Esperimenti di fisica nucleare con ioni leggeri per applicazioni in adroterapia

- Hadrontherapy & Nuclear physics
- The ^{12}C fragmentation measurement
- The FIRST detector
- Summary & conclusion

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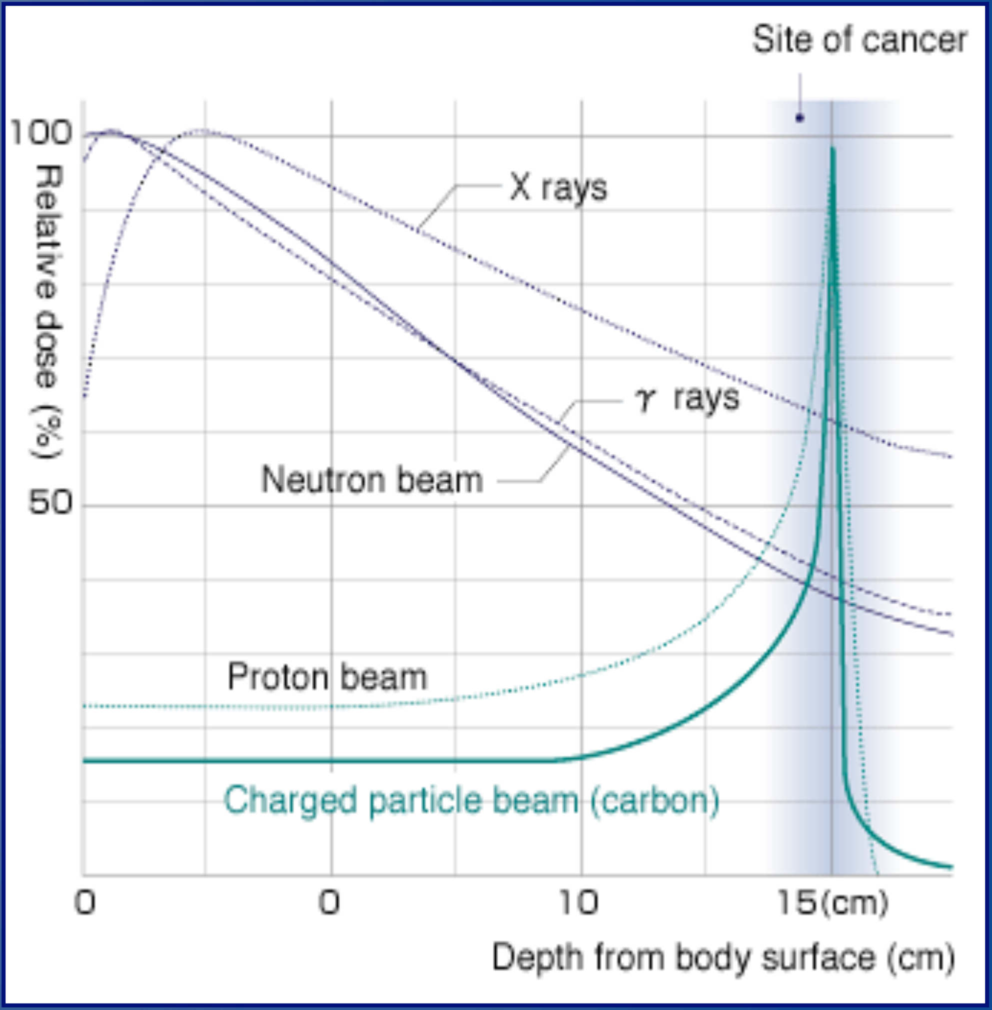
Hadrontherapy Motivation

Light ions advantages in radiation treatments of tumor wrt IMRT:

- ✓ Better Spatial selectivity in dose deposition: (p, ^{12}C)
- ✓ Reduced lateral and longitudinal diffusion (^{12}C)
- ✓ High Biological effectiveness (^{12}C)

Treatment of highly radiation resistent tumours, sparing surrounding OAR



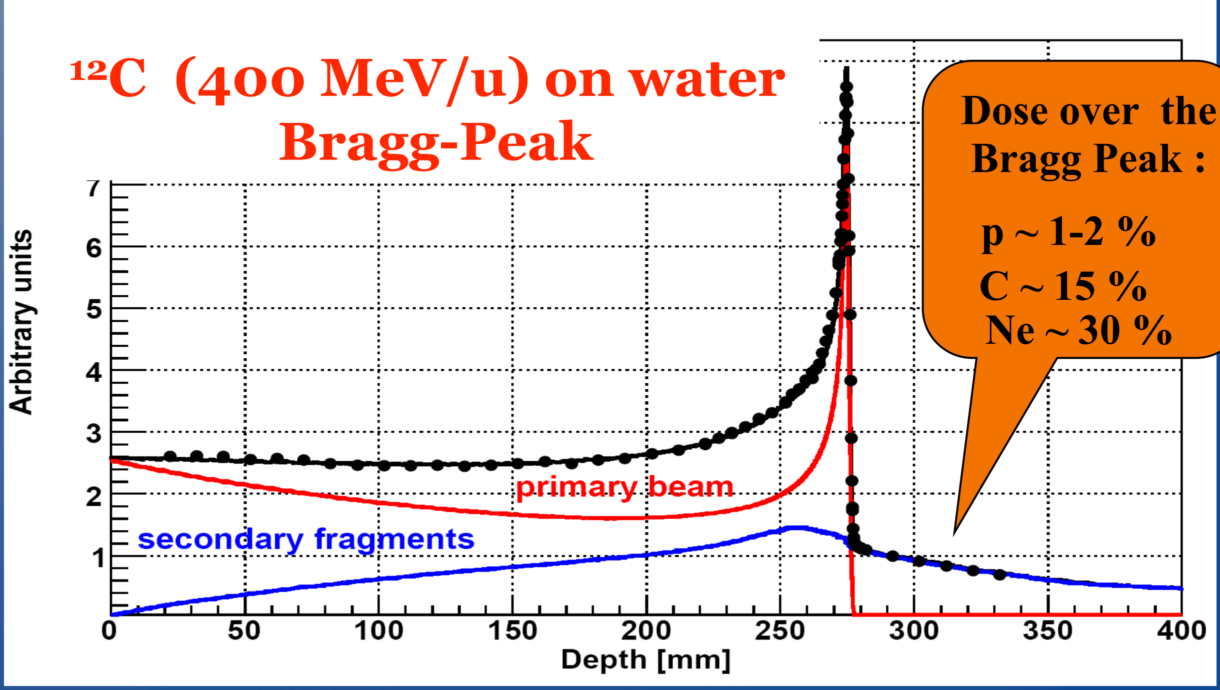
INFN has a long standing activity in this field, not only in beam facility realization (CNAO) but also in Treatment Planning System development (TPS INFN-IBA joint project)

FRAGMENTATION OF ^{12}C in biological tissue

Dose release in healthy tissues with possible long term side effects, in particular in treatment of young patients → must be carefully taken into account in the Treatment Planning System

- Production of fragments with higher range vs primary ions
- Production of fragment with different direction vs primary ions

- *Mitigation and attenuation of the primary beam*
- *Different biological effectiveness of the fragments wrt ^{12}C*

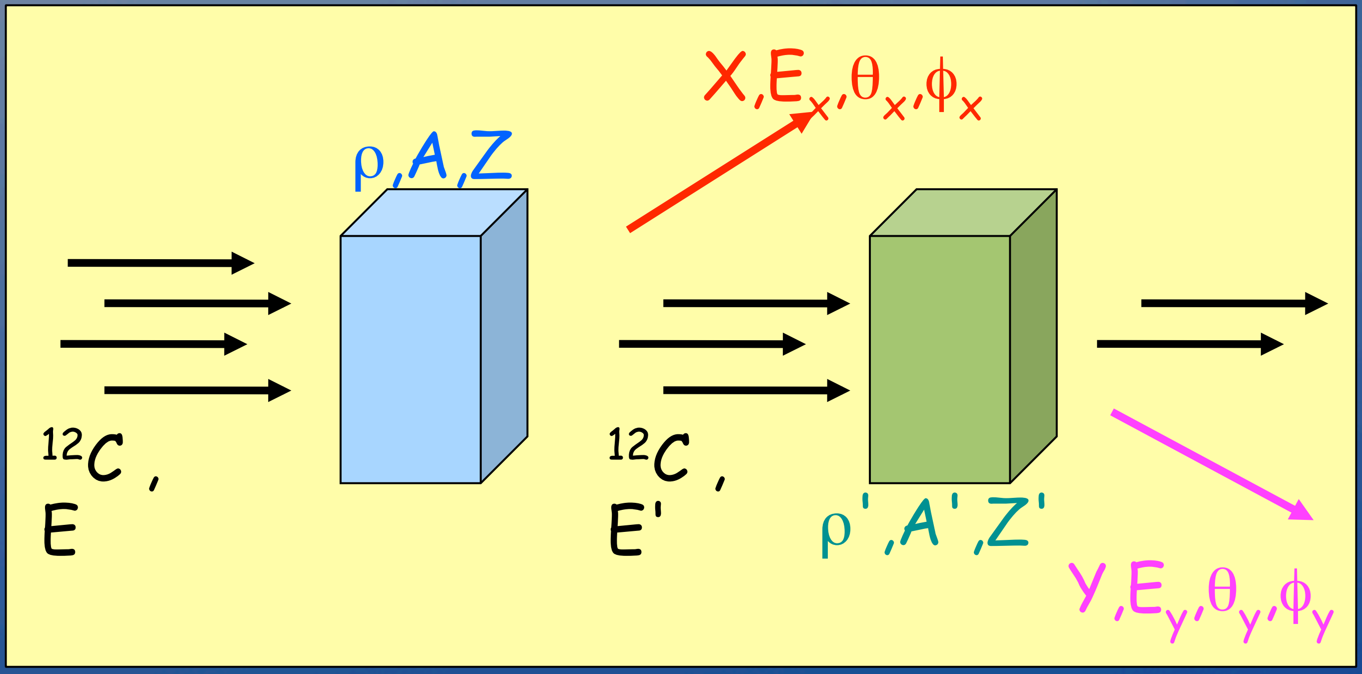


Exp. Data (points) from Haettner et al, Rad. Prot. Dos. 2006
Simulation: A. Mairani PhD Thesis, 2007, Nuovo Cimento C, 31, 2008

Courtesy of Andrea Mairani

What should we know about ^{12}C fragmentation?

- Production yelds of Z=0,1,2,3,4,5 fragments
- $d^2\sigma/d\theta dE$ wrt angle and energy, with large angular acceptance
- For any ^{12}C energy of interest (100-300 MeV/nucl)
- Measurements on thin target of all materials crossed by C beam
- Detect the correlation between emitted fragments



Not possible a complete DB of measurements

We need to train a nuclear interaction model with the measurements!!

What we already know: thick target measurement

Projectile	Energy[MeV/N]	Target	
^{4}He	100, 180	C, Al, Cu, Pb	
^{12}C	100, 180,400	C, Al, Cu, Pb	
^{20}Ne	100, 180,400	C, Al, Cu, Pb	
^{28}Si	800	C, Al, Cu, Pb	HIMAC by Kurosawa et al.
^{40}Ar	400	C, Al, Cu, Pb	
^{56}Fe	400	C, Al, Cu, Pb	
^{126}Xe	400	C, Al, Cu, Pb	
^{20}Ne	337	C, A, Cu and U	BEVALAC by Schimmerling et al.
^{93}Nb	272	Al, Nb	BEVALAC by Heilbronn et al.
^{93}Nb	435	Nb	
^{4}He	155	Al	NSRL by Heilbronn et al.
^{12}C	155	Nb	
^{4}He	160	Pb	SREL by Cecil
^{4}He	180	C, H_2O, steel, Pb	
^{12}C	200	H_2O	GSI by Günzert-Marx et al.
^{12}C	400	H_2O	GSI by Haettner et al.

A lot of integral measurements measurements are already around.. But very few for the correct triplet of projectile,target and energy

Tentative & incomplete list

Courtesy of M. Durante

What we already know: thin target measurement

A lot of measurements on thin target are already around.. but not wrt production angle and energy

Projectile	Energy[MeV/N]	Target	
^{4}He	135	C, Poly, Al, Cu, Pb	
^{12}C	135	C, Poly, Al, Cu, Pb	Sato et al.
^{20}Ne	135	C, Poly, Al, Cu, Pb	
^{40}Ar	95	C, Poly, Al, Cu, Pb	
^{12}C	290, 400	C, Cu, Pb	
^{20}Ne	400, 600	C, Cu, Pb	Iwata et al.
^{40}Ar	400, 560	C, Cu, Pb	
^{4}He	230	Li, C, CH_2, Al, Cu, Pb	
^{14}N	400	Li, C, CH_2, Al, Cu, Pb	
^{28}Si	60	Li, C, CH_2, Al, Cu, Pb	Heilbronn et al.
^{56}Fe	500	Li, C, CH_2, Al, Cu, Pb	
^{12}C	400	C, Poly	Toshito et al.

