ASTRA a novel Range Telescope for pCT

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on behalf of César Jesús-Valls, Thorsten Lux, Tony Price and Federico Sánchez https://arxiv.org/pdf/2109.03452.pdf

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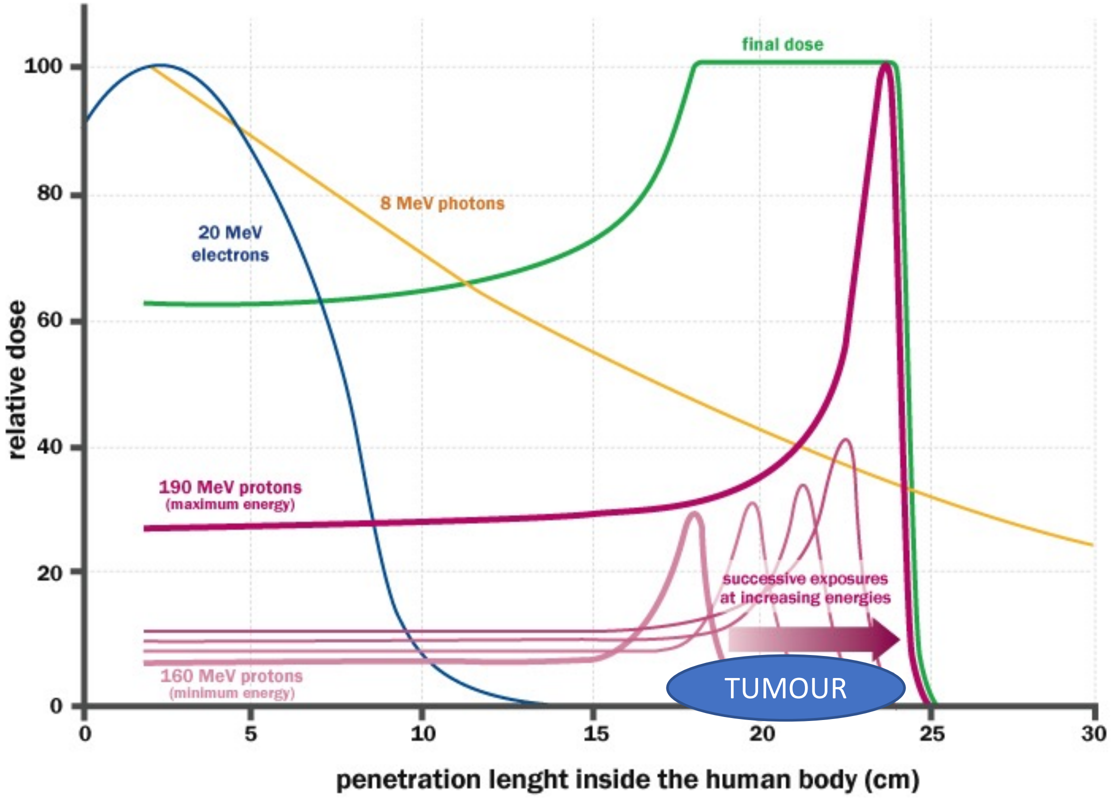
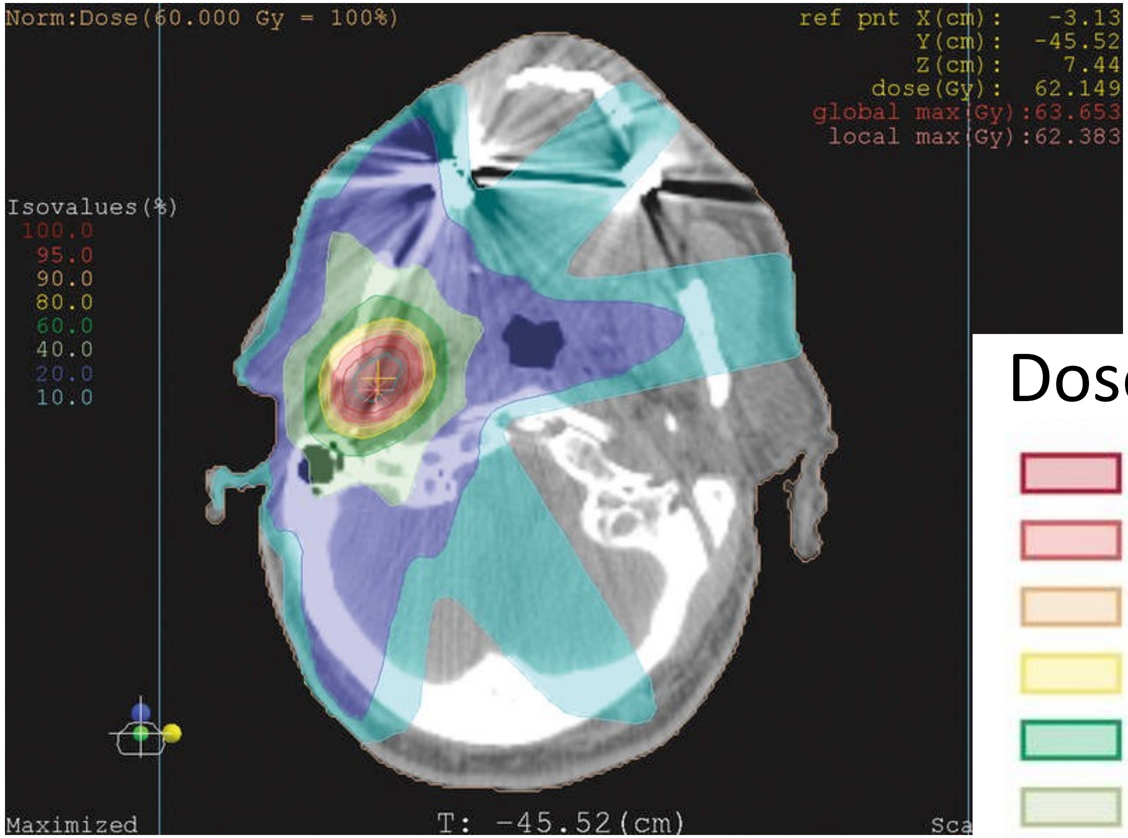
Overview

