

Positron Emission Tomography in Particle Therapy



Particle Therapy

What & why

Open issues (range monitoring)

Prospects

How to design, build, operate a PET detector

the INSIDE project (in-beam PET in Particle Therapy)

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Cancer Statistics

Cancer Statistics

Cases

14.1 million

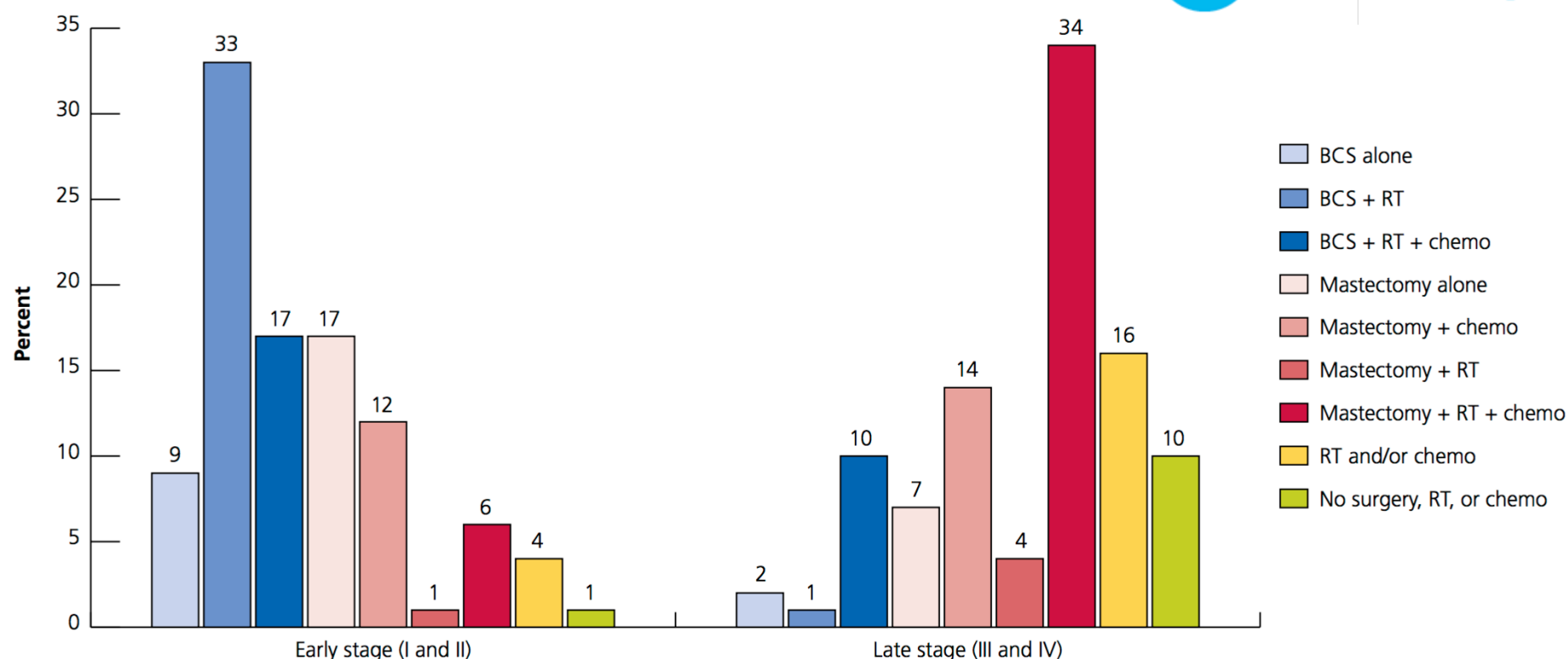


Deaths

8.2 million



Female Breast Cancer Treatment Patterns (%), by Stage, 2011

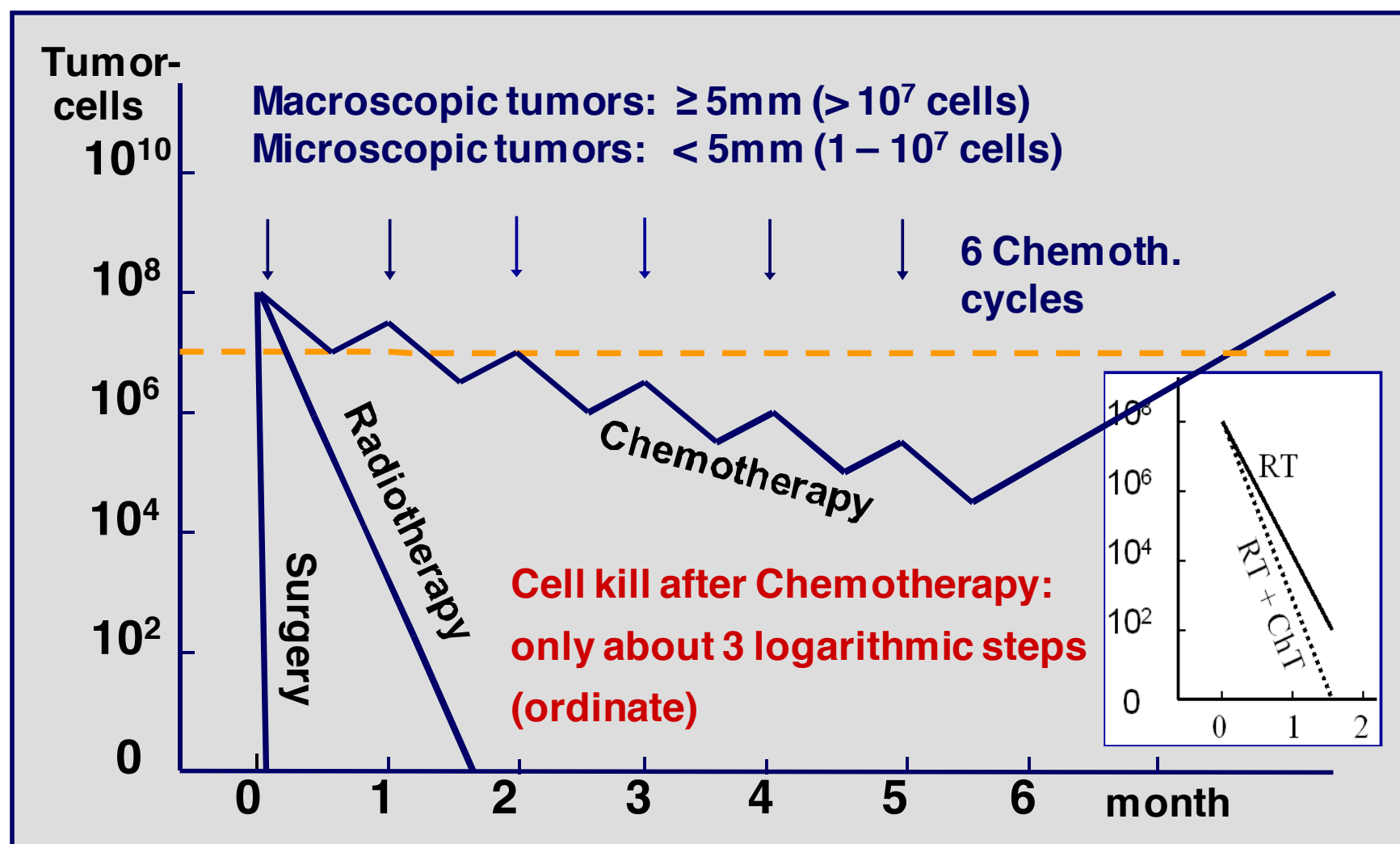


BCS = breast-conserving surgery; RT = radiation therapy; Chemo = chemotherapy and includes targeted therapy and immunotherapy drugs.