Tentative & incomplete list

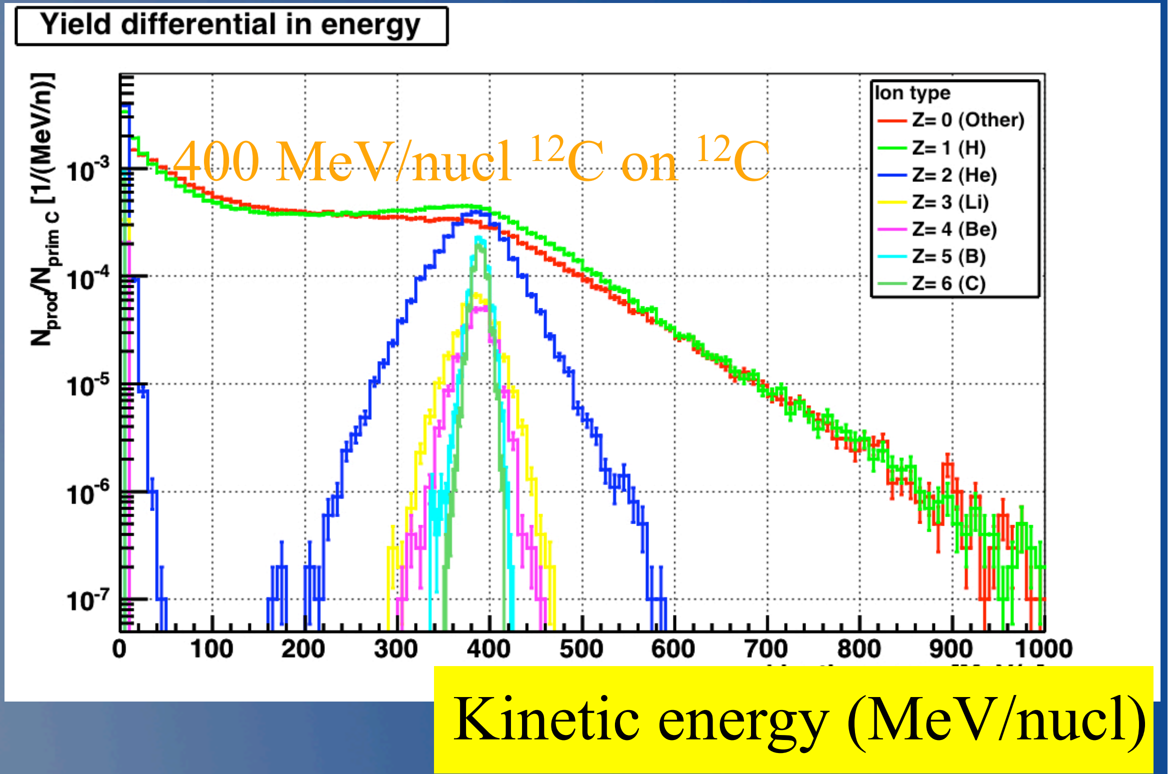
only with detectors at ~ 0°

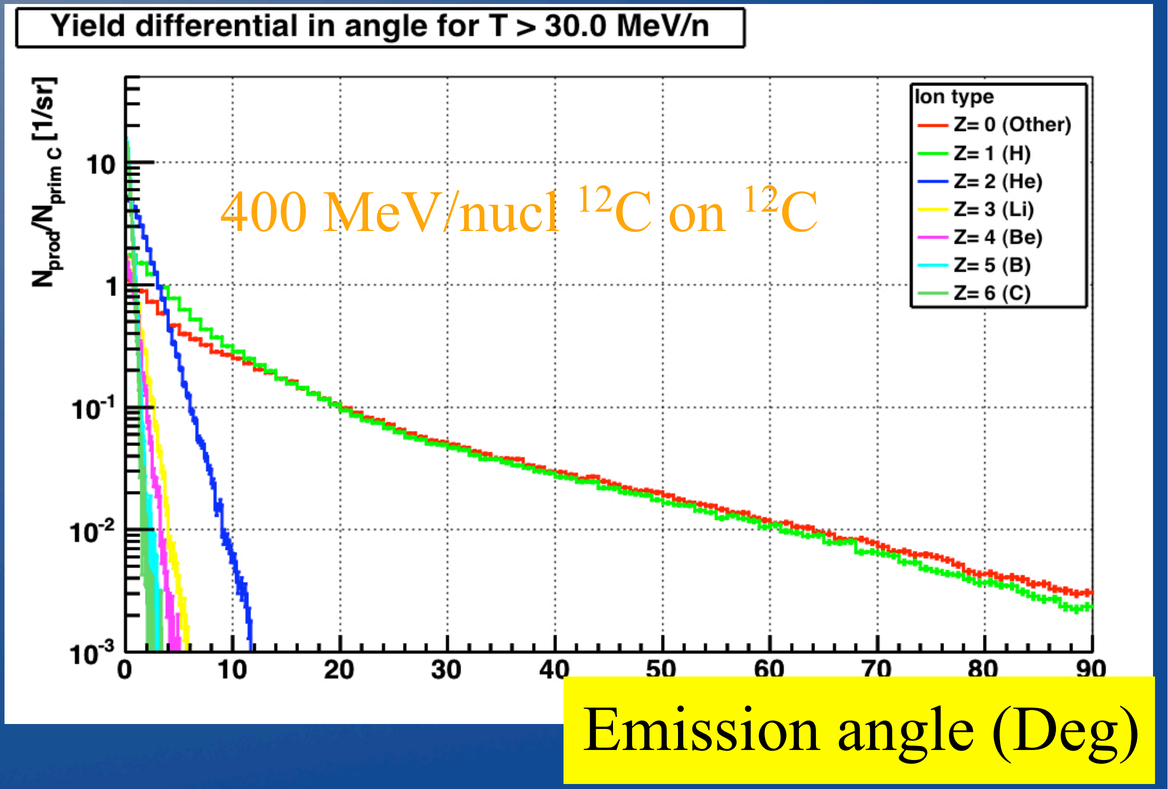
Toshito et al. → Emulsion Chamber: angle ok
E ~OK, low stat, no corr

Courtesy of M. Durante

What do we expect from MC (FLUKA)?

- The Z>2 produced fragments approximately have the same velocity of the ^{12}C beam projectiles and are collimated in the forward direction
- The protons are by far the most abundant fragments with a wide β spectrum $0<\beta<0.6$ and with a wide angular distribution with long tail
- The Z=2 fragment are all emitted within 20^0 of angular aperture
- The DE/DX released by the fragment spans from ~2 to ~100 m.i.p.





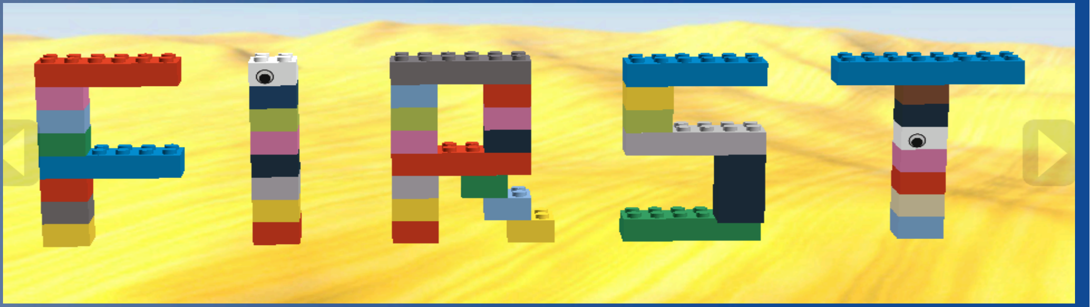
The IDEAL detector

On an event by event basis, the ideal detector should:

- Identify all the fragment produced, i.e. detect charge , with 0 < Z < 6 and detect mass, on all the solid angle
- Detect the energy of the fragments (from 0 to 700 MeV p)
- Measure the emission angle of the fragments (0-90 deg)
- Detect all the correlations, with systematic below few % (rescattering in TG, out of TG fragmentation, etc..)

Starting from scratch, such a detector would be VERY, VERY expensive , would take LONG, LONG time and a VERY LARGE group to be designed and built.

The FIRST collaboration



INFN: Cagliari,LNF,LNS,Milano,Roma3,Torino: C.Agodi, G.Battistoni, M.Carpinelli, G.A.P.Cirrone, G.Cuttone , M.De Napoli, B.Golosio, Y.Hannan, E.Iarocci, F.Iazzi, R.Introzzi, A.Mairani, V.Monaco, M.C.Morone,P.Oliva, A.Paoloni, V.Patera, L.Piersanti, N.Randazzo, F.Romano, R.Sacchi, P.Sala, A.Sarti, A.Sciubba, C.Sfienti, V.Sipala, E.Spiriti

DSM/IRFU/SPhN CEA Saclay, IN2P3 Caen, Strasbourg, Lyon: S.Leray, M.D.Salsac, A.Boudard, J.E. Ducret, M. Labalme, F. Haas, C.Ray

GSI: M.Durante, D.Schardt, R.Pleskac, T.Aumann, C.Scheidenberger, A.Kelic, M.V.Ricciardi, K.Boretzky, M.Heil, H.Simon, M.Winkler

ESA: P.Nieminem, G.Santin

CERN: T.Bohlen

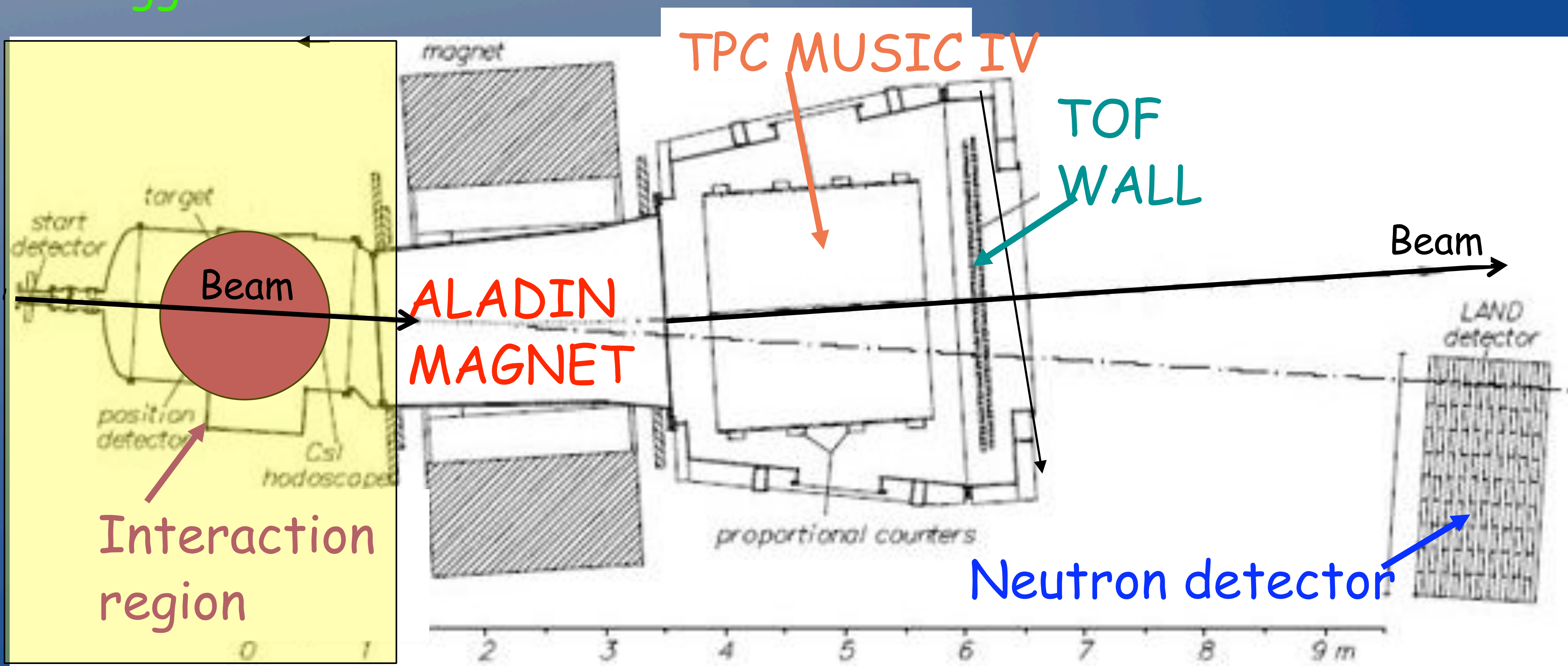
FIRST stands for: Fragmentation of Ions Relevants for Space and Therapy → S371 is the GSI label

The ALADIN setup @GSI

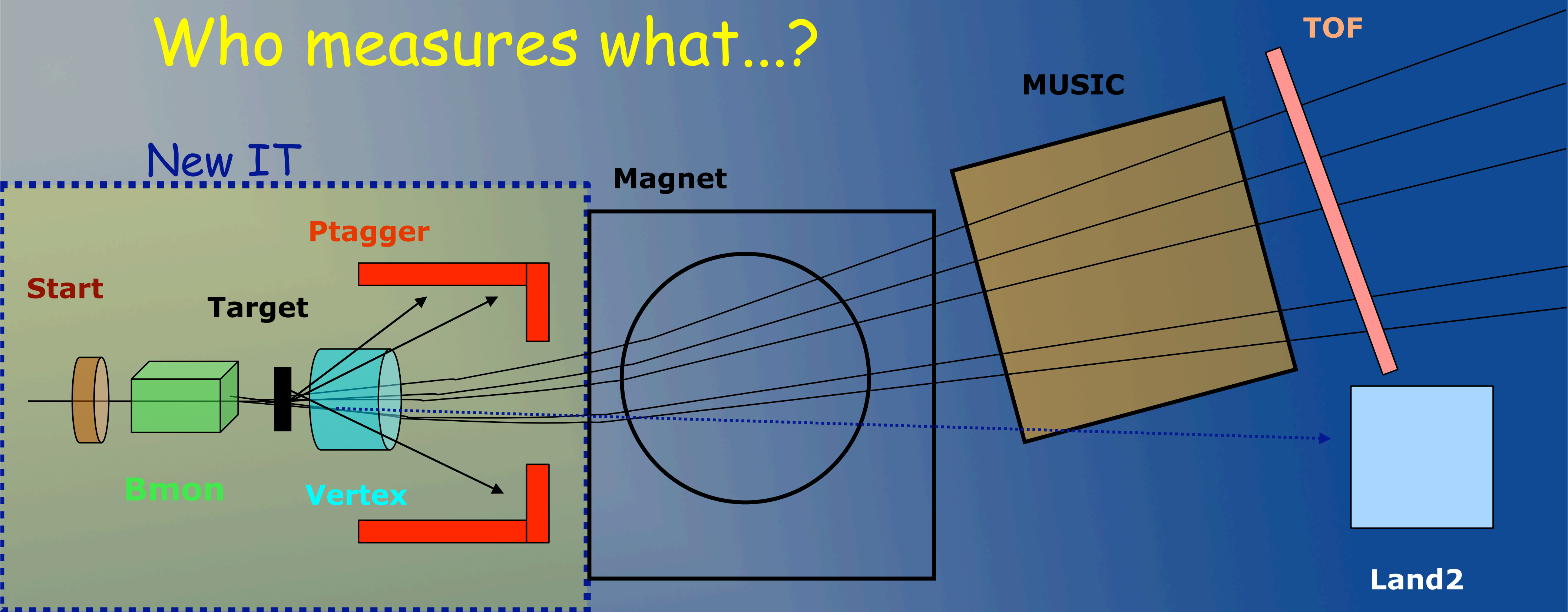
The choice of GSI has 2 main motivations:

- ✓ "Terapeutical" beam of ^{12}C @ 200-400 MeV/u available
- ✓ Existing setup designed for higher E and Z fragments: Dipole magnet, Large Volume TPC, TOF Wall, low angle Neutron detector.

New detectors added to optimize the Interaction Region for this measure: Vertex tracker, Start Counter, Beam Monitor, Proton Tagger



Who measures what...?



