CT Imaging with Hadrons for Cancer Radiotherapy

AIME26, 12/11/26

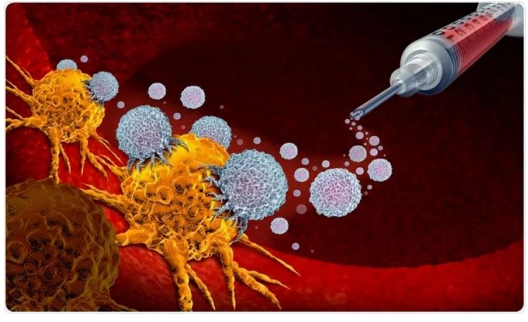
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Introduction





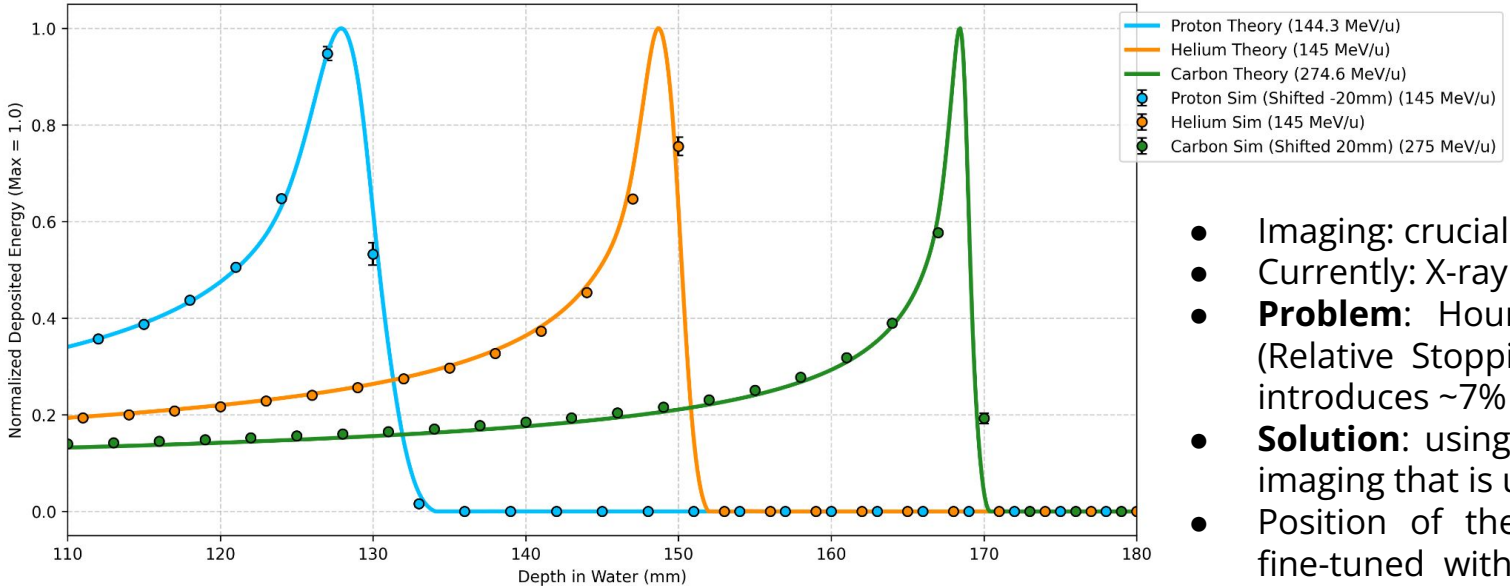




Cancer treatment

- Surgery
- Chemotherapy
- Immunotherapy
- **Radiotherapy - uses ionization to damage the DNA of cancerous cells**

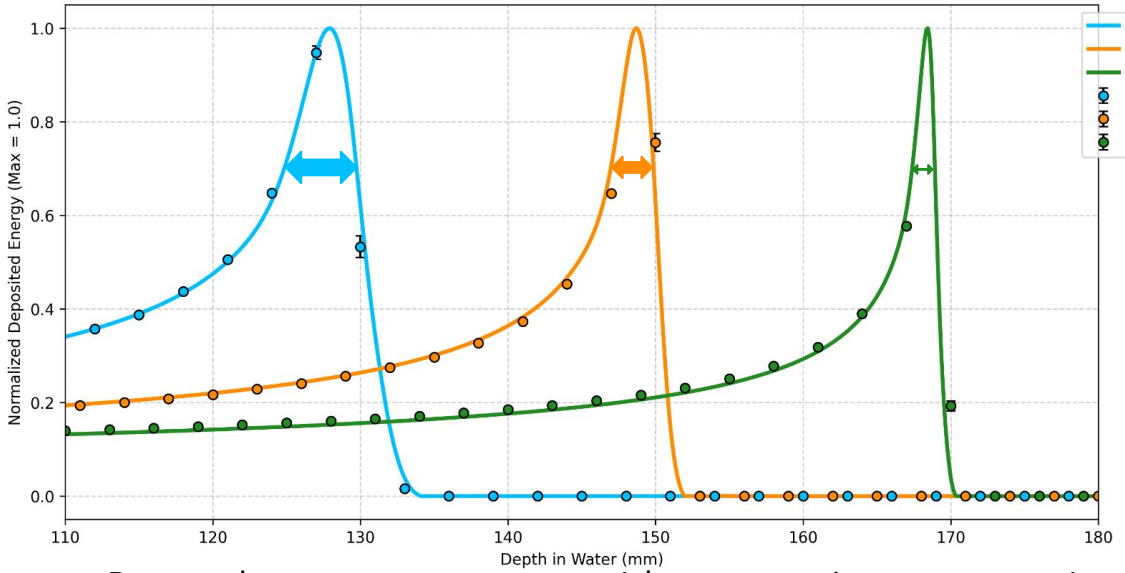
Introduction

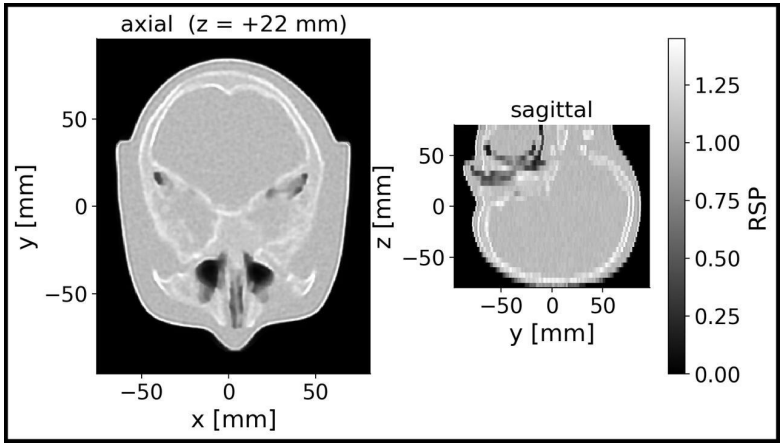


- Done with photons, protons or light ions (helium, carbon)
- Especially efficient: hadron therapy (energy deposit)

- Imaging: crucial part of radiotherapy
- Currently: X-ray CT
- **Problem**: Hounsfield unit → RSP (Relative Stopping Power) conversion introduces ~7% error
- **Solution**: using the same particle for imaging that is used for the treatment
- Position of the Bragg peak can be fine-tuned with the initial energy → we simply use higher initial energy for imaging → Bragg peak is in the detector