Source: National Cancer Data Base, 2011.³⁸

American Cancer Society, Surveillance and Health Services Research, 2014

Tumor therapy comparison

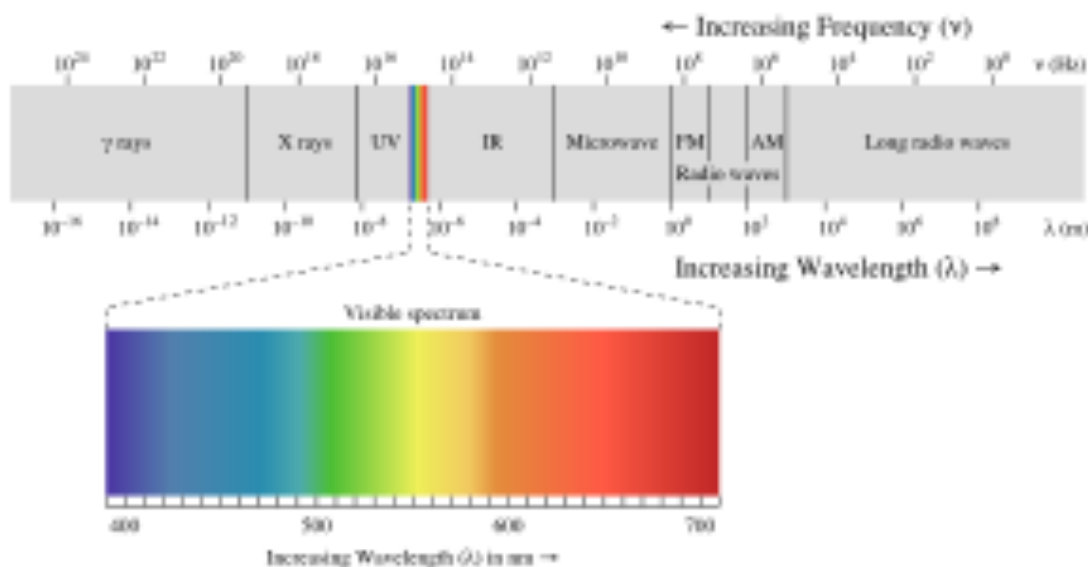


(Molls, TU München; according to Tannock: Lancet 1998, Nature 2006)

Medical Imaging

Medical Imaging

Physics and Medicine have been tightly bound by Medical Imaging technologies for more than a century...



Medical Imaging can be...
... morphological (e.g., CT)



X-rays!!! (Roentgen, 1895)

Medical Imaging

X-rays are absorbed by the target (i.e., the human body)

