Imperial College London

27th February 2019, CCAP seminar

Measuring Fragmentation Cross Sections with the FOOT Experiment.

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i.e…. Nuclear fragmentation and Particle Therapy

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Applied Radiation Physics Group

A group of particle physicists mainly from Istituto Nazionale di Fisica Nucleare and "Sapienza" University of Rome that apply HEP techniques to particle therapy R&D

https://arpg-serv.ing2.uniroma1.it

Particle therapy activities:

- ✓ Fragmentation measurement & PT
- ✓ ^{12}C beam range monitor development
- ✓ Neutron tracker development
- ✓ MC simulation & TPS development on GPU

Oncological application:

- ✓ Probes for radio-guided surgery

Let's start from Radiotherapy

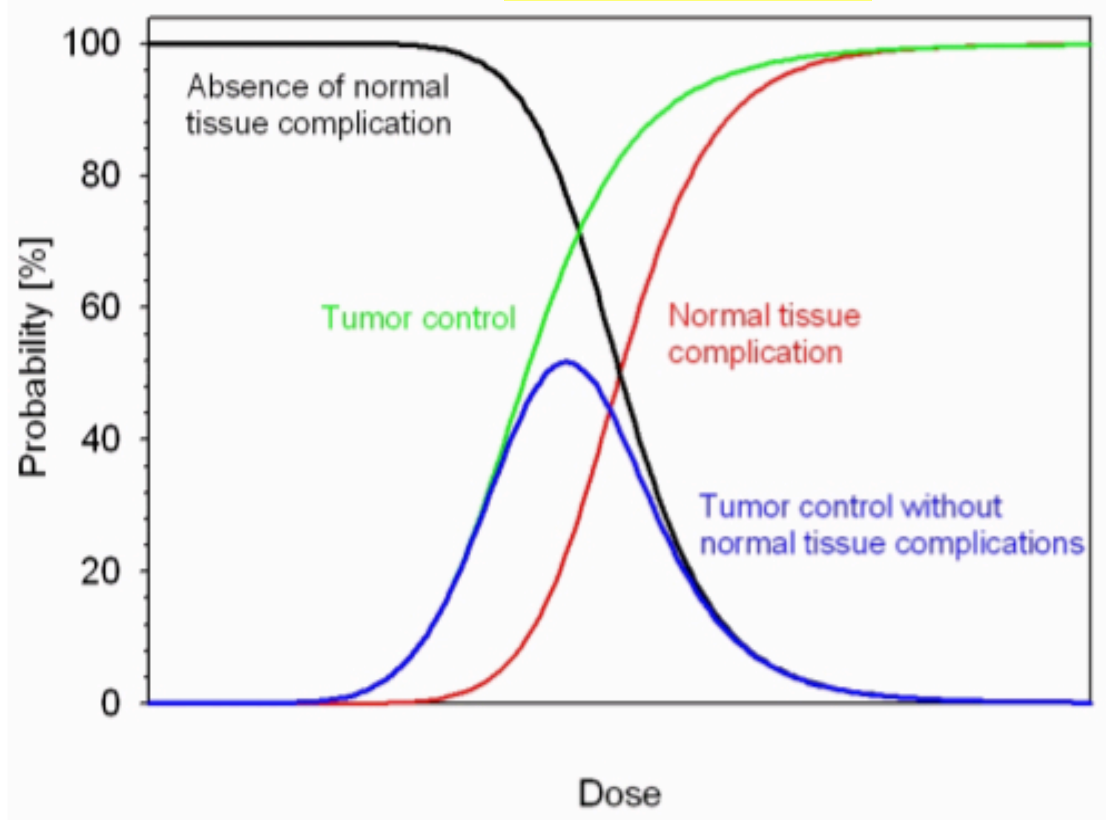
- Part of multi-disciplinary approach to cancer cure
- Useful for 50-60% of all cancer treatment (with or without surgery)
- Can be given for cure or palliation

✓ Mainly used for loco-regional treatment

✓ Benefits and side-effects are usually limited to the area(s) being treated

$$Dose = \frac{dE_{abs}}{dm} (Gray)$$

Therapy window

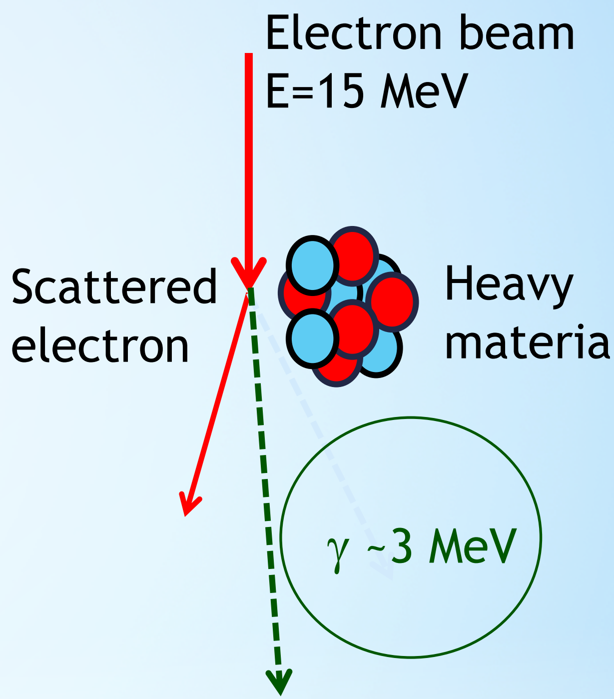


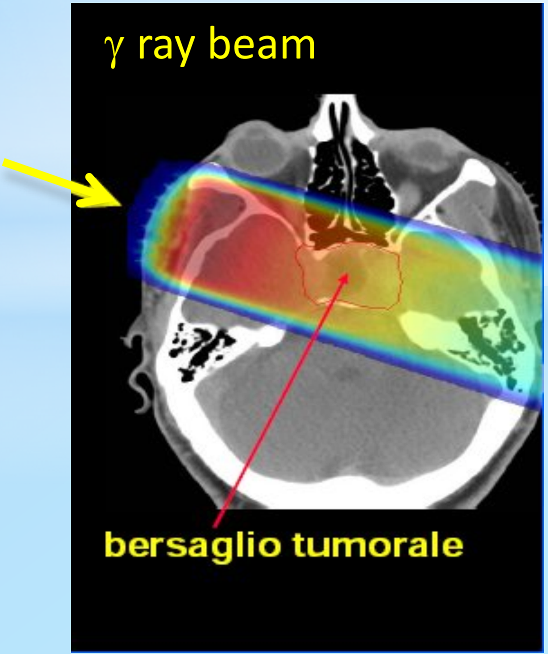
Conventional RadioTherapy

Conventional RT uses γ rays, both emitted from nuclear decays or from electron interaction.

Electron are accelerated in a LINAC before interacting and producing photon beam.

More than 50 years of R&D made photon RT a very optimized, compact, effective technology (IMRT, radio surgery, etc)





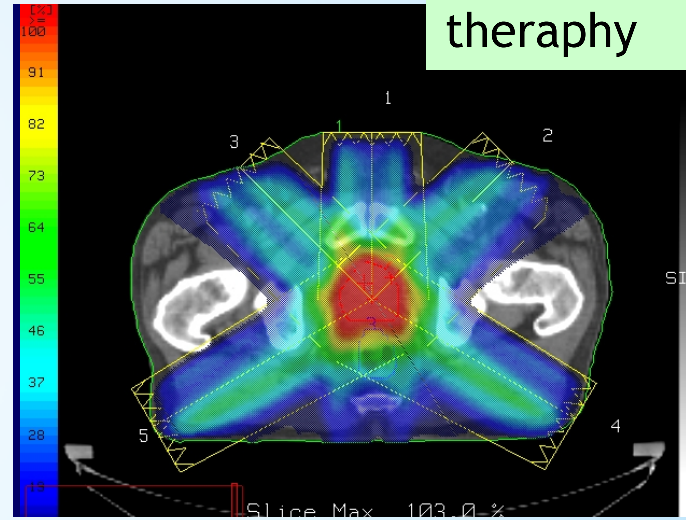
Approximatively half of the tumor are treated with γ RT.
In Italy ~ 200000 patients/year

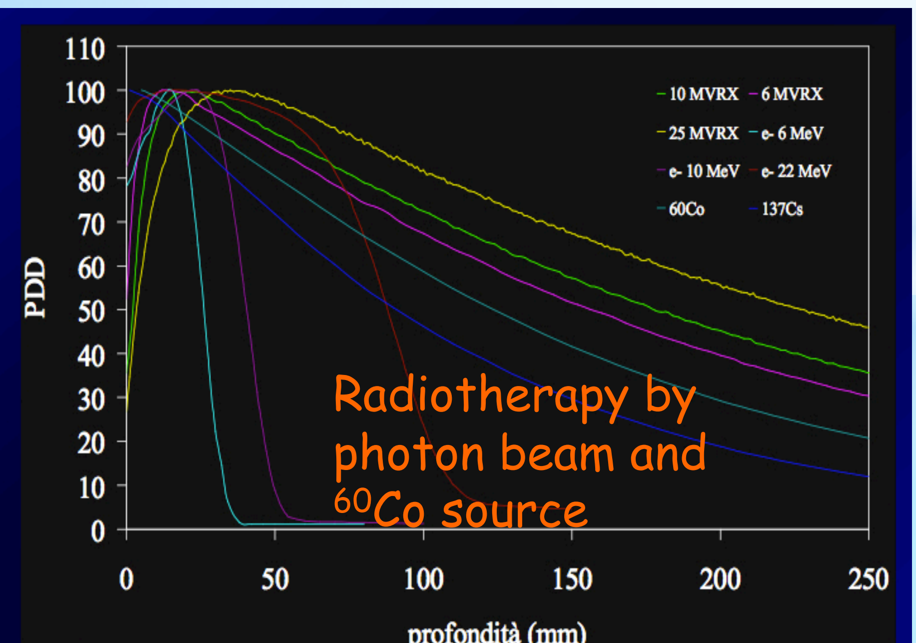
Conventional RT, Archimede and photon physics..

The photon beam has an exponential energy release with the depth inside the patient: not optimal to treat deep tumors

Concentrating more beams with the aid of imaging and complex software (TPS), the dose given on the tumor is maximized with respect to that given to healthy tissues.

5 beams theraphy



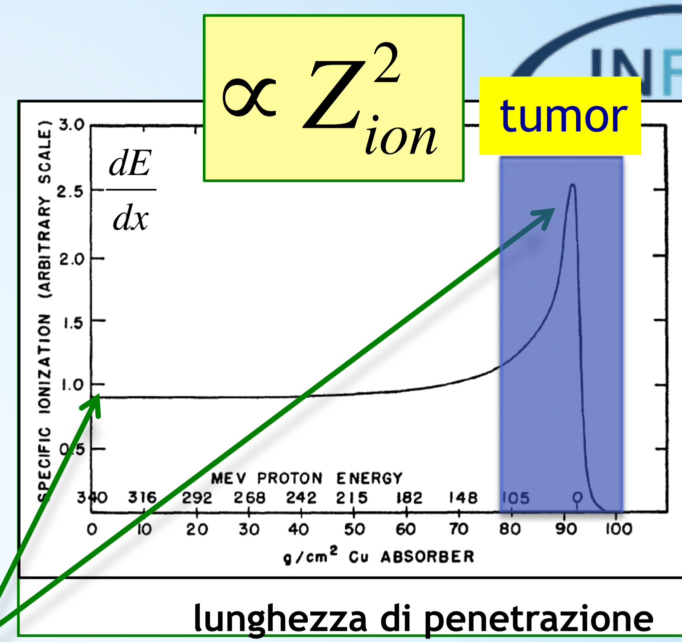


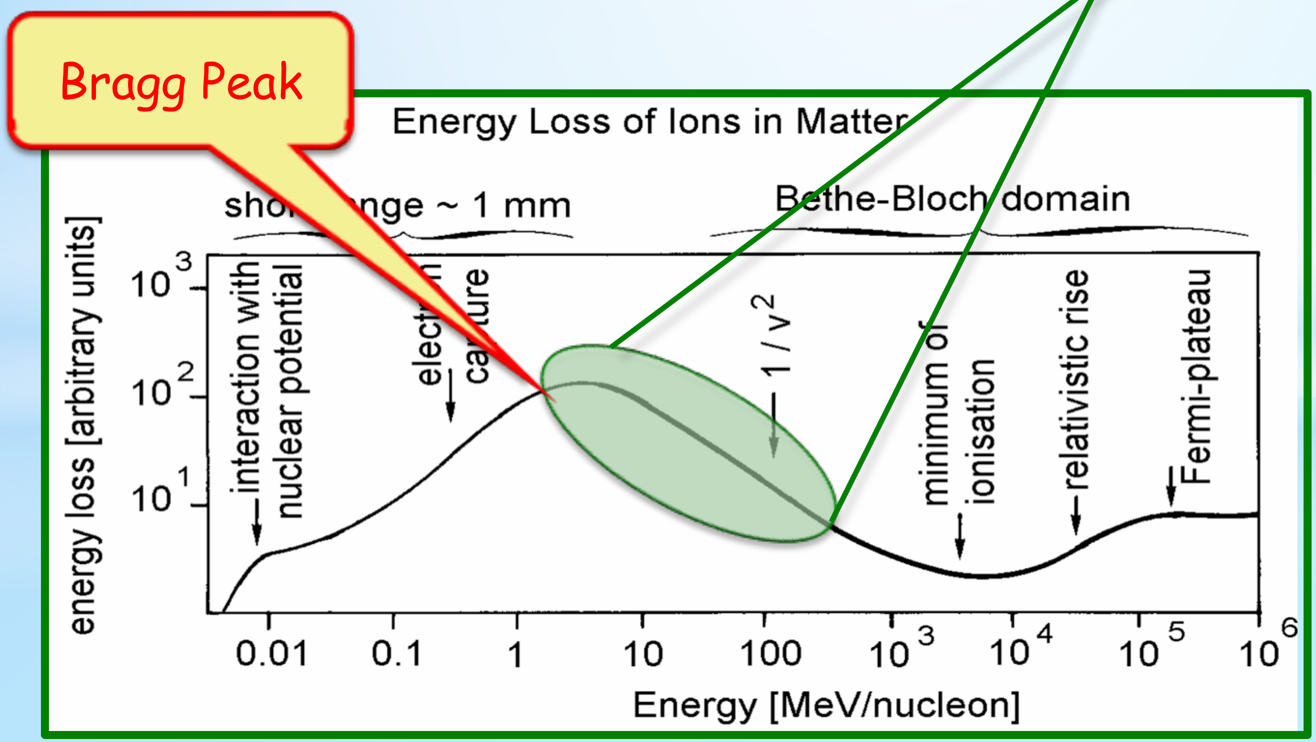
Archimedes did it with solar rays and Roman ships ...

But physics can help…

On the other hand, the release of energy by charged particles has very different, and attractive, features… why not to use them?

BTW: quite and old idea: 1946!!



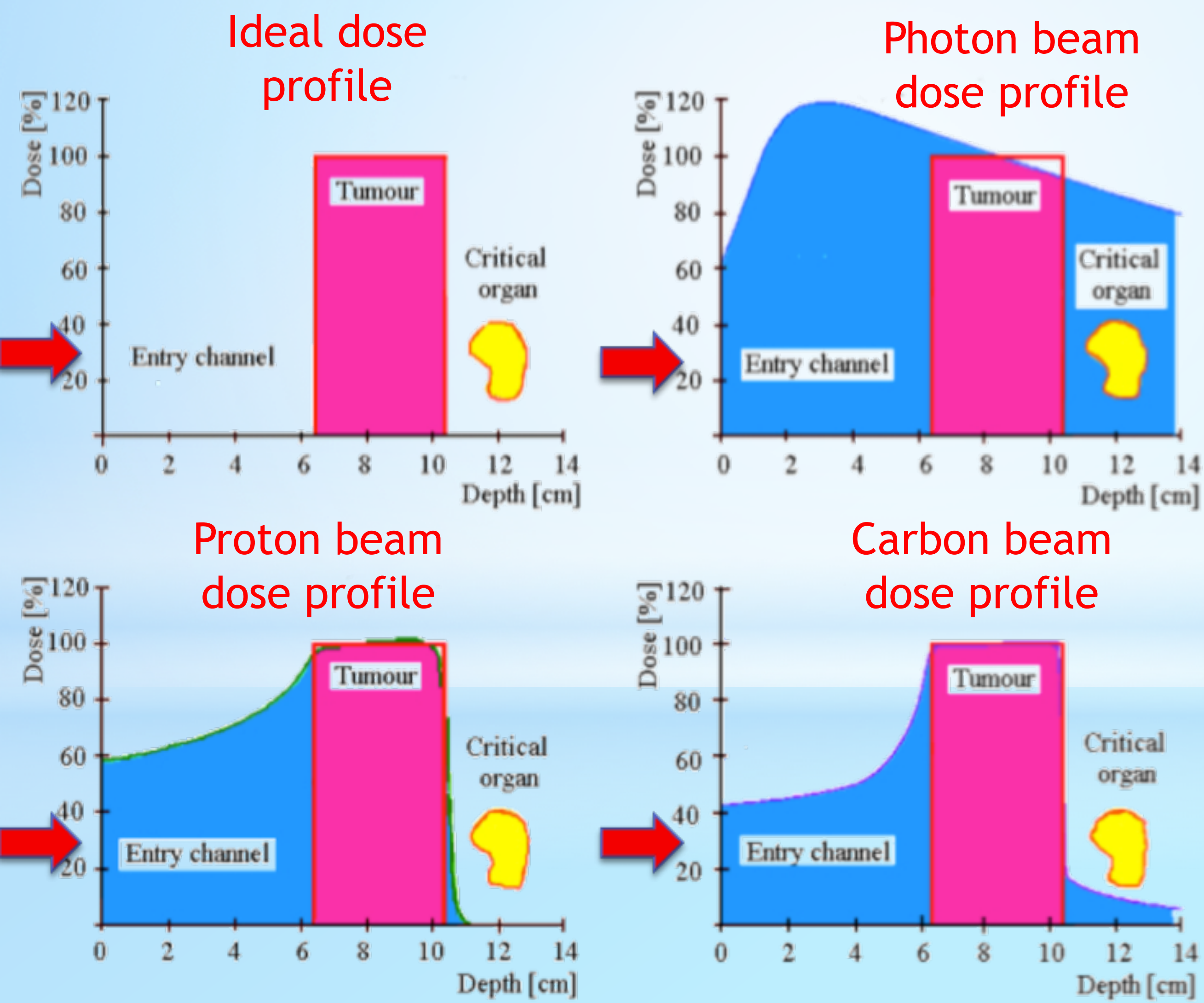


Perfect to release energy (dose) in a tumor buried inside the patient, like a depth bomb..

Mostly proton, few ^{12}C beams.

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

Different beams, different energy release…



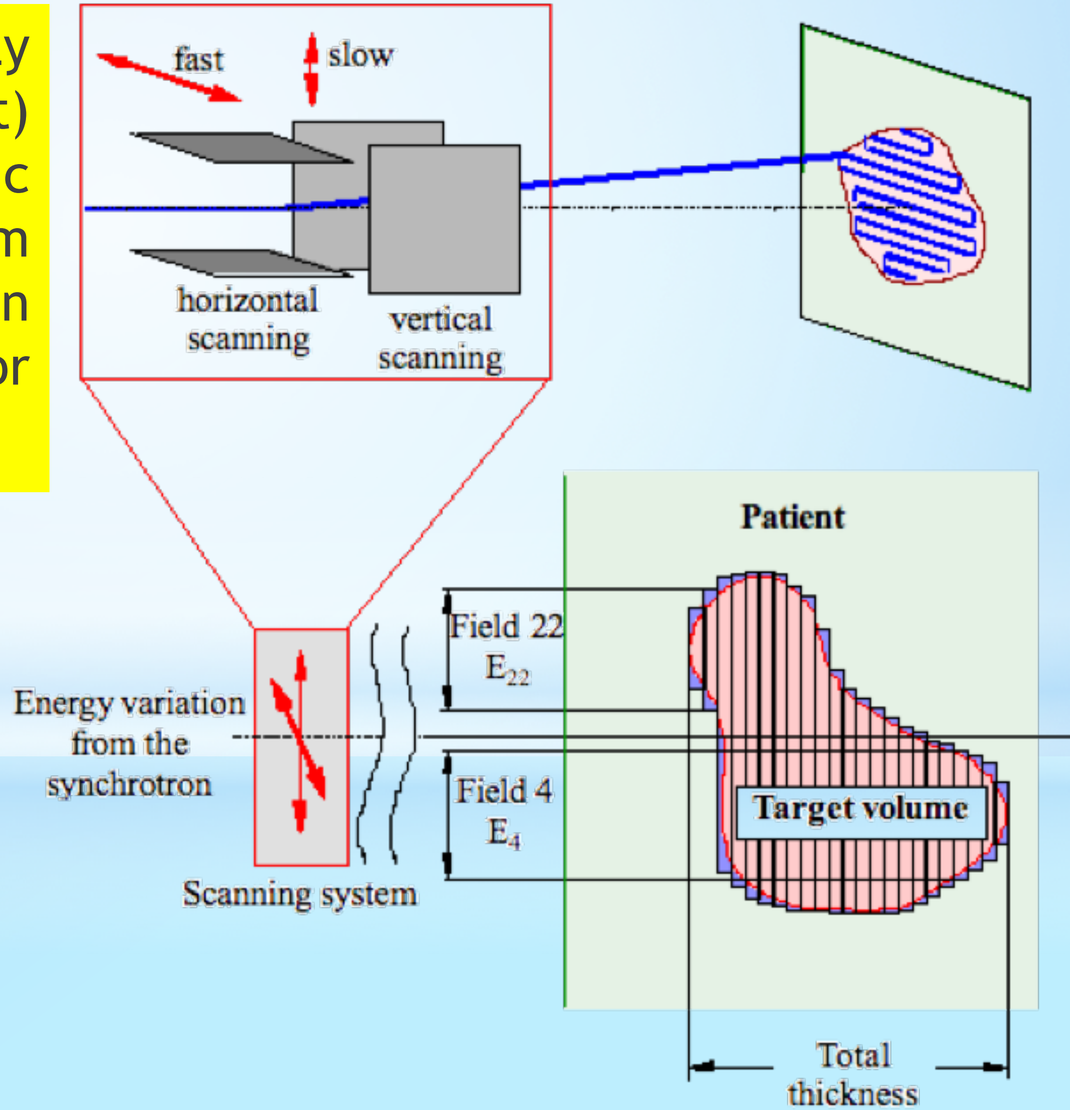
Differently from γ rays, protons or carbon ions release a lot of energy at the end of their path.

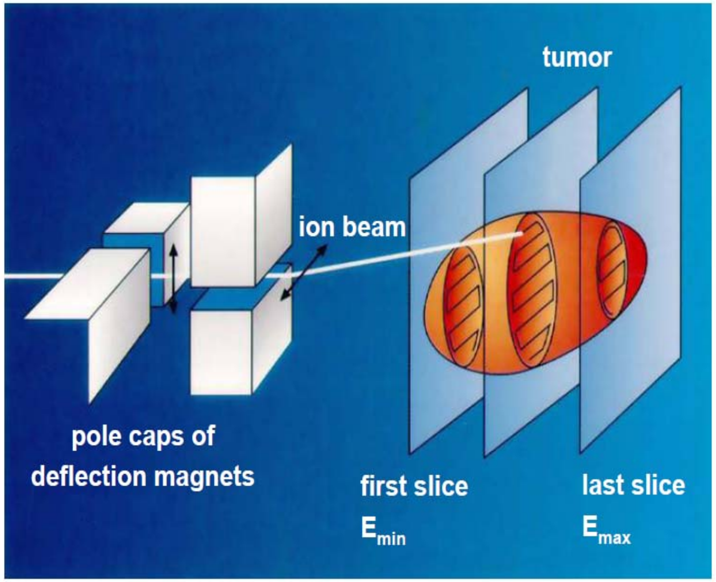
Particle accelerators can give the right energy to proton or carbon beam to stop exactly on the tumor and destroy it as a depth bomb.

Please note the better peak to plateau ration of carbon, but with that nasty tail after the peak…

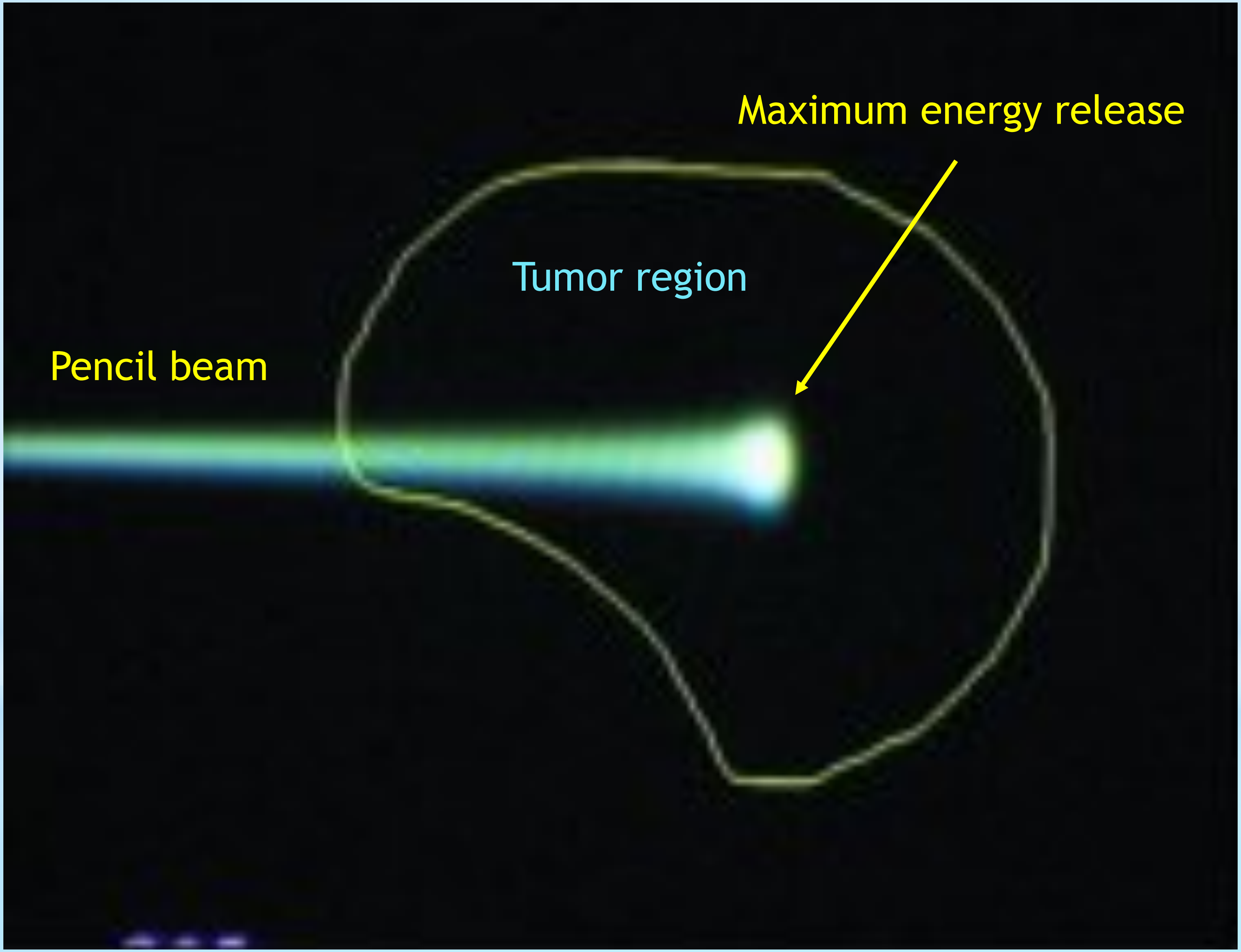
Particle therapy… painting the tumor

A charged beam can be easily deflected (just like al old TV set) by means of electric or magnetic fields, and changing also the beam energy (and so the depth) you can paint with energy all the tumor volume





