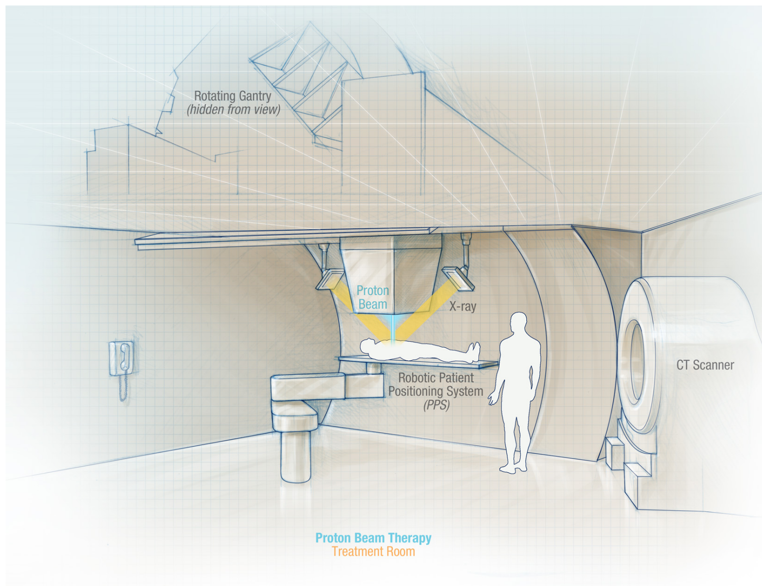
In-vivo range measurement of therapeutic protons from prompt gamma emission



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Outline

- Mayo Clinic and ASU
- Scanning with Pencil Proton Beams
- In-vivo Prompt Gamma Emission
- Detector Development (MCNP) and Results
- Summary and Outlook

High Level PBT - Timeline

Facility	Contract Effective Date	Facility Readiness Date	Guaranteed Phase I Completion	Guaranteed Phase II Completion	Guaranteed Phase III Completion
Rochester	5/1/2011	6/1/2013	3/1/2015	9/1/2015	3/1/2016
Phoenix	5/1/2011	3/1/2014	12/1/2015	6/1/2016	12/1/2016

Rochester:

Construction – Substantially Complete
9/1/2011 to 12/19/2013

6/1/2015 – Patient Treatments Initiated

Mayo Physics
3/1/15 to 6/1/15

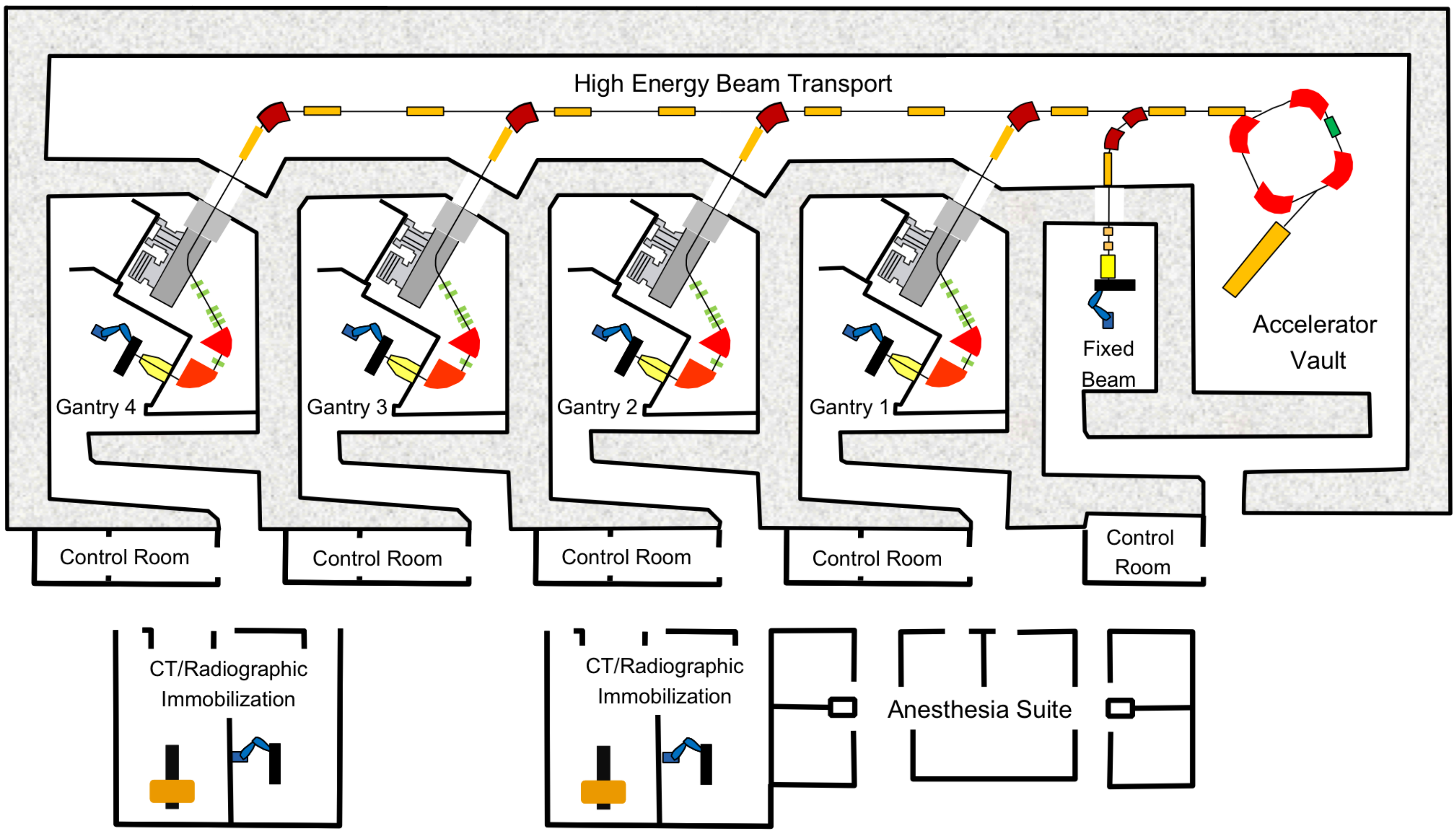
Phoenix:

