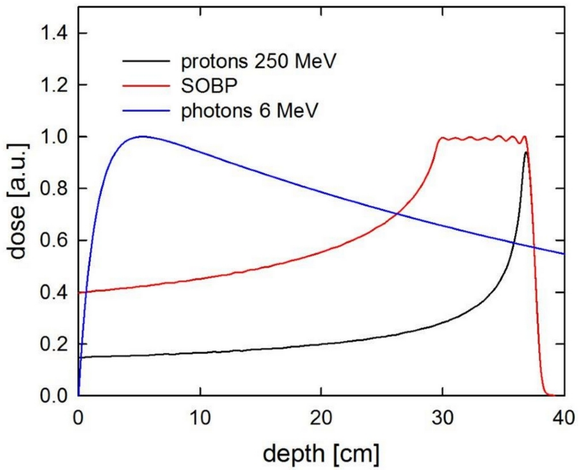
J-PET for range monitoring in proton therapy: a feasibility study using GATE

Karol Brzezinski, Damian Borys, Jan Gajewski, Antoni Rucinski
And on behalf of the J-PET collaboration

Opengate scientific meeting, November 18th, 2021

PET for range monitoring in proton therapy

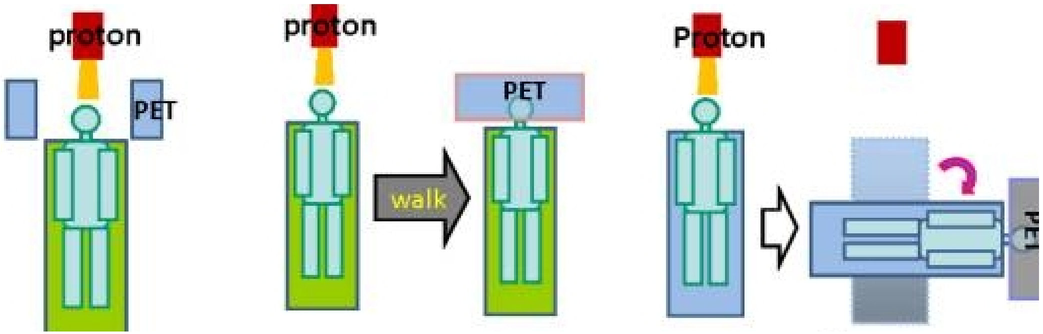


Protons therapy:

- Less dose to normal tissue
  - Tumor dose escalation
  - Organ at risk (OAR) dose reduction
- More sensitive to deviations
  - Ion range uncertainties
  - Day-to-day variations in patient position
  - Anatomical changes in the patient
- *In vivo* range verification
  - Positron emission tomography (PET)

Main PET nuclei produced in patient tissue by the proton beam

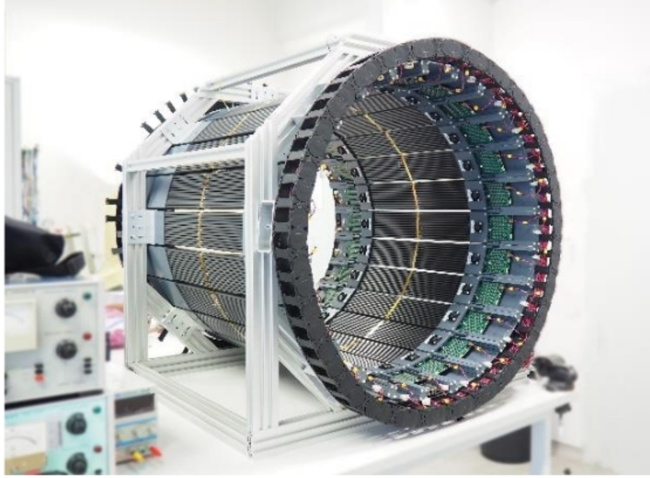
nucleus	$T_{1/2}$	E^{β}_{max} (MeV)	reaction
^{15}O	2.04 min	1.73	$^{16}O(p,pn)^{15}O$
^{14}O	70.6 sec	1.8	$^{16}O(p,p2n)^{14}O$
^{13}N	9.97 min	1.2	$^{16}O(p,\alpha)^{13}N$
			$^{16}O(p,2p2n)^{13}N$
			$^{14}N(p,pn)^{13}N$
^{11}C	20.4 min	0.96	$^{12}C(p,pn)^{11}C$
			$^{14}N(p,\alpha)^{11}C$
			$^{14}N(p,2p2n)^{11}C$
			$^{16}O(p,\alpha pn)^{11}C$
			$^{16}O(p,3p3n)^{11}C$
^{10}C	19.3 sec	1.9	$^{12}C(p,p2n)^{10}C$
^{30}P	2.5 min	3.21	$^{31}P(p,pn)^{30}P$
^{38g}K	7.64 min	2.72	$^{40}Ca(p,2pn)^{38g}K$