Absorption is related to the density via the Lambert-Beer law

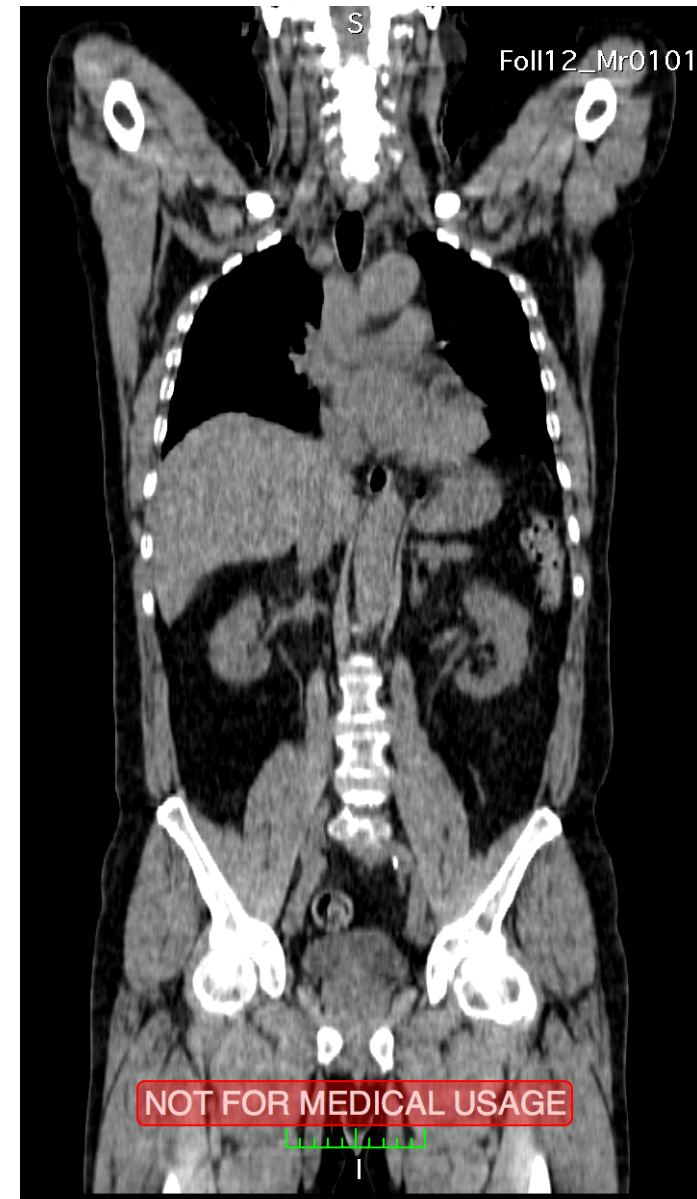
$$I(z) = I(0) \exp(-\mu(\rho)z)$$

$$\rho = \rho(z)$$

By measuring I , μ can be evaluated!

And then the body local density, with an amazing resolution...

Let's take a look at a CT scan...



