FOOT: Fragmentation Of Target Experiment

- Hadrontherapy, Radio Protection
  - Main concepts
- FOOT
  - Main goals
  - Detector
  - Performances
- FUTURE PERSPECTIVE

Bologna, San Domenico, 6/9/2018

Roberto Spighi (INFN Bologna), on behalf of the FOOT Collaboration

spighi@bo.infn.it
**FOOT goals**

**Hadrontherapy**

Target fragmentation
- $d\sigma/dE$ and $d\sigma/d\omega$ with 5% precision of the fragment production $X$ sections in inverse kinematics
- $p$, C, O beams
- Hadrontherapy energies (200-400 $MeV/u$)

Projectile fragmentation
- same but in direct kinematics

**Radioprotection in space**

detailed knowledge of the fragmentation processes to optimize the spacecraft shielding (long term mission)

- $d\sigma/dE$ and $d\sigma/d\omega$ with 5% precision of the fragment production $X$ sections in direct and inverse kinematics
- $p$, He, Li, C, O beams (the most common in space)
- Radioprotection energies (around 700 $MeV/u$)

**Radiobiology request:** to have a more precise **TPS** Treatment Planning System
FOOT approved by the INFN on September 2017 (CSN3)

92 members (60% staff):
- 10 INFN Sections
- 5 laboratories: Frascati, CNAO, Trento, GSI, IPHC (Strasbourg)
- 12 Italian Universities
- 2 foreign Universities: Aachen, Nagoya
- Centro Fermi

Physics program:
- Hadrontherapy:
  - Nuclear fragmentation @ 200 MeV/u
- Radioprotection in Space:
  - Nuclear fragmentation @ 700 MeV/u
Hadrontherapy vs Radiotherapy

Proton/charged ion
- Ionization
- Excitation
- Bremsstrahlung
- Fragmentation

Gamma
- Photoelectric ($\sim Z^4/E^3$)
- Compton ($\sim Z/E$)
- Pair prod ($\sim Z^2/\ln E$)

Pros and cons
- Dose release maximum at the end
- Penetration depends on energy
- Hadron > efficient than $\gamma$
- Hadron < damage outside tumor
- MORE expensive than $\gamma$
Damage on DNA

Tumor is a cellular alteration $\rightarrow$ not controlled proliferation $\rightarrow$ stop the proliferation $\rightarrow$ damage on DNA

Ionization tracks

Gamma radiation
1MeV Protons
1MeV/u alphas.
1MeV/u C-12 ions

$n$ and $C$ on the Bragg Peak

Higher $Z$ $\rightarrow$ Higher damage

but, necessary to know the Nuclear fragmentation cross sections

R. Spighi: FOOT experiment

Double strand break $\rightarrow$ irreparable damage
Target-Projectile fragmentation

- \( p + H \) → No fragmentation
- \( p + C, O \) → target fragments
  - low Energy → low range
- \( C + H \) → projectile fragments
  - High Energy → Long range
- \( C + C, O \) → target/projectile fragments

R. Spighi: FOOT experiment

### Fragmentation Table

<table>
<thead>
<tr>
<th>Fragment</th>
<th>E (MeV)</th>
<th>LET (keV/μm)</th>
<th>Range (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{17})O</td>
<td>1.0</td>
<td>983</td>
<td>2.3</td>
</tr>
<tr>
<td>(^{15})N</td>
<td>1.0</td>
<td>925</td>
<td>2.5</td>
</tr>
<tr>
<td>(^{17})N</td>
<td>2.0</td>
<td>1137</td>
<td>3.6</td>
</tr>
<tr>
<td>(^{12})C</td>
<td>3.0</td>
<td>951</td>
<td>5.4</td>
</tr>
<tr>
<td>(^{12})C</td>
<td>3.8</td>
<td>912</td>
<td>6.2</td>
</tr>
<tr>
<td>(^{13})C</td>
<td>4.6</td>
<td>878</td>
<td>7.0</td>
</tr>
<tr>
<td>(^{10})B</td>
<td>5.4</td>
<td>643</td>
<td>9.9</td>
</tr>
<tr>
<td>(^{8})Be</td>
<td>6.4</td>
<td>400</td>
<td>15.7</td>
</tr>
<tr>
<td>(^{6})Li</td>
<td>6.8</td>
<td>215</td>
<td>26.7</td>
</tr>
<tr>
<td>(^{4})He</td>
<td>6.0</td>
<td>77</td>
<td>48.5</td>
</tr>
<tr>
<td>(^{3})He</td>
<td>4.7</td>
<td>89</td>
<td>38.8</td>
</tr>
<tr>
<td>(^{3})H</td>
<td>2.5</td>
<td>14</td>
<td>68.9</td>
</tr>
</tbody>
</table>