Painting the tumor…



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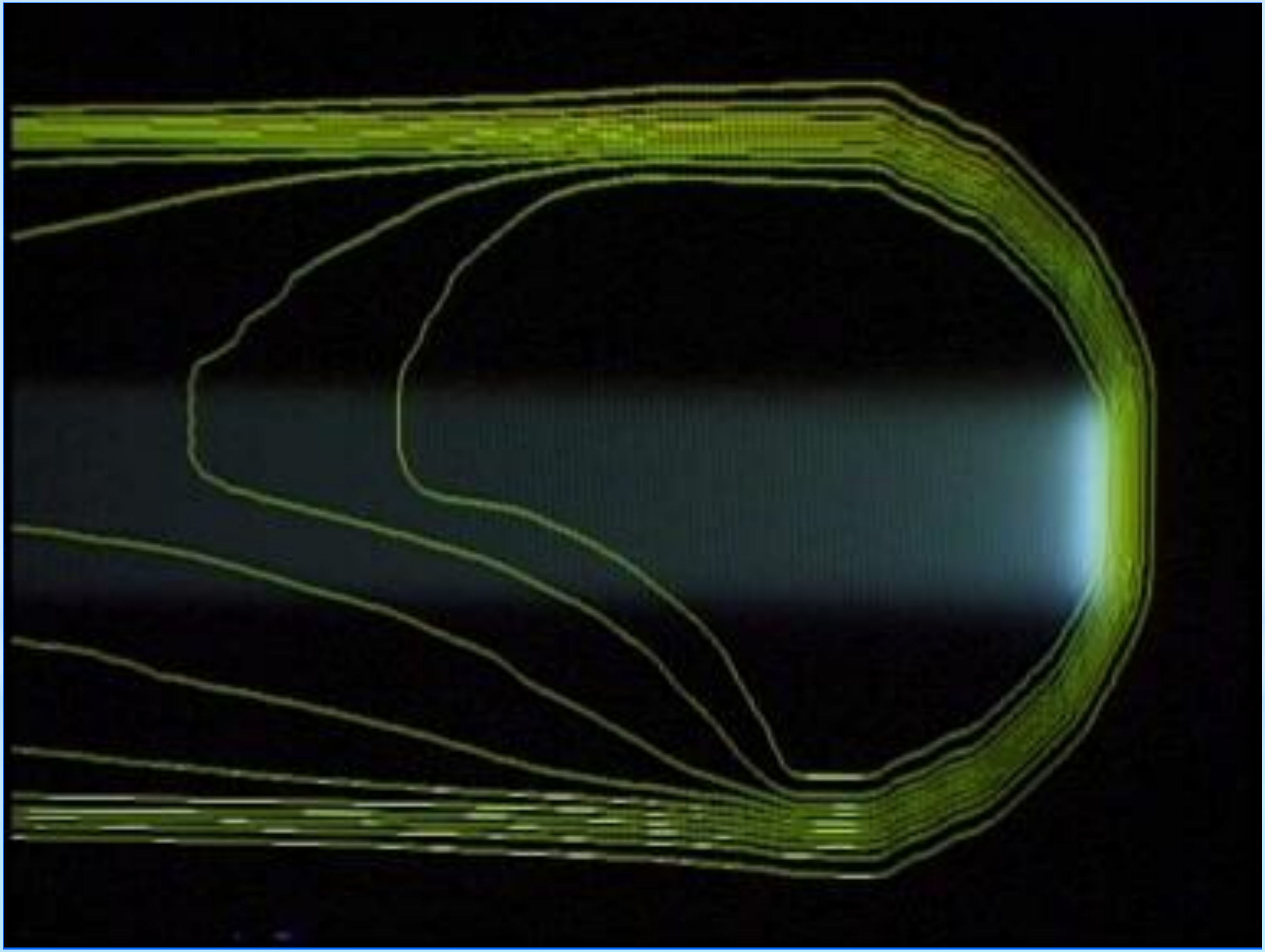

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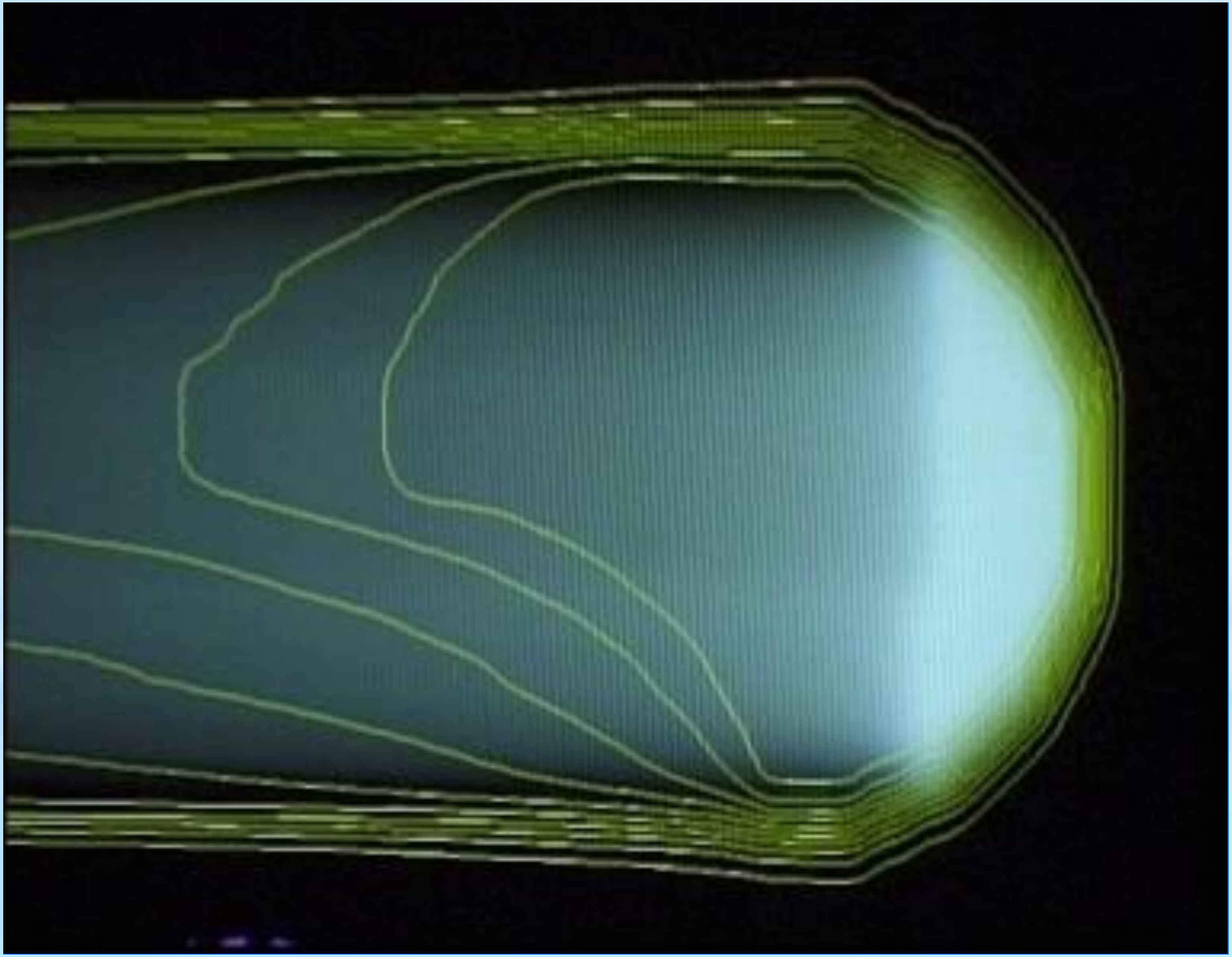
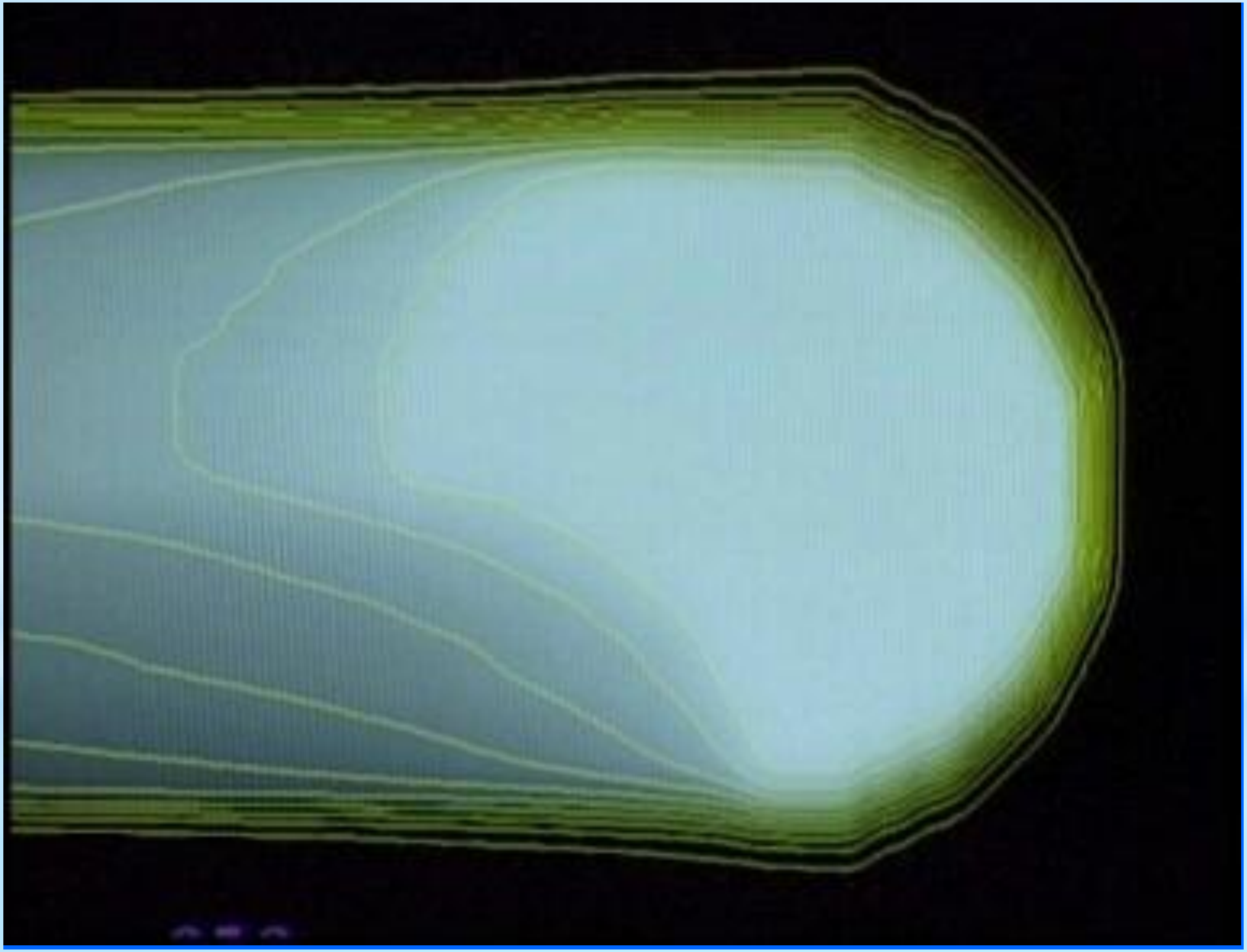


Painting the tumor…

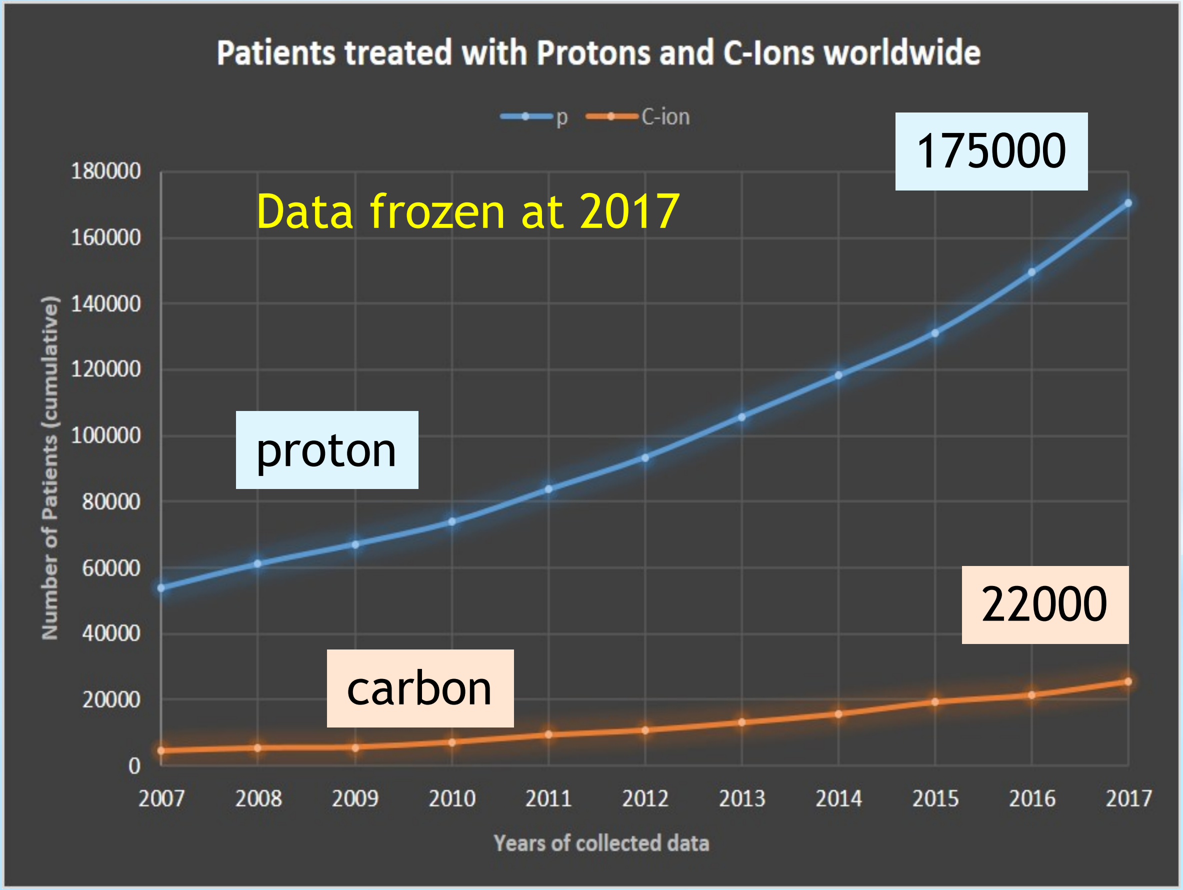


PT patient statistics

Patient statistics > 200000 at 2017

Treatment centers at 2019: 92 in operation, 42 under construction, 19 planning stage

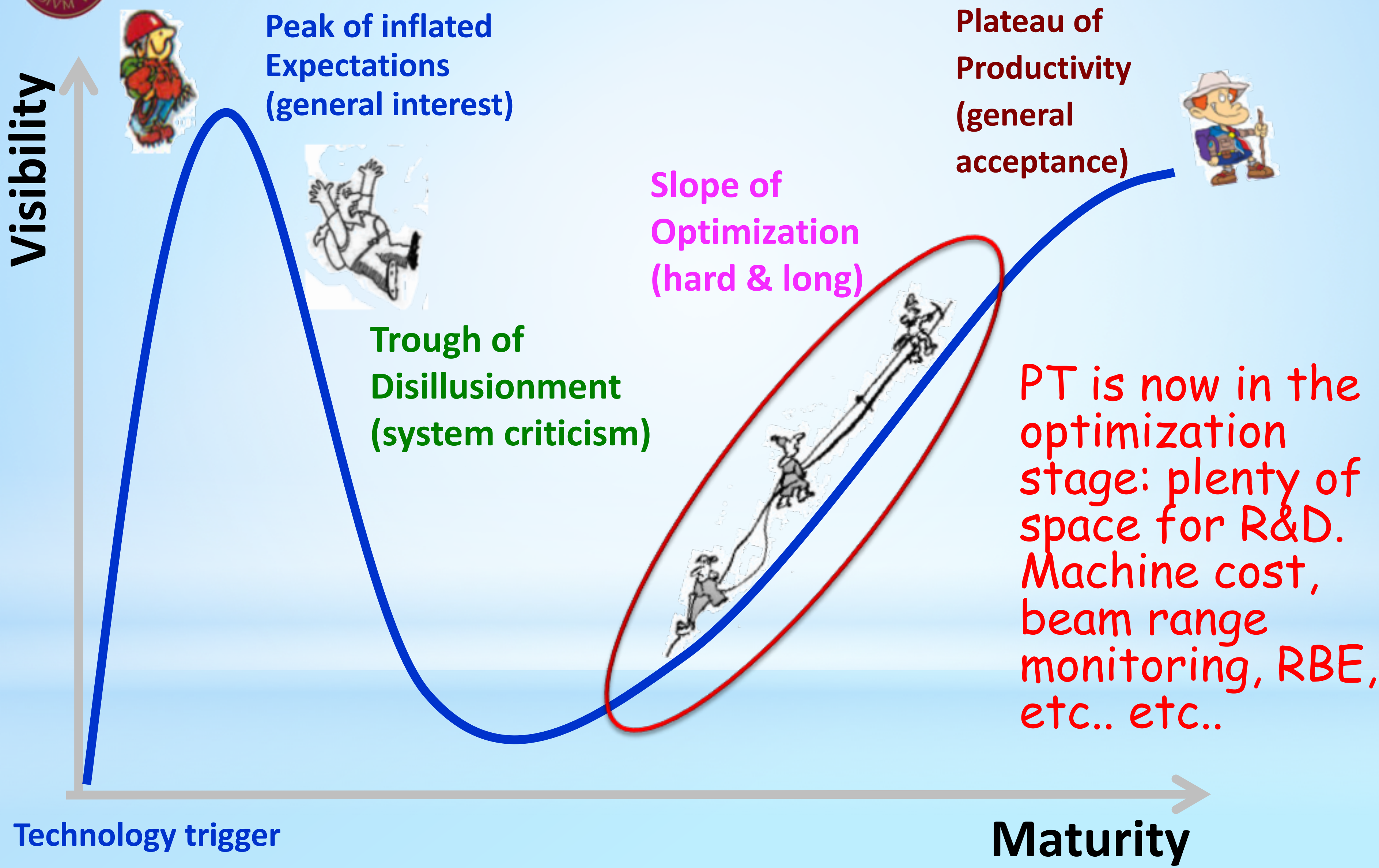
Yet a minimal fraction of photon RT



Community now looking at ^{4}He – ^{16}O beams: begin to be tested at clinical center

Data taken from PTCOG (Partcle Therapy Cooperative Group) web site

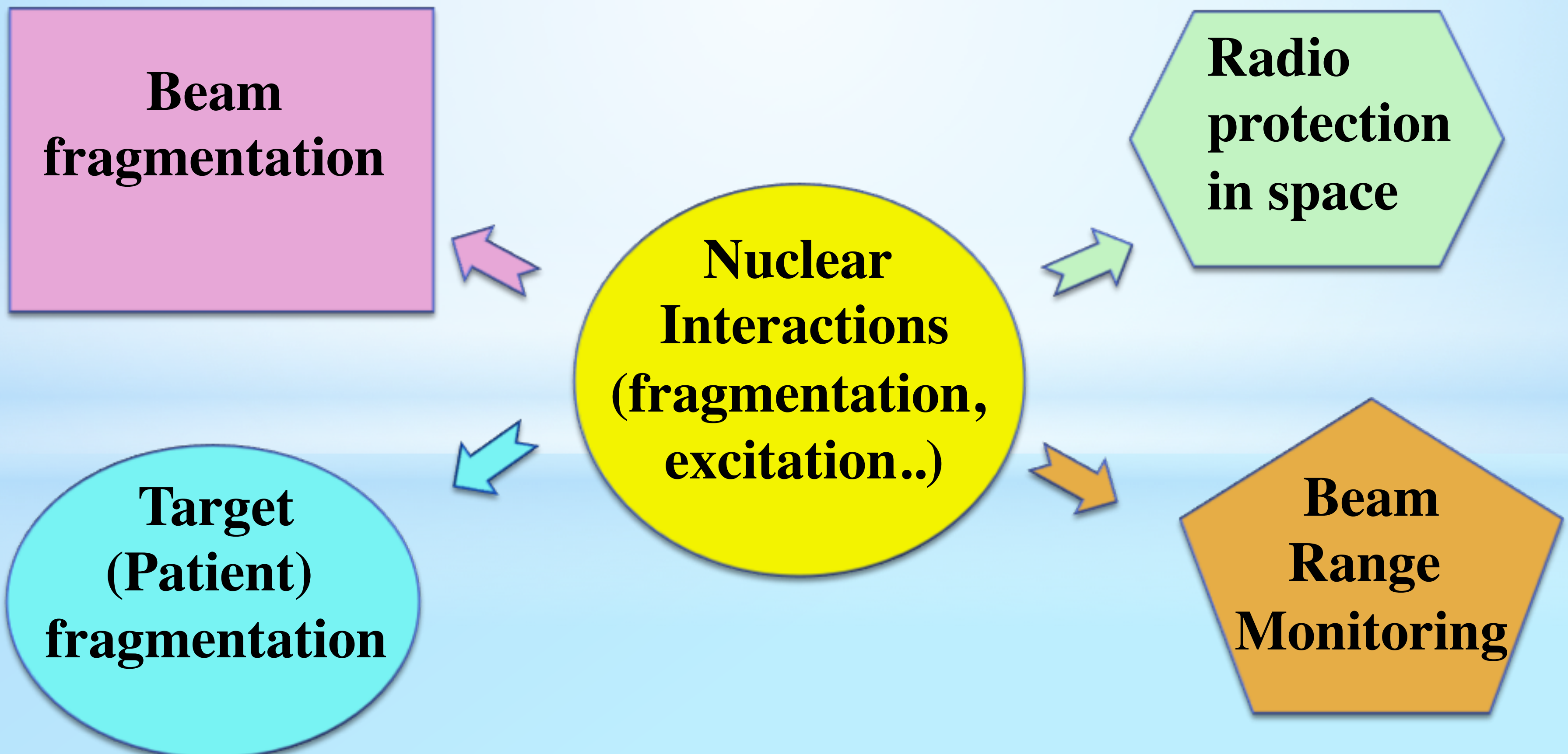
Hype Cycle for Innovation & PT



adapted from Becker & Townsend

Nuclear fragmentation and Health (not only PT)

Nuclear fragmentation plays a role in several aspect of R&D in Particle Therapy but also in radio protection in long term space mission



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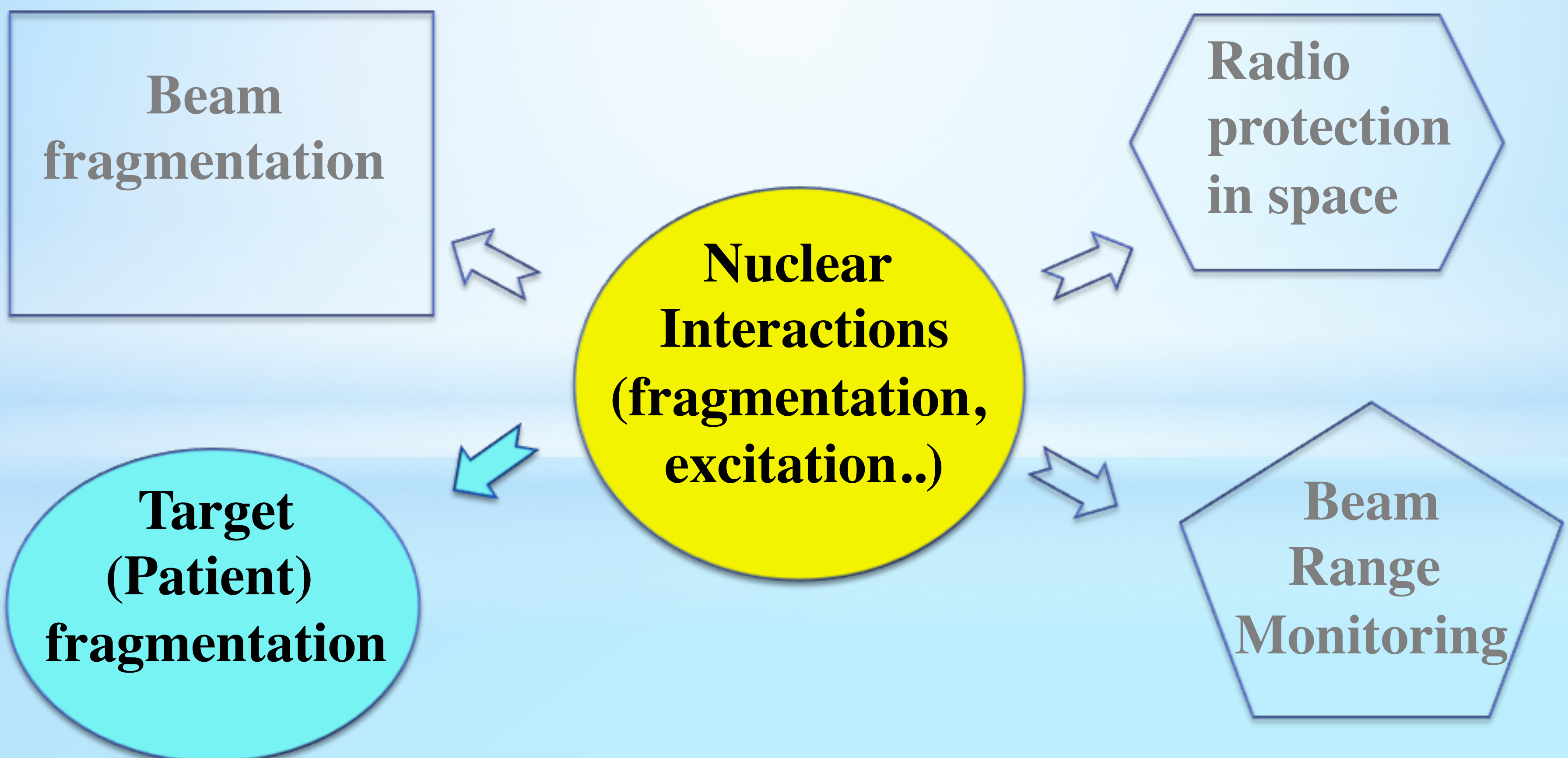
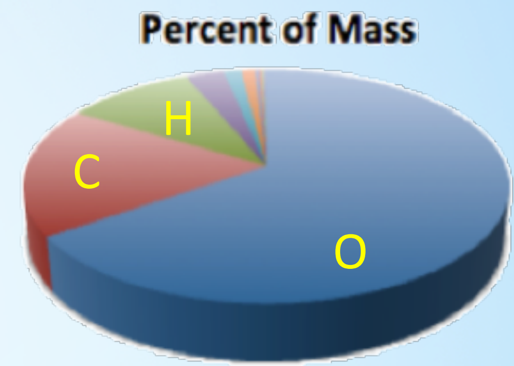


p on patient (O,C) @200 MeV

The elastic interaction and the forward Z=1,2 fragment production are quite well known. Uncertainties on large angle Z=1,2 fragments. Missing data on heavier fragments production.



Highly ionizing heavier fragment not included in dose evaluation in treatment planning: possible problem in healthy tissue where p beam ~ 200 MeV ?

Very low energy-short range fragments, almost isotropic.

MCs confirm this picture but…..

Nuclear model & MC not reliable at the needed level

Needed Z>2 fragment yields and emission energy

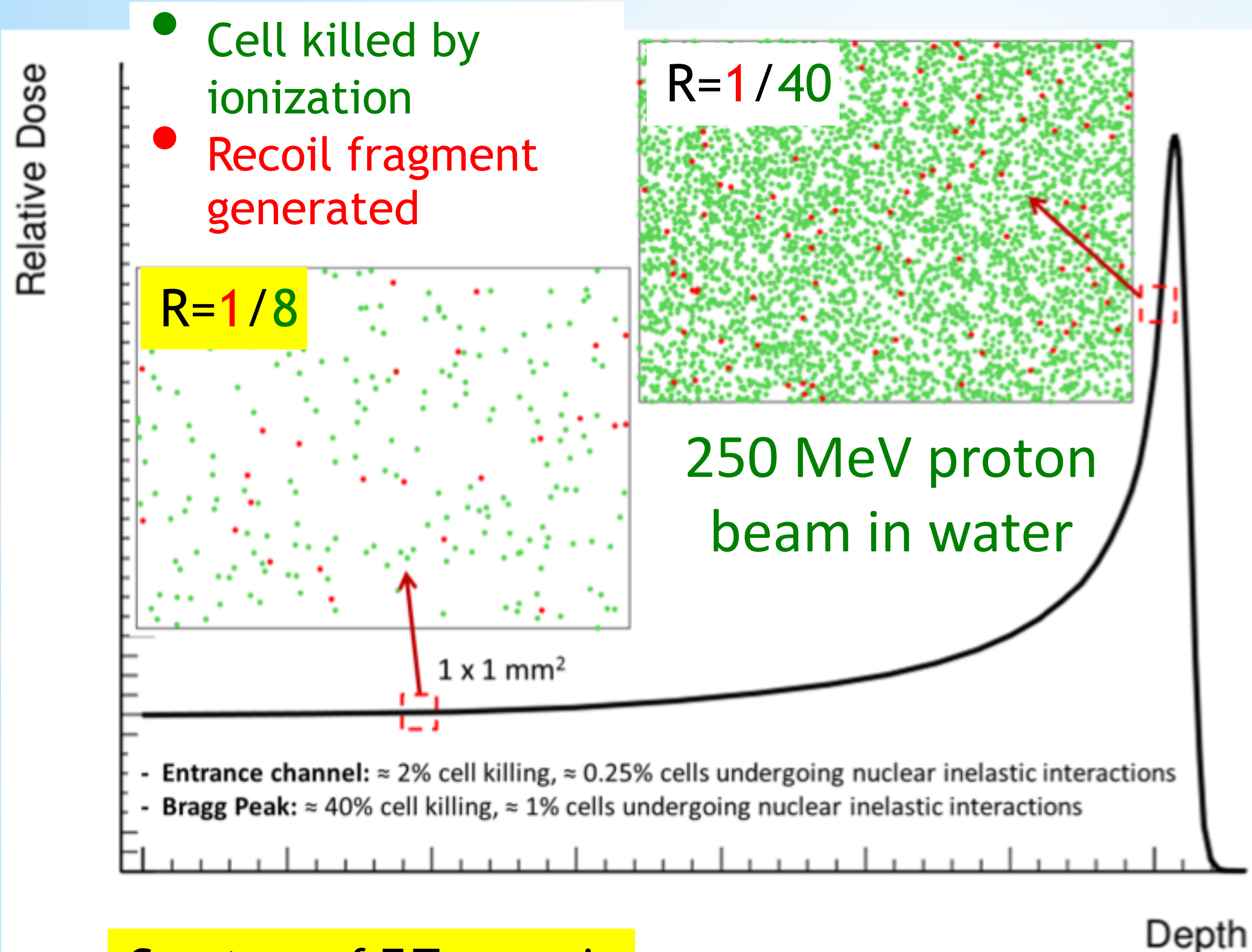
Analytic model results on p->O @200 MeV

Fragment	E (MeV)	LET (keV/μm)	Range (μm)
^{15}O	1.0	983	2.3
^{15}N	1.0	925	2.5
^{14}N	2.0	1137	3.6
^{13}C	3.0	951	5.4
^{12}C	3.8	912	6.2
^{11}C	4.6	878	7.0
^{10}B	5.4	643	9.9
^{8}Be	6.4	400	15.7
^{6}Li	6.8	215	26.7
^{4}He	6.0	77	48.5
^{3}He	4.7	89	38.8
^{2}H	2.5	14	68.9

Cancers 2015,7 Tommasino & Durante

Target fragmentation & PT

Target fragmentation in proton therapy: gives contribution also outside the tumor region!



