Robust and Efficient Methods for Proton Computed Tomography

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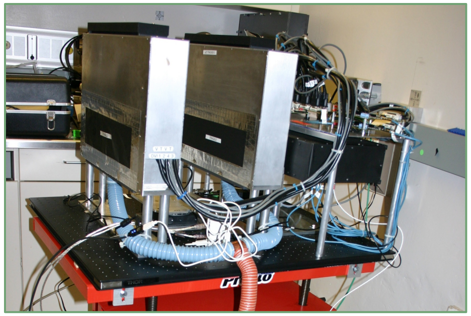

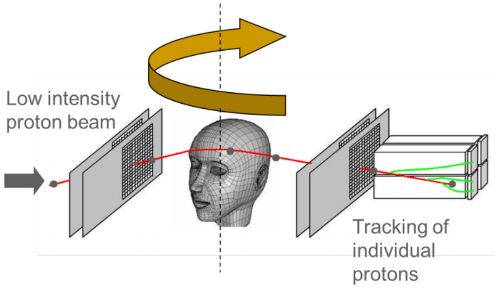

Outline

- Uncertainties in image reconstruction
  - How to address uncertainties
- Distributed GPU-based image reconstruction on a single node

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Slow convergence

- DROP: Sensitive to initial iterate
- FBP used as the initial iterate
  - Teflon ~ -7.0%, PMP ~ -2.31%
- RSP >> 1 -> converge slow
- Incorporating an accelerator: $|1 - x(k)|\eta$

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Robust estimation

- Addressing the uncertainties in a system:
- $x = (A^T \phi A + \Psi I)^{-1} A^T b$
- Select ϕ and Ψ based on the robust method
- Example:
  - Total least squares
  - $\Phi = I$ and $\Psi = -\sigma_{n+1} I$
  - $-\sigma_{n+1} \rightarrow$ smallest singular value of [A b] matrix

Designing sparse compatible robust iterative solver

$$\begin{cases} \text{minimize}_x & \frac{1}{2}\|x - x(0)\|_\Psi^2 \\ \text{subject to} & \Phi^{\frac{1}{2}} A x = \Phi^{\frac{1}{2}} b, \end{cases}$$

- Gradient descent method with the unit step for the dual problem

$$x(k+1) = x(k) + \Psi^{-1} A^T \phi (b - Ax(k))$$

Fully-simultaneous adaptive iterative solver (FSAIS)

$\Psi^{-1} \rightarrow |1 - x(k)|\eta$ $\quad$ $\phi \rightarrow I$

Choosing elements of Ψ^{-1}

- Define intervals <= the number of materials, r
- For each interval r,
  - $if\ (l_r < x(k)_j < u_r)$=> $\psi^{-1}(j) \sim |1 - x(k)_j|\eta_r$
  - Select l_r close to the mean RSP of a known material at the initial iterate
  - $u_r = l_r + w_r$
  - w_r range from 0.04 to 0.5
  - η_r <= 0.00015

Experiments and analysis

- Experiments
  - Normal conditions
  - Removing protons from angle intervals during image reconstruction
    - Available proton energy is too small to penetrate the object in certain directions (e.g. pelvis)
- Experimental Data
  - CTP404
  - Pediatric head phantom