### Comments
- Target fragmentation when using Carbon.
- Tail present only when using Carbon.

### Proton Therapy
- \( p \) beam
- Target beam 400 MeV/c

### Ion Therapy
- \( C \) beam
- \( H, C, O \) (95%)
- Proton therapy
- Ion therapy

### Diagrams
- Graphs showing target and projectile fragmentation.
- Comparison of penetration depth in tissue.
FOOT MAIN GOAL: Target fragmentation in proton therapy

\[ p + \text{C,O} \rightarrow \text{fragments} \]

Target fragments remain in the target

Impossible to detect fragments

**DIRECT KINEMATIC**
- Proton 200 MeV
- C,O at rest

**INVERSE KINEMATIC**
- Proton (H) at rest
- C,O 200 MeV/A
- A the end Lorentz boost

\[ \frac{d\sigma}{dE_{\text{kin}}}(H) = \frac{1}{4} \left( \frac{d\sigma}{dE_{\text{kin}}}(C_2H_4) - 2 \frac{d\sigma}{dE_{\text{kin}}}(C) \right) \]

**Ganil experimental data**

R. Spighi: FOOT experiment
**FOOT Detector (in construction)**

**Electronic Setup**
- Beam Monitor
- Start Counter
- Target
- Tracker Silicon Strip
- Silicon Pixel Tracker
- Magnets
- ΔE-TOF scintillator
- Calorimeter BGO

**Pre-target region**
- Tracking region
- Downstream region

**Emulsion Chamber Setup**
- Section 1: vertexing
- Section 2: Charge Id
- Section 3: momentum

**Electronic Setup Diagram**
- Events normalized against θ
- Charge: n, p, D, T, He
- Angular open ± 10°
- Angular open ± 70°

**Emulsion Chamber Setup Diagram**
- Emulsion layer
- 1 mm C or C₂H₄
- 1 mm Pb layer

R. Spighi: FOOT experiment
250 μm–1 mm thick plastic scintillator (depending on E beam)
50 mm radius
~ 400 optical fibers → 4 bundles to 4 PMTs
Test beam in september in Trento
FOOT

**Tracking region**

**Vertex & Inner Tracker**

- **VTX:** 4 layers of Si pixel (20 x 20 μm)
- **ITR:** 2 layers of Si pixel (20 x 20 μm)
- **MSD:**
  - 3 layers of Si strips (120 μm x 9 cm)

**Magnet**

- 2 permanent magnets
- Hallbach geometry
- B field in y direction (max 0.8 T)

**Micro Strip Detector (MSD)**
40 x 2 cm plastic scintillator bars
3 mm thickness
2 layers of 20 bars
Silicon PhotoMultipler (SiPM)

ΔE-Tof

BGO – (Bi₄Ge₃O₁₂)
Inorganic scintillator

\[ Z_{\text{Bi}} = 83 \]
\[ \rho_{\text{BGO}} = 7.13 \text{ g/cm}^3 \]
\[ \text{Weight} = 1.027 \text{ kg} \]
\[ \text{Total weight} 330 \text{ Kg} \]

SiPM
Pitch 50 μm
Voltage breakdown 53 V
**ΔE-Tof** test beam @CNAO

Proton Carbon

![Graph showing ΔE-Tof results for Protons and Carbon](image)

**Calorimeter**: test beam @HIT

145 BGO crystals

![Image of calorimeter setup](image)

**Emulsion** test beam @LNS and Trento

![Image of emulsion setup](image)

**Conservative Resolutions**

- $\Delta p/p \rightarrow 4\%$
- $\Delta E_{\text{kin}}/E_{\text{kin}} \rightarrow 1.5\%$
- $\Delta \text{tof} \rightarrow 70-140$ ps
- $\Delta(dE)/dE \rightarrow 3-10\%$

**Test beam results**

- Proton $E_{\text{kin}}$ (MeV): 62, 100, 140, 180, 230
- Carbon $E_{\text{kin}}$ (MeV/u): 115, 190, 260, 330, 400

