Novel developments in imaging and dosimetry for Hadrontherapy

Vincenzo Patera
Universita' di Roma "La Sapienza" & INFN

54th Int. Winter Meeting on Nuclear Physics
Bormio, 28 Jan 2016

Outline

- Introduction to Particle Therapy
- The beam range monitor problem
- R&D in range monitoring
- Summary and conclusion

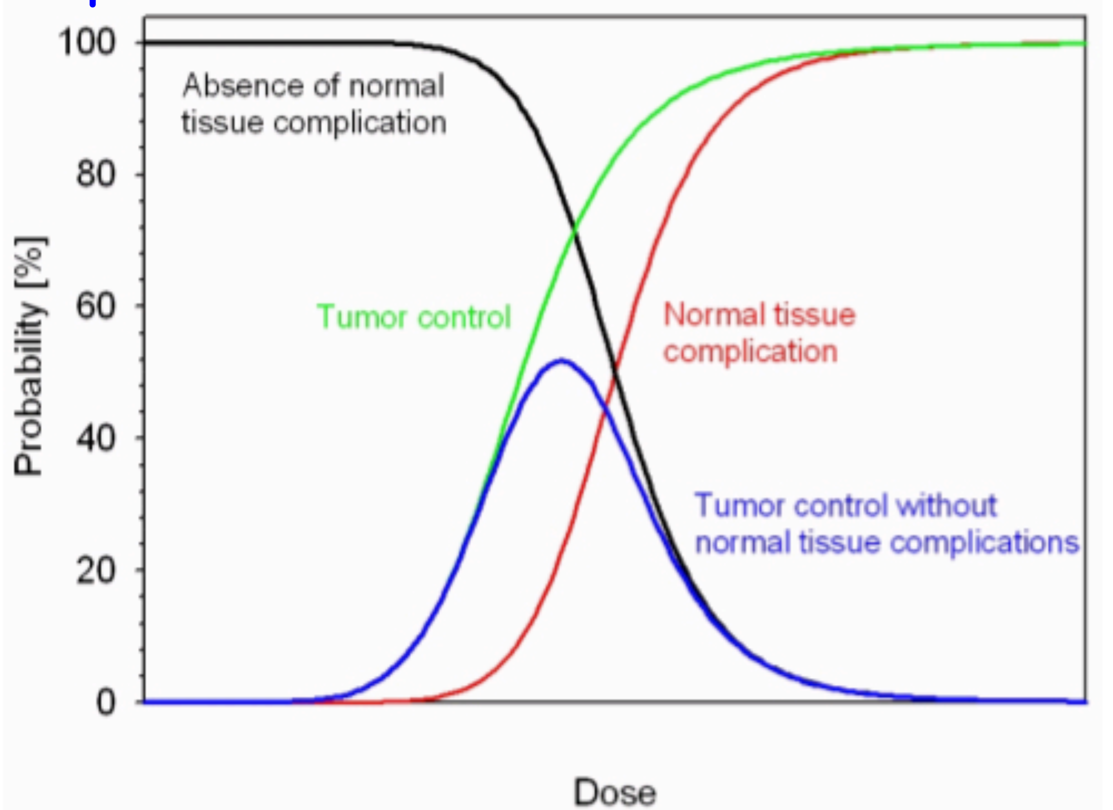
Tumor Control vs Tissue Complication

- Part of multi-disciplinary approach to cancer care
- Useful for 50-60% of all cancer patients (also together with surgery, chemotherapy)
- 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



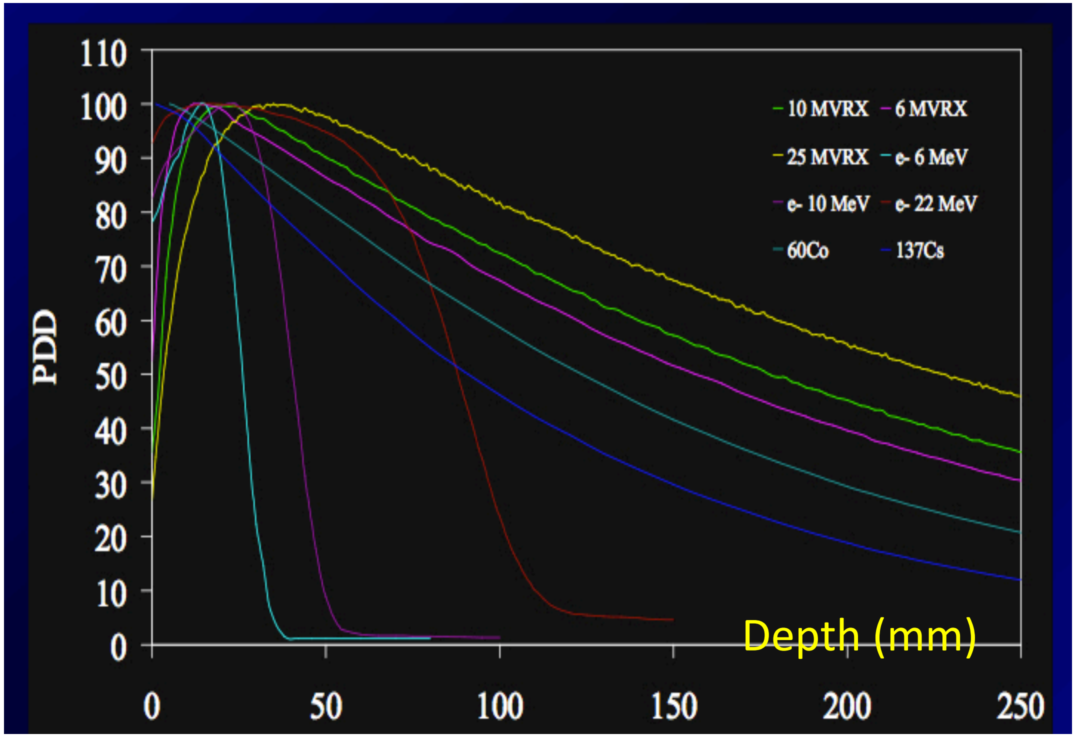
The conventional RT

The photon (and e^-) beams are the most common in RT. Cheap, small, and reliable.

The energy release is not suitable to release dose in a deep tumor.

But the use of sophisticated imaging (CT), superposition of several beams, computer optimization, multi-leaves collimators and >40 year of R&D make IMRT effective and widespread

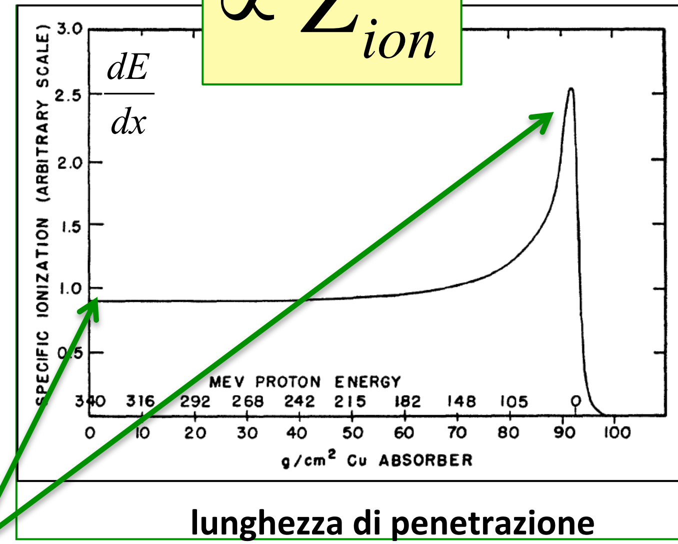
Dose-depth relation for γ and e^-

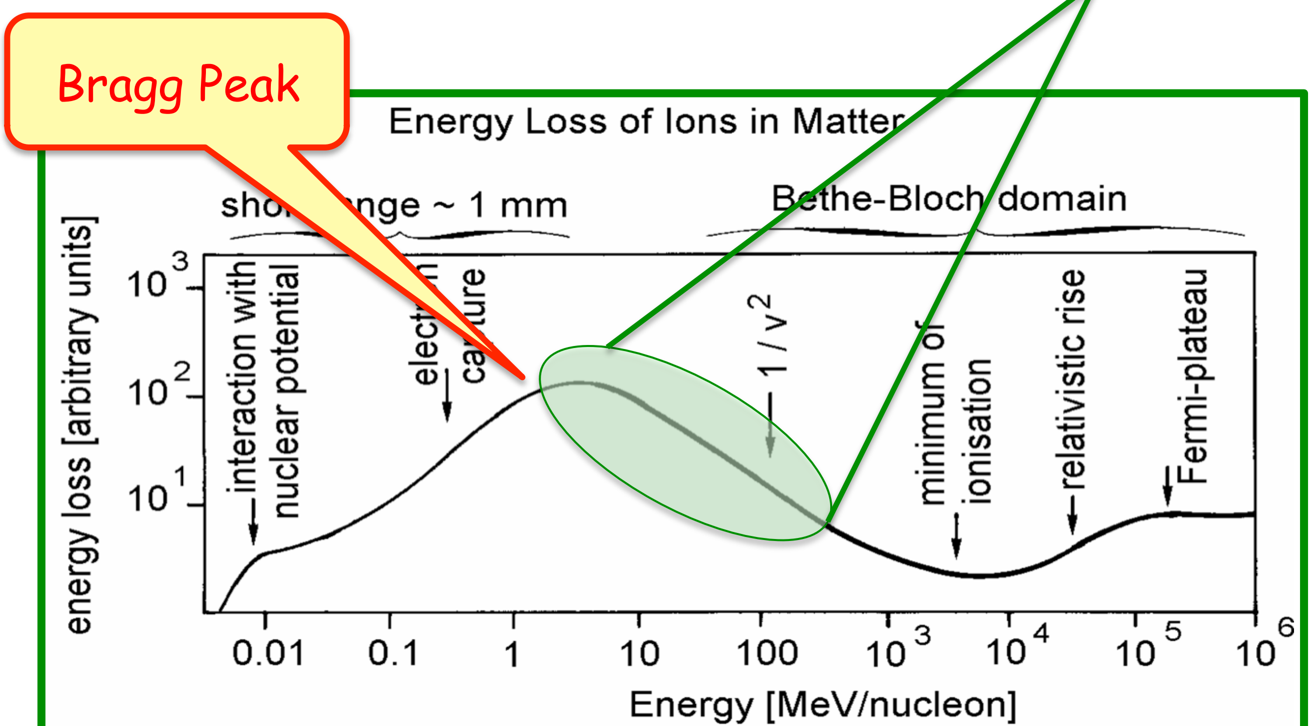


But physics can help…

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

$$\propto Z_{ion}^2$$



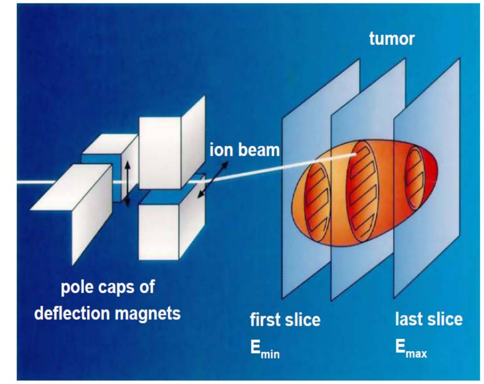


Perfect to release energy (dose) in a tumor buried inside the patient, like a depht bomb..

Mostly proton, few ^{12}C beams.

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

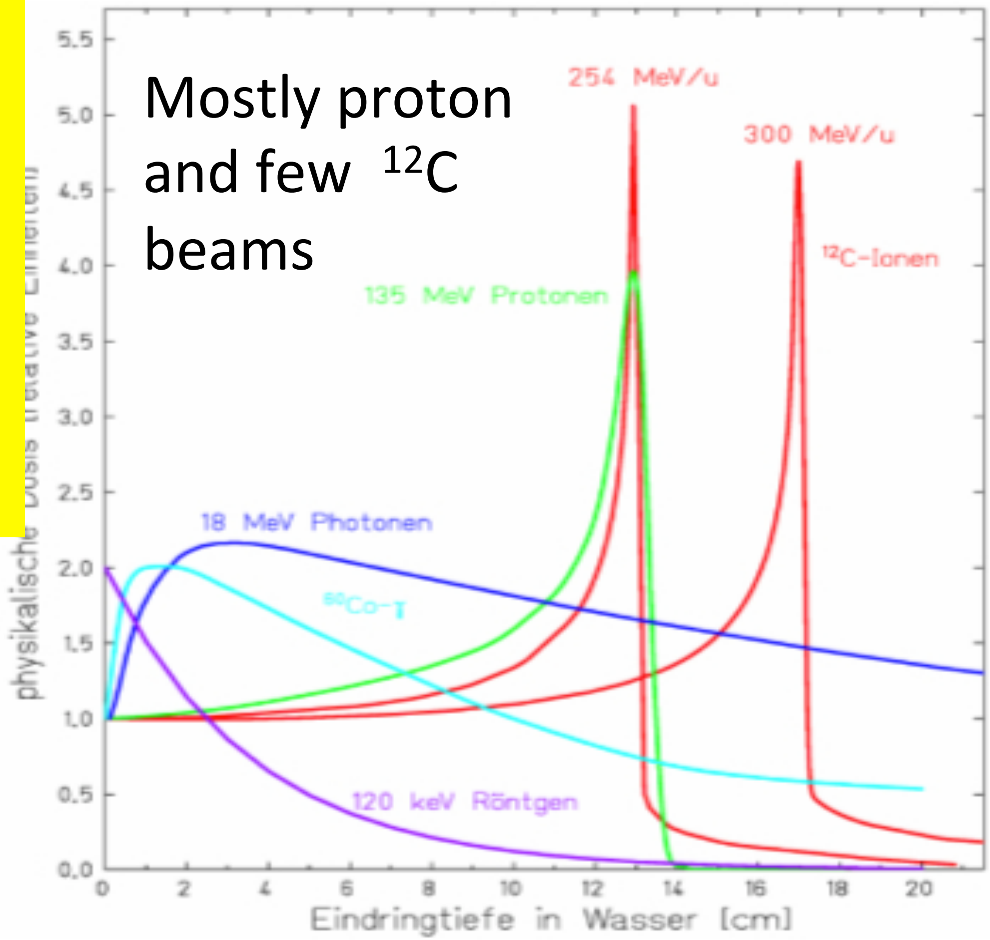
Particle therapy vs Photon RT

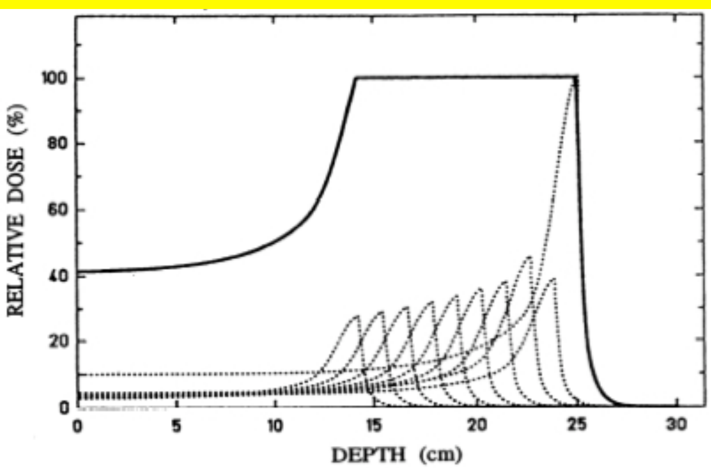


Photon beams are RT baseline. Hard competitors: small, reliable and not so expensive ->40 years R&D

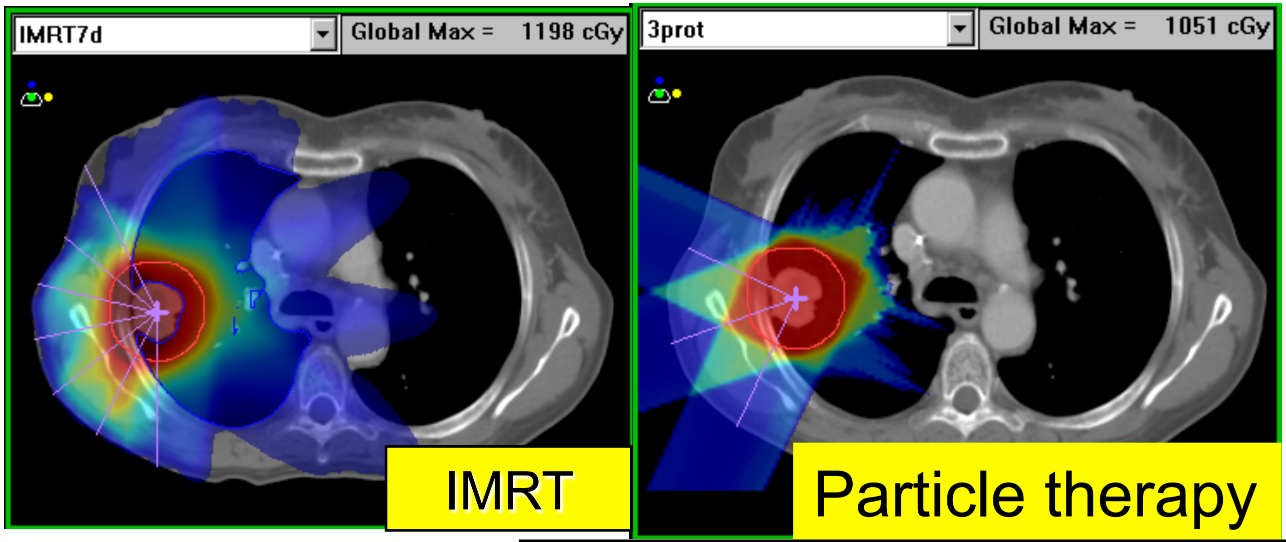
- Beam penetration in tissue function of the beam energy
- Peak of dose released at the end of the track, sparing the normal tissue
- Accurate conformal dose to tumor with Spread Out Bragg Peak

Mostly proton and few ^{12}C beams



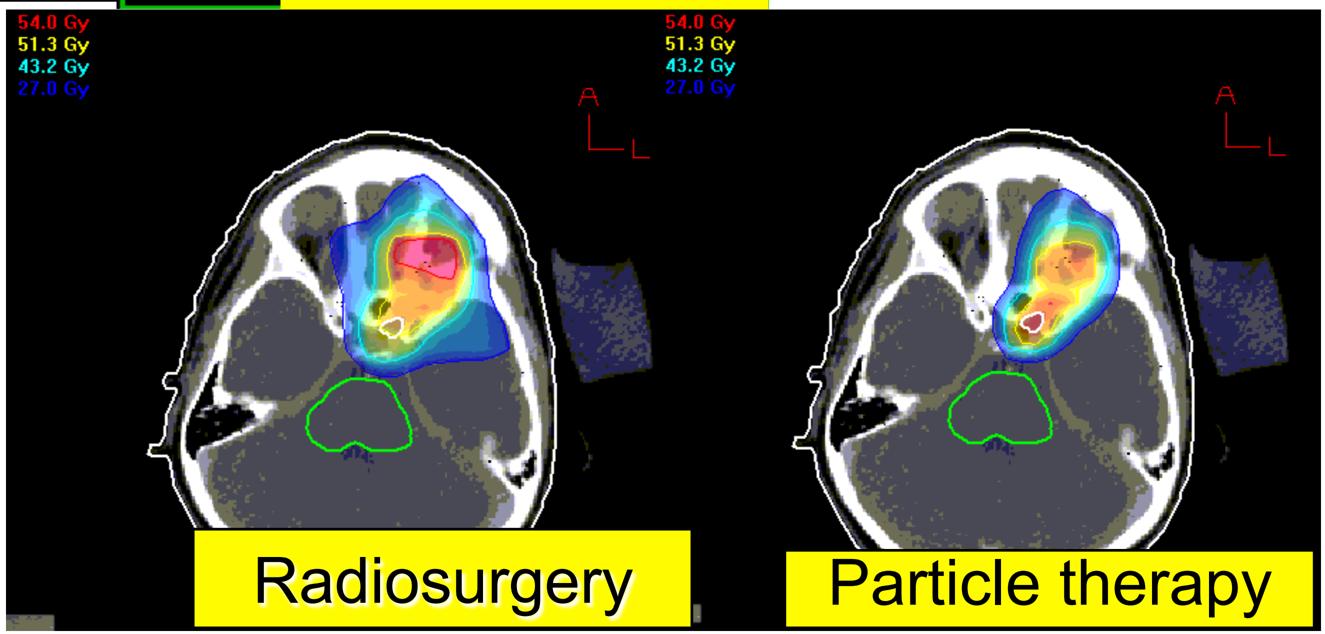


Examples of Photons vs Particle saga…

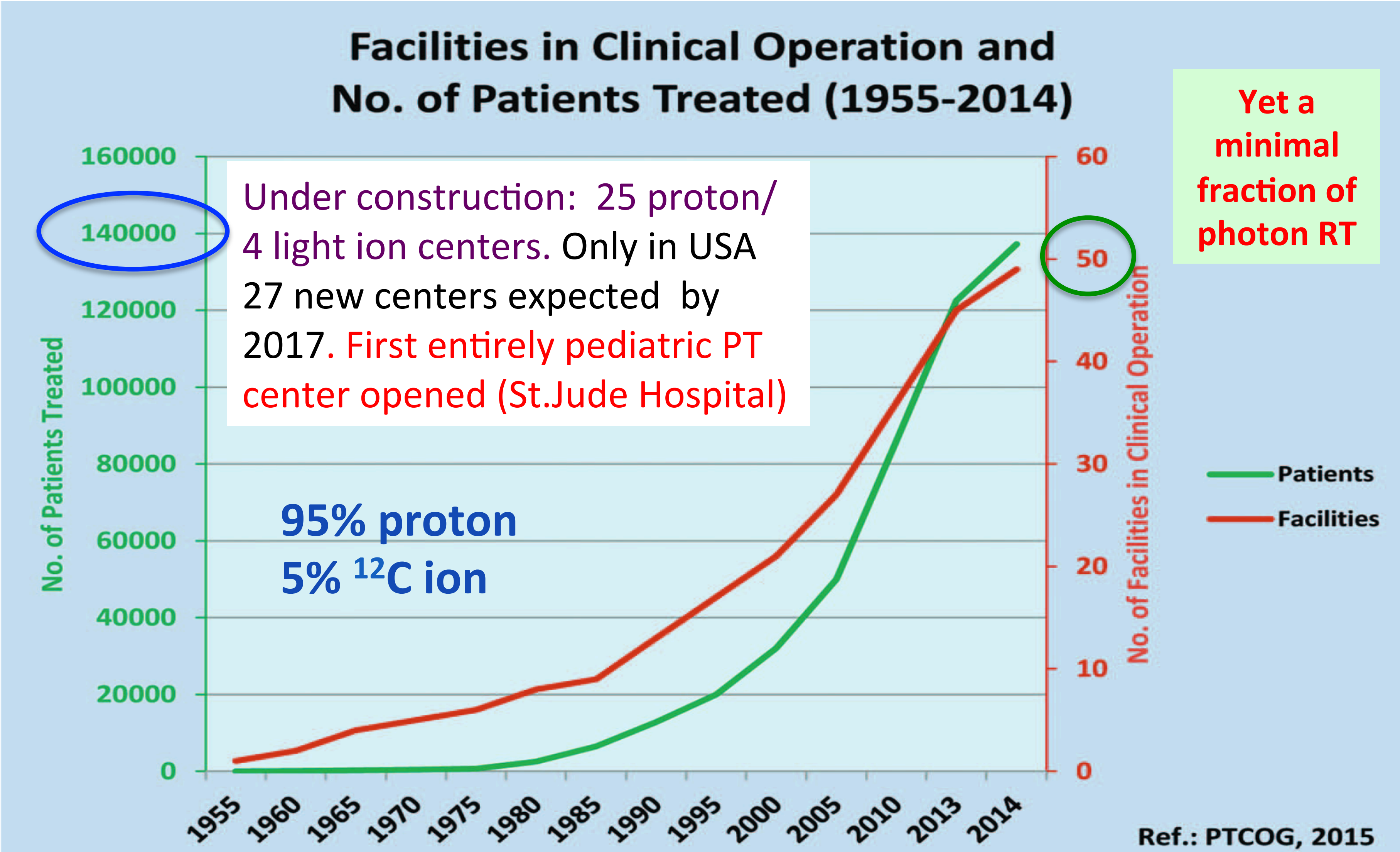


Particle therapy can easily show better selectivity with respect to photon techniques…

Yet, randomized clinical trials seem the only commonly accepted method to assess eventual superiority of PT technique..



Charged Particle Therapy in the world



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

The range verification problem

AAPM, August 2012

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

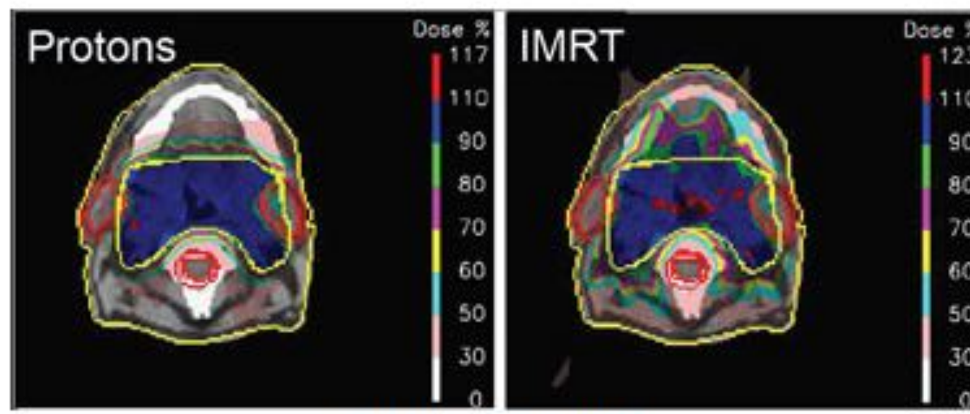
- 35 % unproven clinical advantage of lower integral dose
- 33 % range uncertainties
- 19 % never become a mainstream treatment option

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?