TPC → Z/p , θ,ϕ after bending

TPC → Energy loss $\propto (Z/\beta)^2$

Vertex → Fragments emission θ,ϕ

Start and TOF wall → $TOF= L(p,Z,\theta,\phi)/\beta$

Bmon → Beam direction & impact point

Ptagger → Large angle p (He): position, TOF, DE/DX

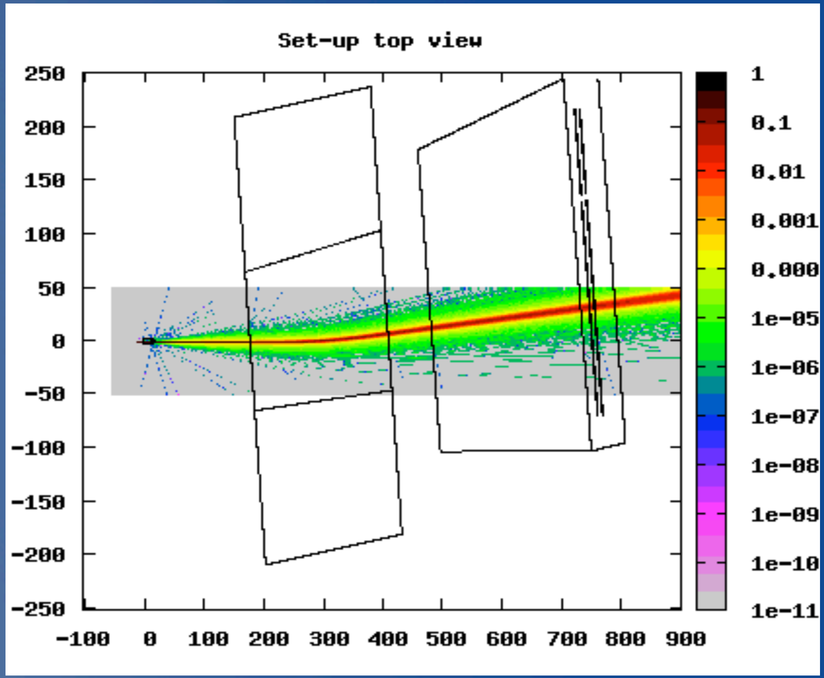
To extract Z, A, θ, E the reconstruction must exploit all the setup information

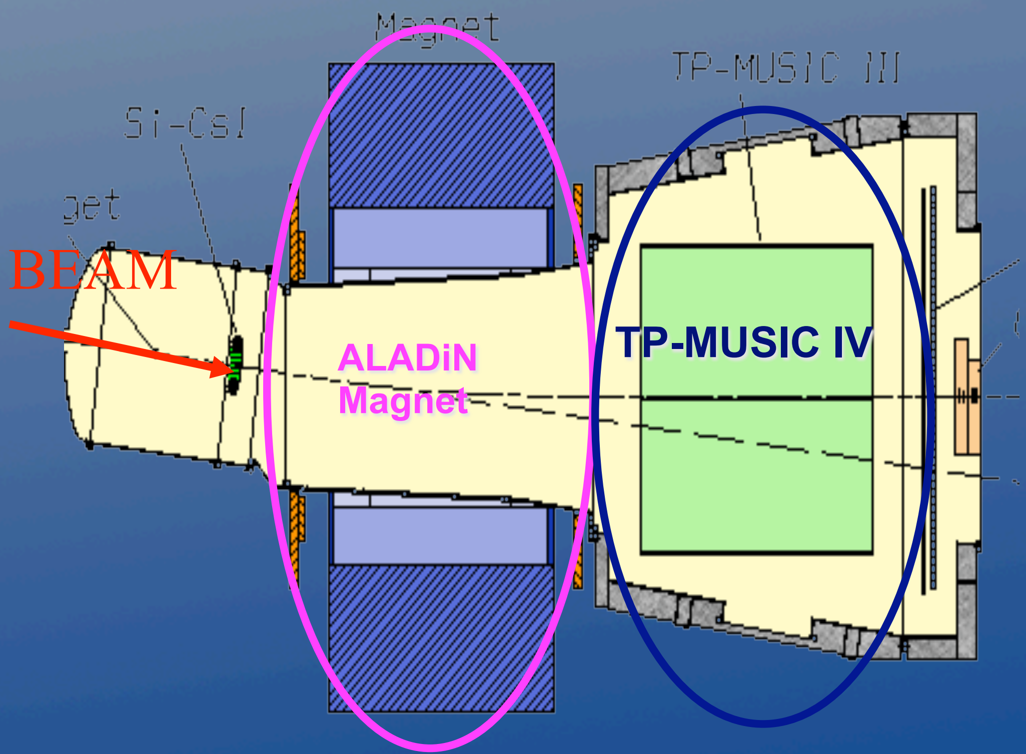
LAND2 → low angle neutron

The Downstream Tracking: Aladin + Music

The core of the setup is Aladin, a large area dipole magnet, coupled with the large volume ($1.8\times0.9\times1.2m^3$) MUSIC IV TPC. The combination provides info on:

- Fragments bending → $R=p/(ZeB)$
- Fragment DE/Dx → $(Z/\beta)^2$





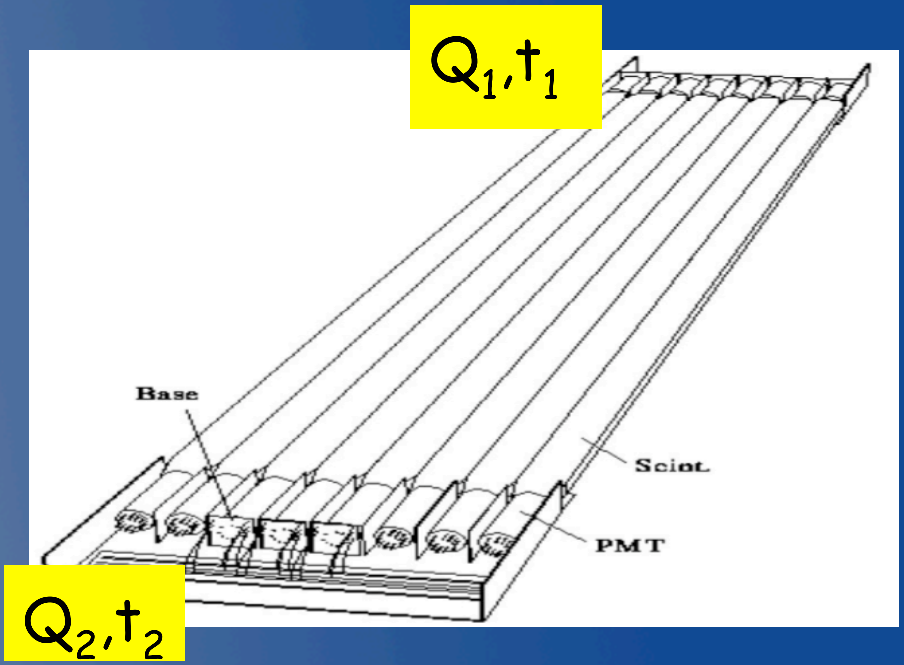
Large dinamic range needed (2-100 m.i.p signal)

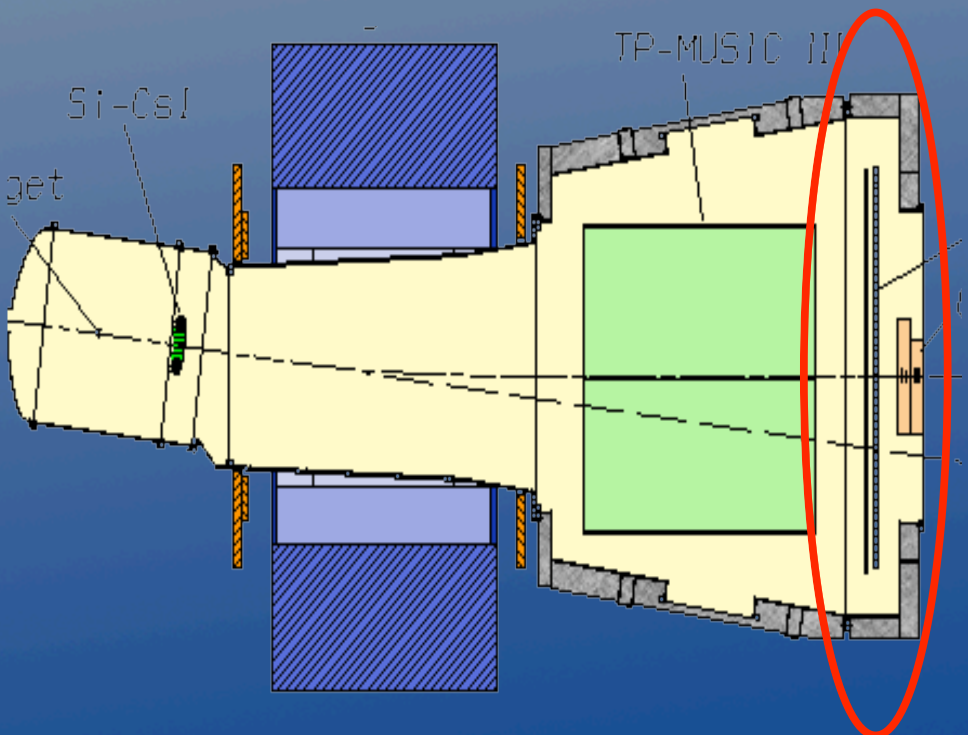
Maximum track rate due to long drift time (~100 μs) of ionization electrons: O(1-2 KHz)

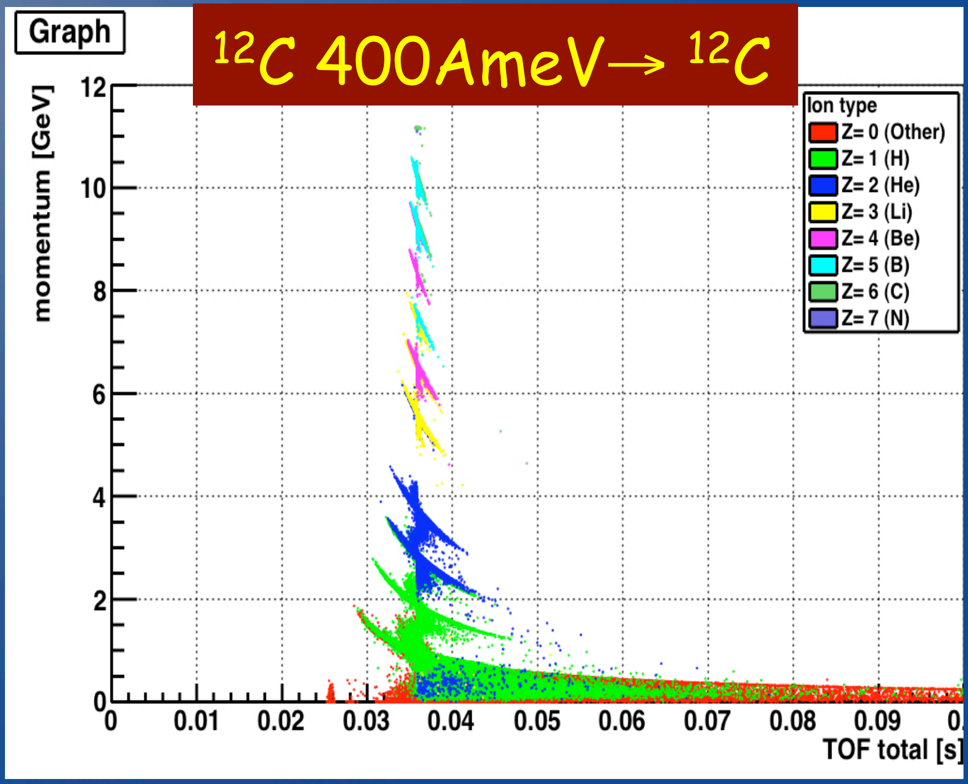
Full geometrical acceptance for frags Z>2, fair for Helium, poor for protons

The TOF WALL

- Gives arrival time and impinging position of the fragments
- Two walls made of 96 2x1x110 cm^3 scintillators read by two PMTs, grouped in 8 slats units
- Expected resolution of 250 ps on 400 MeV/u carbon beam





