Performance tests of the IEM-CSIC proton scanner prototype

Ph. D. student: Amanda N. Nerio

Instituto de Estructura de la Materia (CSIC), Madrid, Spain

Thesis supervisors:

Prof. María José García Borge

Instituto de Estructura de la Materia (CSIC), Madrid, Spain

Ph. D. José Antonio Briz Monago

GFN and IPARCOS, Universidad Complutense de Madrid, Madrid, Spain

Motivation

- Increasing use of proton therapy (also in Spain)
- Advantages of proton therapy

- **Treatment plans use X-ray CT (in HU) to generate the RSP maps**

$$HU = 1000 \times \frac{\mu - \mu_{water}}{\mu_{water} - \mu_{air}}$$

The conversion process induces uncertainties on the proton range[1] (~2.3%)

Using a **pCT** scanner aiming to <1% uncertainties

Absorbed dose[1] for
-an X-ray CT: 30-50 mGy
-a proton CT: ~1.3-1.4 mGy

Treatment plans

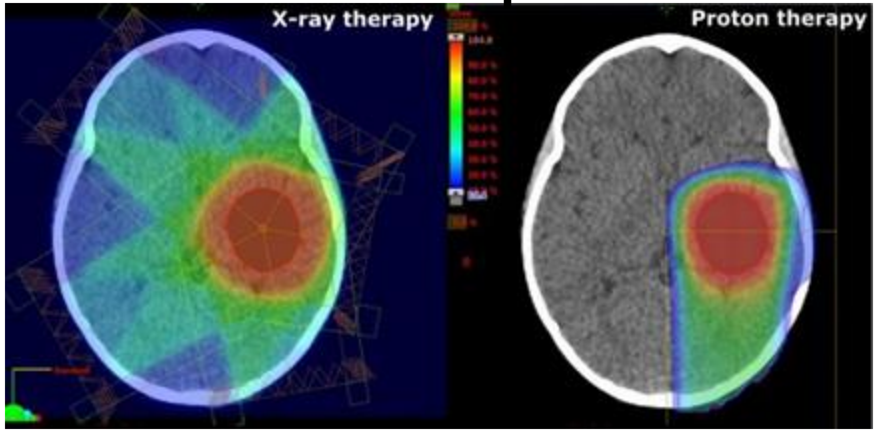


Image from: https://www.newswise.com/articles/media-article/741601

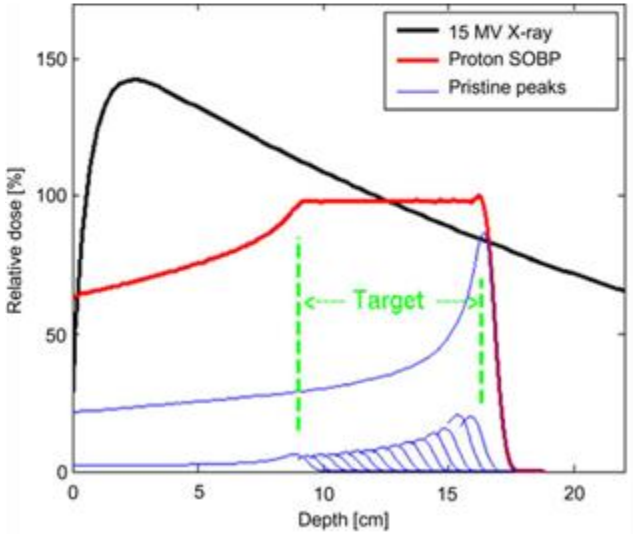
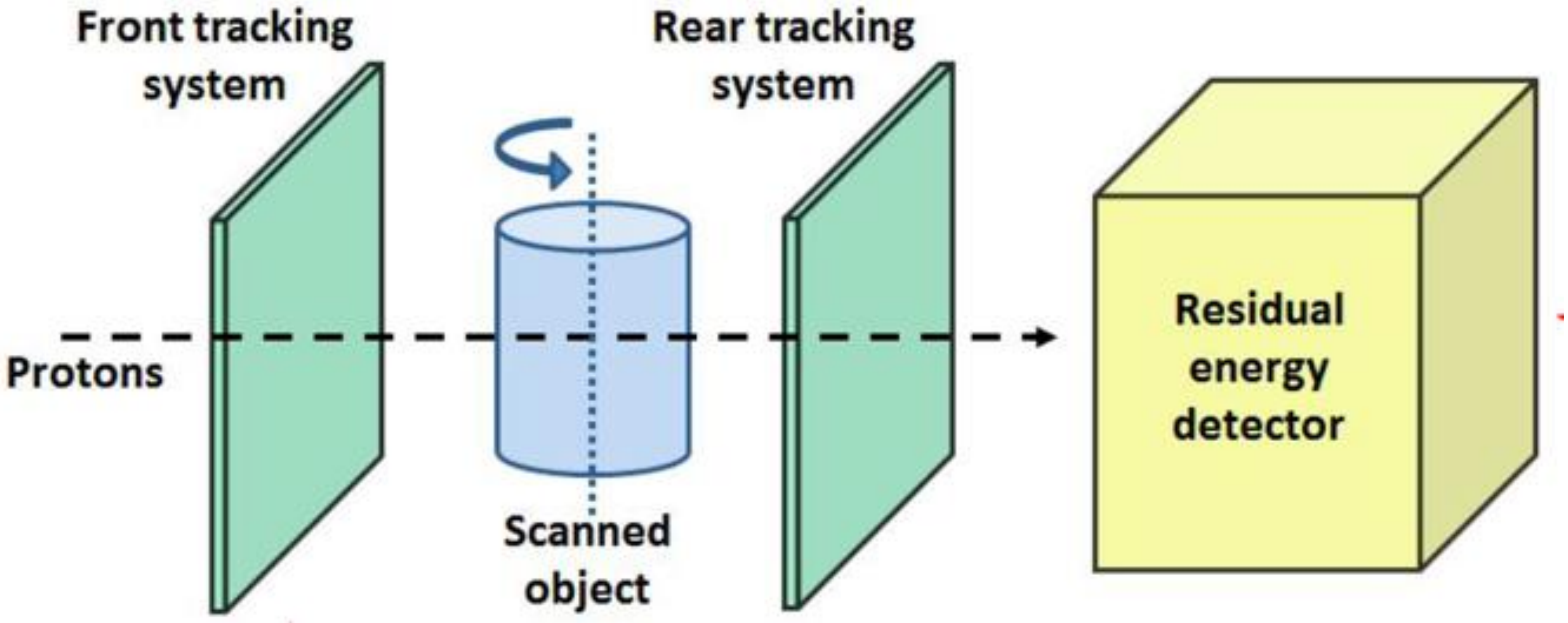


