FOOT emulsion spectrometer

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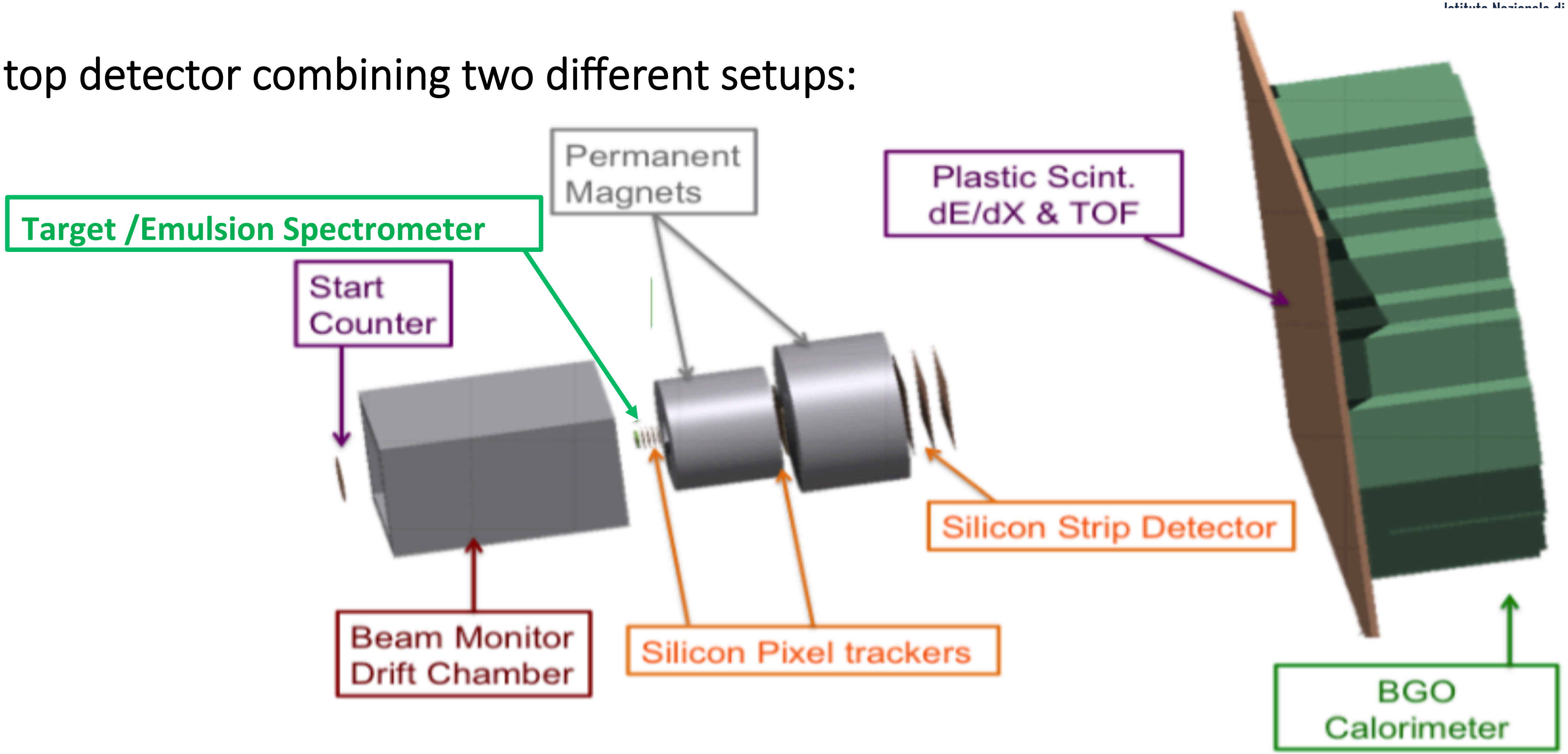
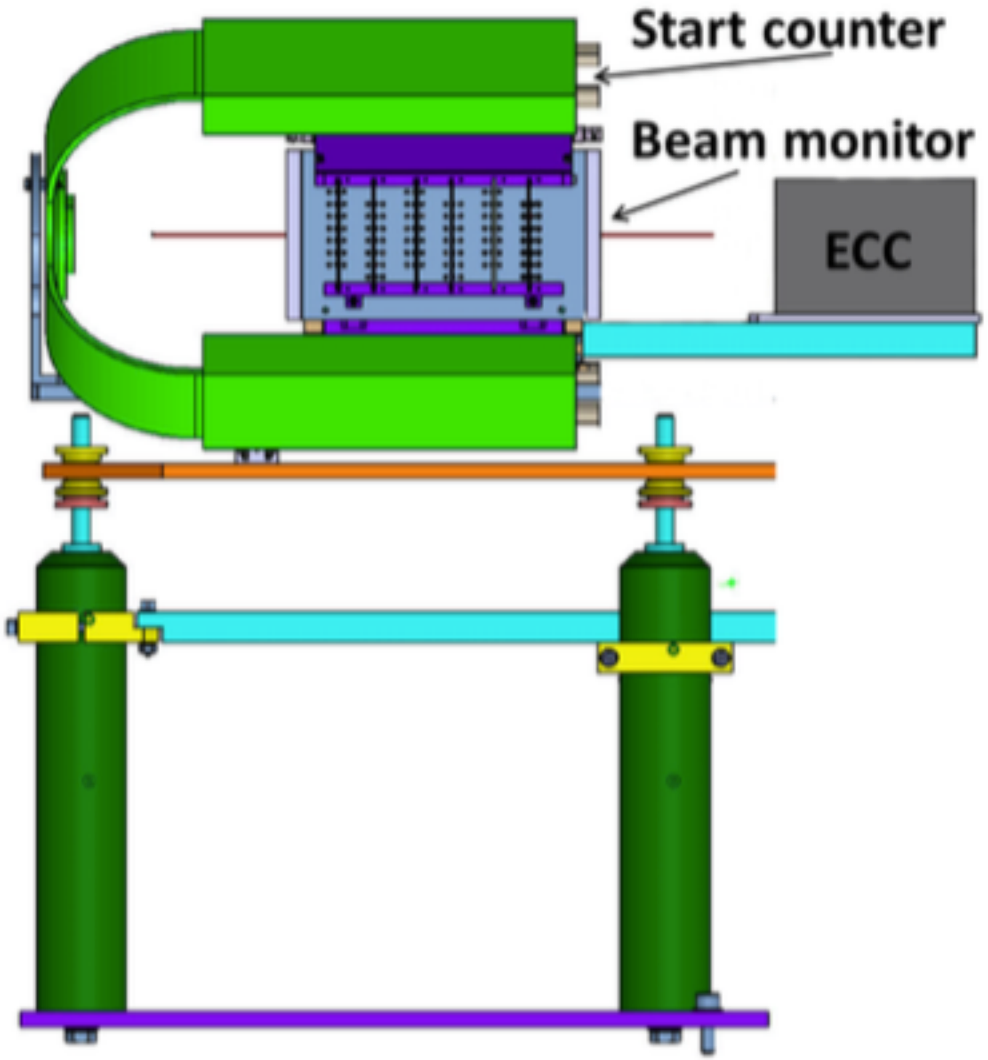
FOOT Detector

➢Table top detector combining two different setups:



- **electronic detectors and magnetic spectrometer** to identify and measure fragments heavier than ^{4}He (angular acceptance +/- 10°)
- **emulsion spectrometer** to measure the production of light charged fragments up to about 70°