Construction – Substantially Complete
12/1/2011 to 8/1/2014

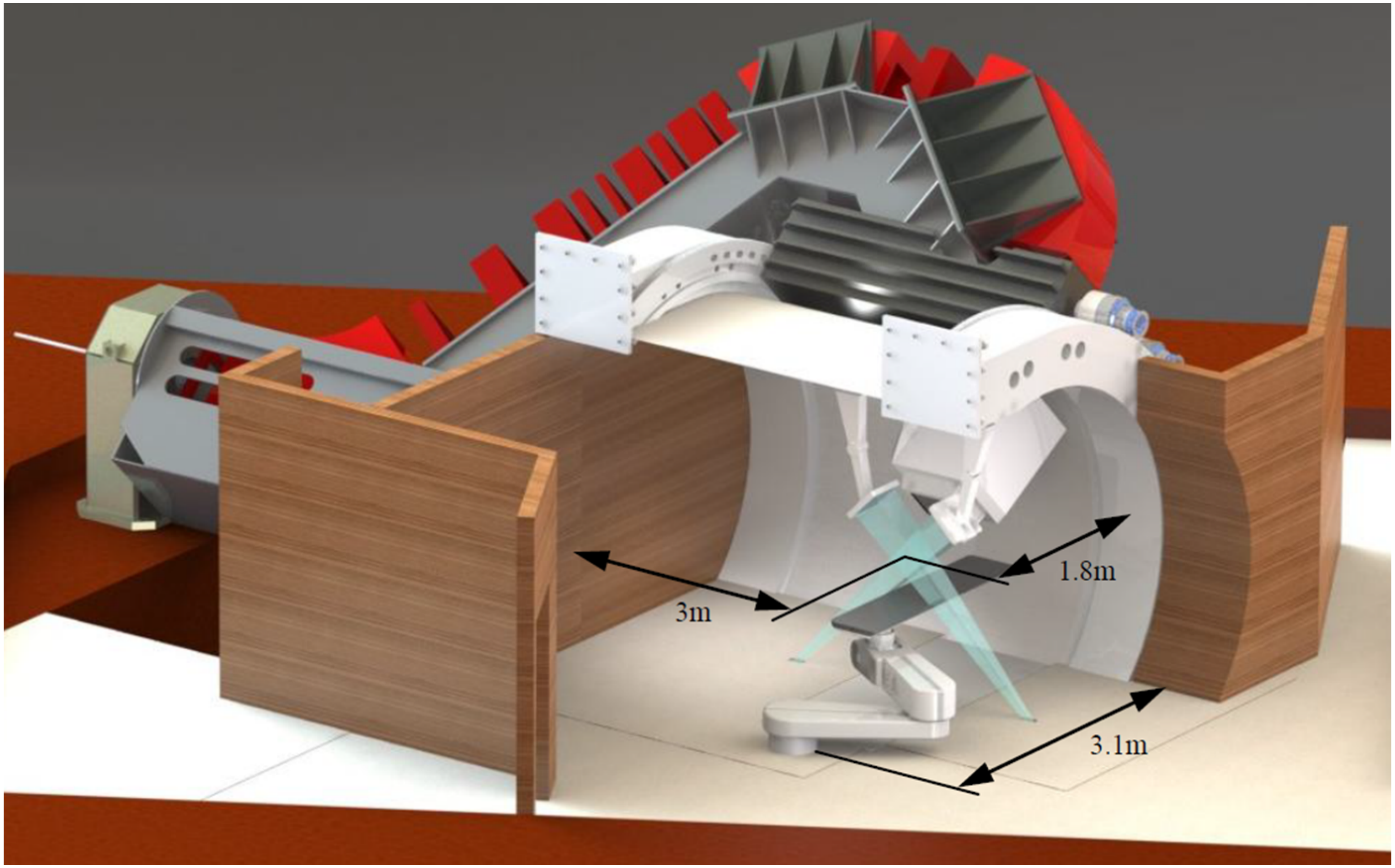
3/1/2016 – Patient Treatments Initiated

Mayo Physics
12/1/15 to 3/1/16

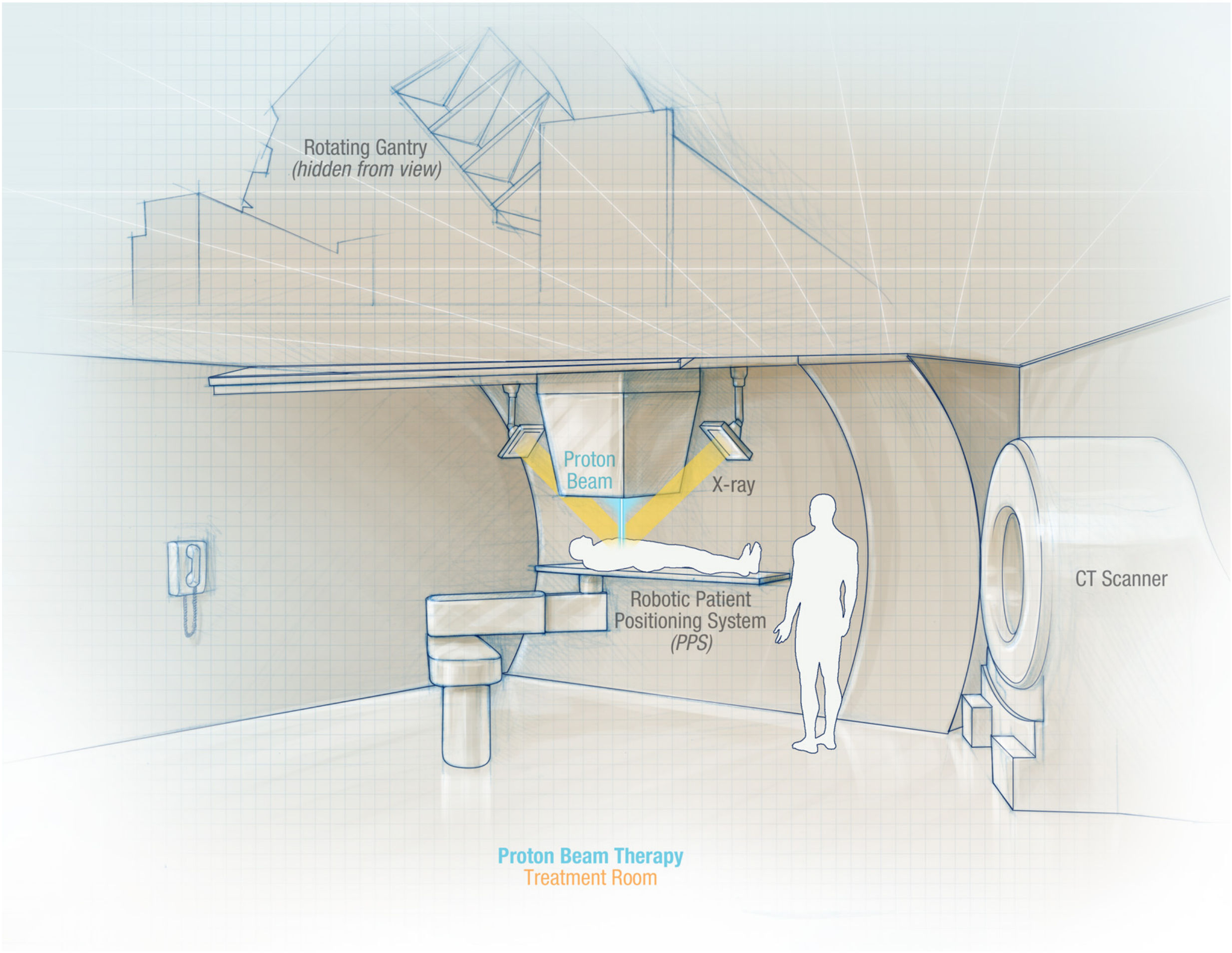
Facility Layout



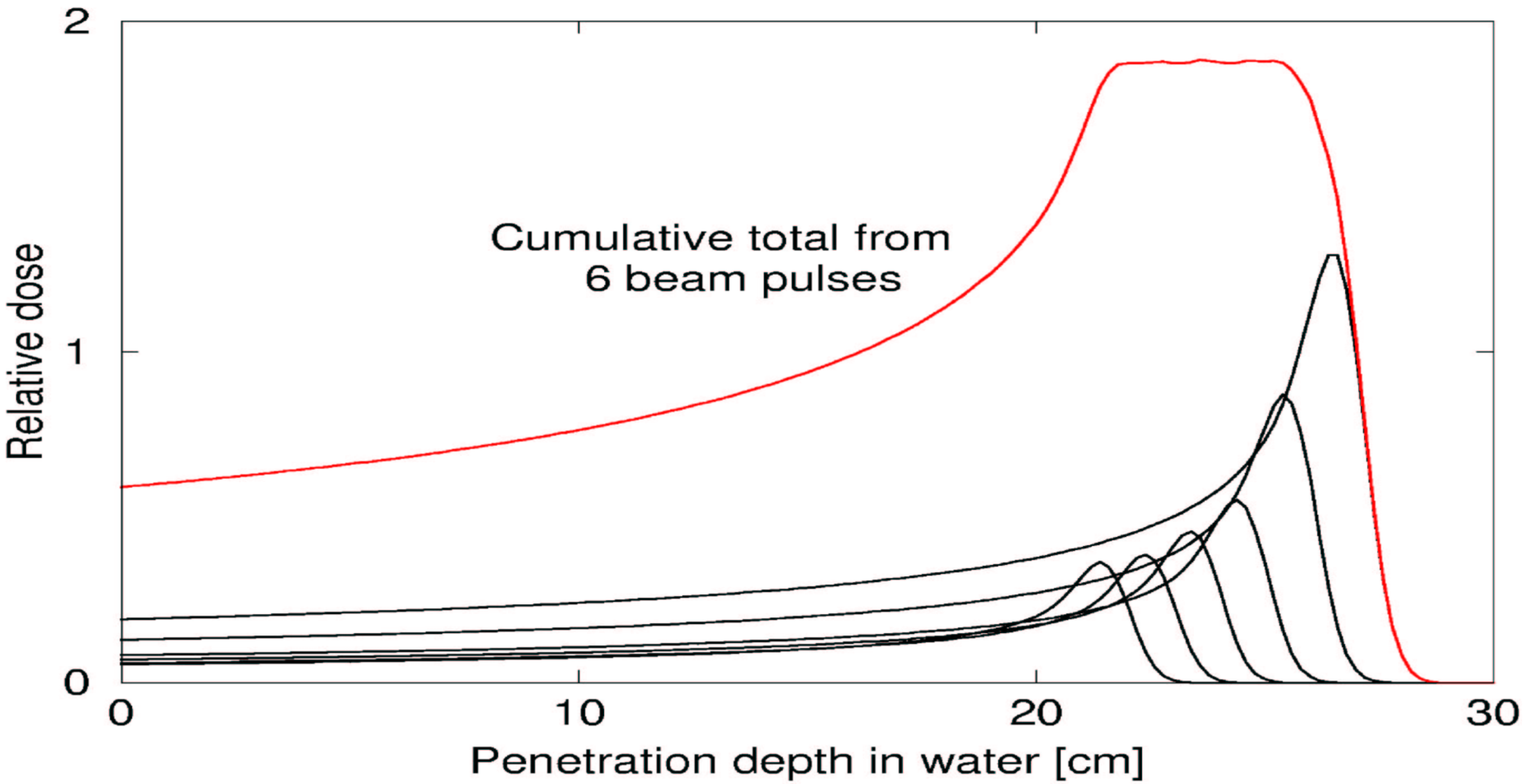
Treatment room



Treatment room (cont.)



Spread out Bragg peak



In-vivo Measurement of Prompt Gamma Rays