- Introduction:
  - Protons vs X-rays
  - State of the art on proton CT
  - Novel technologies
- Simulation work:
  - Position tracker performance
  - Matching tracks with Astra
  - Energy reconstruction
  - pCT
- Further work
- Conclusion

Proton vs X-rays

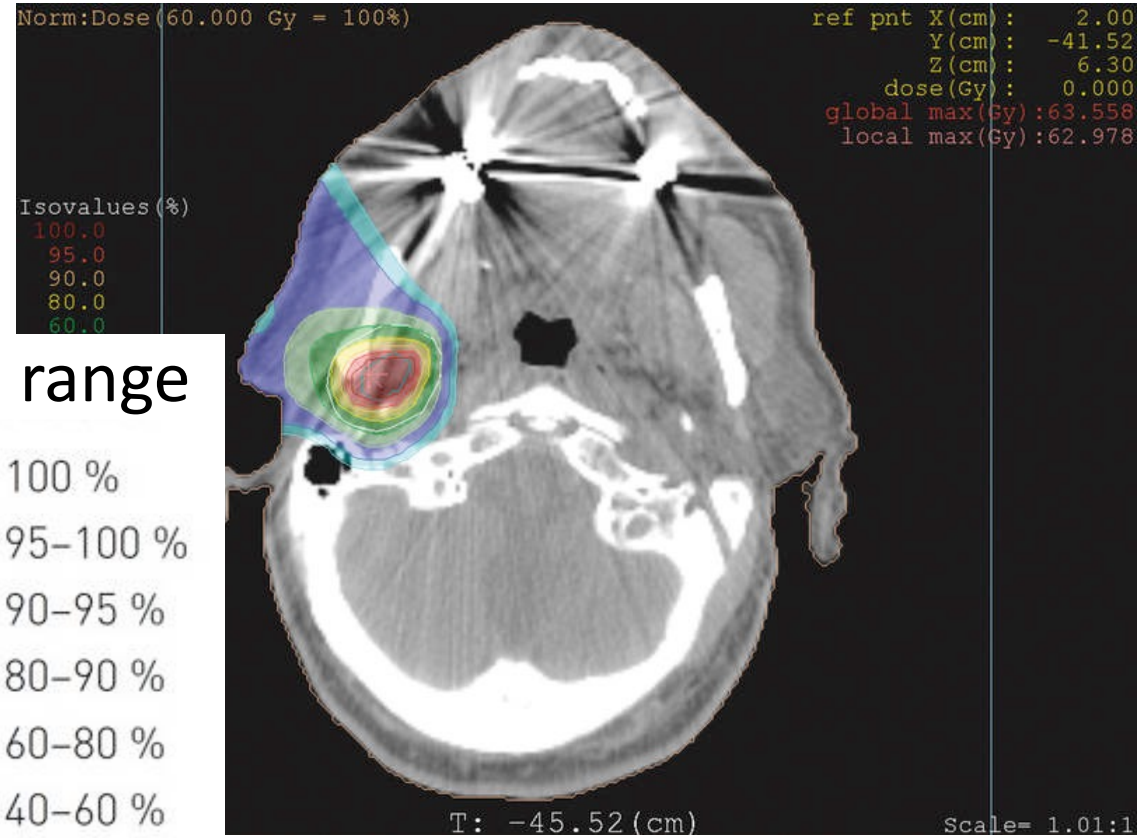


- A beam of photons will deposit energy all along its path following an exponential law due to beam attenuation.
- A proton will lose energy via the Bethe-Bloch formula and as such exhibit a Bragg Peak (BP)
- Most of the energy is deposited just before a proton stops
- Range of charge particle and therefore position of BP set by initial particle energy and materials to be traversed
- No dose deposited after the BP
- Lower dose to healthy tissue reduces the risk of complications in later life and allows for treatment of cancers close to critical organs