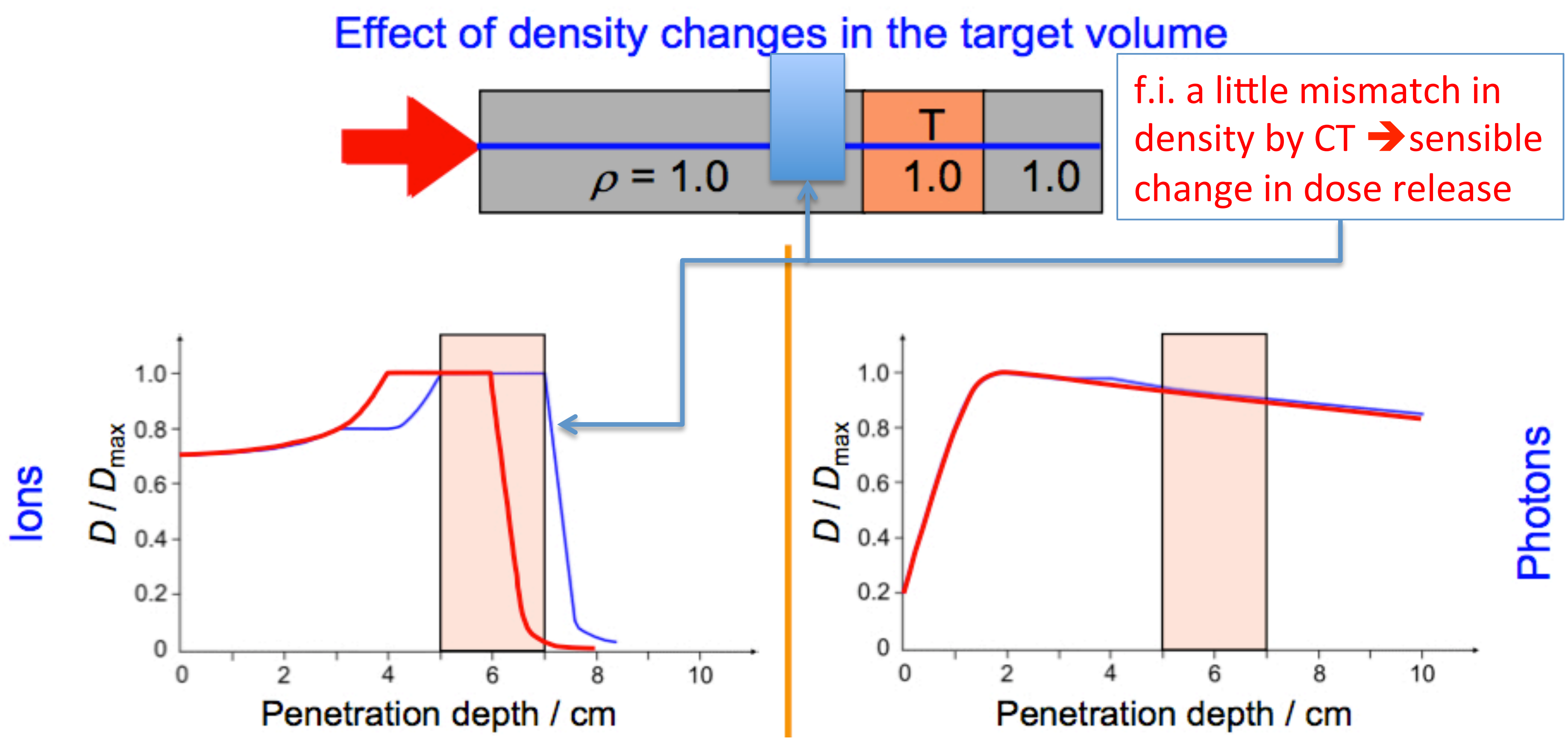
Protons versus IMRT

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

Dose profiling in Particle Therapy

Why is so crucial to monitor the dose in particle therapy with respect to photon RT? It is like firing with machine-gun or using a precision rifle..

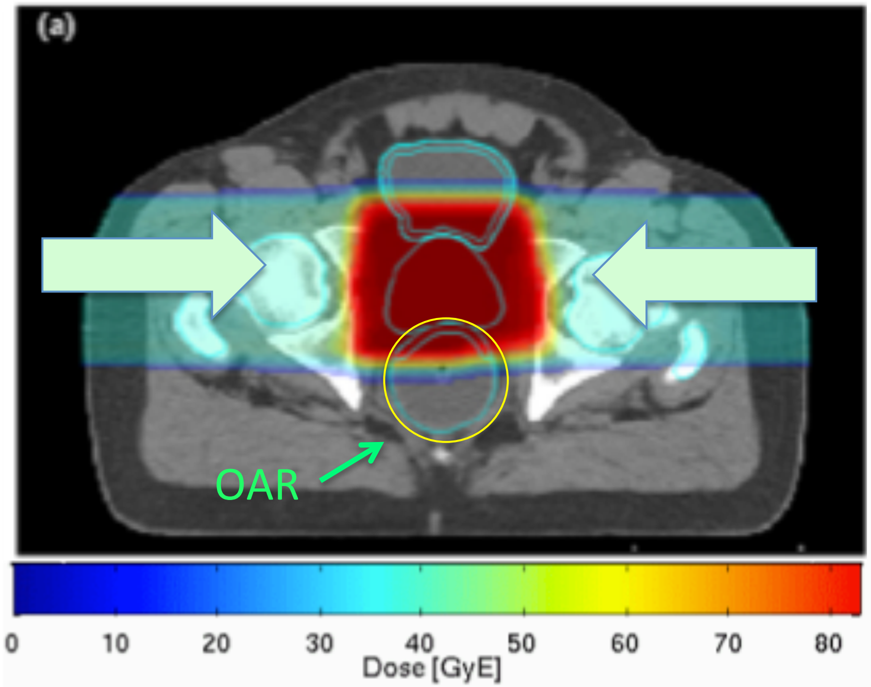
Inhomogeneities, metallic implants, CT artifact, HU conversion, inter session anatomical/physiological changes-> range variations



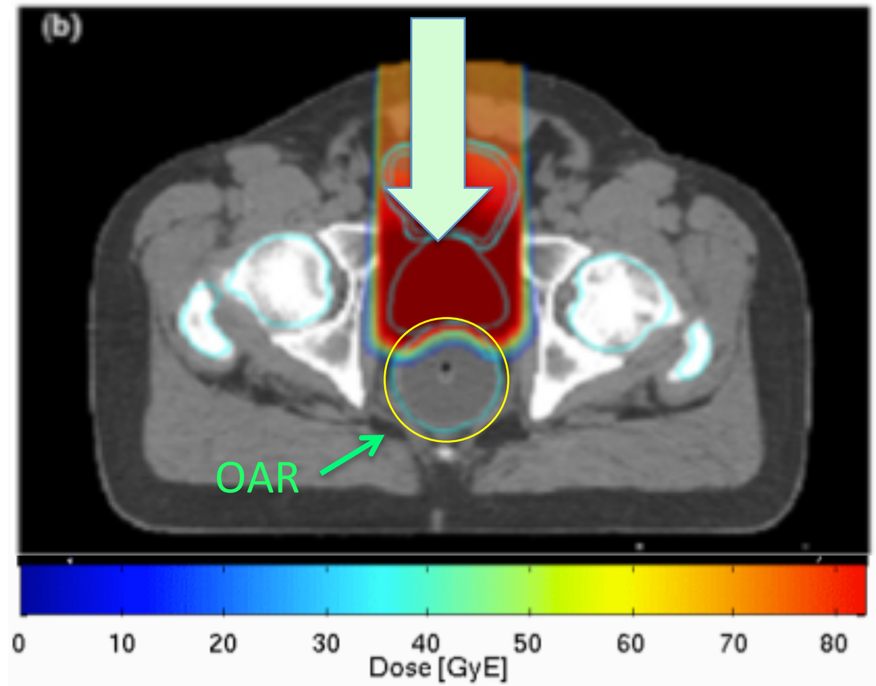
Accounting for uncertainties in the clinical practice

[Tang et al. 2012]

Current approach:
Opposed fields, overshooting



Desirable approach:
Different beam angles and no overshooting



Protons

Spec's of particle therapy monitor

In PT the beam is easily monitored in the transverse direction but longitudinally stops inside the patient. An ideal PT monitor device should measure the shape and (possibly) the absolute value of dose release fulfilling the following spec's:

- ✓ Measurements and feed-back should be provided during the treatment (in-beam). Even better if the monitor response can follow the irradiation scan on line
- ✓ Must relay on the signal by secondary particles, generated by the beam, that comes out from the patient
- ✓ Must deal with the background of the "non signal" secondaries that come out
- ✓ Must be embedded in a treatment room: space, reliability and "easy to run" issues are crucial

Beam secondaries.. Background or Signal?

Indicative secondary flux emitted on full solid angle by ~ 150 MeV p beam

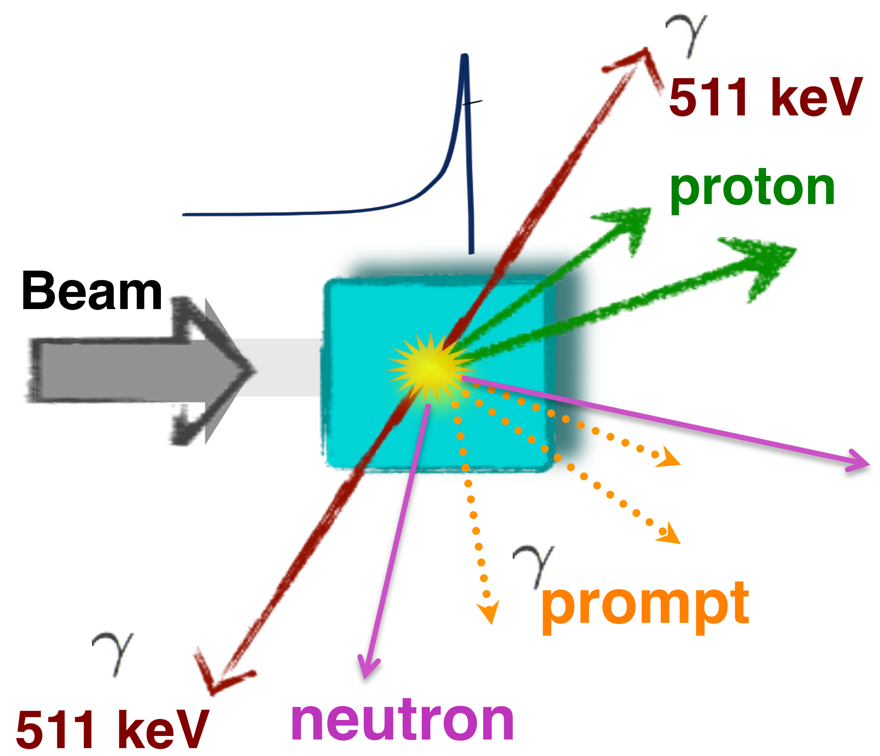
Incident protons:	1.0
Photons	0.3
Neutrons	0.15
Protons	0.005

G4 simulation

How much are the nuclear models reliable? huge experimental and theoretical development effort ongoing to improve model and update MC

The p, ^{12}C beams generate a huge amount of secondaries: prompt γs, PET- γs, neutrons and charged particles (in particular ^{12}C beam)

Can be used to track the tumor path inside the patient

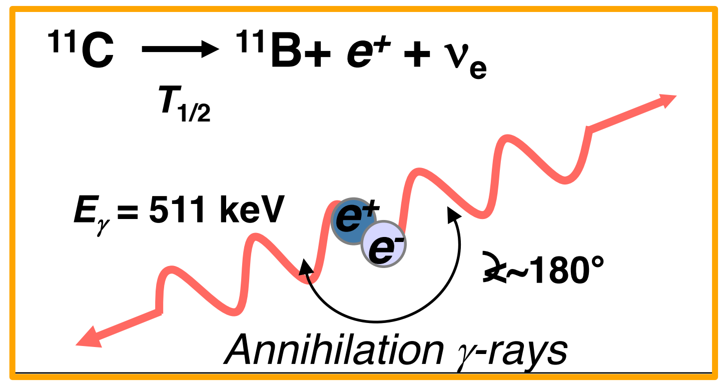


baseline dose monitoring in PT : PET

Baseline for monitor in PT is PET : autoactivation by hadron beam that 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)

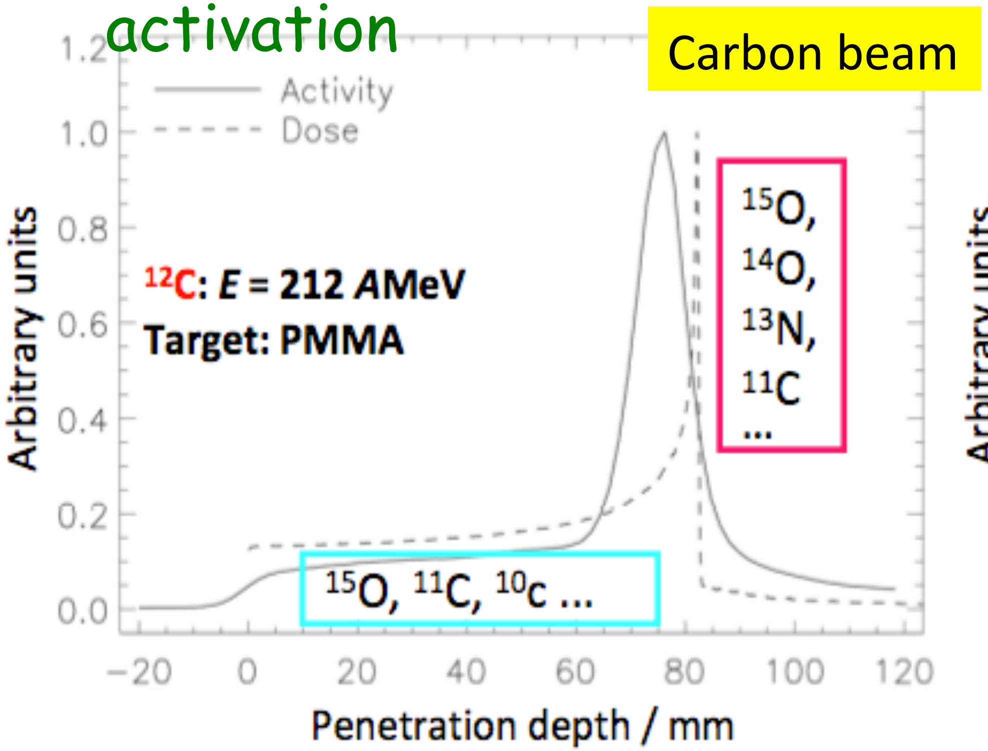


Correlation between β^+ activity and dose

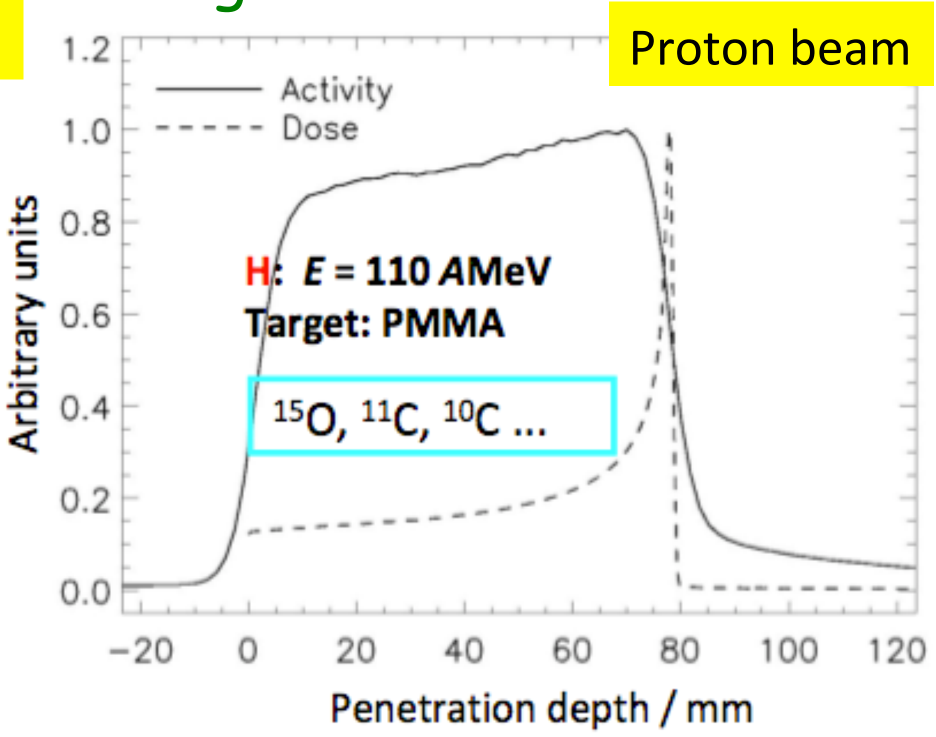
Therapy beam	^1H	^3He	^7Li	^{12}C	^{16}O	Nuclear medicine
Activity density / Bq cm^{-3} Gy^{-1}	6600	5300	3060	1600	1030	$10^4 - 10^5$ Bq cm^{-3}

In a PT treatment are used much more p than ^{12}C (dose ~ Z^2)

beam & target activation

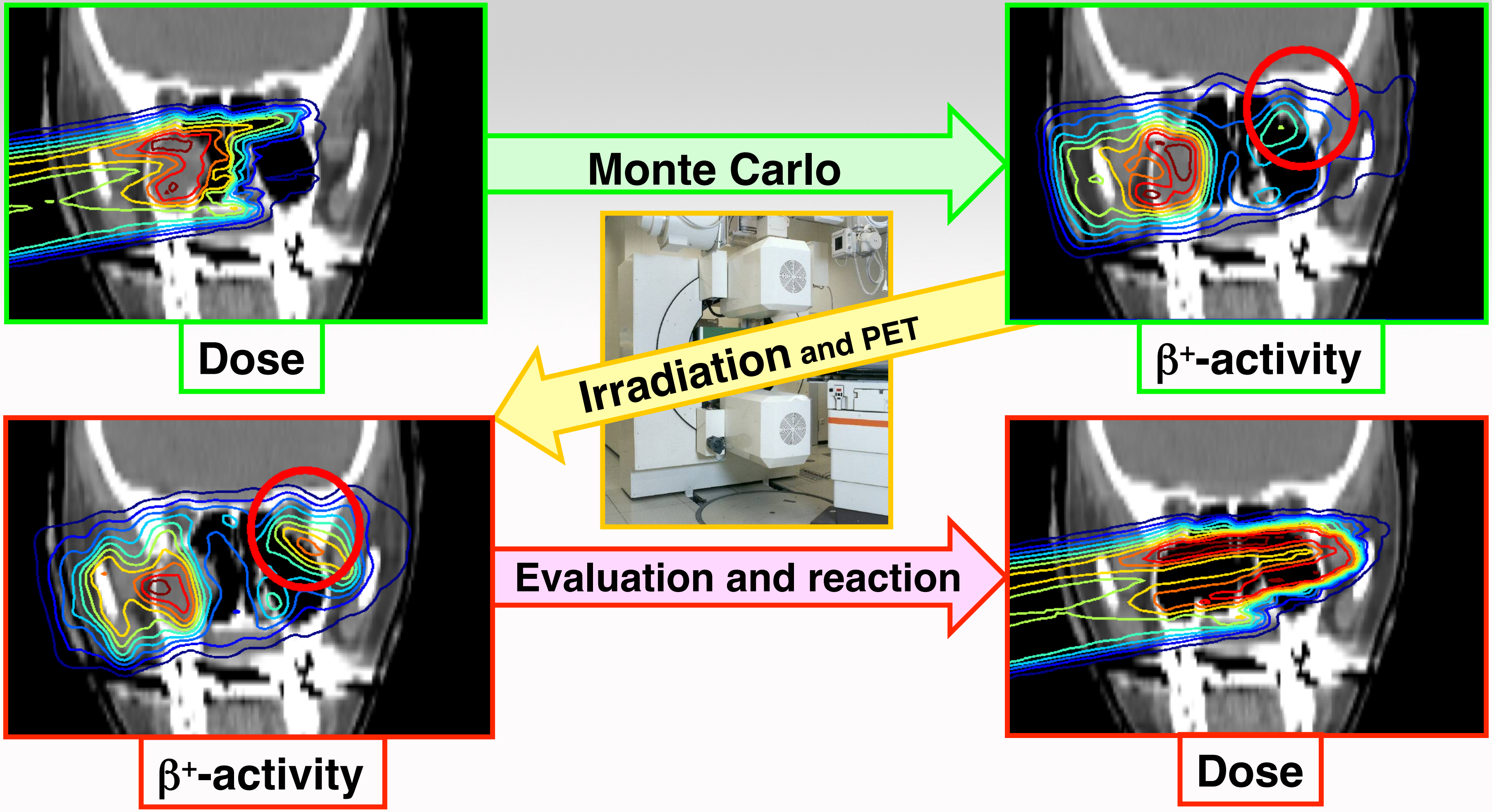


Target activation



In-Vivo range measurement with PET: workflow and potential

W. Enghardt et al.: Radiother. Oncol. 73 (2004) S96

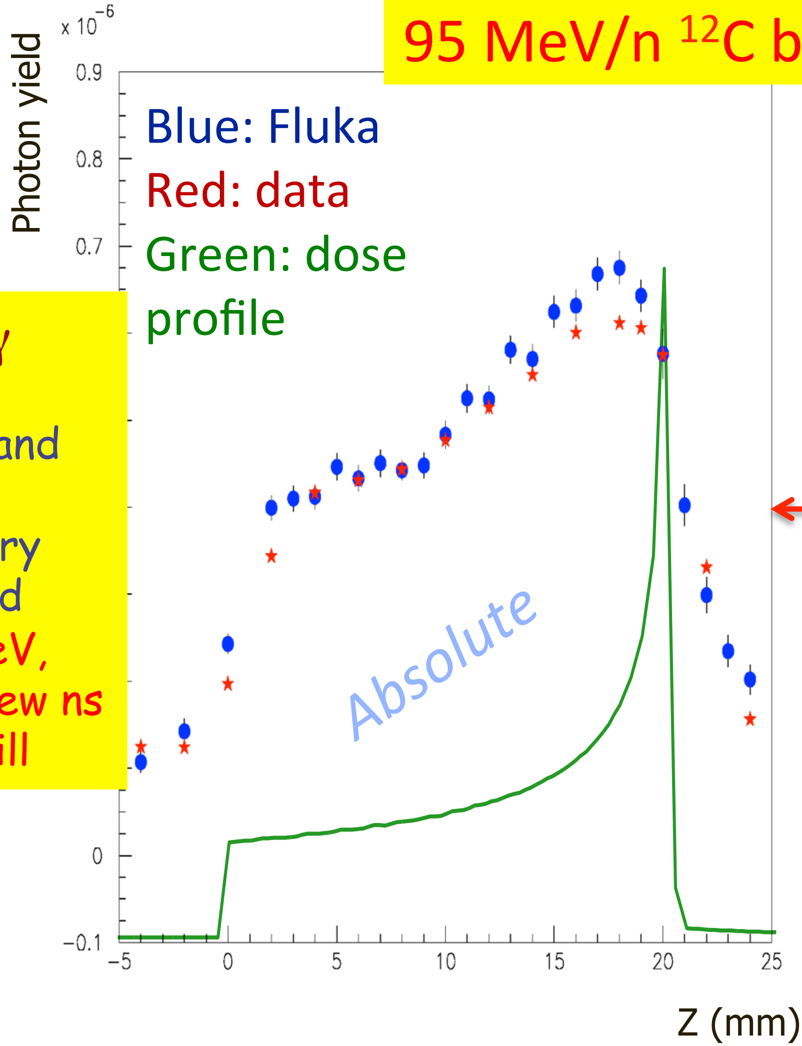


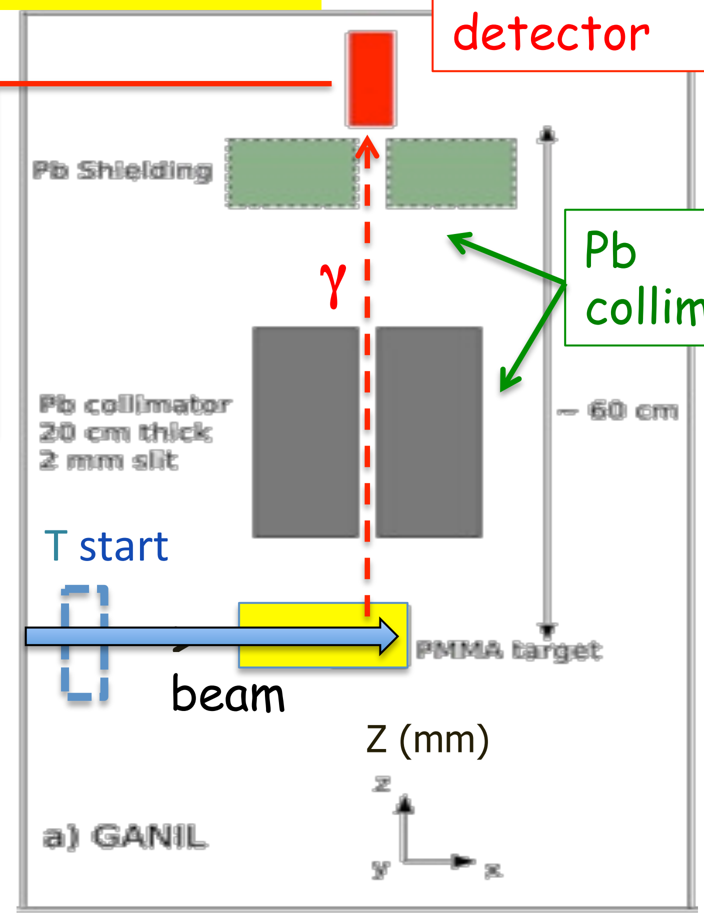
Problem to solve: Metabolic Washout! In-beam measurement is really necessary, but difficult. Trade-off: in-room or off-room measurement after irradiation (Heidelberg for example)

