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Proton Range Verification using Protoacoustics and Artificial Intelligence

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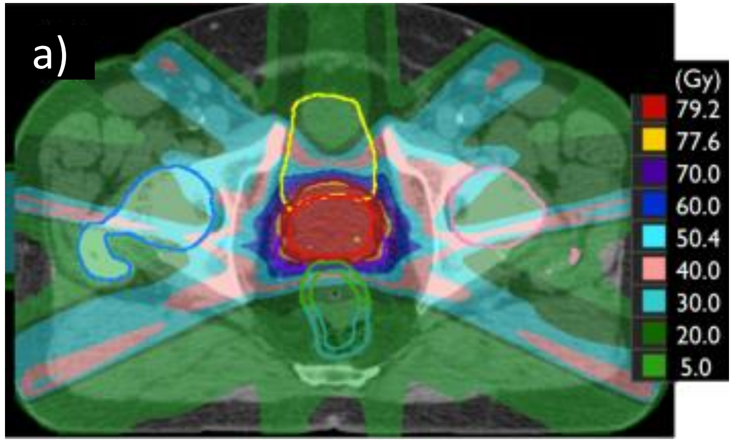
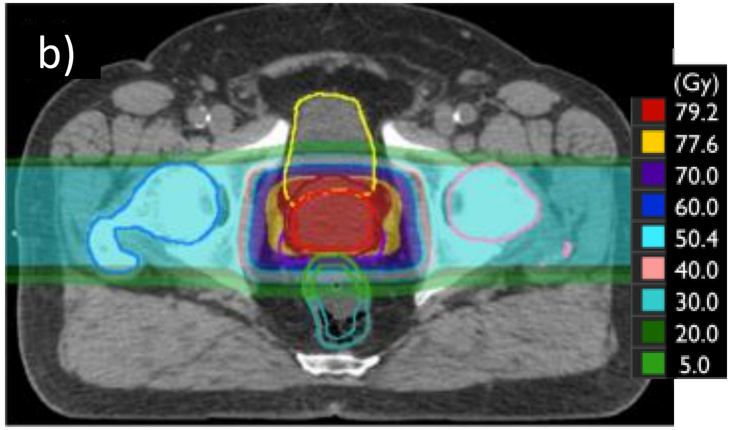
IGFAE workshop on technologies and applied research at the future Galician proton-therapy facility 10/05/2023

Protontherapy



Photon Dose Distribution



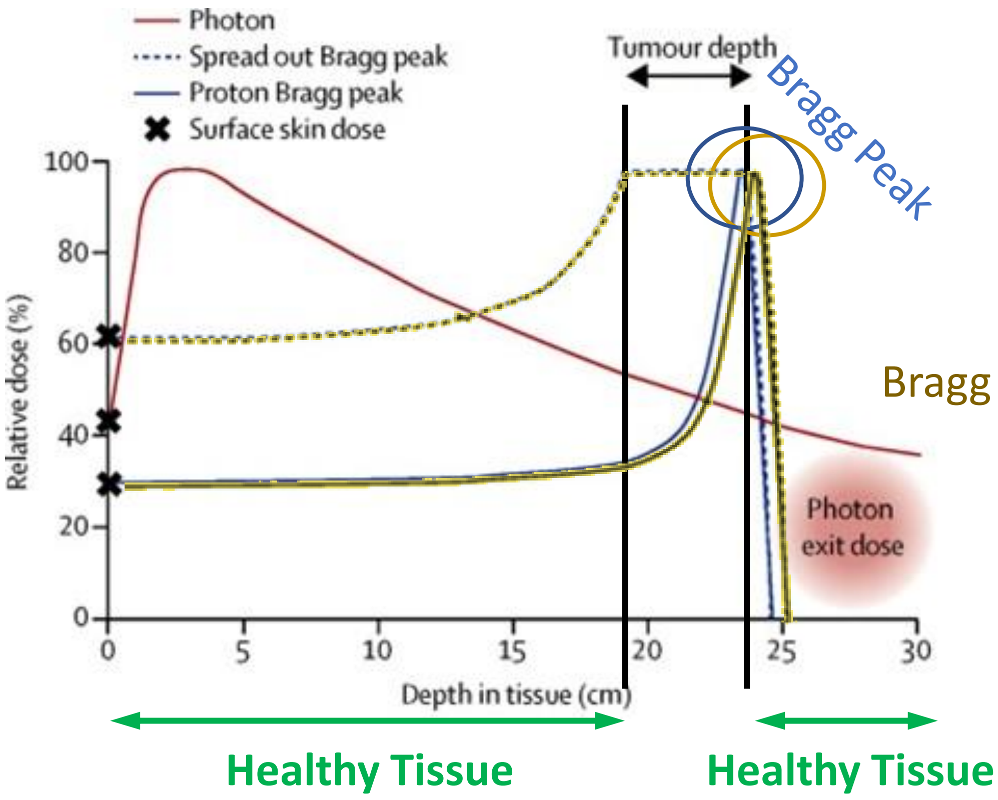
Proton Dose Distribution

Benefits:

- More conformal dose distribution
- Lower dose in healthy tissue

[Kamran et al. Prostate Cancer Prostatic Dis. 22, 2019]

Problem: Proton Range Uncertainty



ERROR

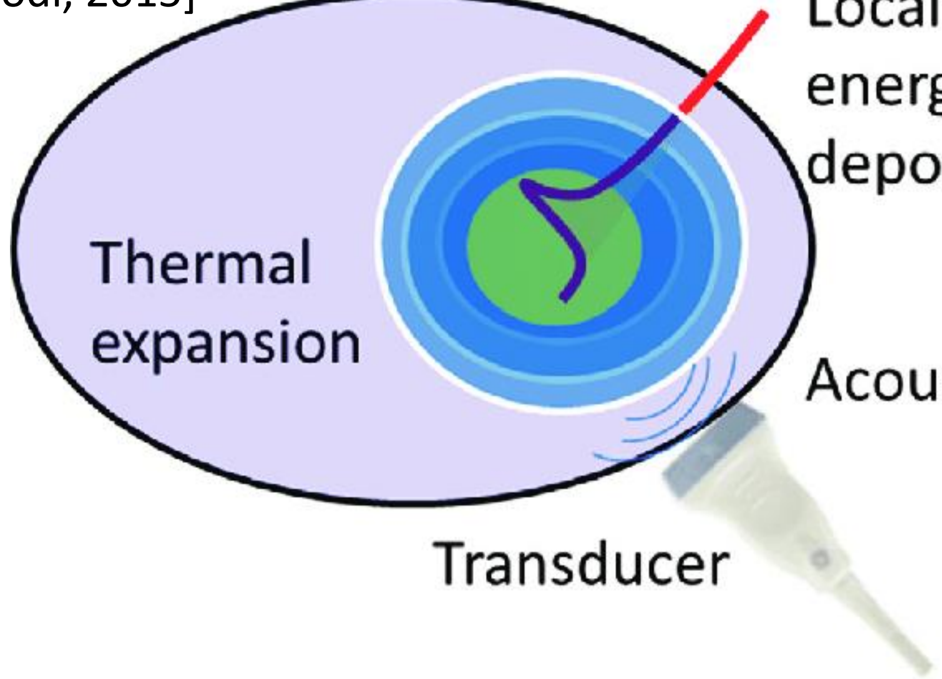
Bragg Peak in Healthy Tissue

Solution: Proton Range Verification

[*Image adapted from* Leeman et al. Lancet Oncol. 18(5), 2017]