Medical Imaging

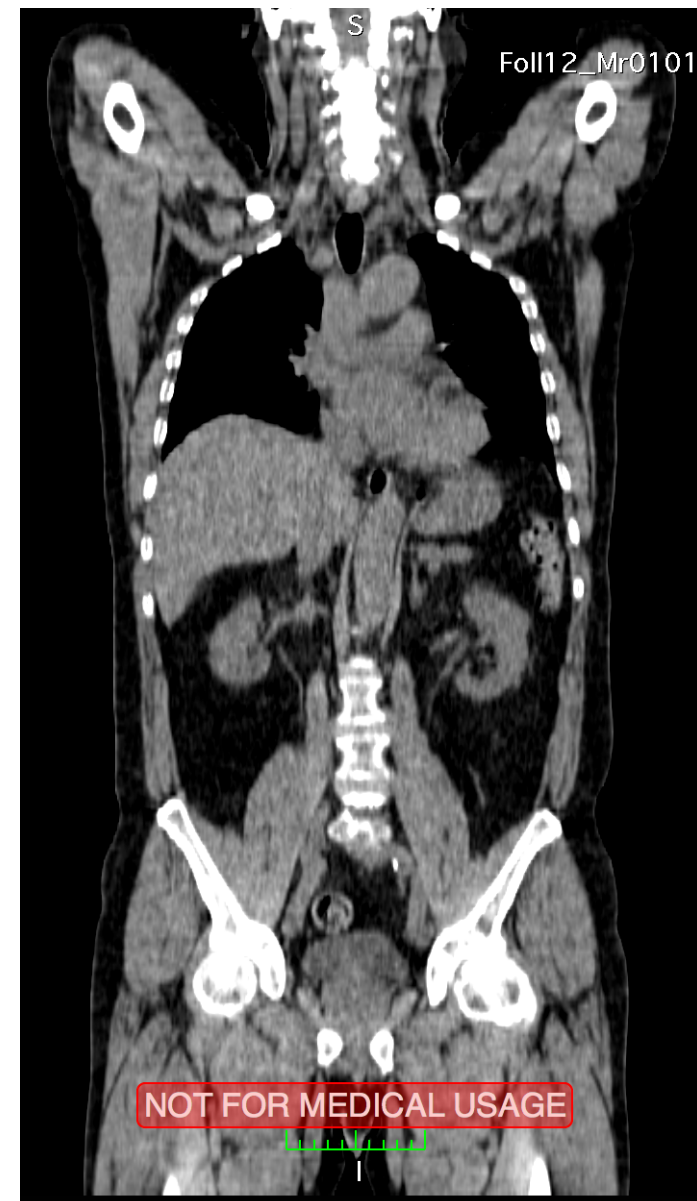
Computed Tomography

Spatial Resolution: $\sim 100 \mu\text{m}$

Time Resolution: irrelevant

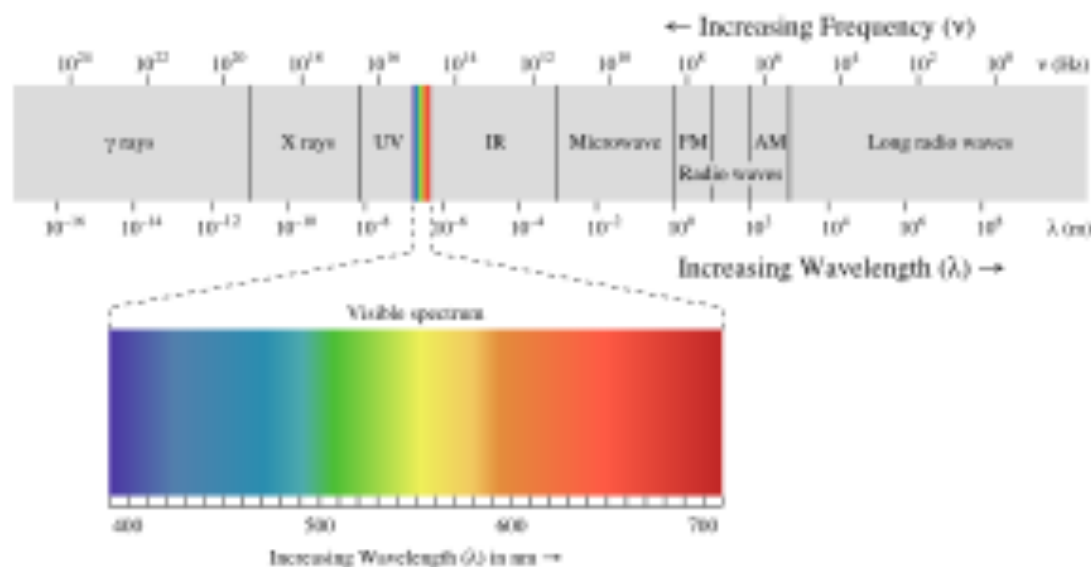
Energy Resolution: irrelevant

is morphological information enough
for diagnosis, staging, follow-up of a
disease?



Medical Imaging

Physics and Medicine have been tightly bound by Medical Imaging technologies for more than a century...



Medical Imaging can be...
... morphological (e.g., CT)
... **functional (e.g., PET)**

X-rays!!! (Roentgen, 1895)

Nuclear Imaging

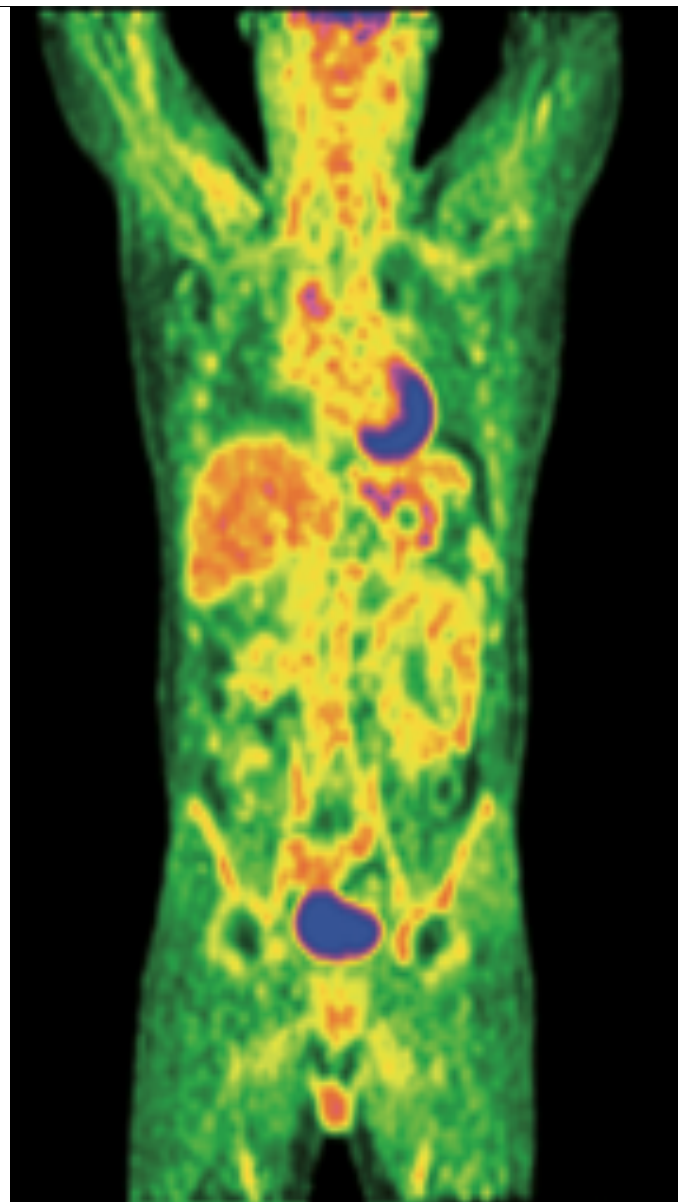
Positron Emission Tomography

Spatial Resolution: $\sim 3\text{-}4\text{ mm}$

Time Resolution: crucial

Energy Resolution: very important

functional information is particularly
relevant for diagnosis, staging,
follow-up



