Enhancing Particle Therapy Through The Use Of Mixed Ion Beams

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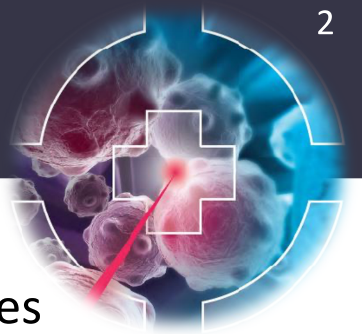
Abstract

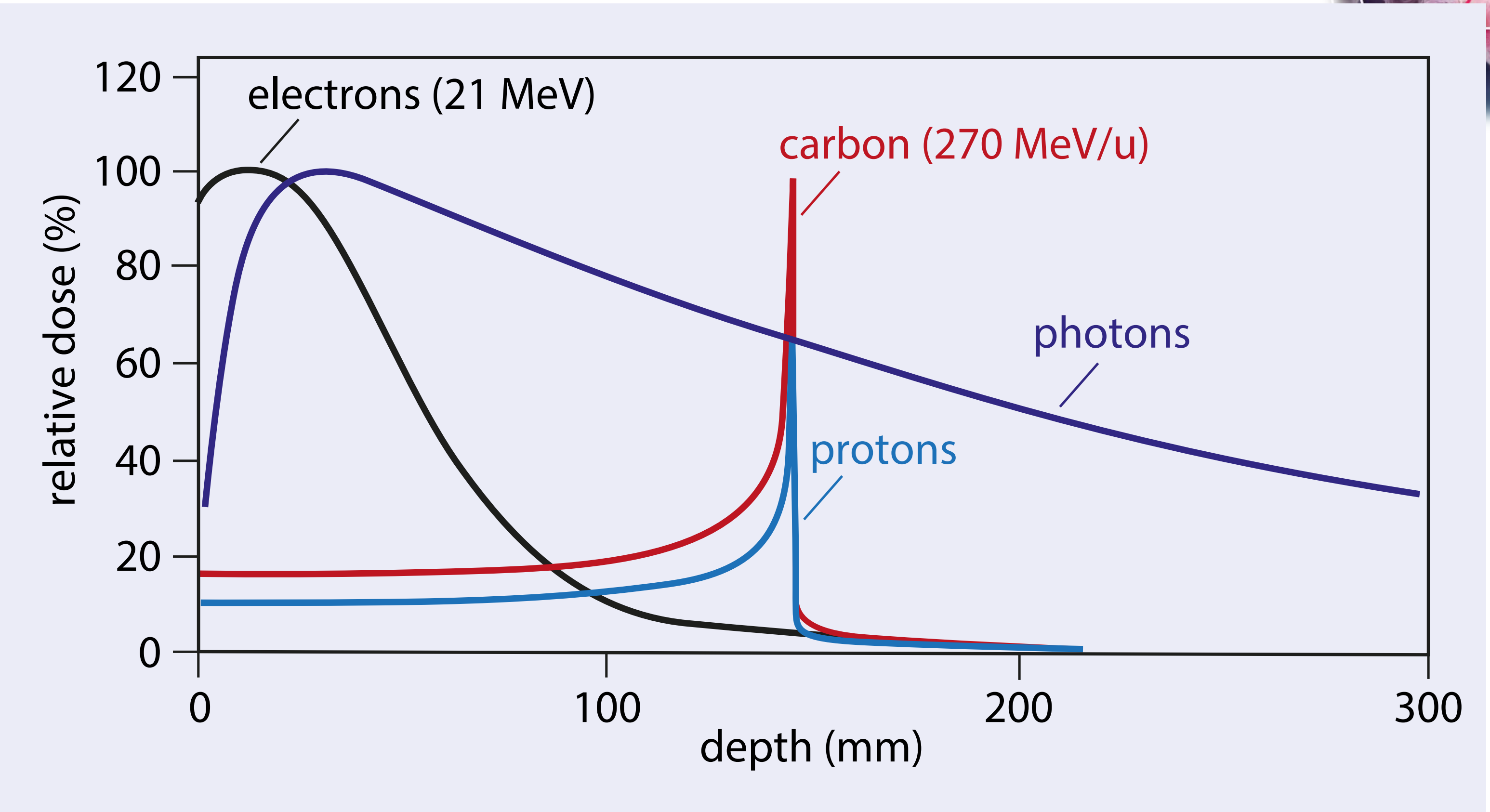


Particle beam therapy treatment with protons and light ions provides significant improvements over conventional X-ray radiotherapy due to the Bragg peak. However, the improved dose conformity of particle therapy requires a corresponding improvement in the accuracy of dose delivery to prevent underdosing of the tumour and overdosing of the surrounding healthy tissue.

In vivo measurements of dose delivery have proved challenging: real-time systems for measuring delivered dose have yet to be realised. One possibility for ion therapy systems is through Helium-Carbon mixing. By diluting the Carbon treatment beam with a small quantity of Helium ions and accelerating to the same energy per nucleon, a diagnostic signal can be obtained: with a negligible increase to the delivered dose, the Helium beam exits the patient, providing diagnostic information on the tissue being treated and thereby providing real-time information on the position and range accuracy of the delivered dose.

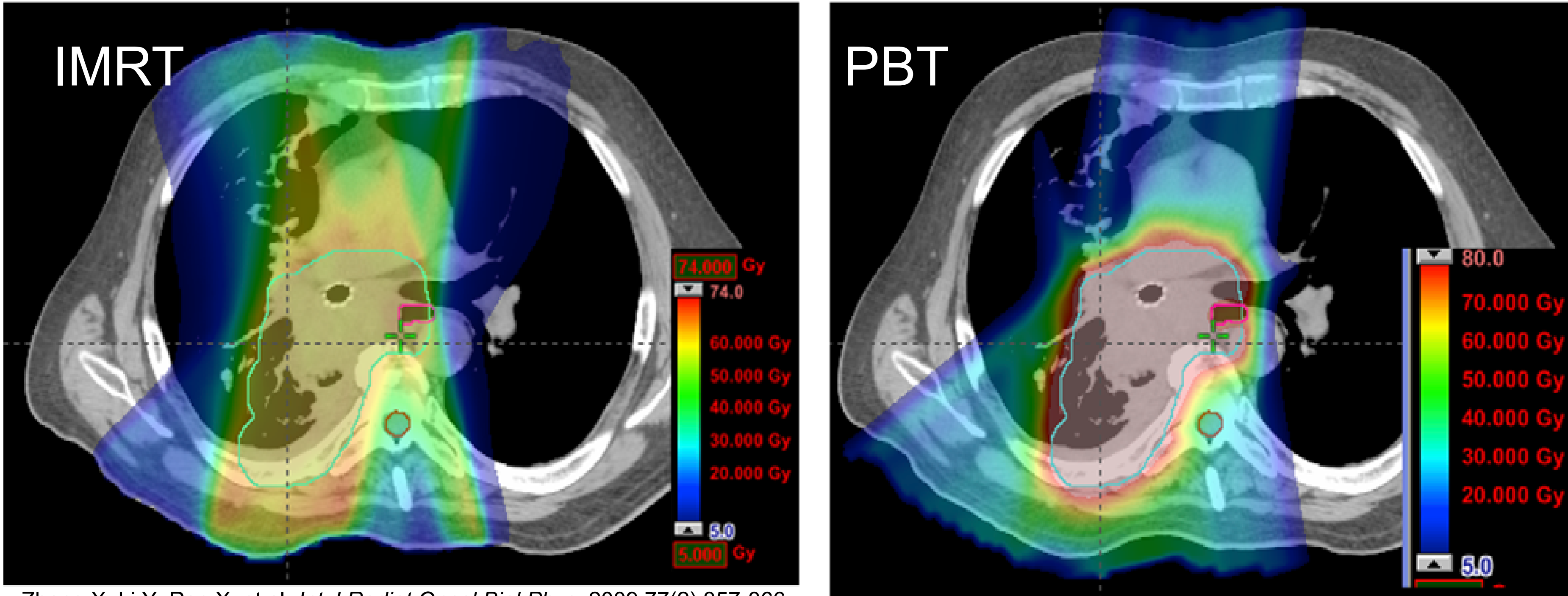
This talk describes the background to ion beam therapy and gives insight into experiments carried out to realise clinical Helium-Carbon mixing. The challenges for future systems are also discussed.