Experimental CTP404 - DROP

Teflon: -8.54 %

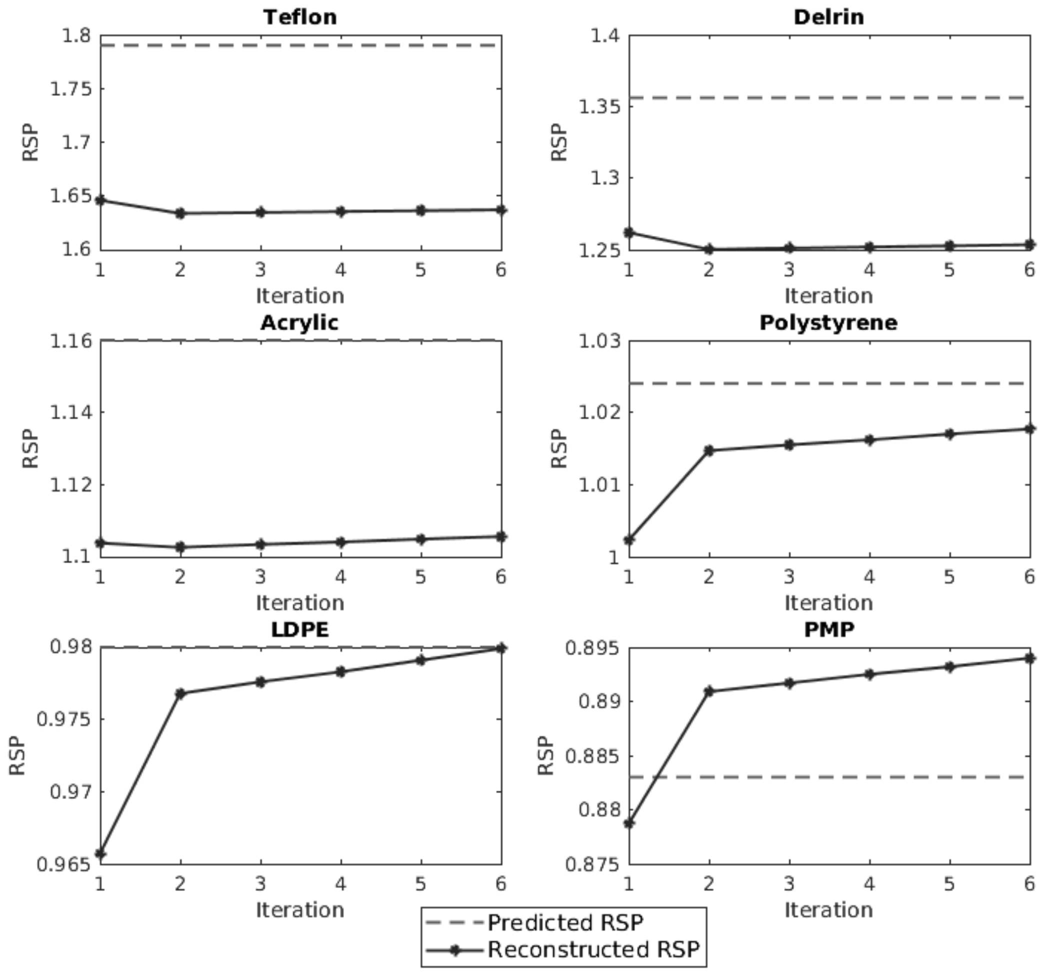
Delrin: -7.56 %

Acrylic: -4.69 %

Poly: -0.61 %

LDPE: -0.01 %

PMP: 1.25 %



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Experimental CTP404 - FSAIS

Teflon: -0.43 %

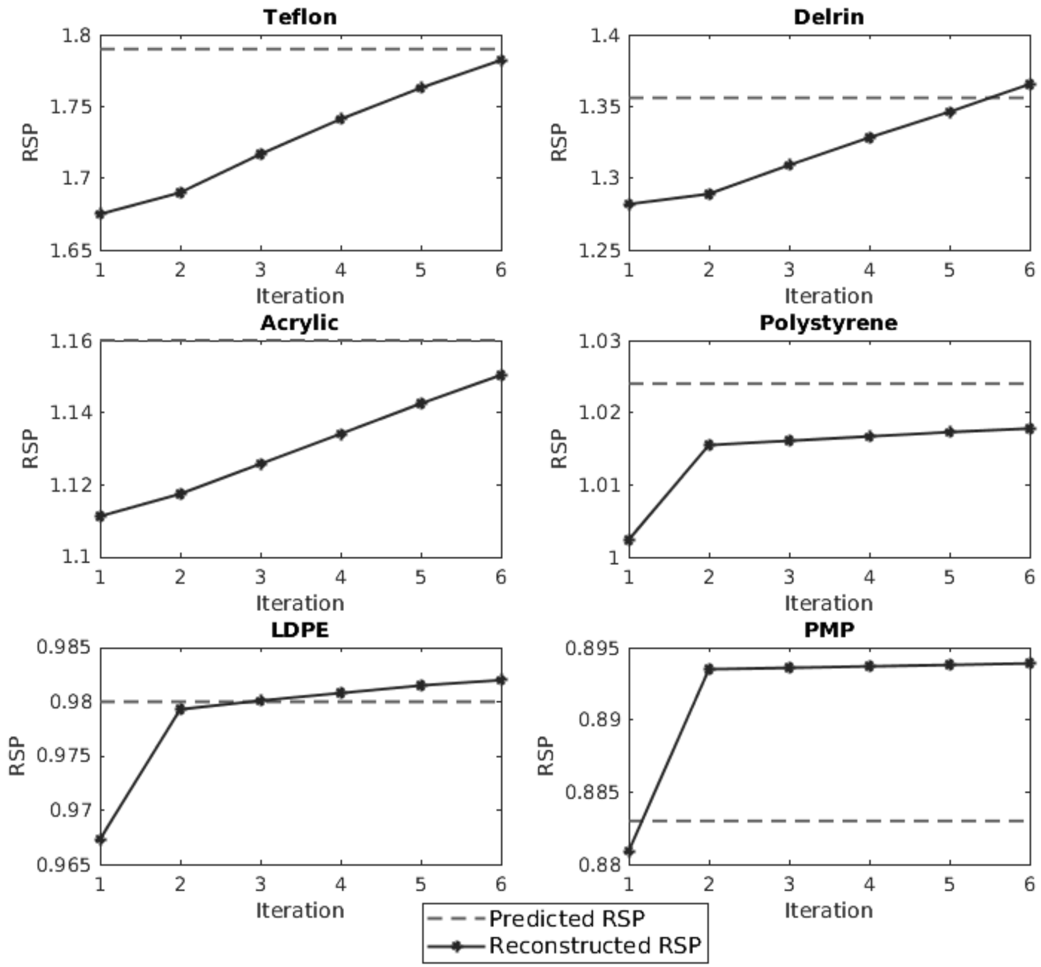
Delrin: 0.7 %

Acrylic: -0.83 %

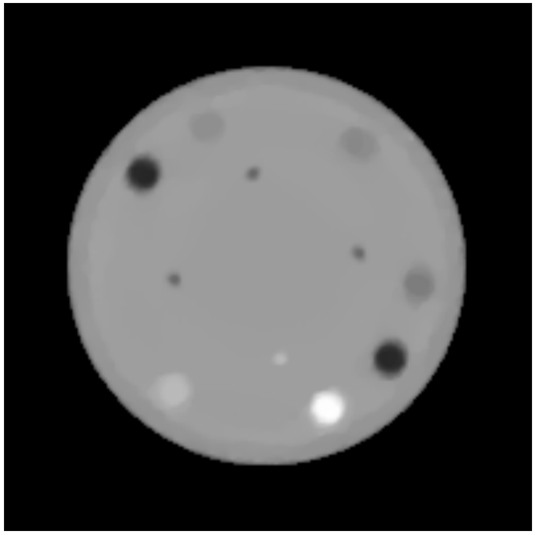