Image from: H. Suit et al., Radiother. Oncol. (2010) 95, 3–22

[1] Robert P. Johnson et al. Rep. Prog. Phys. 81 (2018) 016701

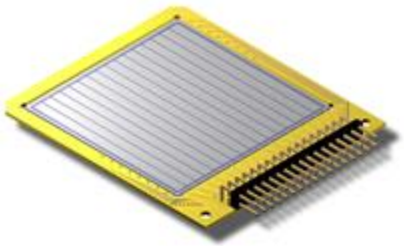
IEM proton scanner prototype

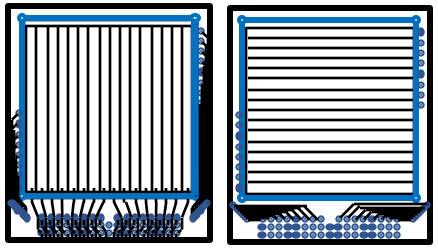


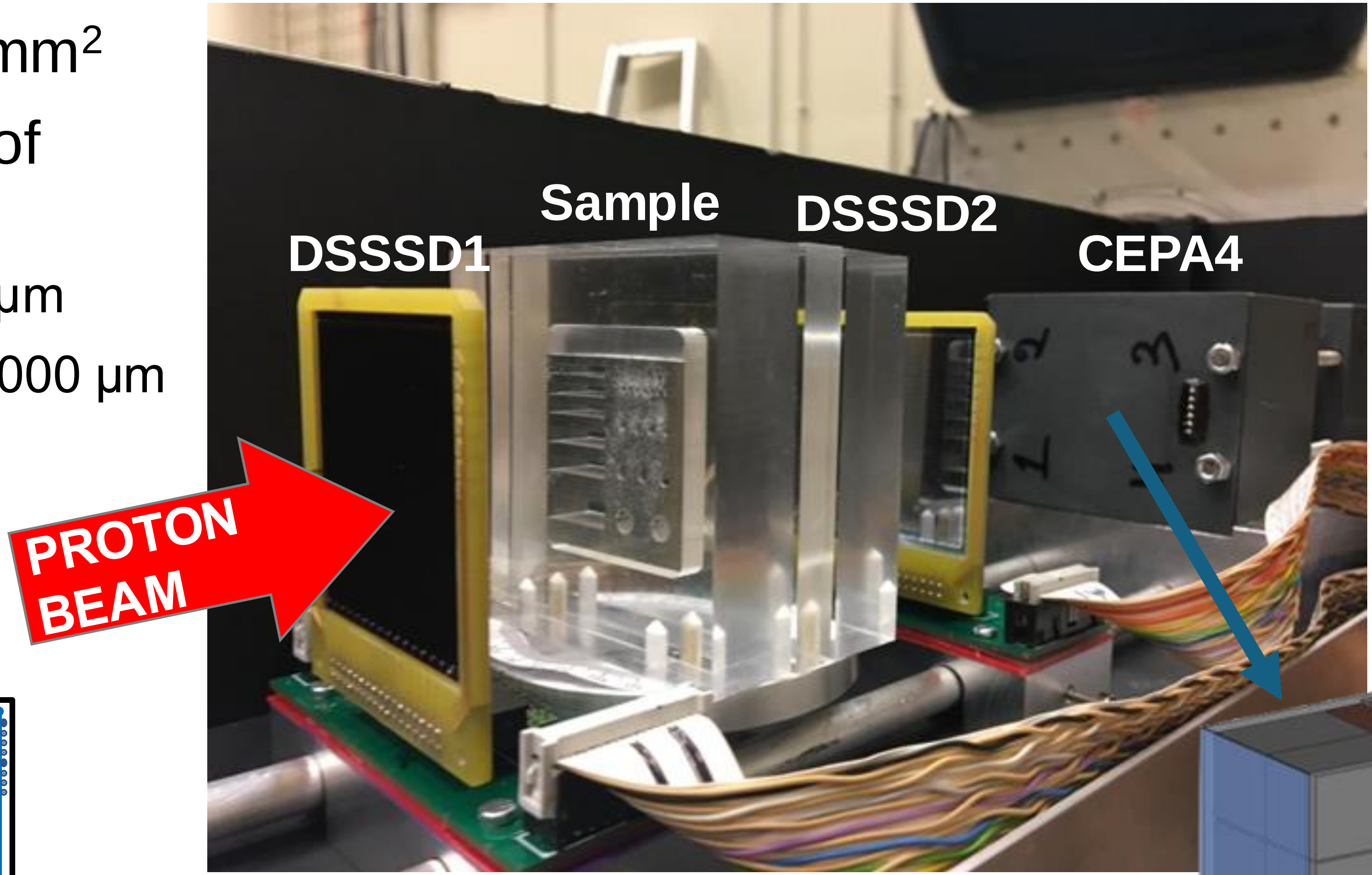
IEM proton scanner prototype

<u>DSSSDs:</u>

- Area: 50x50 mm^2
- 16x16 pixels of 3x3 mm^2
- DSSSD1: 1000 µm
- DSSSD2: 300-1000 µm