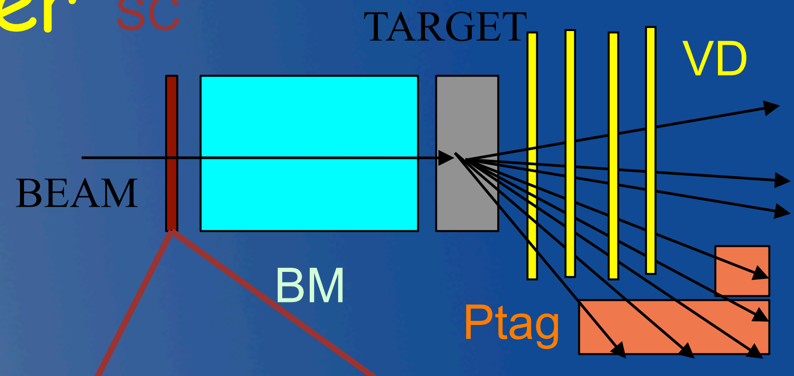


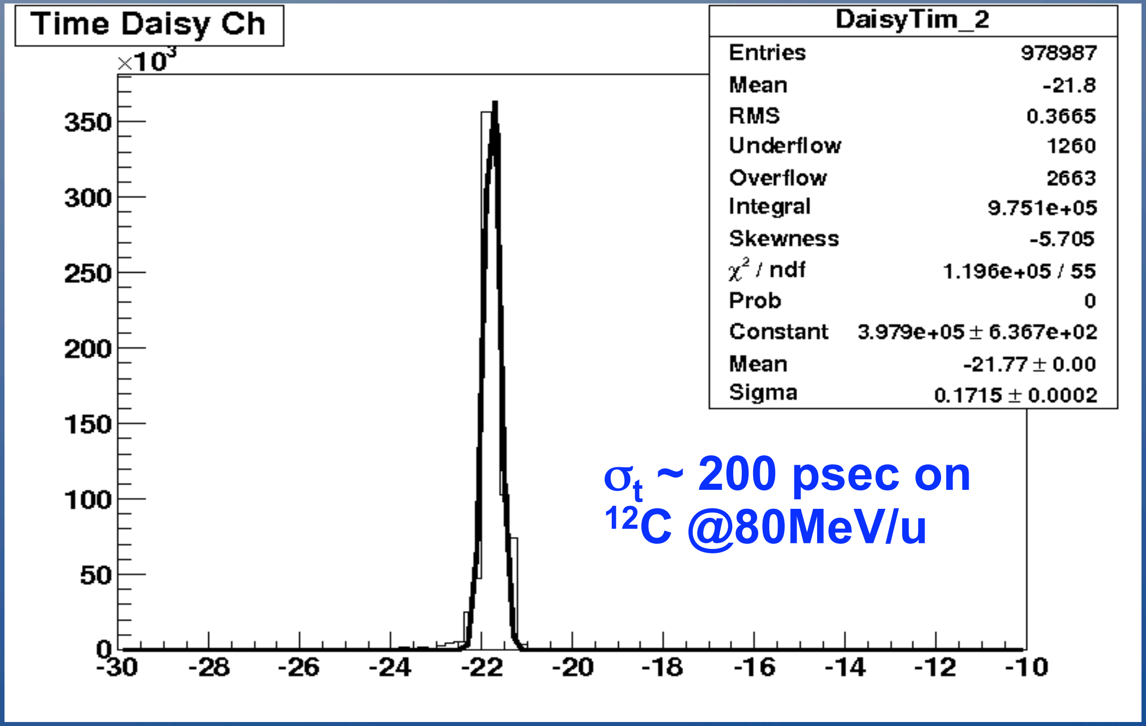
New target region: Start Counter

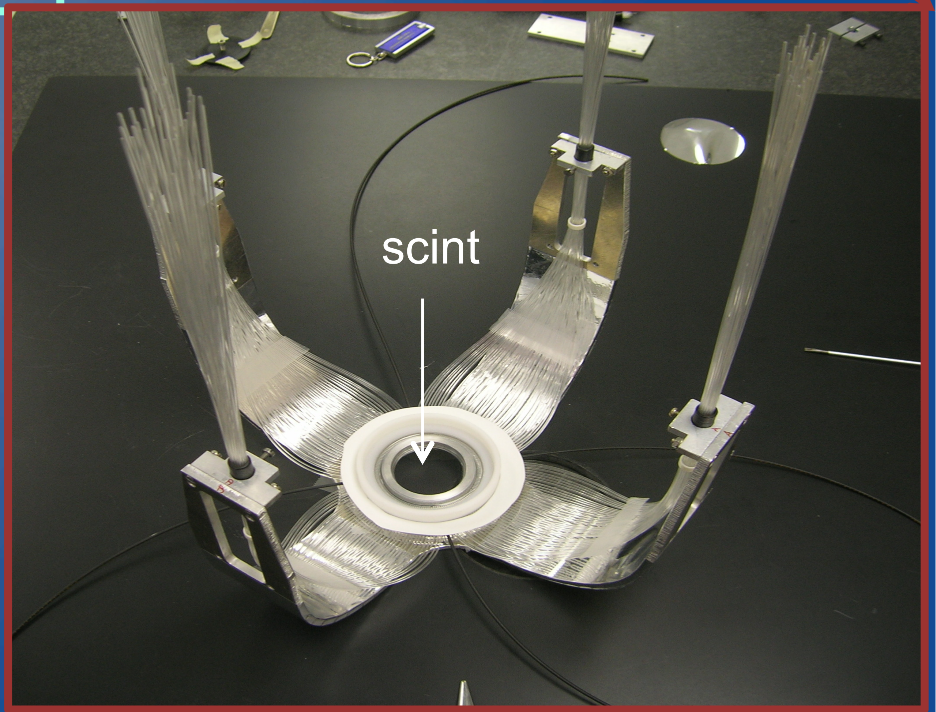
Start TOF measurement. Very thin to avoid carbon interaction. Birks saturate the light yeld

150 micron thick fast scintillator, with radial fibers read-out.

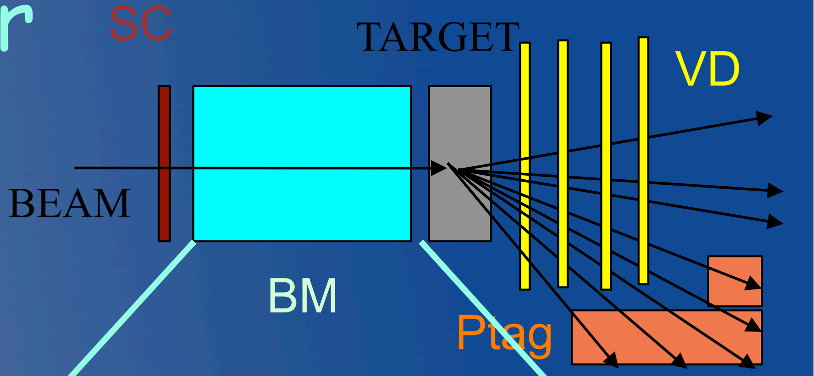
HAMAMTSU H10721-210 40% q.e. 250ps/"(p.e.)



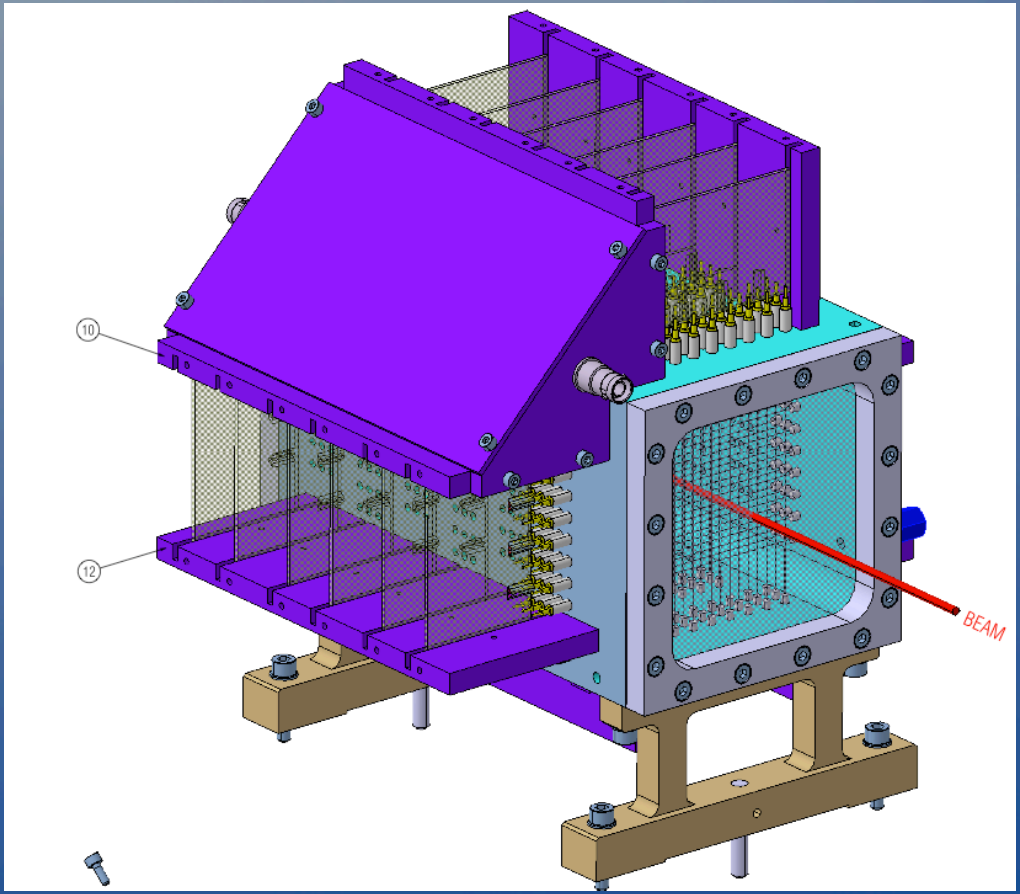


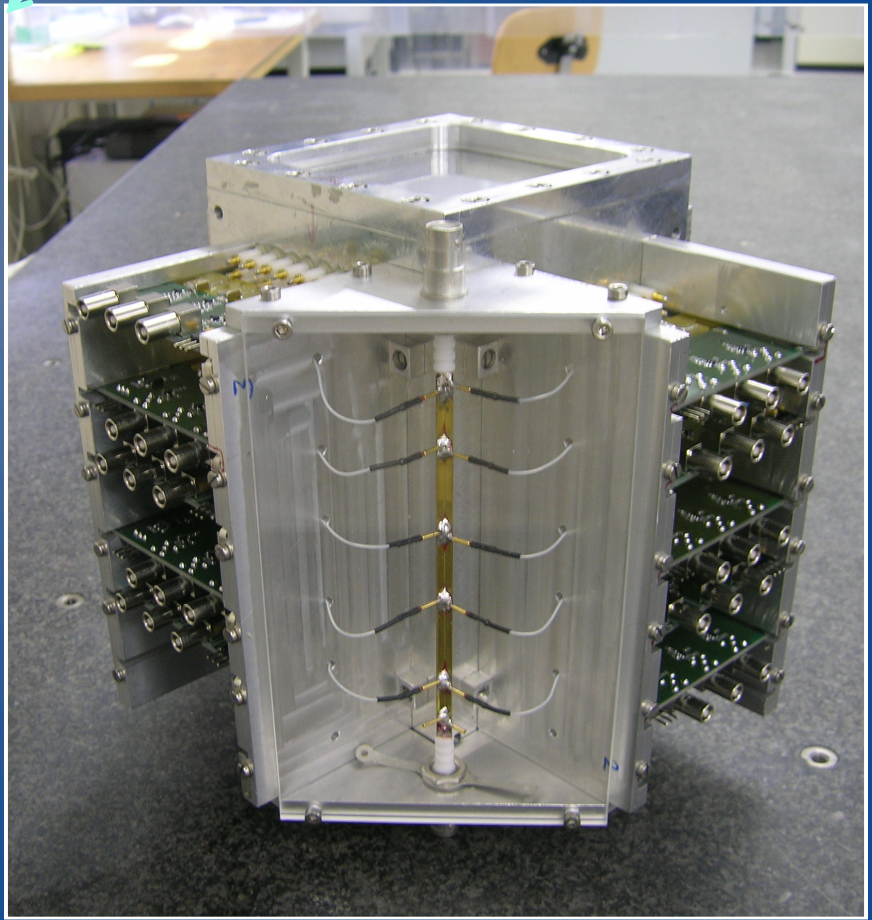


New target region: Beam Monitor

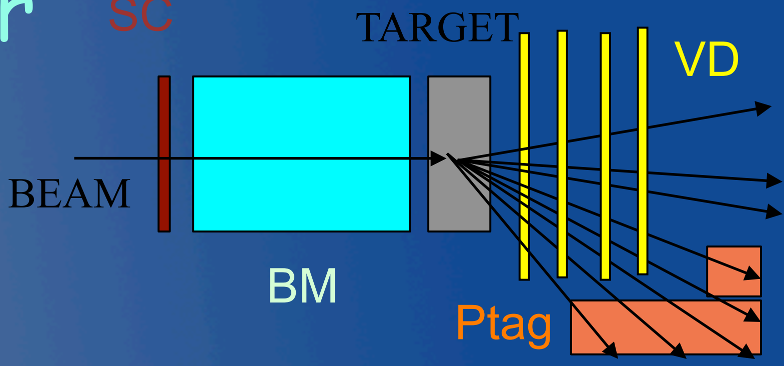


- Drift chamber: measures the impact point of the beam on the target
- 3 rectangular cell/plane (8x5 mm^2)
- 6 planes for each U-V views
- Ar-CO2 89/20 gas mixture





