FramentatiOn
Of Target

The FOOT experiment

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Wednesday 22-07-2020

Istituto Nazionale di Fisica Nucleare

Outline

- Introduction:
  - Particle therapy
  - Motivations of FOOT
- FOOT experiment:
  - Organization
  - Measurement strategy
  - Detector
  - Pisa contributions
- Results
- Outlook and conclusions

Cancer treatment

Surgery
Removal of cancer cells using surgery

Radiotherapy
Destruction of cancer cells using radiation

Chemotherapy
Destruction of cancer cells using drugs (anti-cancer agents)

Some numbers for Italy:

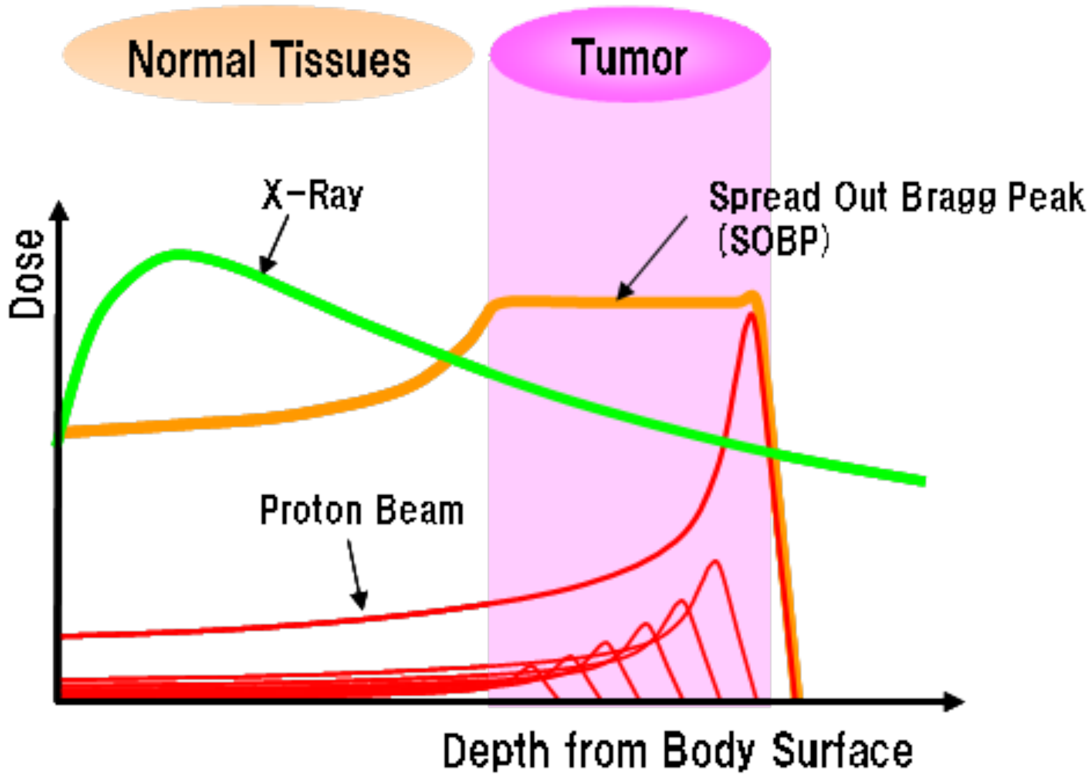
- 373.000 new cases/year
- 180.000 deaths/year
- More than half of all patients receive radiotherapy
- Small fraction of these receive particle therapy:
  - >3000 total nr of patients treated today
  - 3 centers (Catania, CNAO, Trento)

From: http://www.salute.gov.it

Particle therapy

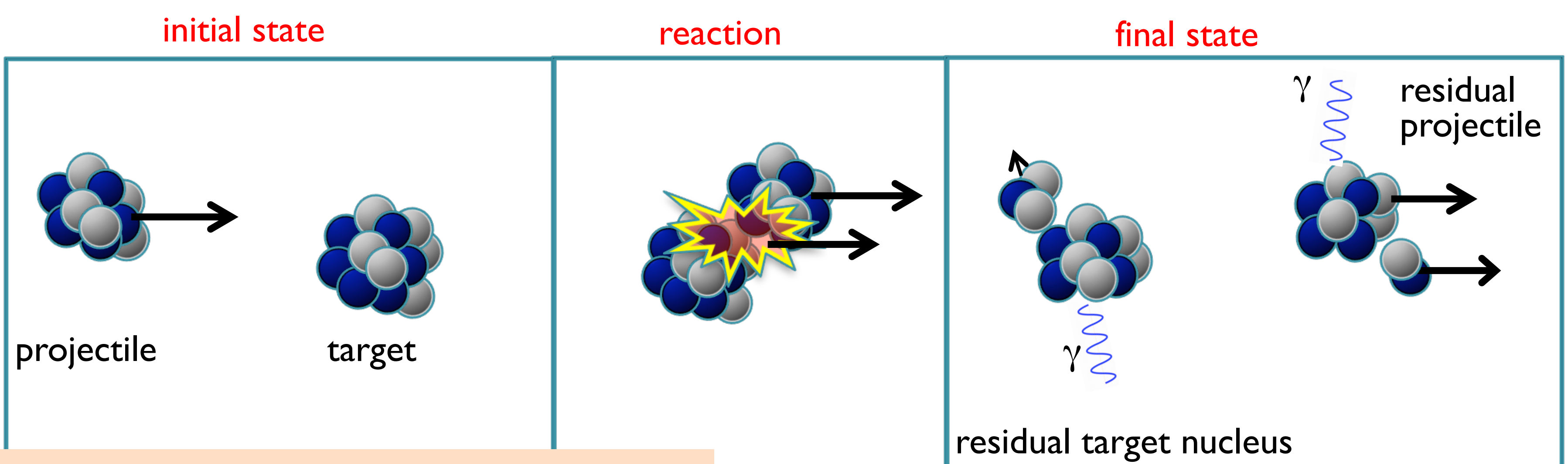
- Tumor treatment with p or ^{12}C beams
- Beam energy up to 250 MeV (p) or 400 MeV/u (^{12}C)
- Favorable dose profile (Bragg peak)

- Established treatment method
- Pencil beam technique: delivered dose results from combining thousands of ion beams



Uncertainties

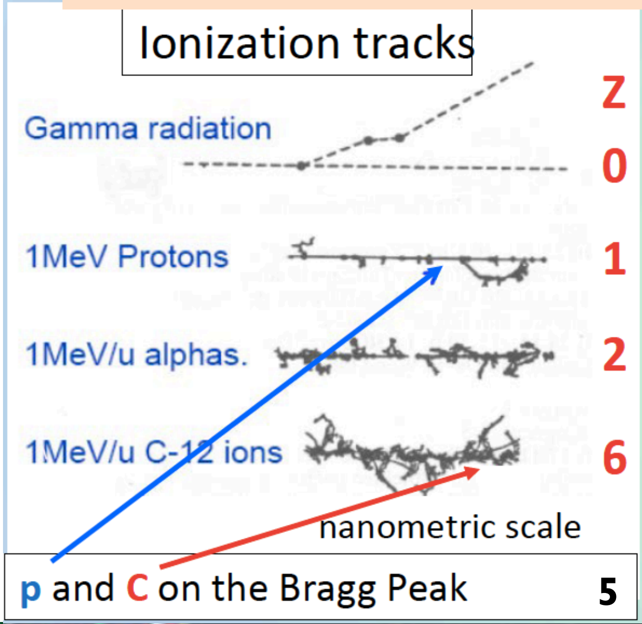
- Key of treatment accuracy is to predict and achieve a given dose in a patient
- Many uncertainties:
  - Patient 3-D knowledge
  - Setup uncertainties
  - Anatomical (tumor changes, movement, etc)
  - Effect of nuclear physics interactions in human body
    - Primary beam: beam attenuation (on average about 40% of carbon ions undergoes inelastic interaction) Durante, Paganetti: Rep. on Prog. Physics, 79 (9), 2016
    - Secondary particle production



From: A.Kraan, Frontiers in Oncology 2015

DNA damage

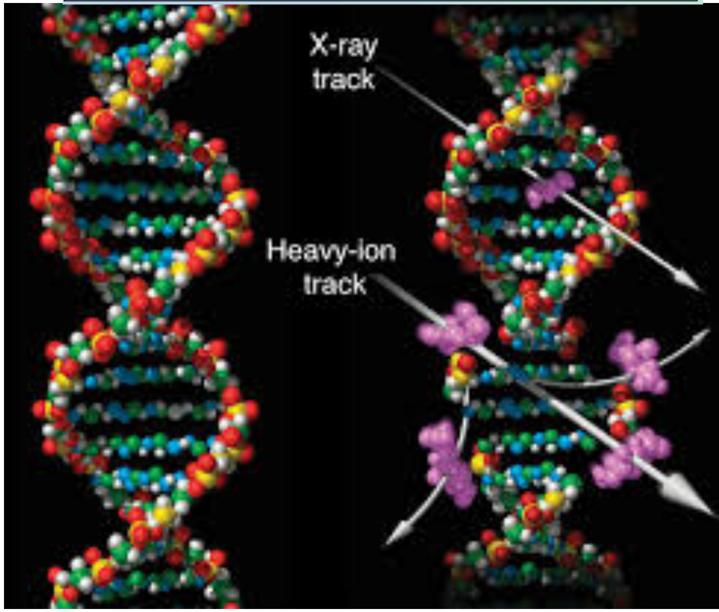
From R. Spighi, presentation EuNPC2018



- DNA damage is different in particle therapy compared to X-ray therapy, due to different density of ionization tracks
  - From primaries
  - From secondaries

  } "mixed field"
- Spatial distribution of ionizing events is defined by Linear Energy Transfer (keV/μm)
- Different ionization density (on DNA/cell scale), has different biological impact.
- Knowing the characteristics (Z, A, energy, angles, amounts) of secondary particles produced is important!!!

→**nuclear fragmentation cross sections!**

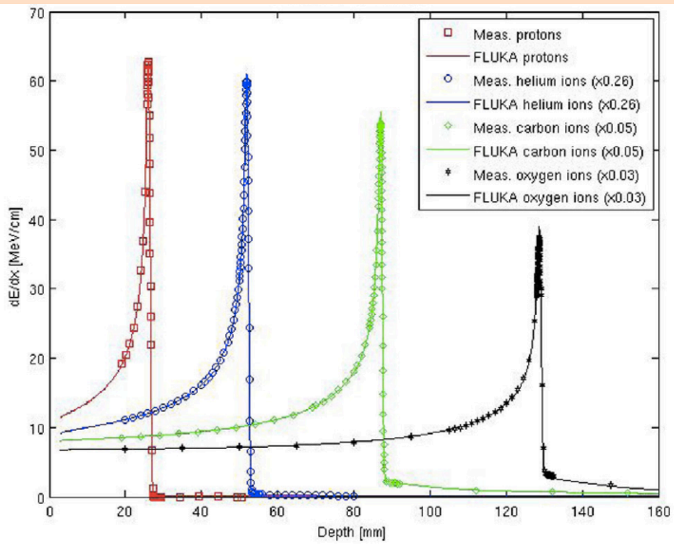


What do we still need to know today?

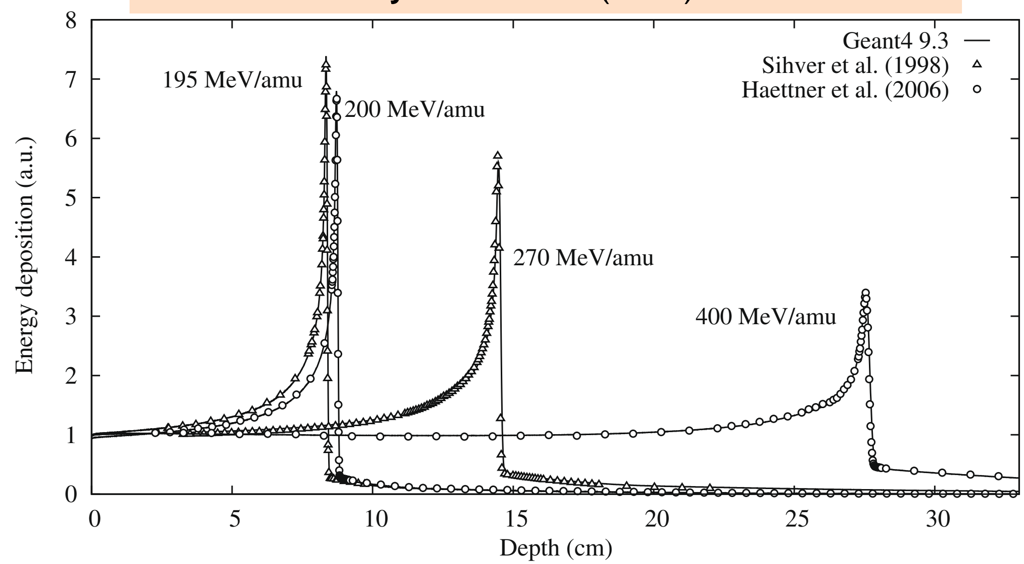
Are current nuclear physics models good enough?

- Yes, for physical dose they are good enough
  - If cross sections were totally wrong, fluence prediction and thus dose profiles would not be agreeing so nicely
  - Perfect depth-dose curves can be predicted!

G. Battistoni et. al., Frontiers in Oncology 2016



A. Lechner et. aJ, NIM. B 268 (2010) 2343–2354



What do we still need to know today?

Are current nuclear fragmentation models good enough?