Protoacoustic. Thermoacoustic effect

[Parodi, 2015]



Initial pressure distribution

Dose Density

$$p_0(\vec{r}) = \Gamma\, D(\vec{r})\, \rho(\vec{r})$$

$$\Gamma = \frac{\beta c^2}{C_p}$$

Grüneisen coefficient

$$\Gamma_{water} = 0.11$$

$$p_0(\vec{r}, t) = p_0(\vec{r})\mathrm{G(t)}$$

proton pulse temporal profile

Wave propagation:

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right) p\,(\mathbf{r}, t) = -\Gamma \frac{\partial}{\partial t}\mathcal{H}\,(\mathbf{r}, t)$$

Wave equation

Source term: deposited energy

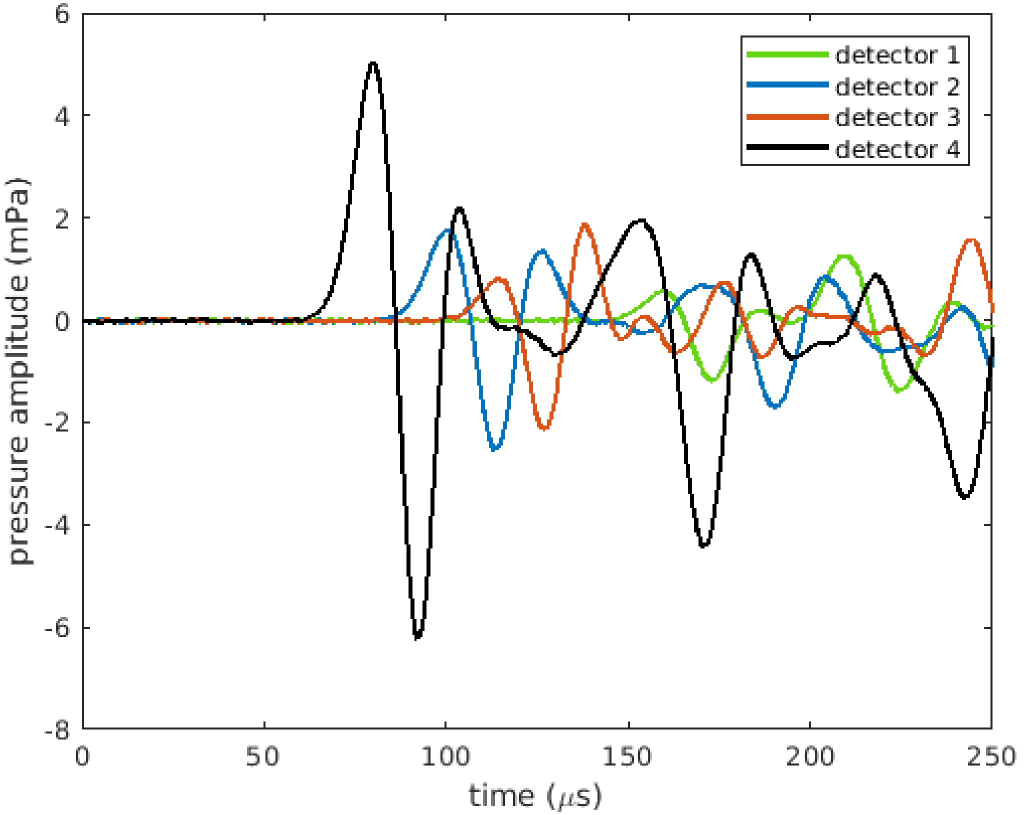
Solution (in homogeneous media):

$$p\,(\mathbf{r}_s, t) = \frac{1}{4\pi c}\frac{\partial}{\partial t}\int_{|\mathbf{r}_s - \mathbf{r}| = ct} \frac{p_0\,(\mathbf{r})}{|\mathbf{r}_s - \mathbf{r}|}\delta\,(t)\, d\mathbf{r}$$

