Radioactive Ion Beam Studies with FLUKA for Hadrontherapy

Early-Career Researchers in Medical Applications @CERN

29/8/2016

R.S. Augusto – CERN-PhD Student (EN-STI-FDA)

r.s.augusto@cern.ch

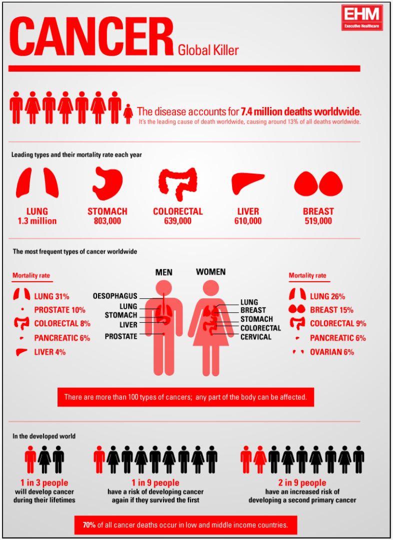
Supervisors: Prof. K. Parodi & Prof. A. Ferrari

Introduction

Cancer treatment options:

- Surgery
- Chemotherapy
- Immunotherapy
- Radiation Therapy
  - ↪ Conventional (photons, electrons)
  - ↪ Hadrontherapy
    1. Neutrons
    2. Protons
    3. Ions (C, O, He, *etc.*)

Can be combined to improve treatment efficiency.



http://executivehm.com/

Hadrontherapy Facilities – Worldwide Overview & History

Chronology

1895 – Discovery of X-Rays (W. Röntgen)

1932 – First cyclotron (E. Lawrence)

1946 – Proton Therapy proposed, exploiting the Bragg Peak (R. Wilson)

1954 – First patient treatment with different ions (Lawrence Berkeley National Lab)

1957 – First patient treatment in Europe (Uppsala, Sweden)

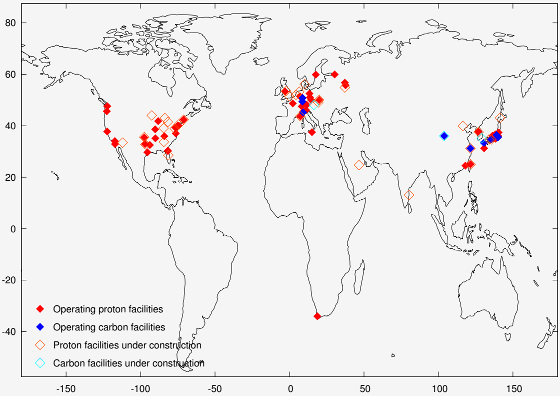
1969 – Start of ITEP, Moscow (Oldest proton facility still in operation)

1994 – First facility dedicated to Carbon Ions (HIMAC, Japan)

1997 – First patient treated with Carbon Ions at GSI, Germany

2009 – First European proton/carbon ion facility (Heidelberg, Germany)

"ENLIGHT" History of Hadron Therapy.



"Particle Therapy Co-Operative Group" Particle therapy facilities in operation **(as of 8-3-2016)**.

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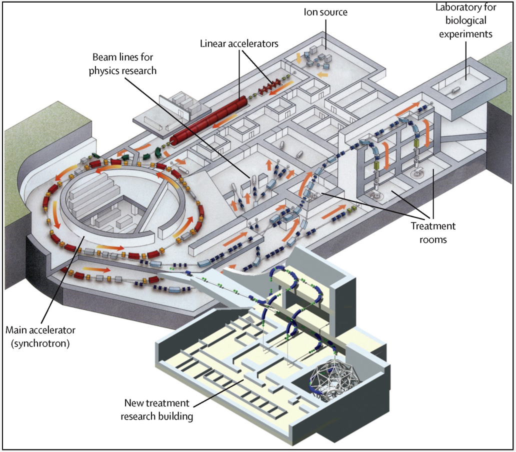

Kamada, T. *et al "Carbon ion radiotherapy in Japan: an assessment of 20 years of clinical experience" Lancet Oncol.*, **16**, 93-100 (2015)

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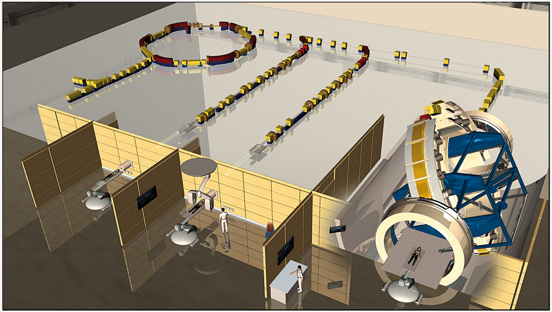
"ENLIGHT" History of Hadron Therapy.