Poly: -0.61 %

LDPE: 0.21 %

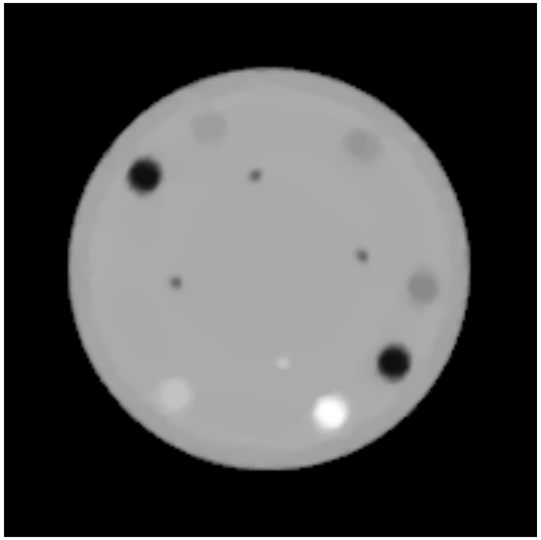
PMP: 1.25 %



Reconstructed pCT images



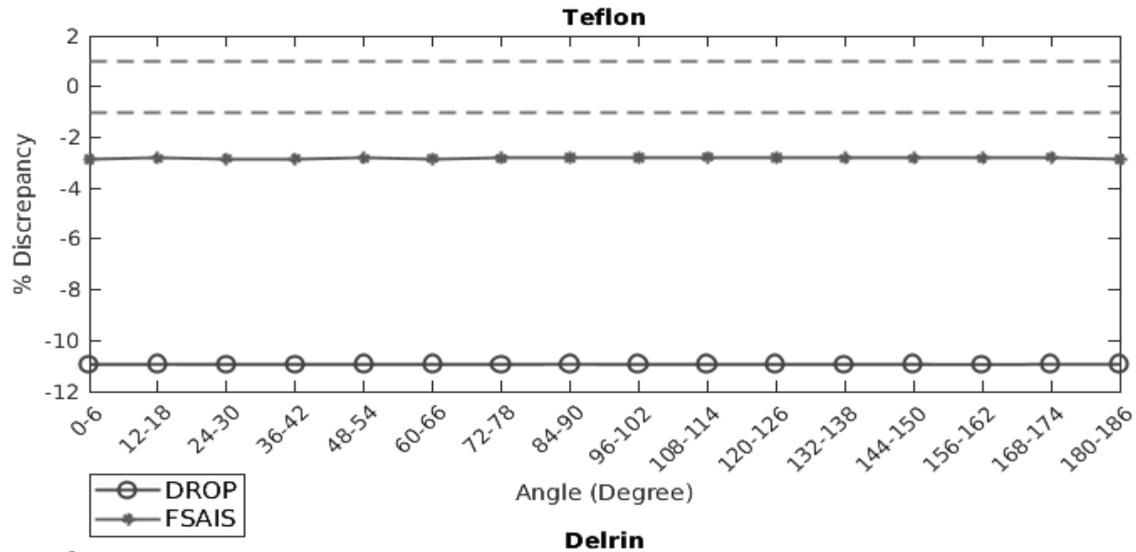
FSAIS



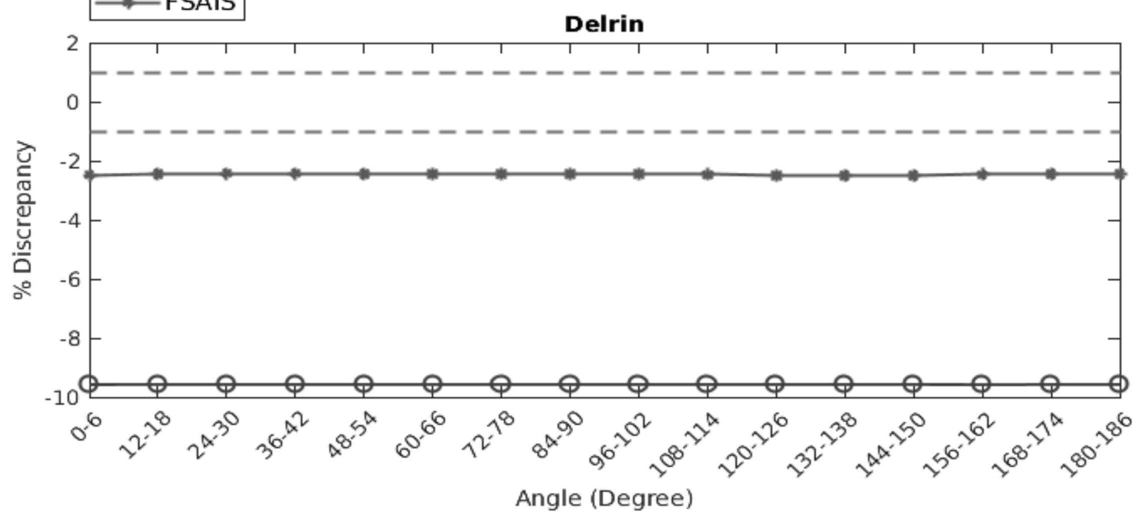
DROP

Removing protons before performing the iterative solver

Initial iterate Teflon
RSP: -7.0%

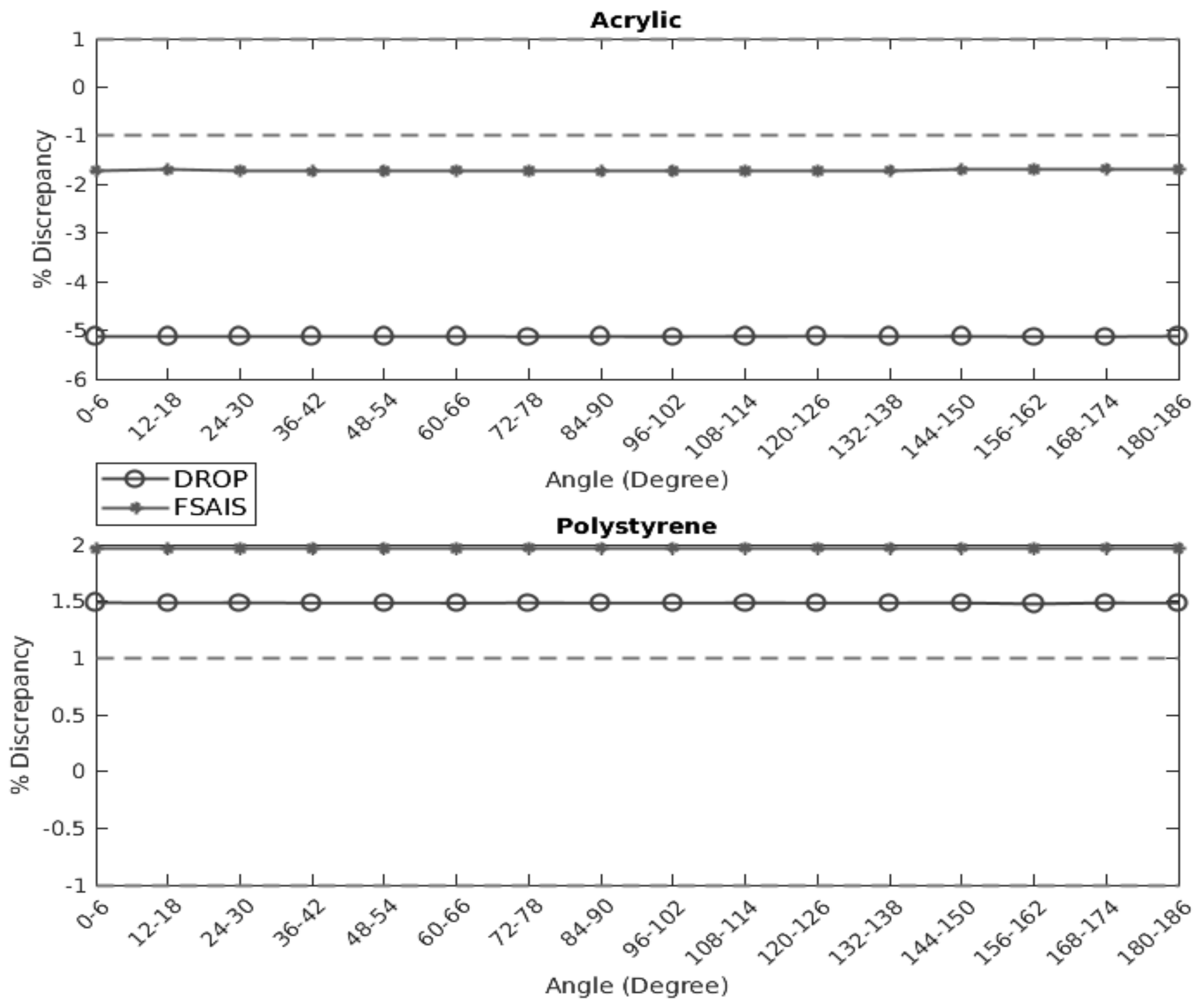