From: Zhu and El Fakhri (2013) *Theranostics* 3 (10)

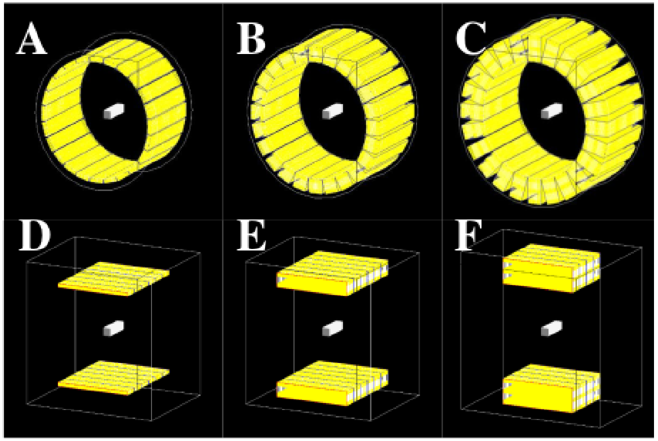
J-PET for range monitoring in proton therapy

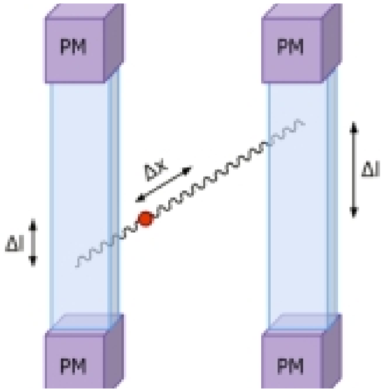
PET based on plastic scintillators



- Cheap, light, portable, easy to reconfigure
- 24 modules
- Each with 13 single plastic strips (5x24x500 mm^3)
- Compton instead of photoelectric absorption

A. Single layer barrel – 24 modules
B. Double layer barrel – 48 modules
C. Triple layer barrel – 72 modules
D. Single layer dual-head – 12 modules
E. Double layer dual-head – 24 modules
F. Triple layer dual-head – 24 modules





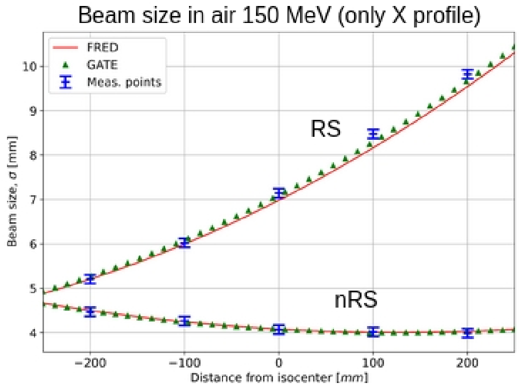
TOF for z position in strip

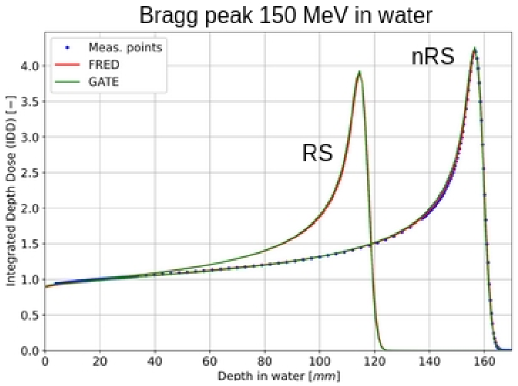
J-PET

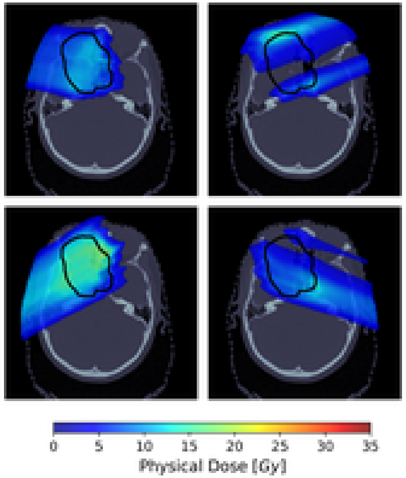
Patient data and beam model from CCB proton facility

