VI Scuola Nazionale "Rivelatori ed Elettronica per Fisica delle Alte Energie, Astrofisica, Applicazioni Spaziali e Fisica Medica

INFN Laboratori Nazionali di Legnaro, 23-27 Marzo 2015

Rivelatori di frammentazione di particelle: applicazioni nello Spazio e in terapia

V. Patera

Universita' di Roma "La Sapienza" & INFN Roma1

Outline

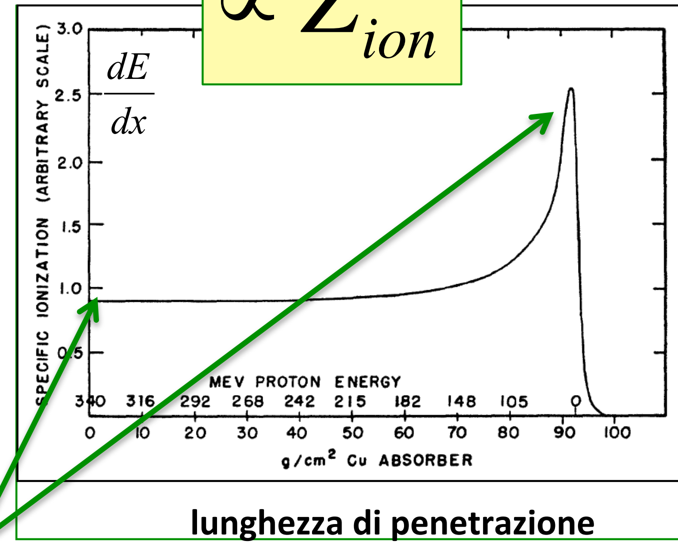
Bouncing from fundamental physics to applied physics and back...

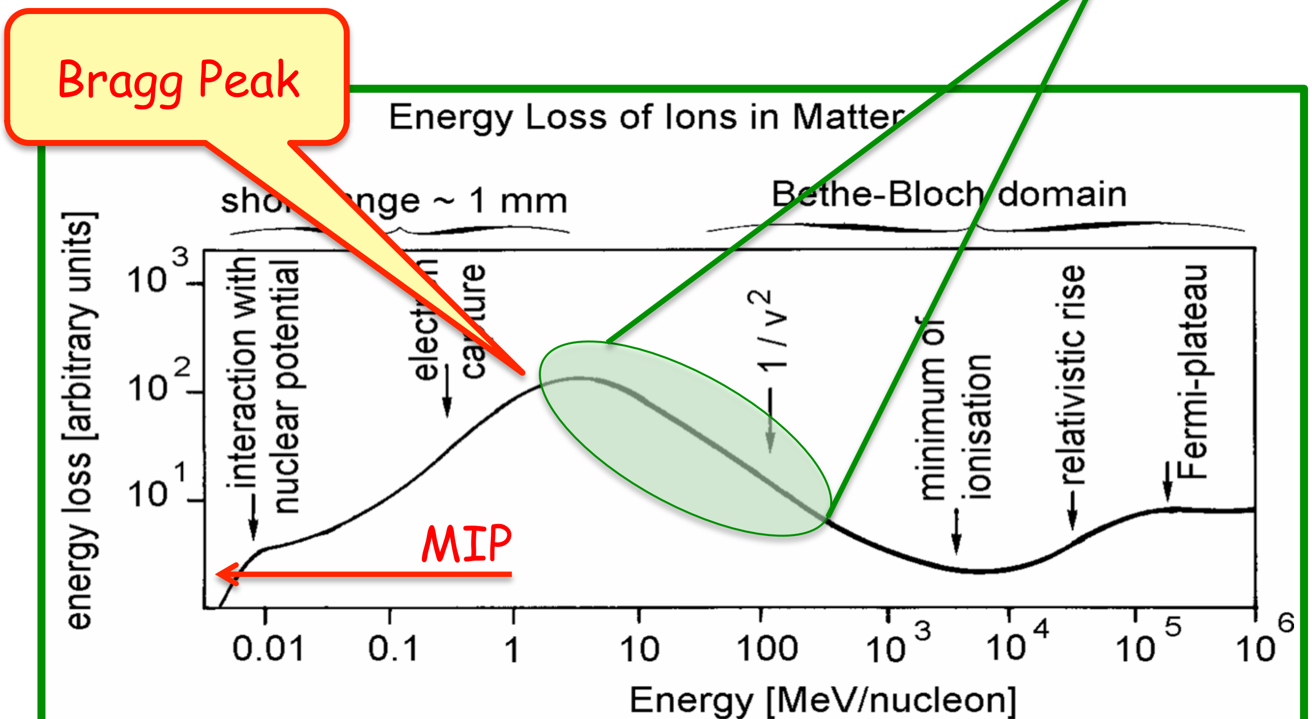
- Overview: fragmentation in PT and space
- Some recent fragmentation experiment
- Fragmentation & dose monitoring
- Summary and conclusions

Particle Therapy vs Particle Physics point of view

The release of energy by charge particles has very attractive, features… why not to use them?

$\propto Z_{ion}^2$





Perfect to release energy (dose) in a tumor buried inside the patient, like a depht bomb..

Mostly proton, few ^{12}C beams.

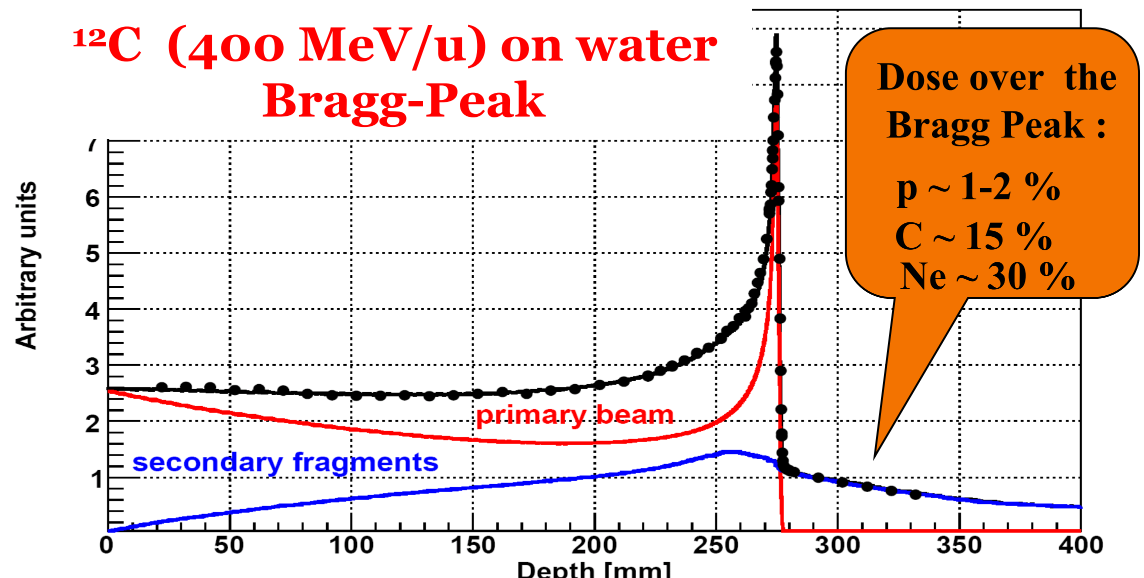
Future ^{4}He, ^{16}O ?

Heavier is better? -> Fragmentation!

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

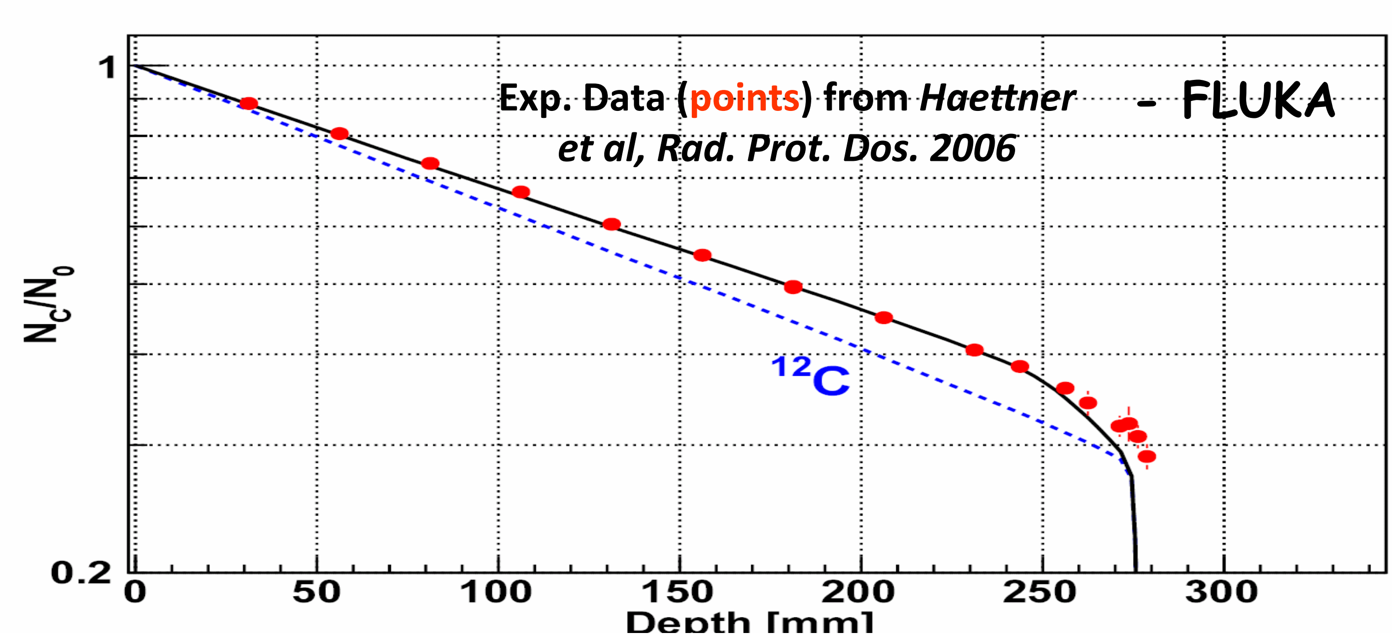
- ✓ Production of fragments with higher range vs primary ions
- ✓ Production of fragment with different direction vs primary ions

- ✓ *Mitigation and attenuation of the primary beam*
- ✓ *Different biological effectiveness of the fragments wrt the beam*



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

400 MeV/n ^{12}C on water: Attenuation of the primary beams



The 70 % of the carbon ions undergo nuclear reactions altering considerably the radiation field

Fragmentation rules out beams heavier than Oxygen and must be carefully taken into account in TPS even for ^{12}C

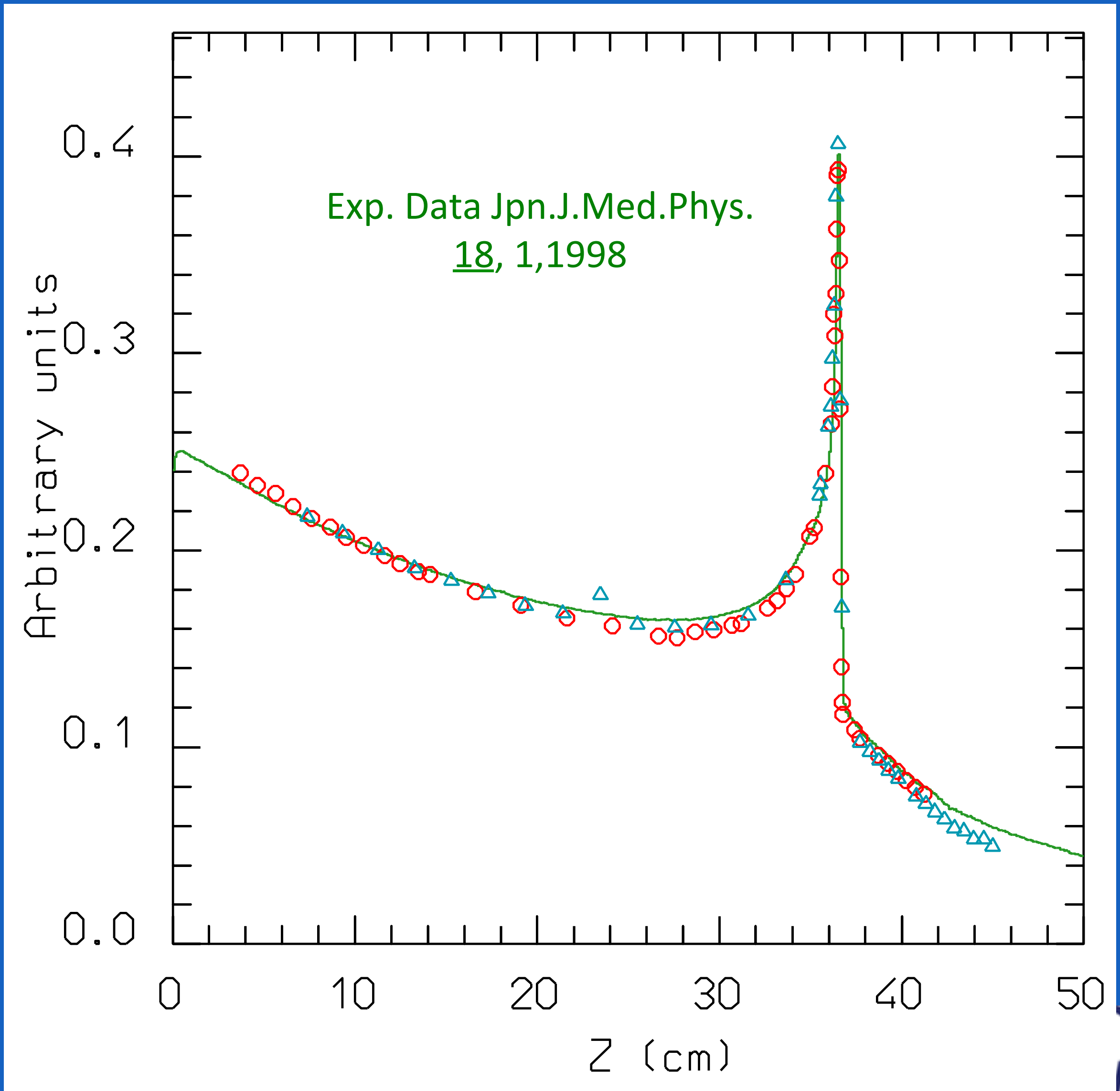
Fragmentation of ^{20}Ne @ 670 MeV/n

Dose vs depth distribution for 670 MeV/n ^{20}Ne ions on a water phantom.

The green line is the FLUKA MC prediction

The symbols are exp data from LBL and GSI

Huge dose contribution after the BP due to fragment

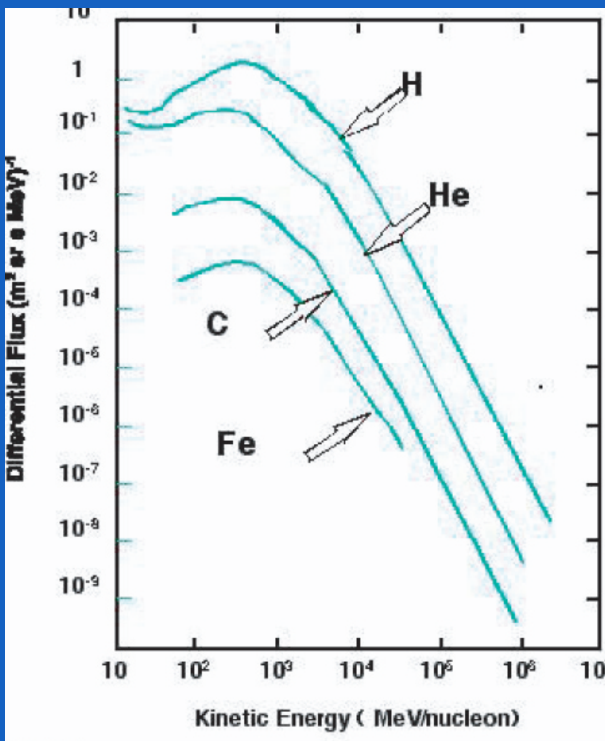


Fragmentation in space

Galactic Cosmic Rays

spectrum: 87% protons, 12% He ions and 1% heavier ions (in fluence) with peaks at 1 GeV/n

flux: ~4 particles/(cm^2 s) at solar min.



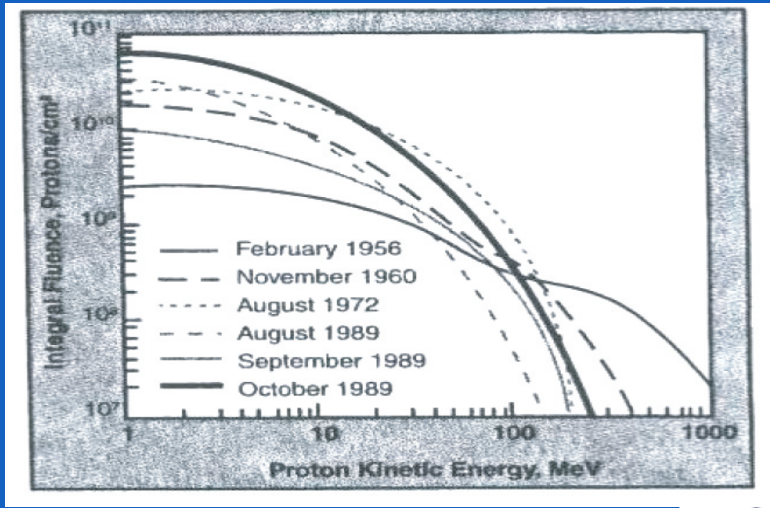
NASA pub. 1998

Solar Particle Events

spectrum: 90% protons, 10% heavier ions with energy mainly below ~200 MeV

flux: up to ~10^{10} particles/cm^2 in some hrs.

dose: order of Sv, strongly dependent on shielding and organ



NASA pub. 1998

Courtesy of Alfredo Ferrari

Dose rates in space missions

Shuttle  0.23 mSv/day

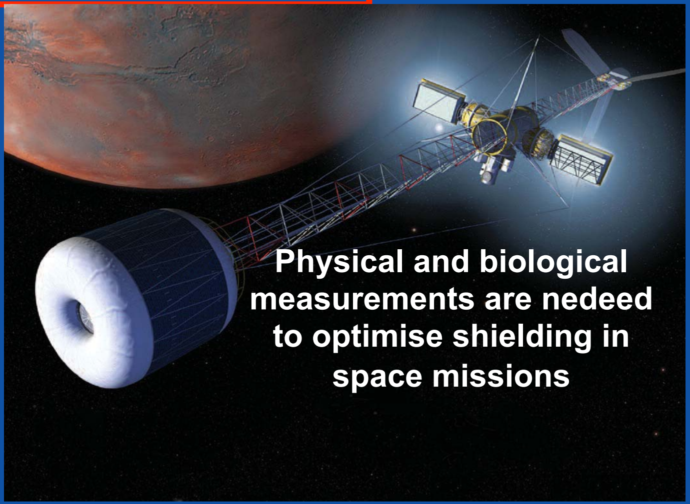
ISS  0.5-1 mSv/day

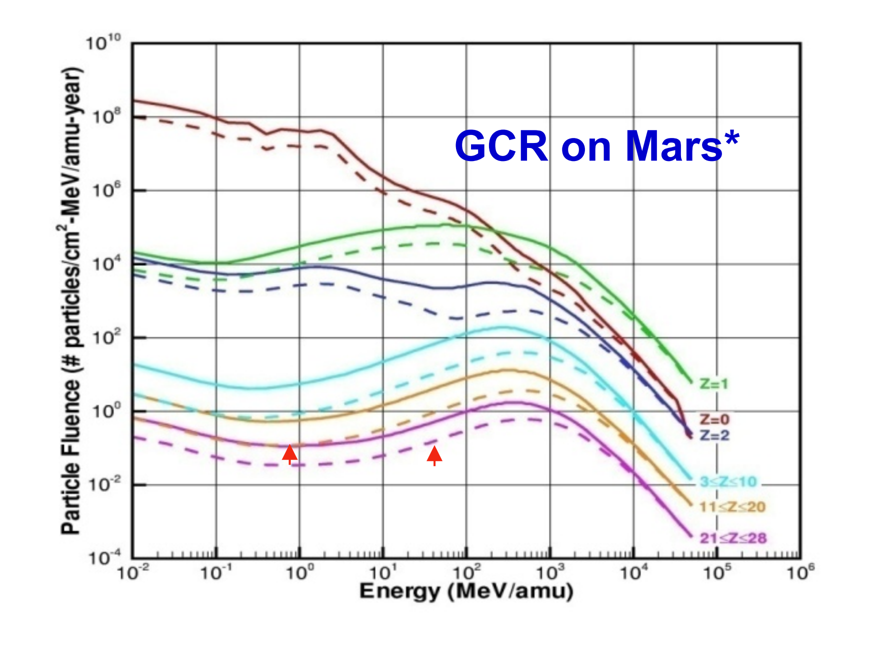
Apollo  .3 mSv/day

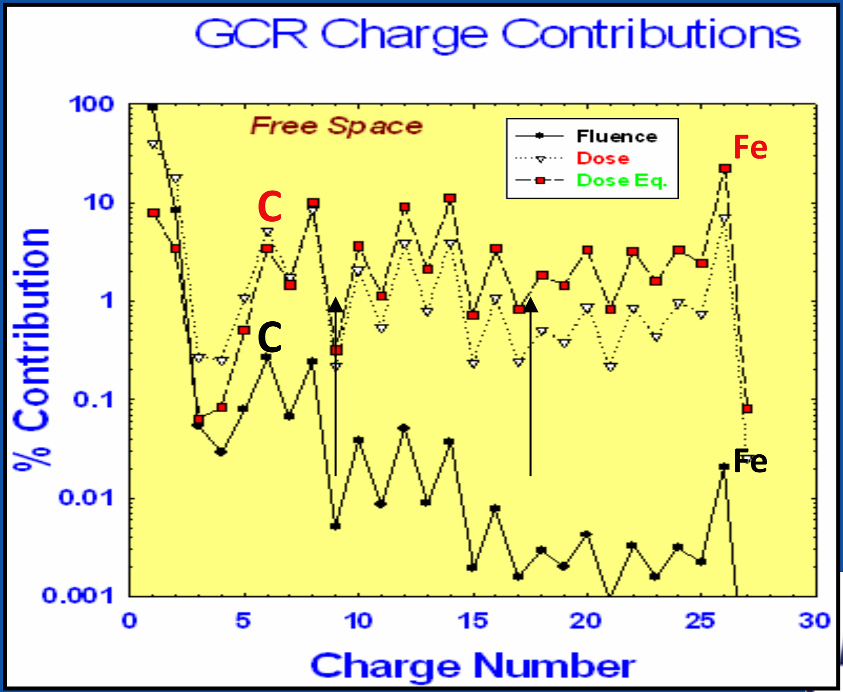
by comparison: an intercontinental flight rarely implies doses larger than 0.1 mSv; the radiation background on Earth is ≈ mSv/_year_

Radioprotection & shielding

- Shielding are needed to have the possibility of long space missions.
- GCR fragmentation on the shielding must be carefully be taken into account, both for astronauths and for equipments

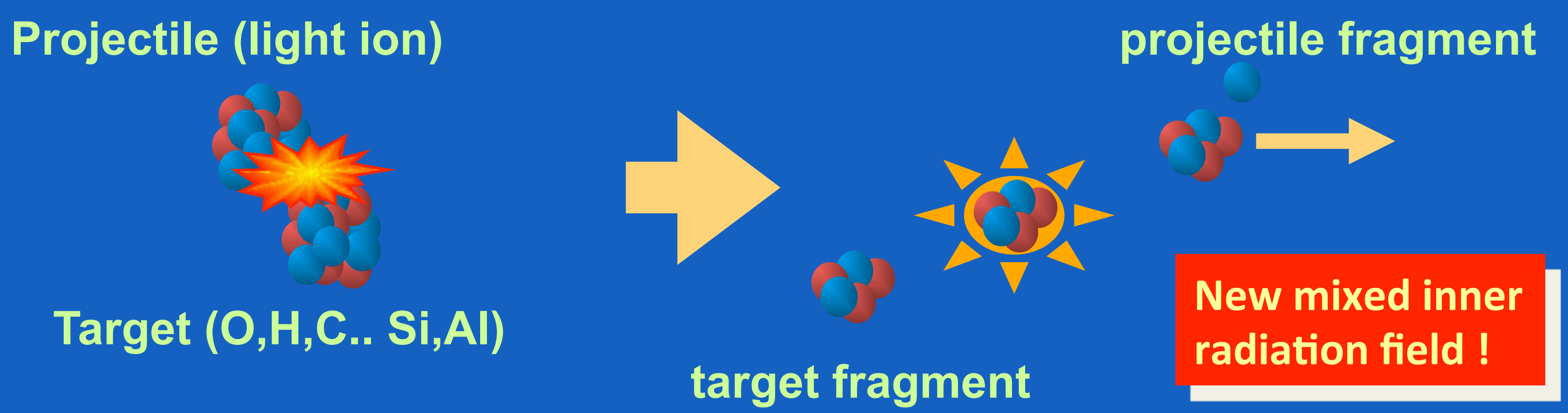






Fragmentation features at 100-500 MeV/nucl

- Disclaimer.. Experimental point of view!!
- Standard ablation-abrasion process



Interaction of the projectile with the patient body or the spacecraft hulls, etc..

Target Fragments

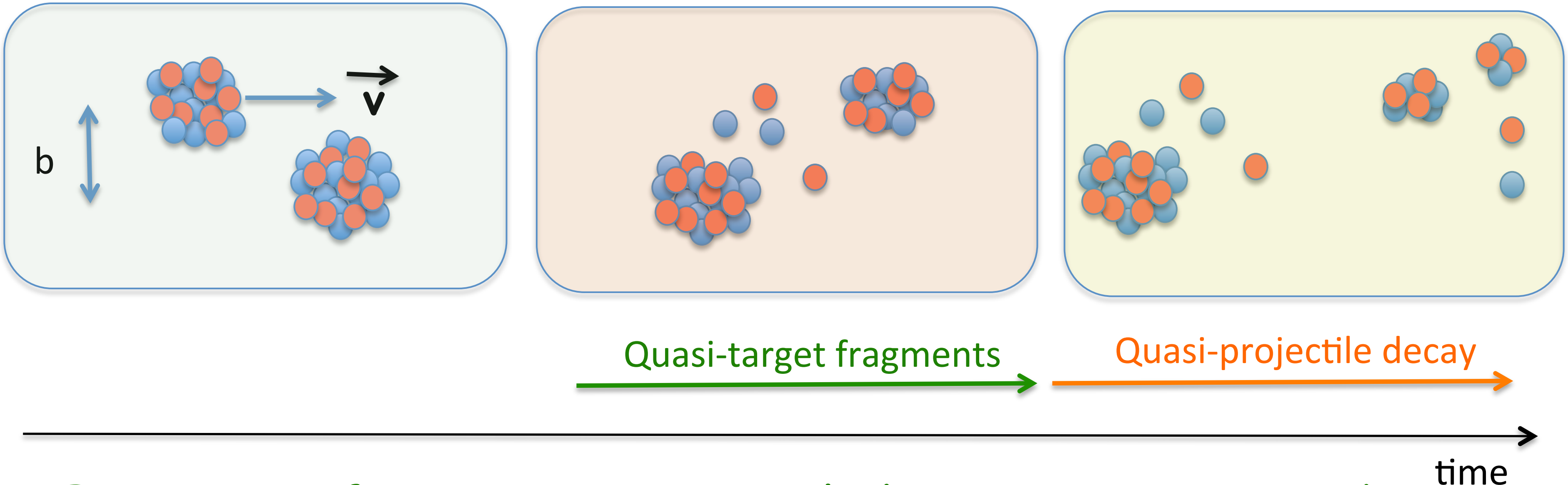
... lower charge than target
... high LET
... short ranges

Projectile fragments

... lower charge than primaries
... mixed LET
... long ranges

NB !!: Only target fragmentation for proton beam/projectile !!!!

