The FOOT (Fragmentation Of Target) experiment

International Workshop on Multi facets of Eos and Clustering
22 May 2018

Serena Marta Valle on behalf of the FOOT collaboration
➢ Radiotherapy and particle therapy
➢ Nuclear fragmentation in hadrontherapy
➢ The FOOT experiment goals
➢ Experimental strategies
➢ Experimental setups
   ✓ Emulsion setup
   ✓ Electronic setup
➢ Fragment identification
➢ Test beams
➢ Conclusions
Radiotherapy employs different kinds of radiation to destroy cancer cells, by damaging their DNA and thus invalidating their duplicating capability.

**Conventional radiotherapy**

- Mainly **photons** (linear accelerator ~10 MV) and sometimes electrons
- Several beams from different directions are superimposed
- Not so expensive, well known and reliable

**Particle therapy or hadrontherapy**

- Relatively new and expensive technique
- Mainly **protons** and **carbon ions** (but also helium and oxygen)
**Why Particle Therapy?**

Better *tumor local control* because of:

- **Spatial selectivity**
  - higher conformity of dose to the target volume (**Bragg Peak**)
  - smaller lateral scattering
  - better sparing of normal tissues

- **Biological effectiveness**
  - greater biological effectiveness (increases with the charge)
  - radioresistant tumors

**But:**

- More complex and expensive instrumentation is needed
- Sensitive to target motion

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**Graphical Representation:**

- **Beam**
- **EXTRA DOSE**
- **dE/dx**
- **Depth**
- **Spatial selectivity**
  - **Bragg Peak**
  - **Ideal**
- **Biological effectiveness**
  - **greater biological effectiveness**
  - **Radioresistant Tumors**

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**Visual Elements:**

- **Photon**
- **Protons**
- **Particles**
- **X-rays**

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**Mathematical Expression:**

\[
\frac{dE}{dx}
\]
The role of nuclear fragmentation

Proton Therapy

- Target fragmentation
- Low energy fragments: small range (~tens of μm)
- Most abundant fragments expected: He, C, Be, O, N
- No experimental data for heavy (Z≥3) fragments
- High Z fragments: high cell killing effectiveness ($\propto dE/dx \rightarrow$ increases with the charge)
- Increase of biological damage (~10%) in the entrance channel (Grun 2013)
- Higher production cross section in the entrance channel (increases with beam energy)

Ion Therapy

- Both projectile and target nuclei fragmentation
- Same velocity but lower mass wrt primary particles: long range
- Unwanted tail beyond the Bragg peak
- Mixed particle field of different cell killing effectiveness: considered in $^{12}$C treatment, but still scarce validation data. Effect to be studied with new beams: $^4$He, $^{16}$O

MC nuclear models not enough reliable.

Improve the knowledge of the $p\rightarrow$patient ($p \rightarrow H,C,O$) interaction at therapeutic energies (100–200 MeV) is needed to implement sound radiobiological models.
FOOT GOALS

INFN
Istituto Nazionale di Fisica Nucleare

APPROVED

Particle therapy

- Cross section for therapeutic beams at therapeutic energies:
  - 200 MeV for protons
  - 250 MeV/u for He ions
  - 350 MeV/u for C ions
  - 400 meV/u for O ions
- Tissue-like target (H, C, O)

Space radioprotection

- Cross section for high energy:
  - 700 MeV/u for He ions
  - 700 MeV/u for C ions
  - 700 meV/u for O ions
- H, C, O targets

➢ Fragments production cross sections (at level of 5%)
➢ Fragments energy spectra $d\sigma/dE$ (energy resolution ~1 MeV/u)
➢ Charge ID (at the level of 2-3%)
➢ Isotopic ID (at the level of 5%)
Estimation of the angular distribution of target fragments, obtained with the FLUKA MC code.

Heavy (Z>2) fragments produced at small angle (<10°).
Light fragments produced in a broader angle.