Dose range

- 100 %
- 95–100 %
- 90–95 %
- 80–90 %
- 60–80 %
- 40–60 %
- 20–40 %
- 10–20 %

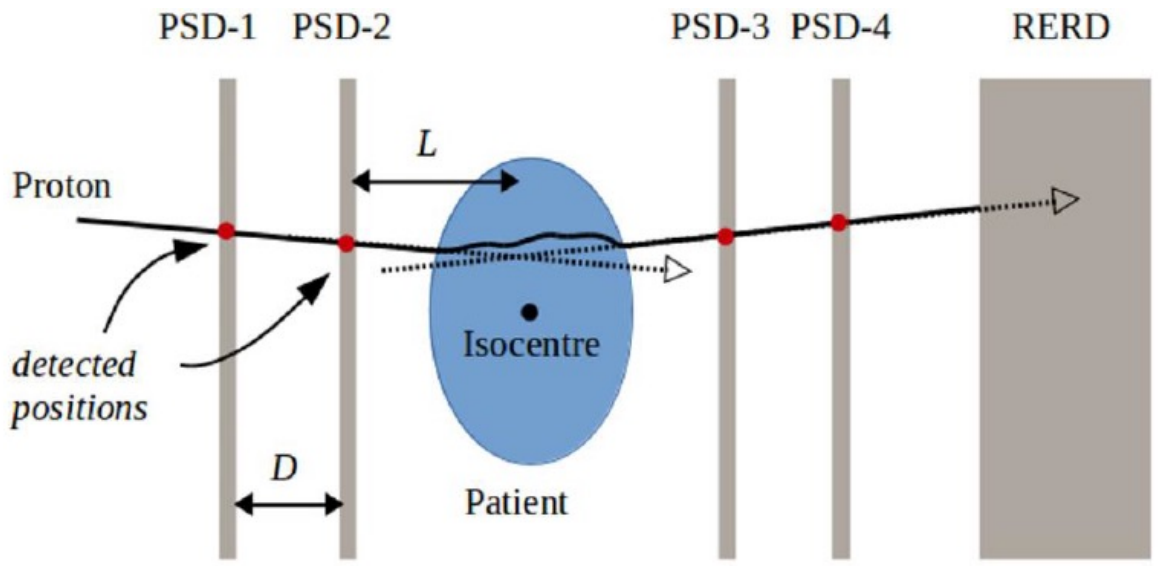


X-ray radiotherapy **Proton radiotherapy**

Needs for proton CT

In order to obtain a proton Computed Tomography (pCT) one needs to know:

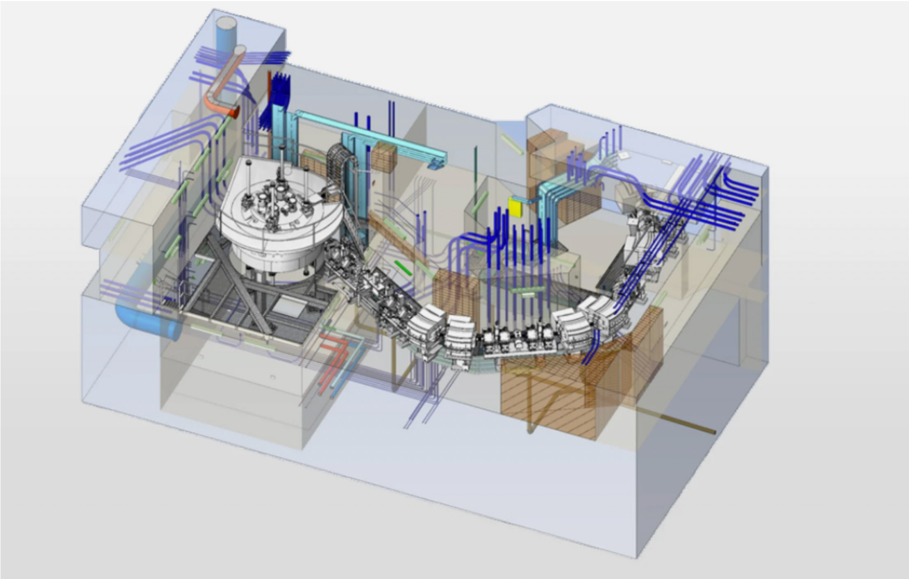
- The protons' entering and exiting points of the imaged body.
- The residual energy after trespassing the phantom.
- How to reconstruct the path within the patient/phantom.



Note: For this work, a Most Likely Path (MLP) algorithm written for the PRaVDA collaboration was used. This algorithm requires from energy measurements.

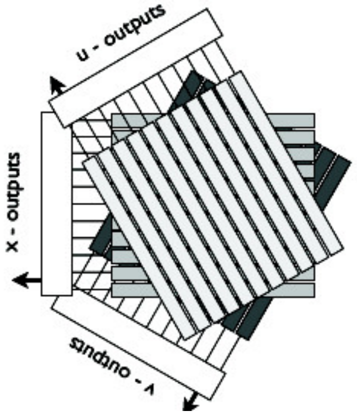
State of the art on pCT

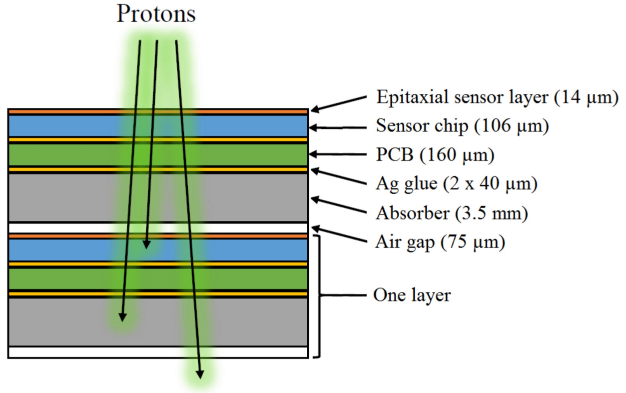
- Clinical beam using energies up to 250 MeV
- The currents provided by the clinical beams during treatment are of the order of 10^9 protons/s:
  - These values aim to be reduced for imaging purposes but there are limitations due to the accelerator properties.
  - Beam time is gold so the faster the better.
- Proton bunch density follows a Poisson distribution.
- Pencil beam used for imaging → Gaussian beam with $\sigma \leq 10$ mm