The prompt photons solution

95 MeV/n ^{12}C beam in PMMA

90 deg γ signal
Energy and ToF of secondary recorded
E_γ > 2 MeV, within few ns from spill



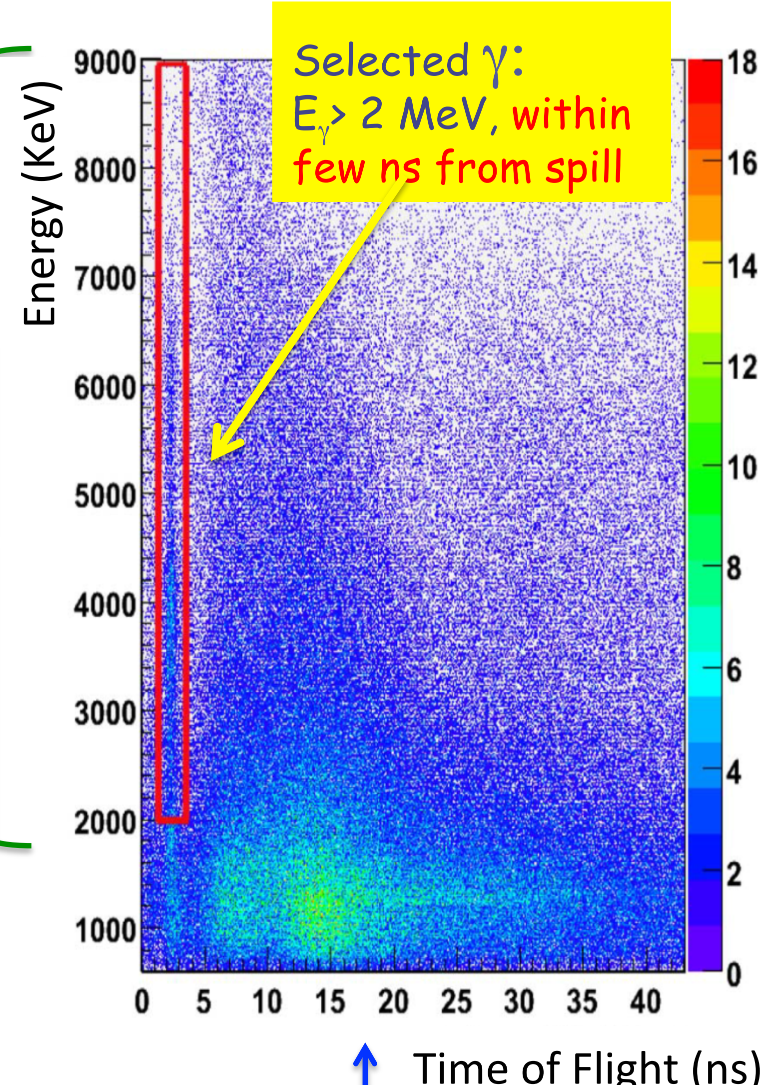


Courtesy of Alfredo Ferrari

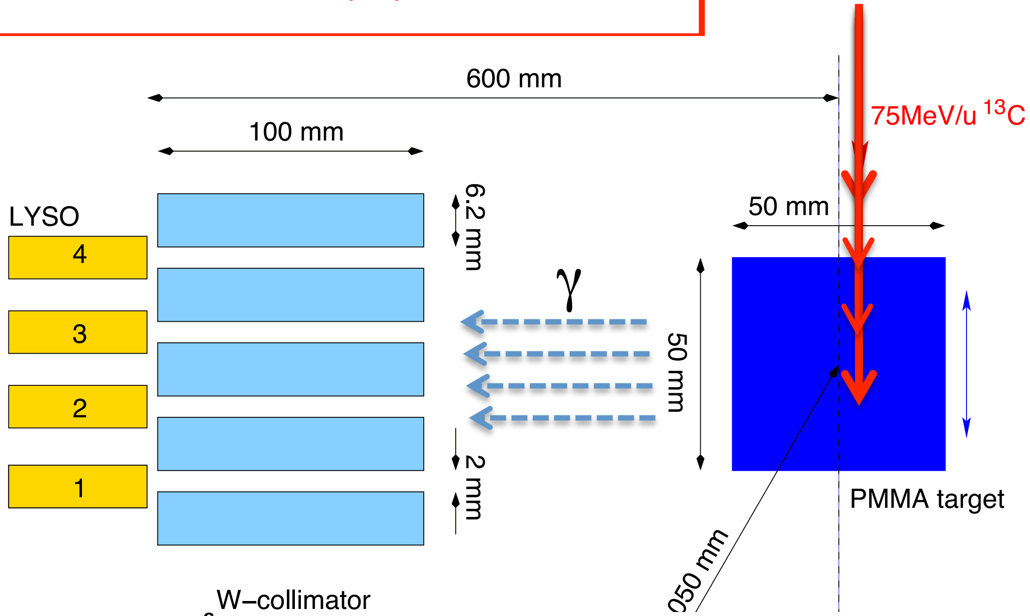
[sketch and exp. data taken from F. Le Foulher et al IEEE TNS 57 (2009), E. Testa et al, NIMB 267 (2009) 993. exp. Data reevaluated in 2012 with substantial corrections

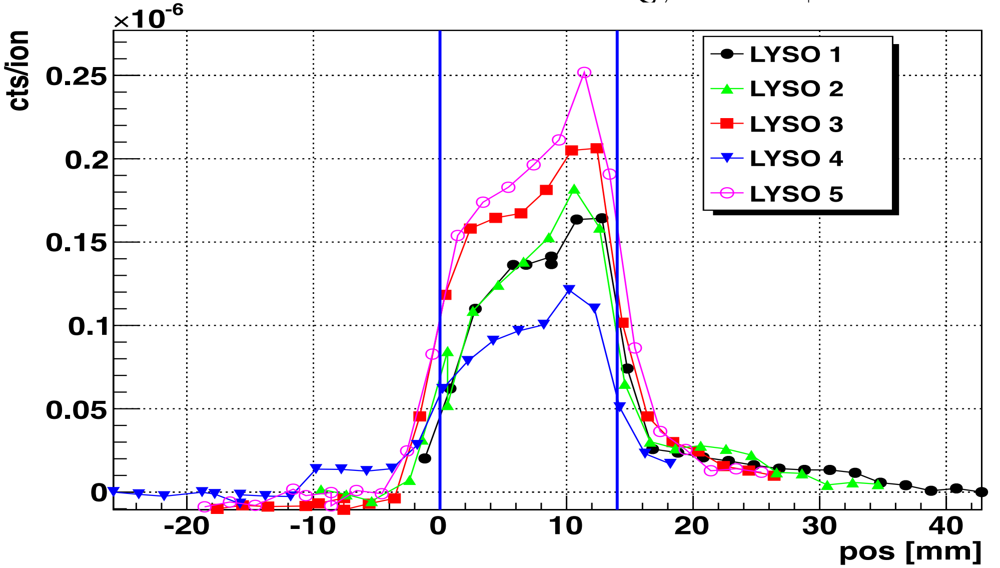
The prompt γ emission: summary

- 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.
- It's not simple backpointing the γ direction: the γ energy is in the 1-10 MeV range-> much more difficult to stop and collimate with respect to ^{99}Tc 144 KeV γ in standard SPECT imaging
- Huge background (beam, energy and site specific) due to neutrons & uncorrelated γs produced by neutrons. TOF not easy to exploit in clinical practice



Pγ detectors: multi-slit approach





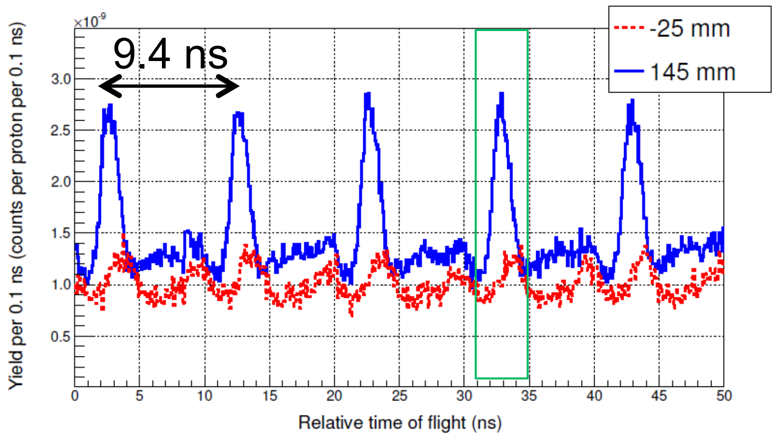
- Longitudinal prompt γ ray profiles at 2 mm level
- Selection of prompt-gamma events in TOF spectra
- energy cut: Eγ > 1100 keV

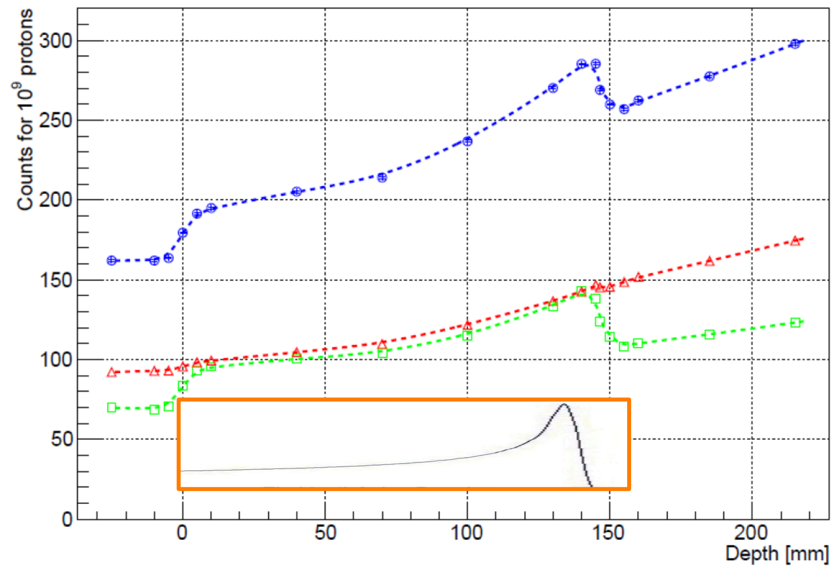
Courtesy of J. Krimmer (IPNL)

J. Krimmer et al. submitted to JINST

Influence of TOF on PG profiles (collimated cameras)

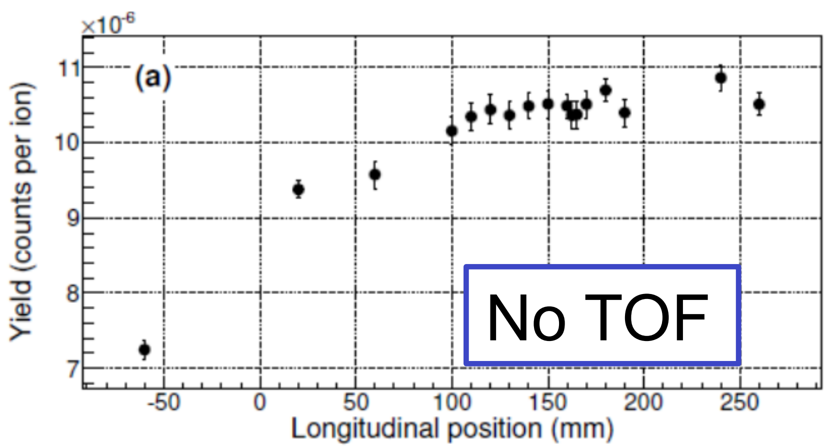
160 MeV protons in PMMA
IBA C230 cyclotron

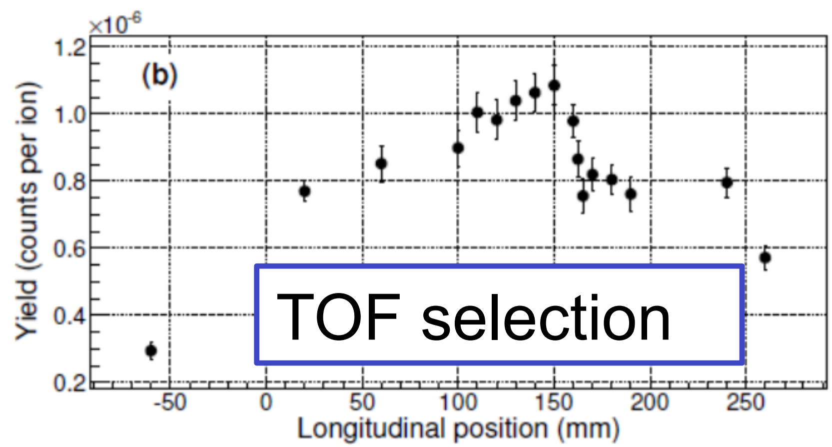




Roellinghoff PMB 2014

310 *A*MeV carbon ions in PMMA





TOF : mandatory for carbon ions
Not easy with clinical beam!!!

M. Pinto, submitted New J Phys

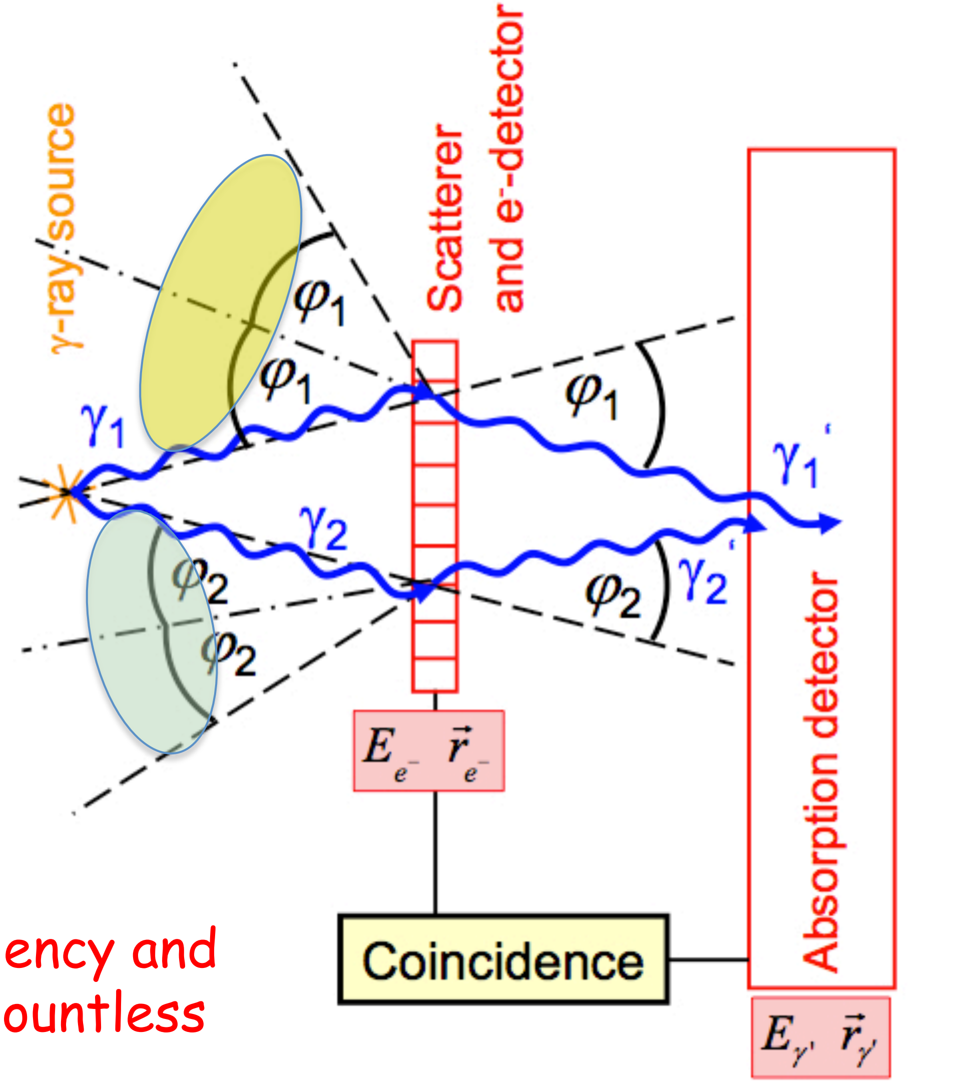
Courtesy of D. Dauvergne

Compton camera: Electronic collimation

$$\cos\varphi = 1 - m_0 c^2 \left(\frac{1}{E_{\gamma'}} - \frac{1}{E_\gamma} \right)$$

Based on γ Compton scattering: if known E_γ, measure $E_{\gamma'}$, $\mathbf{r}_\gamma$, $\mathbf{r}_{\gamma'}$ ➔ obtain f. But…

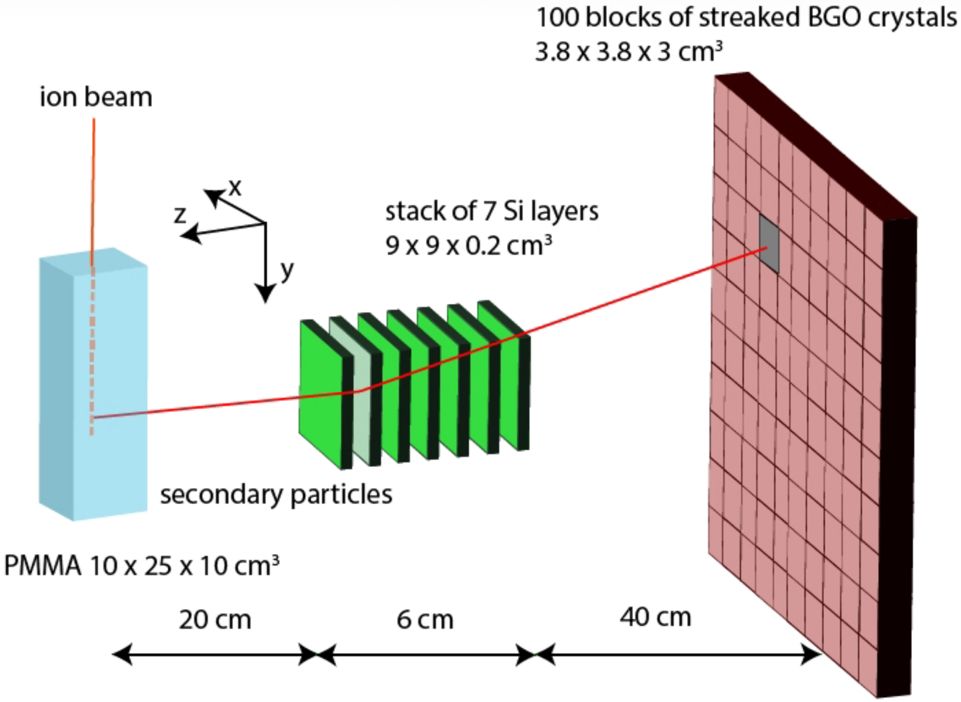
- E_γ not fixed ➔ continuous γ spectra. Must be measured E_e
- γ' must be completely absorbed in the second detector
- Very good resolution needed on $E_{\gamma,e}$ -> solid state detector. (must be fast!)
- Difficult trade off between efficiency and resolution. Plenty of activity and countless groups and institutions !!



Compton camera: I

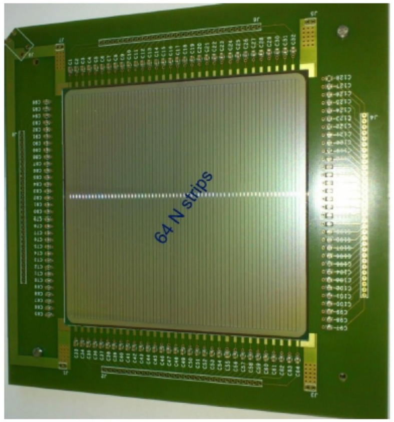
CNRS, UCB Lyon

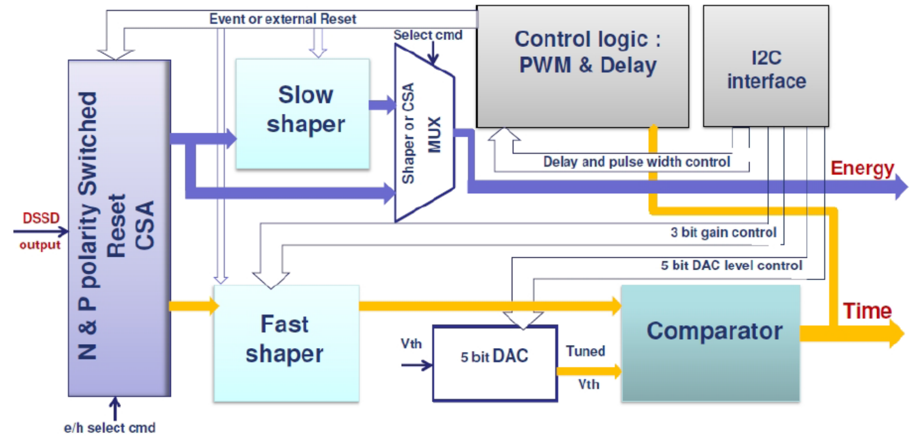
Compton camera: Scatterer: Double sided Si strip detectors, Absorber: Scintillator



Scatterer:

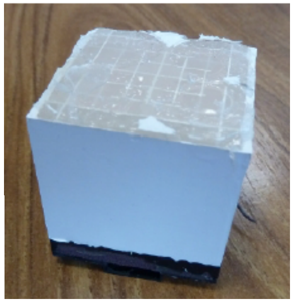
- Large size detector bonded on PCB,
- Dedicated low-noise ASIC

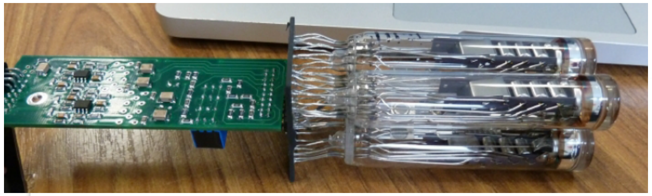




Absorber:

- BGO 35 × 38 × 30 mm^3
- 4 PMT





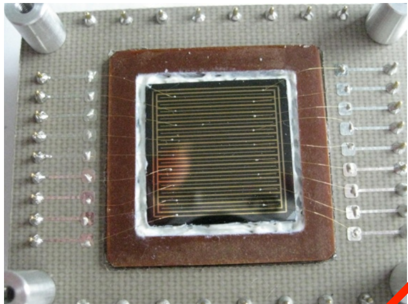
Compton camera: II

ENVISION Meeting Geneva 2014

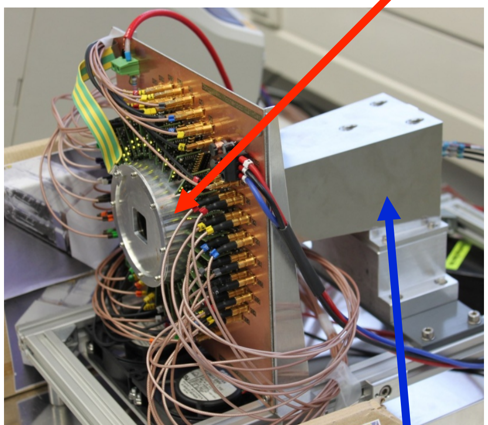
Compton camera:

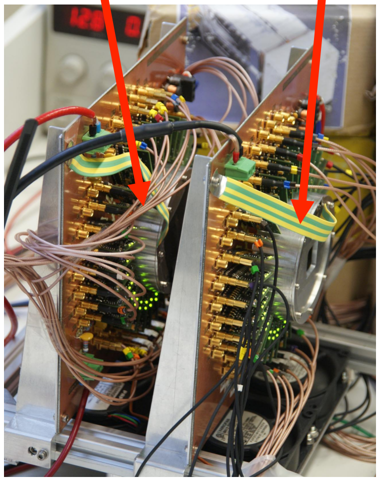
Scatterer: CdZnTe, Absorber: Scint. (LSO, BGO)

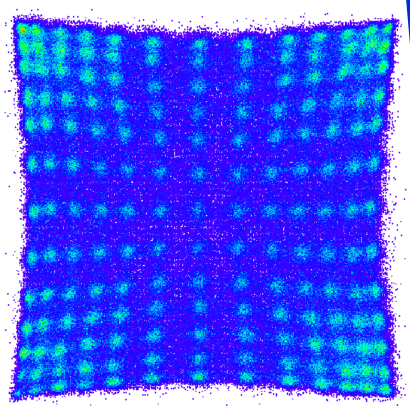
Scatterer: CdZnTe, Absorber: CdZnTe



CZT cross strip detector
($20 \times 20 \times 5$ mm^3)
Bruker Baltic, Riga





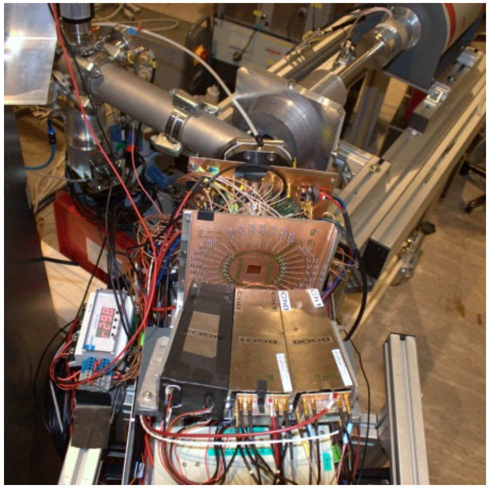


Biograph
LSO block detector,
$54 \times 54 \times 20$ mm^3
Siemens, Knoxville

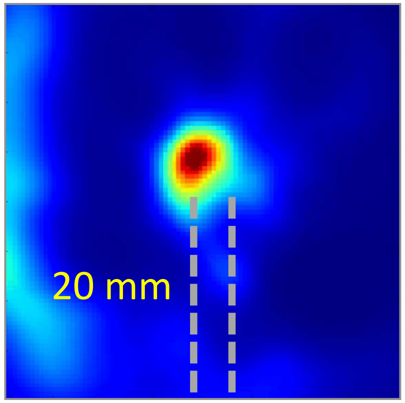
In-beam Compton imaging
Tandetron of HZDR:

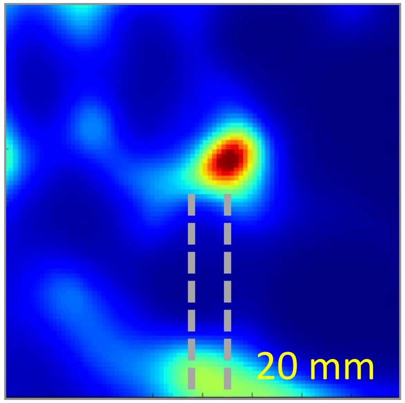
~1 MeV protons

4.44 MeV γ via
$^{15}N(p, \alpha)^{12}C$



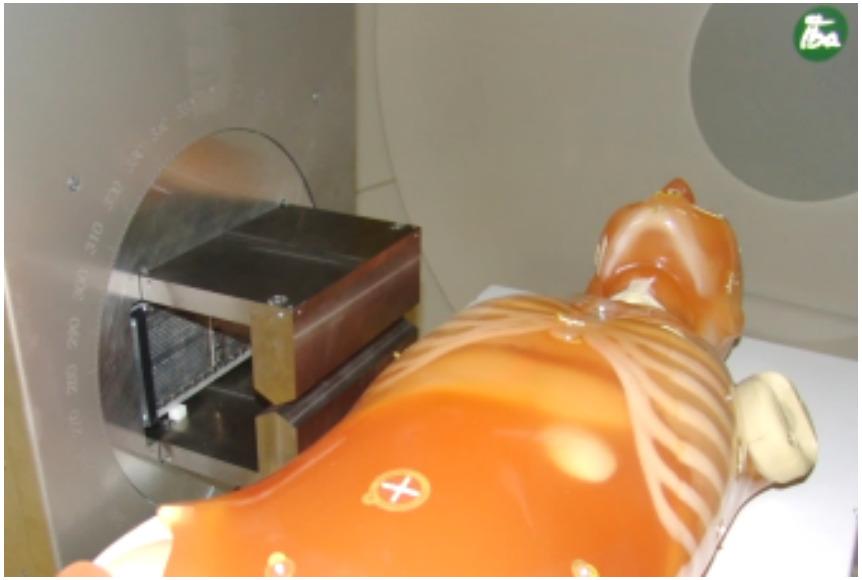
TU Dresden

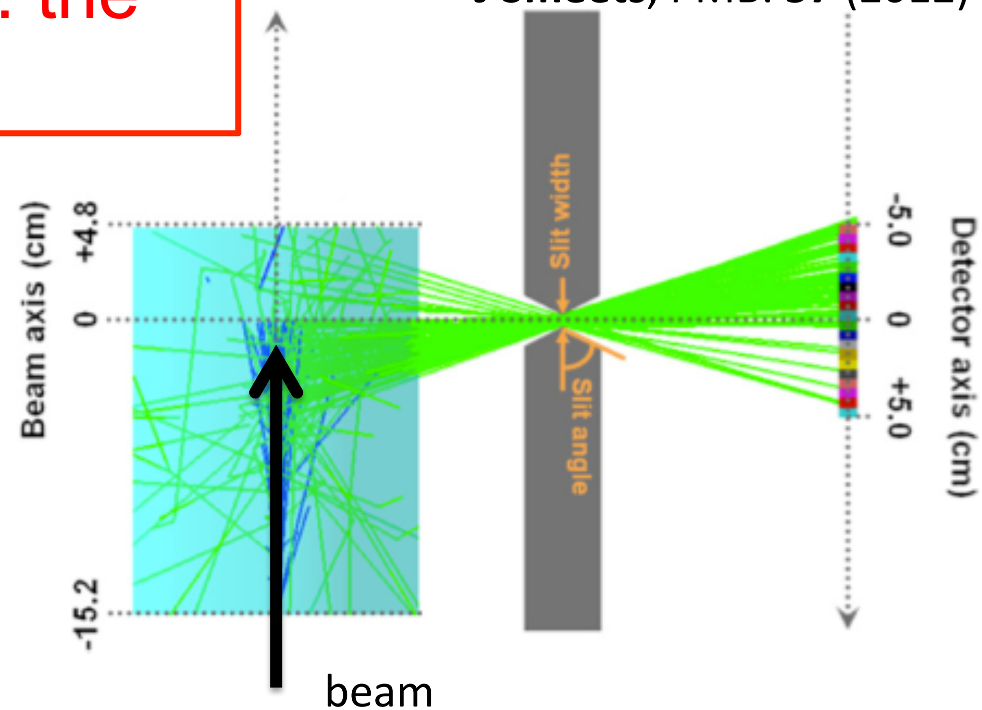




T. Kormoll, et al.: Nucl. Instrum. Meth. A626 (2011) 114, C. Golnik, et al.: IEEE NSS-MIC, Anaheim, 2012

The simpler, the better: the IBA slit camera





Designed and assembled by IBA, in collaboration with Politechnic Milano.

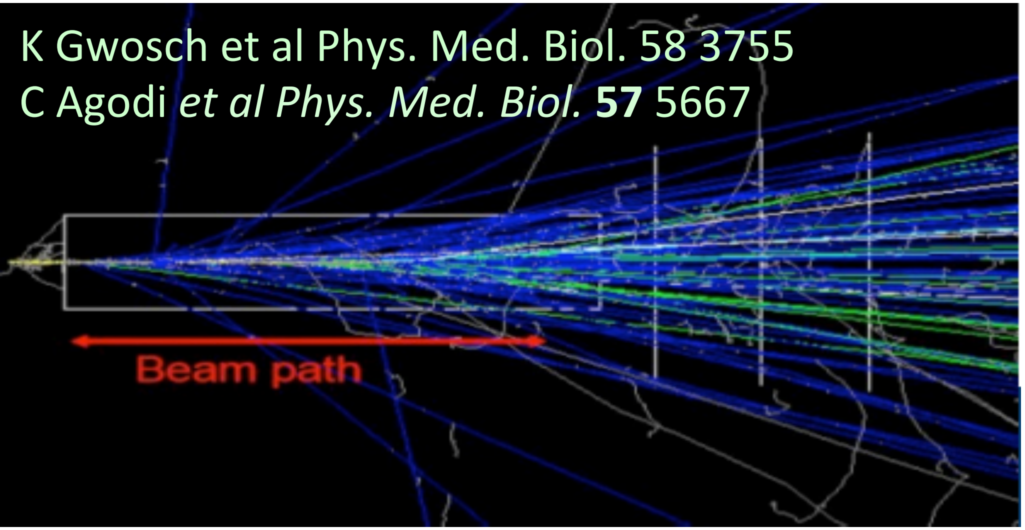
Benchmarking against alternative detection methods (multi-slit) with U. Lyon and Oncoray-Dresden

Close to clinical use, few mm accuracy

What about heavier beam (^{12}C) ? LET grows as Z^2 and the nuclear interaction increase with A. Thus, for the given dose, ^{12}C gives:

- less prompt γ than proton
- more background than proton

Non proton beams : something else useful?
Charged fragments (protons)



Charged secondaries have several nice features as

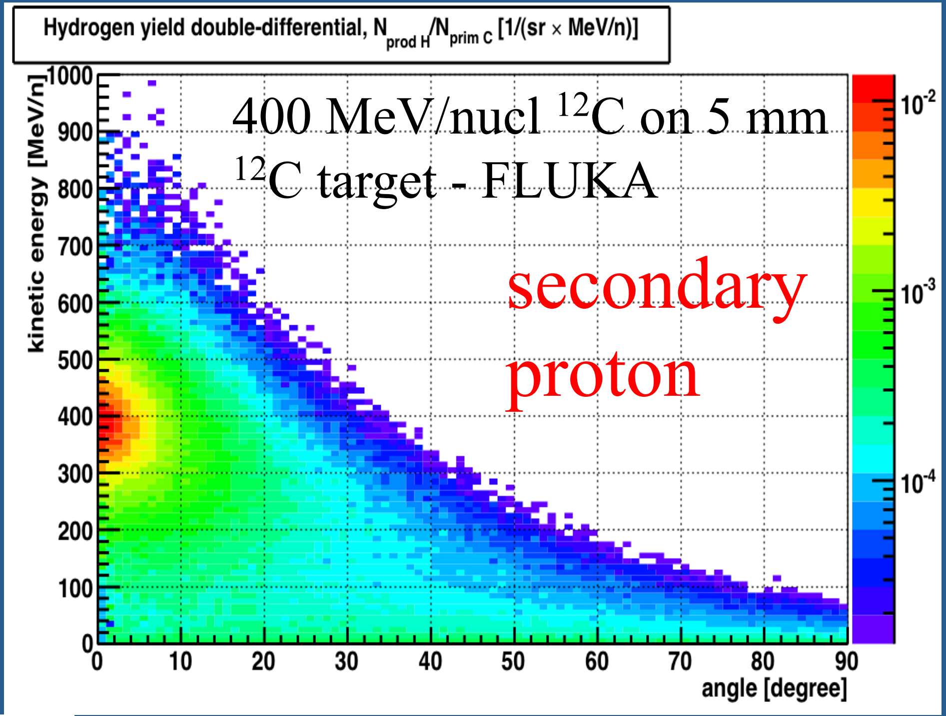
- The detection efficiency is almost one
- Can be easily back-tracked to the emission point-> can be correlated to the beam profile & BP

BUT…

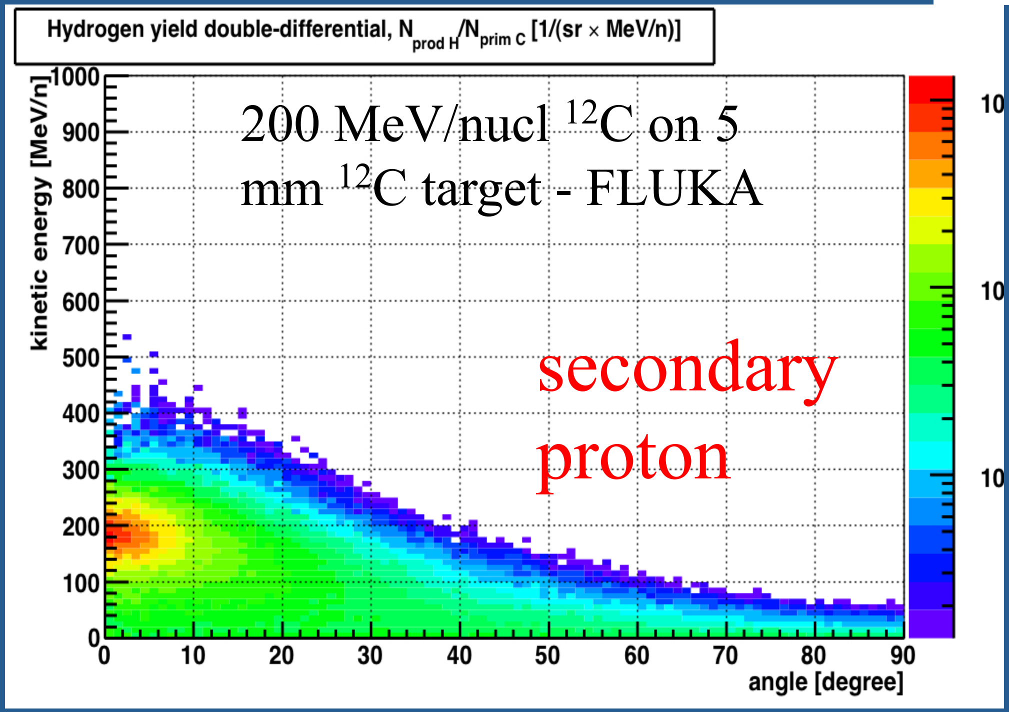
- They are forward peaked
- Energy threshold to escape the patient ~ 80-90 MeV
- They suffer multiple scattering inside the patient -> worsen the back-pointing resolution

MC highly unreliable, probing the very tail of the angular distribution of secondary

Secondary proton: angle vs energy



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



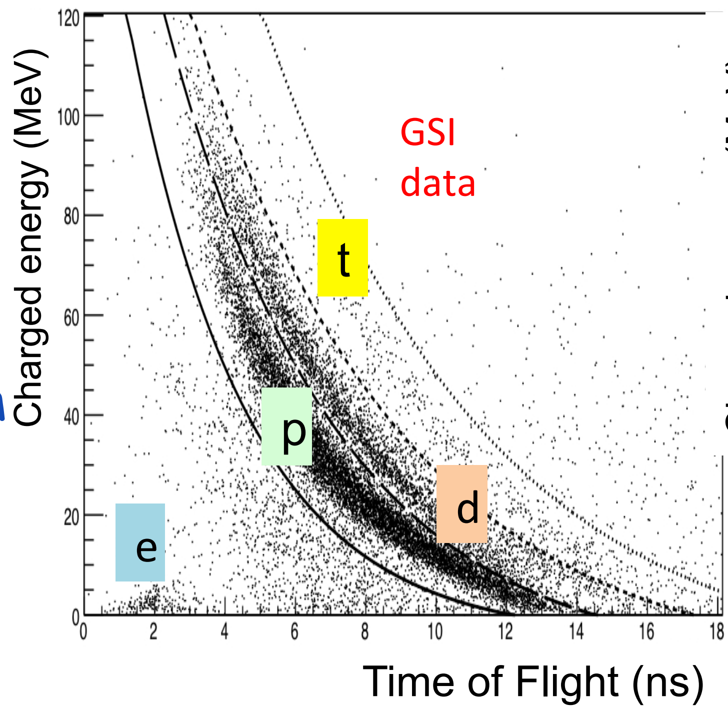
The proton flux at large angle is mainly made by low energy particles.. Can be of any use for monitoring???

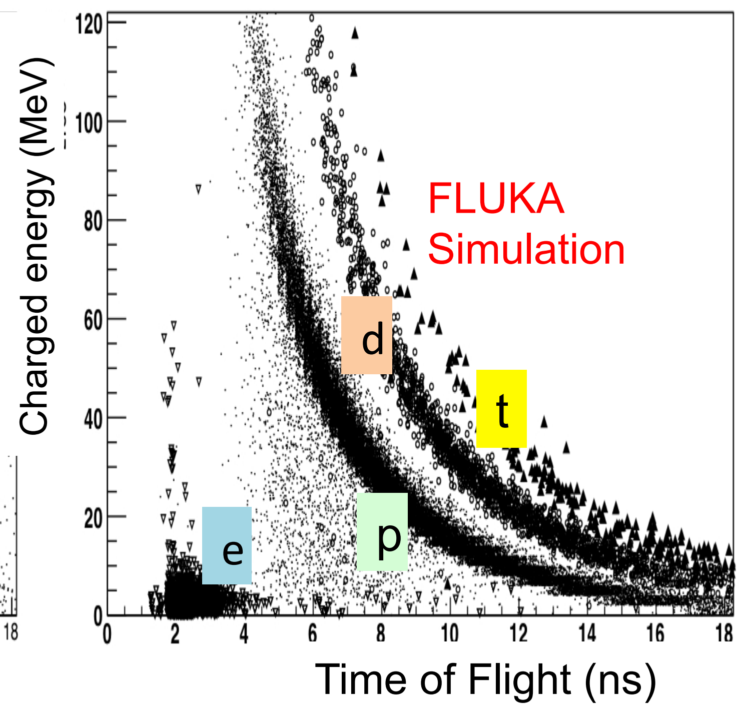
WATCH OUT!! How much are MC reliable at the moment? They are rapidly improving, but...

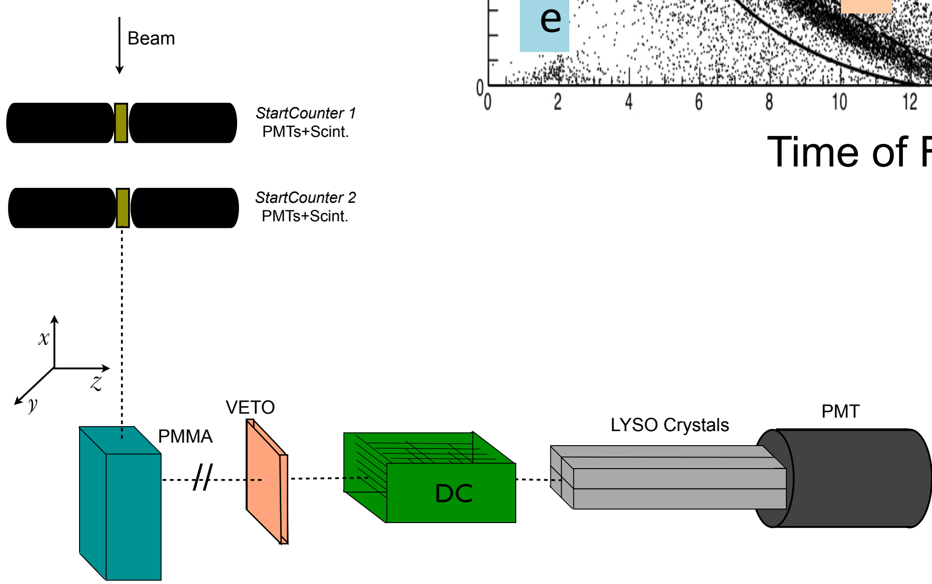
charged secondaries & ^{12}C beam radiography

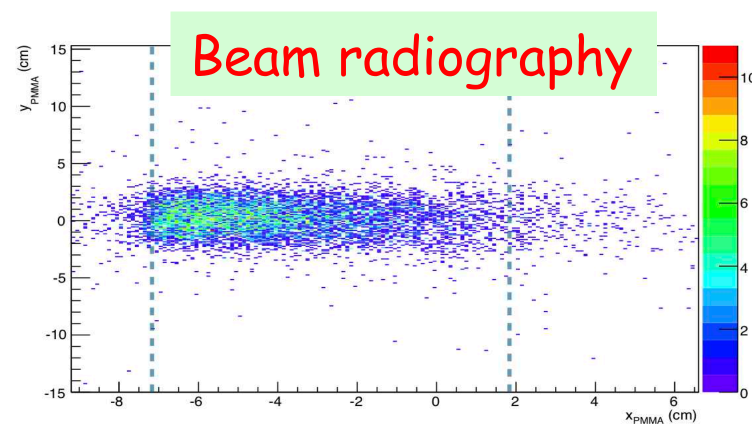
L.Piersanti et al. PMB, 2014

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







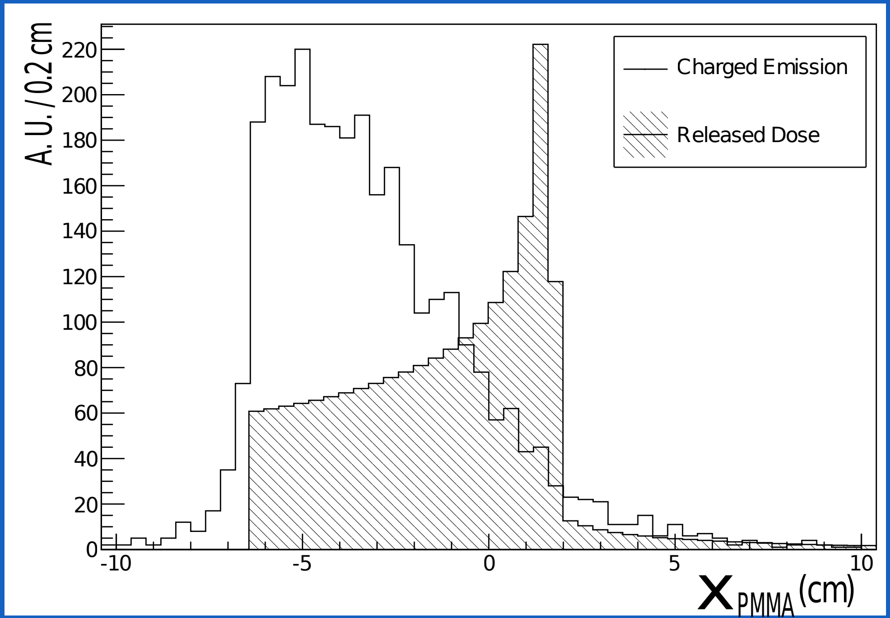


Secondary emission point, BP and the patient

The materials crossed to exit from the patient modifies the detected distribution (absorption & MS). Similar approach of PCT needed: exploiting the knowledge of the pencil beam transverse position and the CT deconvolute the emission shape

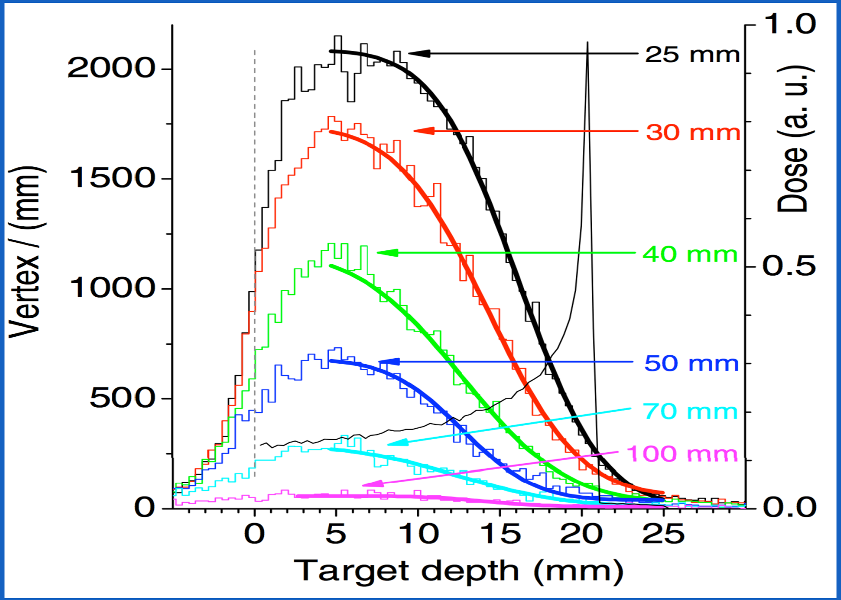
Measured emission shape of protons outside a 5 cm thick PMMA at 90^0 wrt the direction of 220 AMeV ^{12}C beam

L.Piersanti et al. PMB, 2014



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

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

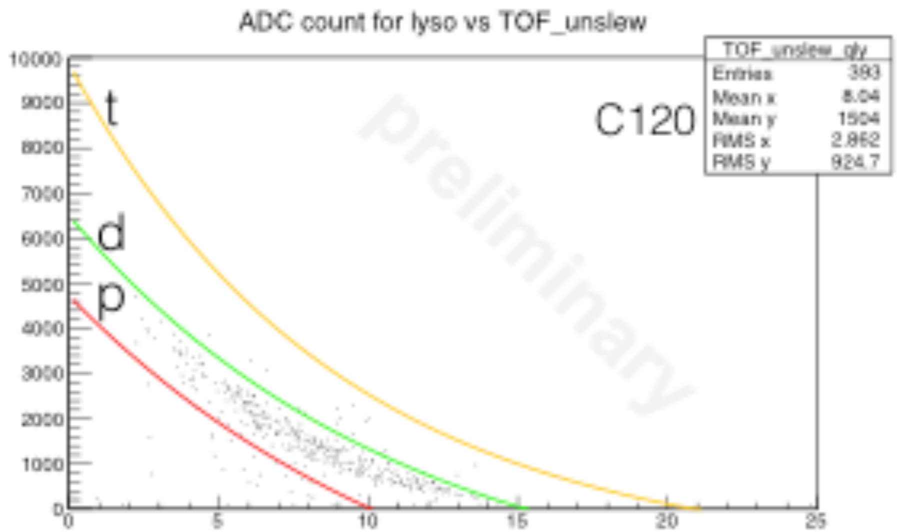


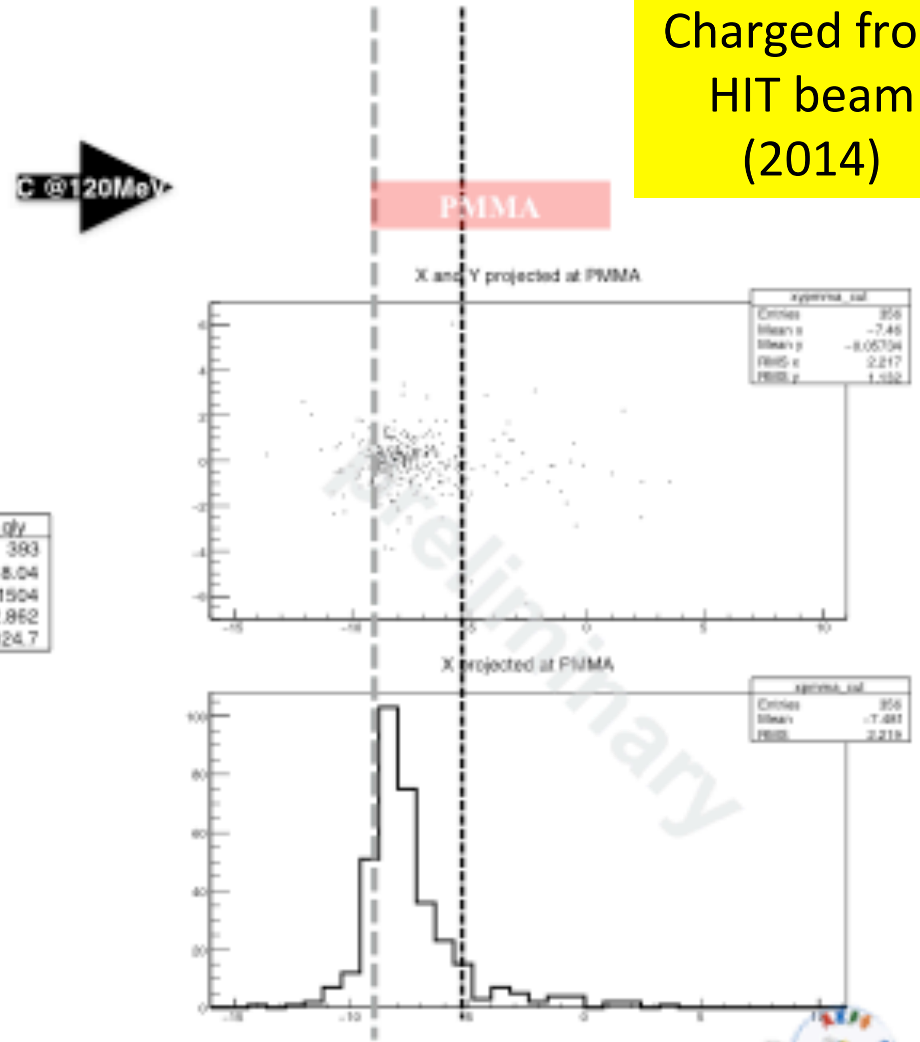
Carbon beam @90° (reference runs)

Charged secondaries monitoring

A non negligible production of charged particles at large angles is observed for all beam types.