Courtesy of F.Tommasino

About 10% of biological effect in the entrance channel due to secondary fragments

Largest contributions of recoil fragments expected from
He, C, Be, O, N

See also dedicated MC studies:
- Paganetti 2002 PMB
- Grassberger 2011 PMB

Direct measurements : mission impossible

REMARK: For radiobiology effectiveness of p beam the measurement of the fragment spectra is compulsory !!

- The fragments travel few μm in the target-> difficult to directly detect them, even for very thin target (10 μm?)
- The energy loss of the fragment in the target would be substantial and would be a severe systematic to be evaluated
- Such a very thin target produces very few events -> very careful control of the background.
- Possible solution from JET target techniques, where the target is a focused flux of gas crossing the beam in vacuum: difficult and expensive

Inverse kinematic strategy

Let's shoot a β=0.6 patient (C,O,N nuclei) on a proton at rest and measure how it fragments!! Then if we apply an inverse velocity transformation, we got the result.

DIRECT KINEMATIC

proton
200 MeV

C,O at rest

p + C,O → fragments

INVERSE KINEMATIC

Proton (H)
at rest

A the end Lorentz boost

C,O 200 MeV/A

C,O + p → fragments

The target can be thick as few mm, since now the fragments will have ~ 200 MeV/nucl with range larger than several cm.

But what about H target?

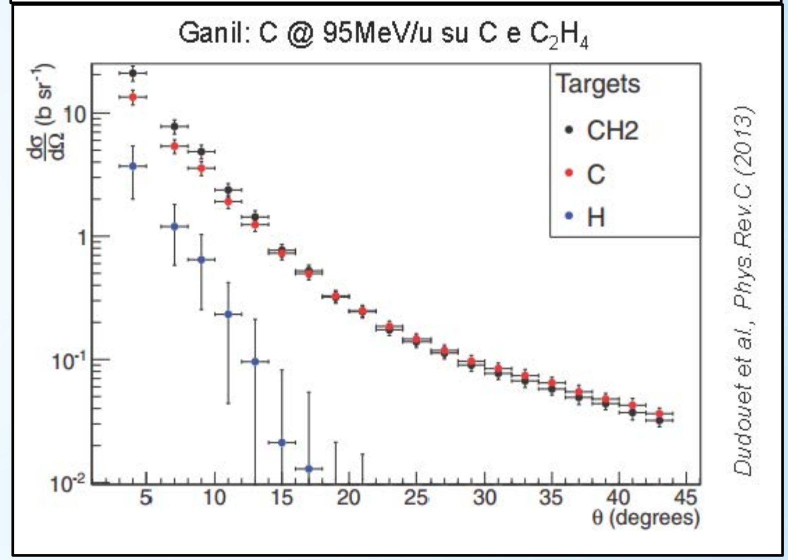
Inverse kinematics and the target

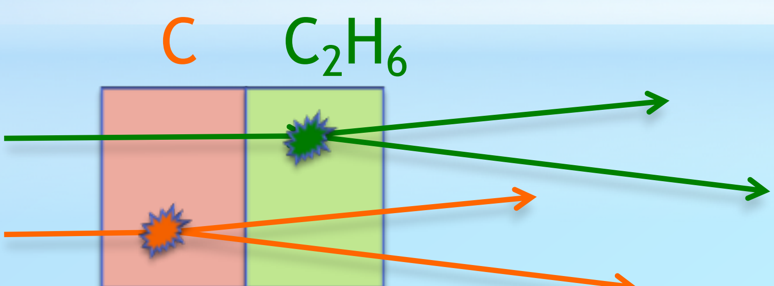
The target can be thick as few mm, since the fragment range is larger than several cm.

Fragmentation on H can be extracted by subtraction of twin C and C_2H_4 targets.

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

Ganil experimental data





Simultaneous double target data taking can to minimize systematic, if the setup has good vertexing capability along beam line

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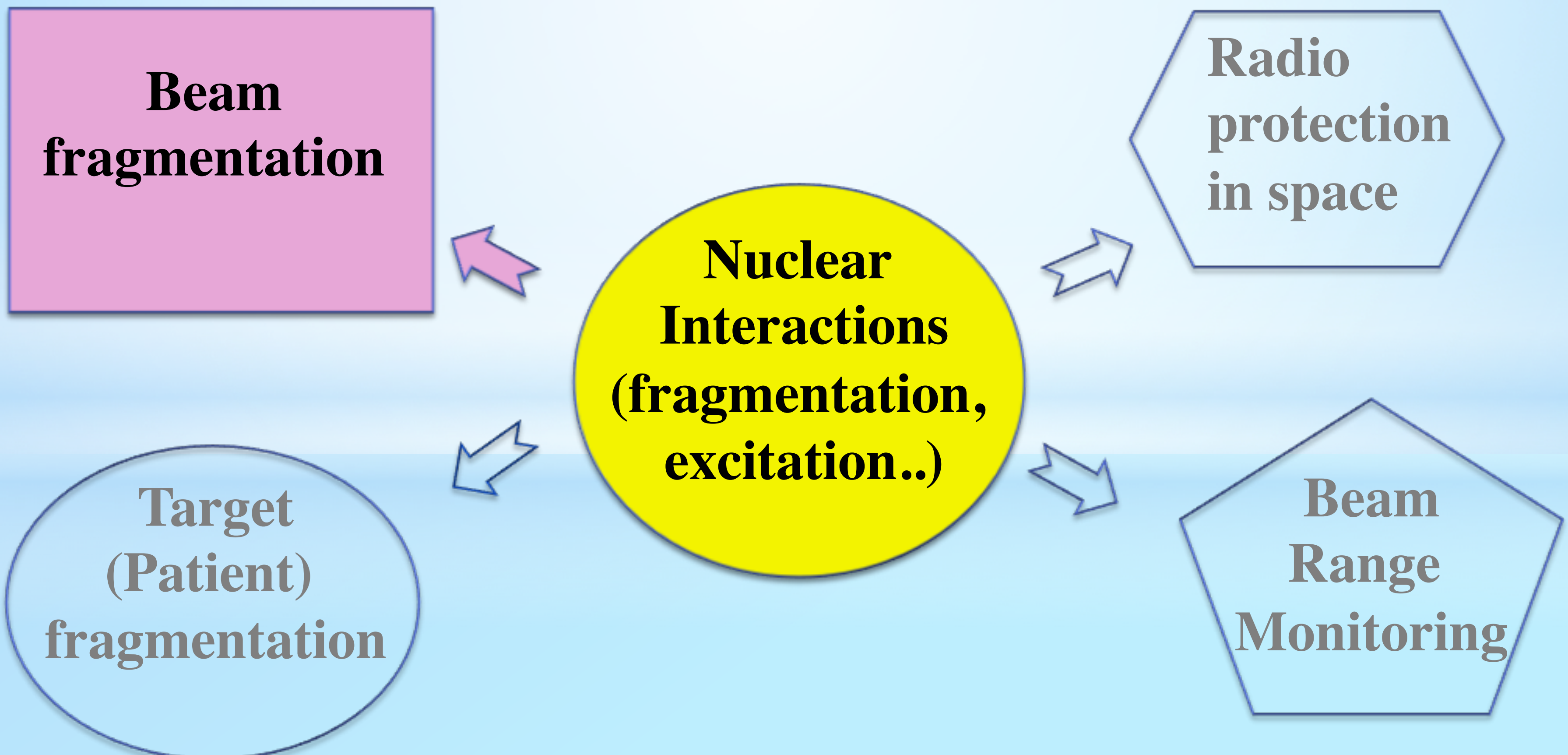
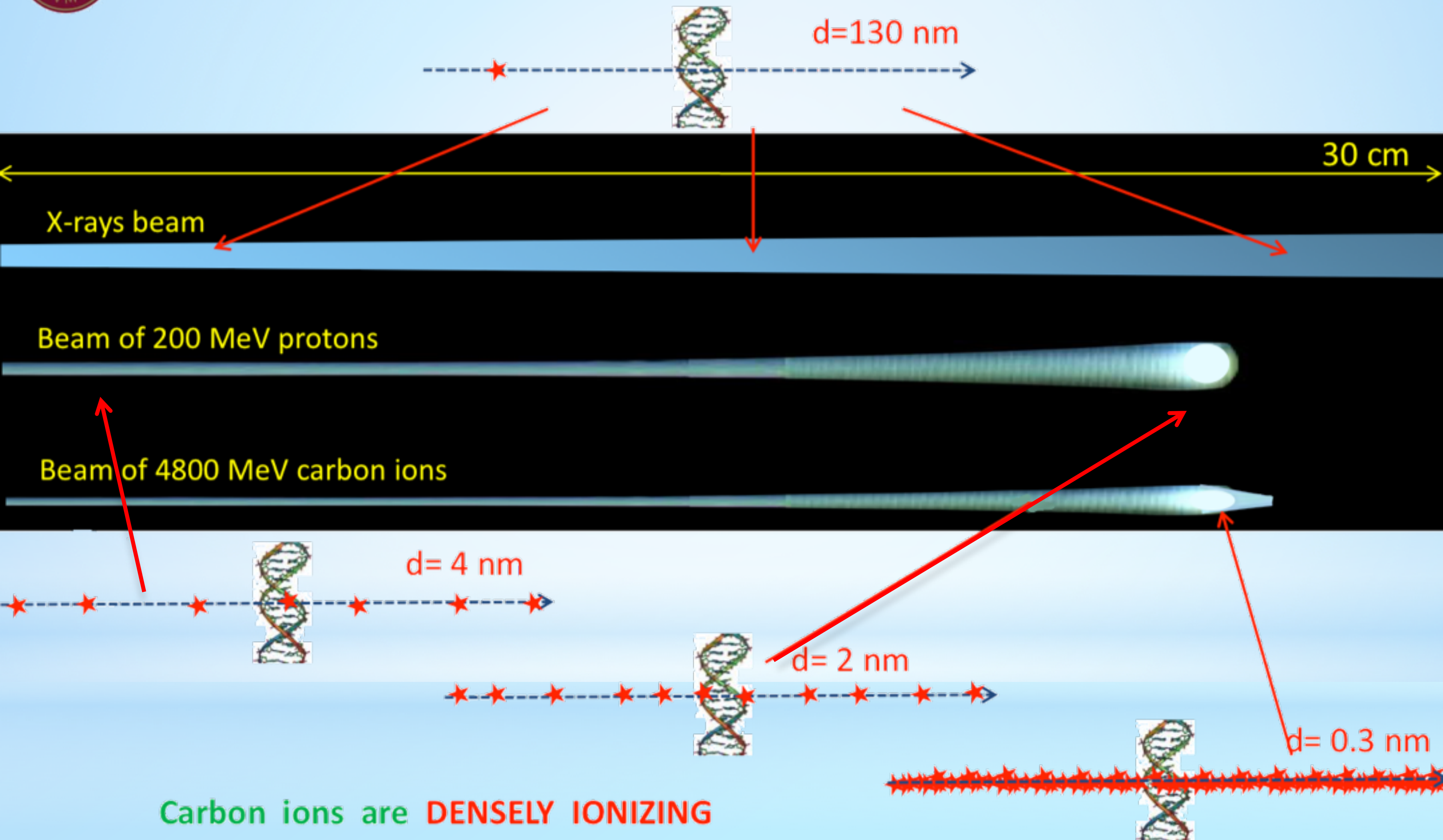


Different bullet, different effects



Carbon ions are **DENSELY IONIZING**
(higher biological effectiveness)

Courtesy U.Amaldi

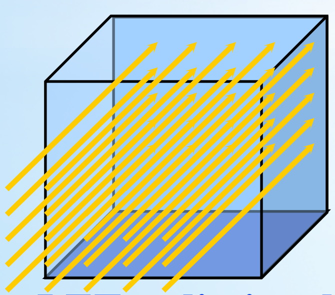
^{12}C Rabio Biology Effectiveness for Dummies

Low LET radiation produces isotropic damage to organized targets.

High LET radiation produces correlated damage to organized targets.

Carbon (and Oxygen) beams can be very effective in the treatment of radio resistent tumors due to their high RBE

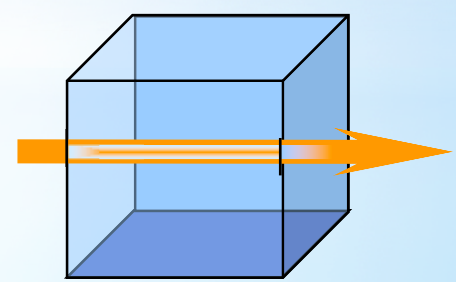
1 Dose Unit



Low LET radiation deposits energy in a uniform pattern

Linear Energy Transfer (LET) and RBE

1 Dose Unit



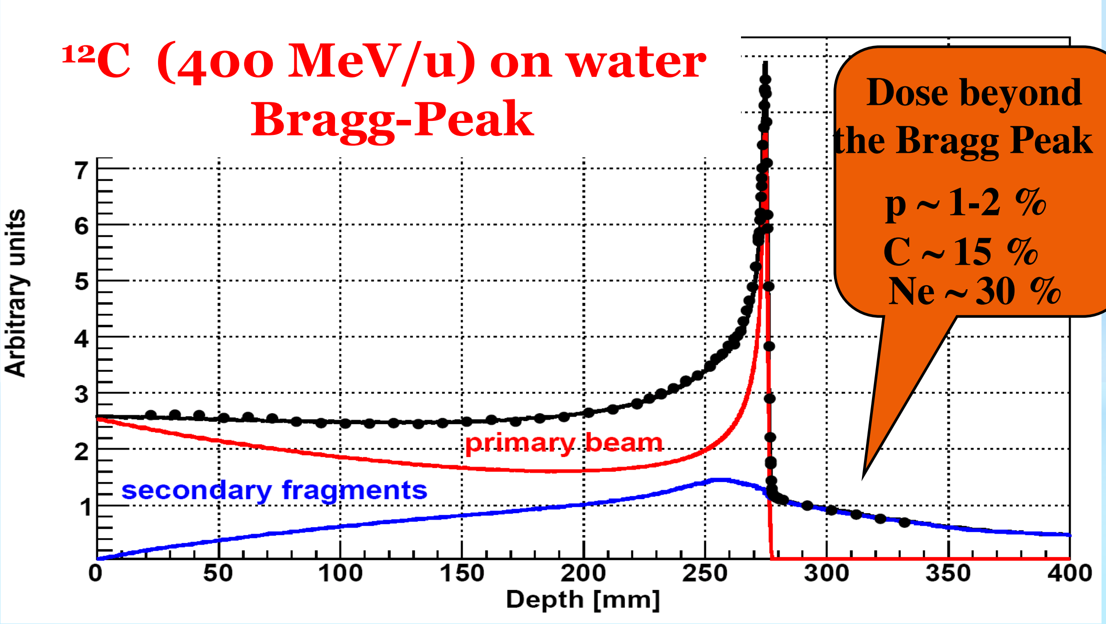
High LET radiation deposits energy in a non-uniform pattern

^{12}C (^{16}O) Beam 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



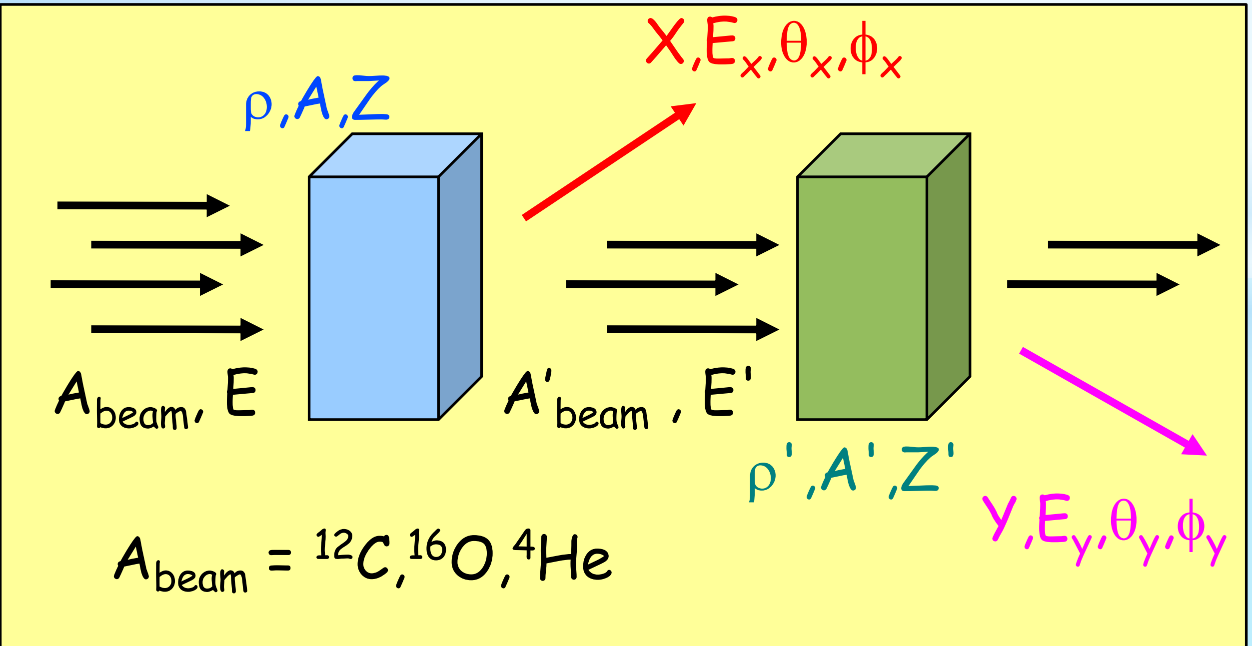
Exp. Data (points) from Haettner et al, Rad. Prot. Dos. 2006
Simulation: A. Mairani PhD Thesis, 2007, Nuovo Cimento C, 31, 2008

Courtesy of Andrea Mairani

What we still miss to know about light ions fragmentation in 2019?

We need to know, for any beam of interest and on thin target:

- Production yields of all $Z \leq Z_{beam}$ fragments, if possible of all $A \leq A_{beam}$
- $d^2\sigma/d\Omega dE$ wrt angle and energy, with large angular acceptance
- For any beam energy of interest (100-300 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!!

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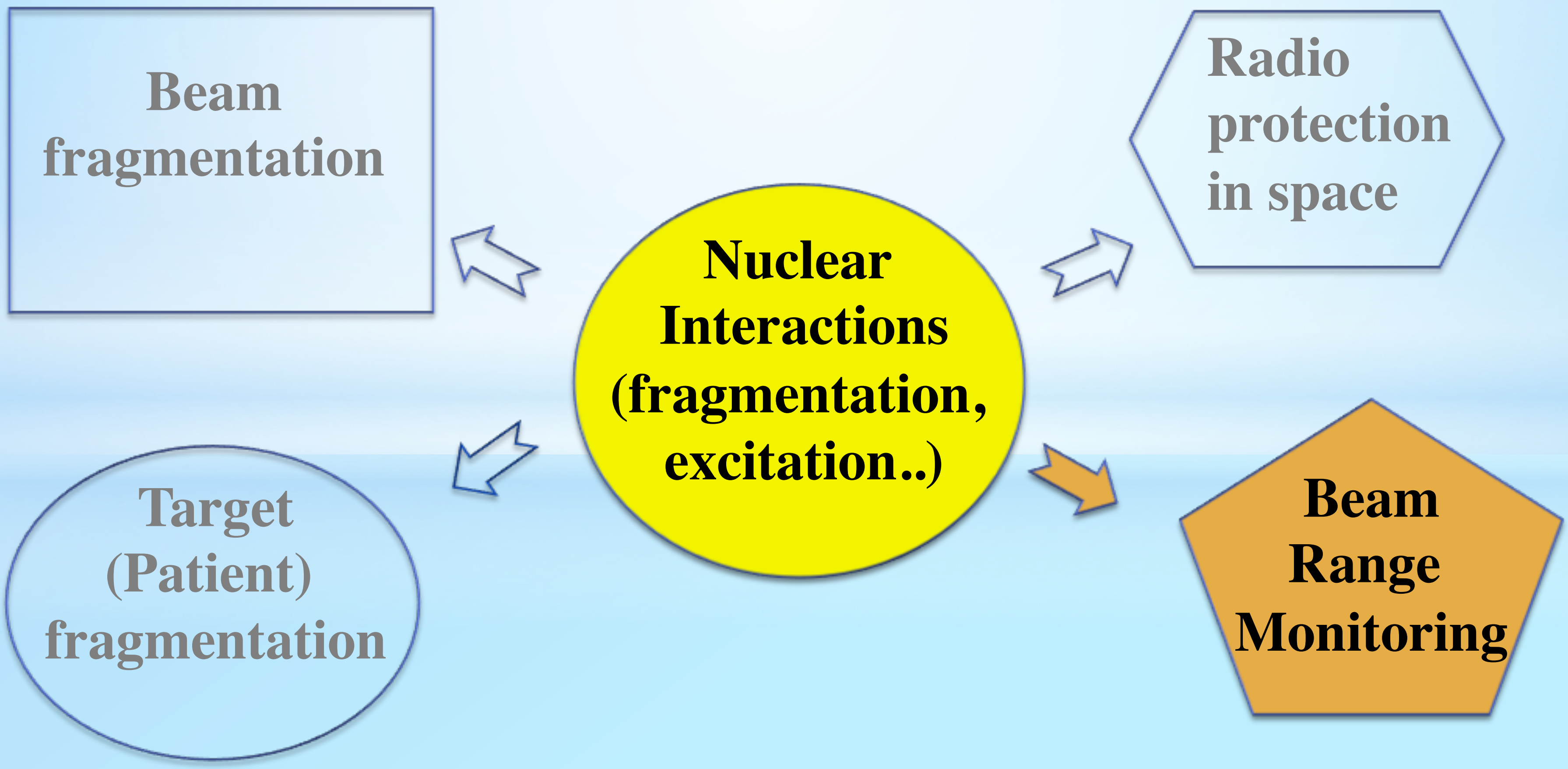
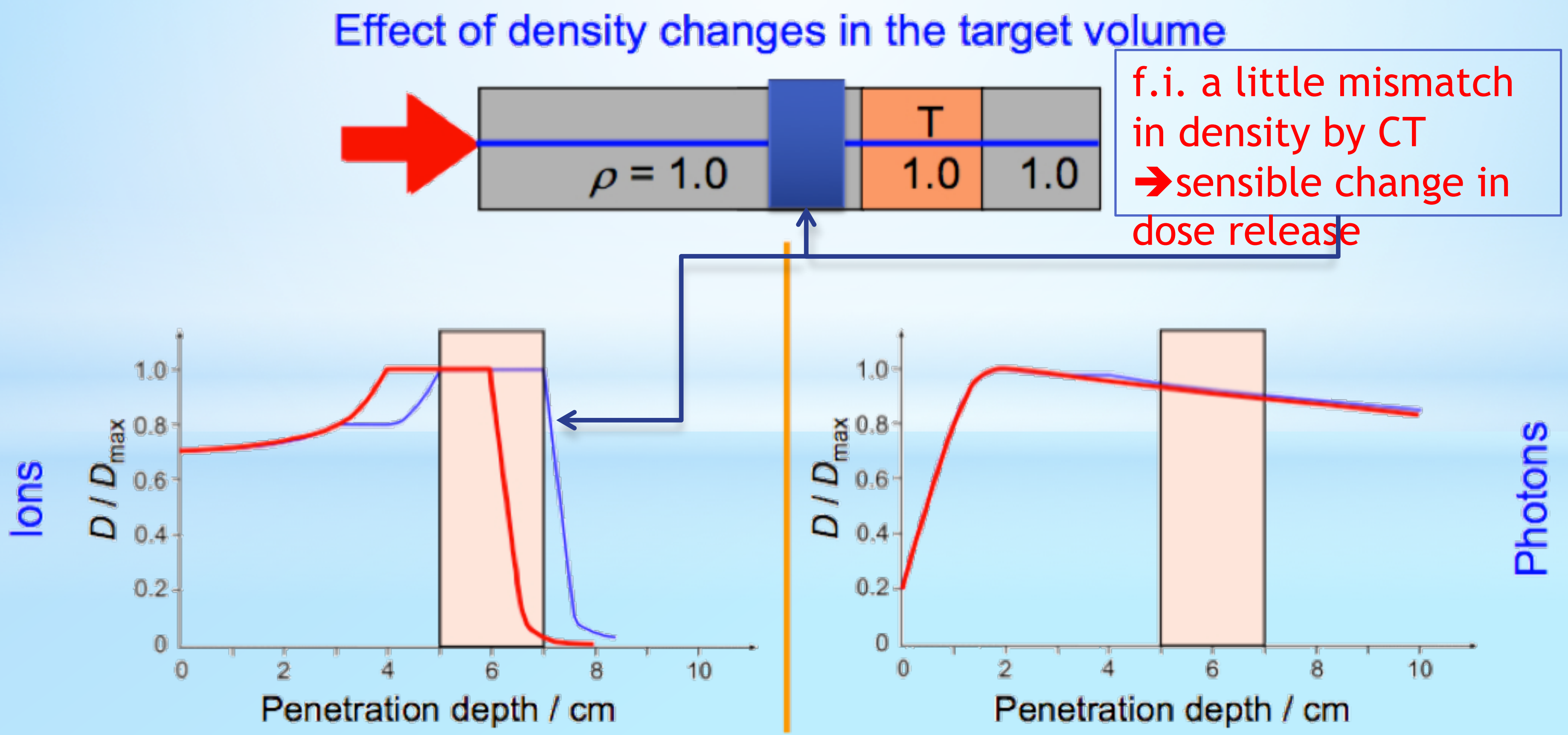


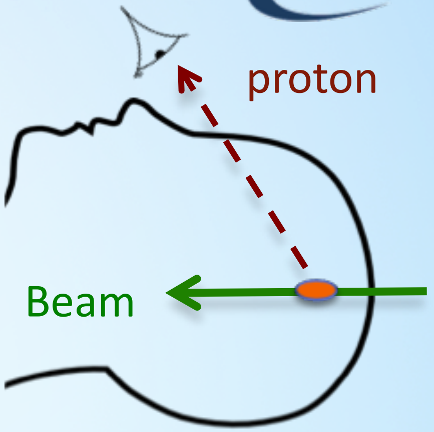
Beam monitoring in PT

Beam monitor in PT is crucial with respect to photon RT. It is like firing with machine-gun or using a precision rifle..