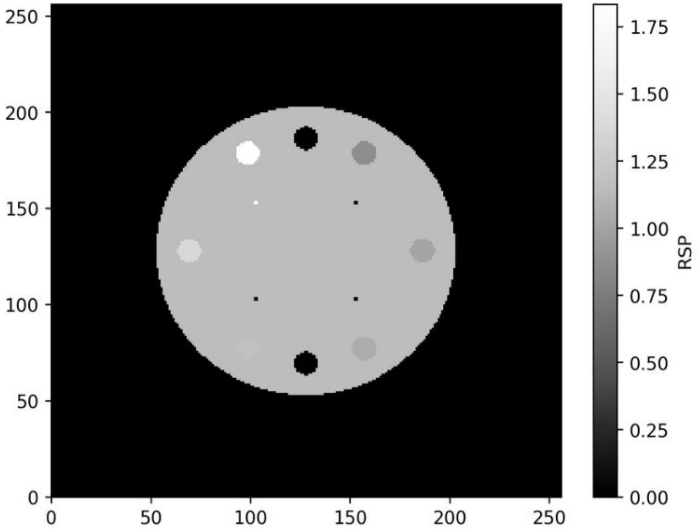
Protons vs. light ions



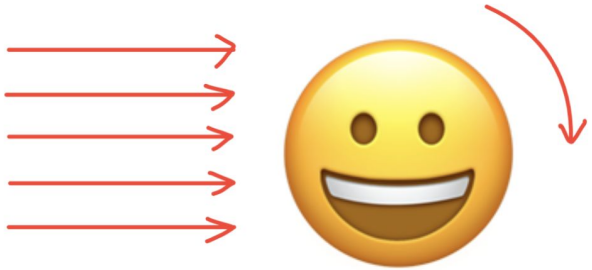


- Proton therapy: more common (cheaper, easier to carry out)
- Light ions: narrower Bragg peak, more precise treatment, greater biological effectiveness
- Imaging before ion therapy with ions? - advantage: same device can be used; but we have to examine
  - the quality of the imaging
  - the biological dose deposited by the imaging particles

Monte Carlo simulations - CTP404 phantom



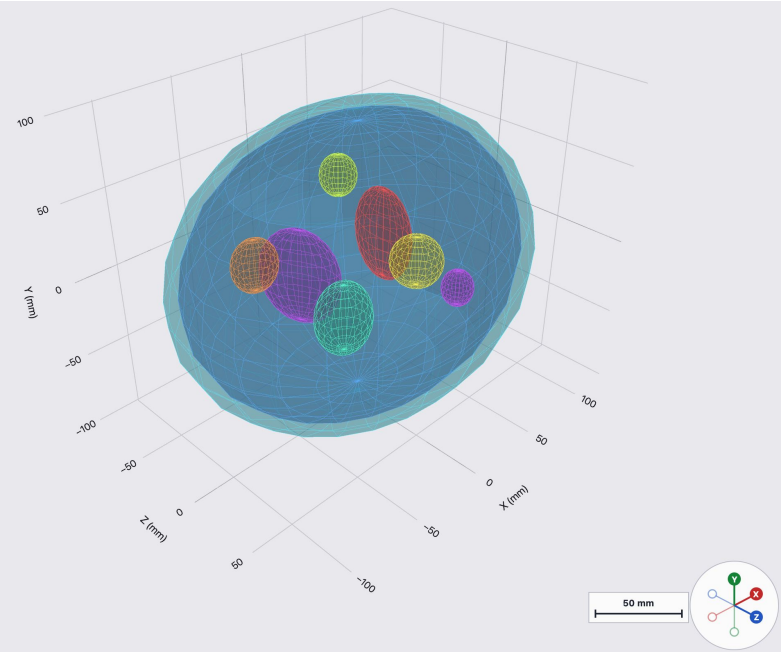
- **Geant4** & **GATE** simulations
- "Scanning" of the phantom
  - 360°, in every 1°
  - 155 mm, in every 1 mm
  - 1000 primary particles
- Initial energies:
  - proton: 230 MeV/u
  - helium ion: 230 MeV/u
  - carbon ion: 430 MeV/u



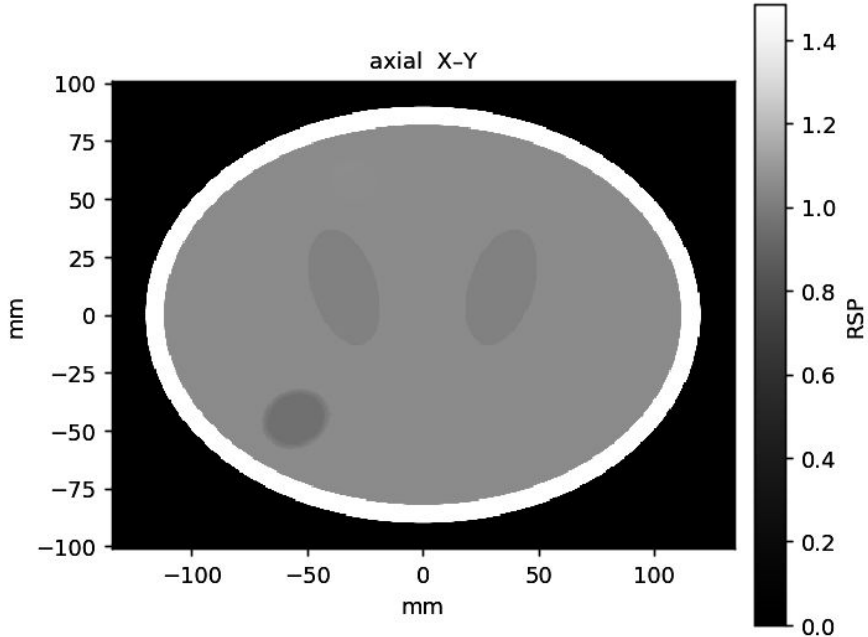
2D simulation!

- D=150 mm
- 8 cylinders, d=12.2 mm, made of different materials
- For measuring RSP reconstruction accuracy

Monte Carlo simulations - Shepp-Logan(-like) phantom



- 3D ellipsoids with RSP values of tissues in the human head
- 120 mm, 90 mm axis lengths
- 5 kg



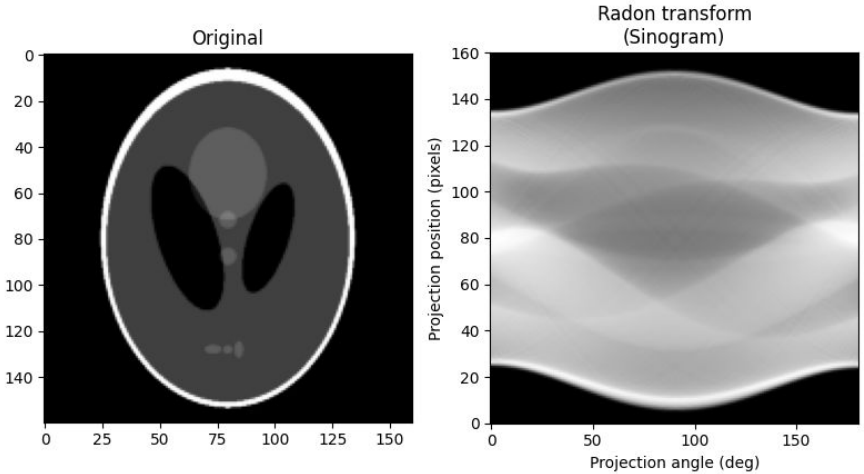
- **Geant4** & **GATE** simulations
- Measuring physical dose using *DoseActor*
- 360 x 132 x 32 x 300 primary particles (rotating + scanning through 2 axes)

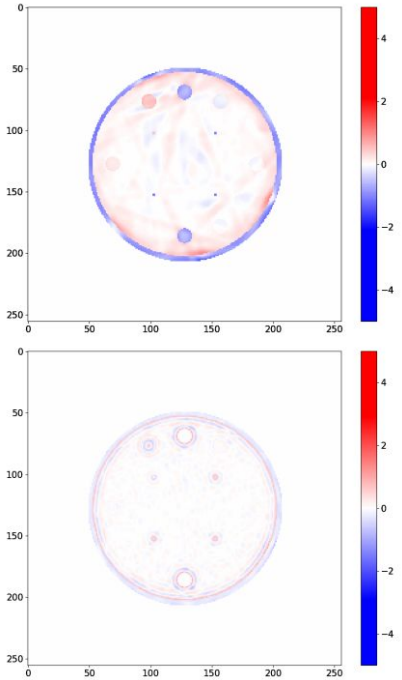
Image reconstruction

Integral transformations
(don't work for hadron CT)

