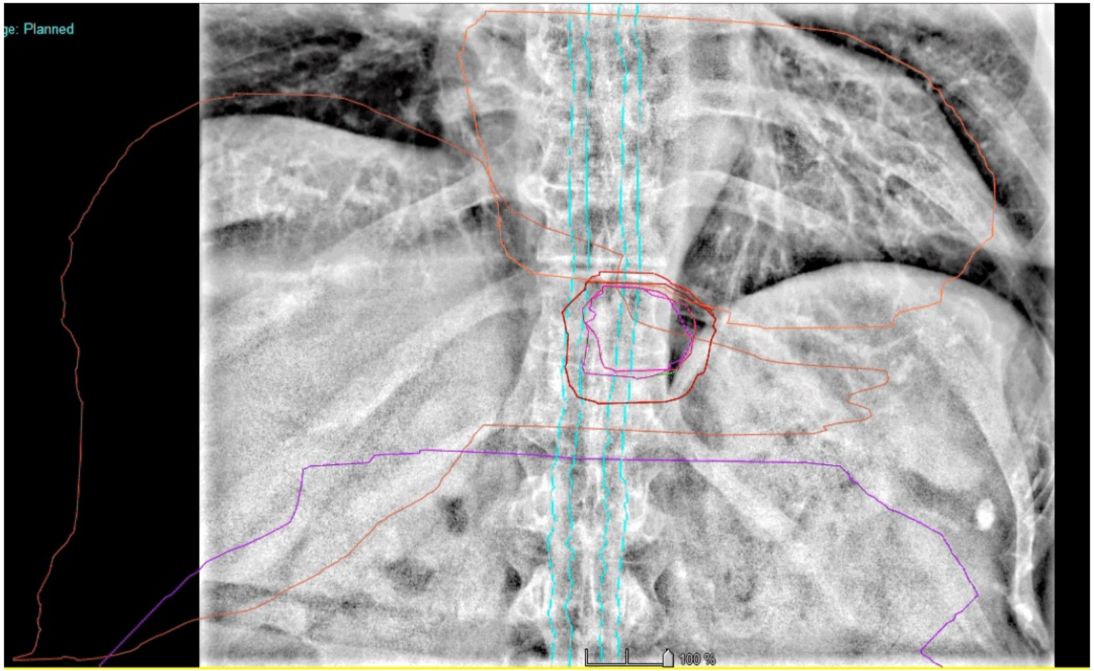


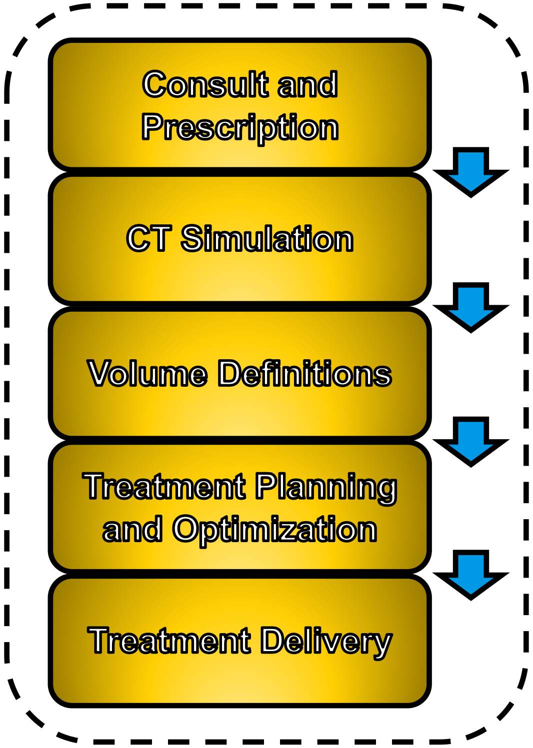
Radiation Therapy Delivery



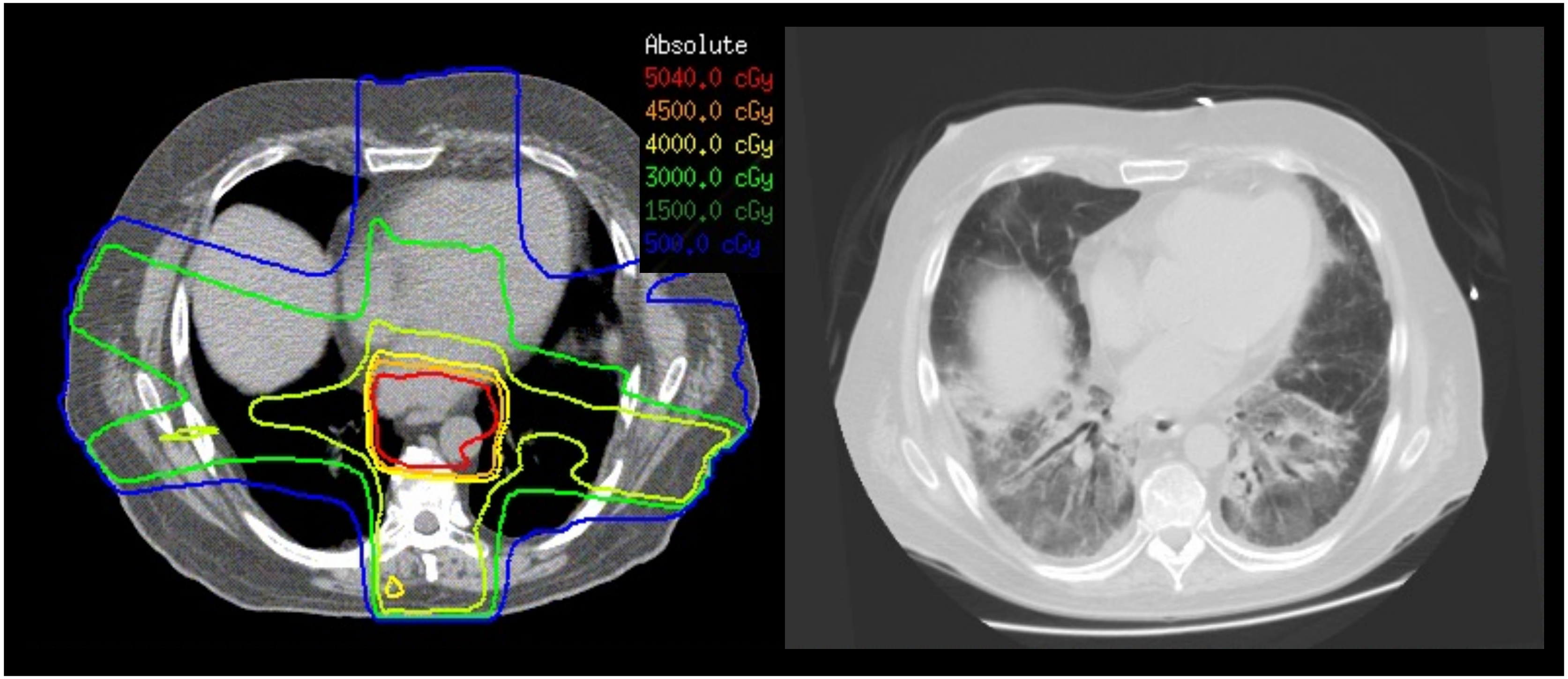


Radiation Therapy Delivery





Radiation Therapy Follow-Up



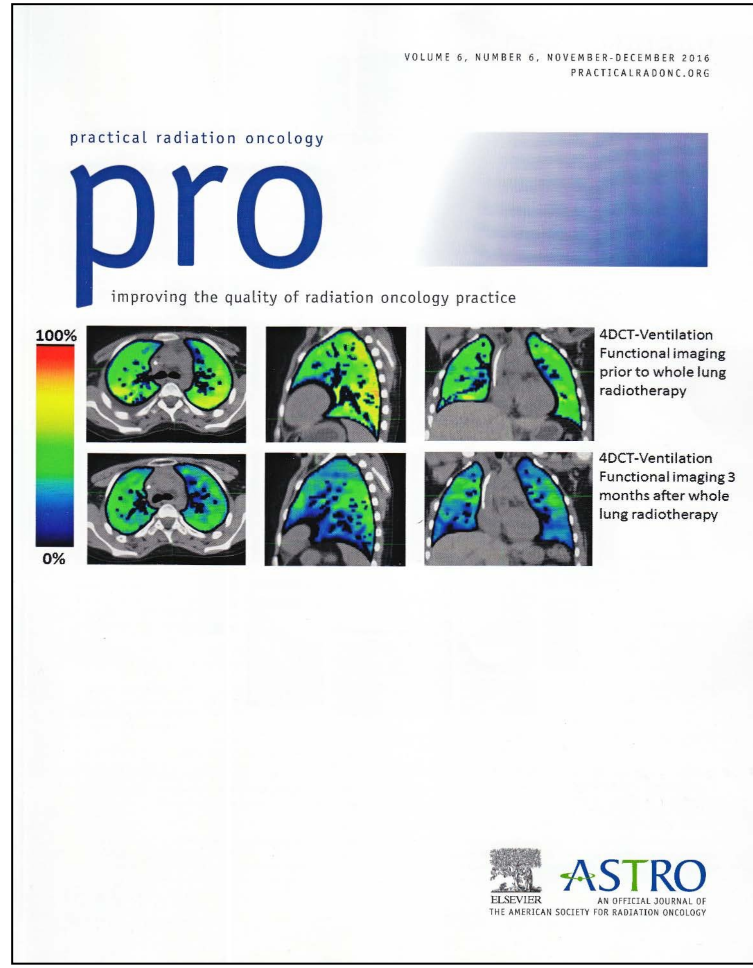
Ongoing Research

"Medical physics is … translational research where basic experimental and theoretical discoveries are rapidly implemented into benefiting humanity through improved procedures in diagnosis and treatment of disease"

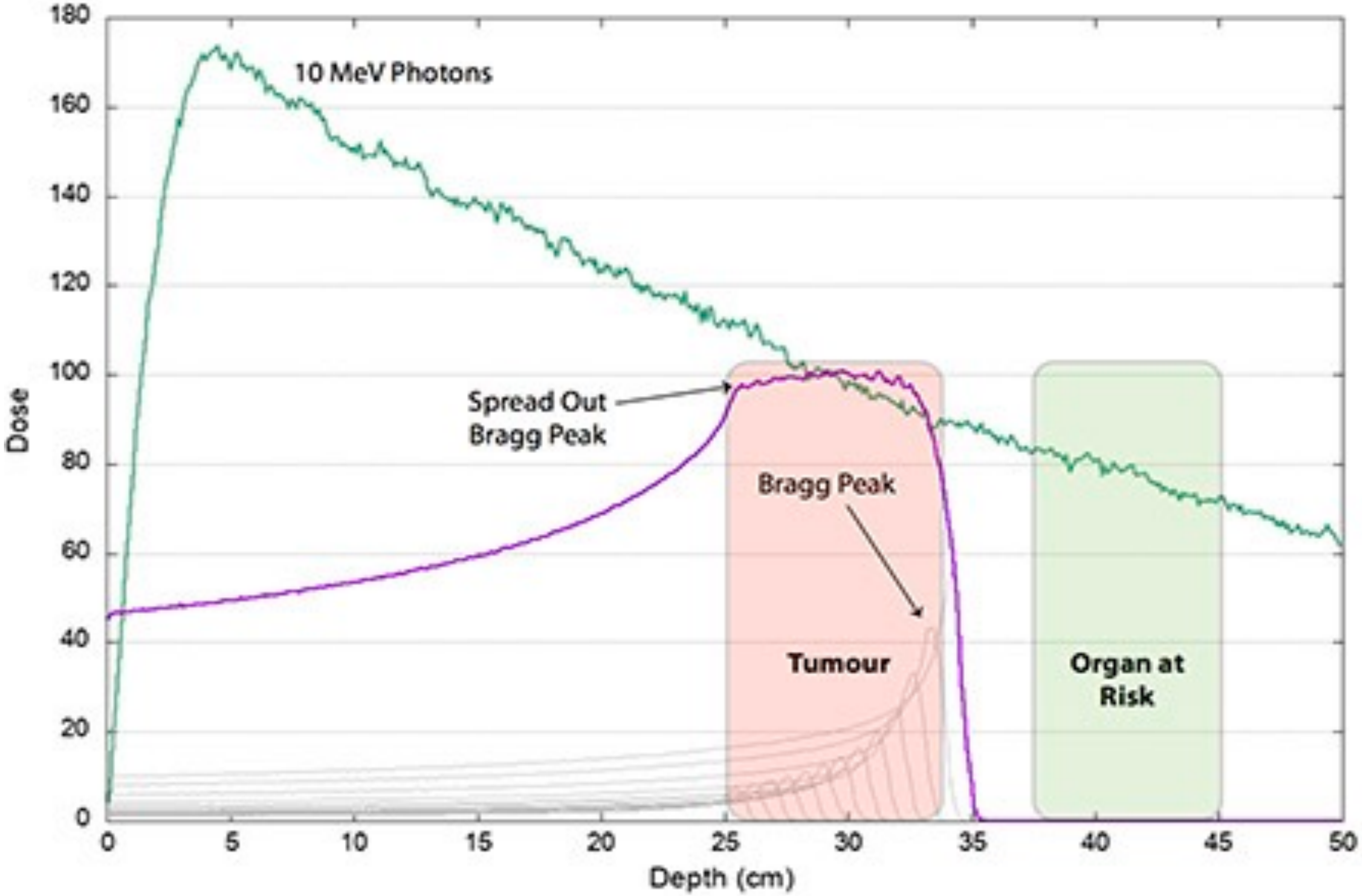
Active computational, theoretical, and translational research in all aspects of the radiation therapy process

- **Image segmentation**
- **Automated and knowledge-based treatment planning**
- **Novel optimization criteria**
- **Deformable image registration**
- **Dose response modeling**
- **Outcomes prediction**
- **Novel image markers for outcome or response**
- **…**

Podgorsak, EB. Radiation Physics for Medical Physicists. 3rd ed. 2016



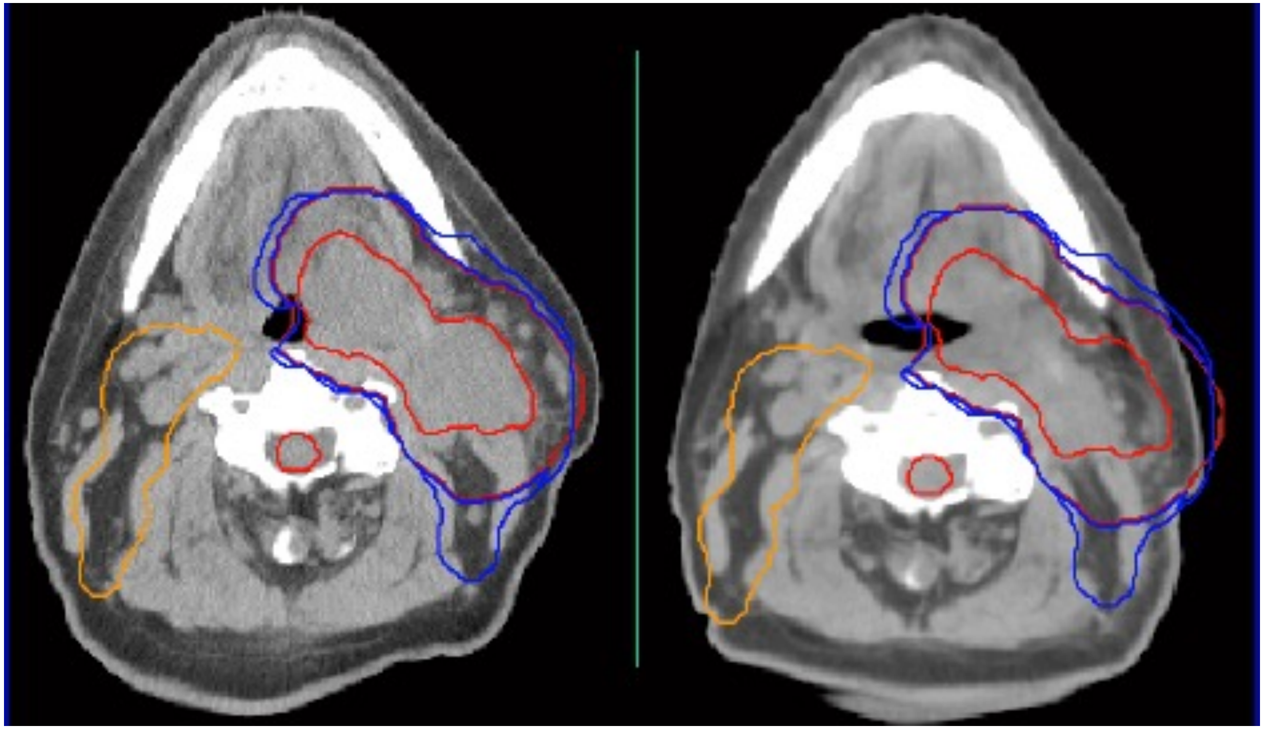
Cancer Treatments



- Treating cancer both photons and protons are effective
- Protons are advantageous because the stop, sparing healthy tissue
- There exist an uncertainty where they stop

Problem with Protons

- Changes to Anatomy
- Setup errors
- Tumor/Organ Motion
- Patient Motion



Permission from H. Paganetti

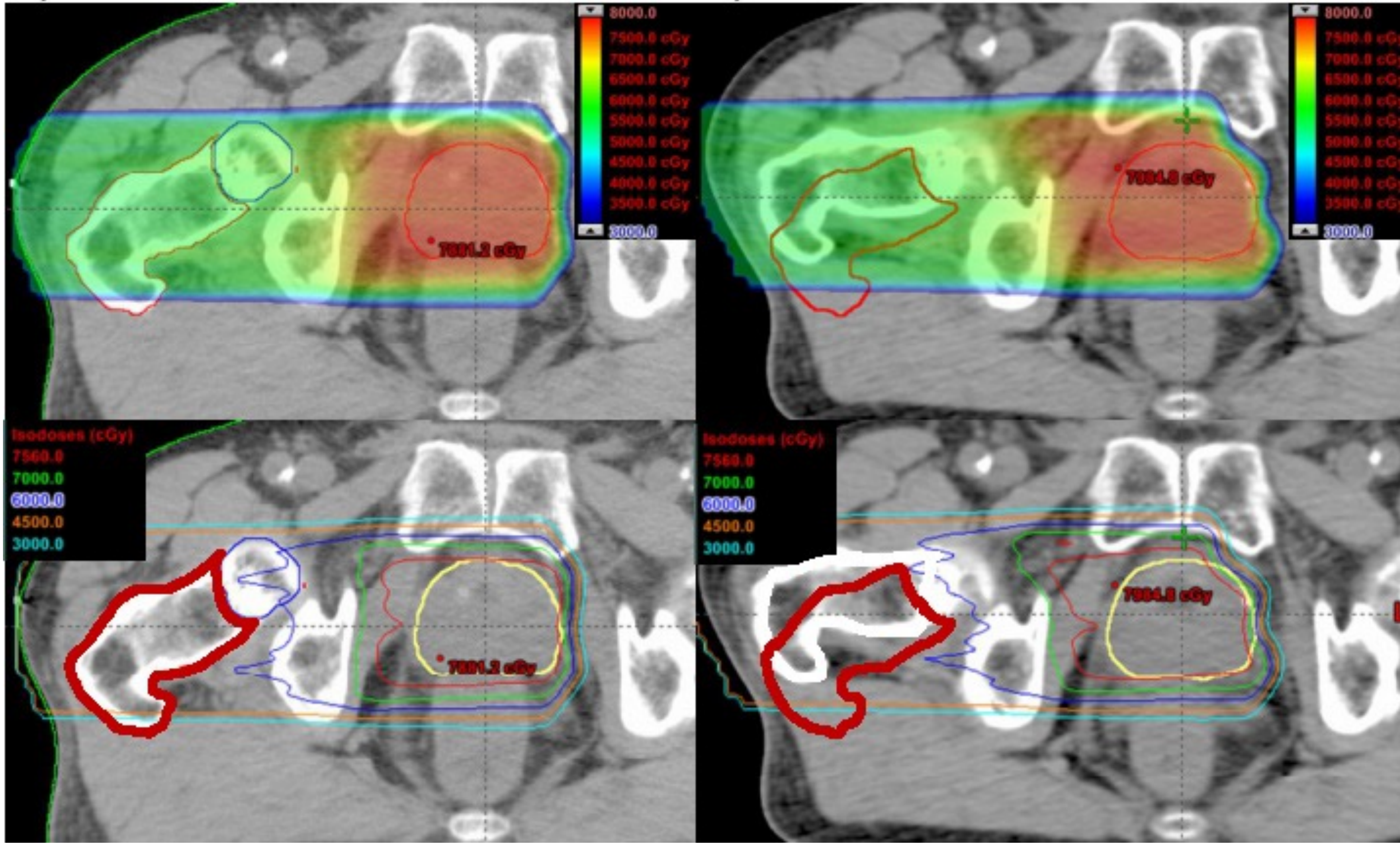
Anatomical Changes During Treatment

Before treatment

After 3 weeks

Barker *et al*, Inter. J. of Rad. Onc.* Biology* Physics, 2004. 59

Setup Errors - Prostate



A. Melancon, MDACC, 2010

Summary of Typical Penetration Uncertainties

standard energy (or range)	± 0.6 mm
energy (or range) reproducibility	± 1.0 mm
bolus WET	± 0.9 mm
alignment devices*	± 1.0 mm
CT# accuracy (after scaling)	± 2.5%
RLSP of tissues and devices	± 1.6%
energy dependence of RLSP	± 1.0%
CT# to RLSP (soft tissues only)	± 1.5%
bolus position relative to patient	variable
heterogeneity straggling	variable
patient motion	variable