Inhomogeneities, implants, CT artifact, HU conversion, inter session physiological changes-> can cause range variations

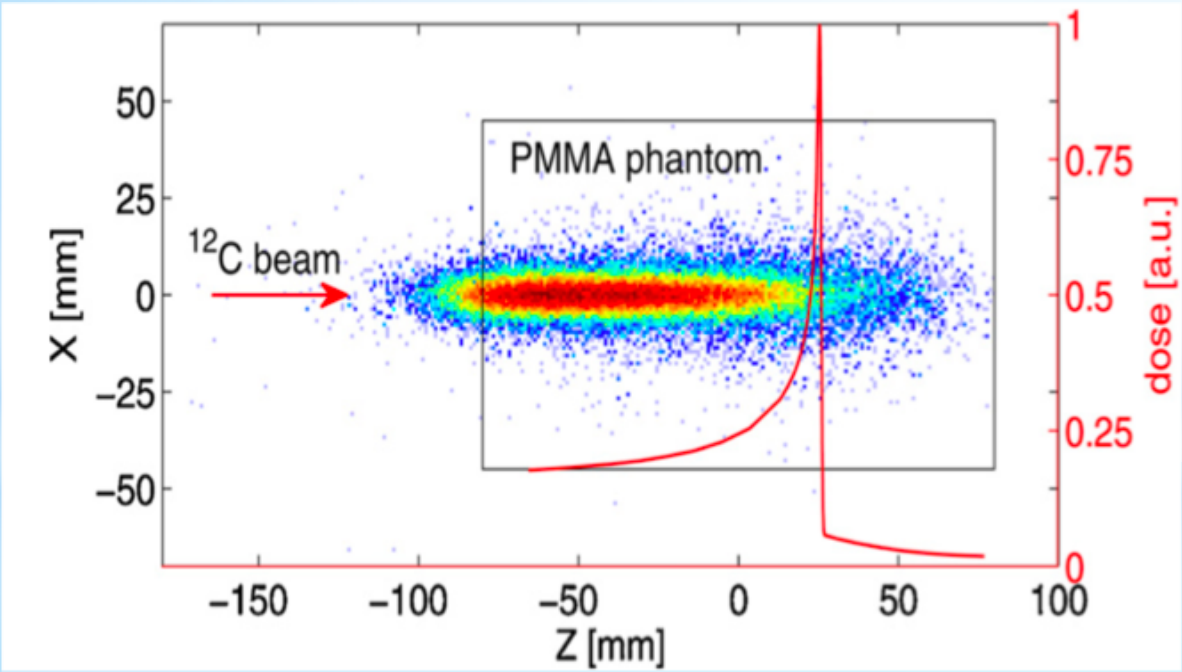


^{12}C beam beam monitor : exploiting charged fragments



Charged secondaries 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



Space distribution of point of closest approach of the charged secondaries to the beam direction

MC not too reliable, in particular at large emission angle wrt beam direction

K Gwosch et al Phys. Med. Biol. 58 3755

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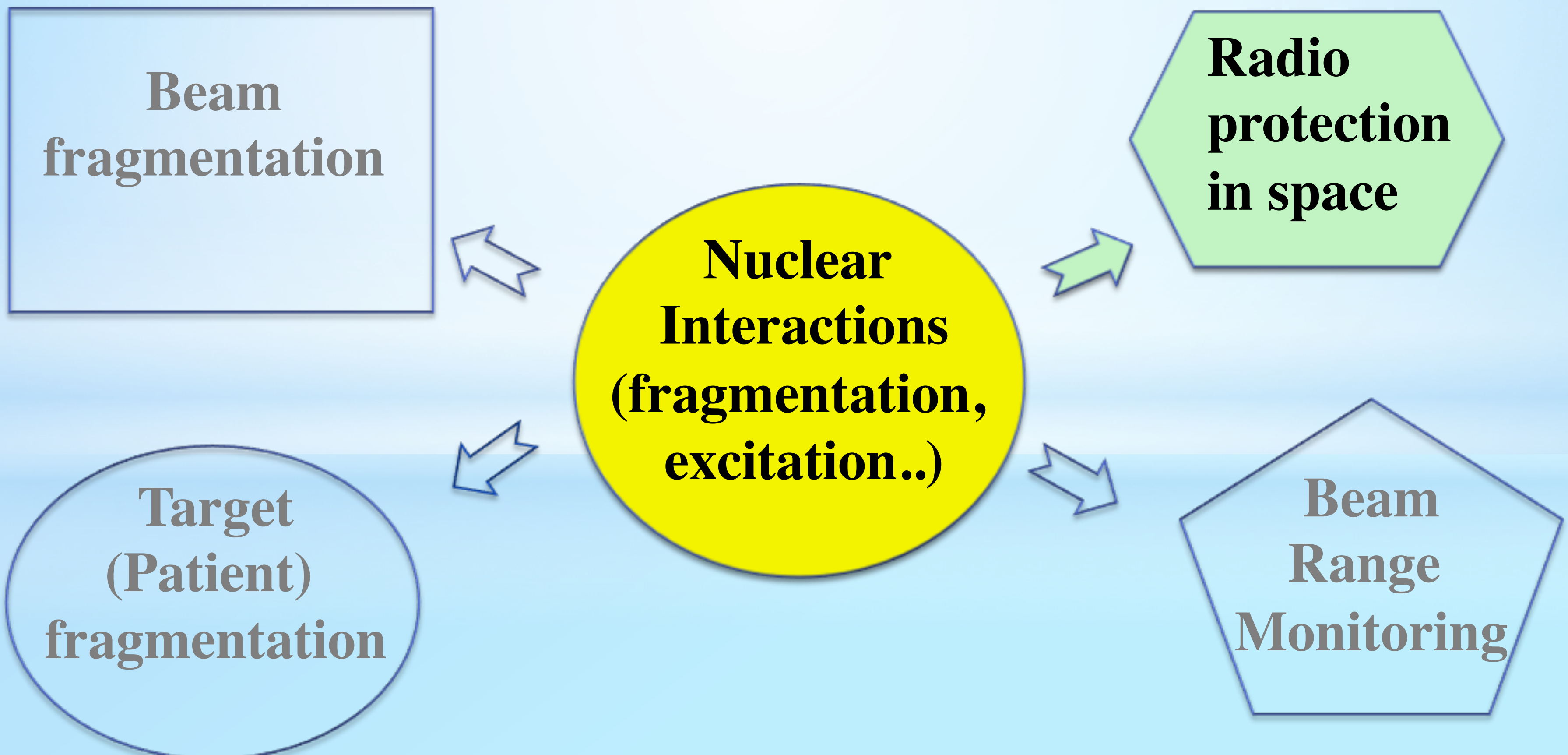
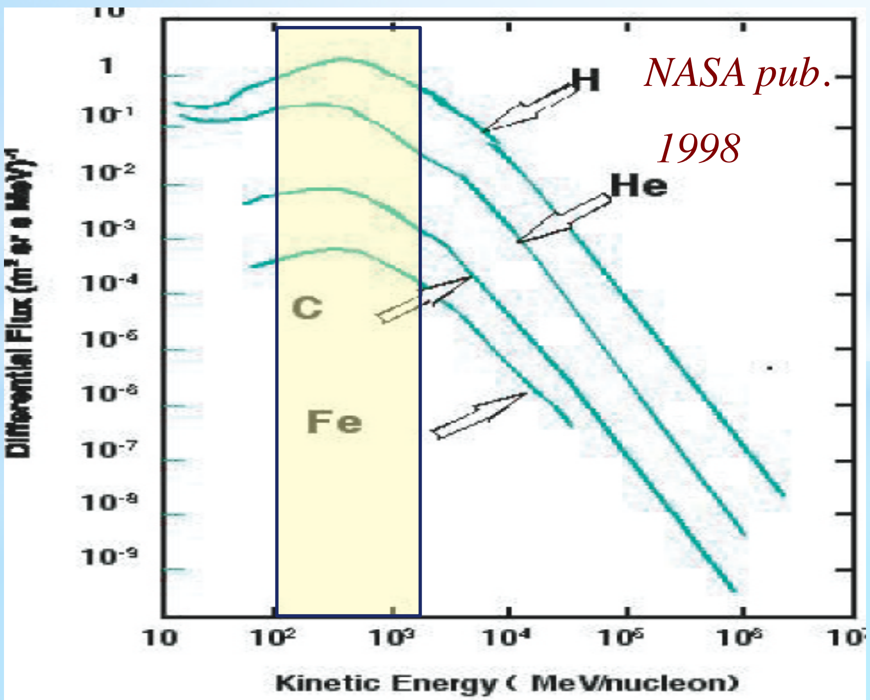


From treatment room to space

Long term mission ()Mars) : the astronauths will be exposed to Galactic Cosmi Ray for year(s) with daily equivalent dose of ~ 1 mSv/day

Threat also from Solar Particle Events: rare (~10 years) but with lethal dose: order of Sv from low energy protons

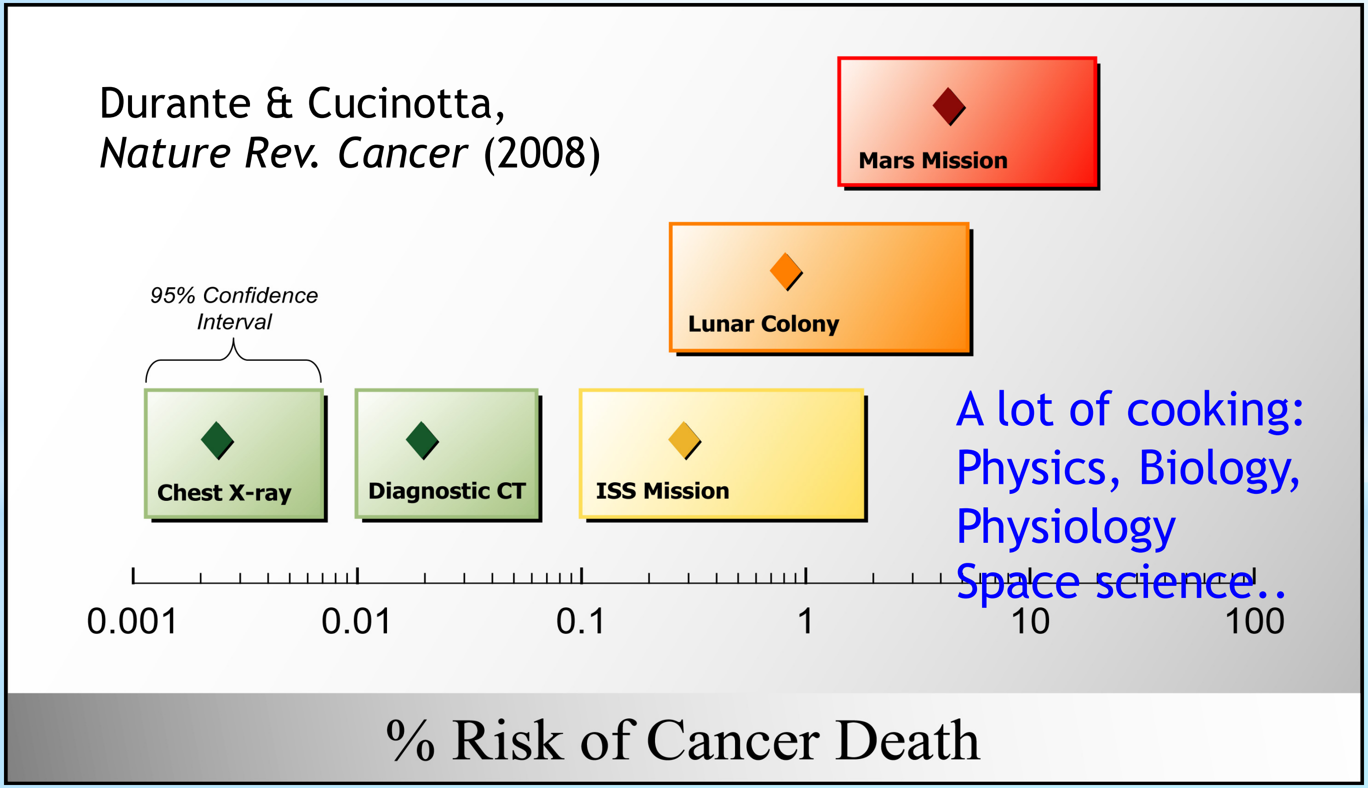


spectrum: 87% protons, 12% He ions and 1% heavier ions (mainly O,C,N) with peaks at 0,7- 1 GeV/n

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

Death from the star?

* Long term mission in space expose the astronauths to a huge dose release: shielding is compulsory
* He, C, O, Fe components of the Galactic Cosmic Rays fragment on the shields and contribute to the integrated dose: material of shielding matters



To choose the shielding material He, C, O fragmentation X section on shields are needed at 0.7-1 GeV/nucl

"Best" shielding materials ?

- Liquid H_2
- Liquid CH_4
-
- Polyethylene (CH_2)
-
- H_2O
-
-
- Al—Inadequate shielding
-
-
- Pb
-

Best

Worst

Potential range for new and multi-functional shielding materials: CH_4 adsorption on carbon forms; polymer composites; hydrides and hydride/carbon or hydride/polymer composites

Trial and error approach based on measurements: no reliable data available

The best shield material is the same of needed to estimate the fragmentation effect in particle therapy.

FOOT can provide ^4He, ^{12}C, ^{16}O → C, C_2H_4 @ 700MeV/u

The FragmentatiOn Of Target (FOOT) experiment

The FOOT collaboration wants to tackle the issues of PT and RPS related to light nuclei fragmentation in the energy region 200 MeV/u - 1 GeV/u

Nagoya University (Japan), GSI (Germany)

Aachen University (Germany), IPHC Strasbourg (France), CNAO (Italy)

10 Italian University/INFN sections

most of the funding from INFN (2017-2022)

80 researchers, 60% permanent, 40 FTE

Main issue is the ^{16}O, ^{12}C beams availability. In Europe are not easy to find in laboratory (GSI, ??) but can be available in treatment center (HIT, CNAO,…) -> the detector must have limited size and be movable

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

Focus of FOOT physics program

Method of cross section difference is crucial to obtain X section on pure elements:

- Using C, C_2H_4 ➔ cross sections on C and H
- Using C, C_2H_4, PMMA ➔ cross sections on C, O and H

PMMA is a combination of C,O,H.

Phys	Beam	Target	Energy (MeV/u)	Inv/direct
Target Frag. PT	^{12}C	C, C_2H_4	200	inv
Target Frag. PT	^{16}O	C, C_2H_4	200	inv
Beam Frag. PT	^{12}C	C, C_2H_4, PMMA	350	dir
Beam Frag. PT	^{16}O	C, C_2H_4, PMMA	400	dir
Beam Frag. PT	^{4}He	C, C_2H_4, PMMA	250	dir
Rad. Prot.space	^{4}He	C, C_2H_4, PMMA	700	dir
Rad. Prot.space	^{12}C	C, C_2H_4, PMMA	700	dir
Rad. Prot.space	^{16}O	C, C_2H_4, PMMA	700	dir

These are specific measurements related with PT & RPS. But we are open to physics program enlargement..

Radiobiology requests & detector constraints for Target Fragmentation

To implement Normal Tissue Complication Probability models requirements are very strict. Lorentz boost in the patient frame asks for good energy and angular accuracy in the lab frame

- Heavy fragment (Z>2) production cross section with uncertainty of 5%
- Relative accuracy on fragment energy of the order of few %
- Good charge and isotopic identification capability of fragments
- Accuracy on light ions production also at large angle
- Angular resolution on the beam-fragment emission angle at mr level

TOO MUCH ?!?!

Fragments from ^{12}C beam (E_{kin}=400 AMeV) on ^{12}C

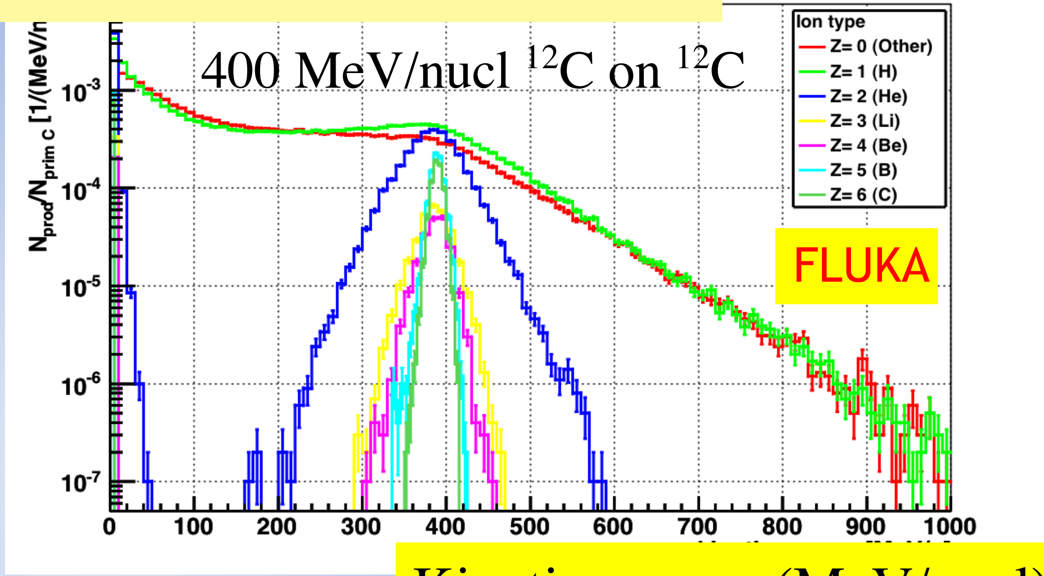
The Z>2 fragments have ~ same velocity of the beam and are emitted in the forward direction

The protons are the most abundant fragments with a wide angular and β spectrum

The Z<3 fragment are all emitted within 10^0 of angular aperture

- ✓ emulsion setup for Z<3, large angle fragments
- ✓ electronic setup== fixed target detector for Z>2, forward peaked fragments

Do not trust MC too much!



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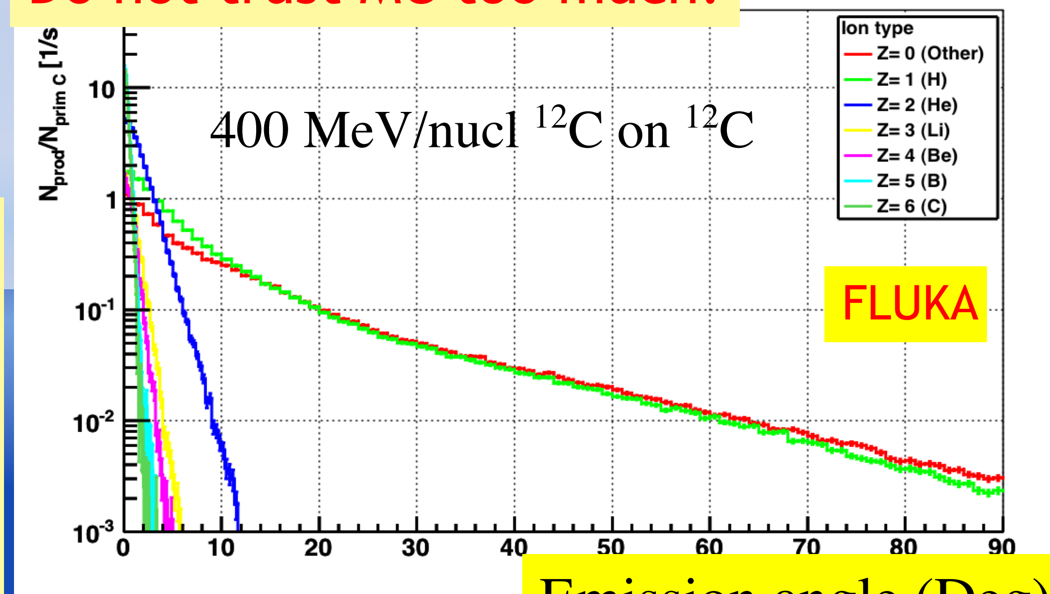
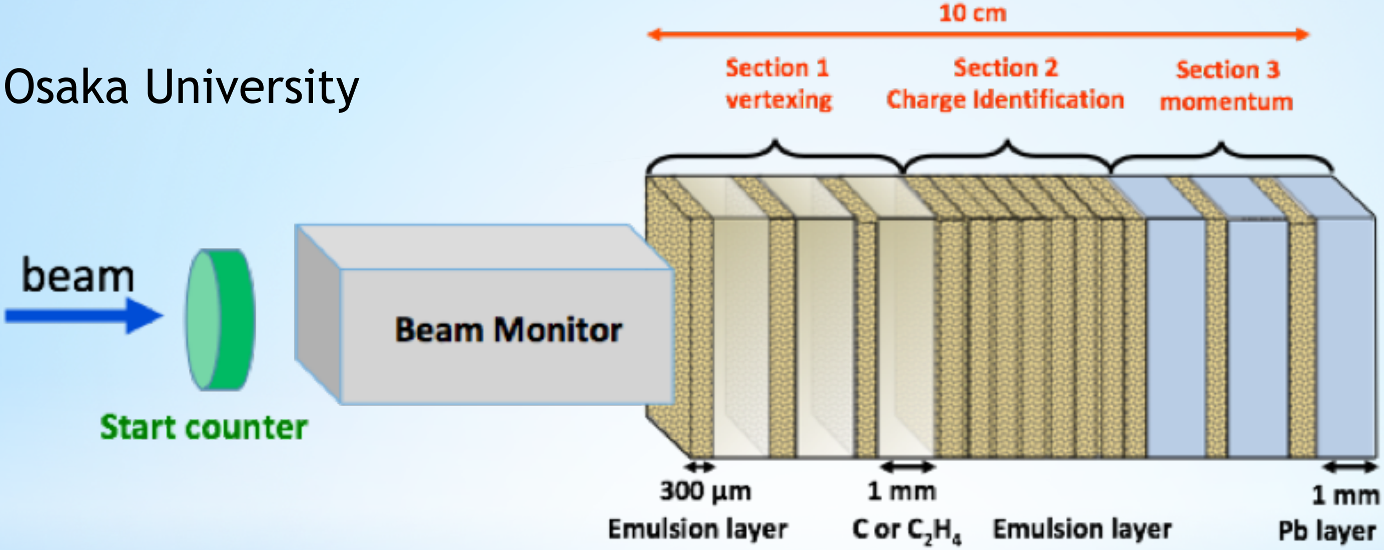


Light fragments:emulsion setup

By Osaka University

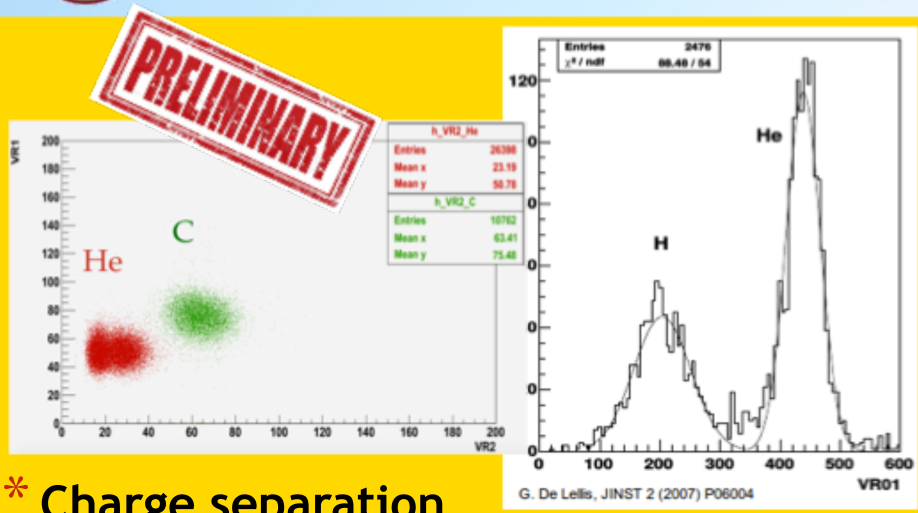


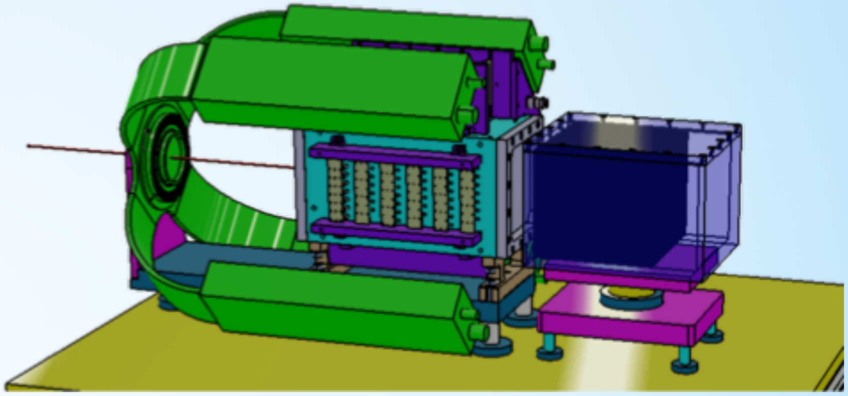
High speed automated scanning

- ✓ Both target and detector integrated in a very compact setup
- ✓ Accurate reconstruction of the interactions inside the target (sub-micrometric resolution)
- ✓ Fragment charge detection eff > 99%
- ✓ Automated scanning system : very fast and with wide angular acceptances

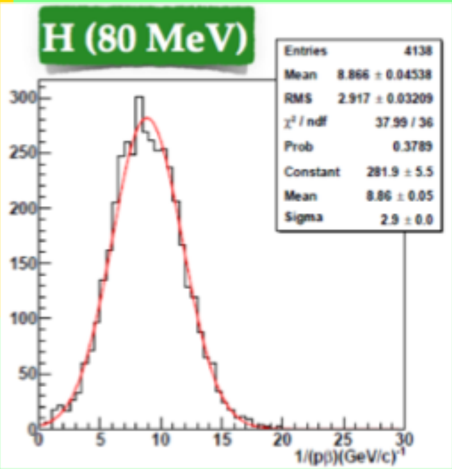
- optimised for light (Z≤3) fragments
- less than 1m: can be easily movable to fit the space limitations from experimental and treatment rooms
- angle setup: ±75°

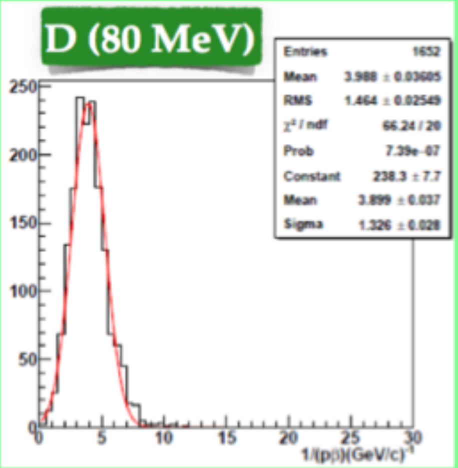
ECC performances





- Charge separation
- Z ∝dE/dx ∝ grain density ∝ track volume
- **Charge identification efficiency ~ 99%**



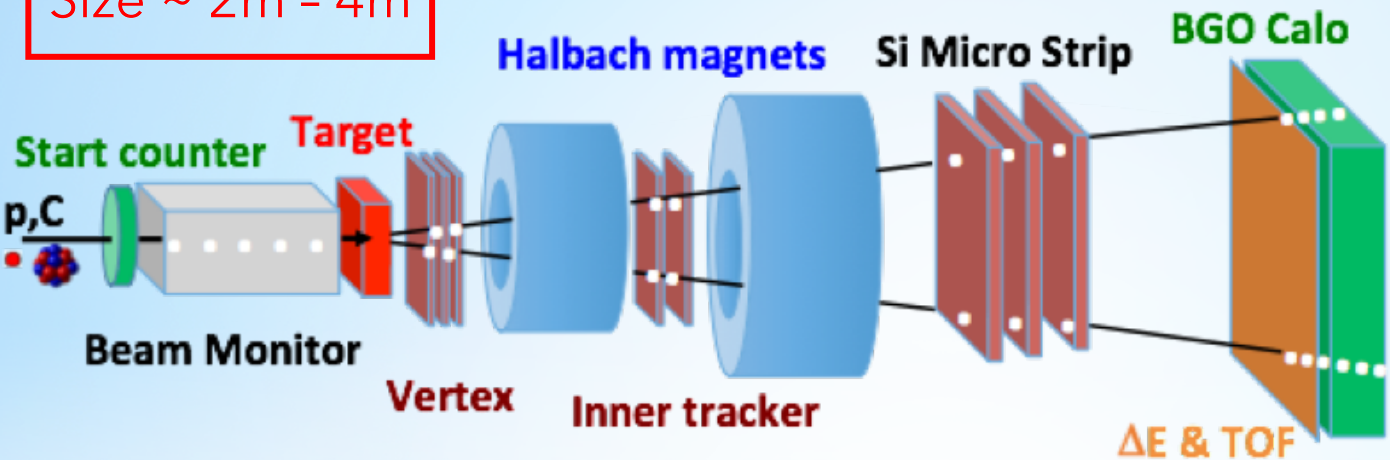


Test performed at LNS p, ^{4}He and ^{12}C beams

- **light isotope separation (preliminary study)**
- Particle range and multiple coulomb scattering measurements could provide a isotope identification

The FOOT electronic setup

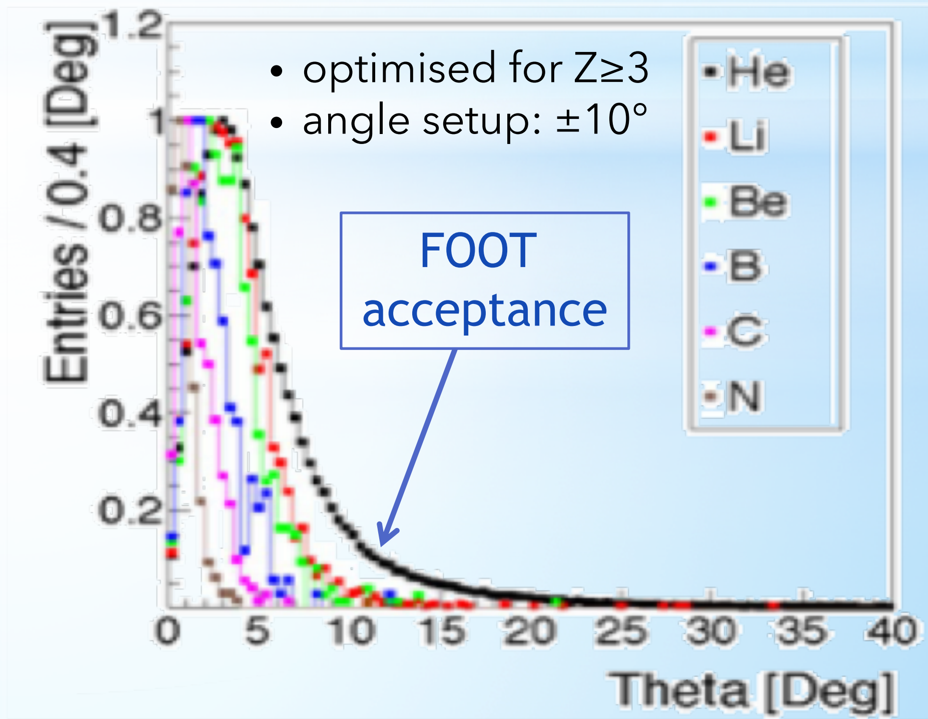
Size ~ 2m – 4m



Target performances

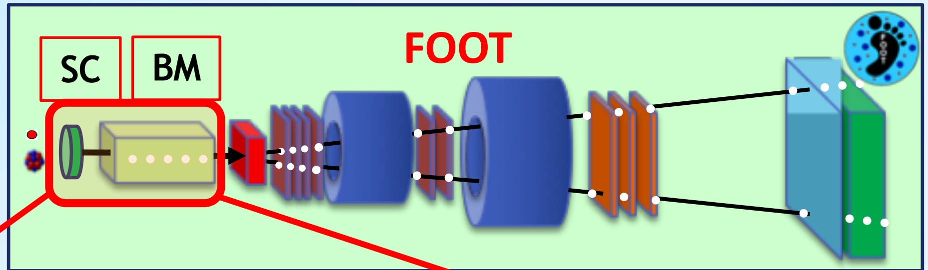
- **Δp/p** <3.5%
- **Δ_{TOF}** <70ps
- **ΔEkin/Ekin** <2%
- **Δ(dE)/dE** ~3%

Sub-detector	Main characteristics
Start counter	plastic scintillator 250 μm
Beam monitor	drift chamber (12 layers of wires)
Target	$C+C_2H_4$ (2 mm)
Vertex	4 layers silicon pixel (20x20 μm)
Magnet	2 permanent dipoles (~ 1 T)
Inner tracker	2 layers silicon pixel (20x20 μm)
Outer tracker	3 layers silicon strip (125 μm pitch)
Scintillator	2 layers of 20 bars (2x40x0.3 μm)
Calorimeter	360 BGO crystals (2x2x14 μm)