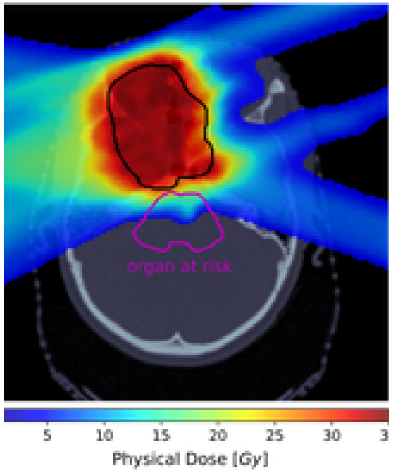
- Validated beam model in GATE
- Patient database with a range tumor sites and volumes
  - 95 head & neck + brain patients treated at CBB with IMPT
    - 2 - 6 fields per patient
    - Target volumes: 10-1000 cm^3
    - From 300 to 12000 pencil beams per field
    - From 2E9 to 7.5E10 primary protons per field
  - Treatment plans
  - CT 3D images

Cyclotron Centre Bronowice









2-stage GATE simulations using patient data

1st stage

Patient irradiation and β+ production

- ^{15}O, ^{14}O, ^{10}C, ^{11}C, ^{30}P, ^{13}N, ^{38g}K
- Treatment plans (multiple fields)
- Phantom from CT
  - Cropped & rebinned to 2.5mm
  - HU to material definitions
- Introduce shifts of HU (+/- 2%) and patient position (+/-2,4 mm) in x, y, z
- Output: production maps of positron-emitting isotopes

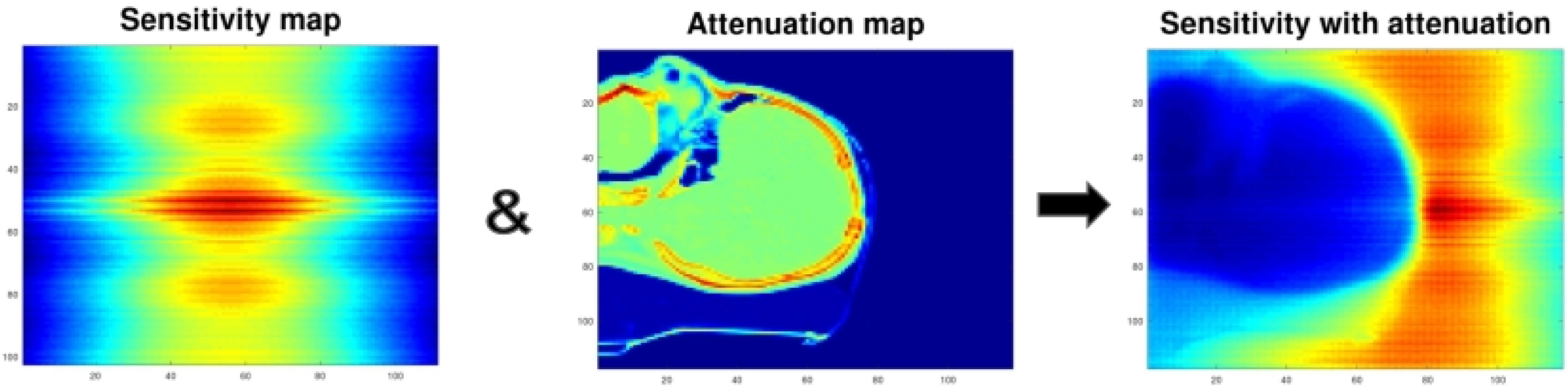
2nd stage

PET acquisition

- J-PET geometries
- Phantom from CT
- Treatment isocentre z-component to scanner axial centre
- Activity source calculated from production maps of positron-emitting isotopes
- Positron energy spectra defined for each isotope