FOOT Emulsion Spectrometer

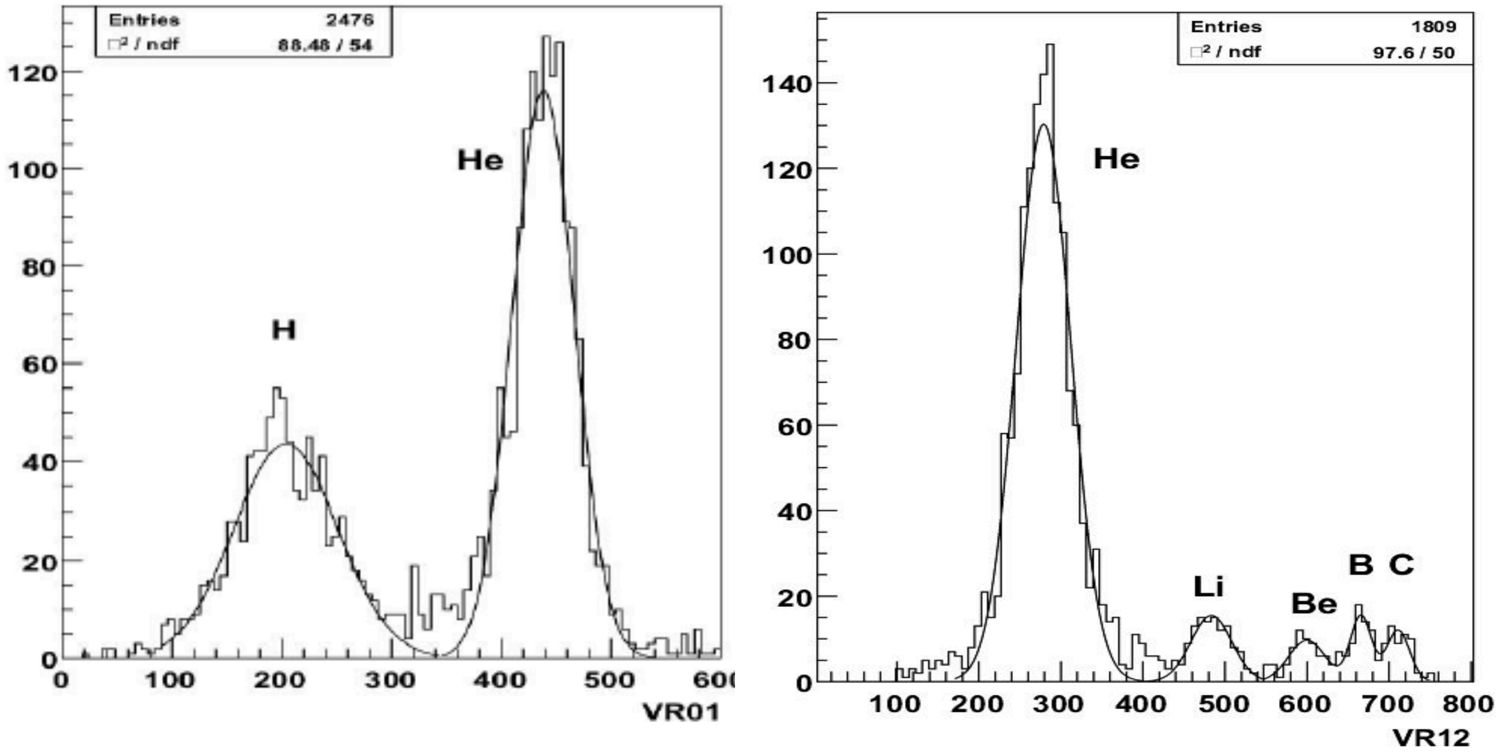


- To measure fragments with Z <= 3 emitted within a wide angular acceptance (up to 70 degrees)
- Detector based on the concept of Emulsion Cloud Chamber – ECC
- Nuclear emulsion films sensitive to ionizing particles. Films are interleaved with passive material
- Emulsion films produced at Nagoya
- ECC integrates target and detector in a very compact setup and provides a very accurate reconstruction of the interactions occurring inside the target
- New generation fully-automated optical microscopes developed in Naples are capable of reconstructing the fragments produced in the ECC

G. De Lellis et al., Nuclear Emulsions. In Fabjan,C.W.& Schopper,H.(eds) Detectors for Particles and Radiation. Part 1: Principles and Methods, 262–287 (Springer Berlin Heidelberg 2011).

FOOT Emulsion Spectrometer: past experience

- The emulsion technique already exploited to study the fragmentation of Carbon ions in polycarbonate at HIMAC (Chiba, Japan): identification of the secondary nuclei produced by fragmentation of 400 MeV/n ^{12}C achieved with high significance