- Kinetic energy resolution at 1-2%
Performances: charge Z reconstruction

Fragment univocally defined by Z and A

energy deposited in SCN

reconstructed Z

Fluka simulation

<table>
<thead>
<tr>
<th>Element</th>
<th>Z</th>
<th>1H</th>
<th>4He</th>
<th>7Li</th>
<th>9Be</th>
<th>11B</th>
<th>12C</th>
<th>14N</th>
<th>16O</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1.01±0.09</td>
<td>2.01±0.06</td>
<td>3.03±0.08</td>
<td>4.05±0.09</td>
<td>5.06±0.10</td>
<td>6.09±0.12</td>
<td>7.11±0.14</td>
<td>8.15±0.15</td>
</tr>
<tr>
<td>Z Resolution</td>
<td></td>
<td>9%</td>
<td>3%</td>
<td>2.0%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

wrong charge assignment < 1%
Performances: Number of mass A (ex of $^{12}\text{C}$)

$$A_1 = \frac{p}{U \beta \gamma}$$

$$A_2 = \frac{E_{\text{kin}}}{U(\gamma - 1)}$$

$$A_3 = \frac{p^2 - E_{\text{kin}}^2}{2E_{\text{kin}}}$$

Fluka simul $^{16}\text{O}$ (200 MeV/u) $\rightarrow$ $\text{C}_2\text{H}_4$

Fit cut the wrong reconstructed fragments

FIT Methods:
- Standard $\chi^2$
- Augmented Lagrangian (ALM)
FOOT Performances: Number of mass reconstruction

Simulation by Fluka

$^{16}\text{O} (200 \text{ MeV/u}) \rightarrow \text{C}_2\text{H}_4$

Conservative Resolutions
- $\Delta p/p \rightarrow 4\%$
- $\Delta E_{\text{kin}}/E_{\text{kin}} \rightarrow 1.5\%$
- $\Delta t_{\text{of}} \rightarrow 70 - 140 \text{ ps}$
- $\Delta(dE)/dE \rightarrow 3 - 10\%$

Resolution for heavy fragments $\sim 3-4\%$

Possibility to disentangle isotopes

R. Spighi: FOOT experiment
FOOT Performances: Isotopes separation (example of C)

Conservative Resolutions
- $\Delta p/p \rightarrow 4\%$
- $\Delta E_{\text{kin}}/E_{\text{kin}} \rightarrow 1.5\%$
- $\Delta t_{\text{tof}} \rightarrow 70 - 140$ ps
- $\Delta (dE)/dE \rightarrow 3 - 10\%$

Resolutions from Test Beam
- $\Delta p/p \rightarrow 4\%$
- $\Delta E_{\text{kin}}/E_{\text{kin}} \rightarrow 1.0\%$
- $\Delta t_{\text{tof}} \rightarrow 50 - 100$ ps
- $\Delta (dE)/dE \rightarrow 3 - 10\%$

Data simulated by Fluka

$^{16}\text{O} (200 \text{ MeV/u}) \rightarrow \text{C}_2\text{H}_4$

Test beam on ToF
- Proton
- Carbon

Test beam on Calorimeter
- Resolution 1% (C)

R. Spighi: FOOT experiment
Mars mission: radio protection in space

Mars: NO magnetosphere and very thin atmosphere ➔ no protection from GCR and SPE

Radiation:
- Travel: 1.8 mSv/day (GCR + SPE)
- On Mars: 0.64 mSv/day
- On Earth: 2.64 mSv/year

~ 1 Sv (increase the cancer probability of ~3%)

\[
\frac{\text{Rad on Mars}}{\text{Rad on Earth}} \approx 280
\]

shielding is needed (interaction on it?)

90% of particles are proton (9% \(^4\text{He}, \ldots\))

Large Intersection with the hadrontherapy measures but higher energy

R. Spighi: FOOT experiment
Fluka Simulation: $^{16}\text{O}$ (700 MeV/u) on C2H4

**Angular distribution**

Z>2 fragments inside 4°

- Same acceptance as @ 200 MeV/u
- High resolution on $\beta$
- Crucial for Z & A determination

**Emulsion Chamber**
Different geometry and number of layers
Z reconstruction performance @700 MeV/u

Energy deposited in SCN

![Graph showing energy deposition for different charges at 700 MeV/nucl and 200 MeV/nucl.]

