Super-resolution integrated mode proton imaging from paired proton-carbon data

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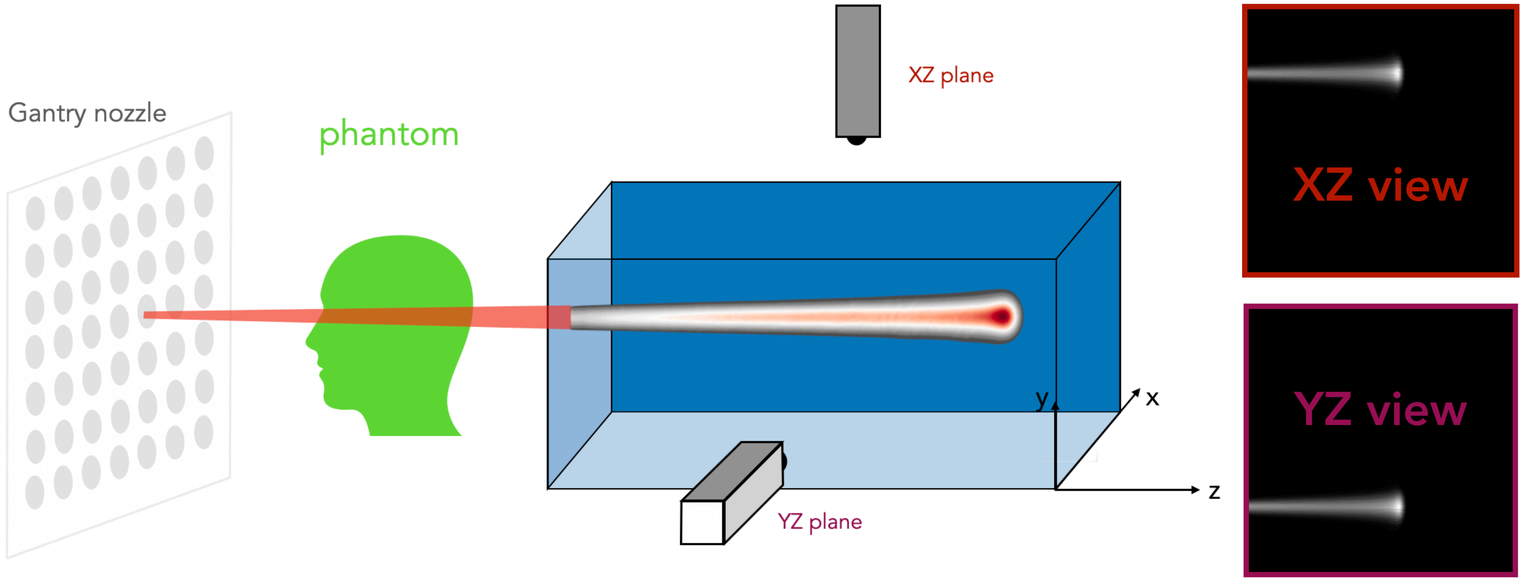
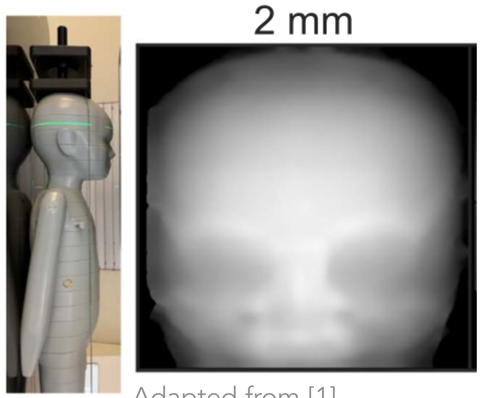
Introduction
Integrated mode proton radiography

- In a pencil beam scanning approach, we use a scintillator-based device that captures images of each individual pencil beam with two camera views (lateral and top).
- The two views are combined to reconstruct proton radiographs [1, 2].





Adapted from [1].

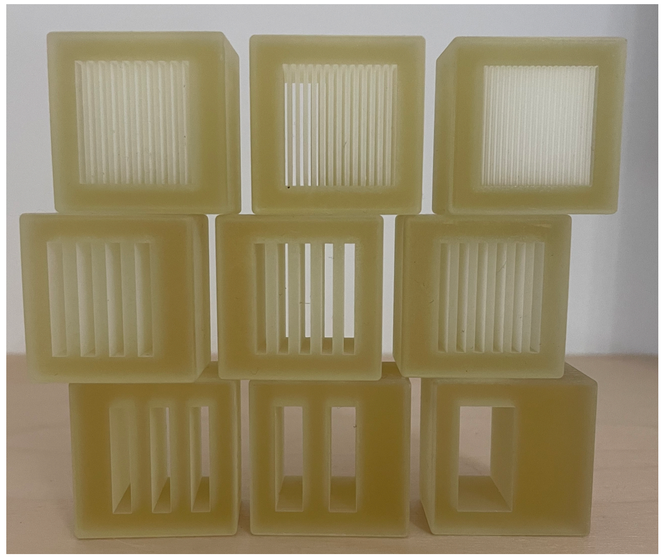
- While images can be quickly acquired with a clinical beam line and are therefore useful for image guidance, image quality is limited due to strong MCS with proton beams.
- Need to improve image resolution for integrated mode pRads.