- No, predictions of biological dose ("RBE-weighted" dose) are not fully satisfactory
  - This is the quantity of clinical interest!

$$RBE = \frac{D_X}{D_R}$$

ref

particle

RBE= complex function depending on many parameters

Physical: irradiation type, energy, LET, dose, …

Chemical: e.g. oxygen concentration

Biological: radio sensitivity of tissue, cell cycle phase, ...

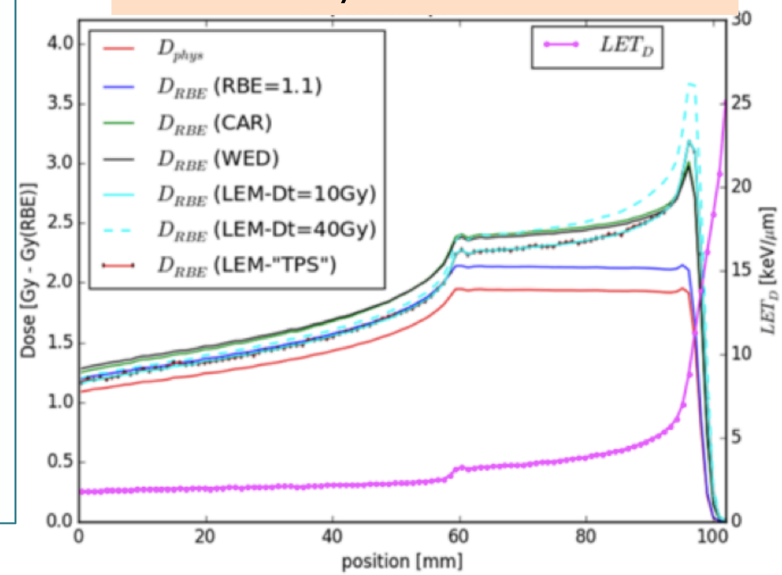
Multi-disciplinary

Multi-scale problem

0.1 nm

cm

Chaudhary et al.,(2014) Int J. Radiation Oncol Biol Phys, 90:27-35

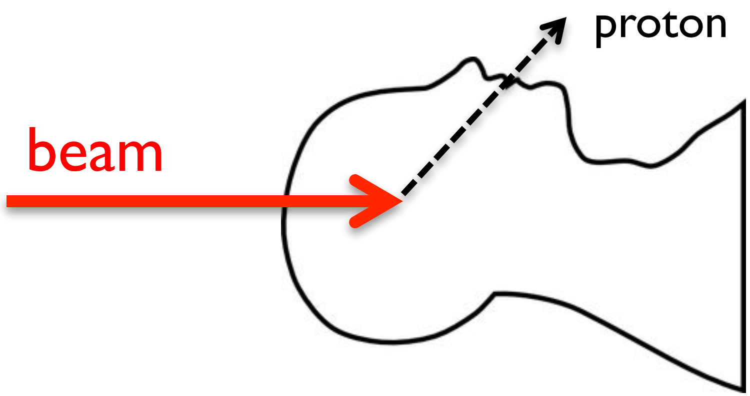


Nuclear fragmentation cross sections improve accuracy of RBE estimate

What do we still need to know today?

Are current nuclear fragmentation models good enough?

- No, still many uncertainties in range monitoring



- Correlation between reconstructed emission point and beam profile
- MC models unreliable at large angles, missing data
- See for instance:

K. Gwosch et. al, Phys. Med. Biol. 58 (2013) 3755–3773

Agodi C, et al flux. Phys. Med. Biol. 57 (2012)5667.

A. Rucinski . Med. Biol.63(2018) 055018.

Nuclear fragmentation cross sections improve accuracy of range monitoring

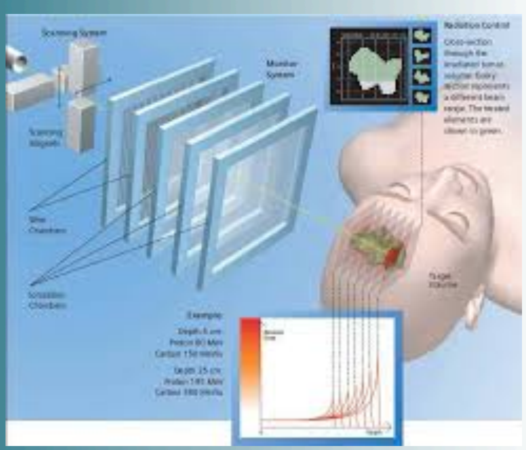
What do we still need to know today?

A limited amount of total nuclear interaction cross section measurements is available for tissue-like targets (100 < E< 800 MeV/u)

- Mostly 'old' measurements with large uncertainties
- In therapeutic energy range (<400 MeV/u), very few single or double differential cross section measurements on thin targets (only ^{12}C)
  - Helium and Oxygen not available at all
- Not enough to tune MC models needed to estimate physical (and biological) impact

Need new fragmentation measurements!!

Particle therapy



- RBE calculations
- Range monitoring methods

Radiation protection in space

- Shielding materials
- Dose calculations

The FOOT collaboration

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FOOT approved by the INFN on September 2017 (CSN3)

- Italy: 10 INFN sections/labs, CNAO
  - Pisa since 2017
- Germany: GSI, Aachen University
- France: IPHC Strasbourg
- Japan: Nagoya University
- ~90 researchers 34 FTE, tecnologi 1.5 FTE

Fixed target experiment, physics program:

- Hadrontherapy:
  - Nuclear fragmentation @ 200 - 400 MeV/u
- Radioprotection in Space:
  - Nuclear fragmentation @ 700 MeV/u

Web site: https://web.infn.it/f00t/index.php/en/

The FOOT collaboration

FOOT at INFN Pisa

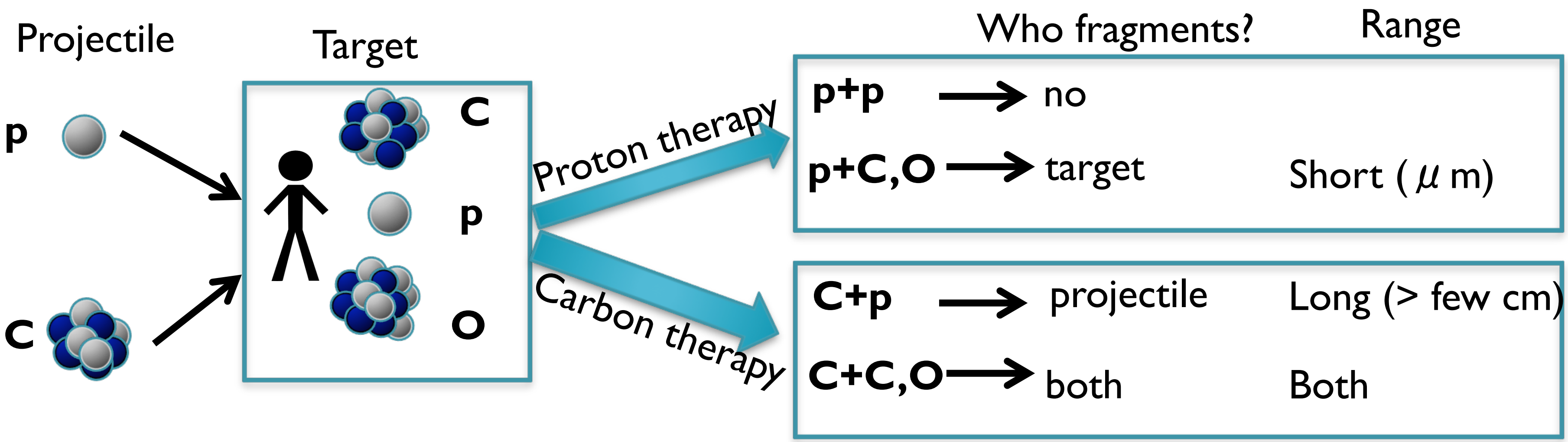
INFN:
- 2 researchers:
  - L Galli
  - A.Kraan
- 2 tecnologi:
  - M. Massa
  - A. Moggi
- Borsista:
  - R. Zarrella

University:
- staff members
  - N. Belcari
  - G. M. Bisogni
  - M. Morrocchi
  - V. Rosso
  - G. Sportelli
- PhD candidate:
  - Carra Pietro
- Postdoc
  - E. Ciarrocchi
  - M. Francesconi

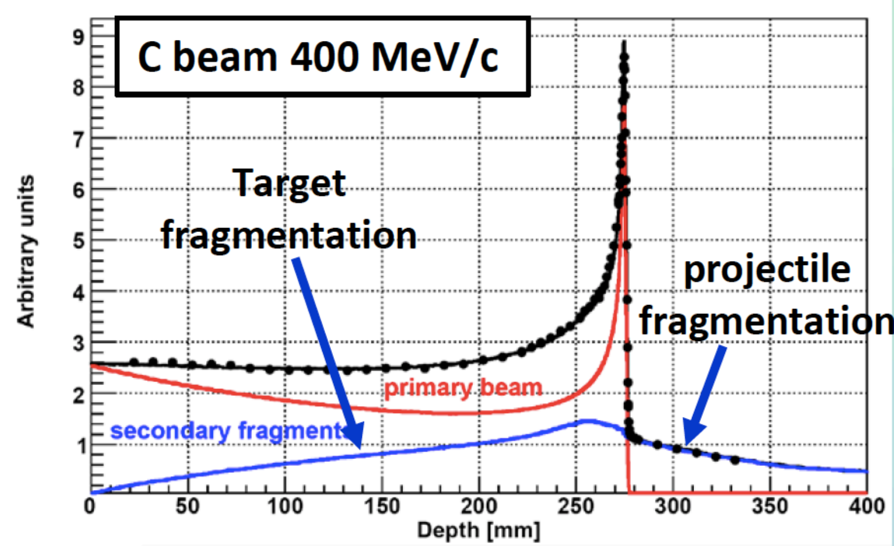
Responsabile locale e CNS 3: Giuseppina Bisogni

2020: FTE: 4.7

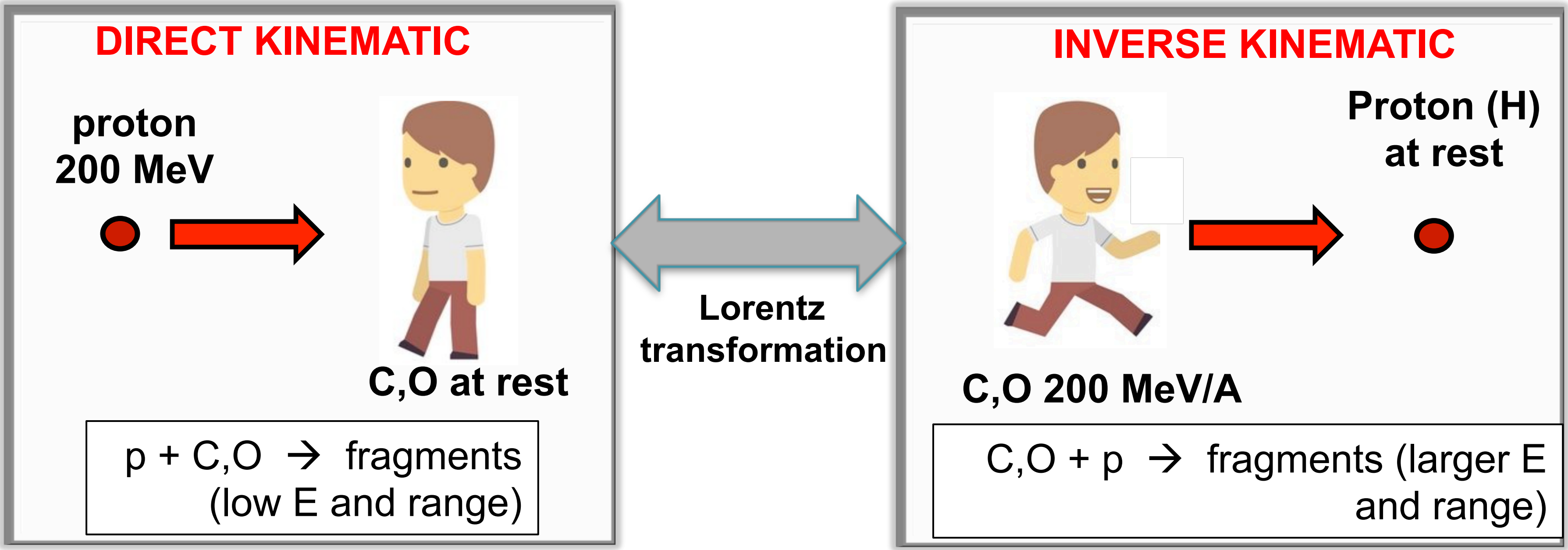
How to measure the fragmentation spectrum?