The emission shape is correlated to the beam entrance face and BP position as already measured with ^{12}C at GSI.
[Piersanti et al. PMB, 59 (2014)]





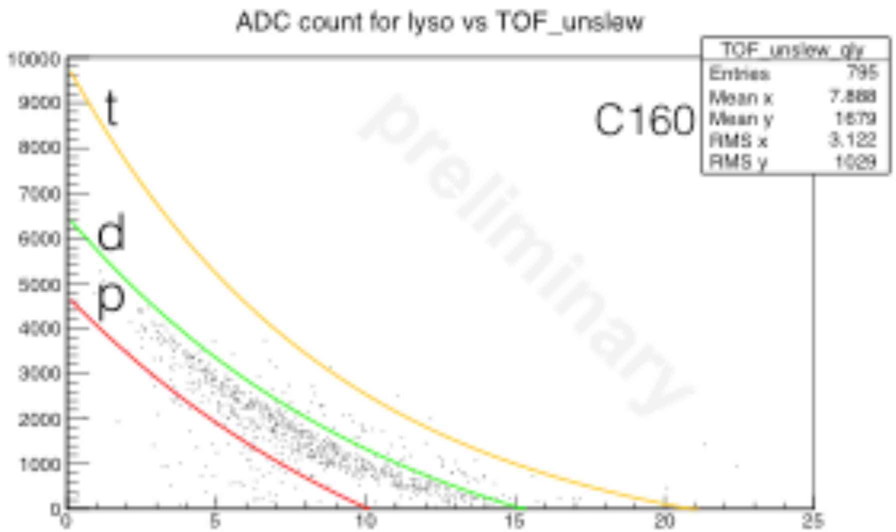
Charged from HIT beam (2014)

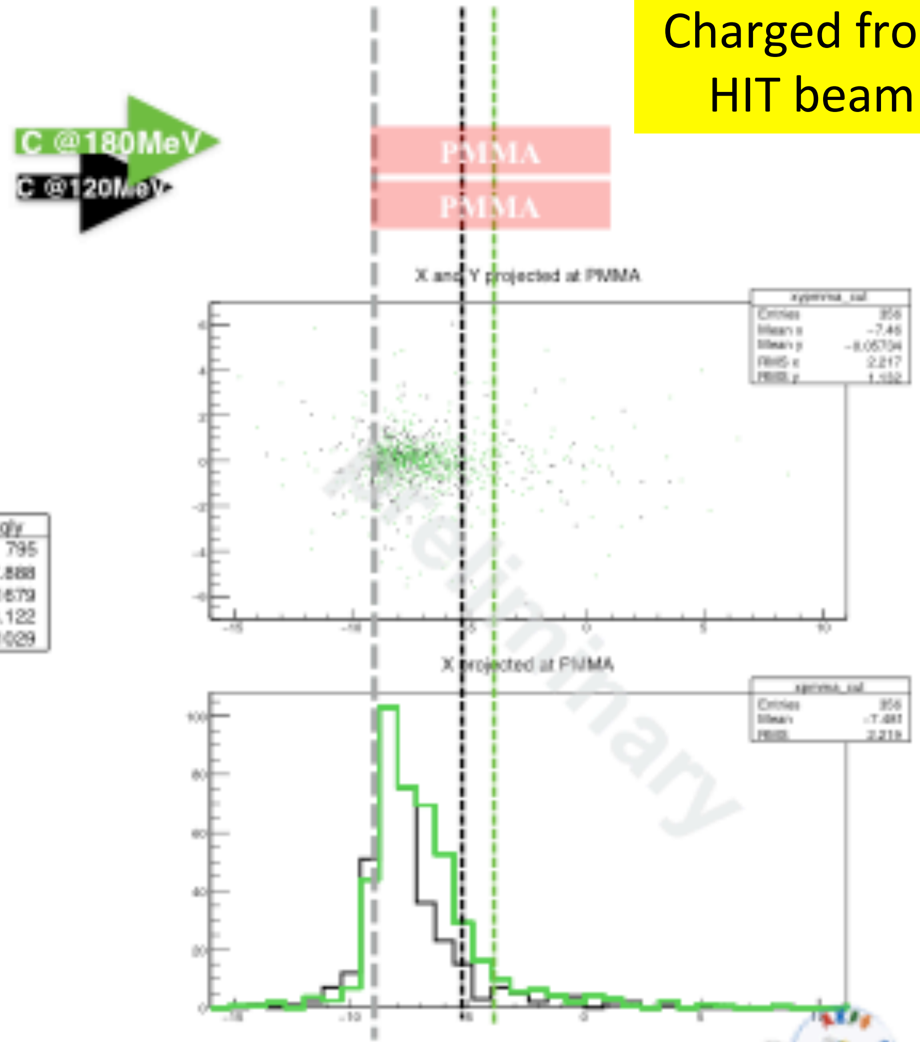
Carbon beam @90° (reference runs)
Charged secondaries monitoring

Charged from HIT beam

A non negligible production of charged particles at large angles is observed for all beam types.

The emission shape is correlated to the beam entrance face and BP position as already measured with ^{12}C at GSI.
[Piersanti et al. PMB, 59 (2014)]





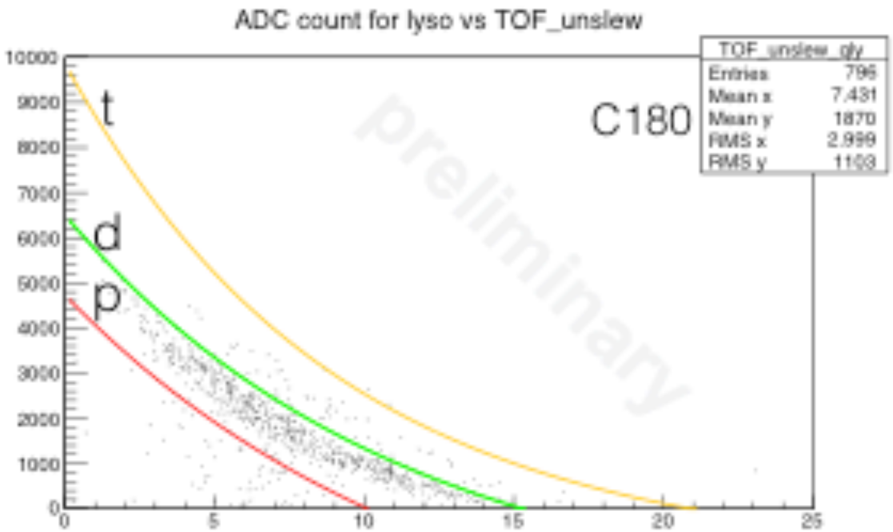
To be submitted to PMB

preliminary

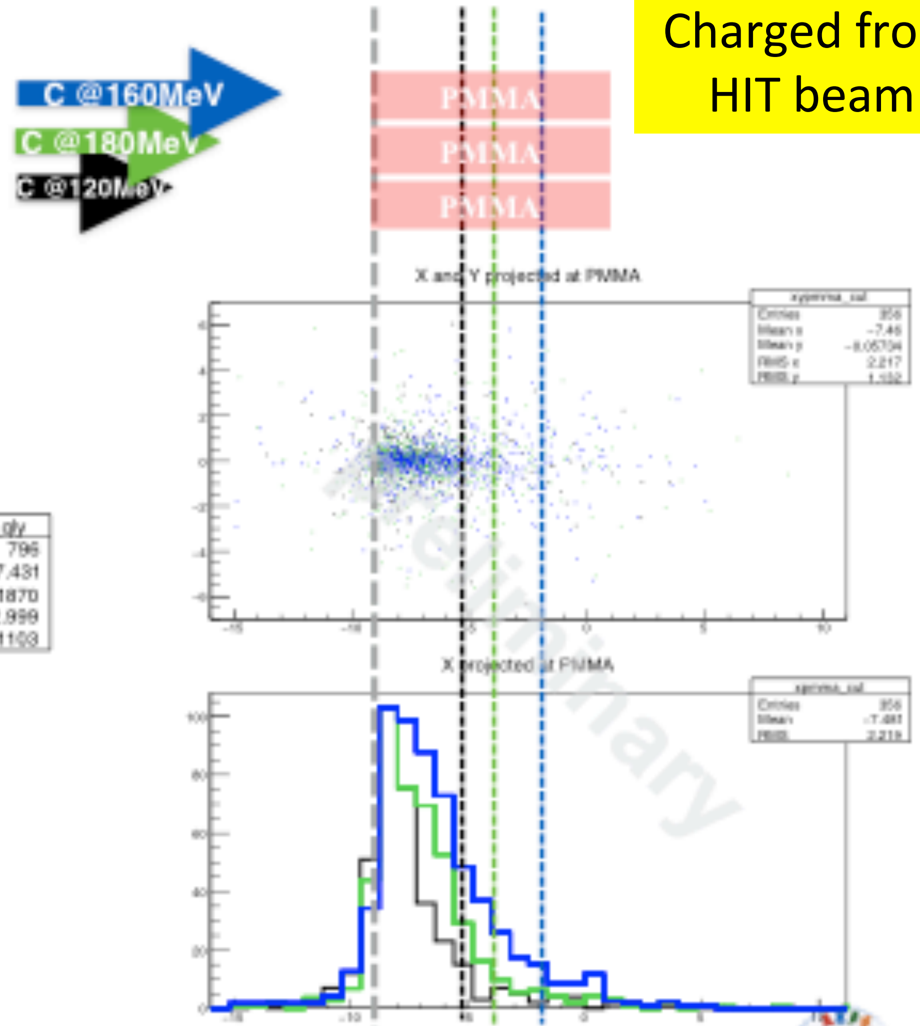
Carbon beam @90° (reference runs)
Charged secondaries monitoring

A non negligible production of charged particles at large angles is observed for all beam types.

The emission shape is correlated to the beam entrance face and BP position as already measured with ^{12}C at GSI.
[Piersanti et al. PMB, 59 (2014)]



Charged from HIT beam



To be submitted to PMB

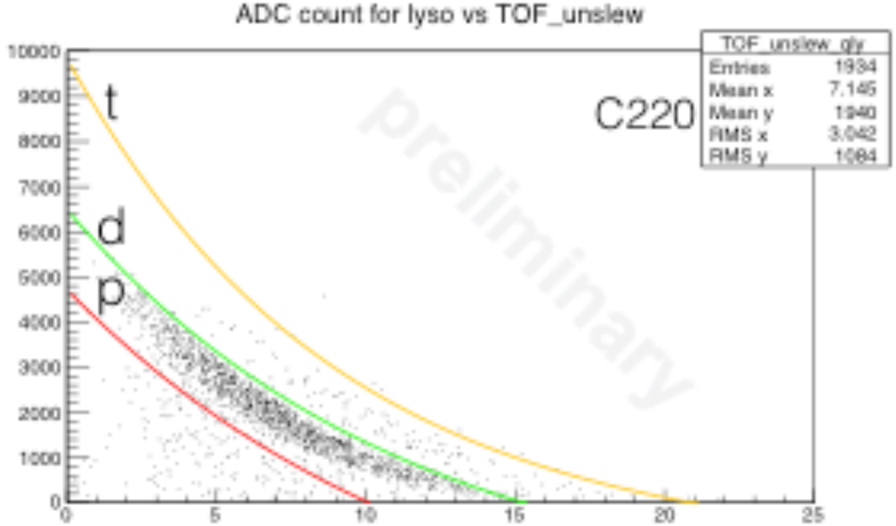
preliminary

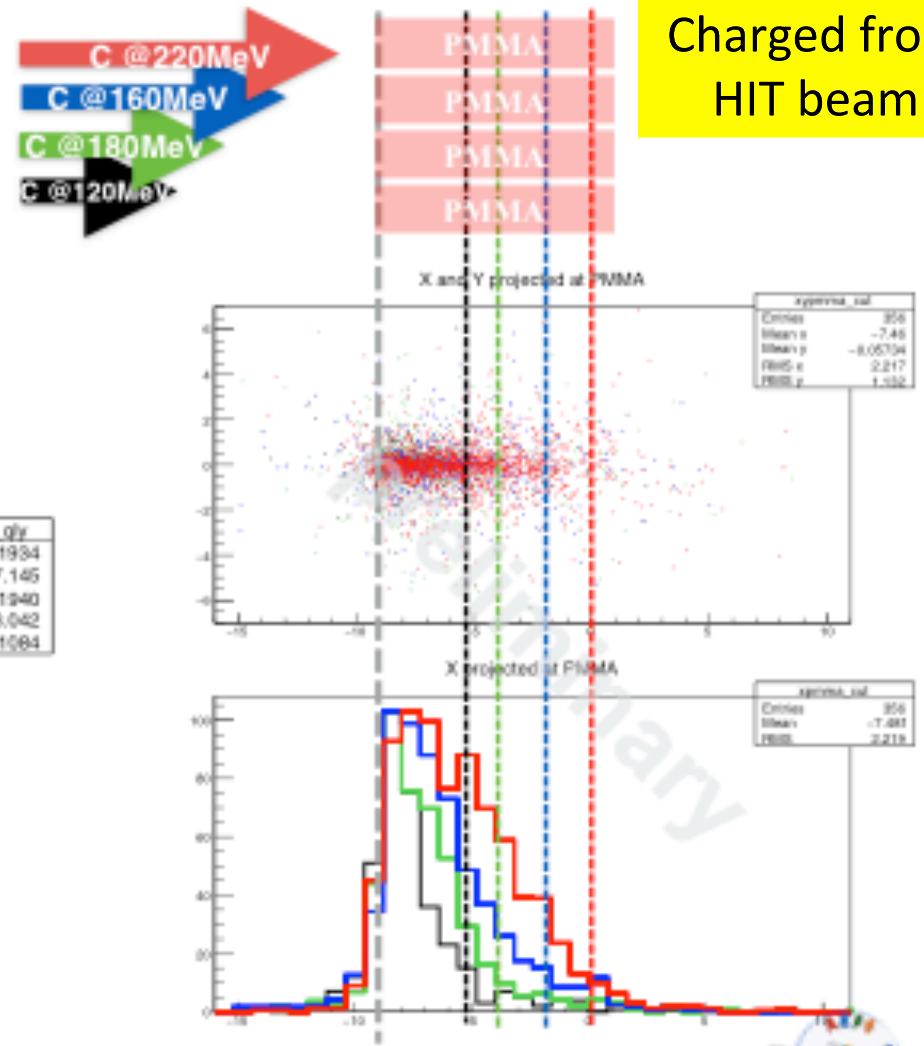
Carbon beam @90° (reference runs)

Charged secondaries monitoring

A non negligible production of charged particles at large angles is observed for all beam types.

The emission shape is correlated to the beam entrance face and BP position as already measured with ^{12}C at GSI.
[Piersanti et al. PMB, 59 (2014)]



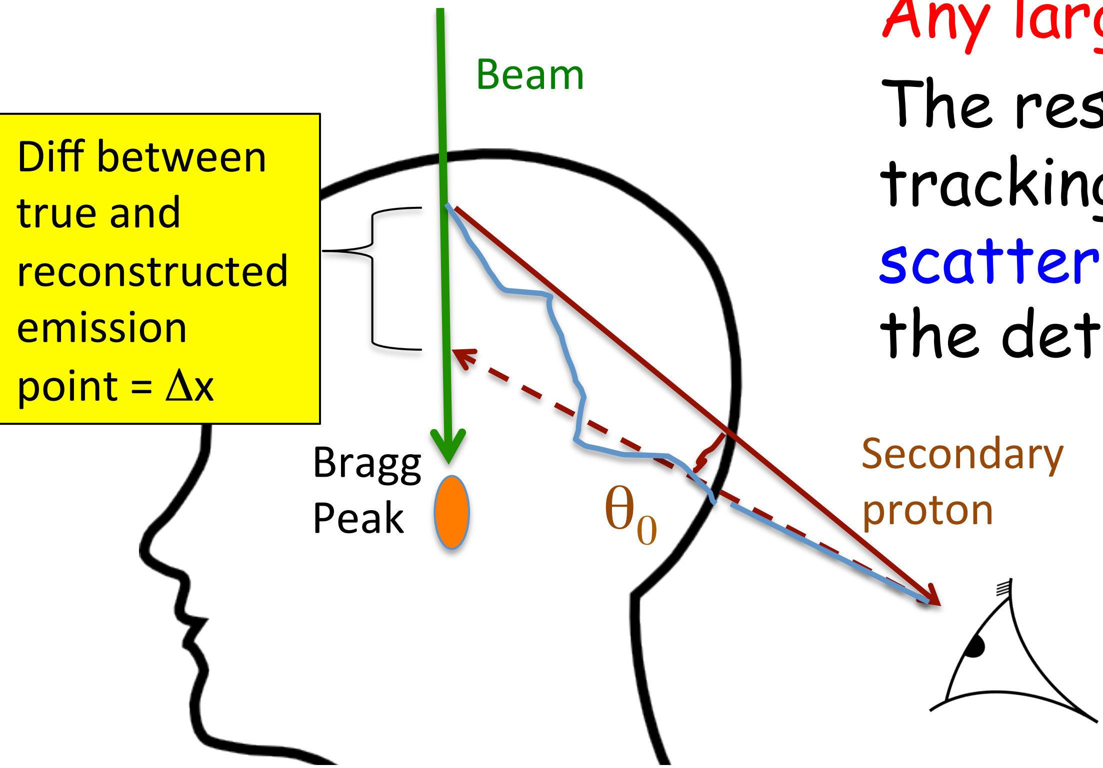


Charged from HIT beam

To be submitted to PMB

preliminary

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

The InSide Project

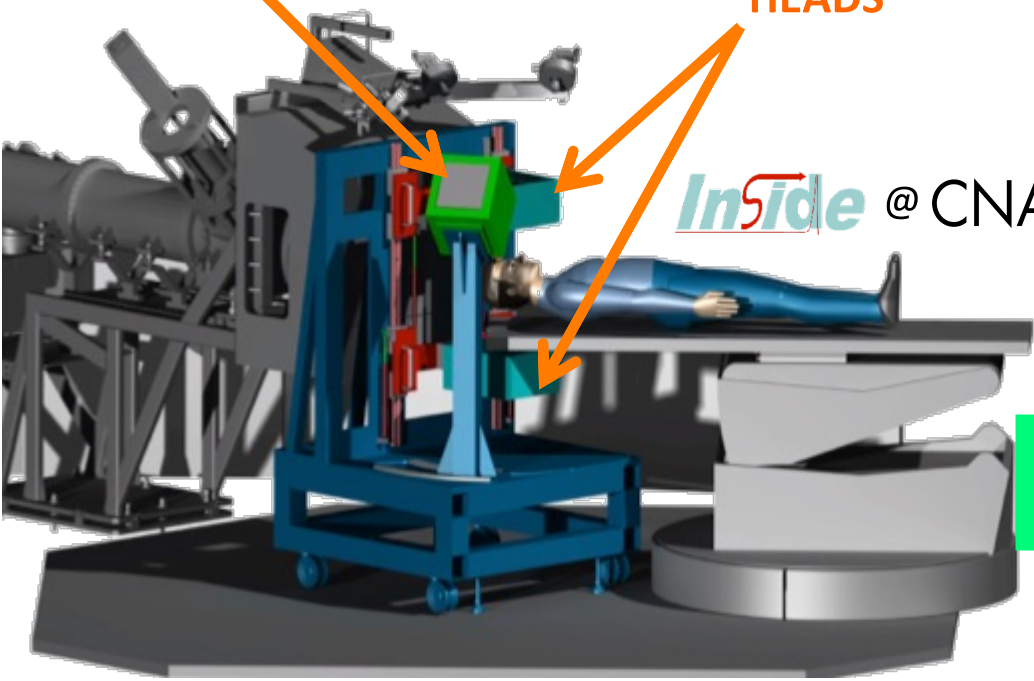
Prompt secondary particles emission

Tracker + Calorimeter = DOSE PROFILER

β^+ activity distribution

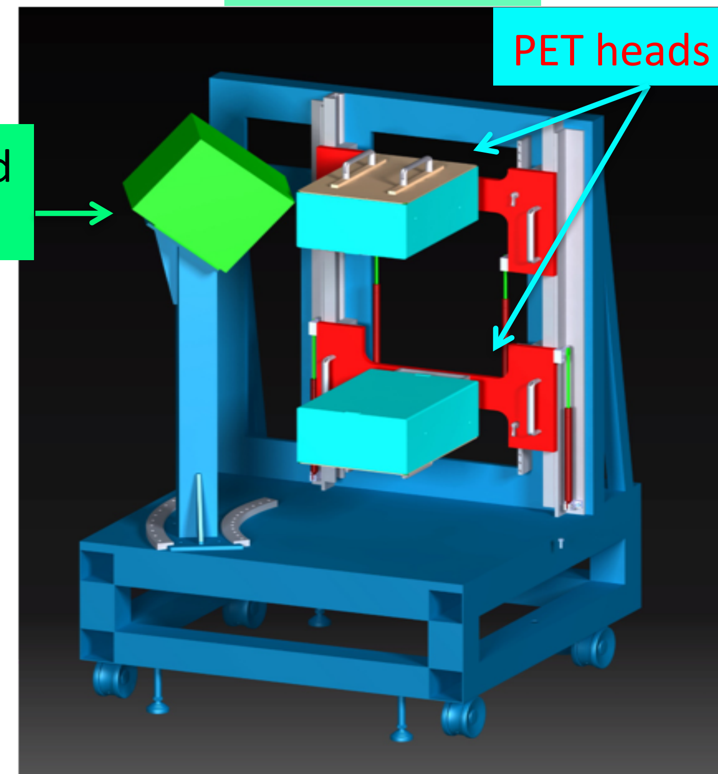
IN-BEAM PET HEADS

INnovative **S**olutions for **I**n-beam **D**osim**E**try in Hadrontherapy



InSide @ CNAO

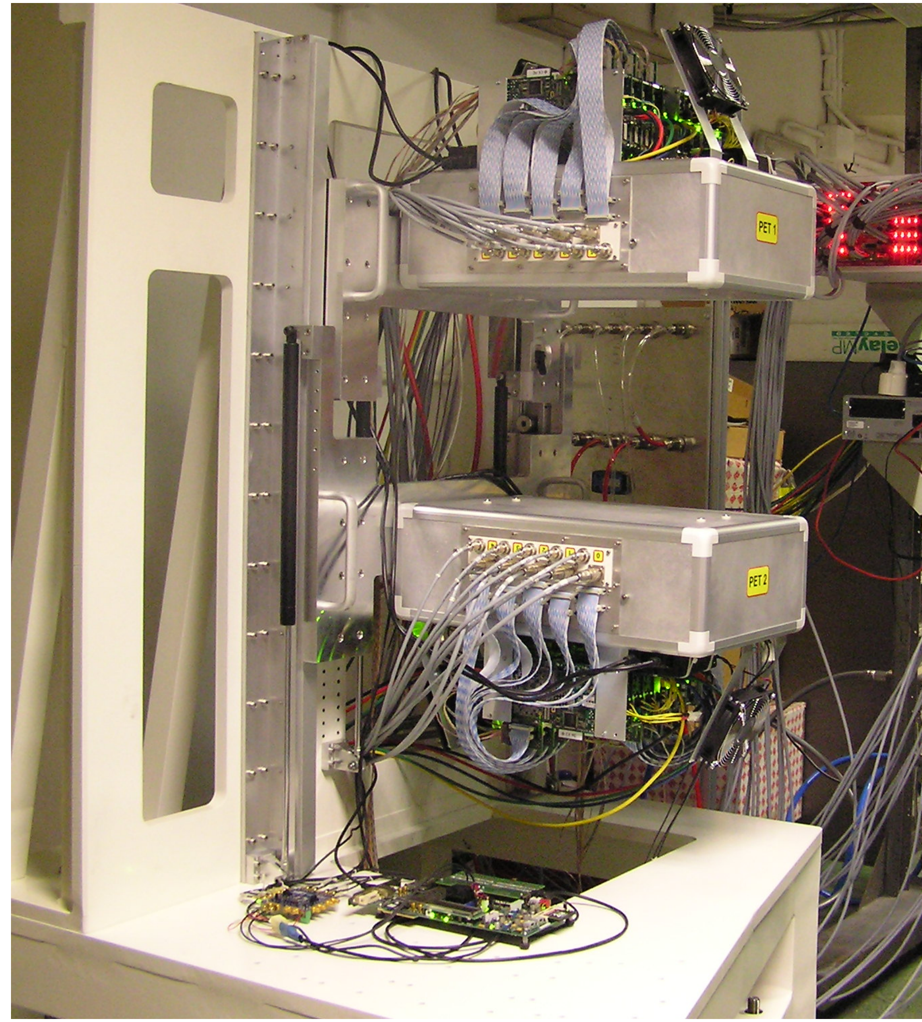
PRIN + Centro Fermi + INFN project



- ✓ integrated in treatment room of Centro Nazionale di Adroterapia Oncologica (CNAO)
- ✓ operated in-beam
- ✓ IMMEDIATE feedback on the particle range
- ✓ Effective both on proton and ^{12}C beam