2 main types

Iterative reconstruction techniques:
solving a linear equation system





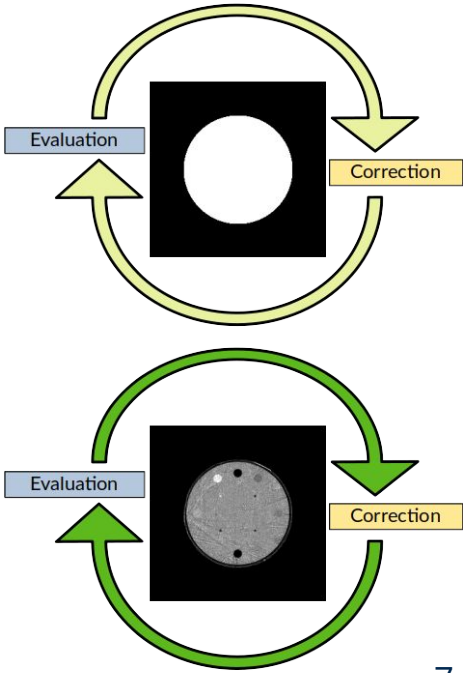


Image reconstruction

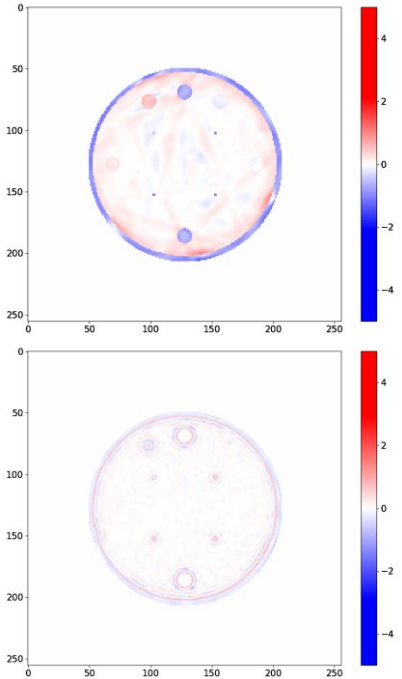
Iterative reconstruction techniques

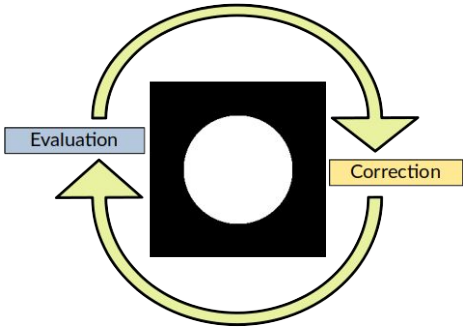
➔ they converge into a fix point solution

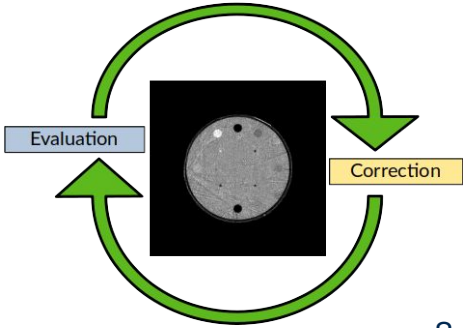
➔ different techniques, eg.:

SART (Simultaneous Algebraic Reconstruction Technique)→ additive

RL (Richardson-Lucy based reconstruction algorithm) → multiplicative







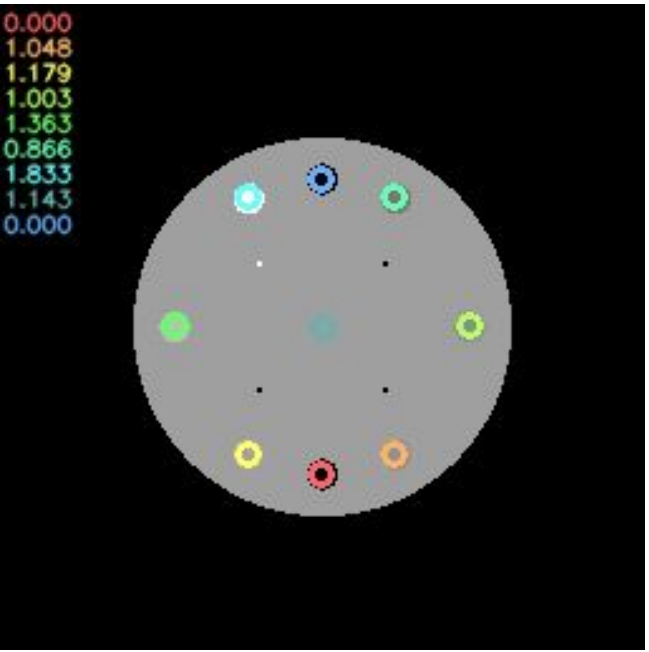
➔ ~10^6 particle trajectories → computationally challenging

➔ GPU usage: C++ code sped up with CUDA

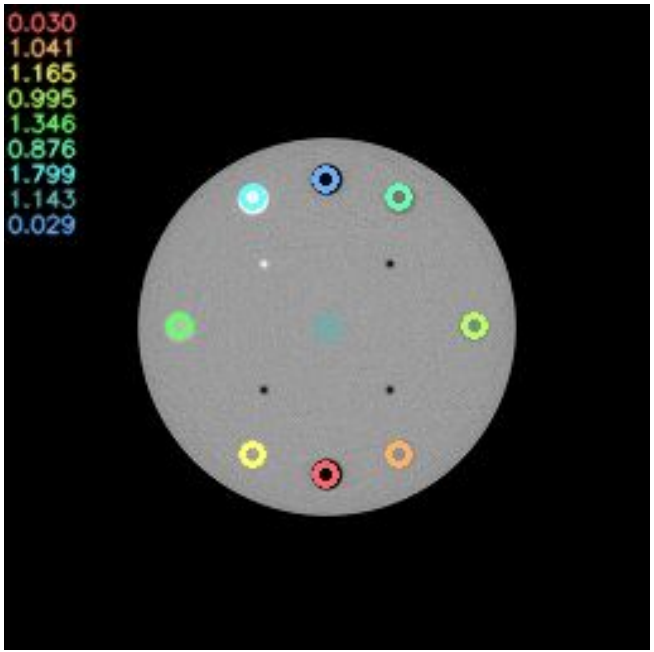
- Iteration cycle runs in GPU kernels (WSCLAB)
- Goal: maximizing resolution + minimizing runtime