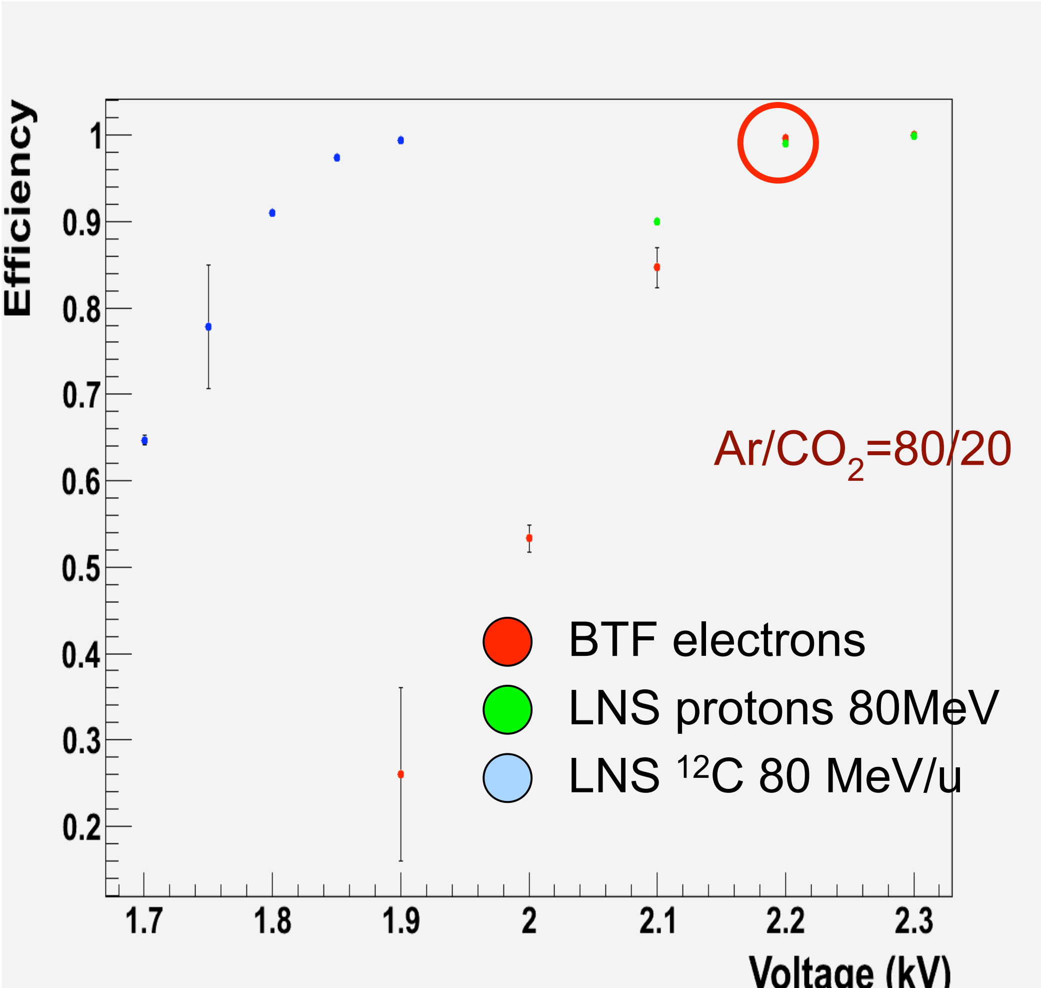
New target region: Beam Monitor

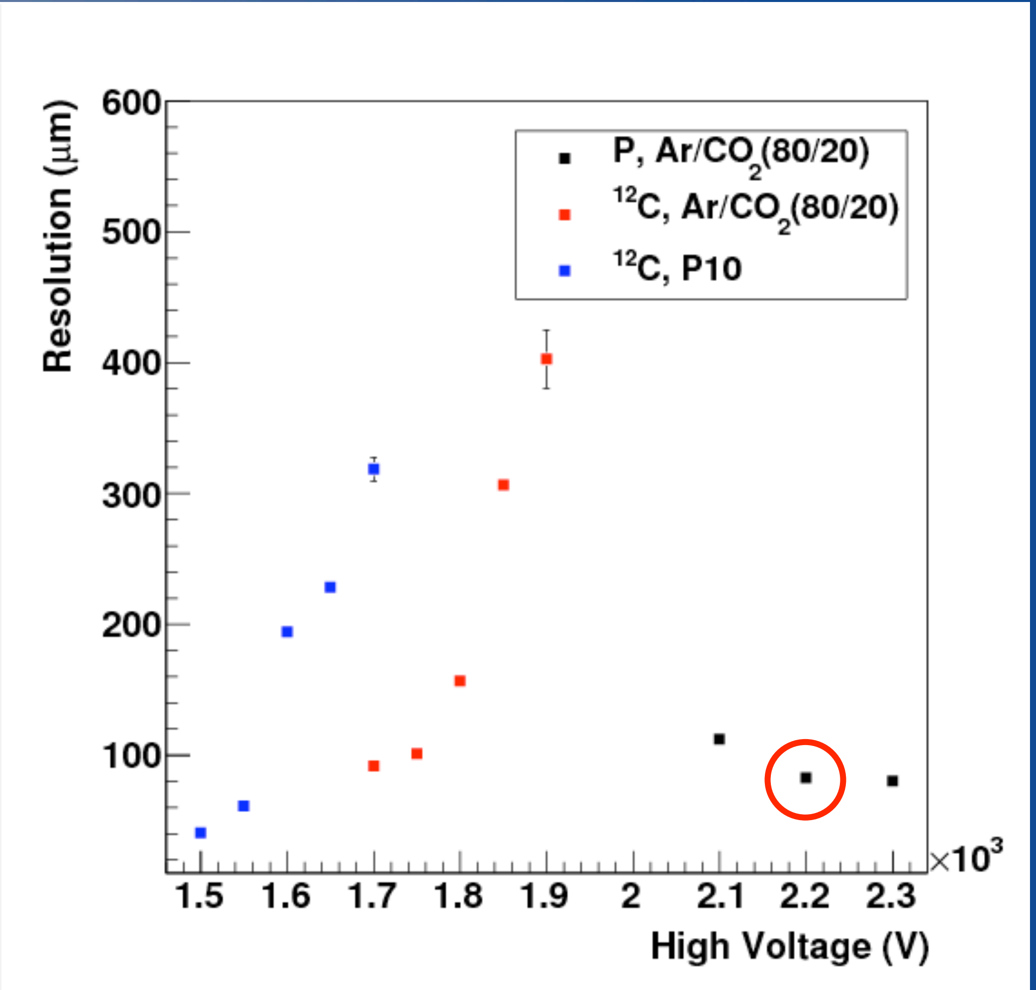


Performance foreseen at GSI ^{12}C beam:

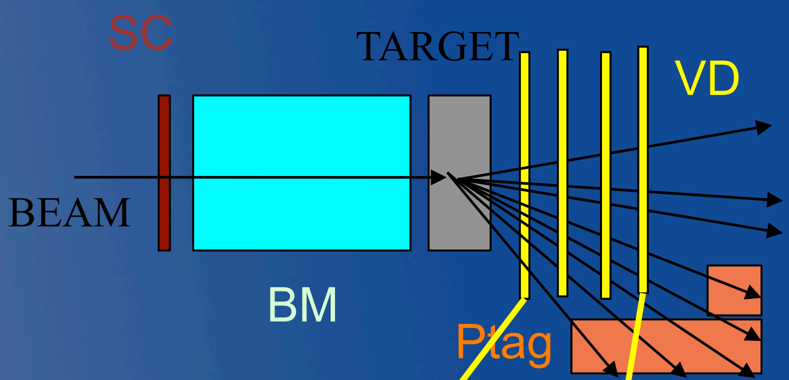
Detector eff≈ 98%

Spatial resolution ≈ 100μm



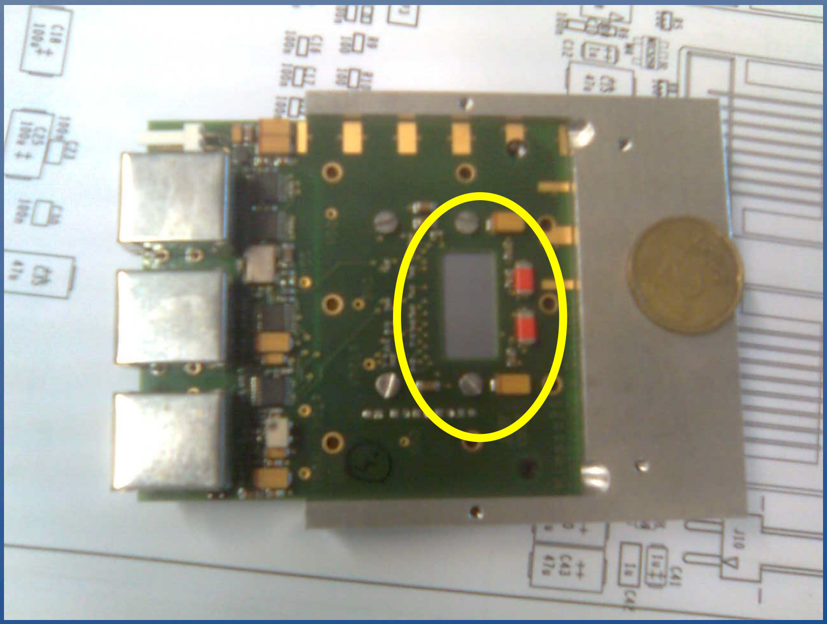


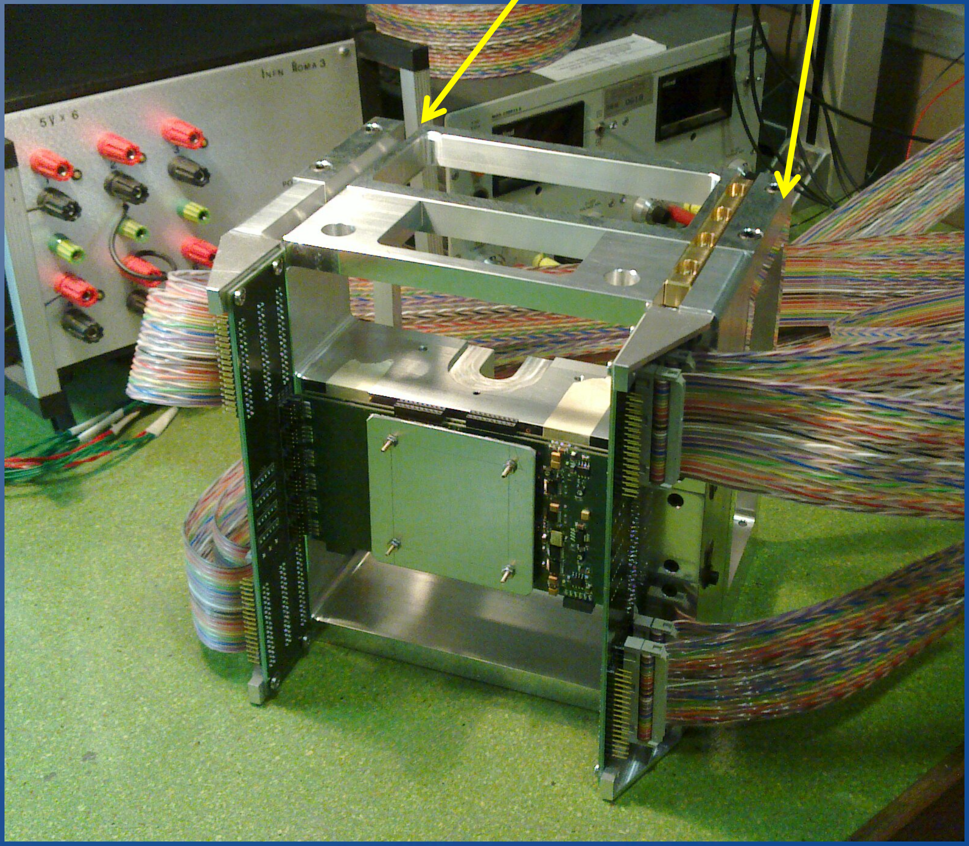
New target region: Vertex



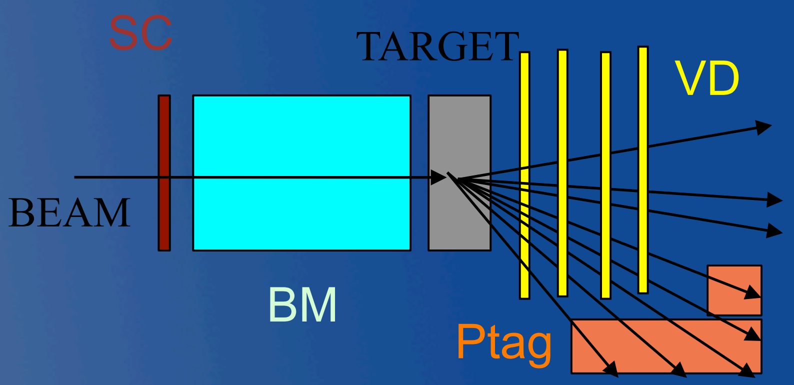
Vertex Detector: track all the charged fragment just downstream the target, from 0^0 to 60^0.

Based on 4 planes of 2x2 cm^2 active area, made of two MIMOSA 26 silicon pixel detectors, 3mm spaced.



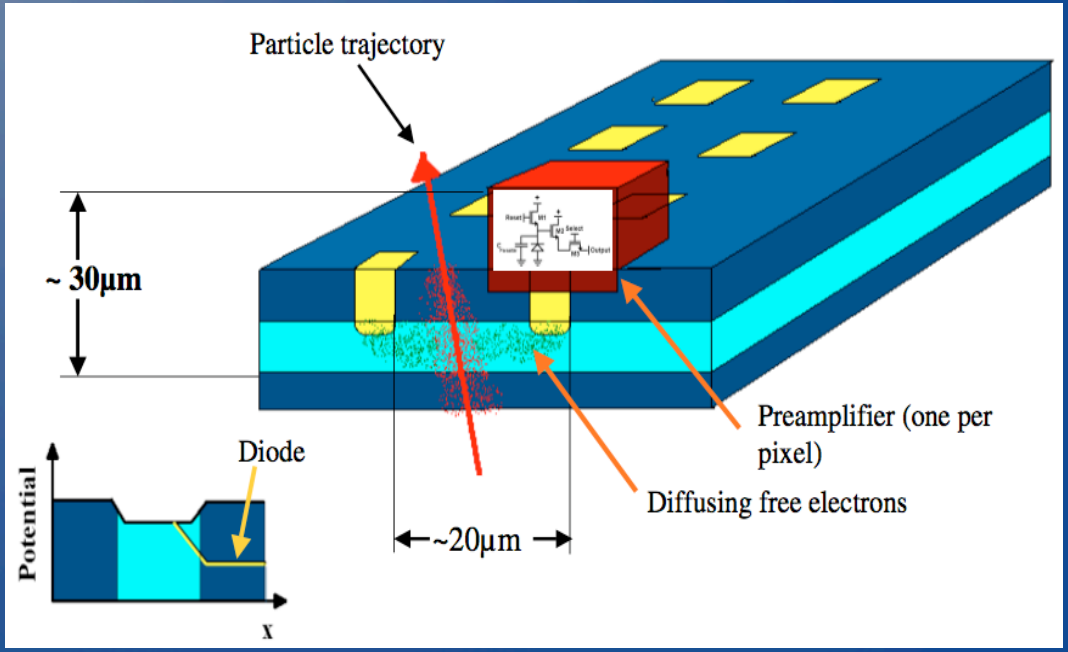


New target region: Vertex

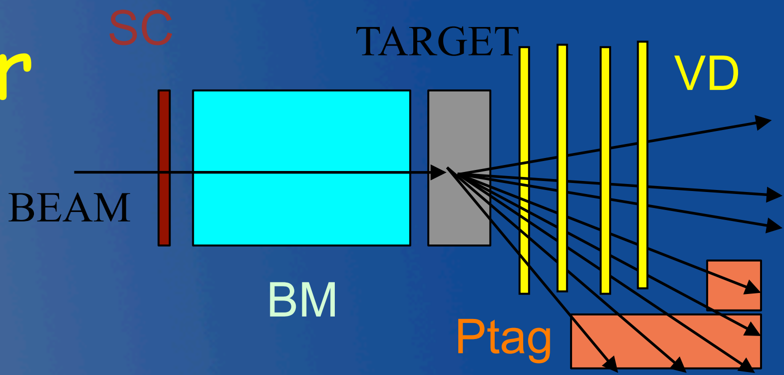


- Active surface :1152 columns of 576 pixels (21.2x10.6mm^2)
- Pitch: 18.4 μm →0.7 Mpixel → σ_{sp}~5μm
- Digital readout at 10 Khz rate
- On chip electronic to process the signal in few μm layer
- Zero suppression on board
- Thinned at 65 μm

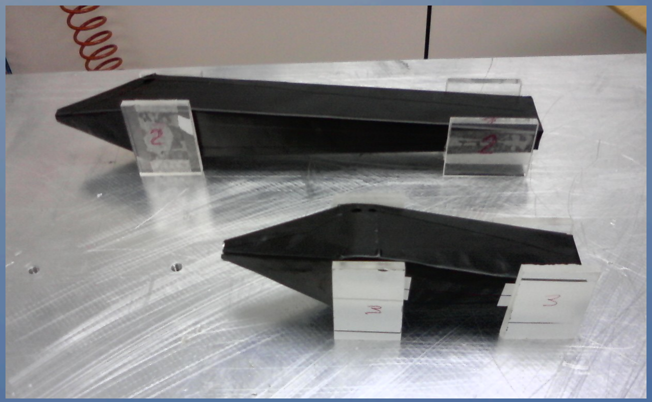
Angular resolution better than 0.2^0
Separation of clusters of pixels ≈50 μm