Particle Therapy

Standard of care: Radiotherapy



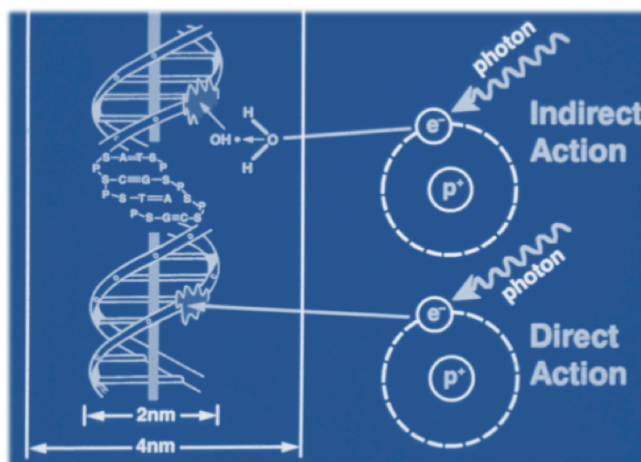
Photons

→ $E_{\max} = 6 \text{ MeV}$

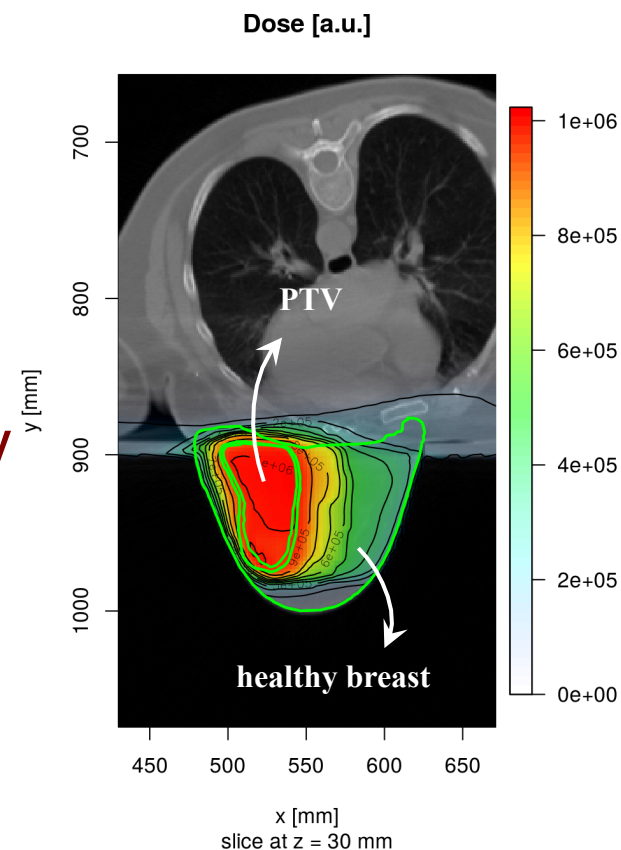
Daily Dose : ~ 2 Gy

Sessions: ~ 10 - 20

Total Dose: ~ 20 - 40 Gy