Evaluating the reconstruction: RSP accuracy

Ground truth

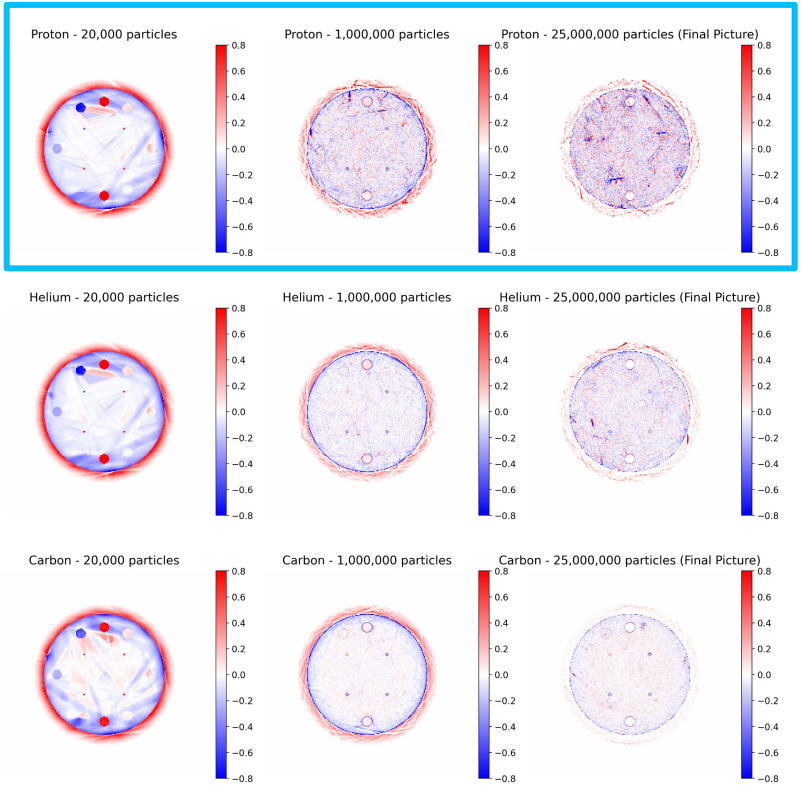


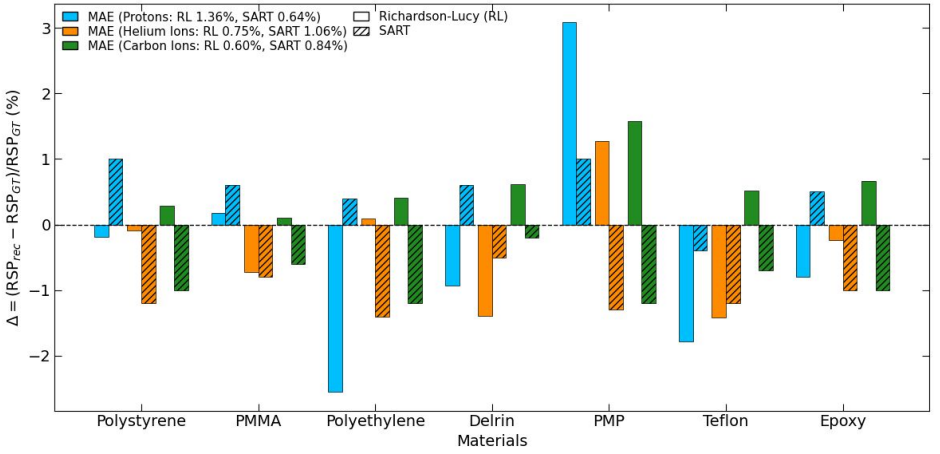
Reconstruction

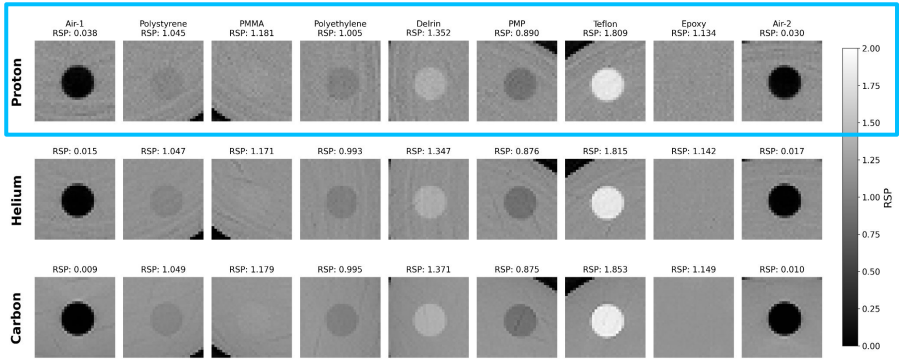


1. Defining center of inserts on the ground truth image (perfect contrast, no noise or blur)
2. Measuring average RSP in the previously defined positions on the reconstructed image
3. Comparing RSP values

