9th Annual Loma Linda Workshop on Particle Imaging and Radiation Treatment Planning

Range Guided Treatment Planning with Mixed Carbon – Helium Beams

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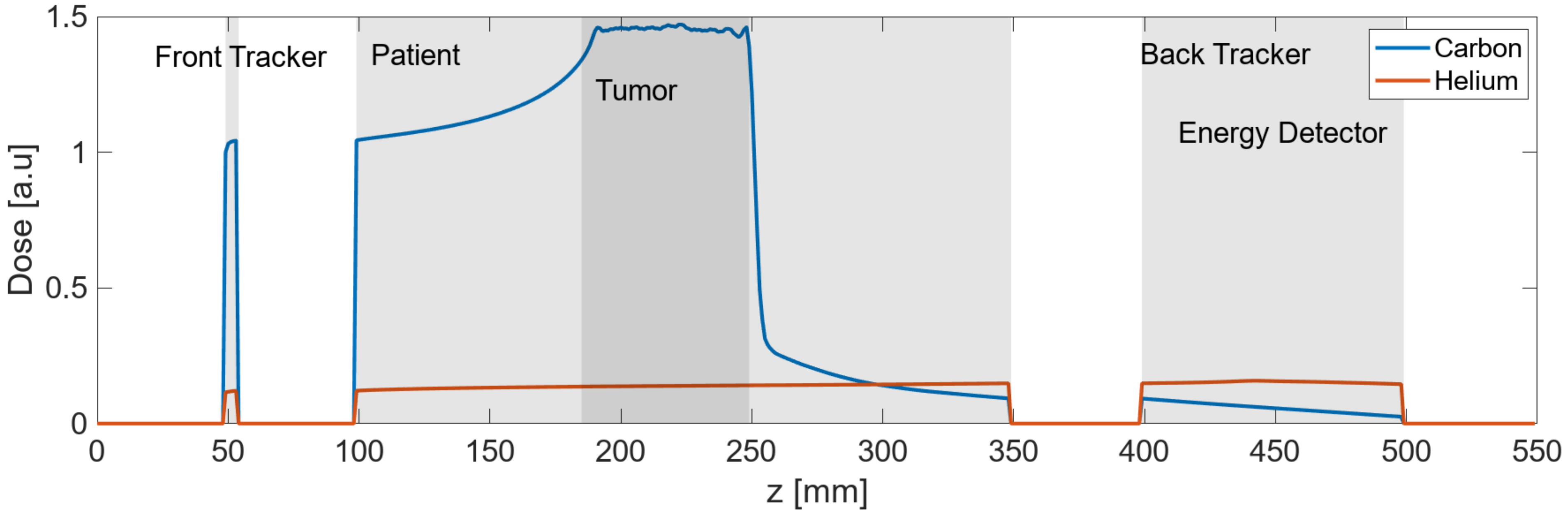
Research for a Life without Cancer

Mixed Carbon-Helium Beam

- $^{12}C^{6+}$ and $^{4}He^{2+}$ have the same mass/charge ratio
- Can be accelerated together in a mixed beam
- Mixing ratio 10:1 [1]

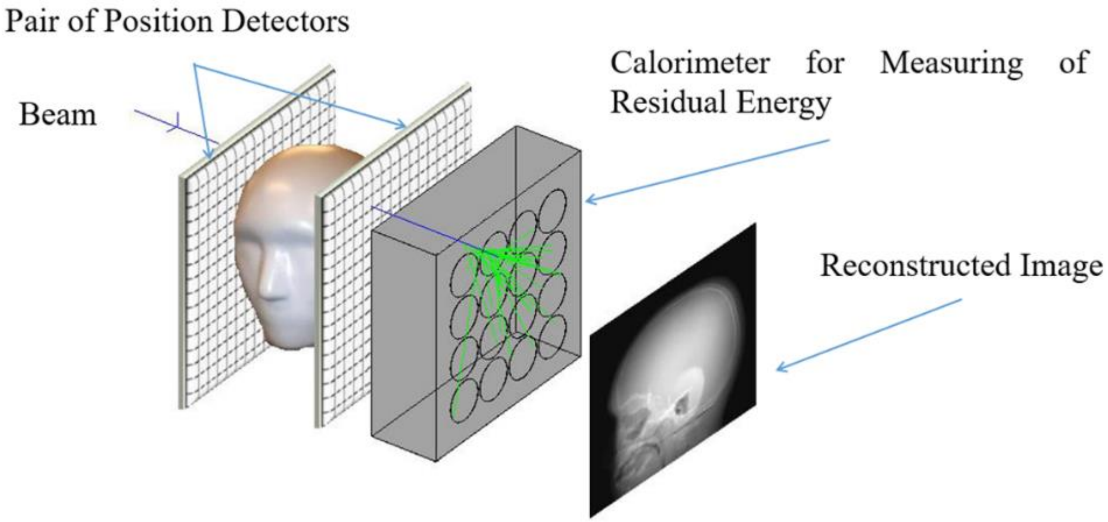


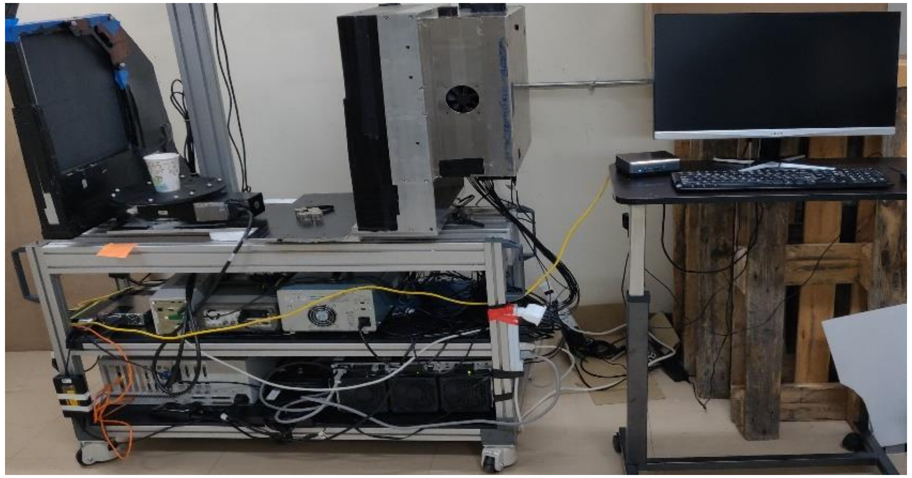
[1] L. Volz et al., "Experimental Exploration of a Mixed Helium/Carbon Beam for Online Treatment Monitoring in Carbon Ion Beam Therapy," *Physics in Medicine & Biology* (2020), https://doi.org/10.1088/1361-6560/ab6e52.