- Long range fragments can be measured directly
- But how to measure short range fragments?
  - Difficult to directly detect them, would need very thin target
  - Such a very thin target produces very few events (+background).
  - Other techniques: difficult/expensive



Inverse kinematics approach



Target can be as thick as a few mm (range of fragments is or order ~ few cm)

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

Webber et al, Phys Rev C (1990) 41(2); 520
Dudouet et al, Phys Rev C (2013) 88(2):064615

FOOT physics program

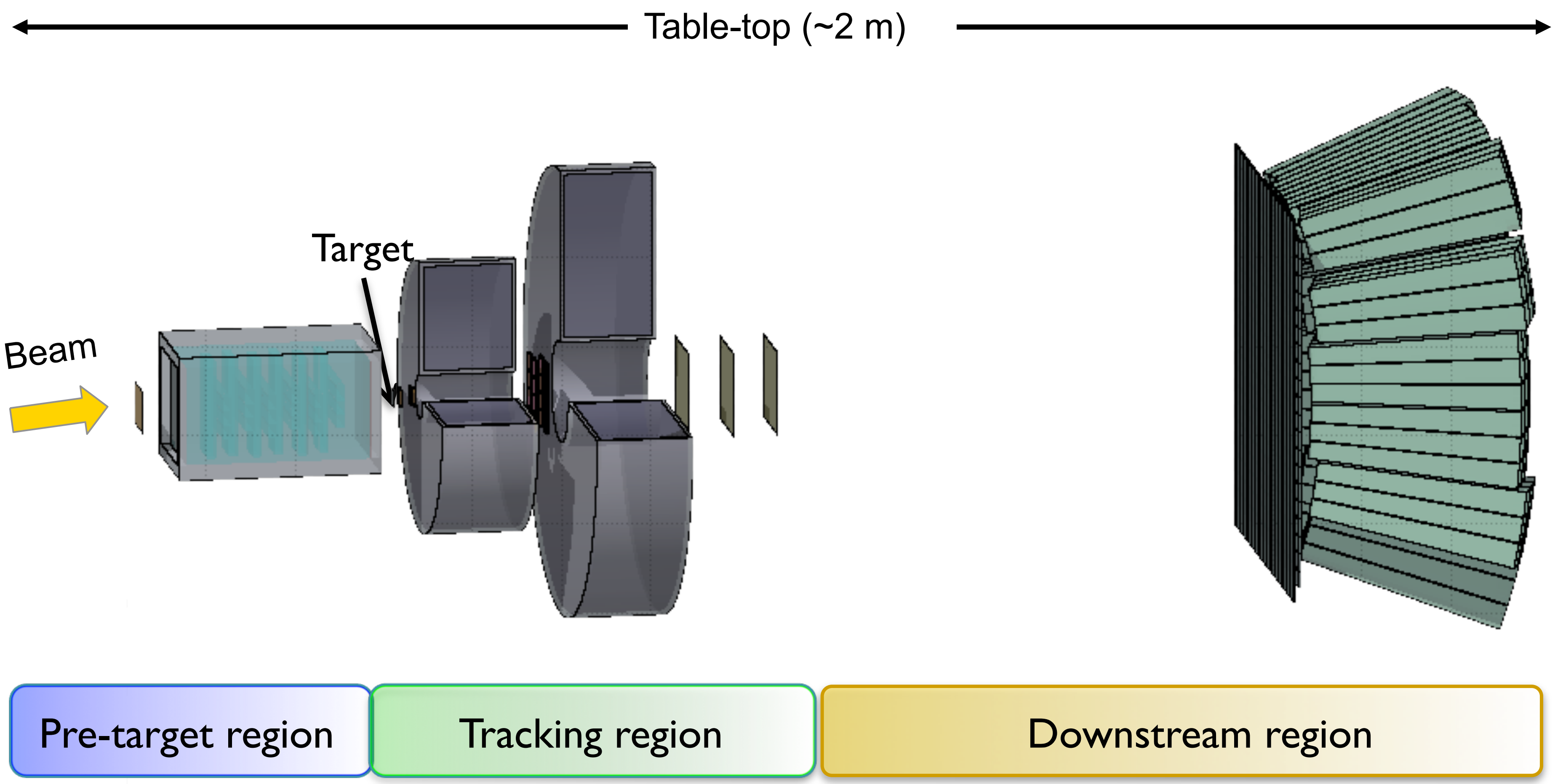
Physics	Application field	Beam	Target	Upper Energy (MeV/nucleon)	Kinematic approach	Goal interaction process
Target fragmentation	PT	^{12}C	C,C_2H_4	200	inverse	p+C
Target fragmentation	PT	^{16}O	C,C_2H_4	200	inverse	p+C
Beam fragmentation	PT	^{4}He	C, C_2H_4, PMMA	250	direct	α+C, α+H, α+O
Beam fragmentation	PT	^{12}C	C, C_2H_4, PMMA	400	direct	C+C, C+H, C+O
Beam fragmentation	PT	^{16}O	C, C_2H_4, PMMA	500	direct	O+C, O+H, O+O
Beam fragmentation	Space	^{4}He	C, C_2H_4, PMMA	800	direct	α+C, α+H, α+O
Beam fragmentation	Space	^{12}C	C, C_2H_4, PMMA	800	direct	C+C, C+H, C+O
Beam fragmentation	Space	^{16}O	C, C_2H_4, PMMA	800	direct	O+C, O+H, O+O

From: G. Battistoni, M. Toppi, et. al., submitted paper ,

Design constraints

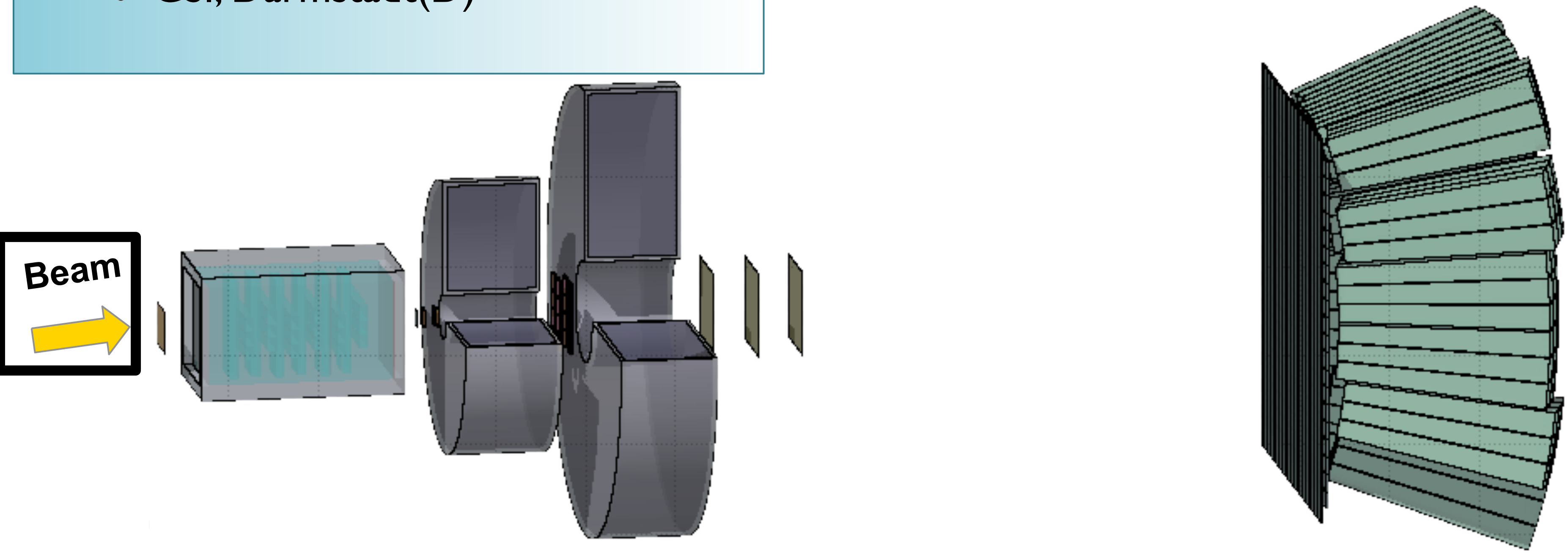
- Required accuracy from PT
  - Accuracy on $d\sigma/dEk_{in}$ better than 10%
  - Accuracy on $d\sigma/(dEk_{in}d\Omega)$ better than 5%
  - Charge Z identification 3%
  - Mass A identification 5%
- Movable, compact (should fit in experimental rooms of centers where these beams are available)
- 2 different setups:
  - 'electronic' setup (Z>2, up to 10°)
  - emulsions (small Z, up to 70°)

The FOOT detector



The FOOT detector

- Protons, Helium, Carbon. Oxygen
- Test at
  - CNAO, Pavia (IT)
  - HIT, Heidelberg (D)
  - GSI, Darmstadt(D)

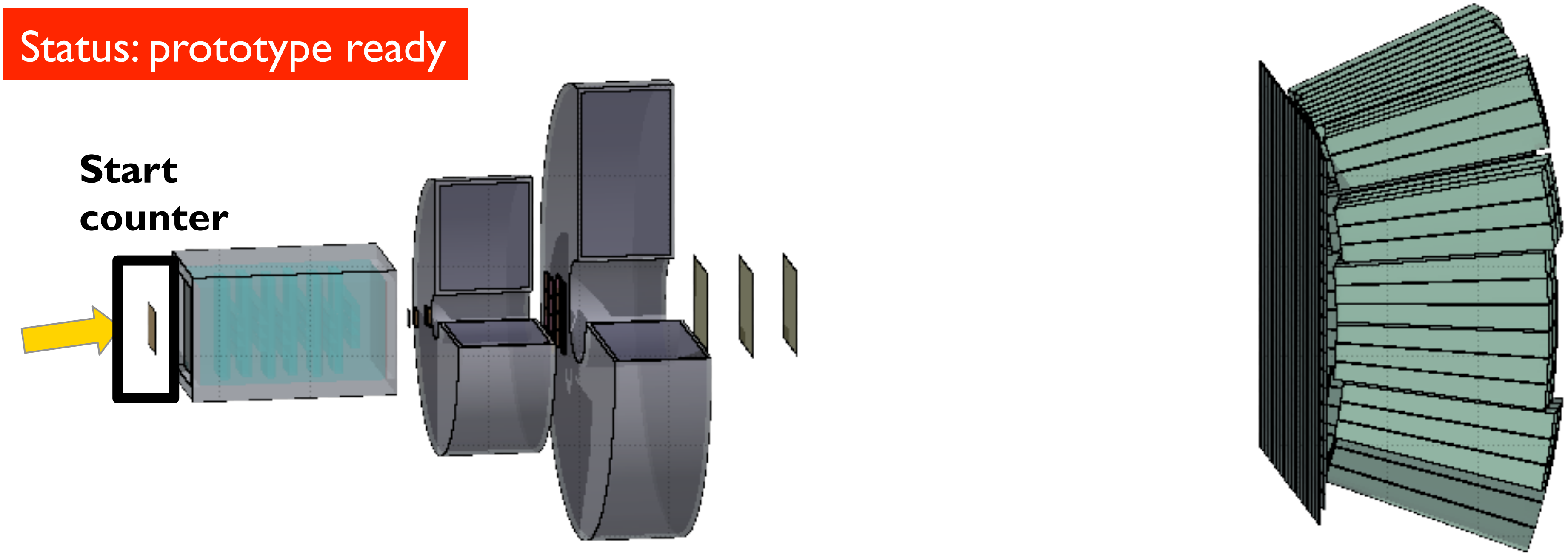


Pre-target region | Tracking region | Downstream region

The FOOT detector

- Very thin (250 μm) plastic scintillator
- Beam **counter**
- Trigger and first time stamp of Time-Of-Flight (**TOF**)