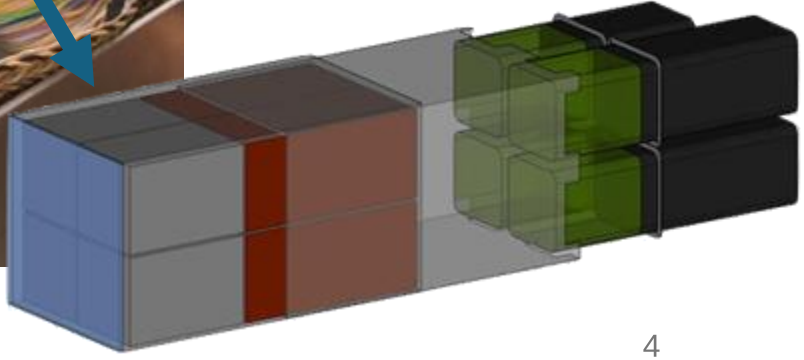




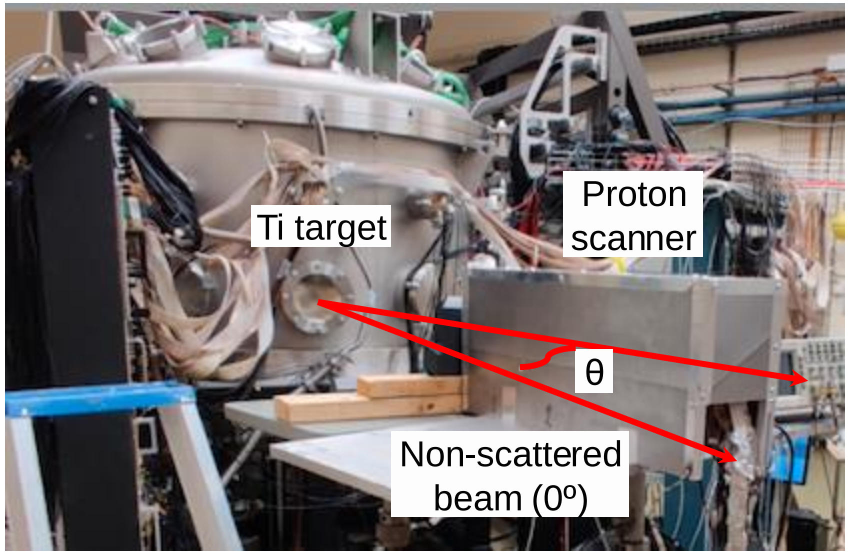


<u>CEPA4:</u>

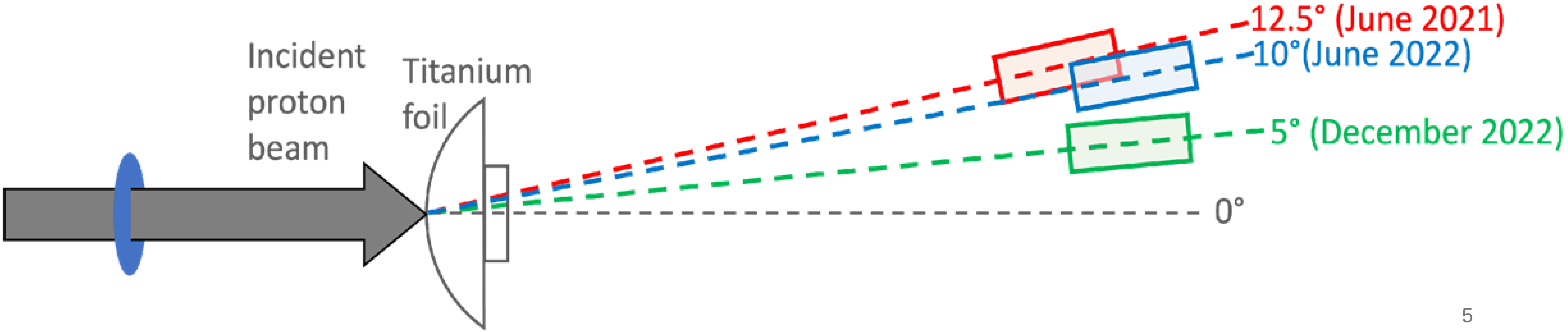
- Area: 54x54 mm^2
- 4 phoswich detectors
  - $LaBr_3$: 4-cm thick
  - $LaCl_3$: 6-cm thick



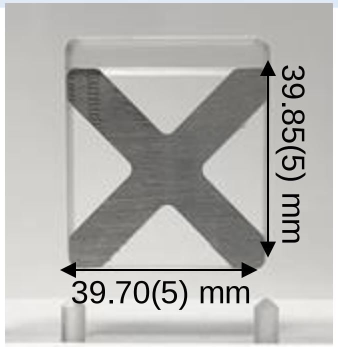
Experimental test at CCB, Krakow



Dates	θ (º)	Beam energies (MeV)	Beam time (hours)
Jun 2021	12.5	95 – 120	40
Jun 2022	10	100 – 210	35
Dec 2022	5	80 – 210	40



Proton Radiographs: how-to get the images?



- The patterns of the samples were reproduced.

Process to get the energy per hit on the scanner detectors ($E=E_{D1}+E_{D2}+E_{CEPA4}$)

Sum of the energy deposited | Number of hits | Energy deposited per proton

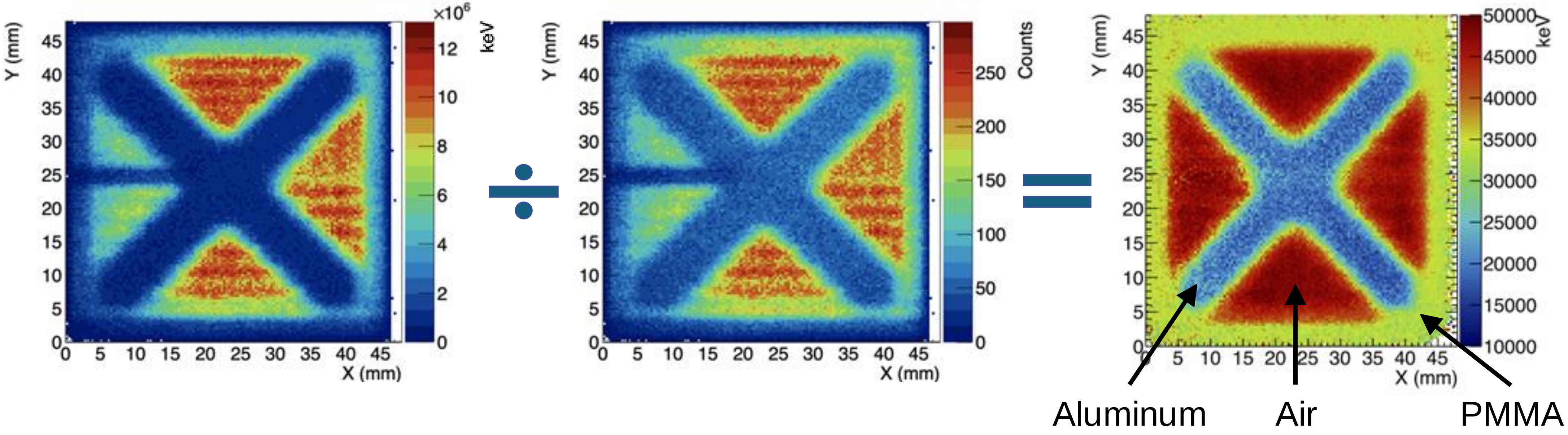
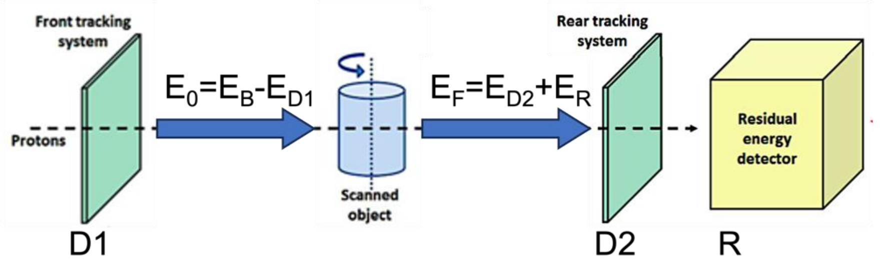