[1] Simard M, Robertson DG, … Collins-Fekete CA. Integrated-mode proton radiography with 2D lateral projections. Phys. Med. Biol. 69 054001.
[2] Fullarton R, **Simard M**, …, Collins- Fekete CA. Imaging lung tumor motion using integrated-mode proton radiography – A phantom study towards tumor tracking in proton radiotherapy. Accepted in Medical Physics.

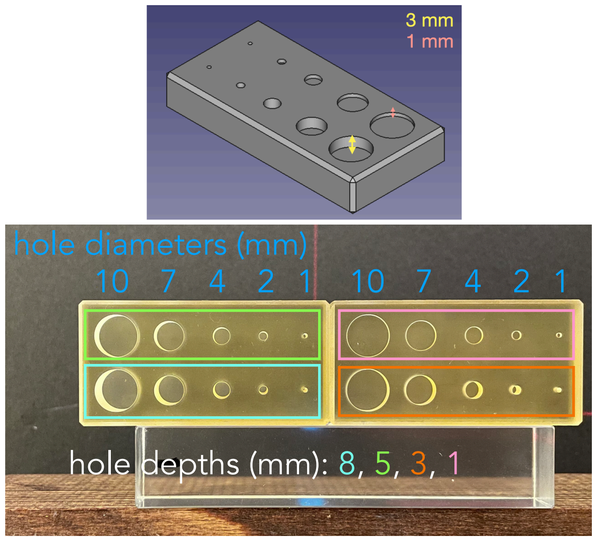
Introduction
Exploring carbon ion radiographs

- With reduced MCS, carbon ion radiographs (cRads) have the potential to produce **much sharper** radiographs.
- Experiments were performed at the **Marburg Ion Therapy Centre** to compare the image quality of carbon ion radiographs (cRads) against pRads, using multiple phantoms [3]:

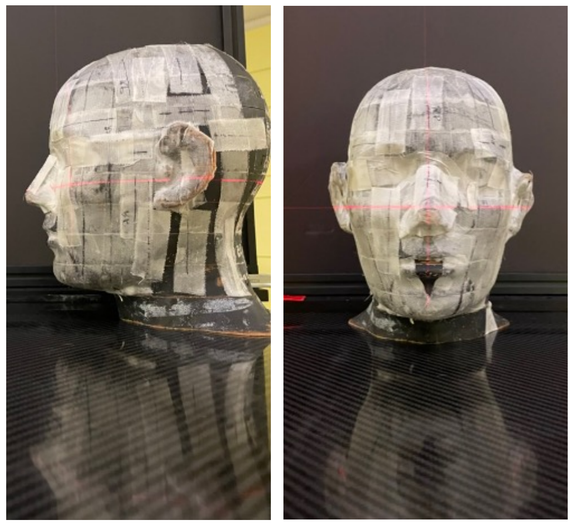
Line pair modules (spatial resolution) **+ 10 cm solid water**



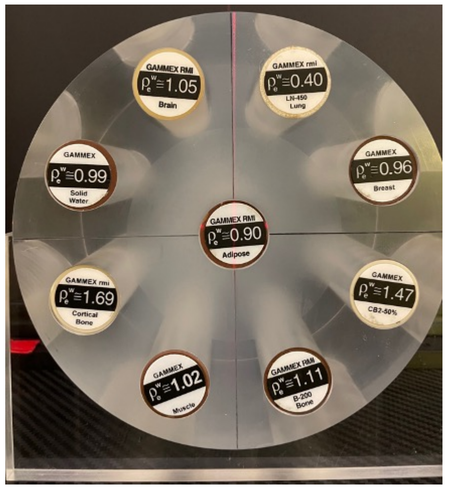
Low contrast modules (contrast) **+ 10 cm solid water**



Anthropomorphic head phantom



Gammex inserts (WET accuracy)



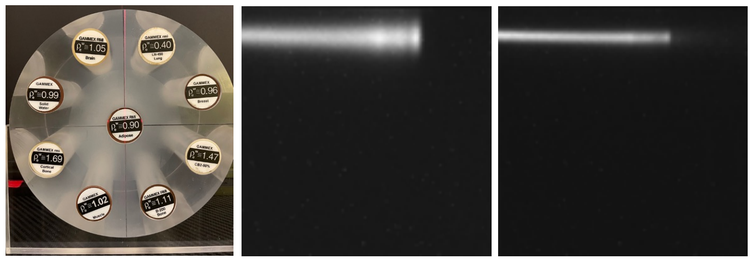
[3] Simard M, Fullarton R, Volz L, Schuy C, Robertson DG, Toltz A, Baker C, Beddar S, Graeff C, Collins-Fekete CA. Comparing Carbon Ions and Protons in Integrated Mode Ion Imaging. Under review in Medical Physics.