- During proton interactions with atoms in tissues, gamma rays, including prompt photons from nuclear reactions and delayed photons from the decay of unstable products, are emitted.

- The rate of secondary radiation used in the measurement is low, making accurate measurement challenging. Typically, 10^3-10^4 photons per beam spot.

- This project involves the development of clinically adaptable, state-of-the-art photon detectors with fast imaging capabilities, with the ultimate goal of tailoring personalized treatment plans on the basis of gamma images:

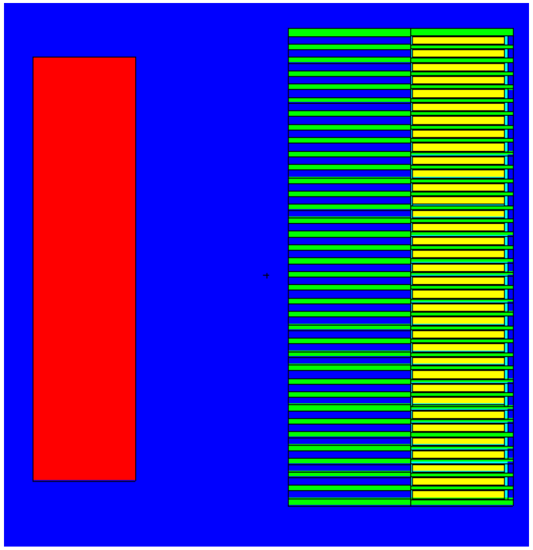
    - Determine location of distal edge within a few mm per each beam spot

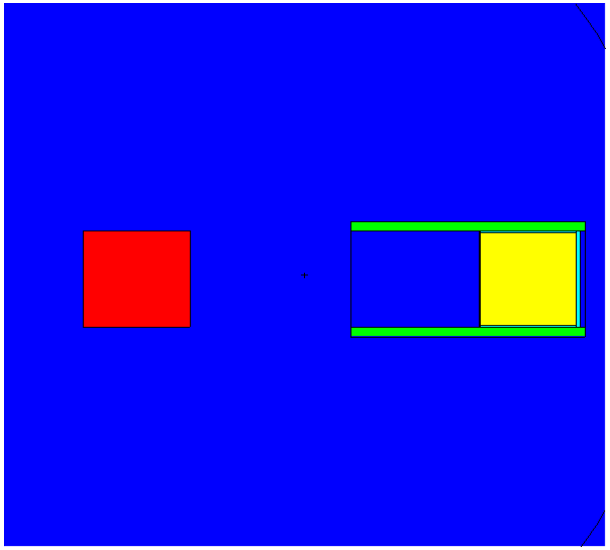
    - Device has to be mechanically versatile (weight, volume, etc.), easy to operate by non- physicists