The Bragg Peak

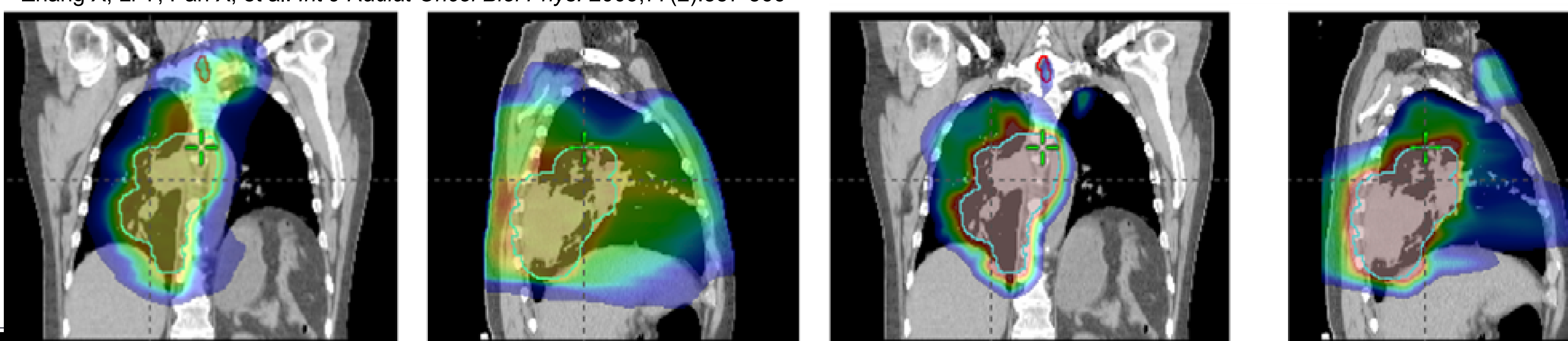


- Charged particles deliver more conformal dose due to Bragg peak: dose peak and end-of-range.
- Heavier particles (He, C, O) have even tighter Bragg peak than protons: better know where they stop…

Non Small Cell Lung Cancer

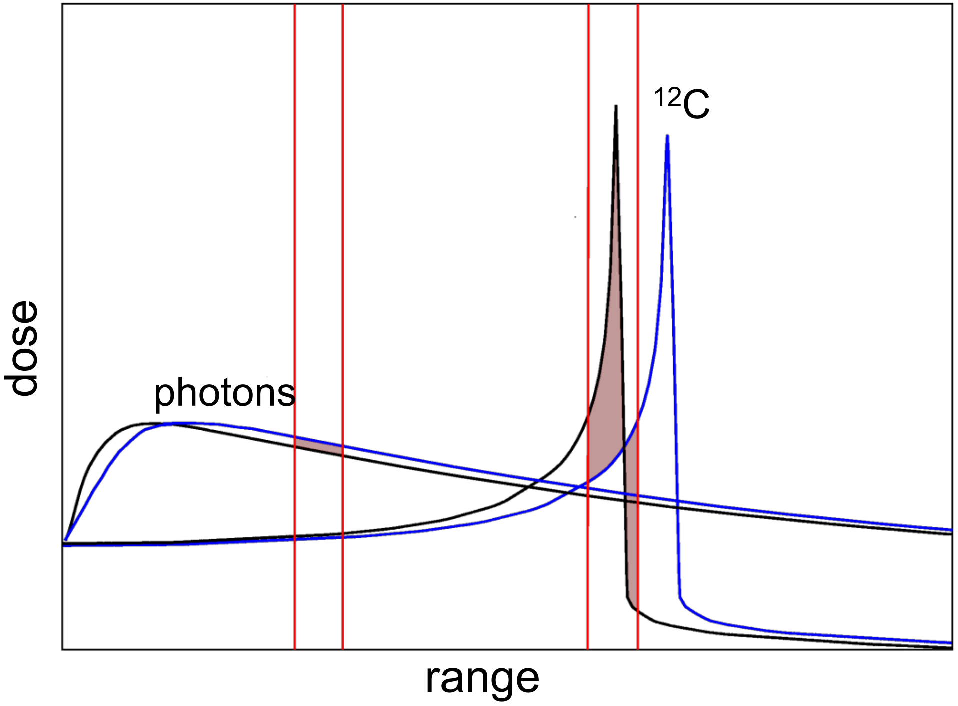


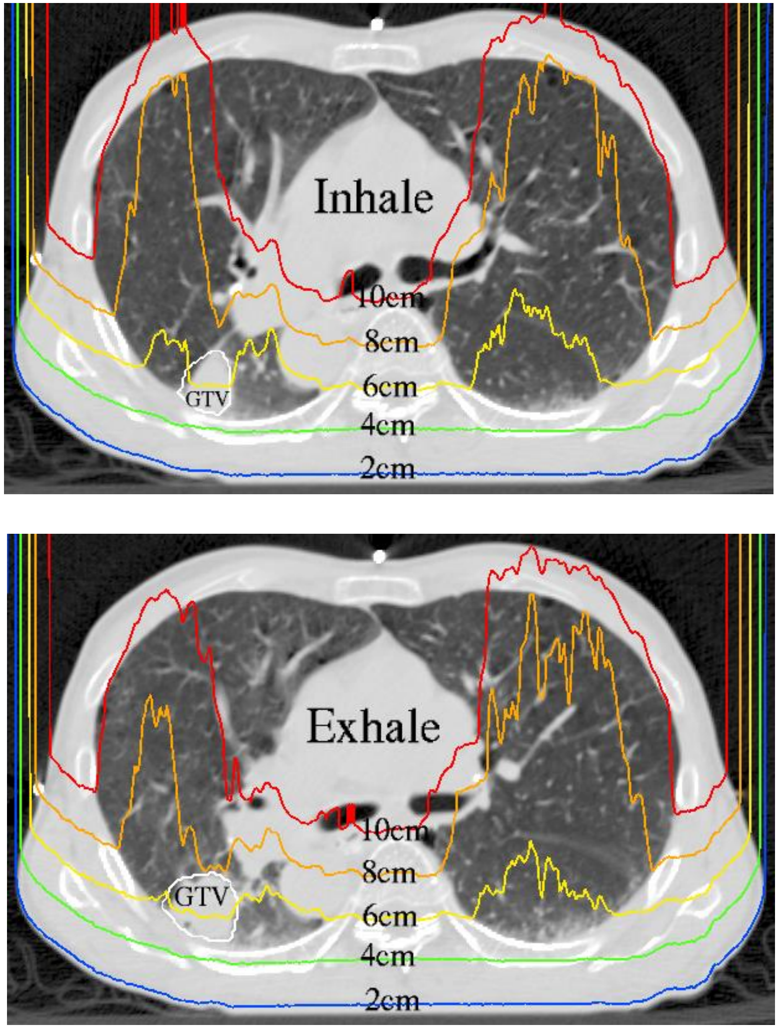
Zhang X, Li Y, Pan X, et al. *Int J Radiat Oncol Biol Phys.* 2009;77(2):357-366



Range Uncertainty

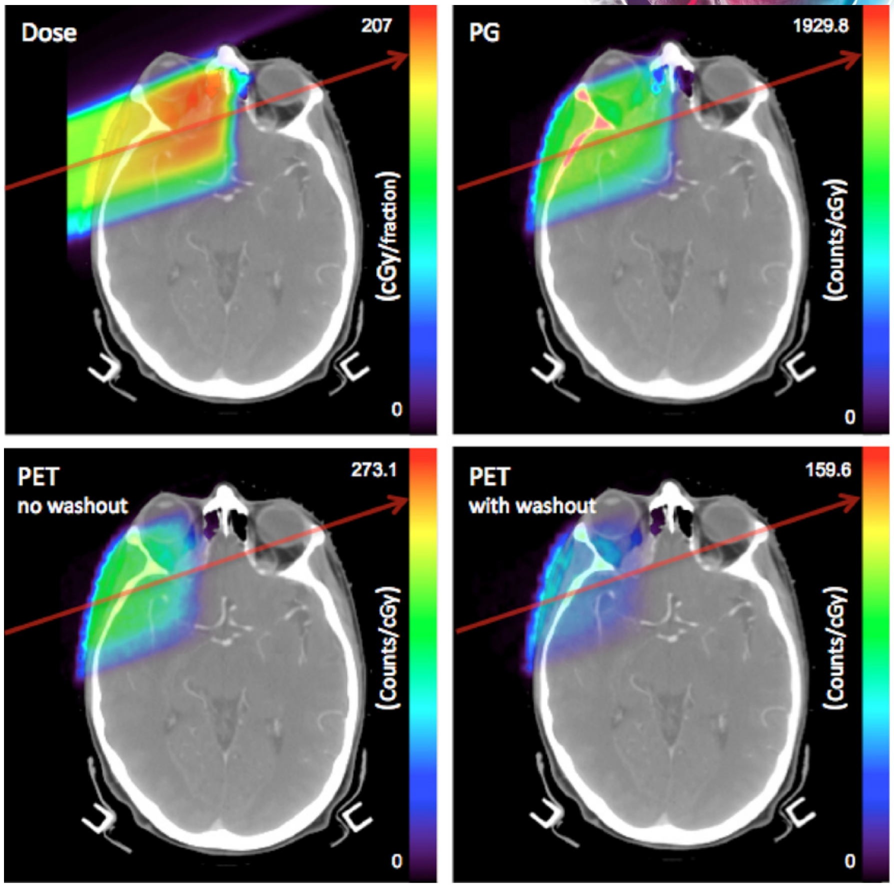
- Range uncertainty is a major issue!
- With tighter conformal dose, how do we make sure that the dose goes where we want it?