Status: prototype ready

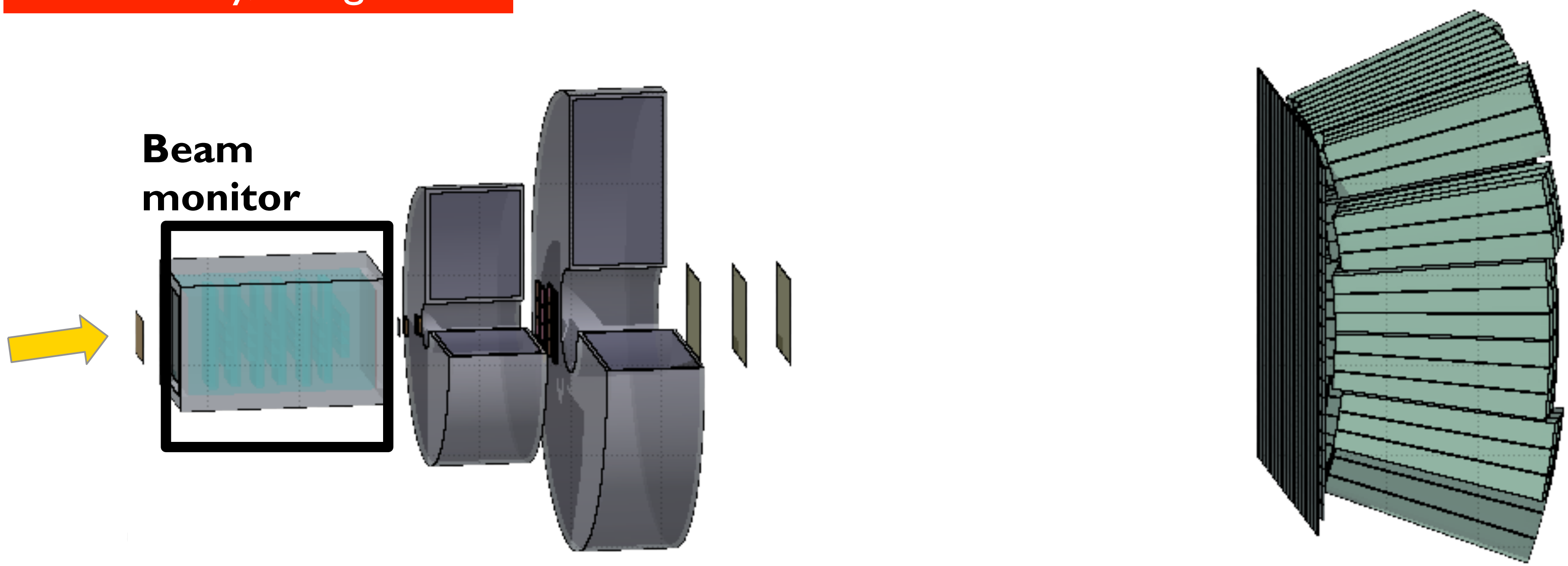


Pre-target region | Tracking region | Downstream region

The FOOT detector

- Drift chamber, from FIRST experiment
- **Position and direction** of particles

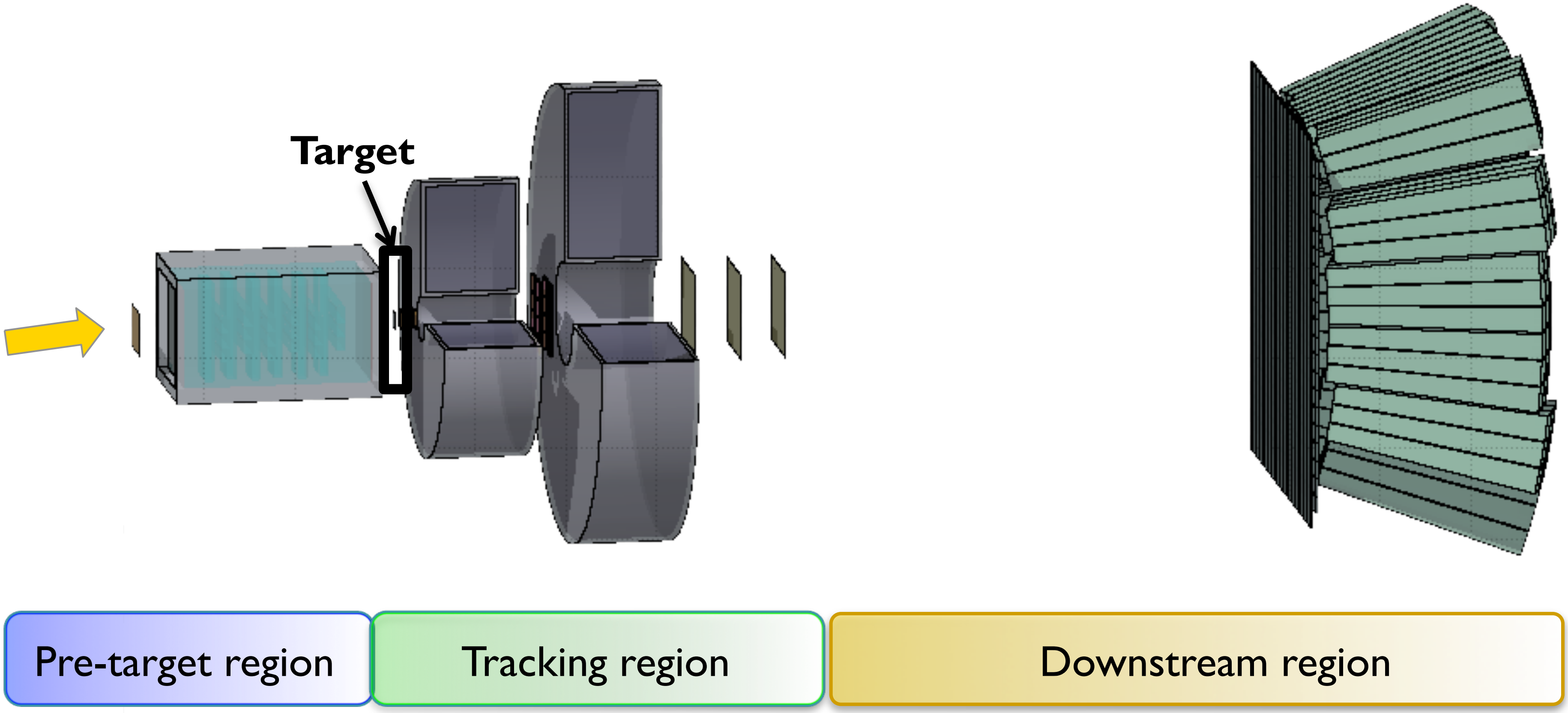
Status: ready, being tested



Pre-target region | Tracking region | Downstream region

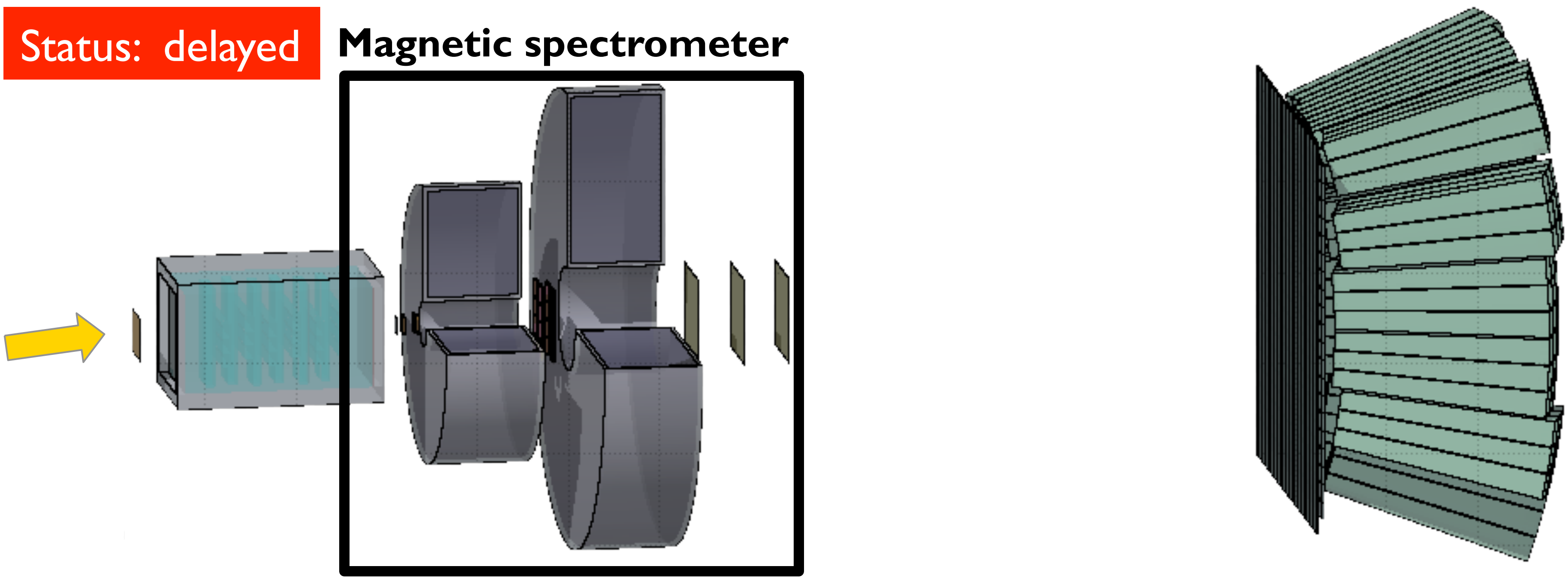
The FOOT detector

- Polyethylene (C_2H_4), graphite (C) target
- 2-5 mm thick



The FOOT detector

- 3 silicon trackers alternated to 2 magnets 0.9 and 1.4 T
- **Momentum** of the fragments and the **dE/dx** in the last silicon station



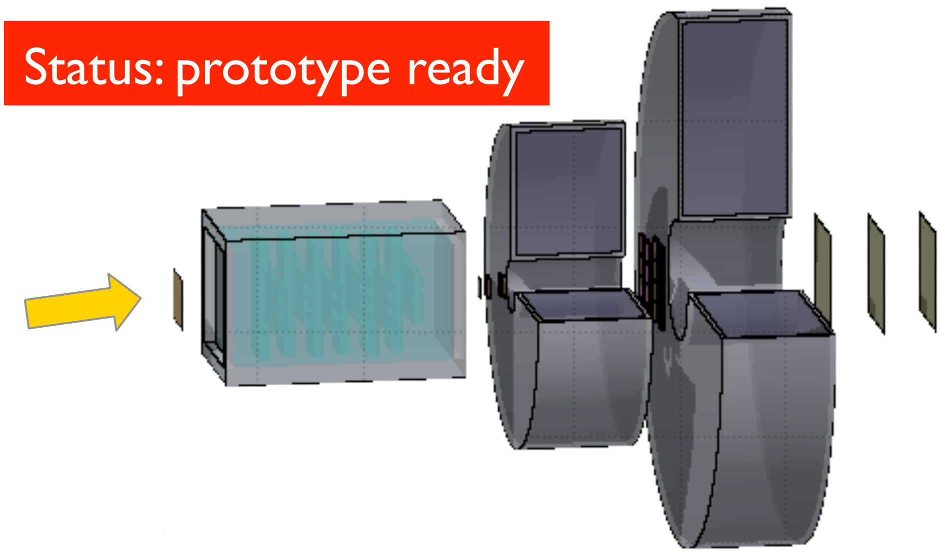
Pre-target region | Tracking region | Downstream region

The FOOT detector

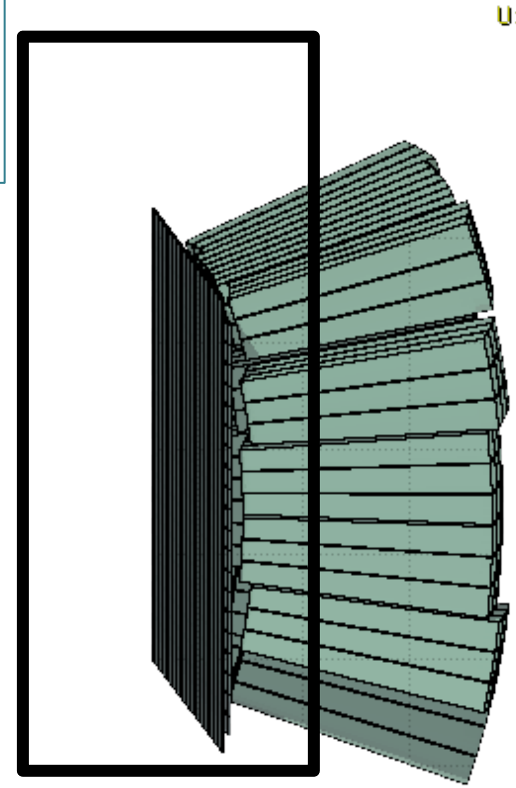
INFN and university of Pisa

- TOF-Wall: thin (3 mm) plastic scintillator bars
- 2 orthogonal layers of bars: 20+20 bars
- TOF Wall measures:
  - **Energy deposited** in the scintillator (ΔE)
  - **Second time stamp for TOF**