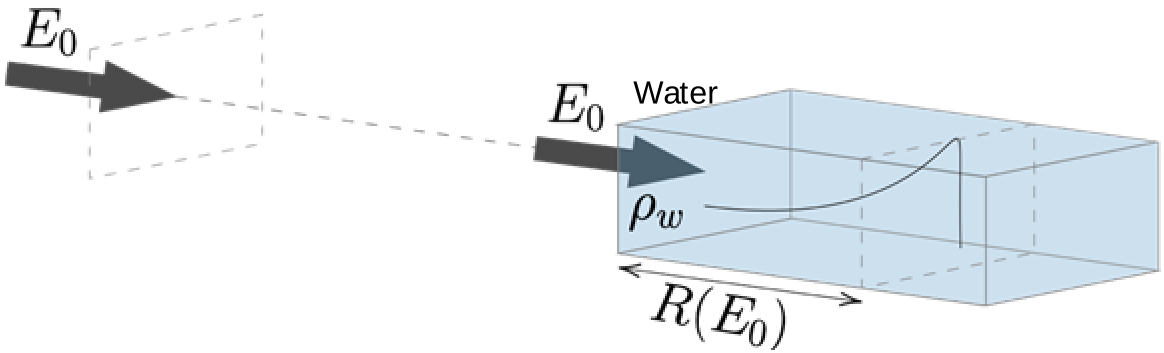
Image from: J. A. Briz *et al.*, IEEE Transactions on Nuclear Science **69**, 696 (2022)

Water Equivalent Thickness (WET)

The WET, or the beam penetration depth in liquid water, can be determined by the range shift related to placing a test object in the proton path.



$$\mathbf{WET} = t_w = R(E_0) - R(E_f)$$



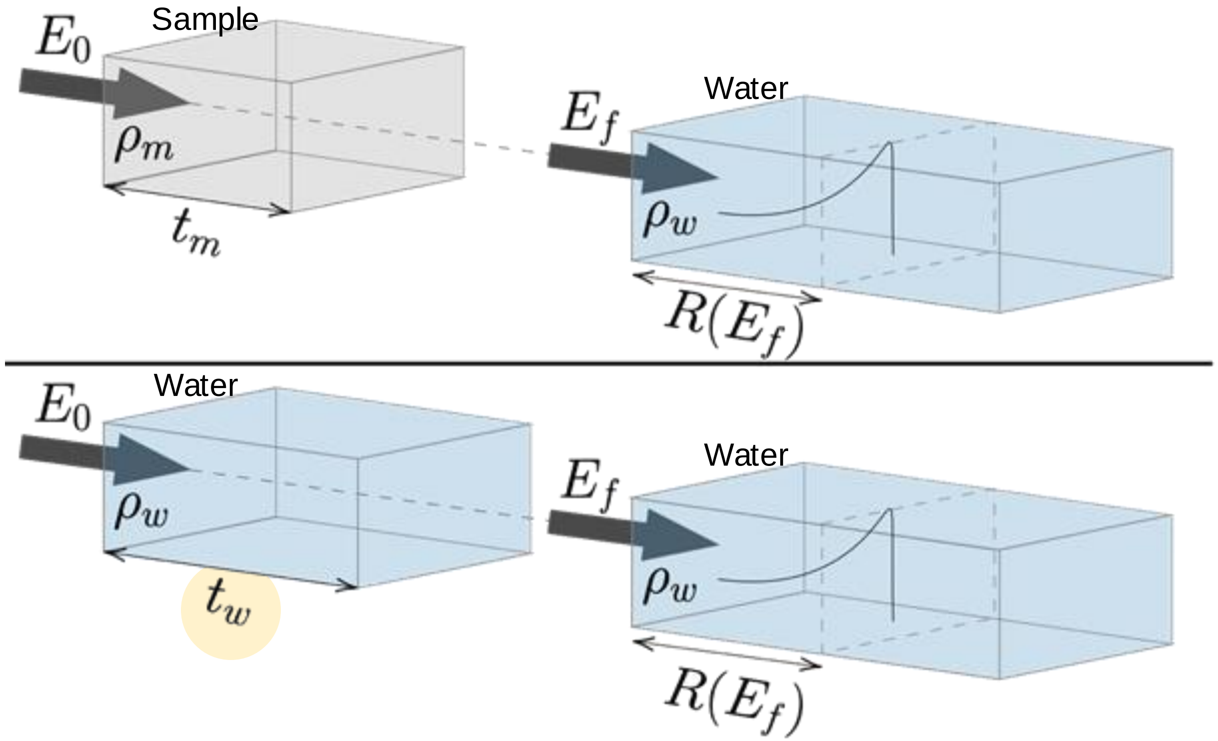
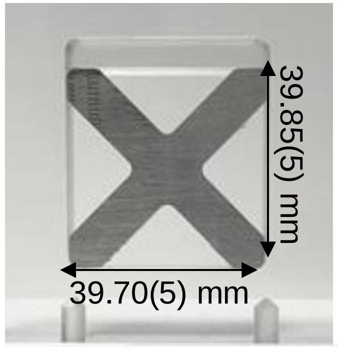
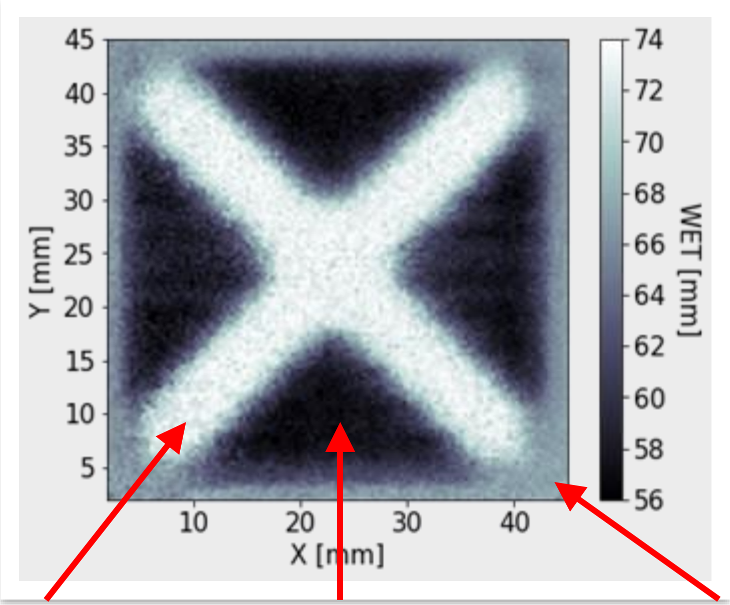