Agenda

1. **Particle Imaging and Treatment Planning**
2. Mixed Carbon Helium Beam in RT
3. RGRT motion management

Principle of particle imaging (pRad and pCT)





Particle imaging beam uses:

- Enough energy to traverse patient
- Ultra-low intensity (~0.01% of treatment intensity)
- Lower dose than equivalent x-ray image

Particle therapy beam uses:

- Lower energy, protons stop in tumor
- Higher intensity, delivers prescribed dose

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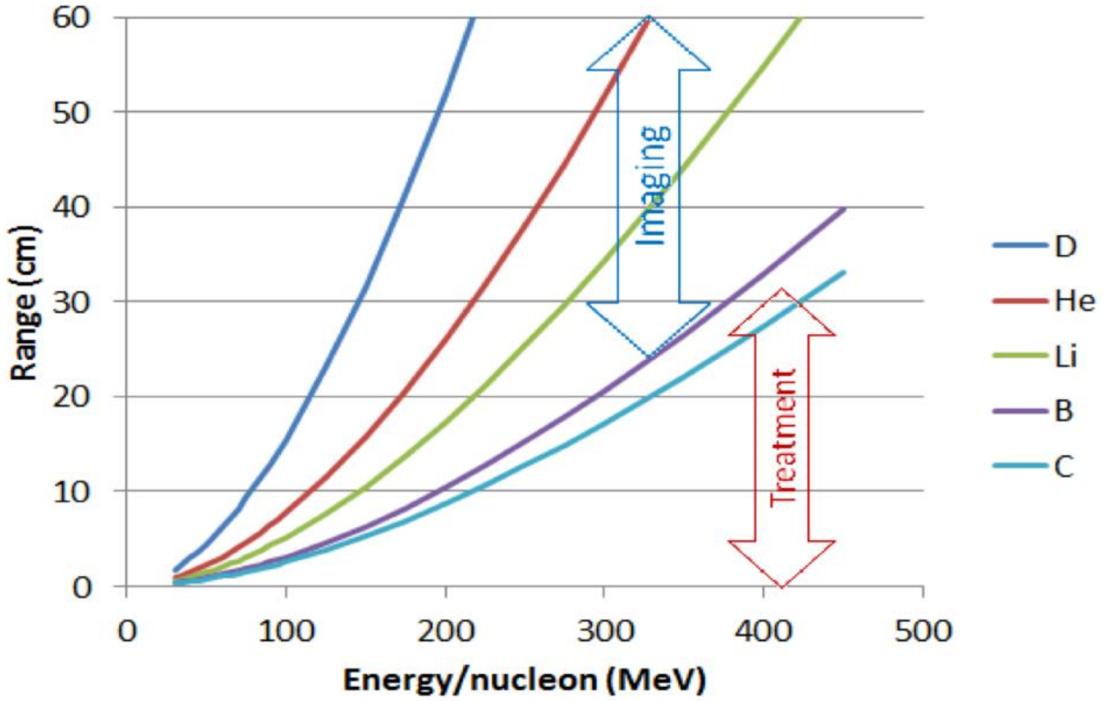
Principle of particle imaging (pRad and pCT)



Treatment system provides:

- Particles with Kinetic Energy calibrated in terms of Range in water
- Particles delivered in pencil beam scanning system calibrated to steer to given locations in isocenter plane

Treatment planning needs:

- 3D map of RSP: d*E*/d*x* in each voxel relative to water to calculate range to tumor $\int (RSP) dx$

Adaptive paradigm:

- WET through patient to check for anatomical changes $\int (RSP) dx$

Particle imaging-based planning adaptive therapy

pRad

Particles from a single angle

Relative to RSP map

- Check alignment
- Check integrated range

pCT

Particles from a full set of positions and angles

Create an RSP map

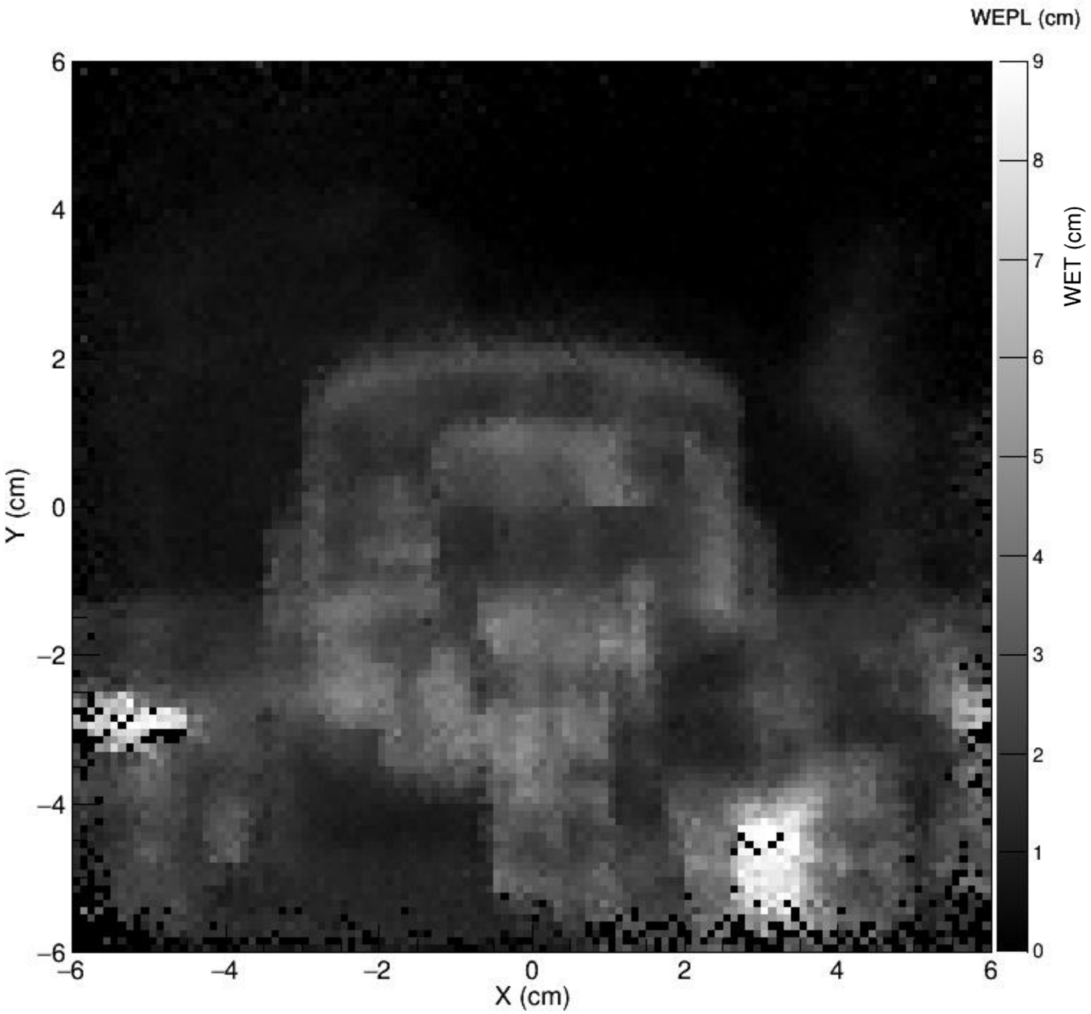
Treatment Plan

Adapted RSP map

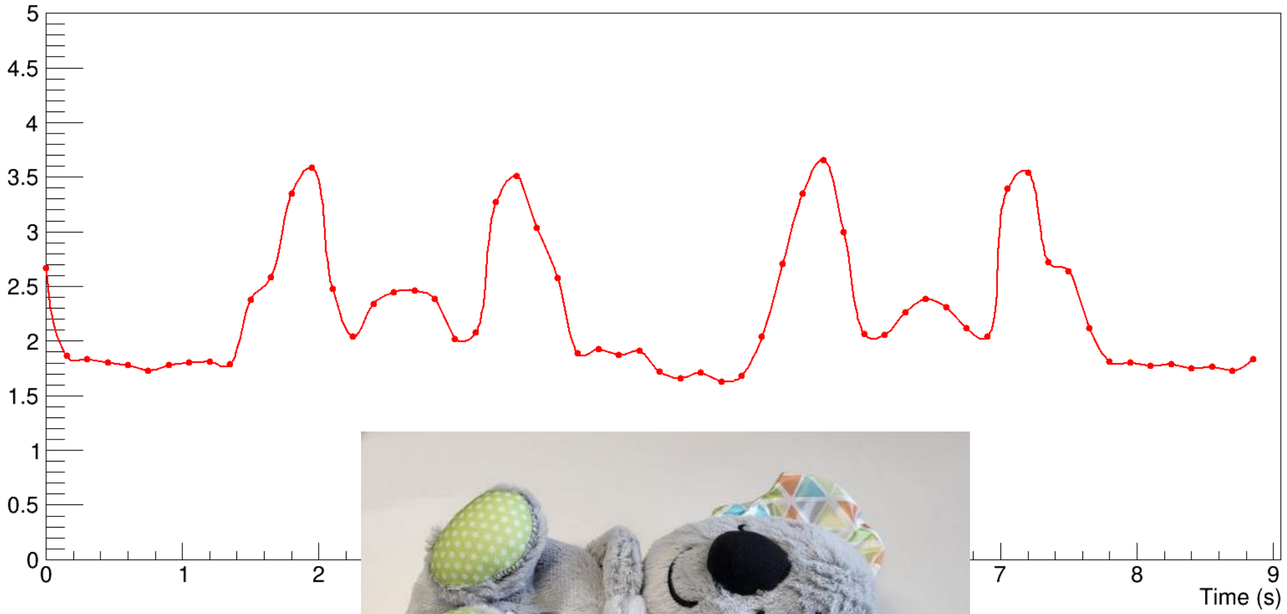
May involve:

- Deformable Image registration
- Treatment plan adaptation
- Quantifying uncertainties

Experimental data: single energy pRAD(t)



pRAD data from 12/2022 Northwestern Medicine Proton Center, 120 MeV protons.



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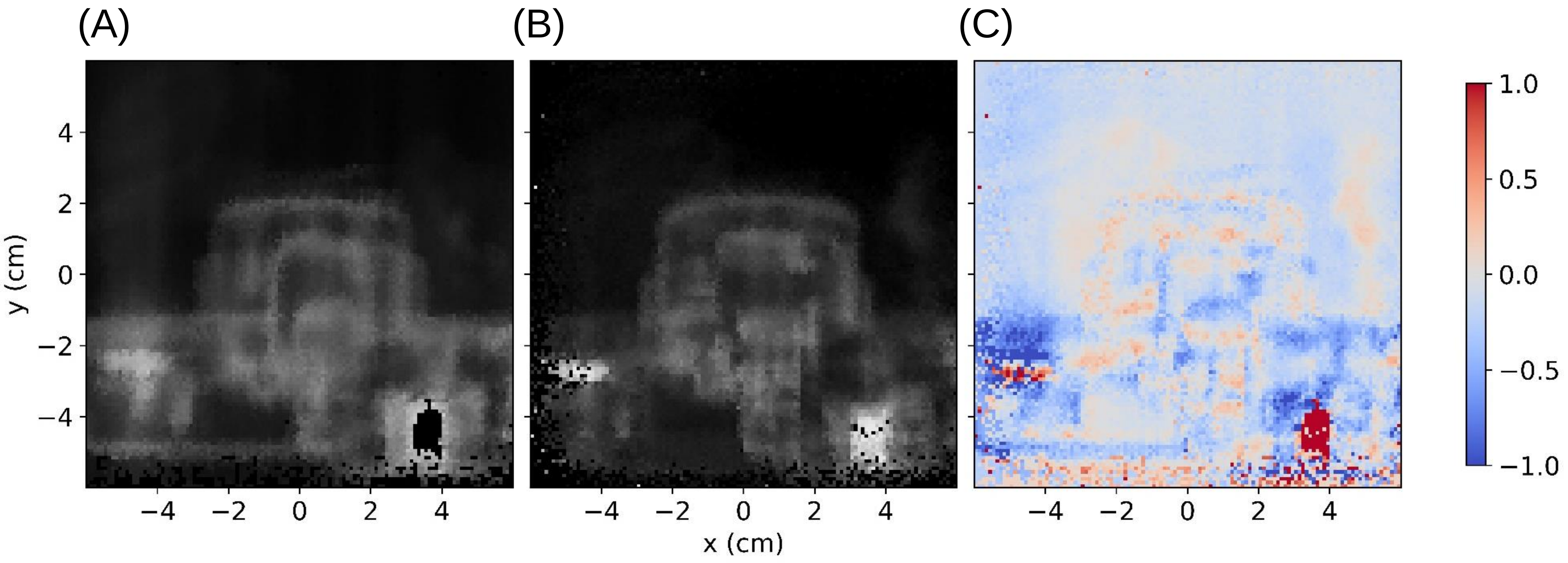
Comparison of simulated and experimental pRad