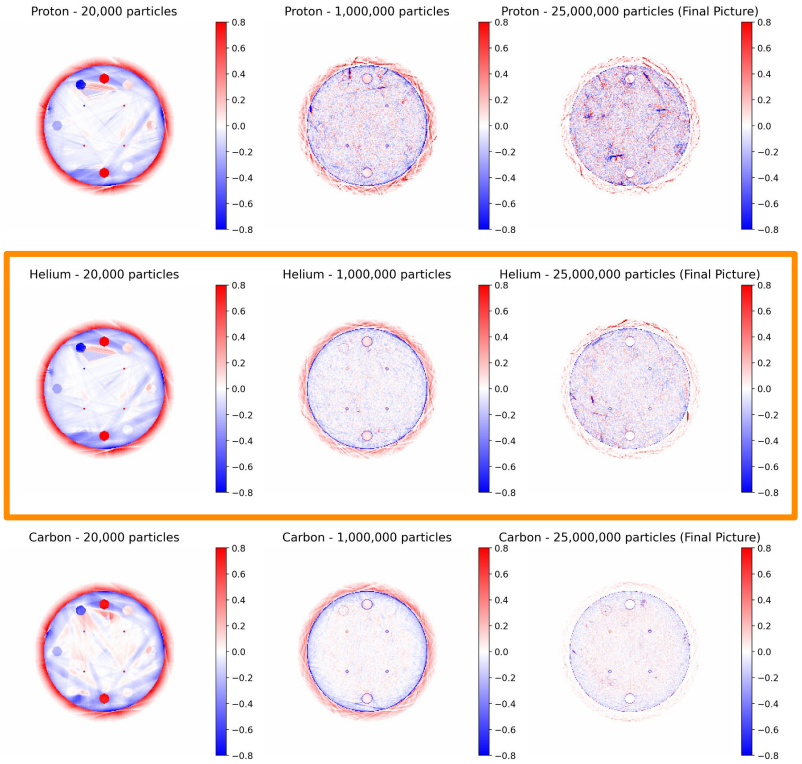
RSP reconstruction accuracy

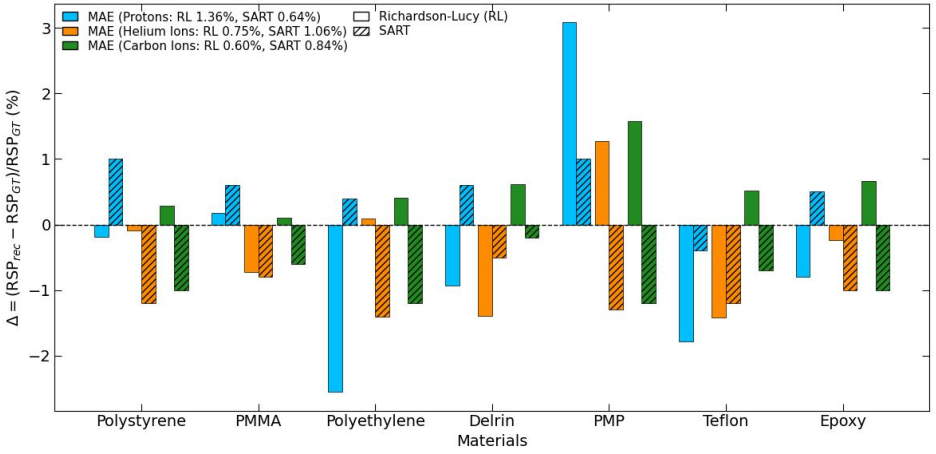


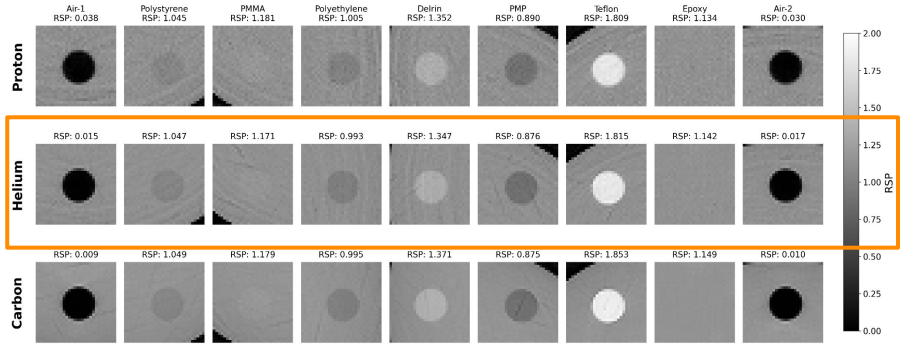




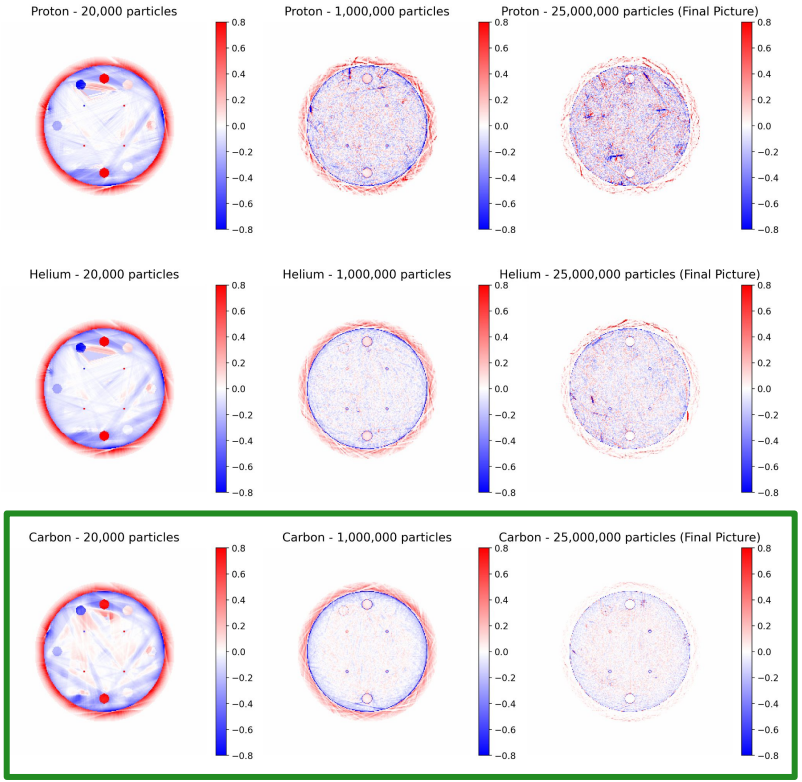
RSP reconstruction accuracy

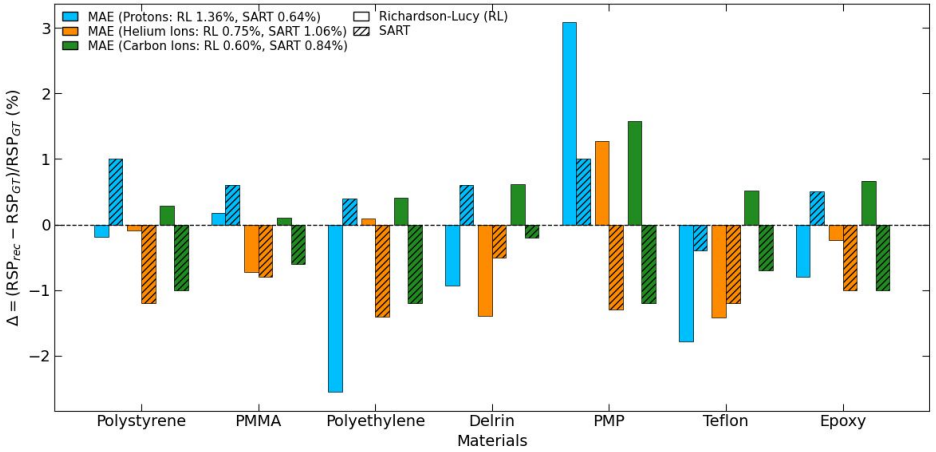


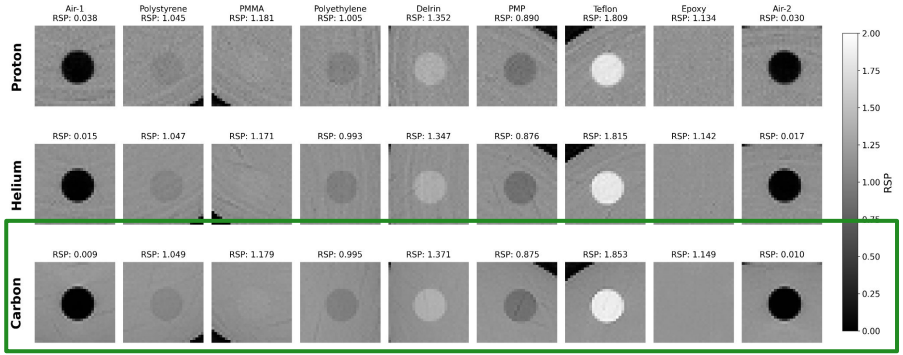




