Using Prompt gamma ray emission to address uncertainties in proton therapy

Jerimy C. Polf, PhD, DABR

Department of Radiation Oncology

University of Maryland School of Medicine

AAPM 2013

Disclosures and Announcements

Funding:

IRG-08-061-01, American Cancer Society
R21CA137362, National Institute of Health

Therapy Scientific Session:

Proton Range Uncertainty, Thursday, 10:30-12:30 pm, Room 144

Experimental Study of Discrete Prompt Gamma Lines for In-Vivo Proton Range Verification
J. Verburg*, K. Riley, J. Seco

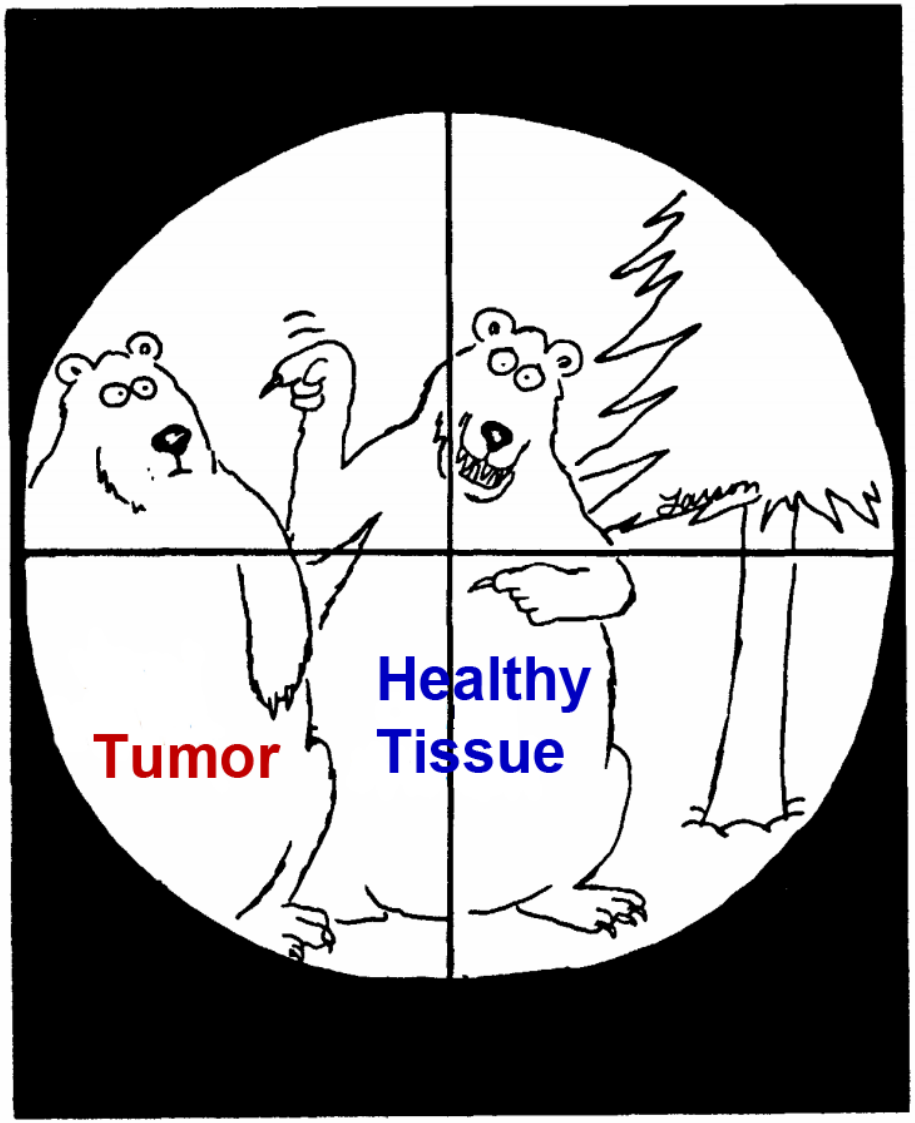
Characterizing Prompt Gamma Signal During Proton Radiotherapy
J. Polf*, D. Mackin, E. Lee, S. Avery, D. Dolney, S. Beddar

On the Feasibility of Prompt Gamma Imaging in Heterogeneous Patient Anatomy
E. Sterpin*, G. Janssens, J. Smeets, D. Prieels, F. Stichelbault, F. Roellinghoff, E. Clementel, A. Benilov, S. Vynckier

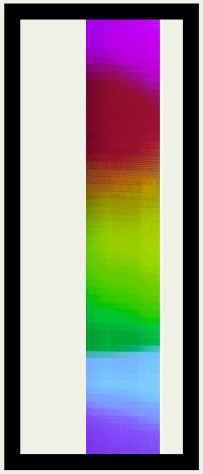
Goal of radiation therapy

- Maximize the dose of ionizing radiation to malignant (cancer) cells

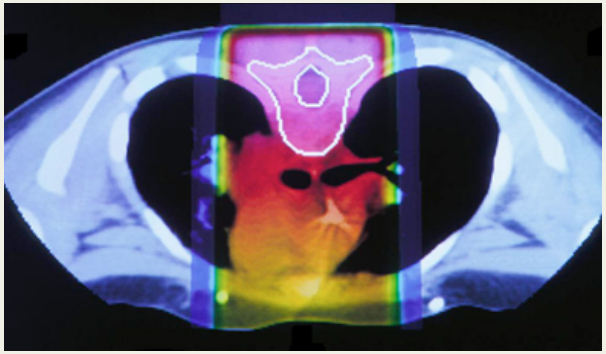
- Minimize the dose of ionizing radiation to healthy tissue



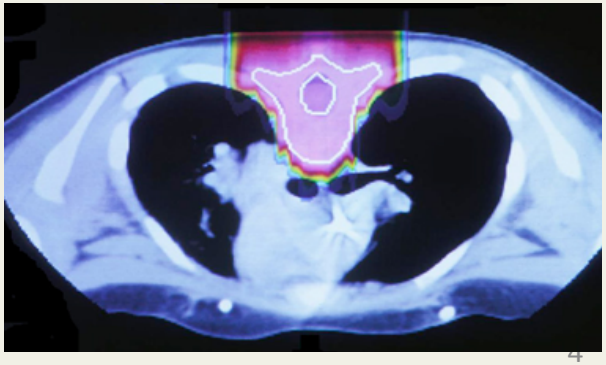
Proton vs. x-ray dose delivery



X-Rays



PROTONS



This gives many pictures of how wonderful Protons are (in a perfect world).

In reality there are many uncertainties in Proton treatment delivery due to a wide range of factors:

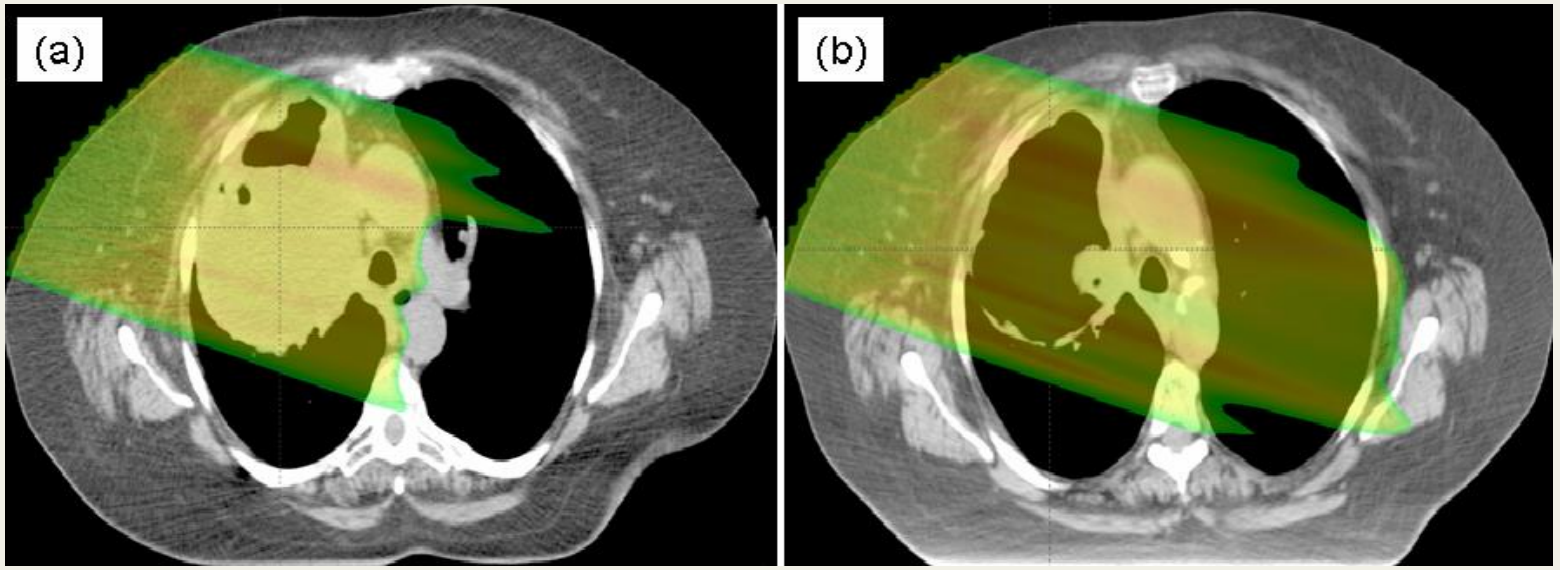
- Treatment setup,
- CT# conversion,
- Tumor motion,
- Tissue response to proton irradiation
- Etc.