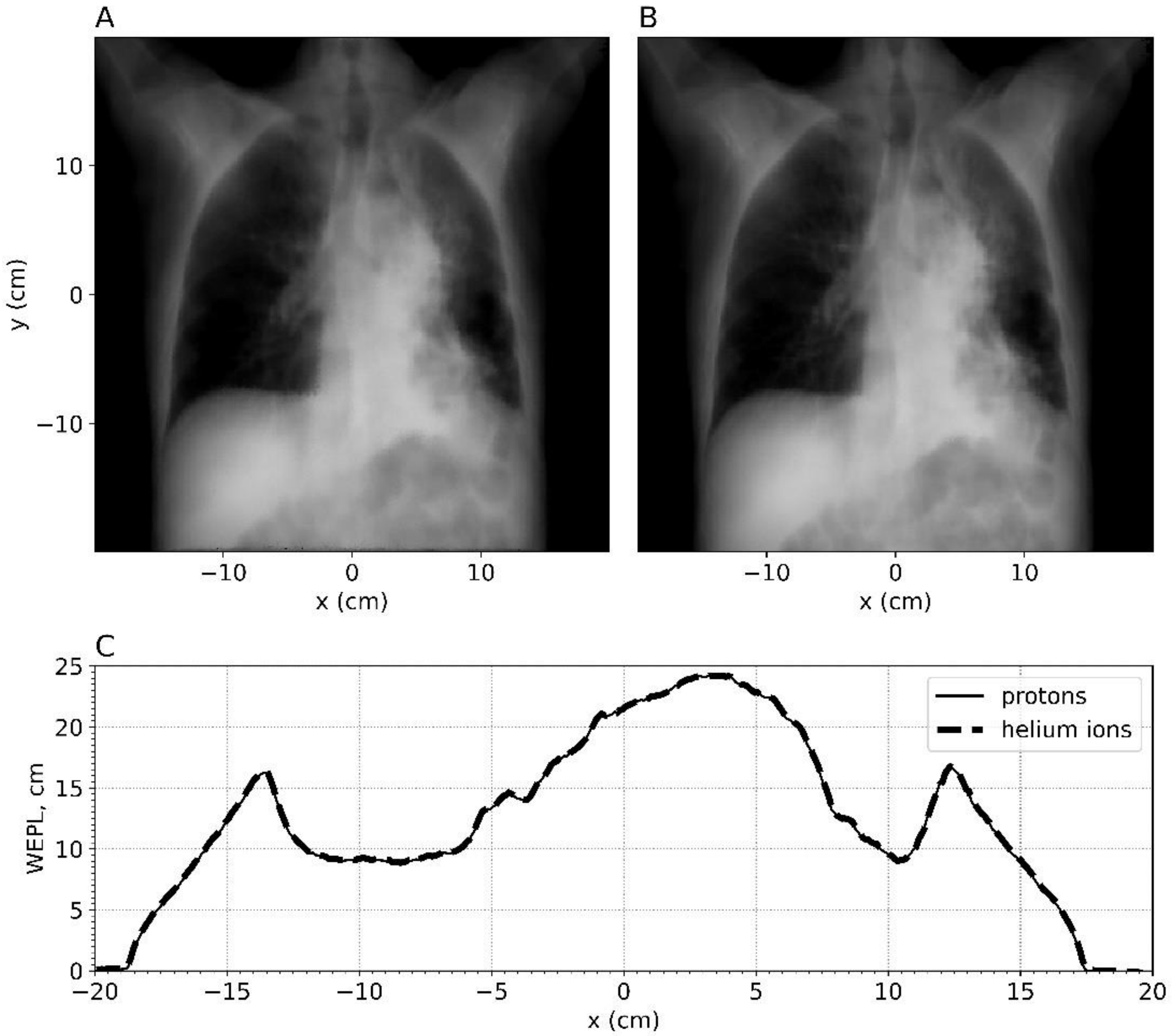


(A) Simulated pRad using CT data;

(B) Experimental pRad corresponding to the selected CT phase;

(C) Difference in absolute value of WEPL between simulated CT-based pRad and experimental pRad

Simulated full-scale pRad and HeRad comparison



(A) pRad, phase 0

(B) HeRad, phase 0

(C) line profiles along the X-axis for Y coordinates from -0.2 cm to 0.2 cm.

2000 particles in both cases

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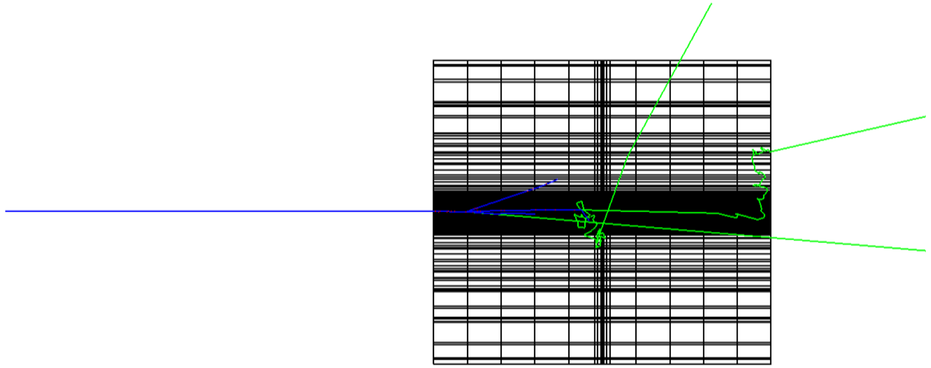
Calculating the Mixed Carbon Helium Treatment Plan

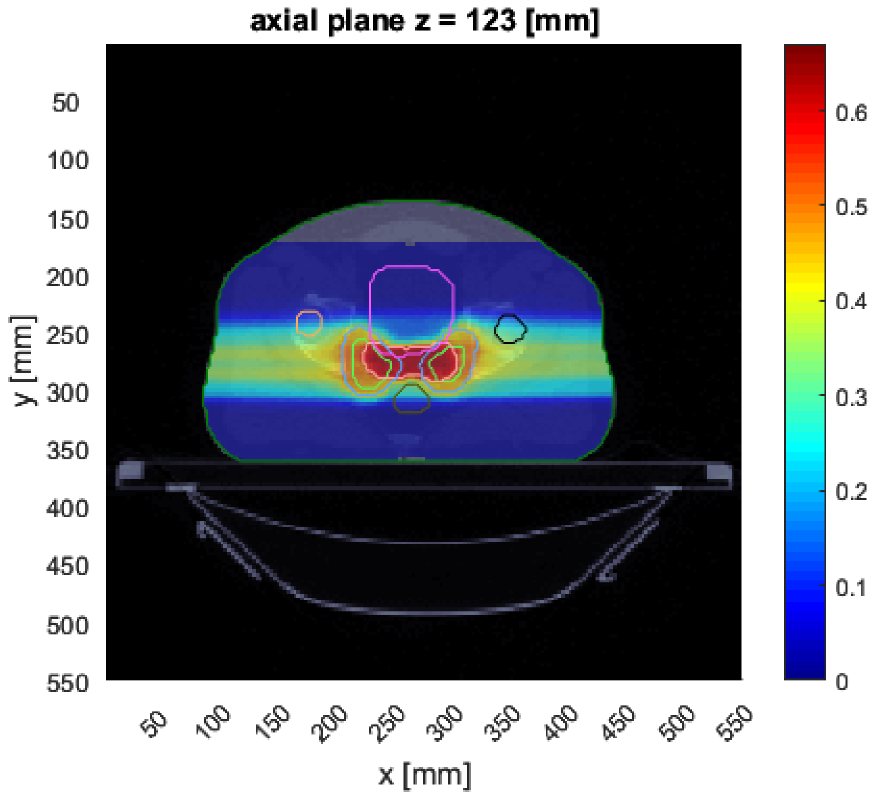
- Problem: No Machine/Beam delivery data available for Helium energies matching the carbon treatment energies
- Solution: Simulate Base data with Monte Carlo (TOPAS)
- Energys: 88.83 MeV/u – 430.1 MeV/u
- Ranges: 63 mm – 932 mm
- Score Deposited Energy lateral and in depth
- Fit lateral profile with a sum of three weighted Gaussian functions