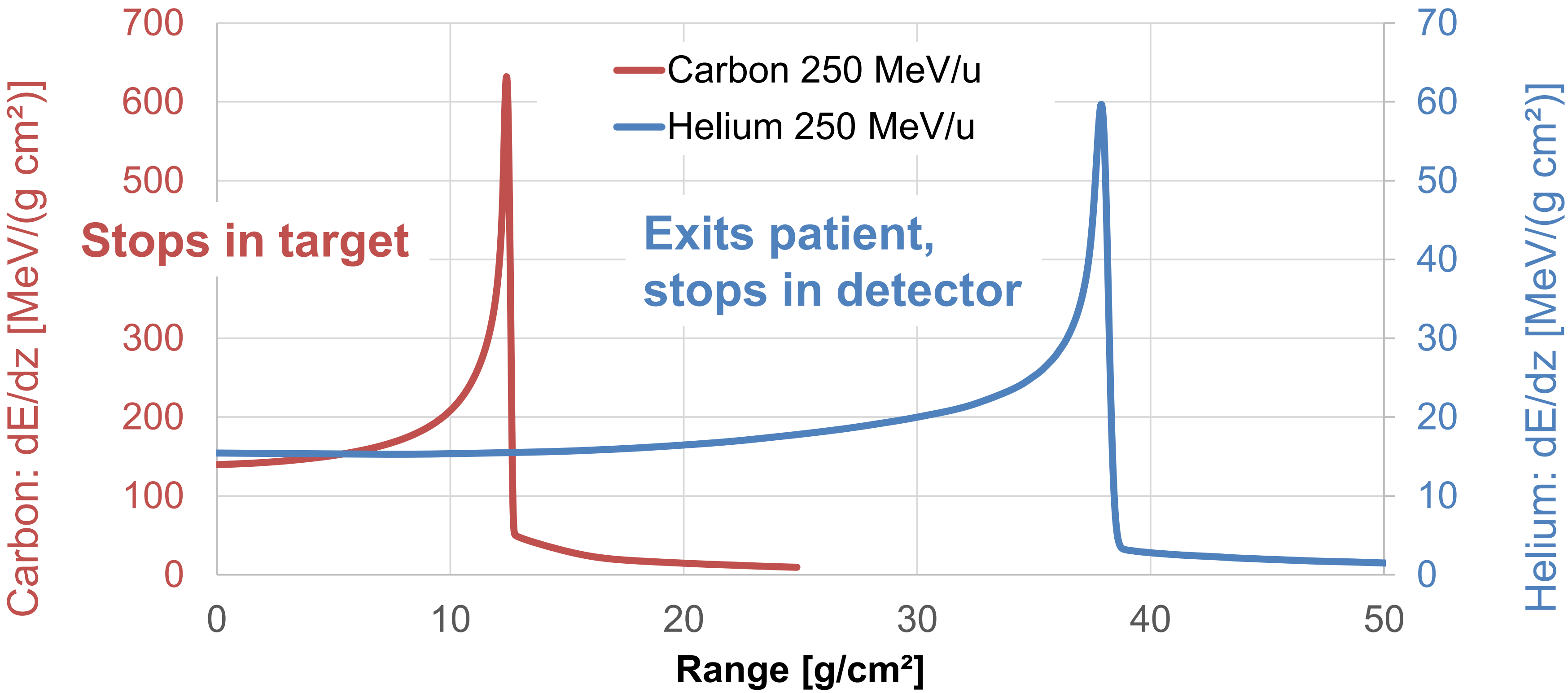
Online Range Monitoring

- How do you know where you're delivering the dose?
- Two main areas under study for protons:
  - Prompt gamma (PG).
  - PET emission.
- Both have drawbacks:
  - Intensity of signal.
  - Dose-signal correlation.
- What can we do with ions?



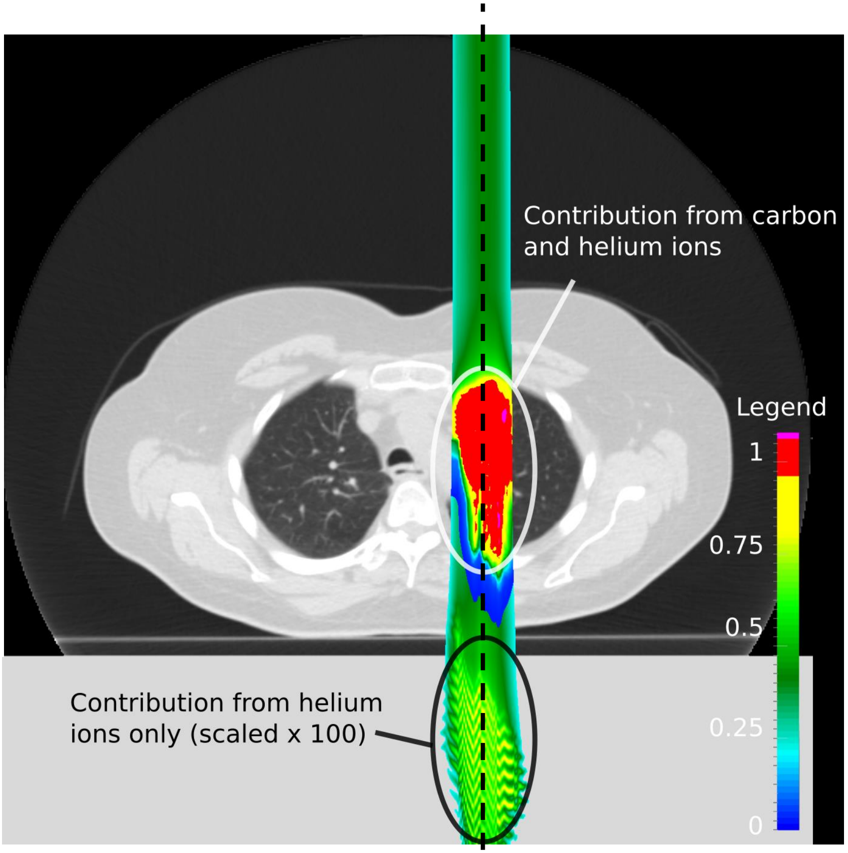
Moteabbed *et al*, *Phys. Med. Biol.* **56** (2011) 1063 Doi: 10.1088/0031-9155/56/4/012

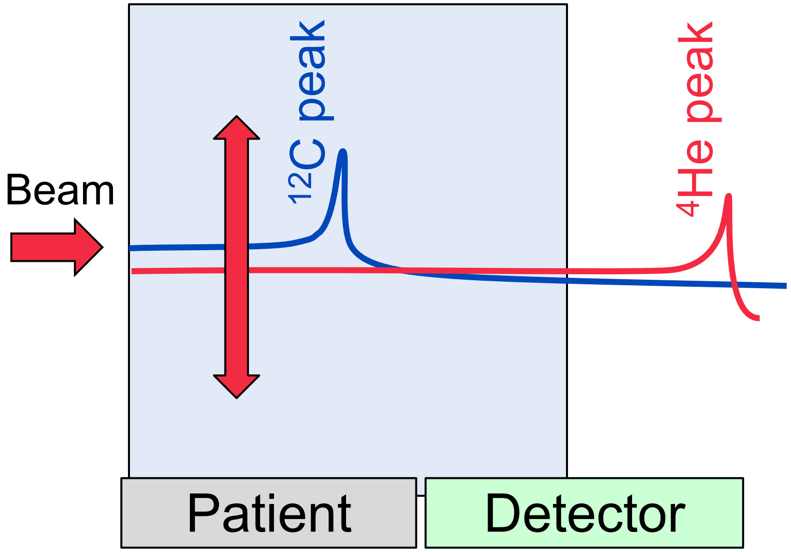
Mixed He-C Beams



- Fully ionized Helium and Carbon – (nearly) same mass:charge ratio (difference of 0.065%)
- Simultaneous acceleration to same velocity - range of $^{4}He^{2+}$ ≈ 3 x range of $^{12}C^{6+}$