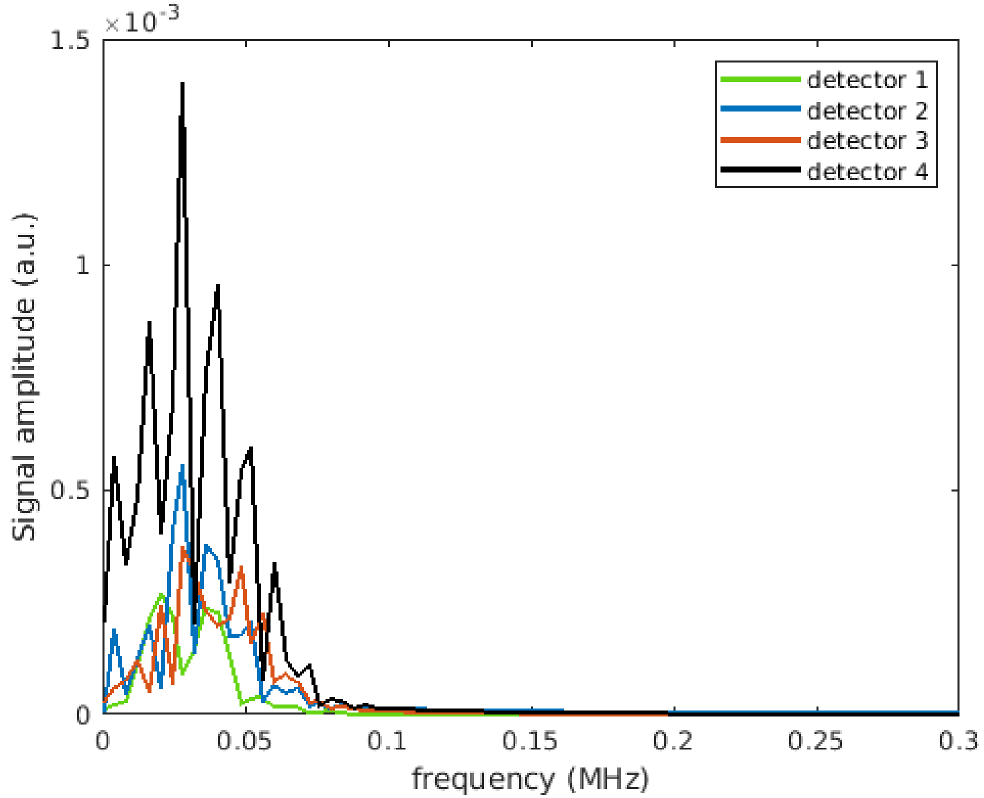
Time dependence Spatial dependence

Example of Protoacoustic Signals

Simulated Acoustic Signals induced by Proton Beam



Maximum pressure amplitude ~**mPa**

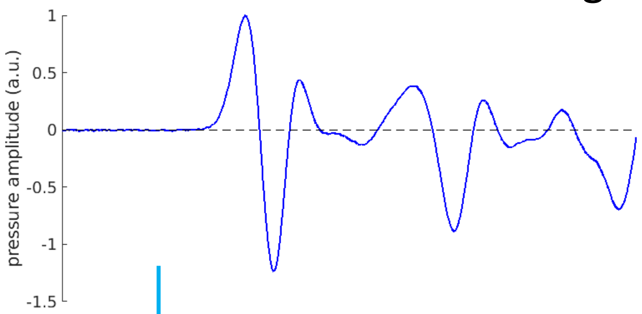


- Frequency spectrum from **8 to 100 kHz**
- Central frequency of **28 kHz**
- Frequency ≪ 1 MHz → **Attenuation negligible** in **soft tissue**

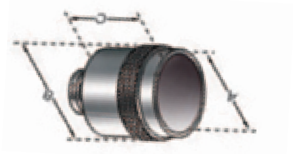
In Vivo Range Verification Techniques

- **Nuclear** activation **techniques**: **PET** and **prompt-**gamma imaging
- **Alternative technique**: **Protoacoustics**

4 Acoustic signal

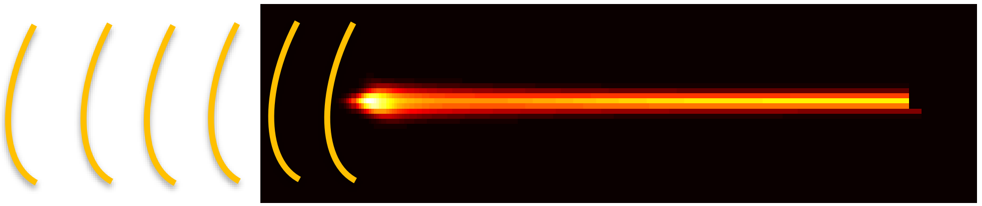


3 Ultrasonic Detector



2 Acoustic waves

1 Proton Beam Dose deposition



5 Dose image reconstruction

Advantages

- Less bulky equipment
- More cost-effective

Disadvantages

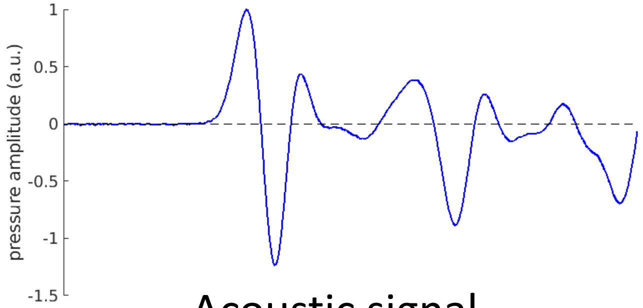
- Transducers should be placed in contact with the patient
- High computational cost

Dose Reconstruction from Protoacustic Signals

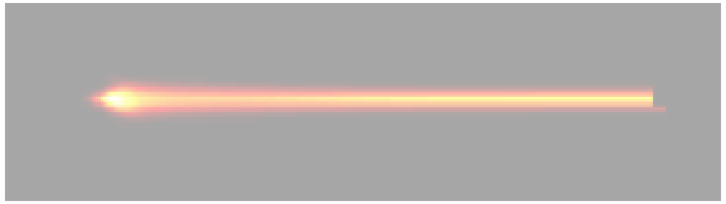
METHOD 1 – Iterative Reconstruction

METHOD 2 – Dictionary-based Reconstruction

METHOD 3 – Deep-Learning-based Reconstruction



Acoustic signal



Dose image reconstruction

1) Dose Reconstruction with a Linear Model

Measured Pressure (y)

Model Matrix (A)

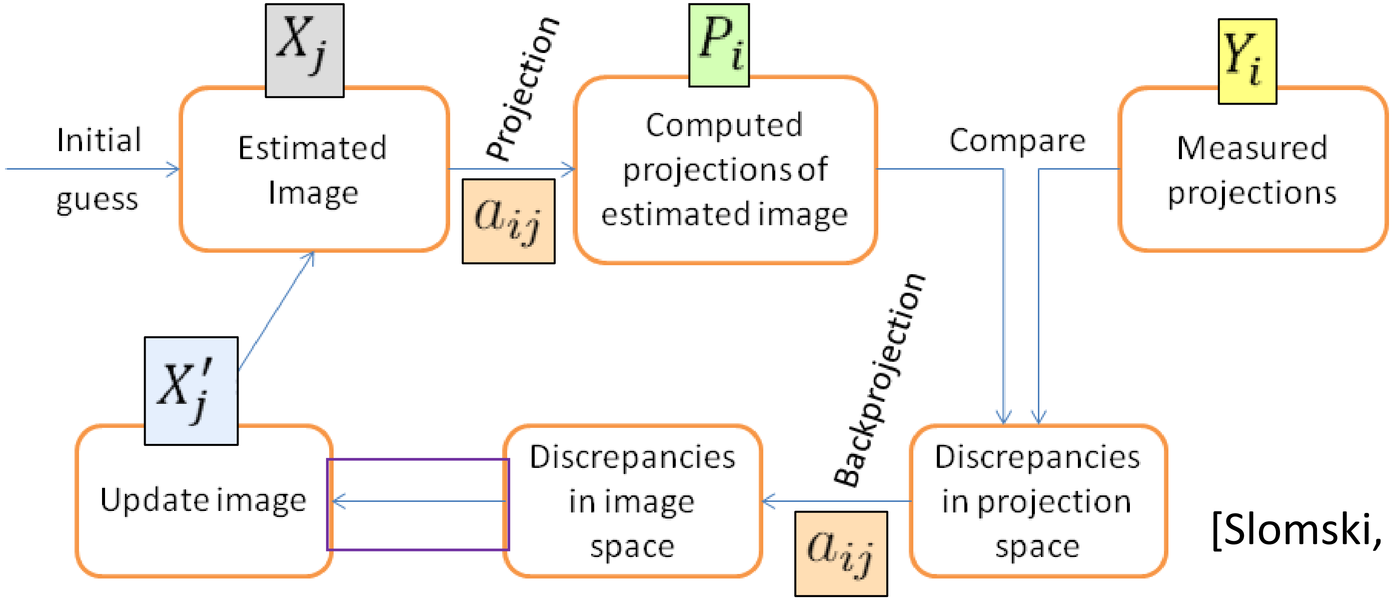
Initial Pressure (x)

$$p_0(\vec{r}) = \Gamma D(\vec{r})\rho(\vec{r})$$

$$p(\vec{r}_s, t) = \frac{1}{4\pi c}\frac{\partial}{\partial t}\int_{|\vec{r}_s - \vec{r}| = ct} \frac{p_0(\vec{r})}{|\vec{r}_s - \vec{r}|}\delta(t)\, d\vec{r}$$

$$y = Ax$$

1) Iterative Reconstruction Algorithms



[Slomski, 2014]