Range Uncert.
2 mm

CT Uncert.
3.5%

Planning
bolus expansion
multiple angles

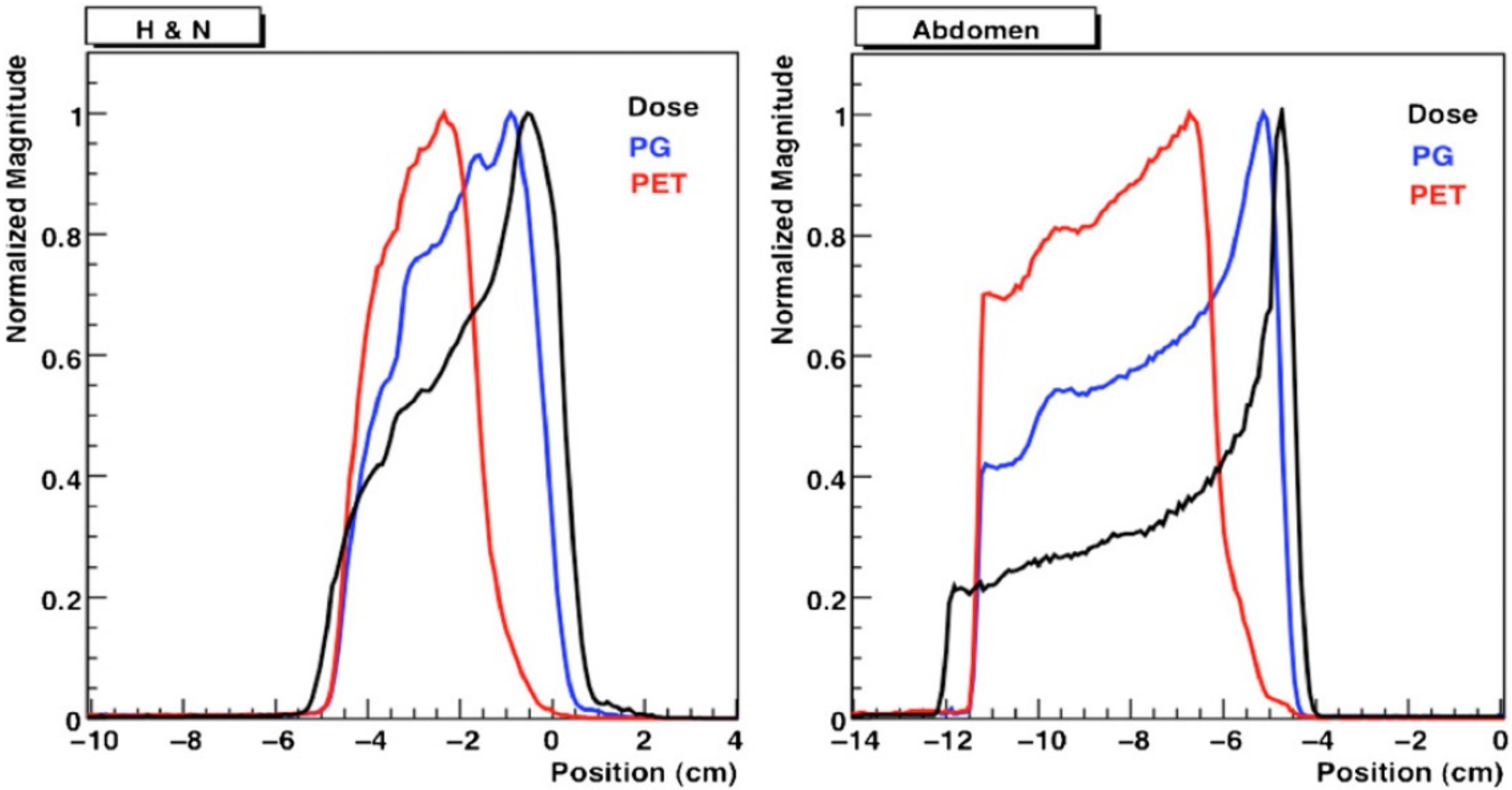
Moyers PTCOG 2008

Proton Treatment Verification

1. **Verify proper dose delivery**
2. **Measure tissue response**

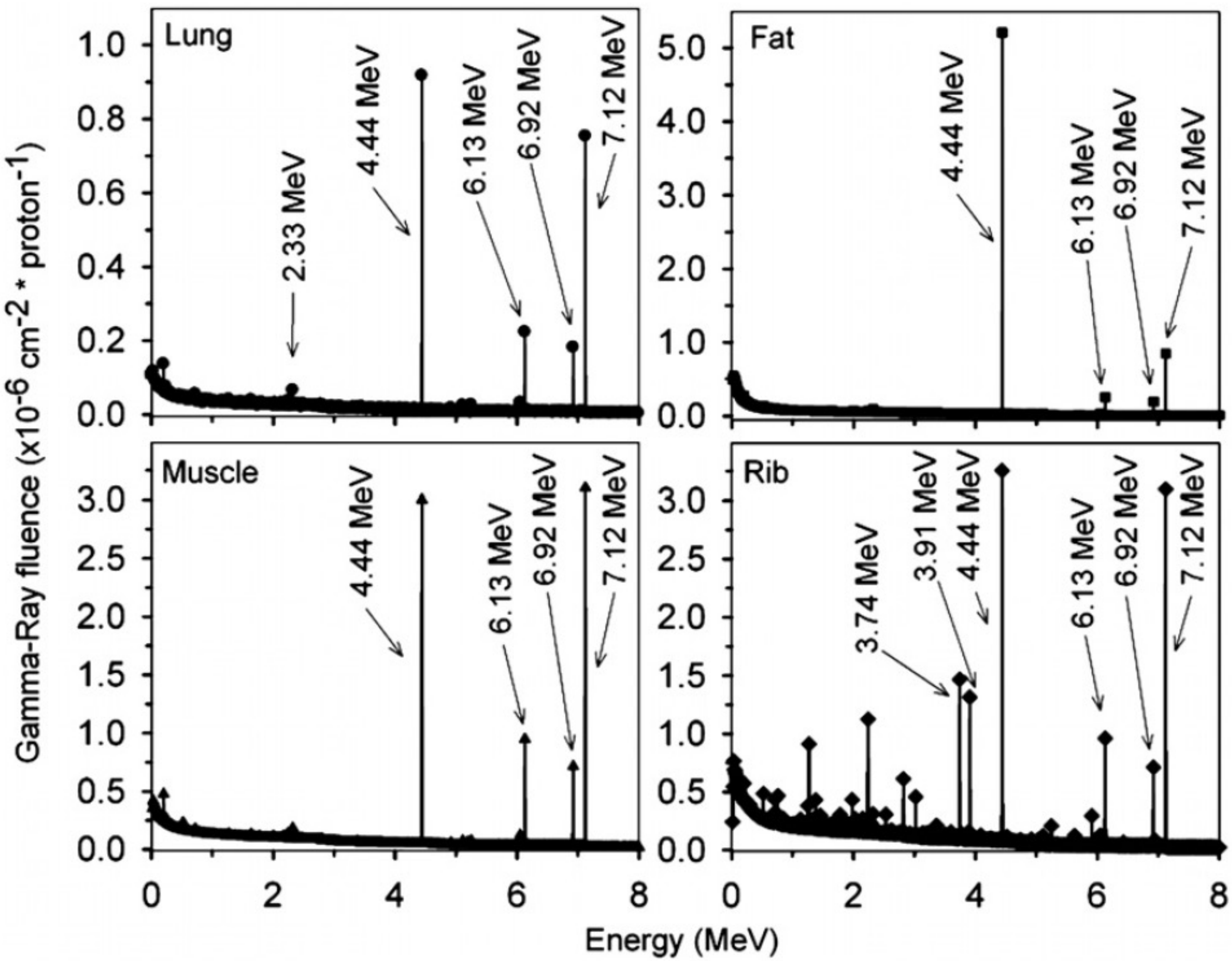
- **Present Verification Methods**
  - Repeat CT Scans
  - Post Treatment PET imaging
  - Follow up MRI imaging

Prompt gamma production correlated with dose



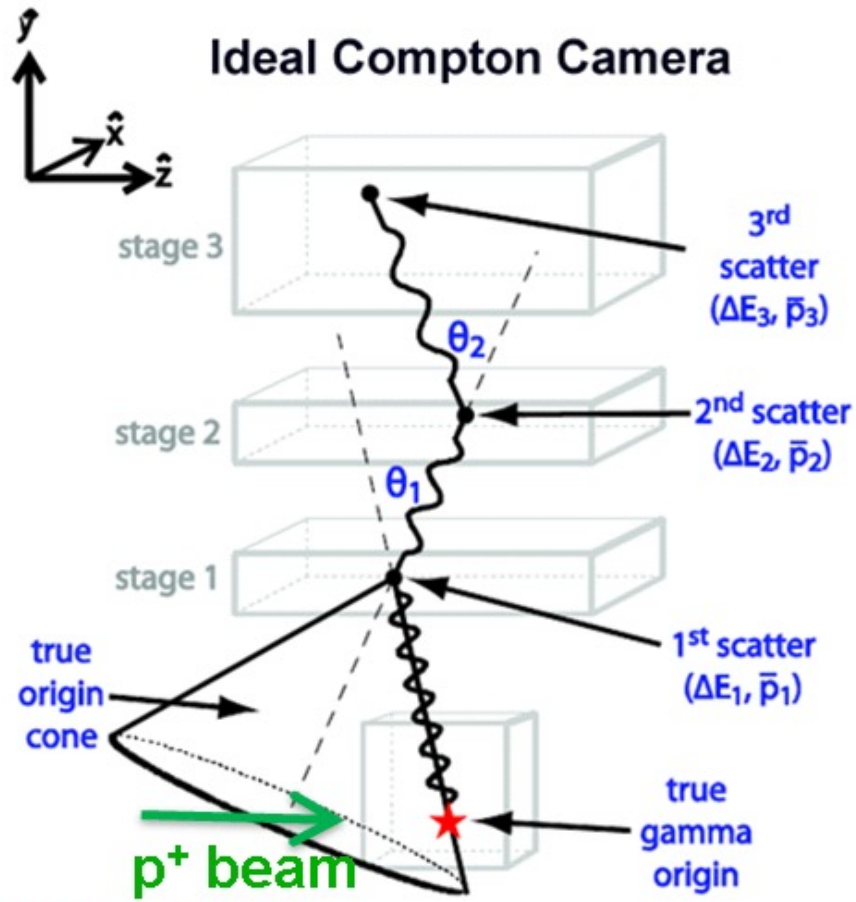
Moteabbed, *et al, Physics in Med. and Bio., 2011, 56*

Tissue Spectroscopy



Polf, *et al, Physics in Med. and Bio., 2009, 54*

Compton Camera

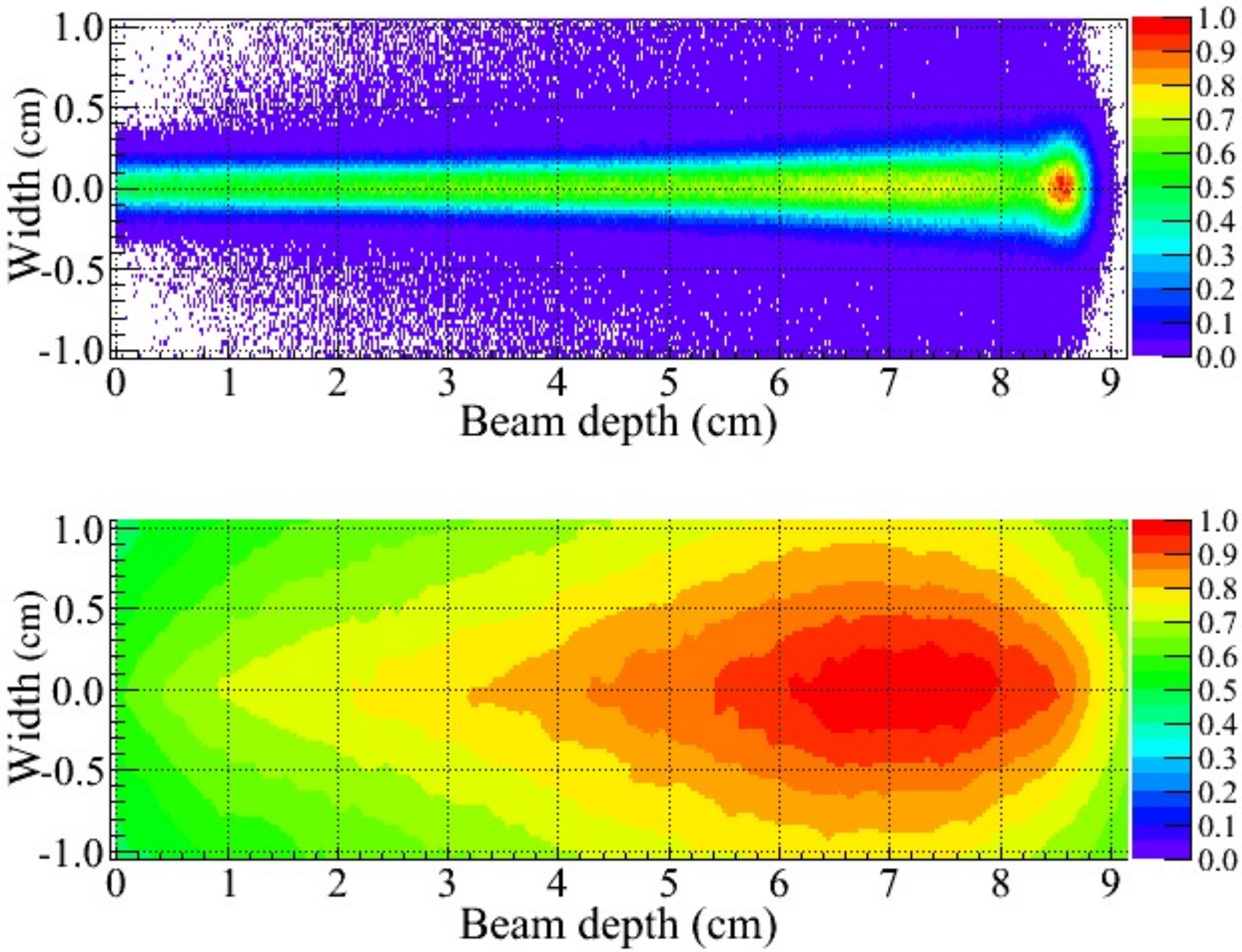


Compton scatter equations

$$E_0 = \Delta E_1 + \frac{1}{2}\left(\Delta E_2 + \sqrt{\Delta E_2^2 + \frac{4\Delta E_2 m_e c^2}{1-\cos\theta_2}}\right)$$

$$\cos\theta_1 = 1 + m_e c^2\left(\frac{1}{E_0} - \frac{1}{E_0 - \Delta E_1}\right)$$

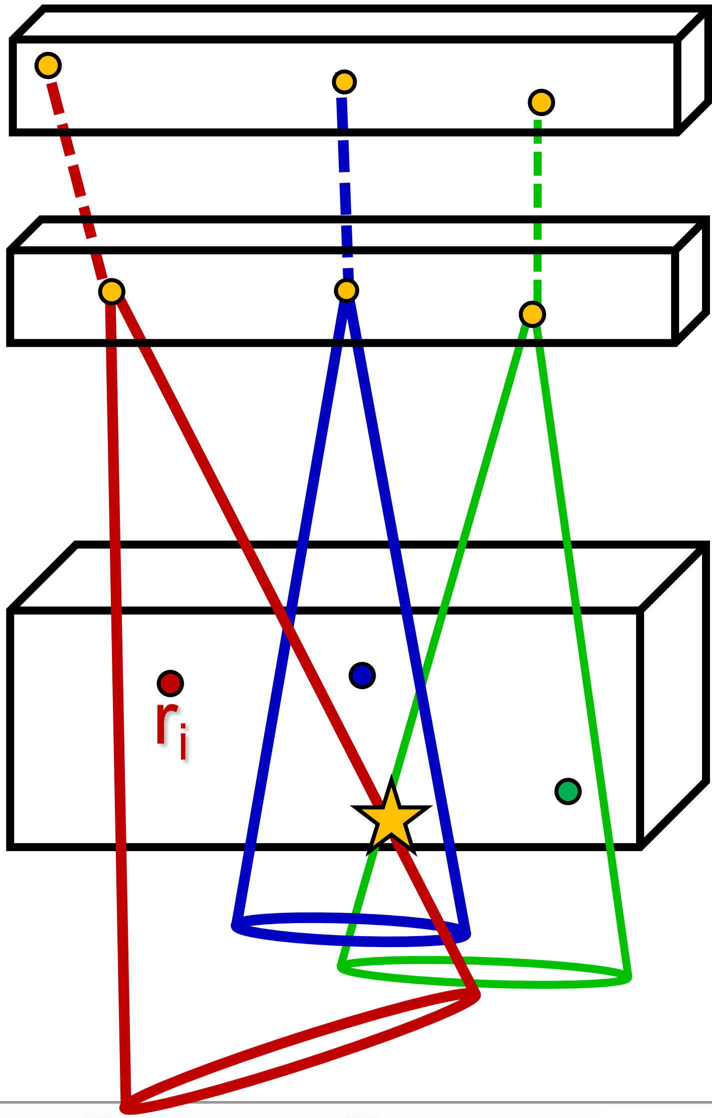
Simple Backprojection



Gamma emission origins calculated with Monte Carlo

Backconstruction

Stochastic Origin Ensembles (SOE) Algorithm



Big Idea from SOE:

Don't reconstruct with the cones;
Reconstruct with a single point on each cone.