Measuring a Mixed Beam



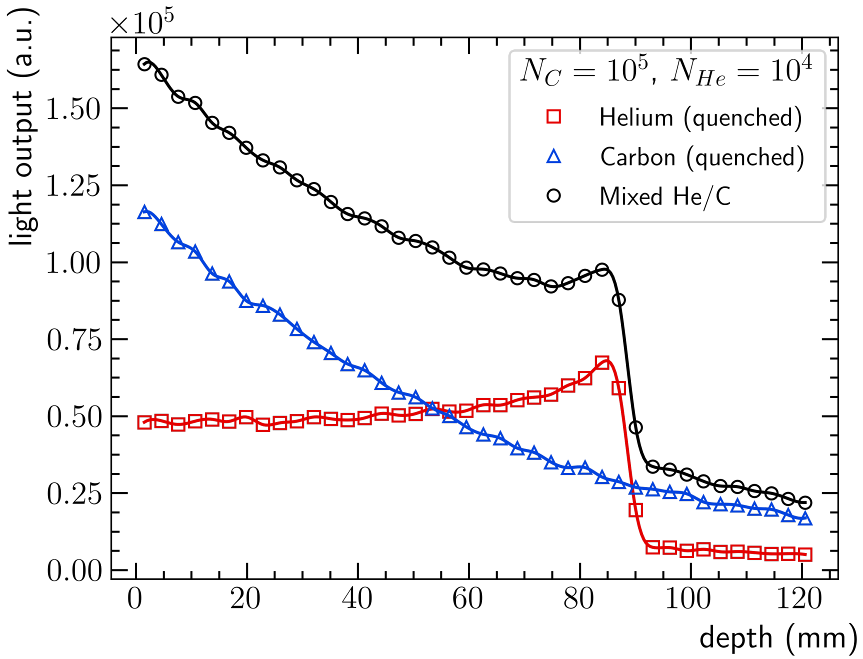


- Carbon beam stops in tumour.
- Helium beam exits patient: measured in detector.

Carbon and Helium Doses

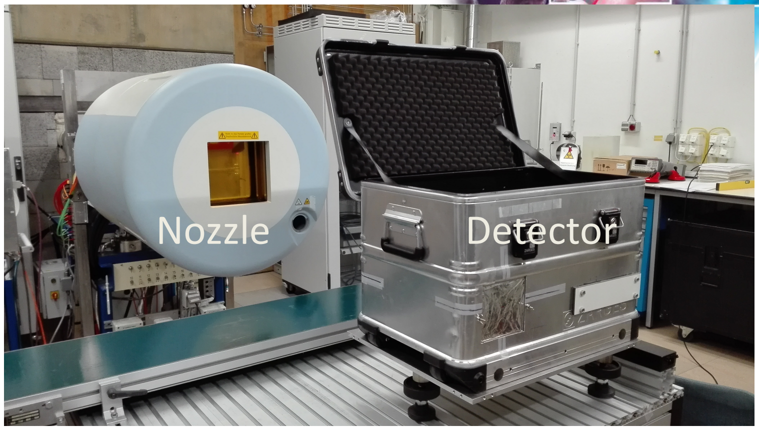
- Dilute Carbon beam with 10% Helium: only 0.5% additional dose.
- Helium Bragg peak gives measurable signal in residual detector.
- Carbon ion fragmentation still measurable: need to subtract from Helium signal.

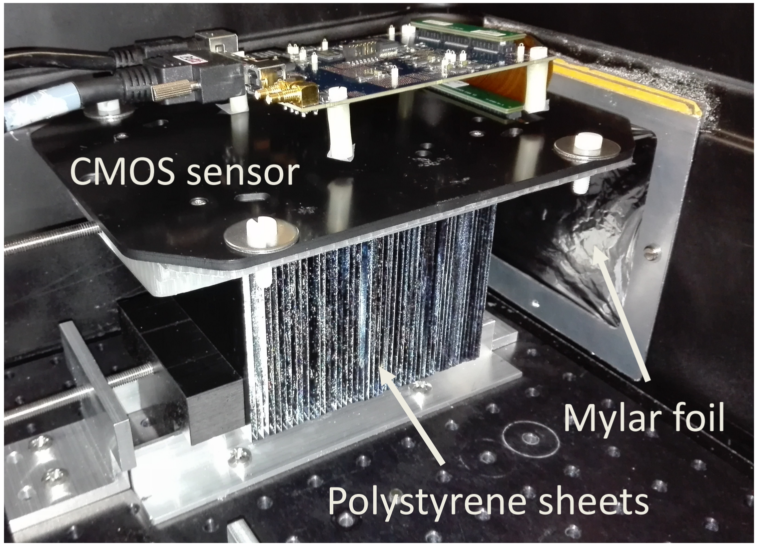
Simulation



Experiments at HIT

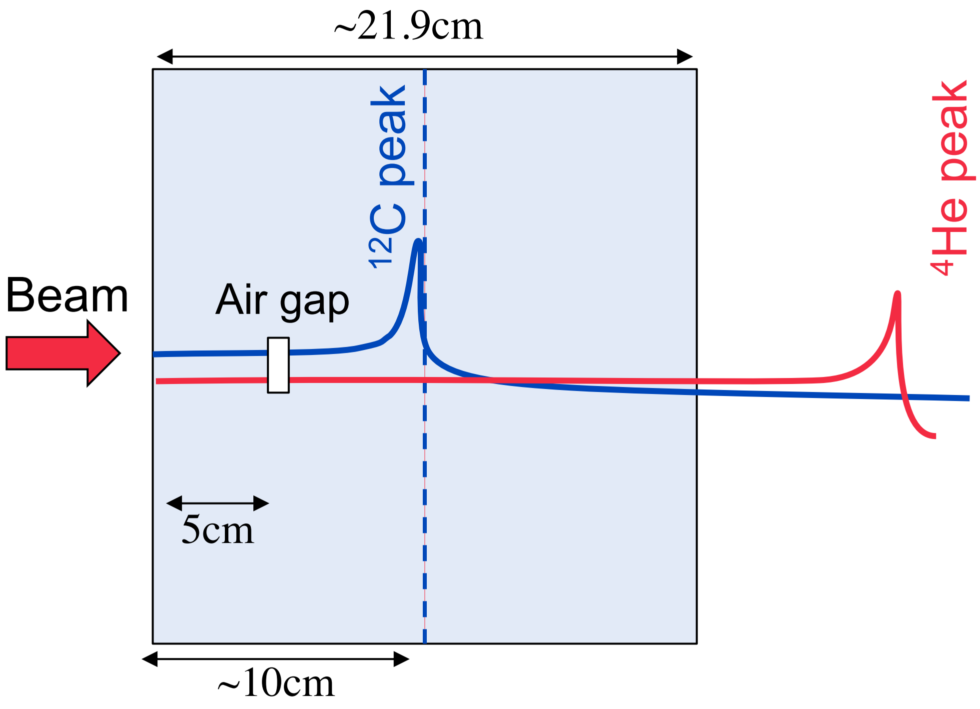
- Experiments at HIT QA cave (2019).
- Deliver Helium and Carbon beams separately to detector and sum contributions.
- Measure residual range with UCL scintillator range telescope:
  - 12 cm stack of thin 2-3 mm scintillation sheets
  - Read out by flat panel CMOS sensor
- Setup simulated in Geant4.