Gradient-descent algorithm

$$X'_j = X_j + 2\lambda \sum_i (Y_i - P_i) \cdot a_{ij}$$

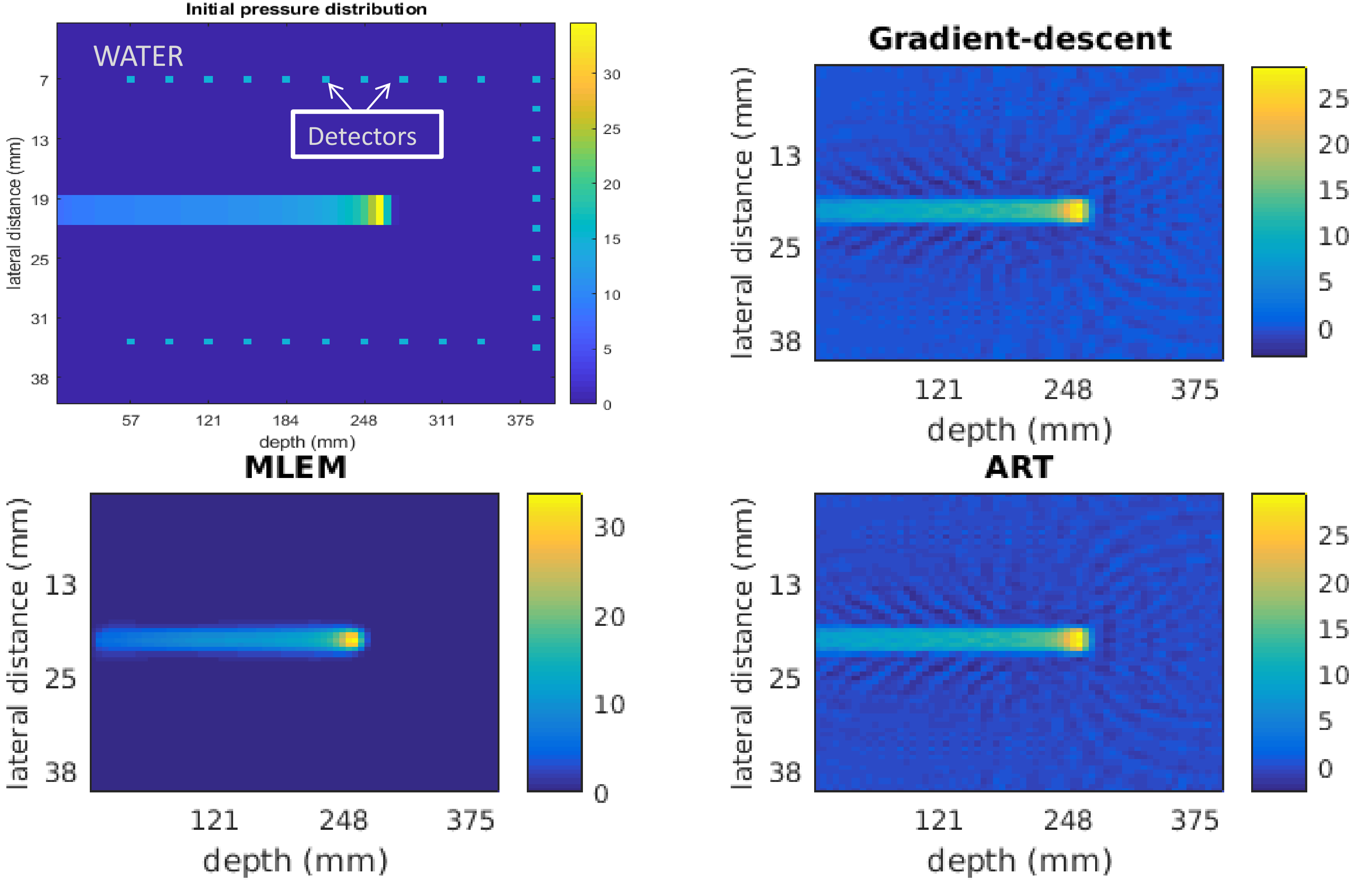
ART algorithm

$$X'_j = X_j + \frac{\sum_i (Y_i - P_i) \cdot a_{ij}}{\sum_i a_{ij}^2}$$

Modified MLEM algorithm

$$X'_j = X_j \cdot \frac{\sum_i (\widehat{Y_i} / \widehat{P_i}) \cdot \widehat{a_{ij}}}{\sum_i \widehat{a_{ij}}}$$

1) Example: Proton Dose in Water Simulation



Acoustic Simulation

k-Wave

A MATLAB toolbox for the time-domain simulation of acoustic wave fields

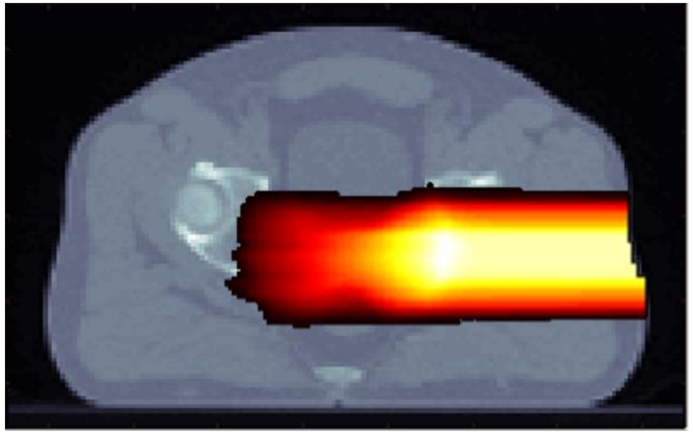
http://www.k-wave.org/

200 MeV
protons
In water

Method 2: Protoacoustic Dictionary

Workflow for Dictionary Construction

Treatment Plan



- Thousands of pencil beams
- Personalized for each patient
- Available at least one day before the treatment session