The abration-ablation paradigm & PT



- Fragments from quasi-projectile have V_{frag}~V_{beam} and narrow emission angle. Longer range then beam
- The other fragments have wider angular distribution but lower energy. Usually light particles (p,d,He)
- The dose beyond the tumor distal part comes from the quasi projectile contribution. Wide angular halo from the rest of the process

"Typical" modeling of nuclear interactions:

Target nucleus description (density, Fermi motion, etc)

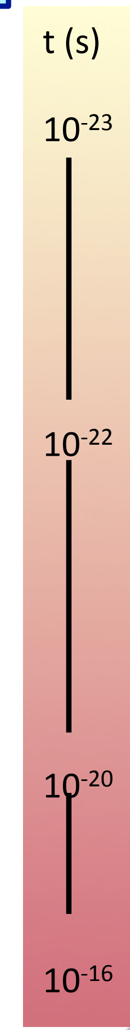
Glauber-Gribov cascade with formation zone

(Generalized) IntraNuclear cascade

Preequilibrium stage with current exciton configuration and excitation energy
(all non-nucleons emitted/decayed + all nucleons below 30-100 MeV)

Evaporation/Fragmentation/Fission model

γ deexcitation



"Typical" modeling of nuclear interactions:

Target nucleus description (density, Fermi motion, etc)

Gla...

- Cross sections: absorption/quasi-elastic
- Transition from single to multiple chains/collisions

  - ✓ Onset of formation zone
  - ✓ Fast light fragments
  - ✓ (Pion interactions below 1 GeV)
  - ✓ (In medium cross-sections)

Preequilibrium stage with current exciton configuration and excitation energy
(all non-nucleons emitted/decayed + all nucleons below 30-100 MeV)

- ❑ Spin and parity…
- ❑ Statistical multi-fragmentation or binary emission?

γ deexcitation

t (s)

10^{-23}

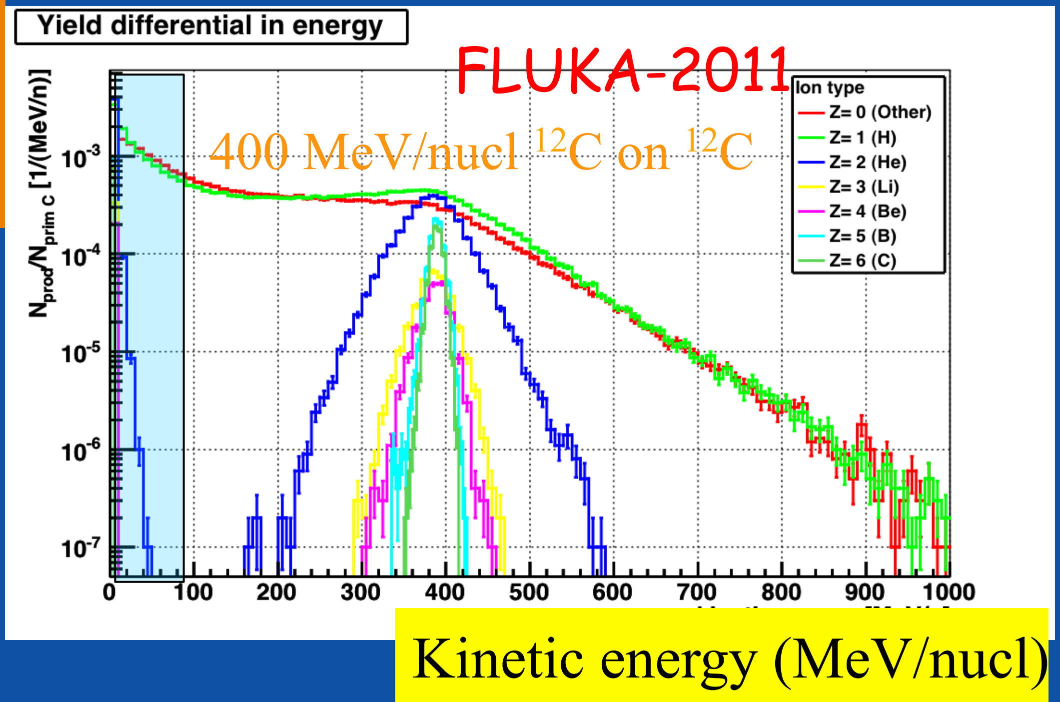
10^{-22}

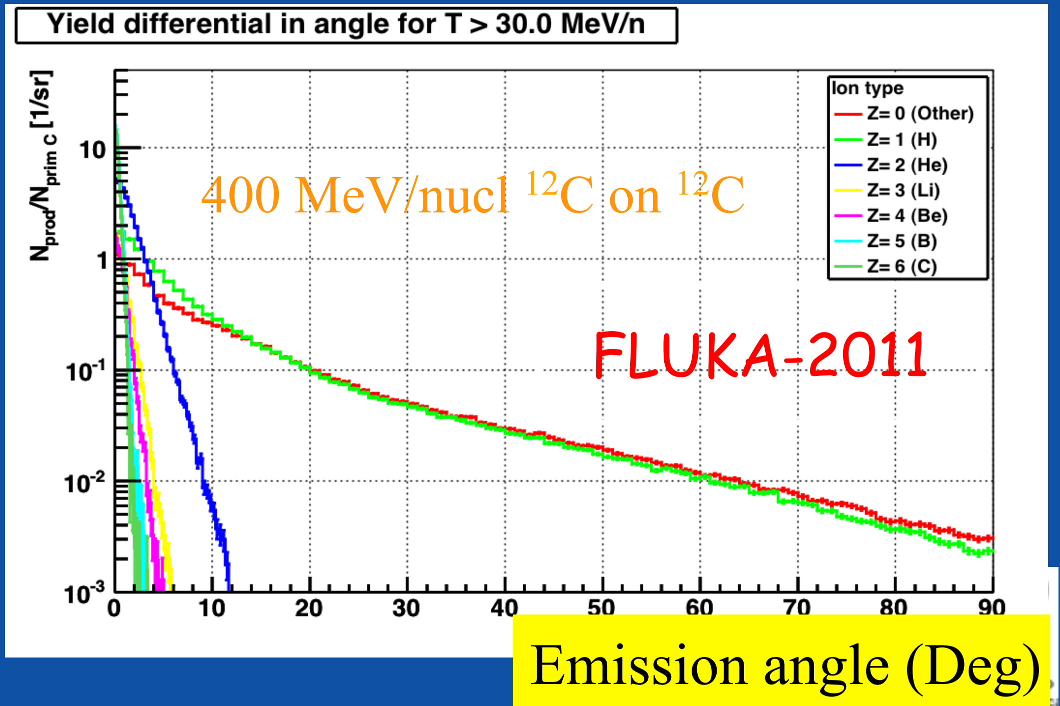
10^{-20}

10^{-16}

Typical example: ^{12}C beam on ^{12}C target

- 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 b 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.

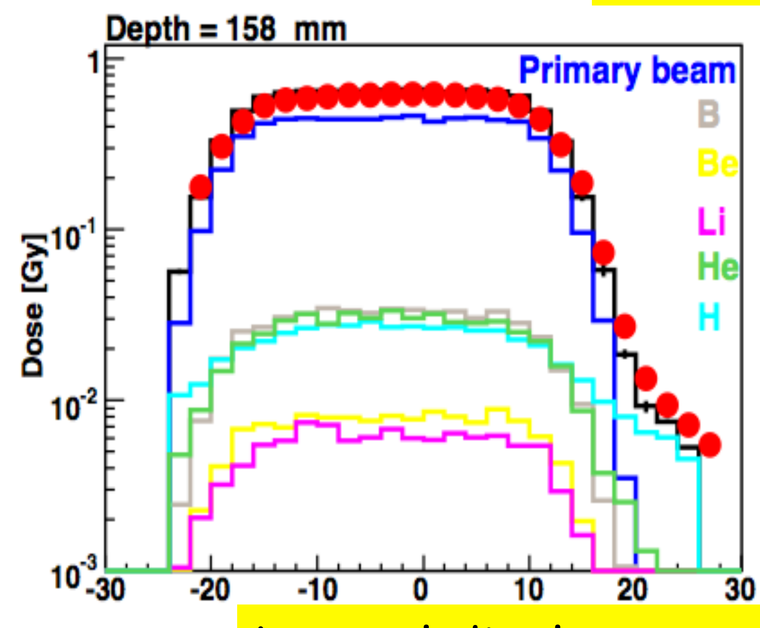




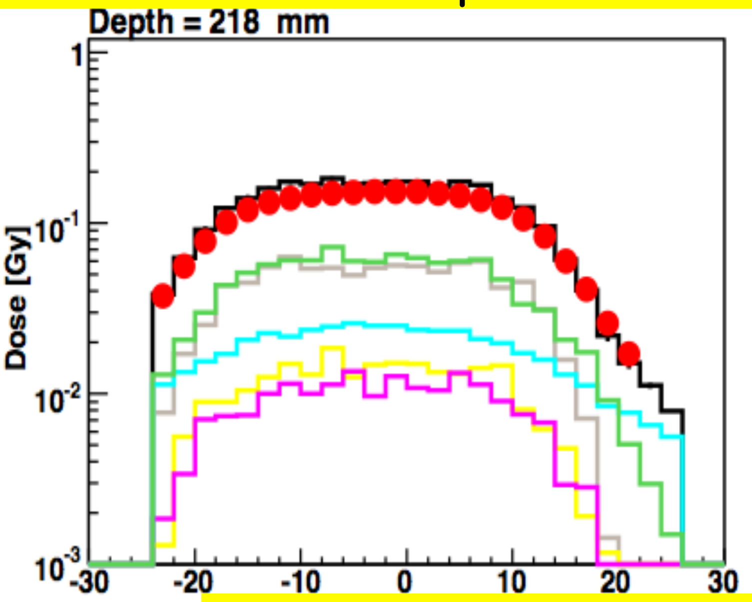
Fragmentation & PT: Beam broadening

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 at 20 cm depht in water



Lateral displacement(mm)



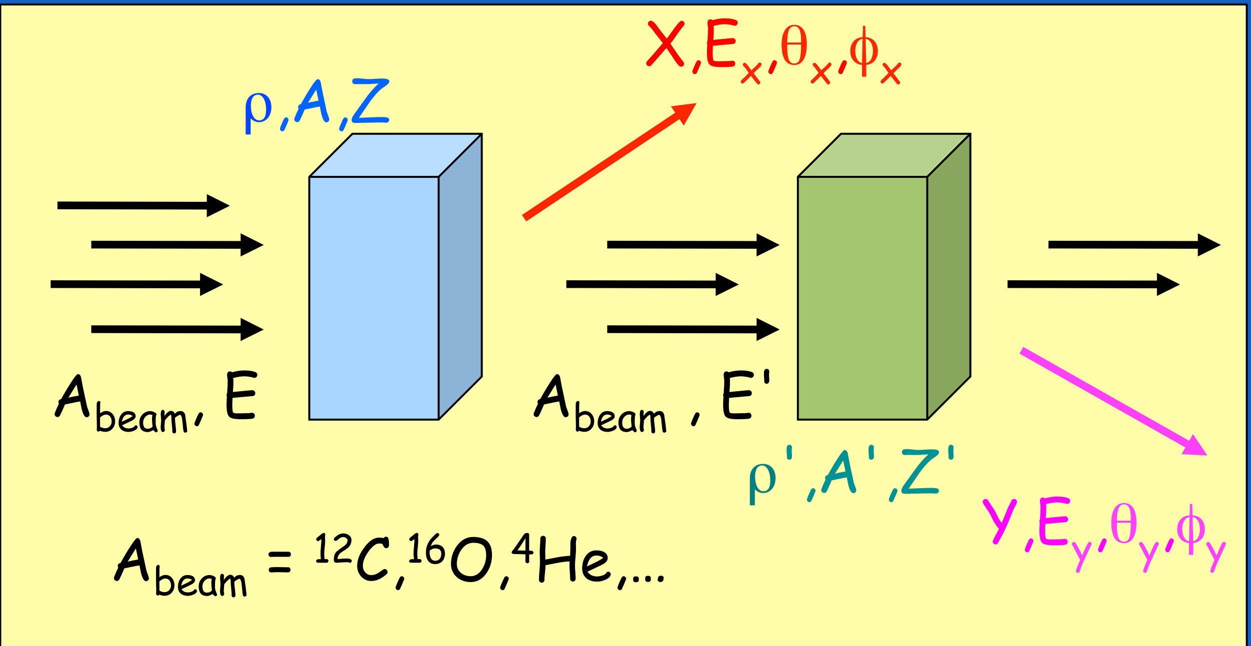
Lateral displacement(mm)

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

What we still miss to know about light ions fragmentation in 2015?

Data exist at 0^0 or on thick target. But we need to know, for any beam of interest and on thin target:

- Production yields 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 beam energy of interest (100-500 AMeV)
- Thin target measurement of all materials crossed by beam



Not possible a complete DB of measurements

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

Fragmentation, TPS, MonteCarlo and all that..

- The nuclear interaction description are embedded in the Treatment Planning System through a "physical" DB generated on the basis of a Interaction Model (by analytical computation or MC code) where the energy releases and the fragment produced by the beam are stored. Thus the benchmarking of the MC with the measurements are getting more and more important due to:

✓ Better representation of the nuclear interaction model wrt analytic calculation

✓ Natural and easy 3D treatment of physics processes

✓ More accurate patient representation wrt w.e. approach

✓ Possibility of exploiting PET online

✓ Easily taken into account the beam features

KEY ISSUES: reliability of physics models -> must be tuned on data

MC for TPS: what is on the market?

The list is absolutely not exaustive

- EGS4, EGSnrc, ETRAN, PENELOPE: electron and photon
- MCNP : only electron, photon and neutron
- VMCpro, ISTAR, MCNPX: only for proton. parametrised nuclear int
- Geant4 , PHITS, FLUKA : general purpose, transport any particle from photon to heavy ion → suitable for ^{12}C beam
- Geant4 : very large user community, optimised version for low energy, OO, flexible
- We will use FLUKA as reference code: very accurate physics description, old style coding (FORTRAN).

MC for physicist is like religion or favorite soccer team: you do not choose it , you are chosen by it, and once you are chosen, no way to change it !! (see the G4 vs FLUKA religion war...)

Data - MC comparison: ^{12}C ions

Build-up of charged fragments for ^{12}C beam @400MeV/n in water

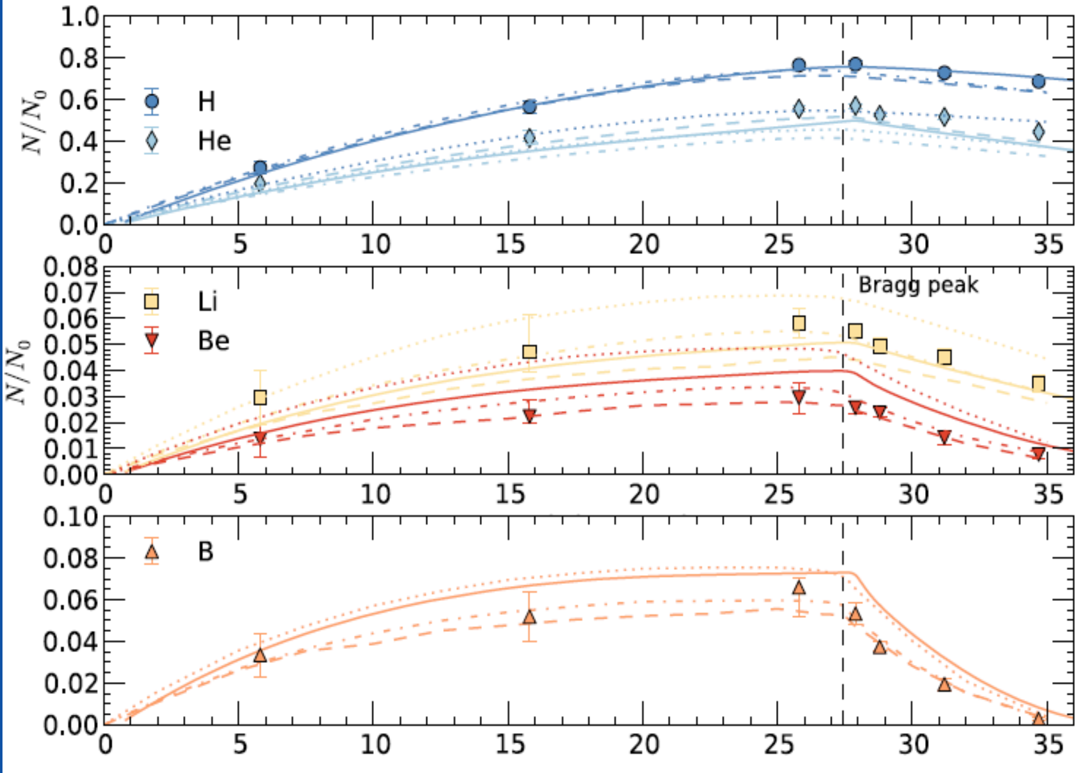
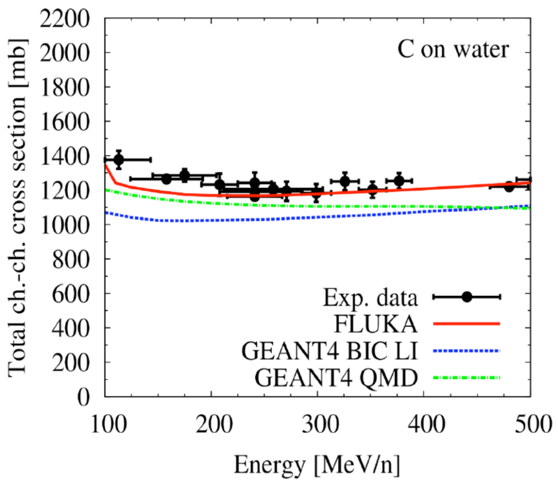


Figure 14. FLUKA, Geant4–QMD, Geant4–BIC LI (Böhlen *et al* 2010) and SHIELD-HIT10A simulations of the relative yield of fragments emitted within a 10° forward angle from a 400 MeV/u ^{12}C beam in water, compared with experimental data (Haettner *et al* 2006). Dashed line: FLUKA simulation. Dashed-dotted line: Geant4–QMD simulation. Dotted line: Geant4–BIC simulation. Solid line: SHIELD-HIT10A simulation. The markers are experimental data. Where error bars are not visible, they are smaller than the markers.

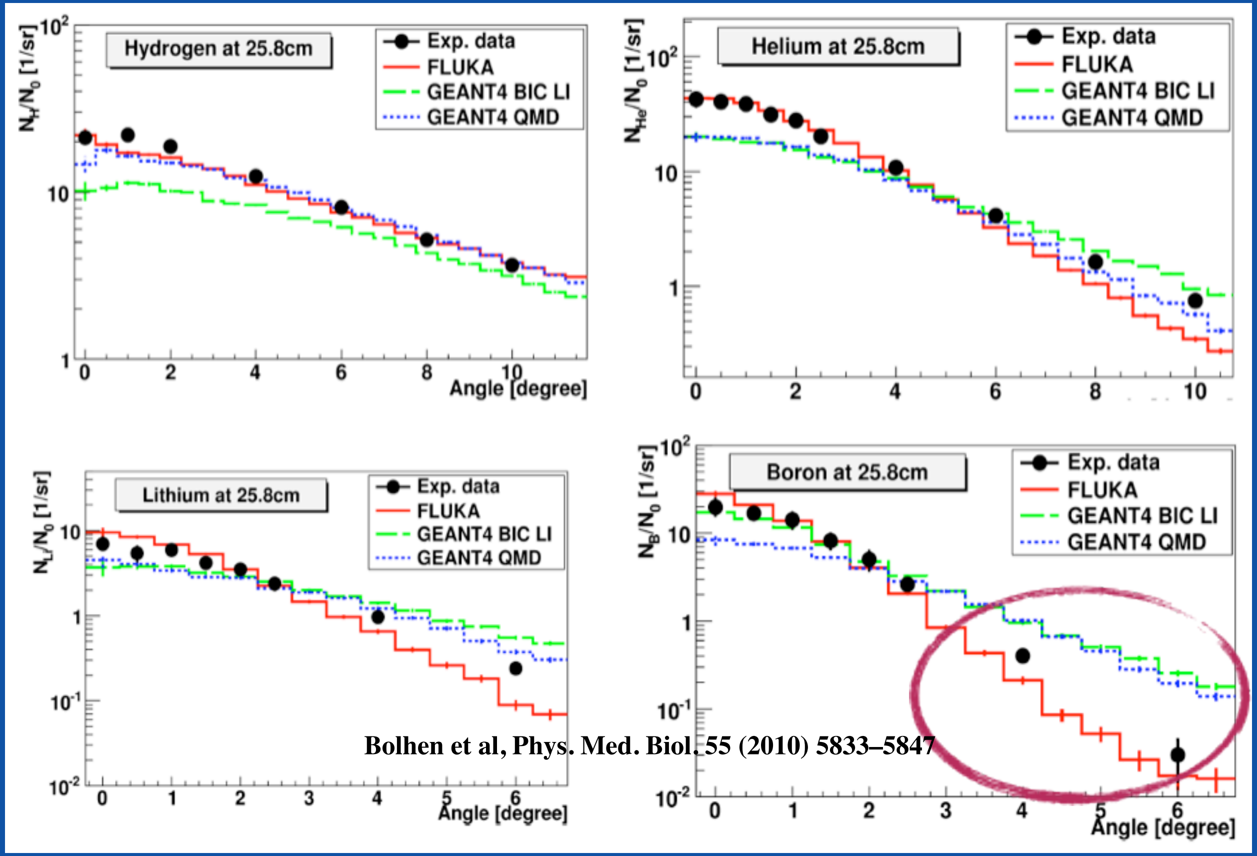
- Integral quantities (fragment yields, charge changing cross sections) are generally within 10-20%

Bolhen et al, Phys. Med. Biol. 55 (2010) 5833–5847



Data - MC comparison: ^{12}C ions

Differential/double- differential quantities (vs angle and/or energy) ➔ larger discrepancies found!



NB: the accuracy on delivered dose MUST be of the order of few %

Some MC benchmarks:
Sommerer et al. 2006, PMB
Garzelli et al. 2006, ArXiv
Pshenichnov et al. 2005, 2009
Mairani et al. 2010, PMB
Böhlen et al. 2010, PMB
Hansen et al. 2012, PMB

Outline

Bouncing from fundamental physics to applied physics and back…

- Overview: fragmentation in PT and space
- Some recent fragmentation experiment
- Fragmentation & dose monitoring
- Summary and conclusions

Frag meas: thick target

A lot of integral measurements measurements are already around..

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.

Tentative & incomplete list at 2011

Courtesy of M. Durante

Frag meas: thin target

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

Projectile	Energy[MeV/N]	Target	
^{4}He	135	C, Poly, Al, Cu, Pb	
^{12}C	135	C, Poly, Al, Cu, Pb	RIKEN by 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	HIMAC 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	600	Li, C, CH_2, Al, Cu, Pb	HIMAC Heilbronn et al.
^{56}Fe	500	Li, C, CH_2, Al, Cu, Pb	
^{86}Kr	400	Li, C, CH_2, Al, Cu, Pb	
^{126}Xe	400	Li, C, CH_2, Al, Cu, Pb	

Tentative & incomplete list at 2011

Courtesy of M. Durante

only with detectors at 0°!

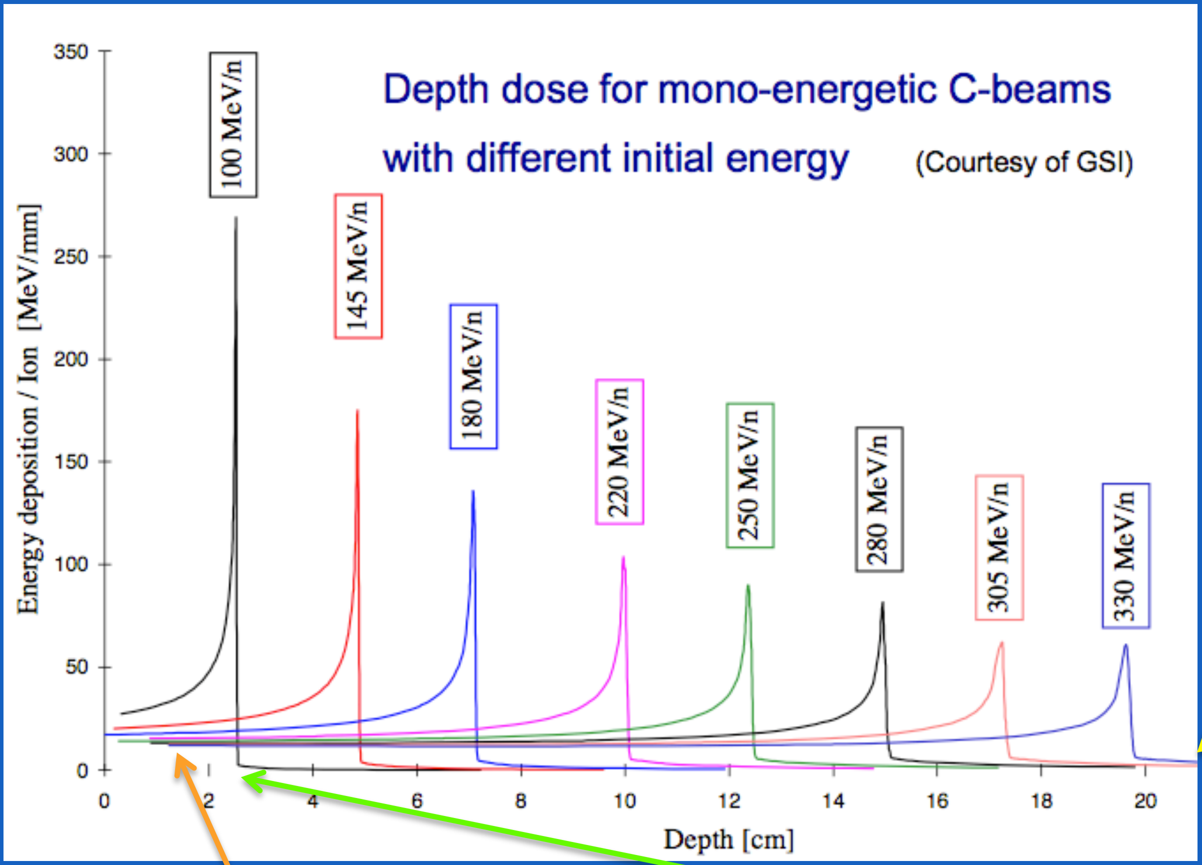
The IDEAL detector

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 expensive , would take LONG time and a LARGE group to be designed and built.

Recent thin target, Double Diff Cross Section C-X measurements



The community is exploring the interesting region for therapeutical application.