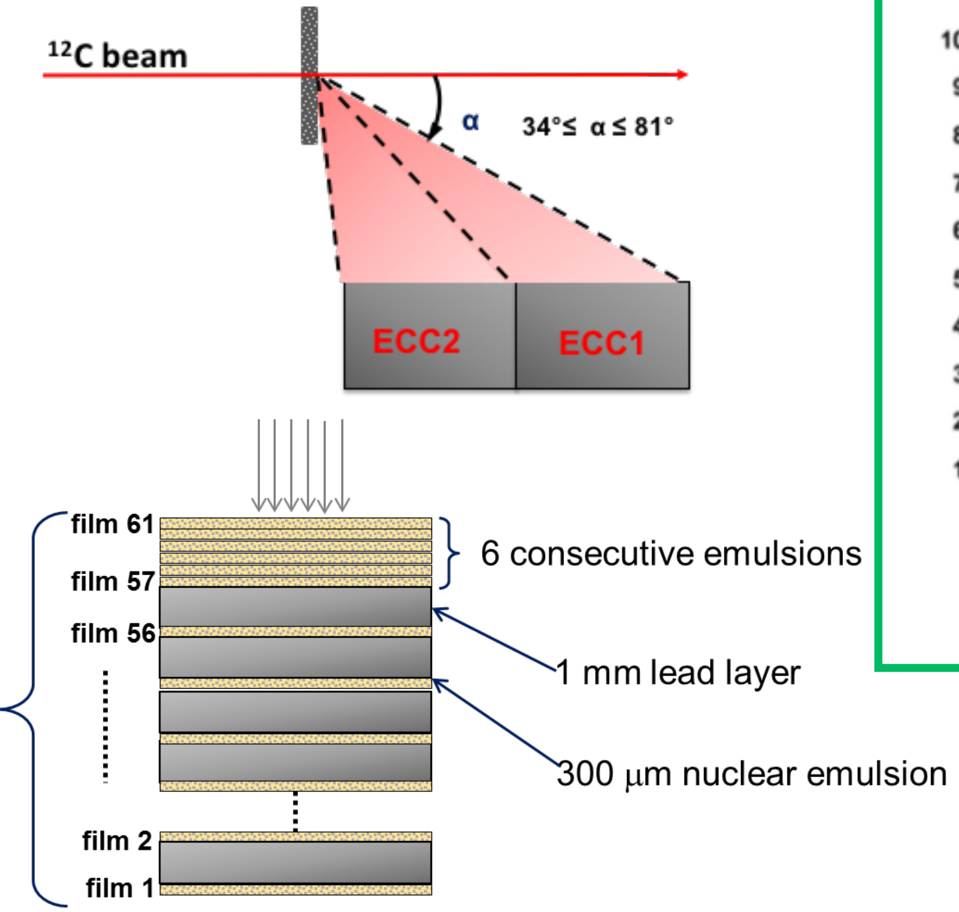


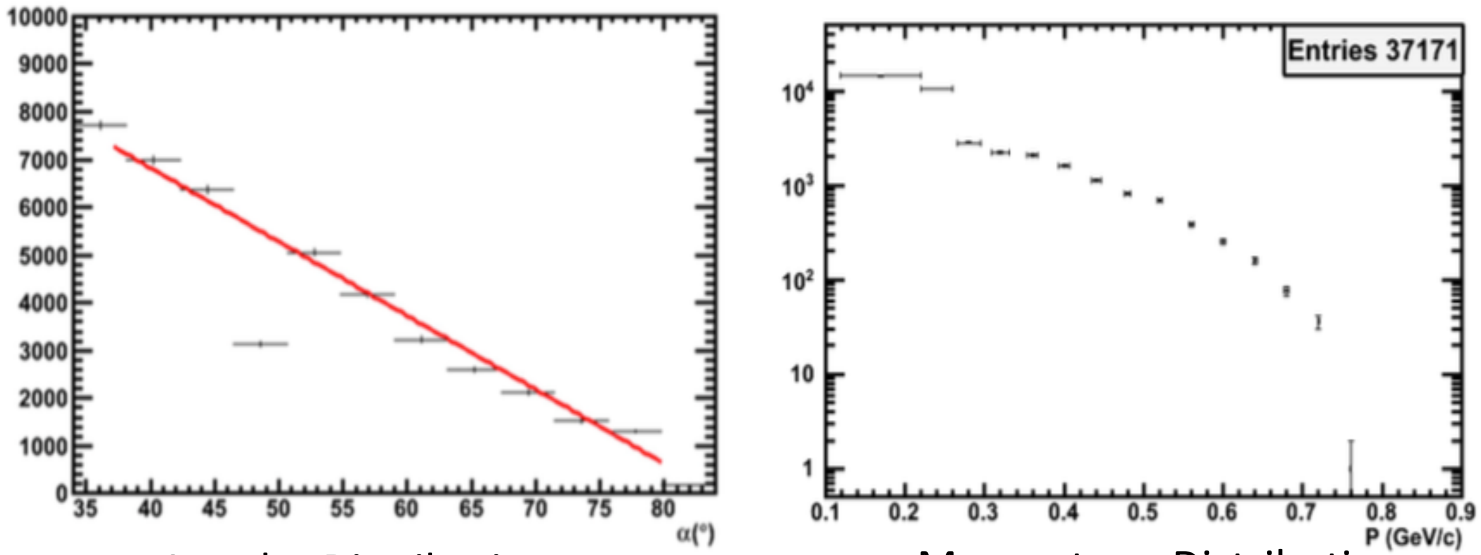
G. De Lellis et al. JINST 2, 2007, P06004

OPERA films

FOOT Emulsion Spectrometer: past experience

- Within the FIRST experiment: large angle fragmentation and momentum measurements of a 400 MeV/n ^{12}C beam impinging on a composite target performed by using two ECC detectors to cover a range from 34° to 81° with respect to the beam axis



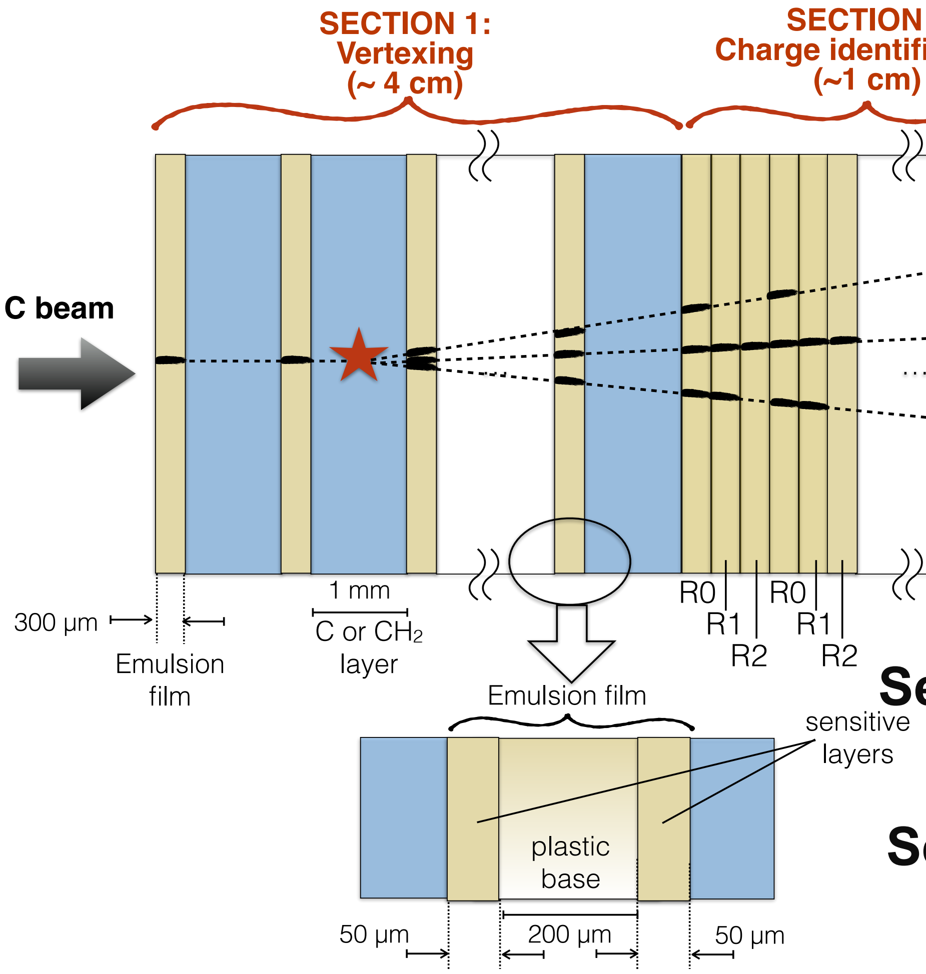


Angular Distribution

Momentum Distribution

A. Alexandrov et al., JINST 12 (2017) P08013

FOOT Emulsion Spectrometer: Layout



Section 1: alternated layers of emulsions and target (C/C_2H_4)

- vertex detector

Section 2: made of emulsion films only

- charge identification for low Z fragments (H, He, Li)

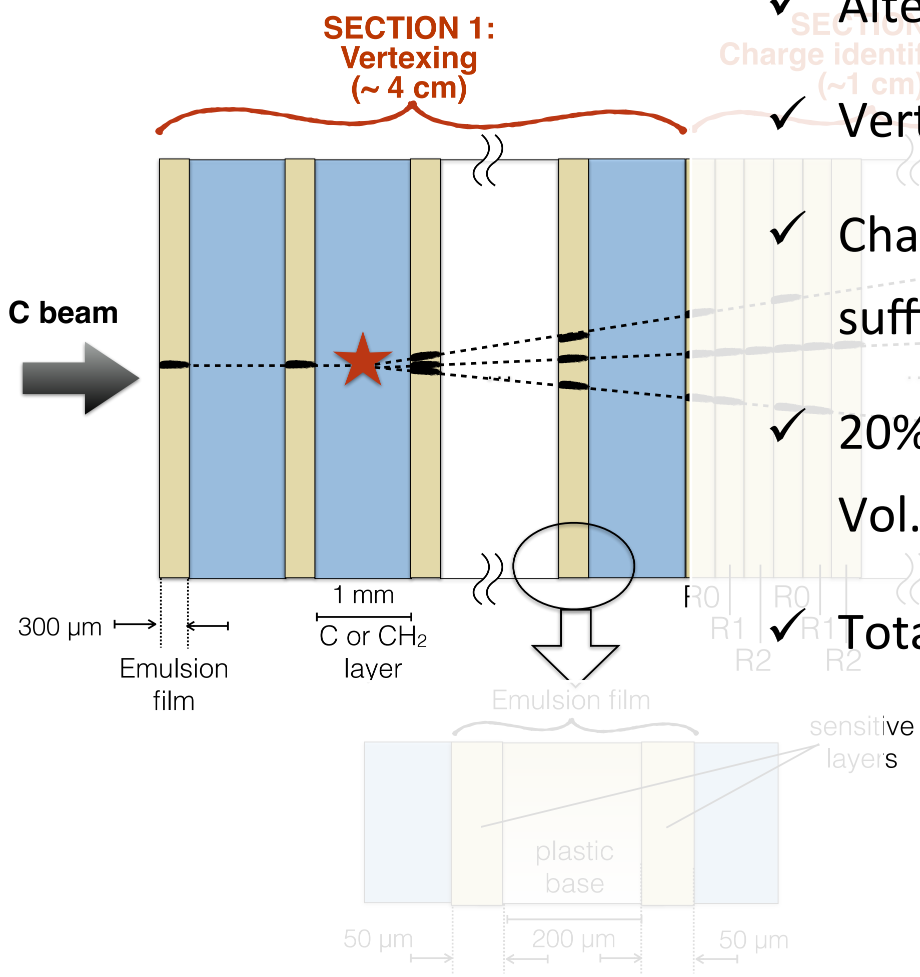
Section 3: alternated layers of emulsions and lead/passive material