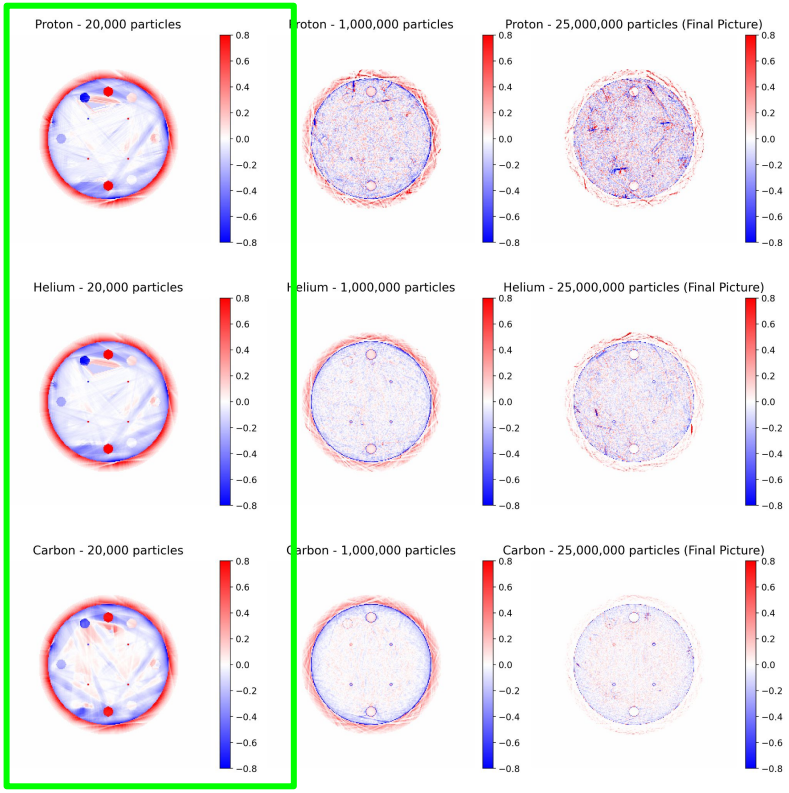
RSP reconstruction accuracy

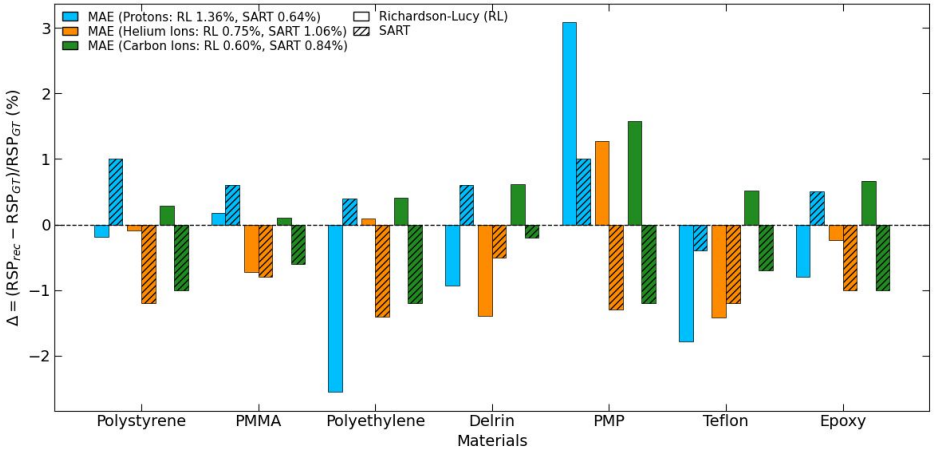


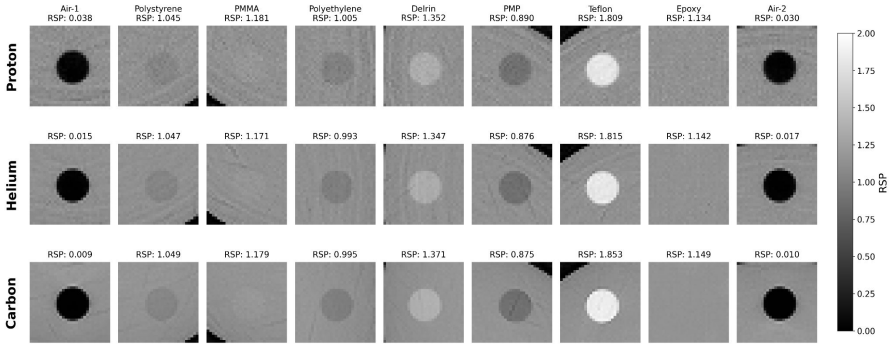




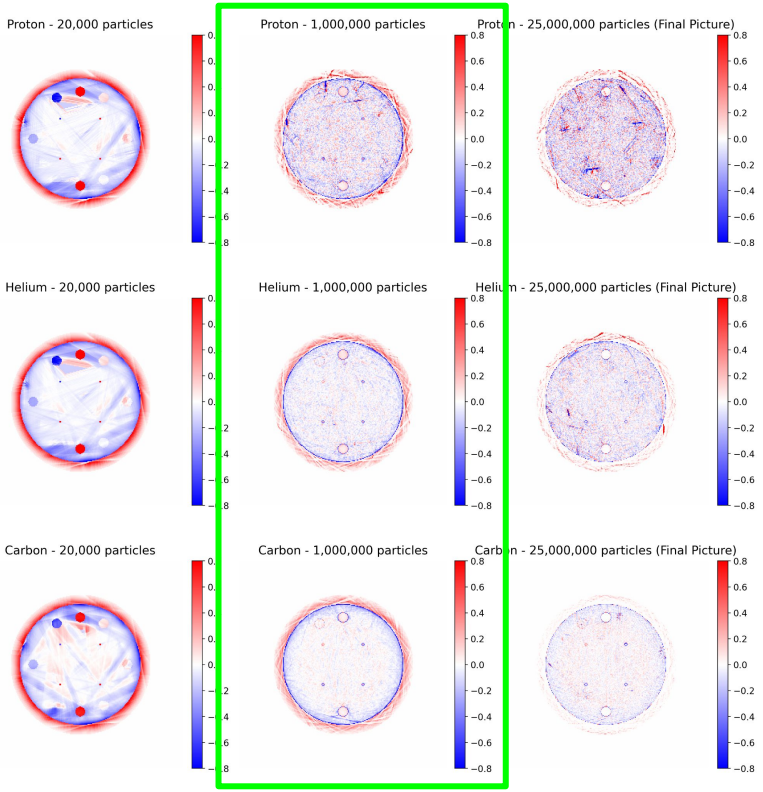
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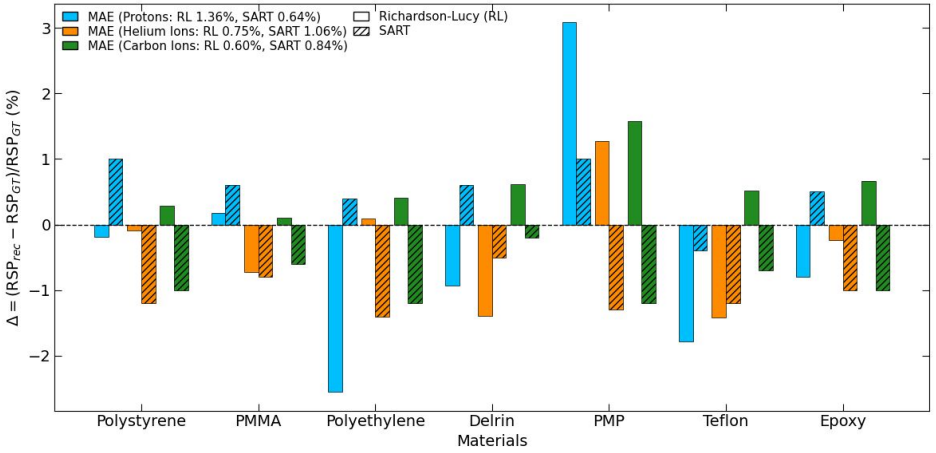


