Design and performance of the FOOT calorimeter with particle-ID capabilities

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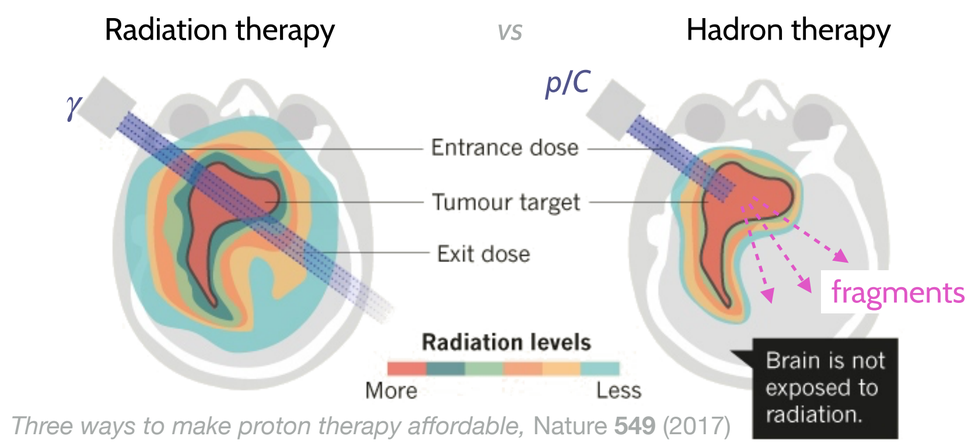
FOOT experiment

Fragmentati**O**n **O**f **T**arget – portable experiment to measure differential fragmentation cross sections relevant for the two major applications: **hadron therapy** and **radio-protection**

1. Hadron therapy (≤400 MeV/u)



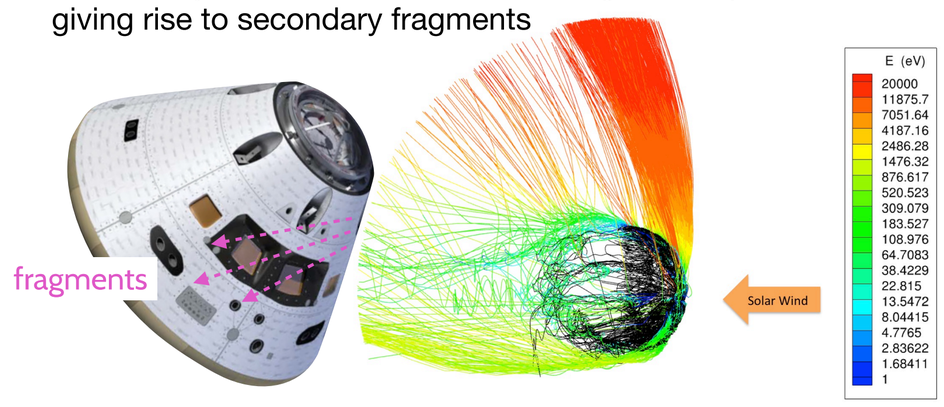
Three ways to make proton therapy affordable, Nature **549** (2017)

simulations not always reliable

- isotopic composition?
- cross section?
- momentum?
- energy?

2. Radio protection in space (≤800 MeV/u)

Cosmic rays interact with walls/shielding of the spacecraft giving rise to secondary fragments



"Real Martians: How to Protect Astronauts from Space Radiation on Mars"
Sarah Frazier, NASA's Goddard Space Flight Center (2015)

Fragments have very short range *(10-100 μm)* → **nearly impossible to measure directly**
↳ use **inverse kinematic** approach → secondary fragments have **boosted energy** + **long range** → **can be measured by a detector**

Detector design

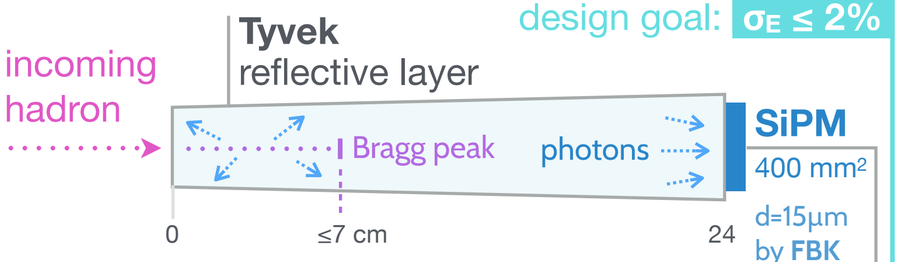
Provides isotope identification by measuring **time of flight** + **momentum** + **energy** of every fragment