- **Z reconstruction performance**
- **Charge Z**
- **Fluka Simulation**
  - $^{16}$O (700 MeV/u) $\rightarrow$ $C_2H_4$
- **Wrong charge assignment < 1%**

<table>
<thead>
<tr>
<th>Z</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resol (200 MeV):</td>
<td>9%</td>
<td>3.0%</td>
<td>2.0%</td>
<td>2.0%</td>
<td>2.0%</td>
</tr>
<tr>
<td>Resol (700 MeV):</td>
<td>9%</td>
<td>4.5%</td>
<td>3.6%</td>
<td>3.0%</td>
<td>2.1%</td>
</tr>
</tbody>
</table>

R. Spighi: FOOT experiment
Problems with higher energy: example of $^{12}$C

Fragments with larger energy $\rightarrow$ higher probability to fragment in CALO

Fraction of deposited energy

Larger neutrons production

A with Tof & Tracker

missed energy in CAL

FOOT redundancy

~ performance @ 700 MeV/u

20% of well reconstructed

R. Spighi: FOOT experiment
Test beam during 2018-2019 at CNAO, Trento, Catania to finalize the detector
- GSI: FOOT approved for the IBER-2017 ESA program
  - Last week 11/2018: 16 h beam (He or C)
    - test of EMC
    - Electronic setup: BM, SC, prototype of MSD, SCN
- GSI: 12/2019 Data taking with almost complete apparatus (~ first data taking)
- 2020-21 Data taking with the complete apparatus

SCN detector (NIM): in publication
- General Apparatus Paper: in preparation
- $d\sigma/dE$ for light fragments (p, d, T, He) at 4 angles (34°, 52°, 60°, 90°): in preparation
  - Data taking at CNAO: C beam from 115-352 MeV/u on H, C, O targets
  - Setup: SCNs for ToF & charge and CAL (LYSO 8 cm) for Energy
Conclusion

- Approved on September 2017

- Wide physics panorama
  - Hadrontherapy
    - Target fragmentation
    - Projectile fragmentation
  - Radioprotection in space

- Detector Status:
  - Simulation phase is well advanced
  - Setup almost established
  - Many tests on beam already made
  - Performance as expected

- Future perspective
  - Scheduled Test Beam on 2018-2019
  - Data taking in 2020-1
  - 3 papers in publication/preparation
Backup slides
Hadrontherapy in the world

Continuous expansion in the last 50 years

Facility (2014):
- operative
  - 44 proton/7 heavy ion centers
- Under construction
  - 25 proton/4 heavy ion centers

Treated patients (2014):
- 120000
  - 107000 with p (in USA 54000)
  - 13000 with 12C (in Japan 11000)

From 2010: 10000 patients per year

In Italy on 18/3/2017 hadrontherapy entered in LEA (Livelli Essenziali di Assistenza) allowing the treatment to 10 tumour pathologies

R. Spighi: FOOT experiment
Hadrontherapy in Italy

- Proton beam till 250 MeV
- Carbon beam till 400 MeV
- Active since 2011
- First 5 years → 828 patients (70-90% success)
- Till now 1200 patients

- Proton beam (till 60 MeV)
- Active since 2002
- Eye tumour: 363 patients (98% survived)

CNAO Pavia
Centro Nazionale Terapia Oncologica

- Proton beam (60-230 MeV)
- Full body treatment
- Experimental halls

Proton therapy Center - Trento

- Active since 2015
- Proton beam (60-230 MeV)
A Reconstruction and fit

**Standard $\chi^2$ Fit**

- Taking into account the correlation between $A_1$, $A_2$ and $A_3$

$$f = \left( \frac{(\text{tof}_{\text{reco}} - t)}{\sigma_{\text{tof}_{\text{reco}}}} \right)^2 + \left( \frac{(\varphi_{\text{reco}} - p)}{\sigma_{\varphi_{\text{reco}}}} \right)^2 + \left( \frac{(E_{\text{kin,\text{reco}}} - E_{\text{kin}})}{\sigma_{E_{\text{kin,\text{reco}}}}} \right)^2 + (A_1 - A) (A_2 - A) (A_3 - A) \begin{pmatrix} C_{00} & C_{01} & C_{02} \\ C_{10} & C_{11} & C_{12} \\ C_{20} & C_{21} & C_{22} \end{pmatrix} \begin{pmatrix} A_1 - A \\ A_2 - A \\ A_3 - A \end{pmatrix}$$

$$C = (A \cdot A^T)^{-1} \quad A = \begin{pmatrix} \frac{\partial A_1}{\partial t} dt & \frac{\partial A_1}{\partial p} dp & 0 \\ \frac{\partial A_2}{\partial t} dt & 0 & \frac{\partial A_2}{\partial E_{\text{kin}}} dE_{\text{kin}} \\ 0 & \frac{\partial A_3}{\partial p} dp & \frac{\partial A_3}{\partial E_{\text{kin}}} dE_{\text{kin}} \end{pmatrix}$$