Introduction
Carbon ion vs proton radiographs

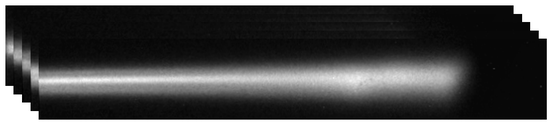
Beam parameters

Species	Protons	Carbon ions
Energy	180.06 MeV	344.62 MeV/u
Beam spacing	1 mm	1 mm
Spot size	9.4 mm	5.2 mm
Field size	15 x 15 cm^2	15 x 15 cm^2

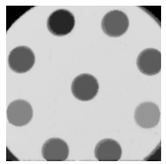
Imaging



22,801 images produced per object (one per PB)

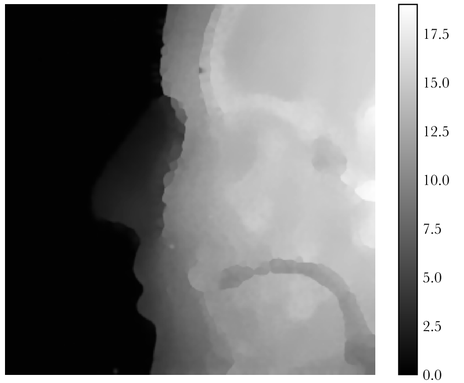


Combine images [1] to reconstruct radiographs

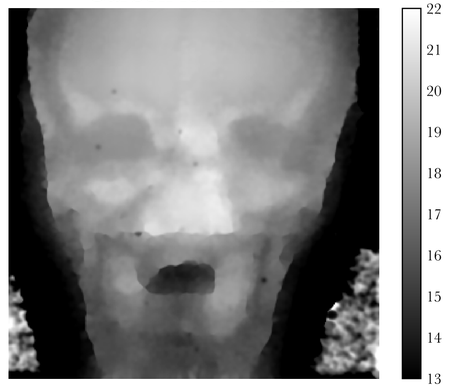


- Sample of results from the study [3]:

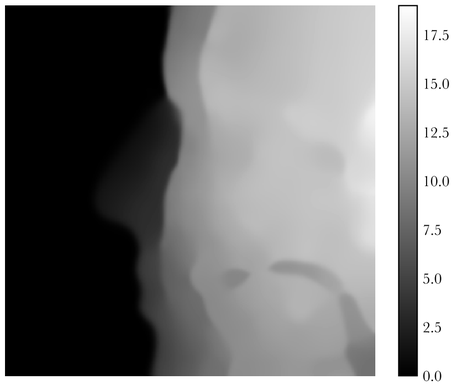
Carbon ions - lateral



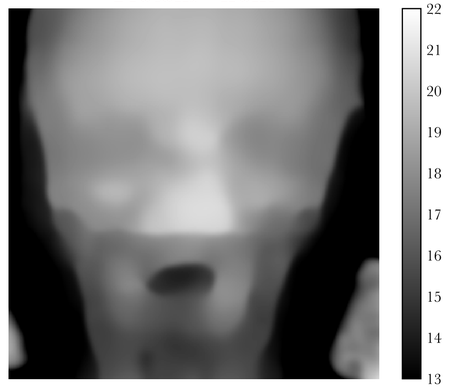
Carbon ions - front



Protons - lateral



Protons - front



- **Overall conclusion**: much better image quality (resolution, contrast) with cRads compared to pRads!

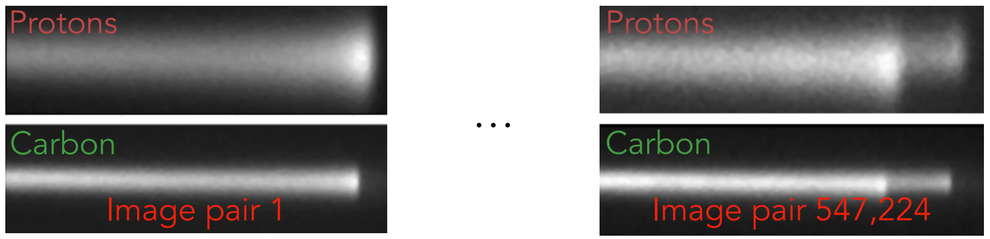
[3] Simard M, Fullarton R, Volz L, Schuy C, Robertson DG, Toltz A, Baker C, Beddar S, Graeff C, Collins-Fekete CA. Comparing Carbon Ions and Protons in Integrated Mode Ion Imaging. Under review in Medical Physics.

Methods
Dataset

- The pRad vs cRad study produced a large amount of images, for each ion species:

12 objects scanned × **2 views** (lateral, top) × **22,801 images** (per view) = 547,224 images*

- Each image represents a (pulled back) pencil beam that crossed the imaged object at a given location.
- Each **proton image** is fully **matched** and **registered** with the corresponding carbon ion image.



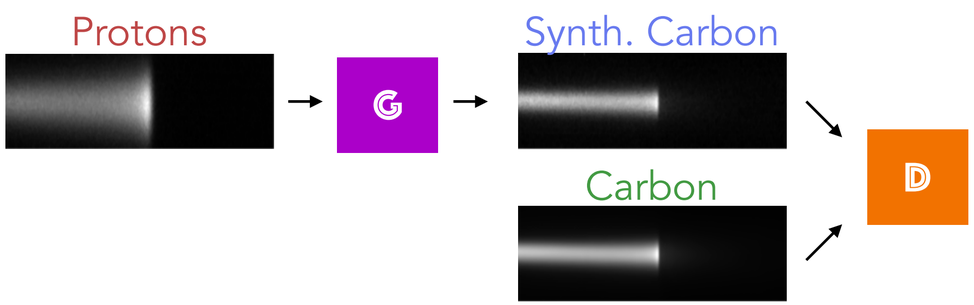
- Can we train a **deep learning model that transfers a proton image to a carbon image**, and improve image quality?