Status: prototype ready



TOF Wall

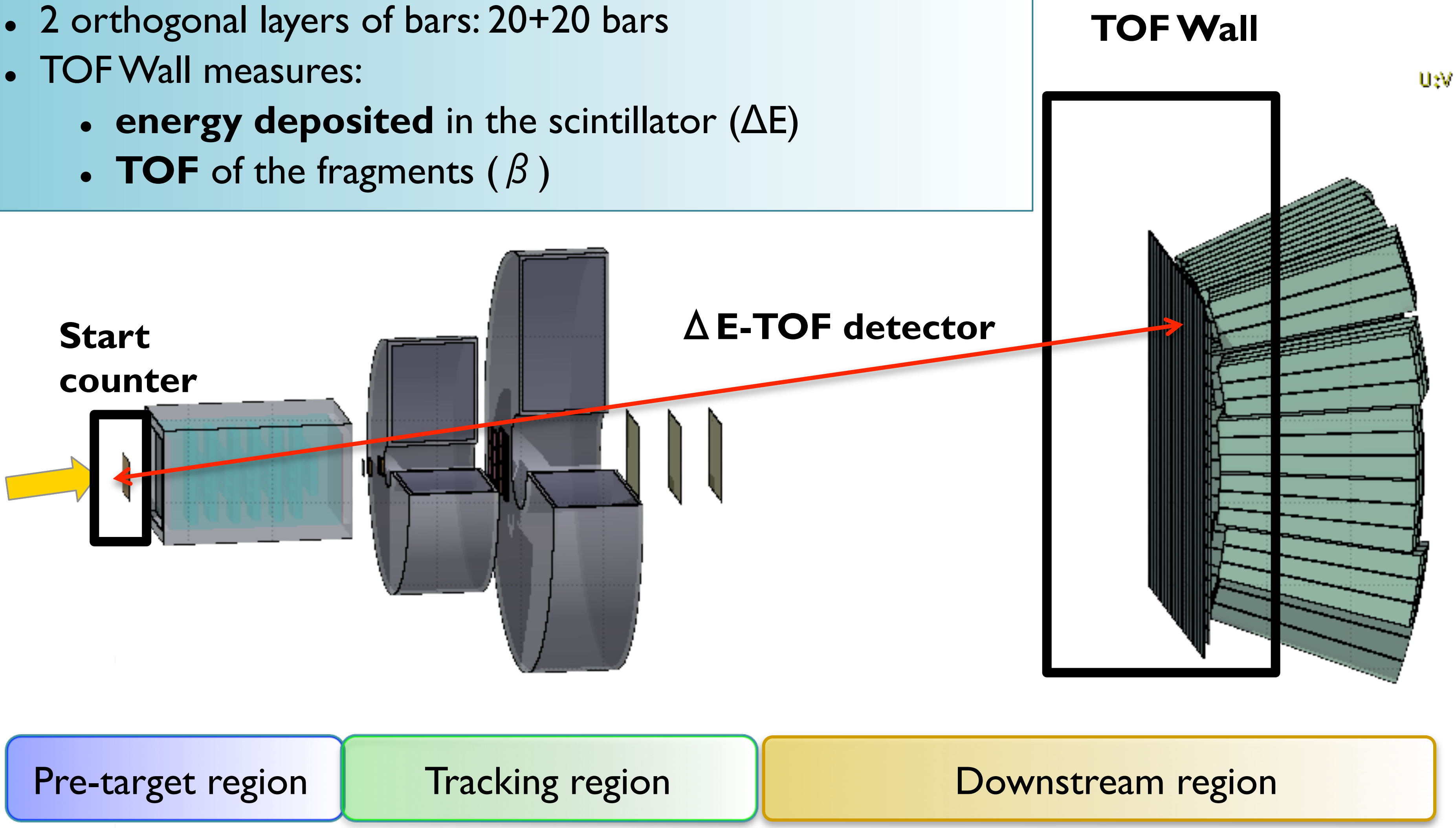


Pre-target region | Tracking region | Downstream region

The FOOT detector

INFN and university of Pisa

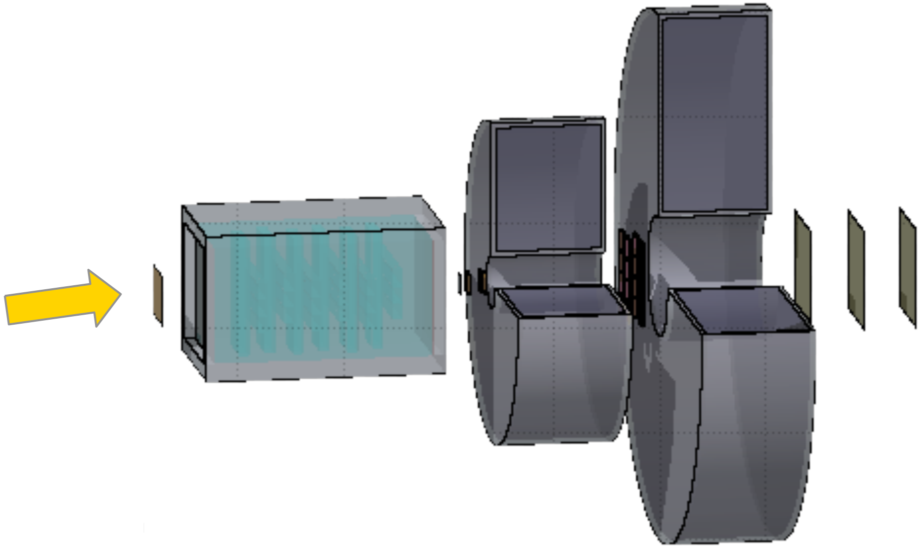
- TOF-Wall: thin (3 mm) plastic scintillator bars
- 2 orthogonal layers of bars: 20+20 bars
- TOF Wall measures:
  - **energy deposited** in the scintillator (ΔE)
  - **TOF** of the fragments (β)



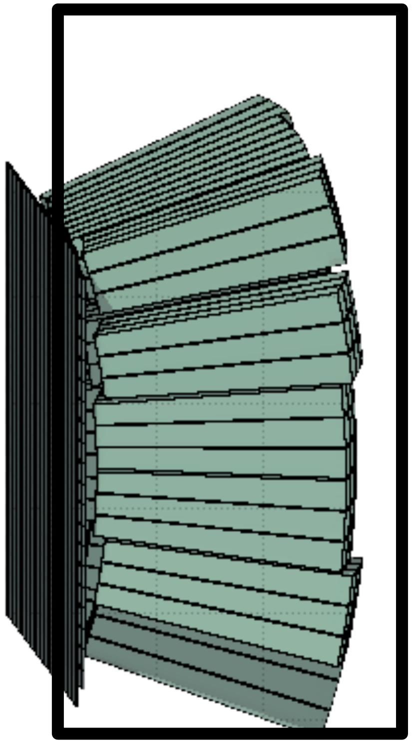
The FOOT detector

- Thick BGO crystal
- **Kinetic energy** of the fragments

Status: first module ready and being tested



calorimeter



Pre-target region | Tracking region | Downstream region

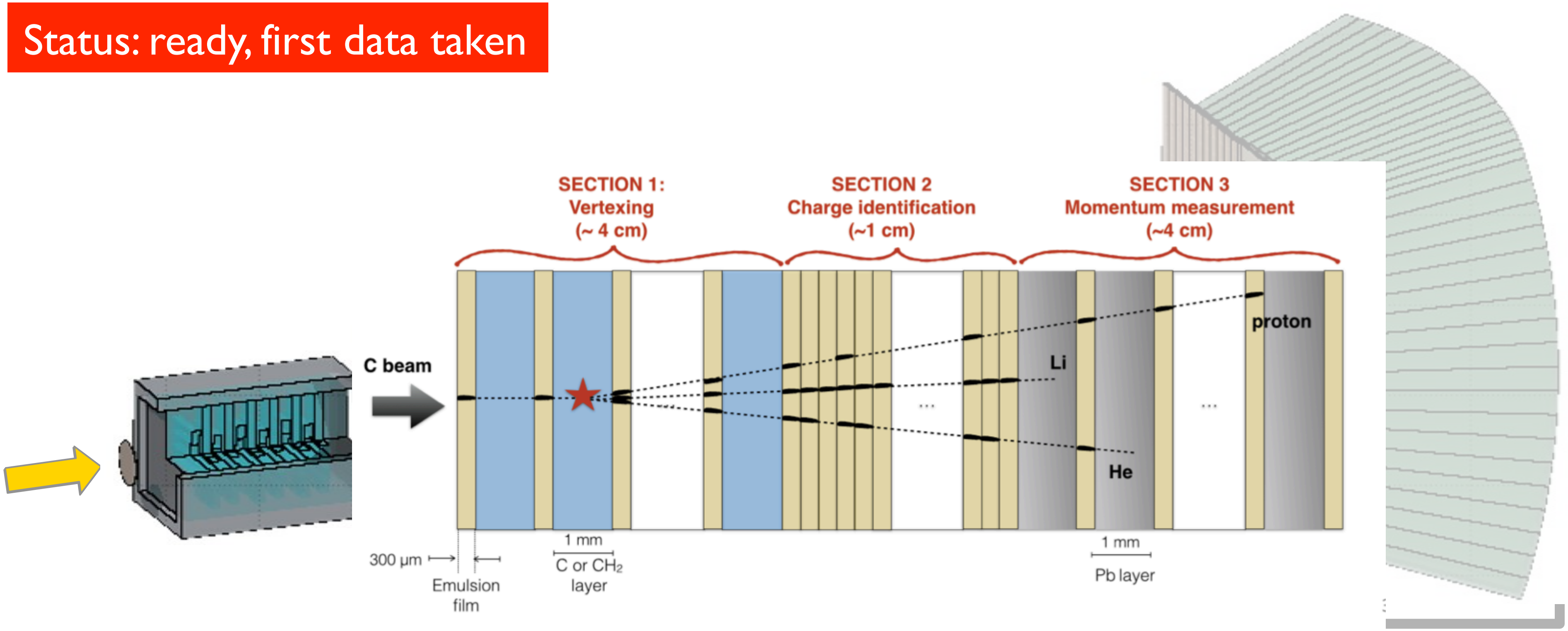
The FOOT detector

Emulsion chamber setup

- Lighter fragments (**Z <= 3**) have wider angular aperture

calorimeter

Status: ready, first data taken

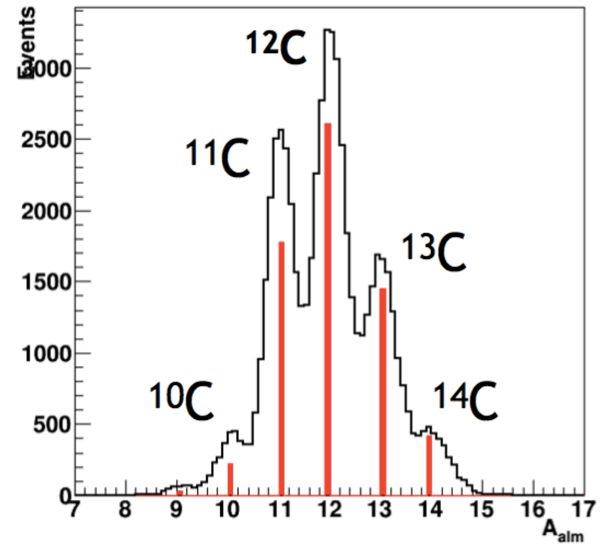


Pre-target region

Fragment identification strategy

- **Charge Z** reconstruction → from delta E and TOF (see next!)
- p/Z from particle tracking in magnetic field
- Velocity β from path L of particle

- **Mass A** reconstruction: 3 ways
  - TOF & Tracker: $p = mc\beta\gamma$
  - TOF & Calorimeter: $E_{\mathrm{kin}} = mc^2(\gamma - 1)$
  - Tracker & Calorimeter $E_{\mathrm{kin}} = \sqrt{p^2c^2 + m^2c^4} - mc^2$



- **Required accuracy:**
  - σ (p)/p ~ 4-5%
  - σ (Ekin)/Ekin ~ 1-2%
  - **σ (TOF)** ~ 100 ps
  - **σ (Δ E)/ Δ E ~ 5%**

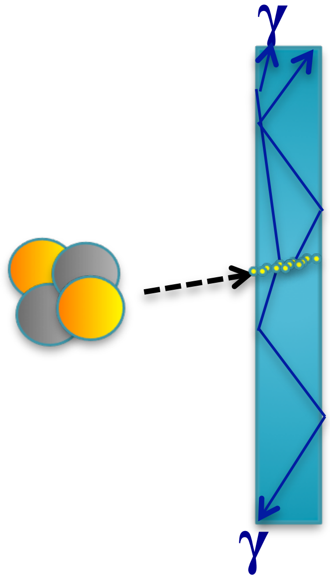
Pisa

Δ E-TOF detector

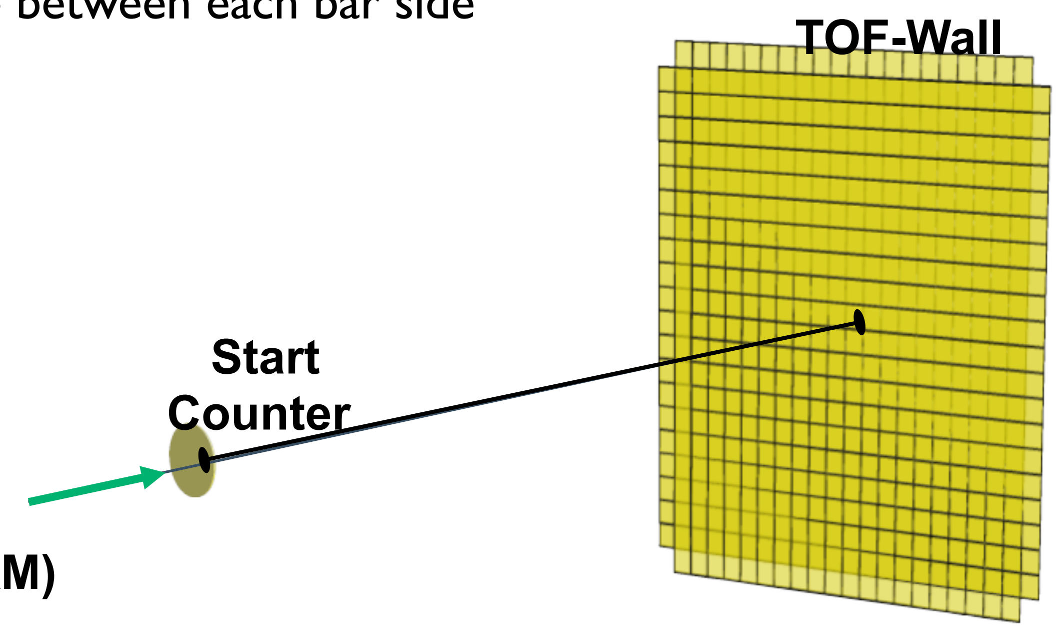
INFN and university of Pisa

Δ E-TOF detector provides:

- **Time-of-flight → β**
  - First time stamp from Start Counter (scintillator)
  - Second time stamp from **TOF-Wall (TW) (scintillator)**
- Deposited energy **Δ E** of fragment in **TW**
- Position of deposit:
  - In 2D by orthogonal arrangement
  - From difference in arrival time between each bar side



Charge Z discrimination (Bethe Bloch)