Uncertainties in Proton Therapy

Dose delivery errors:

- setup errors,
- tumor motion,
- changes to internal anatomy

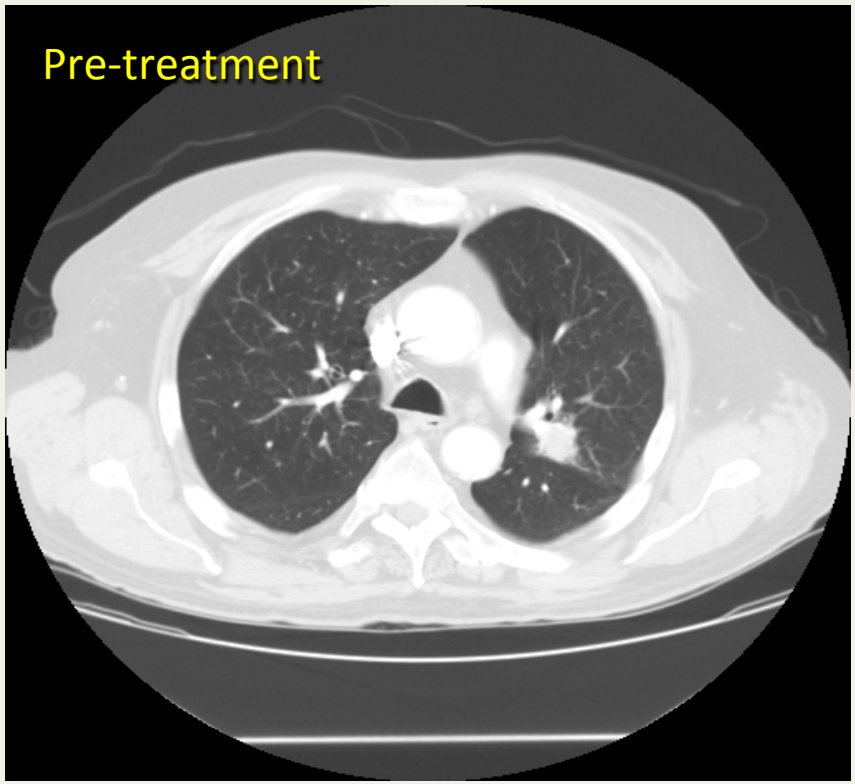
Treatment CT **2 week re-CT**

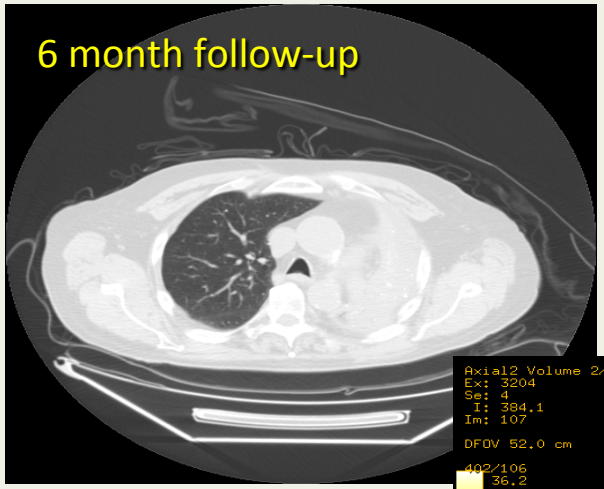


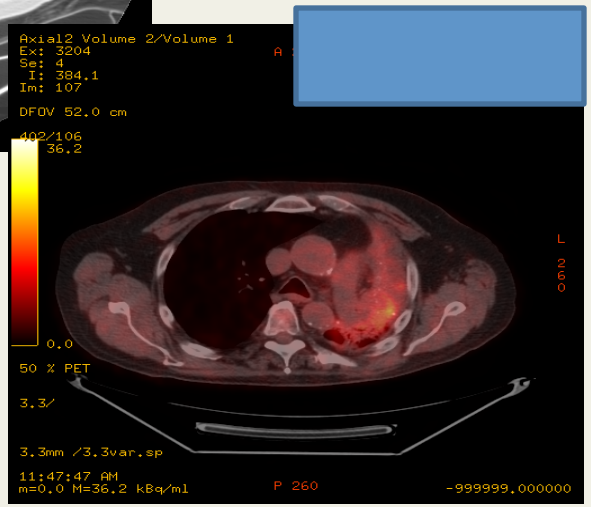
Uncertainties in Proton Therapy

- Tumor and normal tissue response

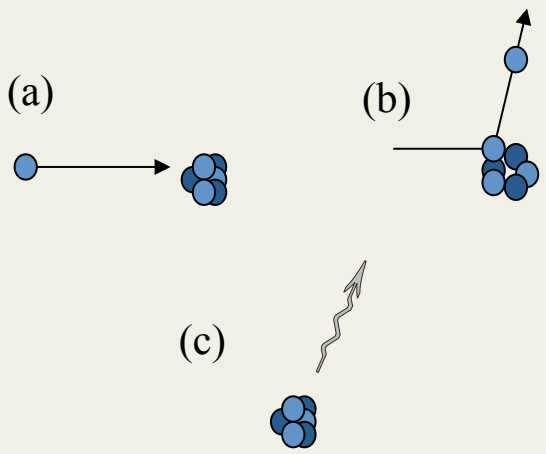
Why does one patient respond adversely, while another does not?







Prompt gamma imaging (PGI) concept



- *Prompt* Gamma Ray Emission

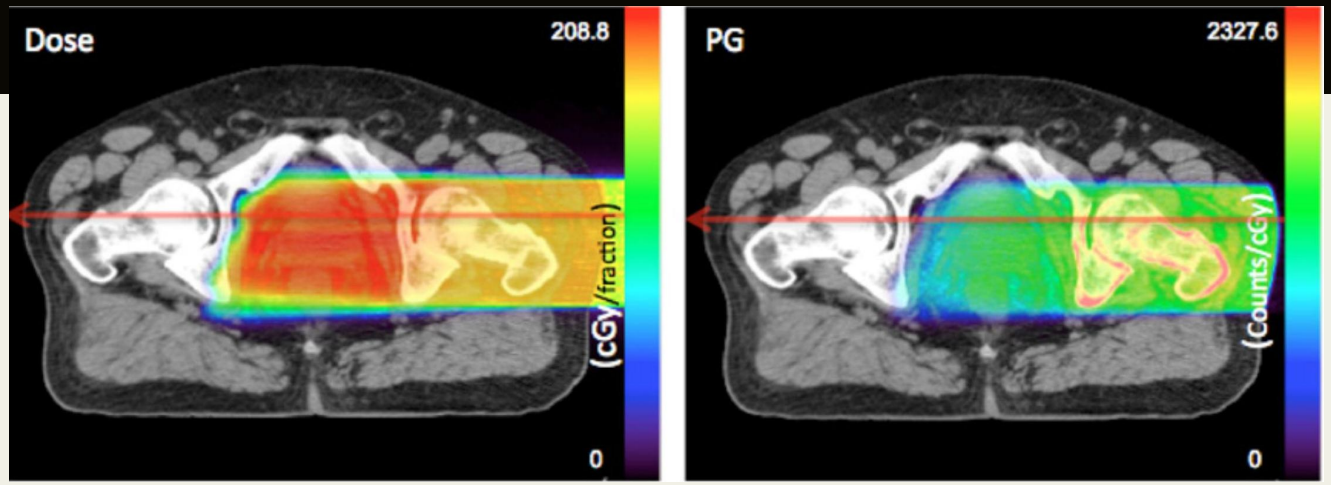
  - occurs within 10^{-9} sec of interaction