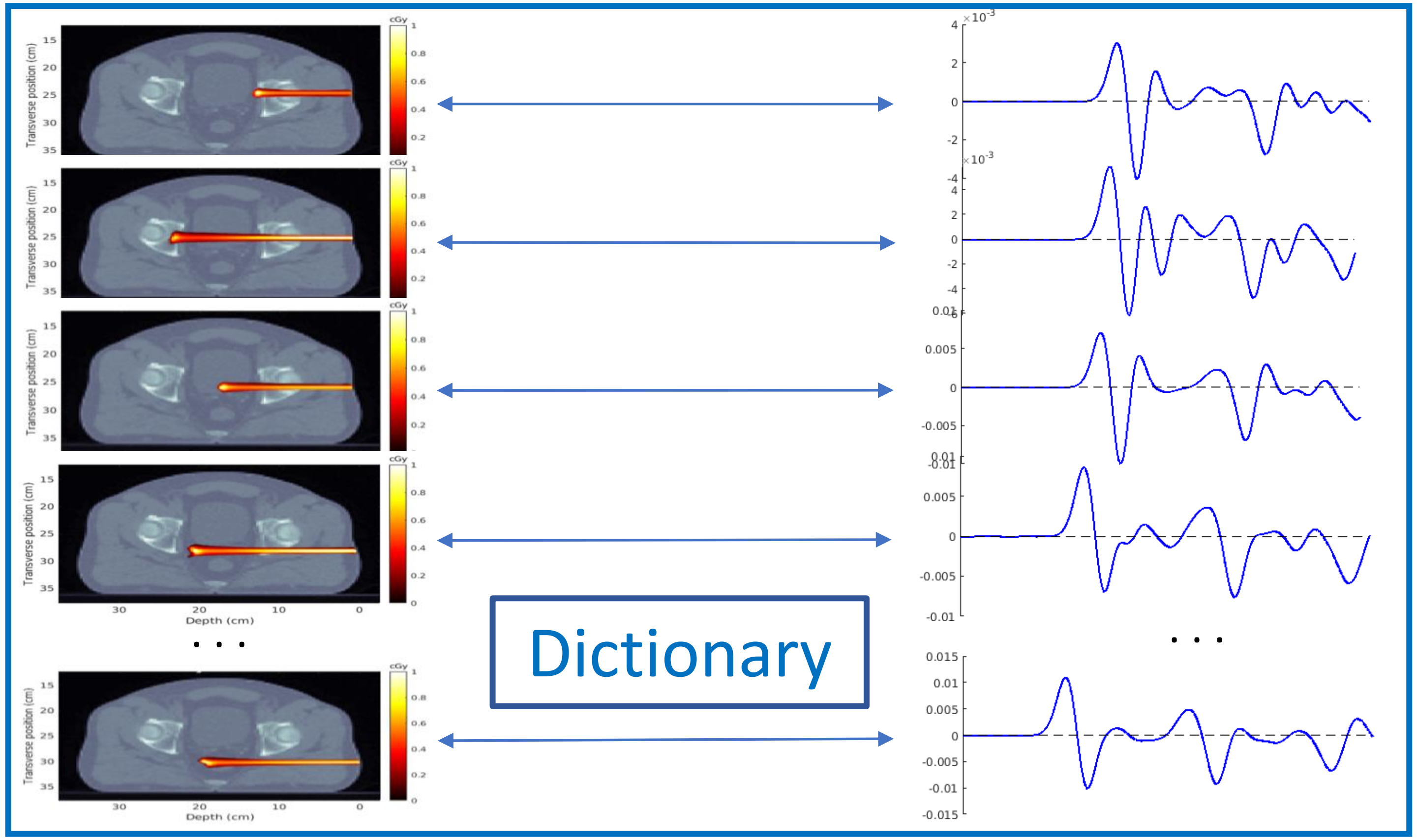
A priori Information

- Energy and pencil beam position
- Density
- Speed of sound

Acoustic Simulation

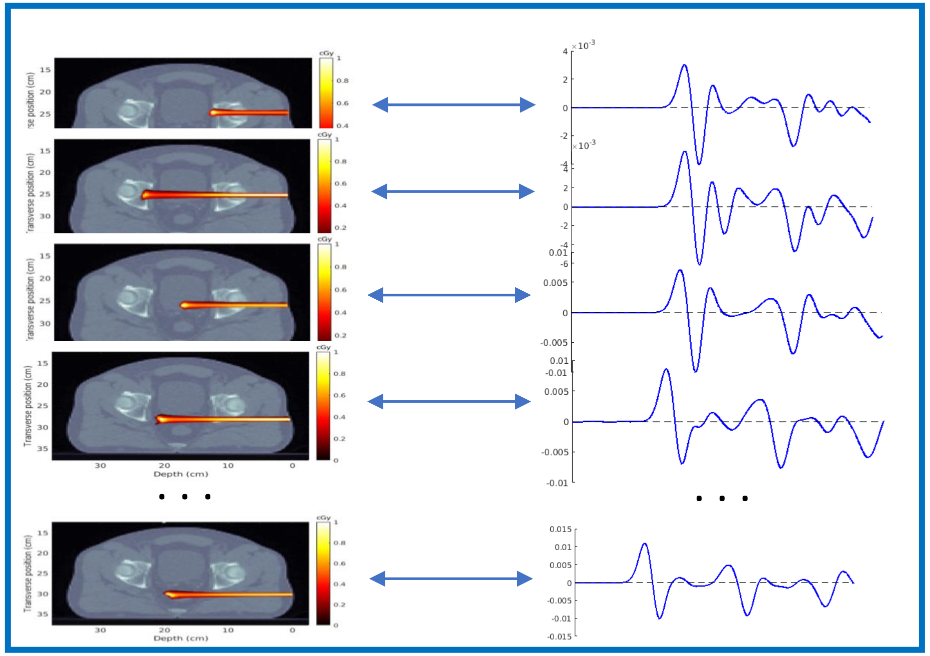
k-Wave
A MATLAB toolbox for the time-domain simulation of acoustic wave fields