TOPAS simulation set up

Calculating the Mixed Carbon Helium Treatment Plan

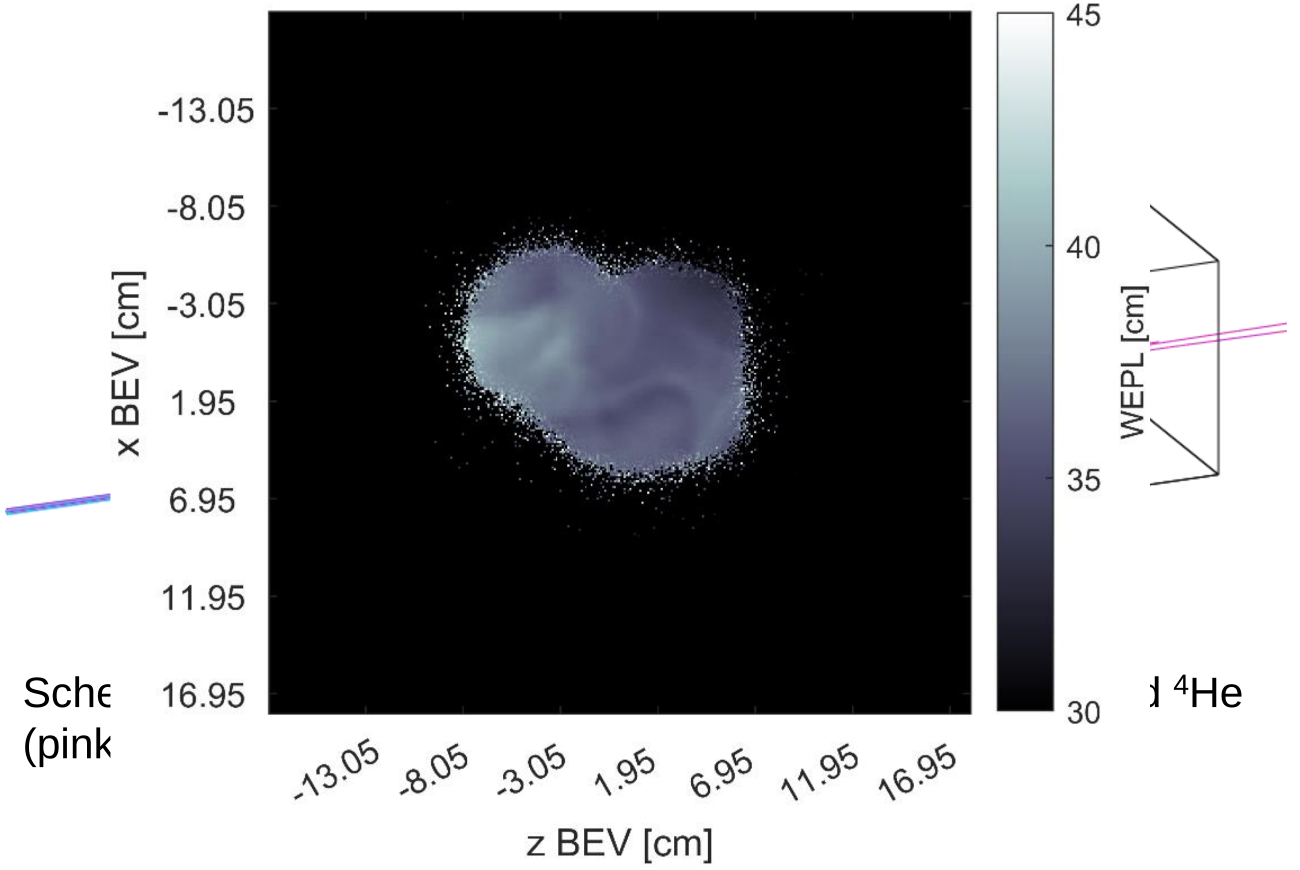
- Optimize and analytically calculate Carbon Ion Dose with matRad
- Calculate Corresponding Helium Ion Dose
- Calculate resulting total Carbon-Helium Dose
- Adding 10% Helium contributes under 2% additional Dose to the physical Dose of the Carbon Ions
- Use matRad – TOPAS interface to simulate Detector during delivery of the Treatment plan



Physical Dose [Gy]

Simulation and Reconstruction of Radiographs

- Score phase space of primary Helium ions at tracker position
- From initial/final energy calculate
  $WEPL = R_{Init} - R_{Final}$
- Reconstruct particle path and calculate intersection point with Isocenter plane
- Calculate mean WEPL in each image pixel



Reconstructed radiograph of prostate case

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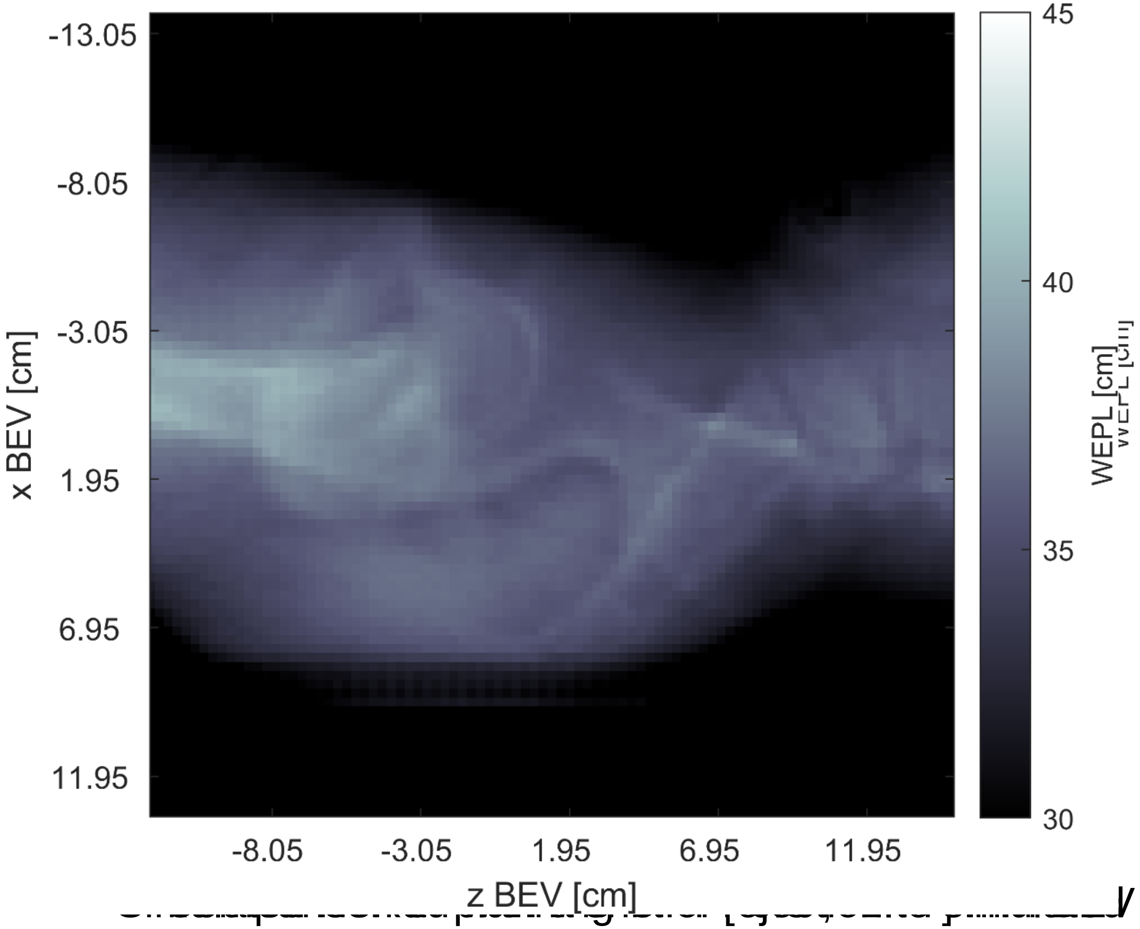
Post Treatment Setup Verification