  - i.e. – “real-time” signal

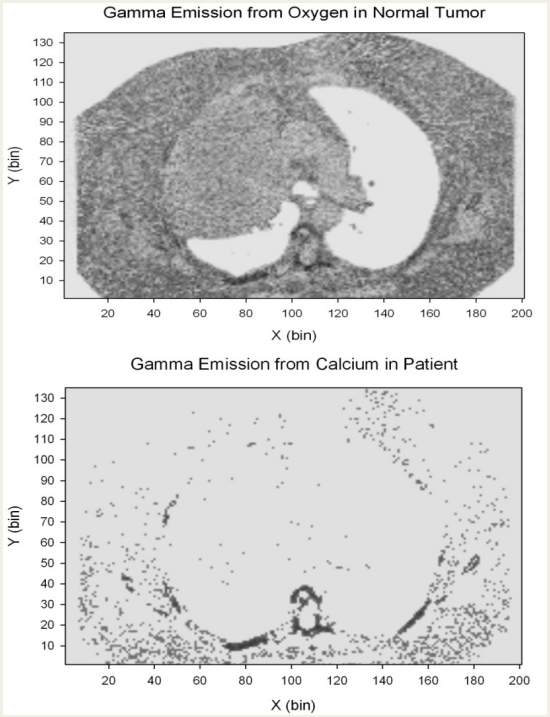
  - each element emits characteristic gamma-rays with different energies

  - gamma rays only emitted where proton beam interacts in the patient (i.e where dose is deposited)

Prompt Gamma Monte Carlo Studies



Moteabbed et al, *Phys. Med. Biol.,* 2011



Polf et al, *AIP conf. proceed.* 2011

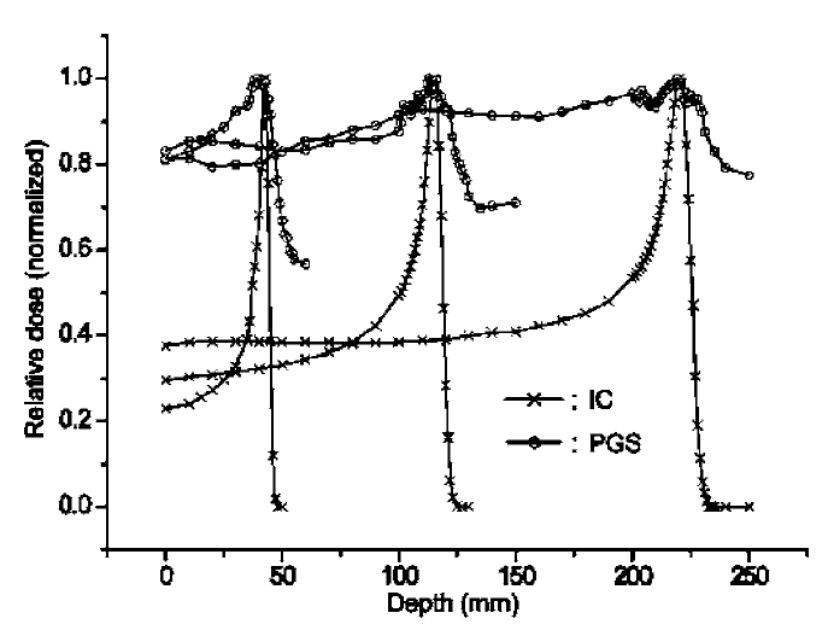
By measuring PG emission, it may be possible to address uncertainties in:

- delivered proton beam range

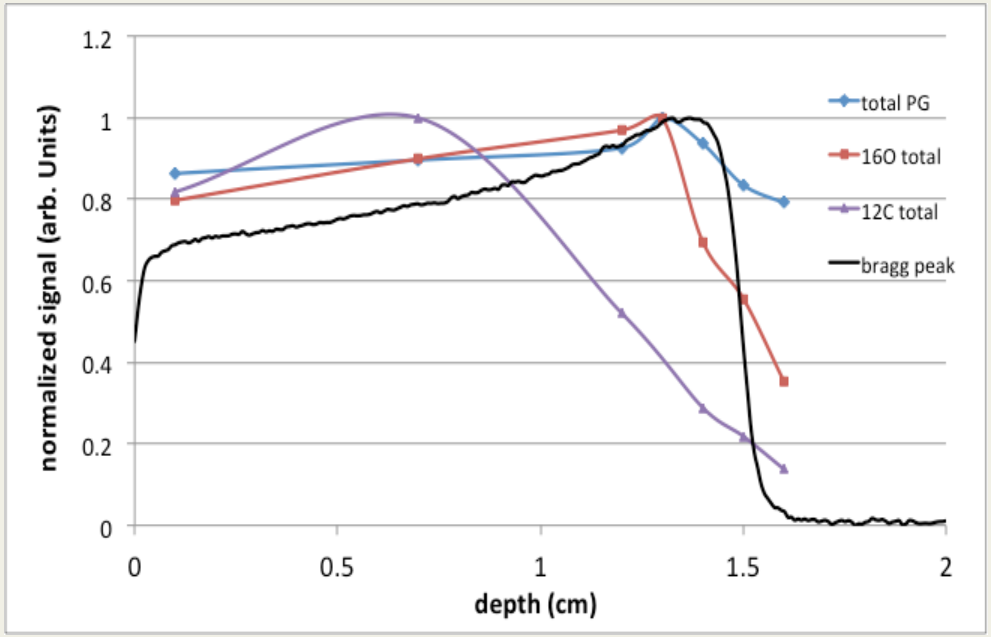
- (changes to) elemental composition of irradiated tissue.

Prompt Gamma Measurements

PG emission vs. depth shown to correlate well to Bragg Peak.

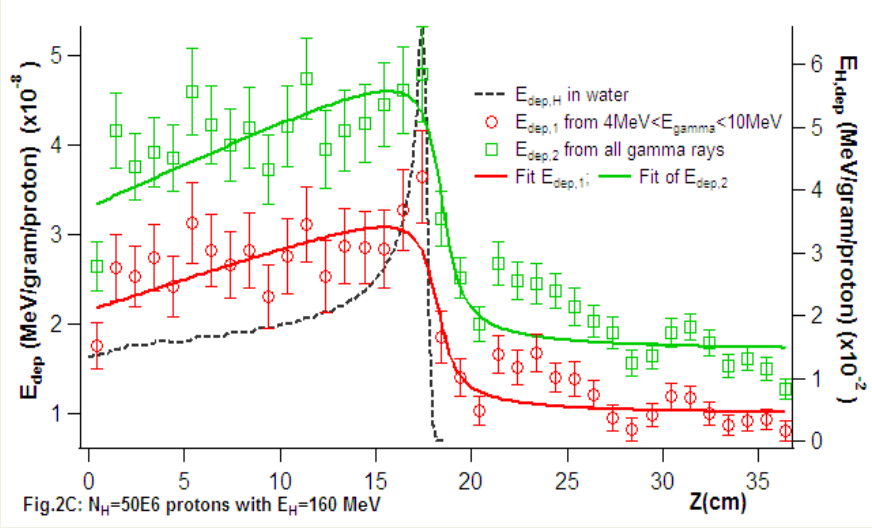


*Min et al., Appl. Phys. Let., **89**:183517 (2006)*



Polf et al., (2013).

Prompt Gamma detection systems



courtesy of M. Fatyga and M. Bues, Mayo Clinic, Phoenix AZ

Early Monte Carlo studies and measurements Have led to the design and development of PG detection and imaging systems.