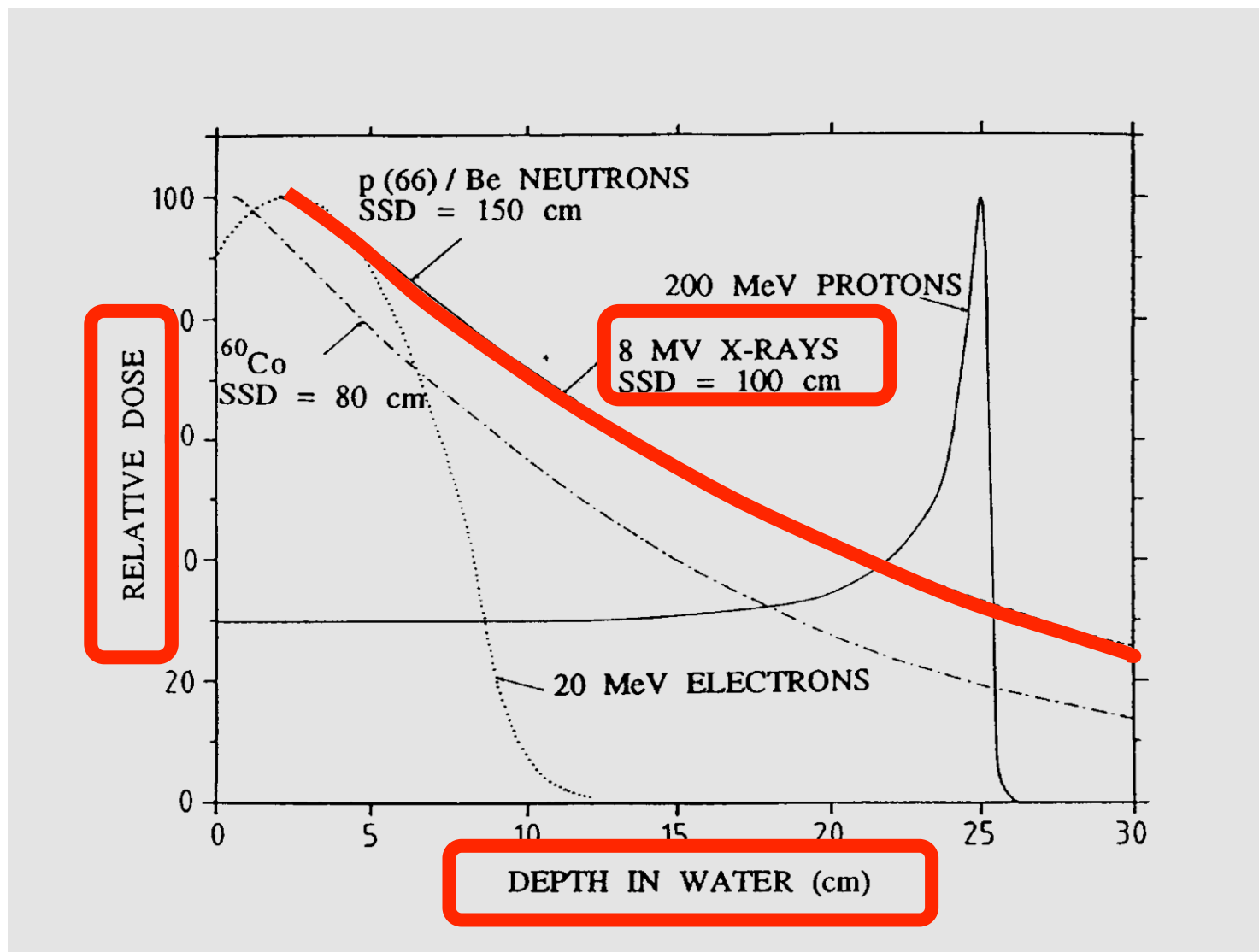


Breast tumour

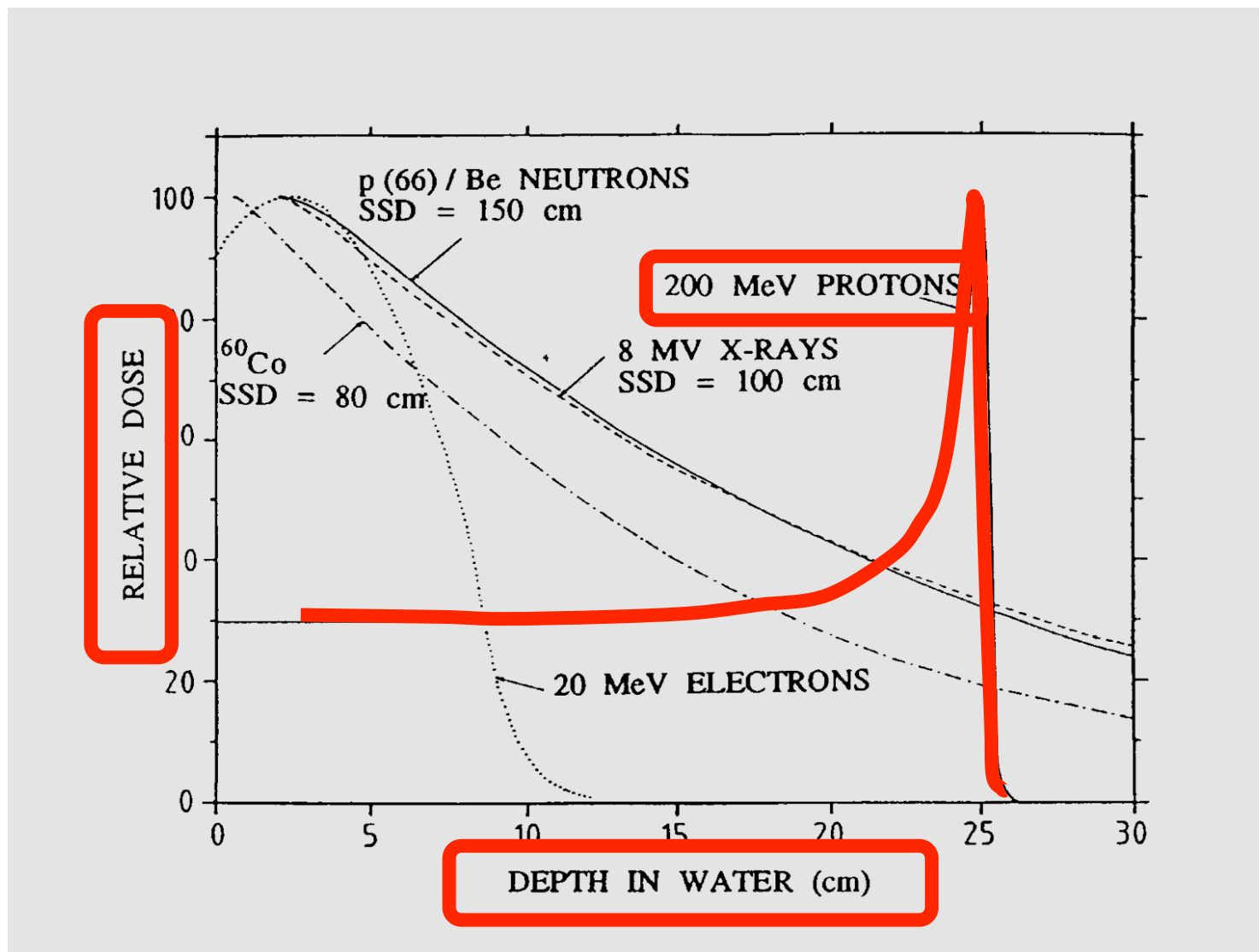


small, reliable and not so expensive ->40 years R&D

Standard of care: Radiotherapy



Particle therapy: the Bragg Peak



Particle Therapy