- Momentum measurement by range and Multiple Coulomb Scattering (MCS)
- Isotopic identification

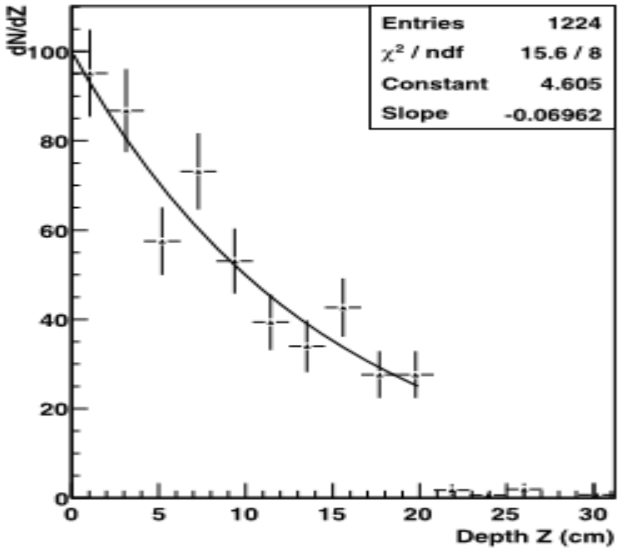
Total emulsion flims: ~ 90

FOOT Emulsion Spectrometer: Vertex

- ✓ Alternate target layers of C or C_2H_4 (1 mm) and emulsion films (300 μm)
- ✓ Vertex detector and particle tracking
- ✓ Chamber thickness defined by the interaction length → obtain a sufficiently high number of interactions
- ✓ 20% of Carbon ions interacting in 3 cm Lexan (G. De Lellis, Nucl. Phys. A Vol. 853, 2011, 124-134)
- ✓ Total length ~ 30 cells = 39mm (~ 30 emulsion films)



G. De Lellis et al. Nucl. Phys. A 853 (2011) 124-134

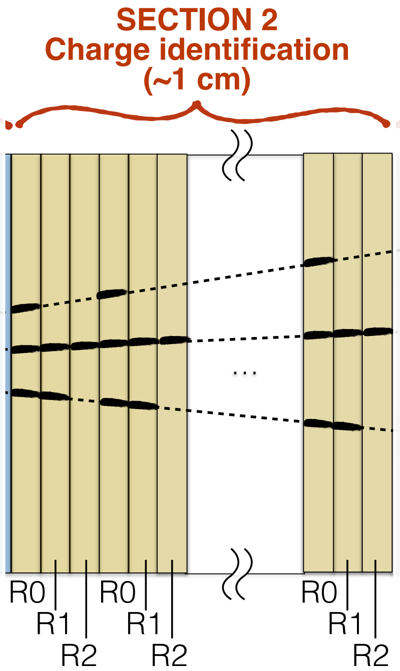


FOOT Emulsion Spectrometer: Charge

✓ Charge identification for low Z fragments (H, He, Li)

✓ Emulsion will have a different thermal treatment according to its position in the elementary cell:

- **R0:**
  - Not refreshed
  - **Sensitive to m.i.p.**
- **R1:**
  - Appropriate refreshing for protons
  - **Sensitive to protons**
- **R2:**
  - Appropriate refreshing for He
  - **Sensitive to He**



Cells	3	9	13	20
H-He	3.3	4.5	6.5	
He-Li	2.6	3.9	4.3	5.0
Li-Be	1.7	2.7	3.1	3.5

To obtain 3σ He-Li separation, ≥ 9 cells (27 emulsion films) needed

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

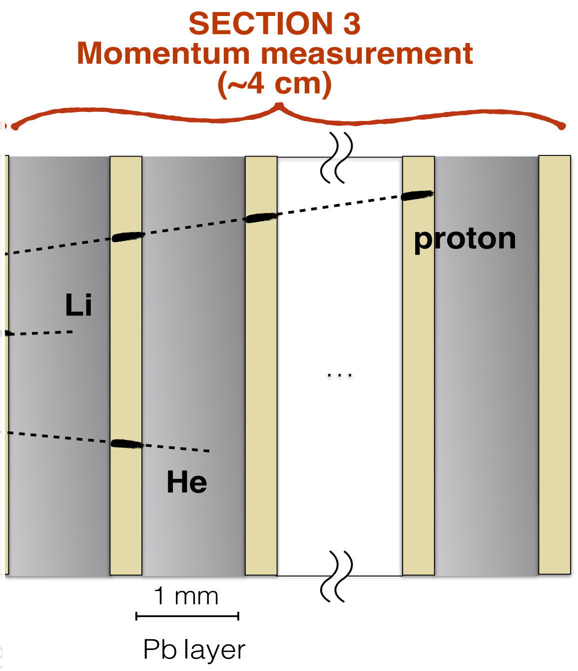
✓ New emulsion batches are under characterization (beam exposure at LNS – Catania, IT – and at Proton Therapy Center – Trento, IT) to tune the thermal treatment required for the charge separation at Z ≤ 3

FOOT Emulsion Spectrometer: momentum/mass

- ✓ Emulsion films interleaved with passive material (lead or stainless steel, thickness to be optimized to lower the threshold)
- ✓ Range: the kinetic energy of the fragment estimated on the basis of the range measurements, assuming the particle mass
- ✓ The MCS estimates the particle momentum through the measurements of the position and the slope of the particles trajectory

$$p\ (\mathrm{MeV/c}) = \frac{13.6}{\beta\ \delta\theta(mrad)}\sqrt{\frac{x}{X_0}}$$

- ✓ Isotopic identification: two independent methods for momentum measurements, both mass dependent → mass value
- ✓ Use a likelihood approach



emulsion films: ~ 30

Test @ LNS, 19-26 July 2017

- ✓ Aim:
  - ✓ Assess the optimal refreshing condition for charge separation at $Z \leq 3$ with the new emulsion batches
  - ✓ develop the algorithm to identify isotopes by combining MCS and range measurements and validate it with data