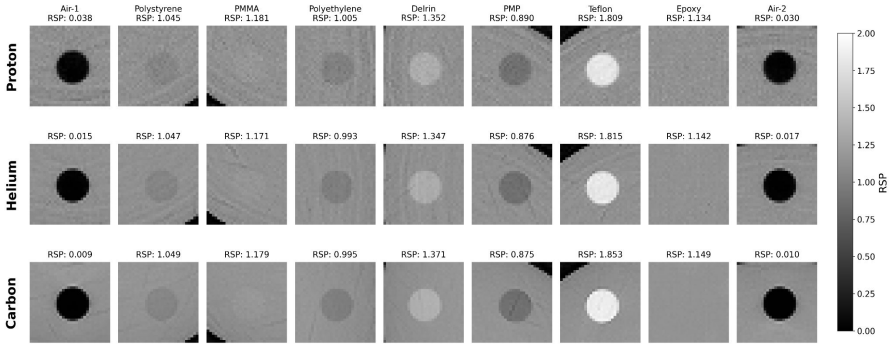




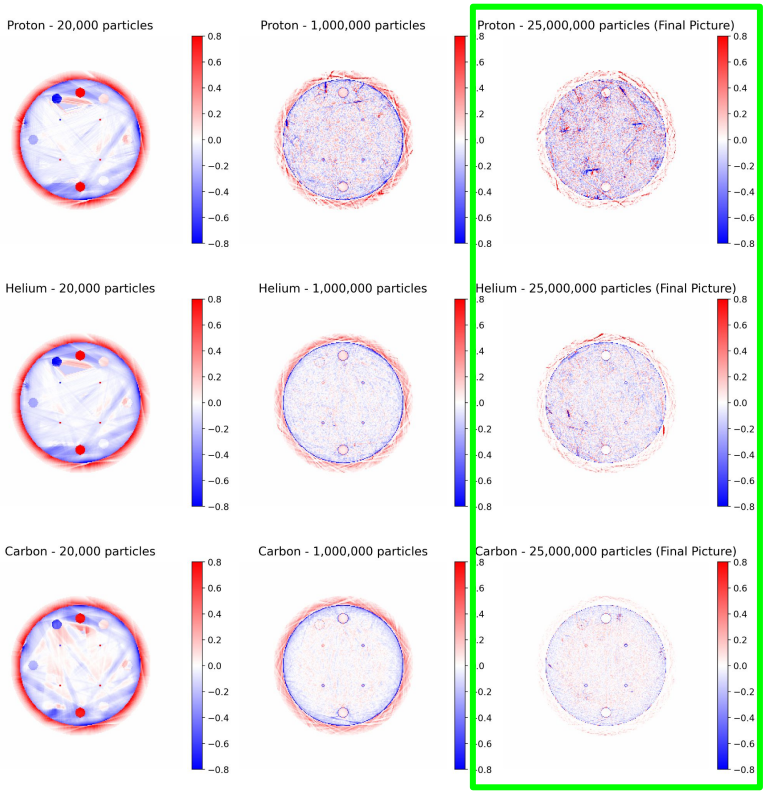
RSP reconstruction accuracy

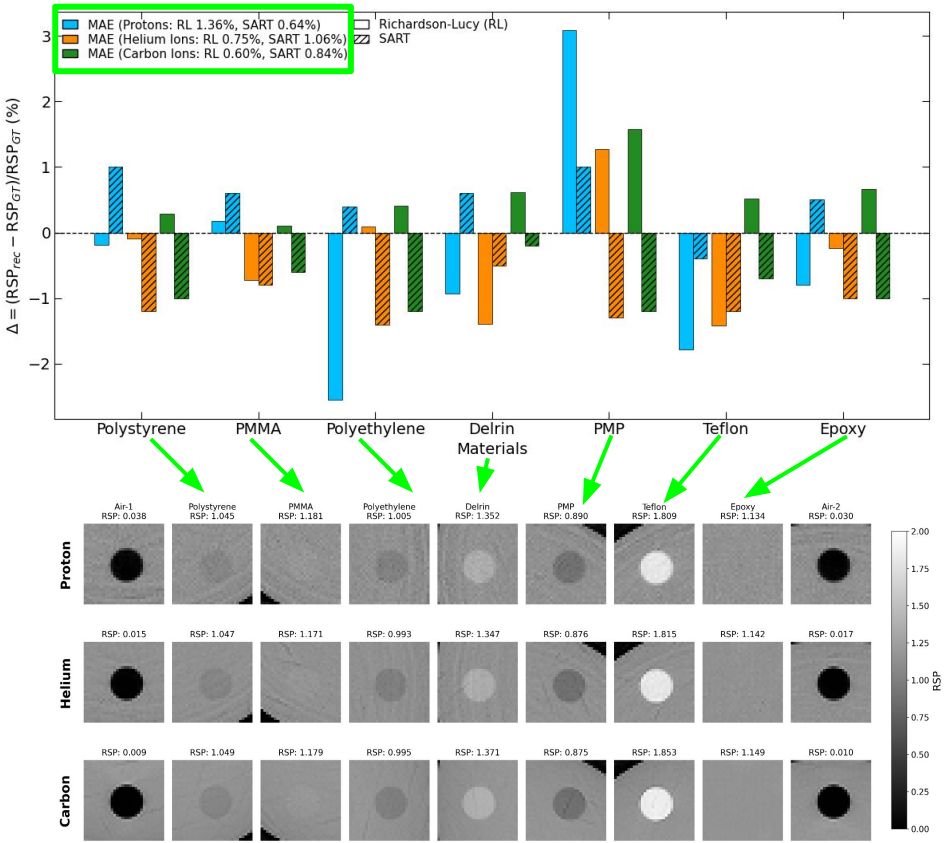




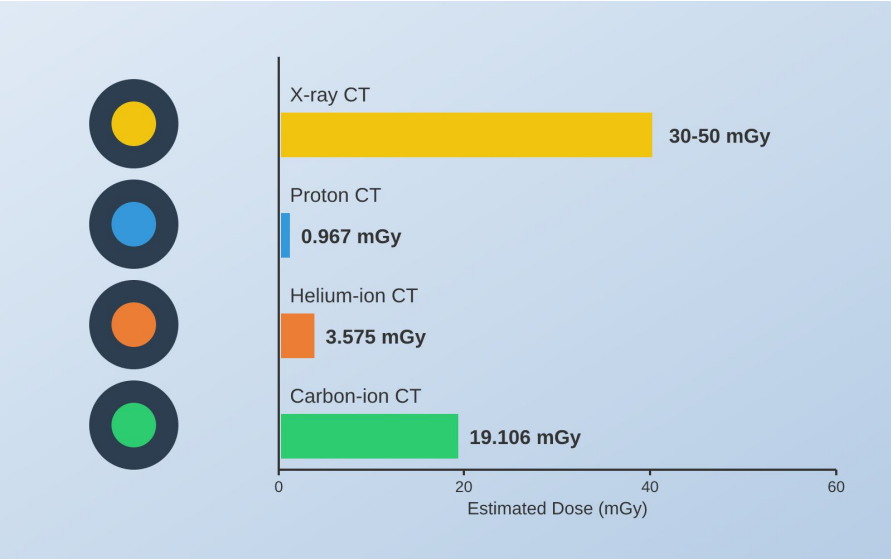


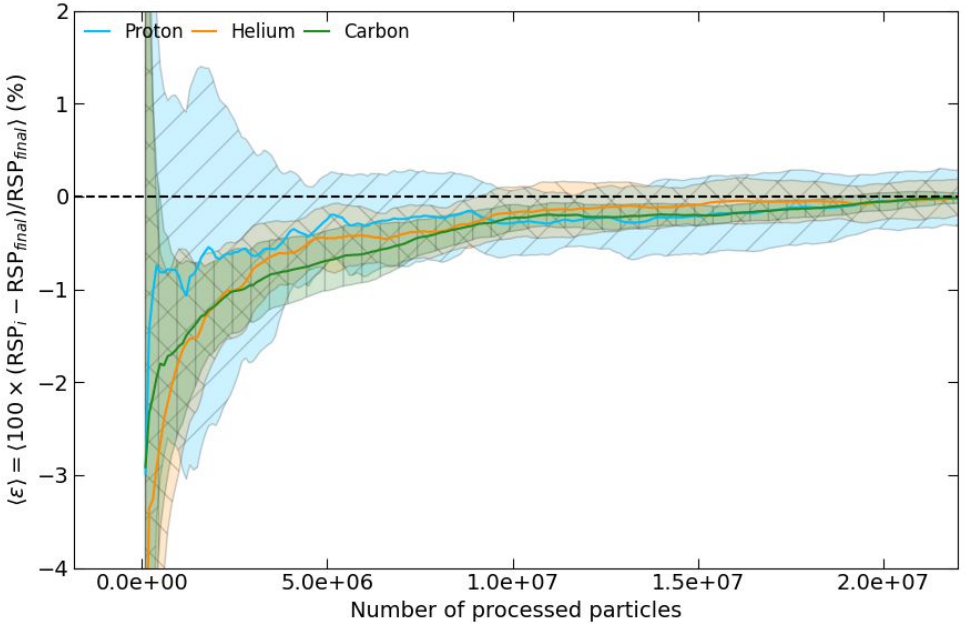
RSP reconstruction accuracy





Dose calculation

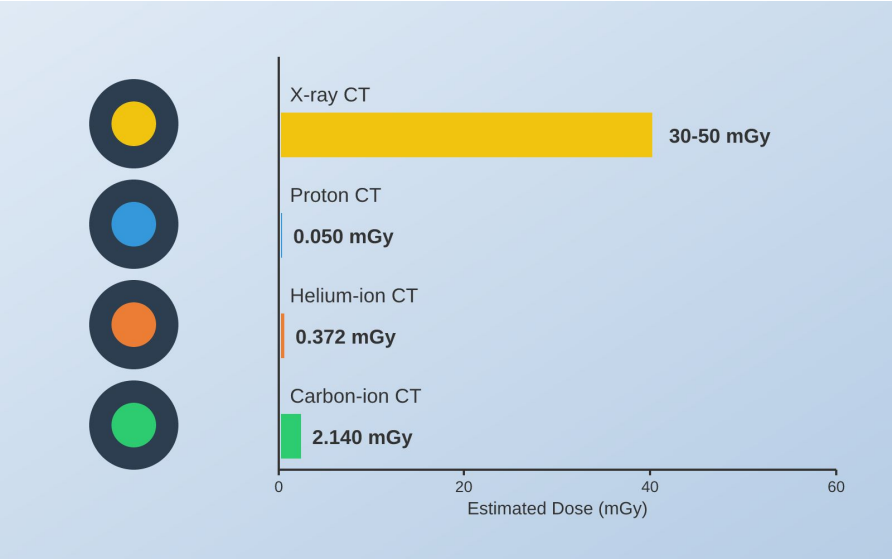


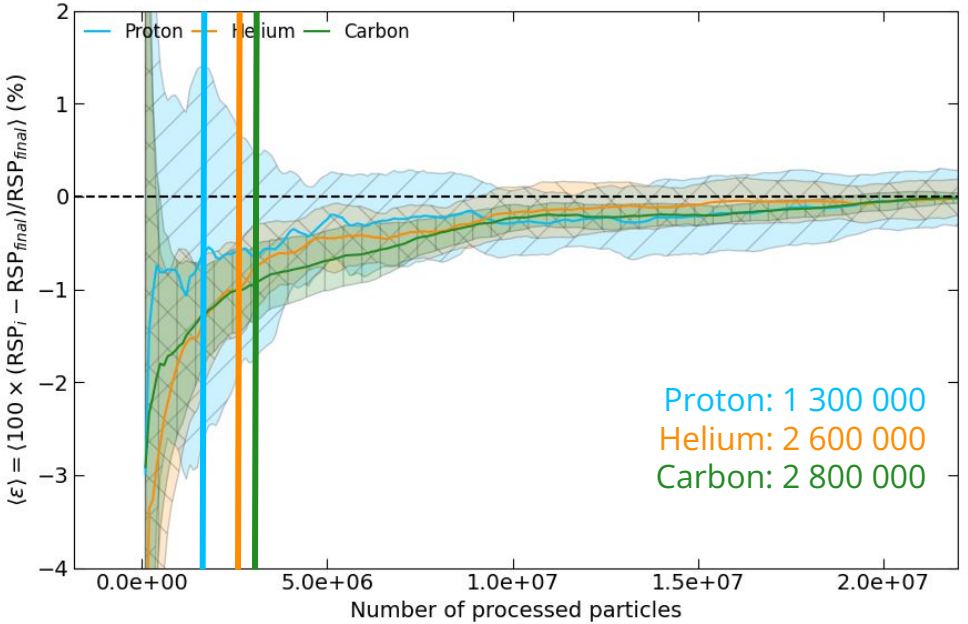


Physical dose calculated from simulations: less than the conventional X-ray CT dose for all three particles

Taking into account that the reconstruction accuracy converges → sufficient accuracy is available using less particles