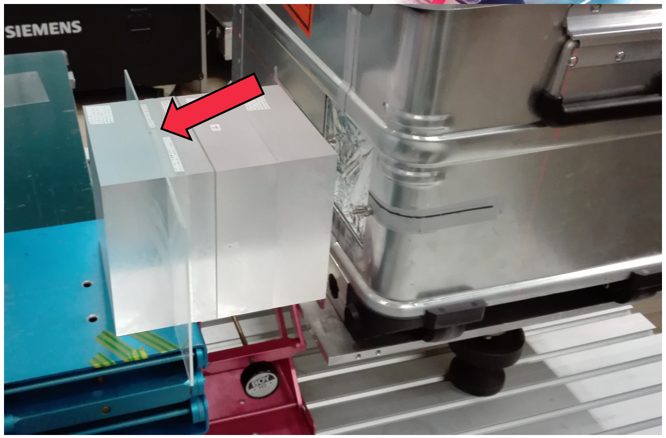


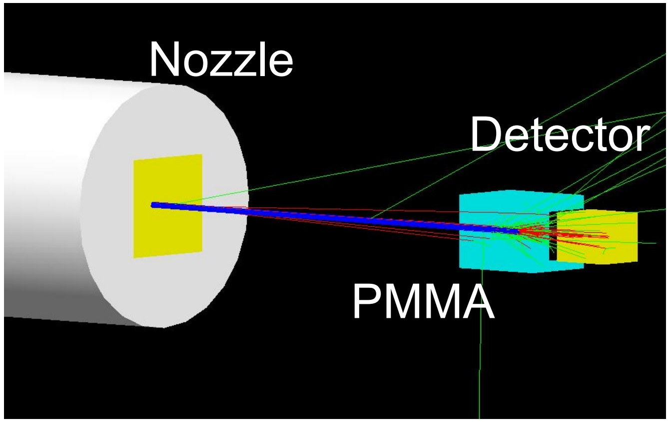


- UCL range telescope at HIT

Simple PMMA Setup



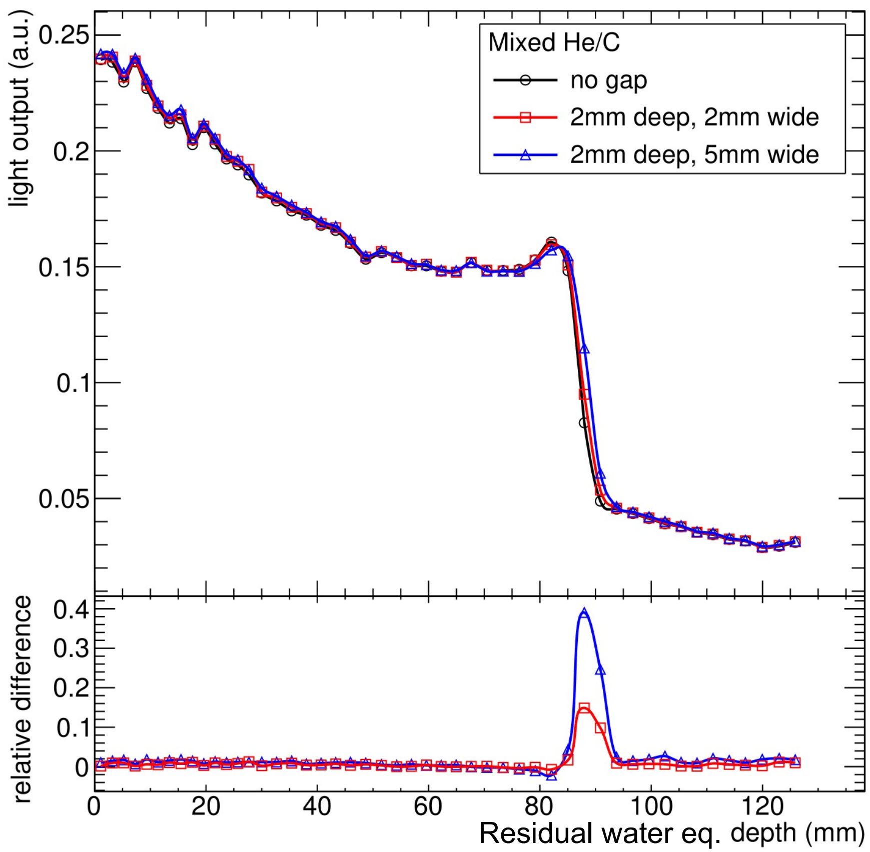




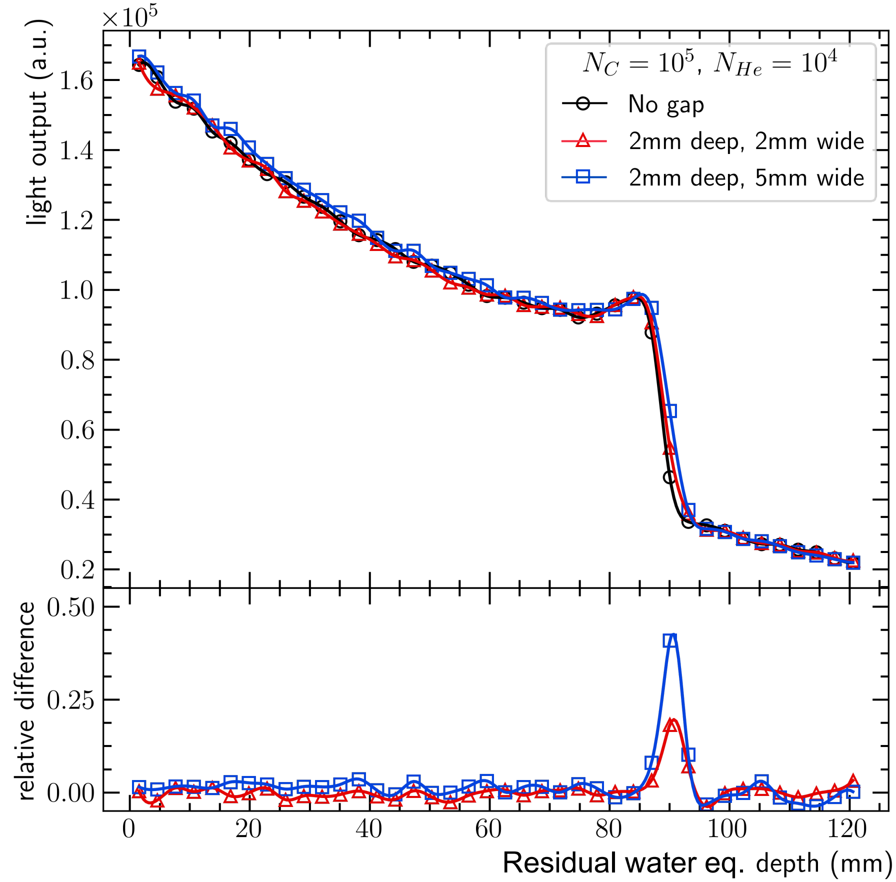
- ^{12}C: 219.19 MeV/u (~10cm range), ^{4}He: 220.5 MeV/u (~30cm range)