GSI 400 AMev C beam FIRST experiment

LNS 62AMev C beam FRAG experiment

GANIL 95AMev C beam - E600 collaboration (2011)

Fragments detection techniques

Standard techniques exploit the de/dx measurement (ΔE), calorimetric E measurement, Time of Flight (β) measurement

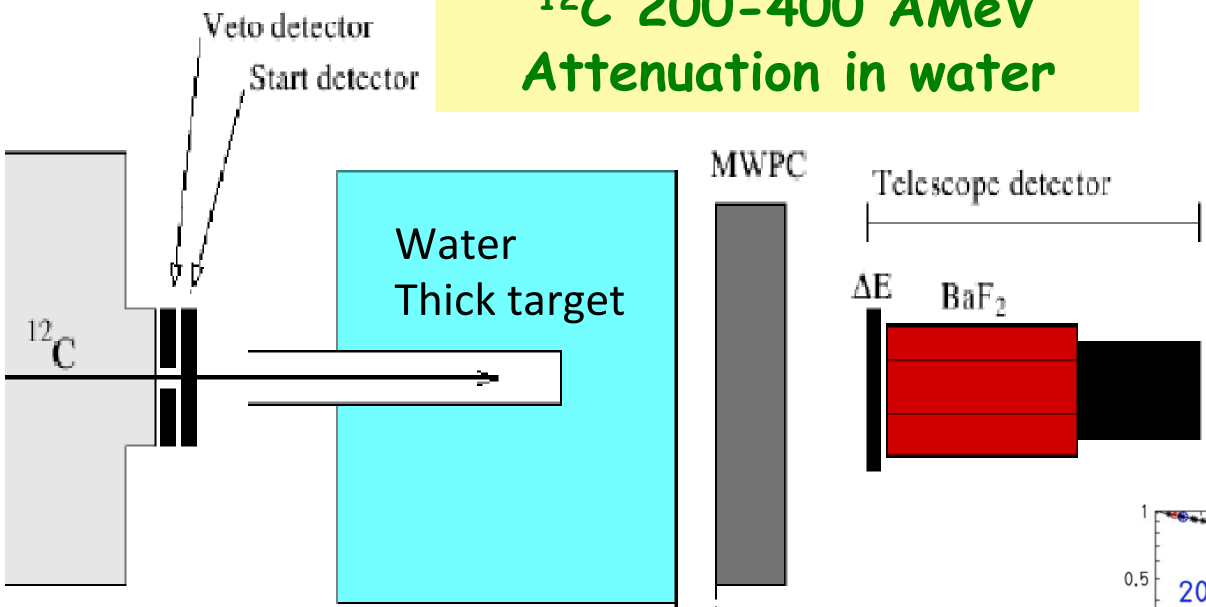
All this measurement are closely related with the particle identification (PID)

- ΔE vs E -> PID
- ΔE measurement provided PID -> E
- ToF (β) measurement provided PID -> E

particle	Ekin/nucl (MeV)	De/dx (MeV/cm)	Range (cm)
proton	10	42.6	0.1
proton	100	7.4	7.6
He	10	186	0.1
He	100	29	7.6
Be	10	78	0.06
Be	100	114	4.4
Carbon	100	259	2.5
Carbon	400	108	26.3

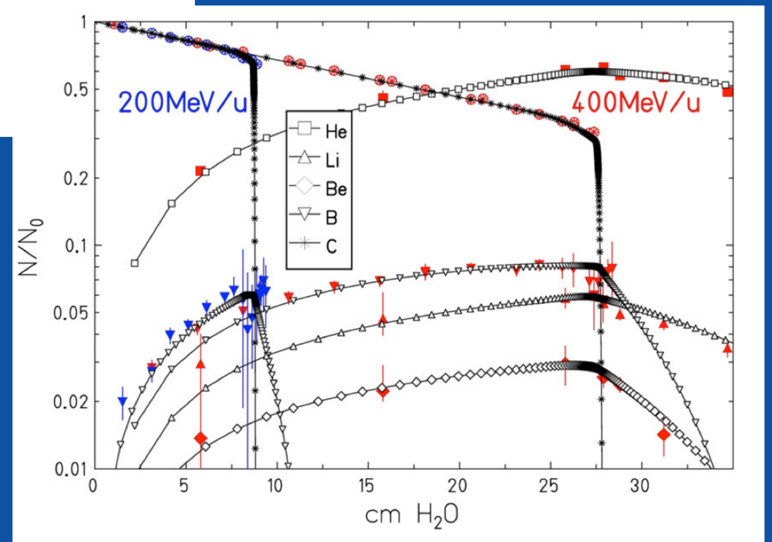
Typical PT fragmentation setup

^{12}C 200-400 AMeV
Attenuation in water



ΔE-BaF_2: energy loss and total energy

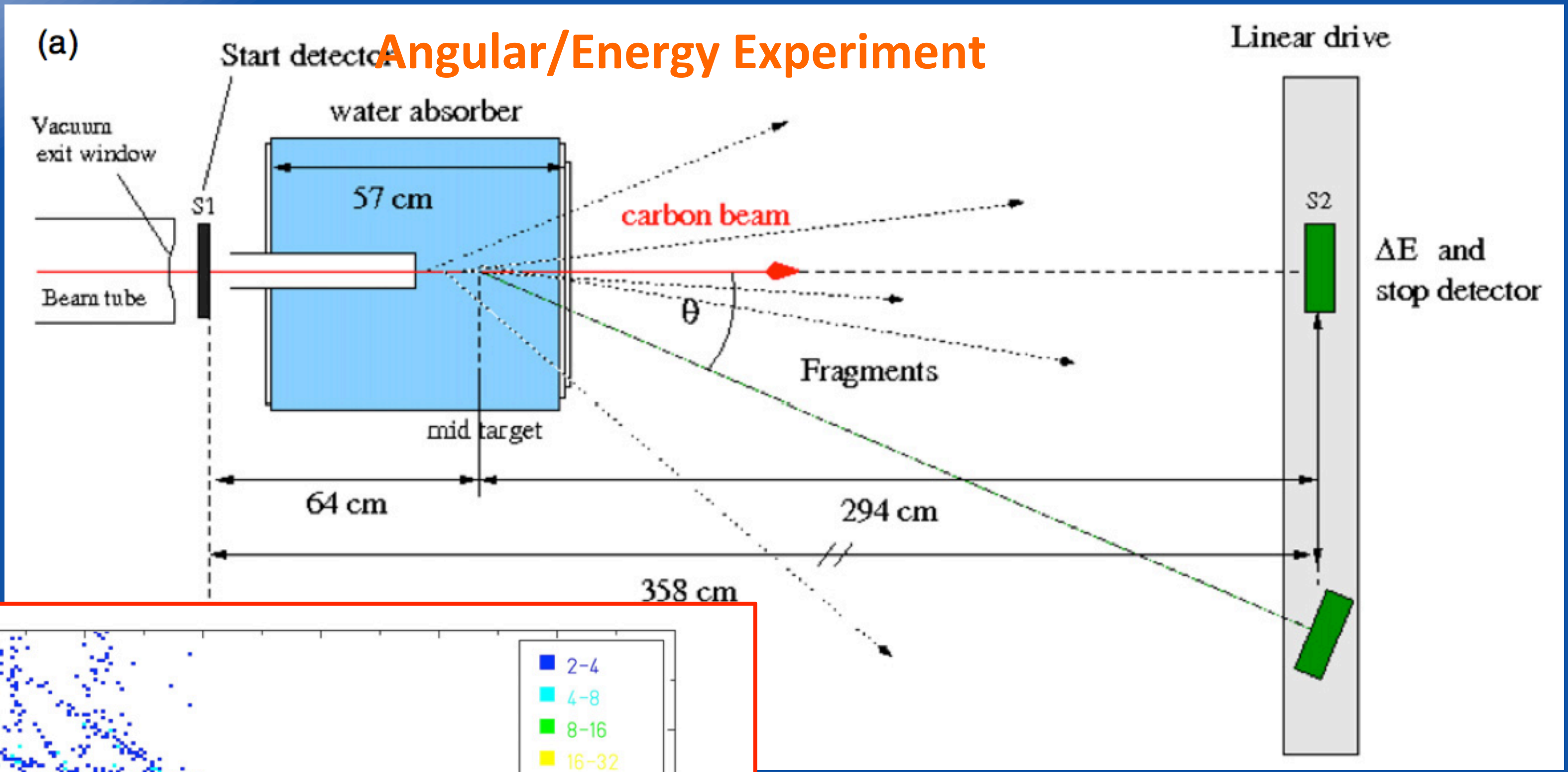
ToF: total energy

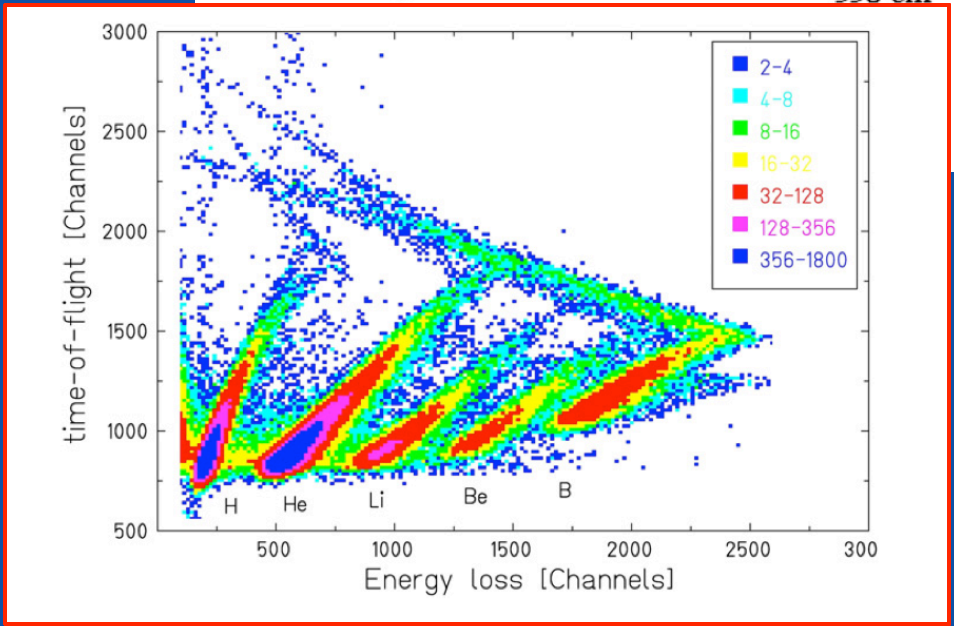


provide the number of surviving C ions leaving the water phantom as a function of its thickness.

E Haettner Phys. Med. Biol. 58 (2013)

Typical PT fragmentation setup





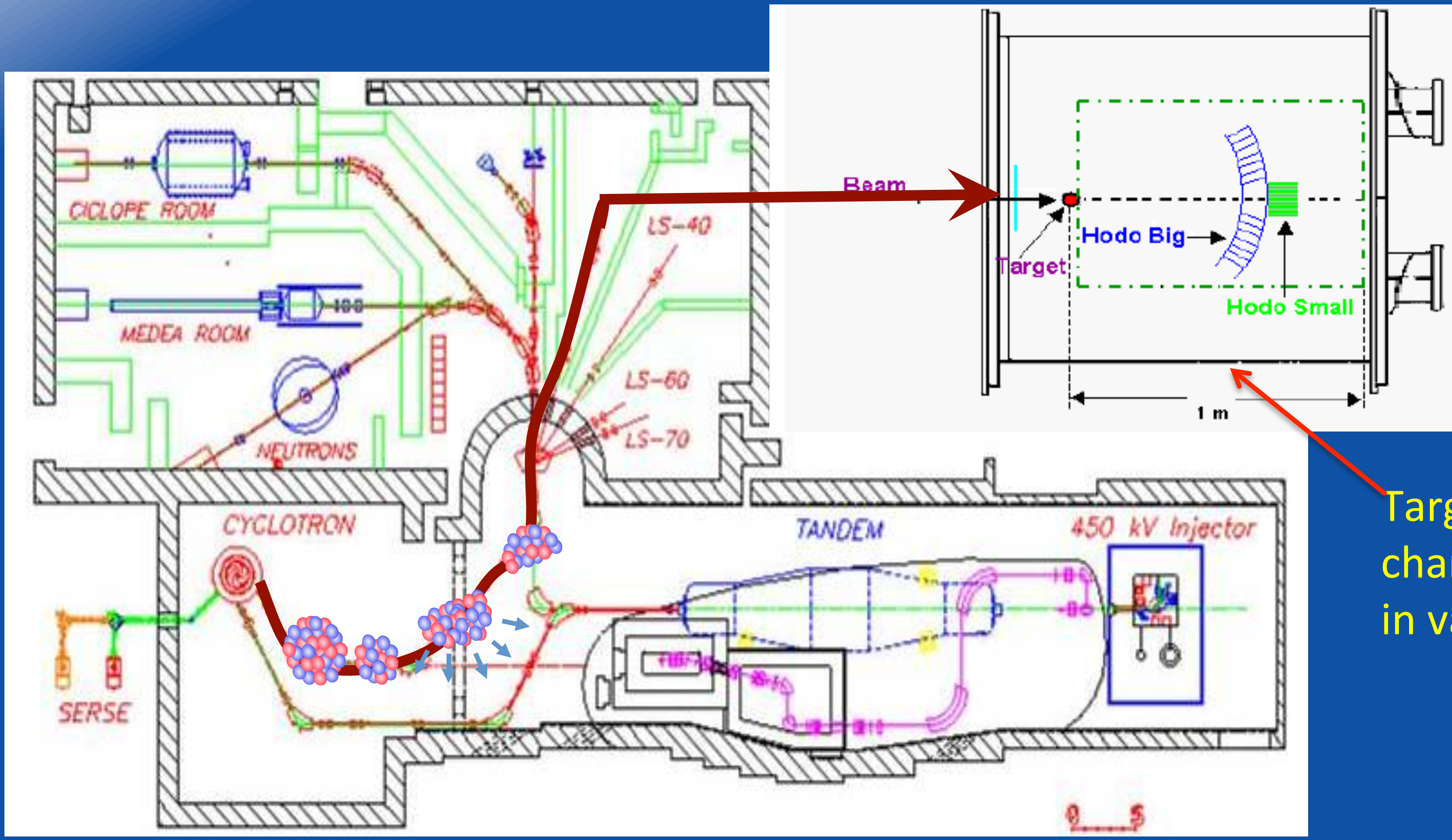
E Haettner Phys. Med. Biol. 58 (2013)

measure the angular & energy distributions of secondary fragments

H1: energy loss

ToF: total energy

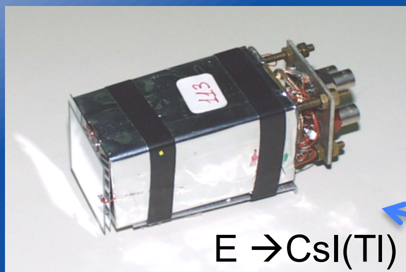
Frag Experiment at LNS

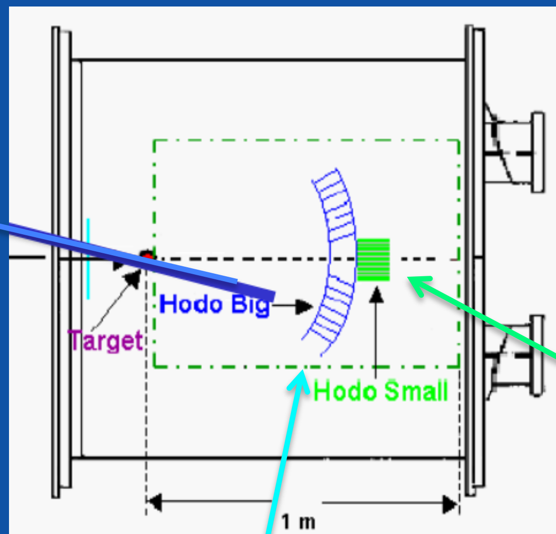


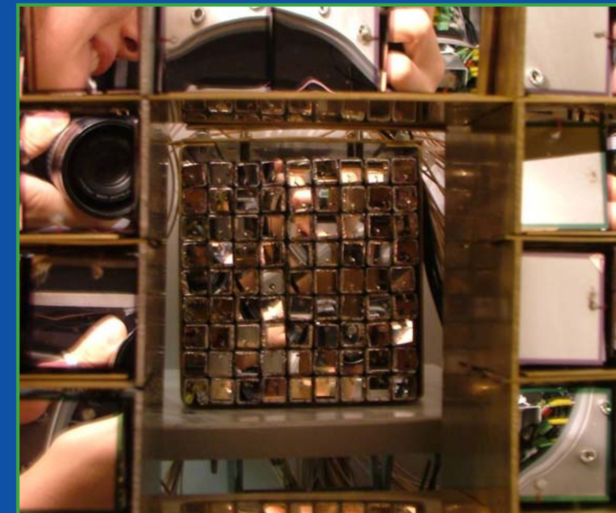
Target chamber in vacuum

: ^{12}C 63AMeV beam on ^{12}C

Frag Experiment at LNS



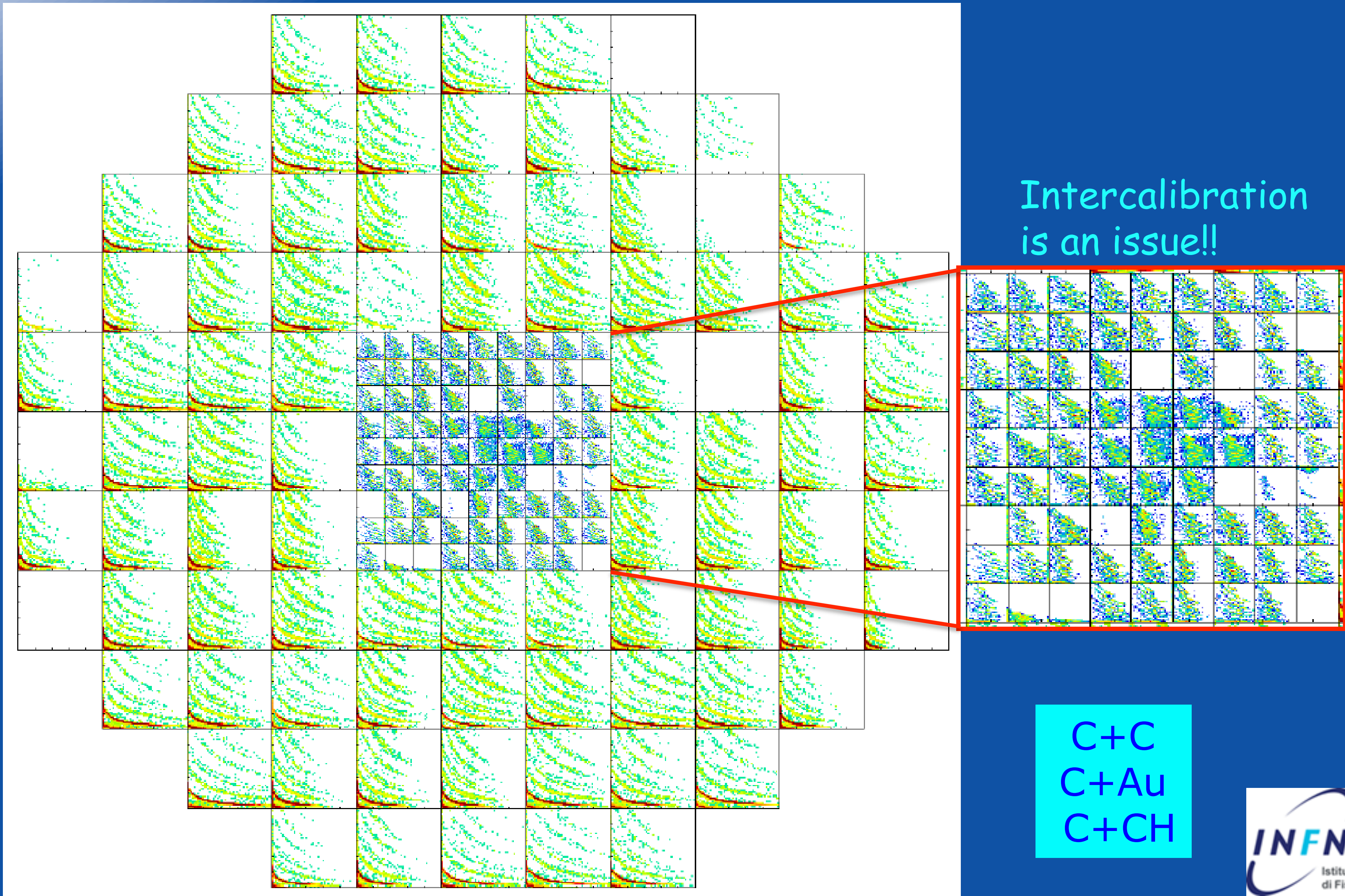




The **Hodo-small**, set up at a distance of 80 cm from the target consisted of 81 two-fold telescopes: 300 μm Silicon detectors 1x1 cm^2 of active area followed by a 1x1 cm^2 and 10 cm long CsI(Tl) and covered the angular range θ_{lab}=±4.5°.

The **Hodo-big**, set up at a distance of 0.6 m from the target, consisted of 89 three-fold telescopes 50 μm + 300 μm Silicon detectors both having 3x3 cm^2 surface followed by a 6 cm long CsI(Tl)of the same surface. It covered the angular range θ_{lab} between ±4.5° and ±20°

Frag @LNS :Fragment ID by ΔE vs E



Intercalibration is an issue!!

C+C
C+Au
C+CH

Measurement @95AMeV : ^{12}C beam

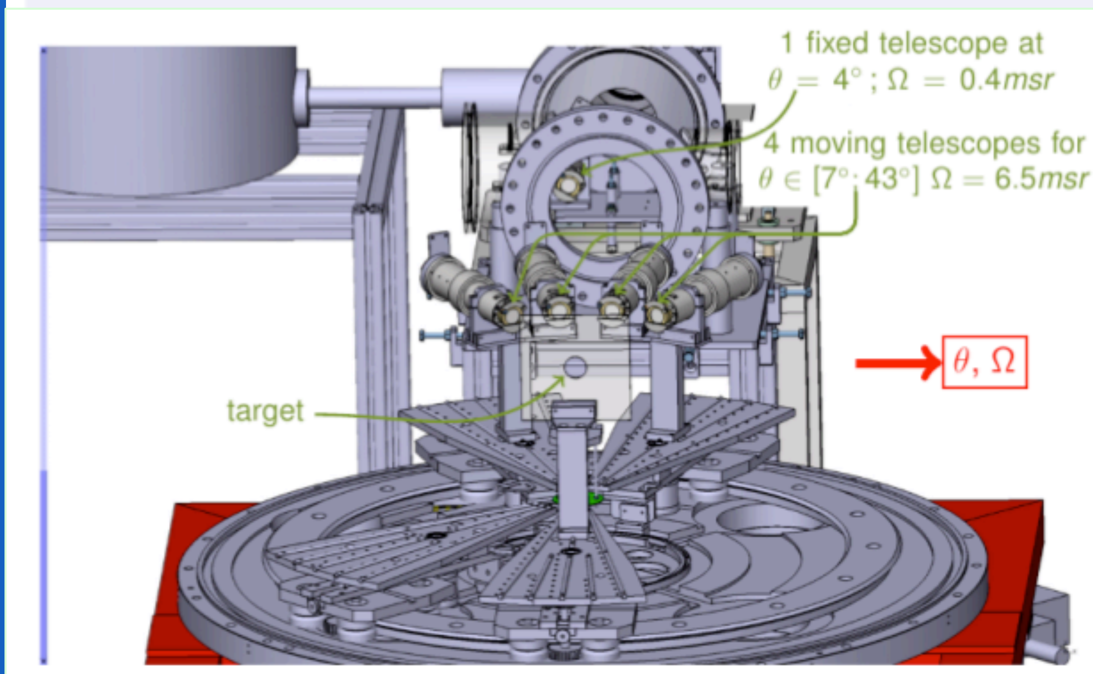
E600 experiment at GANIL (Caen ; may 2011)

Courtesy of M. Labalme

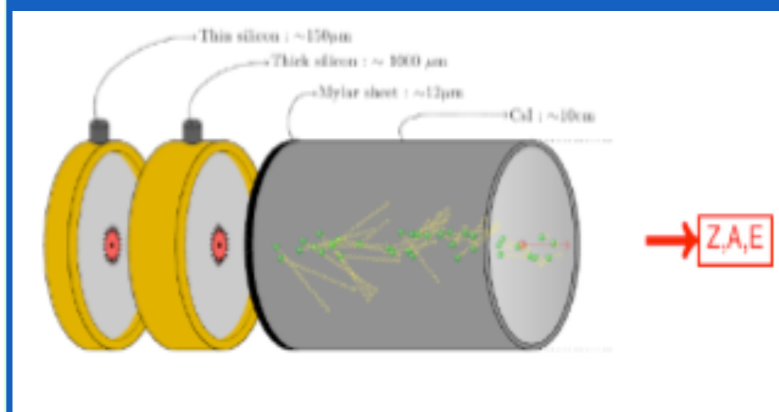
- Projectiles : 94.6 MeV/u ^{12}C
- Thin Targets ($\sim$50mg/cm^{-2}) : C, CH_2, Al, Al_2O_3, Ti

$\Rightarrow \frac{\delta^2\sigma}{\delta E \cdot \delta\Omega}$ fragmentation measurements of ^{12}C on C, H, O, Ca ($A_{Ti} \sim A_{Ca}$)