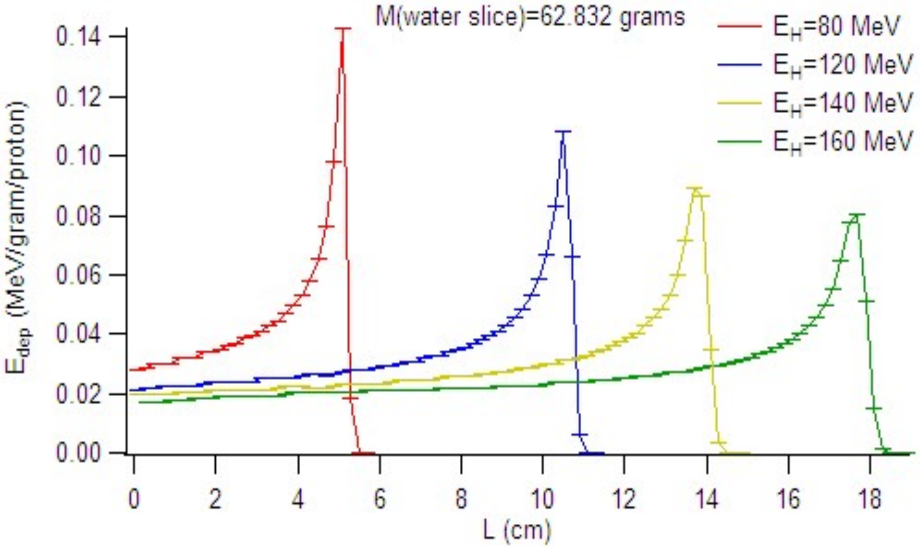
    - Device has to be an integral part of the patient Quality Assurance (QA)

Feasibility Study: MCNP Model

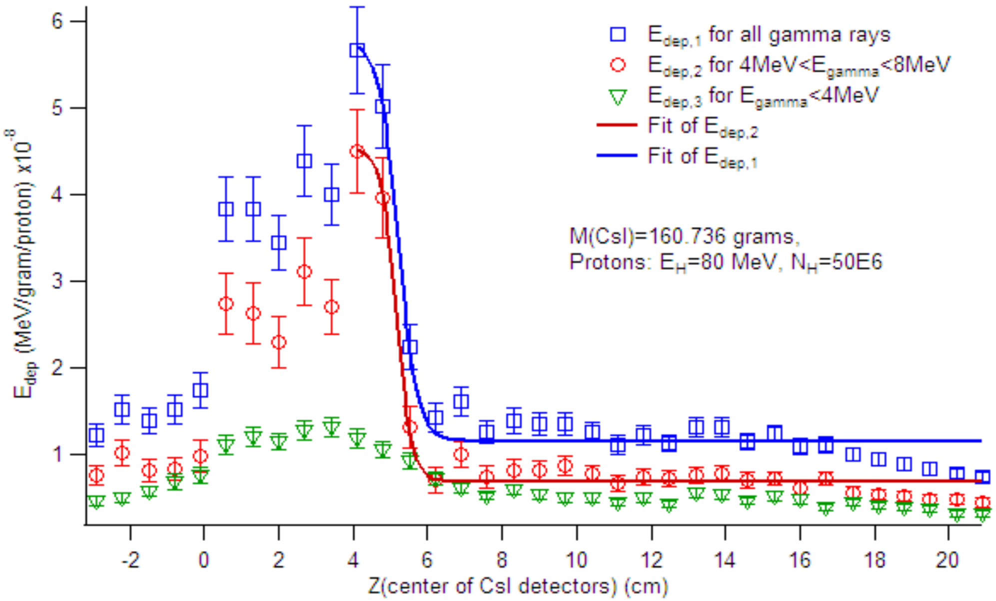
- Array of thin CsI crystals (0.3-0.4 cm), each separated by Pb collimator plates (C. H. Min et al. (Med. Phys. 39 (4), 2012)







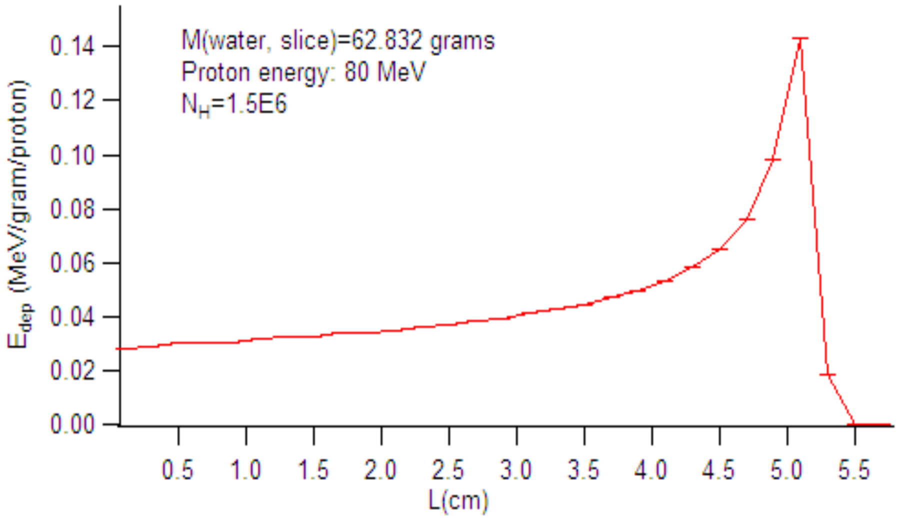
Distal edge calculations for 80 MeV protons