Dose calculation

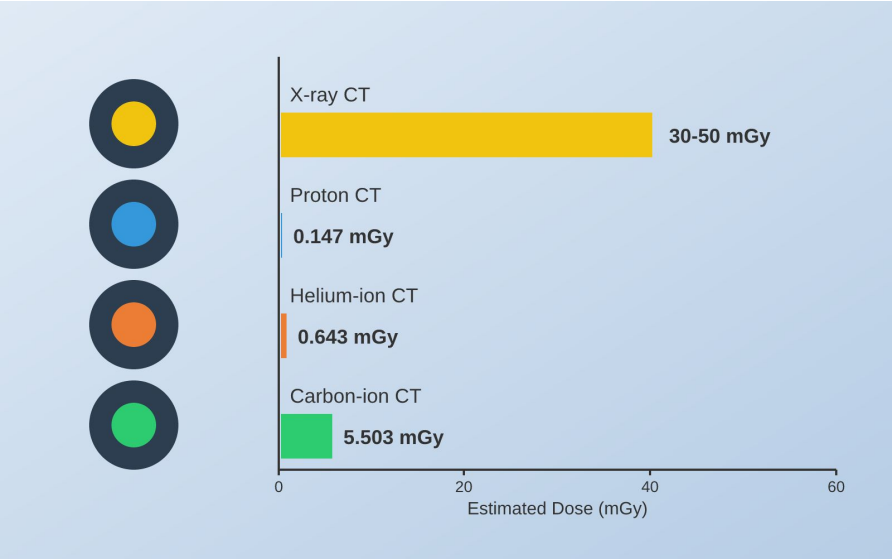


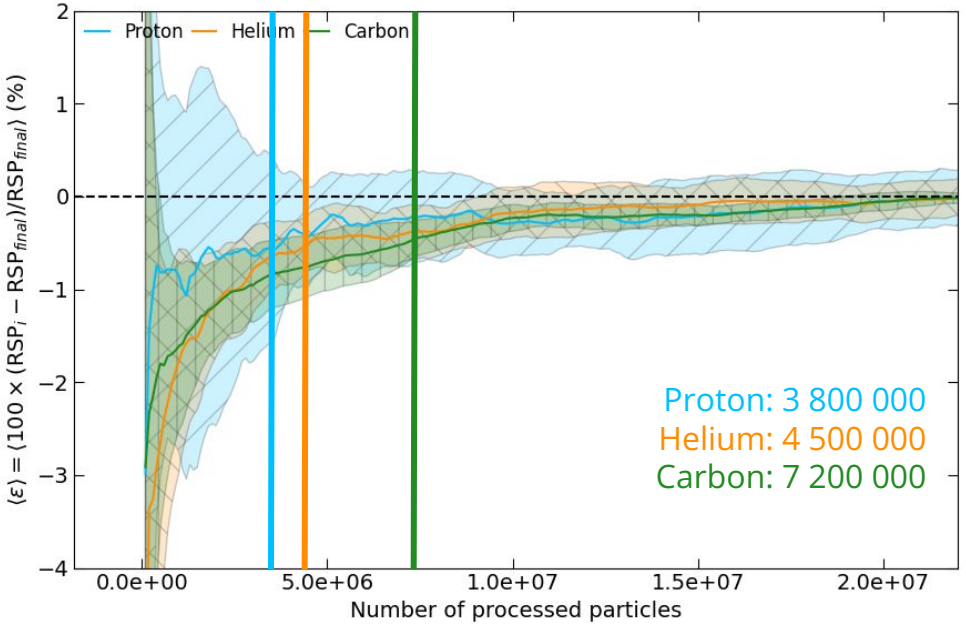


Taking into account that the reconstruction accuracy converges → sufficient accuracy is available using less particles

$\varepsilon \leq 1.0\%$

Dose calculation

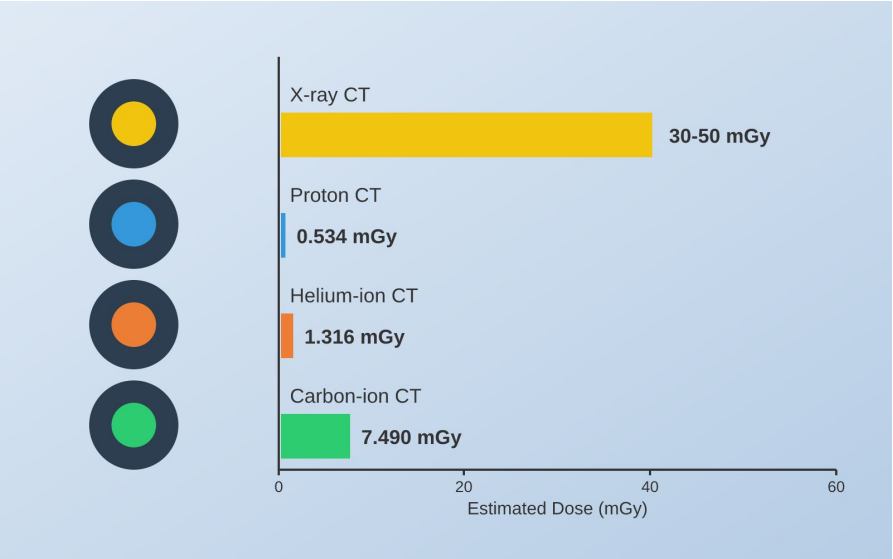


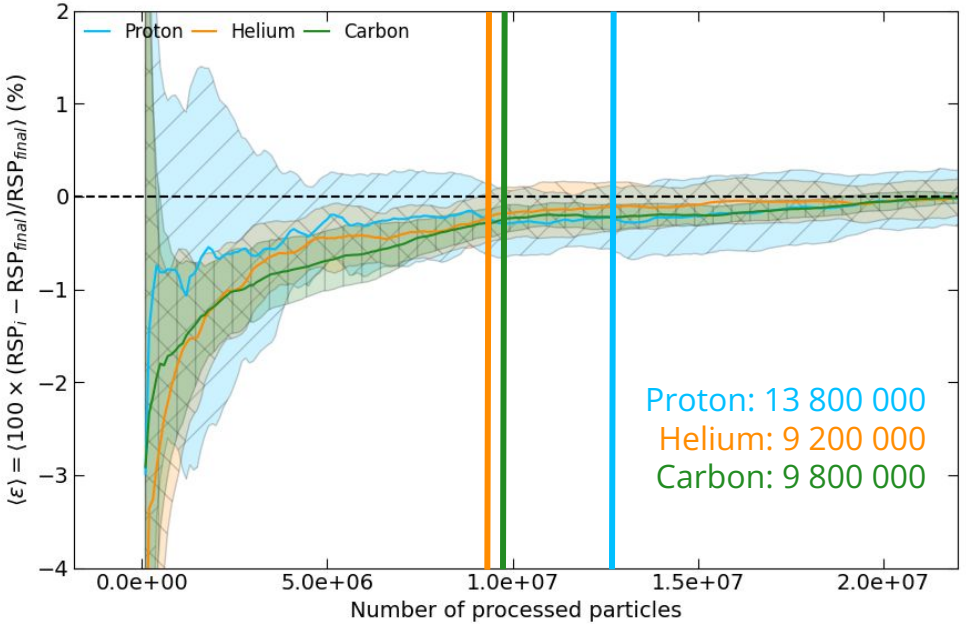


Taking into account that the reconstruction accuracy converges → sufficient accuracy is available using less particles

$\varepsilon \leq 0.5\%$

Dose calculation





Taking into account that the reconstruction accuracy converges → sufficient accuracy is available using less particles

$\varepsilon \leq 0.25\%$

Summary and Acknowledgements

- We compared different particles for CT imaging used in hadron therapy
- We made simulations on the CTP404 and Shepp-Logan phantoms, then reconstructed images with Richardson-Lucy deconvolution and SART algorithm
- Good RSP reconstruction accuracy in all cases (especially outstanding for helium and carbon ions, <1% error for most cases)
- Estimated dose deposit is smaller than for a conventional X-ray CT for all three particles
- Publication: Jólesz, Zsófia et al. (2026). Comparison of proton, helium-ion, and carbon-ion CT imaging for hadron radiotherapy using Monte Carlo simulations. *Physics in Medicine & Biology*. 10.1088/1361-6560/aeaf40.
- Future plans: extended testing, using realistic 3D phantoms, etc.

Thank you for your attention!

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