http://www.k-wave.org/



2) Dictionary-based Proton Range Verfication

Pre-Computation

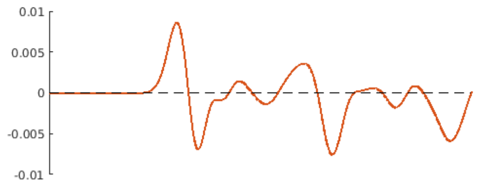


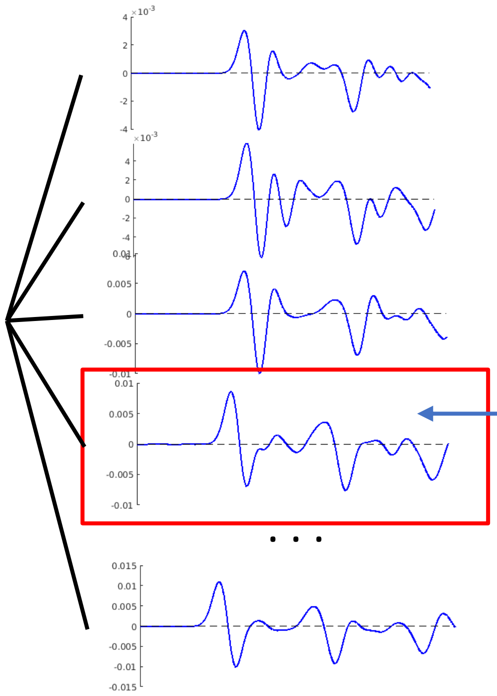
Individualized Dictionary

→ 500 pencil beams ~ 100 min

Real Time

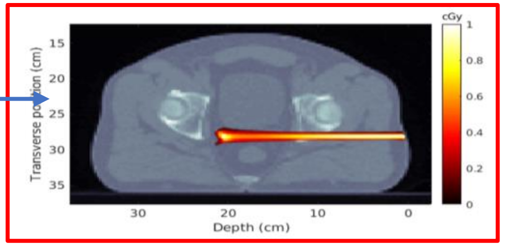
Similarity
Measured vs Dictionary
signals





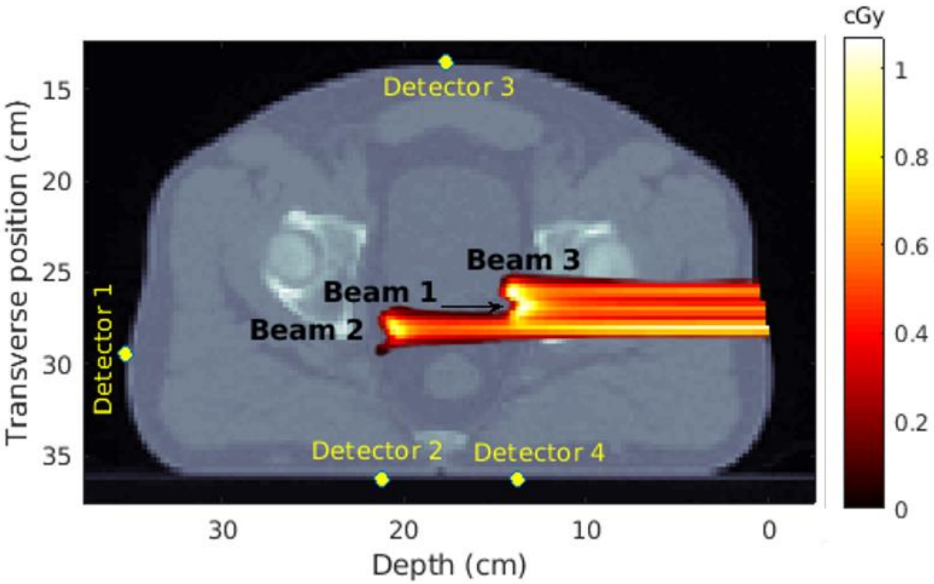
In-house developed **algorithm** based on **L1 norm** (100 ms)

Most probable Bragg peak (BP) position



2) Detection of Deviations from Protontherapy Plan SETUP

Simulation Setup

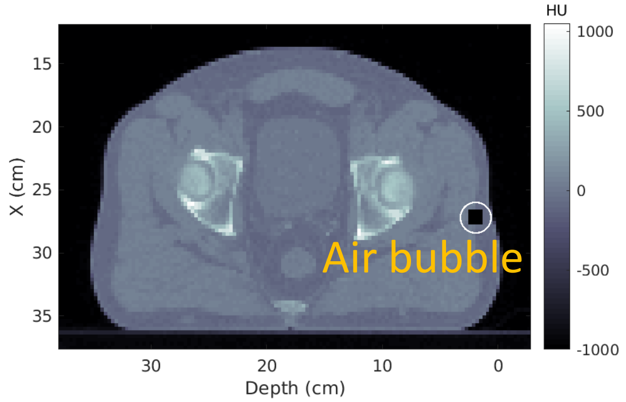


- Treatment plan for **prostate** tumor
- **4** ideal **detectors**
- Dictionary for axial **central slice**
- **GPU** k-Wave simulation (~ 90 min in NVIDIA GeForce RTX 2080 Ti)
- **Noise** added

Robustness Evaluation

Changes from the original plan:

1. Air bubble
2. Weight gain
3. 1 mm Shift in patient position
4. 3.5 % error in HU to relative stopping power conversion