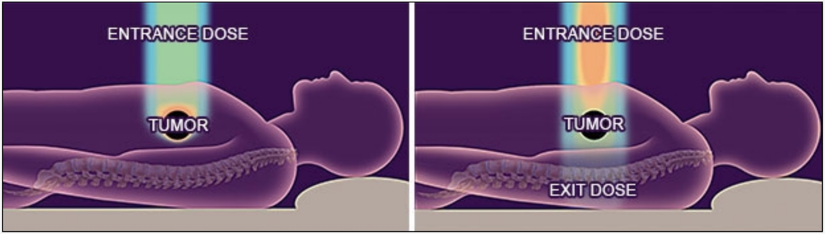
HIT
Heidelberger Ionenstrahl-Therapiezentrum



"Heidelberg Ion Therapy Center" HIT Bildergalerie.

Hadrontherapy vs Conventional Radiation Therapy

- **Charged Hadrons can deliver high doses even to deep seated tumours, relatively sparing healthy tissue.**



Targeted Proton Therapy:
Deposits most energy on target

Conventional radiation Therapy:
Deposits most Energy before target

University of Florida – Proton Therapy Institute.

Hadrontherapy with Ions

- **Exploiting the characteristic shape (*i.e. Bragg peak*) of charged hadrons', greater precision can be achieved.**

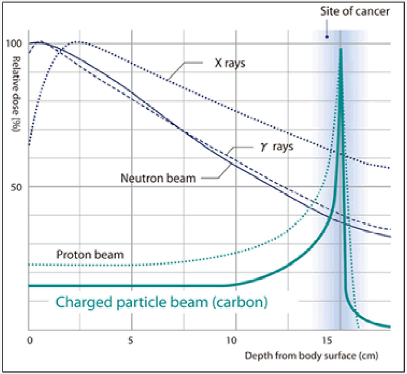
General Advantages

- Better ballistic properties
- Higher LET & RBE

Drawbacks

- Fragmentation tail dose
- Complexity – production, dose delivery control *etc*

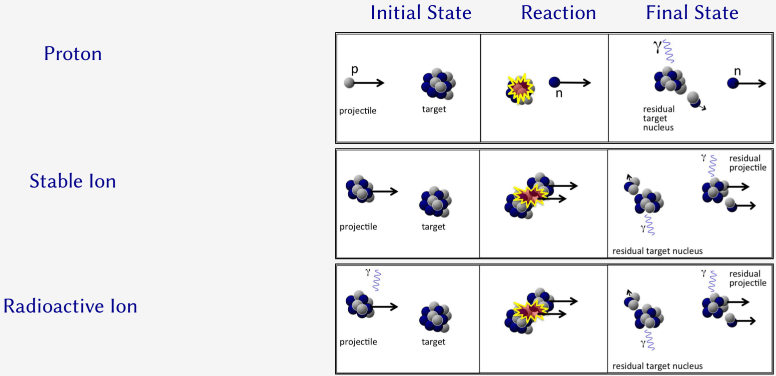
↪ Treatment Planning Systems (TPS) relatively inaccurate for ions...



"National Institute of Radiological Sciences" *NIRS*

Why use Radioactive Ion Beams? (RIB)

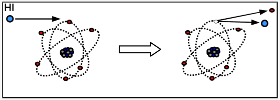
Exploring the RIB, and its radioactive fragments (*i.e.* β^+ emitters), one may **monitor the peak position** (*e.g.* using Positron Emission Tomography – PET devices) **even during beam time!**



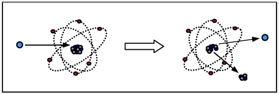
Kraan, A.C. *"Range Verification Methods in Particle Therapy: Underlying Physics and Monte Carlo Modeling"* *Frontiers in Oncology*, **5**, 150 (2015) (Adapted).