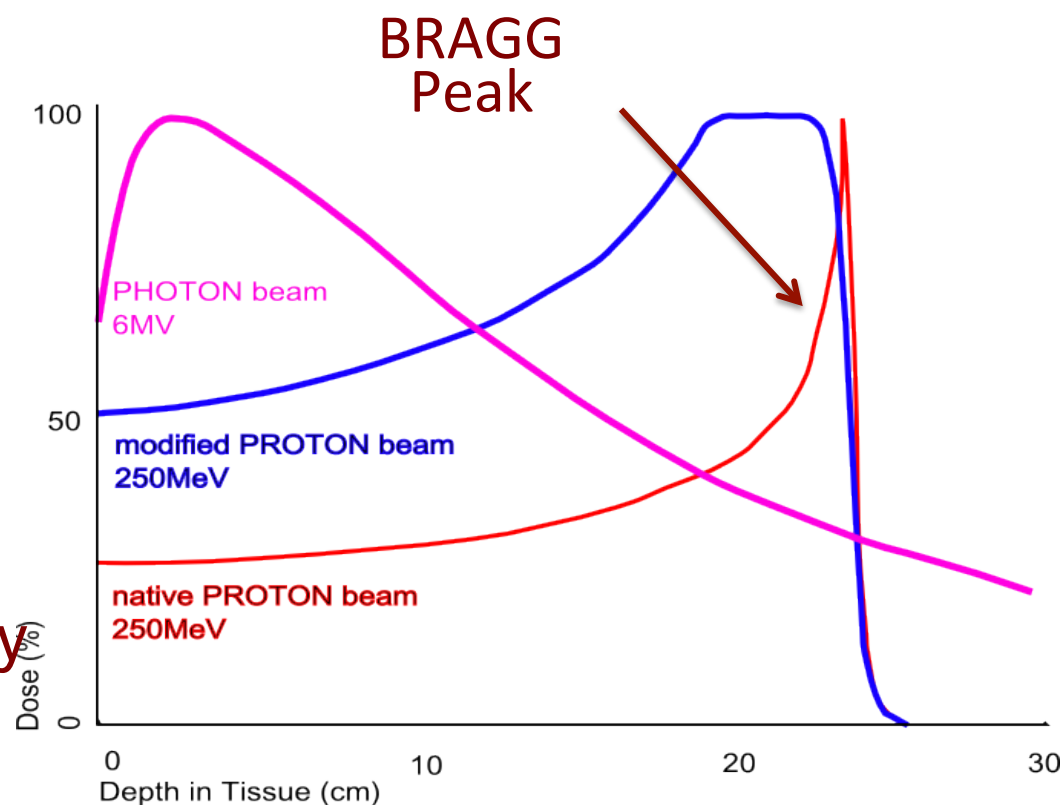
Daily Dose: ~ 2 Gy
Sessions: ~ 10 - 30
Total Dose: ~ 20 - 60 Gy

Protons

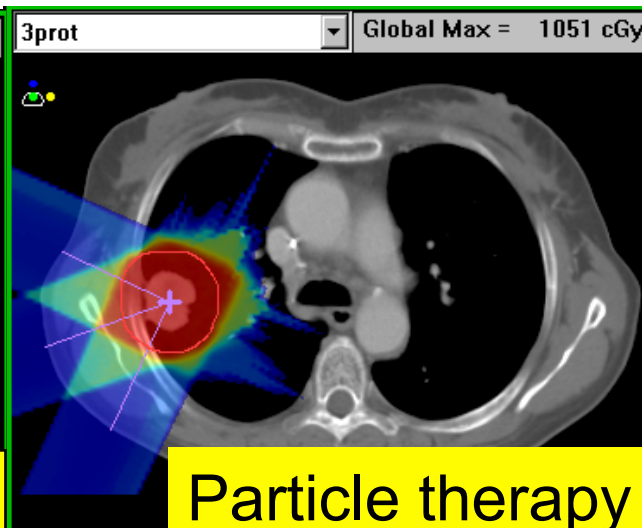
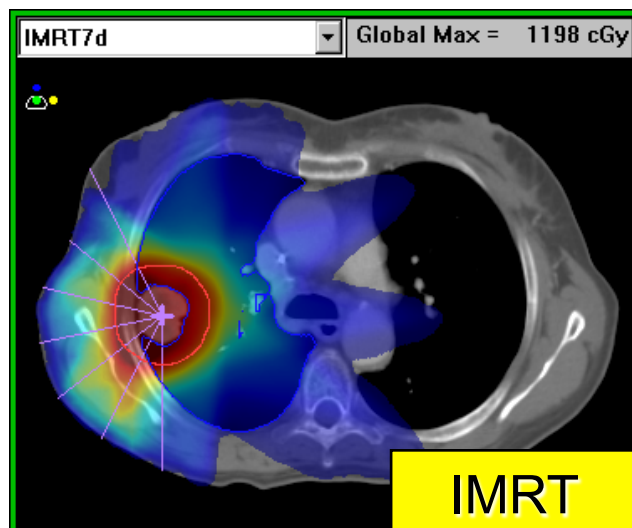
→ $E_{\text{max}} = 250 \text{ MeV}$