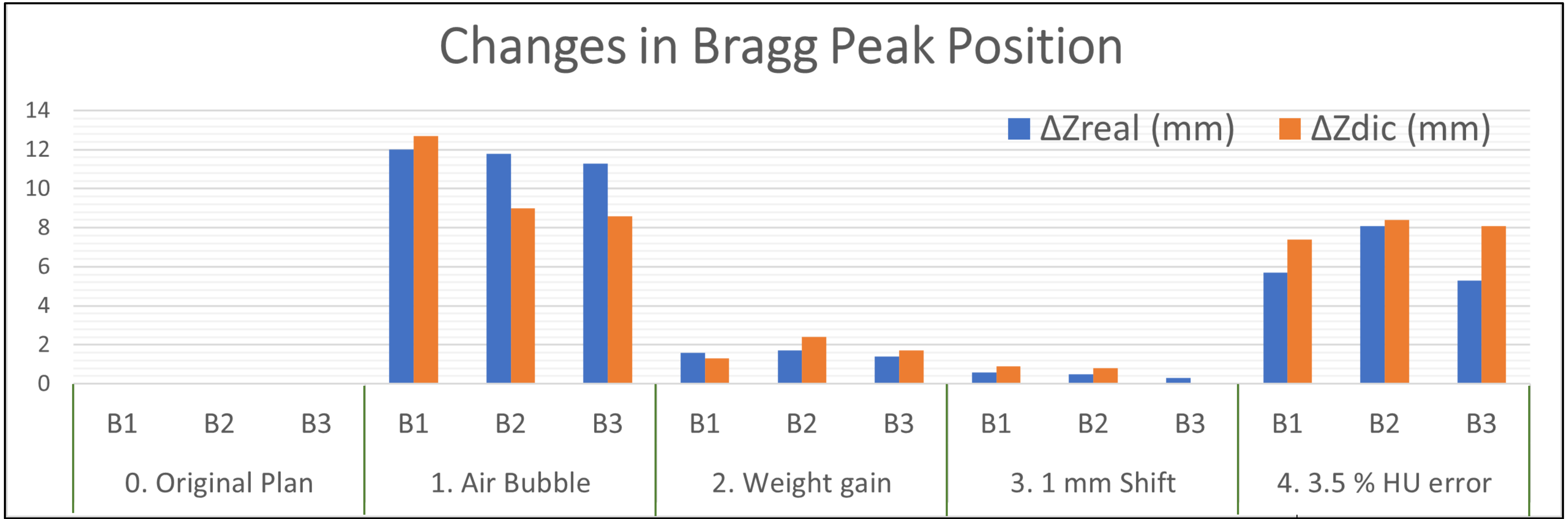


ΔZ_{real} Real change in BP position

vs

ΔZ_{dic} Change detected in BP position

2) Detection of Deviations from Protontherapy Plan RESULTS



Largest changes caused by **air bubble** and **HU** conversion error

The **dictionary** method **detects** the **deviations** in all cases

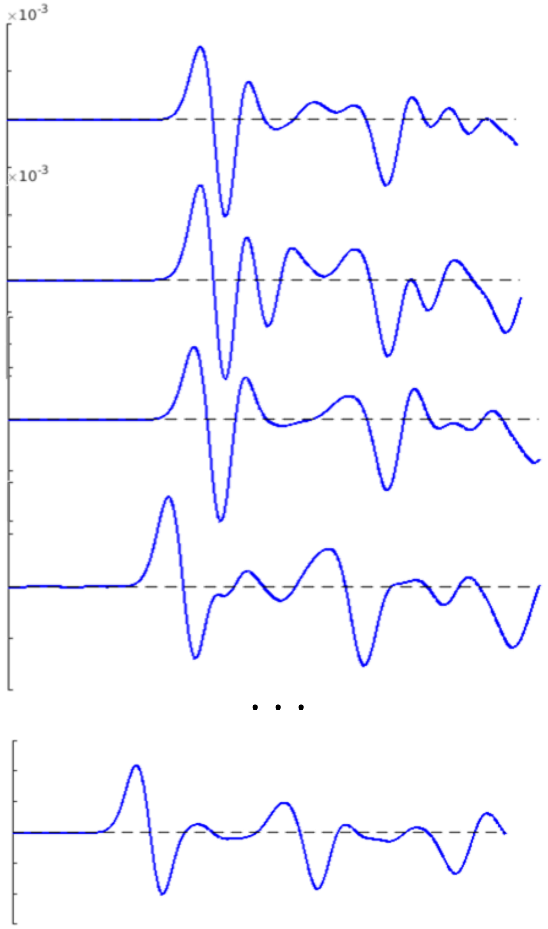
It could **alert** of **errors**

1.1 mm Average Accuracy (<0.7 %)

Dictionary-based protoacoustic dose map imaging for proton range verification. Clara Freijo et al. Photoacoustics, 21, 2021, 100240

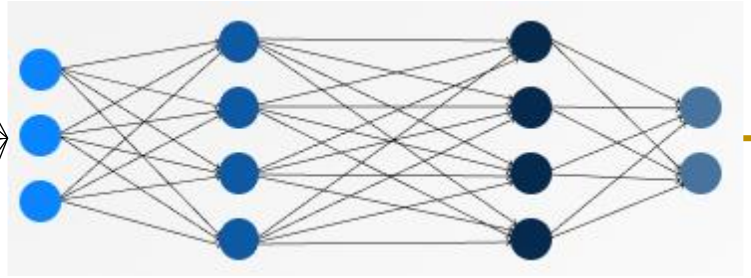
Method 3: Deep-Learning

Input: Acoustic signals



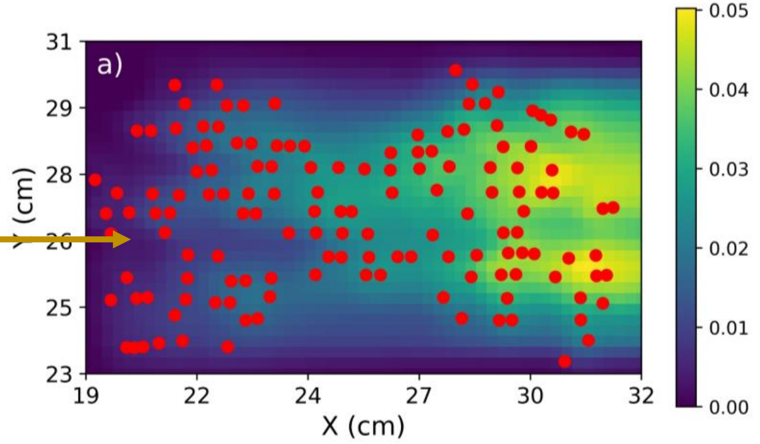
Neural Network

- 1.5M parameters
- 430 cases: 290 training / 140 validation



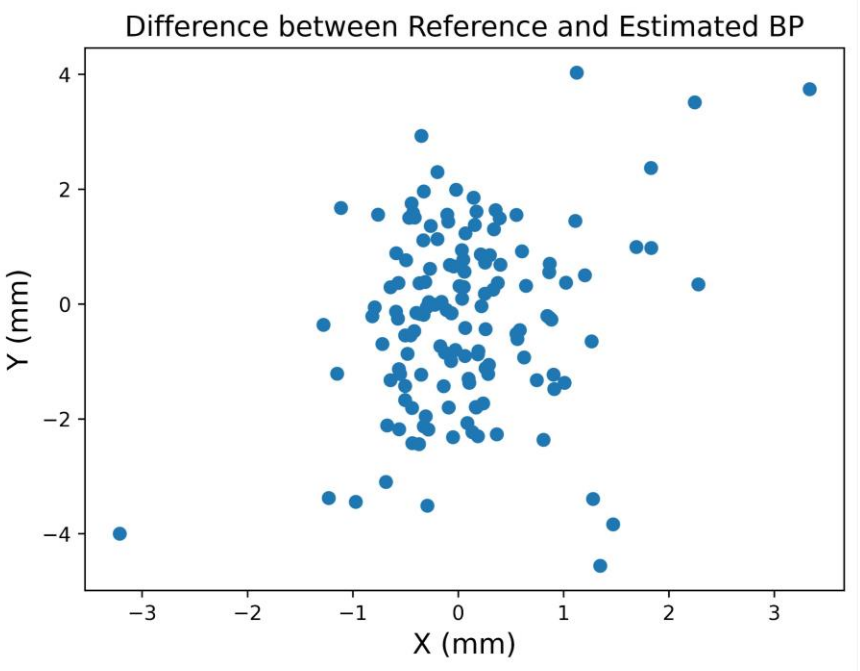
- Loss function: Mean Squared Error (MSE)
- Training time: 20 min

Output: Bragg Peak positions (X,Y)