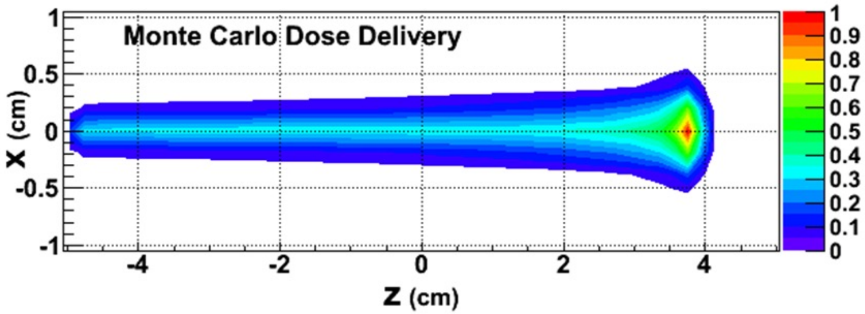
Goal of SOE algorithm:

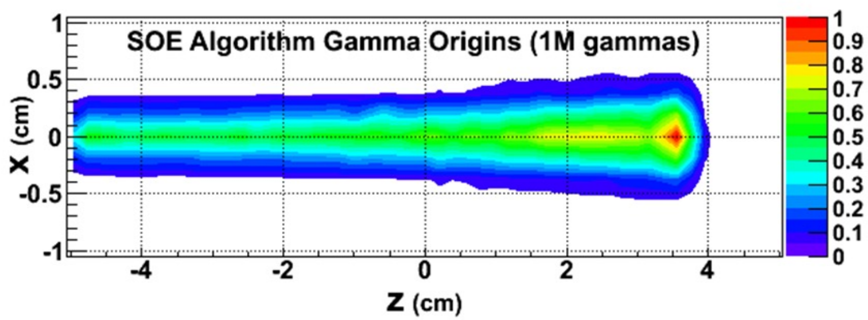
Select a "good" representative point for each cone.

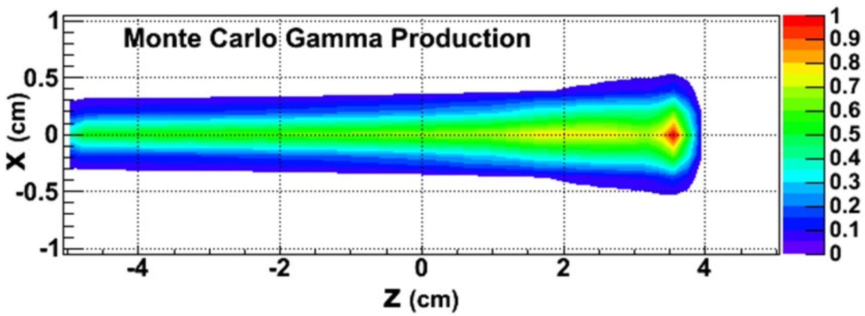
- A. Andreyev et al., *IEEE Trans. Nucl. Sci.*, vol. 57 (2010)
- A. Sitek, *Phys. Med. Biol.*, vol. 53 (2008)

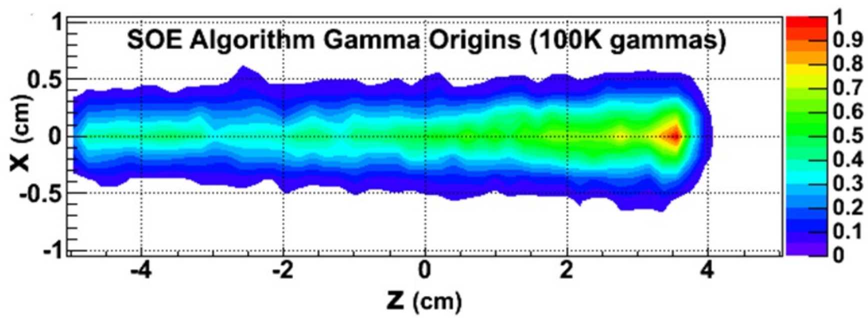
SOE 2-D proton pencil beam

Dose and gamma origins from Monte Carlo

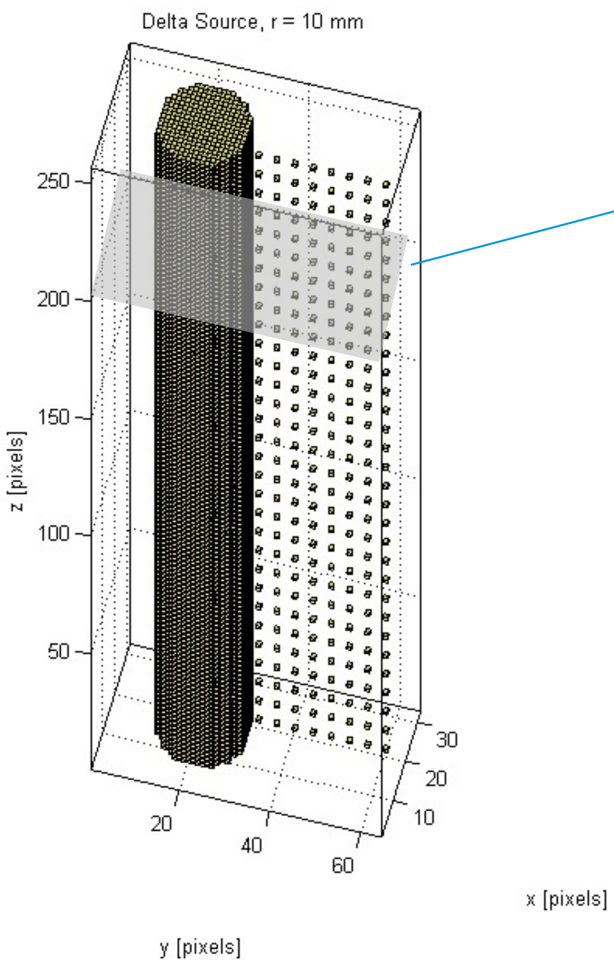




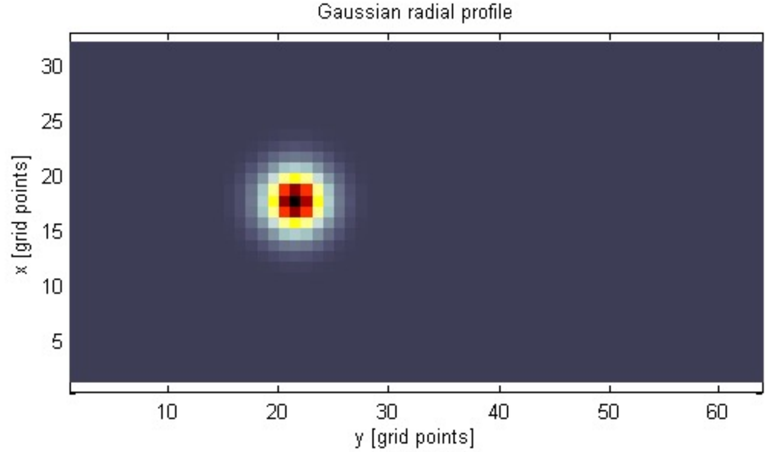


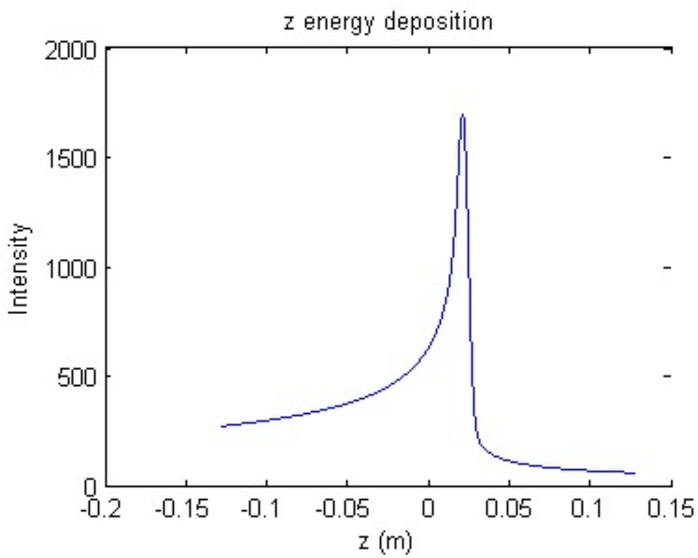


Thermo acoustic measurement



Gaussian(x) * Gaussian(y): FWHM 5 mm

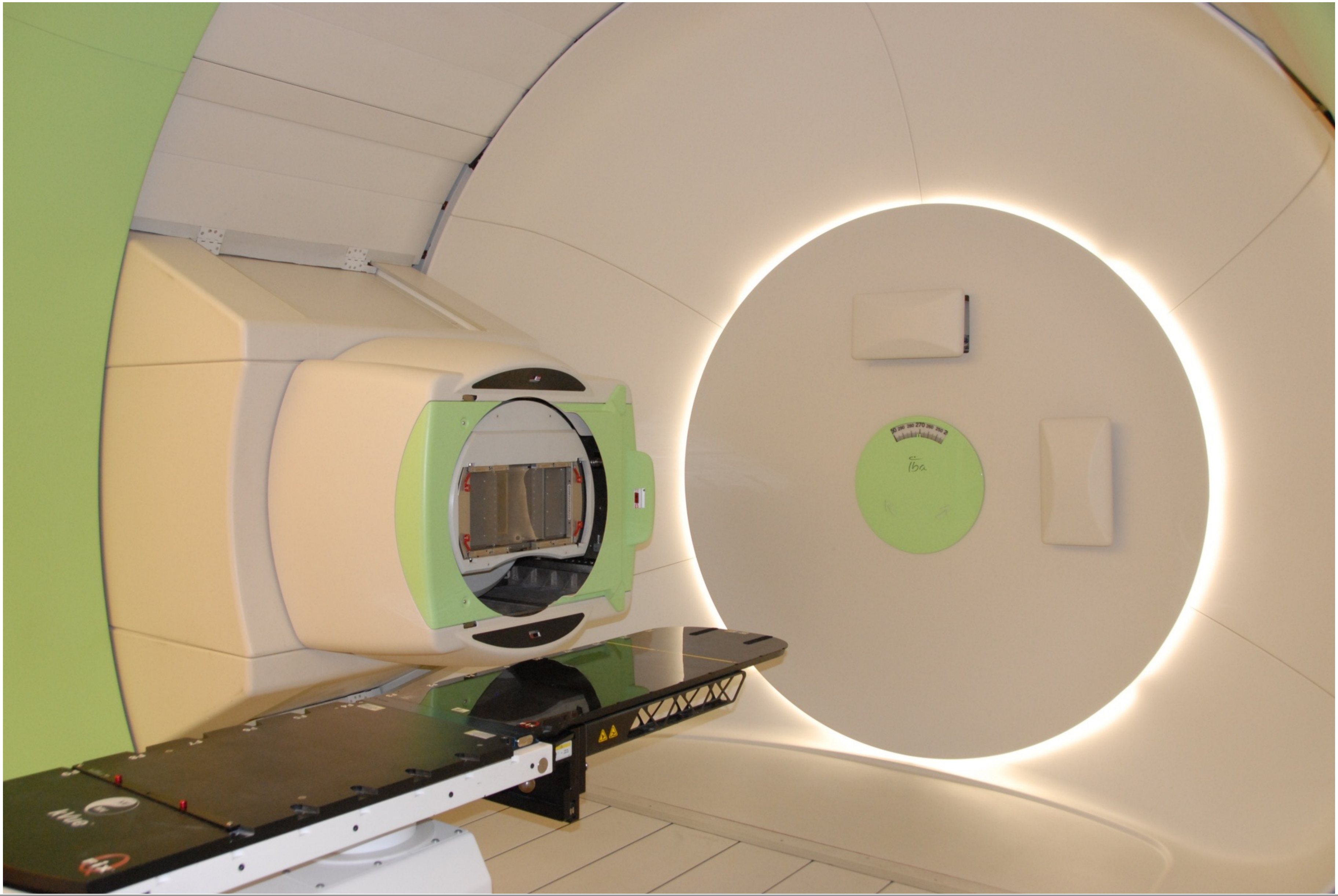




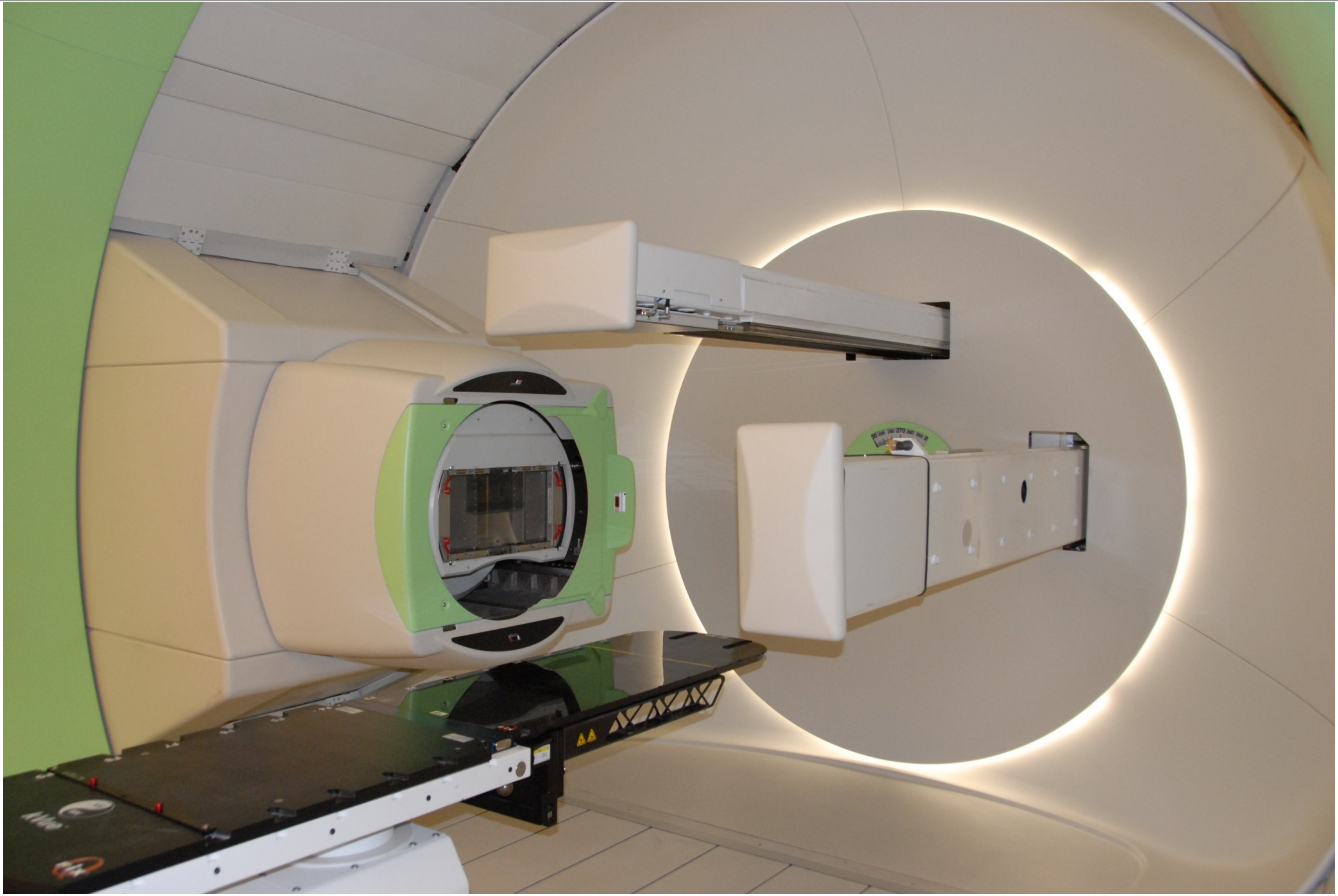
$$\frac{dE}{dz} = \frac{1}{p\alpha^{1/p}}\left(R_0 - z\right)^{\left(\frac{1}{p}-1\right)}$$

http://gray.mgh.harvard.edu/content/dmdocuments/HST%20protons.pdf

CBCT on a Proton Gantry



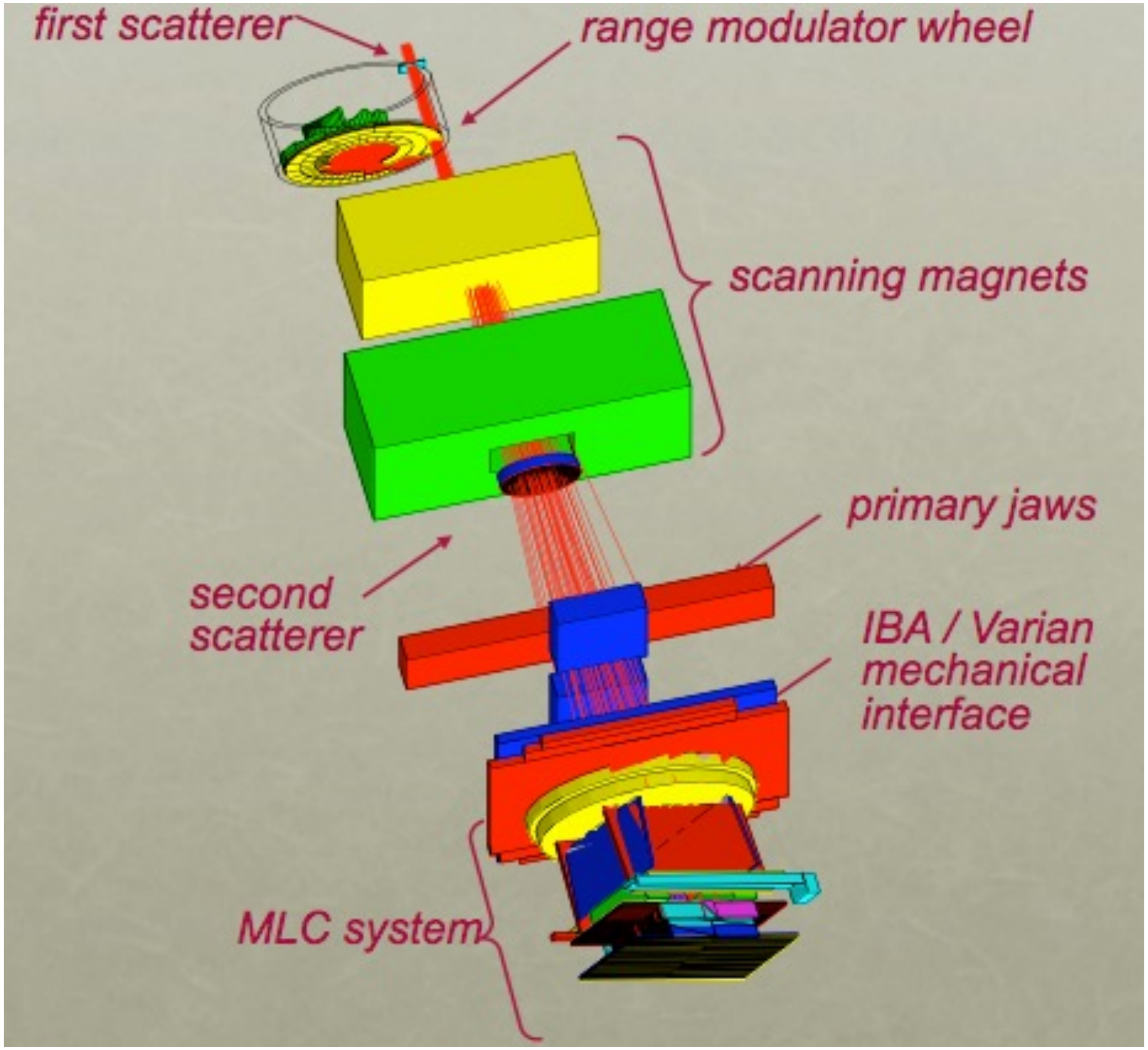
CBCT on a Proton Gantry



On-site Installation and Testing

- On-site gantry flex tests completed with existing imaging system.
- X-ray tube and imaging panel up-date required on one of the orthogonal x-ray systems.
- On-site upgrades, system testing and final implementation in progress.