Analogous to learning a deconvolution operation with a spatially variant PSF.

Methods
Image translation network: Proton2Carbon

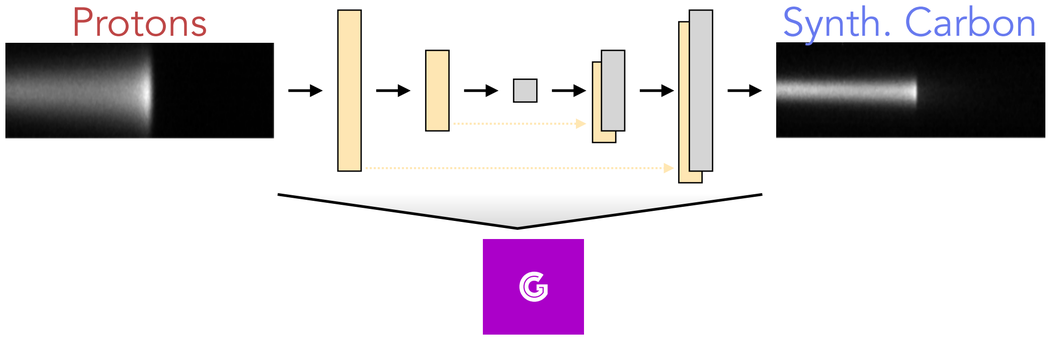
- Conditional generative adversarial network (GAN) based on pix2pix [4] - **proton2carbon**

Training pipeline:

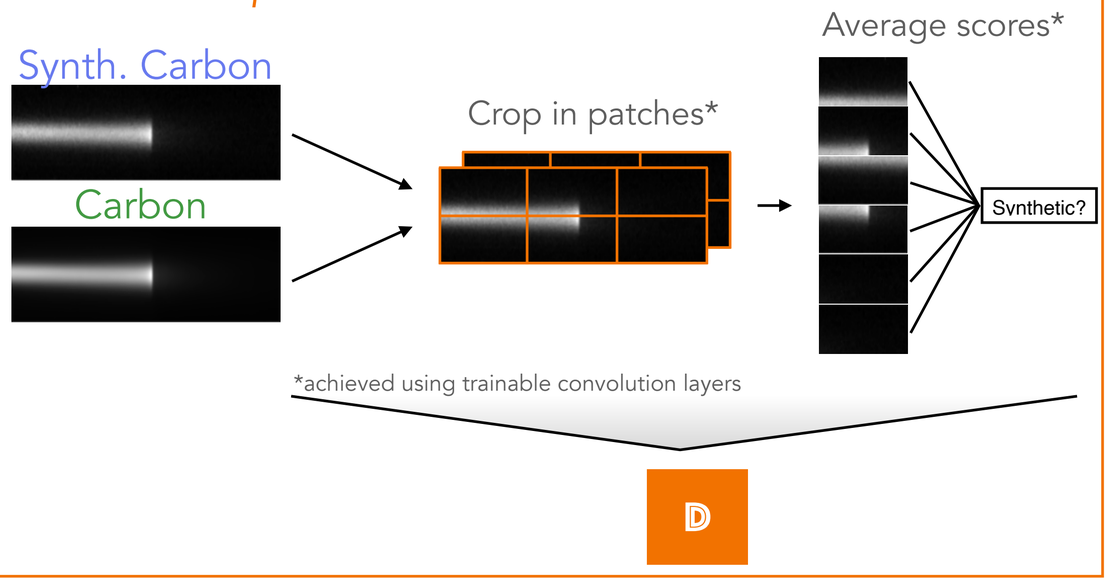


- Implementation in PyTorch Lightning, ~ 8h of training on 4x3090RTX.
- 80/20 train/val split. When results are shown on a given geometry, it is assumed that we trained a model without any data from this geometry.