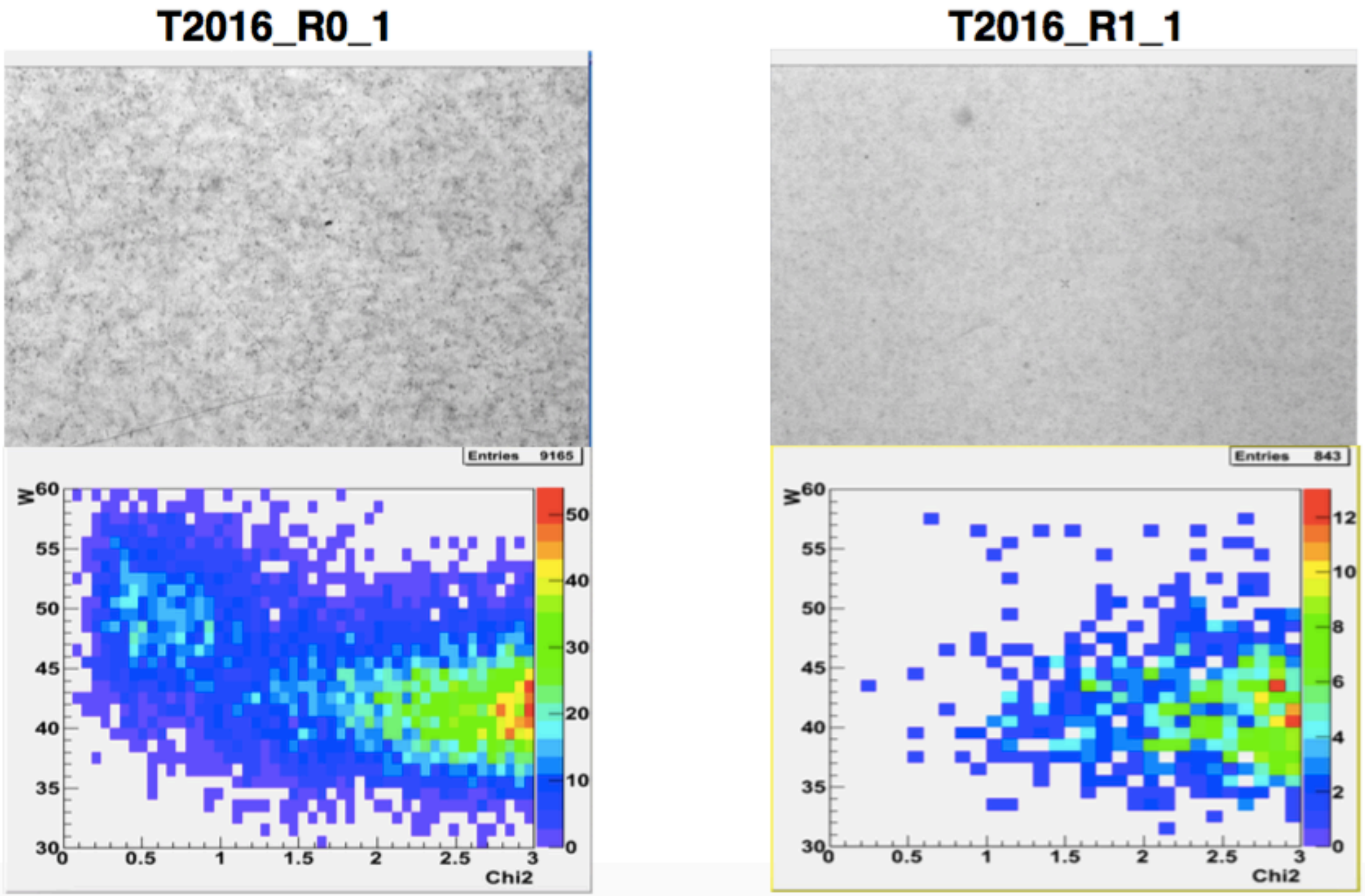
- ✓ Two emulsion spectrometer structures for corresponding exposures:
  - **20 Emulsion Pairs**: each consisting of two emulsion films (5 cm $\times$ 4 cm) sealed with a light tight aluminium envelope and exposed to 80 MeV p, D, He and C;
  - **2 ECC** with 21 emulsion films (5 cm $\times$ 4 cm) interleaved with 20 stainless steel layers (0.5 mm thick) packed with a light tight aluminium envelope. Exposed to protons and Deuterium for mass identification

80 MeV He equivalent to Li at the typical FOOT energies
47 MeV p equivalent to He at the typical FOOT energies → not delivered
Maximum energy – 80 MeV → protons of the FOOT energy unavailable

Refreshing machine at LNGS

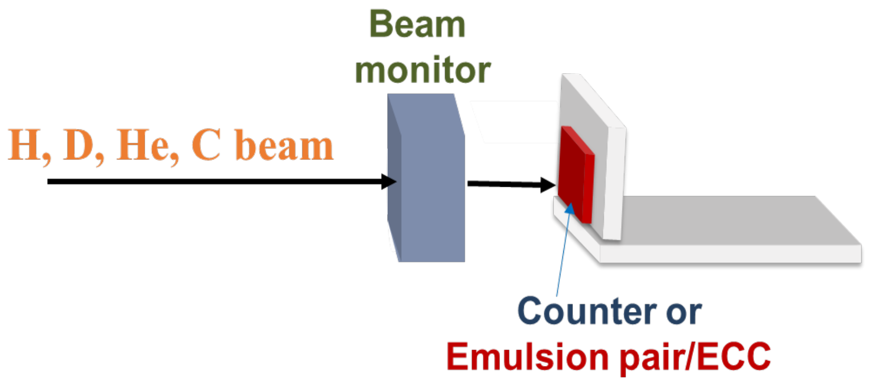
Commissioning in dark room at LNGS during a preparatory phase

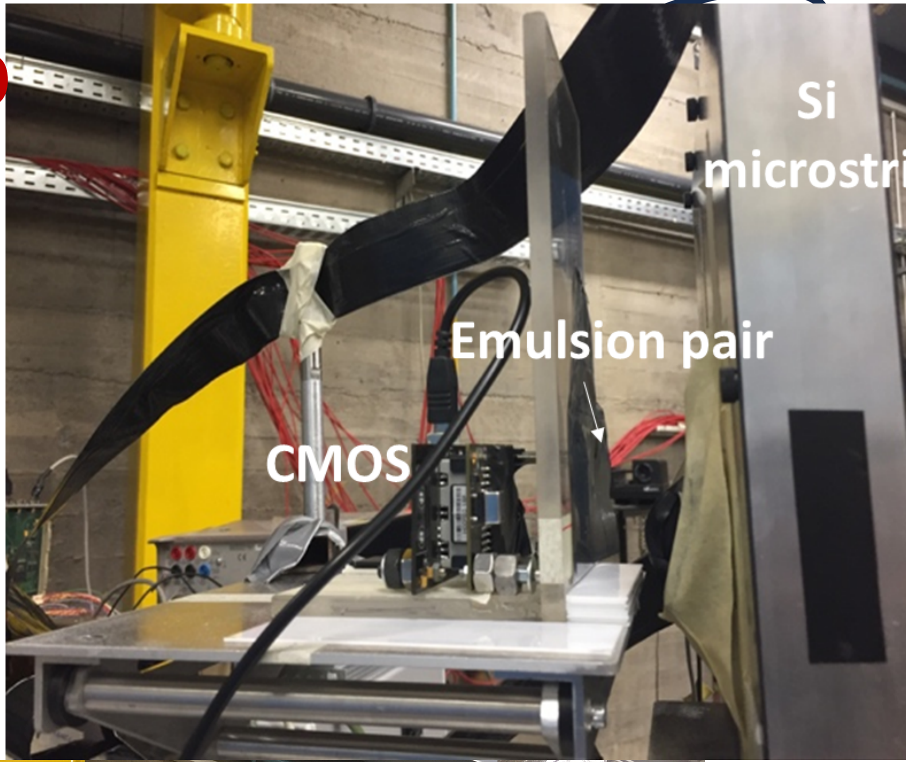
Testing the procedure (24 h at 95% R.H. and 28 °C) with films exposed to cosmic-rays