Monte Carlo role in Hadrontherapy

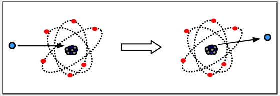
Currently, TPS rely on algorithms, which are unable to correctly reproduce all the physical events, due to their complexity:



Energy Losses throughout collisions with atomic electrons (Bethe–Bloch)



Nuclear Reactions (fragmentation tail and other secondary particles)



Multiple Coulomb Scattering (MCS) (Deflections)

The Bethe–Bloch equation with its various corrections (below for spin 0) conveys some of the stopping power's calculation complexity:

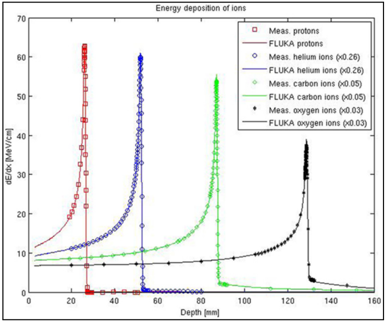
$$\left(\frac{dE}{dx}\right)_{e-} = -4\pi N r^2 mc^2 \rho \frac{Z}{A}\frac{z^2}{\beta^2}\left[\frac{1}{2}(2mc^2\beta^2\gamma^2\Delta E_{\text{Max}}) - \beta^2 - \ln I - \frac{C}{Z} - \frac{\delta}{2} + \xi z L_1 + z^2 L_2 + K_{\text{M}}(z,\beta)\right]$$

To **adequatedly** account for the nuclear reactions and MCS contribution, a Monte Carlo particle transport code such as FLUKA[1][2] is required. Note that:

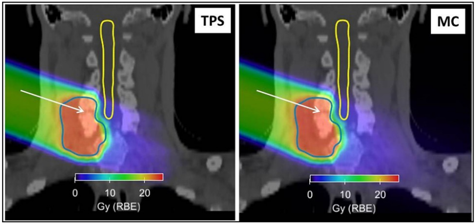
- Monte Carlo is unable to compete with commercial TPS, as it is far too slow.
- It can be used for benchmarking purposes, and also combined with TPS.

Validation Work[4][5]

Validation of FLUKA results using data from HIT and CNAO



FLUKA simulations of depth–dose profiles of various ions against measured data at HIT.



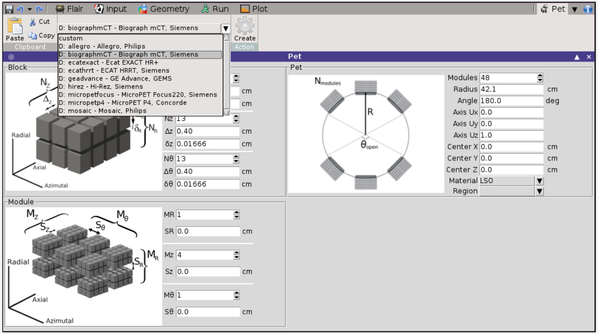
2D overlays of D_{RBE} over TP CT image, from TPS (left) and FLUKA (right) near the spinal cord.

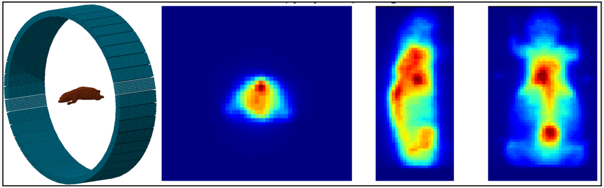
A good agreement is observed between the TPS and the MC calculations.

PET tools[4][6]

FLUKA GUI *flair*[3] incorporates a dedicated **PET scanner tool**, covering all steps from PET ring creation to the reconstruction of the image from the coincidence events.

- Infer the dose map from the β^+ emitter distribution.
- Test new PET designs/options.

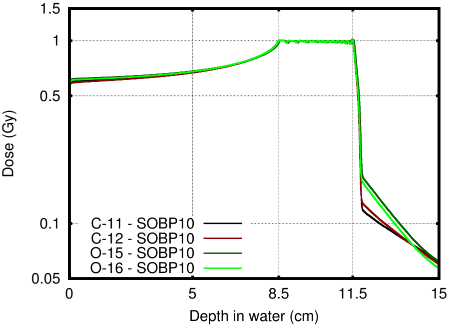


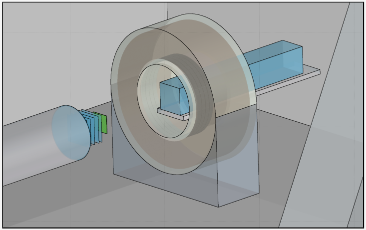


Radioactive Ion Beams in Clinical Scenarios

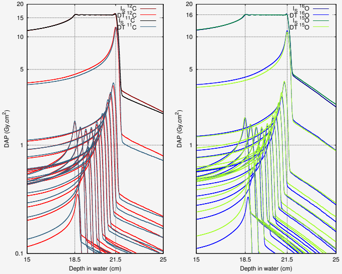
SOBP[7]

Studies in water with different ions, under realistic (HIT) conditions: Almost equivalent dosimetric performance in Spread-Out Bragg Peaks (SOBP).