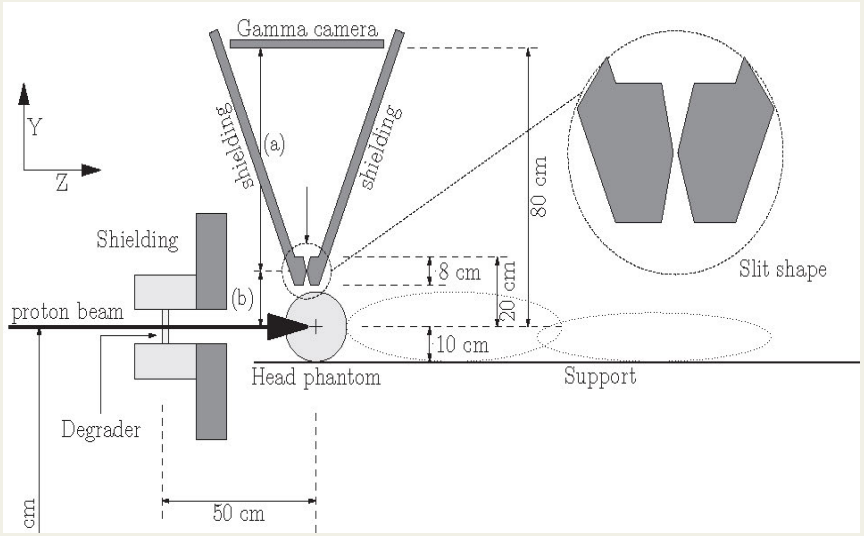
These include:

- Pinhole/slit cameras
- Linear detector arrays
- Compton cameras
- Energy-time resolve detection

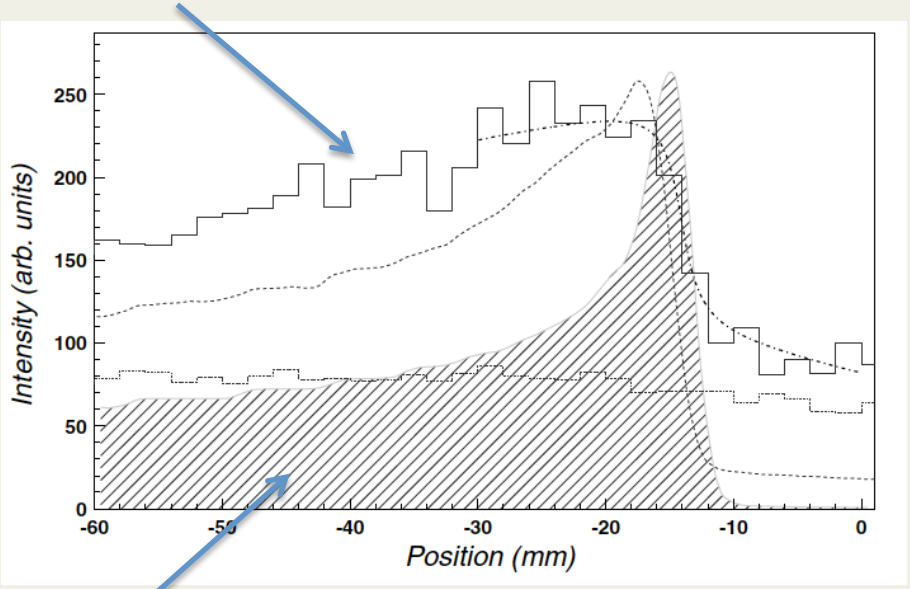
Prompt Gamma range verification

Knife edge slit camera

Bom et al., *Phys. Med. Biol.*, **57** (2012) 297-308.



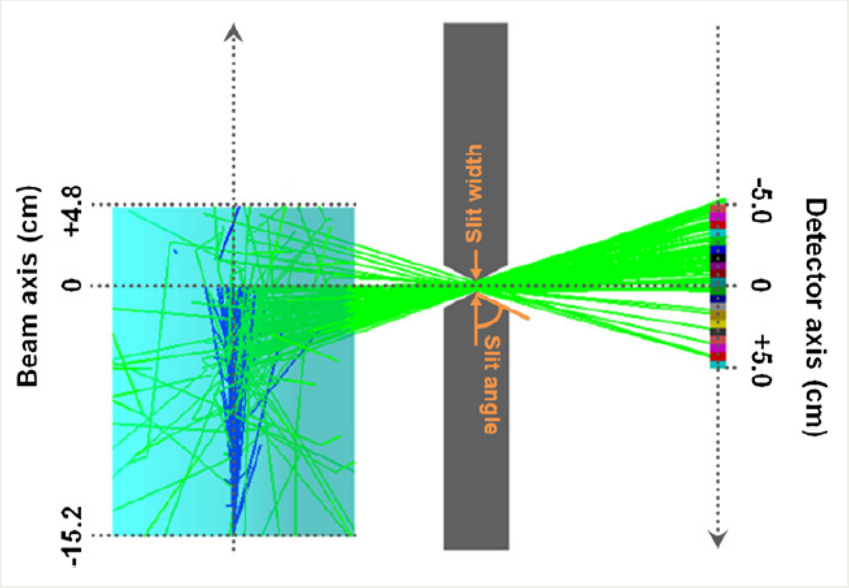
Prompt Gamma



Dose

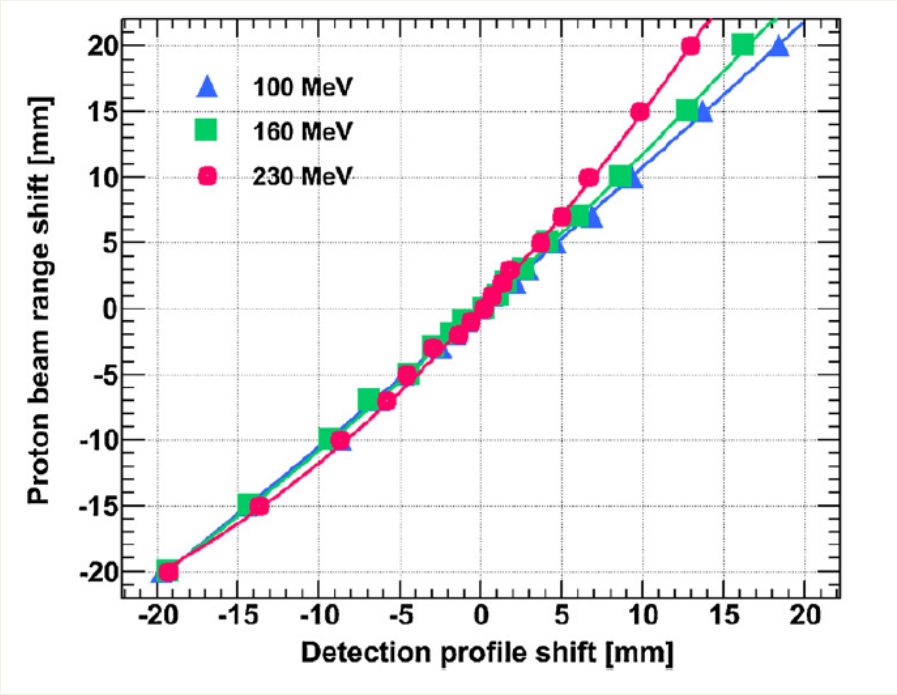
Prompt Gamma range verification

Knife edge slit camera



Smeets et al., *Phys. Med. Biol.*, 57 (2012) 3371-3405.