$\approx$ 95% of a human body composition

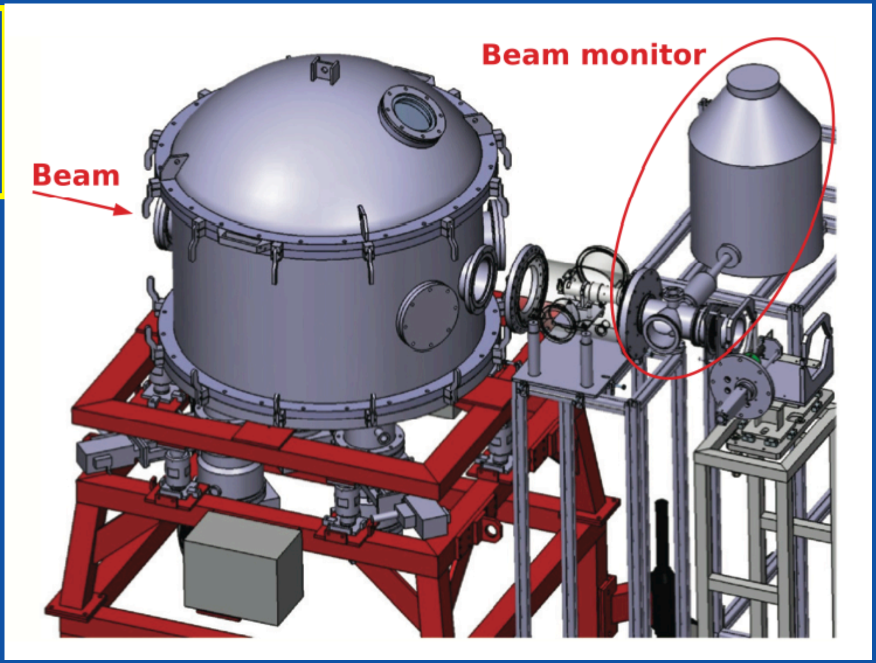


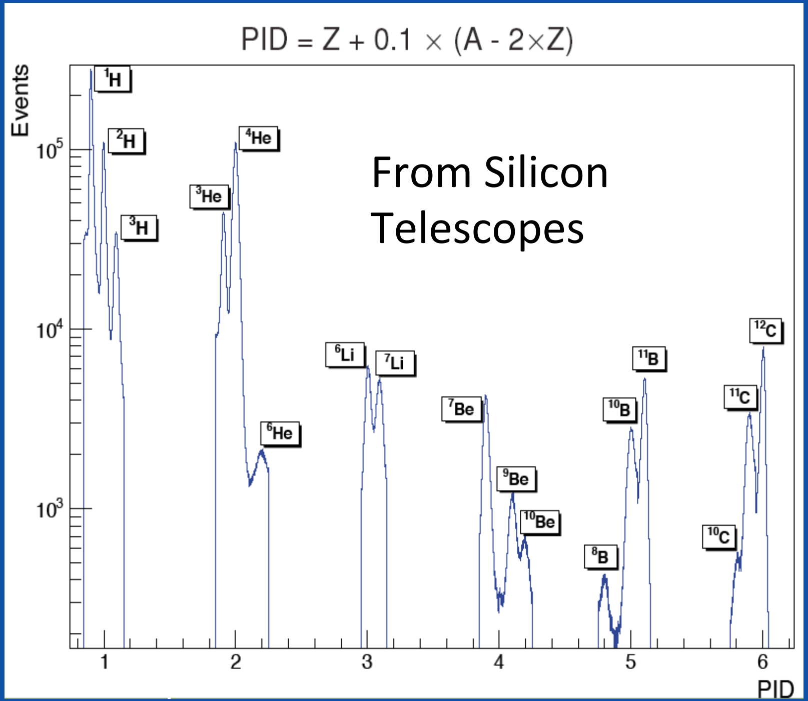
Array of 5 SI + CsI telescopes

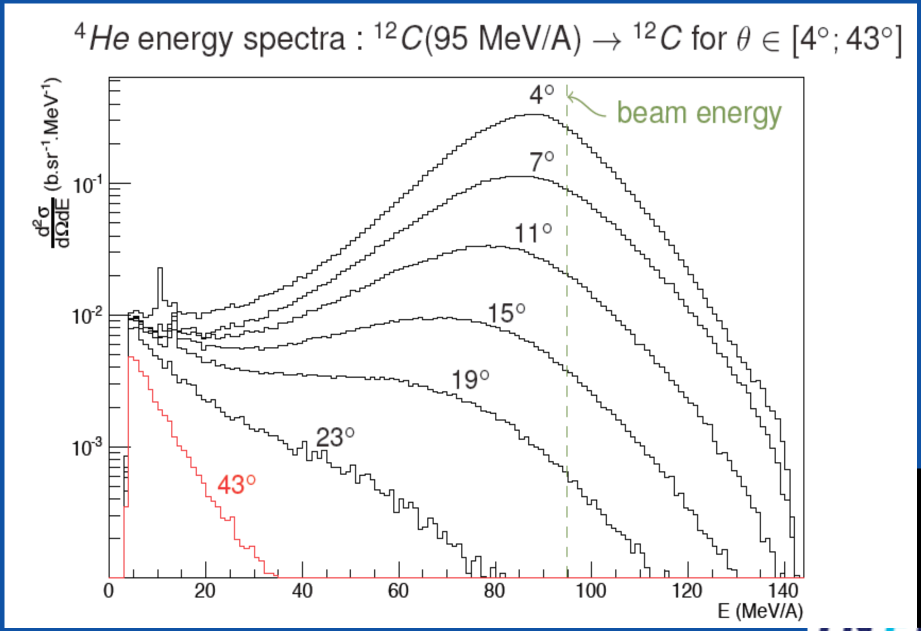


E600 (Ganil)

- Very good particle identification
- Currently focusing on: assessing systematics and comparing with MC to benchmark difference nuclear MC models



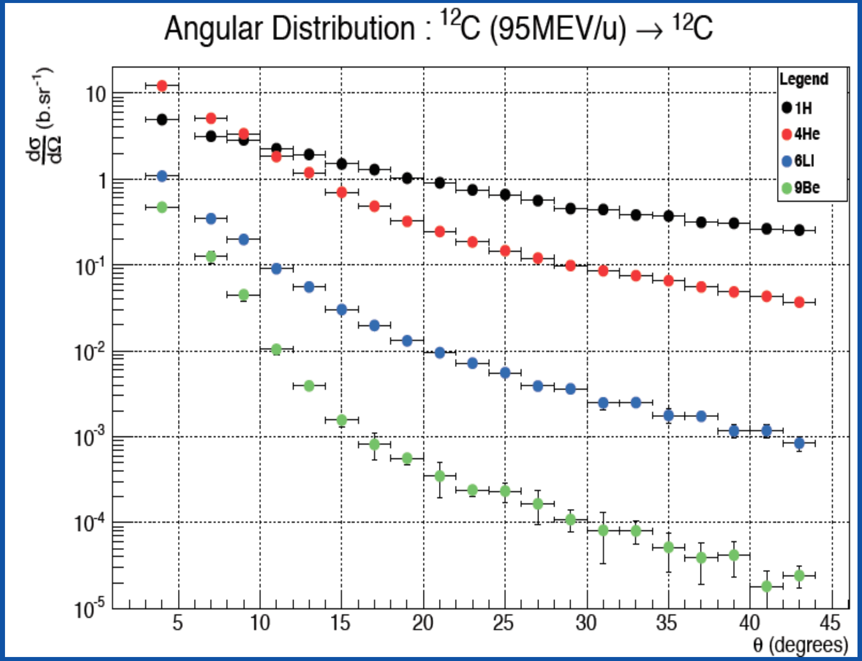


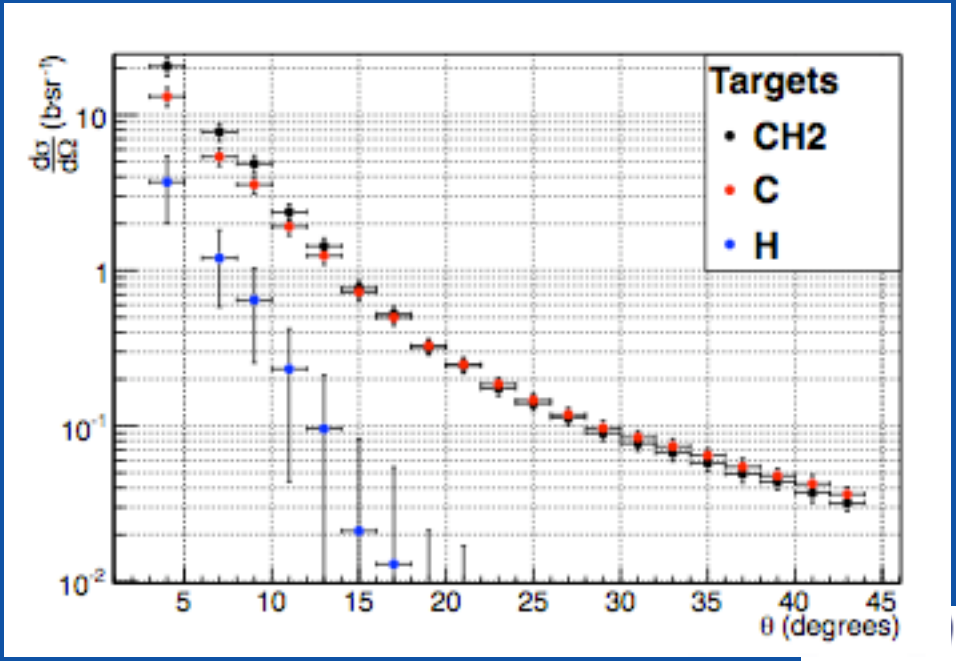


Measurement @95AMeV : ^{12}C beam

Courtesy of M. Labalme

- Obtained results for Single and Double Diff. X Section.
  - one interesting conclusion: Composite targets can be deduced from the cross sections of elemental targets (-> organic tissues)

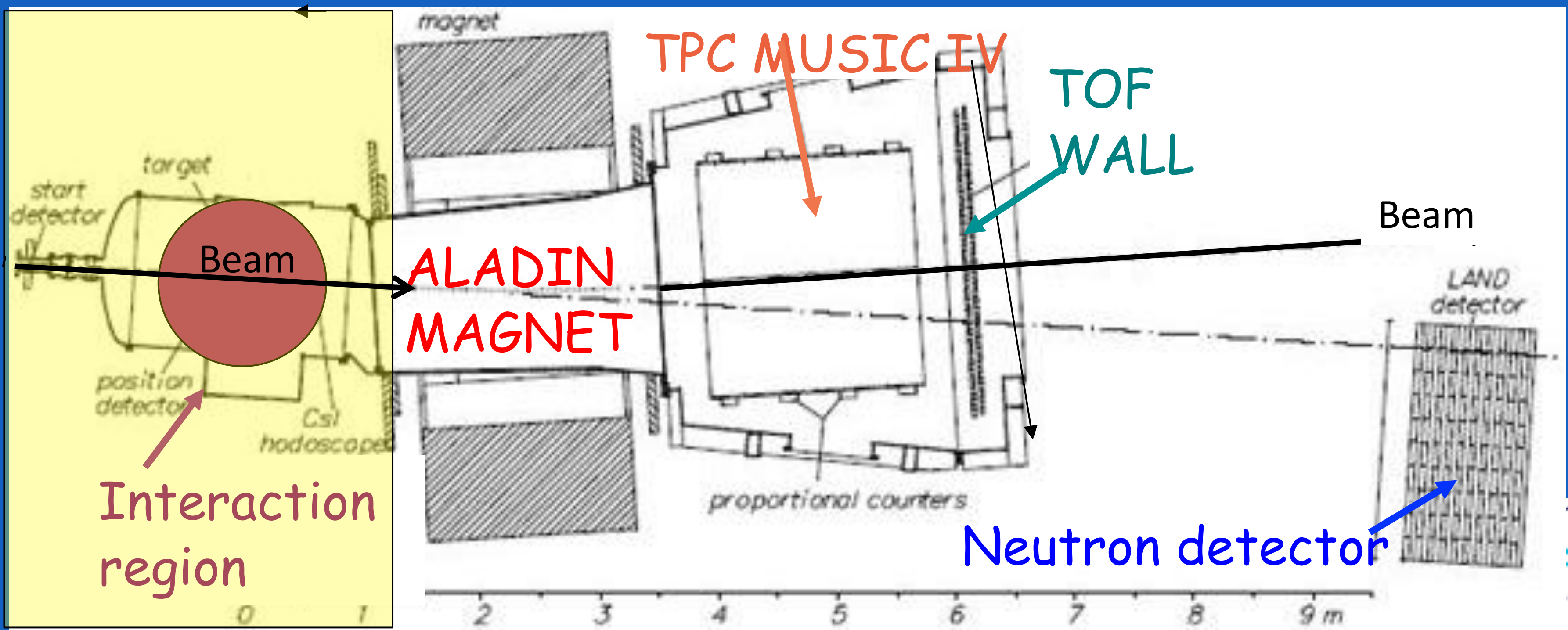




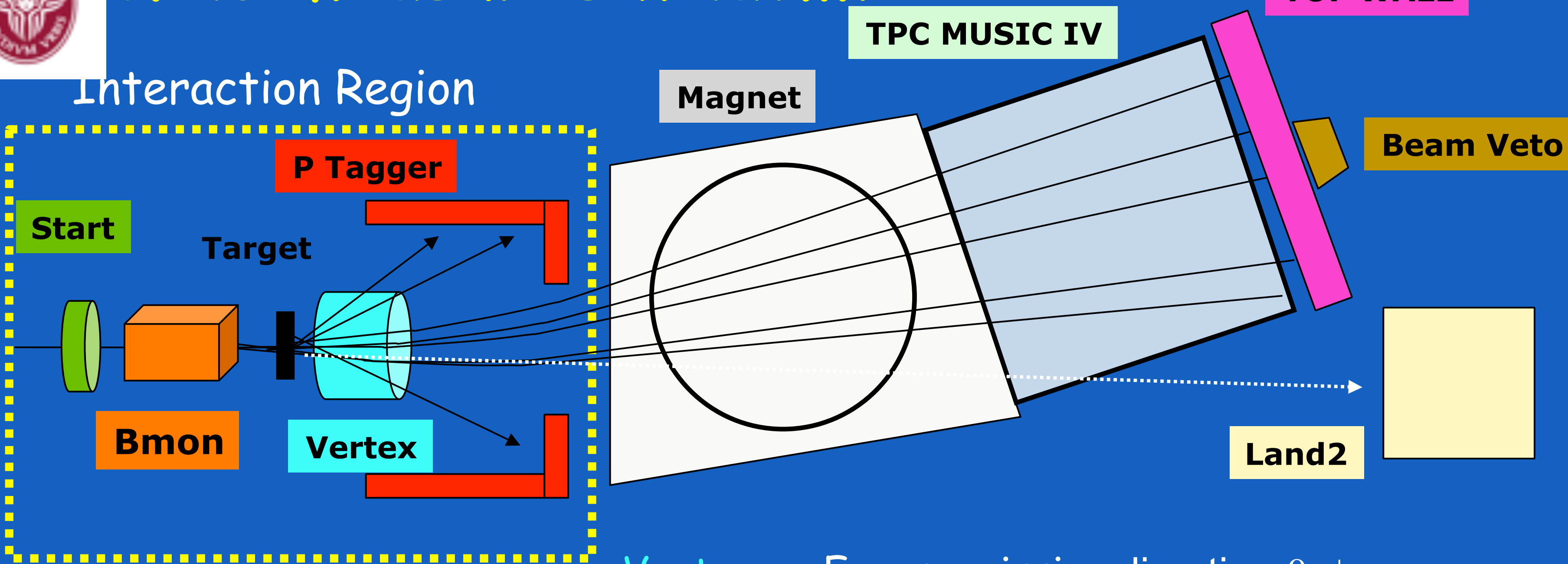
Higher energy-> FIRST exp. @GSI

Experimantal setup of dimensions, complexity and cost typical of medium size nuclear physics experiment.

- Existing setup designed for higher E and Z fragments: Dipole magnet, Large Volume TPC, TOF Wall, low angle Neutron detector.
- *Added Vertex Tracker, Start Counter scintillator counter, Beam Monitor drift chamber, scintillator Proton Tagger/Calorimeter*



Who measures what...?



Vertex → Frags emission direction θ, φ

Start → start TOF and trigger

TOF WALL → frags position & TOF, trigger

Beam mon → Beam direction & impact point

Tagger → Large θ frags: position, TOF, dE/dX

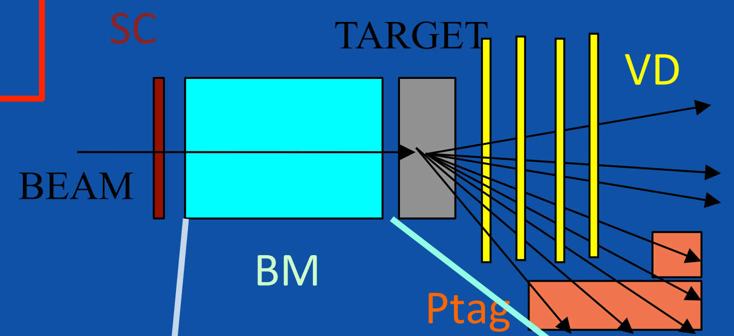
TPC MUSIC → θ,φ, dE/dx after bending

LAND2 → low angle neutron

Setup redundancy ➔ allows calibration and systematic checks of the reconstructed fragment features: Z, A, θ, E.

Beam Veto → Veto of the non interactiong beam

Beam Monitor

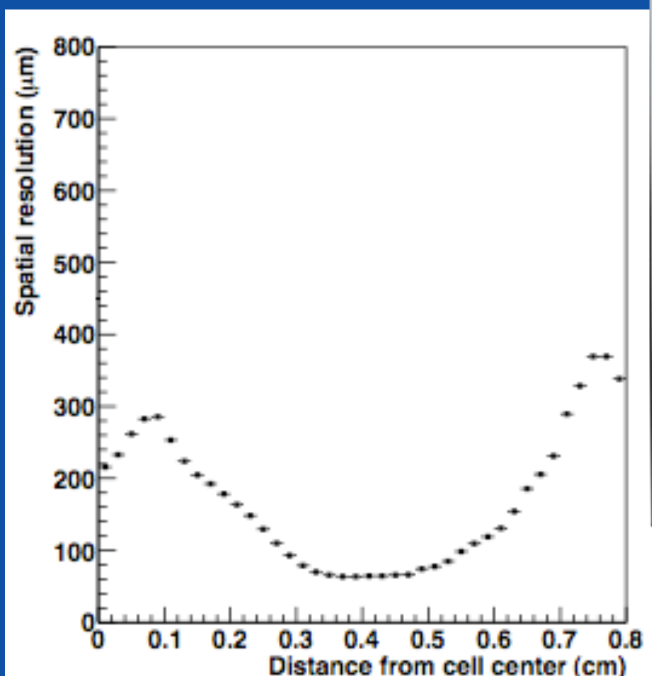


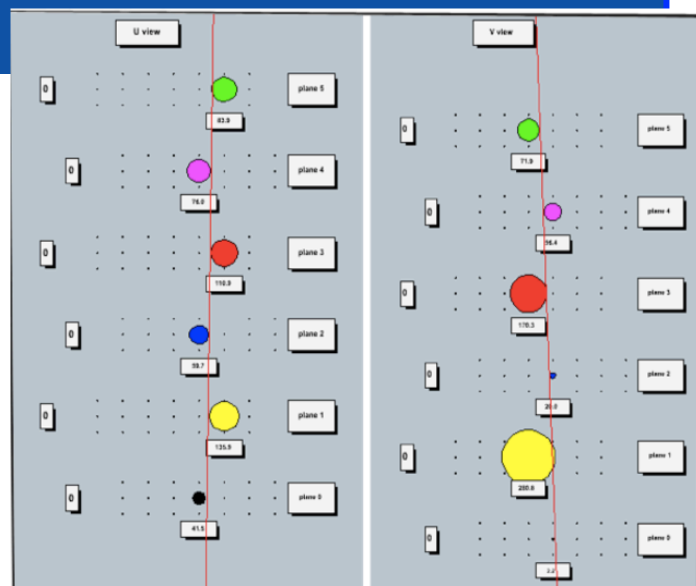
Drift chamber: measures the direction and the impact point of the beam on the target

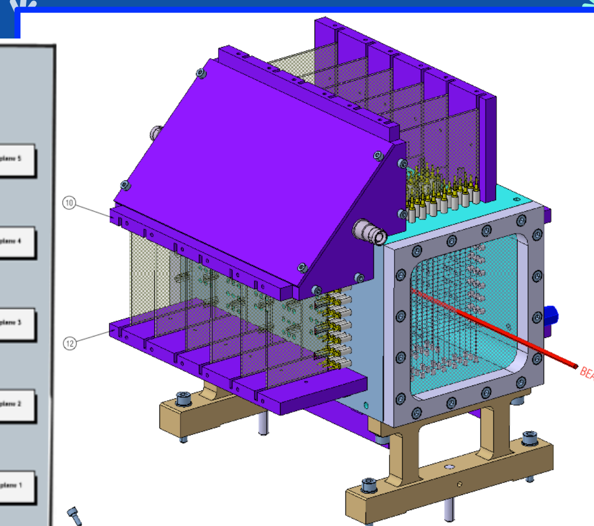
3 rectangular cell/plane (8x5 mm^2)

6 planes for each U-V views

Ar-CO_2 80/20 gas mixture @ 2.2 kV©v



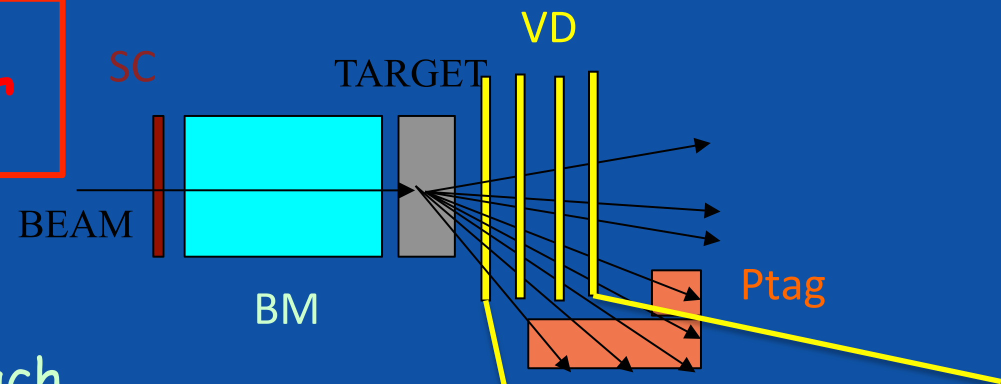




Correct matching of the correct carbon track among possible pile-up beam track in the “slow” vertex detector

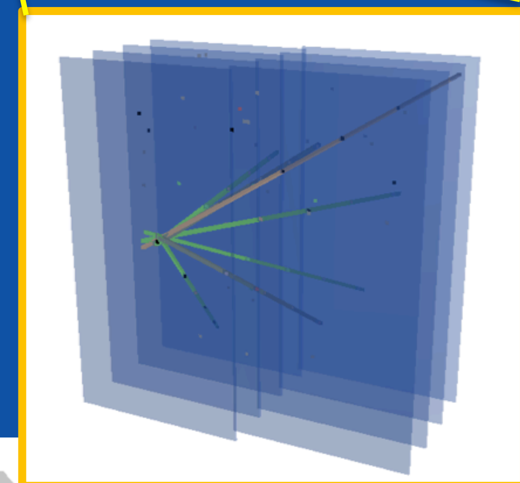
Input position and direction of the 12C projectile (beam spot ~ 6mm FWHM)

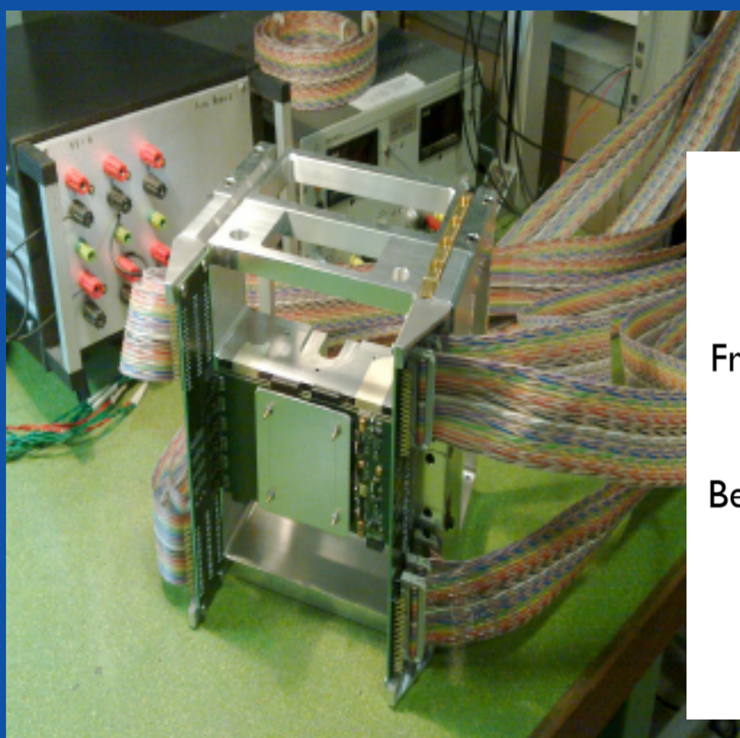
vertex detector

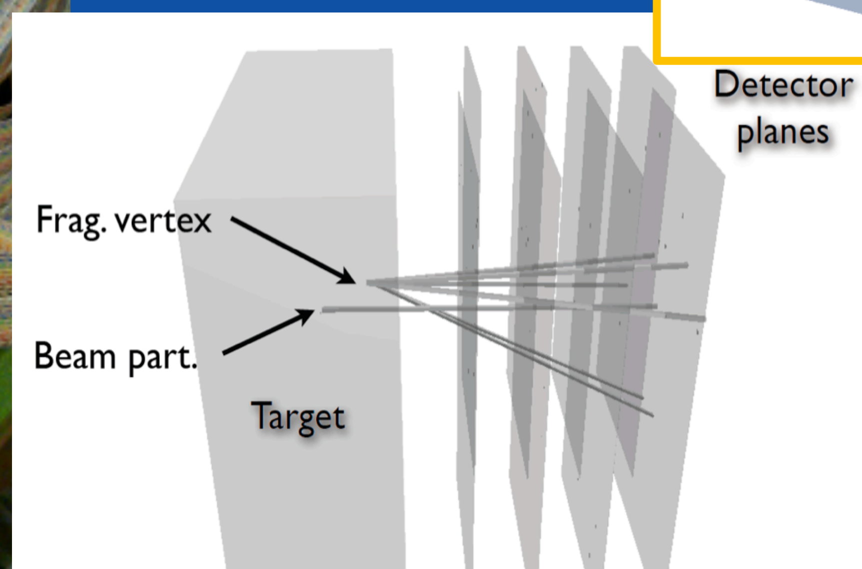


Tracks all the charged fragments downstream the target (<60 deg)

4 planes of 2x2 cm^2 active area, each made of two MIMOSA 26 silicon pixel detectors (MAPS), 3 mm spaced, 18.4 μm pitch, 60 μm thick, 10^6 pixel/layer





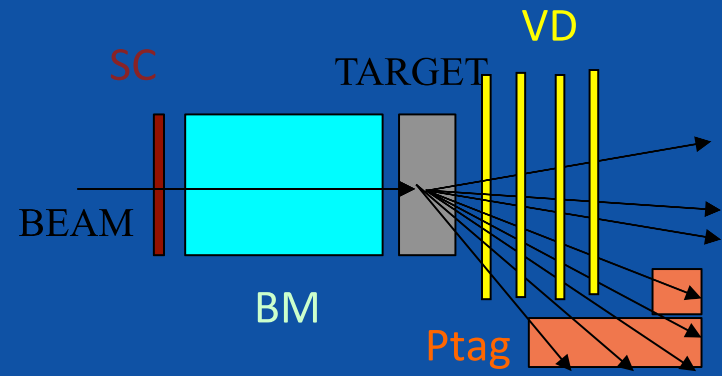


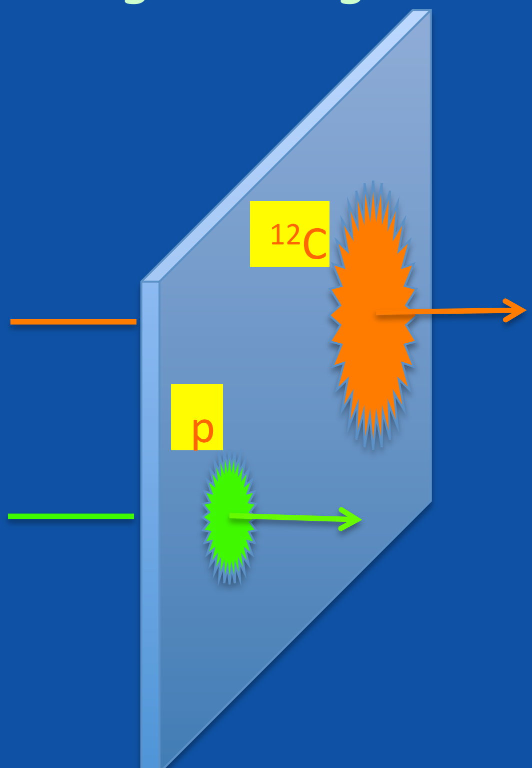
Vertex Detector

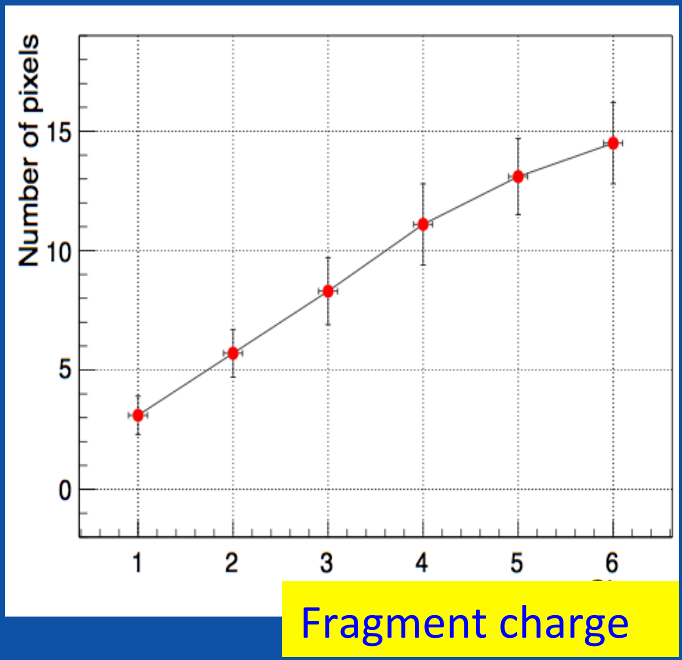
Tracking resolution ~ 10 μm (x,y) and 60 μm (z) is fundamental to correctly extrapolate the fragment track along ~ 6m to the TOF wall