320 × $Bi_4 Ge_3 O_{12}$ $\sigma_t \leq 100$ps $\sigma_p \sim 4\%$

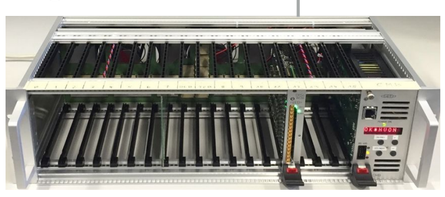
event rate of ~1 kHz × low occupancy of ~1%

BGO Calorimeter

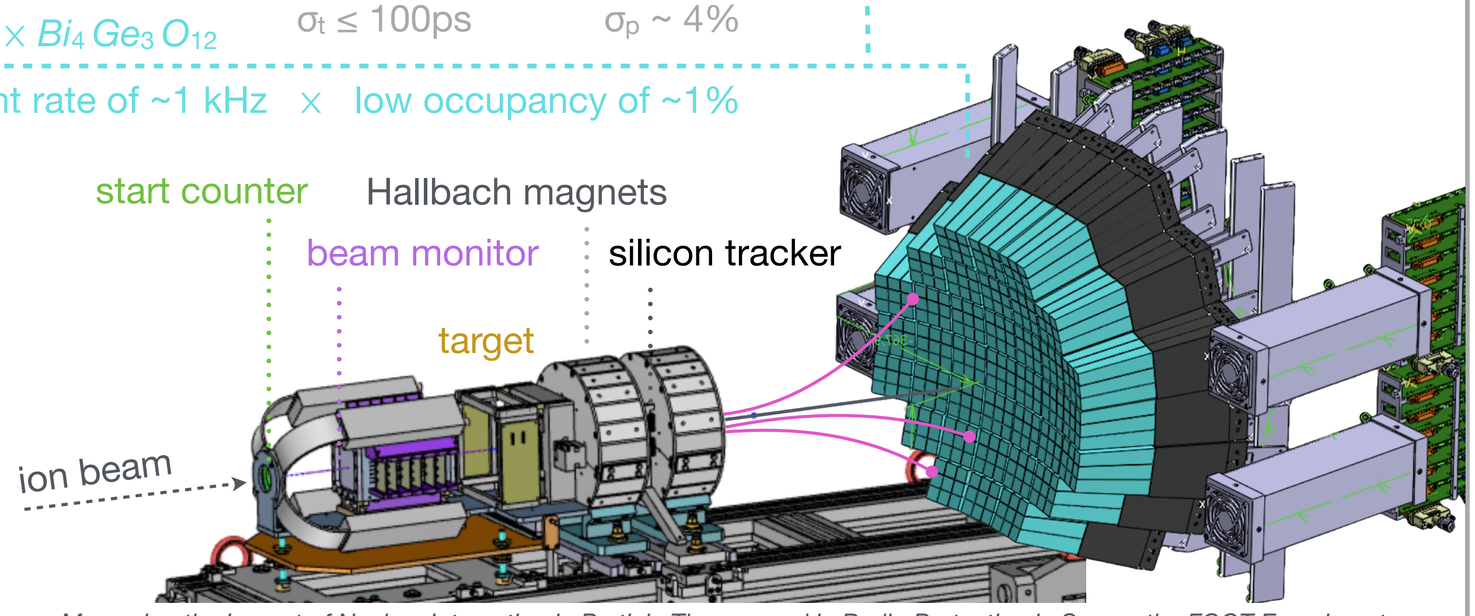
design goal: $\sigma_E \leq 2\%$



Digitizer + DAQ



WaveDream
12 bit at 2.5 GS/s
allowing pulse-shape analysis for particle identification

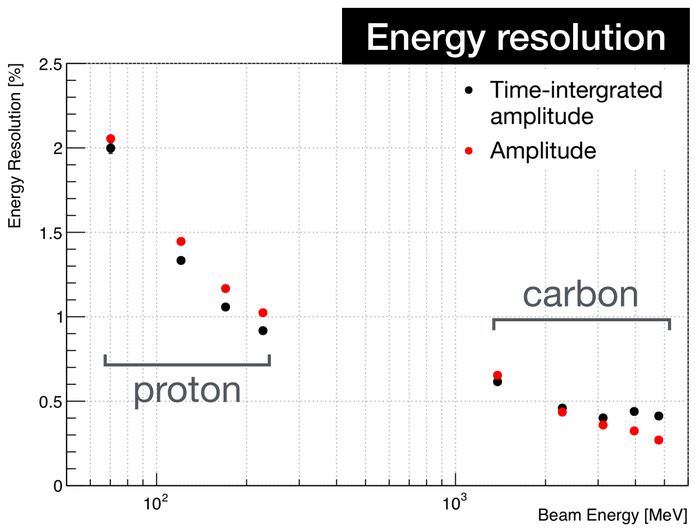


Measuring the Impact of Nuclear Interaction in Particle Therapy and in Radio Protection in Space: the FOOT Experiment
FOOT Collaboration, Front. Phys. **8**:568242 (2021), doi: 10.3389/fphy.2020.568242