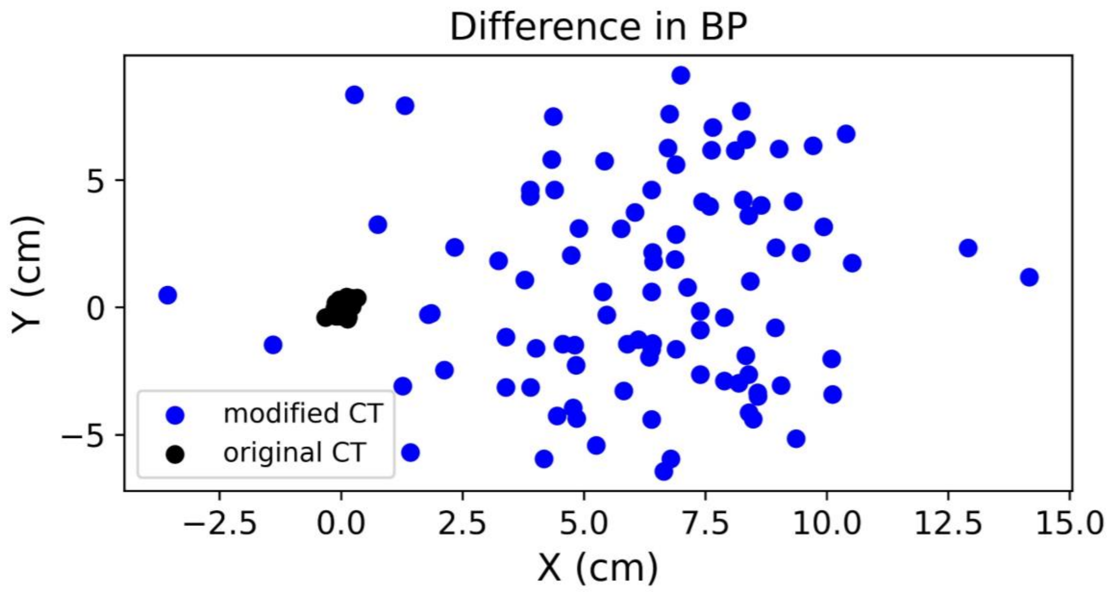
3) Protoacoustic Neural Network

Original CT



0.9 mm Average Accuracy

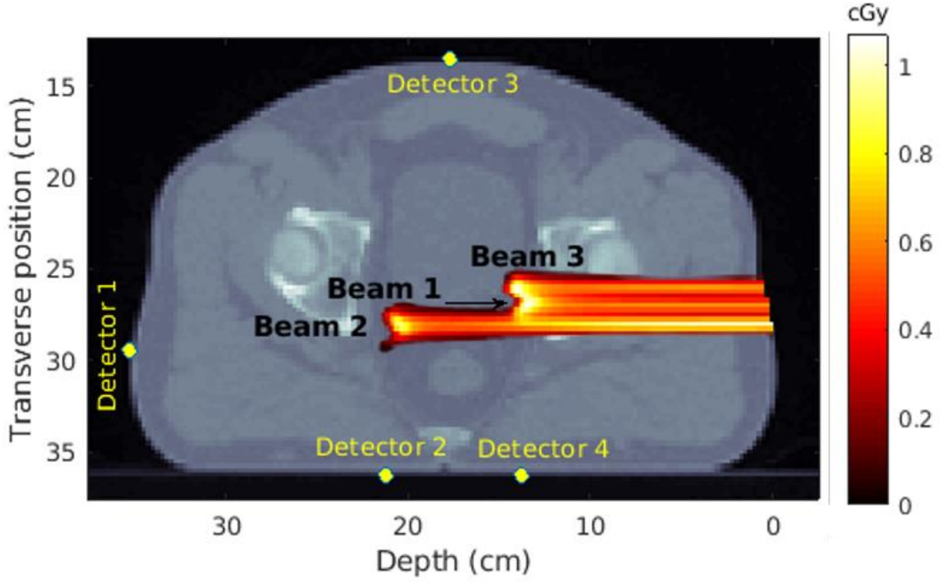
Modified CT: Air Region



Detection of deviations from the original BP position

Future Work

- **Real data will be acquired with phantoms** at Hospital Quirón in Madrid in the following weeks.
- Combination of ultrasound imaging at low frequencies with protoacoustics may provide complementary information (anatomy and dosimetry).
- Combination of protoacoustic information with prompt-gamma and/or PET measurements.



Conclusions

- Novel approaches for proton range verification based on a protoacoustic data.
- A proof-of-concept study demonstrated the feasibility of implementation of the proposed method.
- Experiments in proton facilities to test the method in a real scenario.
- REFERENCES:

Iterative Reconstruction Methods in Protoacoustic Imaging" Book Chapter "Horizons in Computer Science Research V. 18“ Nova Science Publishers may. 2020

Dictionary-based protoacoustic dose map imaging for proton range verification. Clara Freijo et al. Photoacoustics -Volume 21, March 2021, 100240

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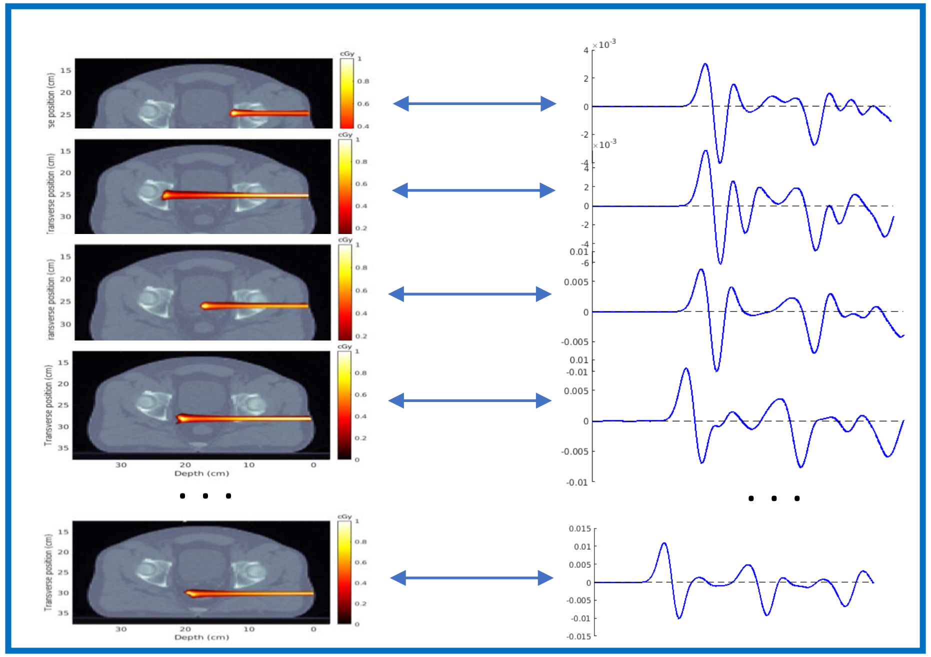

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