GEANT4 Monte Carlo

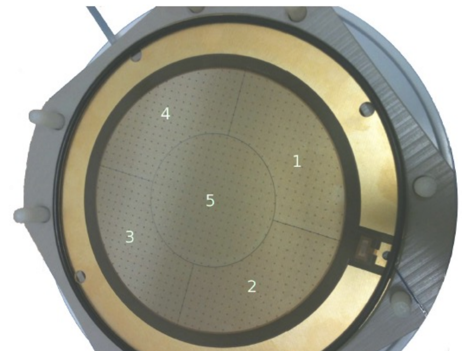


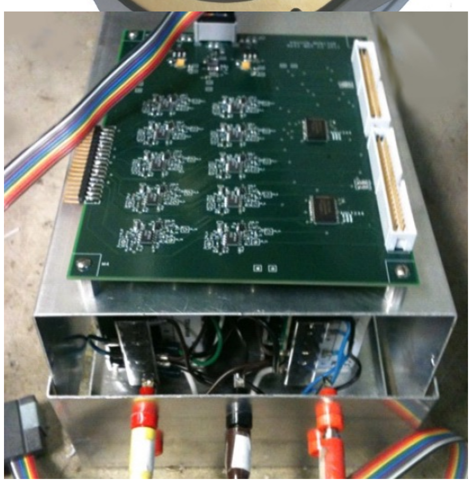
Radiation Oncology / Physics Collaboration

A new technology for fast two-dimensional detection of proton therapy beams

Robert Hollebeek,[1] Mitch Newcomer,[1] Godwin Mayers,[1] Brian Delgado,[1] Gaurov Shukla,[1] Richard Maughan,[2] and Derek Dolney[2]

[1]*Department of Physics, University of Pennsylvania, Philadelphia, PA 19104.*
[2]*Department of Radiation Oncology, University of Pennsylvania, Philadelphia, PA 19104.*





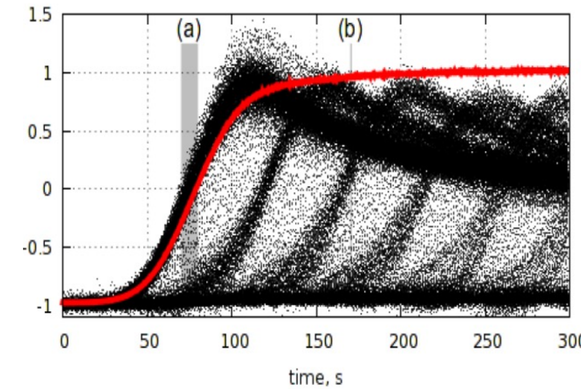
Detector/electronics design & signal processing in Physics Department

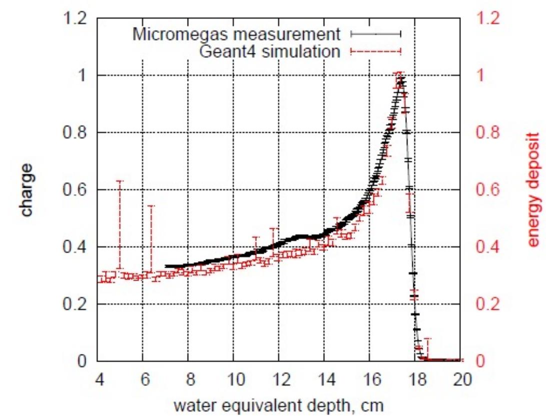
Detectors fabricated at CERN

Medical Physics Divison
Radiation Oncology Department

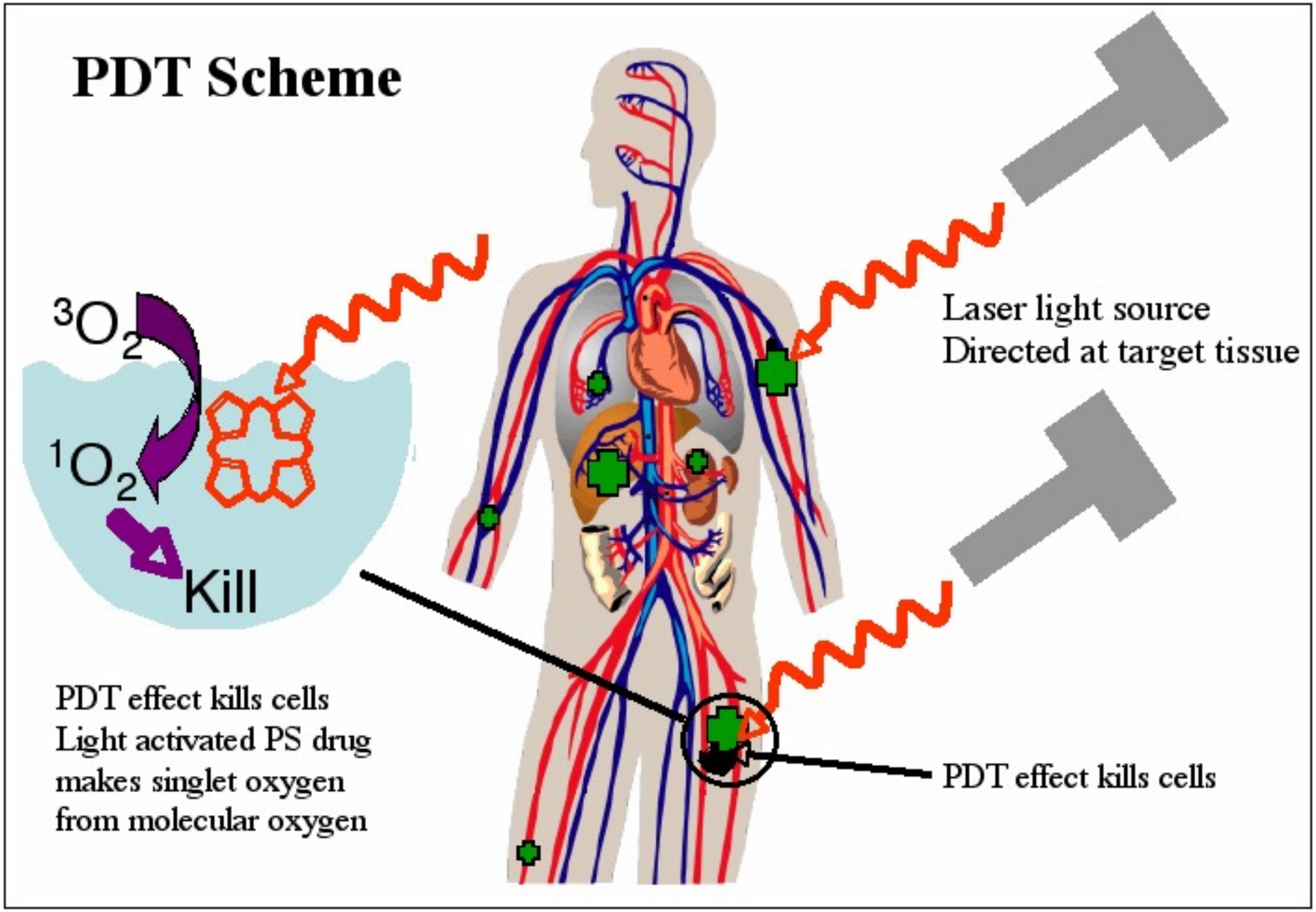
Proton Beam in PCAM

Monte Carlo simulation with GEANT4





Photodynamic Therapy



Whole-body TOF PET/CT

<u>Philips Gemini TF scanner installed at Penn 2005</u>

- LYSO detectors - state-of-art performance
  4.7 mm spatial resol., 11.5% energy resol.
- 600 ps timing resolution - TOF
- Stable electronics and timing calibrations
- Multi-node computer cluster: iterative reconstruction

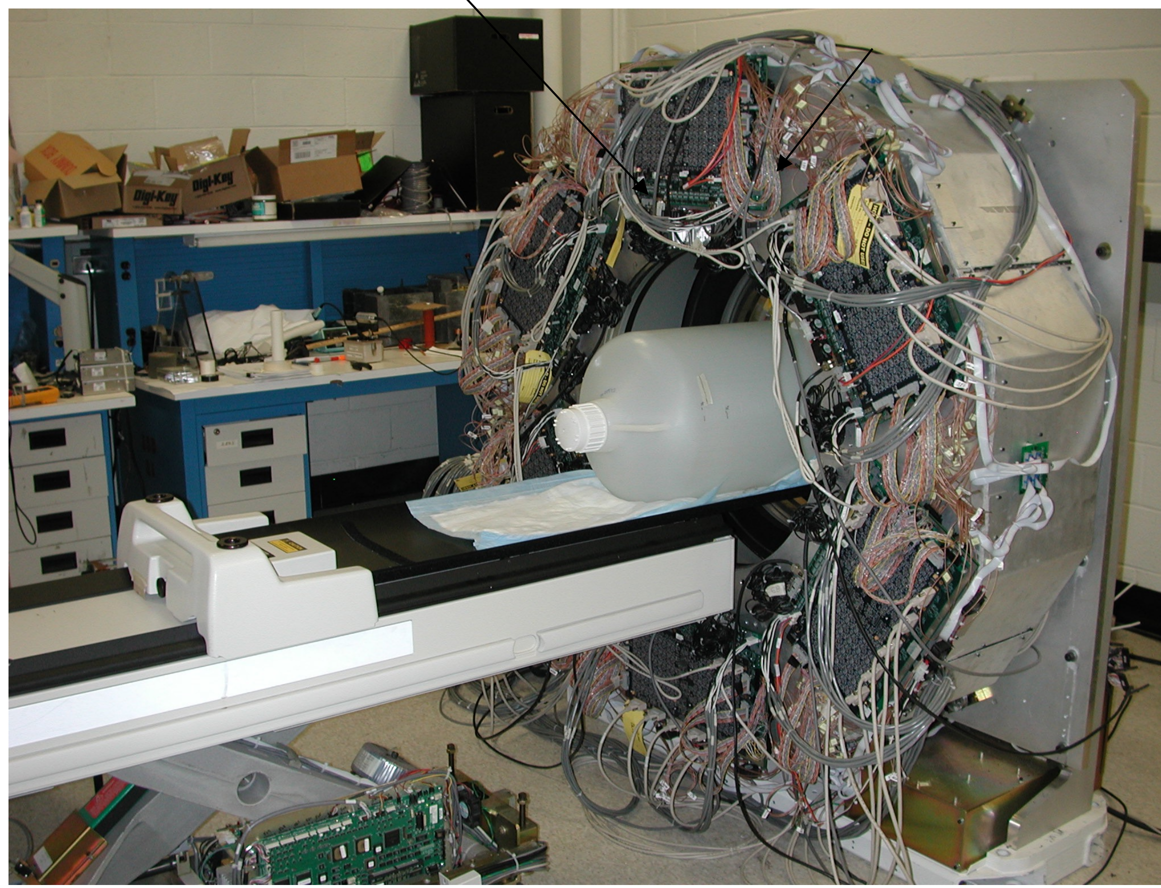
PET shows increased FDG uptake in region of porta hepatis
CT demonstrates that this uptake corresponds to the gallbladder representing acute cholecystitis, not bowel activity

Proto-type Scanner

24 detector modules

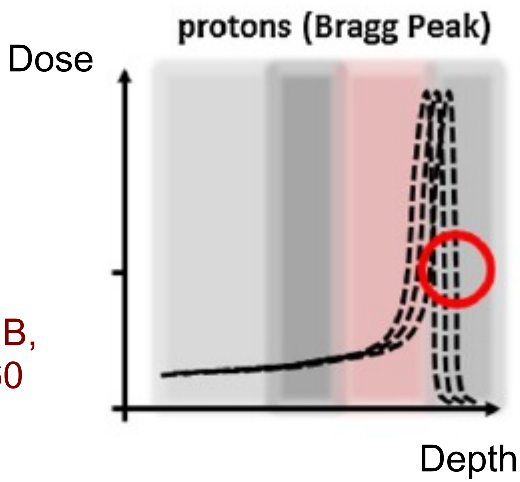
PMT digitization/integration board -> position, energy

trigger board-> timing

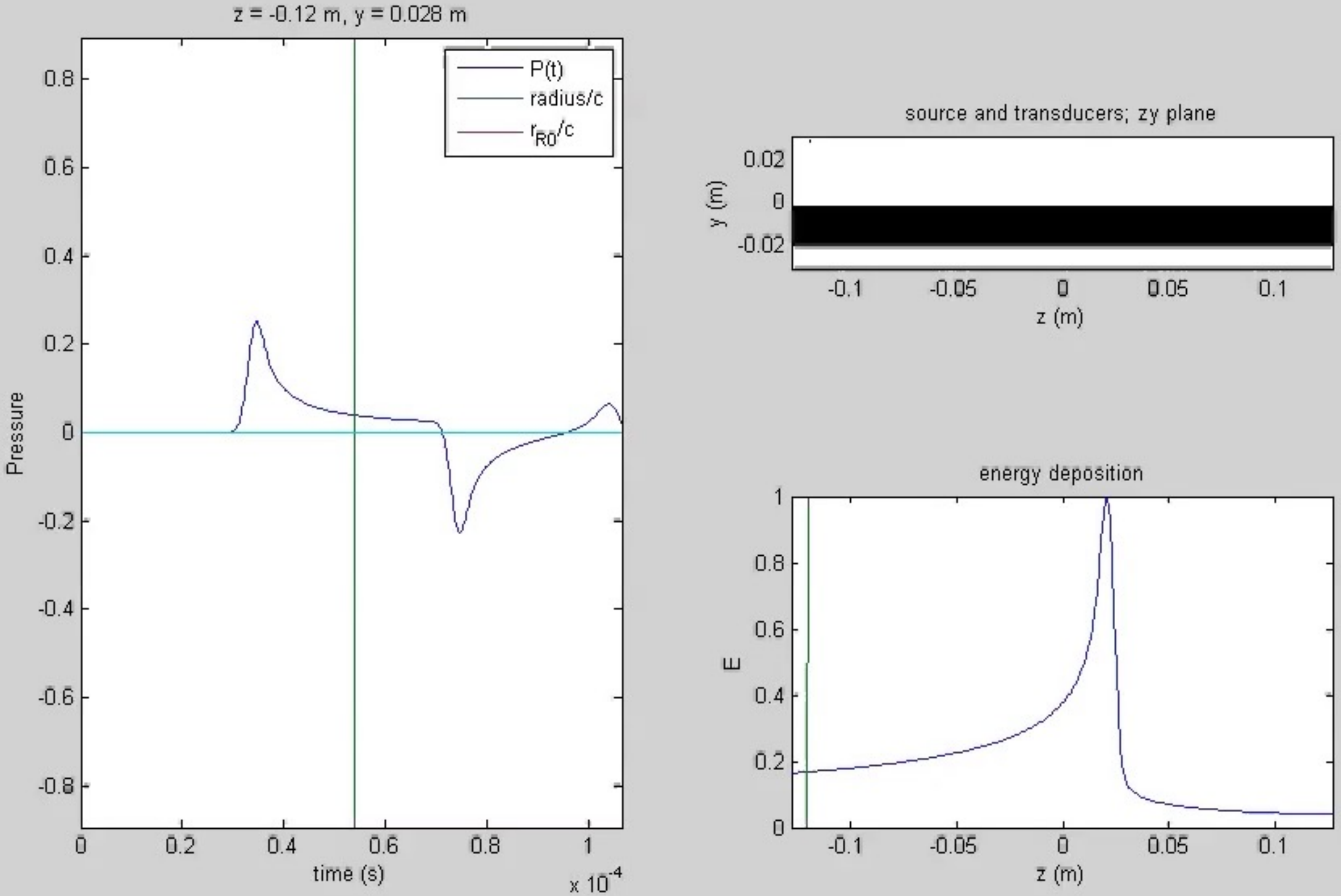


Motivation

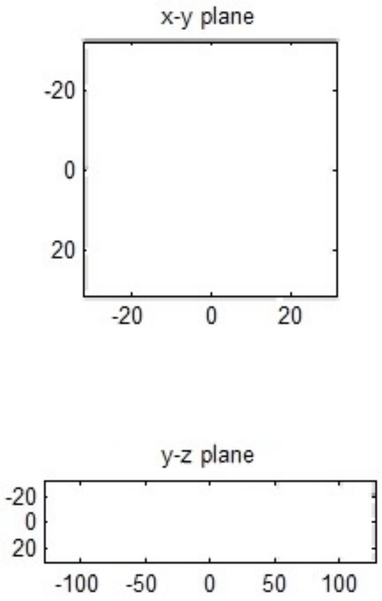
- Due to CT scan errors, imaging artifacts, and changes in patient anatomy, there is proton range uncertainty.
- To account for these uncertainties…
  - Increase treatment volume
    - Typically 3.5% of the proton range + 1-3 mm
- *in vivo* determination of the proton range will reduce the uncertainty
  - PET
  - Prompt Gamma
  - Proton Radiography
  - Acoustic-Based Range Verification: “Protoacoustics”
    - Collected during treatment
    - Simple
    - Low cost