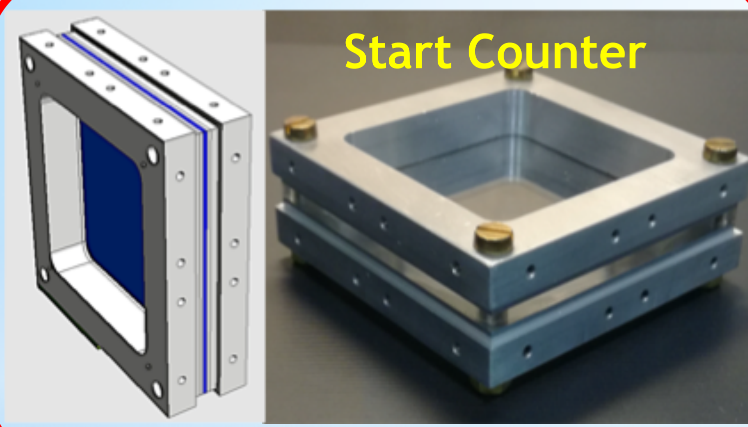


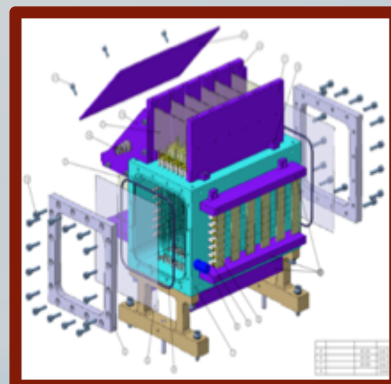
FOOT interaction region

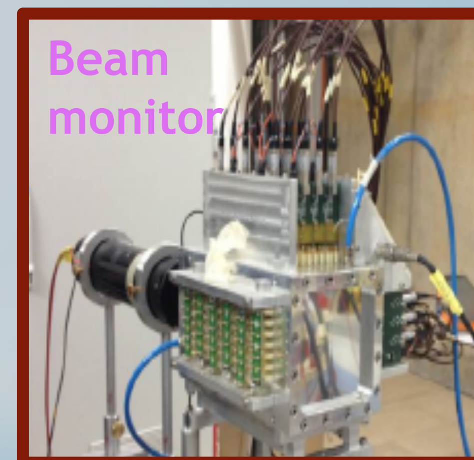
Accurate TOF start
Minimize beam fragmentation



Accurate beam position and direction measurements







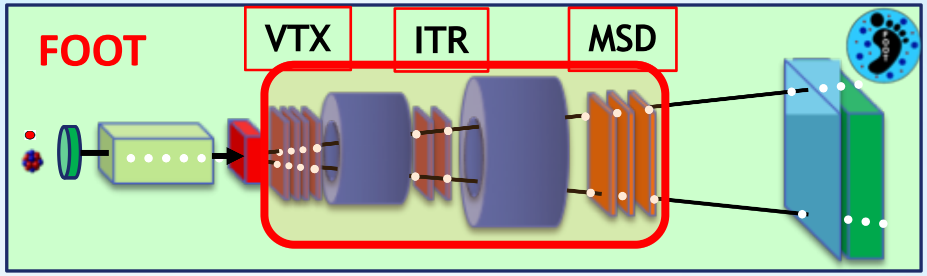
- 250 μm plastic scintillator read out by 48 SiPM (12/side)
- Readout by WFD at 5 Gsample/s.
- Time resolution: 65 ps for ^{12}C beam @ 200 MeV/nucl

- Drift chamber with 6+6 XY planes
- Gas: Ar/CO_2 (80/20%)
- Hit resolution on ^{12}C beam @ 400 MeV/nucl : <150 μm

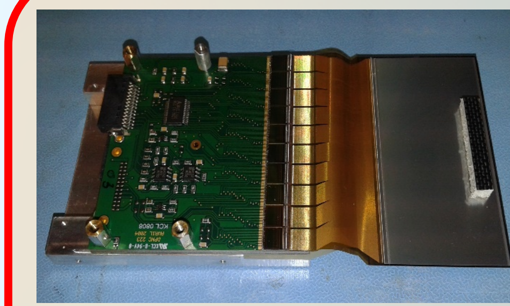
Tracking region

Vertex & Inner Tracker

VTX: 4 layers of Silicon MAPS pixel (20 x 20 μm^2)
ITR: 2 layers of Silicon MAPS pixel (20 x 20 μm^2)
50 μm thickness

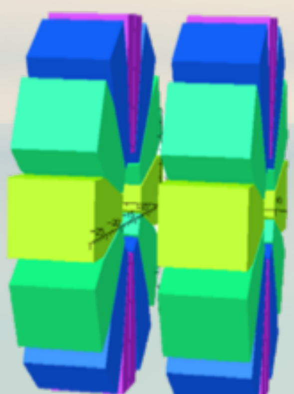


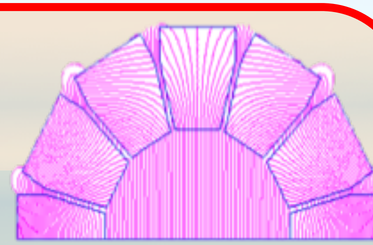
2 permanent dipole magnets in Hallbach geometry
B field in y direction (max 1.1 T)



Micro Strip Detector

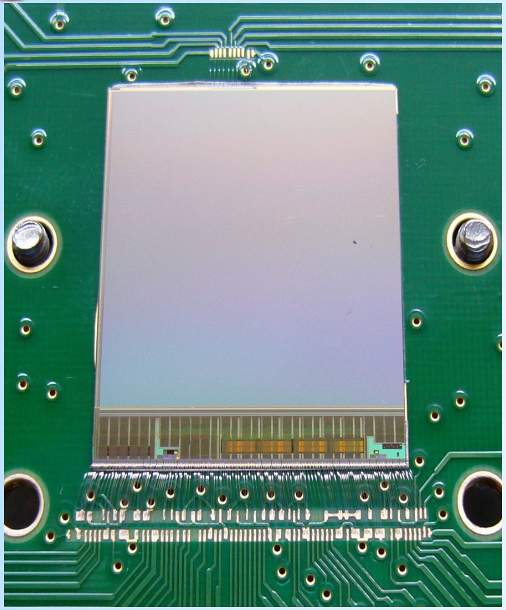
MSD:
3 layers of Silicon MicroStrips detectors (120 μm x 9 cm)
150 μm thickness





2 permanent Magnet

Pixel detector & p resolution

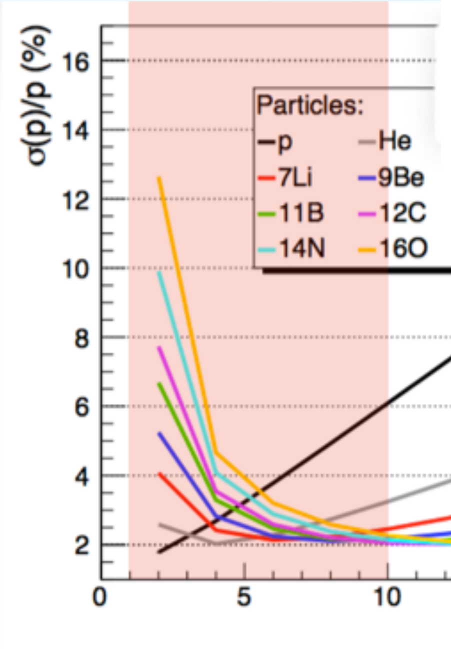


The core of the tracking system is the MIMOSA 29 pixel silicon detector (VTX and Inner Tracker)

- MAPS (AMS 0.35 µm, 15 µm epi-layer)
- 928 (rows) x 960 (columns) pixels
- 20.7 µm pitch
- Size 20.22 mm x 22.71 mm x 50 µm (thickness)
- chip readout time 185.6 µs
- Digital Zero Suppressed Output

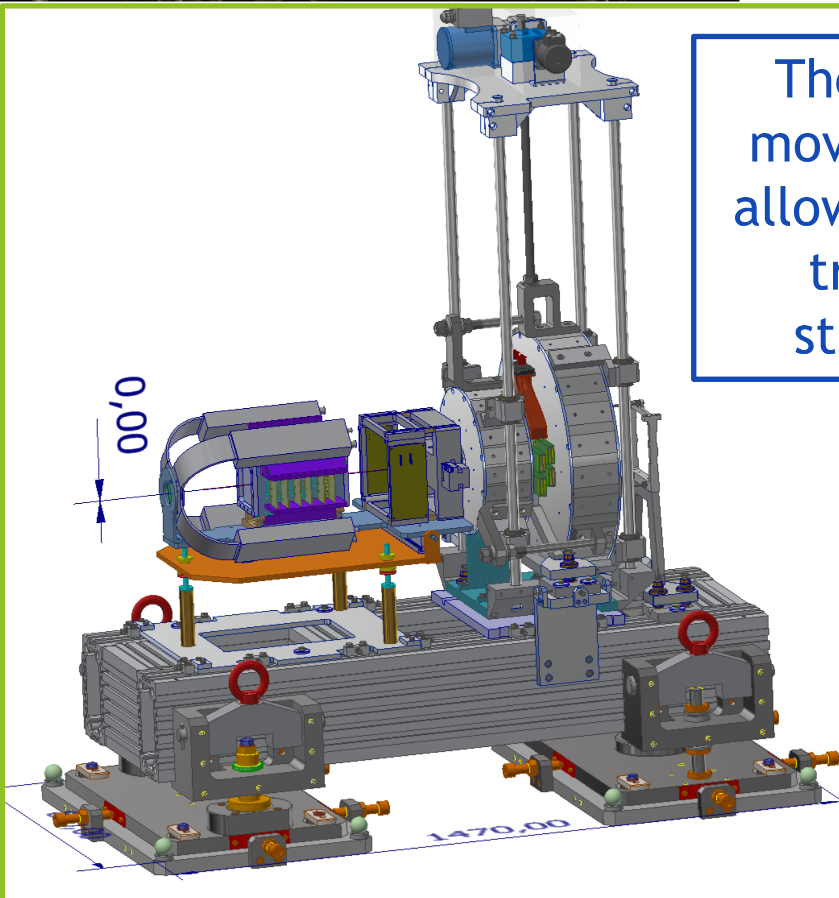
By IPHC In2p3 Strasbourg

The trade off betwen the MS and the tracking system resolution provides a 4 - 2.5% momentum accuracy at 200-700 MeV/u almost flat for Z>3 ions

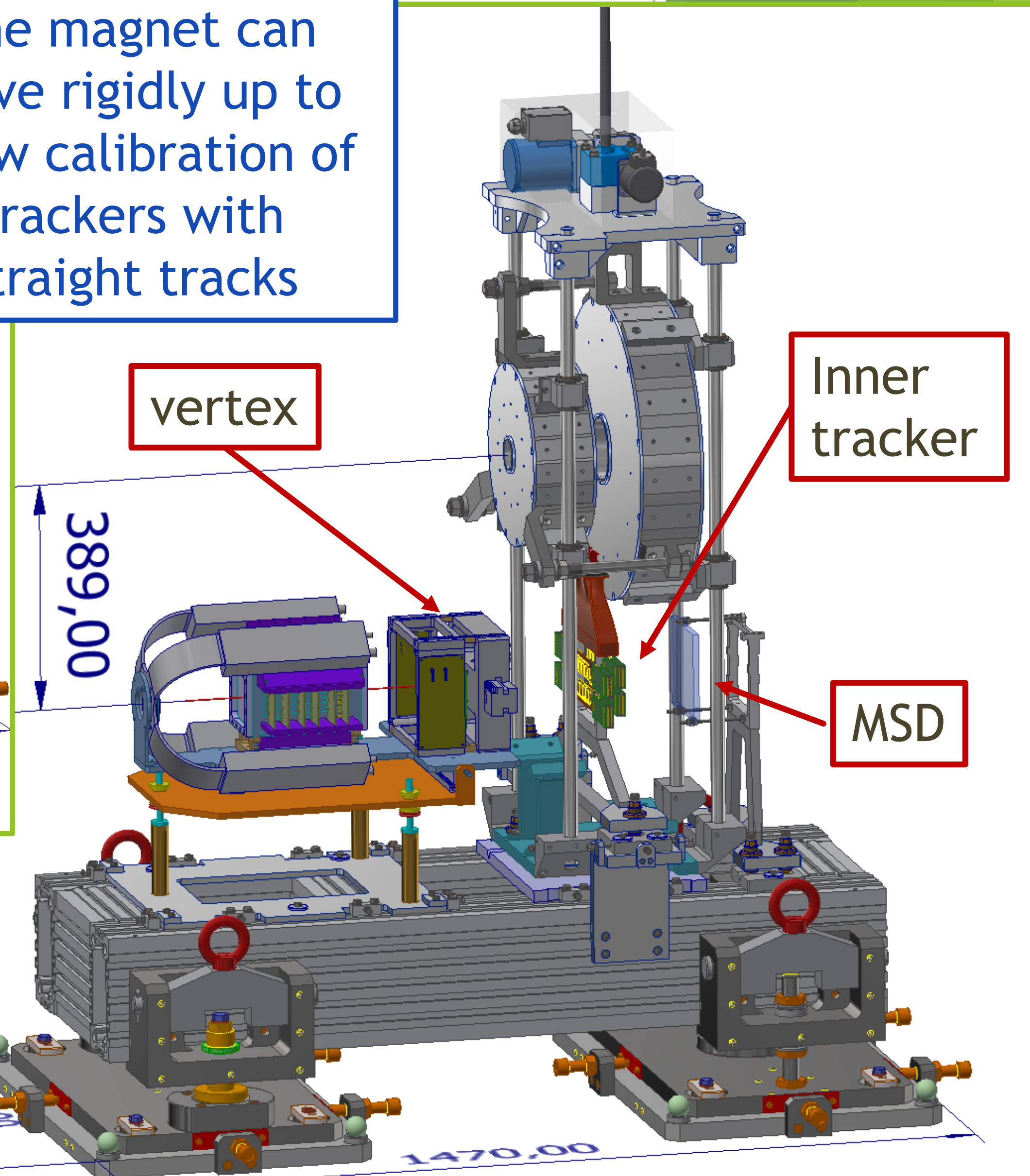


Limit from MS at low energy and from σ_{point} at high energy

Calibration with straight tracks

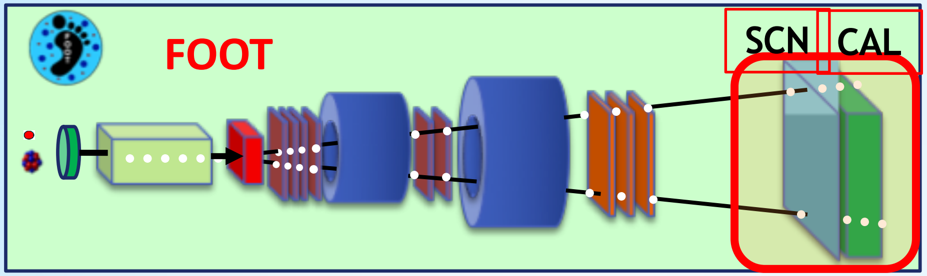


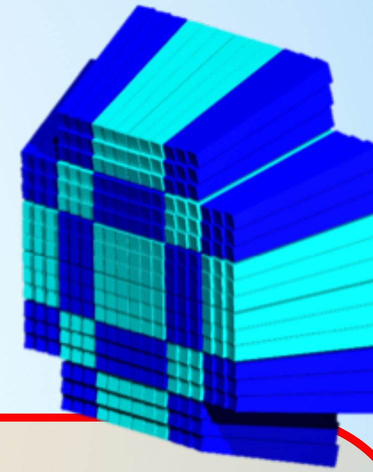
The magnet can move rigidly up to allow calibration of trackers with straight tracks



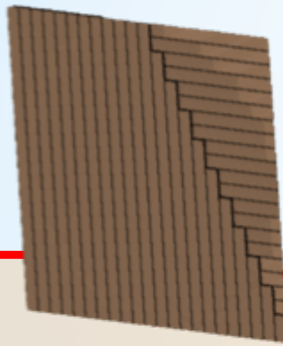
Mechanical structure derived from the ELI beam line mechanics

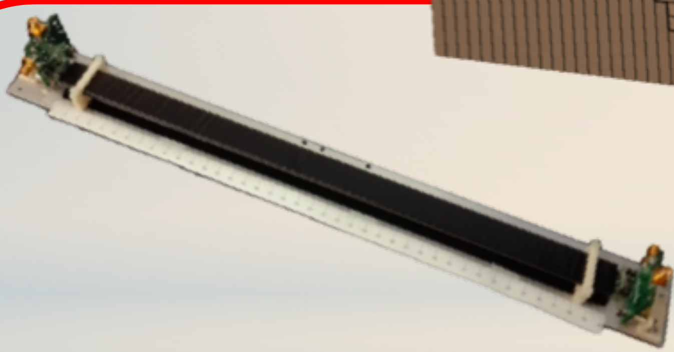
Downstream region





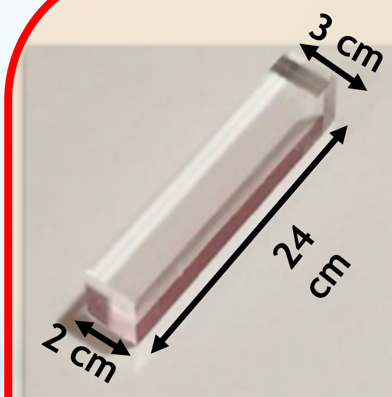
Plastic Scintillator ΔE/TOF measurement





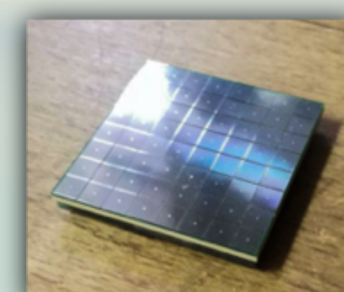
40 x 2 x 0,3 cm3 plastic scintillator bars
2 XY layers of 20 bars
Readout: 4 x 3mm^2 SiPM/bar
35 ps resolution @ 12C at 200 MeV/nucl (CNAO)

BGO Calorimeter



400 BGO crystals
Z_{eff} = 74
P_{BGO} = 7.13 *g/cm³*
Weight = 1.027 kg
Total weight 330 Kg

Readout:
SiPM 8x8 mm^2
cell 20 μm
Voltage breakdown 53 V

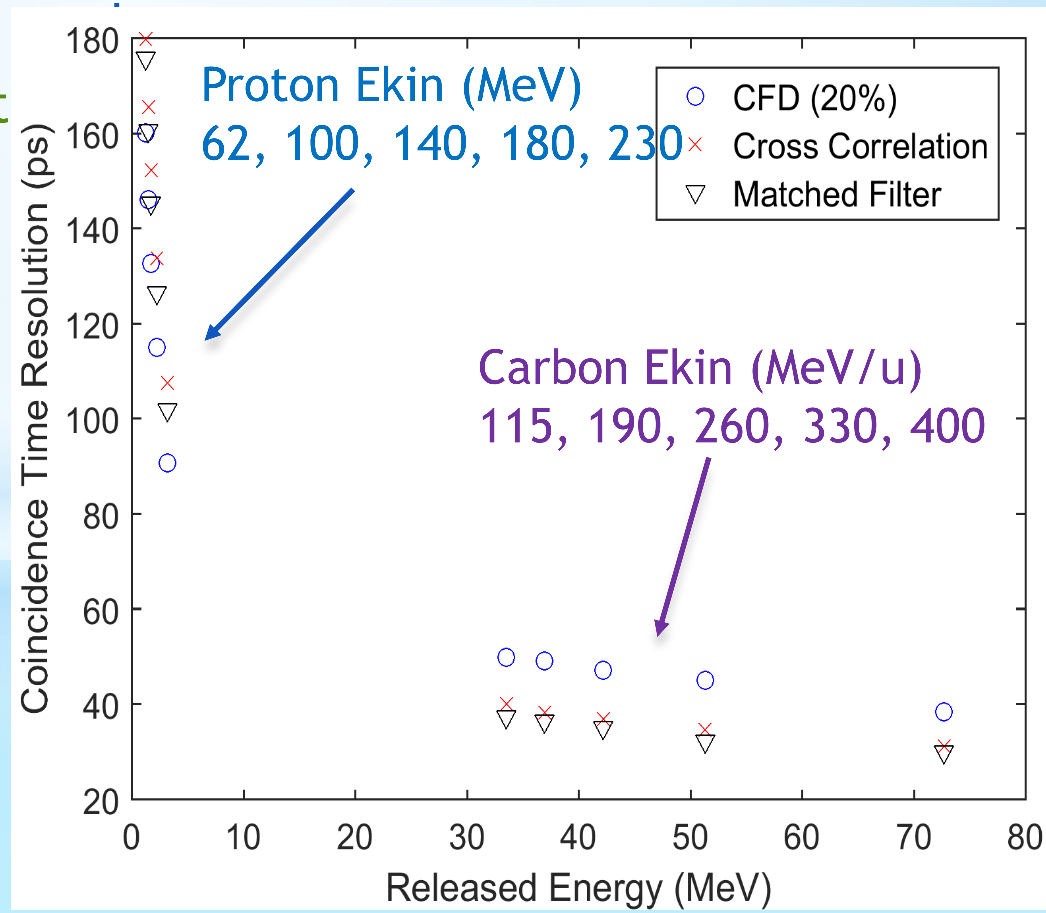


ΔE/TOF test @ CNAO p & ^{12}C beam

- Each bar side readout by 2 parallel of 2 SiPM powered in series (Hamamatsu SiPM 25 um cell size)
- Each bar side readout by 4 SiPMs powered in series (Avant SiD 40 um cell size)

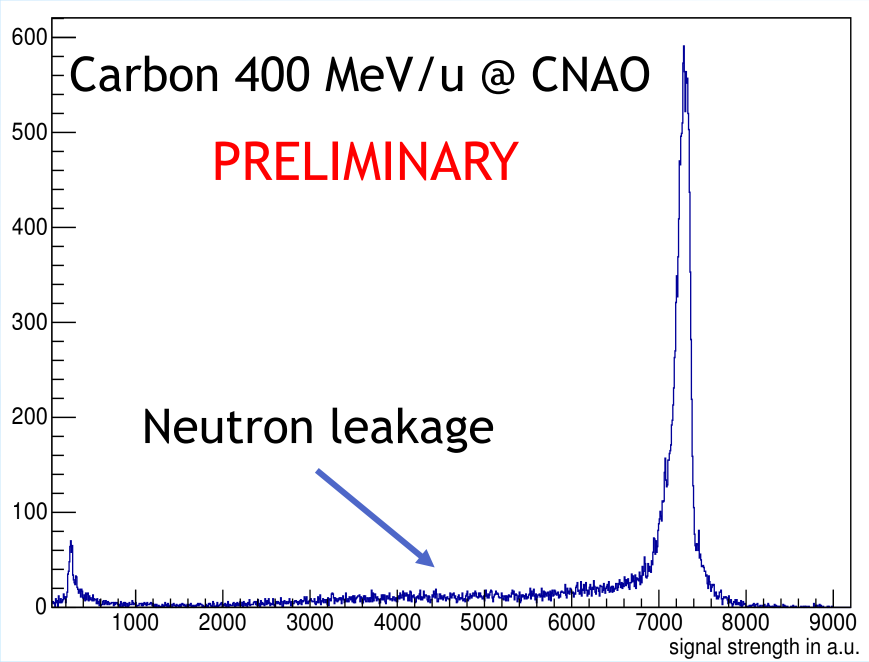
Tested 2 EJ-200 Scintillator bars 20 x 3 x 400 mm^3

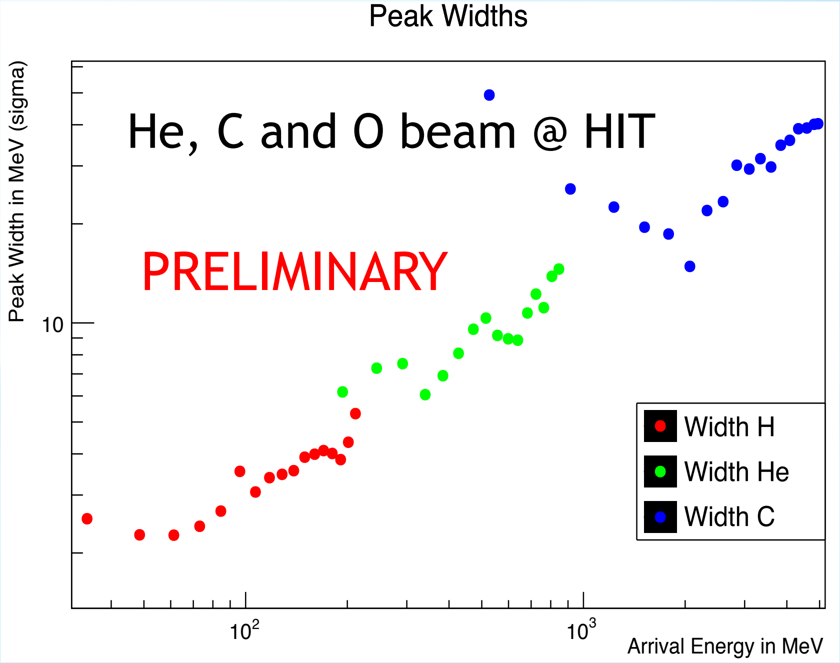
Time resolution 30-40 ps for ^{12}C



BGO crystal test @ HIT& CNAO

- The data confirmed that resolution in the range of 1-2% can be obtained for carbon fragment at 200-400 MeV/u
- The energy resolution seems to scale as sqrt(E_{kin}) as expected
- The neutron contribution is sizeable (higher for lighter fragments)





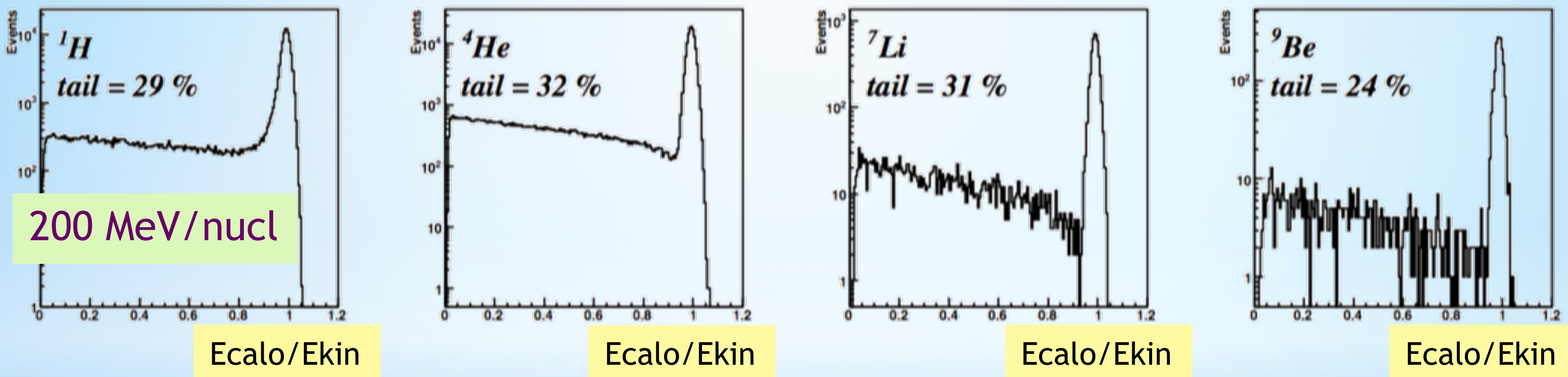
BGO calo VS neutron leakage

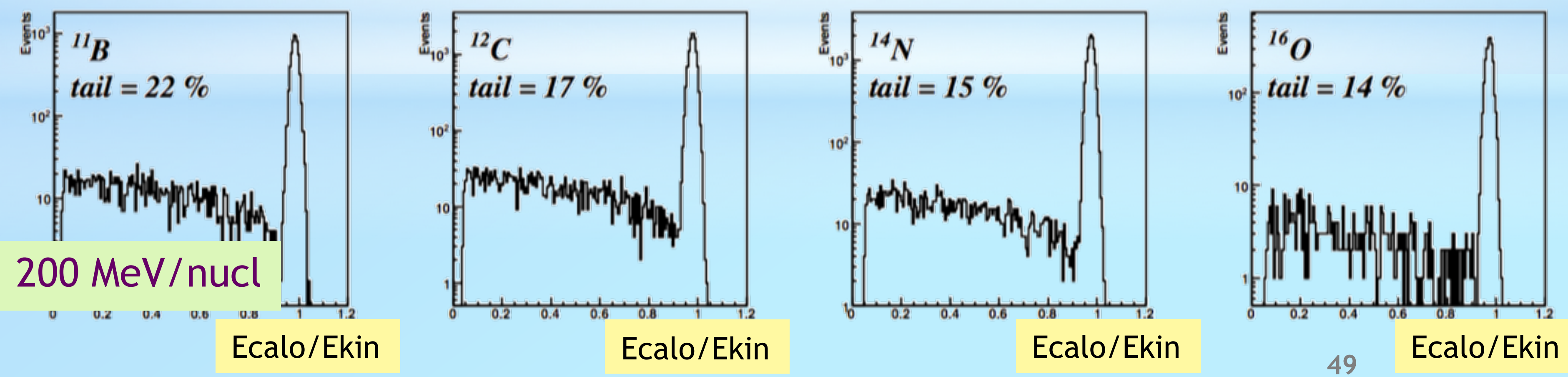
The neutron leakage in BGO seems to be important for energy higher than 200 MeV/nucl and for light fragments

Neutron int. length in BGO at this energy ~ 30-40 cm

The fit constrained can tag such events, but they must be minimized to keep the systematic under control.