Initial iterate Delrin
RSP: -5.94%

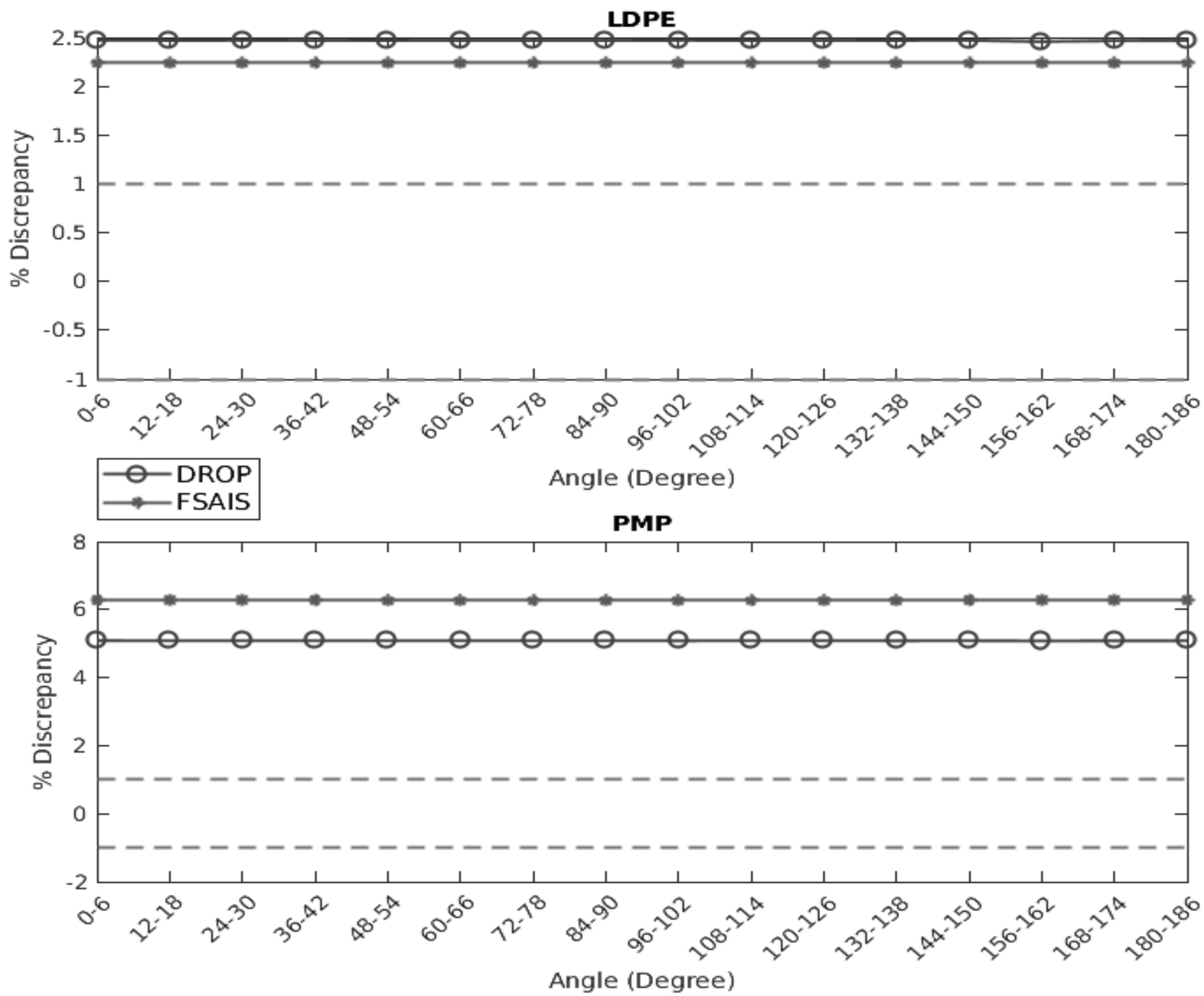


Removing protons during performing the iterative solver

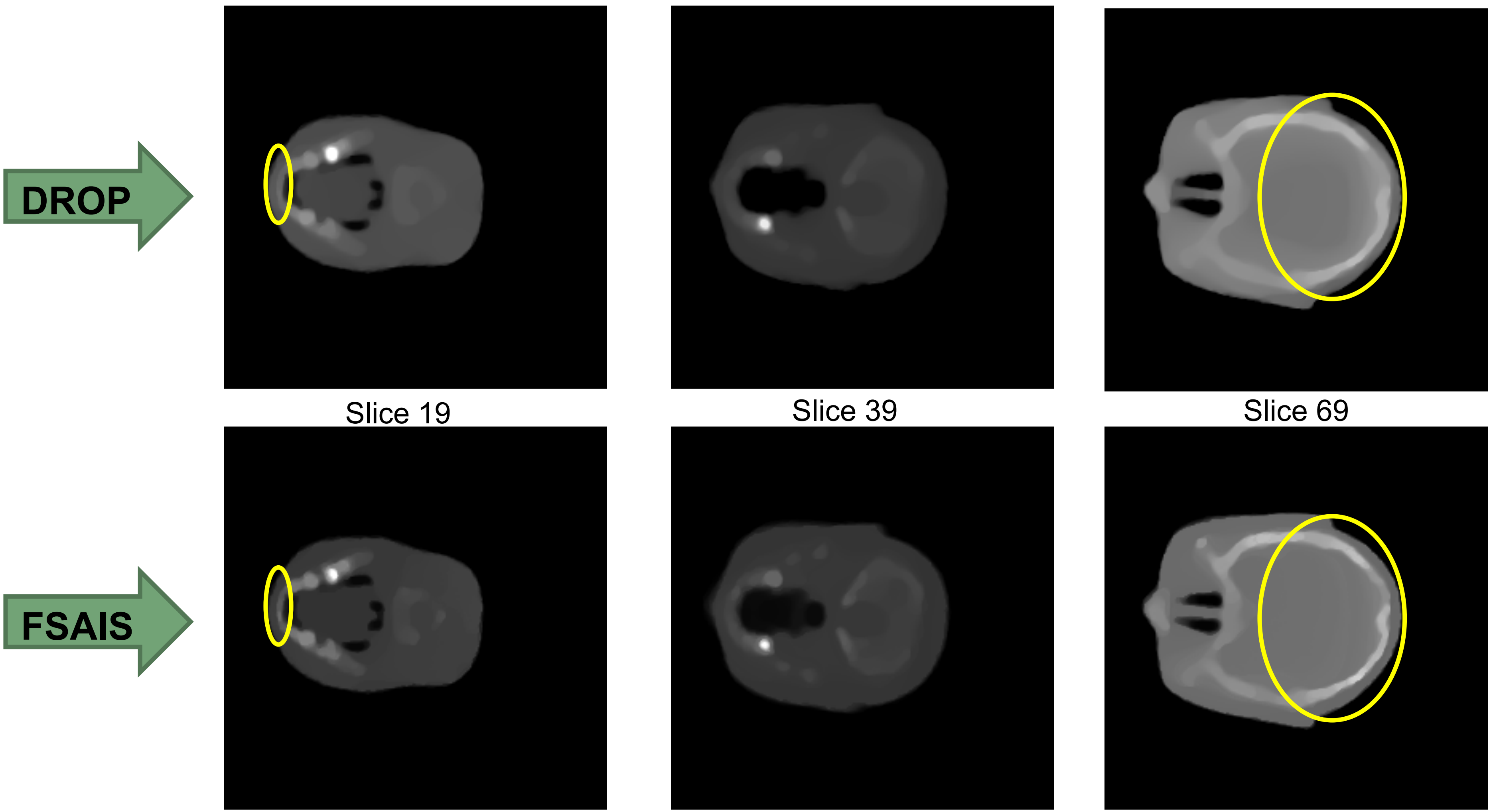
Initial iterate Acrylic RSP: -4.75%



Removing protons during performing the iterative solver



pCT images of experimental PedHead



Experimental pediatric head RSP accuracy

Material	DROP (Mean RSP ± SD)	% Discrepancy	FSAIS (Mean RSP ± SD)	% Discrepancy
Soft Tissue	1.0423 ± 0.0222	0.51	1.0432 ± 0.0234	0.6
Brain Tissue	1.0572 ± 0.001	0.97	1.0485 ± 0.0025	0.14
Trabecular bone	1.1077 ± 0.0033	-0.03	1.1169 ± 0.0117	0.8
Tooth Dentin	1.3857 ± 0.0372	-8.41	1.7359 ± 0.0692	9.73
Tooth Enamel	1.3857 ± 0.0372	-22.5	1.7359 ± 0.0692	-2.91