Image reconstruction

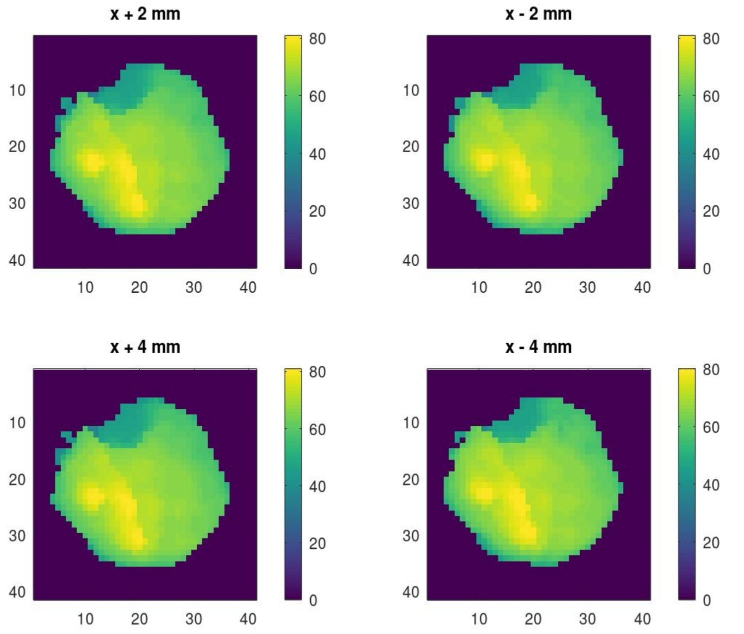
- Iterative methods implemented in CASToR
- Sensitivity map with patient attenuation included
    1. Simulation of homogeneous activity filling the PET FOV
    2. Calculation of attenuation map from CT and position at z-isocentre
    3. Backprojection of acquired coincidence data through attenuation map
- Post-reconstruction smoothing (Gaussian with sigma = 1 voxel)
- Stopping criteria: Iteration minimizing NRMSD with emission map



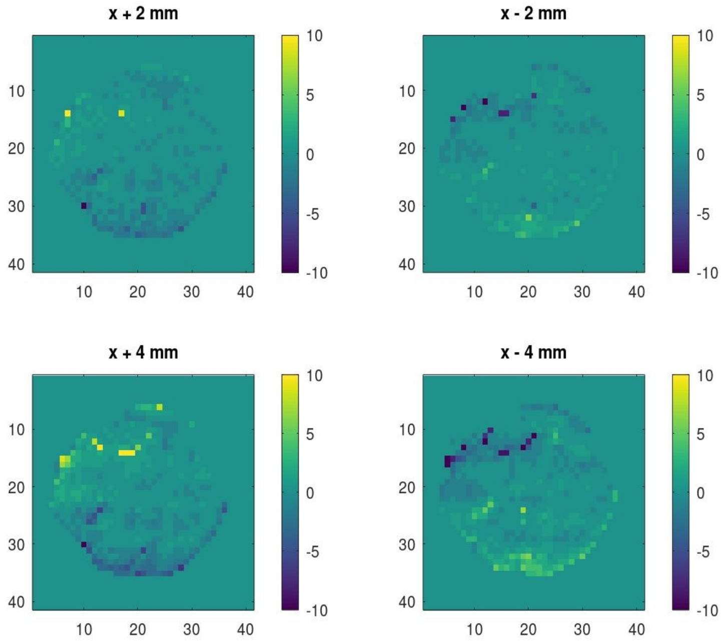
Range measurements

Difficult due to activity from overlapping fields → concentrate on last field

- Compare beam's-eye-view 2D maps of range shifts in **dose** and **PET activity** distributions (PET images). Is a shift in **dose** reflected the **PET images**?



Dose range map in BEV (at 70-80% of max)



Dose range shift map in BEV

Implementation

- Workflow is scripted automatized
- Run split Gate simulation using SLURM queue system
- Computer cluster “Ziemowit” (Silesian Univ. of Technology, Gliwice) www.ziemowit.hpc.polsl.pl
  - 80 ibm nodes (12cores/node, min. 36GB RAM) - old CPU (intel x5650) - in total 960 cores
  - 28 quanta nodes (20cores/node, 256GB RAM) - newer CPU (intel E5-2660v3) - in total 560 cores

Silesian University of Technology

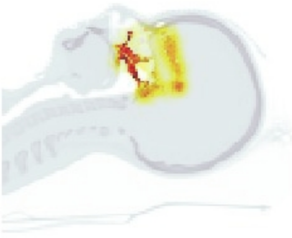
- 1st stage simulations
  - Ibm node performance : ~ 355 Primary per sec (PPS)
  - Quanta node performance : ~650 PPS (no HT)
  - One field from one patient takes several hours (quite slow)
  - May transition to FRED