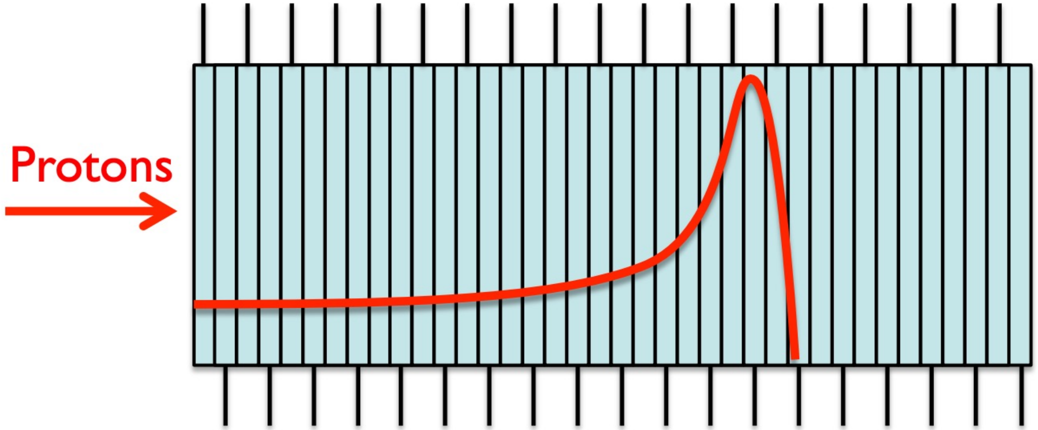


State of the art on pCT

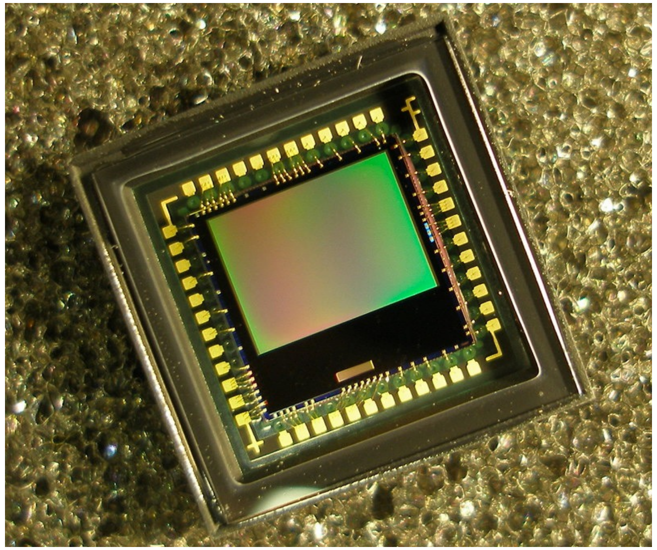
- **Position trackers:**
  - **PRaVDA** strip modules:
    - Old technologies (30 years old). Strips sensors (**1D resololution!**) are used in order to track the protons before and after trespassing the phantom.
    - Large budget material.
    - Larger amounts of data.
    - Hard to decouple ambiguities.
- **Energy tagging:**
  - New technologies under development example
    - **ALPIDE** based calorimeters (Top right).
      - Expensive (silicon)
      - **Slow sampling rate** few micro seconds.
    - The plastic scintillator design from **Loma Linda** or the **SUPER-NEMO** based range telescope (bottom right)
      - Layers of plastic scintillator
      - **Not capable to deal with multi protons**
      - Unable to deal with “kinks”



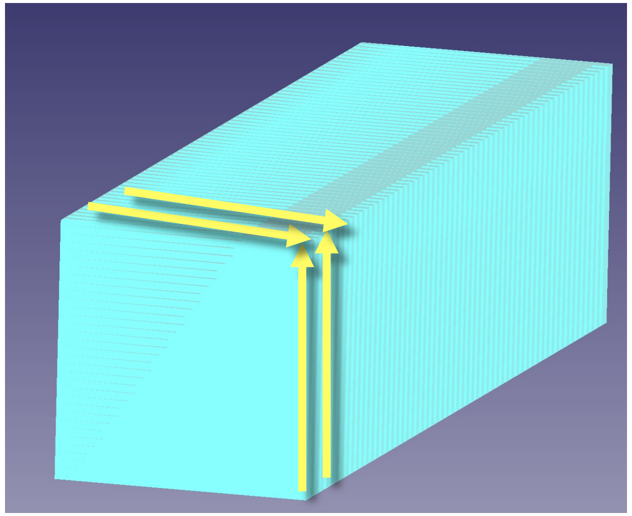




New technologies



- Depleated Active Pixel Sensors (DMAPS) are a modification of APS but faster and able to cope with radioactive environments.
    - Same tech you have in your phone, but cooler.
- **A S**uper **T**hin plastic **RA**nge telescope:
    - Fine segmentation achieving 1D resolution to be able to track individual protons was suggested.
    - The sketch on the bottom right shows the ASTRA module segmented in bars oriented in perpendicular directions to the beam.