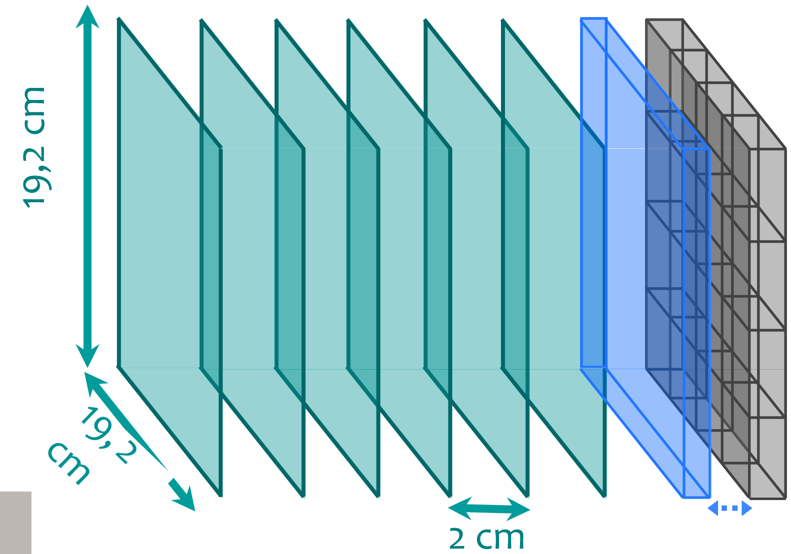
The INSIDE PET system

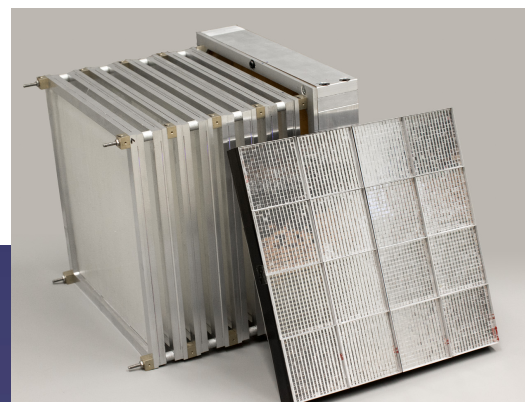
- DAQ sustains annihilation and prompt photon rates during the beam irradiation
- Two planar panels each 10 cm x 20 cm wide. Each panel will be made by 2 x 4 detection modules
- Each module is composed of a pixelated LYSO scintillator matrix 16 x 16 pixels, 3x3 mm^2 crystals, 3.1 mm pitch, for a total sensitive area of 5x5 cm^2
- One SiPM array (16x16 pixels) is coupled to each LYSO matrix. 200 ps FWHM TOF capability

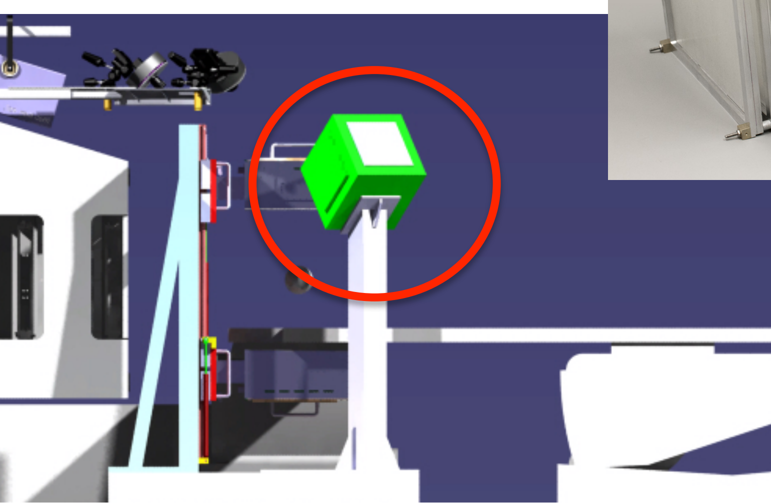


INSIDE: charged tracker

- 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





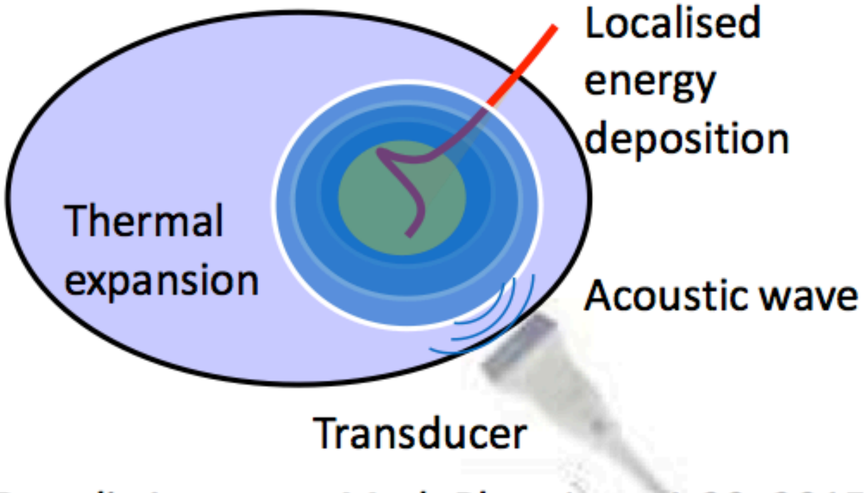


- ✓ 4x4 LYSO pixellated crystals tracking planes: 50 x 50 x 16 mm^3
- ✓ Plastic absorber 1.5 cm thick in front of LYSO to screen electrons
- ✓ Crystals read out by 64 ch Hamamatsu MultiAnode

"Ionoacoustic" imaging

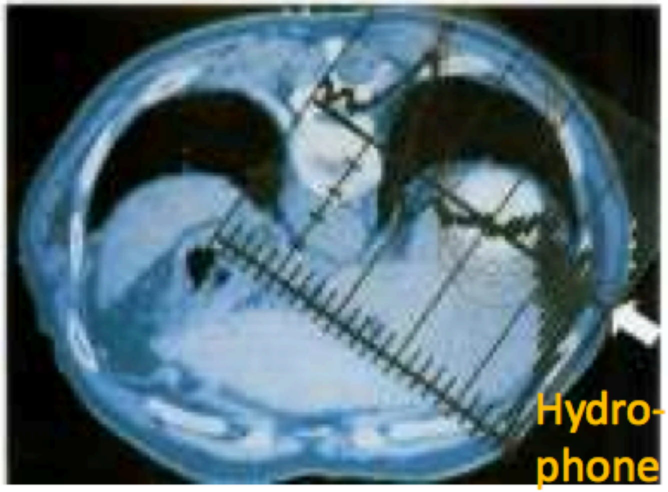
NEW Approach!!!!

The principle



Parodi, Assmann, Mod. Phys. Lett. A 30, 2015

The history



Hayakawa et al, Rad. Onc. Invest. 3 (1995) 42

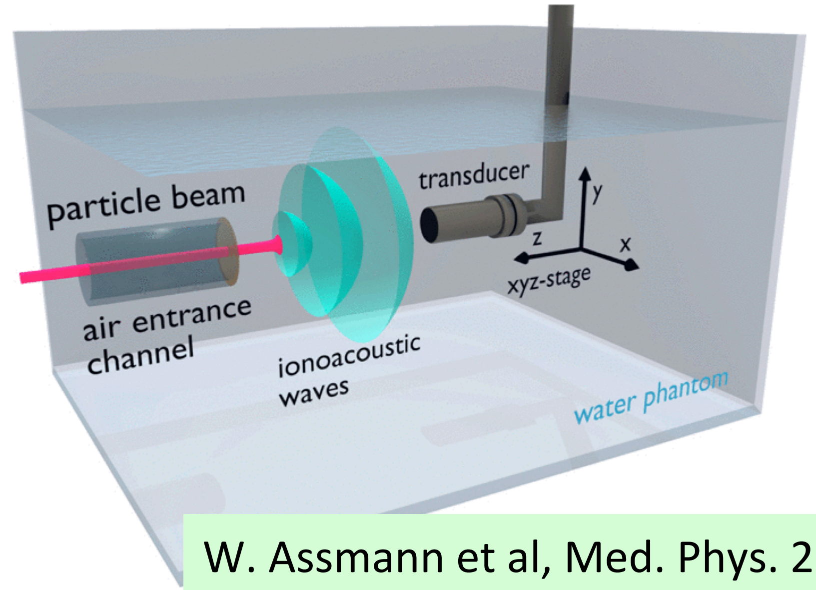
Encouraging results obtained with hydrophones at low frequency

Will modern detectors enable **millimetre-accurate range verification** and even **tomography**?

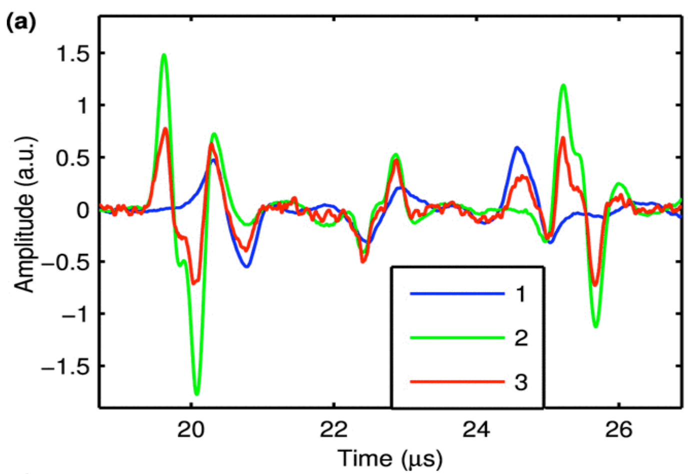
Courtesy of K. Parodi

Ionoacustic: proof of principle

Experimental setup at the MLL Tandem accelerator:
- water phantom
- 3.5 – 10 MHz US detector, remotely controlled
- Beam pulse width 8ns–4ms
- 10^4 – 10^8 protons per pulse



W. Assmann et al, Med. Phys. 2015



Range reduction by Al plate [μm]	
measurement	1020 +/- 60
Geant4 simulation	1060

- Lowest detectable signal of 10^4 p per pulse -> 10^{12} eV (earlier exp.: 10^{14} eV)
- Sub-millimeter range resolution possible
- 2D and 3D imaging capabilities
- Good agreement between simulation (Geant4 + K-Wave) and measurements

Summary & conclusions

- Particle therapy is becoming a new tool to help oncologist in the multi-approach war to cancer.
- Monitoring the beam range is a necessary step to meet the quality standard of a mature clinical technique
- The nuclear interactions of the beam provide the signal to monitor the released dose: PET-γ from β^+ emitters, prompt γ from nuclear excitation and light charged fragments from fragmentation
- Very fast R&D: solutions close to clinical practice for proton, yet on the way for ^{12}C: multimodal approach
- Ionoacustic? Cheap and reliable… maybe in the future

Thanks….

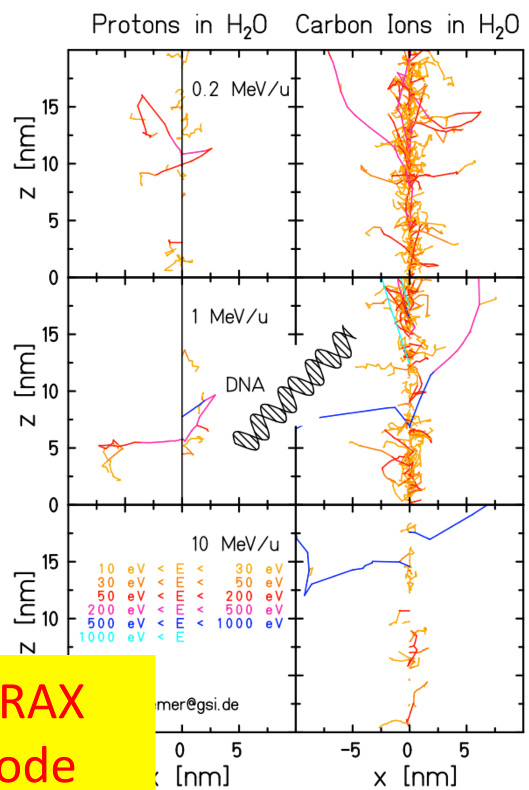
CREDITS

I am in debt for a lot of slides, plots, comments, discussions and with many collegues…

M.Durante, G.Battistoni, K.Parodi, D. Dauvergne & many others…

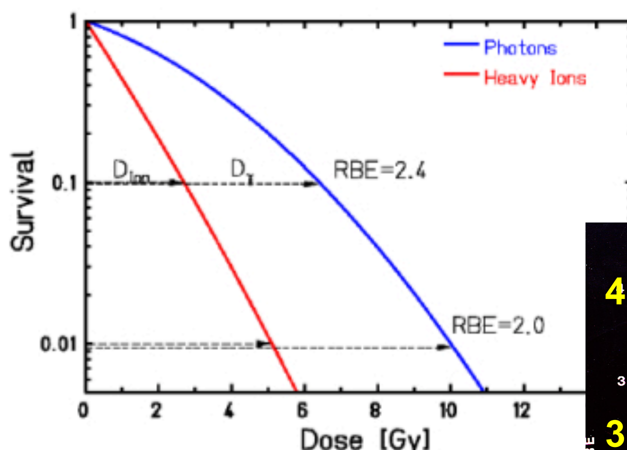
Better than proton? Maybe yes (^{12}C)

M.Kramer et al. JoP 373 (2012),

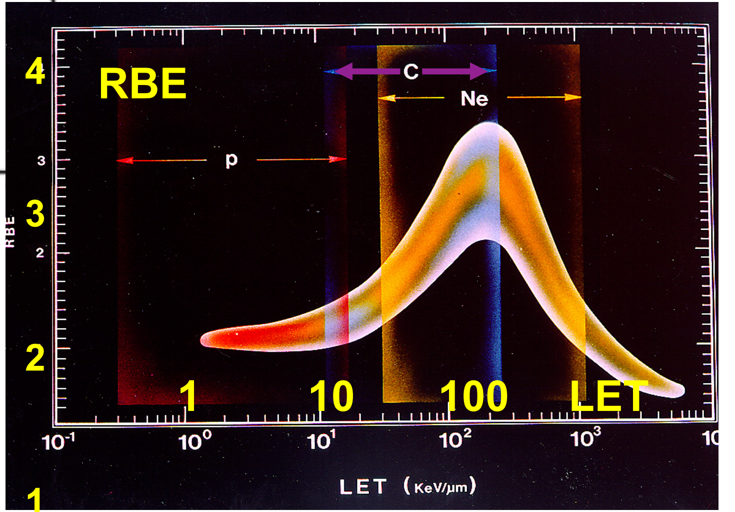


TRAX code

- The heavier ions are much better at killing the tumur cells with respect to the X rays (and p) for a given ➔high RBE
- Heavier ions have better plateau/peak ratio (less dose to the healthy tissue in a treatment) wrt to proton beams



$$RBE = \frac{D_\gamma}{D_{Ion}}\Bigg|_{Isoeffect}$$



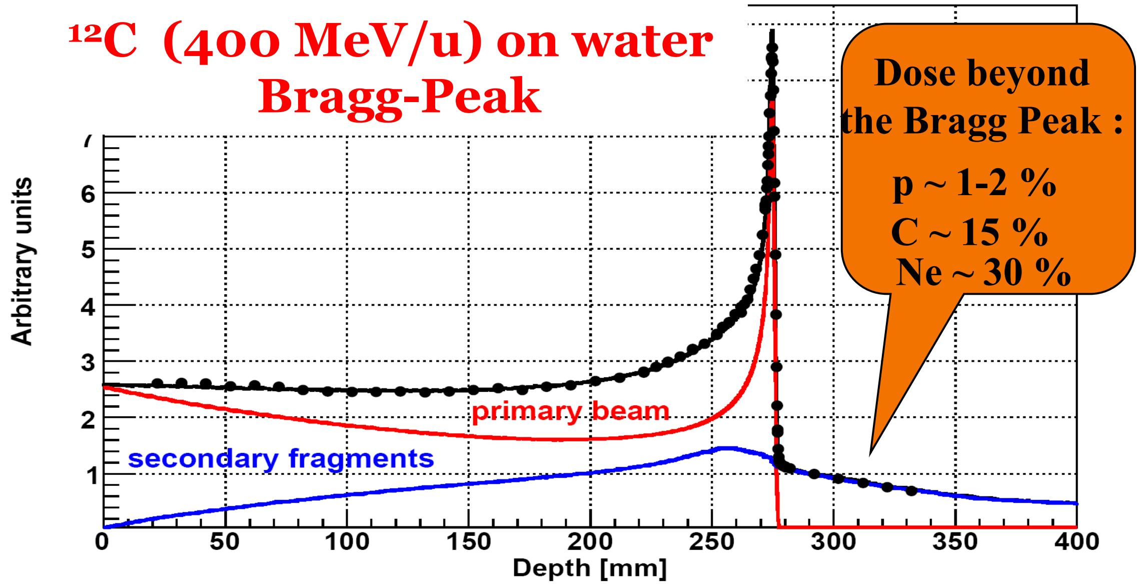
N.B. As far as money (and the space) is the main concern.. protons win easily!

Heavier is better? STOP 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*

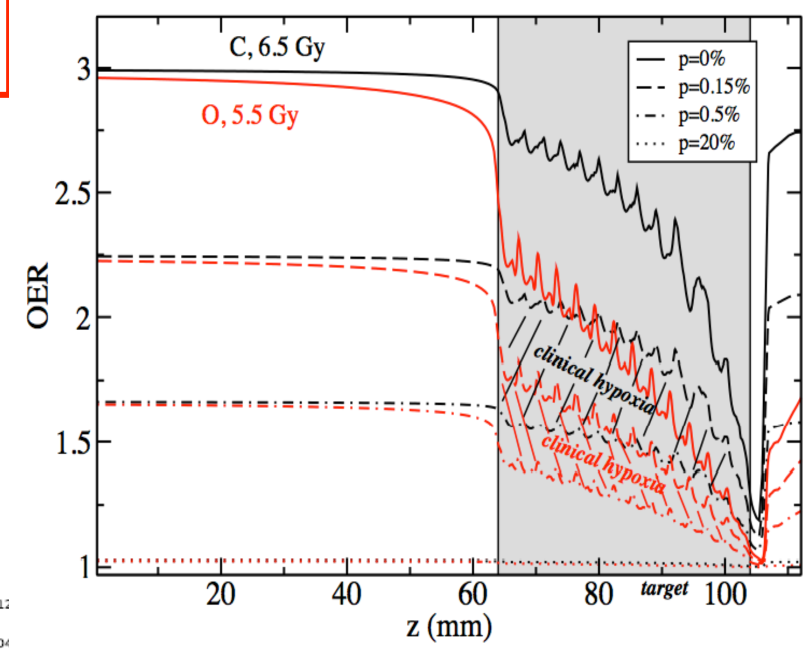


Exp. Data (points) from Haettner et al, Rad. Prot. Dos. 2006
Simulation: A. Mairani PhD Thesis, 2007, Nuovo Cimento C, 31, 2008

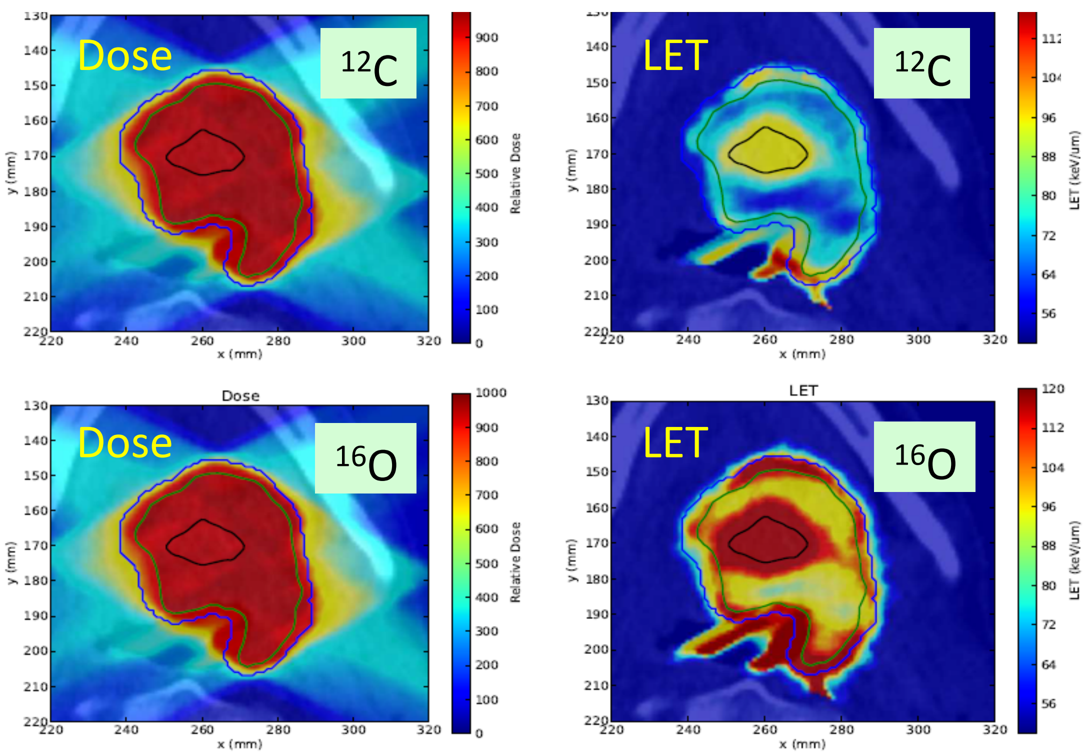
OER and ^{16}O beam

The high LET of the ^{16}O beam is effective against radio-resistant hypoxic tumors (low Oxygen Enhancement Ratio)

M.Kramer et al. JoP 373 (2012),



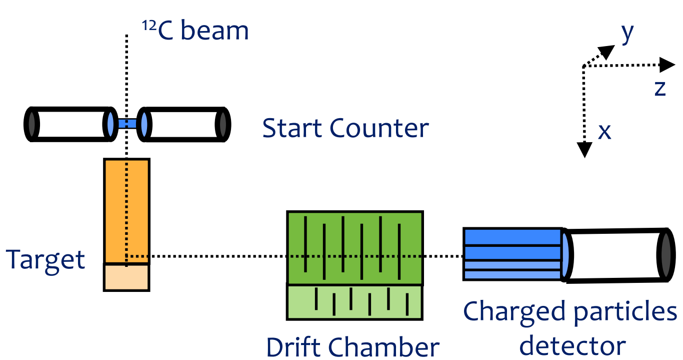
Bassler et al., Acta Oncol 2013

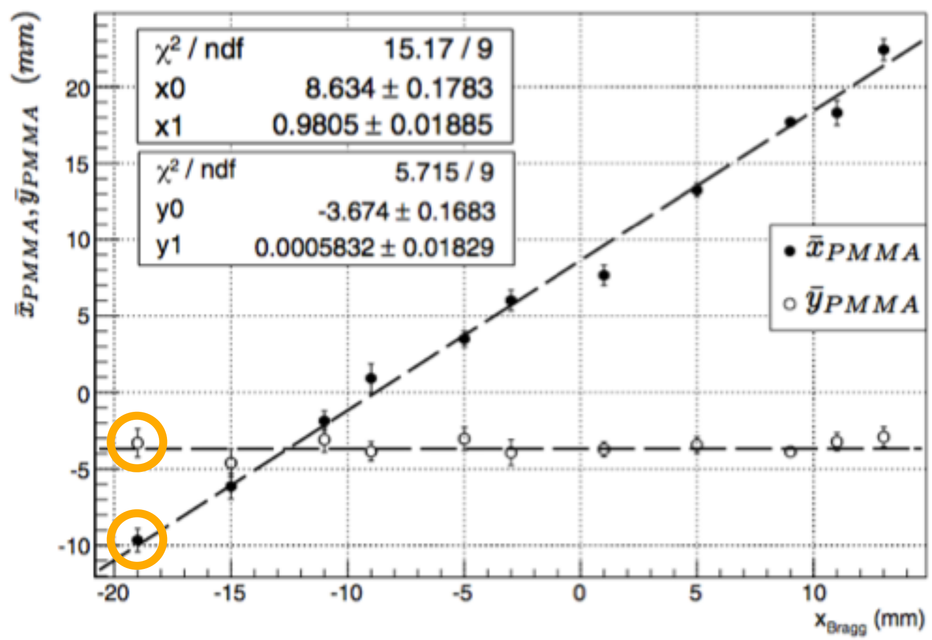


Full treatment or simple boost session with ^{16}O with hypoxic can be a clear improvement with respect to conventional Radiotherapy

Charged secondary emitted from BP ?