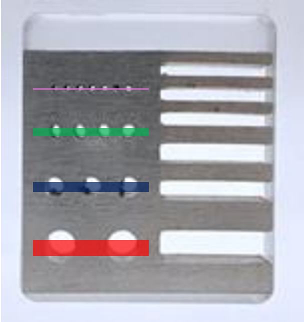
Image from: A. N. Nerio et al. (2023). EPJ Web of Conferences **290**, 08004 (2023)

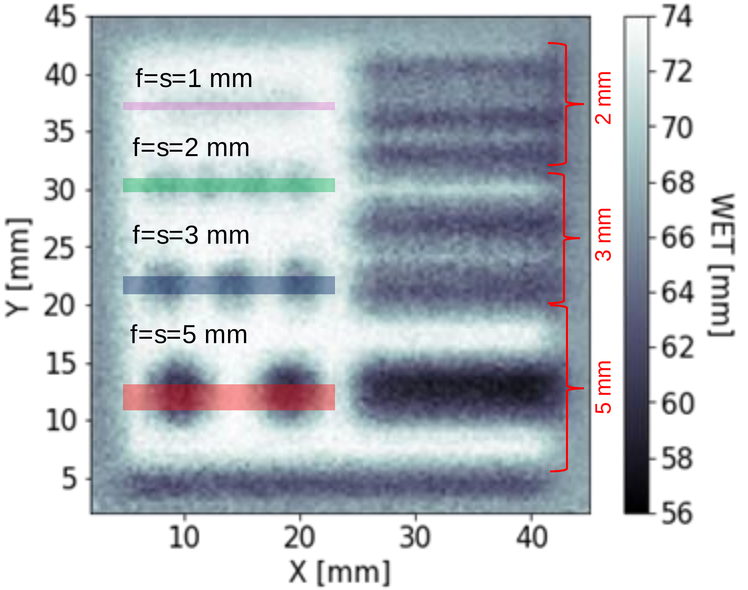
Proton Radiographs and WET

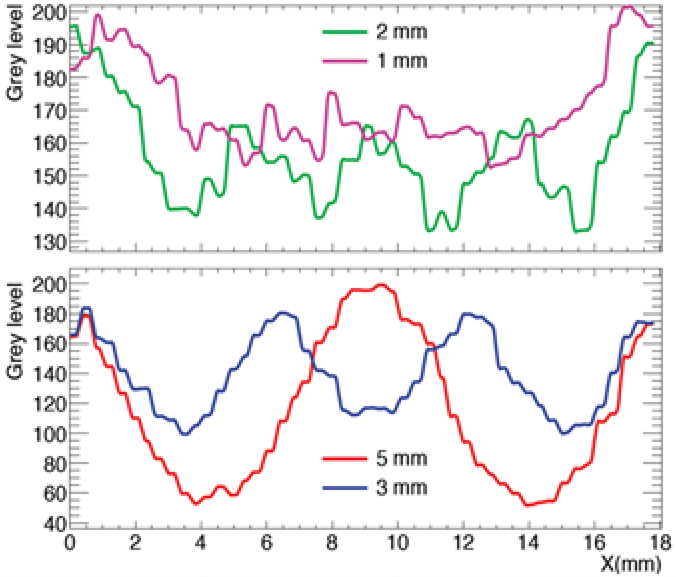




Aluminum Air PMMA





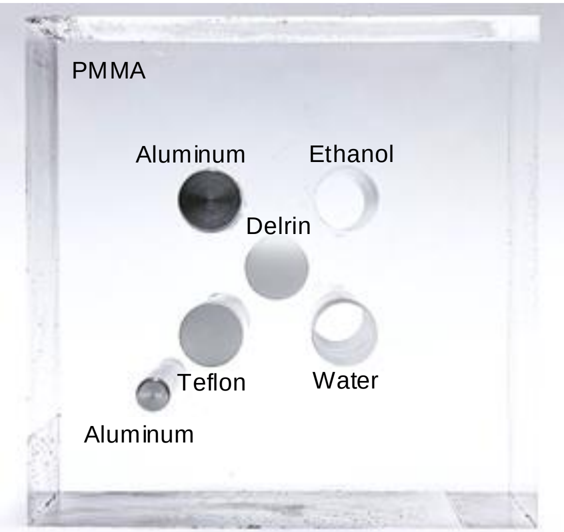


The prototype Modulation Transfer Function at 10% is **0.3 lp/mm** (1.6 mm)

Images from: J. A. Briz *et al.*, IEEE Transactions on Nuclear Science **69**, 696 (2022)
A. N. Nerio *et al.* (2023). EPJ Web of Conferences **290**, 08004 (2023)