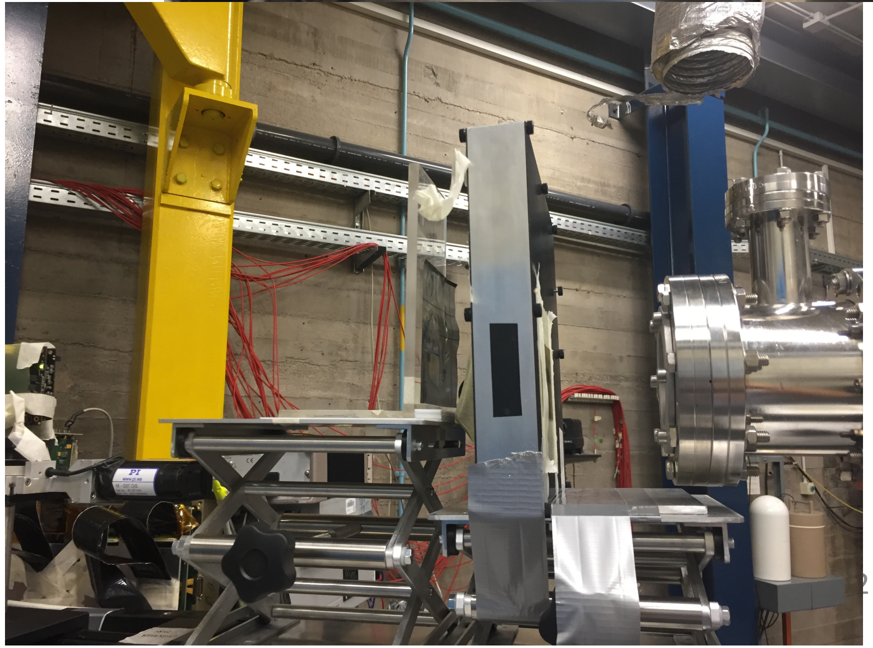


- Temperature range: [-70, 180]°C (± 0.1, ± 0.3)
- Humidity range: [10, 98]% (± 0.5 ÷ ± 1.5)
- Inner Volume: 550x400x550 cm^3 (120 L)

Test at LNS: experimental set-up







Beam Monitor by the Perugia group: silicon microstrip detector (strip pitch 250 μm, thickness 350 μm, total area 8x8cm^2)

Counter by the Perugia group: beam intensity registered by a CMOS detector (up to 3 MHz)

Main difficulties coped with: make the beam uniform over the emulsion surface and reduce the beam intensity down to 10^3 particles/cm^2

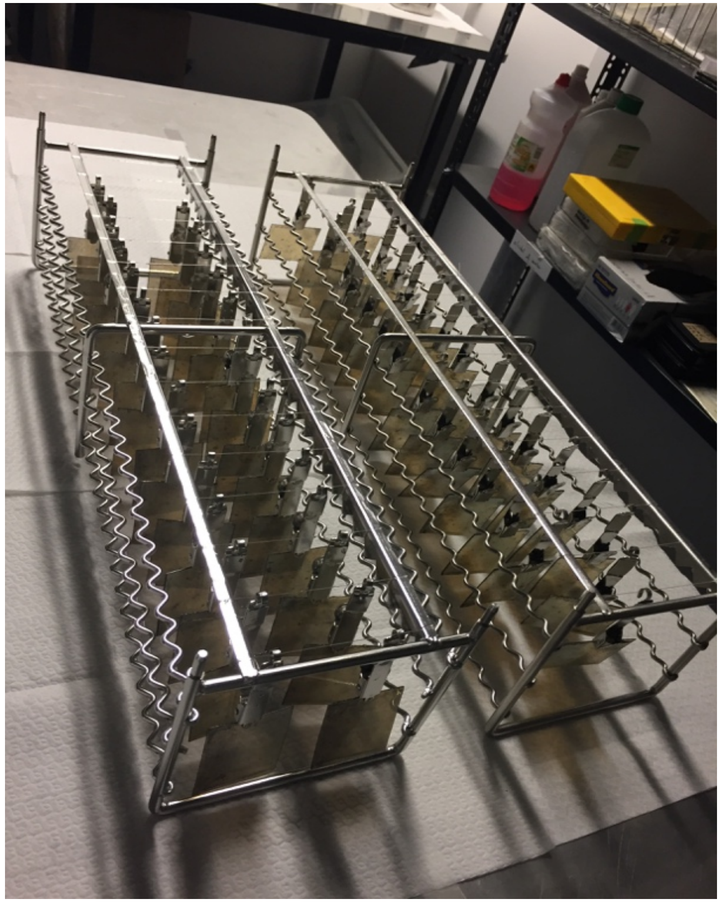
Refreshing and chemical development @ LNGS

- R1 refreshing: 24 hours at 95 % R.H. and 28°C;

The process erases Minimum Ionizing Particles and the emulsion films become sensitive to particles with higher ionization (e.g. protons)

- R2 refreshing: 24 hours at 95 % R.H. and 34, 36, 38°C;

The process makes the emulsions sensitive to particles with higher ionization, as helium ions. Test the optimal configuration



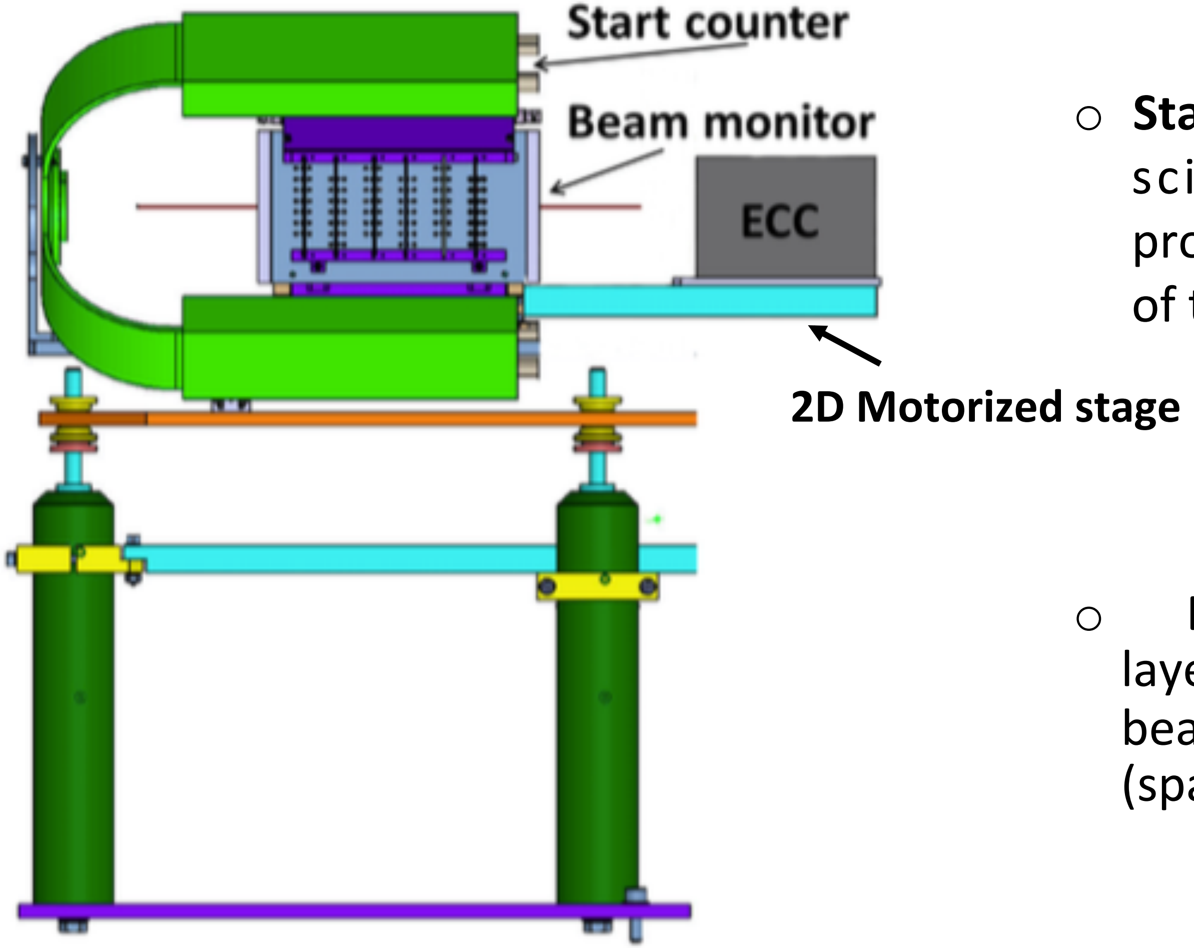
Complementary activity to be carried out in 2017