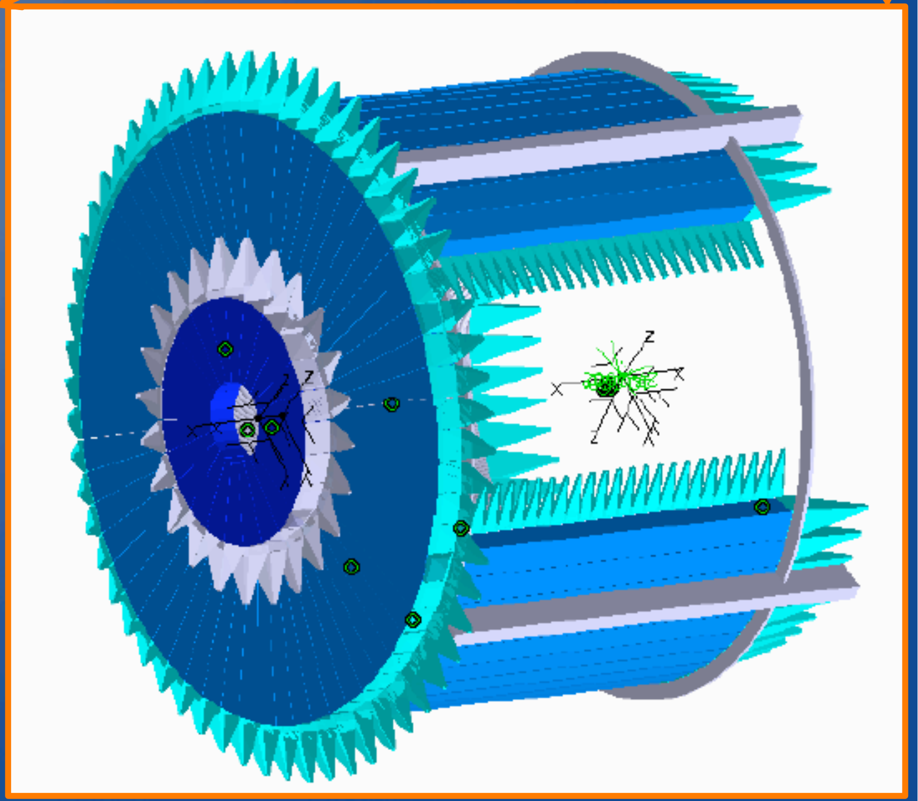


New target region: Proton tagger



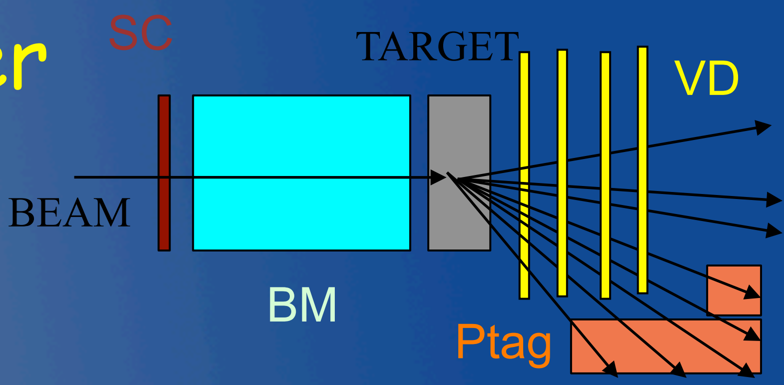
Detect large angle (10^0-60^0) slow protons (He) with β<0.5. Measures TOF, ΔE and impact position. Needs vertex info to obtain DE/Dx and separate He/P :





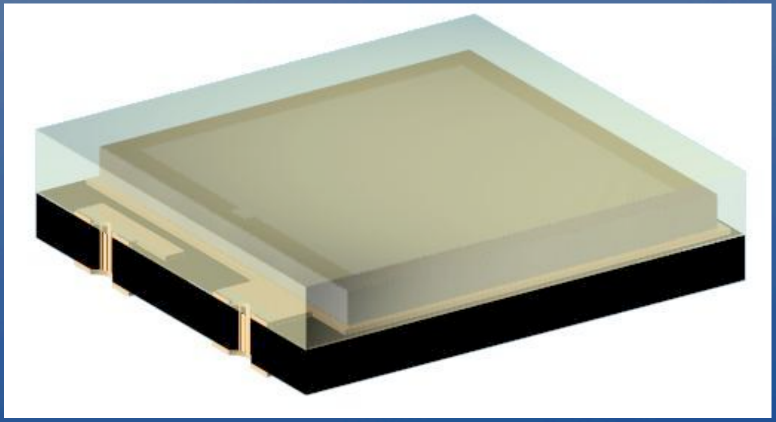
- EJ-200 fast scintillator by Scionix
- Decay time 2.1 ns
- Light yield 10000 photons/MeV
- 425 nm wavelength of max emission

New target region: Proton tagger



The scintillators are read by SiPM:

- AvanSiD (IRST/FBK) 4x4 mm^2 active area
- Peak sensitivity wav 480 nm
- Photon Detection Eff 22%



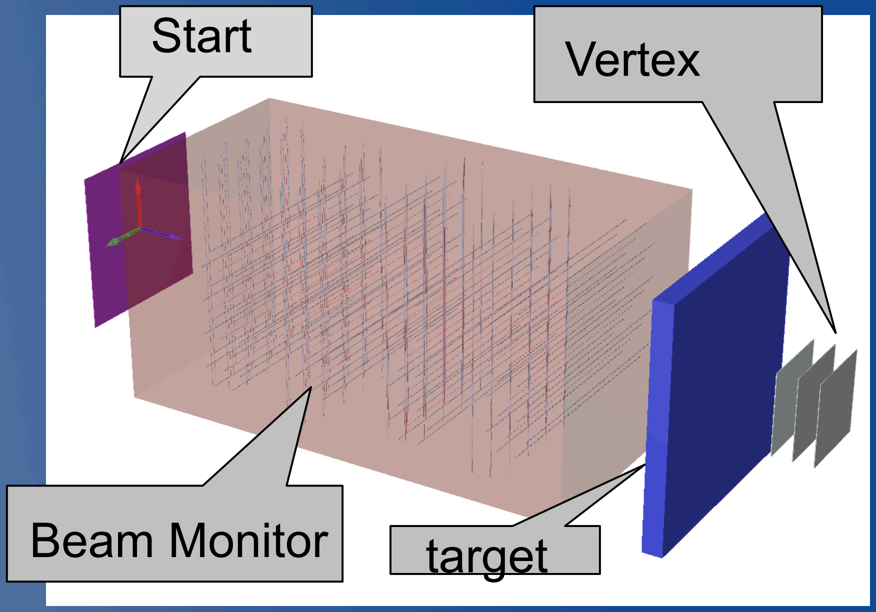
Custom FEE 8 ch boards:

- Individual control of SiPM Supply Voltage
- Signal amplification and split output to TDCs and ADCs
- Trigger signal

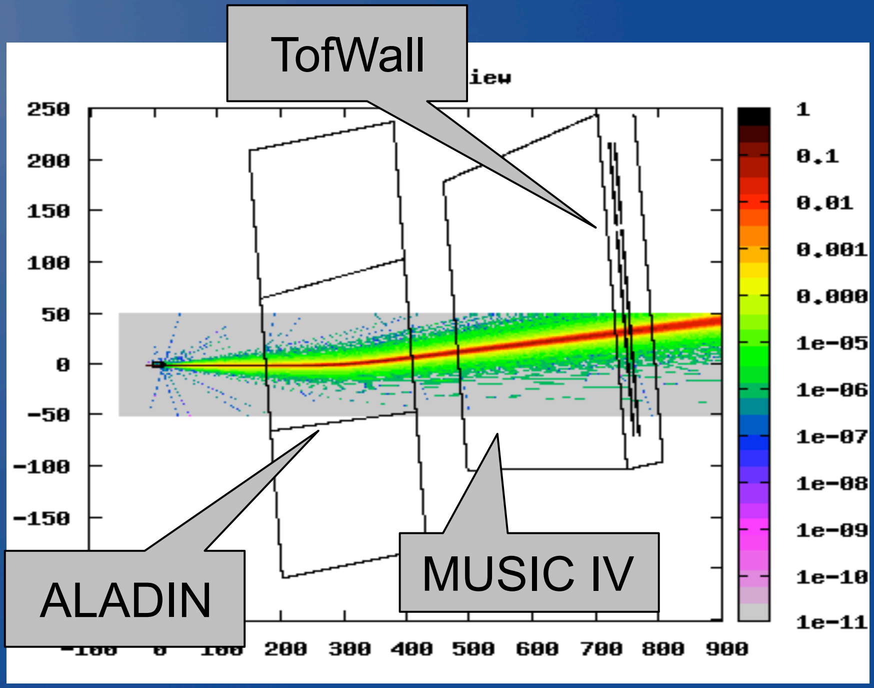
Time resolution achieved on 510 electron beam with two endcap modules: ≈ 300 ps

Not only detectors...

- Reconstruction software: the redundancy of information from the detecto must be properly combined to exploit PID, detect out of target fragmentation, rescattering in the target an so on..
- Detector simulation is a central part of the analysis: detector efficiencies & geometrical acceptance (and correlations!!) can be taken into account only by MC
- DAQ, FEE, TRIGGER, Calibrations.. anything can induce systematic errors on the measure (es: dead time, pile up, alignment, stability of det. response)



FLUKA SIM



Summary & conclusions

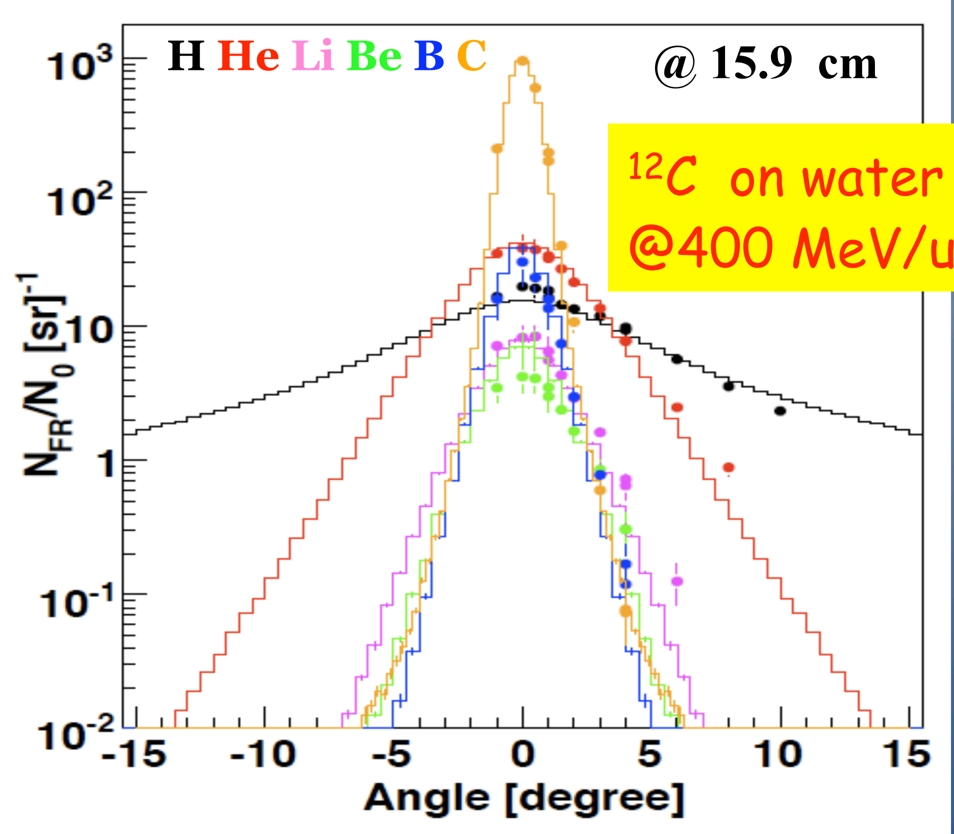
- ✓ An international collaboration (France, Germany, Italy) is going to measure at GSI the $d^2\sigma/d\theta dE$ fragmentation cross section of interest for the application of hadrontherapy to clinical routine.
- ✓ The detector is an evolution of a pre-existing setup, optimized for the detection of the Z<6 fragment with large angular acceptance and accuracy at the few % level
- ✓ Data taking will be during summer 2011 (August)
- ✓ In future (2013) the experimental setup can be seen as a facility to measure the fragmentation of light ions (He, Li, O projectiles on different target of interest) and for fragmentation measurement of interest for space radioprotection (mainly Fe projectiles)

Spare slides

Mixed Radiation Field in Carbon Ion Therapy

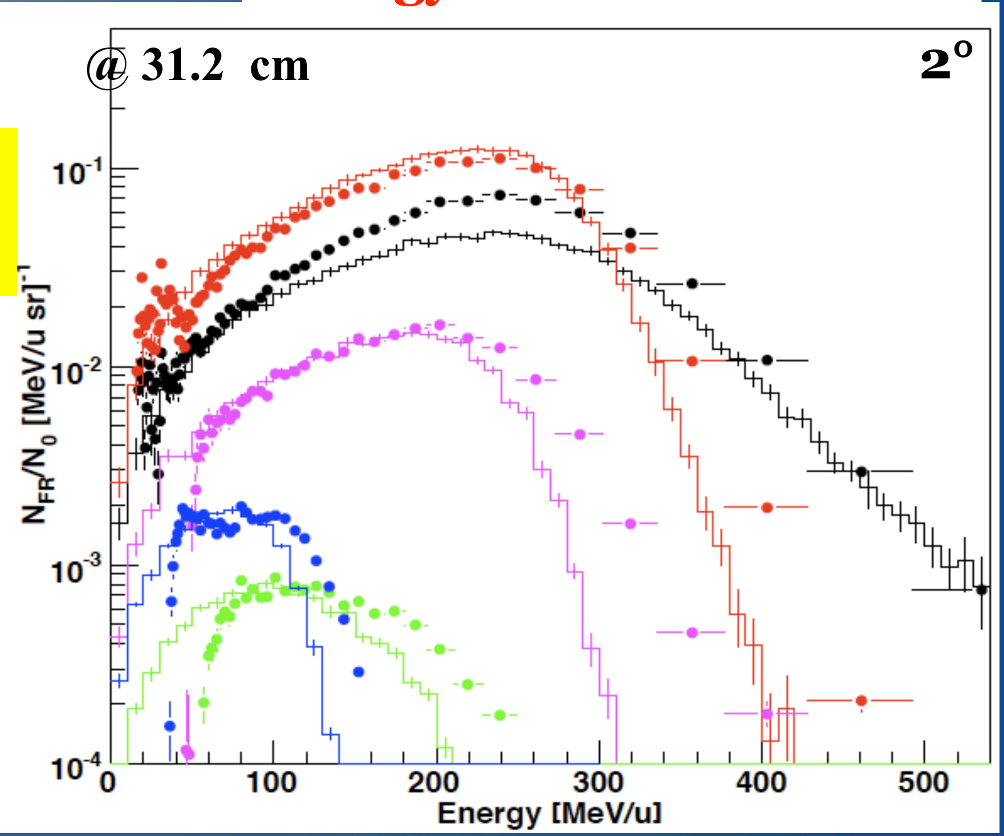
The secondary fragments broad the lateral dose profile and go beyond the tumor region.