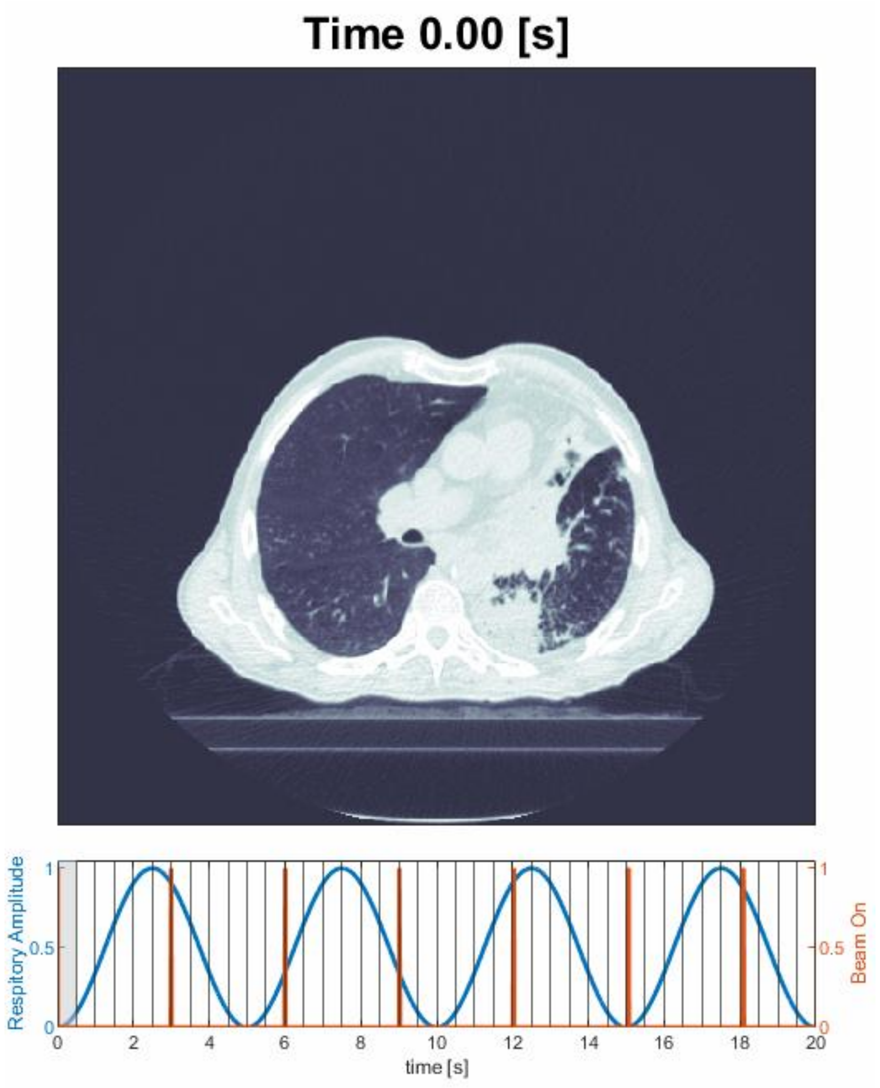
- Prostate Patient
- Post Treatment Reconstruction of Radiograph
- Small Range Changes are visible
- Can be used to verify Treatment Position
  - Estimate potential Patient setup shift thru comparison to planning CT projections
- Quality Assurance and Dose reconstruction



Projected CT along BEV
Radiograph with a shift of [-0.8 , -1.77] mm BEV

Extending to 4D

- Optimize Treatment plan on 1st Phase
- Use Beam Sequence Delivery Parameters to calculate which treatment spot is delivered in which CT phase
  - Energy Switching Time = 3 s
  - Spill Intensity = 4 * 10^8 Hz
  - Scanning Speed = 10 m / s
- Use a time feature in TOPAS to switch to the correct CT phase cube during simulation
- Reconstruct every energy layer as a separate Radiograph



4D CT of a Lung Patient, 10 phases, Motion Period = 5 s

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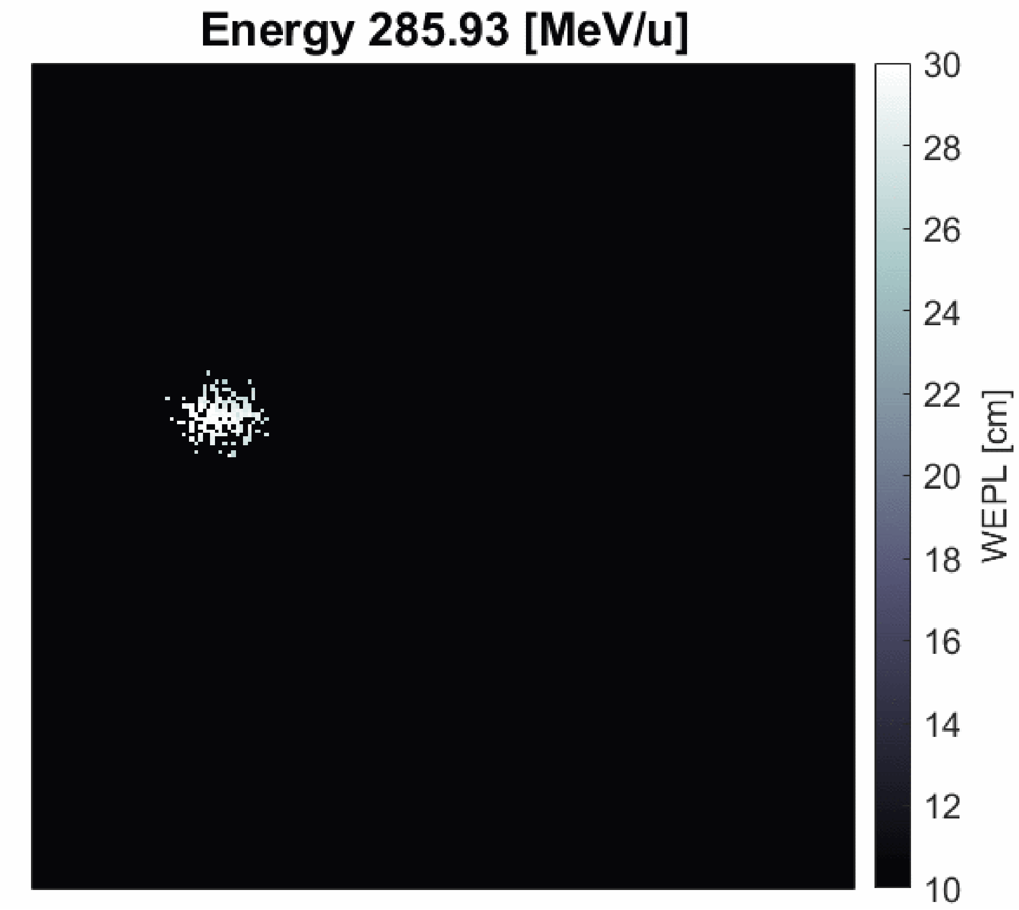
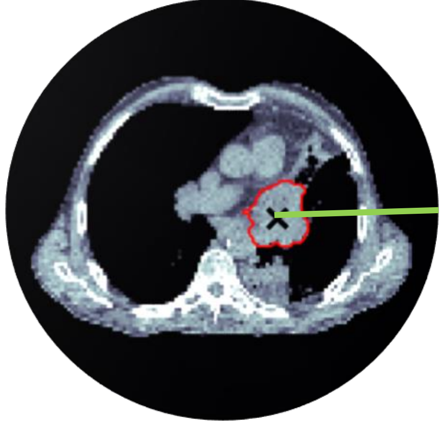
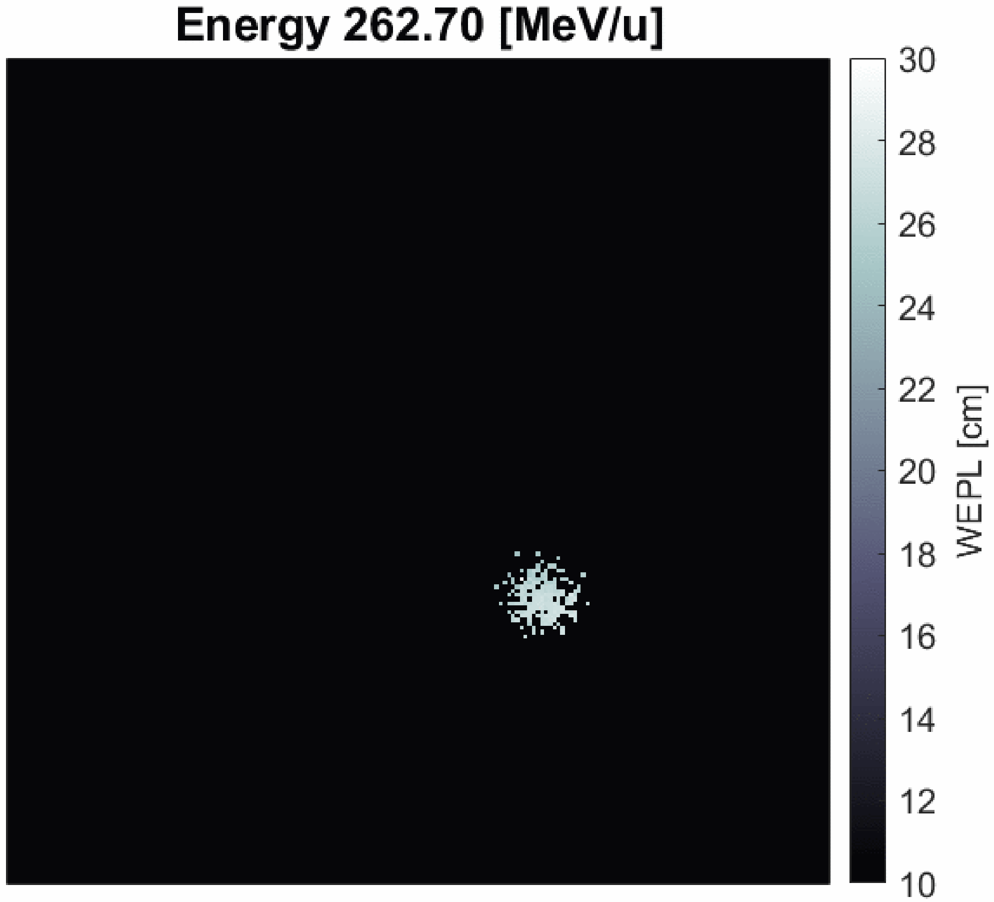
4D Single Energy Helium Radiographs (SEHeRad)