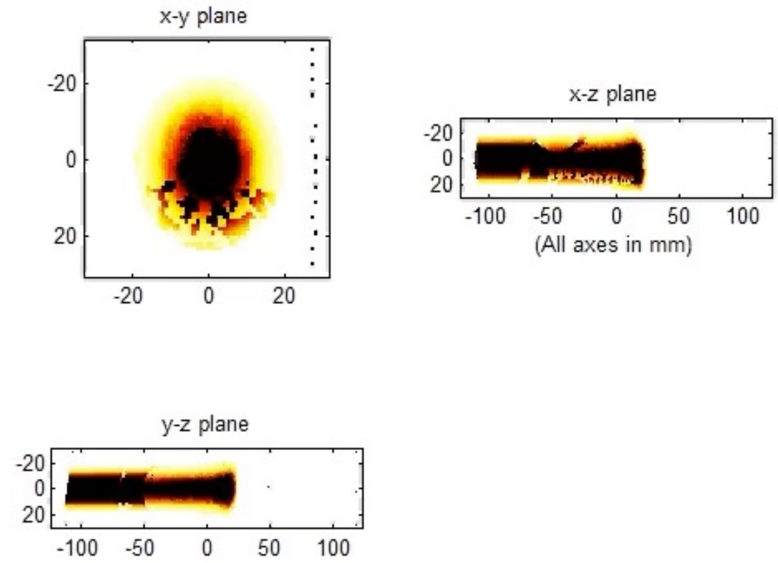


Knopf + Lomax, PMB, **48** (2013) R131-R160

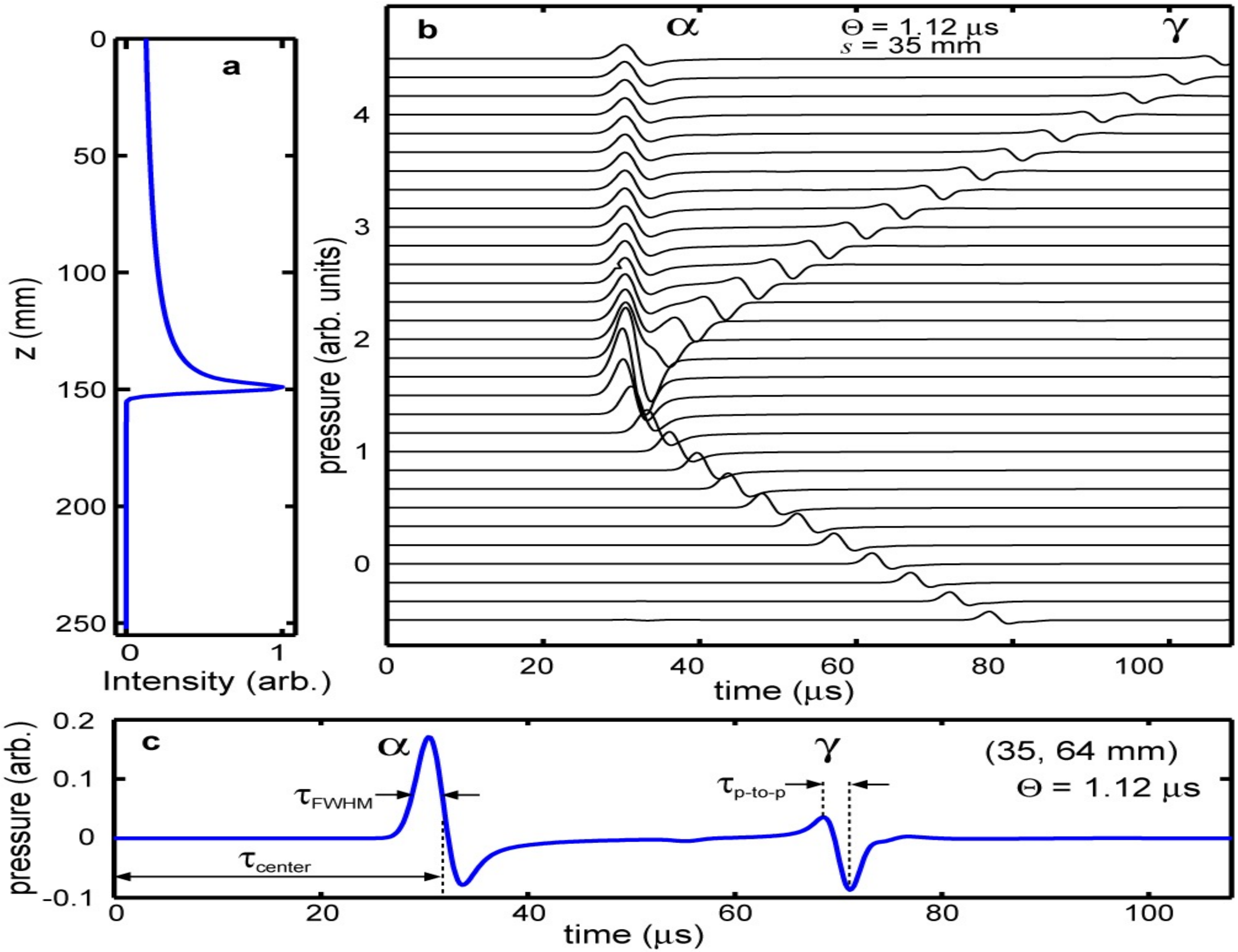

z = -0.12 m, y = 0.028 m
P(t)
radius/c
r_{R0}/c
Pressure
time (s)
x 10^-4
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
0
0.2
0.4
0.6
0.8
1
source and transducers; zy plane
y (m)
0.02
0
-0.02
z (m)
-0.1
-0.05
0
0.05
0.1
energy deposition
E
1
0.8
0.6
0.4
0.2
0
z (m)
-0.1
-0.05
0
0.05
0.1

Homogeneous and Heterogeneous





Range Verification



Generating a Short, Sharp Proton Pulse

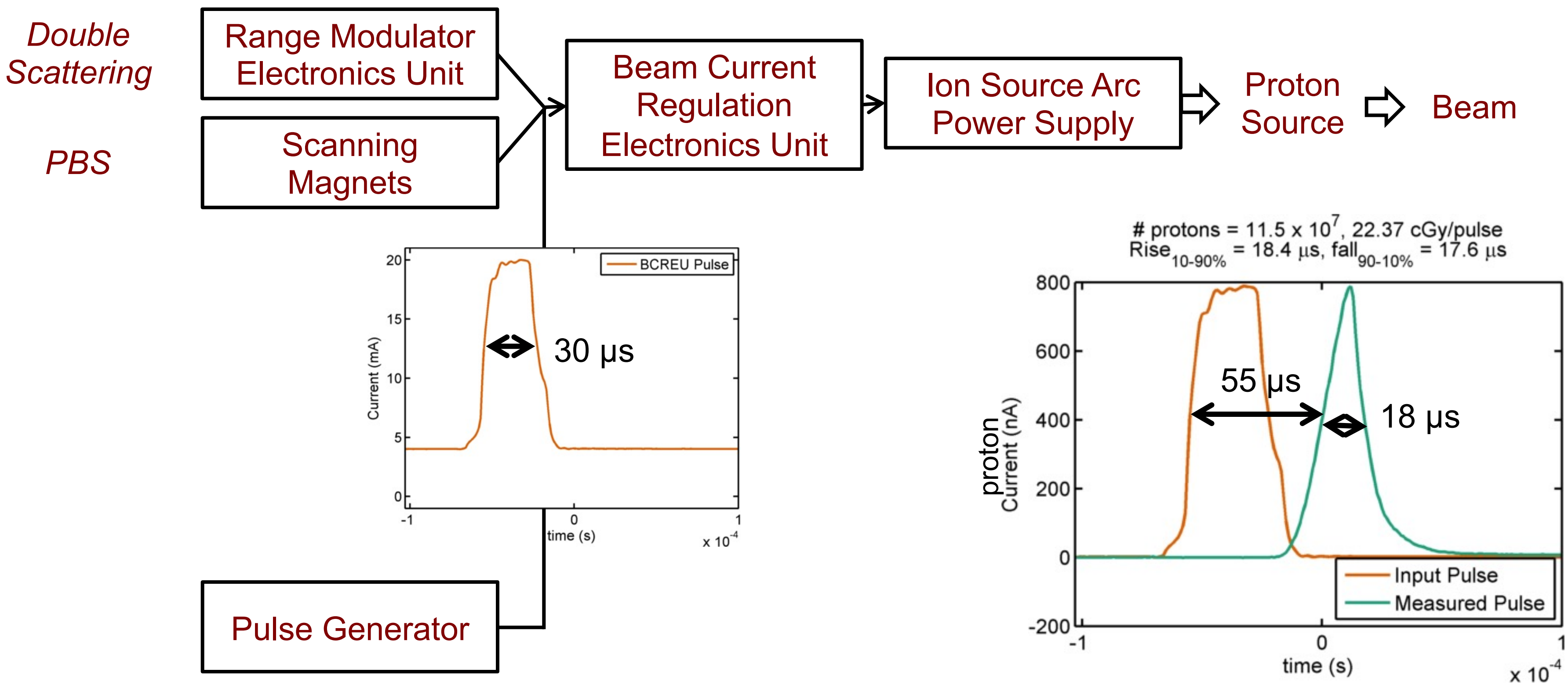
Pulse Length:

Double Scattering: minimum proton spill time = 100 ms / 256 wheel segments = 390 μs

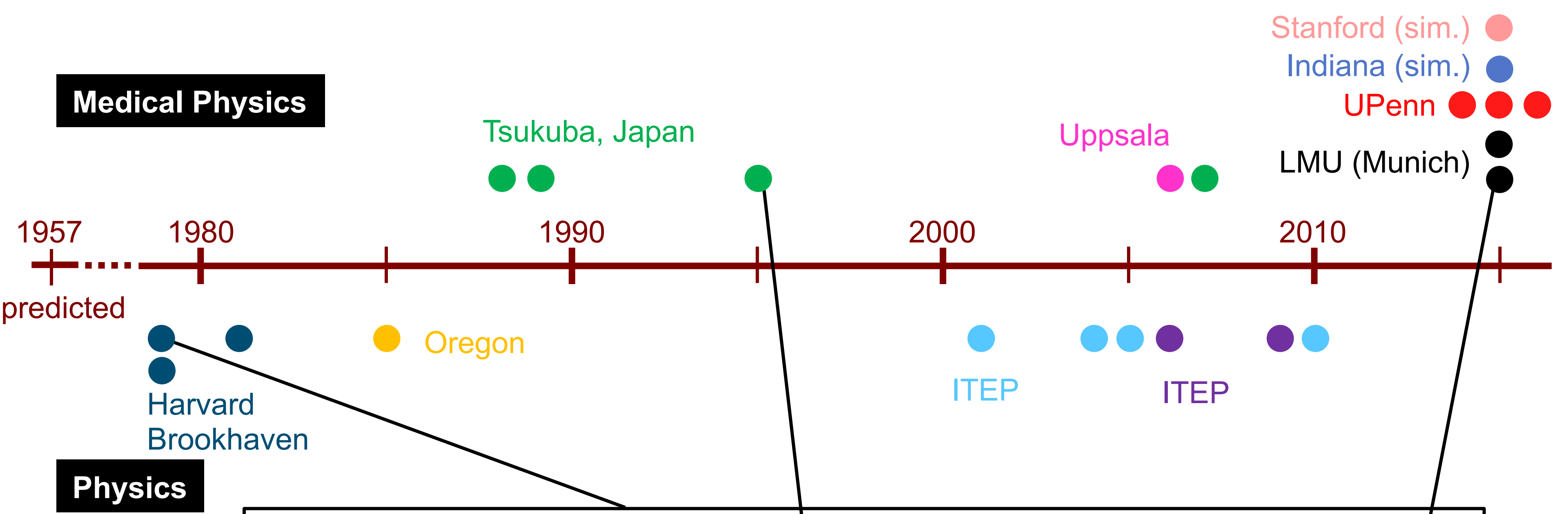
PBS: minimum proton spill time ~ 1 ms

Rise/Fall Times: <50 μs (PBS rise = 120 μs, fall = 30 μs)

Maximum Current: <300 nA proton current *at exit of cyclotron*



History of proton acoustics

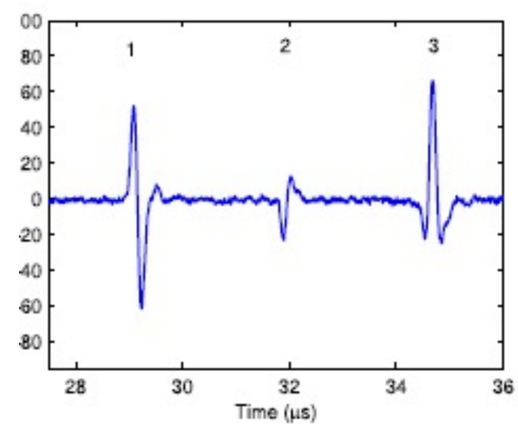


Medical Physics
The International Journal of Medical Physics Research and Practice

Ionoacoustic characterization of the proton Bragg peak with submillimeter accuracy

W. Assmann, S. Kellnberger, S. Reinhardt, S. Lehrack, A. Edlich, P. G. Thirolf, M. Moser, G. Dollinger, M. Omar, V. Ntziachristos, and K. Parodi

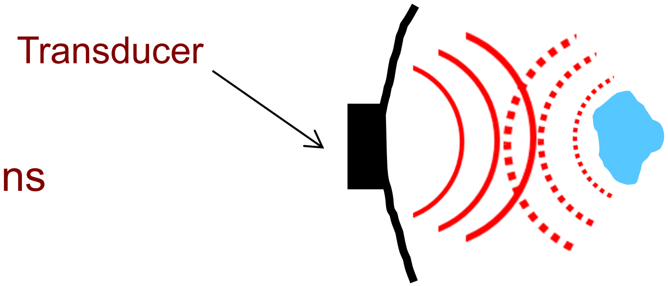
Citation: Medical Physics **42**, 567 (2015); doi: 10.1118/1.4905047



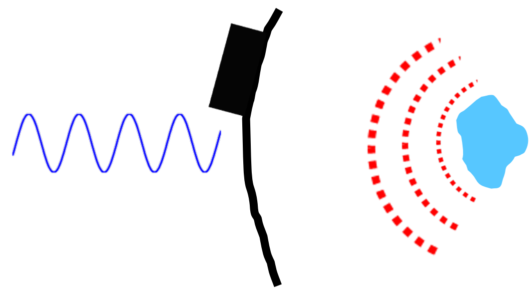
Hayakawa et al. Rad. Onc. Invest. **3** (1995) 42-45
Sulak et al. Nucl. Instr. Meth. **161** (1979) 203-217
Assmann et al. Med. Phys. **42** (2015) 567-574

Acoustic Imaging/Range Finding Techniques

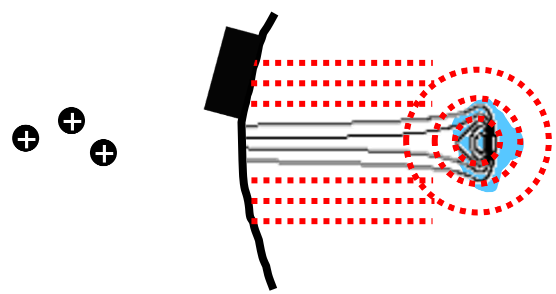
Ultrasound:
Transmit sound then receive reflections



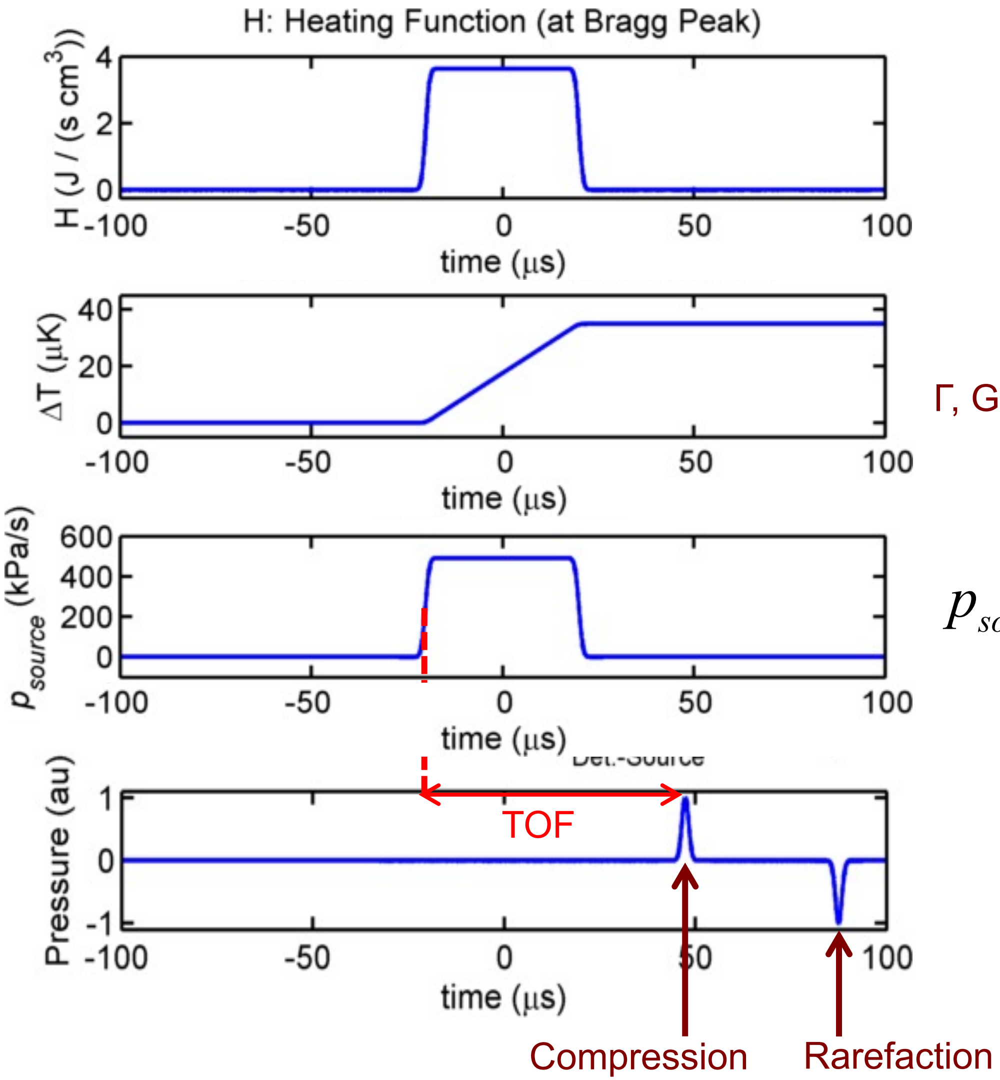
Thermoacoustics/Photoacoustics:
Transmit electromagnetic radiation, then receive generated acoustic signal



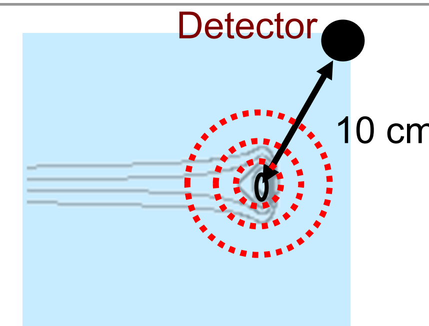
Protoacoustics/Ionoacoustics:
Irradiate with protons, then receive generated acoustic signal



Protoacoustics: Conceptualization



If we just consider the volume at the Bragg peak



Γ, Grüneisen Parameter

$$p_{source} = \boxed{\frac{\beta c_s^2}{C_p}} H$$

H: heating function $\left(\mathrm{J} / \mathrm{s} \times \mathrm{m}^3 \right)$

p_{source}: source pressure $\left(\mathrm{Pa} / \mathrm{s} \right)$

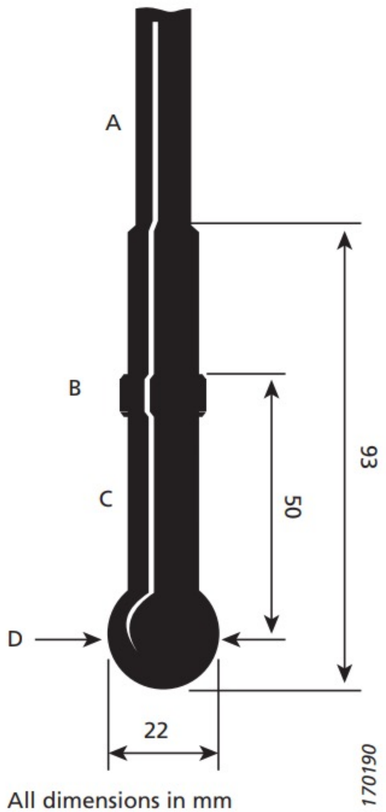
C_p: heat capacity $\left(\mathrm{J} / \mathrm{K} \times \mathrm{Kg} \right)$

β: expansion coefficient $\left(1 / \mathrm{K} \right)$

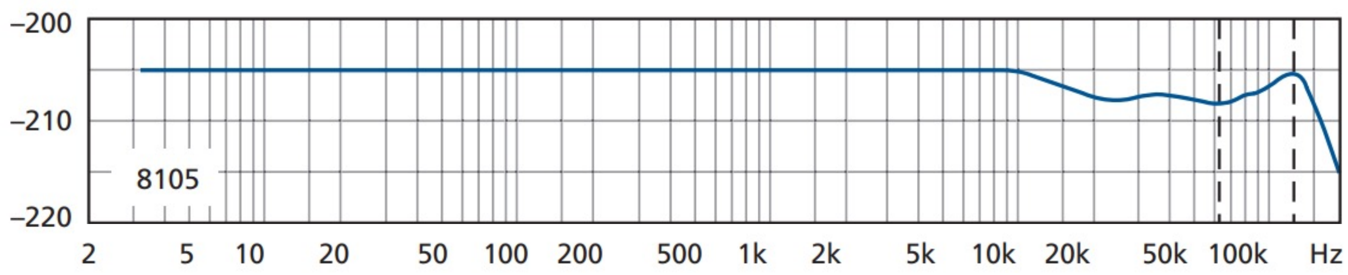
c_s: speed of sound $\left(\mathrm{m} / \mathrm{s} \right)$