Angular distribution



^{12}C on water
@400 MeV/u

Energy distribution



FLUKA benchmark against thick target data

Exp. Data (points) from Haettner et al, Rad. Prot. Dos. 2006
Simulation: A. Mairani PhD Thesis, 2007, PMB *to be published*

Courtesy of Andrea Mairani

The FIRST experiment time schedule

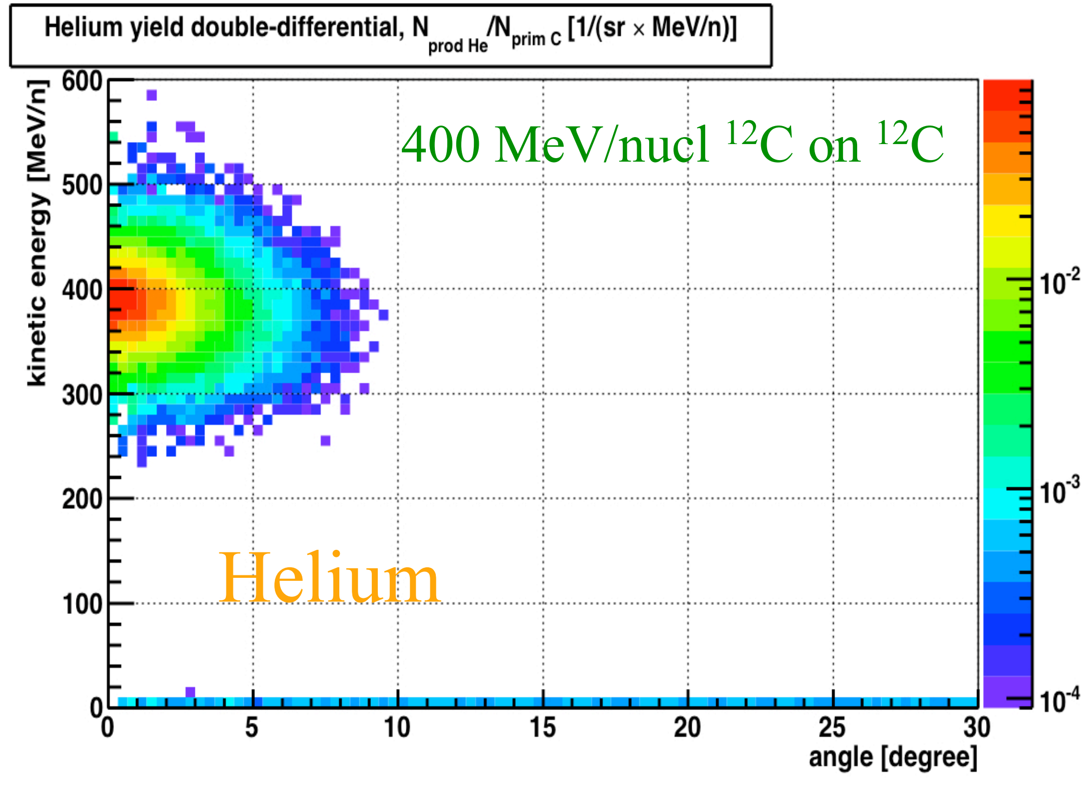
Target: Double differential cross section (with respect to the emission θ and E) for each of the produced fragments in C-C, C-Au (Fe-C, Fe-Si, O-C) interaction, with 3% accuracy.

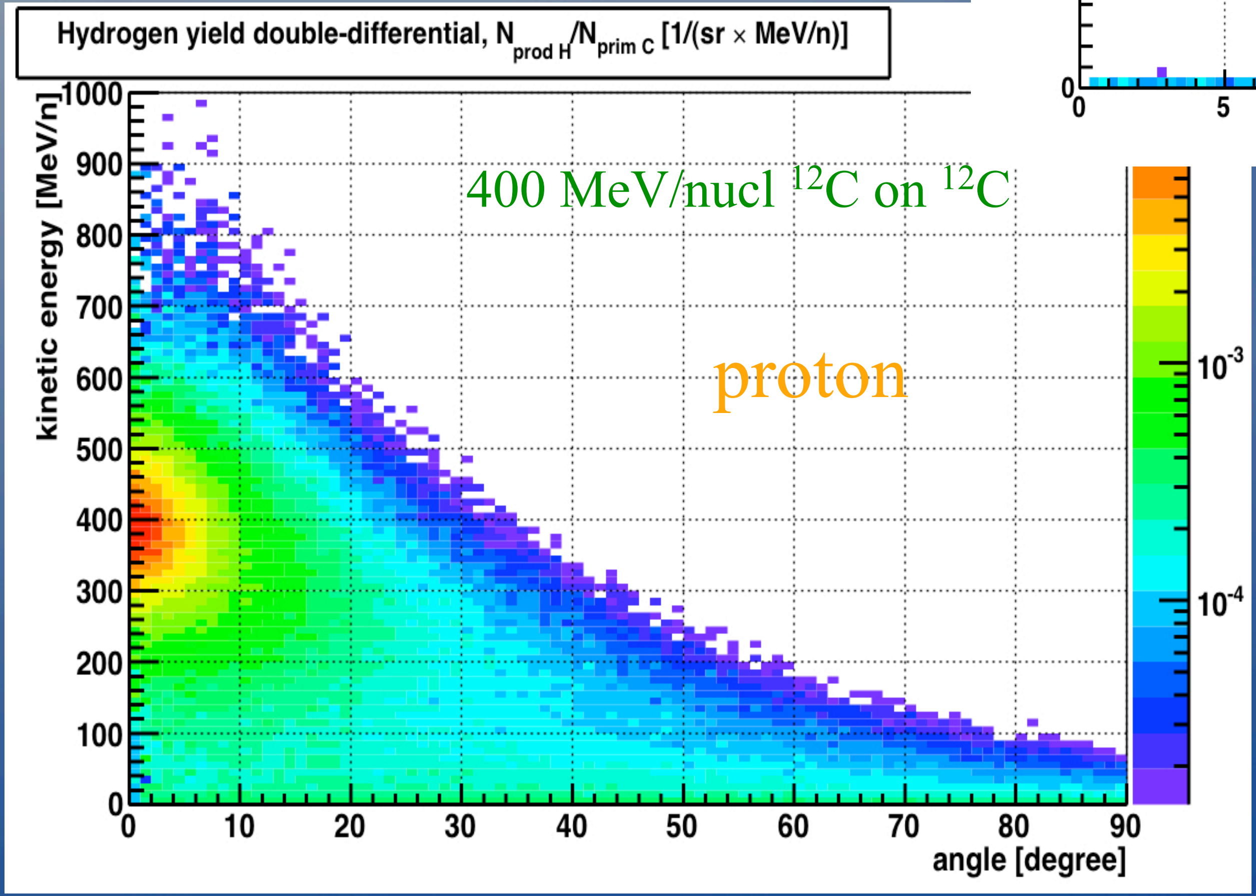
27 Feb. 2009 the GSI G-PAC approved the beam for FIRST in mid 2011

• **Control of setup**	**1 day per period of beam**
• **C+C @ 0.2, 0.4 and 1.0 AGeV**	**6 days**
• **C+Au @ 0.2, 0.4**	**4 days**
• **O+C @ 0.2, 0.4**	**4 days**
• **Fe+Si @ 0.5 and 1.0 AGeV**	**4 days**
• **Fe+C @ 1.0 AGeV**	**2 days**
• **Calibration**	**2 days**

Protons and He: angle vs energy

At 400 (200) Mev/nucl beyond 10^0 (15^0) is emitted only a lot of protons!!



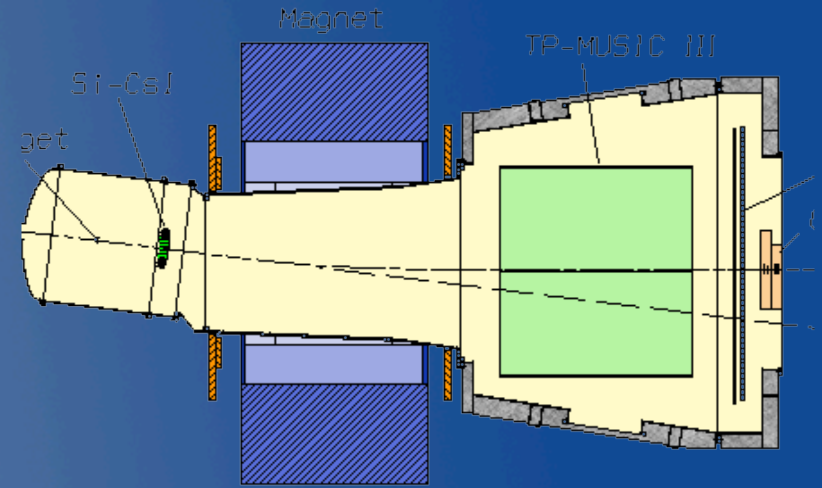


CAVEATs:

a) How much is FLUKA reliable on the tails?

b) Low energy proton release all their energy in the patient

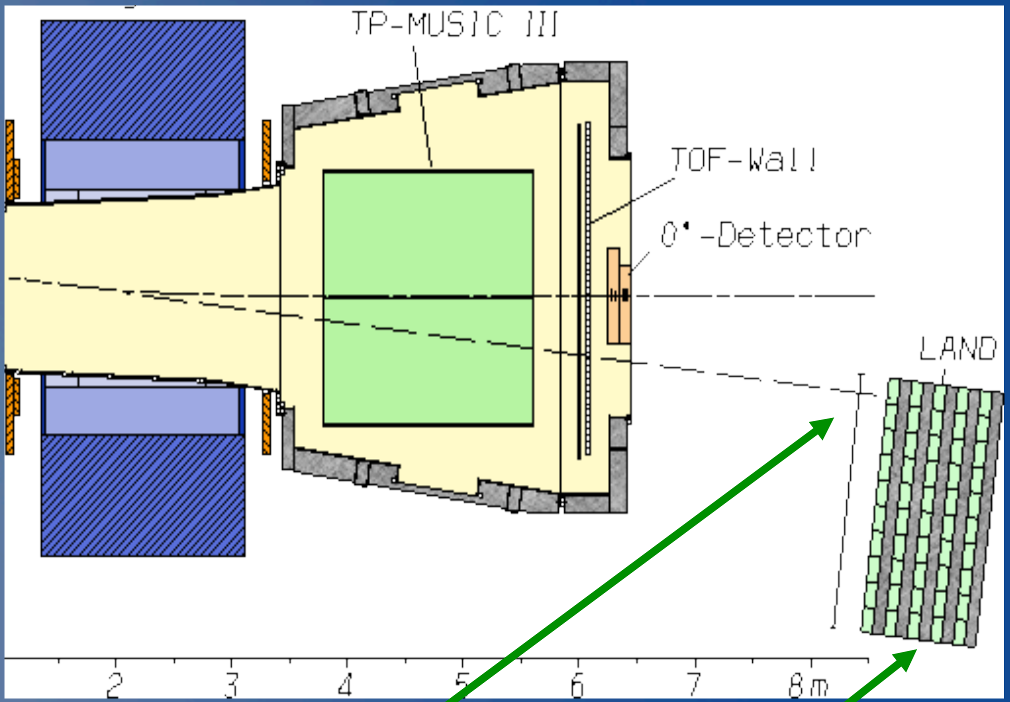
Some other boundary conditions

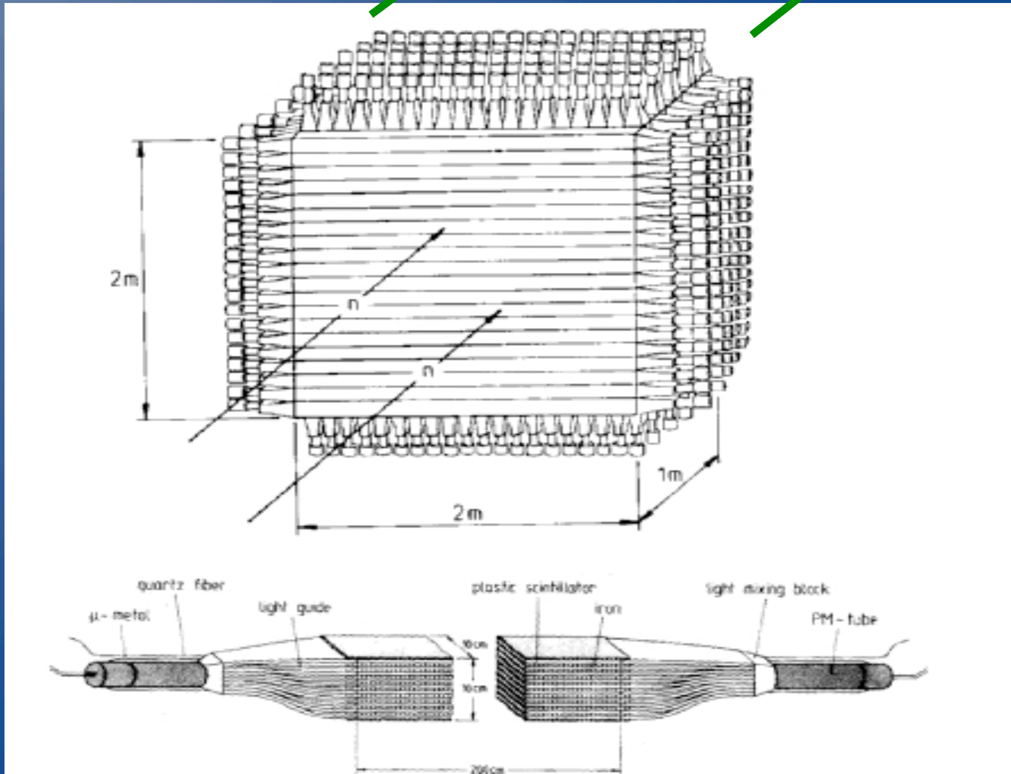


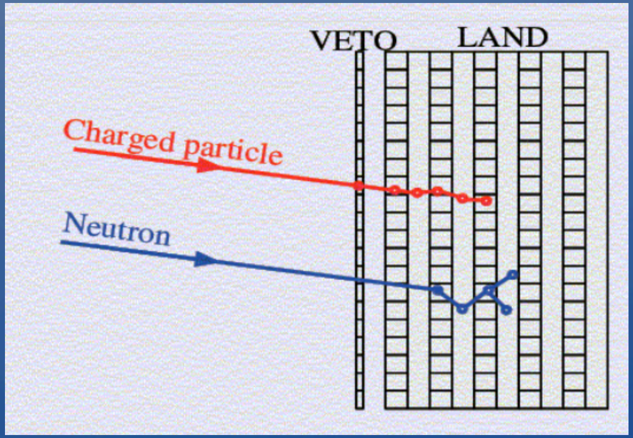
- Out of target interactions must be kept below ~ per cent level with respect to on target interactions.
- Trigger rate must be ≤ kHz due to pile-up in the MUSIC TPC (10% pile-up @4kHz)
- Considering a maximum target thickness of 10 mm, we expect at maximum ~10% of interaction probability.
- The beam spot for Carbon projectiles can be ~ 3mm FWHM
- The geometric acceptance of the ALADIN magnet for the produced fragments is ~4° in θ and ~9° in ϕ

LAND, the neutron detector

- Active volume: 2x2x1 m^3
- Divided in 200 paddles 200x10x10 cm3.
- Each paddle made of 11 sheet of iron ad 10 sheet of scintillator 5 mm thick
- Veto in front of the detector for charged particle