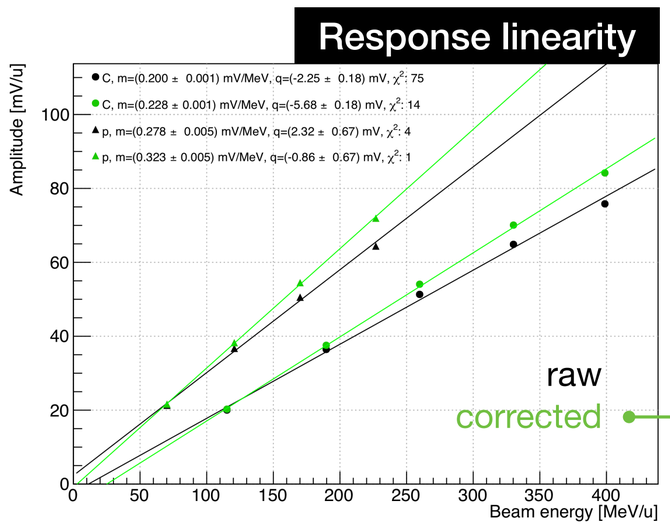
Calorimeter performance

A series of testbeam campaigns with **proton** and **carbon** beams carried out at CNAO *(Pavia, Italy)* to evaluate **energy resolution** + **response linearity** vs energy / temperature / range / particle type

Energy resolution



Response linearity



Temperature correction compensating for detector response variations *(T measured on SiPM)*

↳ no thermostat → **simple mechanical design**

Range correction compensating for dependence of the Bragg-peak position on atomic number and energy

↳ affects the photon's path length and the number of reflections before reaching the SiPM

Particle ID

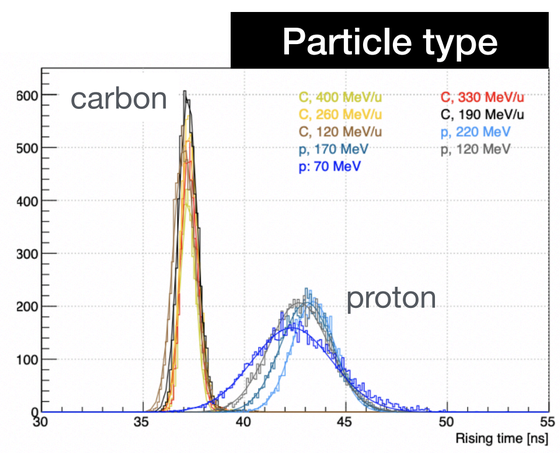
The **number of scintillation photons** detected by the SiPM is **not a direct representation** of the fragment's energy
↳ **type of the particle** needs to be identified for the **ultimate ADC → MeV conversion precision**

Pulse shape sensitive to the particle type and range

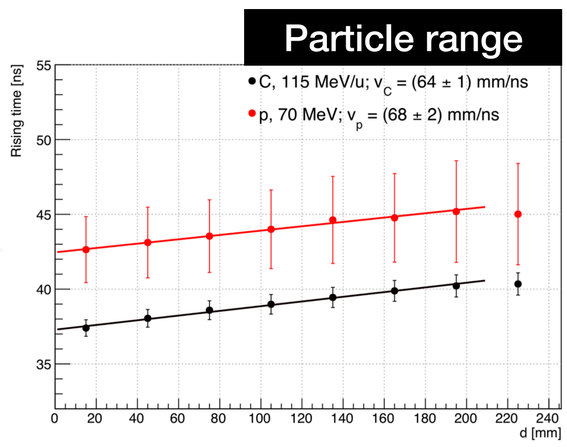
Extracted pulse parameters can be used in an iterative particle-reconsturction algorithm

$$A(t) = A_{max} \cdot \exp\left[k_s \cdot \ln^2\left(\frac{t - t_0}{t_r}\right)\right]$$

Particle type



Particle range



Longer optical paths of the photons increase the rising time of the SiPM pulse

To be combined with the **measured trajectory + p_T + TOF** for finding **the best hypothesis** of the particle type for correct energy reconstruction

Summary

1. **The target energy resolution** of 0.3-2.0% achieved by the BGO calorimeter with SiPM readout and offline temperature correction
2. **Particle type identification** simplifies the conversion of the measured number of photons to the actual energy in MeV
3. **Rising time of the SiPM pulse** provides sensitivity to the type and range of the particle necessary for energy reconstruction