Exposure at:
47 MeV protons, not delivered at LNS last July
200 MeV protons, relevant for FOOT

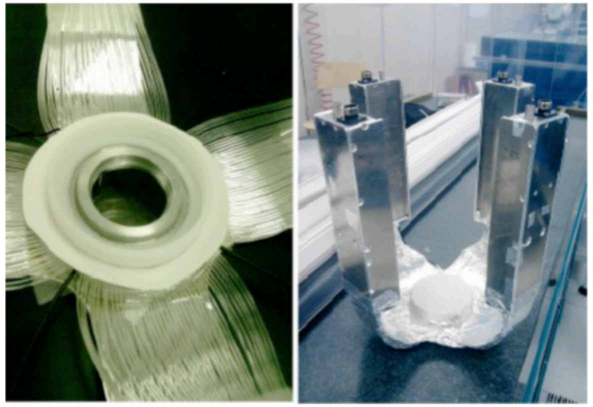
Extra activity in 2017 at TIFPA	KEuro
Run at Trento (3 persons for 7 days: 3 days for exposure at Trento, 4 days for emulsions chemical development at Gran Sasso Lab) 7 x 150 € + 2 x 200 € (travel) ~ 1500 per person	4.5
Run cost at Trento	1.5
Total (k€)	**6**

FOOT emulsion spectrometer: 2018 data taking

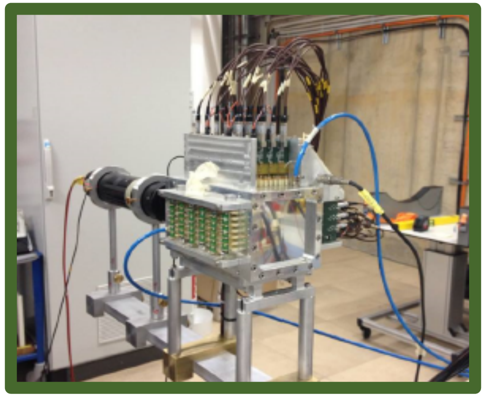
- Exposure of emulsion spectrometers with **C and C_2H_4 target** to C and O ion beams at



- **Start counter**: thin plastic scintillator (250 μm) providing the start signal of the TOF (100 ps)



- **Beam monitor**: twelve layers of wires measuring beam direction and position (spatial resolution 140 μm)

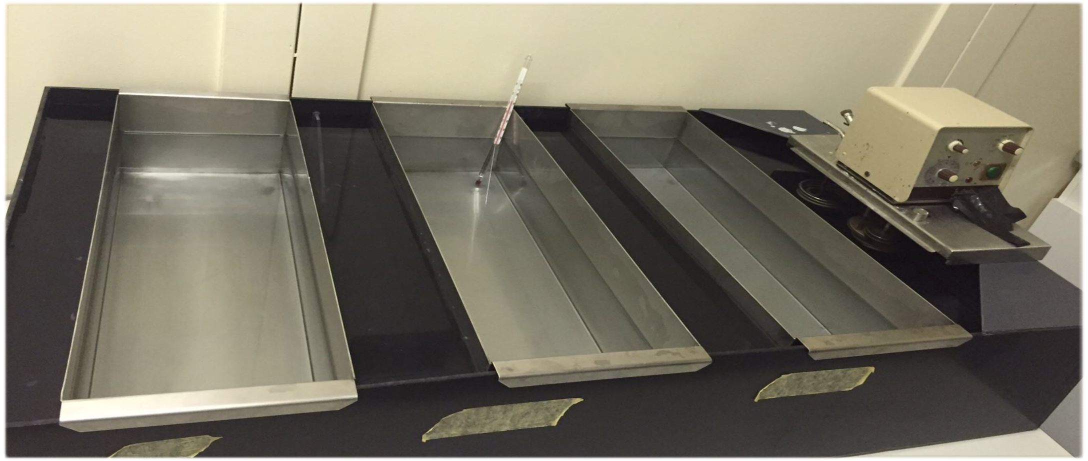


The Emulsion facility at CERN

Dark room previously used by the CHORUS and OPERA experiment to perform:

- Target units assembling
- Emulsion development
- Glycerin treatment

Thermalized tanks for emulsion development



Other thermalised tanks brought from Japan

FOOT emulsion spectrometer: 2018 data taking

- Exposure at O and C @200-400 MeV/n at Heidelberg Ion-Beam Therapy Centre
- 2 Emulsion spectrometers with Carbon target
- 2 Emulsion spectrometers with Polyethylene target
- Emulsion films from one exposure: ~ 400 → 250 x 400 cm2 = 10^5 cm2 → ~ 3 months of data taking with last generation microscope developed in Naples
- Similar amount from the second exposure
- **A new generation automated microscope dedicated to Foot is needed**

Automated microscope for FOOT: assessed performances

- New reconstruction software to extend track recognition angular acceptance from θ = 30° to θ = 72°, A. Alexandrov et al., JINST 10 (2015) no.11 P1100

- Development of a new generation scanning system (NGSS) with new hardware: new objective lens (Nikon Plan Fluor 20X 0.75 NA) and CMOS digital camera (Mikrotron MC-4082camera) with a processing approach based on GPU (Graphics Processing Unit) extend the scanning speed up to **190 cm^2/h** (A. Alexandrov et al., JINST 11 - 2016 - 6002, A. Alexandrov et al., *Nature Scientific Reports* **7** - 2017 - 7310)