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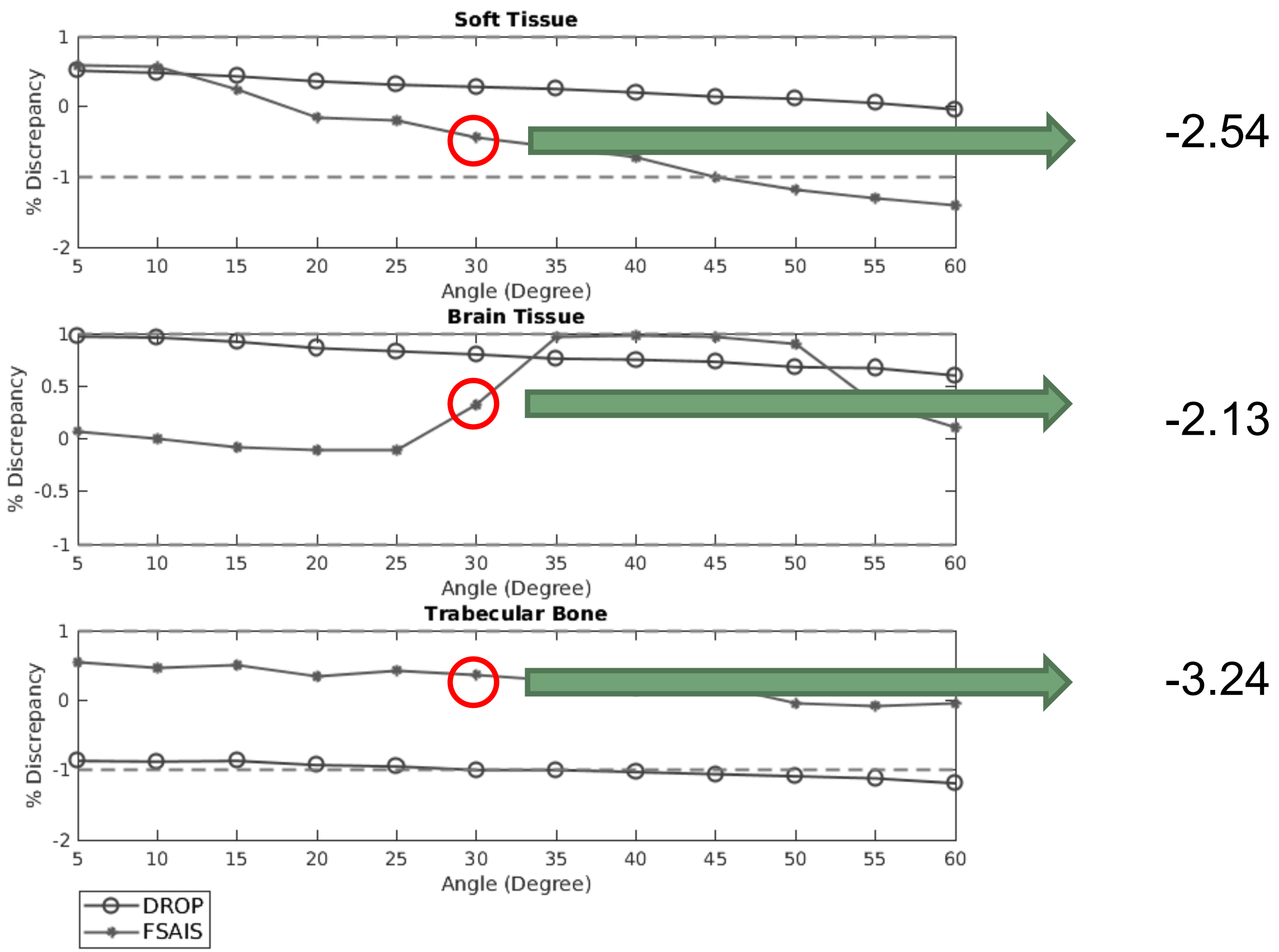
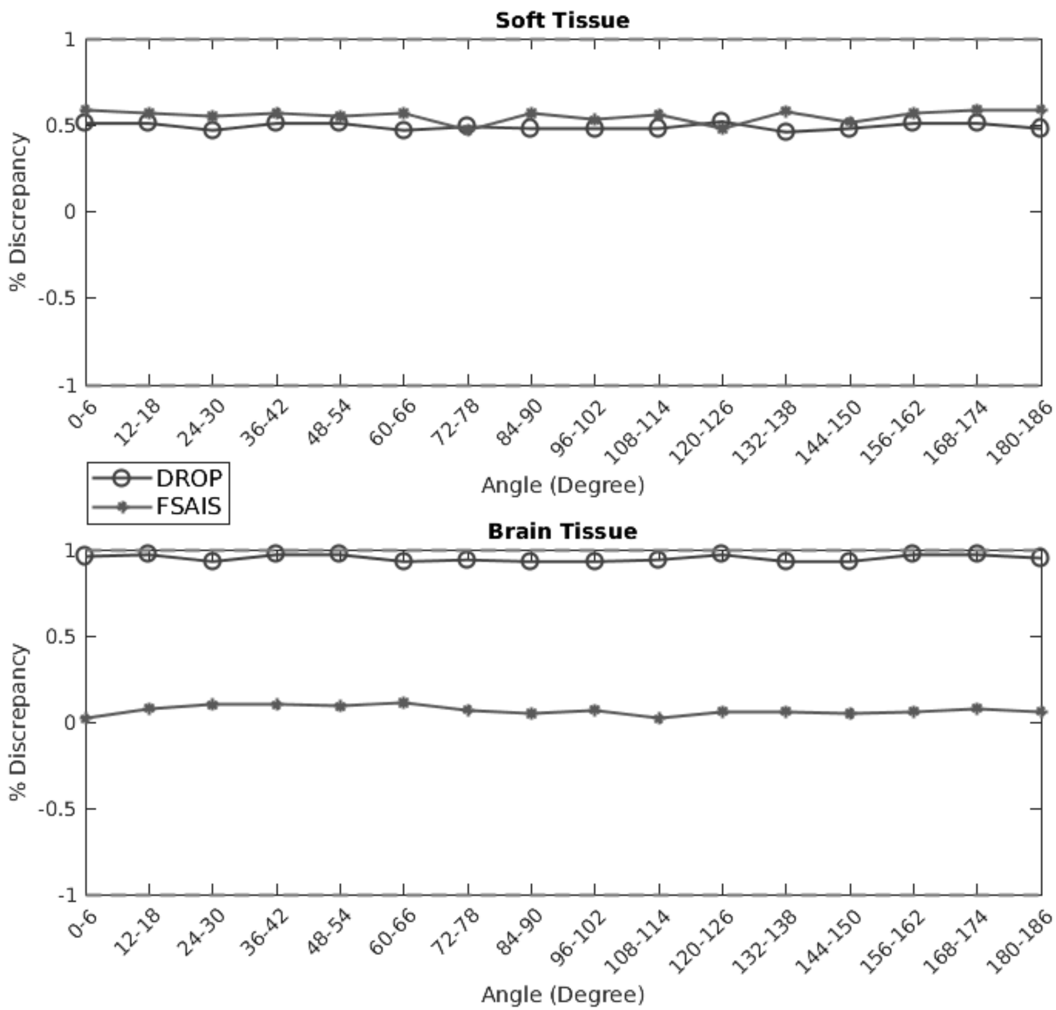
Removing protons before performing the iterative solver on PedHead dataset