Tracking efficiency for fragments ~ 99%

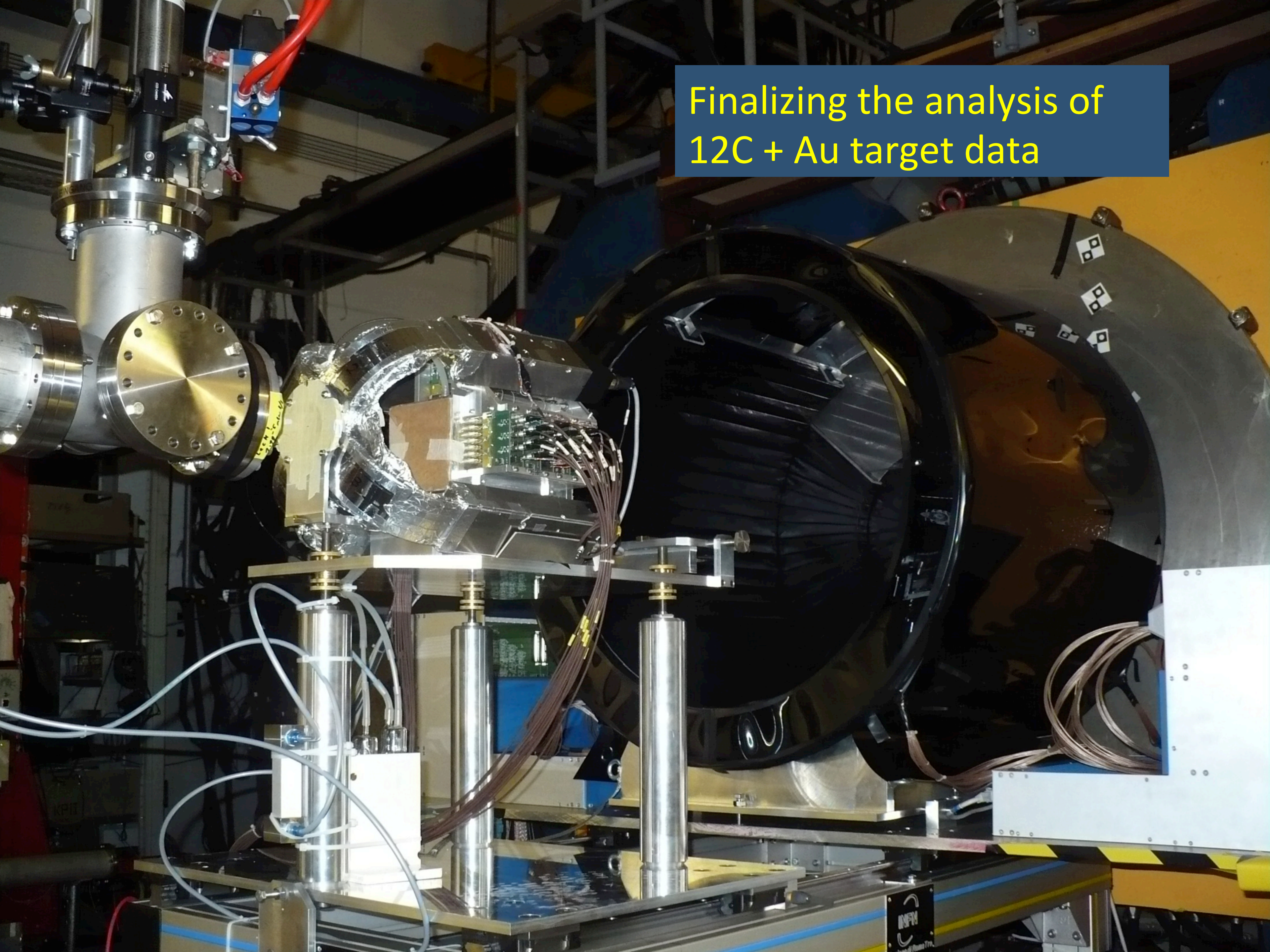
The vertex provides also information on the fragment charge looking at the number of fired pixels





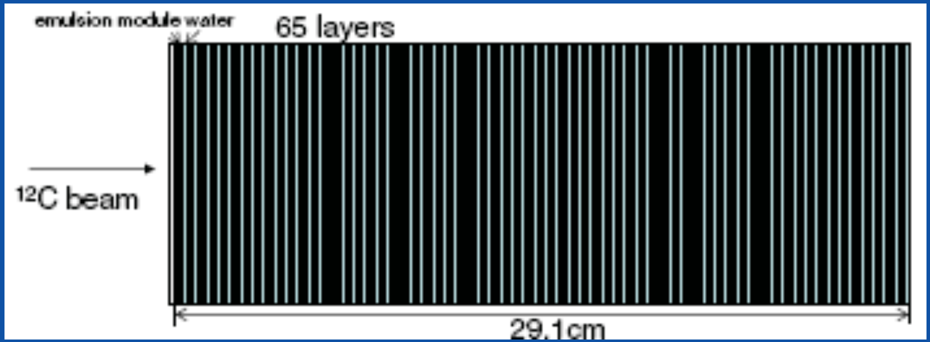


Finalizing the analysis of 12C + Au target data

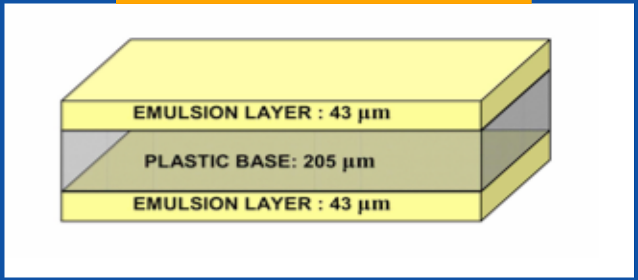


A "new" approach: Emulsion Chamber

Density grain is proportional to energy loss



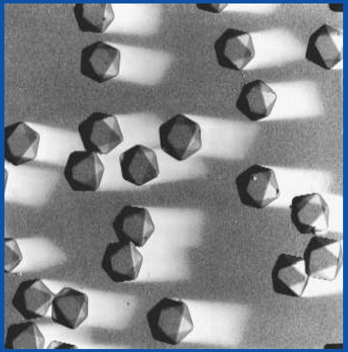
Chamber unit layer



PROs
- ✓High spatial resolution (~μm)
- ✓High angular resolution (~0.5 mrad)
- ✓Multiparticle separation

CONs:
- ✓No event by event informations
- ✓No correlation info
- ✓Limited flux integrated

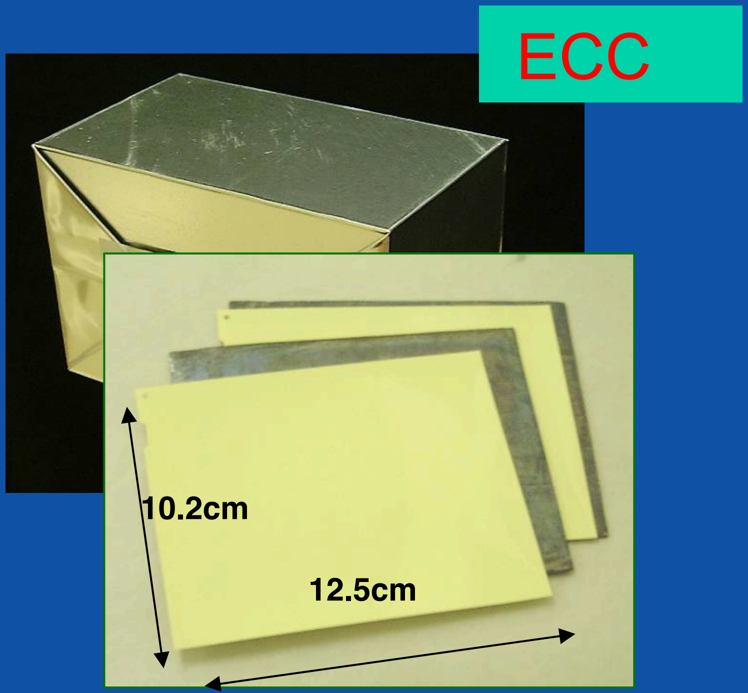
AgBr crystal (0.2 μm) is the unit active detector

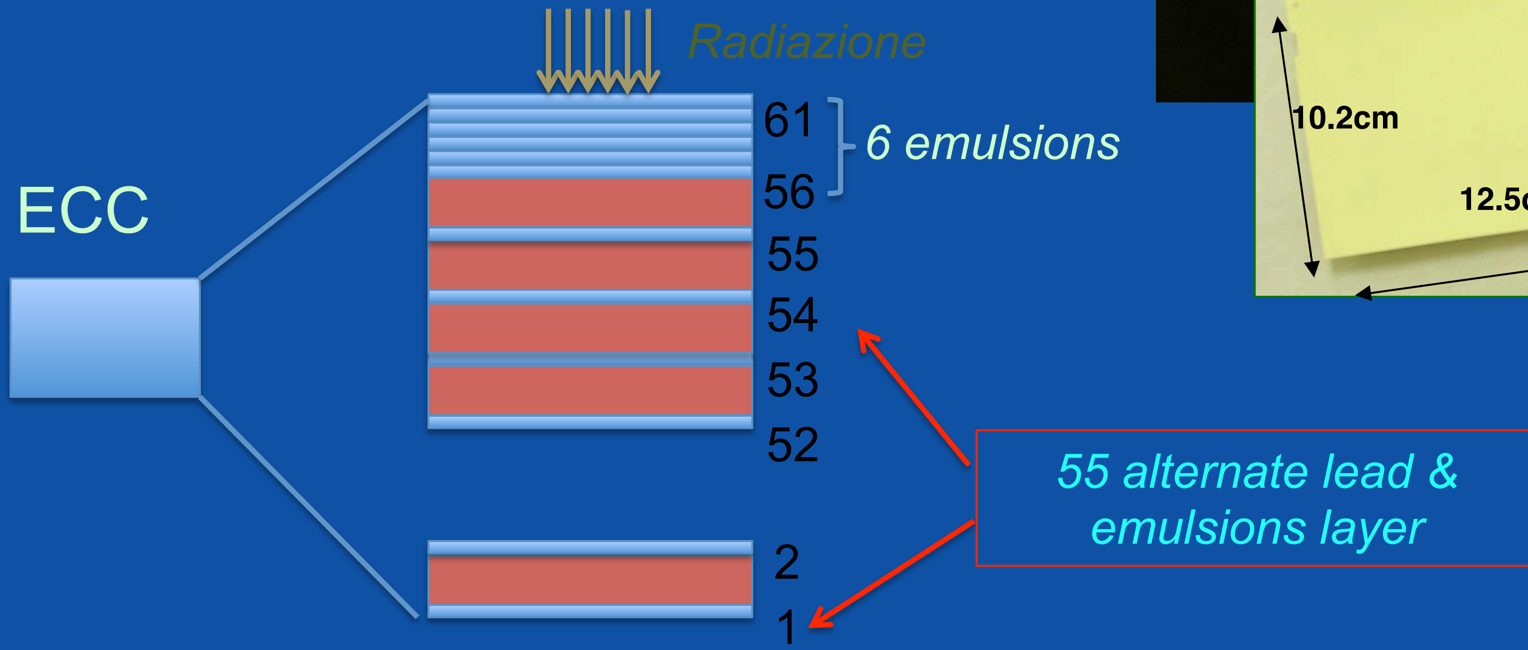


Toshito. et al., *Phys. Rev. C.*, 2008

Emulsion Cloud Chamber (ECC) for fragmentation measurement

Emulsion Cloud Chamber (ECC) (10.2 x 12.5 x 7.5 cm) for frag. measurement is made alternating 1mm lead layer and (300 μm) emulsion layer.



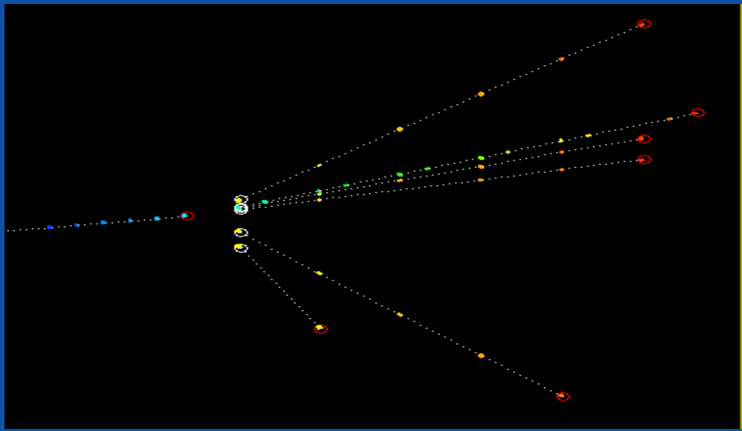


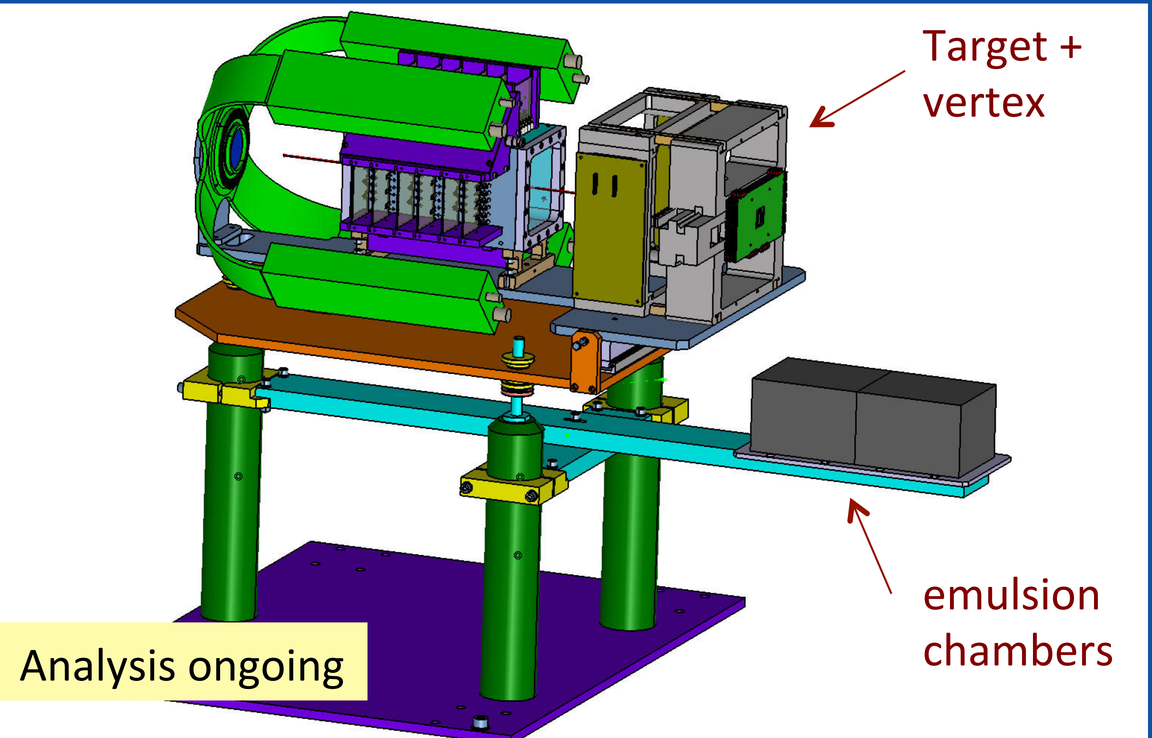
Emulsion Chambers @ FIRST

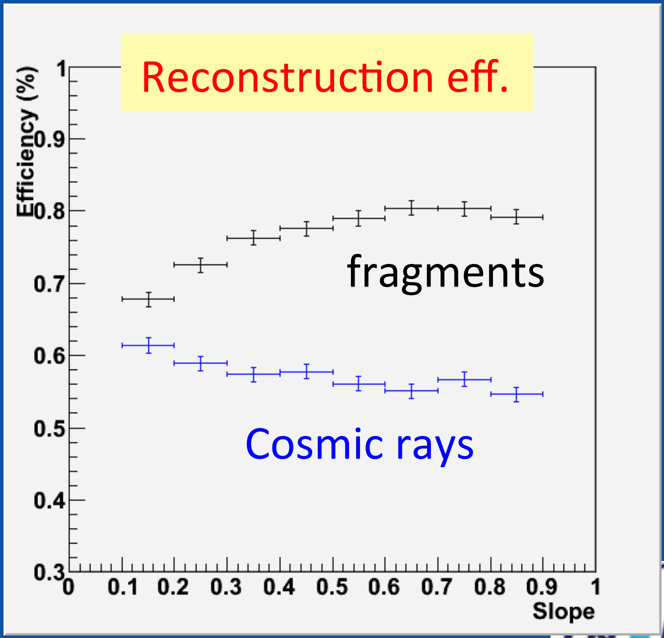
2 cloud emulsion chambers by OPERA experiment have been exposed to fragments (2 hours) by G. De Lellis and coworkers from Napoli University

Detect fragments at large angle, mainly He and protons, $30^0 < \theta < 75^0$

Comparison on going with the proton tagger distributions







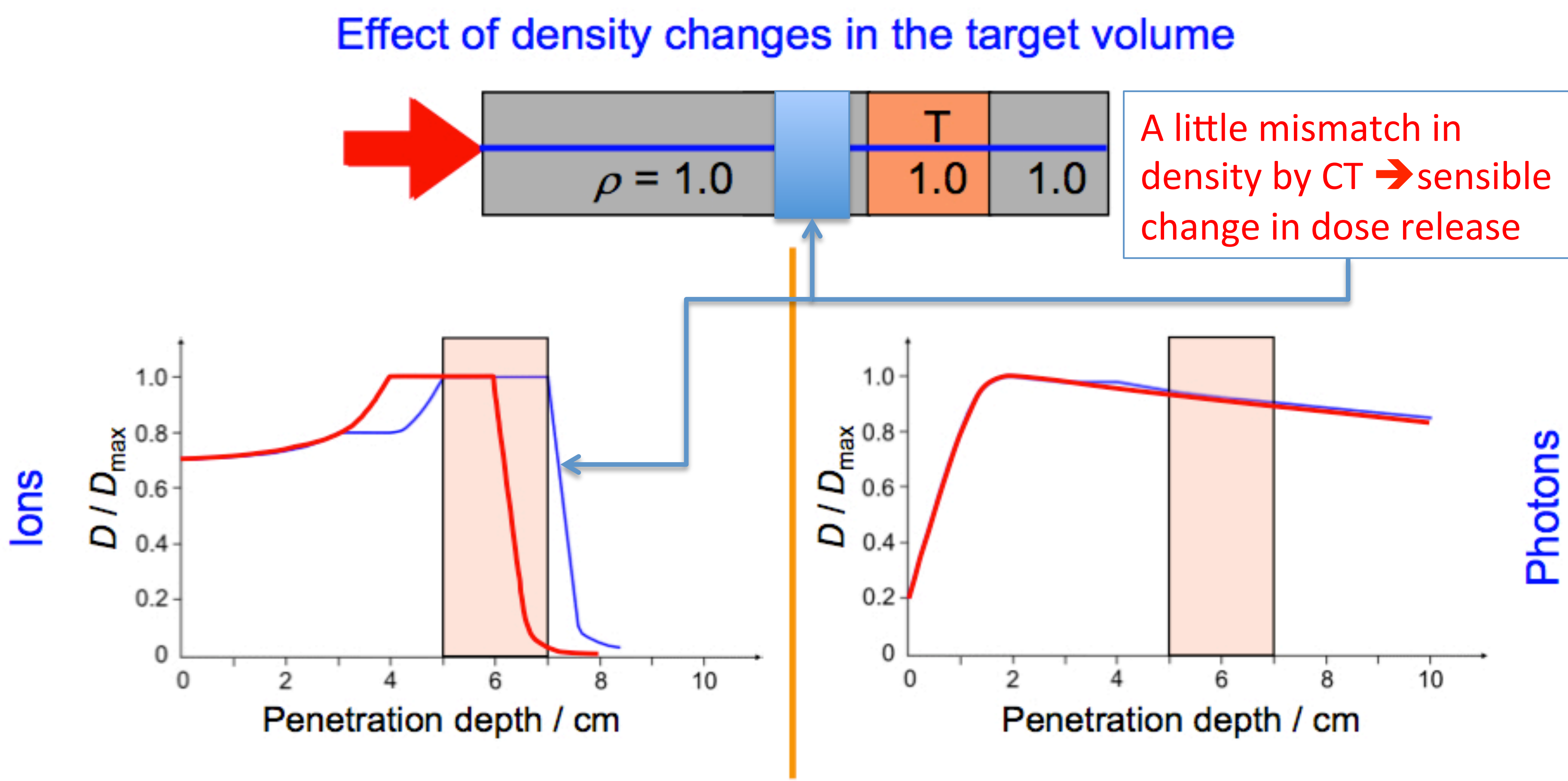
Outline

Bouncing from fundamental physics to applied physics and back…

- Overview: fragmentation in PT and space
- Some recent fragmentation experiment
- Fragmentation & dose monitoring
- Summary and conclusions

Monitoring the dose in HT

- Why is so crucial to monitor the dose in hadrontherapy with respect to conventional (photon) RT? Is like firing with machine-gun or using a precision rifle..



The range verification problem

AAPM, August 2012

Delegates were asked what they considered as the main obstacle to proton therapy becoming mainstream:

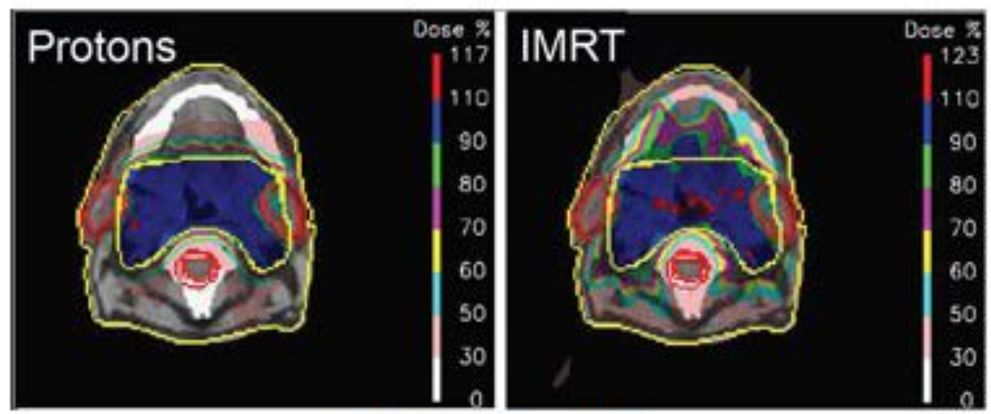
- 35 % unproven clinical advantage of lower integral dose
- 33 % range uncertainties
- 19 % never become a mainstream treatment option

RESEARCH

Aug 22, 2012

Will protons gradually replace photons?

The dose distribution advantages offered by proton therapy, particularly with the introduction of pencil-beam scanning, have stimulated increasing interest in this modality. But is the large capital expenditure required to build a proton therapy facility hindering the widespread implementation of this technique? And how big a problem is range uncertainty, which can prevent proton therapy from meeting its full potential?



Protons versus IMRT

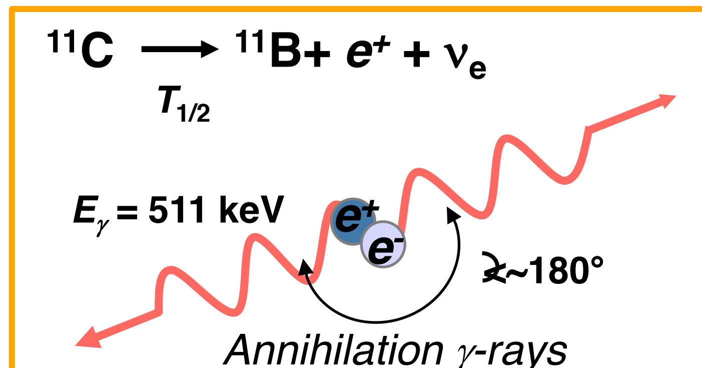
http://medicalphysicsweb.org/cws/article/research/50584

baseline dose monitoring in PT : PET

Baseline for monitor in PT is PET : fragmentation by hadron beam creates β^+ emitters.