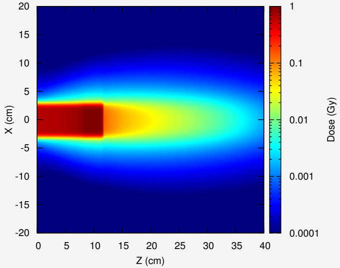


Disentanglement of different Pristine Bragg Peaks from simulated SOBP.

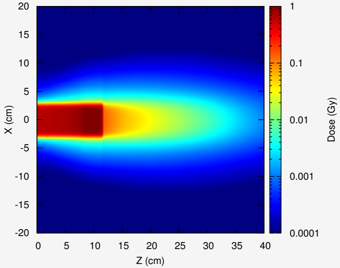


Dose Maps[7]

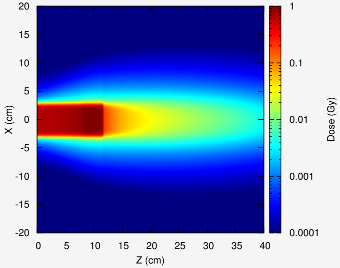
C-11



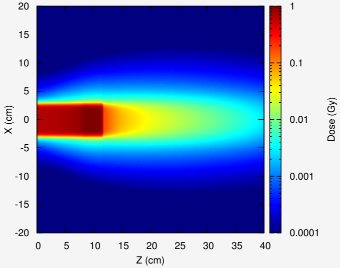
C-12



O-15



O-16



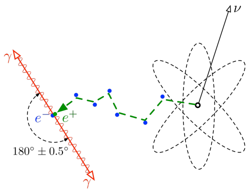
Imaging Potential[7]

Event Mapping

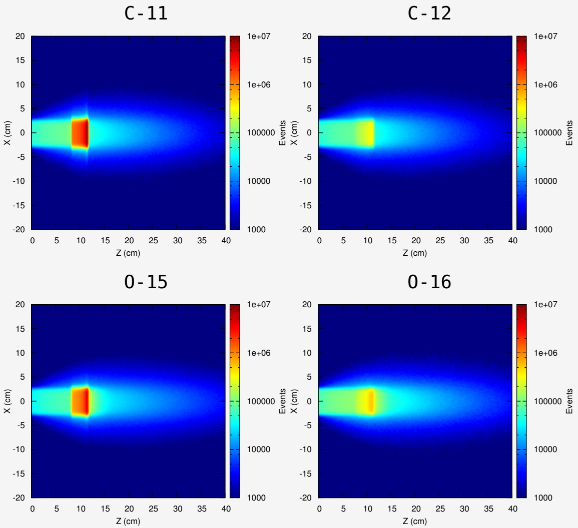
Positron Emission

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + e^{+} + \nu_e $$

Annihilation Events



Annihilation Events are a powerful indicator of the imaging potential, as the resulting γ can be detected for reconstruction with PET-CT scans.

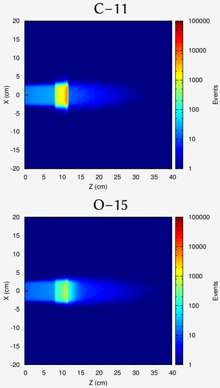


For SOBPs of 1 Gy: Tenfold improvement with RIB!

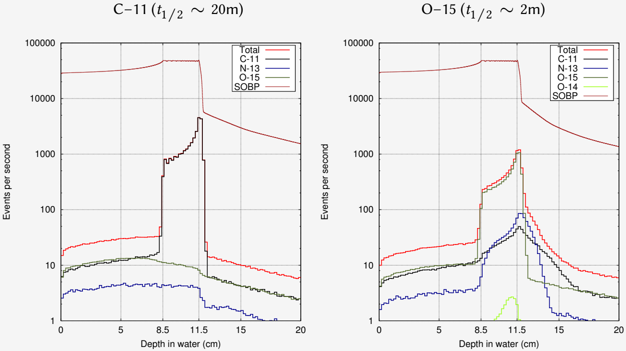
Imaging Potential Evolution in Time

Parent Isotope Study

Different RIB types can have different imaging potential. The latter evolves in time depending on the beam half-life...and the half-life of the fragments produced:



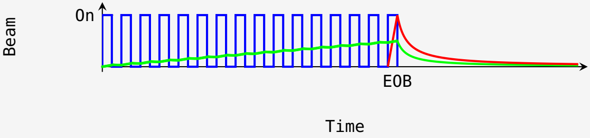
Annihilation Events at Rest (rate), 12 minutes End-Of-Beam (EOB)



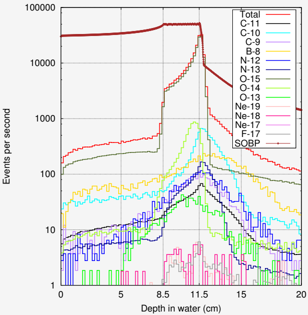
Different parent isotope contribution to the overall Annihilation Events' rate.

