Diagnostic Proton Computed Tomography Using Laser-Driven Ion Ion Acceleration

Kaley Woods
RadiaBeam Technologies, LLC
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Outline

• Need for low-dose diagnostic computed tomography (CT)
• Proton CT (pCT)
  • Potential advantages of diagnostic pCT
  • Principles of pCT
• Current research at Loma Linda University Medical Center (LLUMC)
• Project approach and system requirements
• Challenges and possible solutions
Need for Low-Dose Diagnostic CT

- Over 62 million X-ray CT scans each year in U.S.
- High contrast and high spatial resolution of CT make it a crucial diagnostic tool
- X-ray CT dose 2 orders of magnitude higher than radiographs
  - Responsible for half of radiation from medical imaging in the U.S.
  - Radiation risk from CT in children is a special concern

Typical organ radiation doses from various radiologic studies

<table>
<thead>
<tr>
<th>Study Type</th>
<th>Relevant Organ</th>
<th>Relevant Organ Dose (mGy or mSv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dental radiography</td>
<td>Brain</td>
<td>0.005</td>
</tr>
<tr>
<td>Posterior–anterior chest radiography</td>
<td>Lung</td>
<td>0.01</td>
</tr>
<tr>
<td>Lateral chest radiography</td>
<td>Lung</td>
<td>0.15</td>
</tr>
<tr>
<td>Screening mammography</td>
<td>Breast</td>
<td>3</td>
</tr>
<tr>
<td>Adult abdominal CT</td>
<td>Stomach</td>
<td>10</td>
</tr>
<tr>
<td>Barium enema</td>
<td>Colon</td>
<td>15</td>
</tr>
<tr>
<td>Neonatal abdominal CT</td>
<td>Stomach</td>
<td>20</td>
</tr>
</tbody>
</table>

[D.J. Brenner et al, 2007]
Potential solution: Proton CT

- Estimated dose 0.03 – 0.3 mGy
  - ~100 times smaller than X-ray CT dose
- Not evaluated from absorption, like X-ray CT
- Quantitative imaging – faithful reproduction of small differences in electron density
- Many common applications:
  - Lung cancer screening
  - Bone density measurements
  - Kidney or urinary stone detection

Reconstructed images based on GEANT4-simulated 200 MeV pCT data of the illustrated phantom.

Principles of pCT

- Proton energy needed depends on object size
  - 250 MeV protons: 37.7 cm range in water
- Position-sensitive detectors track entry and exit of individual protons
- Energy detector/range counter measures energy loss of individual protons
- Iterative reconstruction algorithms use most likely path concept

Monte Carlo simulation of most likely paths for 200 MeV protons.

[Image of low intensity proton beam and tracking of individual protons.
[Courtesy of Reinhard Schulte, LLUMC]
Proton CT at LLUMC – Phase I

- pCT for improved treatment planning in proton therapy
- Proton relative stopping power reconstructed directly
- 2008 – 2010: Phase I scanner as proof of principle
  - Silicon strip detectors and data readout from Fermi Space Telescope
  - Multi-segmented crystal calorimeter
  - FPGA-based DAQ and GPU-based reconstruction

Proton radiographs of head (left) and hand phantoms (right).

[Courtesy of Reinhard Schulte, LLUMC]
2011 – 2015: Phase II scanner
- Twice the detector area
- “Slim-edge” silicon detectors
- Simple 5-stage scintillator-based energy detector

ASIC for data acquisition times <5 minutes
GPU cluster for reconstruction times <10 minutes

[Courtesy of Reinhard Schulte, LLUMC]
Diagnostic pCT System

LLUMC pCT scanner
- For treatment planning
- Uses therapeutic synchrotron
- 3-story, 90 ton gantry

Proposed pCT scanner
- For diagnostic use
- Uses laser-driven accelerator
- Compact, single-room
Diagnostic pCT Collaboration

RadiaBeam Technologies
- Accelerator components & diagnostics

Baylor University
- Dept. of Elec. & Comp. Eng.
- Computation

University of Haifa
- Dept. of Mathematics
- Reconstruction

Loma Linda University
- Dept. of Radiation Medicine
- pCT & medical expertise

Univ. of Texas at Austin
- Dept. of Physics
- Acceleration system

Univ. of Calif., Santa Cruz
- Inst. of Particle Physics
- Detector system

Ludwig-Maximilians-Universität München
- Dept. of Exp. Med. Physics
- International collaborator

pCT system for low-dose diagnostic imaging
• Need a compact, less expensive proton accelerator
• Must provide sufficiently high-energy and low-intensity
• Test the feasibility of using laser-driven ion acceleration (LDIA)
• Collaborating with Dr. Manuel Hegelich at UT Austin
• Demonstrated record-breaking laser-driven proton energies >160 MeV at LANL
• Now using Texas Petawatt Laser
### System Requirements

#### Specifications

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>330 MeV (60 cm range in water)</td>
</tr>
<tr>
<td>Intensity</td>
<td>$10^6$ protons/sec</td>
</tr>
<tr>
<td>Detection rate</td>
<td>&gt;1 MHz</td>
</tr>
<tr>
<td>Size</td>
<td>Single room</td>
</tr>
<tr>
<td>Scan time</td>
<td>~5 minutes</td>
</tr>
<tr>
<td>Cost</td>
<td>Comparable to X-ray CT</td>
</tr>
</tbody>
</table>

[Sadrozinski, NIMA 2012]
Potential Challenges

• Cost
  - Laser costs steadily decreasing as the technology advances
• Low intensity and high repetition rate required
  - Experiment with new acceleration techniques
  - Could instead improve spatial and time resolution of detectors
• Faster data acquisition and reconstruction
  - Develop ASIC for high-resolution tracking and energy detectors, use parallel reconstruction algorithms and GPGPU cluster for parallel processing
Acknowledgements

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