Acknowledgments

Keegan McNamara, Damien C. Weber, Antony Lomax, and Carla Winterhalter

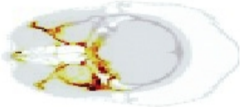
from Paul Scherrer Institute

Isotope production maps

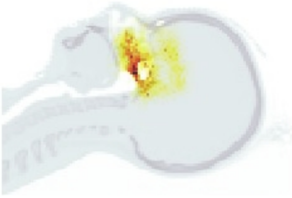
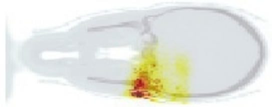


^{15}O, produced on oxygen



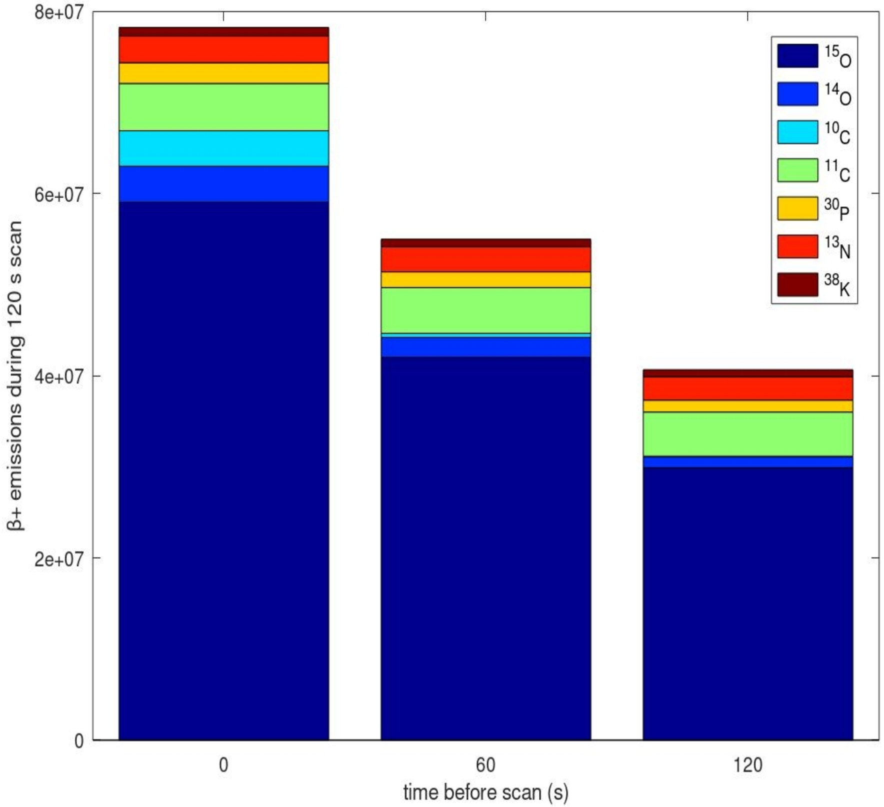


^{30}P, produced on phosphorus

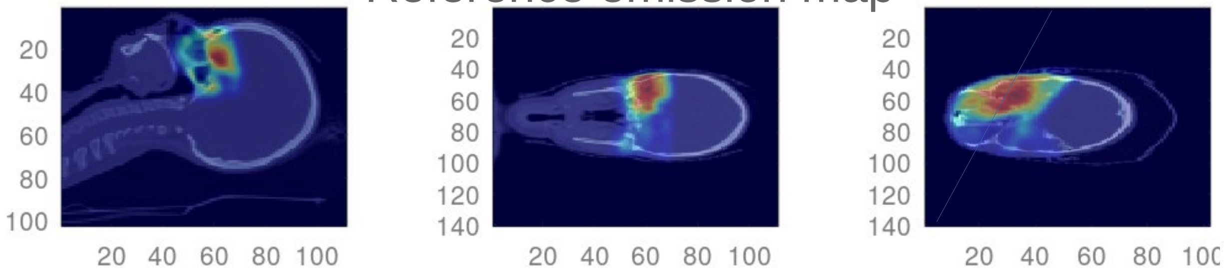