Removing protons during performing the iterative solver on PedHead dataset – Soft and brain tissues



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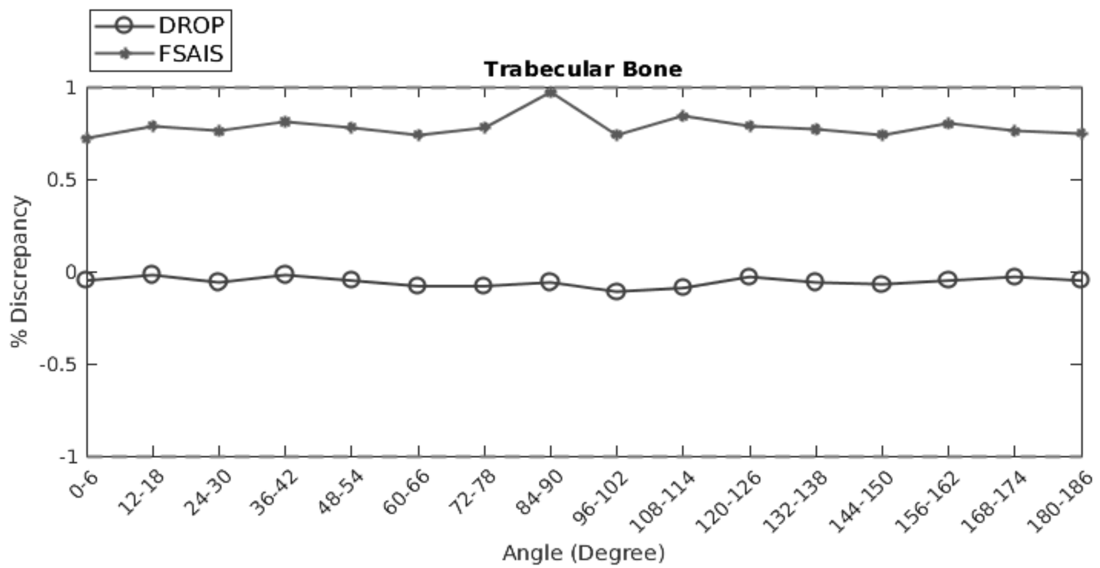
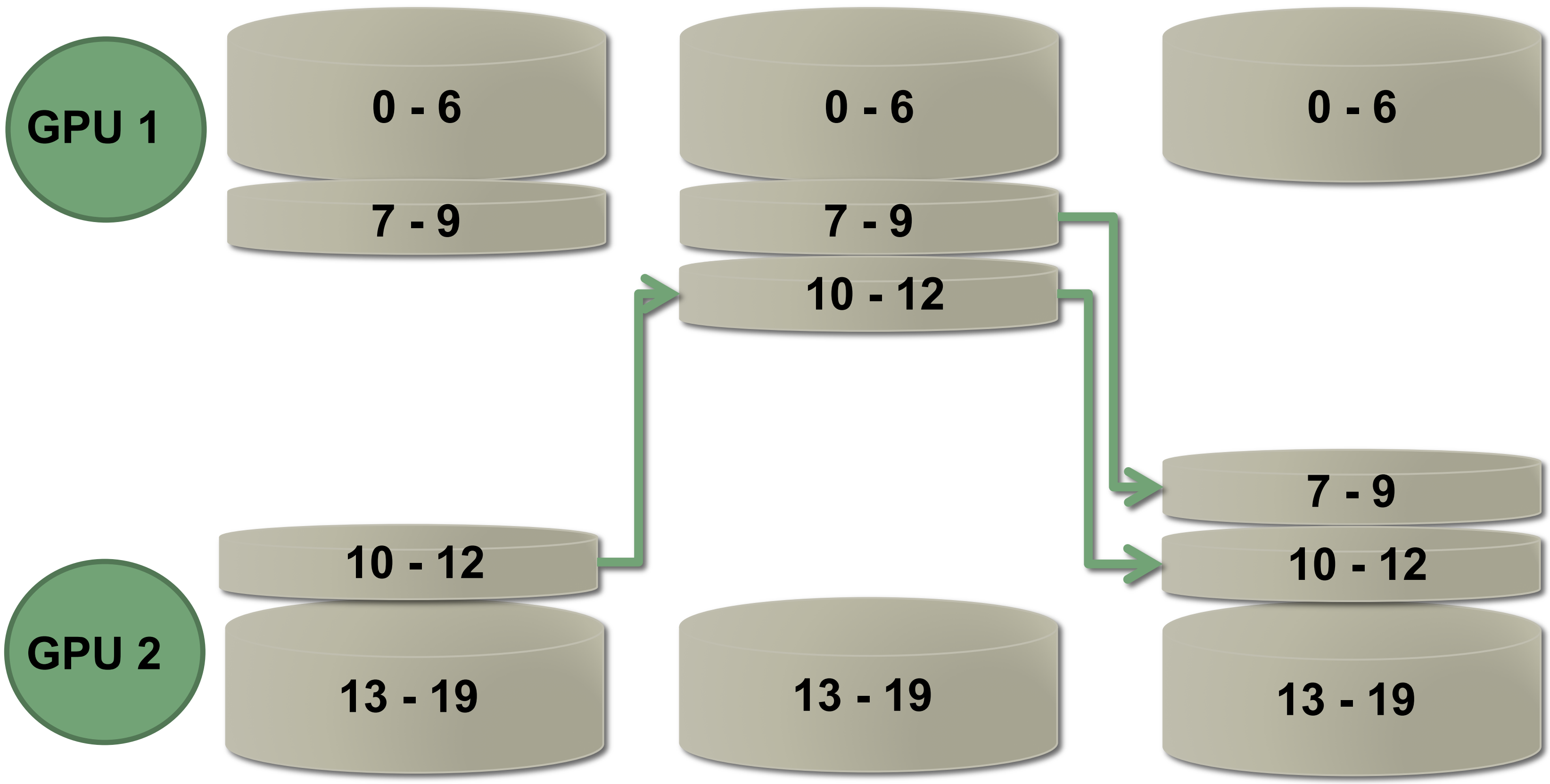
Removing protons during performing the iterative solver – Trabecular bone