Accounting for the beam time structure

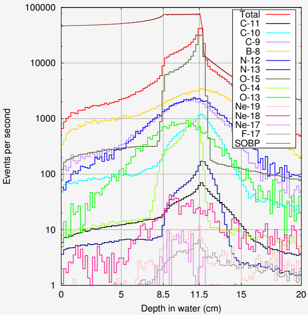
Furthermore, it is essential to account for the decay impact during beam time:



Note: The diagram above is only a scheme and is *NOT* numerically accurate.



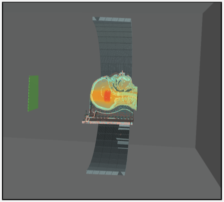
O-15 — EOB – **Realistic**



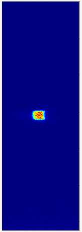
O-15 — EOB – **Approximate**

PET tools – Preliminar results with RIBs

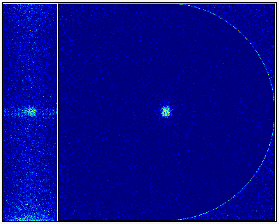
- Enables imaging study with in-beam PET or at different EOB time windows.



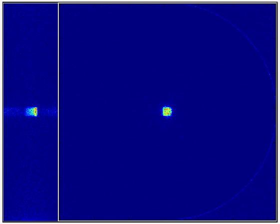
- Realistic Beam Time Structures (130 s)
- Only account Acquisition Time Window Events (20 m)
- Reconstruction of a PET result with MLEM[9]:



- Translate imaging potential gain in better imaging quality.



C-12

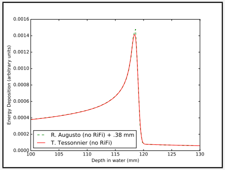


C-11

Current Studies

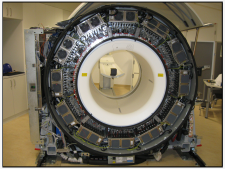
RIB

- ⋆ SOBP fast generation tools, for studying additional RIBs
- ⋆ Benchmarking of stable beams, comparing their performance with RIBs.



PET

- ⋆ Enhancement of Reconstruction Algorithms' Quality.
- ⋆ Replication of different PET models (*e.g.* Siemens Biograph) geometry, and their performance, based on realistic information.



Acknowledgements: T. Tessonnier, C. Gianoli, P.G. Ortega, Y. Toufique, W.S. Kozłowska and V. Vlachoudis!

Experimental Activities & Future Work

HIMAC

- ⋆ Beam time with ^{11}C, ^{12}C, ^{15}O and ^{16}O in HIMAC (Chiba) in June. The data is being processed/simulated.
  - In-beam PET imaging data collected.
  - **Obtention of fragmentation dose tails' data in pristine peaks, and position. For all beams.**

Acknowledgements: Y. Eiji, T. Yamaya and HIMAC Imaging Physics Team!

Conclusions and Future Work

- **Dosimetry** – Comparable performance.
- **Imaging potential** tenfold improvement with RIB, but:
  1. **Validation** – Simulations of ^{11}C and ^{12}C ongoing.
  2. **Clinical conditions** – All accounted for, tests ongoing.
  3. **Patient data** – To verify imaging improvement with RIBs.

- T.T. Böhlen *et al*, *Nuclear Data Sheets* **120**, 211-214, 2014
- A. Ferrari *et al*,*CERN-2005-10 (2005), INFN/TC05/11, SLAC-R-773*
- V. Vlachoudis, *Proc. Int. Conf. on Mathematics, Computational Methods & Reactor Physics* (M&C 2009), Saratoga Springs, New York, 2009
- G. Battistoni *et al*, *Front. in Onc.*, **6**-116, 2016
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- P.G. Ortega, *FLUKA Collaboration Meeting* (May 2015), CERN, Switzerland.
- R.S. Augusto *et al*, *Radiotherapy and Oncology*, **118**-1, 2016
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- D. Gürsoy *et al*, *J. Synchrotron Rad.* **21**, 1188–1193, 2014.

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THANK YOU!!!

Questions?

r.s.augusto@cern.ch,

http://www.fluka.org & http://home.cern