Distance between proton beam axis and Pb collimator: **20 cm**

Bragg peak position from gamma ray yield in CsI detectors:
W_2=5.35 ± 0.19 cm

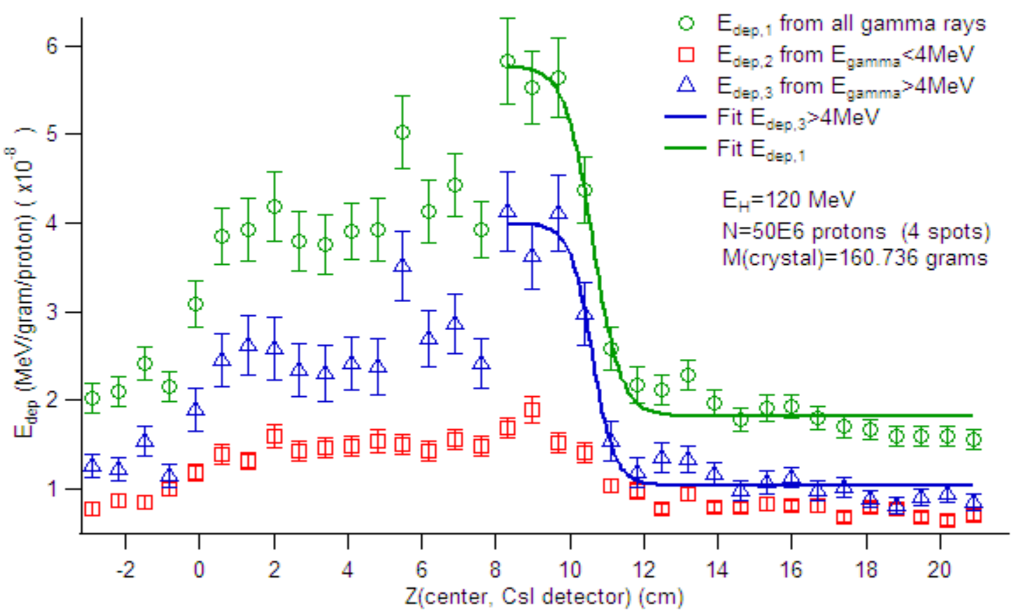
Energy deposited all detected gammas (blue) and with E<4MeV (green) and E>4MeV(red).



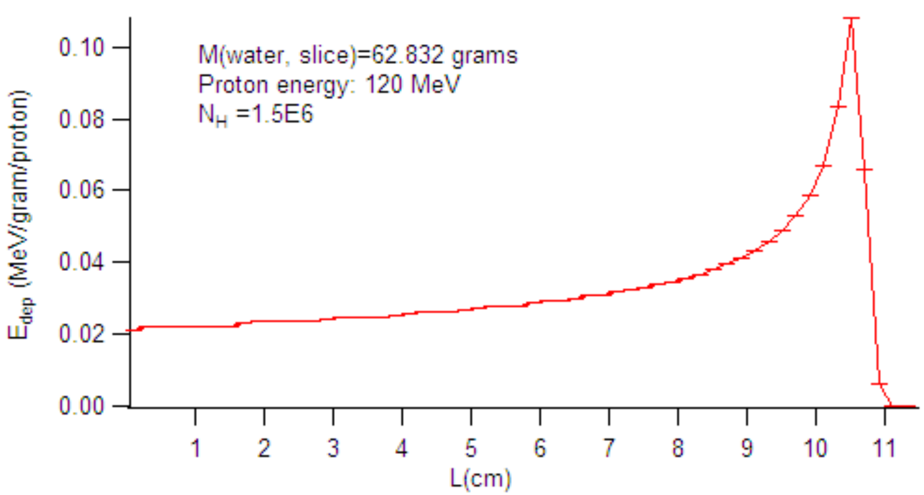
Bragg peak position
L_B=5.3 ± 0.2 cm

Energy deposited in water is calculated for 0.4 cm thick slices of water.

Distal edge calculations for 120 MeV



The estimated distal edge from gamma ray yield in CsI detectors:
W_2=10.57 ± 0.19 cm



Bragg peak position:
L_B=10.6 ± 0.2 cm

Preliminary Conclusions

- The model originally proposed by C. H. Min et al. (Med. Phys. 39 (4), 2012) works reasonably well to track the distal edge with a few mm accuracy. It can be used as a benchmark for further studies.

- In addition we have studied: i) the effect of a water phantom with $Ca_3(PO_4)_2$ (bone-like cells) and ii) different misalignment beam angles (± 5°)

- We decided to converge on the following parameters:

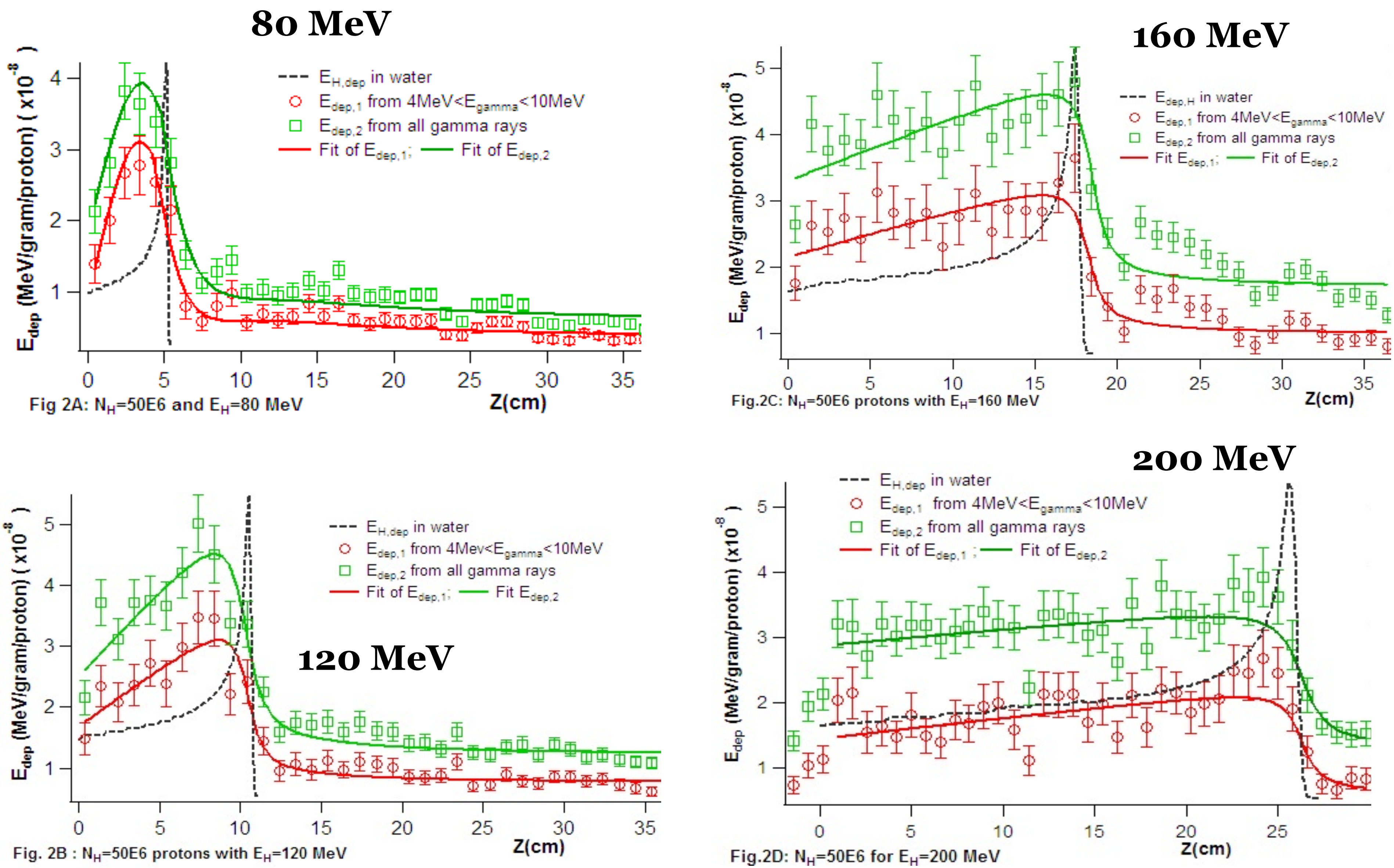
  - Distance from beam direction to entrance collimator: 40 cm

  - Crystals dimensions: 7.5 cm tall, 0.46 cm thick, and 9 cm deep

  - Use an array of 37 crystals

  - Pb collimator: 12 cm long, 9 cm tall and 0.2 cm thick

- Developed a fitting procedure for the entire array



The gamma ray energy deposited in each CsI crystal, for 80, 120, 160 and 200 MeV protons, and 5×10^7 protons. The distance between the proton axis and the lead collimator plates is 40 cm.

Fitting Results

E_H (MeV)	Y_0 10^{-8}	A 10^{-8}	B 10^{-8}	Z_0 cm	Z_B cm
80	2.41±0.21	-1.28±0.14	-0.48±0.11	5.11 ± 0.21	5.15 ± 0.05
100	1.87±0.12	-0.70±0.08	-0.13±0.04	7.96 ± 0.24	7.55 ± 0.05
120	3.34±0.16	-1.35±0.10	-0.22±0.04	10.4 ± 0.22	10.50 ± 0.05
160	2.24±0.11	-0.80±0.07	-0.06±0.02	18.18 ± 0.30	17.40 ± 0.05
200	1.44±0.08	-0.55±0.06	-0.26±0.07	26.27 ± 0.38	25.65 ± 0.05

E_H (MeV)	Y_0 10^{-8}	A 10^{-8}	B 10^{-8}	Z_0 cm	Z_B cm
80	3.44 ±0.24	-1.79±0.16	-0.82 ±0.15	5.07 ± 0.18	5.15 ± 0.05
100	1.89 ±0.12	-0.72±0.08	-0.18 ±0.05	7.89 ± 0.28	7.55 ± 0.05
120	3.45 ±0.17	-1.43±0.11	-0.30 ±0.05	10.22 ± 0.22	10.50 ± 0.05
160	3.46 ±0.13	-1.15±0.08	-0.10 ±0.02	18.38 ± 0.24	17.40 ± 0.05
200	2.42 ±0.10	-0.75±0.07	-0.03 ±0.01	26.29 ± 0.36	25.65 ± 0.05

Summary and Outlook

- The array of thin CsI crystals separated by thin Pb collimators is a simple device that can be used to measure the distal edge of the Bragg peak for each proton beam spot with a few mm accuracy.

- The two steps non-linear fit can be done automatically for each energy of the proton beam and for each beam spot if the number of protons incident in the spot is at least 1.5×10^7.

- Additional sources of errors are electronic noise and gamma rays from neutron capture and proton scattering in the beam nozzle.