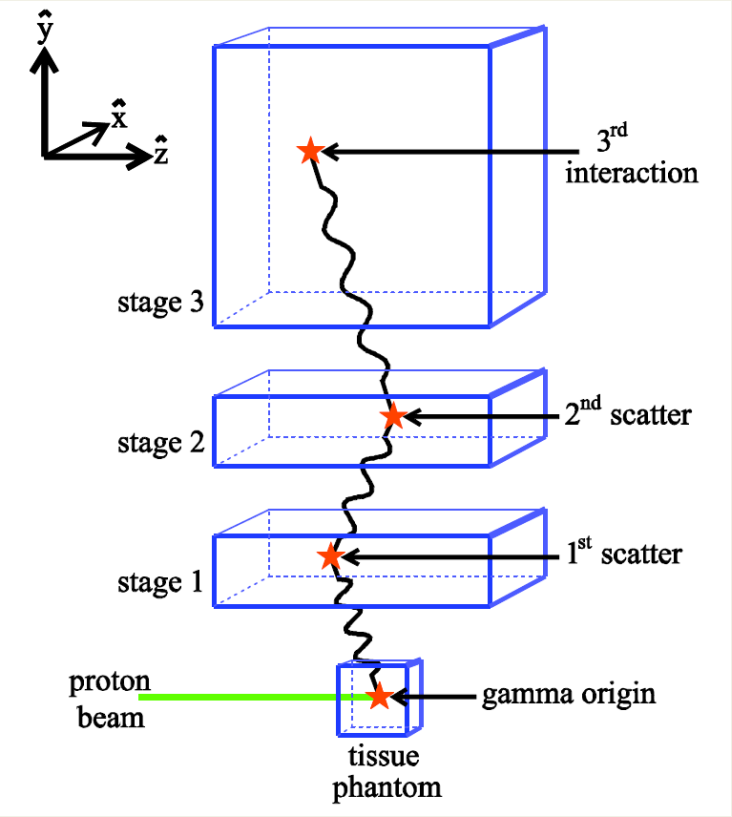
Correlation between range shift and PG profile shift