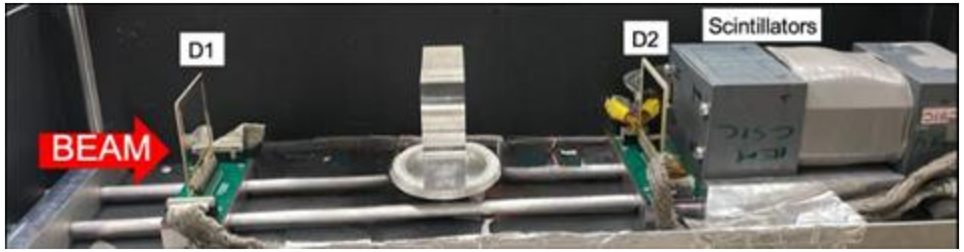
pRads: Effect of Multiple Coulomb Scattering

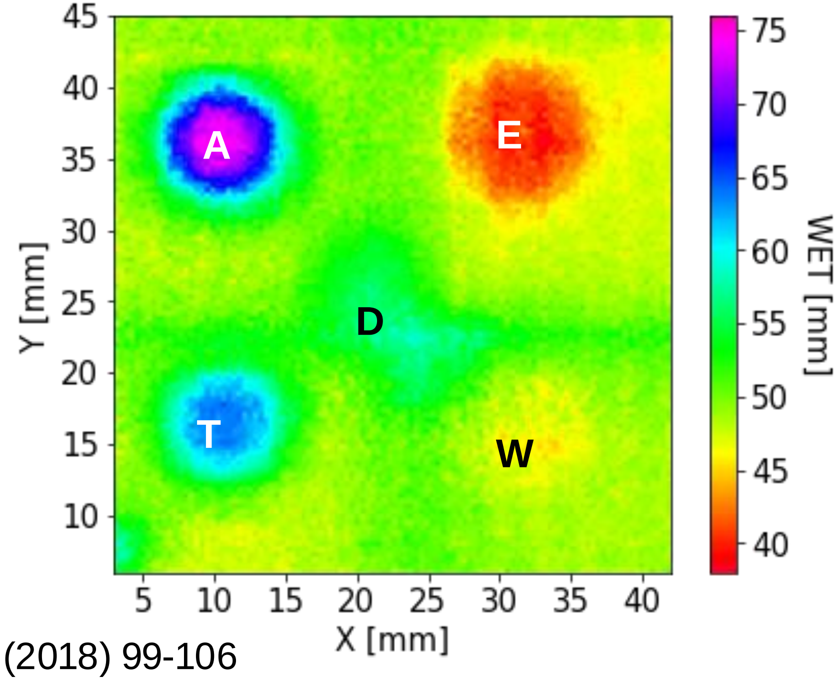
Material	RSP[3]
Aluminum	2.129
Teflon	1.788
Delrin	1.353 [4]
PMMA	1.168
Water	1.000
Ethanol	0.822



120 MeV proton beams

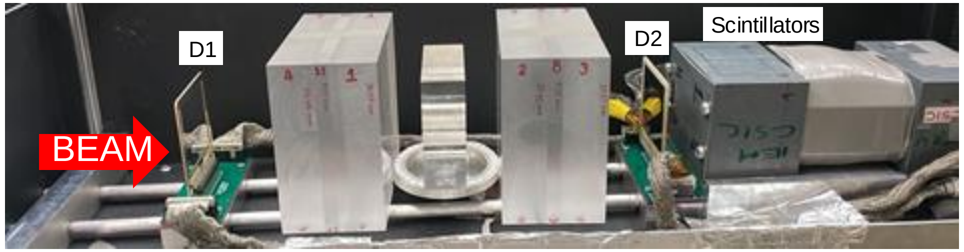
Sample without PMMA degraders

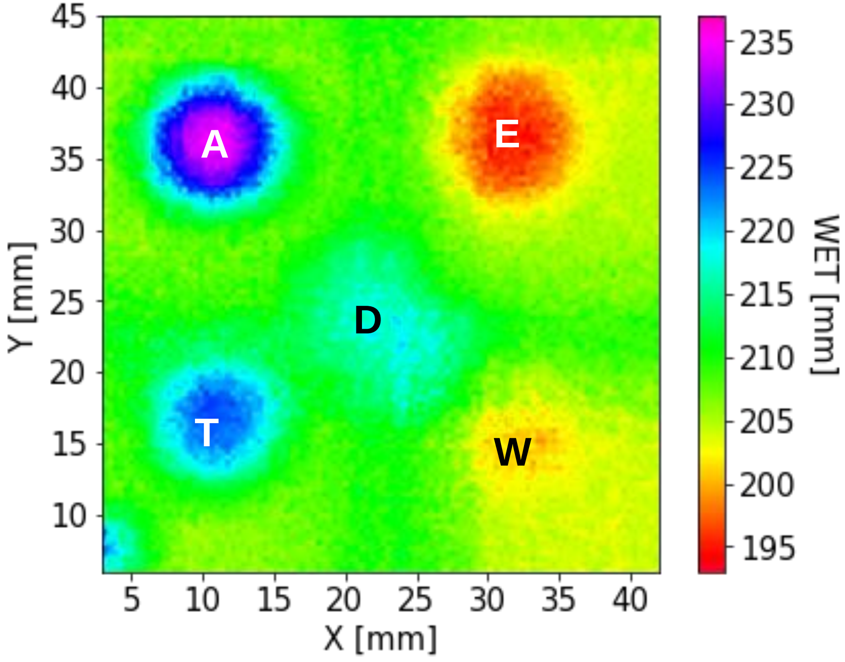




200 MeV proton beams

Sample with PMMA degraders





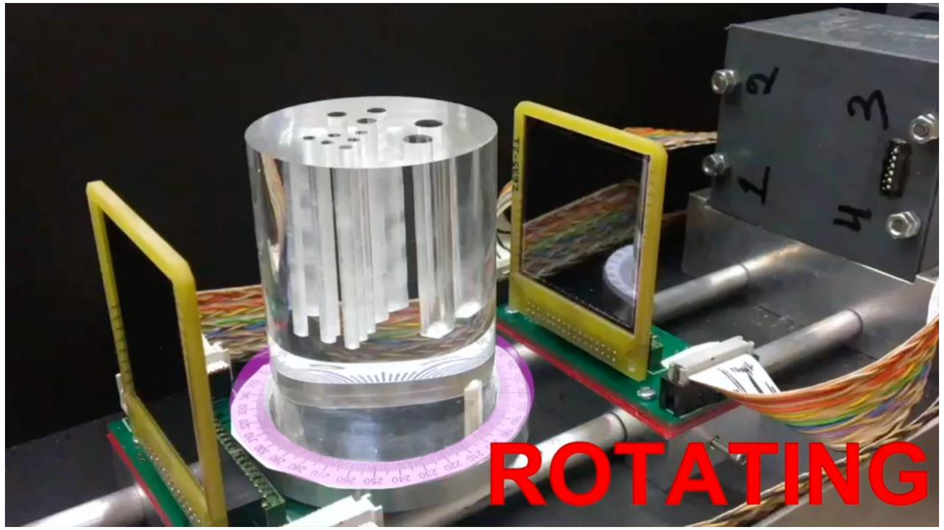
[3] J. K. van Abbema et al., NIM B **436** (2018) 99-106

[4] B. Schultze et al. 2015 *IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC)*. IEEE, 2015.