∆ E-TOF detector

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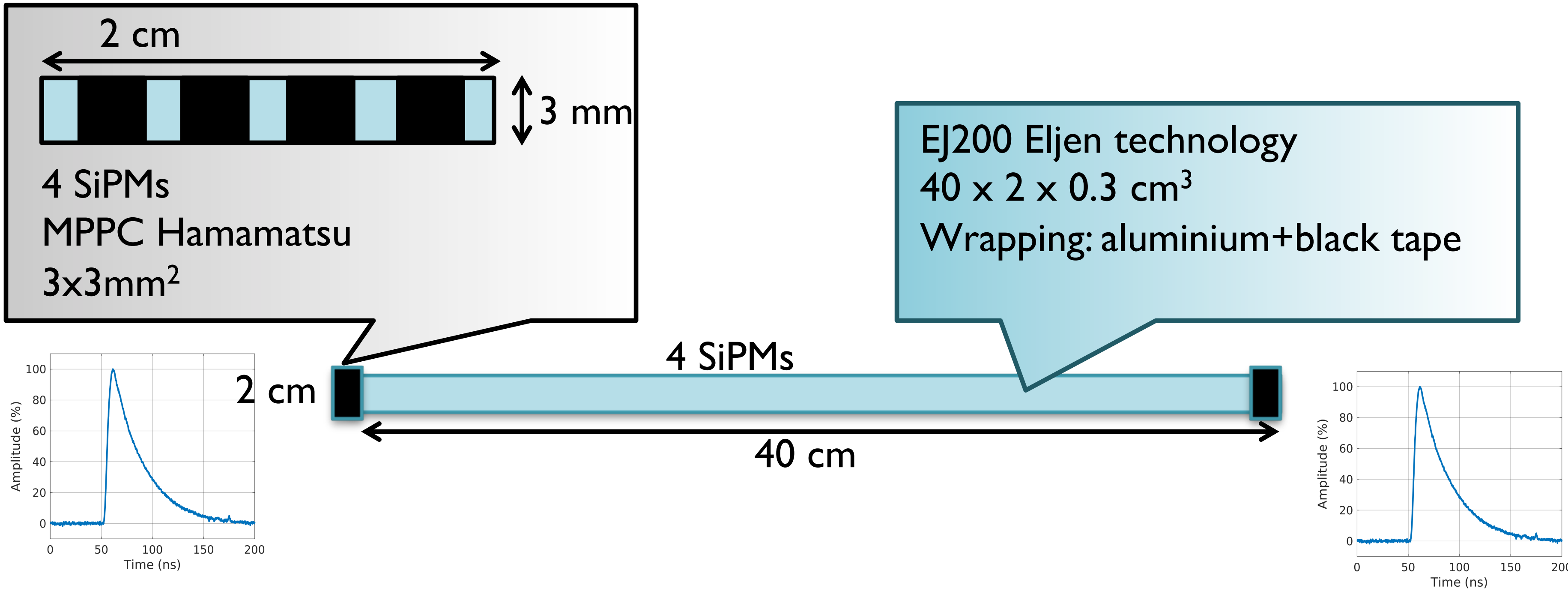
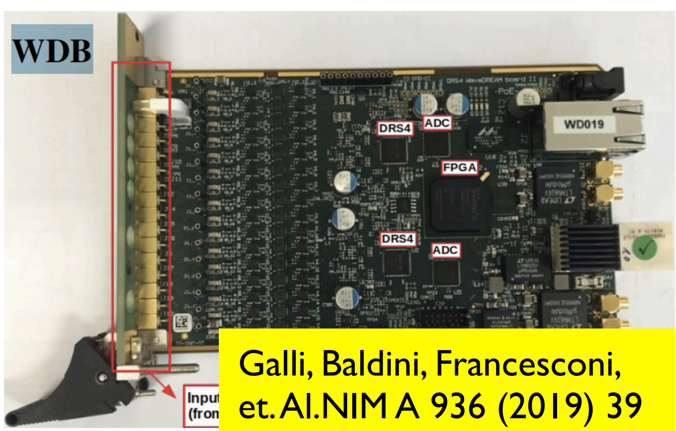


- DAQ system (WaveDAQ) developed at PSI (MEG)
- Collaboration PSI-INFN → fundamental contribution!
    - Based on DRS-ASIC (Stefan Ritt)
    - Channels from each bar connected to custom board WaveDREAM (WDB)
- Connected to trigger board
- Each channel: waveform → time stamp and energy



Galli, Baldini, Francesconi, et. Al. NIM A 936 (2019) 39

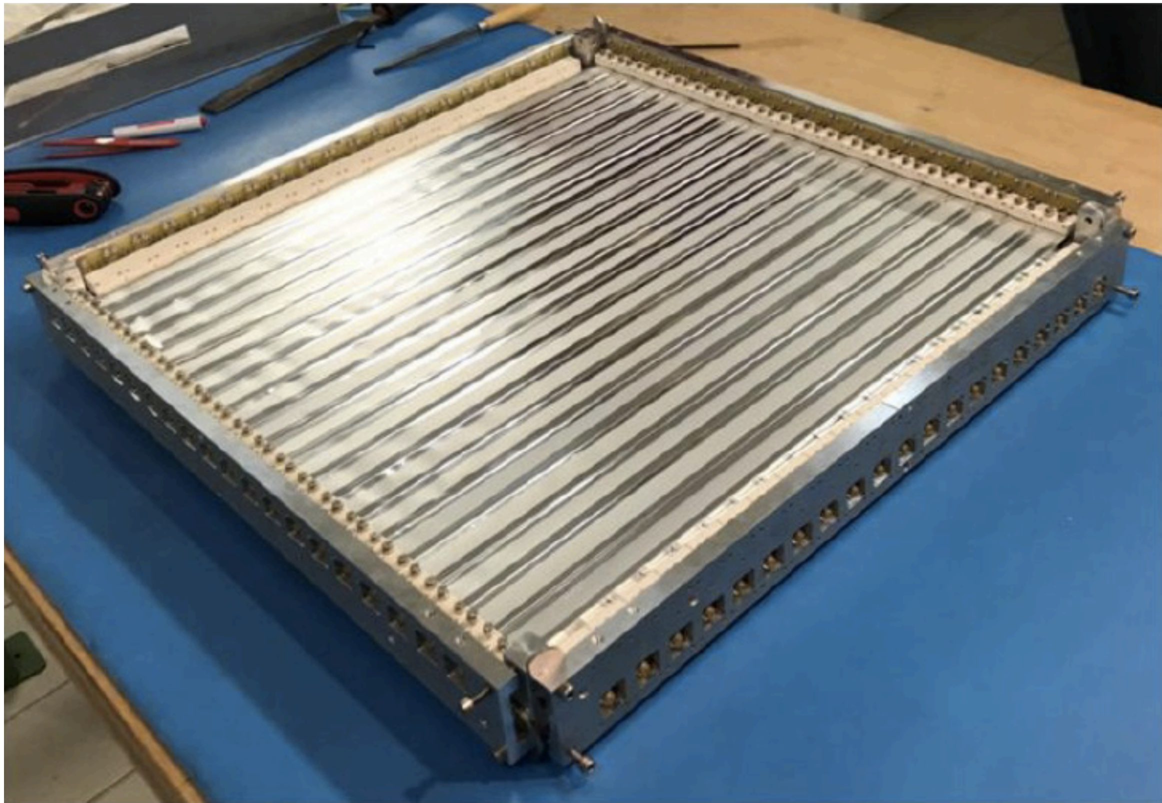
Δ E-TOF detector

INFN and university of Pisa

M. Morrocchi et al. NIM A 916, 2019.
E. Ciarriocchi et al. NIM A 936, 2019
Galli. et. al. NIM A 953, 2019
Kraan et.al. NIM A 958, 2019
2 paper to be submitted

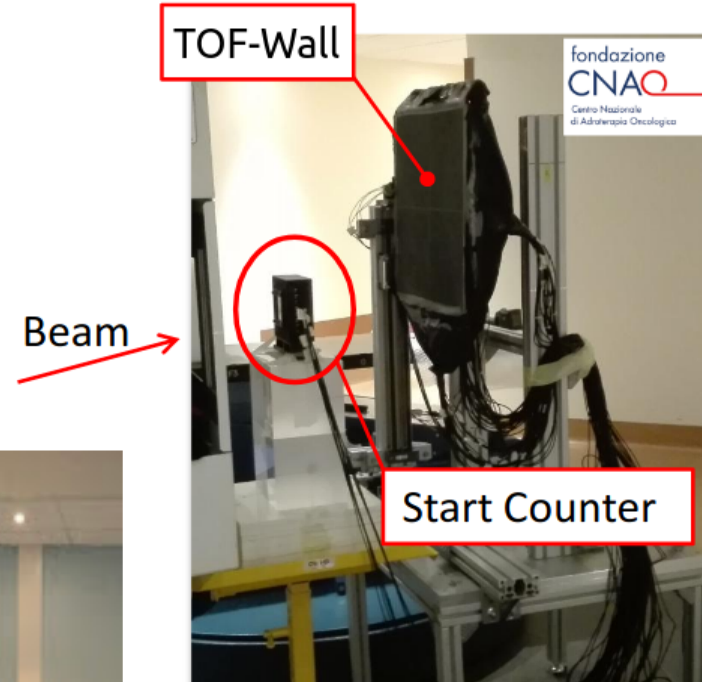
- **2017**: First design and tests
- **2018**: Single bars tested with particle beams at CNAO
  - Performance in energy resolution and time resolution
- **2019**: Full prototype system constructed
  - 40 bars ($44x2x0.3 \text{ cm}^3$) of plastic scintillator divided in 2 orthogonal layers
  - Total active area $40x40 \text{ cm}^2$
  - Tested with start counter
    - CNAO
    - GSI
- **2020**:
  - Design of second prototype
  - Analysis of performance at CNAO and GSI!

→ **Some first results**



Test beam at CNAO

First full prototype for the first time tested at CNAO (March 2019) to calibrate TOF and energy (MC)



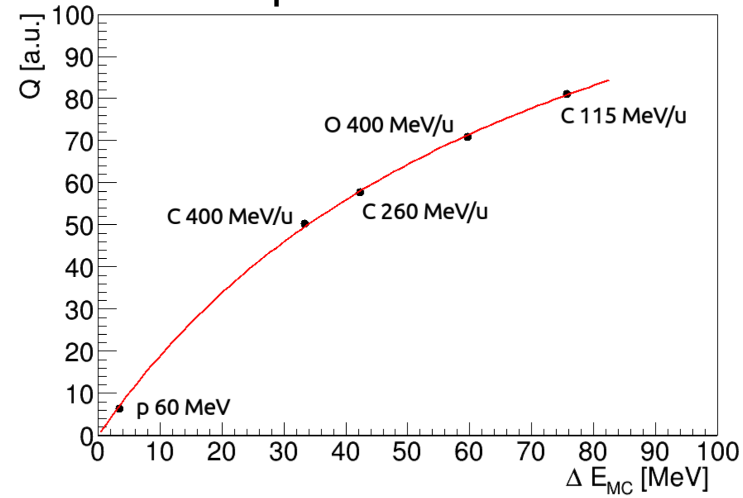
fondazione
CNAO

Test beam at CNAO

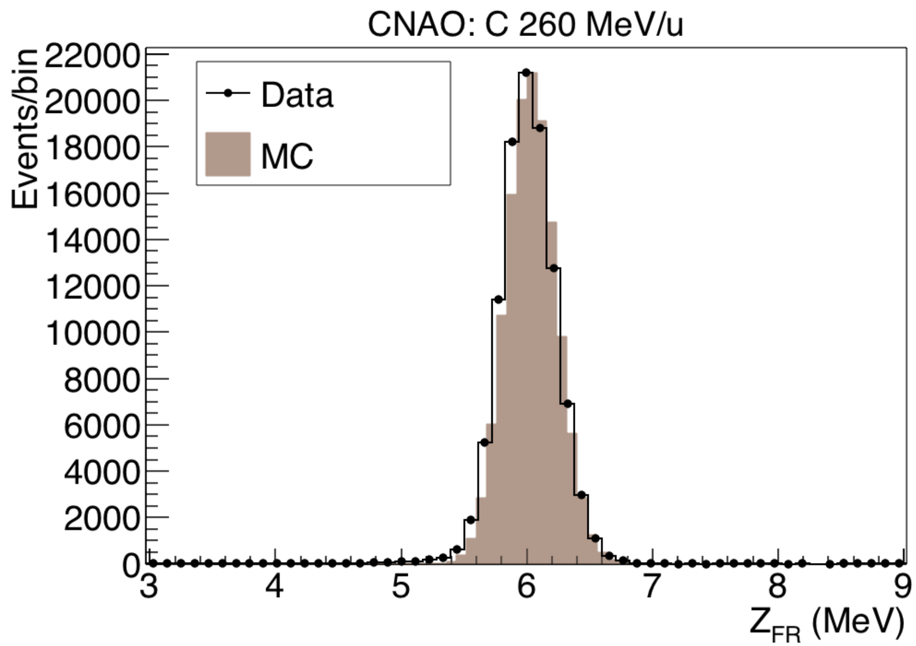
INFN and university of Pisa

- Beams:
  - Protons (60 MeV/u)
  - Carbon ions (115, 260, 400 MeV/u)
- Energy calibration: detector response is not linear → calibrate response with different particles of different energy
- Calibrate TOF
- Reconstruct Z

Example of calibration curve



- Energy resolutions σ(ΔE)/ΔE:
  - 4.0% to 4.7% for carbon
  - 5.3% for protons
- TOF resolutions σ(TOF)
  - 54 ps to 73 ps for carbon
  - 264 ps for protons
- Z resolutions:
  - 0.15 to 0.24 for Carbon: **~2.5 to 4%**
  - 0.06 for protons: ~6%



Test beam at CNAO

INFN and university of Pisa

- Beams:
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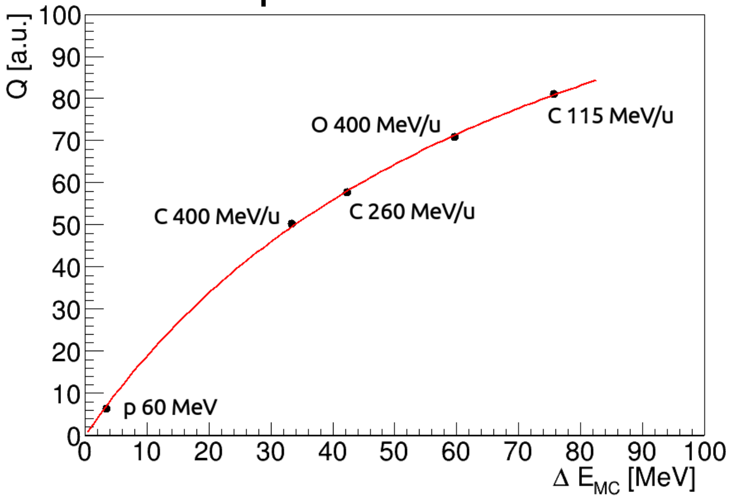
Example of calibration curve