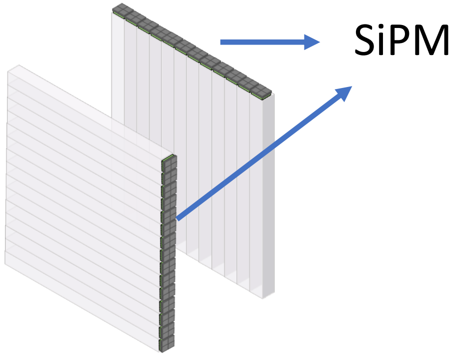


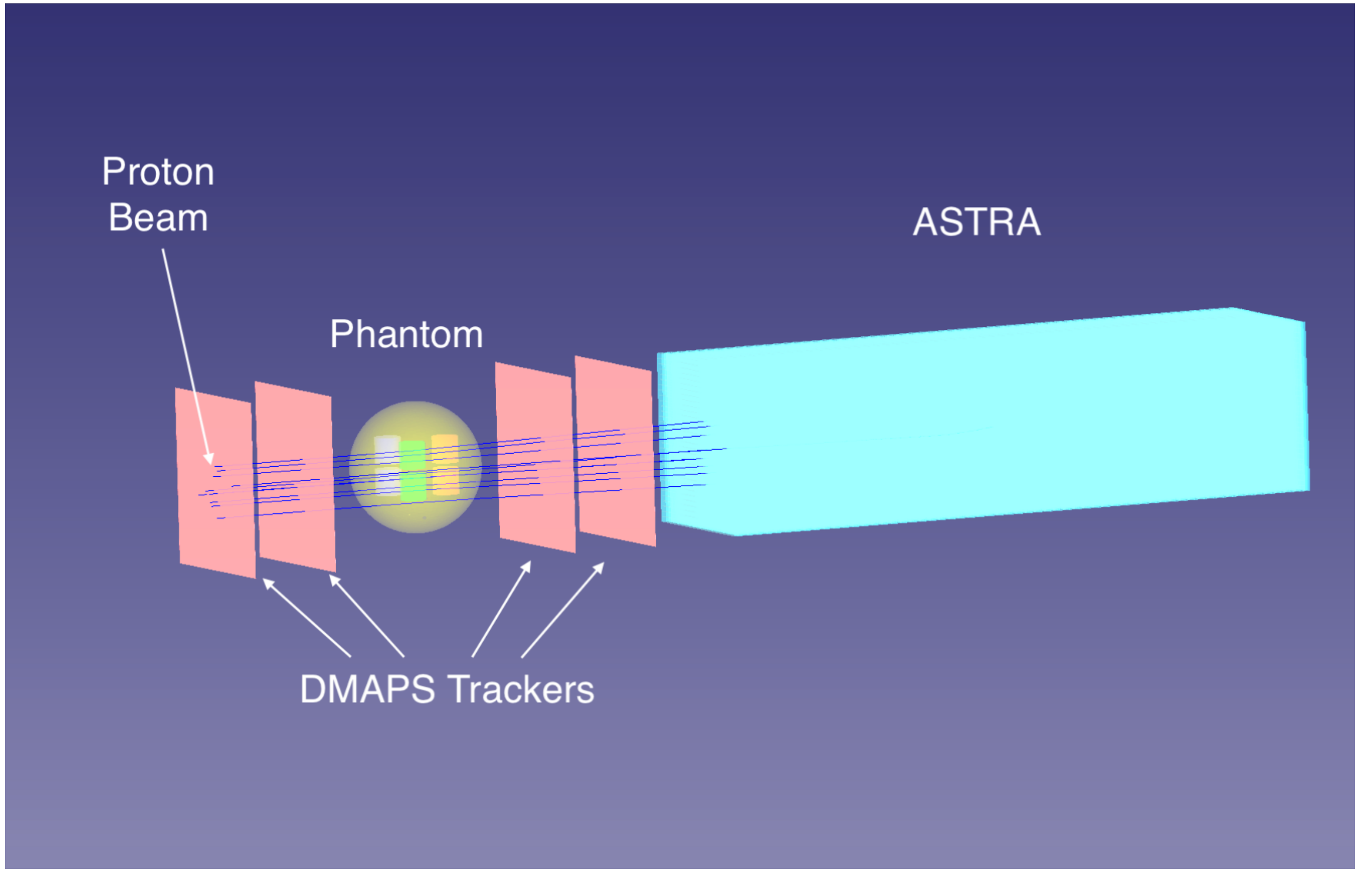
Simulation work

The technologies suggested for the GEANT4 simulation were:

- **DMAPS** with for the front (2) and back (2) tracking system with pixels of 40x40μm^2 and a full size of 10x10cm^2

- **ASTRA** for the residual energy measurement with 120 layers of 36 bars of 9.6x0.3x0.3 cm^2.





Efficiency and purity

The figure of merit for the front tracker is $Purity \times Efficiency$ defined as:

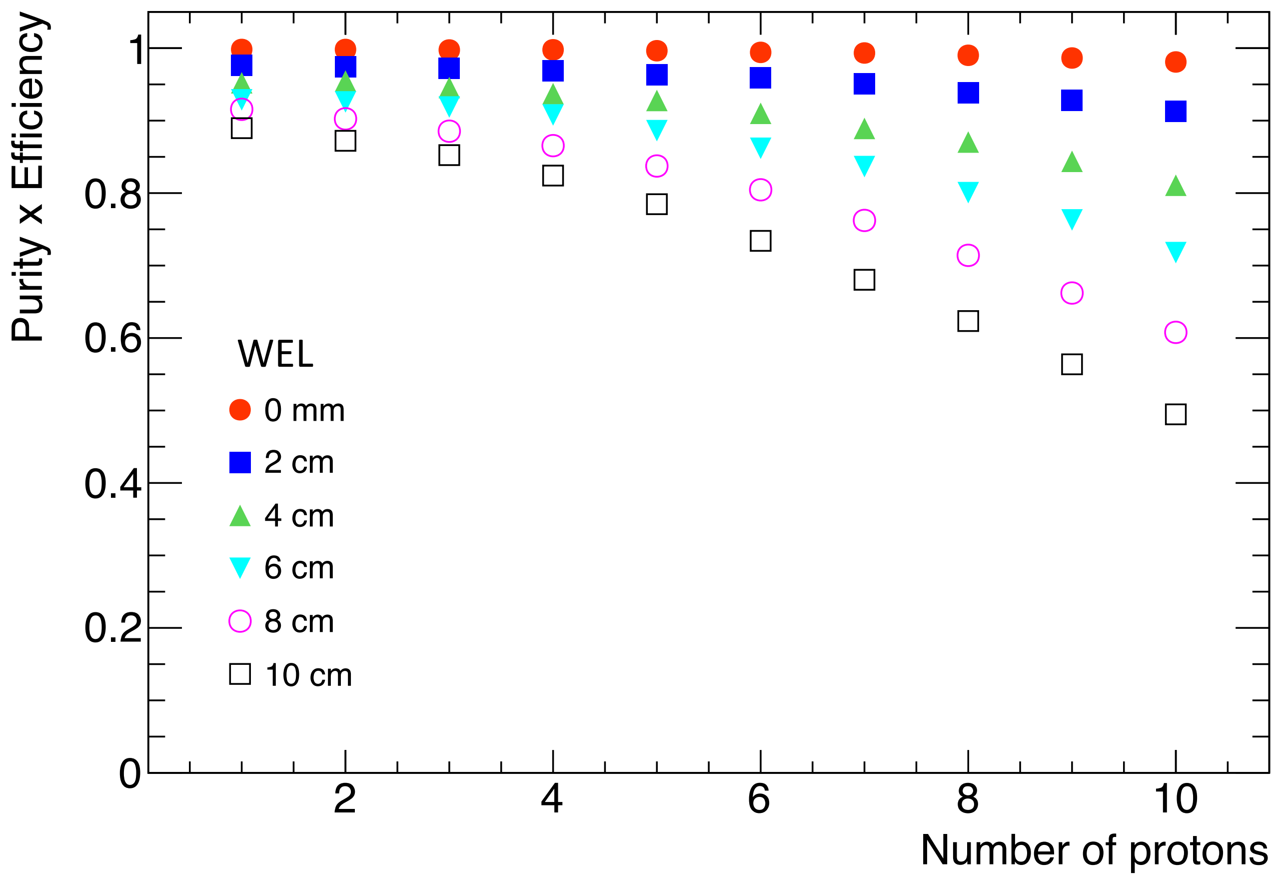
$$Purity = \frac{Well\ Reco\ Tracks}{Total\ Reco\ Tracks}$$