Generator: BasicUnetPlusPlus



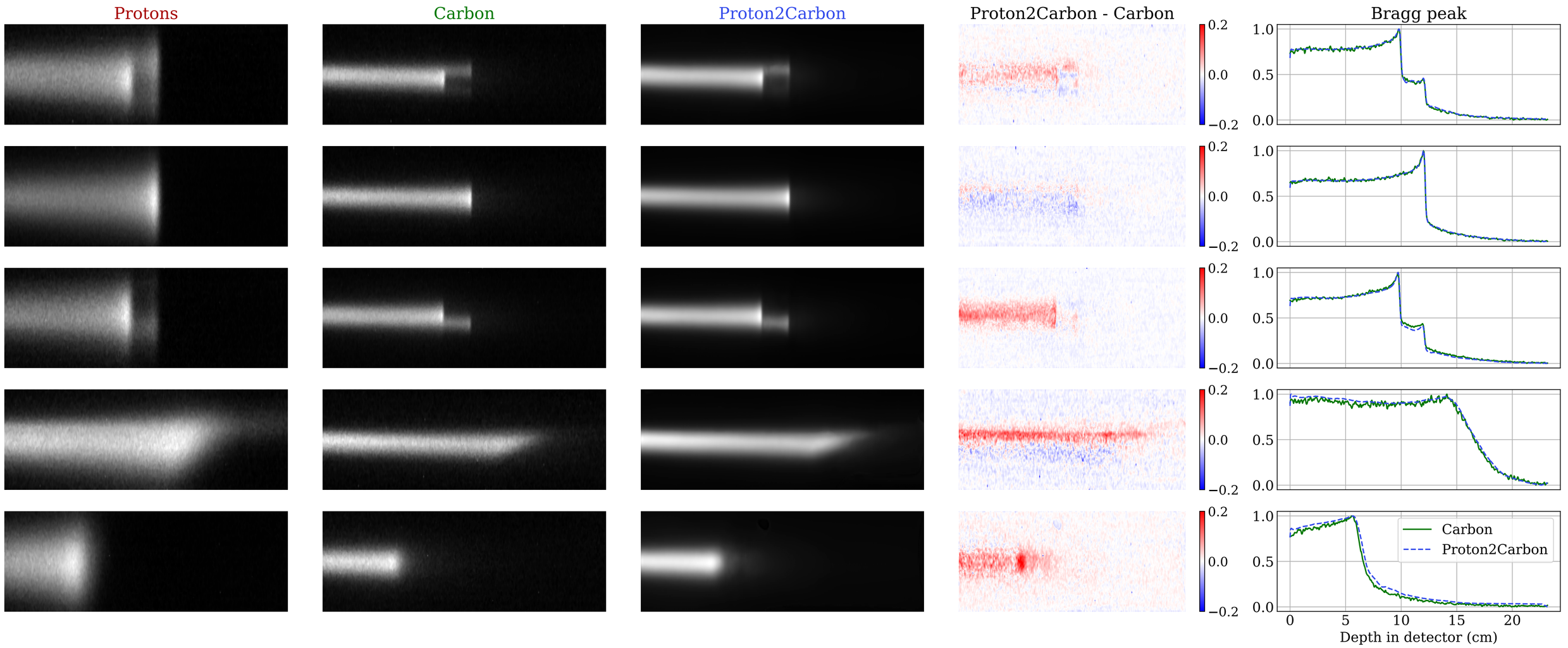
Discriminator: *patchGAN*



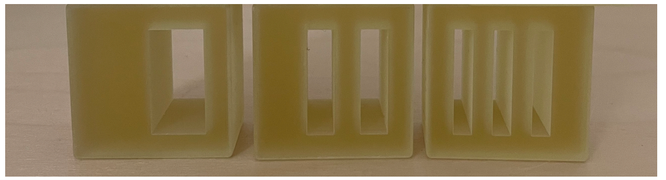
[4] Isola *et al.*, Image-to-Image Translation with Conditional Adversarial Networks. CVPR 2016.