- Energy resolutions σ(ΔE)/ΔE: ✔
  - 4.0% to 4.7% for carbon
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  - 54 ps to 73 ps for carbon
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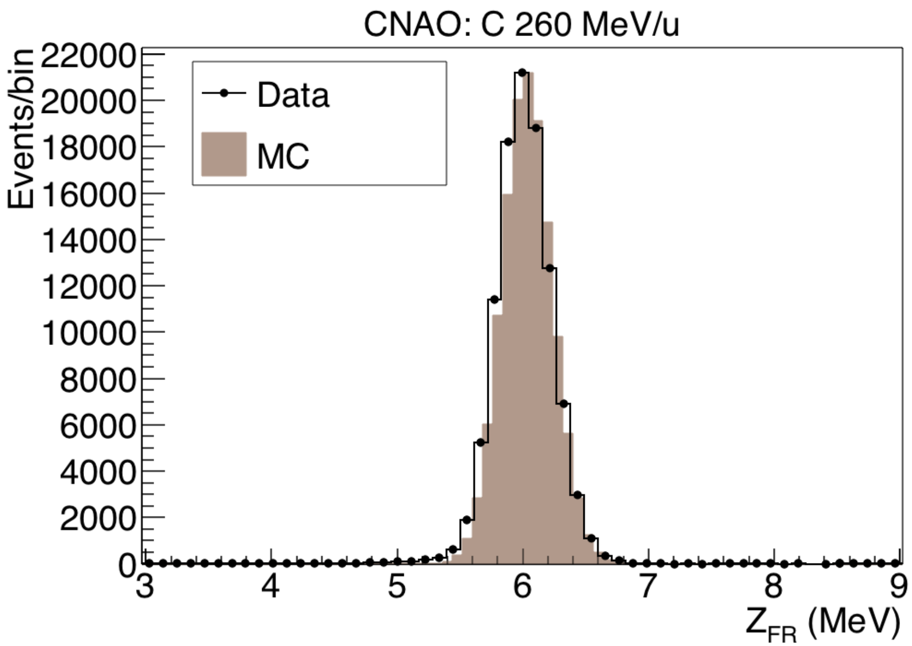
- Z resolutions: ✔
  - 0.15 to 0.24 for Carbon: **~2.5 to 4%**
  - 0.06 for protons: ~6%

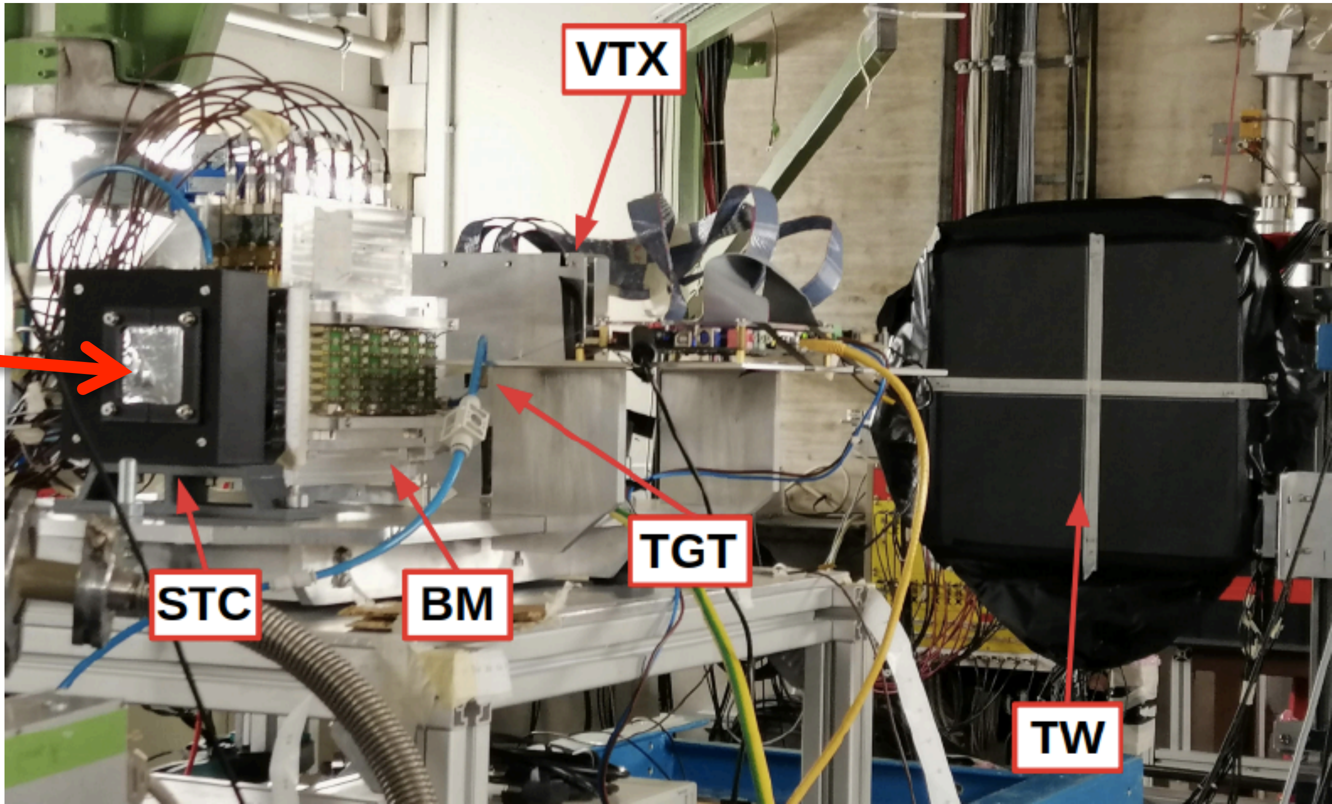


Test beam at GSI

Full prototype plus other detectors of FOOT for the first time tested together at GSI (April 2019) to test them with DAQ system

- Beams:
  - Oxygen (400 MeV/u)
- Setup:
  - Target (carbon)

beam

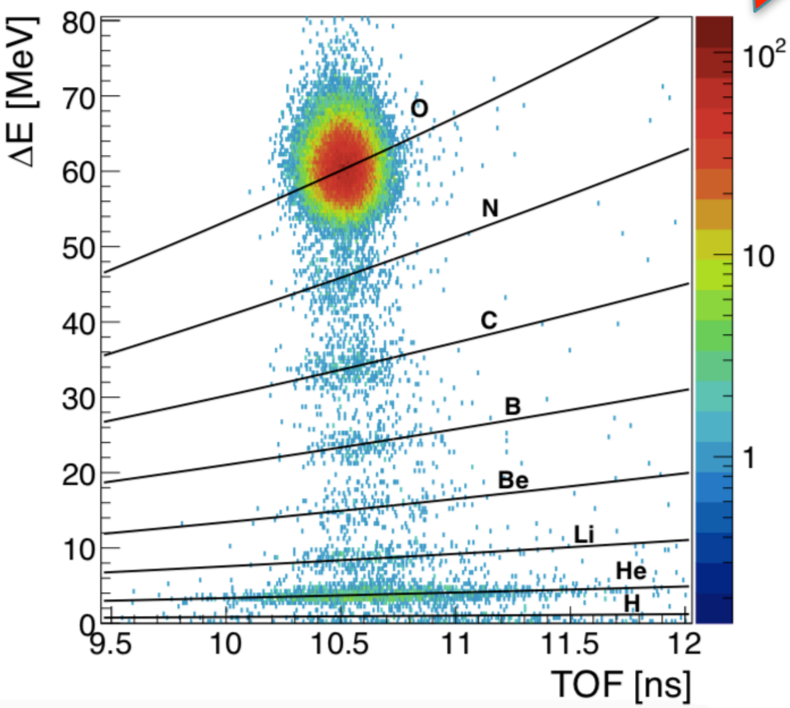


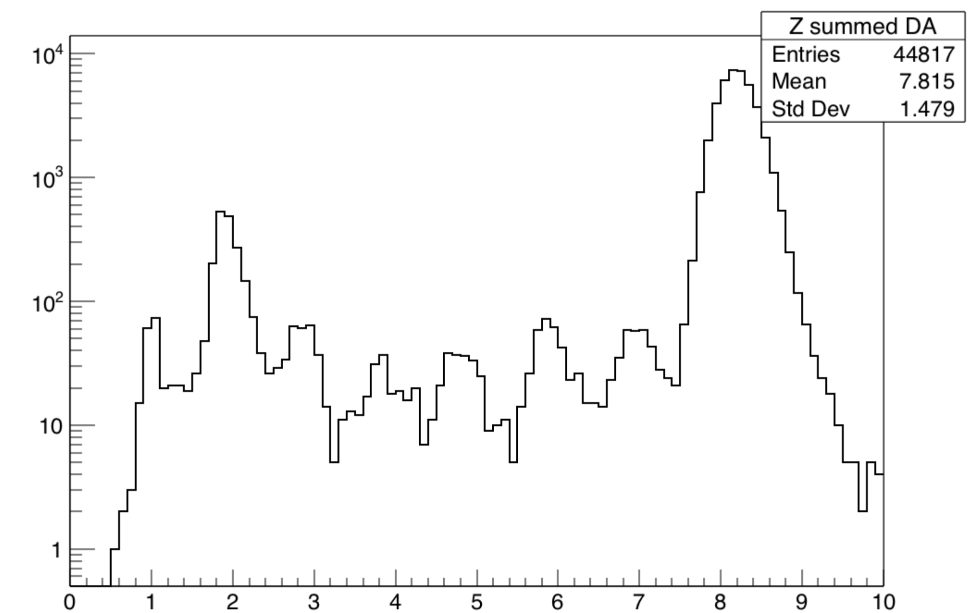
Test beam at GSI

INFN and university of Pisa

Oxygen (400 MeV/u) on
5 mm carbon target

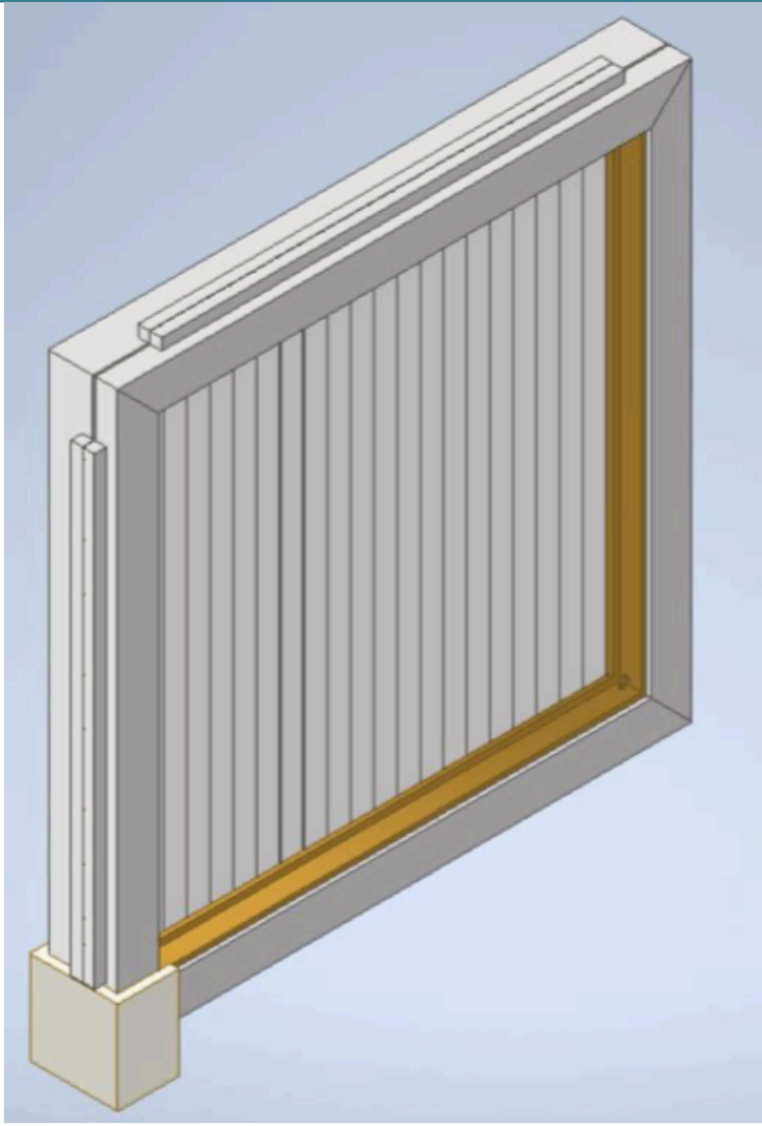
First fragmentation measurement of oxygen on carbon target!!