Tomography

- **Tomography:**

(Scan recording images at multiple positions)



Ethanol-Water inserts

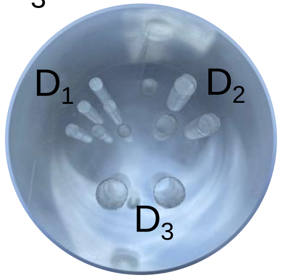
D = 9 mm

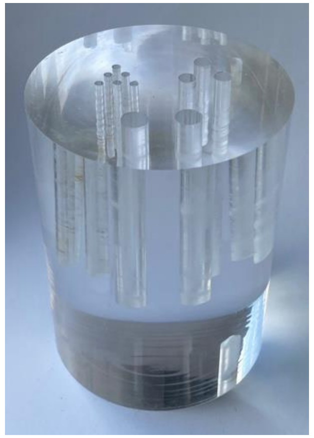
5 inserts (Al, T, D, W, E)

D = 10 mm

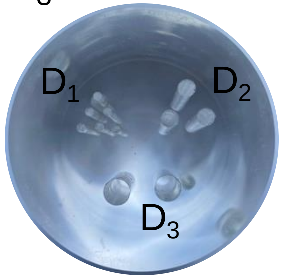
3D Derenzo patterns

D_1 = 3 mm
D_2 = 5 mm
D_3 = 7 mm



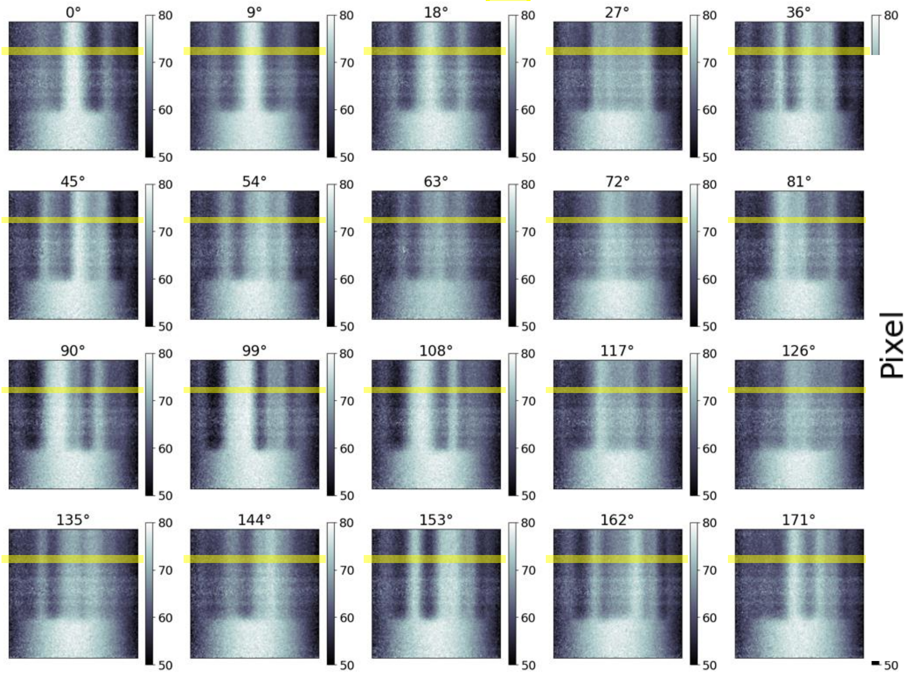


D_1 = 2 mm
D_2 = 4 mm
D_3 = 6 mm

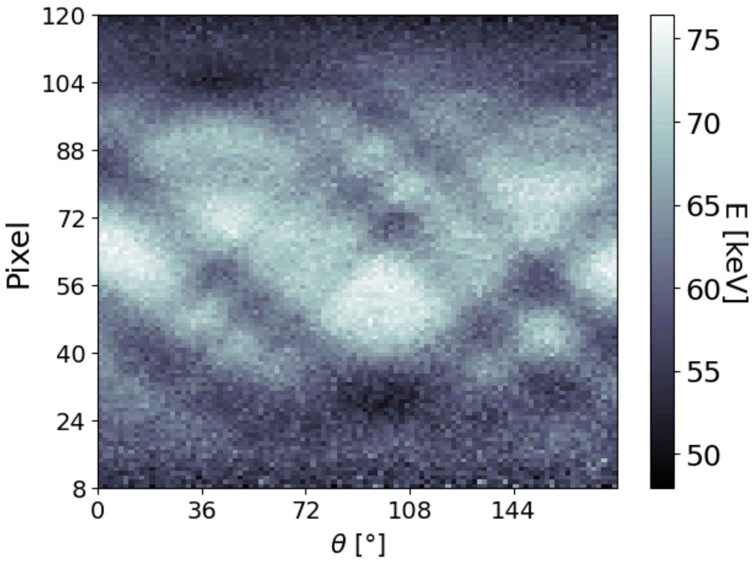


Tomographic reconstruction

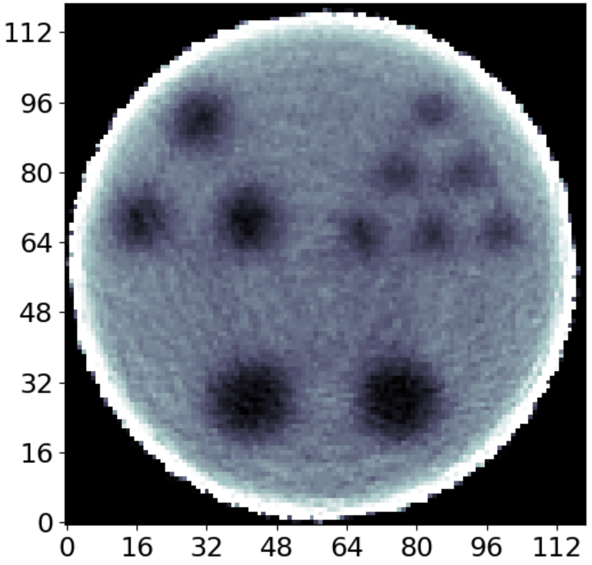
Projections at several positions

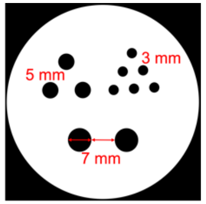


Sinogram



Tomographic reconstruction





Modified form E. Nácher et al., EPJ Plus **139** (2024) 404.