- Isotopes of short lifetime ^{11}C (20 min), ^{15}O (2 min), ^{10}C (20 s) with respect to conventional PET (hours)
- Low activity in comparison to conventional PET need quite long acquisition time (some minutes at minimum)
- Metabolic wash-out, the β^+ emitters are blurred by the patient metabolism

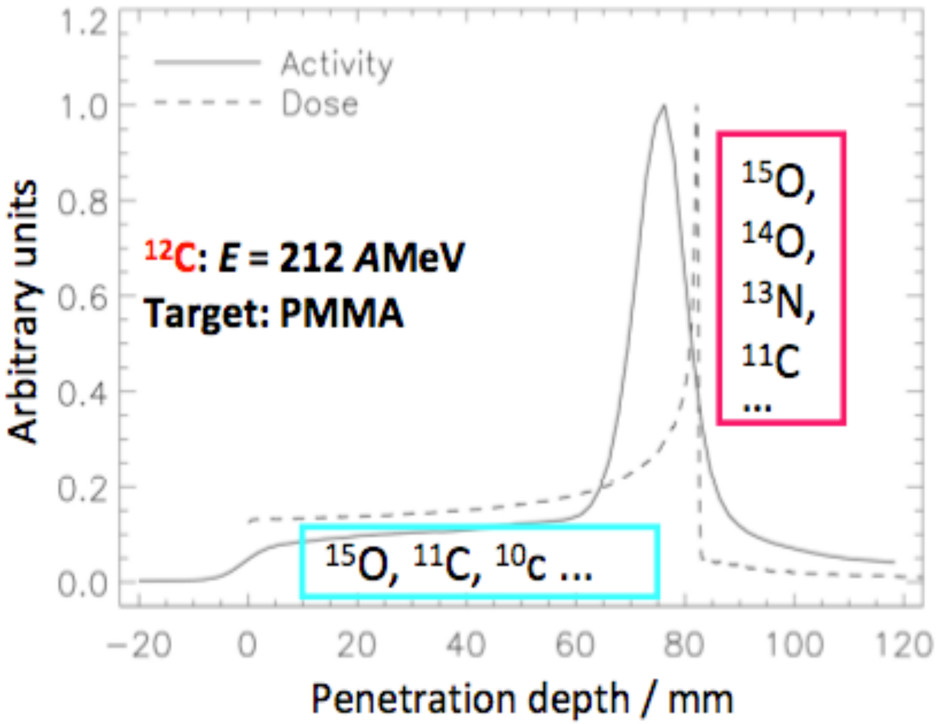
No direct space correlation between β^+ activity and dose release (but can be reliable computed by MC)



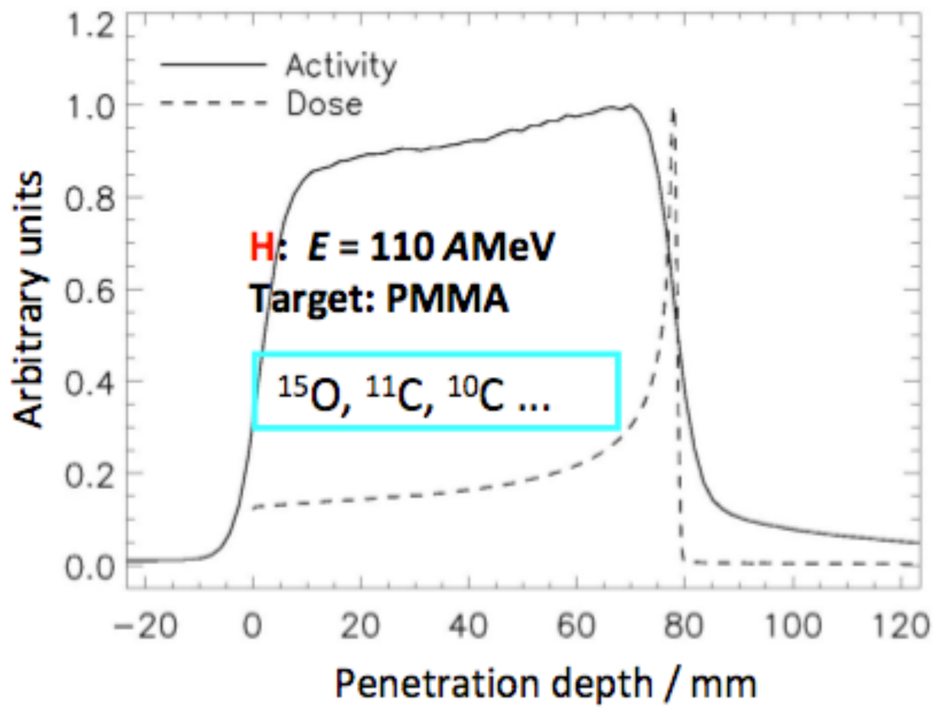
Correlation between β^+ activity and dose

Therapy beam	^{1}H	^{3}He	^{7}Li	^{12}C	^{16}O	Nuclear medicine
Activity density / Bq cm^{-3} Gy^{-1}	6600	5300	3060	1600	1030	$10^4 - 10^5$ Bq cm^{-3}

Projectiles & target fragmentation



Target fragmentation

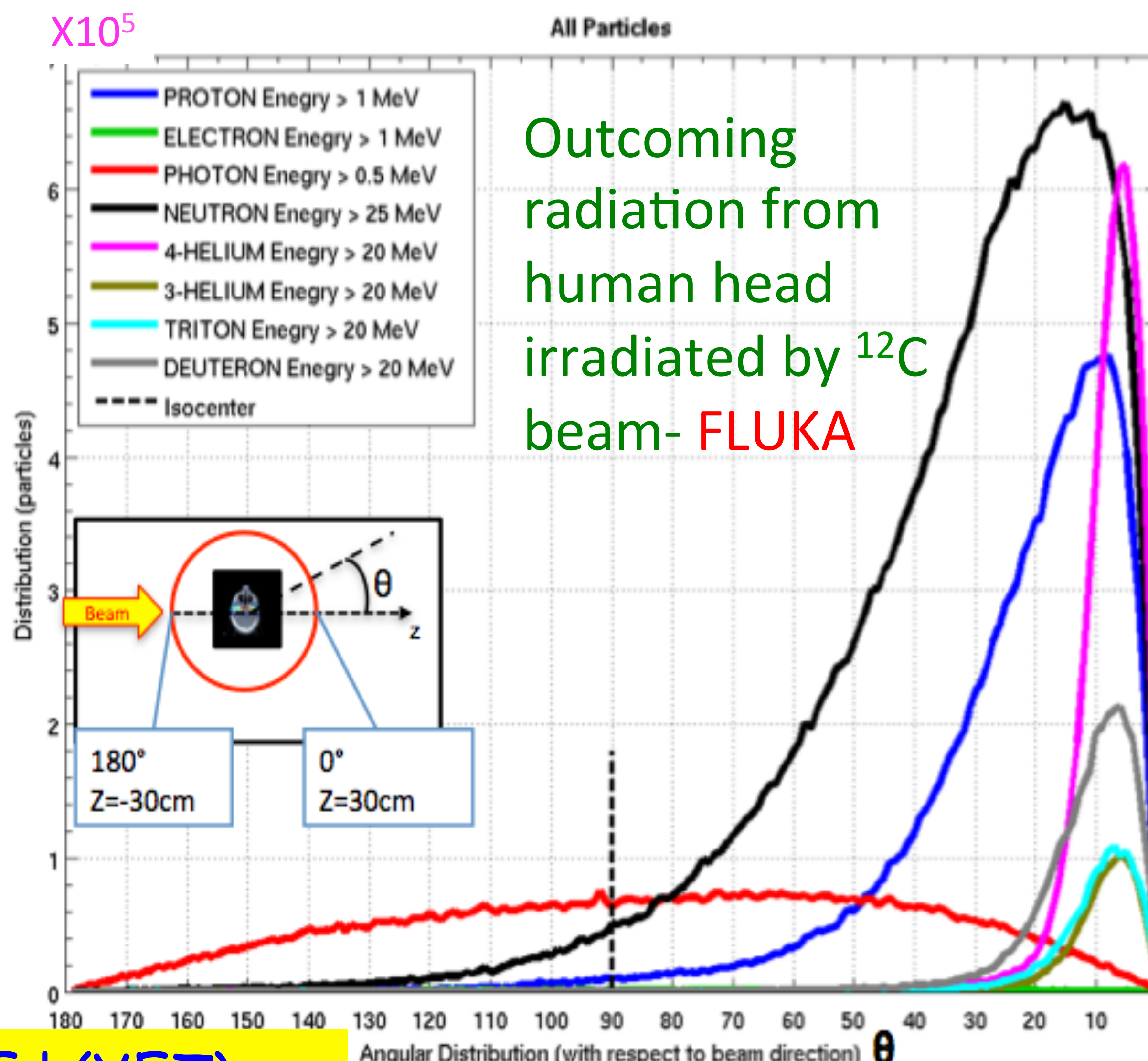


Fragmentation, nuclear excitation, β^+ emitter production…. Background or signal?

The p, ^{12}C beams generate a huge amount of secondaries..

In particular prompt single γs. , PET γs , protons and neutrons.

Can be used to track the beam inside the patient



MC NOT RELIABLE ! (YET)

The prompt gamma saga…

- The gamma are quite copiously produced by proton and ^{12}C beam by nuclear excitation.
- The emission region stretches along all the beam path but has been shown to ends near the Bragg peak for both beams.
- There is a huge background due to neutrons & uncorrelated gamma produced by neutrons. This background is beam, energy and site specific
- It's not simple backpointing the γ direction: take profit by the SPECT technique… but the energy of these γ is in the 1-10 MeV range-> much more difficult to stop and collimate!!

INFN Istituto di Fisica

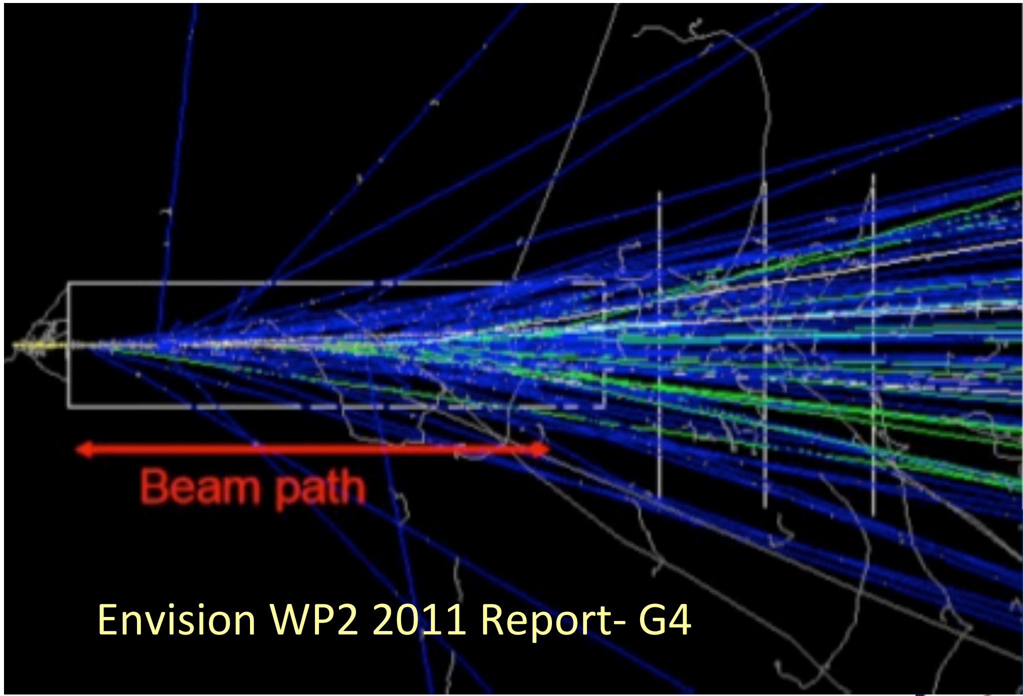
Something else useful?…the fragments!

Low energy protons are surely emitted by hadron beam. Also from region near BP? And with enough energy to exit from the patient body and be detected?

And for a proton beam also?

K Gwosch et al Phys. Med. Biol. 58 3755
C Agodi *et al Phys. Med. Biol.* **57** 5667

- Best space resolution for large angle emission → low statistics
- MC highly unreliable, probing the very tail of the angular distribution of secondary



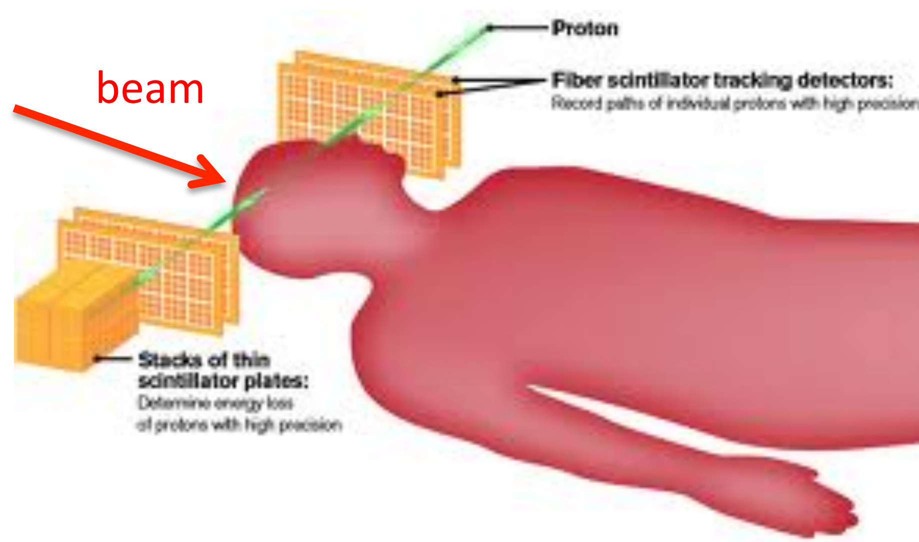
Why so excited about charged particles emitted by the beam??

Charged particles have several nice features as

- The detection efficiency is almost one
- Can be easily back-tracked to the emission point-> can be correlated to the beam profile & BP

BUT…

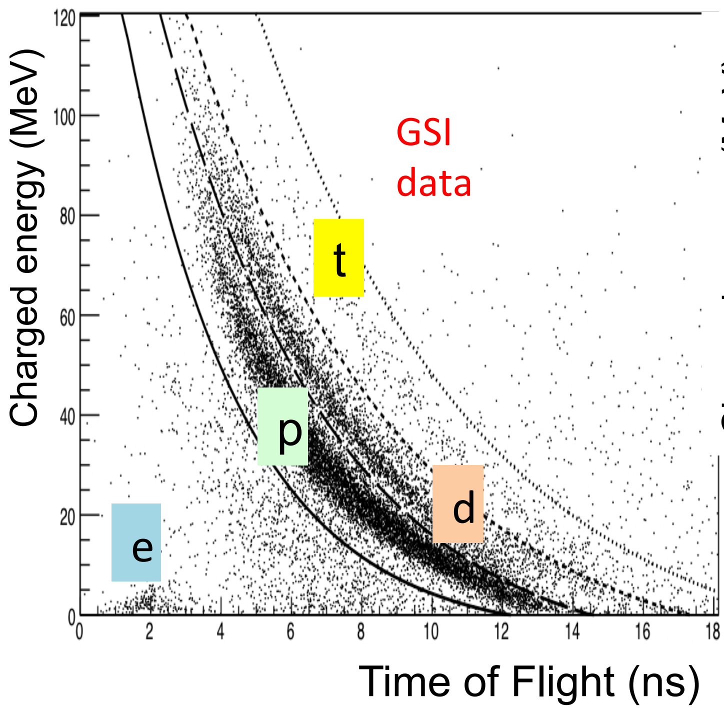
- They are not so many
- Energy threshold to escape ~ 100 MeV
- They suffer multiple scattering inside the patient -> worsen the back-pointing resolution

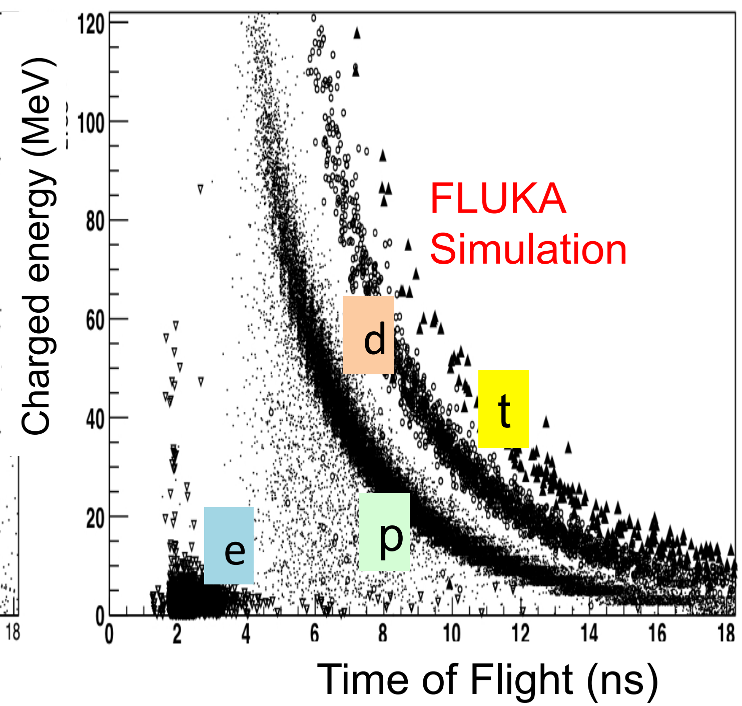


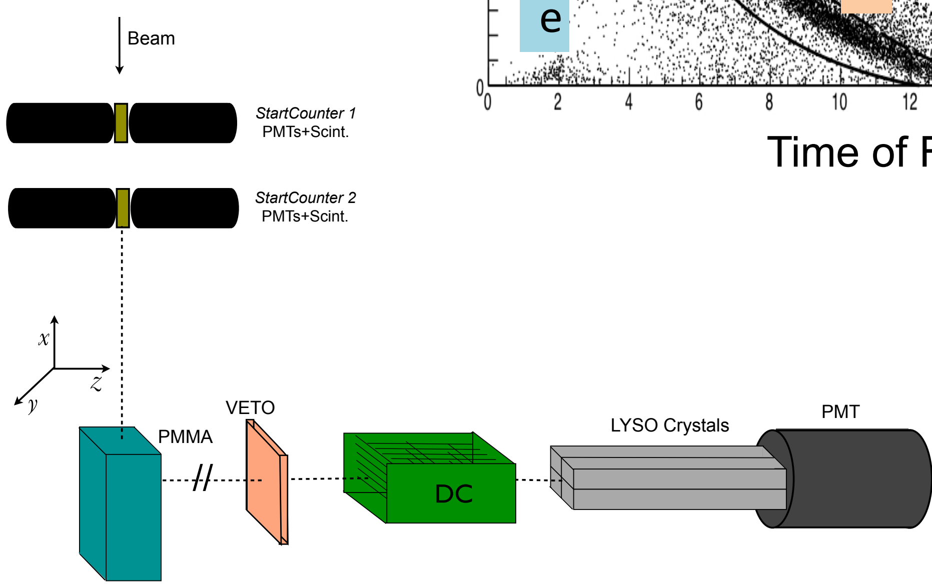
Searching for charged secondaries...

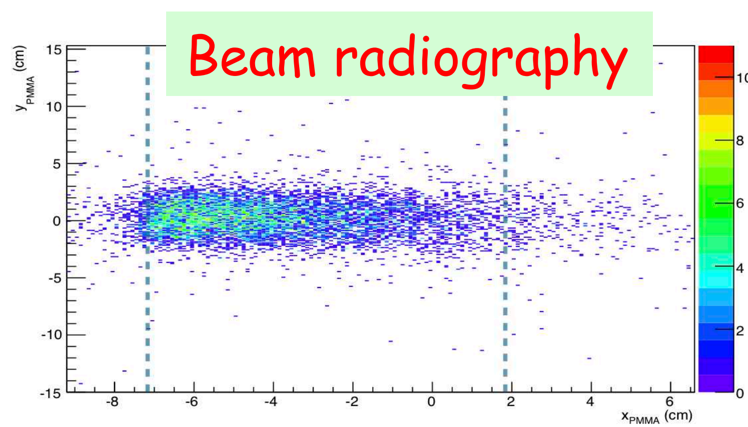
L.Piersanti et al. PMB 2014

Charged secondaries produced at 90^0 wrt the beam from PMMA target on 220 AMeV ^{12}C beam at GSI









Fragmentation & dose monitoring

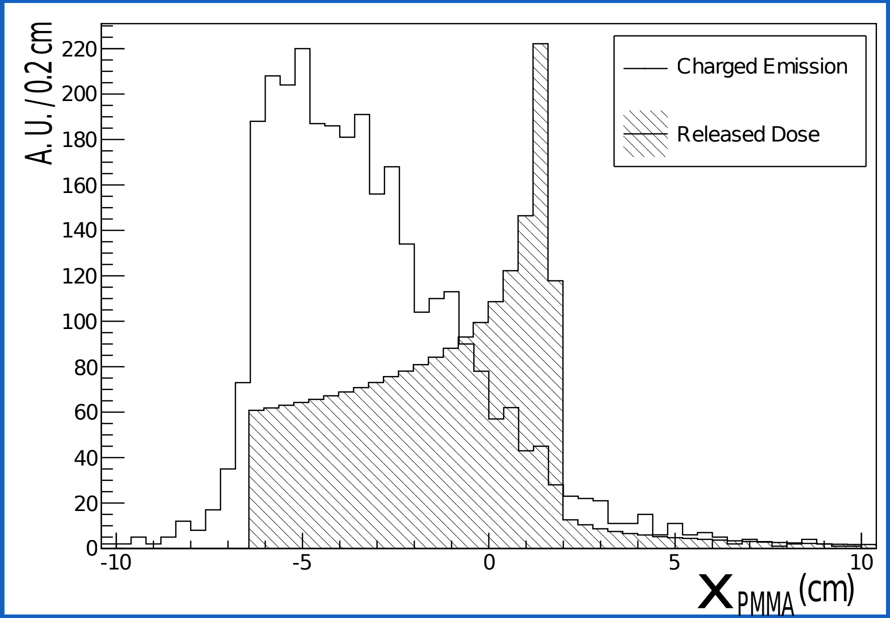
There are indications that emission point distribution of 100-150 MeV secondary protons provides info on the BP position

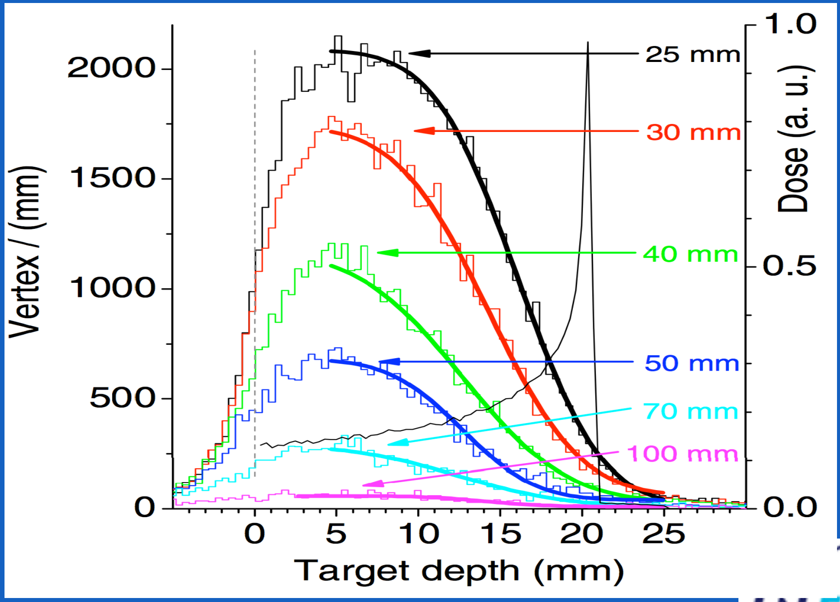
Measured emission distribution shape of protons as detected outside a 5 cm thick PMMA at 90^0 wrt the direction of 220 AMeV ^{12}C beam

L. Piersanti et al Phys. Med. Biol 2014

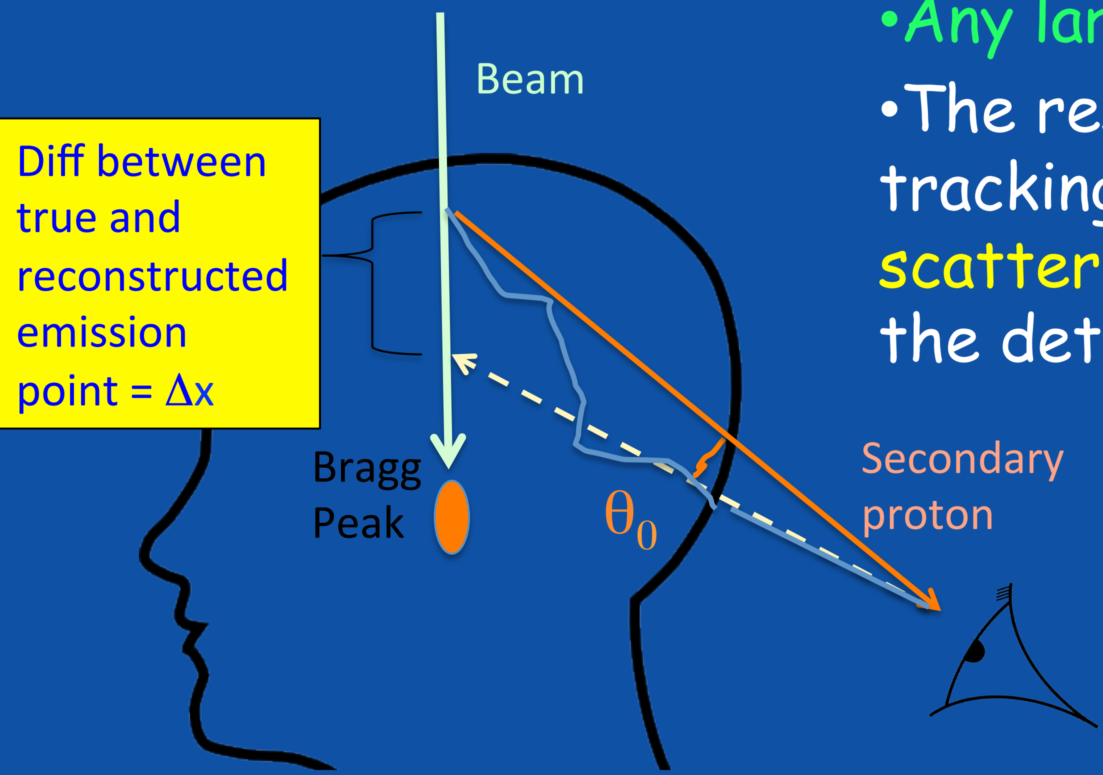
Simulated emission distribution shape of protons as detected ouside different PMMA thickness at 30^0 wrt the direction of 95 AMeV ^{12}C beam

E. Testa et al Phys. Med. Biol. 57 4655





Which detector should be used?

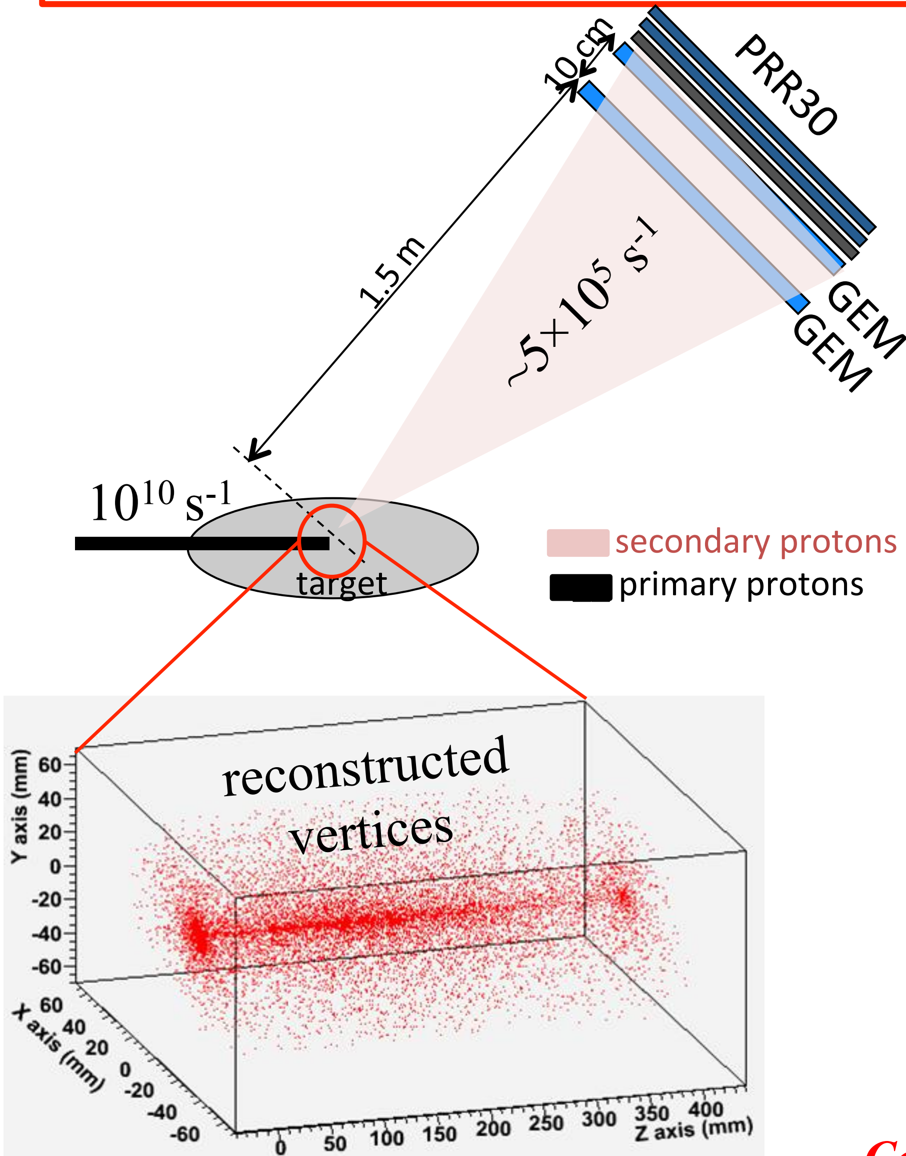


- *Any large tracking detector!!*
- The resolution of the back-tracking is limited by the multiple scattering in the patient, not by the detector resolution..