FLUKA 2017: 14 cm length crystal (NB final FOOT crystal are 24 cm)





Estimated performances: charge Z reconstruction

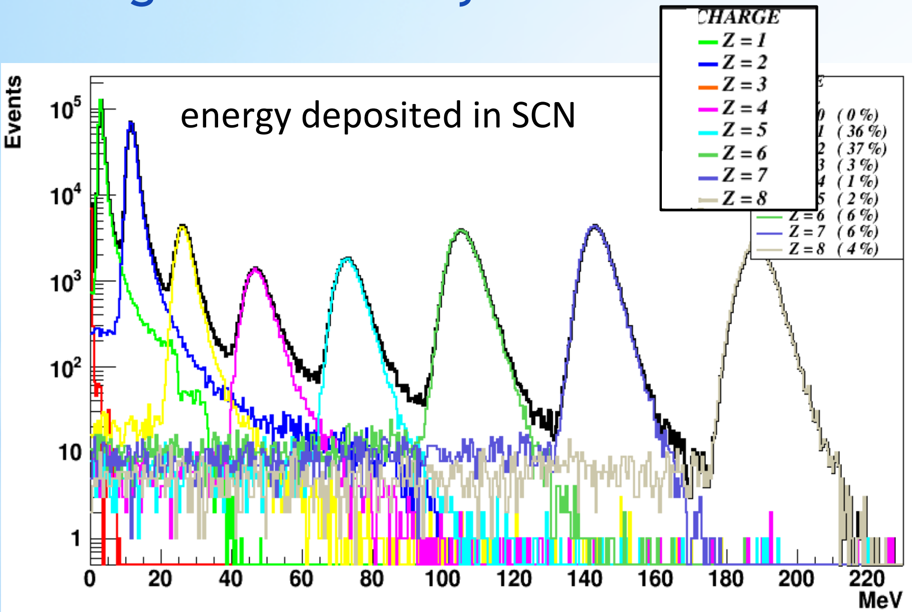
Fragment charge are derived from energy release in DE/TOF scintillator and from the fragment velocity

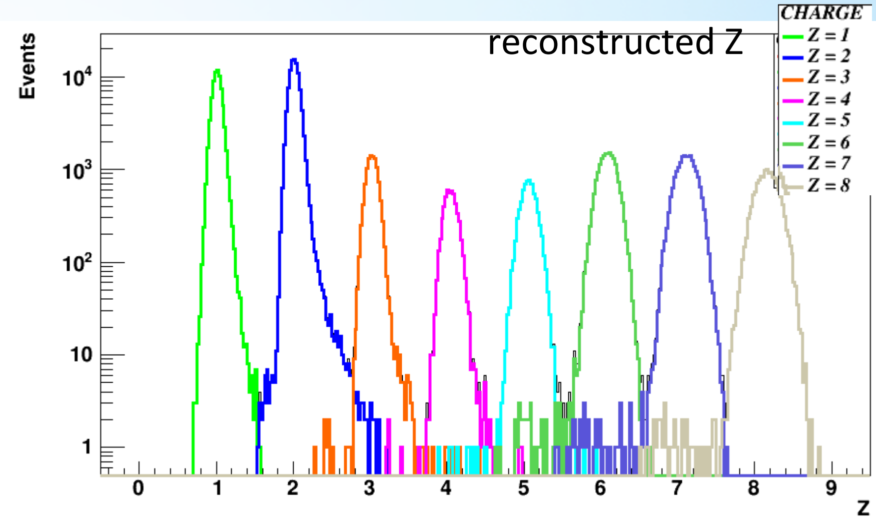
FLUKA simulation : ^{16}O (200 MeV/u)→ C_2H_4

$$-\frac{dE}{dx} = \frac{\rho \cdot Z}{A} \frac{4\pi N_A m_e c^2}{M_U} \left(\frac{e^2}{4\pi\epsilon_0 m_e c^2} \right)^2 \frac{z^2}{\beta^2} \left[\ln\left(\frac{2 m_e c^2 \beta^2}{I \cdot (1-\beta^2)} \right) - \beta^2 \right]$$

ΔE

TOF





	^{1}H	^{4}He	^{7}Li	^{9}Be	^{11}B	^{12}C	^{14}N	^{16}O
	1	2	3	4	5	6	7	8
Z Resolution :	1.01±0.09	2.01±0.06	3.03±0.08	4.05±0.09	5.06±0.10	6.09±0.12	7.11±0.14	8.15±0.15

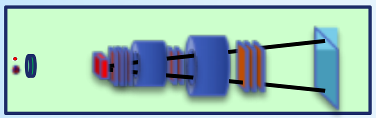
Estimated wrong charge assignment < 1%

Isotopic mass identification

The redundancy in the A measurement allows to use a constrained fit to obtain both fragment mass and the emission 4-momentum.

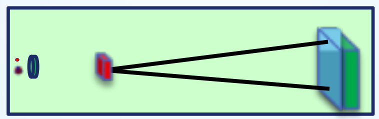
TOF (β) & TRACKER (p)

$$A_1 = \frac{p}{U\beta\gamma}$$



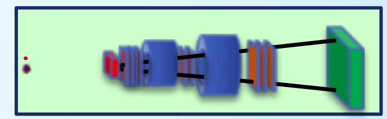
TOF (β) & CALO (Ekin)

$$A_2 = \frac{E_{kin}}{U(\gamma - 1)}$$



TRACKER (p) & CALO (Ekin)

$$A_3 = \frac{p^2 - E_{kin}^2}{2UE_{kin}}$$



$$L = \frac{(P_{fit} - P_{meas})^2}{\sigma_p^2} + \frac{(TOF_{fit} - TOF_{meas})^2}{\sigma_{TOF}^2} + \frac{(E_{fit} - E_{meas})^2}{\sigma_E^2} - \sum_i^{1,3} \lambda_i C_i \left(P, TOF, E\right) + \sum_i^{1,3} C_i^2 (P, TOF, E)$$

$$C_1 = AU\beta\gamma - p = 0$$

$$C_2 = AU(\gamma - 1) - E_{kin} = 0$$

$$C_3 = 2AUE_{kin} - p^2 - E_{kin}^2 = 0$$

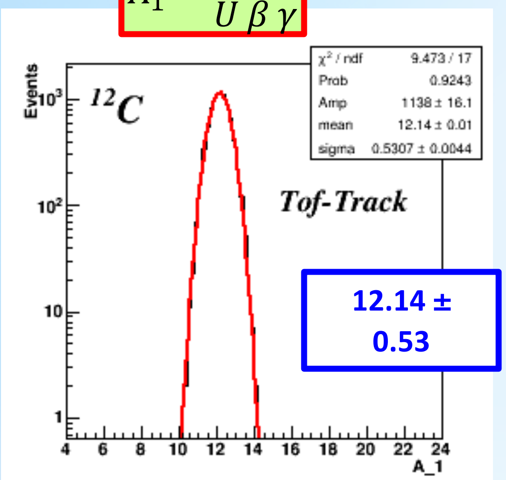
The PID performance evaluation on a 200 MeV/u ^{12}C fragment make use of quite conservative accuracy (with respect to test beam results)

Kinetic energy: $\sigma_E/E \sim 2\%$, Tof: $\sigma_{TOF} \sim 100$ ps, Momentum: $\sigma_p/p \sim 3.5\ \%$

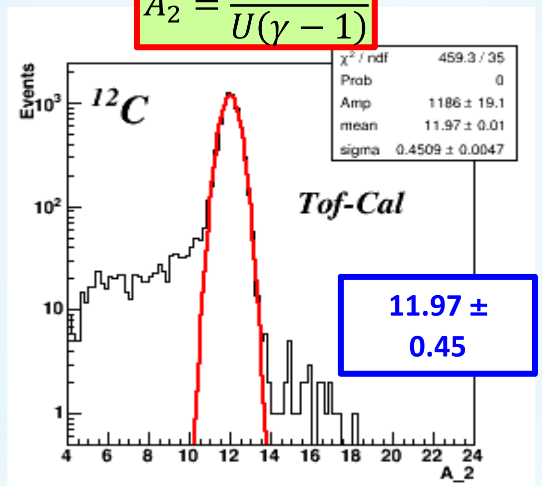
^{12}C mass ID: ^{16}O on C_2H_4 @200 MeV/u

The tails in the A_2 and A_3 distribution are due to neutron leakage in BGO calo: wrong reconstructed events can be filtered using fit χ^2

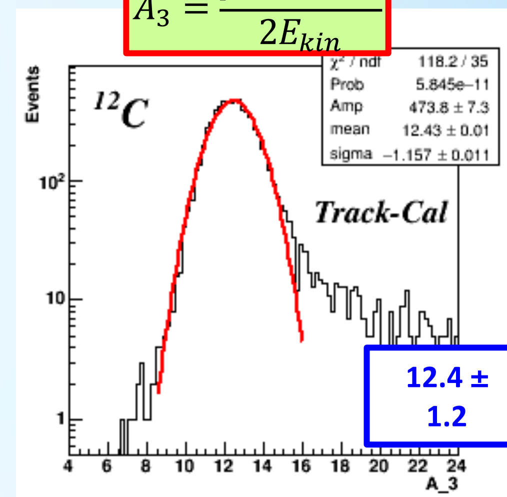
$A_1 = \frac{p}{U\,\beta\,\gamma}$



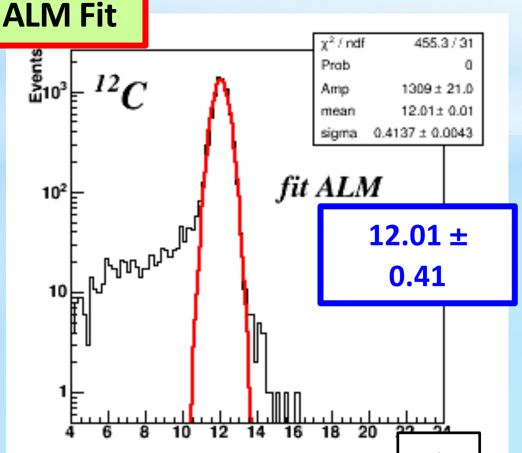
$A_2 = \frac{E_{kin}}{U(\gamma - 1)}$



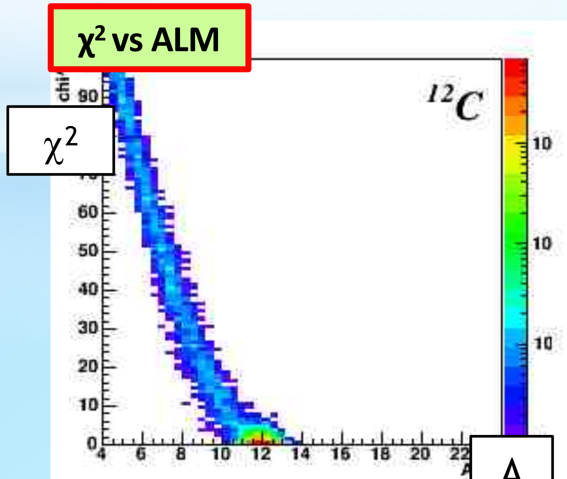
$A_3 = \frac{p^2 - {E_{kin}}^2}{2E_{kin}}$



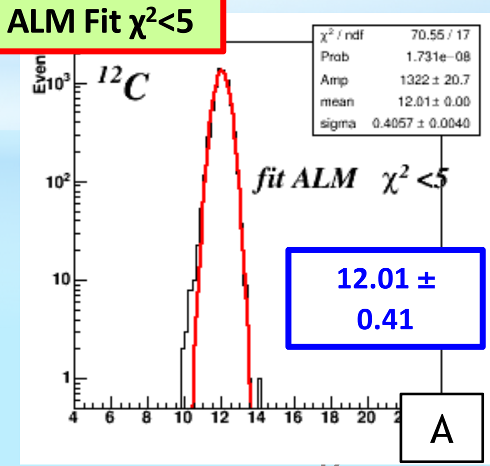
ALM Fit



χ^2 vs ALM



ALM Fit χ^2<5



Future: beams, data taking & schedule

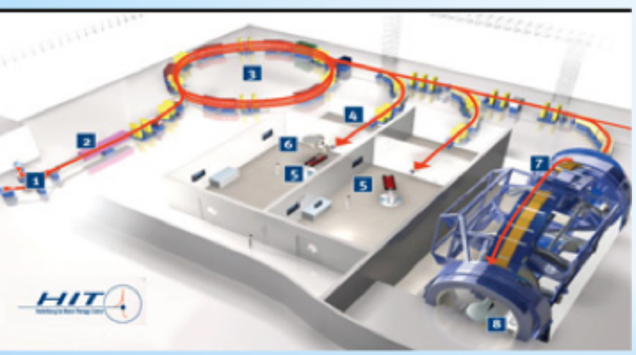
Where can we lay the FOOT?

We need facilities providing ^{4}He, ^{12}C, ^{16}O ions in the 200-700 MeV/u energy range. Possible (affordable-> no BNL, Japan) choices are

GSI : all beams

HIT : all beams only up to 400 MeV/u

CNAO : only ^{12}C, p beams up to 400 MeV/u (since late 2019)



- First data taking at GSI in April 2019 with ^{16}O beam 200-700 MeV/u mainly dedicated to emulsion setup. Beam time from ESA call
- The electronic setup will be completed mid 2020. Engineering data taking April 2019 at GSI
- Electronic setup data taking campaign will start late 2020. It is already funded till 2022

Summary & conclusions

- Nuclear fragmentation plays a role in target fragmentation in proton therapy, beam fragmentation and possibly beam monitoring in carbon (oxygen) therapy
- The radio protection in space (a show-stopper for human exploration of solar system) needs the same knowledge on fragmentation of light ion at intermediate energy of PT
- The FOOT experiment is a medium size particle physics experiment and can address these PT and RPS related issues measuring the relevant fragmentation cross section
- Foot has an open and evolving physics program and collaboration. Proposal to move the focus on neutron and β^+ emitters production in future

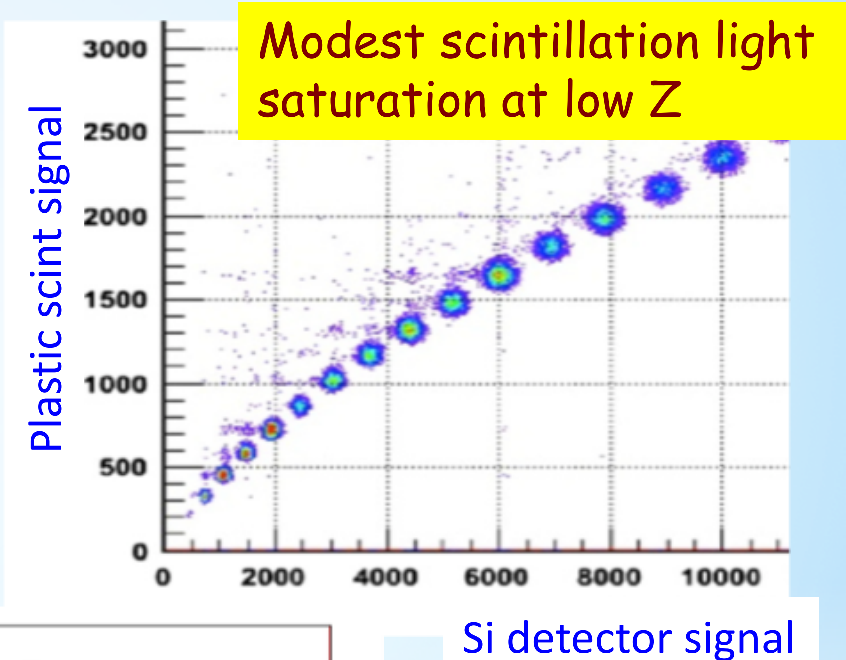
Halbach magnets
Si Micro Strip
BGO Calo
Start counter
Target
Beam Monitor
Vertex
Inner tracker
ΔE & TOF
Thanks...
FOOT website:http://web.infn.it/f00t/index.php/en/

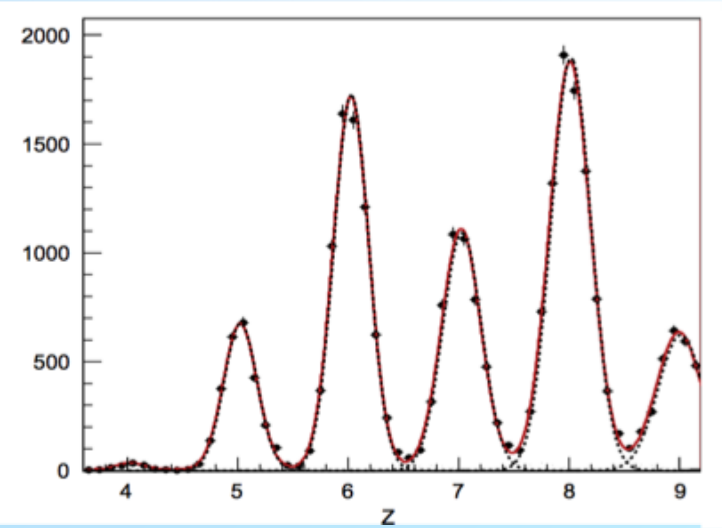
TOF stop & DE/Dx measurement

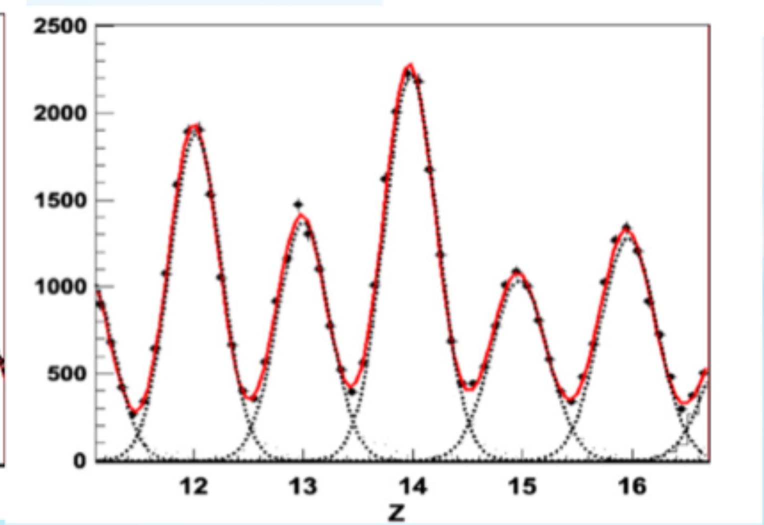
A grid of 400x20x2.5 mm^3 scintillator plastic slabs (XY) can give a very good ΔE (-> Z ID) and TOF measurement.

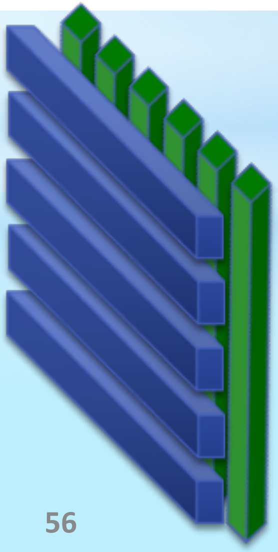
TOF measurement below 50ps with ^{12}C, ^{16}O fragments

Tested with similar fragment energies and experimental setup





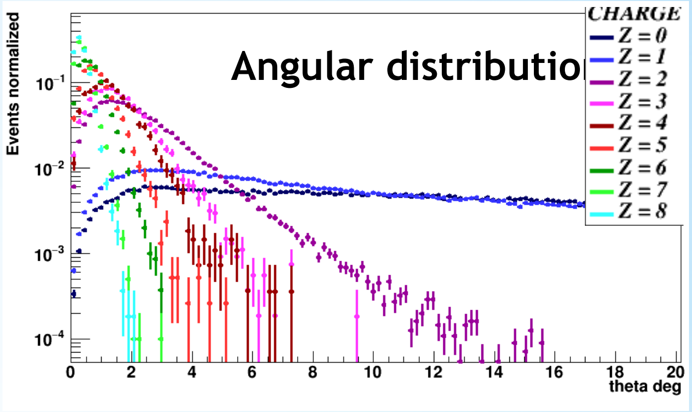




Marrocchesi et al, NIM A 659 (2011) 477–483

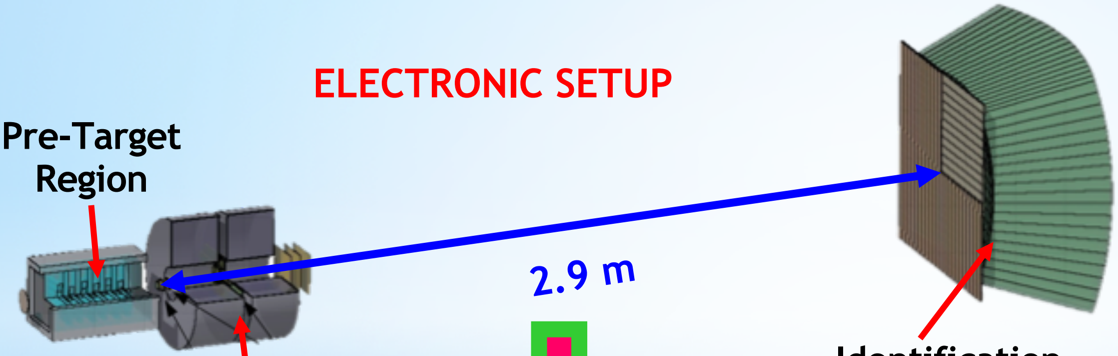
FOOT Setup for higher energy

Fluka Simulation: ^{16}O (700 MeV/u) on C2H4

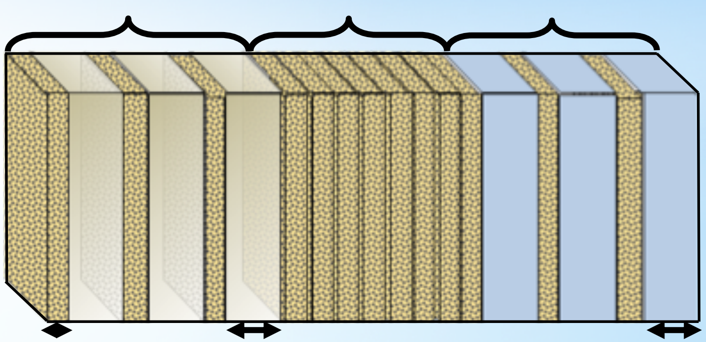


Z>2 fragments inside 4°

ELECTRONIC SETUP



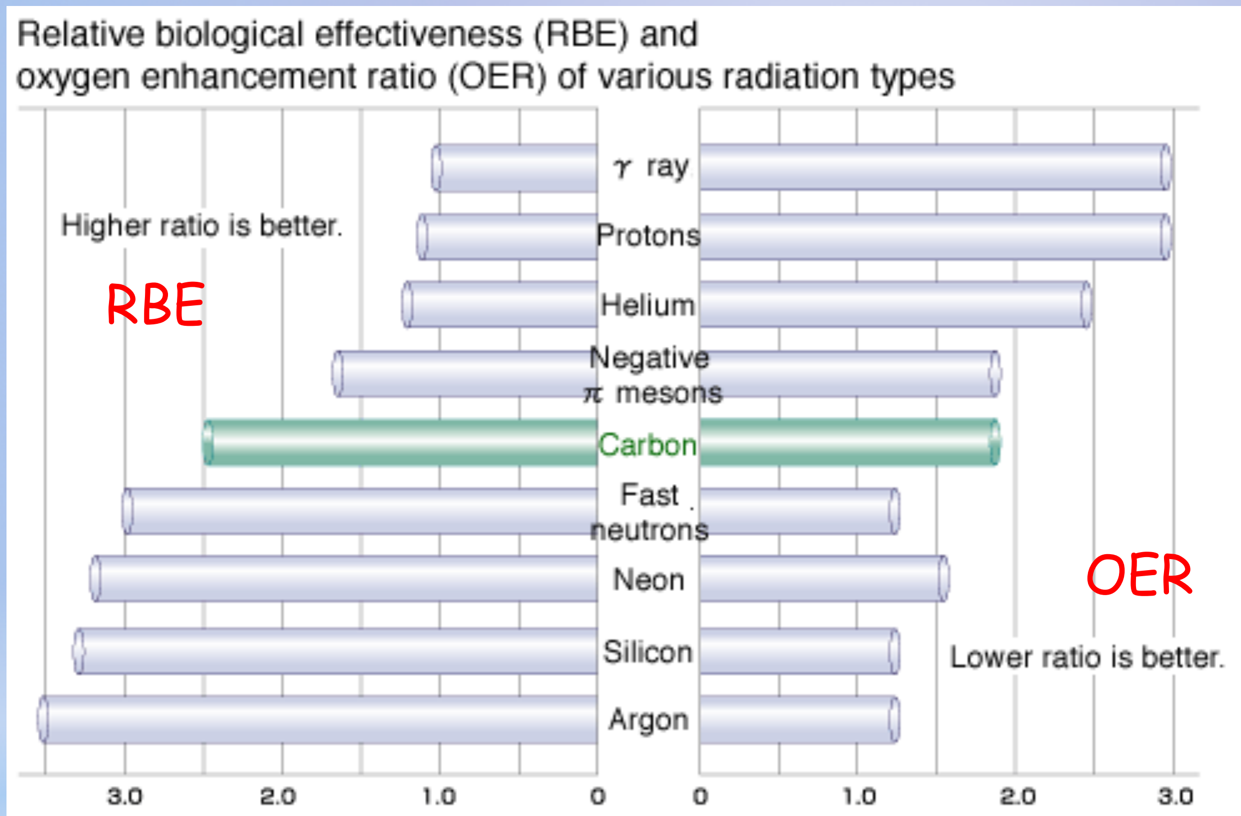
- Same acceptance as @ 200 MeV/u
- high resolution on β
- crucial for Z & A determination

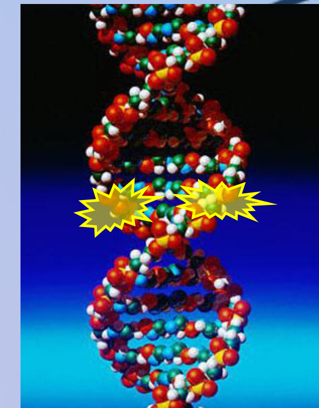


EMULSION CHAMBER

Different geometry and number of layers

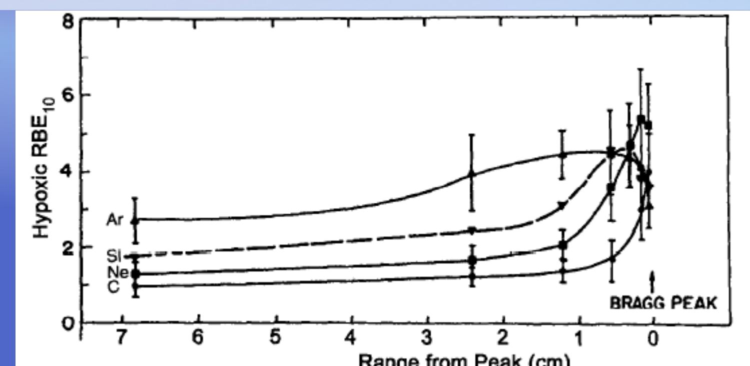
Radiations vs Biological effects





^{12}C -> good compromise between RBE and OER.

Optimal RBE profile vs penetration depth position.



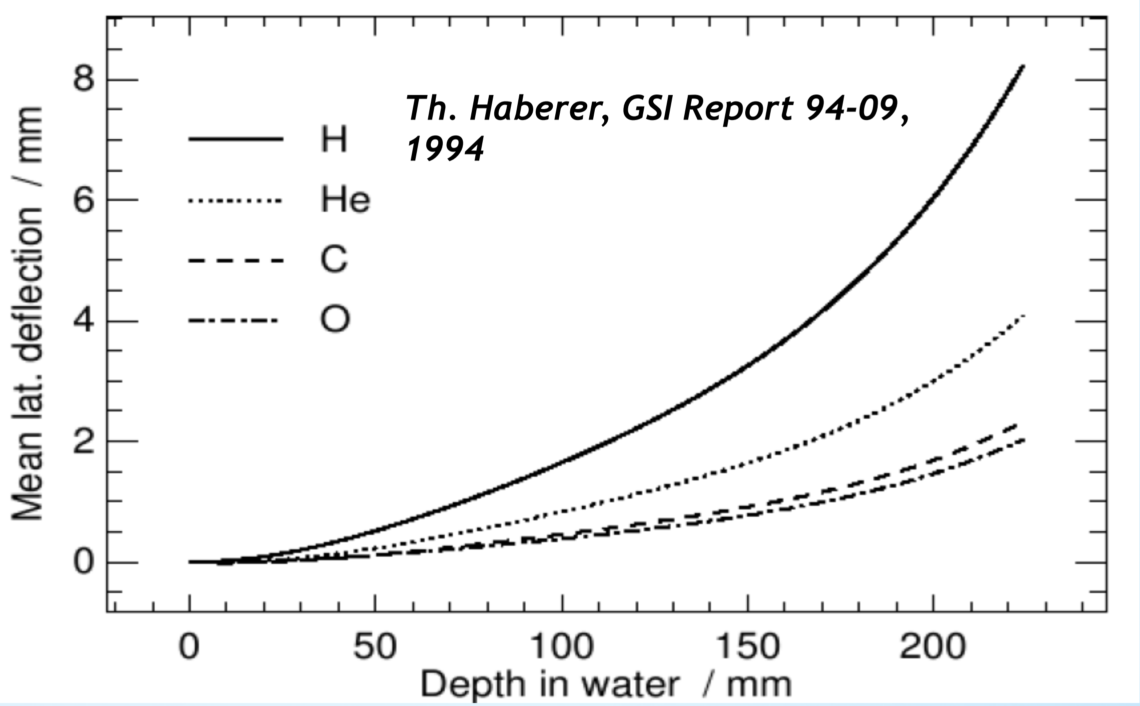
Which is the right beam for therapy?