Time of Flight = distance(source to transducer) / c_s
67.4 µs = 10 cm / (1481 m/s)

Hydrophone – B&K 8105



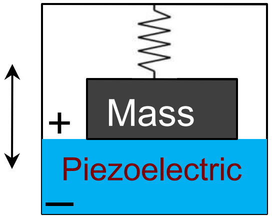
- Frequency range: 0.1 Hz to 160 kHz
- Receiving sensitivity: –205 dB re 1 V/μPa
- Charge sensitivity: 0.41 pC/Pa
- Omnidirectional over full frequency range
- Completely encased in rubber

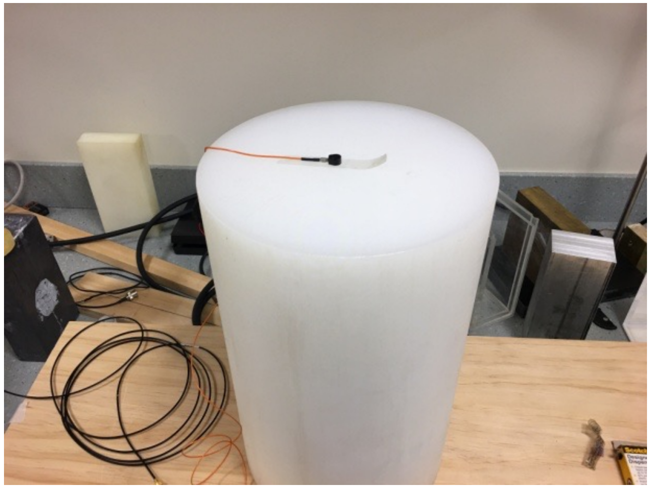


Accelerometer & Vibrometer

B&K Piezoelectric charge Accelerometer (Type 4517-C-001)

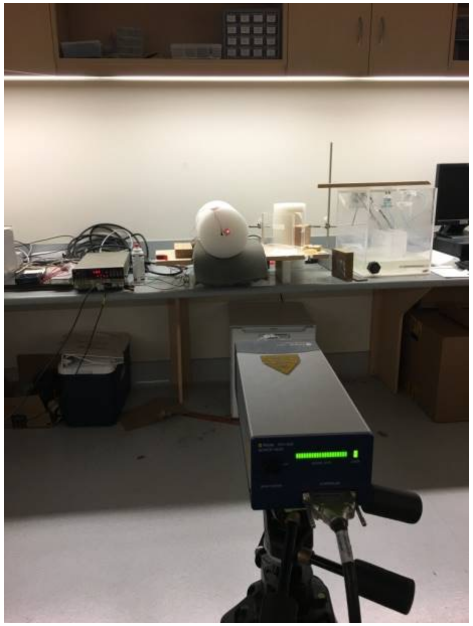
- Low weight; adhesive mounting.
- Frequency range: 1-20kHz





Polytec

- **OFV-5000** Vibrometer controller
- **VD-06** Velocity Decoder: 0.01 μm s^{-1} / √Hz
  0-350 kHz bandwidth
- **DD-900** Displacement Decoder: 15pm Max.
  resolution 0-2.5 MHz bandwidth.
- Programmable scanning.



Pressure-Dose Calibration Curve

Performed TRS-398 (P3) using Markus Chamber in Water Tank

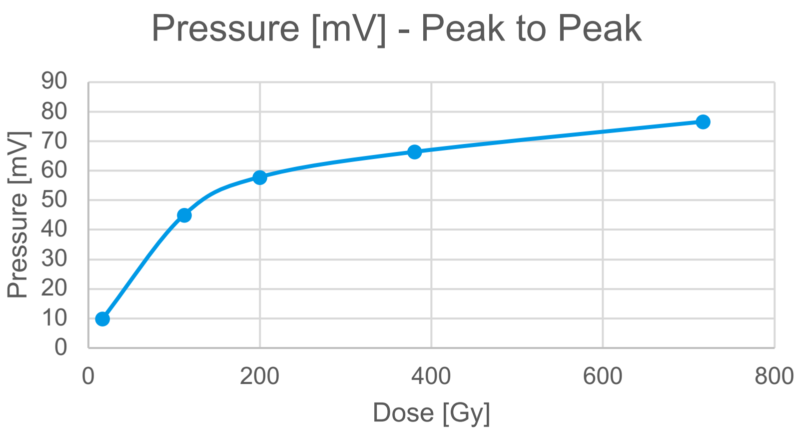
Pulse Width	IC Cyclo Current	Dose Rate
10 µs	1 nA	1.648 Gy/s
30 µs	3.9 nA	11.138 Gy/s
50 µs	4.3 nA	19.929 Gy/s
70 µs	5.5 nA	38.002 Gy/s
100 µs	9 nA	71.652 Gy/s

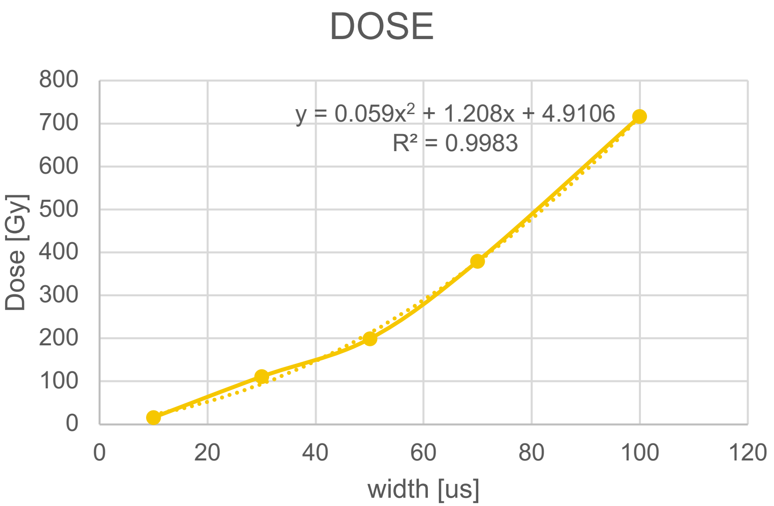
For all measurements:
Frequency 100 Hz
Arc Current 200 nA

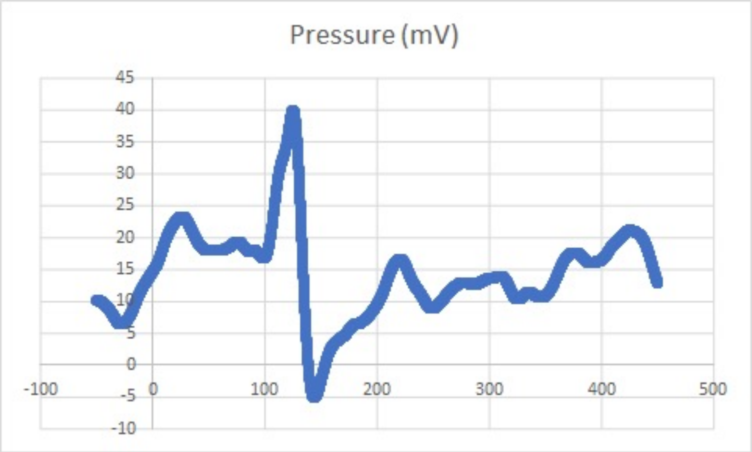
Performed high dose test @ Pulse width 10µs, Frequency 100 Hz

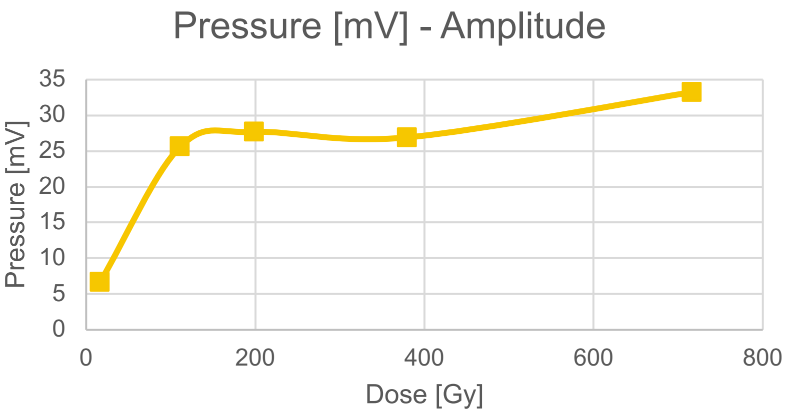
- **Delivered beam at IC cyclo of 80 and 500 nA**

Pressure-Dose Calibration Curve



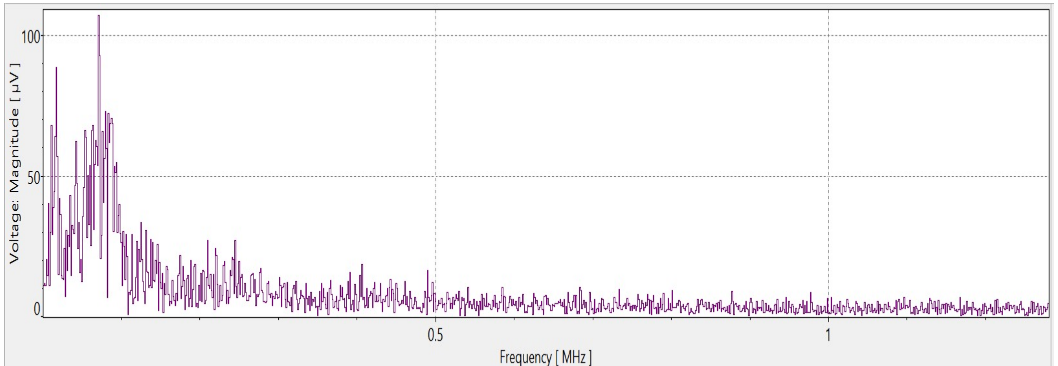


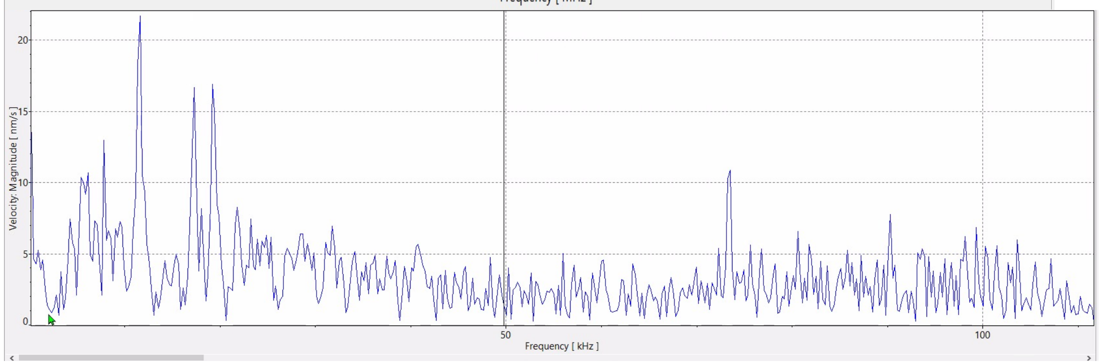




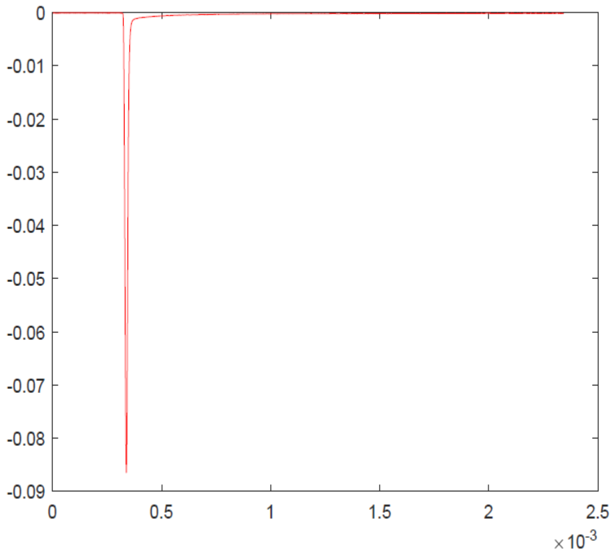
Vibrometer Setting

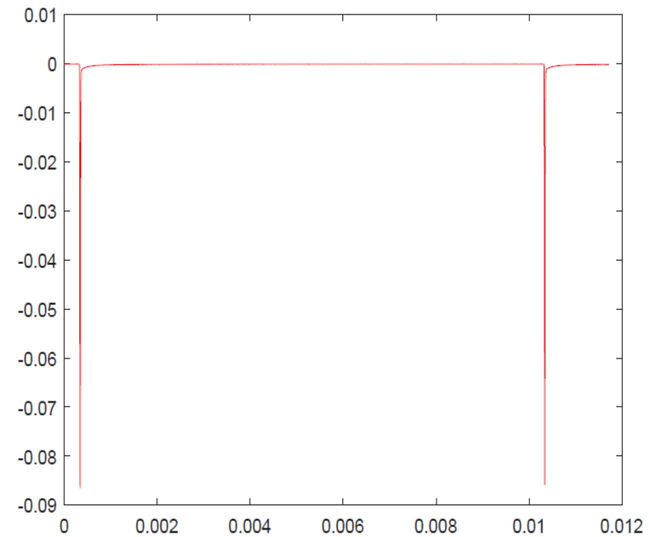
- 5000 averages
- 1.28 MHz sampling rate
- 16384 samples
- 12.8 ms
- 781.3 ns resolution
- 0.5 mm/s/V sensitivity