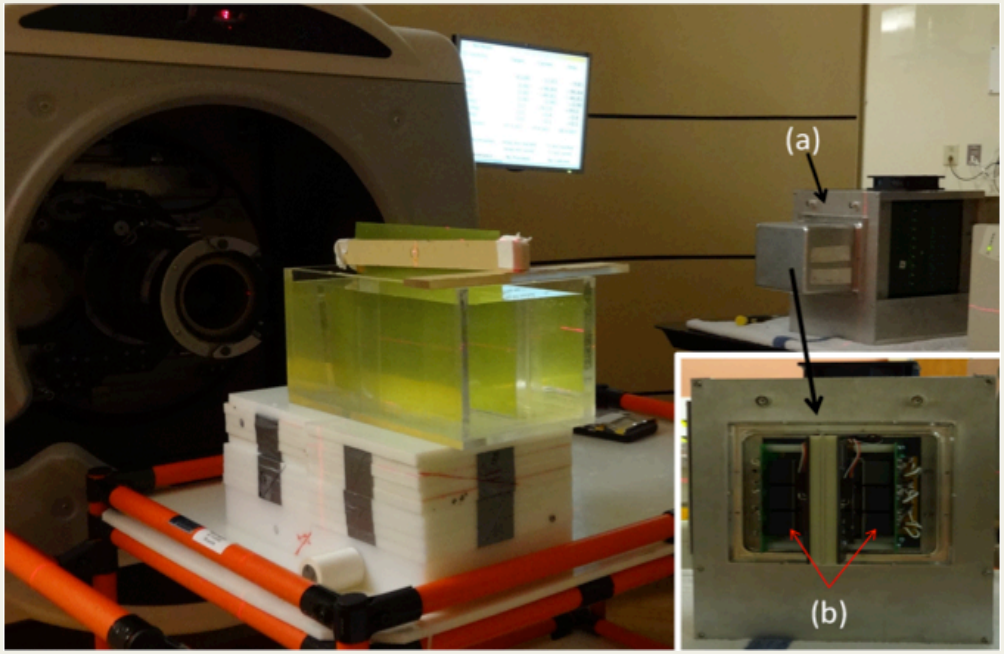


- Estimated that, determination of 1-2 mm shift in BP possible

Prompt Gamma range verification

Compton Camera

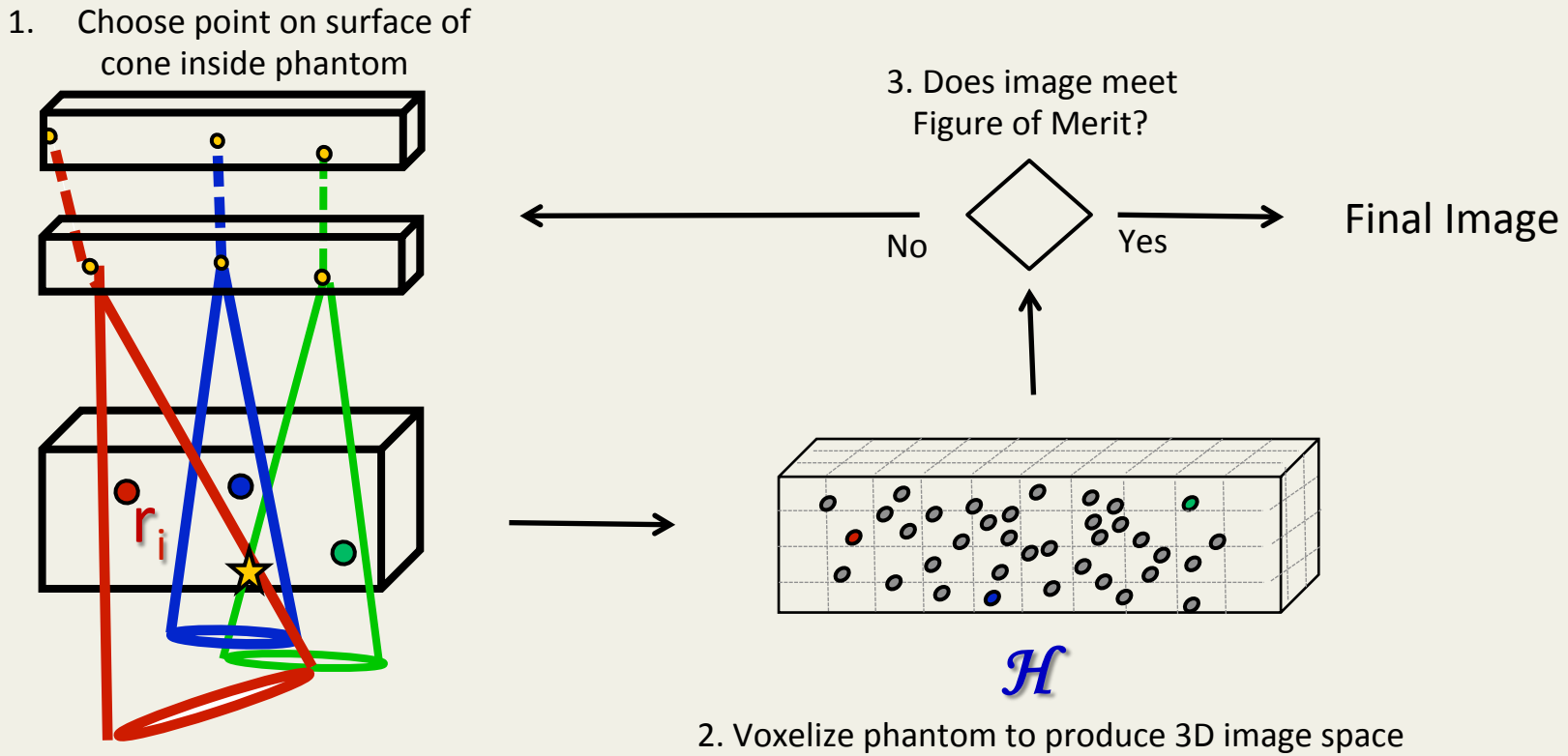




Prompt Gamma range verification

Compton Camera

Iterative Image Reconstruction

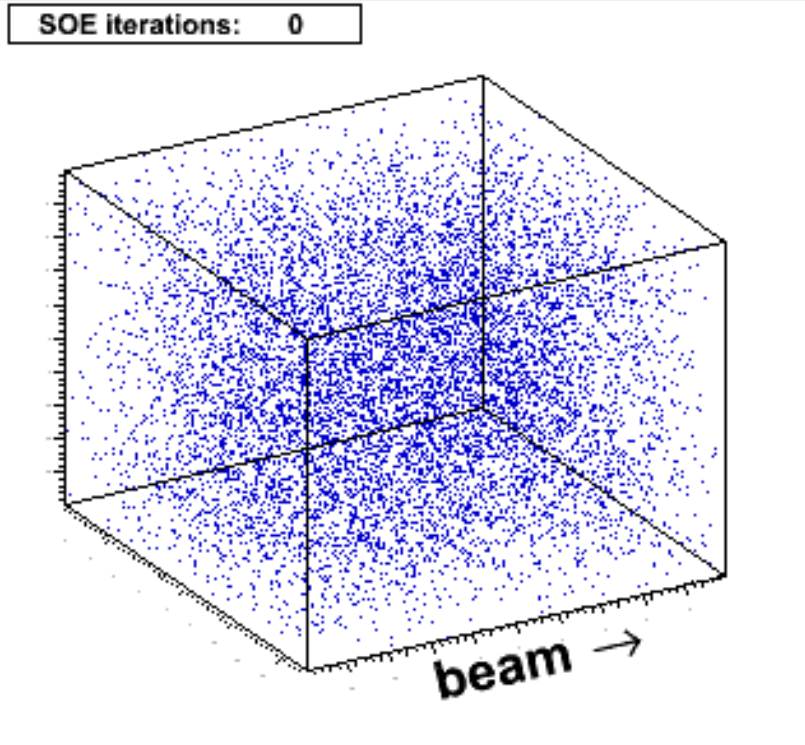


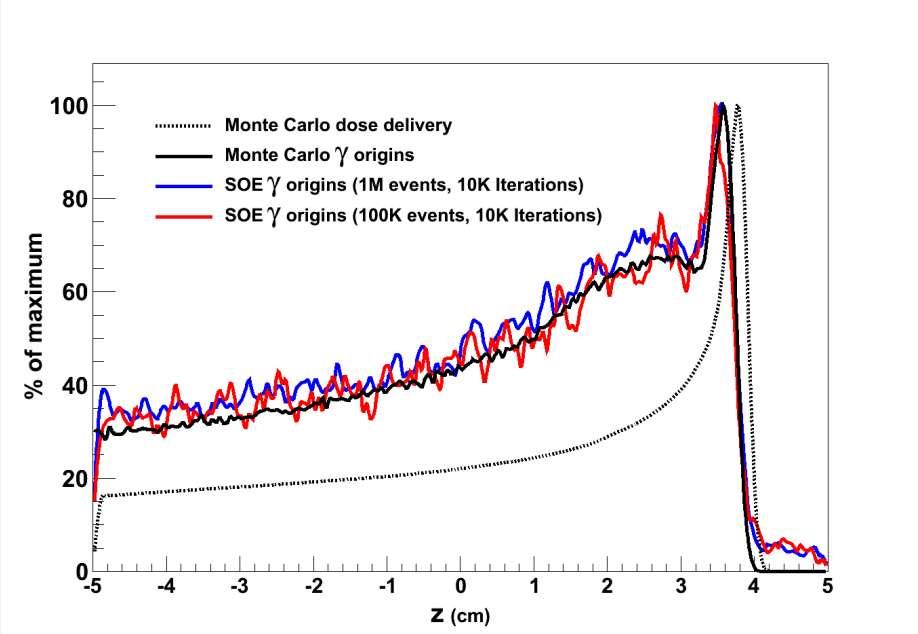
Mackin et al, Phys. Med. Biol., ***57****:3537-3553 (2012).*

Prompt Gamma range verification

Compton Camera

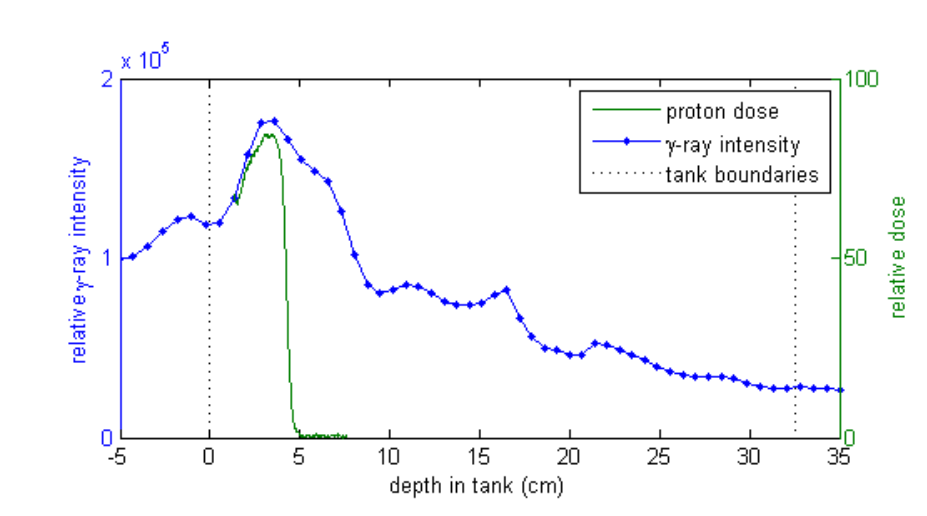
Iterative reconstruction of 3D image of PG emission