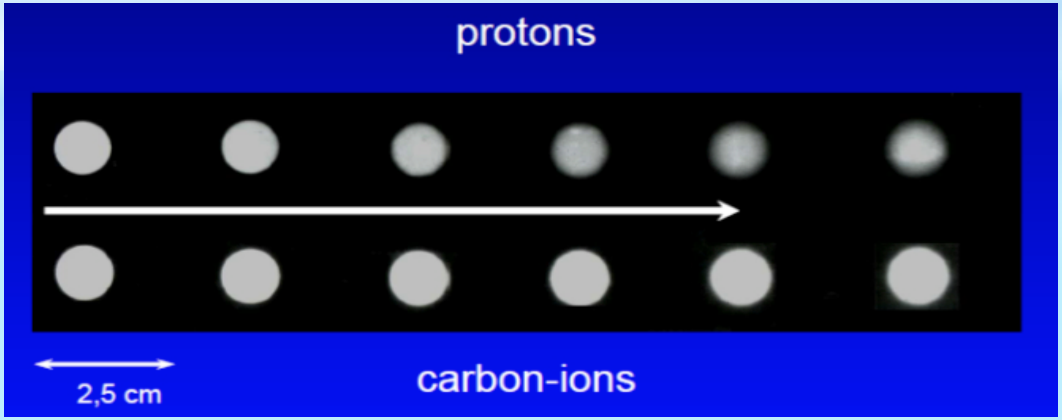
As far as money is the main concern.. protons win easily!

If we come to effectiveness, the landscape can change.

For instance, concerning the beam selectivity, comparing lateral deflection heavier ions have less multiple scattering

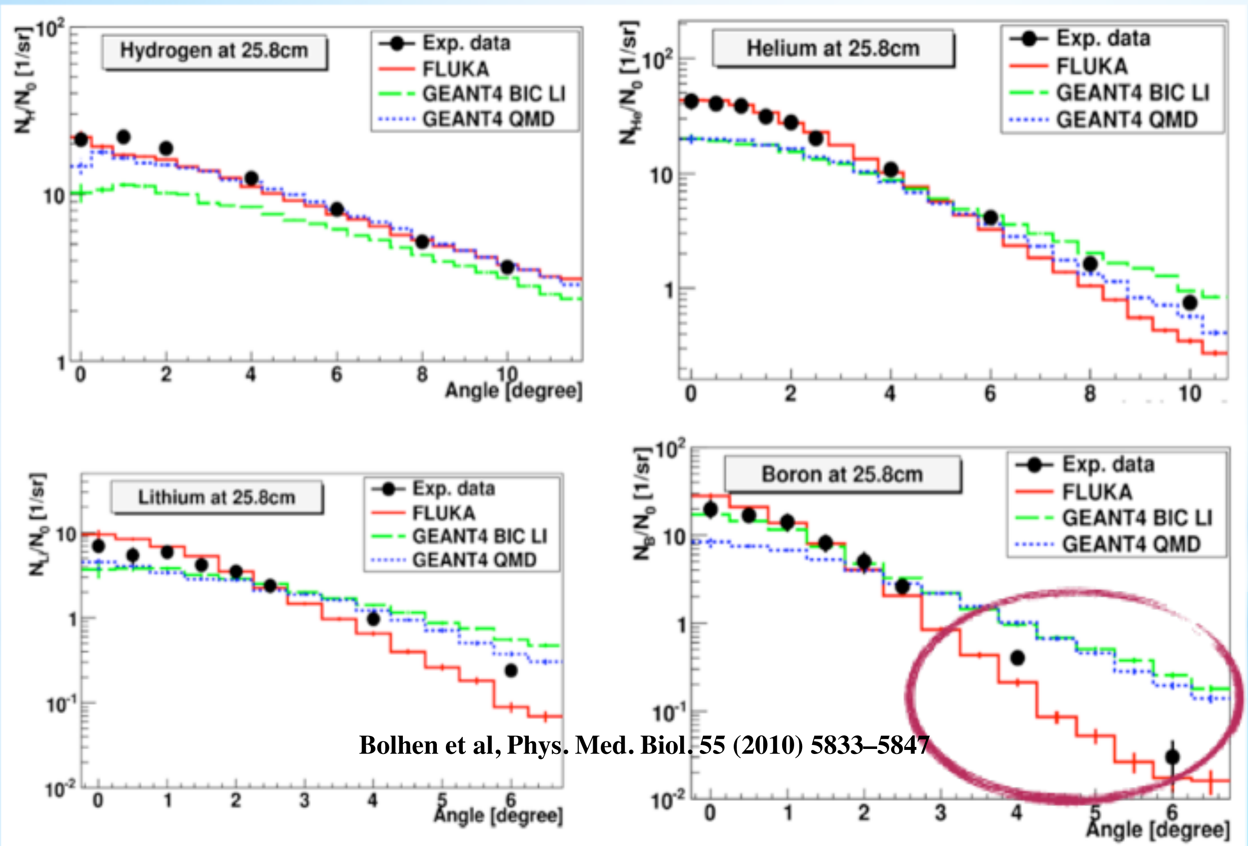
Beam lateral deflection





Data - MC comparison: ^{12}C ions

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

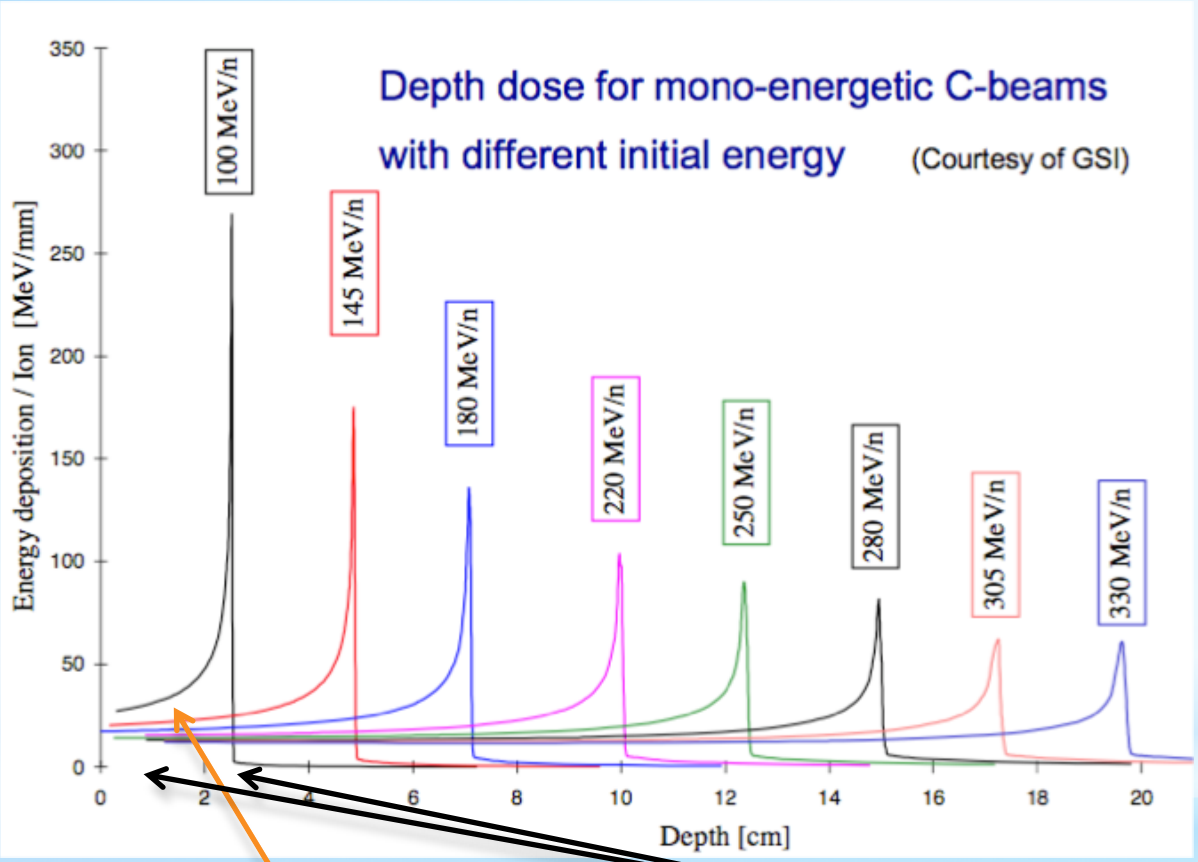


Bolhen et al, Phys. Med. Biol. 55 (2010) 5833–5847

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, JoP
Pshenichnov et al. 2005, 2009
Mairani et al. 2010, PMB
Böhlen et al. 2010, PMB
Hansen et al. 2012, PMB

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



LNS 62AMev C beam (2009)

GANIL 50- 95AMev C beam - E600 collaboration (2011)

The community is exploring the interesting region for therapeutic application, in particular for the ^{12}C beam.

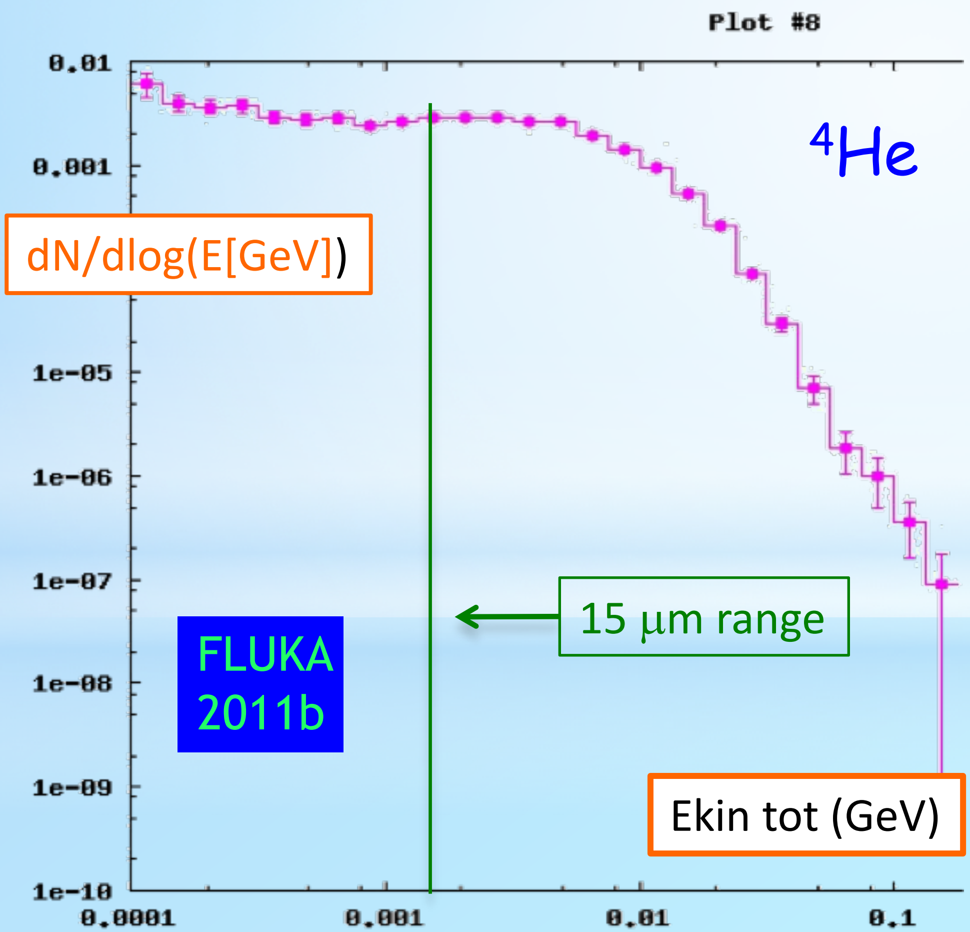
Yet there is a lot of energy range to explore in the range 150-350 AMeV (i.e. 5-22 cm of range…) and need of data also on O, H targets (C,O,H ~ 98% of humen body)

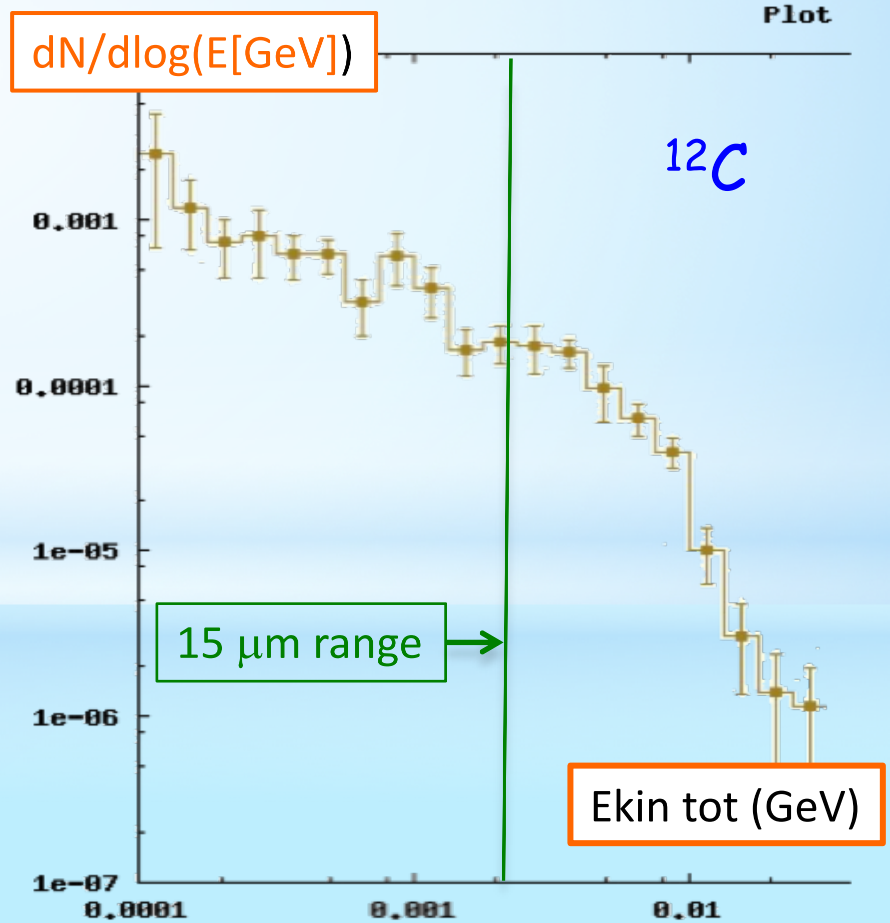
For ^{4}He, ^{16}O beams the need of data is the same

Experiment yet to be made !

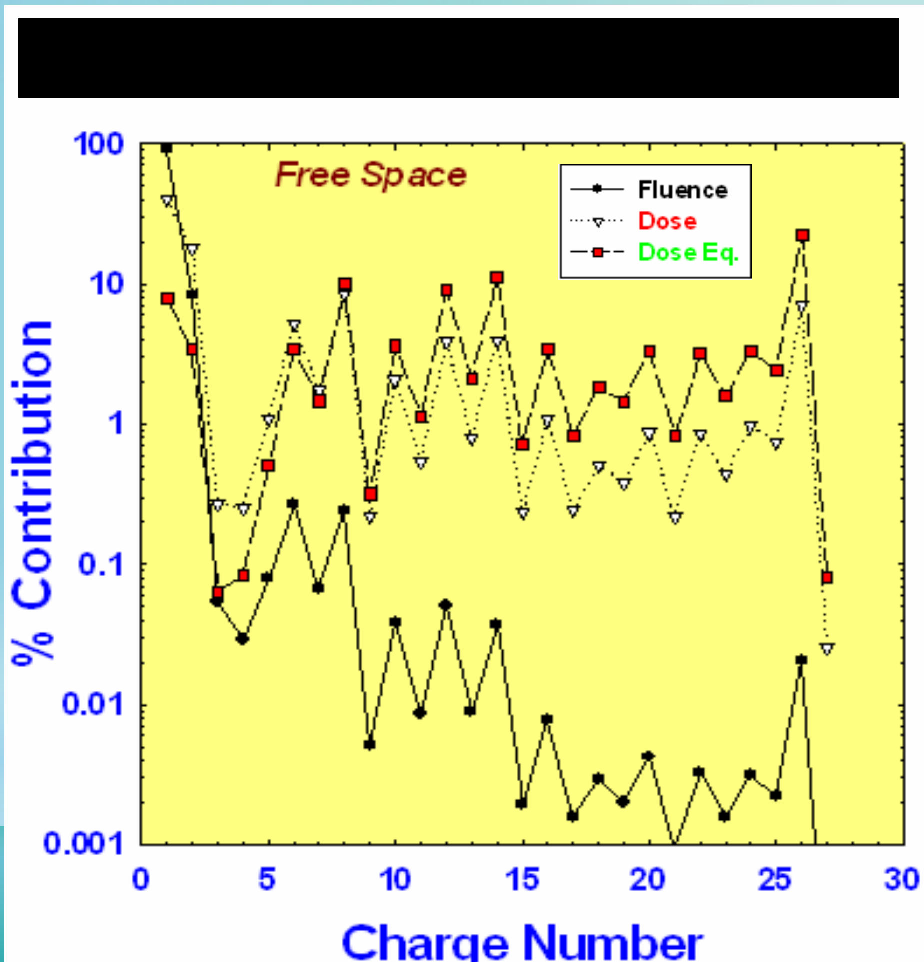
p-> Brain scattering @200 MeV

Also FLUKA MC suggest a low-energy, short range production of heavy frag: 200 MeV p on “BRAIN” : production of He & C





GCR contribution from different particles



Dose (physical) D

D= ΔE/Δm [Gy]=[J]/[kg]

Equivanet Dose = QD [Sv]

The Q constant takes care of the fact that not all particles give the same contribution (remind RBE?)

Dose eq. on **Earth**: 10 μSv/d

Dose eq. on **Mars**: 100-200 μSv/d

Dose eq. on **Moon**: 300-400 μSv/d

Dose eq. Mission to Mars (9 monthes): 1.2 Sv

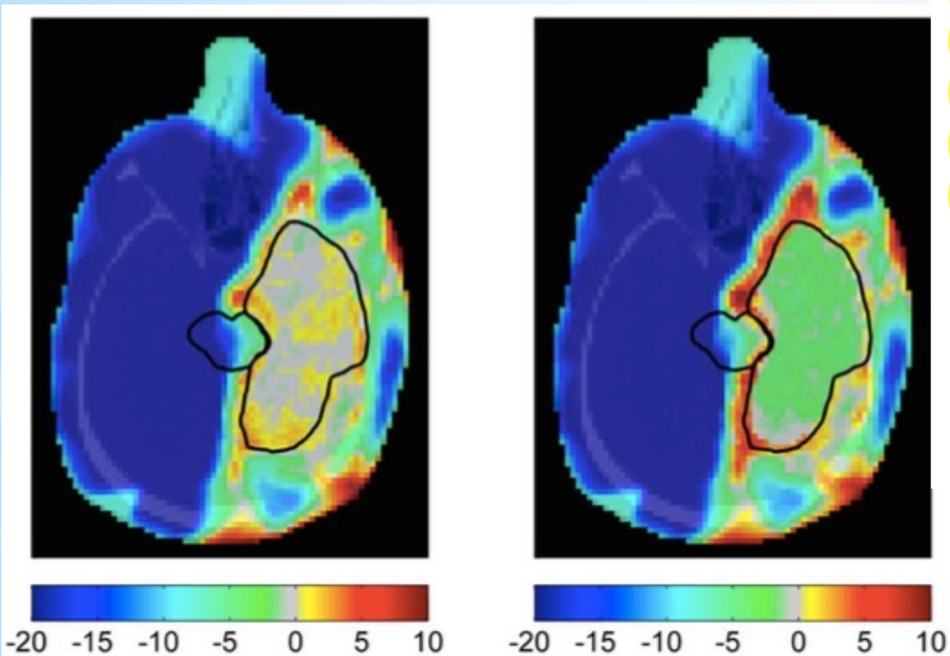
**Francis A. Cucinotta (NASA, Lyndon B. Johnson Space Center), private communication*

Target fragmentation & proton RBE

Currently the contribution of target fragments and of the increasing RBE near the PB is implicit (ICRU reccommendation RBE=1.1)

Lately has been pointed out possible impact of variable proton RBE on clinical NTCP values

RBE=1.1 **Variable RBE**



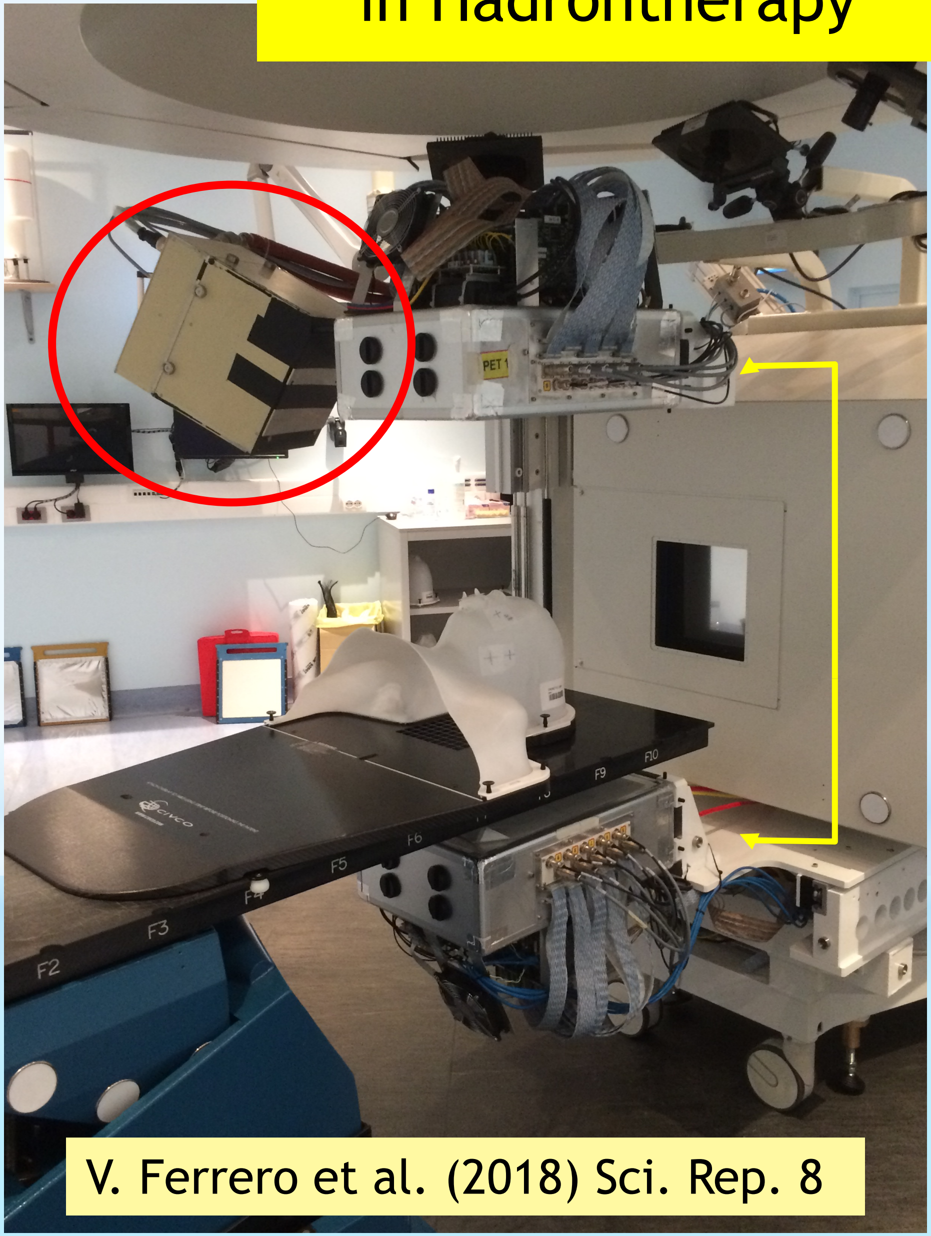
The differences in DVHs and dose distributions are also translated into different NTCP values, shown in Table III. As an example, the probability of necrosis in the brain stem is estimated in case1 to 0.84% for the IMRT plan and 0.57% for the proton plan when assuming a RBE equal to 1.1. However, when assuming a variable RBE the probability increases to 2.13%. Equivalently, the probability for blindness increases from 1.13% (RBE = 1.1) to 4.21% (variable RBE) for protons compared to 1.21% for photons for the optic nerve. The same tendency of estimating a lower NTCP for protons compared to photons when having RBE equal to 1.1, but obtaining a higher NTCP compared to photons when assuming a RBE distribution is also observed for the chiasm and for the other brain cases (see Table III).

Wedenberg 2014 Med Phys

The InSide Project

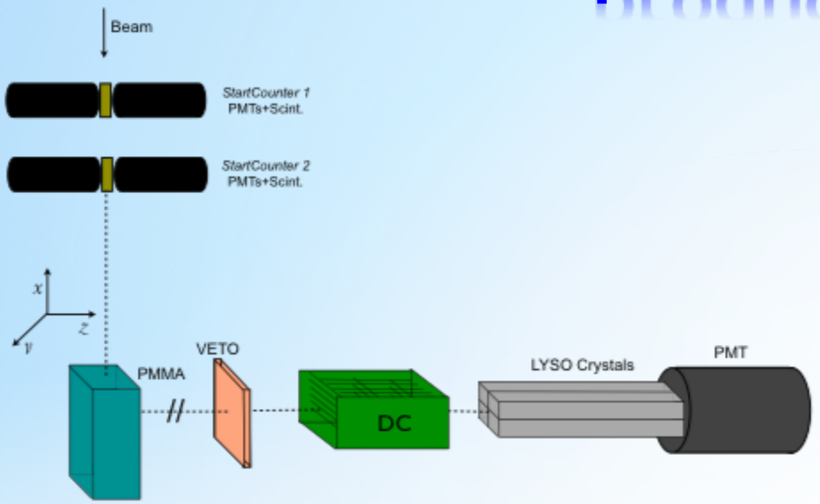
INnovative Solutions for In-beam DosimEtry in Hadrontherapy

- In september 2018 a Dose profiler (fragment tracker) has been installed in Room 1 at CNAO. A clinical test with ~10 patients will start in 2019
- The DP will be operated together two PET heads developed by Pisa and Torino INFN sections
- The first aim of the test is to monitor the physiology change in the patient between the series (~30) of irradiation sessions
- Crucial the knowledge of the fragment production features