- Future work:
    - Additional segmentation, different crystals
    - Position sensitive detectors (pulse signal analysis)
    - Compton camera (DSSSD + LaBr3 crystals read by position PMTs; NF089, INPC2013)

A proton plane for prostate treatment delivered with a pencil beam raster scanning

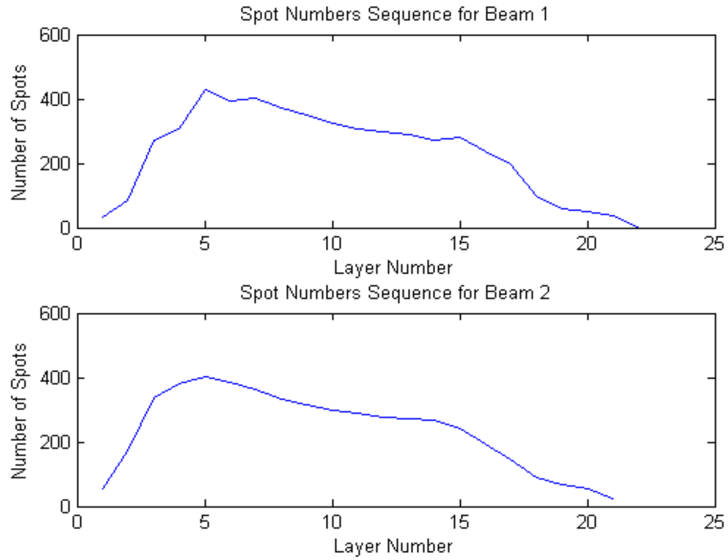


Fig.2: The number of spots in each layer for two beams

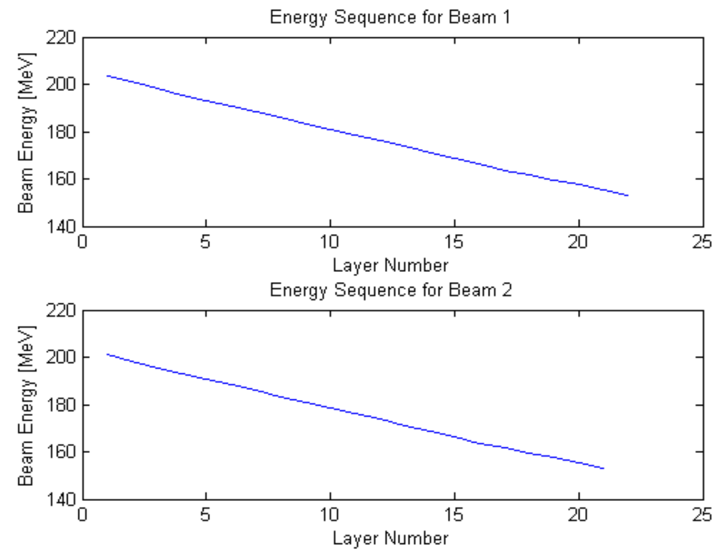


Fig.3: The energy sequence for two beams.

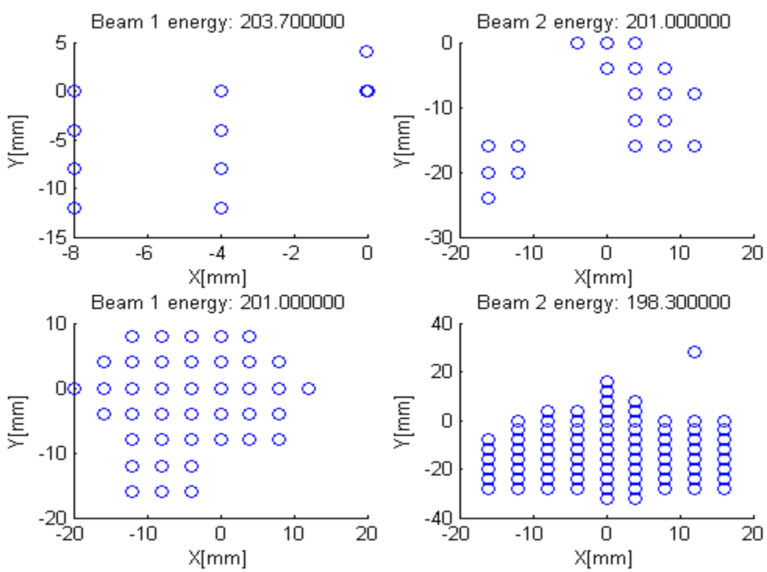


Fig.4: The spot distribution for two beams, each with two proton energies (two layers).

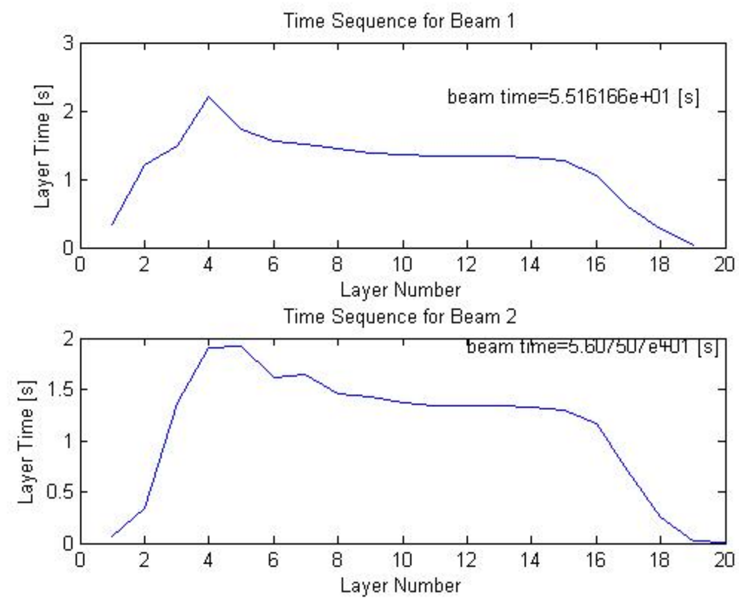


Fig.5: The number of spots in each layers for the two beams.