Typical resolution on Δx is of the order of 6-8 mm

Integrating enough statistic (~ 10^3 events) helps to lower the accuracy on the emission point distribution (and then on the beam profile) to mm level ➔detector size

Vertex imaging…some Results



- $\sigma_{GEM\text{-}spatial} \cong 400\mu m$
- → $\sigma_\theta \cong 6mrad$ Angular resolution
- → Ω~0.3% (0.04 sr) Solid angle

- Large-angles beam diagnostics is feasible
- at an acquisition rate of 10^6 tracks/s

Courtesy of TERA

PRR30

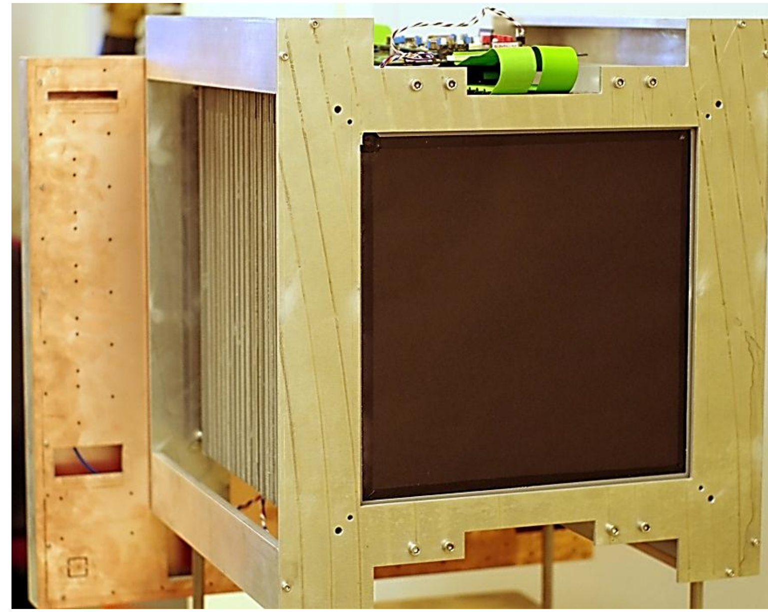
In collaboration with: AGH University, PSI

Scintillators stack: Range/Energy loss

- Plastic scintillators (3mm):
  - 2 modules in coincidence for trigger
  - 48 modules (~15 cm water equivalent)
  - density ~1 (almost tissue equivalent)
- Wavelength shifter fibers
- Silicon Photomultipliers Readout

High intrinsic rate capability (>1 MHz)

30 MeV < RESIDUAL RANGE< 190 MeV



GEMs: Tracker

- 30x30 cm^2 Gas Electron Multiplier (GEM)
- Gas: Ar-CO^2 (70:30)
- HV: 3.9-4.2 kV
- 2D strip readout

High rate (~*1 MHz*)
Radiation resistant

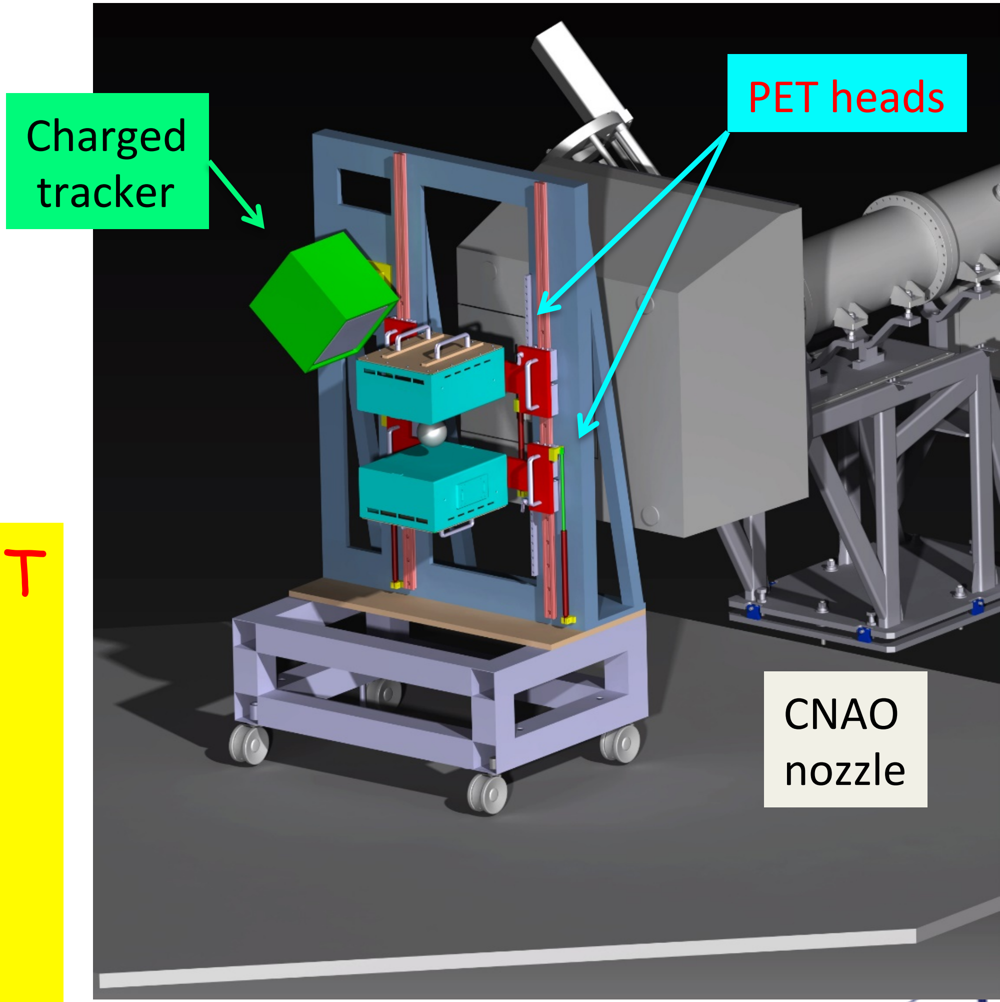
Courtesy of Martina Bucciantonio - TERA Foundation

Multimodal approach: The INSIDE project @CNAO

•INSIDE (Innovative Solutions for In-beam Dosimetry in Hadrontherapy) is a joint project MIUR-INFN-Centro Fermi-CNAO. 40 researchers.

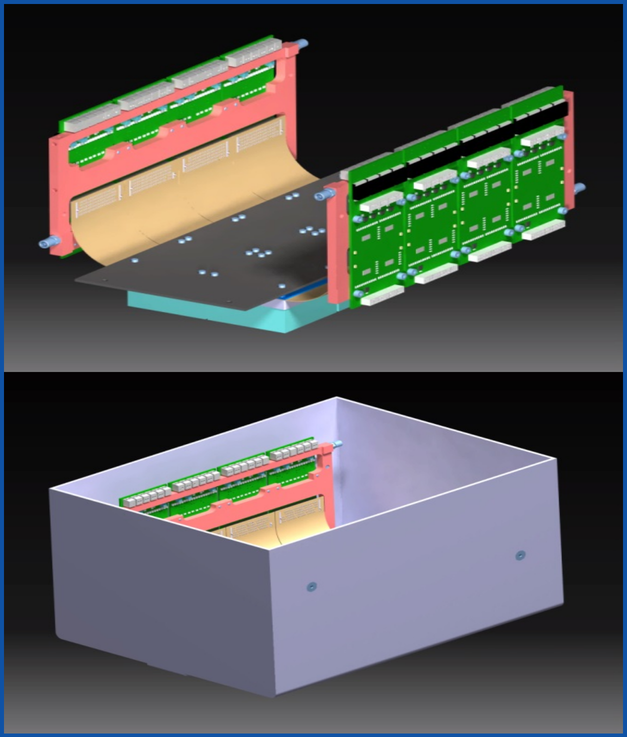
In-beam dose profiling by PET activities and charged secondaries detection.

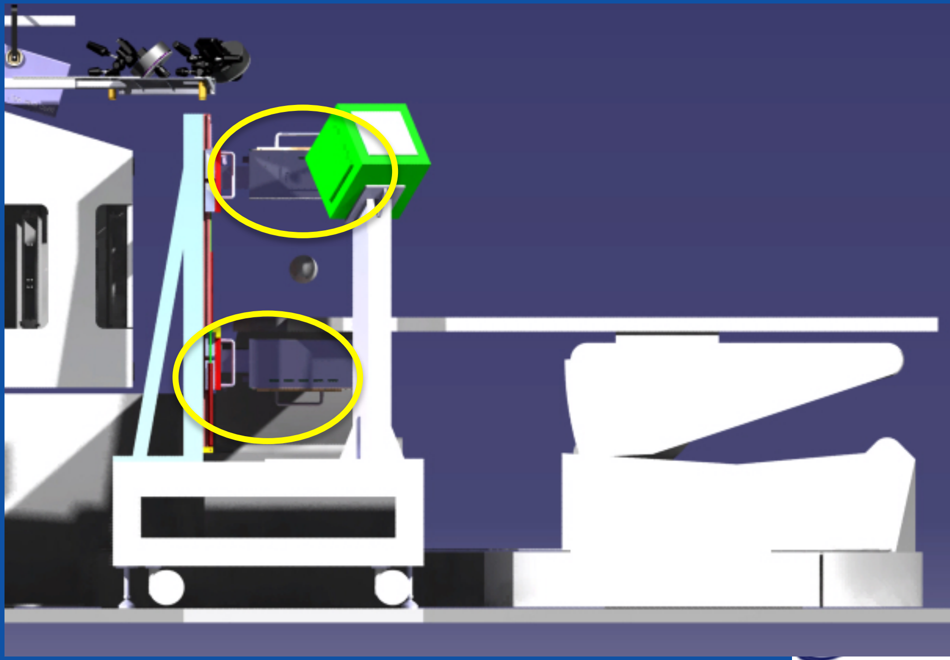
Mechanics and operation optimized to be inserted in the CNAO work-flow



The INSIDE PET system

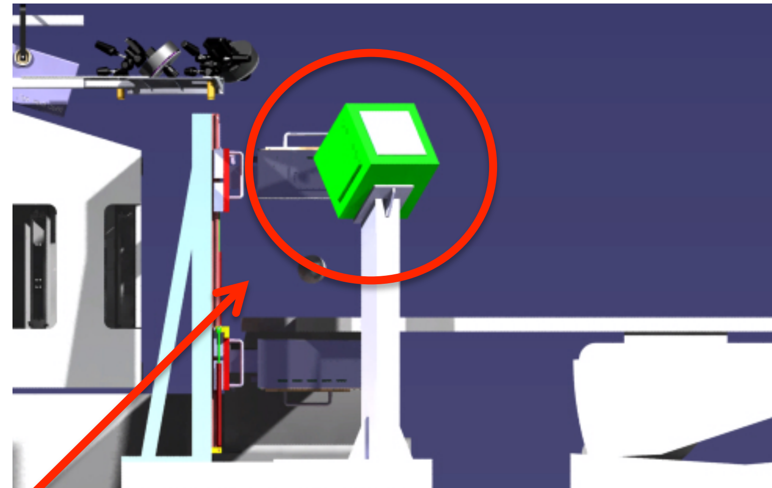
- DAQ sustains annihilation and prompt photon rates during the beam irradiation
- Two planar panels each 10 cm x 20 cm wide. Each panel will be made by 2 x 4 detection modules
- Each module is composed of a pixelated LYSO scintillator matrix 16 x 16 pixels, 3x3 mm^2 crystals, 3.1 mm pitch, for a total sensitive area of 5x5 cm^2
- One SiPM array (16x16 pixels) is coupled one-to-one to each LYSO matrix

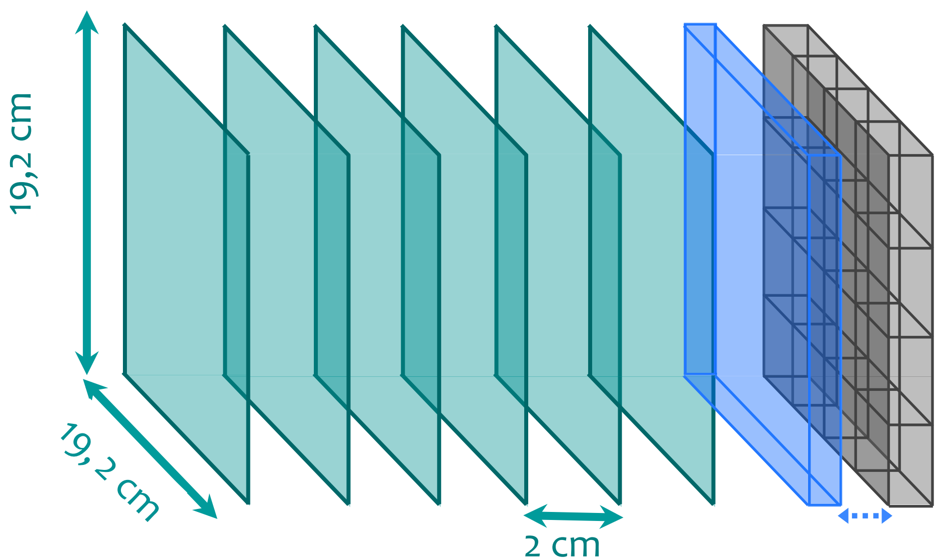




INSIDE: charged tracker

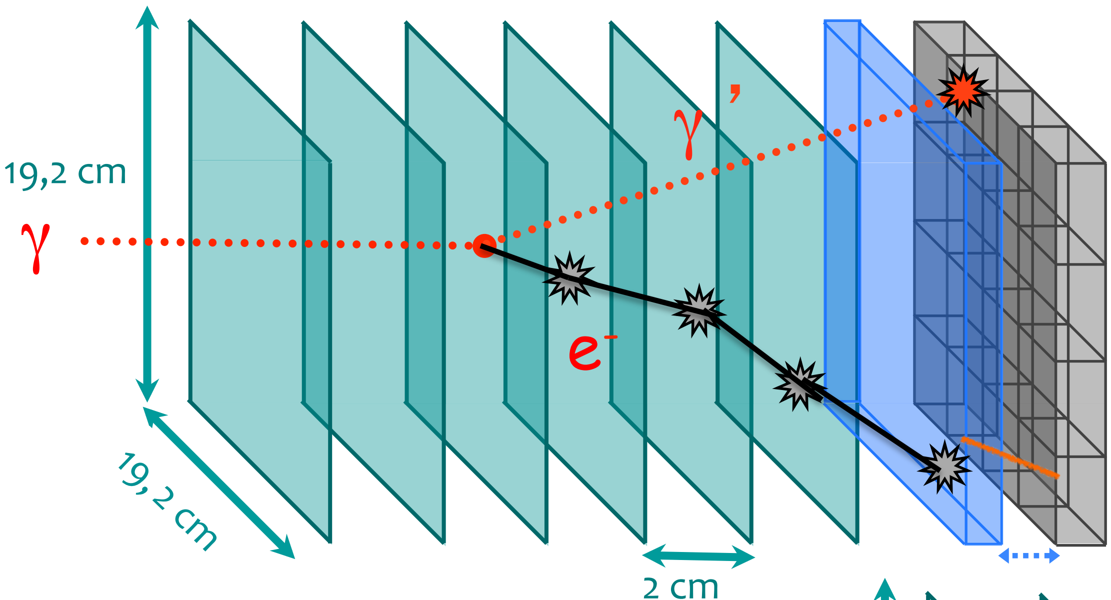
- 6 XY planes with 2 cm spacing. Each plane made of 2 stereo layers of 192 0.5x0.5 mm^2 square scintillating fibers
- 2x0.5 mm squared fibers read out by Hamamatsu 1mm^2 SiPM : S12571-050P
- 32 SiPM feed a 32 ch ASIC BASIC32





- 4x4 LYSO pixellated crystals tracking planes: 50 x 50 x 16 mm^3
- Plastic absorber 1.5 cm thick in front of LYSO to screen electrons
- Crystals read out by 64 ch Hamamatsu MultiAnode

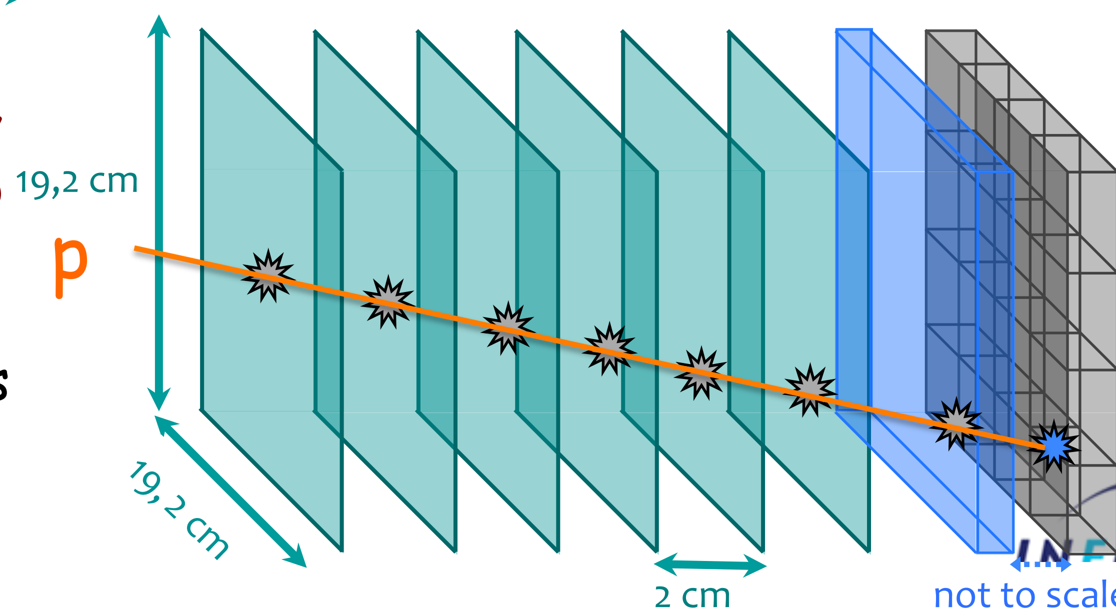
INSIDE Profiler: prompt secondaries



"dual mode" detector

- Compton camera for prompt photons (E_γ~1-10 MeV)
- Tracking device for charged secondaries (E_{kin} ~ 30-130 MeV)

- Heavy charged secondary cross all TRK planes up to LYSO crystals
- Electrons from Compton event have winding tracks (mul. scatt.) and are not detected in the LYSO



Summary & conclusions (I)

- Nuclear fragmentation prevents the use of ions heavier then Oxygen and must be taken into account in the Treatment Planning System for PT and in shielding calculation in Space Radioprotection
- The nuclear measurements go directly in the clinical practice or spacecraft design
- The experiments seems to evolve towards more and more complexity and dimensions
- No mention has been done in this talk of neutrons production due to nuclear fragmentation and their measurement

Summary & conclusions (II)

- The nuclear interaction of the beam with the patient in PT provide also the only method to monitor the released dose, backtracing the produced secondaries from the beam path to the BP: γ from β^+ emitters, prompt photons from nuclear excitation and light charged fragments
- Huge experimental activity that has direct application in the clinical practice

CREDITS

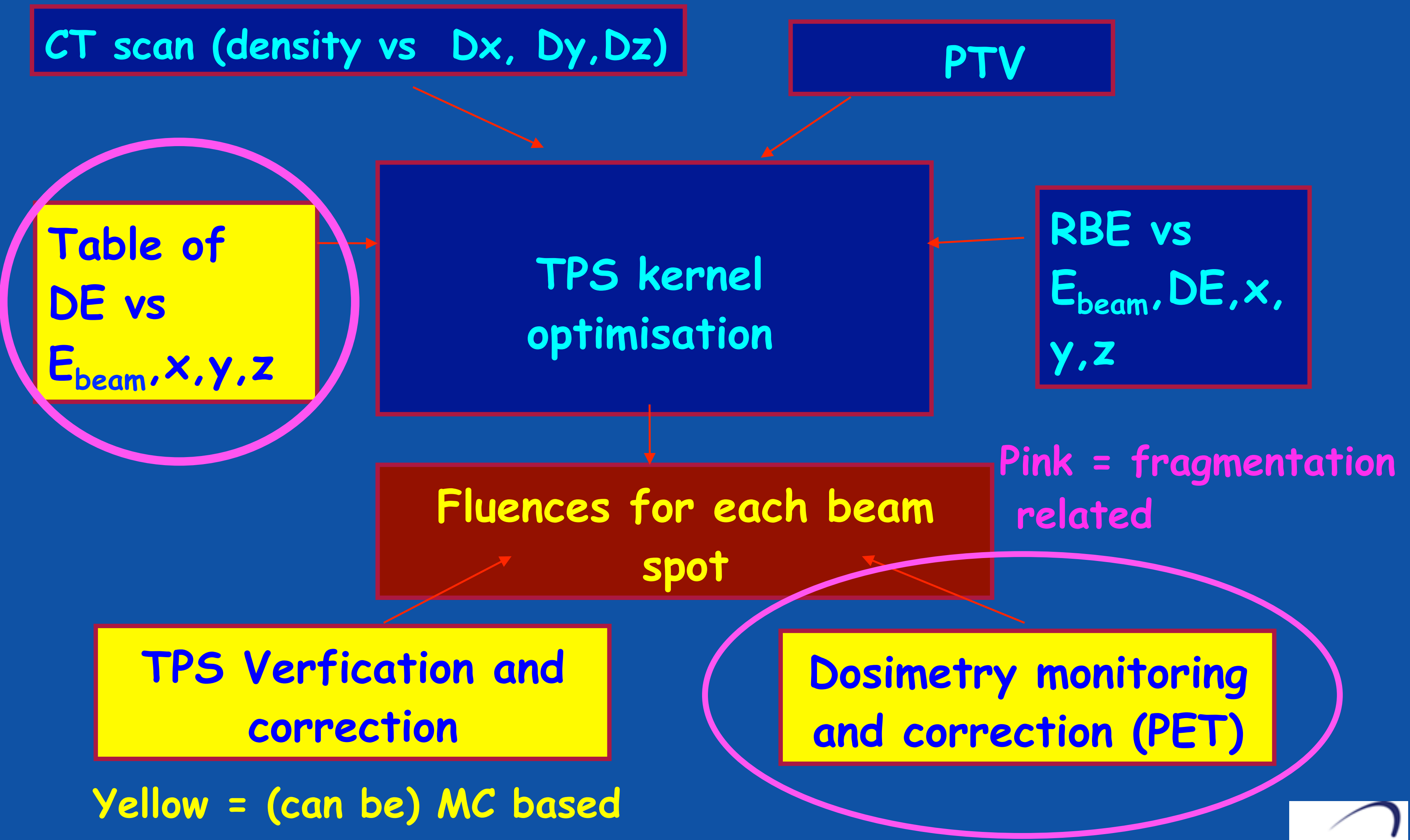
I have been given a lot of slides, plots, comments by many collegues…

- M.Durante
- G.Battistoni
- K.Parodi
- E.Testa
- A.Ferrari
- + others…

Thanks!!

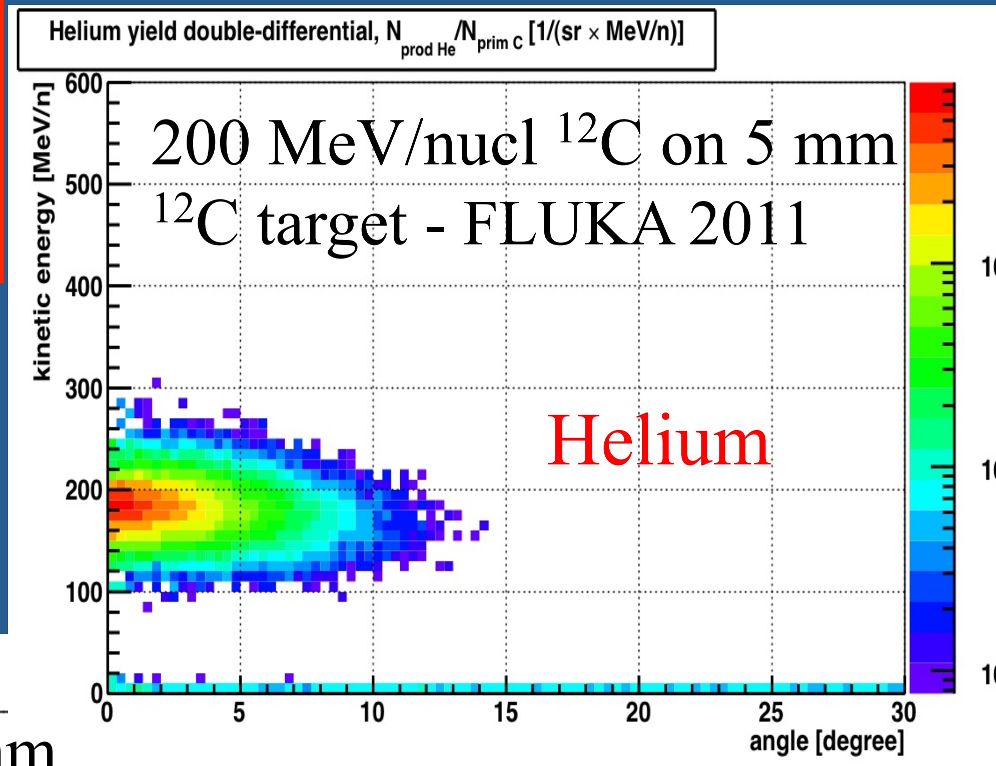
spares

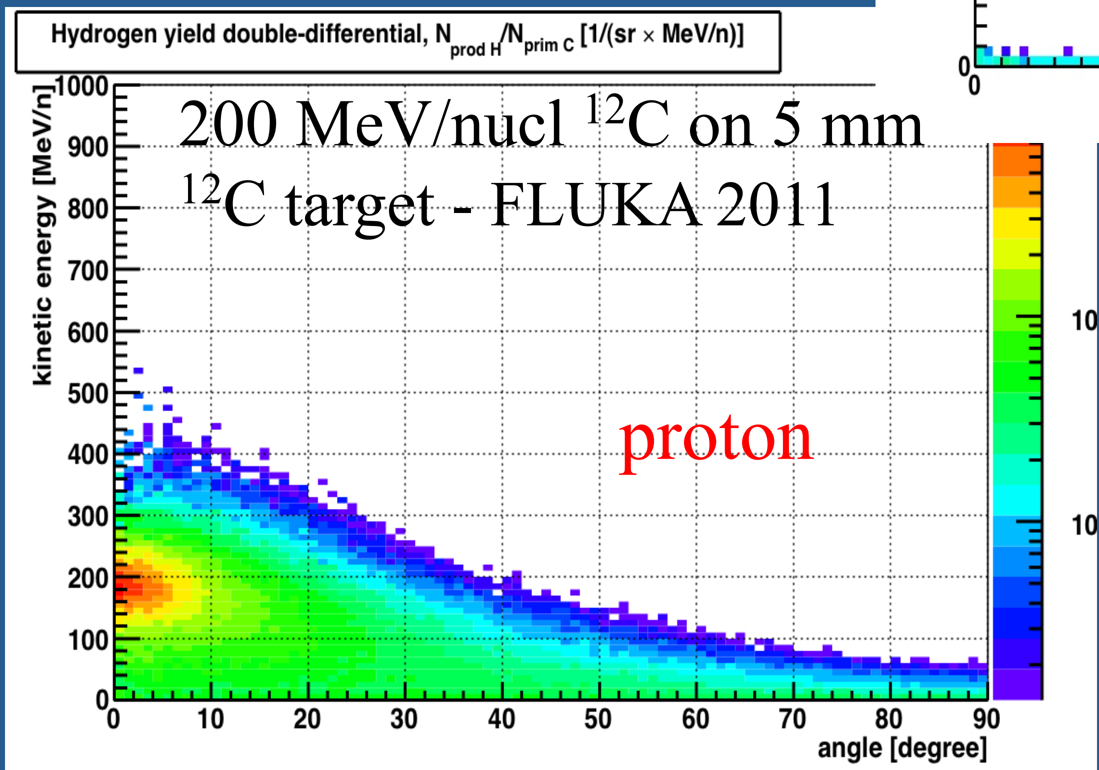
Simplified scheme of a Treatment Planning System



Produced p and He: angle vs energy

The protons could be a possible candidate for beam imaging… if they can escape the patient!! (E_{kin} >100 MeV)





- The proton flux at large angle is mainly made by low energy particles
- WATCH OUT!! How much are MC reliable?