- Measurements at LNS (Catania) ^{12}C beam @ 80 MeV/nucleon. Range in PMMA phantom ~ 1 cm.
- Corresponds to the last part of the path in the patient of higher energy, longer range pencil beam -> signal from BP region
- Moving the target the charged signal follows

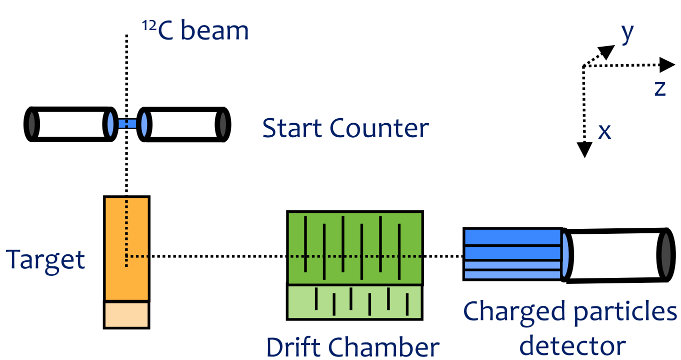


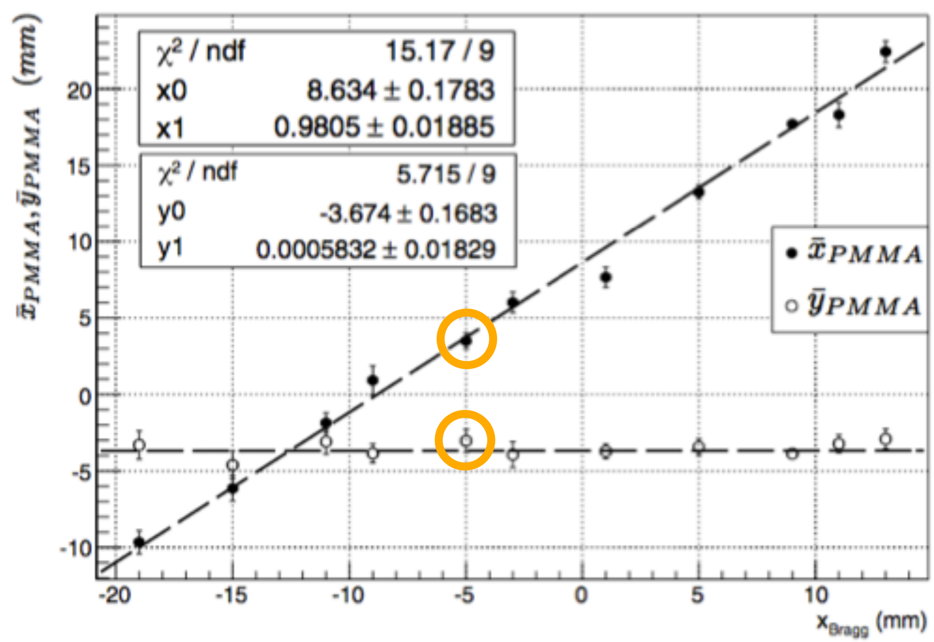


Agodi et al. PMB 2012

Charged secondary from BP ?

- Measurements at LNS (Catania) ^{12}C beam @ 80 MeV/ nucleon. Range in PMMA phantom ~ 1 cm.
- Corresponds to the last part of the path in the patient of higher energy, longer range pencil beam -> signal from BP region
- Moving the target the charged signal follows

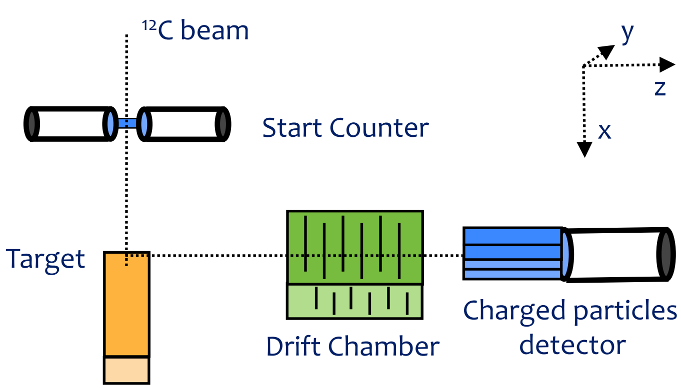


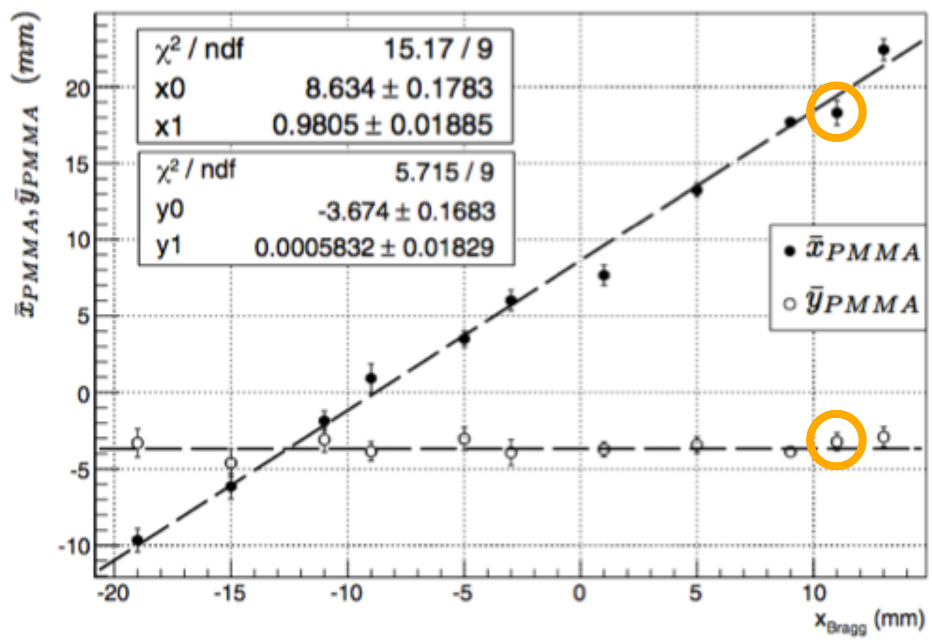


Agodi et al. PMB 2012

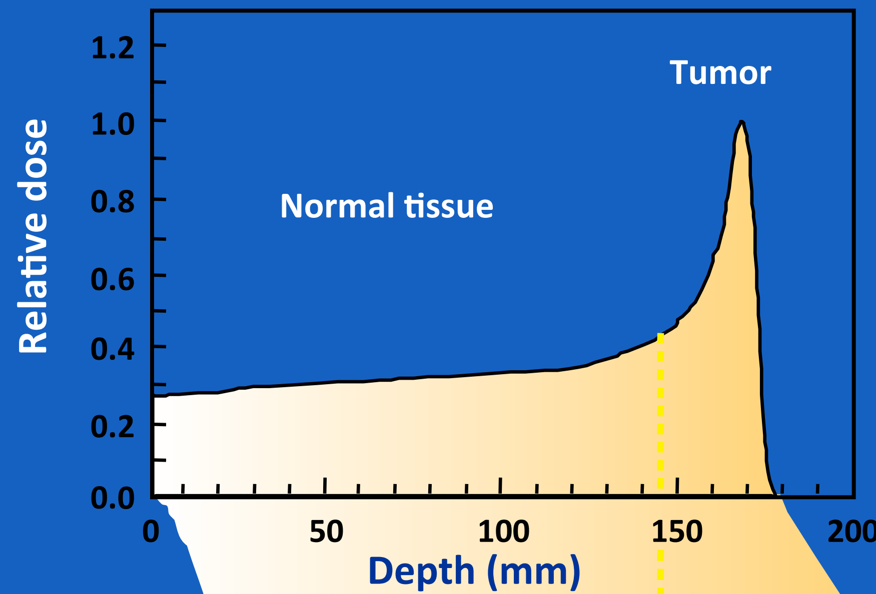
Charged secondary from BP ?

- Measurements at LNS (Catania) ^{12}C beam @ 80 MeV/nucleon. Range in PMMA phantom ~ 1 cm.
- Corresponds to the last part of the path in the patient of higher energy, longer range pencil beam -> signal from BP region
- Moving the target the charged signal follows



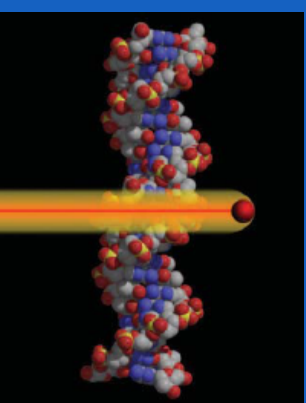


Agodi et al. PMB 2012



Durante & Loeffler,

Nature Rev Clin Oncol 2010



Energy	high	low
LET	low	high
Dose	low	high
RBE	≈ 1	> 1
OER	≈ 3	< 3
Cell-cycle dependence	high	low
Fractionation dependence	high	low
Angiogenesis	Increased	Decreased
Cell migration	Increased	Decreased

Potential advantages

High tumor dose, normal tissue sparing

Effective for radioresistant tumors

Effective against hypoxic tumor cells

Increased lethality in the target because cells in radioresistant (S) phase are sensitized

Fractionation spares normal tissue more than tumor

Reduced angiogenesis and metastatization

Courtesy M.Durante

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

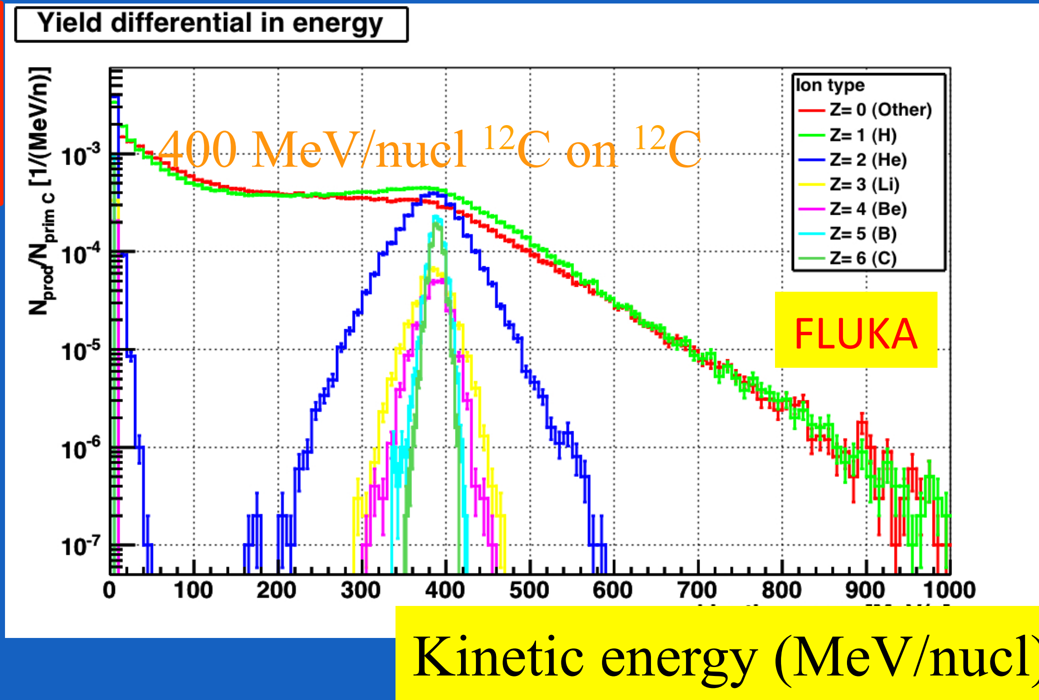
The Z>2 produced fragments approximately have the same velocity of the ^{12}C beam and are collimated in the forward direction

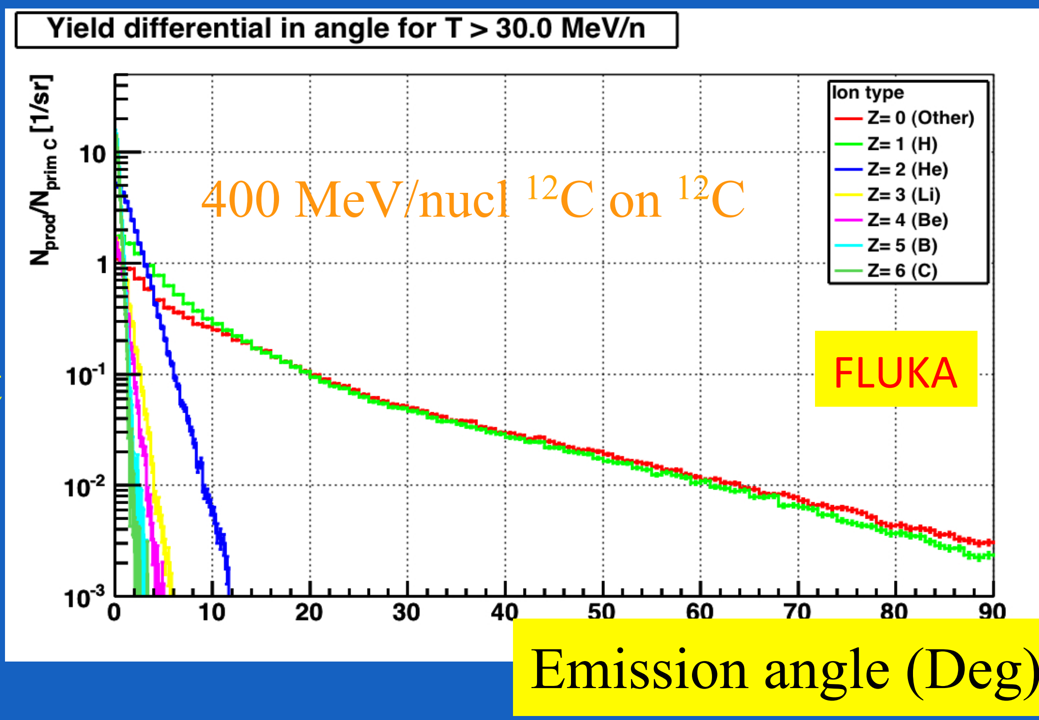
The protons are the most abundant fragments with a wide β spectrum 0<β<0.6 and with a wide angular distribution with long tail

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.

Do not trust MC too much!

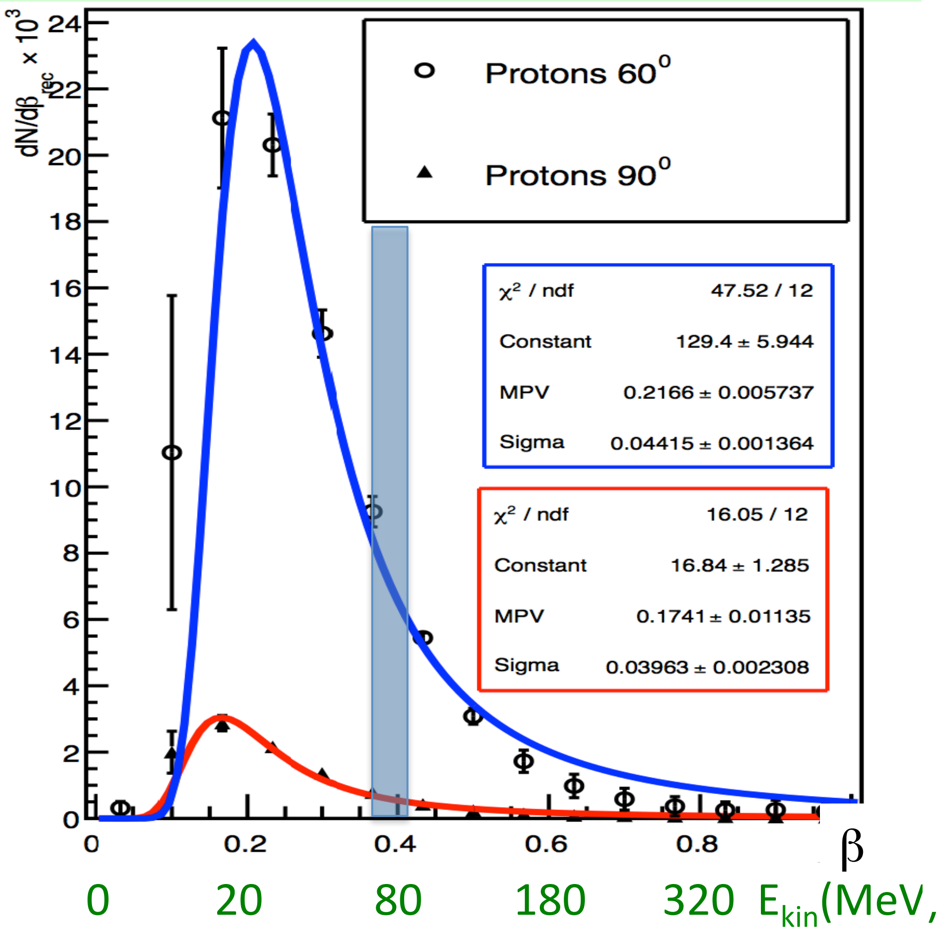




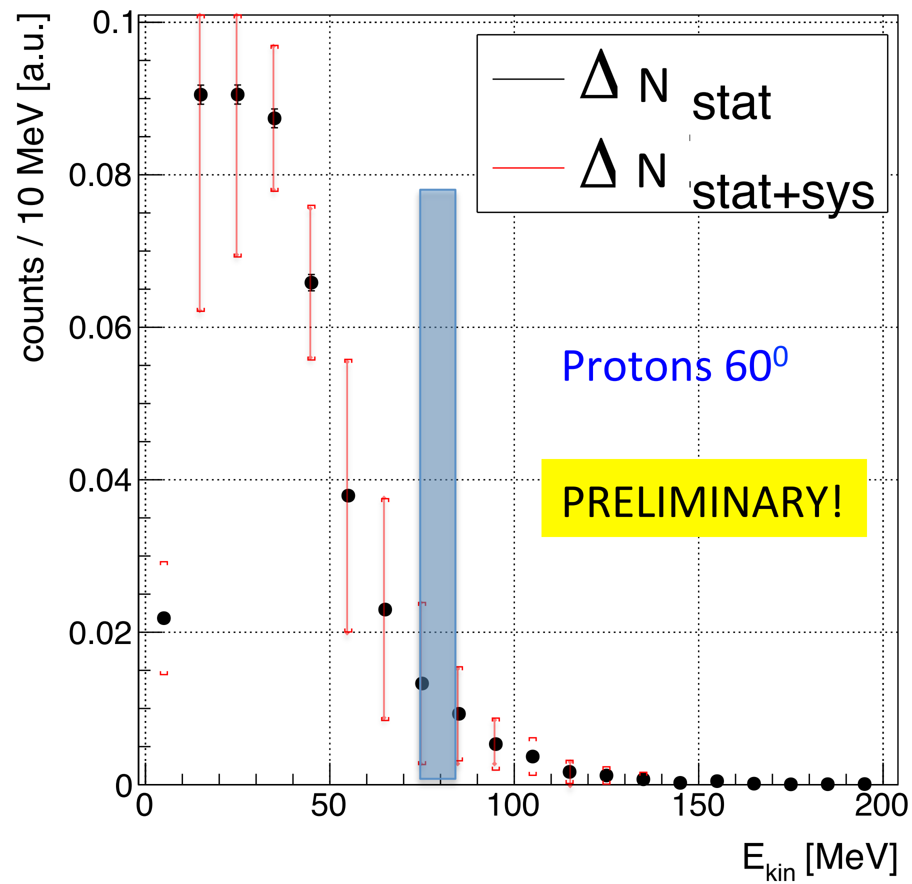
Secondary proton: energy distribution

Only a fraction of the p flux can exit the patient.. 80-90 MeV are needed in the worst case (deep tumor at 8-9 cm from skin)

^{12}C @220 AMeV *L.Piersanti et al. PMB, 2014*

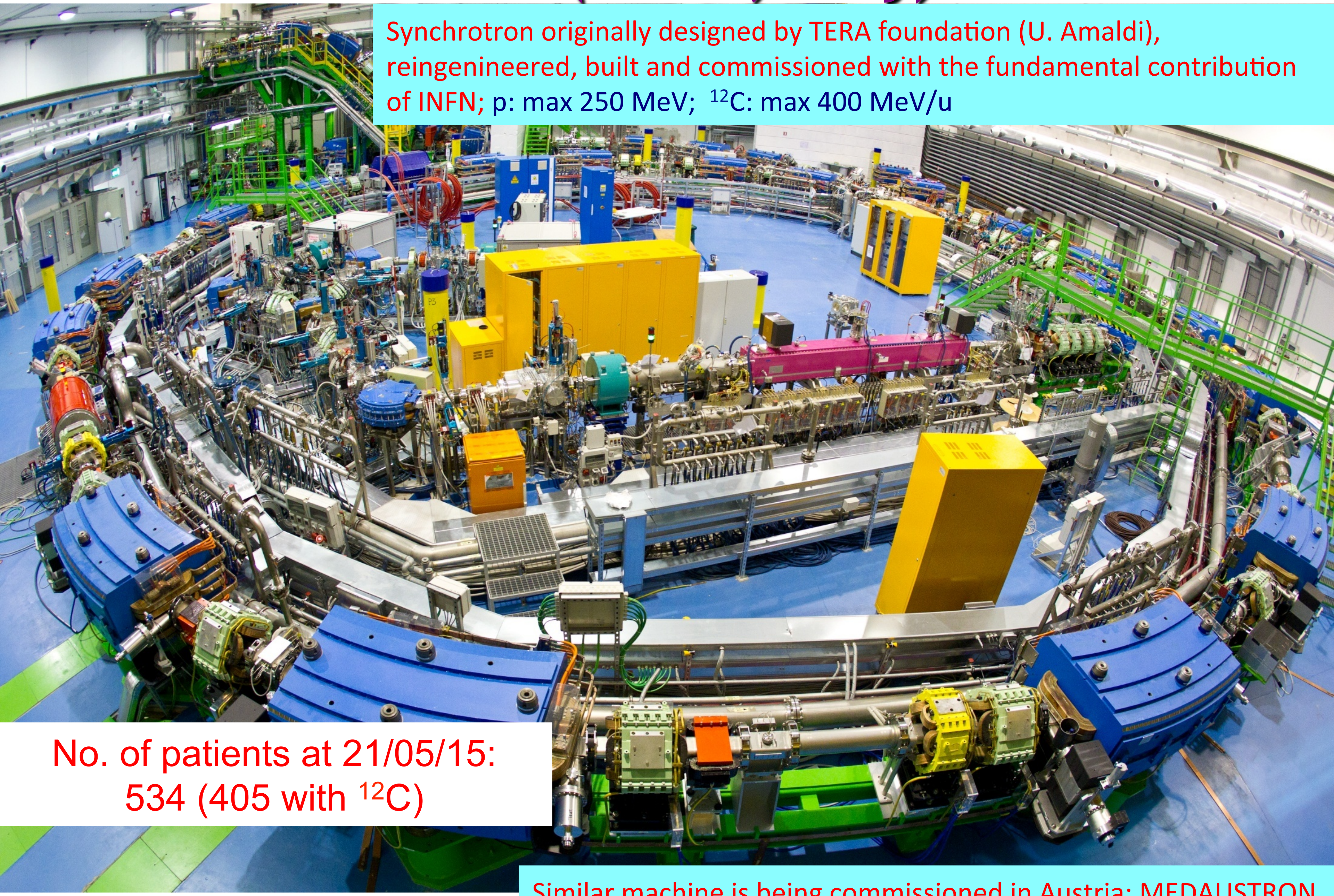


^{4}He @145 AMeV (HIT) to be sub. to PMB



CNAO (Pavia, Italy)

Synchrotron originally designed by TERA foundation (U. Amaldi), reingenineered, built and commissioned with the fundamental contribution of INFN; p: max 250 MeV; ^{12}C: max 400 MeV/u

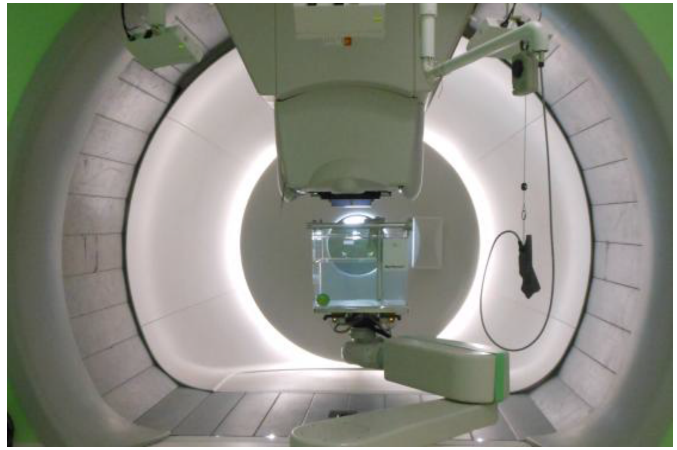


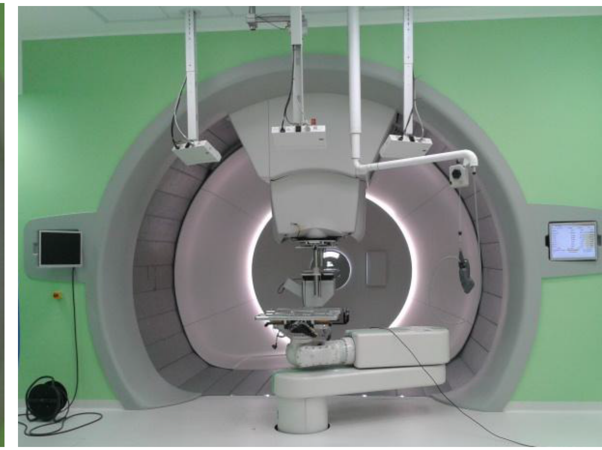
No. of patients at 21/05/15: 534 (405 with ^{12}C)

Similar machine is being commissioned in Austria: MEDAUSTRON

New Proton Therapy in Trento (Italy)