Distributed GPU-based image reconstruction (DGIR) with data transfers



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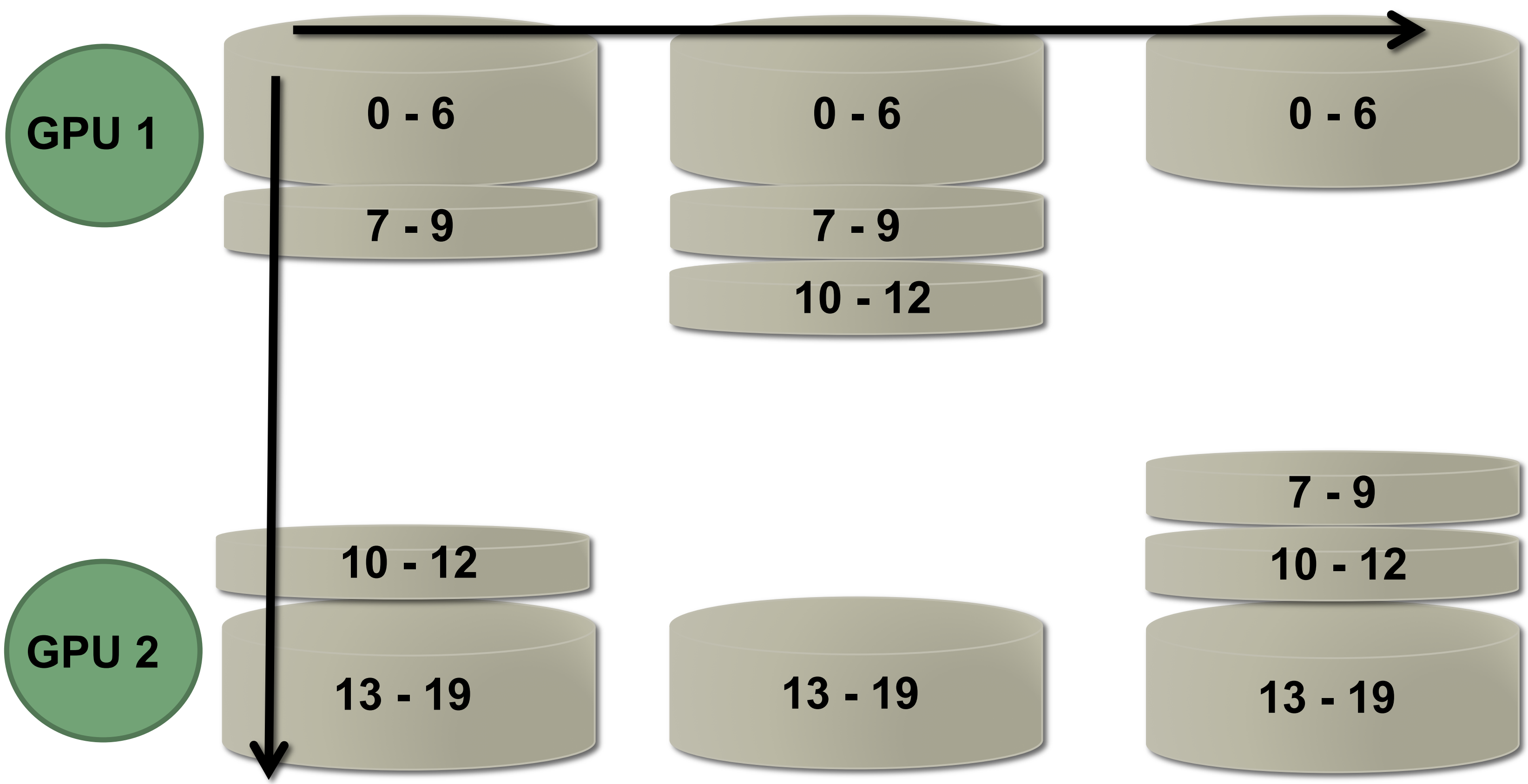
Implementation of distributed GPU-based image reconstruction (DGIR) with data transfers



Runtime of DGIR with data transfers for experimental pediatric head phantom

- Data transfers: P2P
- GPUs: K40
- 251 millions total protons
- Algorithm : DROP
- Total reconstruction runtime: 3.4 minutes

Material	Mean RSP	% Discrepancy
Soft Tissue	1.0329	0.56
Brain Tissue	1.0437	0.4
Trabecular bone	1.1189	-0.24
Tooth Dentin	1.5161	0.2
Tooth Enamel	1.5161	-15.2

Summary

- Goals: accuracy and speed
- Problem: Sensitivity to the initial iterate
- Potential problem: Missing protons from some directions
- Future work
    - Explore different combinations of ϕ and Ψ