PMMA Phantom Results

Experiment

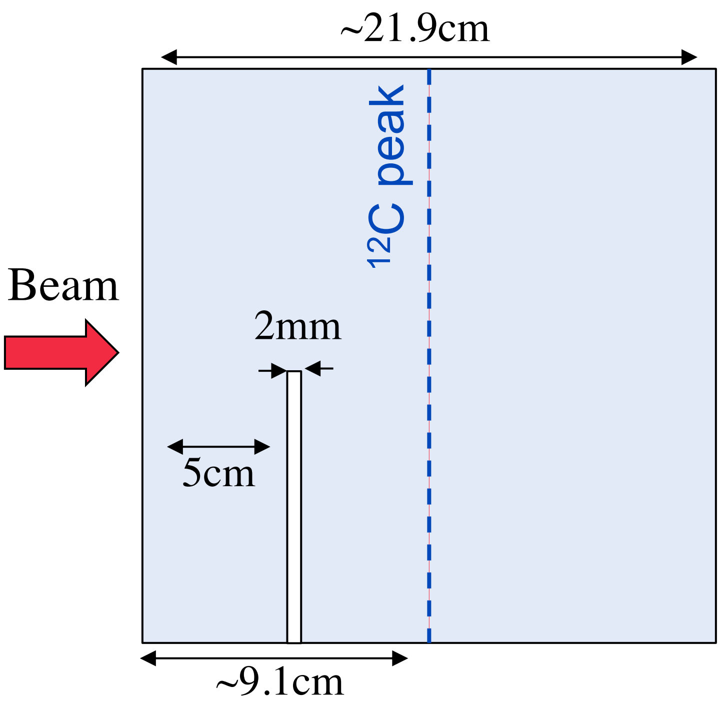


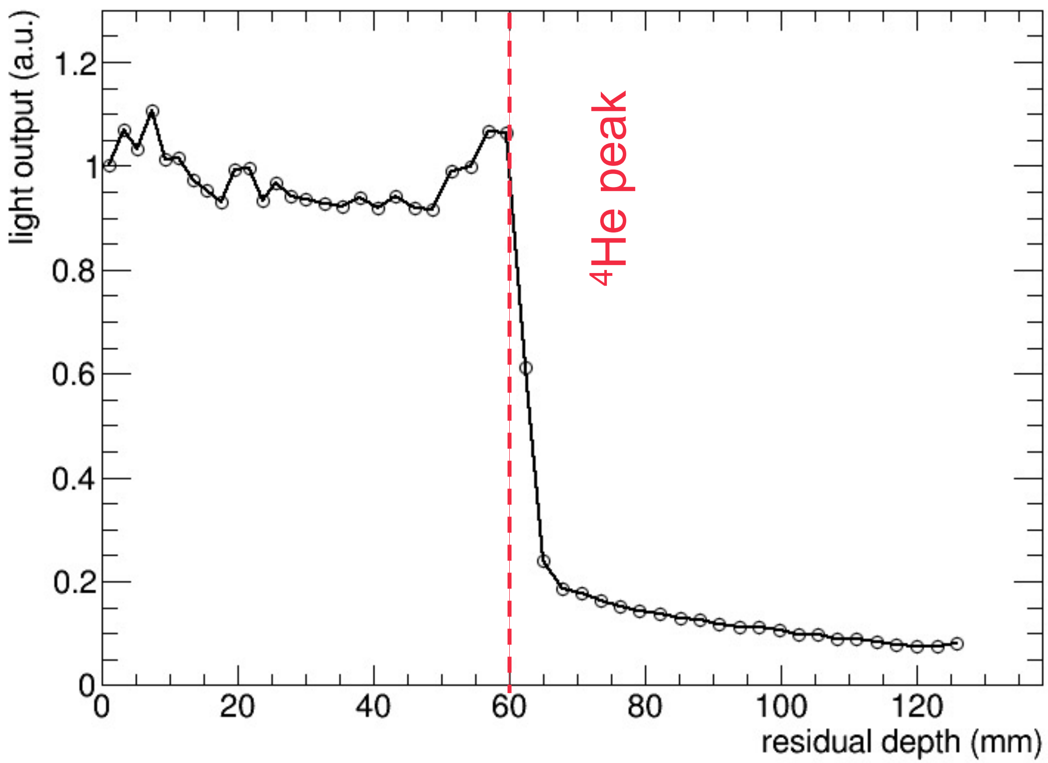
Simulation



Scanned PMMA Phantom

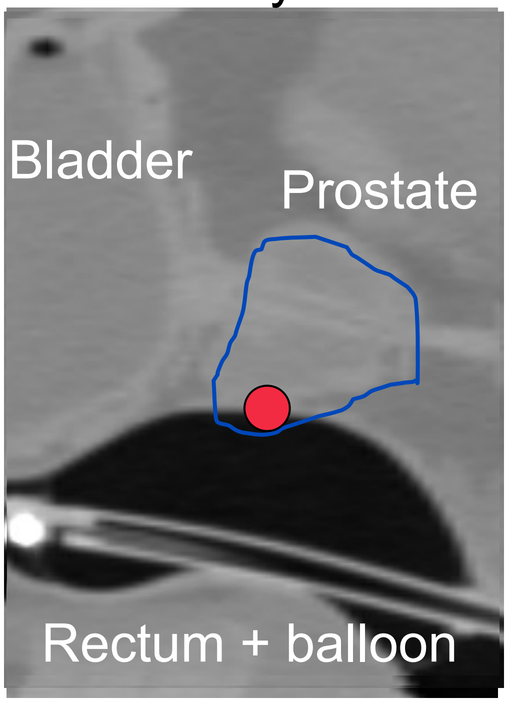
- PMMA degrader (WET ≈ 21.9 cm)
- 2mm PMMA slab covering half the field at ~5cm depth
- 10x10 spots scanned (3mm spacing), ~3x10^6 p/spot, E=210MeV/u, 10 mm FWHM





Anthropomorphic Phatnom

Beams eye view



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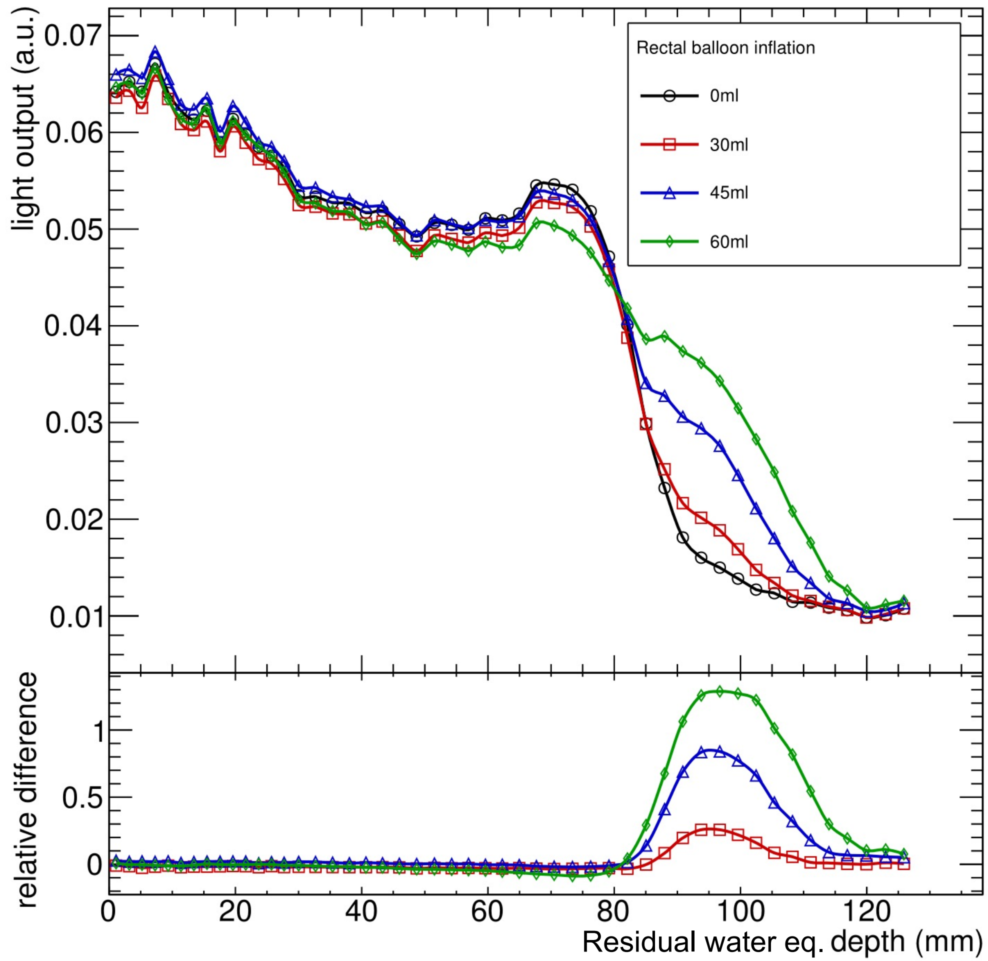
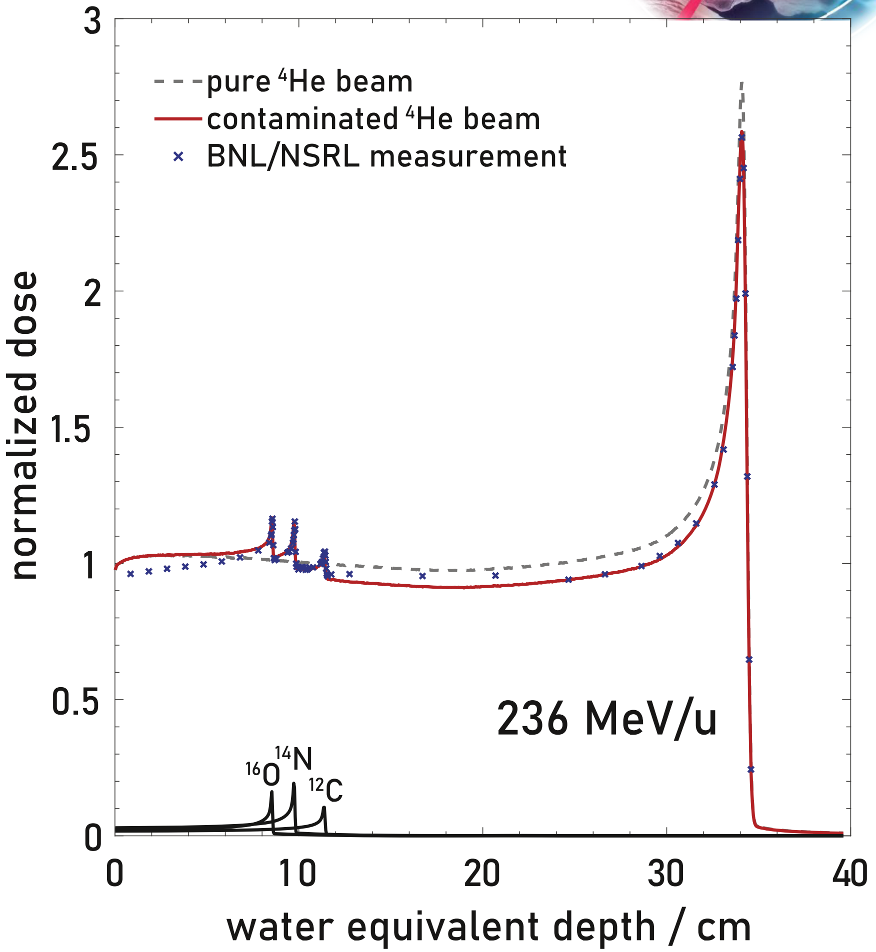