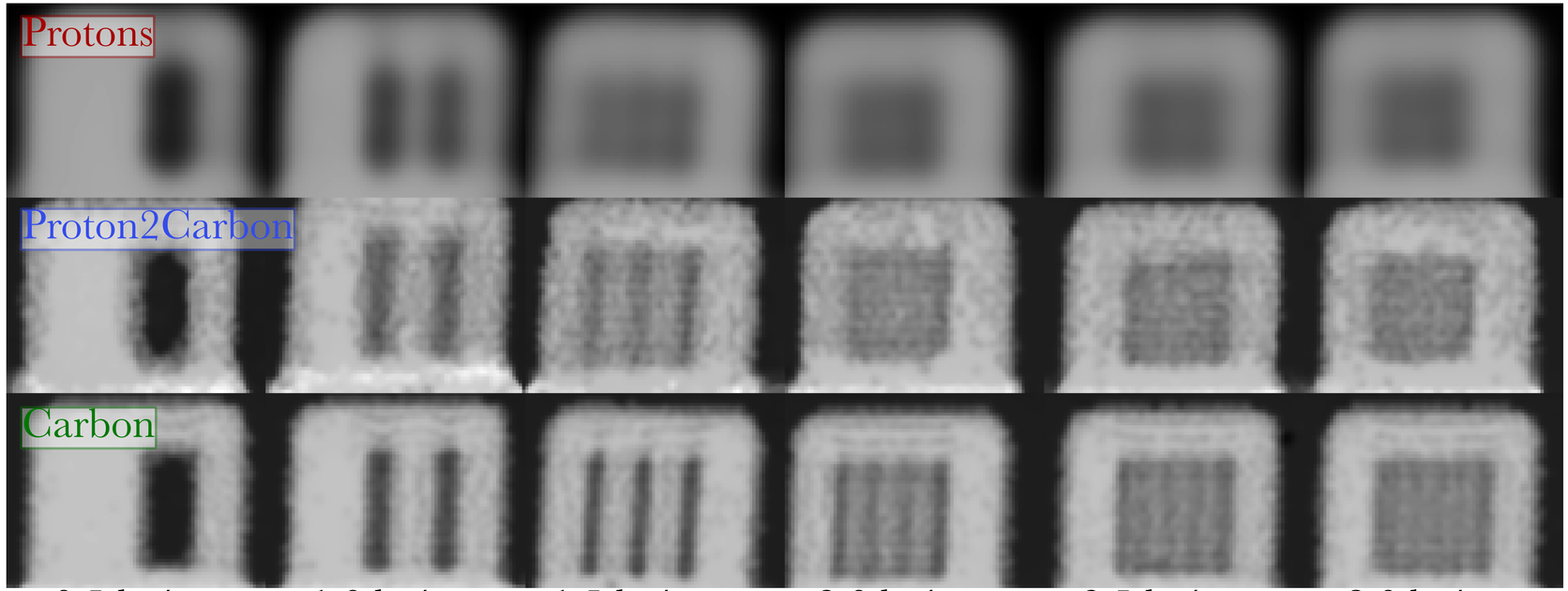
Results

Proton2Carbon on example pencil beams



Results
Spatial resolution improvement





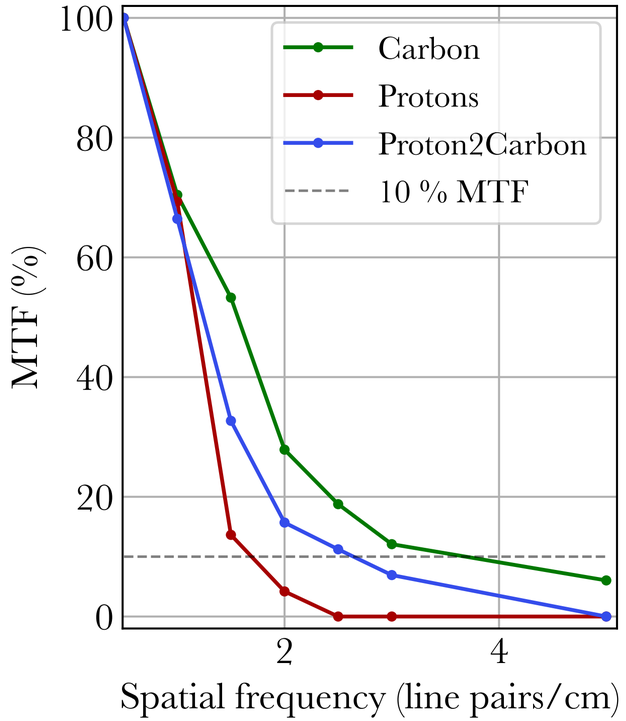
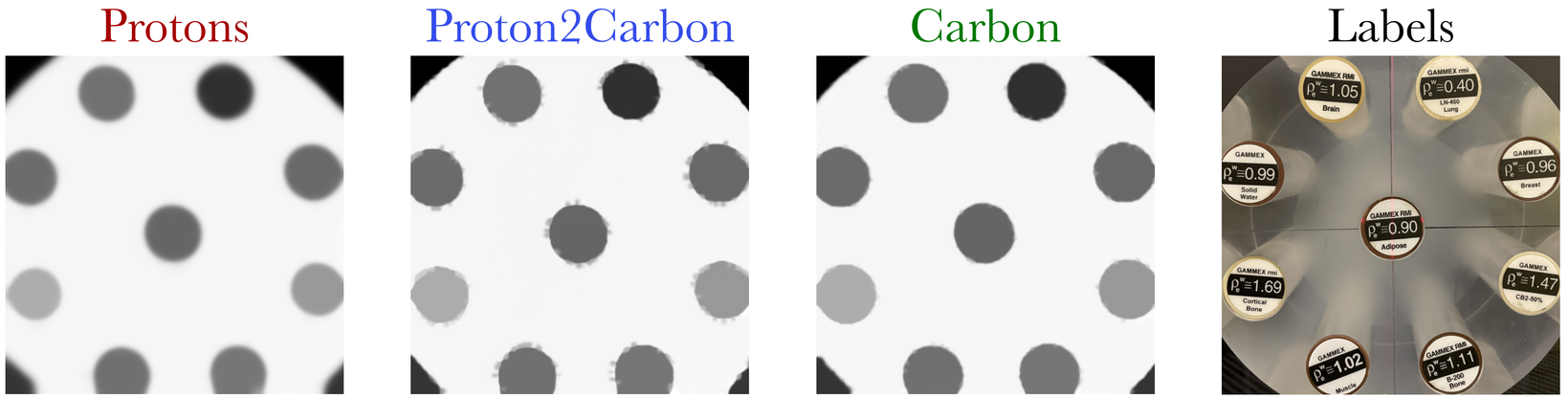
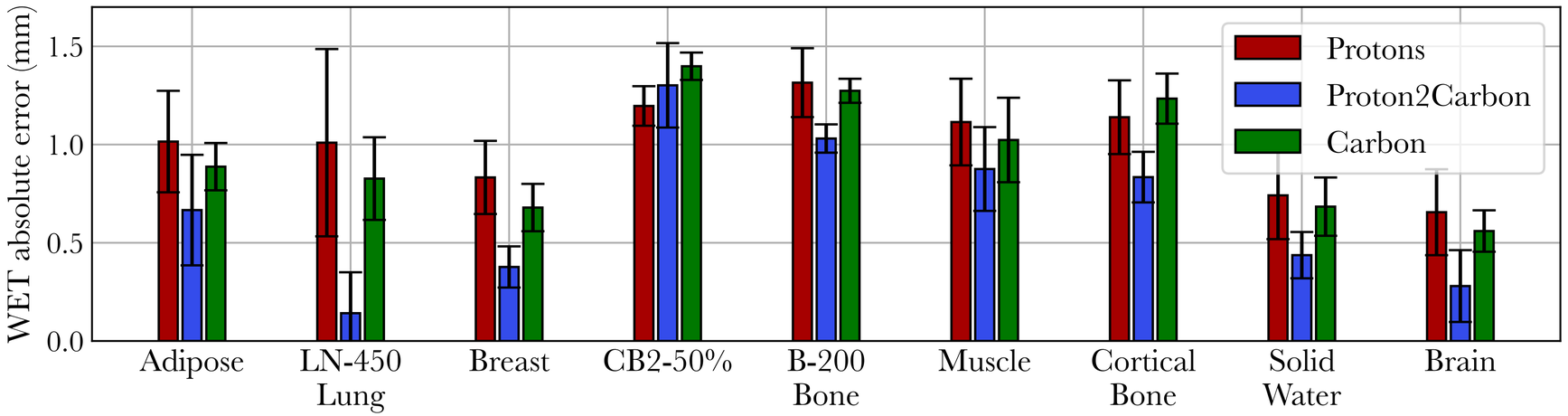