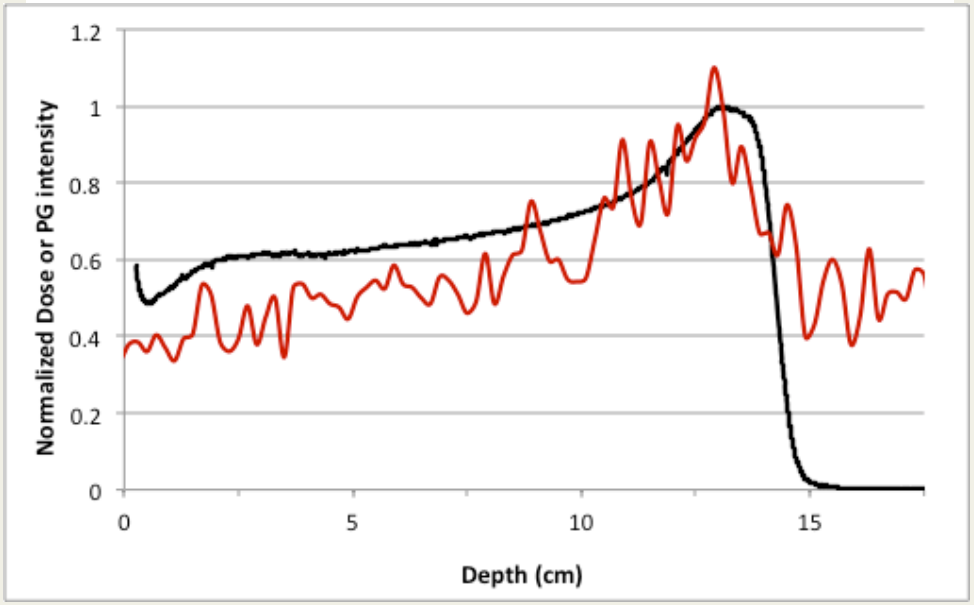


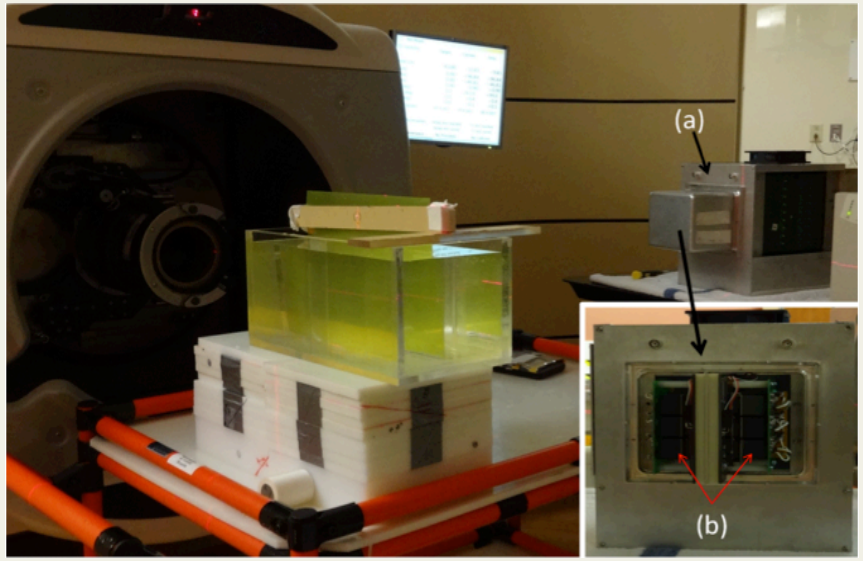


Mackin et al, Phys. Med. Biol., ***57****:3537-3553 (2012).*

Prompt Gamma range verification



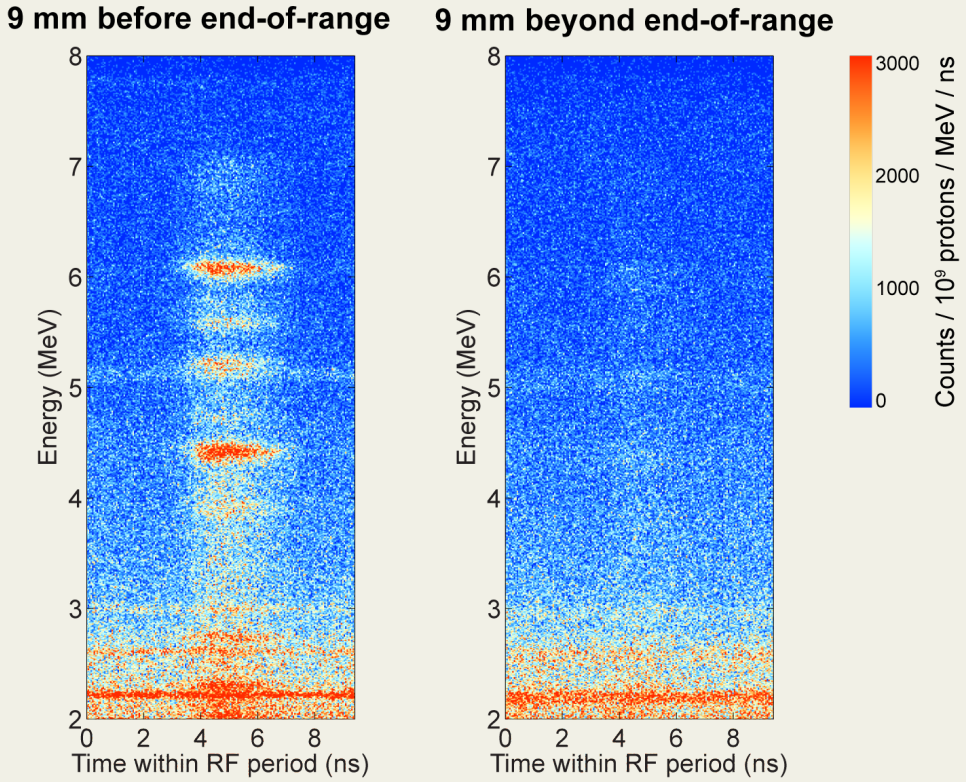




Reconstructed images from PG emission
Measured with prototype Compton camera

Prompt Gamma range verification

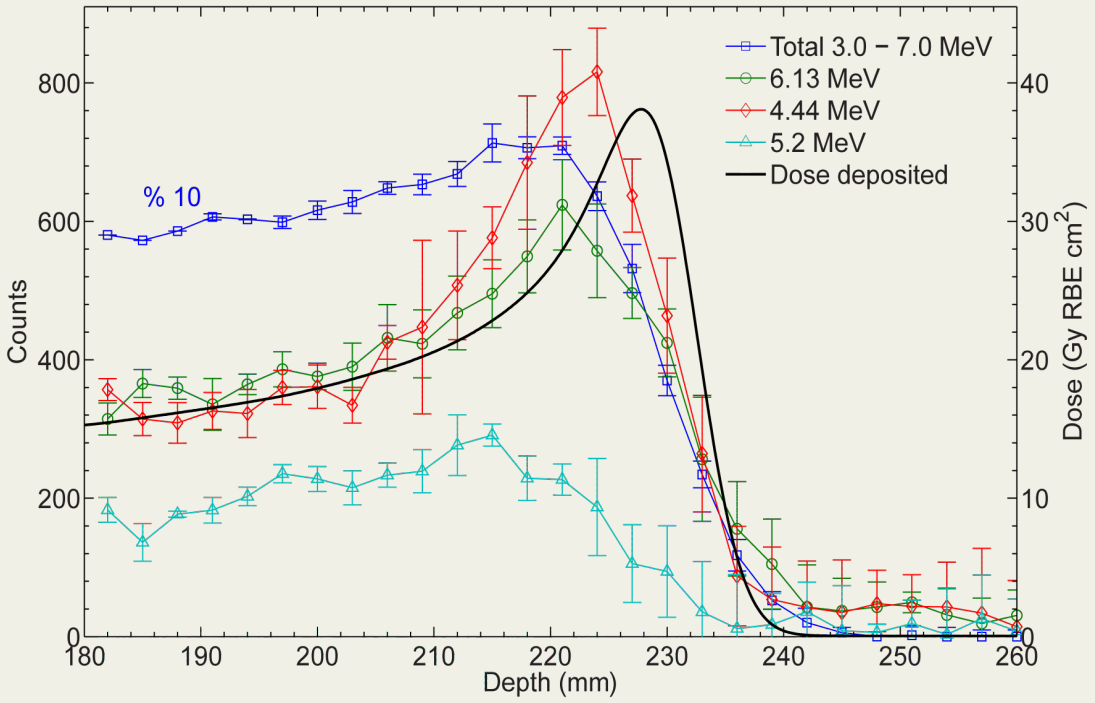
Energy- and time-resolved gamma detection



Prompt gamma spectra before
And after the Bragg peak show
Measureable differences.

Courtesy of: Joost Verburg, Kent Riley, Thomas Bortfeld, Joao Seco,
Massachusetts General Hospital and Harvard Medical School

Prompt Gamma range verification



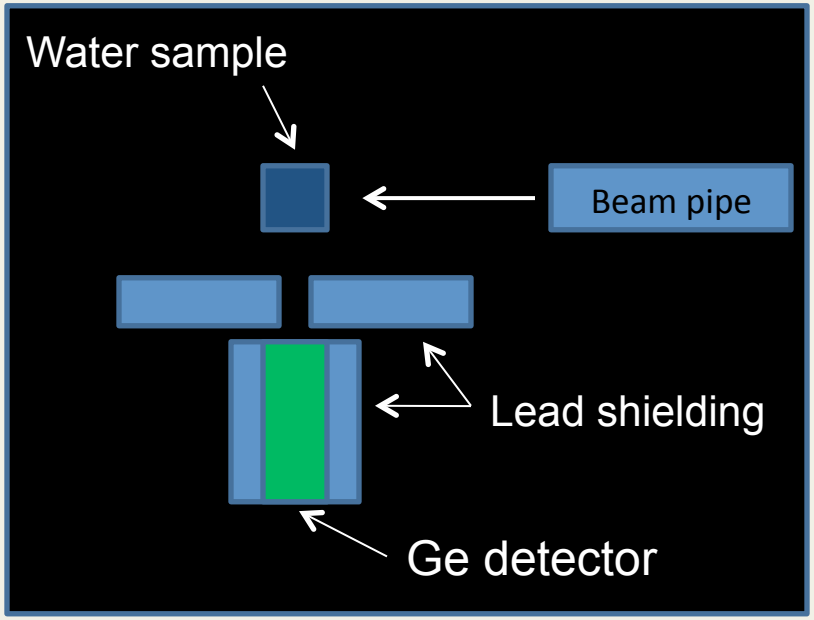
Using energy and time resolved measurement of PG:

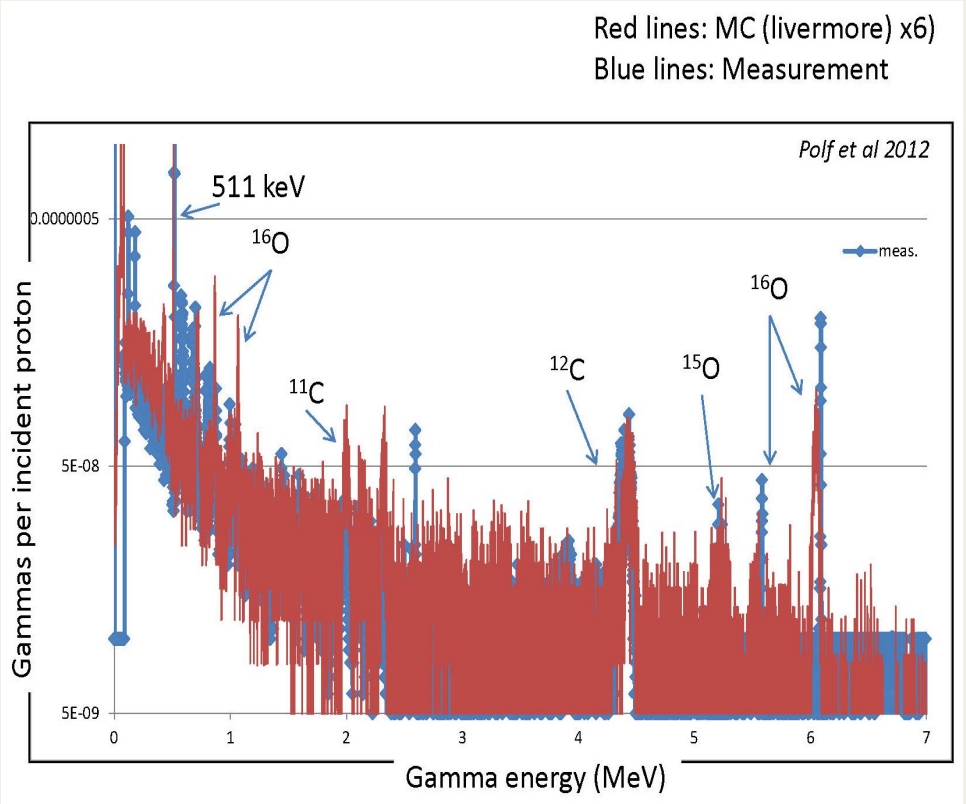
- Can measure PG depth profile from individual elemental PG emission.

Courtesy of: Joost Verburg, Kent Riley, Thomas Bortfeld, Joao Seco,
Massachusetts General Hospital and Harvard Medical School

Prompt gamma spectroscopy

- Measurements (symbols)
- 40 MeV proton beam, ~2 Gy dose





Polf et al, *Phys. med. Biol.*, **54**:N519-N527, (2009)

Prompt gamma spectroscopy

Determination of elemental composition from PG spectra

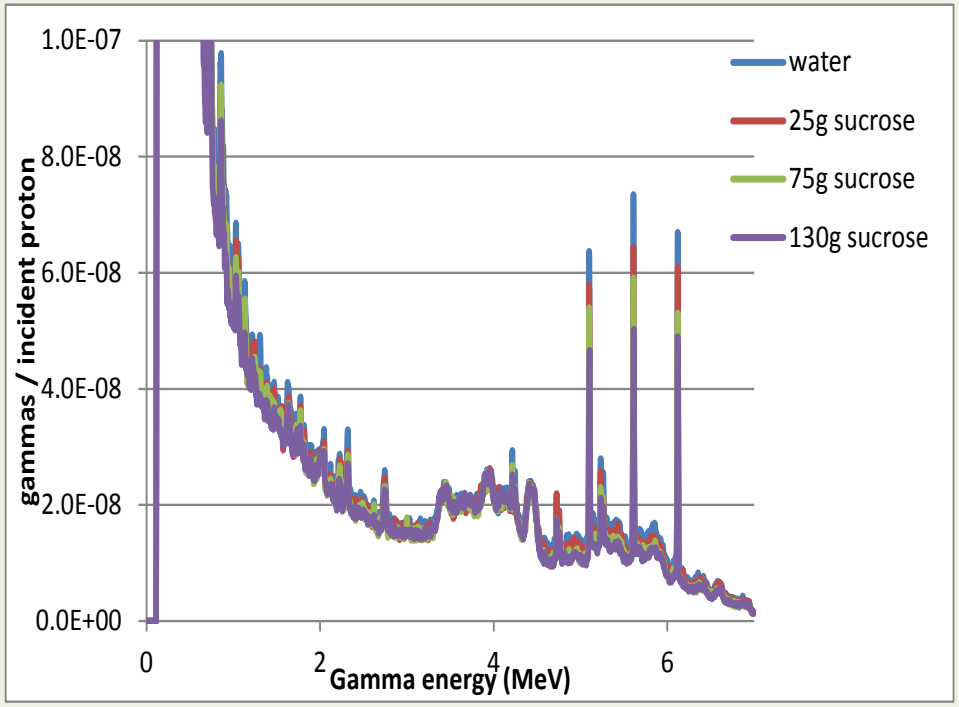
Mixed up samples of water + sugar with 25g, 75g, and 130g of sugar added to 130 g of water. The phantom (130 cc) was then filled with the water+sugar solution.

Table 1. Composition and density of the water-sucrose samples used in our study and of several human tissues with similar composition and density (ICRU 1992).

sample	water (g)	sucrose (g)	density (g/cm^3)	composition (% by mass) oxygen	carbon	hydrogen
1	130	0	1	88.9	0	11.1
2	114.7	22	1.05	82.7	6.9	10.4
3	89.7	52.3	1.1	75.2	15.4	9.4
4	78.6	78.6	1.21	70.2	21.1	8.7
Brain			1.04	71.2	14.5	10.7
Heart			1.05	71.8	13.9	10.4
Liver			1.06	71.6	13.9	10.2
Muscle			1.05	71	14.3	10.2

Polf et al., *Phys. Med. Biol.*, **58**: in press (2013).

Prompt gamma spectroscopy



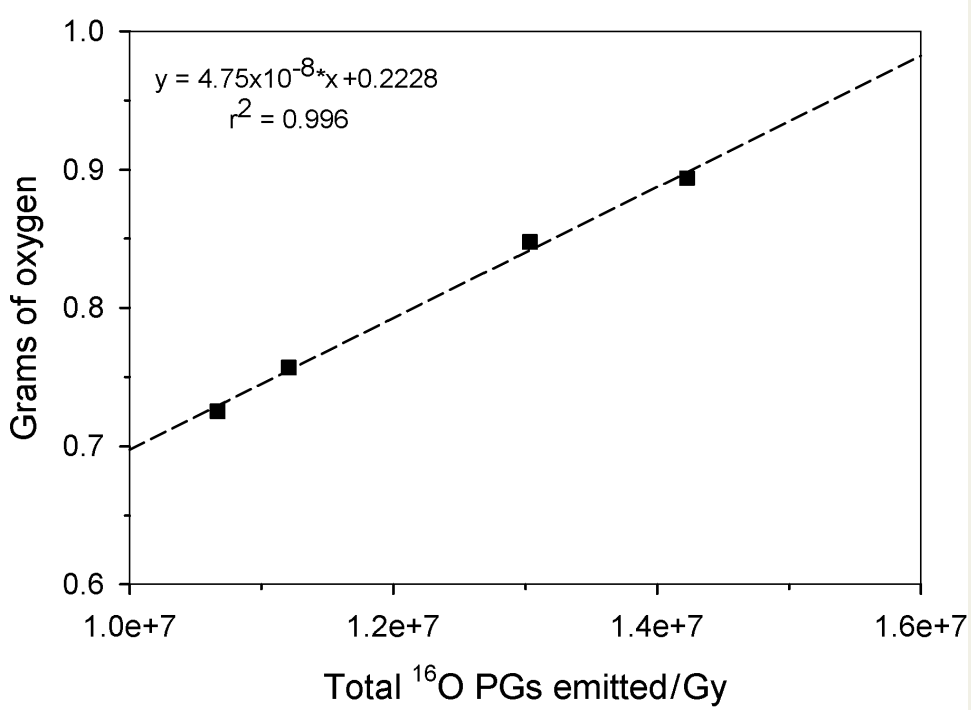
Irradiated samples with proton beam,
And measured PG spectra.

As carbon increased (oxygen decreased):

- 6.13 MeV 16O PG emission decreased
- 5.21 MeV 16O PG emission decreased

- 4.44 MeV 12C PG emission remained constant.

Prompt gamma spectroscopy



From emitted 16O PGs emitted:

- Calibrated #PGs / gram of oxygen
- 1.64 x 10^7 PGs/gram of oxygen/Gy

Polf et al., *Phys. Med. Biol.*, **58**: in press (2013).

- By measuring PG emission, may be possible to determine concentration of oxygen in irradiated volume of tissue.

Conclusions

- PG emission correlates well to Bragg peak
  - total PG and elemental PG
- Measuring 1-2 mm shift in BP position may be possible
- Elemental PG intensity proportional to concentration in irradiated tissue.

How to get to the clinic

- Experimental detectors need to be further developed into clinical systems
- Robust method to determine BP shift from PG emission profile
- Fast method to reconstruct image and overlay onto patient CT data for “real-time” evaluation.