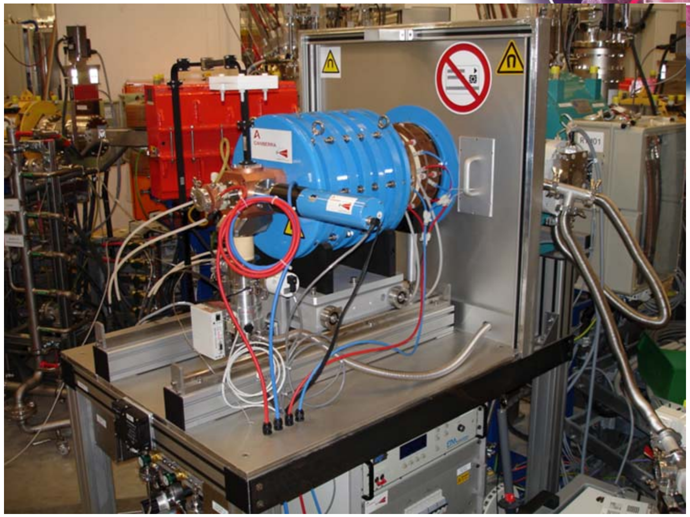
Can We Make Mixed Beams?

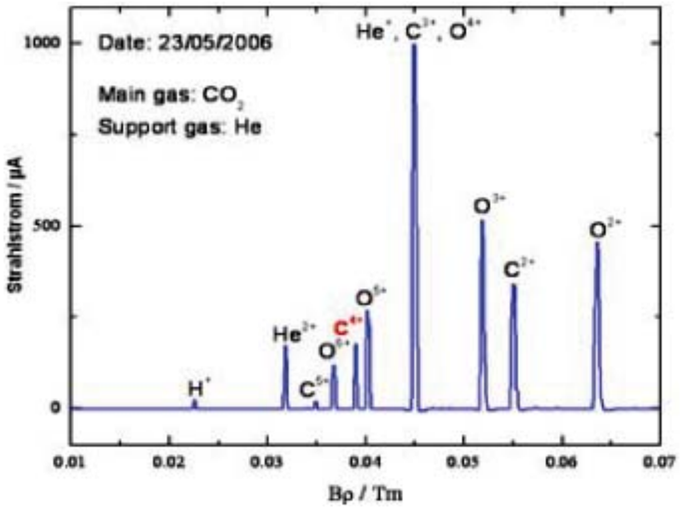
- Yes! Actually produced by accident…
- Horst *et al* observed contamination of He beam with C, N and O.
  - *Phys. Med. Biol.* **66** (2021) 095009
  - Doi: 10.1088/1361-6560/abef88
- The challenge is to produce the right ions in the right quantities…
- Only possible with synchrotrons: degrader in cyclotrons changes *E/v* ratio.



Ion Sources: Mixed Ions

- Carbon production *already* mixes Carbon and Helium:
  - Carbon extracted from CO_2.
  - Helium used as support gas.
- Cannot use fully stripped ions with $A/q = 2$: yield too low.
- $A/q = 4$ possible:
  - $^{12}C^{3+}$ and $^{4}He^{+}$.
  - Same rigidity with suitable yield.
  - Issues with $^{16}O^{4+}$ contamination.



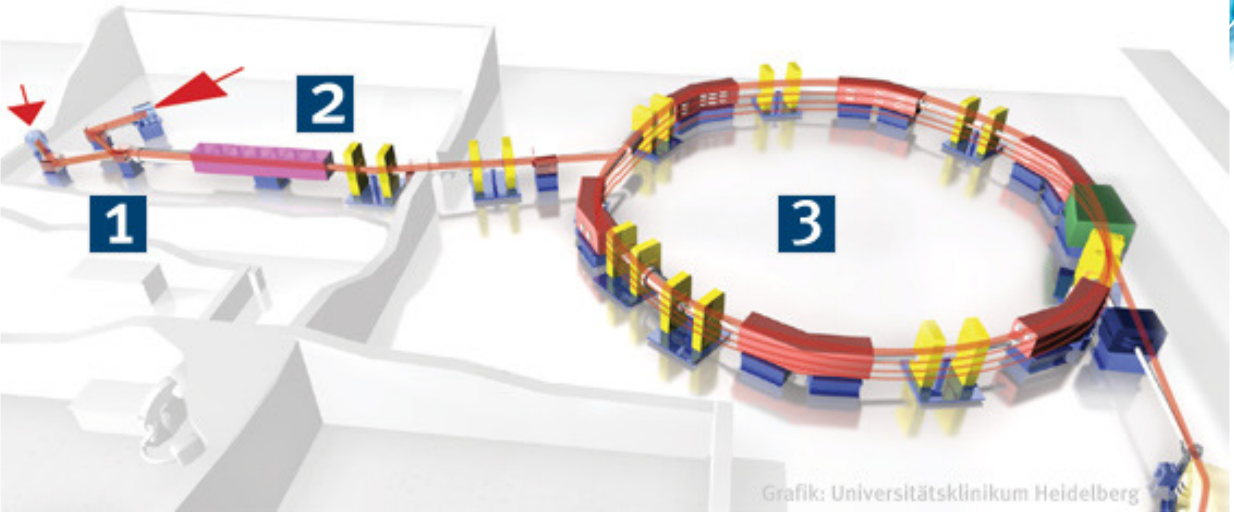


Rev. Sci. Instrum. **79**, 02A331 (2008)
DOI: 10.1063/1.2823952

Linac Acceleration

HIT Layout:

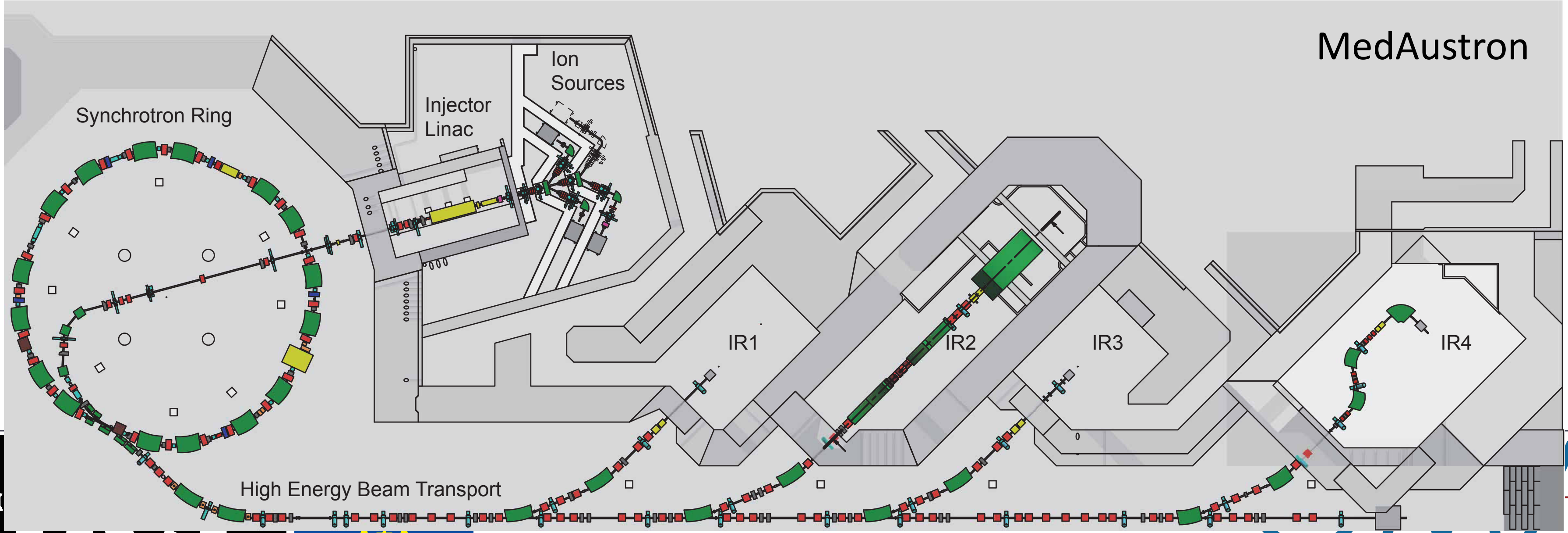
1. Ion Sources
2. Linac
3. Ring



- RFQ+DTL linacs in existing therapy machines currently designed to accelerate ions with *A/q* in range 1–3:
  - Can accommodate protons, $^{4}He^{2+}$ and $^{12}C^{4+}$ but *not* $^{4}He^{1+}$ and $^{12}C^{3+}$.
  - Ions stripped at end of linac: fully stripped in ring.
  - Redesign needed to allow $A/q = 4$.