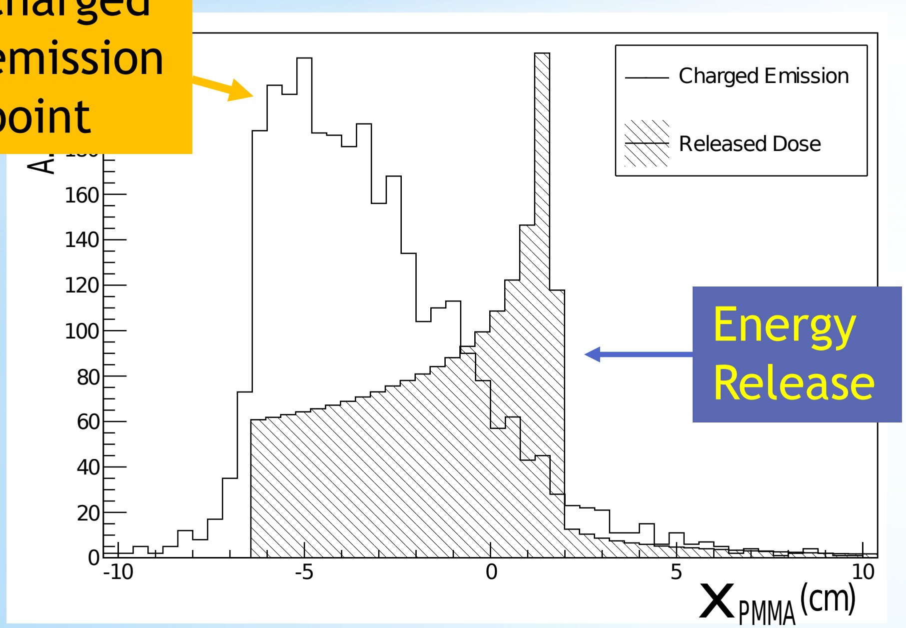


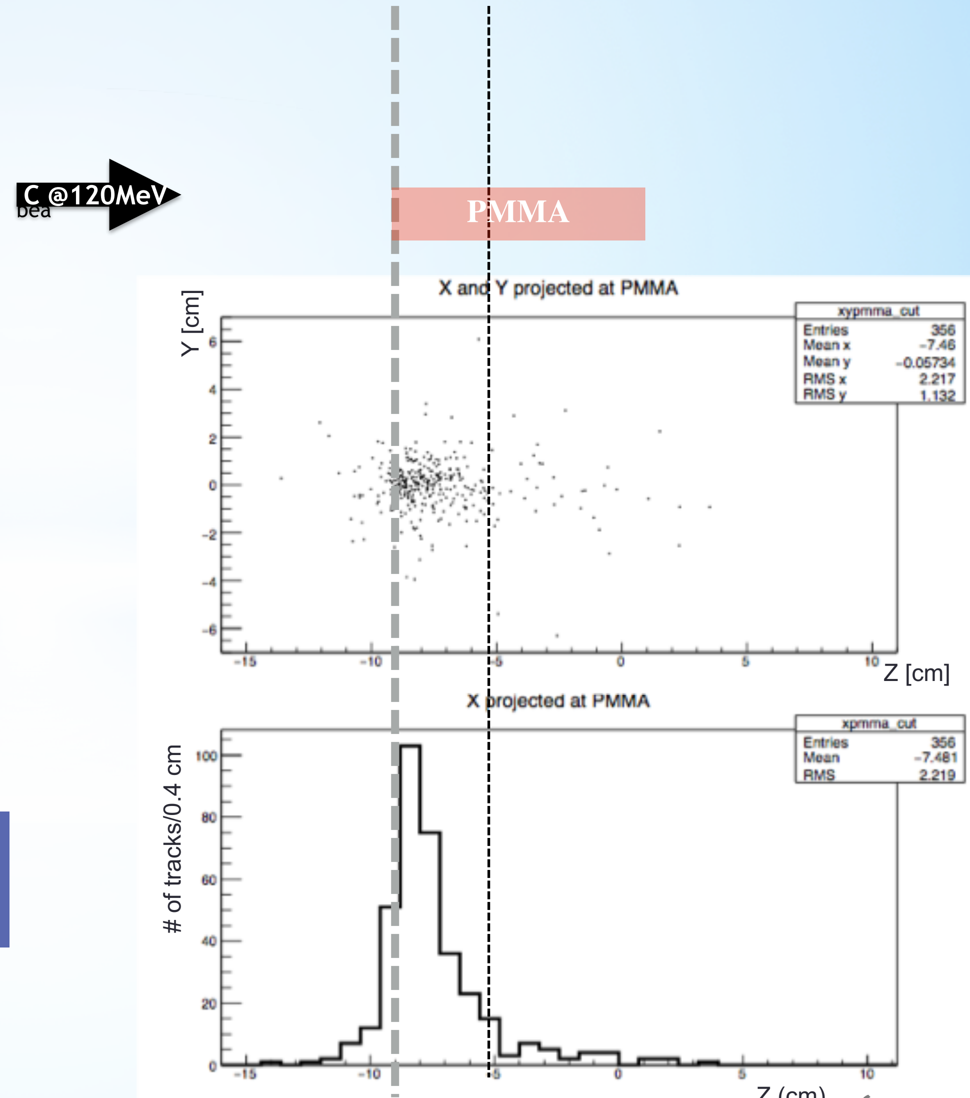
V. Ferrero et al. (2018) Sci. Rep. 8

Large angle charged fragments production: C beam



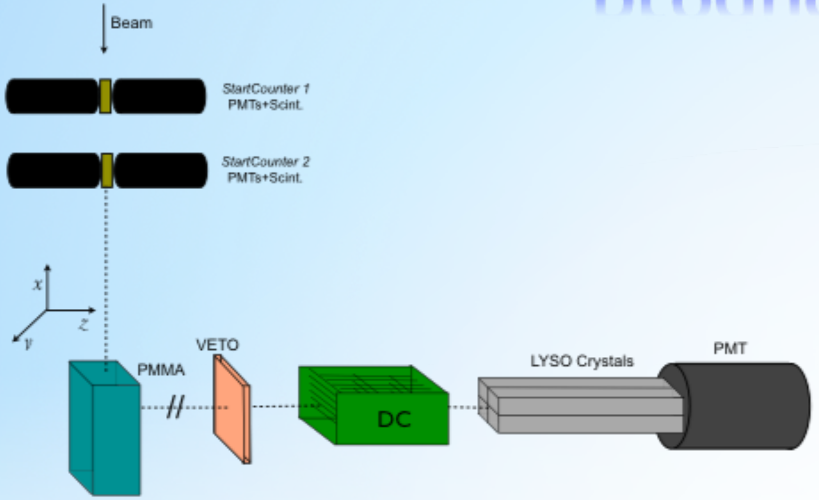
charged emission point

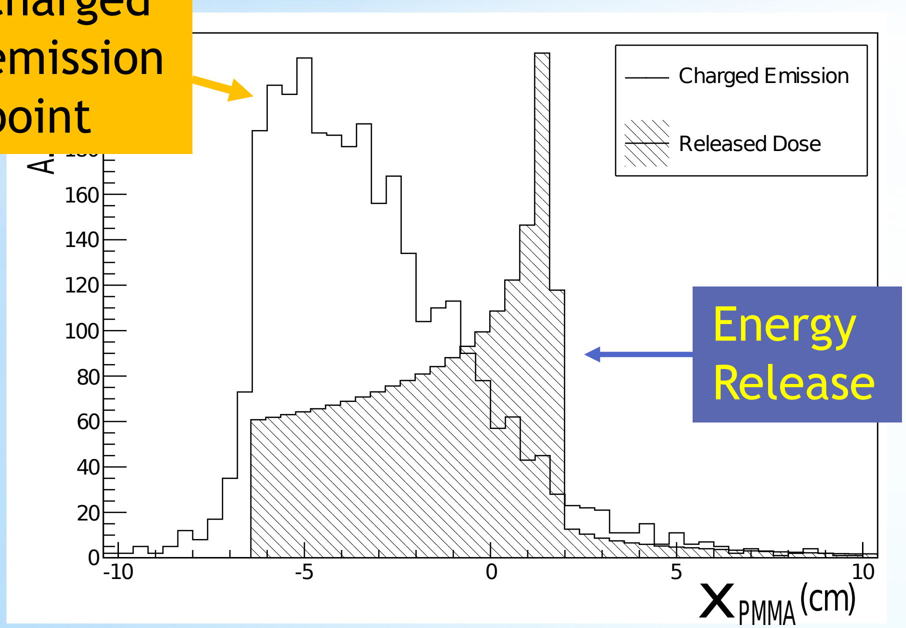


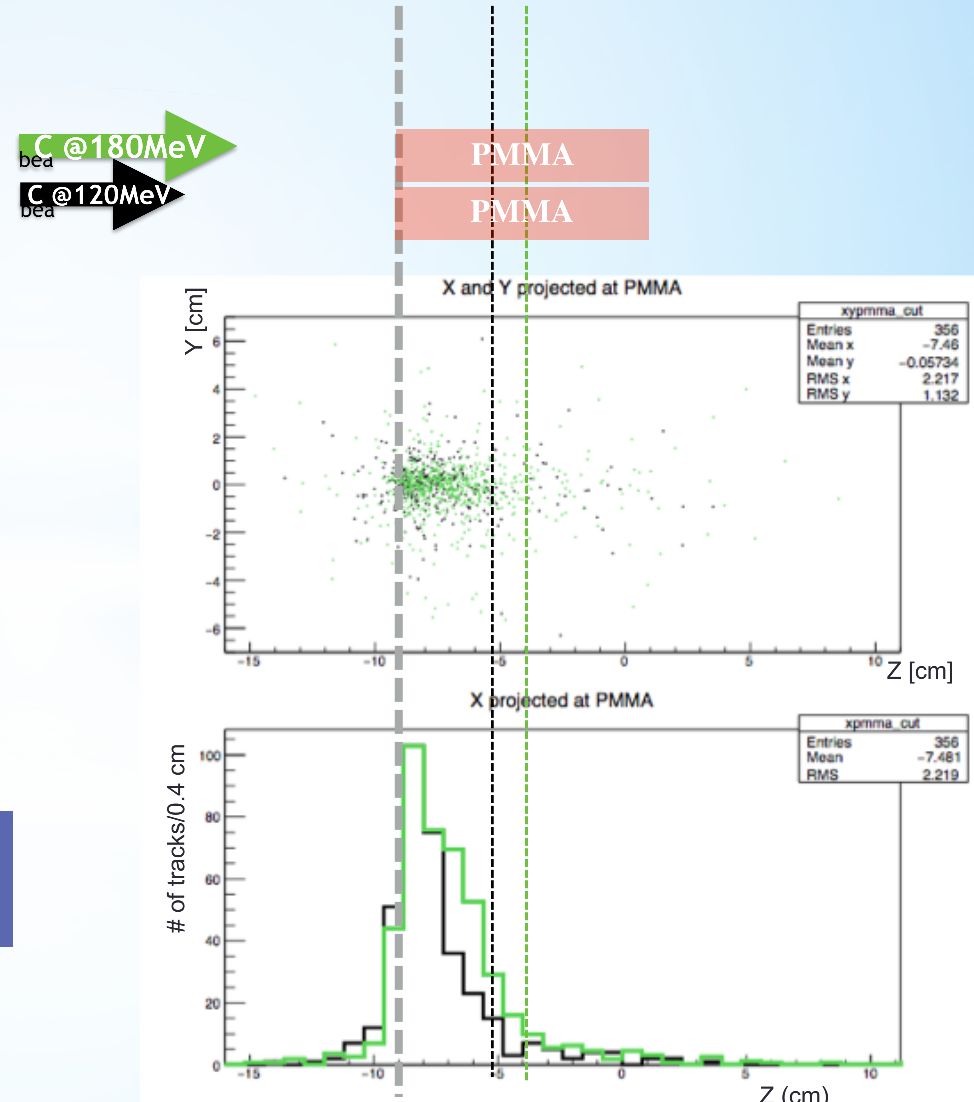


A Rucinski *et al* 2018 *Phys. Med. Biol.* **63** 055018

Large angle charged fragments production: C beam







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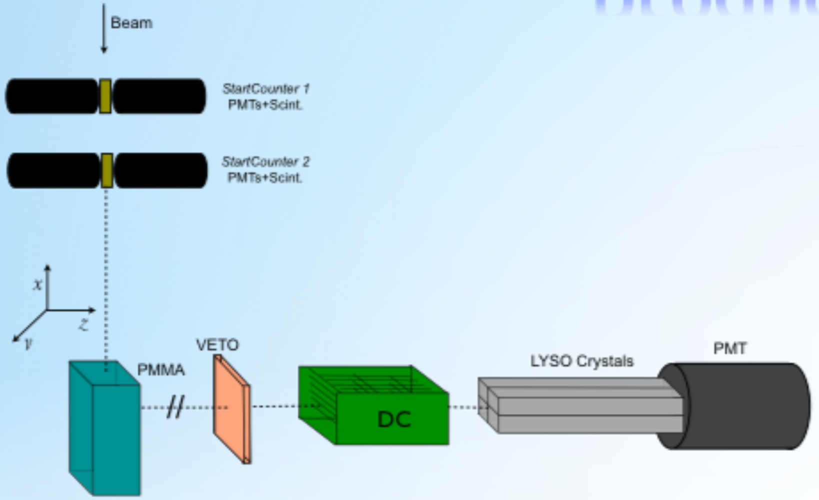

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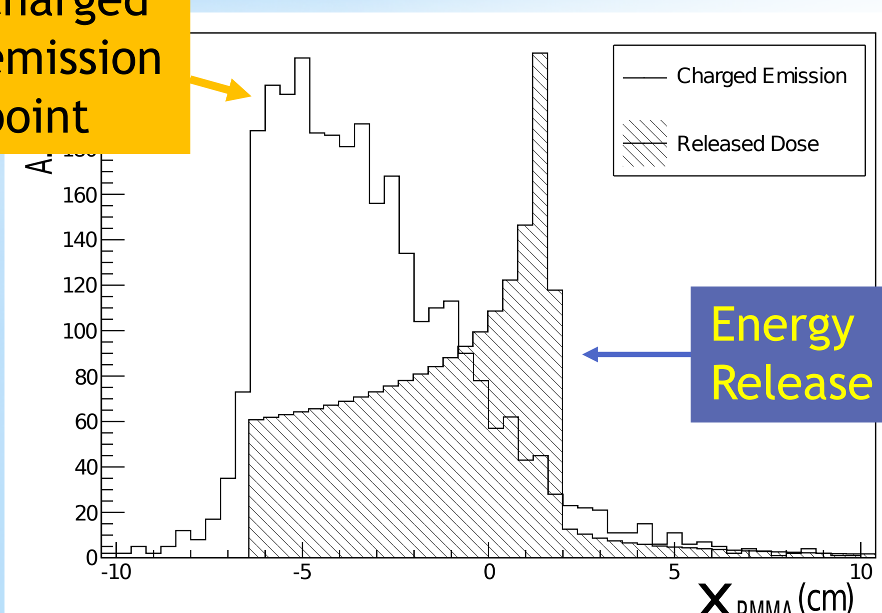
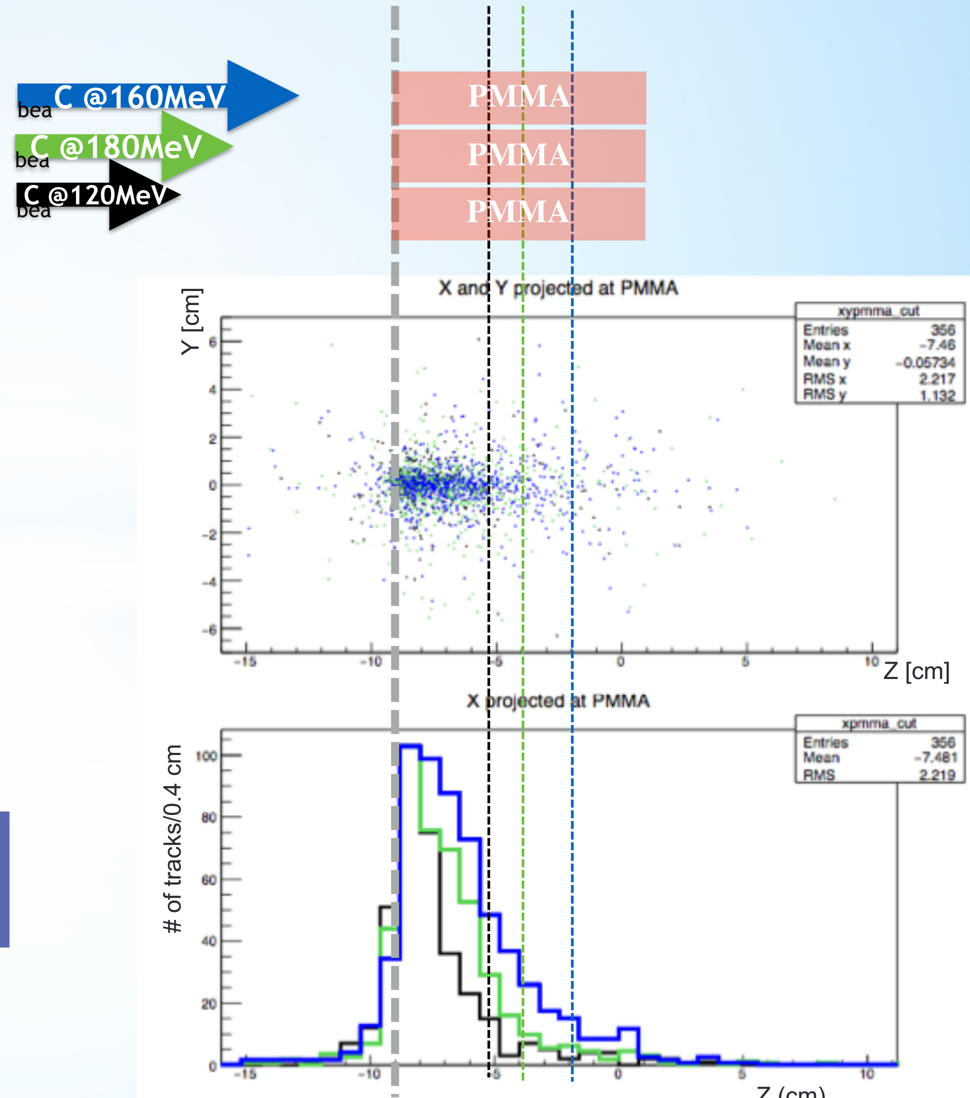


Energy Release



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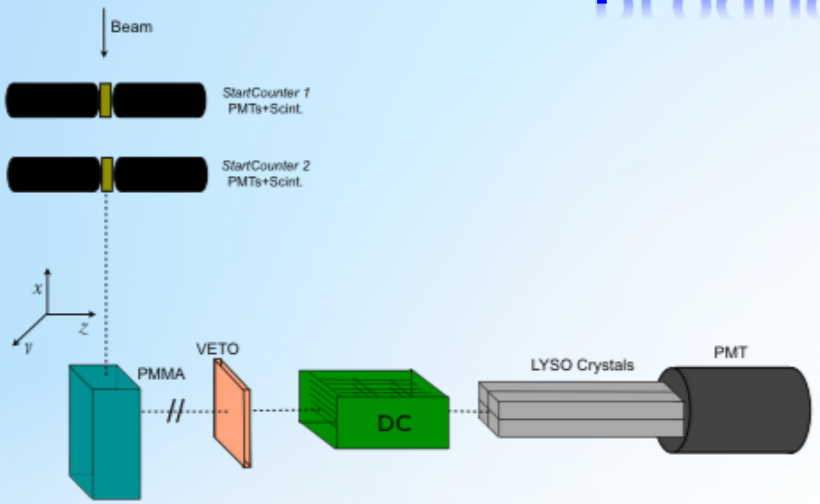
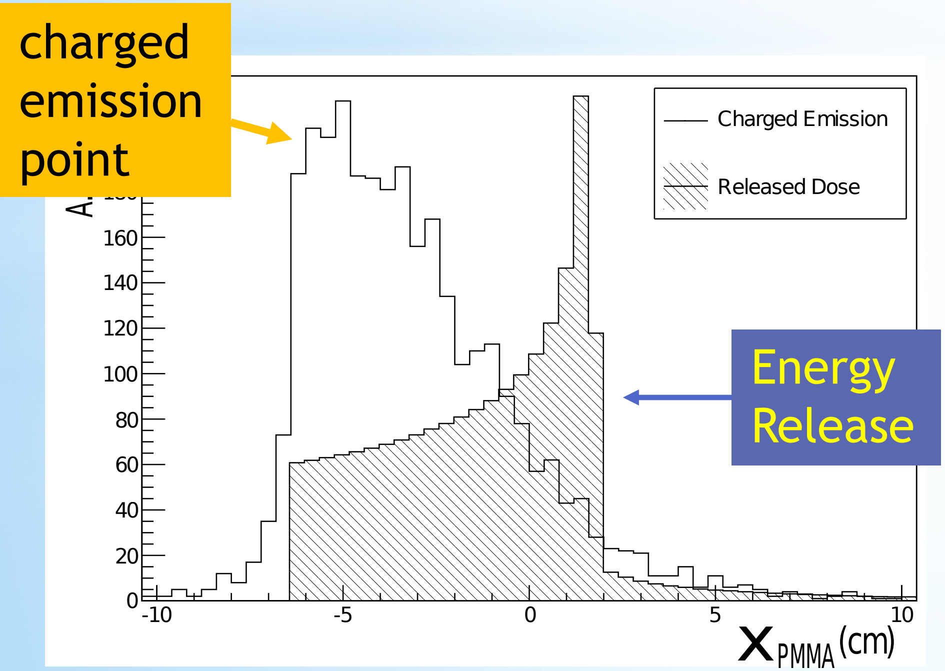
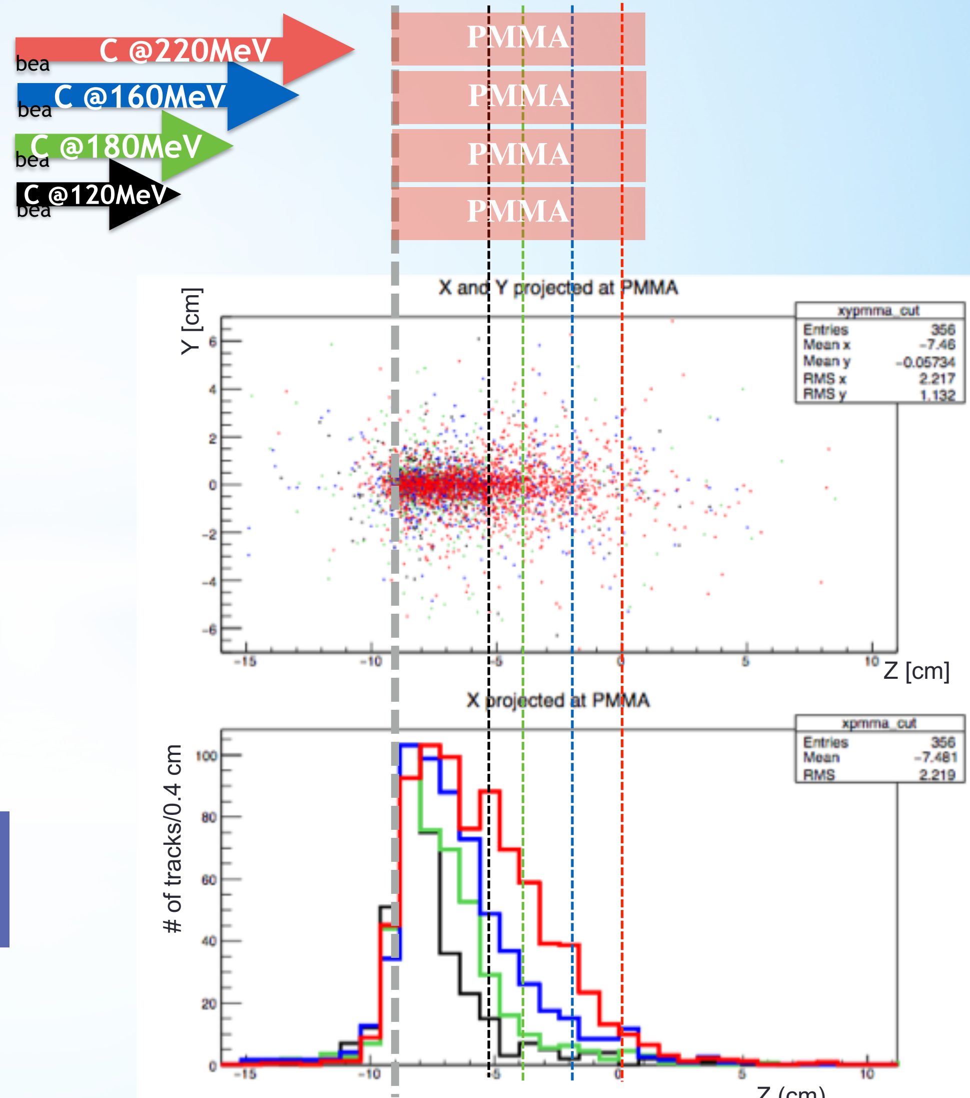
Large angle charged fragments production: C beam







A Rucinski *et al* 2018 *Phys. Med. Biol.* **63** 055018

FOOT & FOOTNOTE

FOOT spin off : 2017 PRIN application:

FOOTNOTE (Forward NeutrOn producTion Experiment)

- Relevant issues for future long duration space missions: need for shielding from Galactic Cosmic Ray induced dose. A significant role is played by neutron production in nuclear fragmentation interactions on the shielding material
- The FOOTNOTE project aims to measure neutron production in the range of interest for radioprotection in space.
- Double setup: an electronic apparatus for the measurements in the forward kinematic region and a setup, dedicated to large angle emission, based on the “Emulsion Cloud Chambers” technique

FOOTNOTE

- 6 Units: Università di ROMA "La Sapienza", Università di PISA , Università di BOLOGNA, Università di TRENTO, Università di Napoli Federico II, Istituto Nazionele di Fisica Nucleare
- Budget requested : **1.199.938,67**

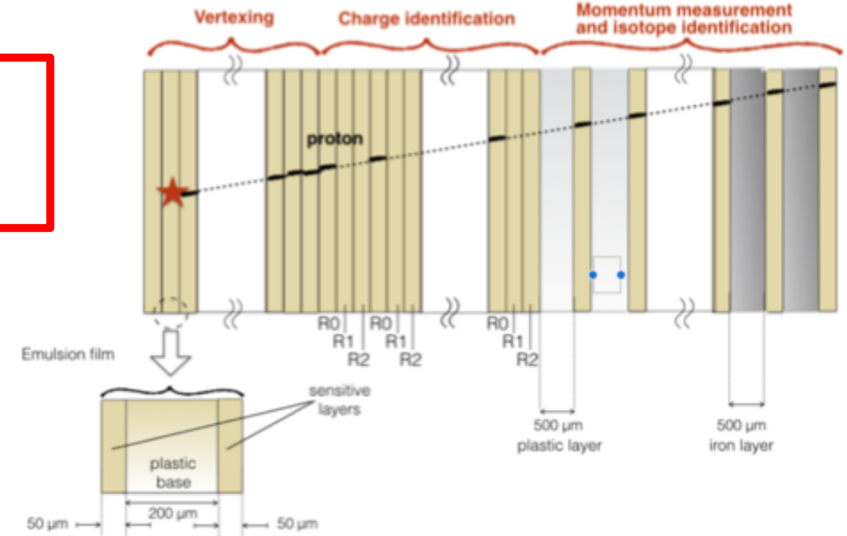
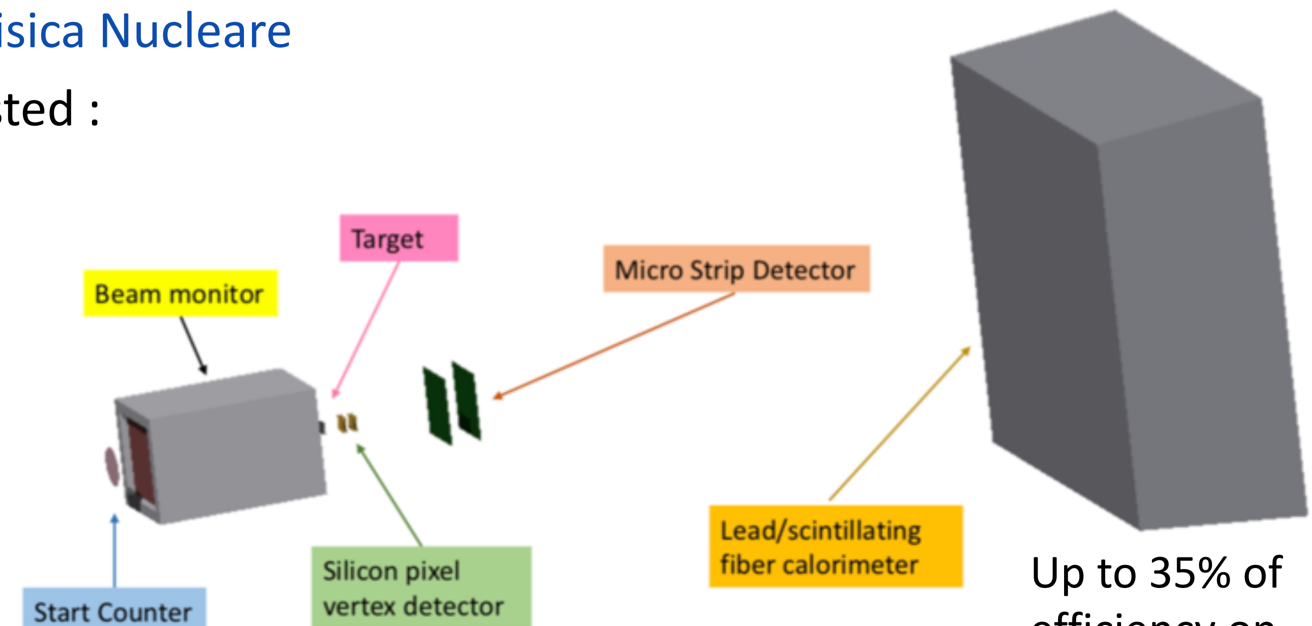


Fig9: Schematic view of the ECC detector



Up to 35% of efficiency on neutrons

Fig.7 : Schematic view of the FOOTNOTE electronic setup

Nuclear Interactions and MC

The nuclear model embedded in MC try to reproduce the phenomenology of the nuclear interaction is generally very complex. Here we report the FLUKA scheme of the nuclear interaction

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 de-excitation

t (s)

10^{-23}

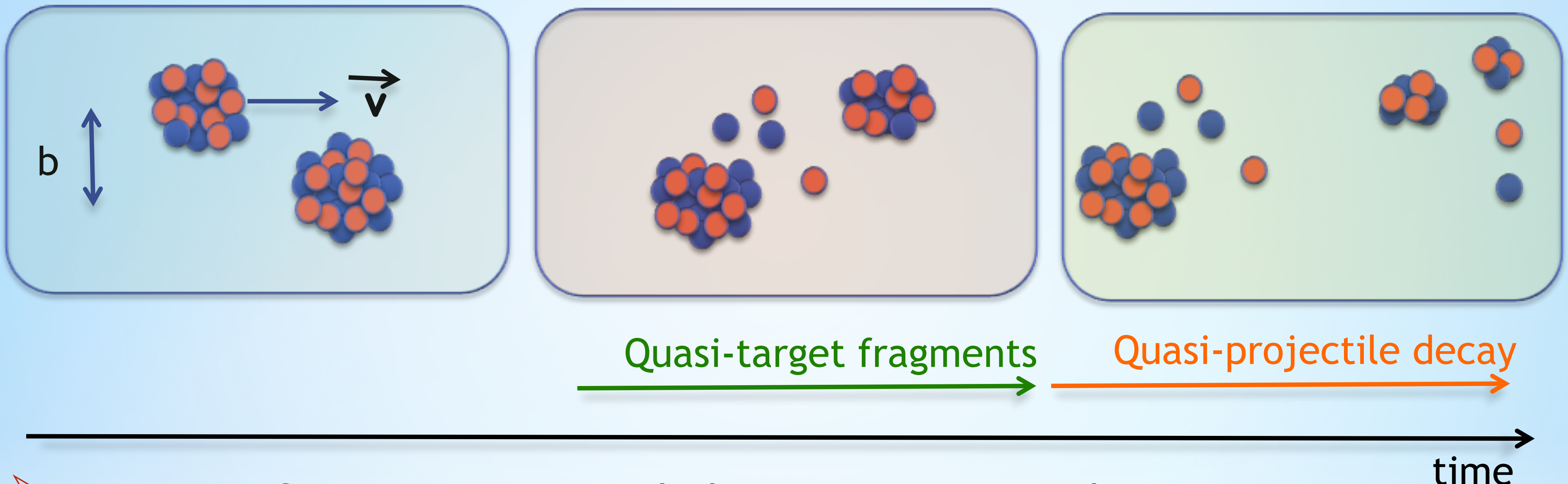
10^{-22}

10^{-20}

10^{-16}

Courtesy of A. Ferrari

The abrasion-ablation view



- Fragments from quasi-projectile have V_{frag}~V_{beam} and narrow emission angle. Longer range then beam
- The target fragments have wider angular distribution and much lower energy.
- Proton and neutron fragments have both angular and energy wide distribution
- The dose beyond the distal part comes from the quasi projectile contribution. Wide angular halo from the rest of the process