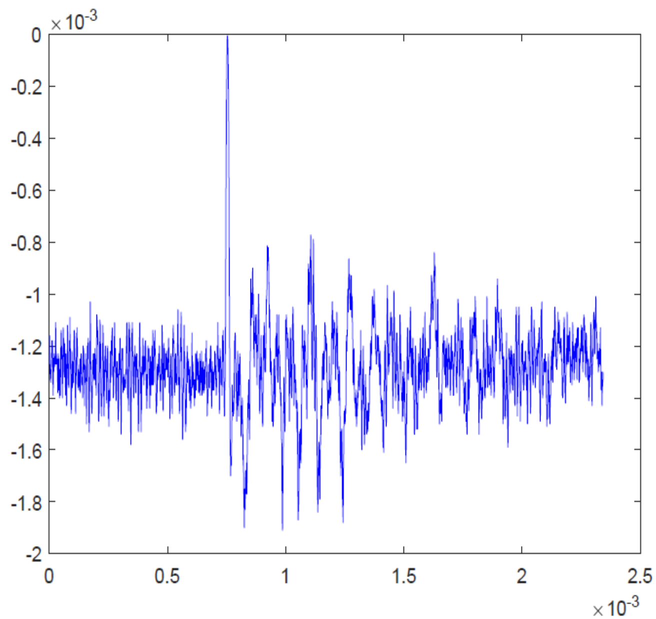


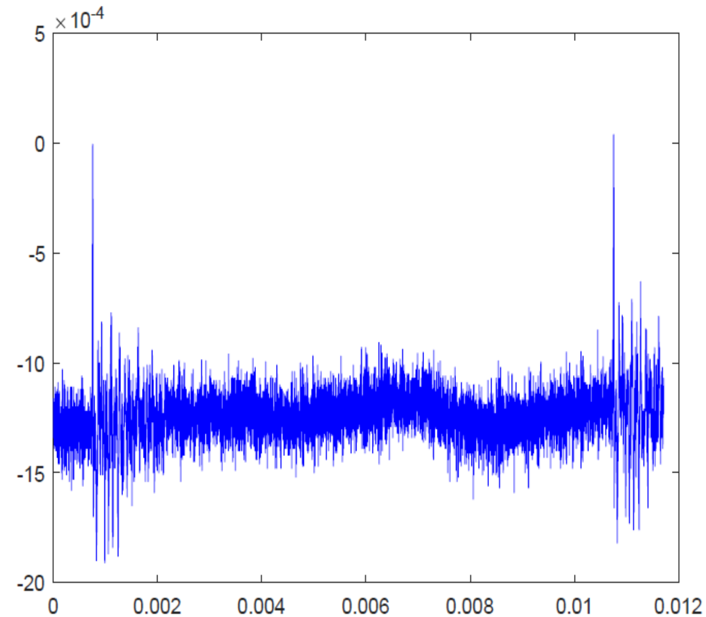


Measurement @ 38 Gy/s

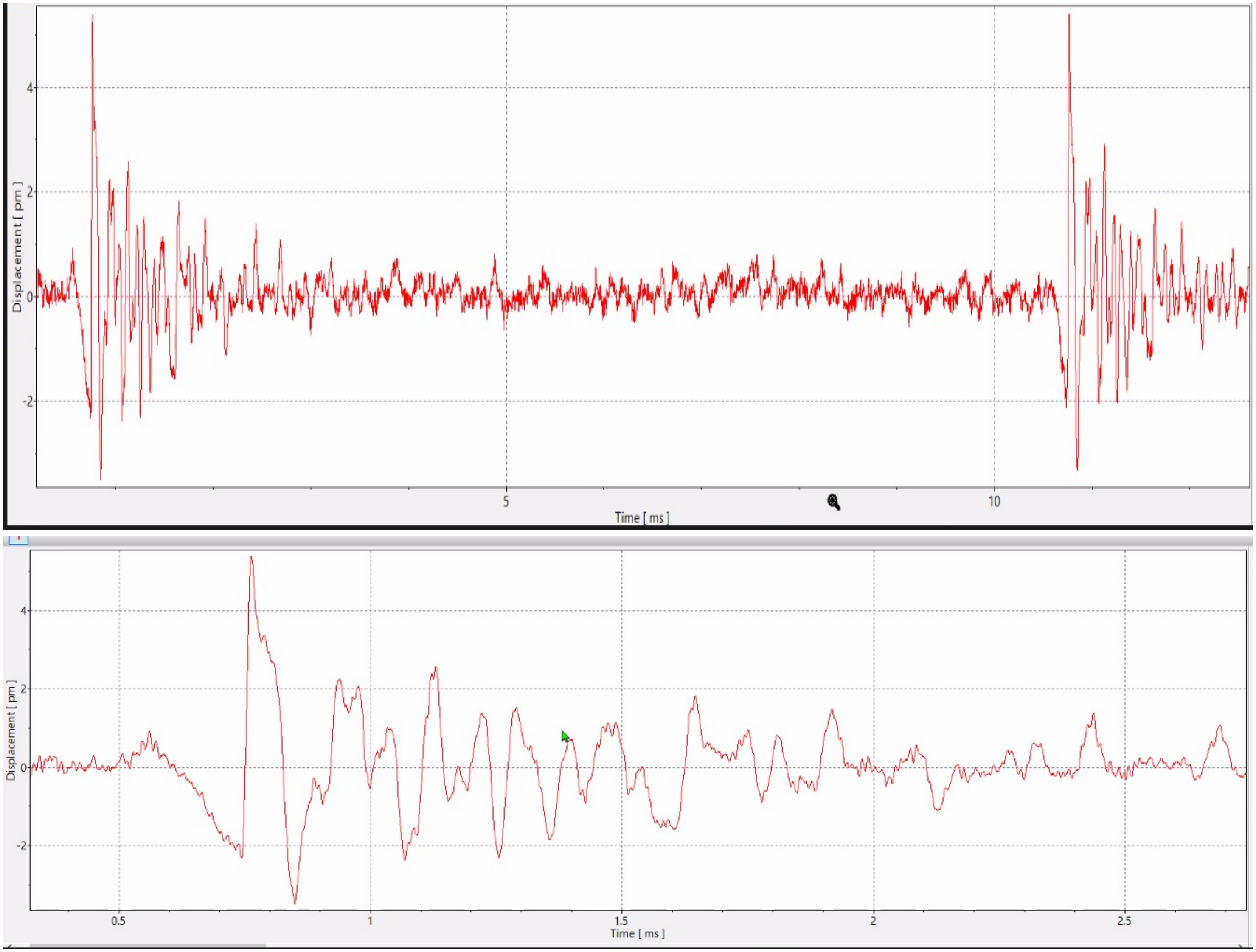








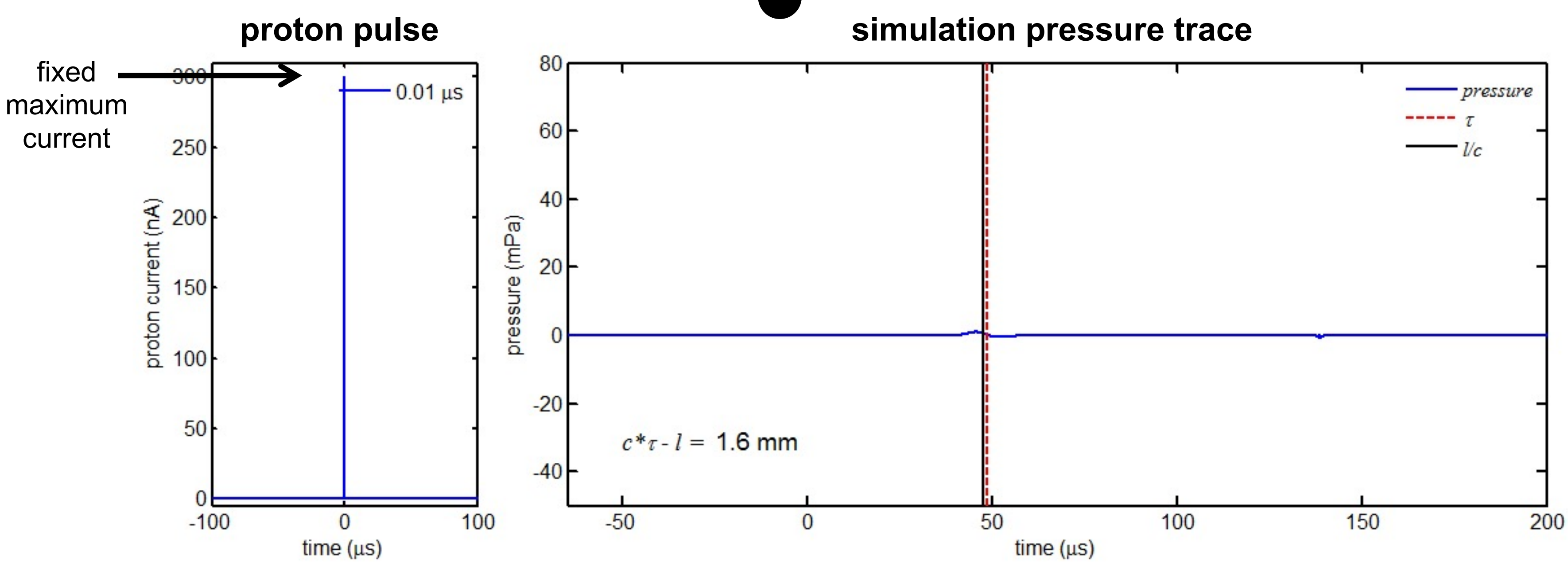
Measurement @ 38 Gy/s



Simulations: Gaussian Proton Pulses

To "efficiently" generate protoacoustic signal, the proton pulse should be shorter than ~ 1.3 μs

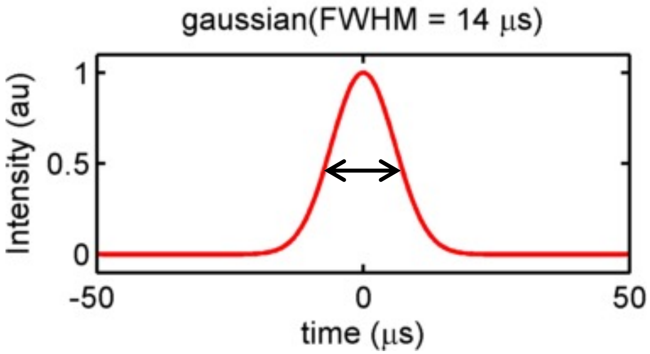
$$p(t) = \left[E(t) * p_\delta(t) \right]$$

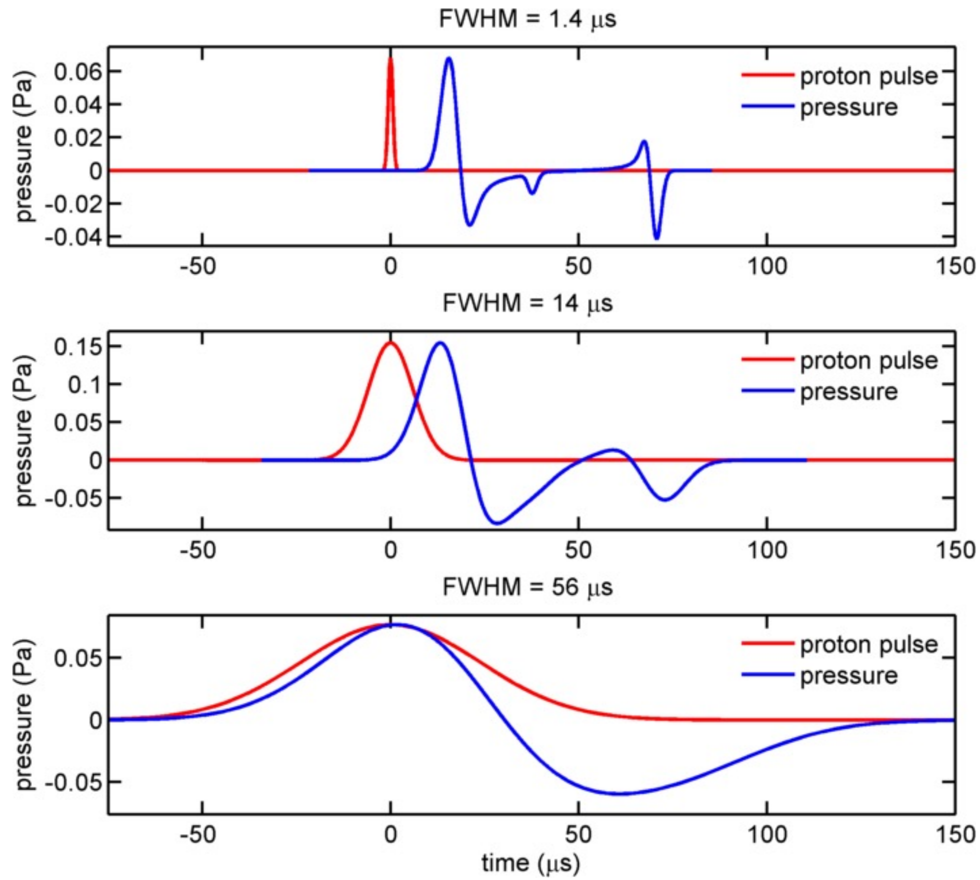


Observation #1: non-monotonic relationship between Gaussian proton pulse FWHM and the pressure amplitude
Observation #2: The TOF distance calculation error ($c*\tau - l$) depends on the proton pulse

Jones, Sehgal, Avery, PMB **61** (2016) 2213-2242

Proton Pulse Shape Dependence



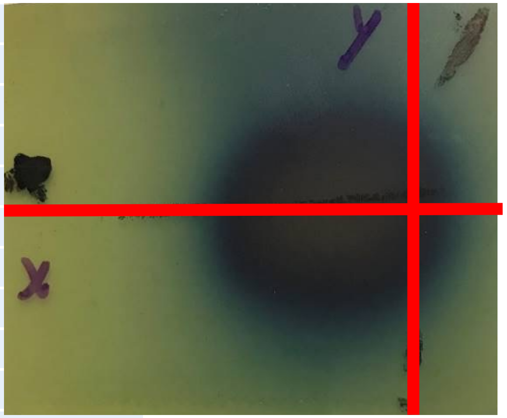


As the proton pulse rise time increases, the acoustic signal broadens and features become “washed out.”

Triangulation Algorithm

Vibrometer Data

	Left 5cm	Lower 5cm	Right 5cm	Upper 5cm	center
Proton peak (us)	338.28	338.67	337.9	338.6	338.28
Vibrometer (us)	758.59	757.81	785.2	754.69	753.91
delta t (us)	420.31	419.14	447.3	416.09	415.63
	4.68	3.51	31.67	0.46	
Proton peak (us)	10338.65	10338.28	10337.5	10338.3	10338.28
Vibrometer (us)	10759.38	10757.81	10786.7	10755.47	10753.13
delta t (us)	420.73	419.53	449.2	417.17	414.85
	5.88	4.68	34.35	2.32	



Accelerometer Data – Previous Experiment

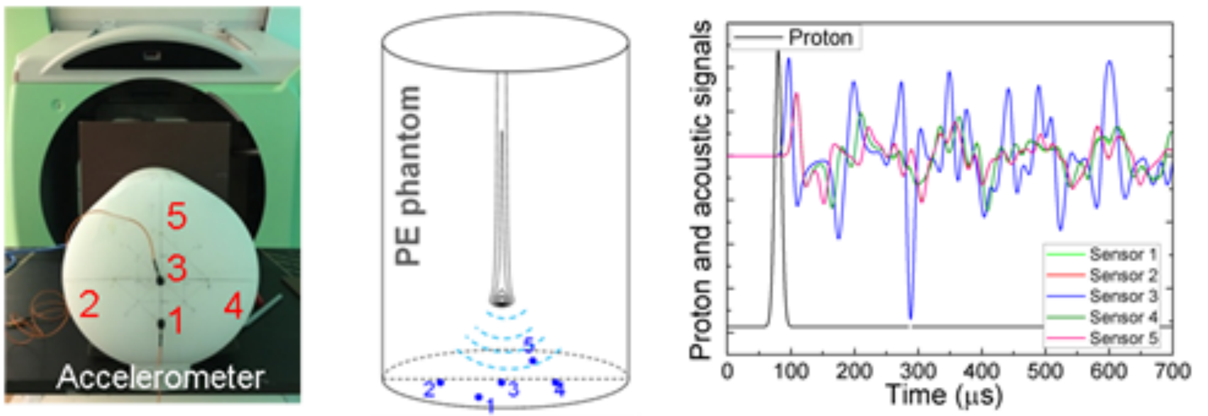
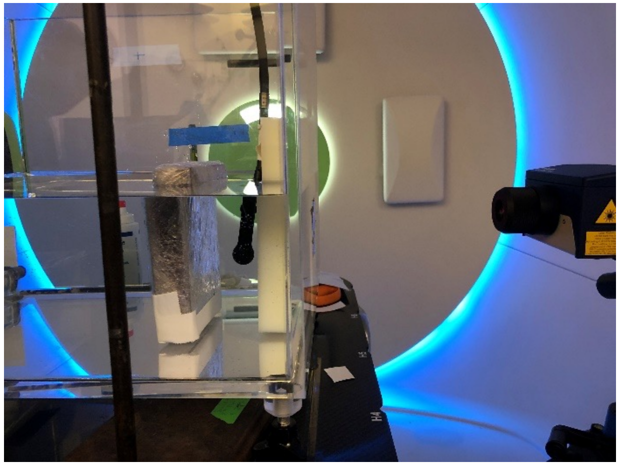
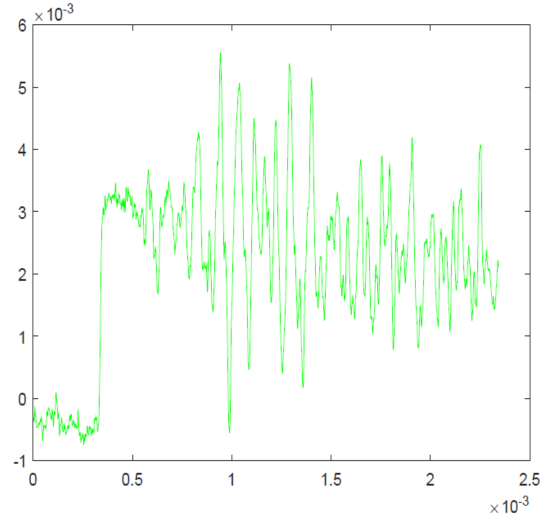
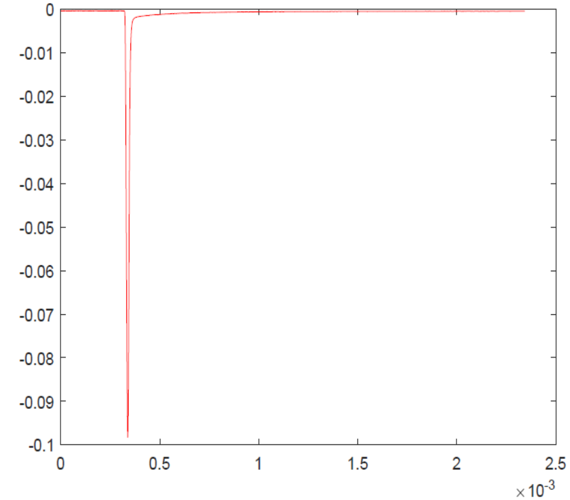


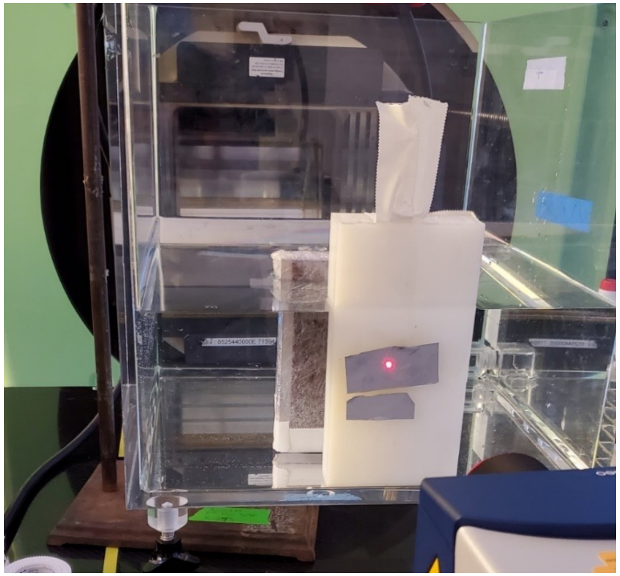
Figure 17. Prototype experiment using the accelerometer system to measure the TOF of protoacoustic waves, then calculate the BP position in a PE phantom through triangulation algorithm. The depth of BP is 37.8 mm (simulation), 37.8 ± 1.4 mm (experimental data), and 37.6 ± 0.2 mm (triangulation algorithm).