Image quality metric	Protons	Protons2Carbon	Carbon
Resolution (lp/cm)	1.7	2.7	3.7

Results
Do we lose quantitative accuracy?





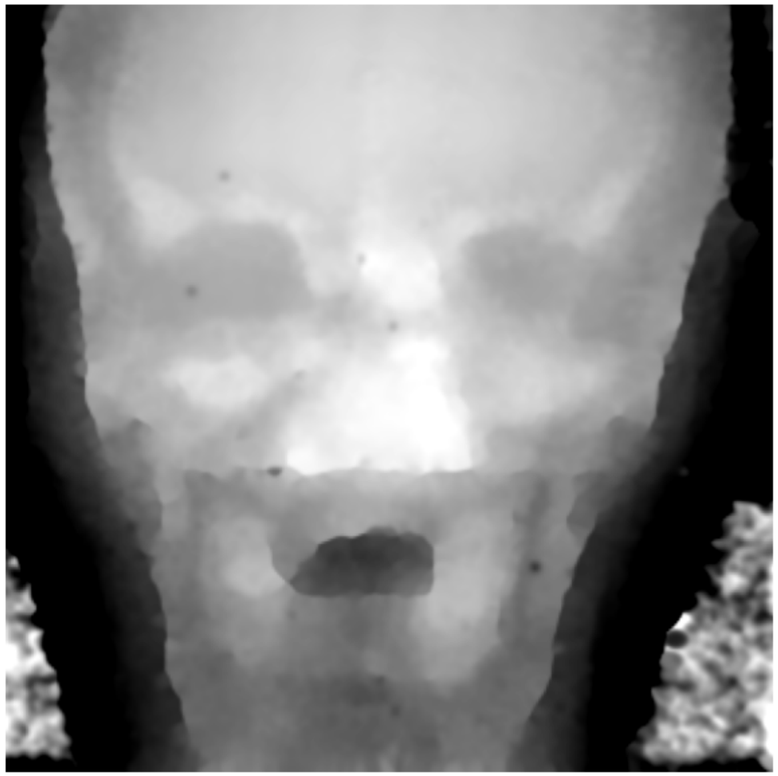
- **Quantitative WET accuracy is similar for all: 1.0 mm (protons), 0.9 mm (Proton2Carbon), 1.0 mm (Carbon)**