$$Efficiency = \frac{Total\ Reco\ Tracks}{Total\ \ Tracks}$$

As function of the number of protons per event for different water equivalent lengths (WEL).

180 MeV protons with a Gaussian beam distribution with $\sigma = 10\ \mathrm{mm}$.

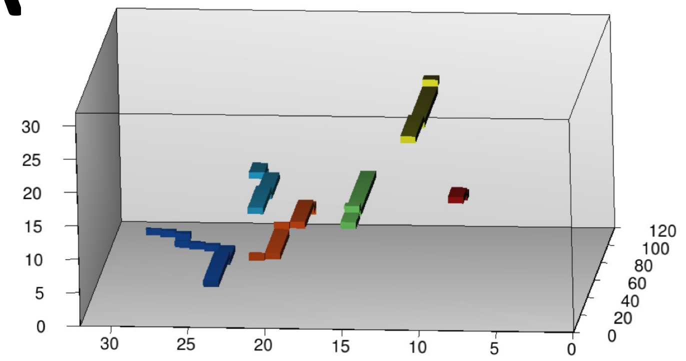
Note that MCS will affect on the efficiency (lost protons) and purity (crossed tracks).

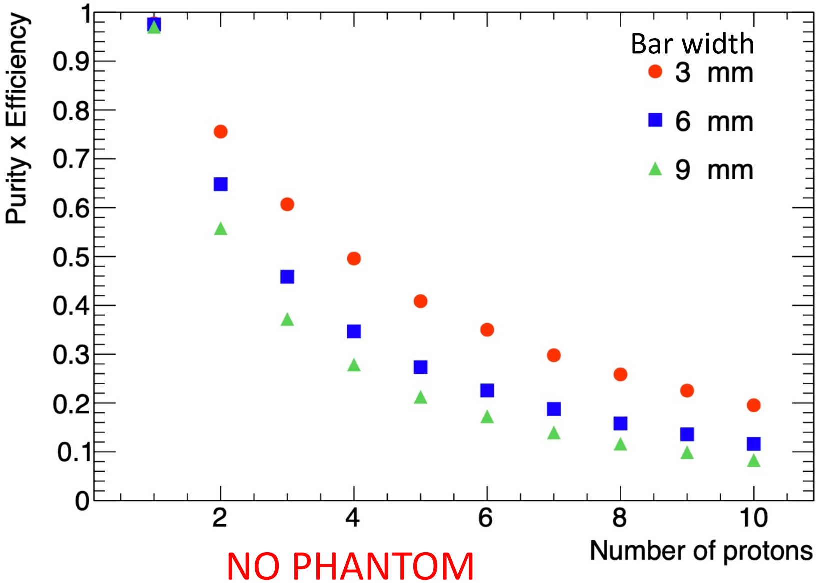


Matching tracks with ASTRA

- Project DMAPS tracks into ASTRA first 2 layers (3D seeding points in ASTRA), connect trajectories that are closer.
- For the seeding points, assume that the track goes forward, look for the next closer 3D point and propagate forward. Hits can not be shared between tracks.
- Different bar sizes where tested trying to study costs and figures of merit such as $Purity \times Efficiency$ and energy resolution.

NOTE: The reconstruction can be improved in the future with dedicated work, we only built a minimal version to show the concept.