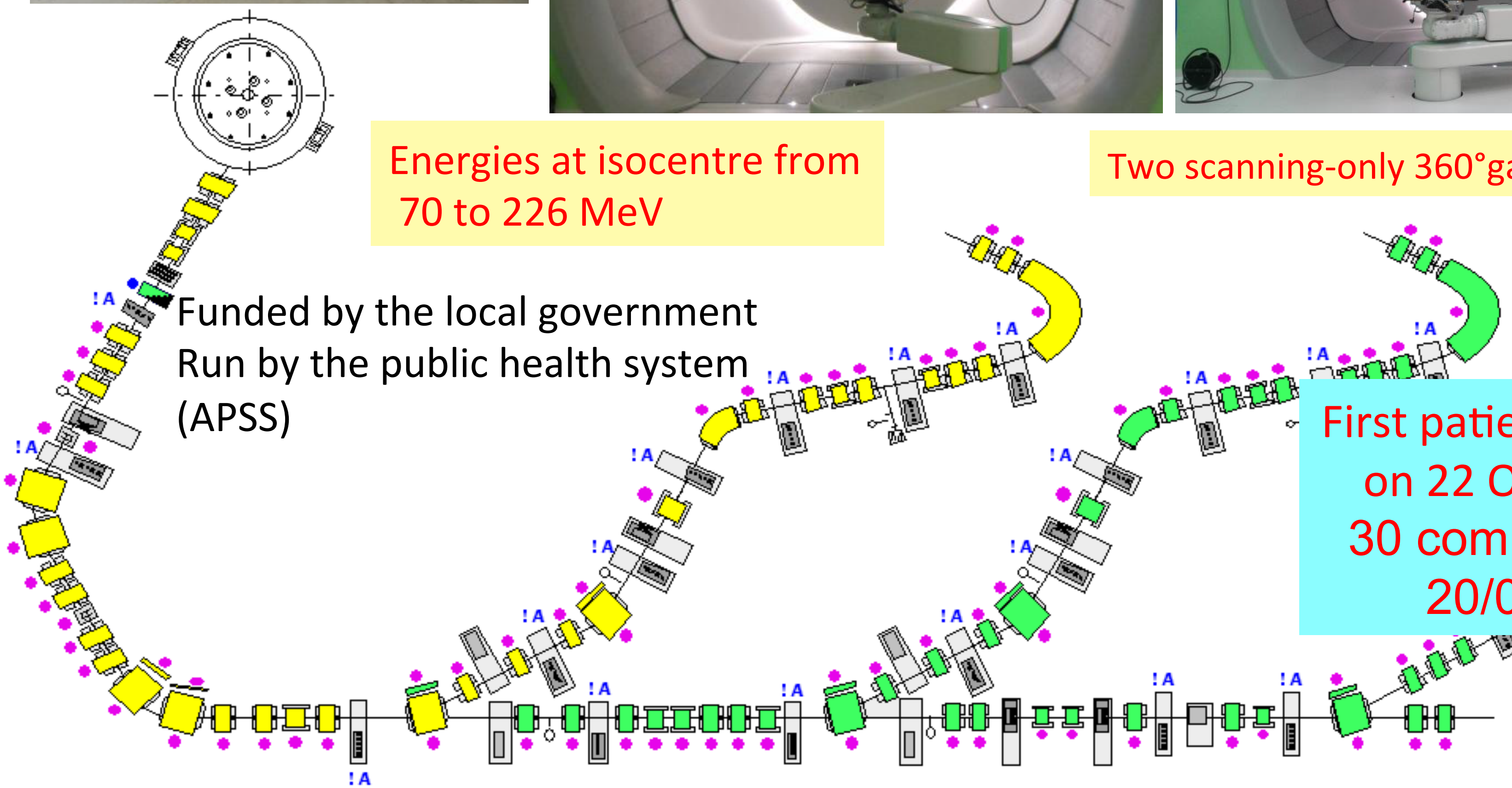
2D imaging in one gantry room Ct on rail being installed in the second gantry room





Energies at isocentre from 70 to 226 MeV

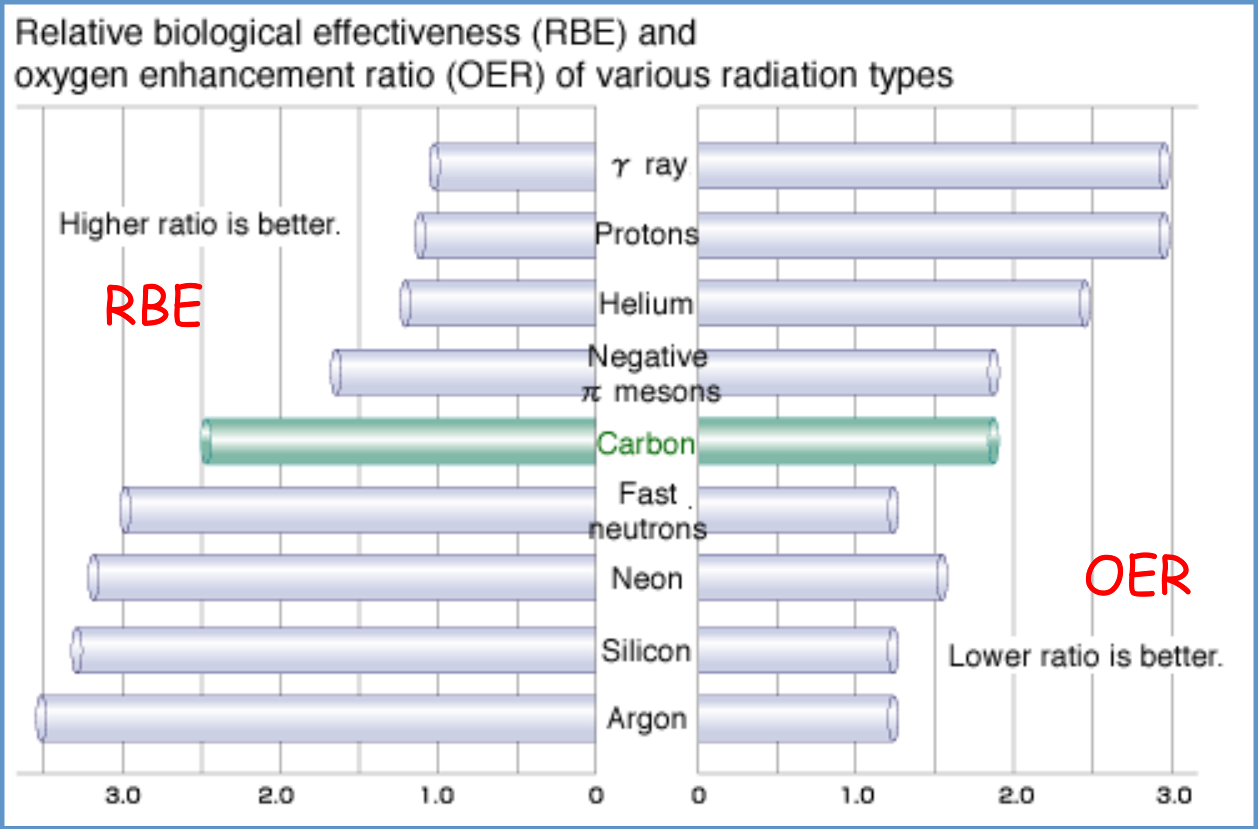
Two scanning-only 360°gantries



Funded by the local government
Run by the public health system (APSS)

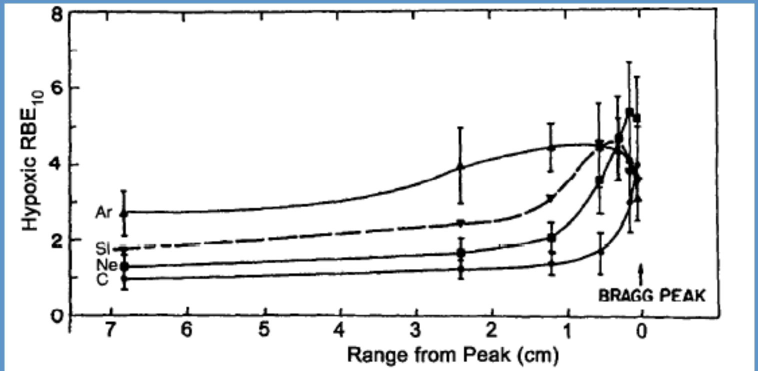
First patient treated on 22 Oct. 2014
30 completed at 20/05/15

Radiations vs Biological effects

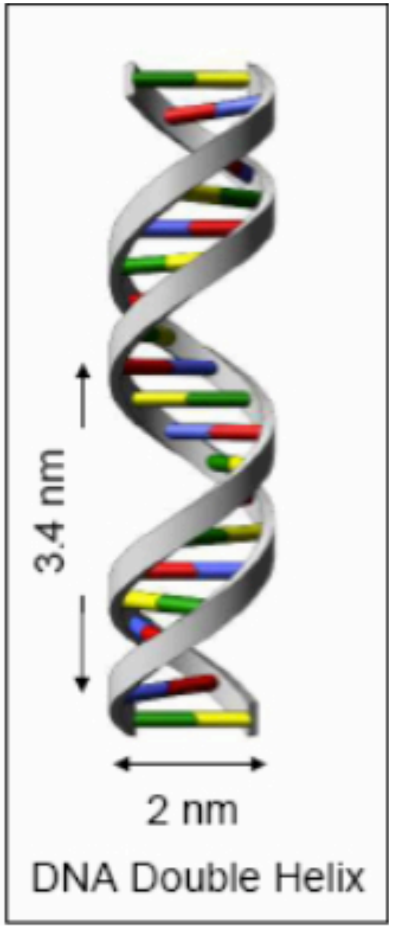


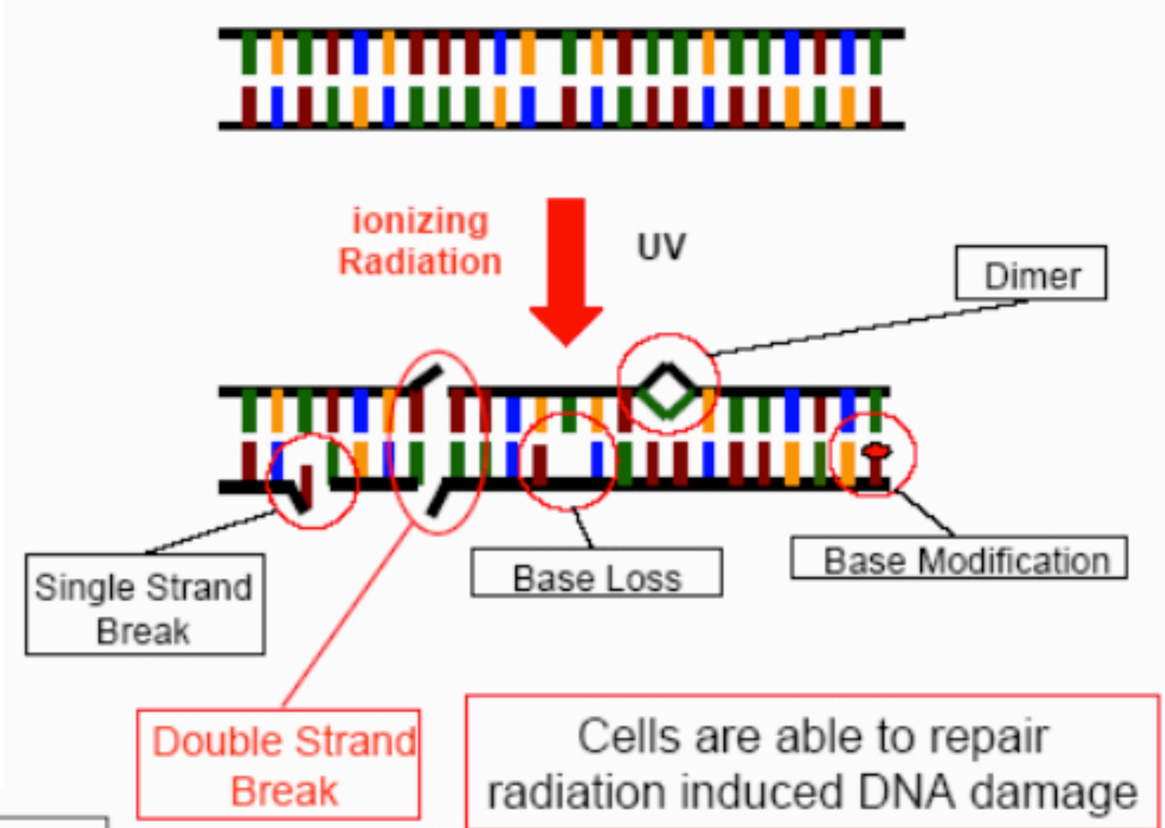
^{12}C -> good compromise between RBE and OER.

Optimal RBE profile vs penetration depth position.



Ionizing radiation and DNA damage

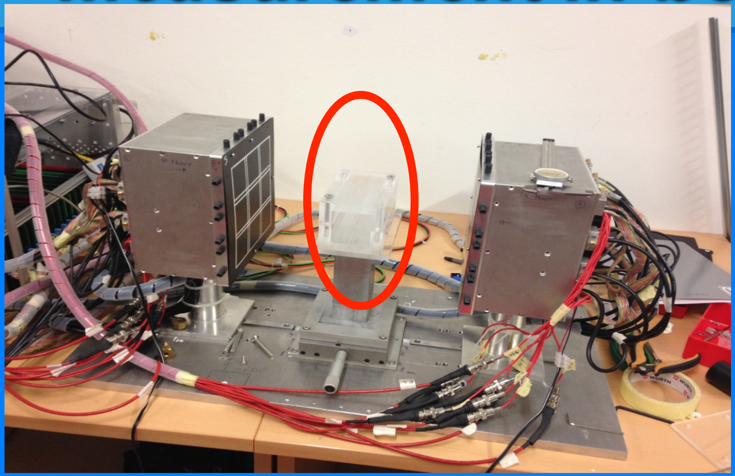


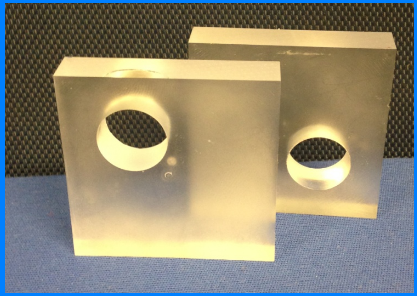


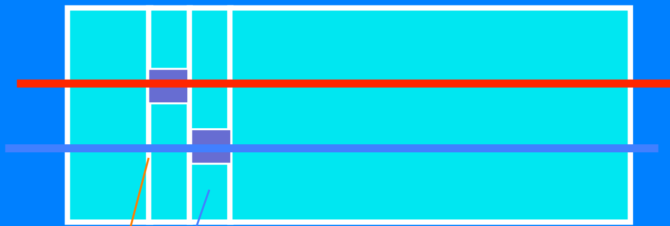
SSB	1000
DSB	30-40
DNA-Protein Crosslinks	50
Complex Damage (SSB+Base lesion)	60

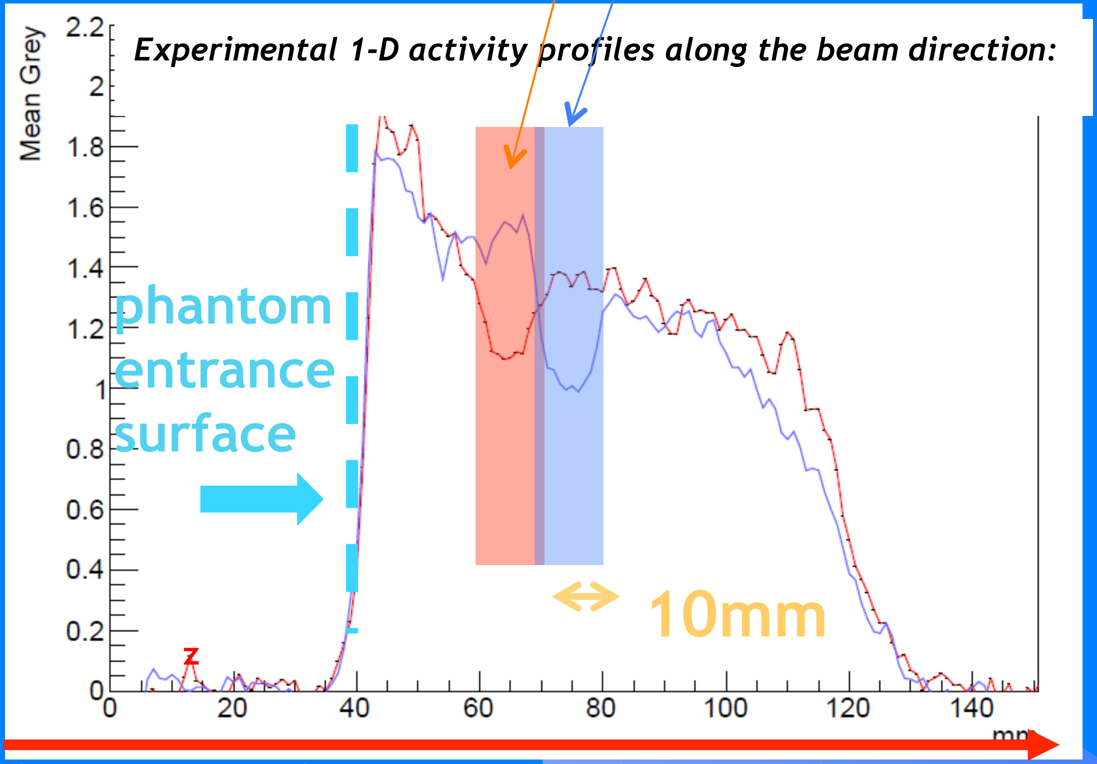
Few meters of DNA packed in the 5-10 μm radius of the cell nucleus

Spotting structures with β⁺ activity measurement in-beam (proton beam at CNAO)







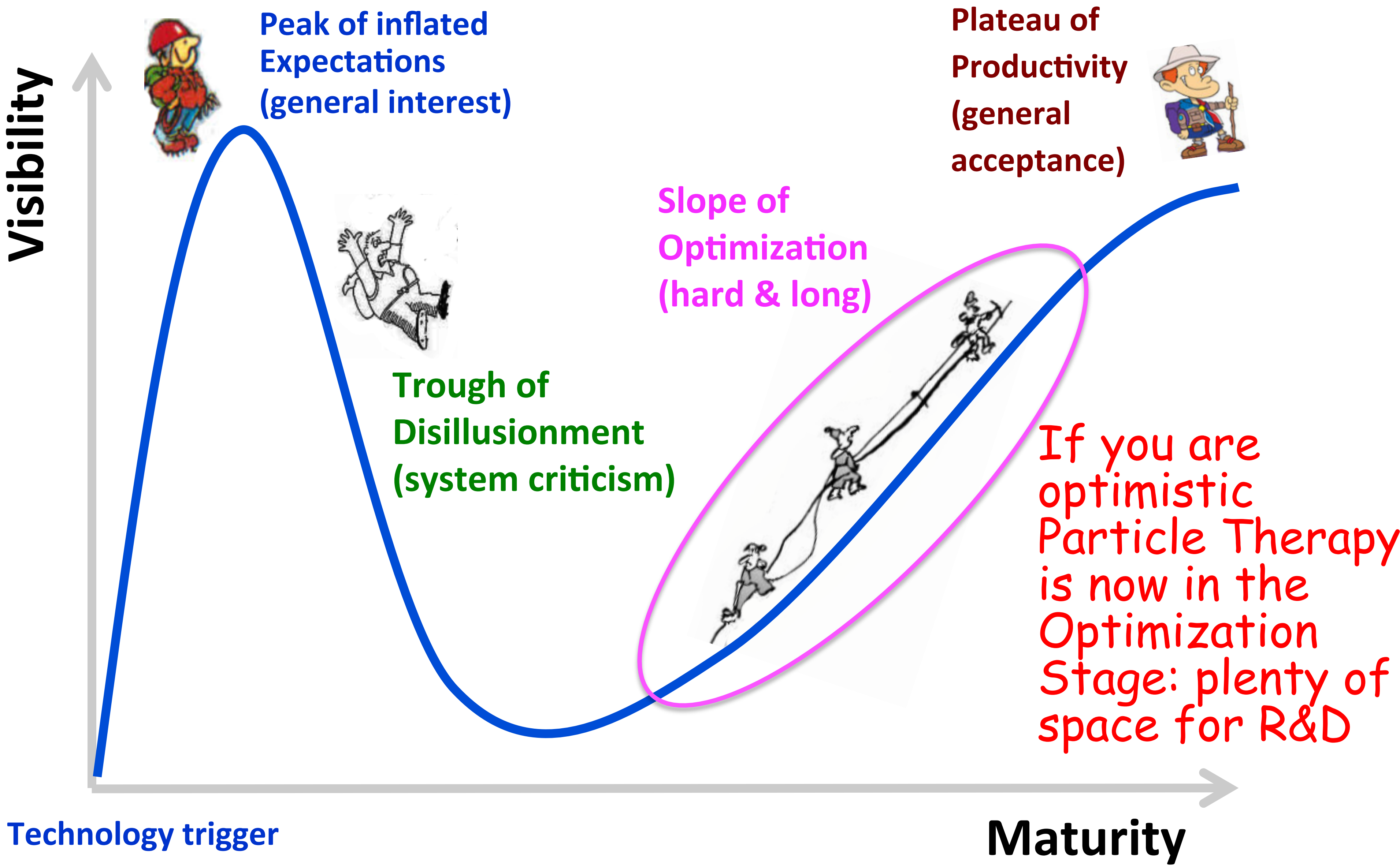


A PMMA phanton with air holes in two different positions was irradiated with protons.
A uniform 2 Gy dose was delivered to a 4x4x6 cm^3 PTV.
The proton TP is composed of 34 energy layers with energies ranging from 62 MeV up to 116 MeV/u.

V. Rosso et al,
Submitted to Nucl. Instr. & Meth.

Each profile was calculated over a volume that passes trough one air cavity. The reported profiles correspond to 360 s data acquisition and the profiles were normalized to the same area.

Typical Hype Cycle for Innovation Technology



adapted from Becker & Townsend

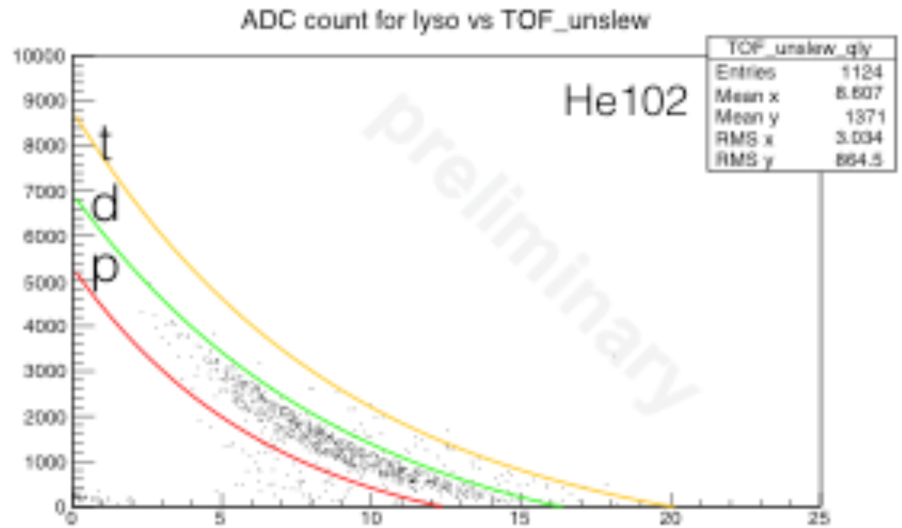
Helium beam @90°

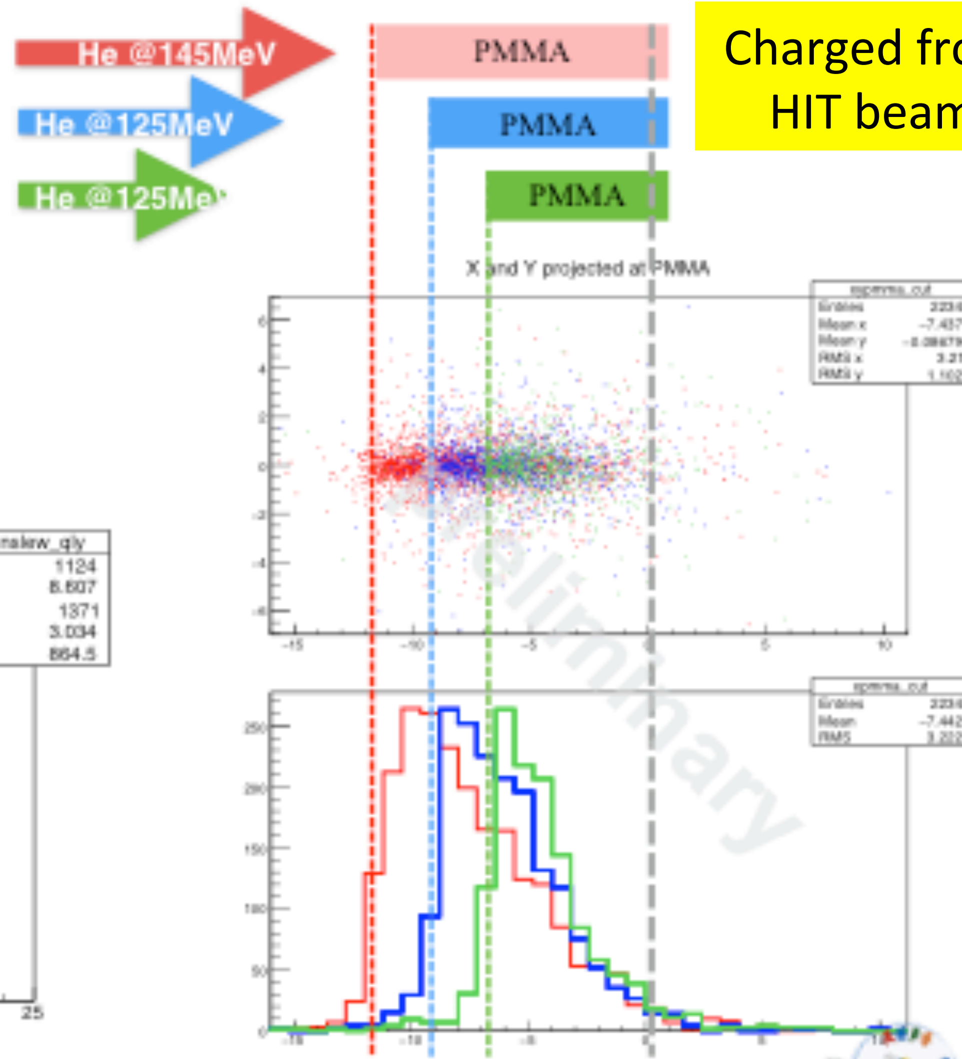
Charged secondaries monitoring

A non negligible production of charged particles at large angles is observed for all beam types.

The emission shape is correlated to the beam entrance face and BP position as already measured with ^{12}C at GSI.
[Piersanti et al. PMB, 59 (2014)]

Charged from HIT beam





To be submitted to PMB

preliminary

Which is the right beam for therapy?

Beam lateral deflection

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