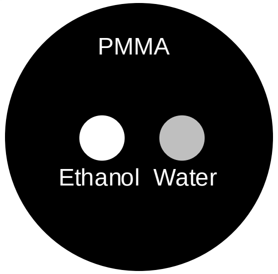
FBP reconstruction

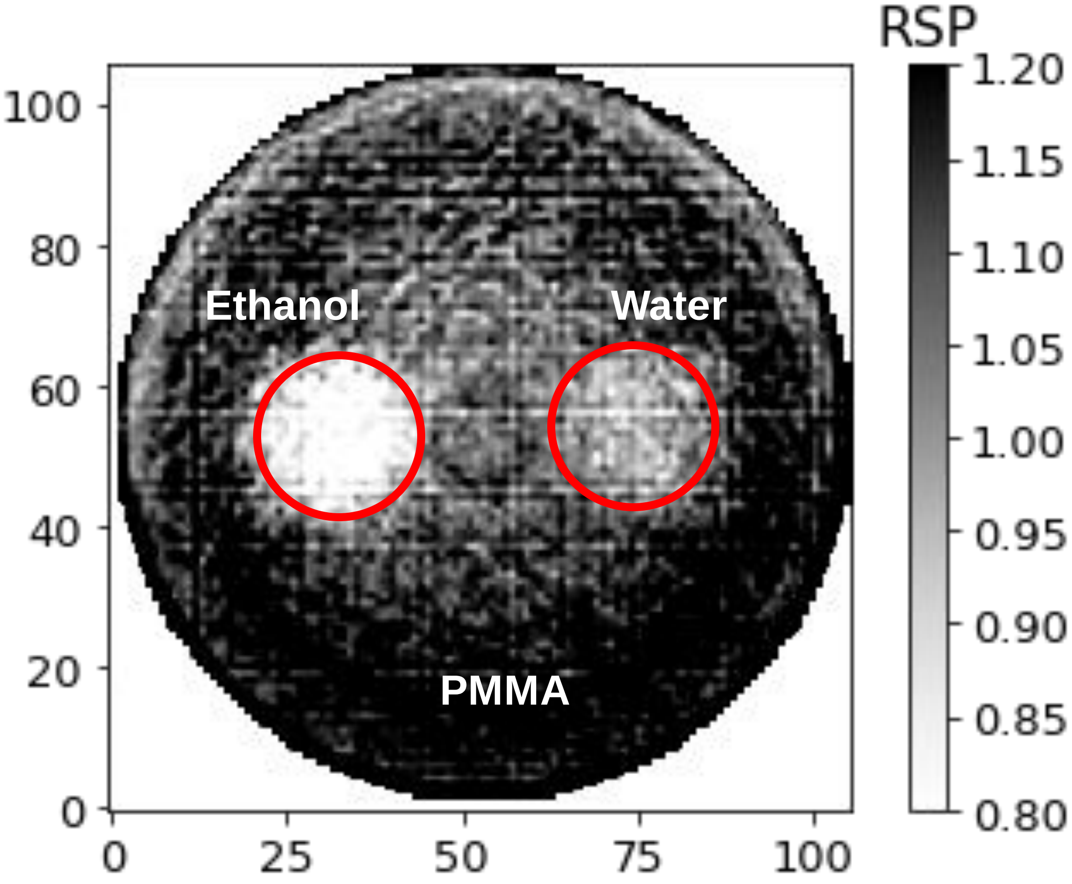
```
from skimage.transform import iradon

theta_0 =  np.linspace(0.,180.,100, endpoint=False)

reconstruction_fbp    = iradon(Sinogram[3:120, :],
                               theta=theta_0,
                               circle=True)
```

Determination of the RSP





RSP values in good agreement with previous works ($R_{80\%}$[3] and pCT[5]).

Region	RSP [3] $R_{80\%}$	RSP [5] pCT	RSP* This work
Water	1.000(4)	1.00(3)	1.000(5)
Ethanol	0.822(3)	0.82(2)	0.829(7)
PMMA	1.168(5)	1.15(3)	1.158(5)

[3] J. K. van Abbema et al., NIM B **436** (2018) 99-106
[5] A.Terakawa et al., Phys. Med. Biol. **68** (2023) 095023.
* E. Nácher et al., EPJ Plus **139** (2024) 404.

Summary and Outlook

- A system for **pRad** and **pCT** imaging has been designed and tested in a proton therapy facility using relevant energies.

- In **proton radiography** reconstruction:
  - Structures as small as **2 mm** were resolved.
  - We distinguished well different materials and **determined WET values**.
  - Multiple Coulomb Scattering does not seem to affect the image quality.

- **Proton tomography** studies are ongoing. Preliminary results show that:
  - Structures of **3 mm** were resolved.
  - We **distinguished different materials**, and RSP values are being determined.

Thanks for your attention

A.N. Nerio[a], J.A. Briz[a,b], M.J.G. Borge[a], E. Nácher[c],

O. Tengblad[a], A. Perea[a], V.G. Távora[a]

[a]Instituto de Estructura de la Materia, CSIC, Madrid, Spain

[b]GFN and IPARCOS, Universidad Complutense de Madrid, Madrid, Spain

[c]Instituto de Física Corpuscular, CSIC-Universidad de Valencia, Valencia, Spain

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Protontherapy and nuclear techniques for oncology

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Collaboration team IFJ-PAN

Cyclotron Centre Bronowice

CCB

A. Maj, P. Olko, M. Zieblinski, N. Cieplicka-Orynczak,

M. Ciemala, W. Parol, M. Matejska-Minda, B. Sowicki, A. Pedracka.