NO PHANTOM

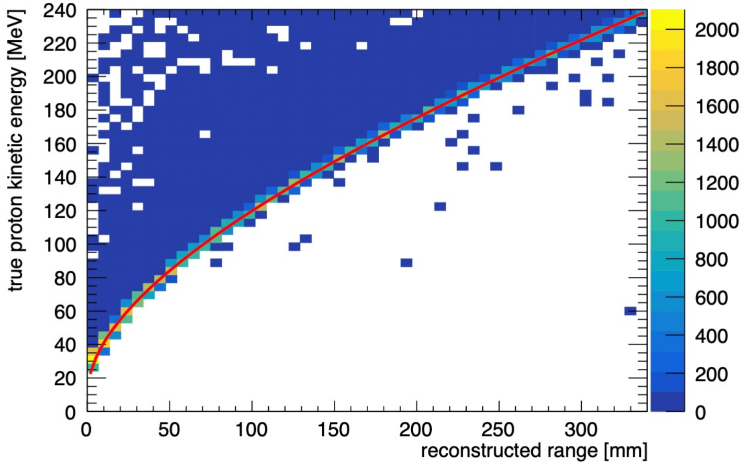
Energy reconstruction

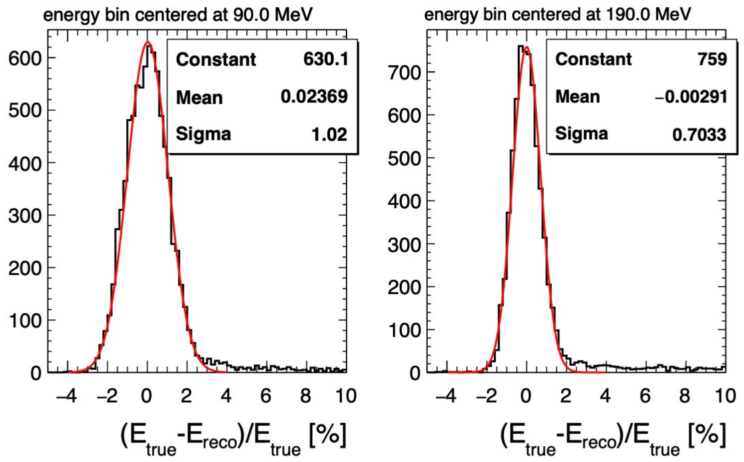
- Energy reconstructed (purely by range) using range reconstructed by the length of each track.

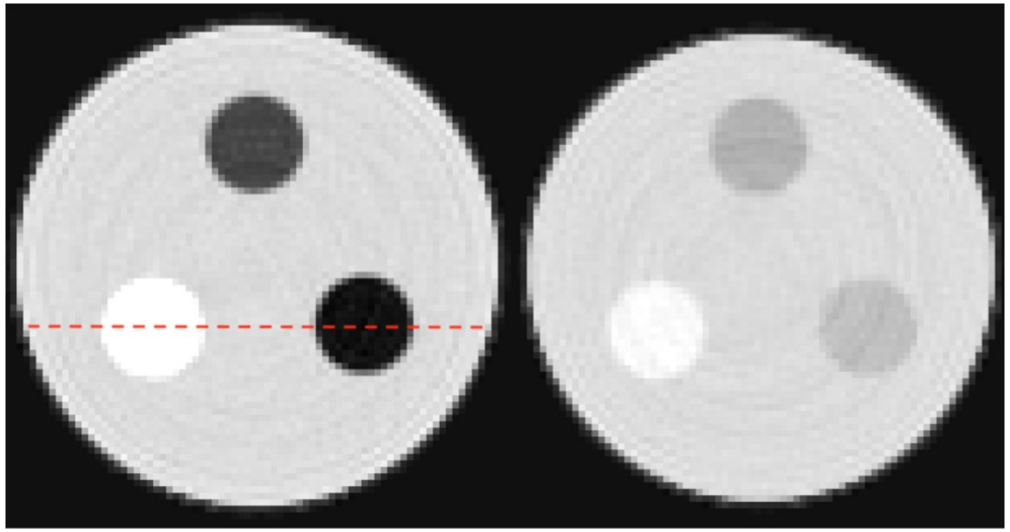
- The use of 4 bits and 12 bits calorimetric information could help to improve the energy resolution and efficiency.

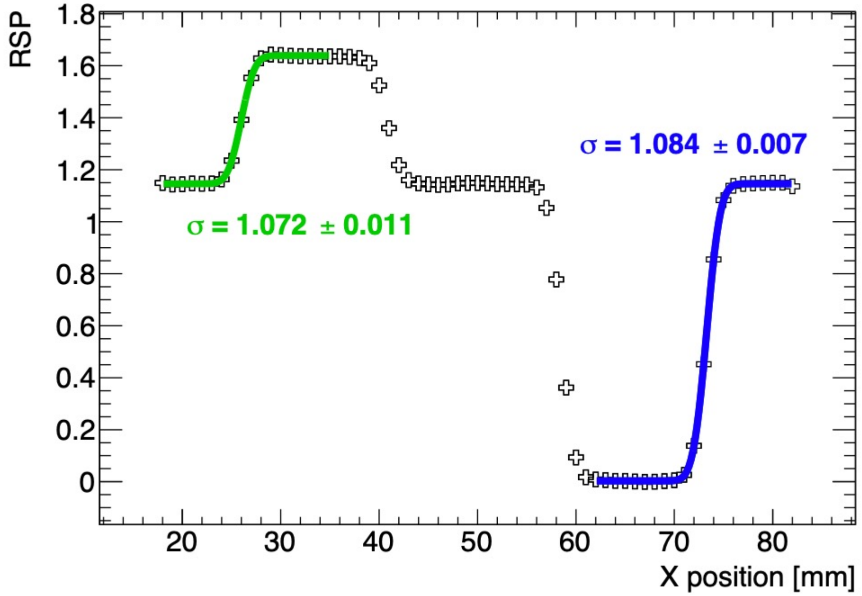
- Long tails due to hard scattering.