Two experimental setups

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200 MeV/u p on Oxygen

<table>
<thead>
<tr>
<th>Fragment</th>
<th>E (MeV)</th>
<th>LET (keV/μm)</th>
<th>Range (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>^15_O</em></td>
<td>1.0</td>
<td>983</td>
<td>2.3</td>
</tr>
<tr>
<td><em>^15_N</em></td>
<td>1.0</td>
<td>925</td>
<td>2.5</td>
</tr>
<tr>
<td><em>^14_N</em></td>
<td>2.0</td>
<td>1137</td>
<td>3.6</td>
</tr>
<tr>
<td><em>^13_C</em></td>
<td>3.0</td>
<td>951</td>
<td>5.4</td>
</tr>
<tr>
<td><em>^12_C</em></td>
<td>3.8</td>
<td>912</td>
<td>6.2</td>
</tr>
<tr>
<td><em>^11_C</em></td>
<td>4.6</td>
<td>878</td>
<td>7.0</td>
</tr>
<tr>
<td><em>^10_B</em></td>
<td>5.4</td>
<td>643</td>
<td>9.9</td>
</tr>
<tr>
<td><em>^9_Be</em></td>
<td>6.4</td>
<td>400</td>
<td>15.7</td>
</tr>
<tr>
<td><em>^8_He</em></td>
<td>6.8</td>
<td>215</td>
<td>26.7</td>
</tr>
<tr>
<td><em>^3_He</em></td>
<td>6.0</td>
<td>77</td>
<td>48.5</td>
</tr>
<tr>
<td><em>^3_H</em></td>
<td>4.7</td>
<td>89</td>
<td>38.8</td>
</tr>
<tr>
<td><em>^2_H</em></td>
<td>2.5</td>
<td>14</td>
<td>68.9</td>
</tr>
</tbody>
</table>


Estimation of the energy and range of target fragments obtained with an analytical model.
**Target Fragmentation: Experimental Strategies**

**Direct Kinematics?**

Proton → Tissue ($^{12}C$, $^{16}O$) → Target fragments: low energy and short range

**Inverse Kinematics**

Tissue ($^{12}C$, $^{16}O$) → Proton

Beam fragments: higher energy and longer range

**Target Choice**

Hydrogen gas target:
- Low interaction probability
- Not allowed in therapy facilities

Hydrogenated target ($C_2H_4)_n$ + Graphite target ($C$)

Fragmentation cross sections on $H$ can be measured by subtracting the cross sections of ($C_2H_4)_n$ and $C$.

By applying the Lorentz transformation, it is possible to switch from the laboratory frame to the «patient frame».
The FOOT Experiment: Emulsion Setup

**Section 1:** Target plates (C/C_2H_4) interleaved with emulsion films
- Vertex detector

**Section 2:** Emulsion films only
- Charge identification for low Z fragments (H, He, Li)

**Section 3:** Lead planes interleaved with emulsion films
- Momentum measurement and isotopic ID
- Low Z (Z<3) fragments emitted at large angles (up to 75° wrt the beam direction)
- The developed emulsions are scanned by an automated microscope
- Images are analyzed by a dedicated software to recognize clusters of aligned dark pixels (i.e. tracks produced by ionizing particles)
The FOOT experiment: electronic setup

**Pre-target region**
- **Start counter**
  - Plastic scintillator 250 μm
  - Counts primaries
  - Starts ToF measurement

**Beam monitor:**
- Ar-CO₂ drift chamber
- 3 cells x 12 XY planes
- Detects pre-target fragmentation
- Measures primaries position and direction

**Magnetic spectrometer**
- **Vertex**
  - 4 layers of silicon pixel detectors 50μm
- Reconstructs vertex position
- **Inner tracker**
  - 2 layers of silicon pixel detectors 50 μm
  - Tracking in magnetic field
- **Microstrip detector**
  - 3 layers of silicon microstrips 150 μm
  - Tracking in magnetic field
- **Magnets**
  - 2 magnets in Hallback configuration
  - Max field 0.8 T

**Calorimeter region**
- **Scintillator**
  - 2 layers of 3 mm thick plastic scintillator bars orthogonally oriented
- Measures ToF
- Measures energy release
- **Calorimeter**
  - 360 BGO crystals 24 cm long
  - Measures kinetic energy

**Minumum required performances**
- 10° polar angle (optimized for Z>2 fragments)
- σ(TOF)~100 ps
- σ(p)/p ~ 5%
- σ(E_k)/E_k ~ 2%
- σ(ΔE)/ΔE ~ 2%
Momentum reconstruction