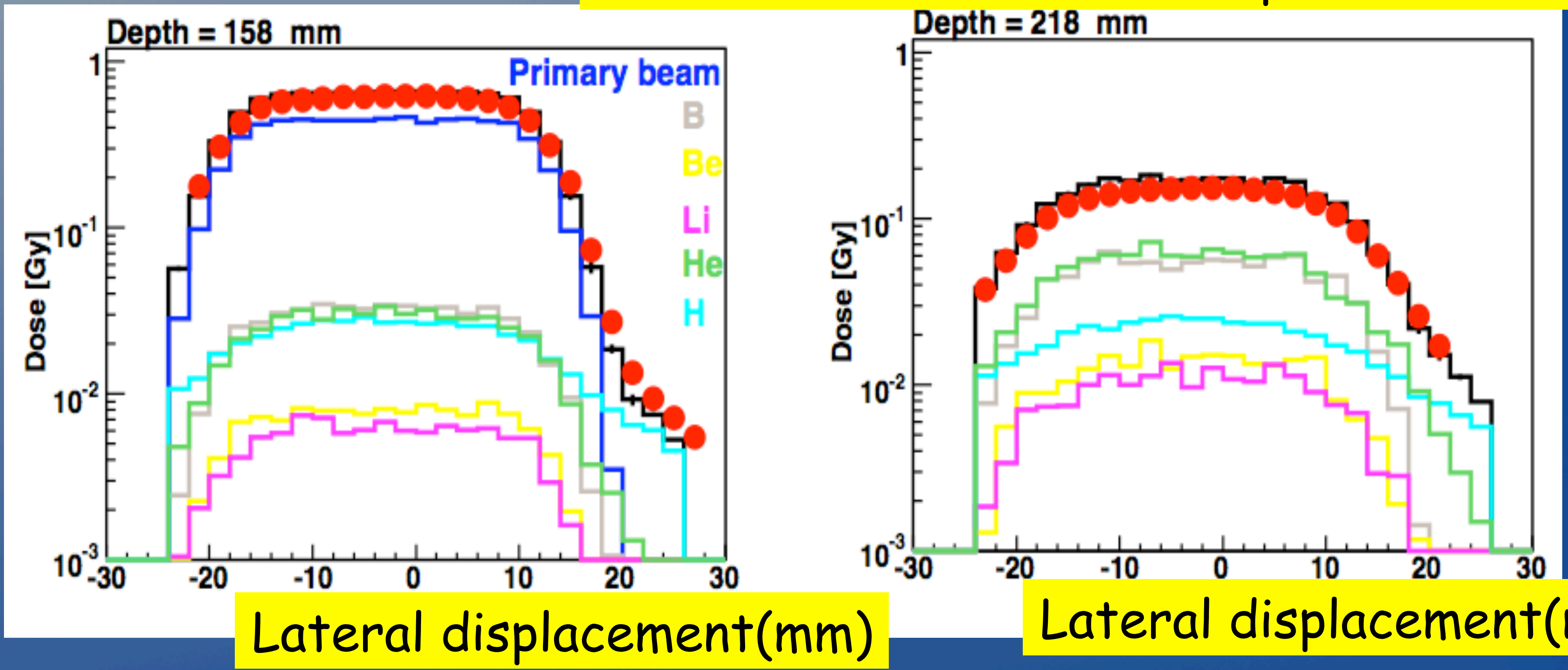




FRAGMENTATION OF CARBON IONS

The secondary fragments, especially the lighter ones such H and He, broad the lateral dose profile.
Effect gets more and more important approaching, and going beyond, the Bragg Peak i.e. the tumor region

SOBP centered al 20 cm depht in water

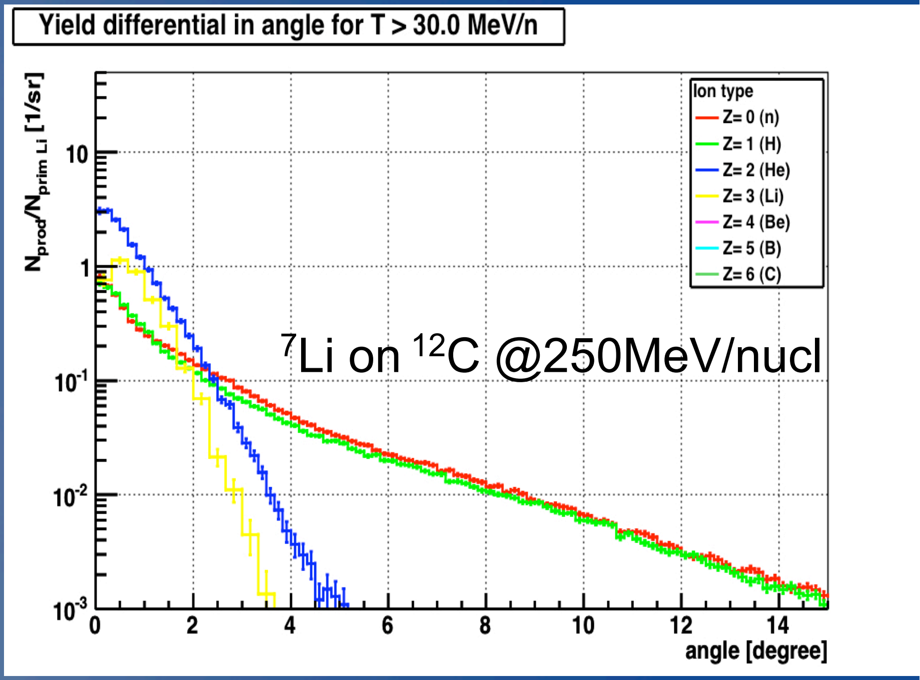


Data: S. Brons & K. Parodi (GSI)
MC-FLUKA: A. Mairani PhD Thesis 2007 Pavia

Courtesy of Andrea Mairani

Future... i.e. After 2011 !!!

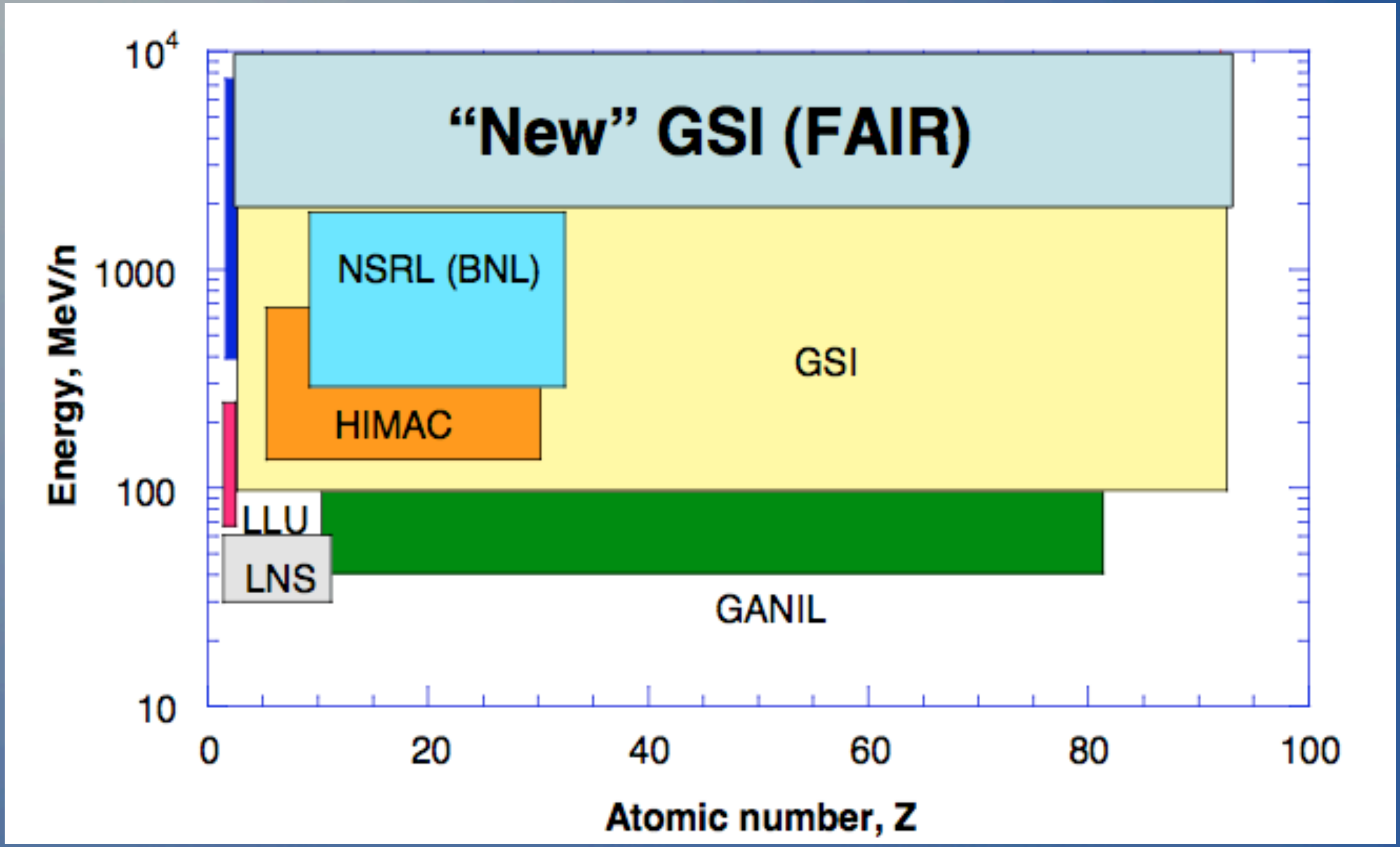
- There is a widespread interest in light ions fragmentation measurement, es: ^{7}Li (April 2010) and ^{16}O (second half of 2010) at GSI or ^{3}He + ^{12}C (thin target) @ 45 e 85 MeV/nucl at iThemba (proposal in prep.)



- The FIRST detector is be able to measure the Fragmentation also with ions like Helium, Litium or Oxigen → GSI interest will be crucial for backing up these measures

The experimental setup is also designed to measure fragmentation cross section also with heavier ions like Fe @ 1Gev/nucl → would be interesting for radio protetion in space. ESA and NASA are also interested in this measures

FIRST: where and when...?

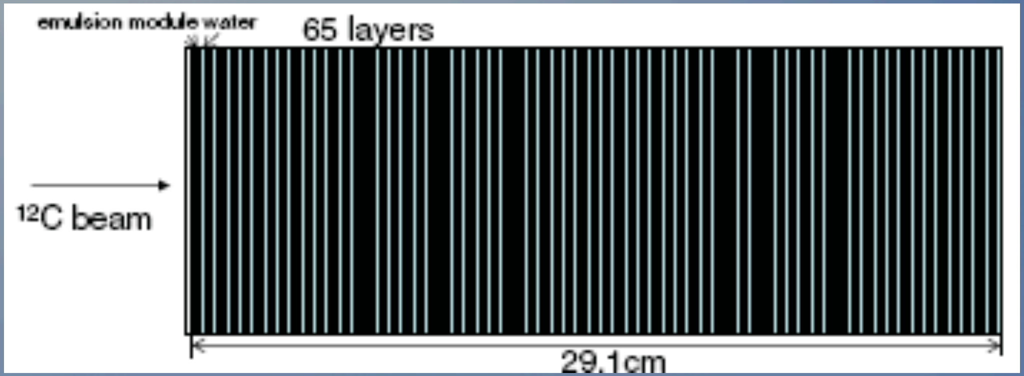


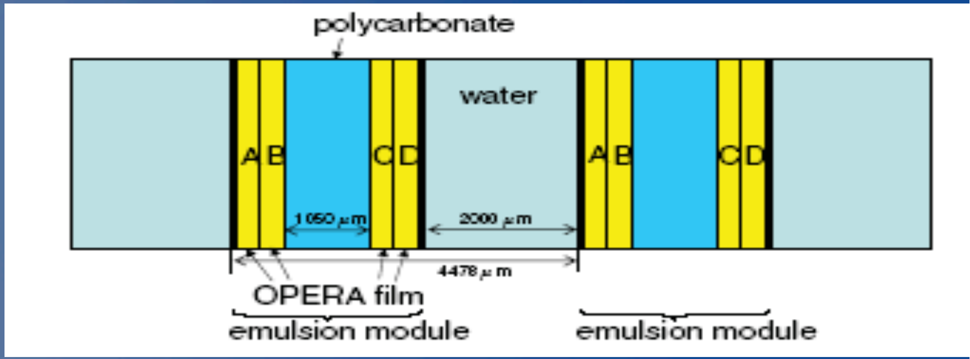
Data taking in august 2011

At GSI there are the proper beam 12C @200-400 Mev/u and a previous setup that has been designed for a similar (but not the same) physics. For our goal we improved, adapt and optimize an existing experimental setup.

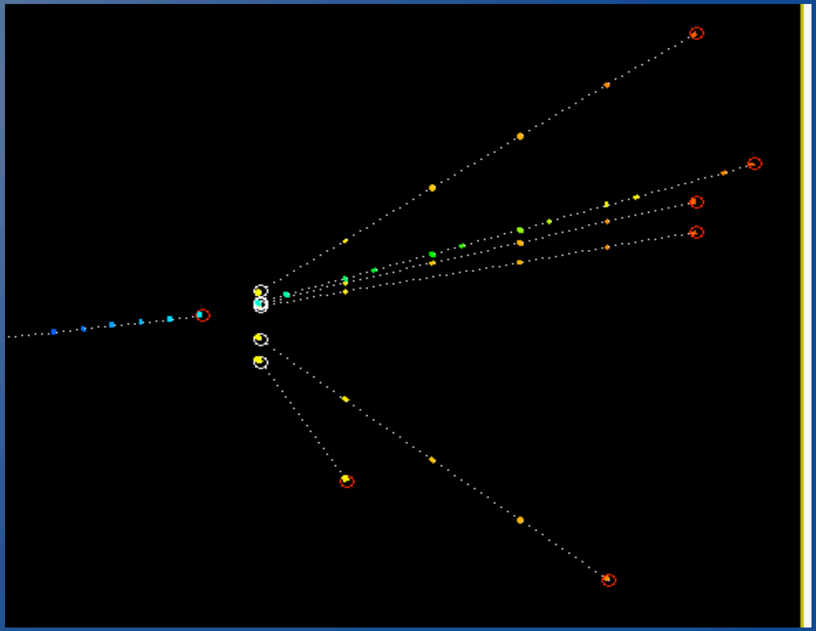
A "new" approach Emulsion Chamber

Density grain is proportional to energy loss





- ✓High spatial resolution (~μm)
- ✓High angular resolution (~0.5 mrad)
- ✓Multiparticle separation
- ✓Refreshing method for extending the dynamic range



Toshito. et al., *Phys. Rev. C., 2008*

LAND, the neutron detector

- Active volume: 2x2x1 m^3
- Divided in 200 paddles 200x10x10 cm3.
- Each paddle made of 11 sheet of iron ad 10 sheet of scintillator 5 mm thick
- Veto in front of the detector for charged particle