**Augmented LagrangianFit (ALM)**

$$\tilde{L}(\vec{x}; \lambda, \mu) \equiv f(\vec{x}) - \sum_a \lambda_a c_a(\vec{x}) + \frac{1}{2\mu} \sum_a c_a^2(\vec{x}).$$
A reconstruction efficiency

Reconstruction efficiency ~ 70-80% depending on the fragment

R. Spighi: FOOT experiment
Number of mass reconstruction: example of $^{12}$C

$$A_1 = \frac{m}{U} = \frac{p}{U\beta\gamma}$$

$$A_2 = \frac{m}{U} = \frac{E_{\text{kin}}}{U(\gamma - 1)}$$

$$A_3 = \frac{m}{U} = \frac{p^2 - E_{\text{kin}}}{2E_{\text{kin}}}$$

$^{16}$O (200 MeV/u) $\rightarrow$ C$_2$H$_4$

Data simulated by Fluka

Tail: nuclear interaction on BGO of calorimeter

STANDARD $\chi^2$ Fit

ALM Fit

ALM $\chi^2 < 5$

$^{12}$C

$\chi^2$ Fit allows to cut the wrong reconstructed fragments
FOOT Performances: Number of mass reconstruction

- Reconstruction
  \[ A_1 = \frac{m}{U} = \frac{p}{U \beta \gamma} \]
  \[ A_2 = \frac{m}{U} = \frac{E_{\text{kin}}}{U(\gamma - 1)} \]
  \[ A_3 = \frac{m}{U} = \frac{p^2 - E_{\text{kin}}^2}{2E_{\text{kin}}} \]

- Fit Methods: STANDARD $\chi^2$ and ALM

- TOF Tracker
- CALO

Resolution for heavy fragments ~ 3-4%

$\text{^{16}O (200 MeV/u)} \rightarrow \text{C}_2\text{H}_4$

Data simulated by Fluka

R. Spighi: FOOT experiment
**brief experimental panorama on proton cross section**

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$E_{\text{Kin}}$ (MeV)</th>
<th>$\sigma_{\text{TOT}}$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p \rightarrow p$</td>
<td>10</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>180-500</td>
<td>25-35</td>
</tr>
<tr>
<td></td>
<td>600-2000</td>
<td>45-50</td>
</tr>
<tr>
<td>$P \rightarrow ^4\text{He}$</td>
<td>150-600</td>
<td>110-120</td>
</tr>
<tr>
<td>$P \rightarrow ^9\text{Be}$</td>
<td>200-600</td>
<td>230-250</td>
</tr>
<tr>
<td>$P \rightarrow ^{12}\text{C}$</td>
<td>50</td>
<td>450</td>
</tr>
<tr>
<td></td>
<td>100-200</td>
<td>230</td>
</tr>
<tr>
<td></td>
<td>200-1000</td>
<td>280-350</td>
</tr>
<tr>
<td>$P \rightarrow ^{16}\text{O}$</td>
<td>20</td>
<td>550</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>350</td>
</tr>
<tr>
<td></td>
<td>200-600</td>
<td>350-400</td>
</tr>
<tr>
<td>$P \rightarrow ^{40}\text{Ca}$</td>
<td>30</td>
<td>900</td>
</tr>
<tr>
<td></td>
<td>100-200</td>
<td>500</td>
</tr>
</tbody>
</table>

R. Spighi: FOOT experiment
brief experimental panorama on $p \rightarrow ^{12}\text{C}$ differential cross section
Relative Biological Effectiveness (RBE)

R.B.E = \left( \frac{D_{X-ray}}{D_H} \right)_{\text{Same effect}}

- \text{LET}
- \text{Dose}
- \text{Depth in the body}
- \text{Beam energy}
- \text{Vivo/vitro}
- \text{Tissue type ...}
- \text{Nuclear interaction}

High RBE \rightarrow \text{high effect wrt radiation}

RBE depends on:

- LET
- Dose
- Depth in the body
- Beam energy
- Vivo/vitro
- Tissue type ...
- Nuclear interaction

proton RBE = 1.1

R. Spighi: FOOT experiment
Nuclear interaction

Hadrontherapy energies:
\[ p \rightarrow 200 \text{ MeV} \]
\[ ^{12}\text{C} \rightarrow 400 \text{ MeV/u} \]

Most probable nuclear process: Fragmentation peripheral interaction between projectile (p, \(^{12}\text{C}, \ldots\)) and target (H, C, O, \ldots)

Protons ≠ photons * 1.1 due to Nuclear interaction

No Standard Treatment Planning for hadrontherapy

Study of the Target-Projectile fragmentation

Abrasion-Ablasion model → 2 stages

R. Spighi: FOOT experiment
**ΔE-Tof** test beam @CNAO

**Calorimeter:** test beam @HIT

**Proton Ekin (MeV):** 62, 100, 140, 180, 230

**Carbon Ekin (MeV/u):** 115, 190, 260, 330, 400

**145 BGO crystals**

**Proton Ekin (MeV):** 62, 100, 140, 180, 230

**Carbon Ekin (MeV/u):** 115, 190, 260, 330, 400

**Tof resolution (C) better 40 ps**

**Resolution 1-2%**

**Kinetic energy resolution at 1-2%**

**Agreement simulation data in few %**

R. Spighi: FOOT experiment
**Test beam and simulation results**

**Tracking** Kalman Filter (simulation)

**Emulsion chamber** test beam @LNS (p, D, He, C) and Trento (p at 50, 80, 200 MeV)

$p \cdot \beta$ by Multiple Coulomb Scatt

Fragments charge determined by volume of points after refreshing

**ECC: charge separation**

$p$ resolution at level of 4%
Target Fragmentation cross sections

dσ/dE\text{kin}(\text{fragment}) in C & C_2H_4 targets (inverse kinematic)

\[ \frac{d\sigma}{dE_{\text{kin}}(\text{fragment})} \]

Fluka Simulation

\[ ^{12}\text{C} (200 \text{ MeV/u}) \rightarrow C_2\text{H}_4 & \text{H} \]

\[ \frac{d\sigma}{dE_{\text{kin}}}(H) = \frac{1}{4} \left( \frac{d\sigma}{dE_{\text{kin}}}(C_2\text{H}_4) - 2 \frac{d\sigma}{dE_{\text{kin}}}(C) \right) \]

Ganil experimental data

Agreement between the two methods

R. Spighi: FOOT experiment
- Optimized for heavy ($Z \geq 3$) fragments
- $< 2 \text{ m} (\text{@200 MeV/u})$ → portability
- Angular acceptance $\rightarrow \pm 10^\circ$

Sub-detector | Main Characteristics
--- | ---
Start Counter | Plastic scintillator 250 $\mu$m
Beam monitor | Drift chamber (12 layers of wires)
Target | C + C$_2$H$_4$ (2 mm)
Vertex | 4 layers silicon pixel (20x20 $\mu$m)
Magnet | 2 permanent dipoles (Halbach geometry 0.8 T)
Inner Tracker | 2 layers silicon pixel (20x20 $\mu$m)
Outer Tracker | 3 layers of Silicon strip (125 $\mu$m pitch)
Scintillator | 2 layers of 20 barrels (2x40x0.3 cm)
Calorimeter | 360 BGO crystals (2x2x14 cm)

R. Spighi: FOOT experiment
C on C @ 200 MeV/nucl FLUKA

Light fragments (Z<3) produced at wide angle (~75°)

FOOT: Emulsion chamber setup

**CHARGE**
- Z = 0
- Z = 1
- Z = 2
- Z = 3
- Z = 4
- Z = 5
- Z = 6
- Z = 7
- Z = 8

**G. De Lellis et al. JINST 2, 2007, P06004**

**C on C @ 200 MeV/nucl FLUKA**

**Light fragments (Z<3) produced at wide angle (~75°)**

**300 μm**

**Emulsion layer**

**300 μm**

**Emulsion layer**

**1 mm**

**Pb layer**

**Emulsion layer**

**1 mm**

**Pb layer**

**Beam monitor**

**Beam**

**Start counter**

**Beam monitor**

**movement to avoid pile-up**

**High speed automated scanning**

**Section 1**
- vertexing

**Section 2**
- Charge Identification

**Section 3**
- momentum

**Beam**

**Emulsion Chamber**

**n, p, D, T, He**

**10 cm**