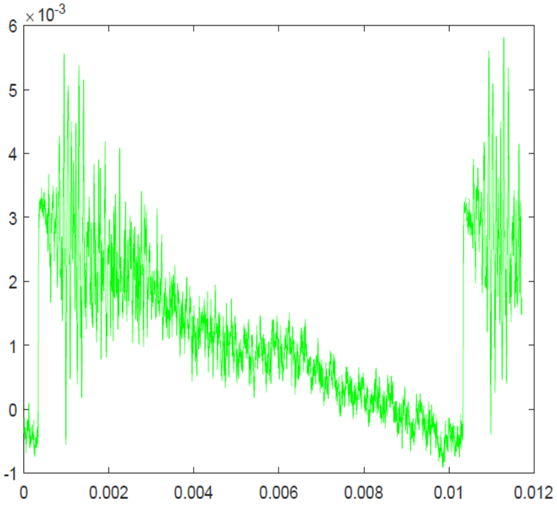
Liver Measurement - Hydrophone

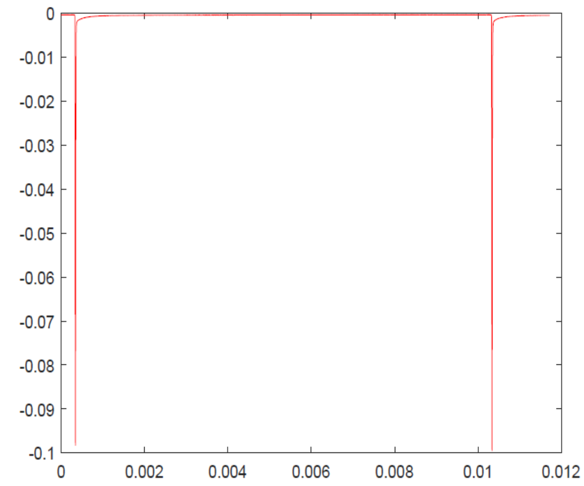




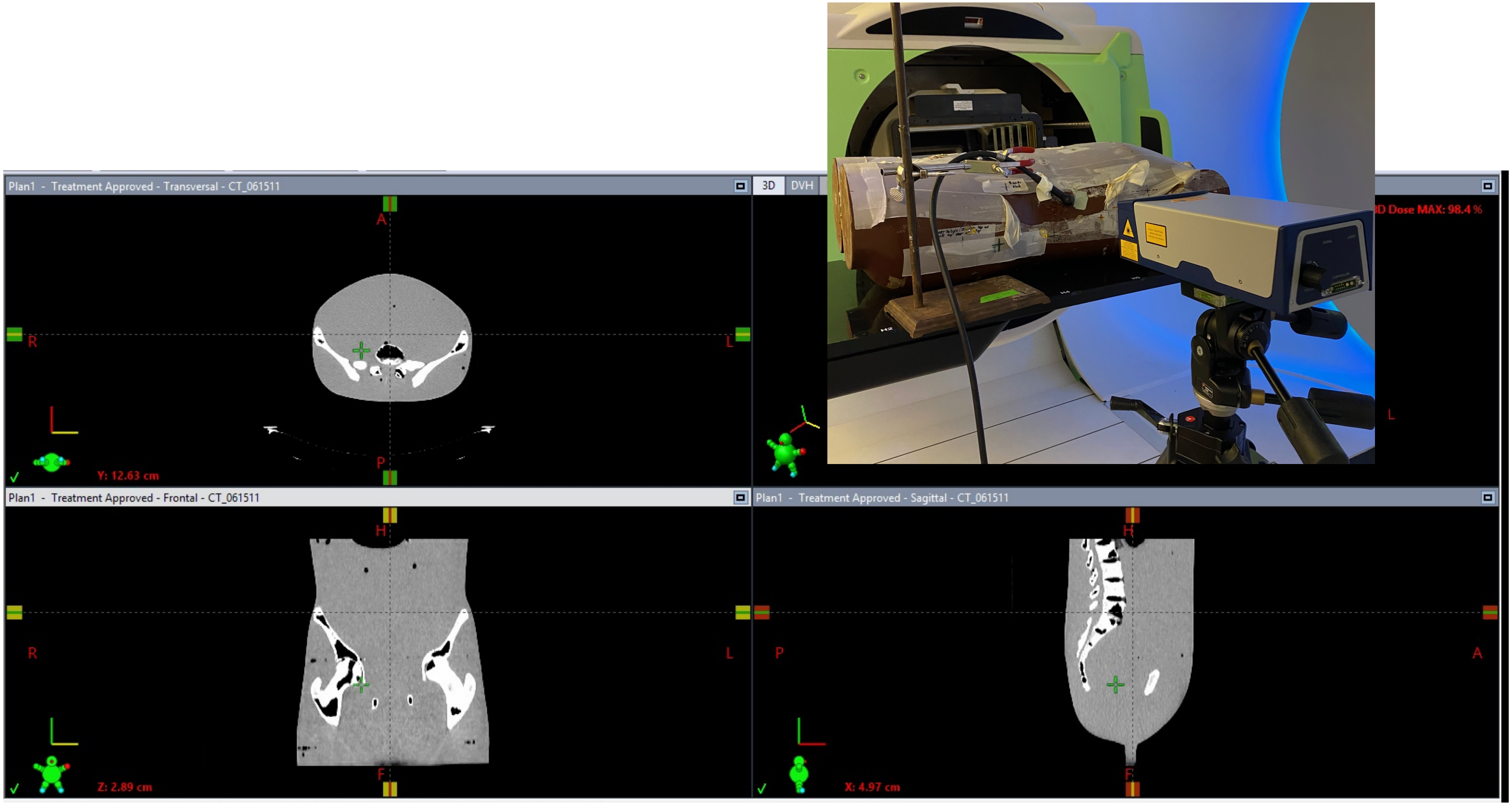




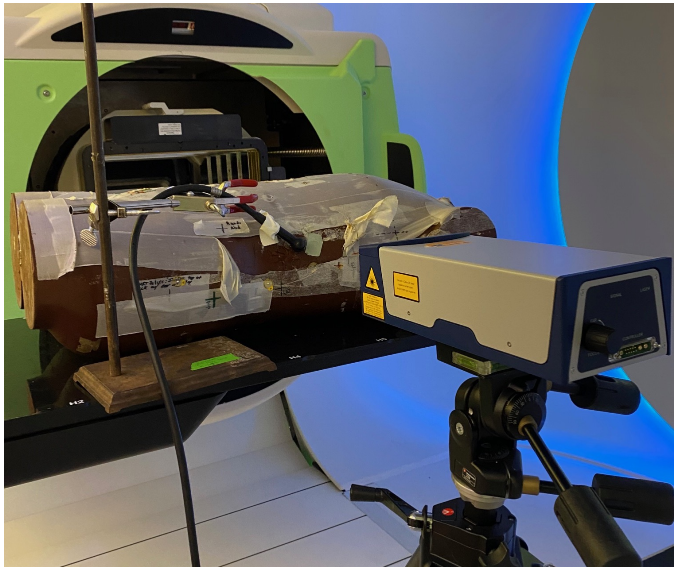


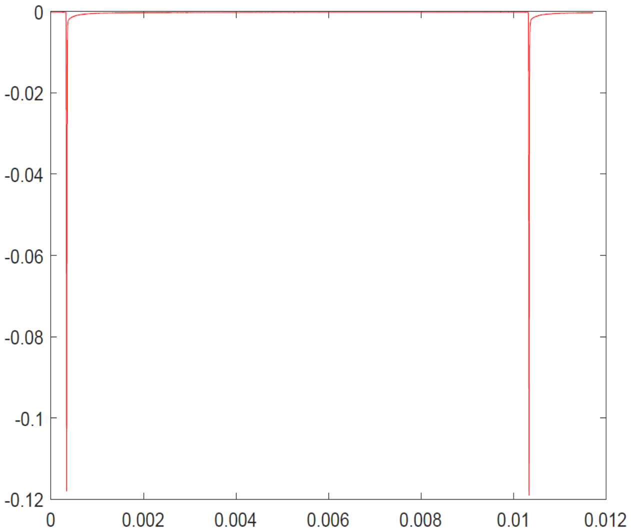


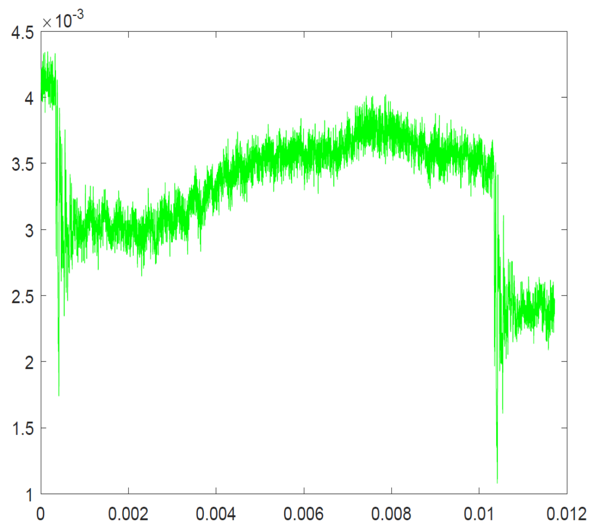
Abdominal Phantom

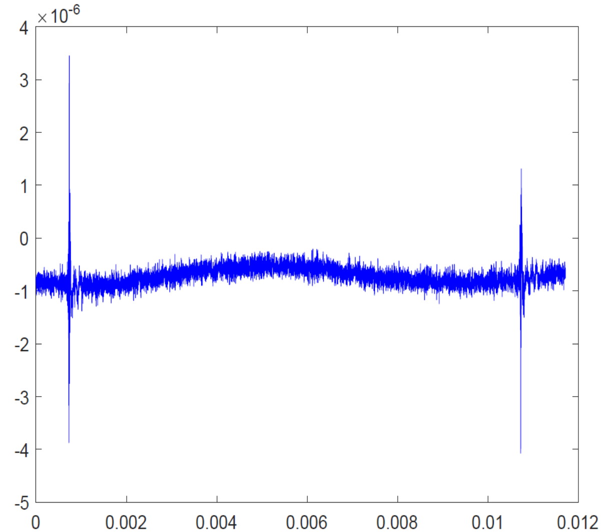


Abdominal Phantom

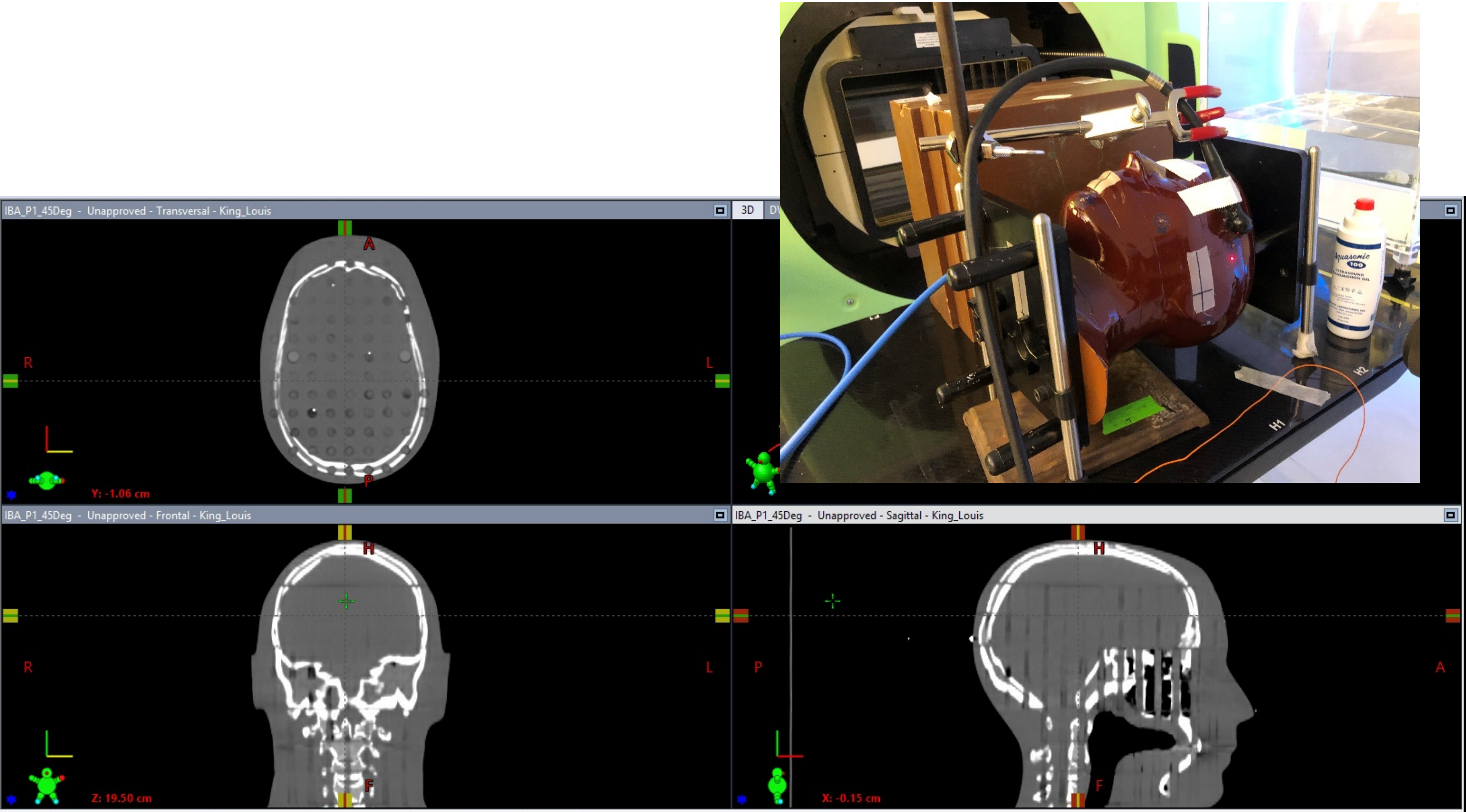




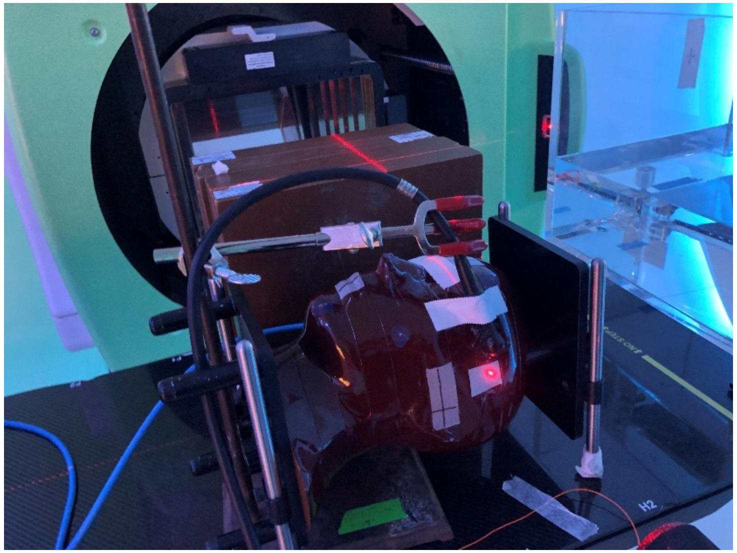


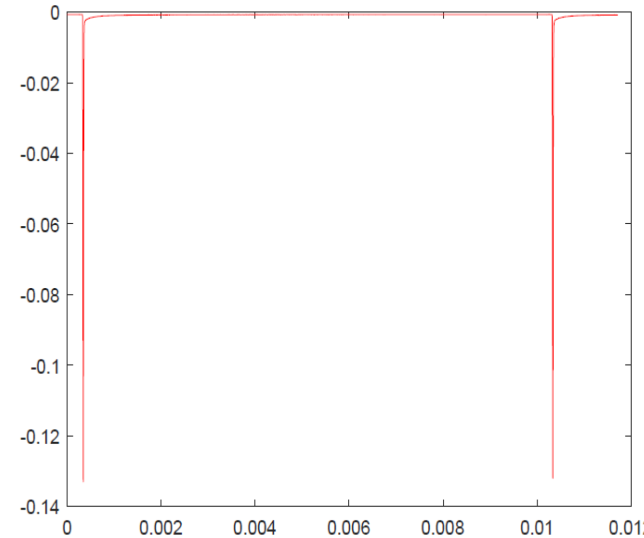


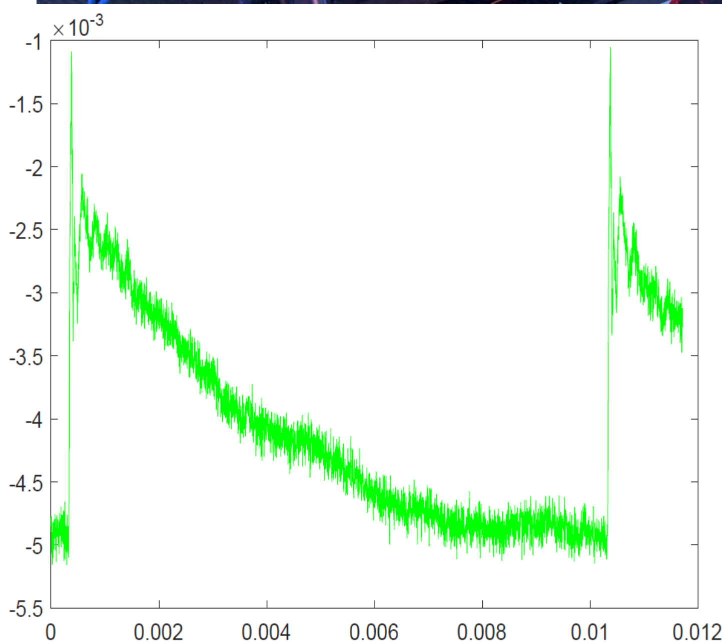
Brain Phantom – King Louie

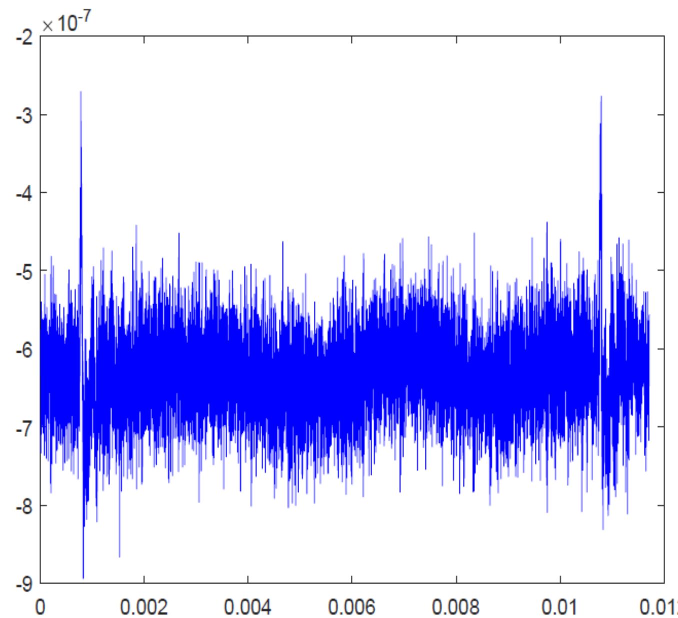


Brain Phantom – King Louie

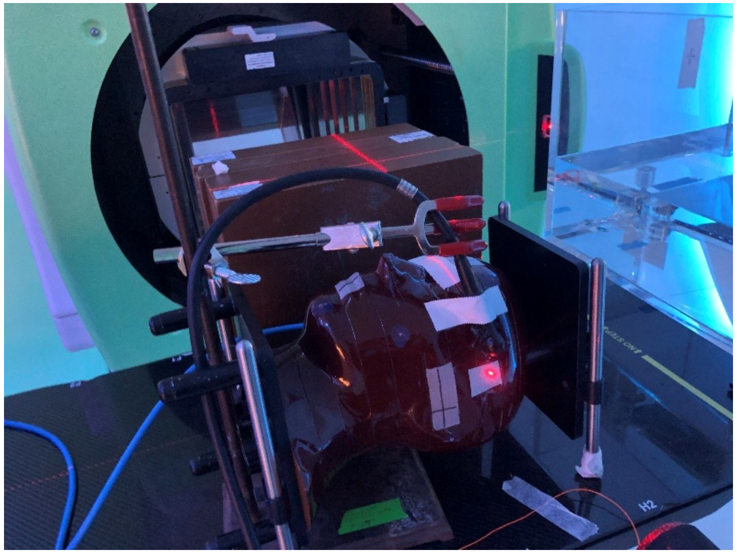


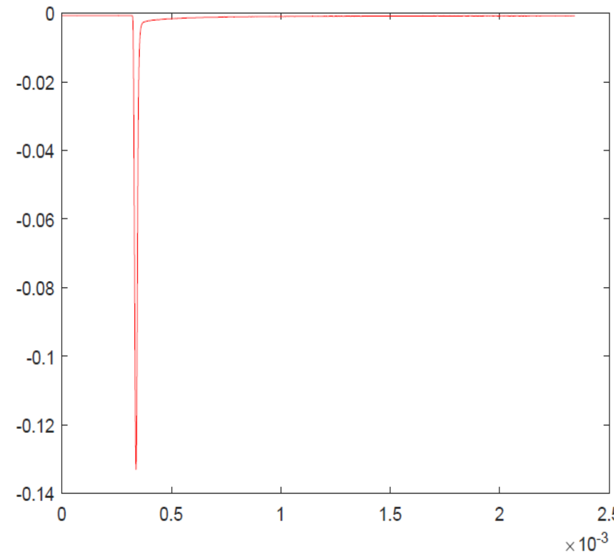


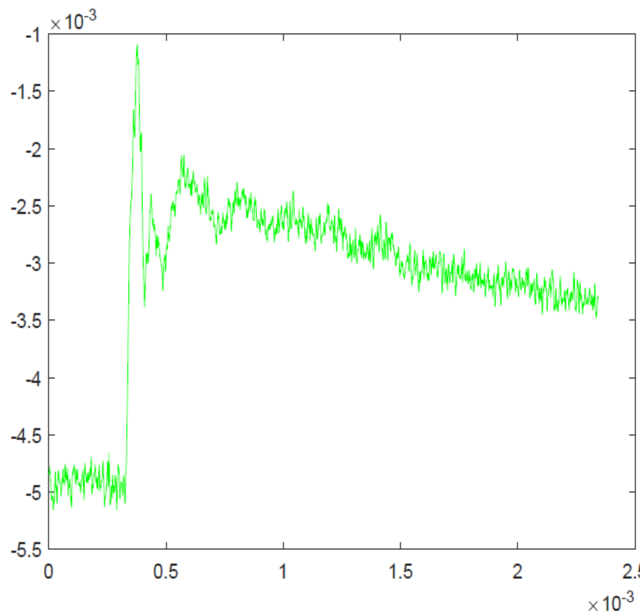


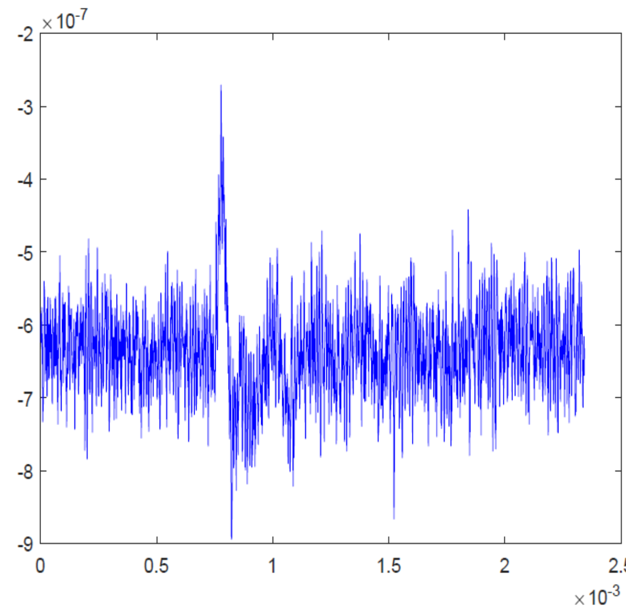


Brain Phantom – King Louie









Stay safe!!