Reconstructed Radiographs for each Energy Layer, Treatment Angle 45˚

4D Single Energy Helium Radiographs (SEHeRad)





Reconstructed Radiographs for each Energy Layer, Treatment Angle 90˚

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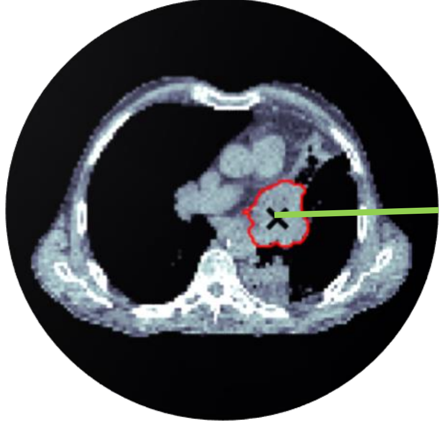
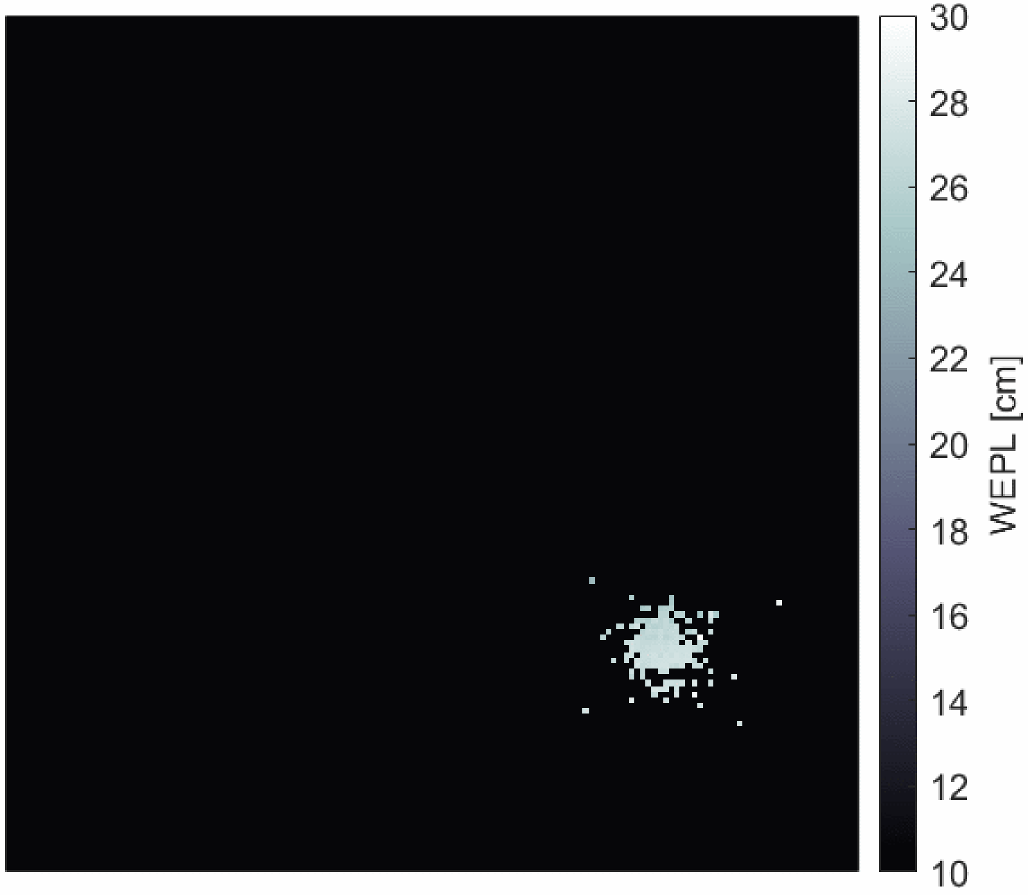
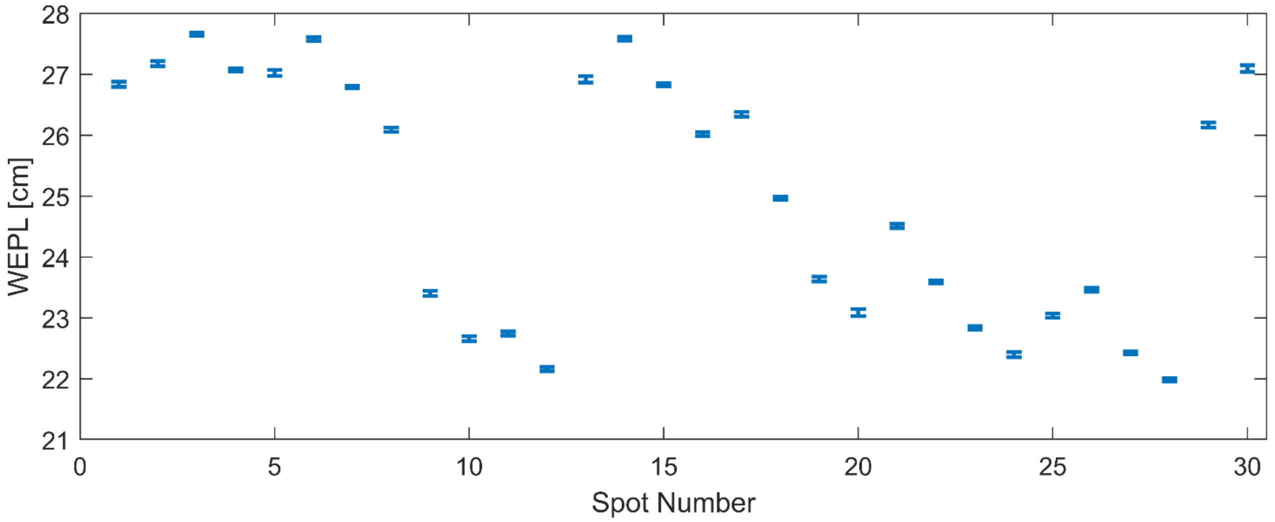
4D Single Spot Helium Radiographs (SSHeRad)