Results
General image quality on an anthropomorphic phantom

Protons

Proton2Carbon

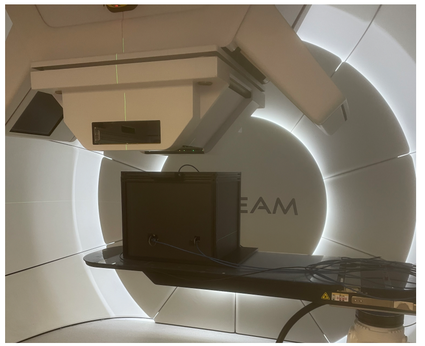
Carbon

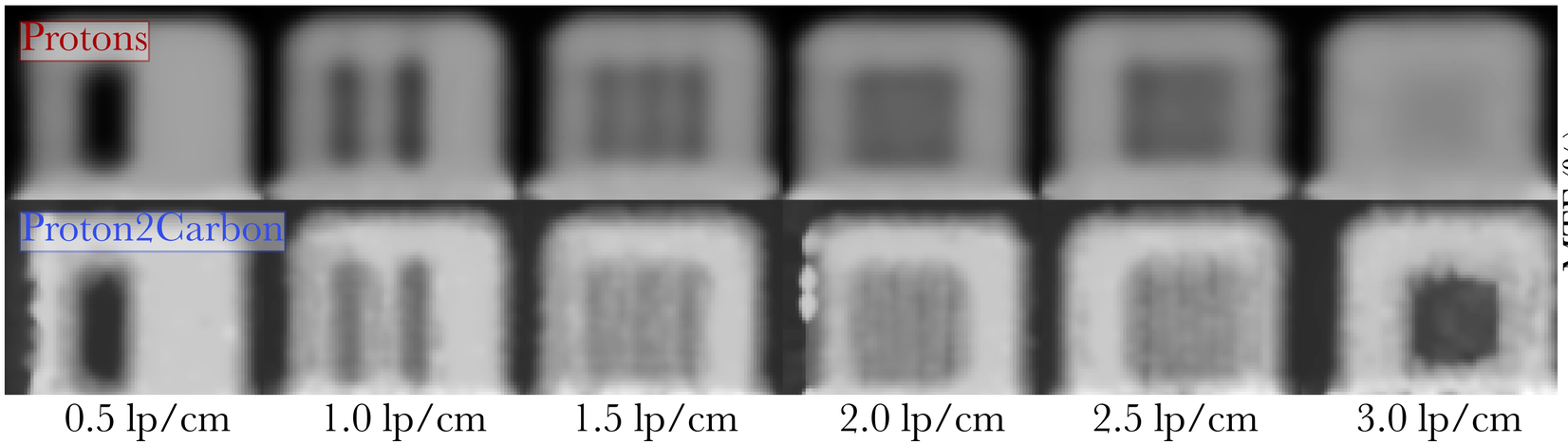


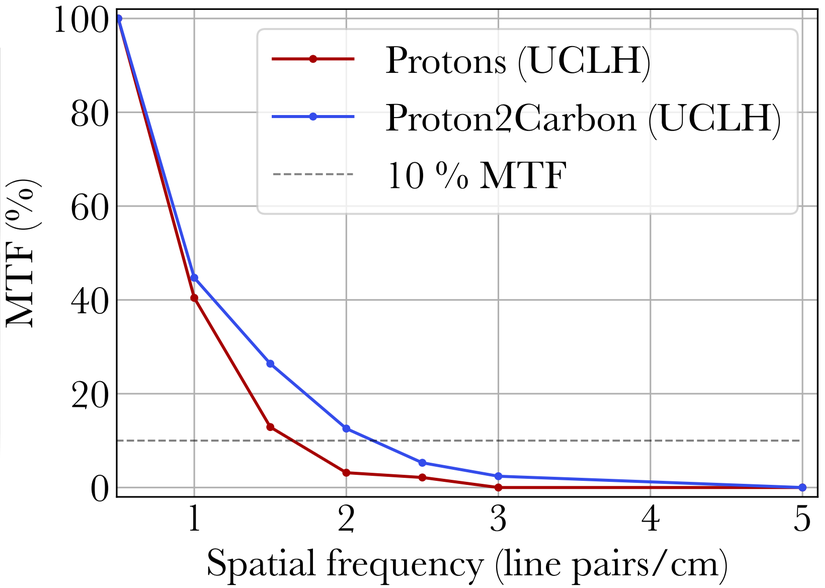
- Images appear sharper, although noisier.

Results
External testing on a different PBT system

- **Up to now:** train/val/test using the Siemens synchrotron in Marburg (spot size 9.4 mm FWHM).
- **Re-scanned** line pair modules on a **different system**: Varian ProBeam cyclotron at University College London Hospitals (spot size ~ 7 mm FWHM).







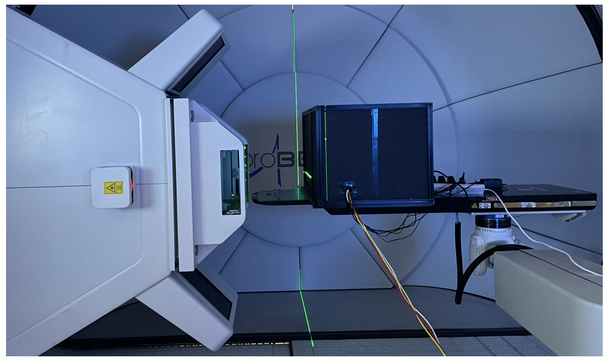
- **Spatial resolution of pRads increased from 1.7 lp/cm to 2.3 lp/cm.**

Conclusion

- We propose a cGAN based on the pix2pix architecture, **proton2carbon**, to create synthetic carbon PB images from proton PB images (for scintillator-based integrated mode proton imaging).

- The approach leads to improved resolution and image quality for integrated mode pRads, and shows promising generalisation capabilities.

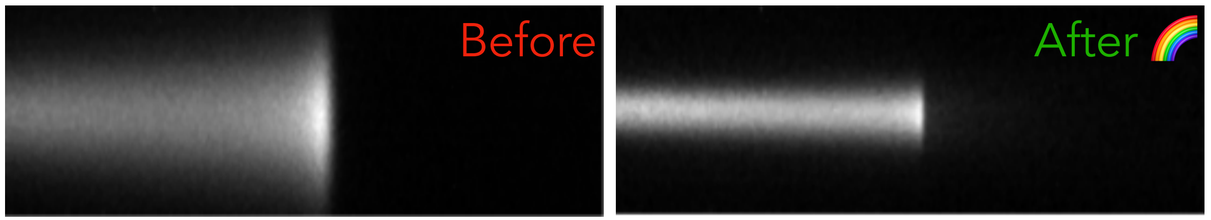
- **Next steps**: scanning more objects at more centres to improve robustness and generalisability. We are open to collaborations!



- The **proton2carbon** model is currently shared on reasonable request - reach out if you want to test!

- The **entire dataset** will be made available alongside with the upcoming publication.

Proton2Carbon: refine your pencil beam's silouhette instantly!



Acknowledgements

- This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 101023220.
- Funding from the National Institute for Health and Care Research (NIHR) i4i programme (NIHR 205508).
- Beamtime @ MIT funded via Philipps University Marburg Grant (MIT-2022-12).
- UCL fellowship incubator award
- Yannick Senger @ MIT