Spec's of hadrontherapy monitor

In conventional RT (i.e. with photons), the beam crosses the patient body and can be used for monitoring. In HT the beam is absorbed inside the patient.

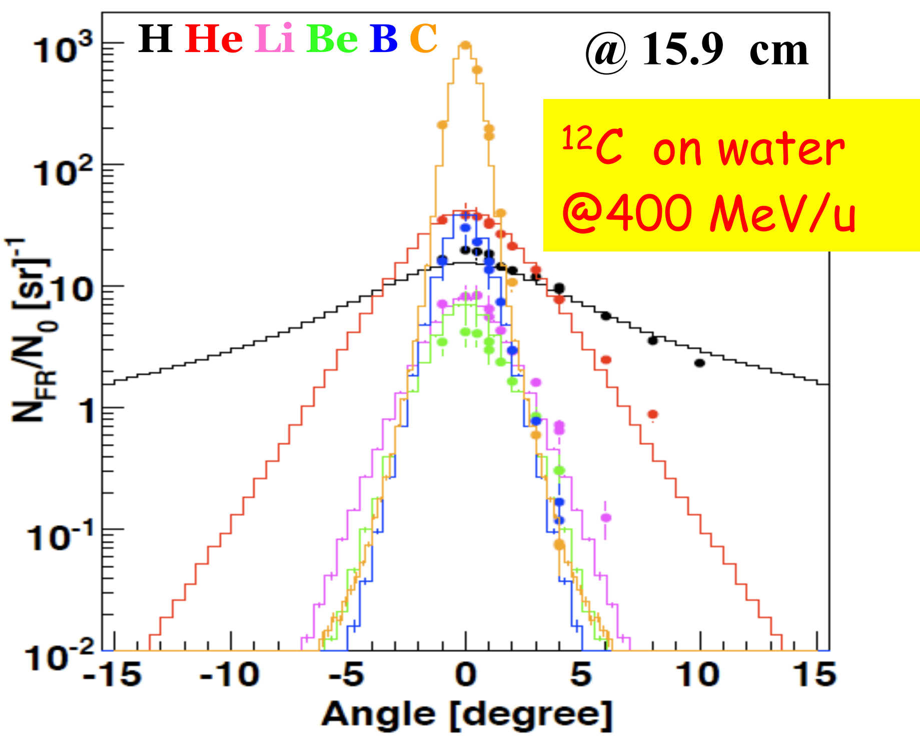
An hadronthrapy monitor device, in principle, should:

- Measure shape and absolute value of dose to check the agreement between the planned target volume and the actually irradiated volume
- The measurement should be done during the treatment (in-beam)
- Must rely on secondaries generated by the beam that comes out from the patient to spot the position of the dose release
- Must be able to deal with the other secondaries that come out that acts like background

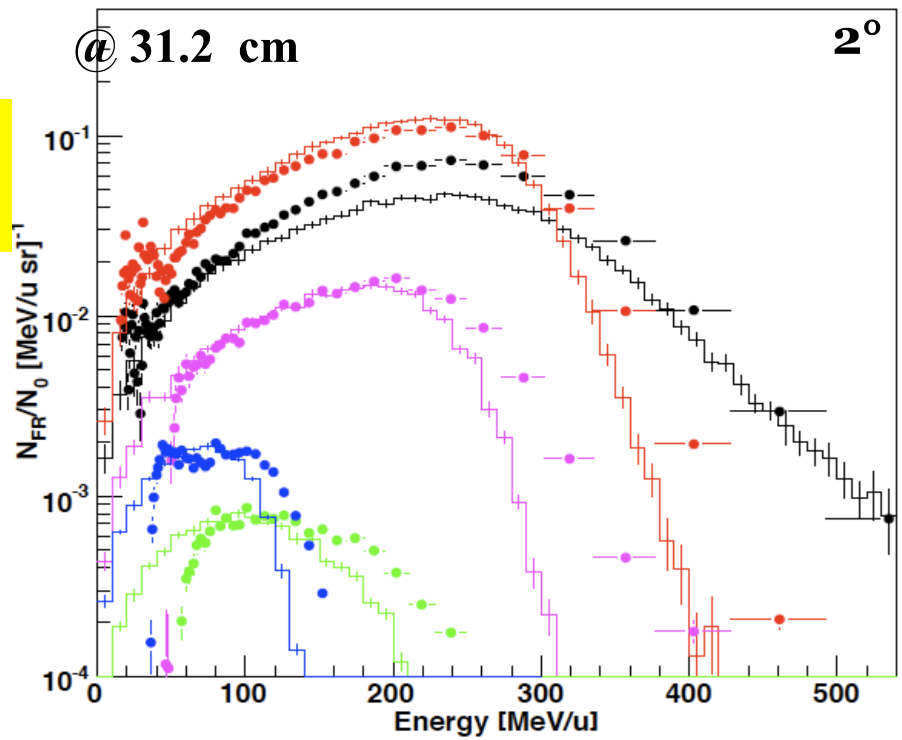
Frag.s production by ^{12}C beam

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

Angular distribution



Energy distribution



FLUKA benchmark against thick target data

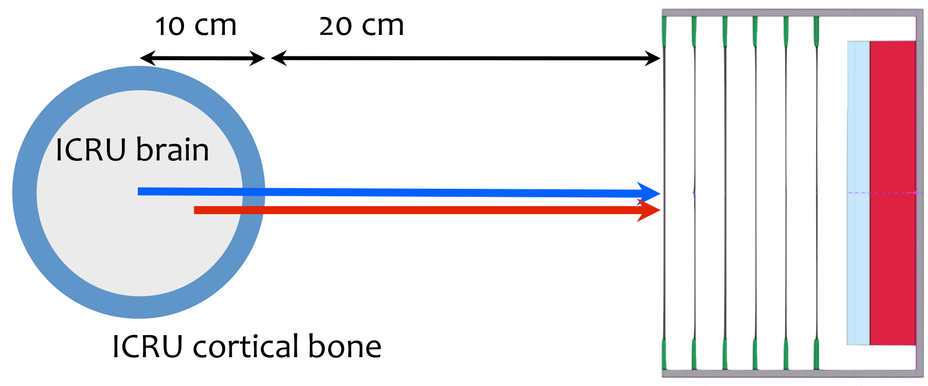
Exp. Data (points) from Haettner et al, Rad. Prot. Dos. 2006
Simulation: A. Mairani PhD Thesis, 2007, PMB *to be published*

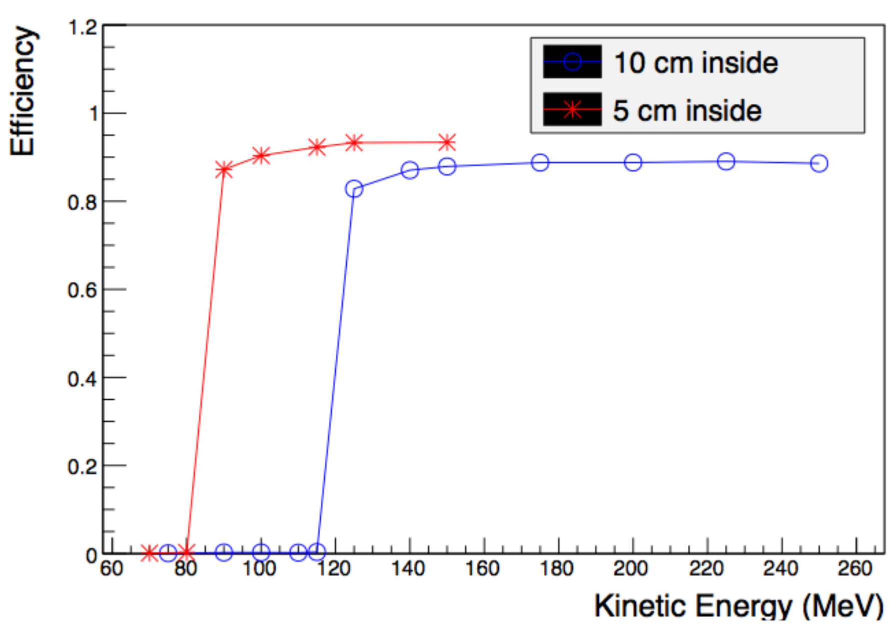
Performance with emitted protons

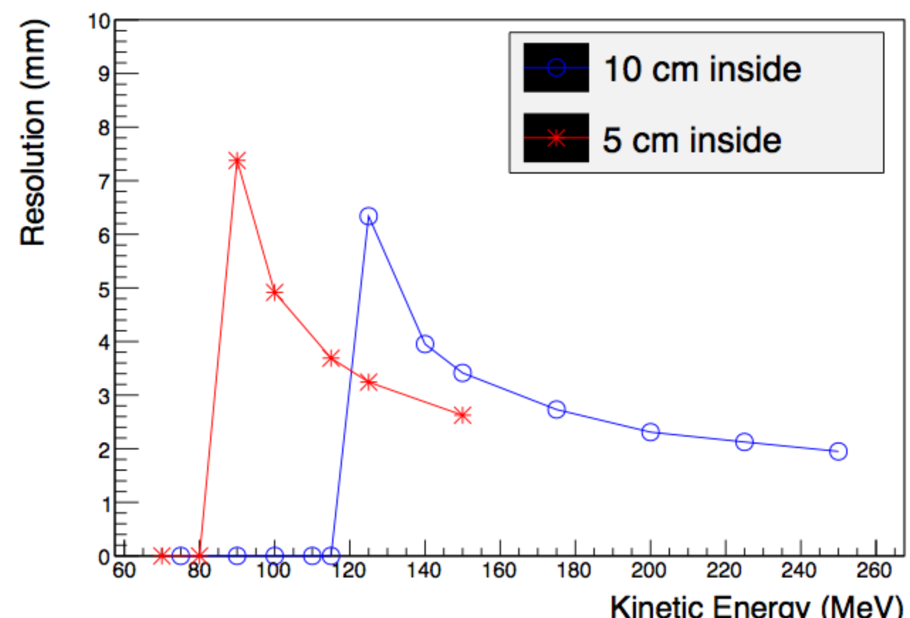
Simulation of a "spherical patient" with ICRU materials, with proton source placed at different depths: 10 cm and 5 cm

Multiple scattering single track

Spatial Resolution ~ few mm





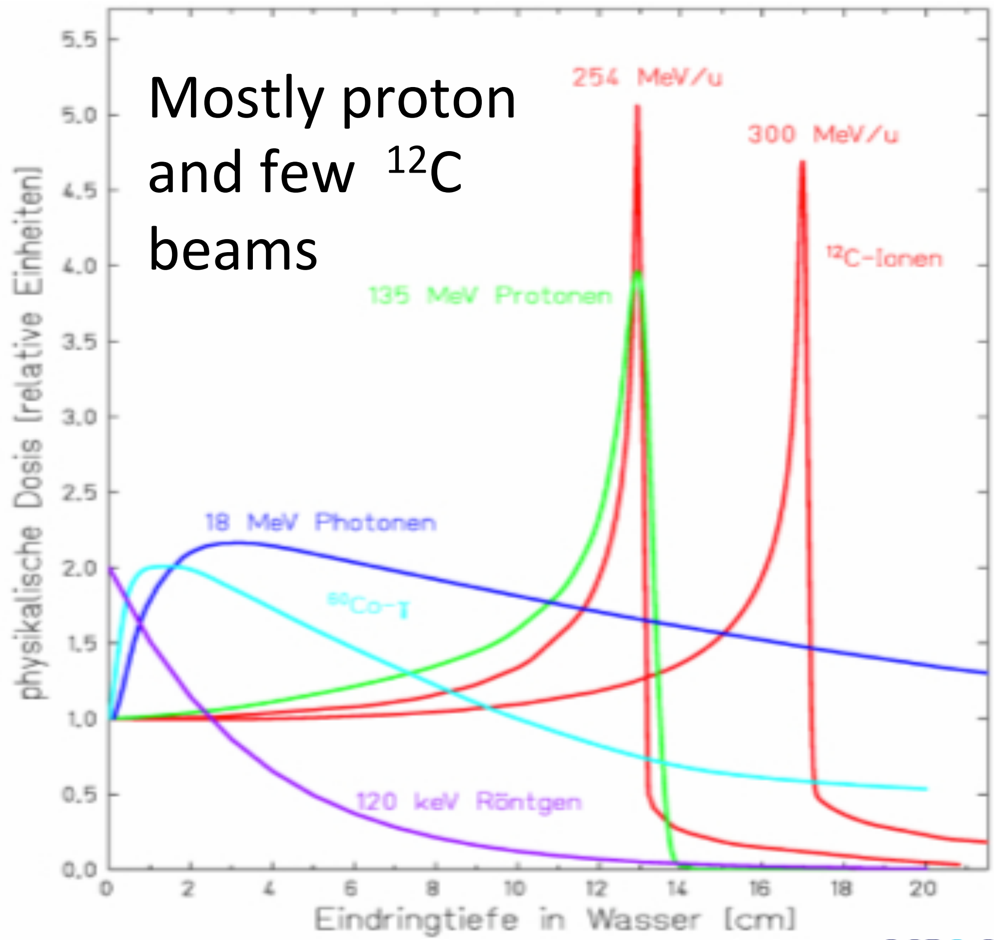


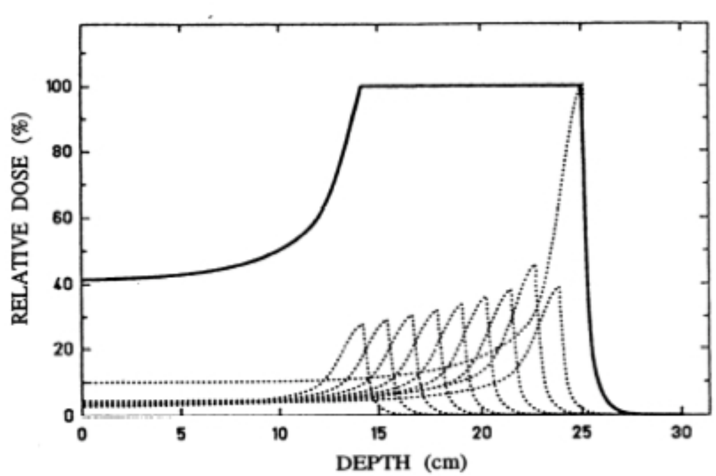
Hadrontherapy vs Photon RT

The highest dose released at the end of the track, sparing the normal tissue

- Length of track function of the beam energy
- Dose decrease rapidly after the BP.
- Accurate conformal dose to tumour with Spread Out Bragg Peak

Mostly proton and few ^{12}C beams



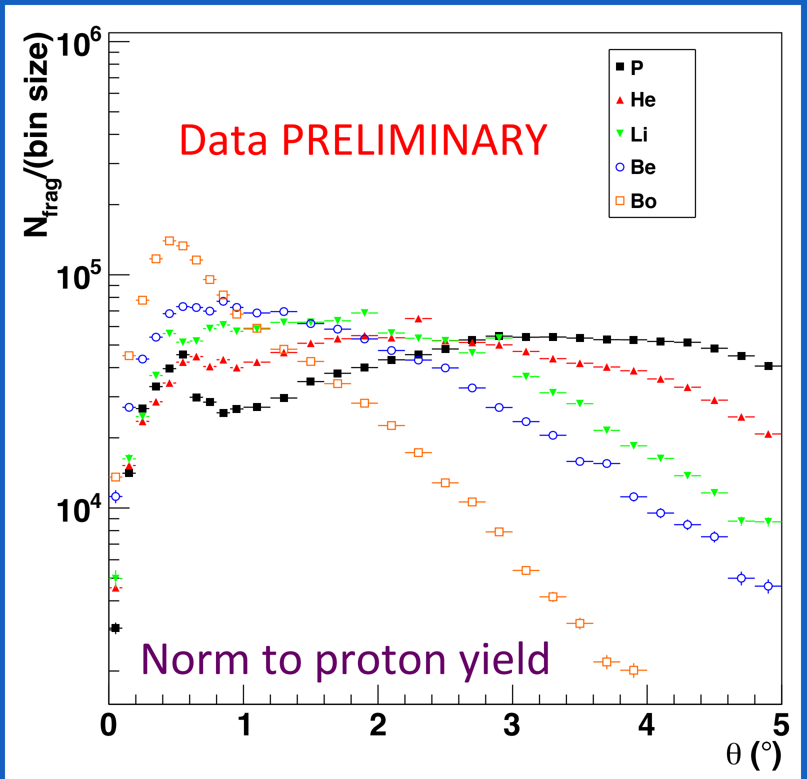


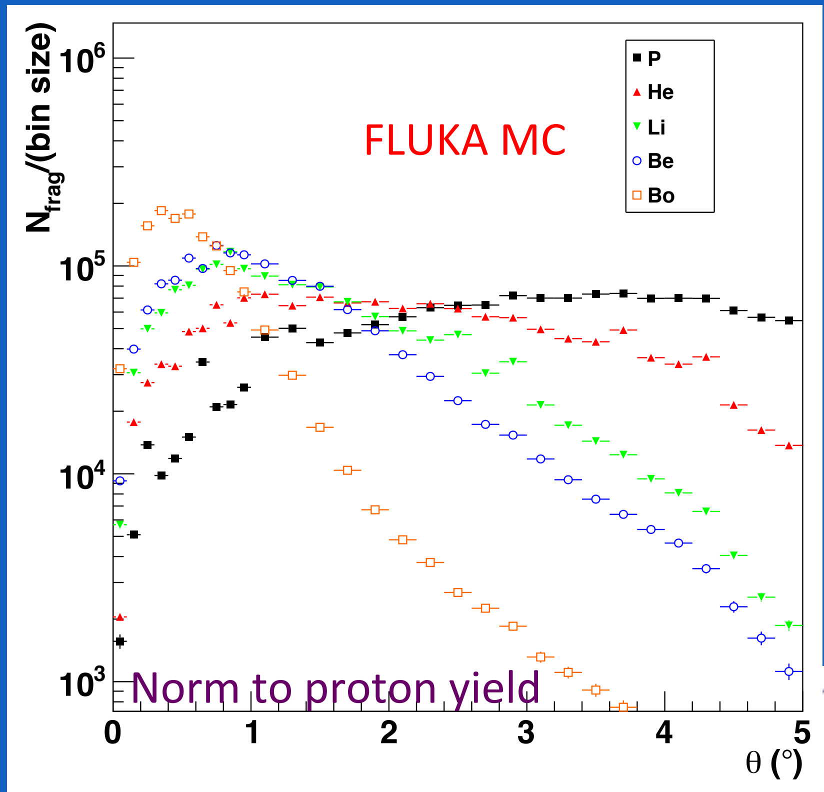
Fragment yields of 12C on composite target (O+C+BrLn) at small angles

First look at small angle -> corresponds to the region that induces the dose beyond the distal part of the treatment region

Reconstructed yields are distorted by the efficiencies (tracking/ selection/etc..) and by acceptance… to be applied

The angle distributions seems to be wider in data than MC





Treatment uncertainties in ion beam therapy

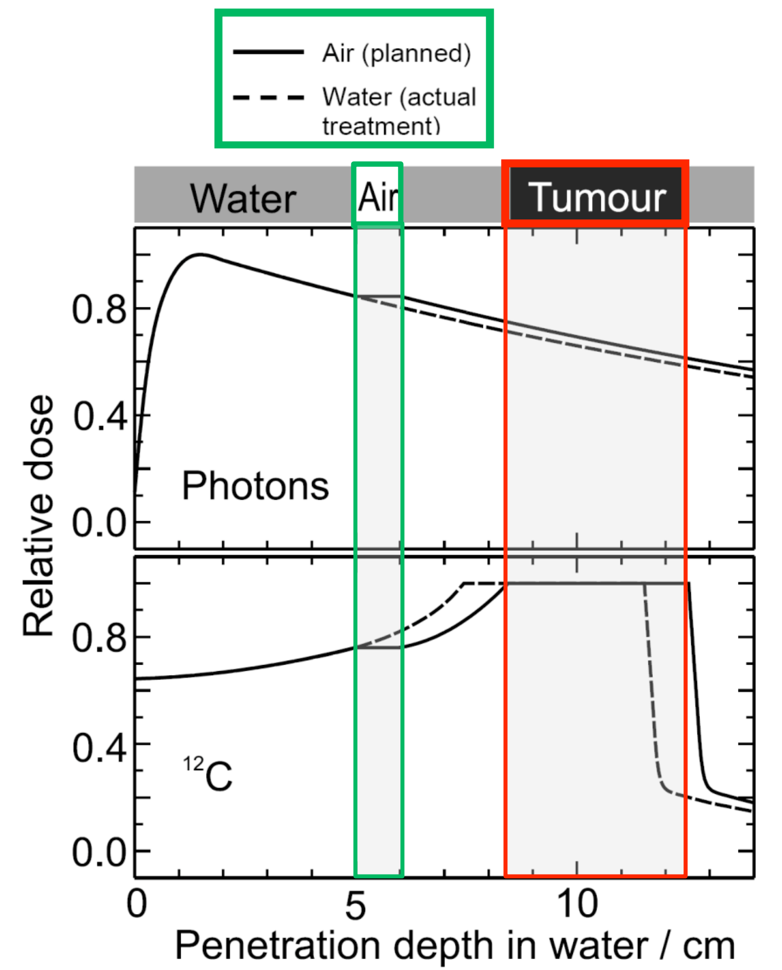
TPS dose calculation errors

- Inhomogeneities, metallic implants
- Conversion HU in ion range
- CT artifacts

Difference TP / delivery

- Daily setup variations
- Internal organ motion
- Anatomical / physiological changes

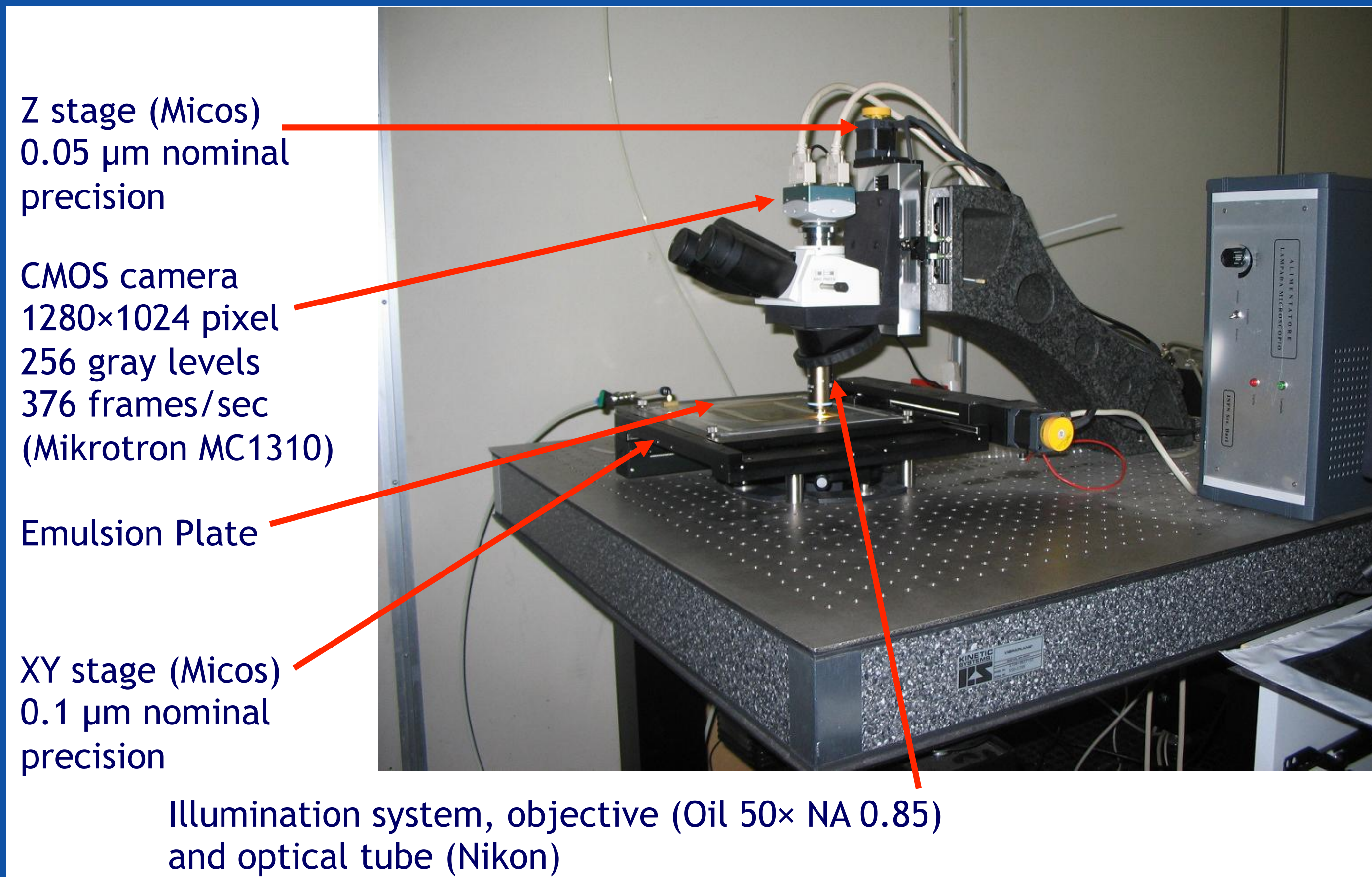
Daily practice of compromising dose conformality for safe delivery



After Enghardt 2005

Courtesy of K.Parodi

Emulsion scanning system



- Scanning rate : 20cm^2/h
- ~0.3 μm spatial resolution
- ~2 mrad angular resolution
- ~95% track detection efficiency

FRAG (April 2009) $^{12}C+^{12}C, ^{197}Au, CH$ @62MeV

C + C ⇨ N° ≈ $5\cdot10^{12}$

I ~ 40 – 80 pA

C + CH_2 ⇨ N° ≈ $1\cdot10^{12}$

I ~ 40 – 60 pA

C + Au ⇨ N° ≈ $11\cdot10^{12}$

I ~ 180 – 230 pA