Reconstructed Radiographs for first 300 Spots, Idealized Detector, Treatment Angle 90˚



Mean and Standard deviation of WEPL values corresponding to each Spot

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Range-guided motion management strategies

Range-guided motion management (RGMM)

→

External surrogate respiratory monitor (SRM) to start irradiation

→

Single-Energy Analysis (SEA)

- SRM stop
- Time to analyze
- Almost ready

Single-Spot Range Probe (SSRP)

- Can stop itself
- Fast response
- Tech Challenge

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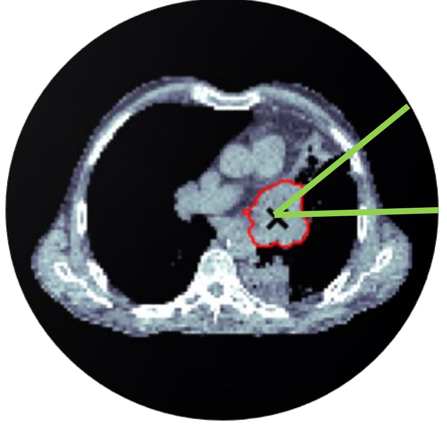
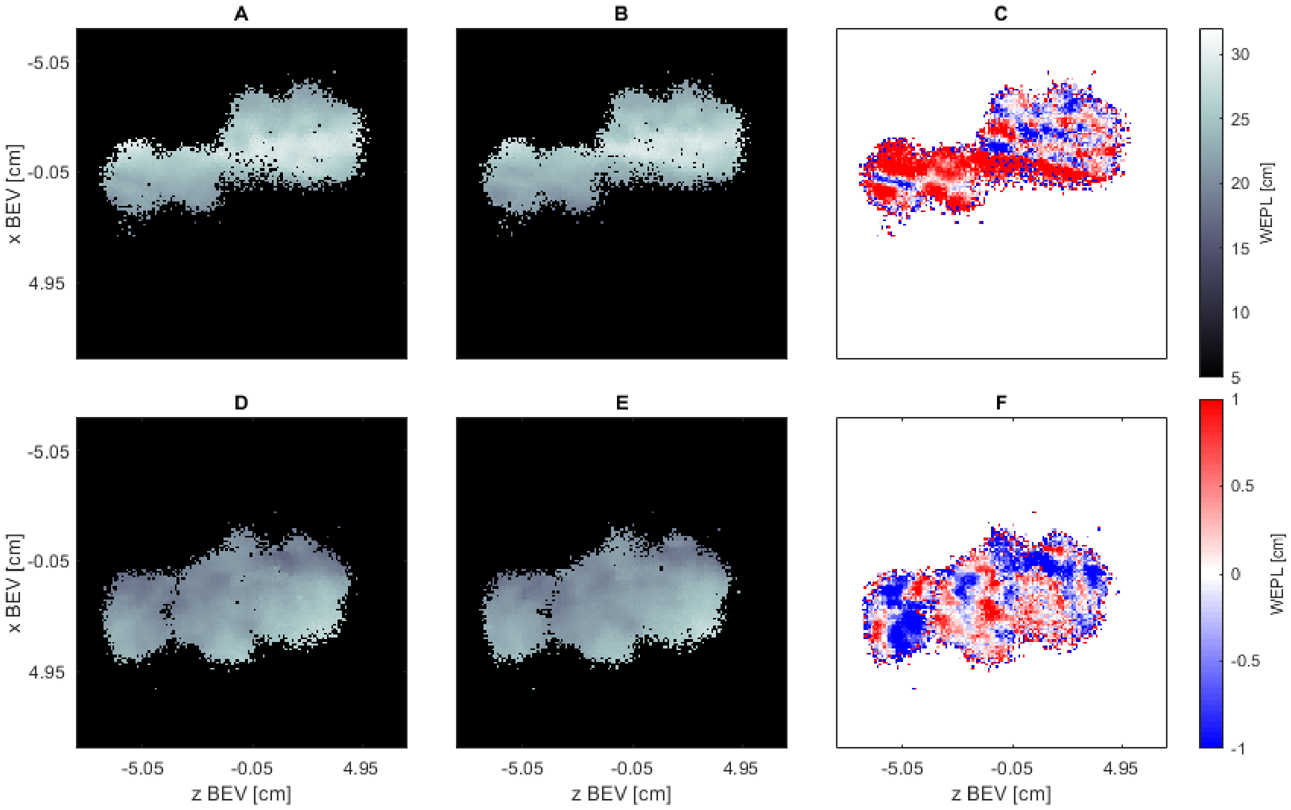
Single-Energy Analysis (SEA) using SEHeRad





(A) SEHeRad 1st field, 1st phase of 4DCT
(B) SEHeRad 1st field, 5th phase of 4DCT
(C) WEPL difference for the execution plan for the 1st phase to the 5th phase for 1st field
(D) SEHeRad 2nd field, 1st phase of 4DCT
(E) SEHeRad 2nd field, 5th phase of 4DCT
(F) WEPL difference for the execution plan for the 1st phase to the 5th pahse for 2nd field.

Challenges and Limitations

- Acceleration of a mixed Carbon-Helium beam
- Influence of Carbon Fragments on the Detector signal in the Mixed-Beam approach
- Mixed Beam method is also sensitive to changes distal of the tumour volume

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Conclusion and Outlook

- Mixed Carbon-Helium method has a high sensitivity to range changes
- Feasible to implement a motion management system based on particle radiography
- ➢ Incorporation of the mixed in Helium Dose in the treatment plan optimization
- ➢ Refine SEHeRad analysis for possible dose reconstruction

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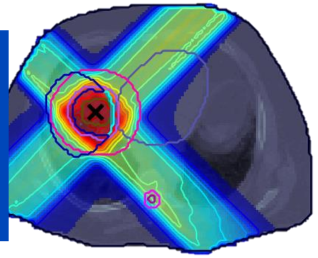
TH  YOU

For your Attention !

This work is funded by the Deutsche Forschungsgemeinschaft (DFG) – Project No. 457509854.

Figure shows the Physical He Dose