- Track information from the magnetic spectrometer
- Recursive algorithm that predicts the trajectory from detector layer to layer, also considering multiple scattering and magnetic field → kalman filter → Genfit
- High filter reconstruction efficiency
- At present no pattern recognition → kalman filter is fed with pre-selected hits corresponding to the same track

\[ ^{16}\text{O} \rightarrow \text{C}_2\text{H}_4 \]

\[ ^{16}\text{O} \rightarrow \text{C}_2\text{H}_4 \]

\[ ^{16}\text{O} \rightarrow \text{C}_2\text{H}_4 \]
The fragment charge can be retrieved from the energy deposited in the scintillator. From the Bethe-Bloch equation:

\[
\frac{dE}{dx} = \frac{\rho \cdot Z}{A} \cdot \frac{4\pi N_A m_e c^2}{M_U} \left( \frac{e^2}{4\pi \epsilon_0 m_e c^2} \right)^2 \frac{z^2}{\beta^2} \ln \left( \frac{2m_e c^2 \beta^2}{I \cdot (1 - \beta^2)} \right) - \beta^2
\]

Energy deposited in scintillator

Z resolution range: 2% (16O) - 5% (1H)
Mass ID

Mass can be calculated by combining the reconstructed quantities:
- Momentum (magnetic spectrometer)
- ToF (scintillator)
- Kinetic energy (calorimeter)

Fit methods used:
- Standard $\chi^2$ fit
- Augmented Lagrangian Method (ALM)

Resolutions for all the reconstructed quantities have been considered:
- Momentum: 4.5%
- Kinetic Energy: 1.5%
- ToF: 70 - 100 ps depending on Z

$$A_1 = \frac{p}{U c \beta \gamma} \quad \quad A_2 = \frac{E_k}{U c^2 (\gamma - 1)} \quad \quad A_3 = \frac{p^2 c^2 - E_k^2}{2U c^2 E_k}$$
**Test Beams**

- **145 BGO crystals tested in Heidelberg**
- **Beams used:**
  - \( p: 50 \text{ MeV} - 220 \text{ MeV} \)
  - \( \text{He: } 50 \text{ MeV/}u - 220 \text{ MeV/}u \)
  - \( \text{C: } 100 \text{ MeV/}u - 430 \text{ MeV/}u \)
- **Contribution from beam energy spread, detectors and electronics included**
- **Energy resolution:** 1%–3%

**Calorimeter**

- **Time resolution:**
  - Protons: 100 – 180 ps
  - C ions: <50 ps
- **Energy resolution:**
  - Landau fluctuations included
  - Protons: 5 – 12%
  - C ions: 7%
The FOOT experiment goal is to experimentally determine the production cross sections of fragments for beams, energy and targets relevant in hadrontherapy and radioprotection in space.

The final electronic experimental setup is still under development. MC simulation (FLUKA) have been and are still used to improve the detector layout and study the performances.

Several experimental tests have been performed in different facilities (LNS, Trento protontherapy center, CNAO), others are planned.

Data taking with the emulsion setup is planned in late 2018 at GSI, while the acquisition with the electronic setup is foreseen in 2020 (GSI/CNAO/Heidelberg Ion Therapy Center).
Thank you!
Spares
Double target strategy

C @ 95 MeV/n on C and C₂H₄

➤ GANIL experimental data

C @ 200 MeV/n on C and C₂H₄

➤ Fluka simulation in the FOOT experiment
MC (FLUKA) comparison between cross section on H target or by difference of C-> C and C-> C₂H₄
Method of cross section difference is crucial to obtain X section on pure elements:

- Using $^{12}$C, $^{12}$C, $^{2}$H, $^{4}$H $\Rightarrow$ cross sections on C and H
- Using $^{12}$C, $^{12}$C, PMMA $\Rightarrow$ cross sections on C, O and H

PMMA is a combination of C,O,H.

<table>
<thead>
<tr>
<th>Phys</th>
<th>Beam</th>
<th>Target</th>
<th>Energy (MeV/u)</th>
<th>Inv/direct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target Frag. PT</td>
<td>$^{12}$C</td>
<td>C, $^{2}$H, $^{4}$H</td>
<td>200</td>
<td>inv</td>
</tr>
<tr>
<td>Target Frag. PT</td>
<td>$^{16}$O</td>
<td>C, $^{2}$H, $^{4}$H</td>
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<td>inv</td>
</tr>
<tr>
<td>Beam Frag. PT</td>
<td>$^{12}$C</td>
<td>C, $^{2}$H, $^{4}$H, PMMA</td>
<td>350</td>
<td>dir</td>
</tr>
<tr>
<td>Beam Frag. PT</td>
<td>$^{16}$O</td>
<td>C, $^{2}$H, $^{4}$H, PMMA</td>
<td>400</td>
<td>dir</td>
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<tr>
<td>Beam Frag. PT</td>
<td>$^{4}$He</td>
<td>C, $^{2}$H, $^{4}$H, PMMA</td>
<td>250</td>
<td>dir</td>
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<tr>
<td>Rad. Prot. space</td>
<td>$^{4}$He</td>
<td>C, $^{2}$H, $^{4}$H, PMMA</td>
<td>700</td>
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</tr>
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</table>
Electronic detector
➢ 250 μm plastic scintillator read out by 48 SiPM (12/side) to improve light collection
➢ Needed for measurements @ 700 MeV/u
➢ Test beam at CNAO carbon in autumn
Drift chamber: 6+6 orthogonal layers of wires, with three drift cells (1.8x1.5 cm²) per layer