^{10}C, produced on carbon

Total β+ contribution from individual isotopes during 120s scan

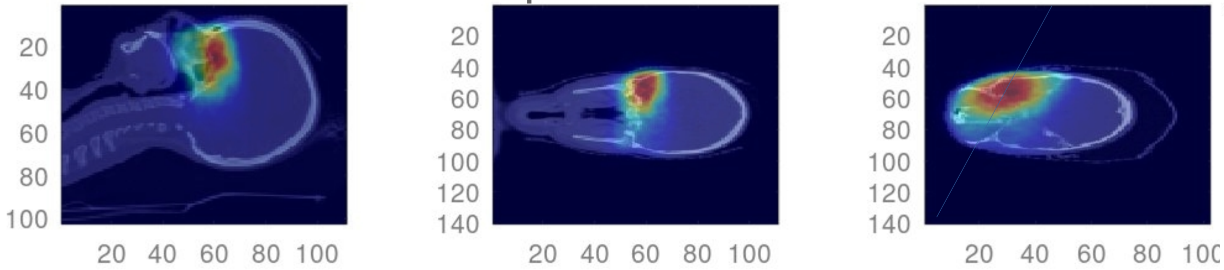


Preliminary results for HU variation

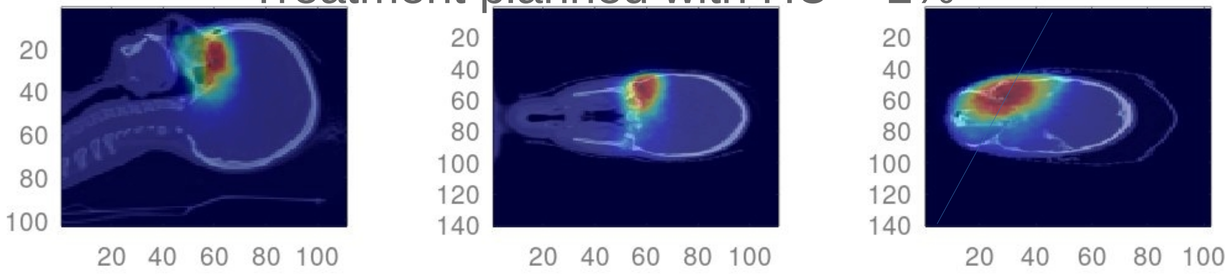
Reference emission map

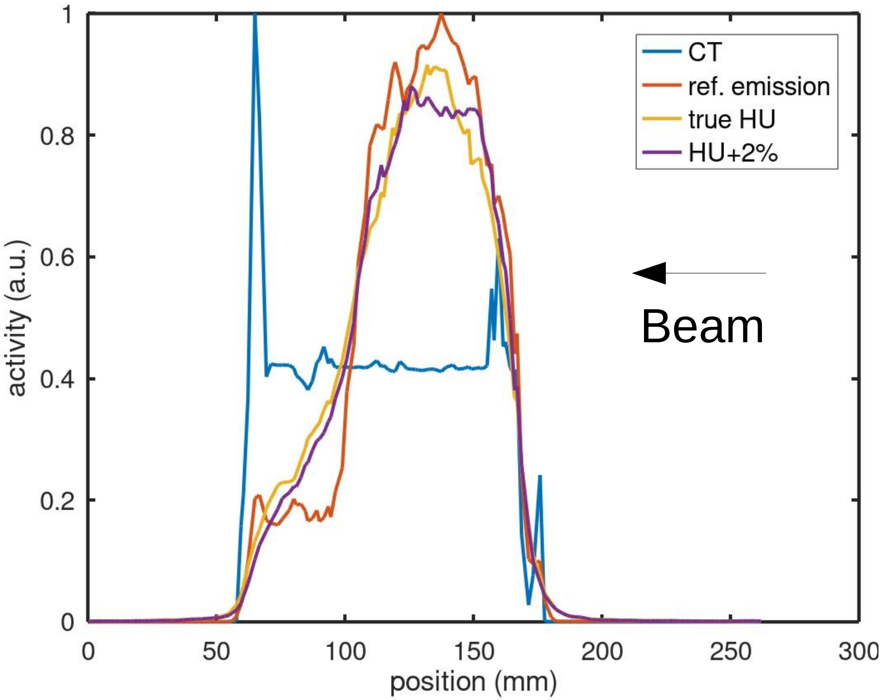


Treatment planned with true HU



Treatment planned with HU - 2%





Next step: Quantify range shift over all patients, protocols and shifts