Current and future work

- Hardware:
  - Previous system disassembled
  - New mechanical frame being realized:
    - More solid structure
    - Better light tightness
    - Easier replacement of SiPMs in case of malfunctioning
    - Pluggable into motion system
  - WaveDAQ available
  - Temperature monitoring
  - To be reassembled in September
- Software/analysis: finalizing GSI analysis



- Magnetic spectrometer: offers arrived (RUP=Andrea Moggi)

Future FOOT data takings

- CNAO (new experimental room): end of 2020
  - New calibration data
  - First measurements with new hardware

- GSI (request to ESA approved yesterday!):
  - higher energy beams for radioprotection in space in 2021-2022

- HIT
  - measurements of both A and Z, with calorimeter for radiotherapy and radiation protection in space

→ main data takings…

Conclusions

- FOOT is a CNS3 experiment to measure nuclear fragmentation cross sections, inspired by:
  - Particle therapy:
    - Clinical need to reduce RBE uncertainty
    - Range monitoring
  - Radiation protection in space
- Started in 2017, currently many subdetectors being assembled and tested
- Δ E-TOF prototype is one of the few subdetectors that has been used already to take data!
  - First prototype tested at CNAO and GSI
  - Second prototype being realized
- Several important data takings coming

backup

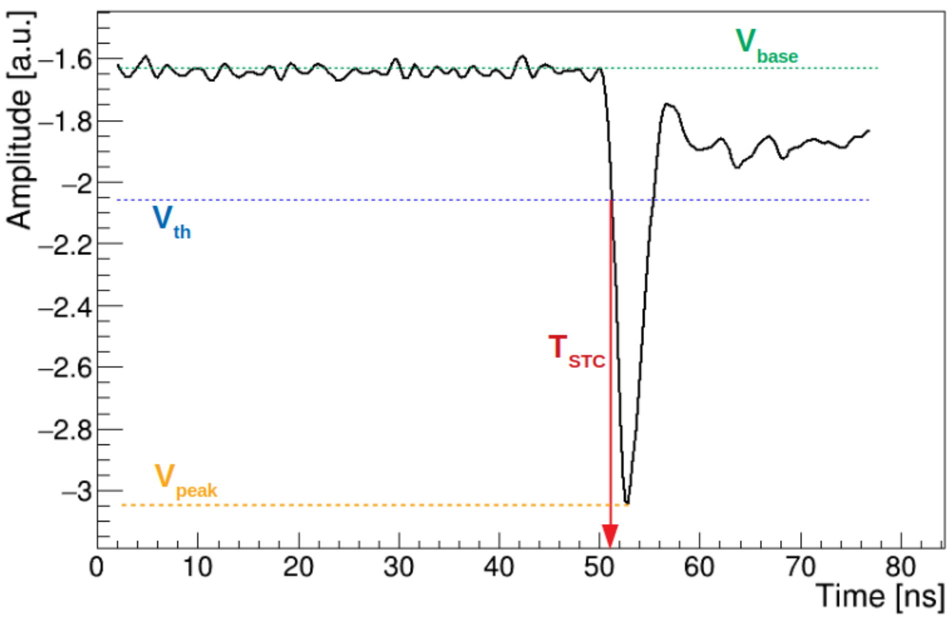
Signal processing

Thanks to Roma group

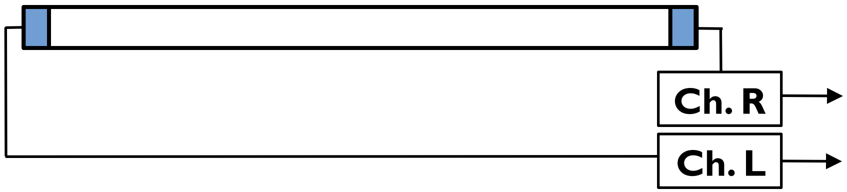
- Sum of the 8 STC waveforms
- Constant Fraction Discriminator:
  - Find baseline and peak
  - Set threshold to a fraction of the amplitude

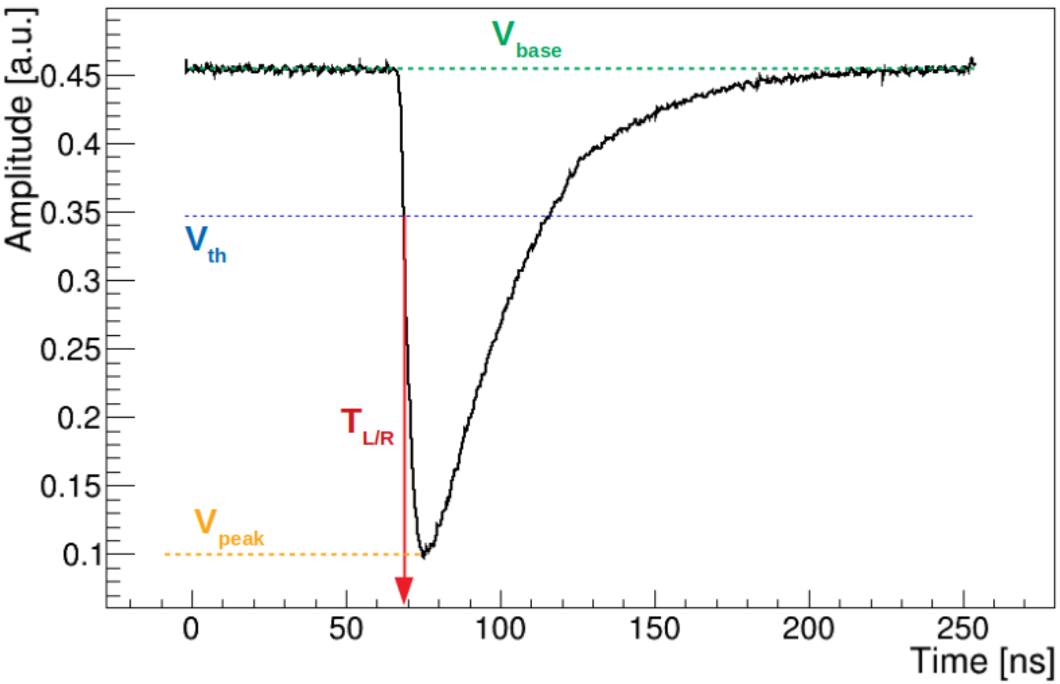
$$V_{th} = V_{base} - f_{CFD} \cdot (V_{peak} - V_{base})$$

  - f_{CFD} = 0.3 from former studies
  - T_{STC} → time when the WF crosses V_t (using interpolation)



Signal processing

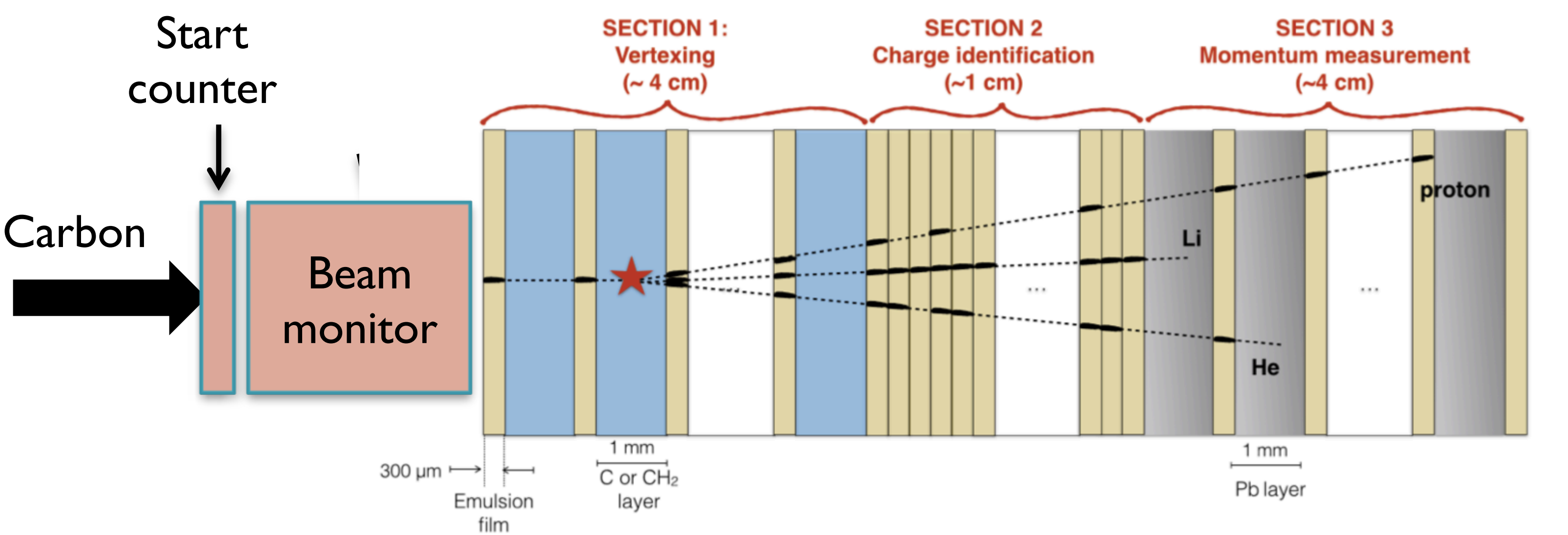




- CFD algorithm applied to both channels of each bar hit in the event
- Extracted data:
  - Time stamp of the channel $T_{L/R}$
  - Total charge collected in the channel $Q_{L/R}$ = integral of the WF

Other recent results

- Emulsion setup: completed data taking at GSI in February 2020
- 700 MeV/u carbon beam



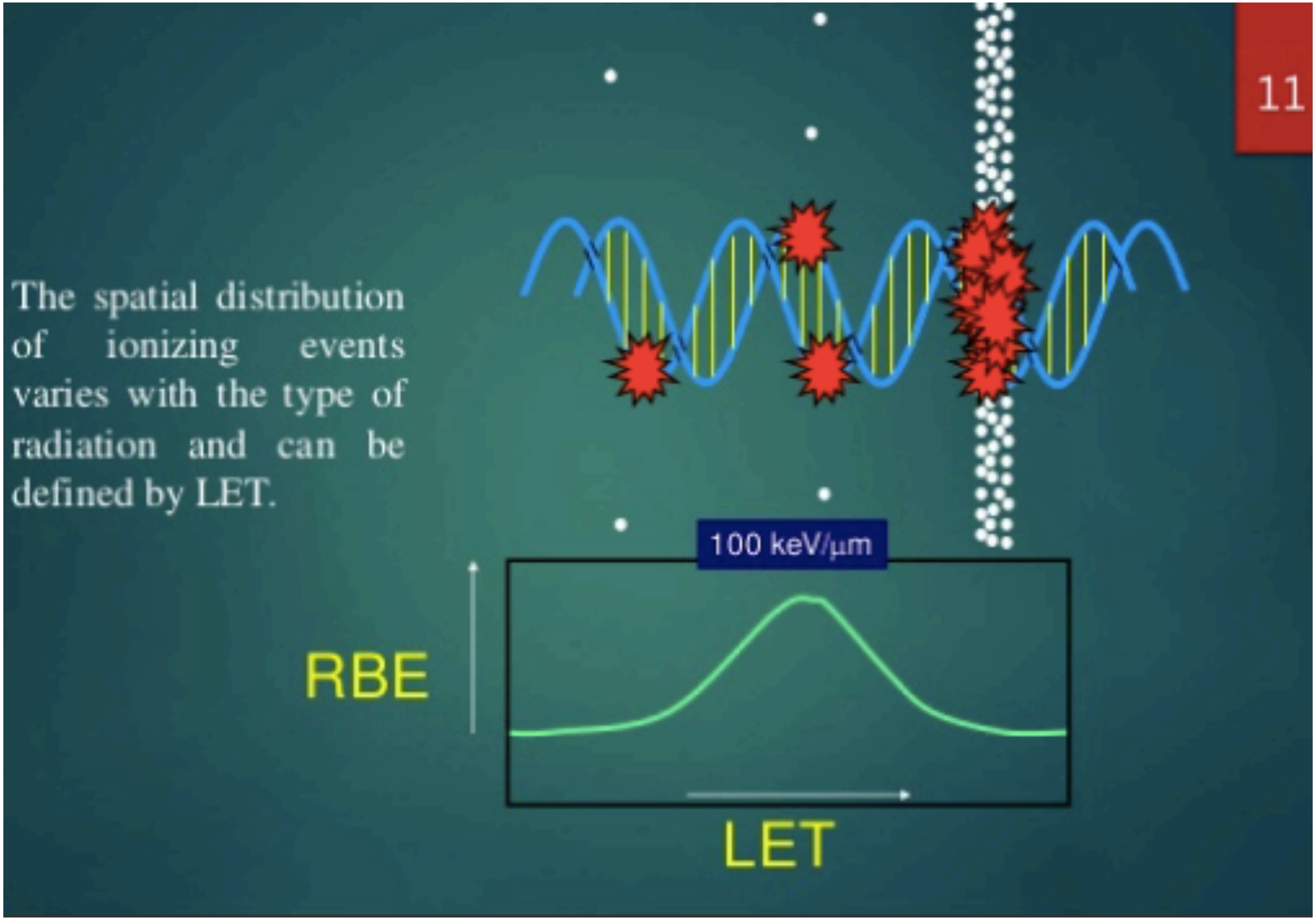
Radioprotection in space

Three types of energetic particles in space:

- Solar Particle Events:
  - Mostly protons emitted from the sun
  - Up to GeV
  - Unpredictable (can be lethal)
- Galactic Cosmic Rays
  - High energy protons (86%), helium (12%) and heavier (2)%
  - Peaking around 100-800 MeV/u
  - From supernovae
- Geomagnetically trapped particles
  - Protons up to a few hundred MeV (and electrons)

Particles interact with spacecraft→ nuclear fragmentation

Important for space craft/instruments and staff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The spatial distribution of ionizing events varies with the type of radiation and can be defined by LET.
100 keV/µm
RBE
LET