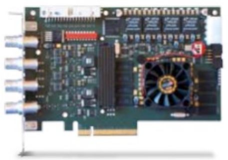
Scanning system hardware upgrade

ESS (European Scanning System) → **NGSS (New Generation Scanning System)**

Matrox Odyssey Xpro SFCL

PCI-X interface
up to 680 MB/sec

→



SiliconSoftware mE5

PCIe 8x interface
up to 2200 MB/sec

Mikrotron MC-1310

SFCL interface
1280 x 1024 pixels
1.2 Mpixel @ 376 fps

→

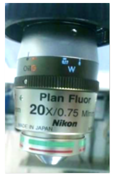
Mikrotron MC-4082

DFCL interface
2336 x 1728 pixels
4 Mpixel @ 563 fps

Nikon Plan

50X Oil	0.31 μm/pix
0.9 NA	396x317 μm

→



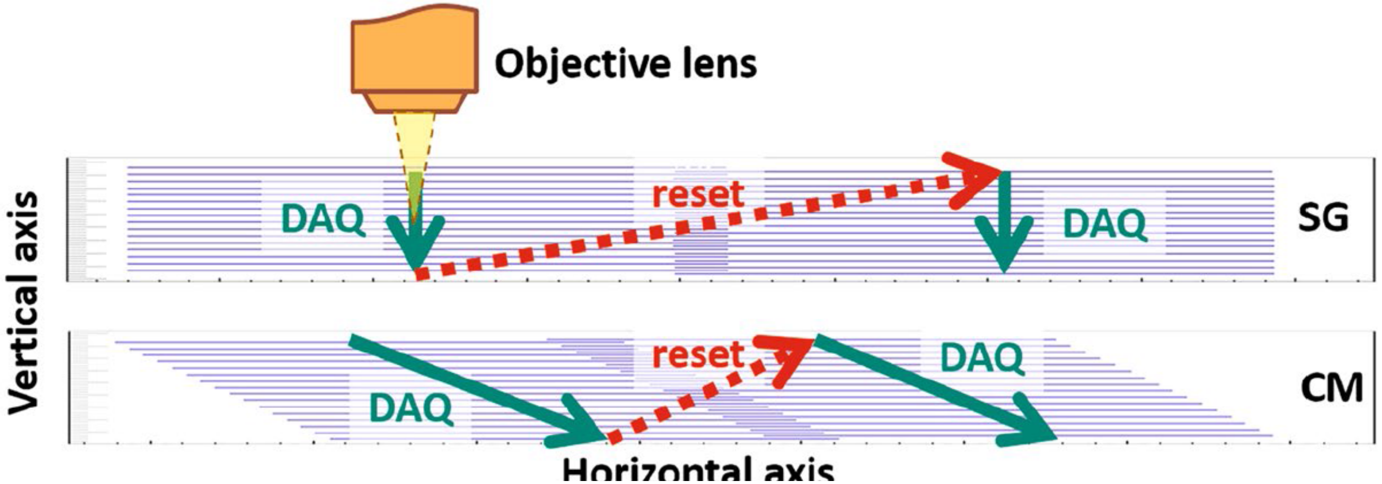
Nikon Plan Fluor

20X Oil	0.34 μm/pix
0.75 NA	794x586 μm

3.7x larger FoV

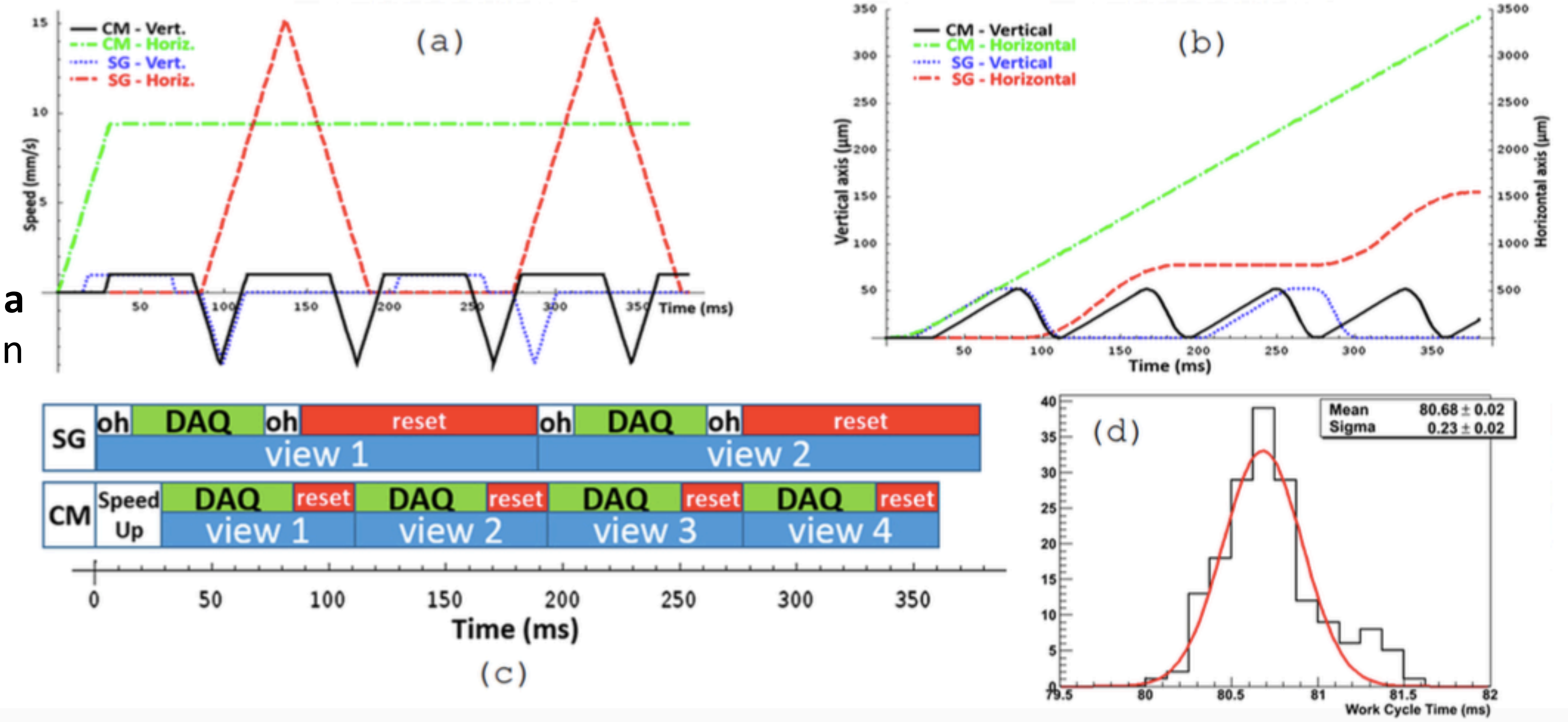
"A new generation scanning system for the high-speed analysis of nuclear emulsions"
in JINST 11 P06002 2016, doi:10.1088/1748-0221/11/06/P06002

Continuous Motion (CM) scanning technique



Stop&Go

Continuous Motion



“The Continuous Motion Technique for a New Generation of Scanning Systems” in Nature Scientific Reports 7: 7310 2017, DOI:10.1038/s41598-017-07869-3

2018 funding request

TASK in 2018	KEuro	
CMOS Sensor (Mikrotron MC-4082) + frame grabber (Matrox Radient eV-CXP)	12.5	Microscope
Precision Z stage with linear encoder Micos HPS-170	13.5	
Precision XY stage with linear encoder Micos V-731	16	
Objective lens (Nikon Plan Fluor 20x 0.75 NA)	4.5	
Motorized mechanics with a 3D stage for emulsion spectrometer	10	
Emulsion spectrometer packaging, oil for microscopy, chemicals for emulsion development	5	
Run at Heidelberg (3 persons for 3 weeks: first week at Gran Sasso Lab. for emulsion spectrometers assembly, second week exposure at Heidelberg, third week emulsions chemical development at Gran Sasso Lab.) (RUN_1) = 63 x 150 + 2 trips (300 euro) x 3 persons = 9450 + 1800	11.5 SJ	
Run at Trento (3 persons for 3 weeks: first week at Gran Sasso Lab. for emulsion spectrometers assembly, second week exposure at Trento, third week emulsions chemical development at Gran Sasso Lab) (RUN_2) = 9450 + 1800	11.5	
2 collaboration meeting (2 days x 4 persons)	3.5	
2 workshop (2 days x 2 persons)	2	
Total (k€)	**87**	