Segmentation → Length of track rather than depth/layer









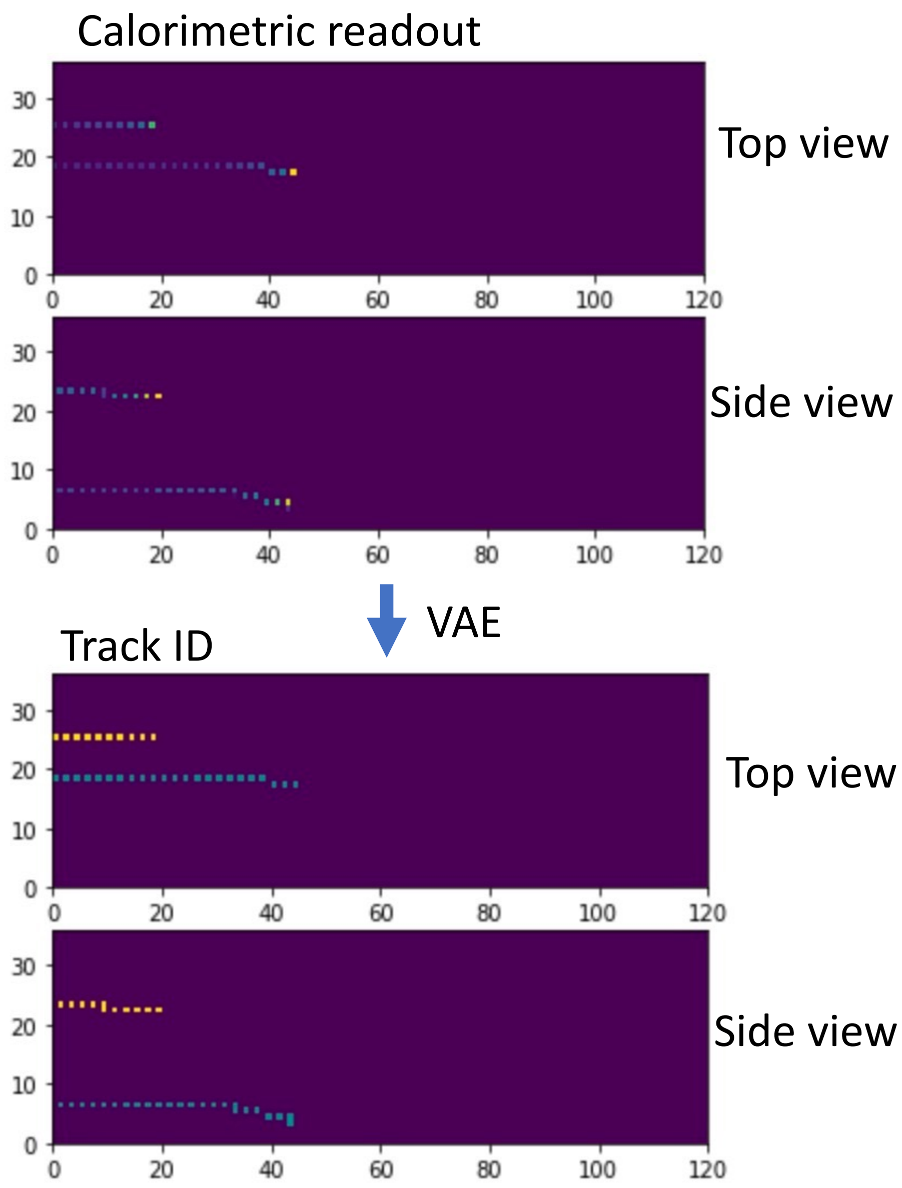
Material	RSP (Reco)	RSP (True)	%diff
Water	0.992 ± 0.002	0.994 ± 0.002	0.201
Air	0.009 ± 0.002	0.008 ± 0.002	-12.5
Adipose	0.916 ± 0.006	0.917 ± 0.005	0.109
Rib bone	1.325 ± 0.003	1.326 ± 0.001	0.075
HC bone	1.641 ± 0.003	1.646 ± 0.002	0.304
Perspex	1.144 ± 0.004	1.149 ± 0.002	0.455
Lung	0.302 ± 0.003	0.302 ± 0.002	0.000

Material	RSP (Reco)	%diff (True)	%diff (1p)
Water	1.033 ± 0.002	3.924	4.133
Air	0.076 ± 0.006	850	744
Adipose	0.96 ± 0.02	3.60	3.71
Rib bone	1.34 ± 0.04	1.06	1.13
HC bone	1.66 ± 0.02	0.85	1.16
Perspex	1.14 ± 0.01	-0.78	-0.35
Lung	0.35 ± 0.02	15.89	15.89

- High RSP contrast with 1 proton (<1% diff)
- Very good position resolution (~1mm)
- Mild degradation for 3 protons.

Further work

- The use of Deep Learning Neural Networks to:
  - Compute the protons' residual energy
  - Decouple tracks from multi proton events from calorimetric information (top) to track ID (bottom) using Variational Auto-Encoders.
- Find the best electronics for the project maybe allowing calorimetric information.
- Build a small prototype to test the feasibility of the project:
  - Practice test beams for energy calibration
  - Produce a proton radiography (and even pCT) of a small phantom using OPTIMA trackers



Summary and conclusions

- Paper on arxiv: https://arxiv.org/pdf/2109.03452.pdf, published by Physics in Medicine & Biology
- Proton computed tomography is key in order to improve proton radiotherapy and increase the number of patients benefiting from it.
- The current systems are not fast enough to be used under clinical conditions or in clinical facilities
- The use of new technologies such as DMAPS and the suggested ASTRA system can be a big step forward in the field.
- A full Monte Carlo simulation has been built able to replicate all the relevant features of the proposed system.
- A preliminary analysis was performed to test the capabilities of ASTRA measuring the RSP of different materials within a phantom.
- The images obtained present an excellent material contrast and a spatial resolution of the order of the mm.
- The results show a proton stopping power values with errors below 0.5 %.
- The University of Birmingham, University of Geneva and IFAE are applying for funding to build a prototype and test it at Birmingham’s MC40 cyclotron and other clinical beams in the following years to proof the capabilities of this technology