Injection & Acceleration

- With fully stripped ions at linac exit, ions with *A/q* = 4 can be injected into ring:
  - With mixed beams extracted from ion source, accelerate together.
  - Possible to do separate injection?
    - Two bunches in ring: $^{4}He^{2+}$ and $^{12}C^{6+}$.
    - Beam dynamics becomes more challenging.
- Stripping at injection: stack beams?



Accelerating He and C Together

- Because of the slight difference in mass per nucleon (mC=12 amu, mHe=4.0026033 amu) the two species have a slightly different momentum per nucleon in order to have the **same revolution frequency** imposed by the **RF cavity**!

$$p_{He,RF} = \frac{f_{0,C} - f_{0,He}}{f_{0,He}} \frac{p_{0,He}}{\left(\frac{1}{\gamma_{0,He}^2} - \frac{1}{\gamma_{tr}^2}\right)} + p_{0,He}$$

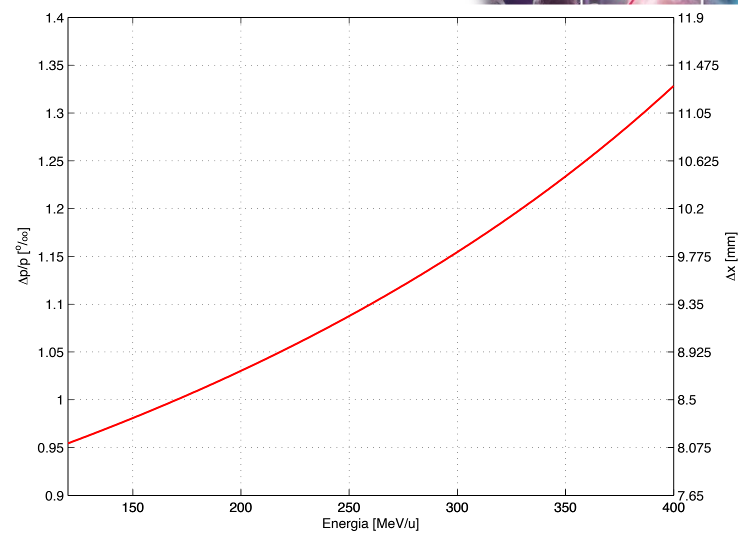
- Where f0,He is the frequency that the helium would have to go through the nominal orbit

Extracting He and C

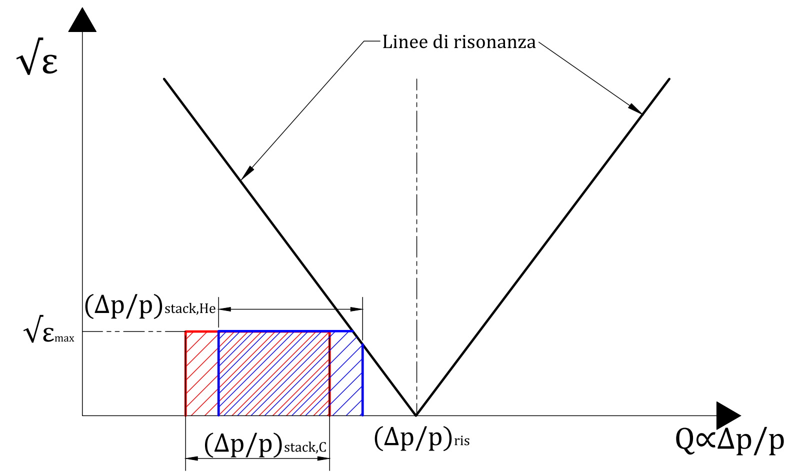
- Synchrotrons normally drive beam into resonant to extract:
  - RF knockout (HIT).
  - Betatron core (CNAO, MedAustron).
- Not clear whether resonance will affect ions in the same way:
  - Can both ions be extracted simultaneously?
  - Will the proportions be maintained?
- For CNAO:

$$\frac{\Delta p}{p} = \frac{p_{He,RF} - p_{0,C}}{p_{0,C}}$$

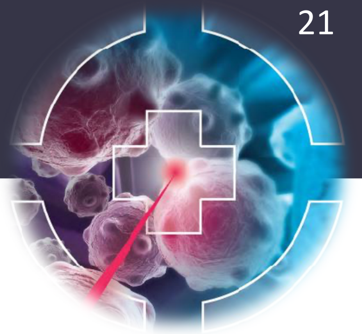
$$\Delta x = D\frac{\Delta p}{p}$$



Betatron core pushes the beams in resonance

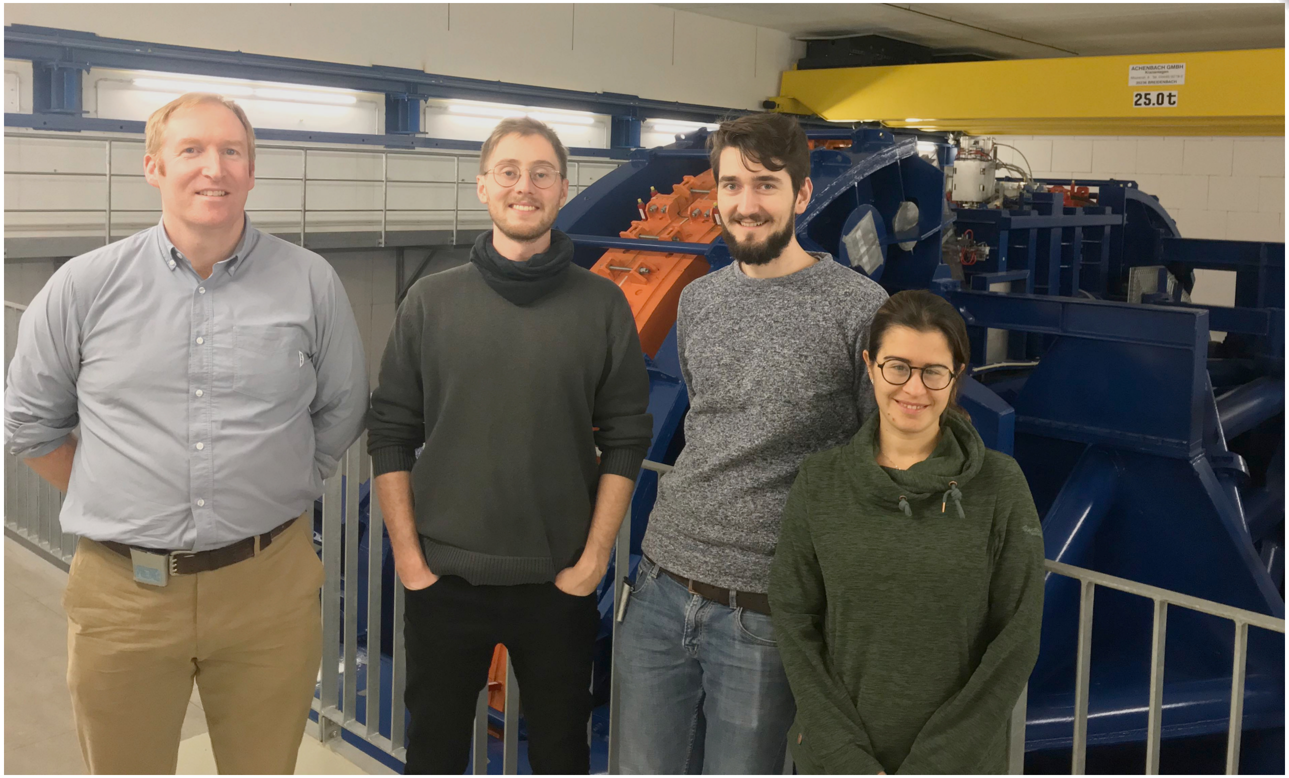


Conclusions



- He-C mixing provides method of on-line beam monitoring:
  - Accidental contamination already observed!
  - Measurable Helium signal in residual range detector with 10% He-C contamination.
  - Provides in-vivo signal, but also sensitive to downstream changes.
- Challenges to be overcome:
  - Requires synchrotron (or linac): cannot be achieved with cyclotron due to beam degrader.
  - Beam with mixed ions possible from ion source:
    - He-C ratio must be correct at ion source extraction.
    - Oxygen contamination from CO_2.
  - Existing linacs will need redesign to accommodate $A/q = 4$.
  - Study needed of synchrotron resonances to allow simultaneous extraction: new extraction methods needed?

Thank You



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