measure the impinging beam angle on the target with mrad angular resolution

Detect beam fragmentation on Margherita

Hit resolution: 150μm on ¹²C beam
Halbach geometry provides uniform transverse magnetic field in a cylindrical geometry: B field proportional to $\ln(R_{\text{out}}/R_{\text{in}})$.

$B=0.8\text{T}$

Thick=8cm
Vertex: MIMOSA28 chip

- MAPS (AMS 0.35 μm, 15 μm epi-layer)
- 50 μm thickness
- 928 (rows) x 960 (columns) pixels
- 20.7 μm pitch
- Size 20.22 mm x 22.71 mm
- Chip readout time 185.6 μs
- Digital Zero Suppressed Output

By IPHC In2p3 Strasbourg
INNER TRACKER

Plume 2011 with 0.35% X₀

SiC Foam 4 %

SMD

2 mm

18 mm

Epoxy glue (few µm)

Mi26 sensor (50µm)

Top Cover Layer (25µm)

Top Metal Al (10µm)

Subtrat Kapton (50µm)

Bottom Metal Al (10µm)

Bottom Cover Layer (25µm)

120µm
Neutron leakage in calorimeter

The neutron leakage in BGO seems to be more and more important for energy higher than 200 MeV/nucl and for light fragments (!)

Even if the TOF and momentum can tag such events, these must be minimized to keep the systematic under control.

FLUKA 2017 Simulation
14 cm length crystal

Ecalo/Ekin
Kalman filter

- Recursive algorithm that accurately takes into account multiple scattering;
- Each layer prediction is corrected using the observed hit -> track uncertainty decreases layer by layer.
- Precise description of geometry and material needed
Isotopic ID

Standard $\chi^2$

$$f = \left( \frac{T_{TOF} - T}{\sigma_{TOF}} \right)^2 + \left( \frac{p - P}{\sigma_p} \right)^2 + \left( \frac{E_k - K}{\sigma_{E_k}} \right)^2 +$$

$$(A_1 - A, \quad A_2 - A, \quad A_3 - A) \begin{pmatrix} B_{00} & B_{01} & B_{02} \\ B_{10} & B_{11} & B_{12} \\ B_{20} & B_{21} & B_{22} \end{pmatrix} \begin{pmatrix} A_1 - A \\ A_2 - A \\ A_3 - A \end{pmatrix}$$

$$|B| = (C \cdot C^T)^{-1}$$

$$C = \begin{pmatrix} \frac{\partial A^+}{\partial T} & \frac{\partial A^+}{\partial P} & 0 \\ \frac{\partial A^+}{\partial T} & 0 & \frac{\partial A^+}{\partial K} \\ 0 & \frac{\partial A^+}{\partial P} & \frac{\partial A^+}{\partial K} \end{pmatrix}$$

ALM

$$L(\bar{x}, \lambda, \mu) \equiv f(\bar{x}) - \sum_a \lambda_a c_a(\bar{x}) + \frac{1}{2\mu} \sum_a \lambda_a^2 c_a^2(\bar{x})$$

$$f(\bar{x}) = \left( \frac{T_{TOF} - T}{\sigma_{TOF}} \right)^2 + \left( \frac{p - P}{\sigma_p} \right)^2 + \left( \frac{E_k - K}{\sigma_{E_k}} \right)^2$$

$$\sum_a \lambda_a c_a(\bar{x}) + \frac{1}{2\mu} \sum_a \lambda_a^2 c_a^2(\bar{x}) = \lambda_1 (A_1 - A) + \lambda_2 (A_2 - A) + \lambda_3 (A_3 - A) +$$

$$\frac{1}{2\mu} \left( (A_1 - A)^2 + (A_2 - A)^2 + (A_3 - A)^2 \right)$$