Ions

→ $E_{\text{max}} = 400 \text{ MeV/u}$

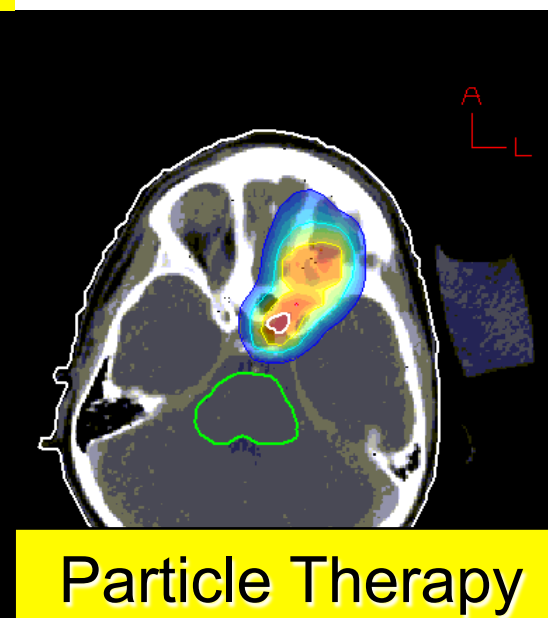
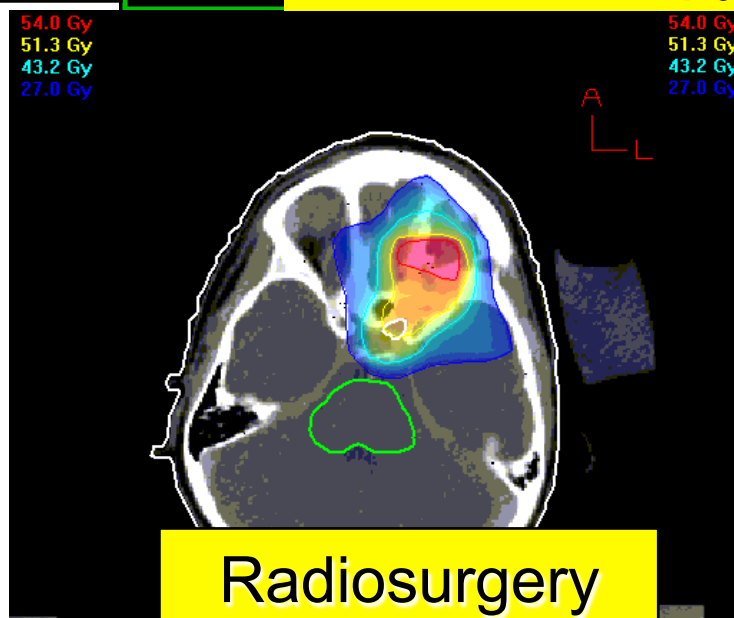


Examples of Photons vs Particles...

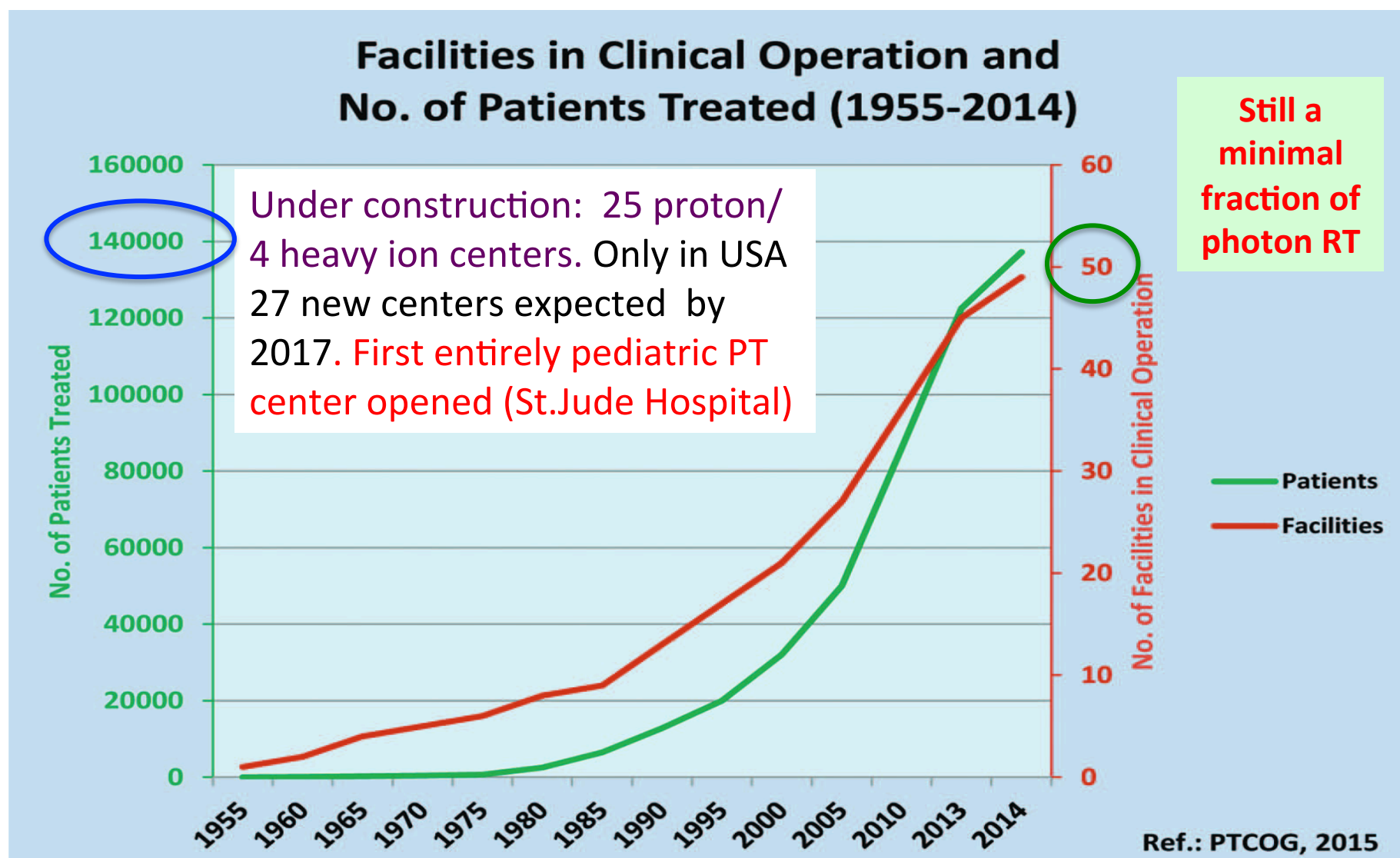


Particle therapy shows better selectivity with respect to photon-based techniques

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

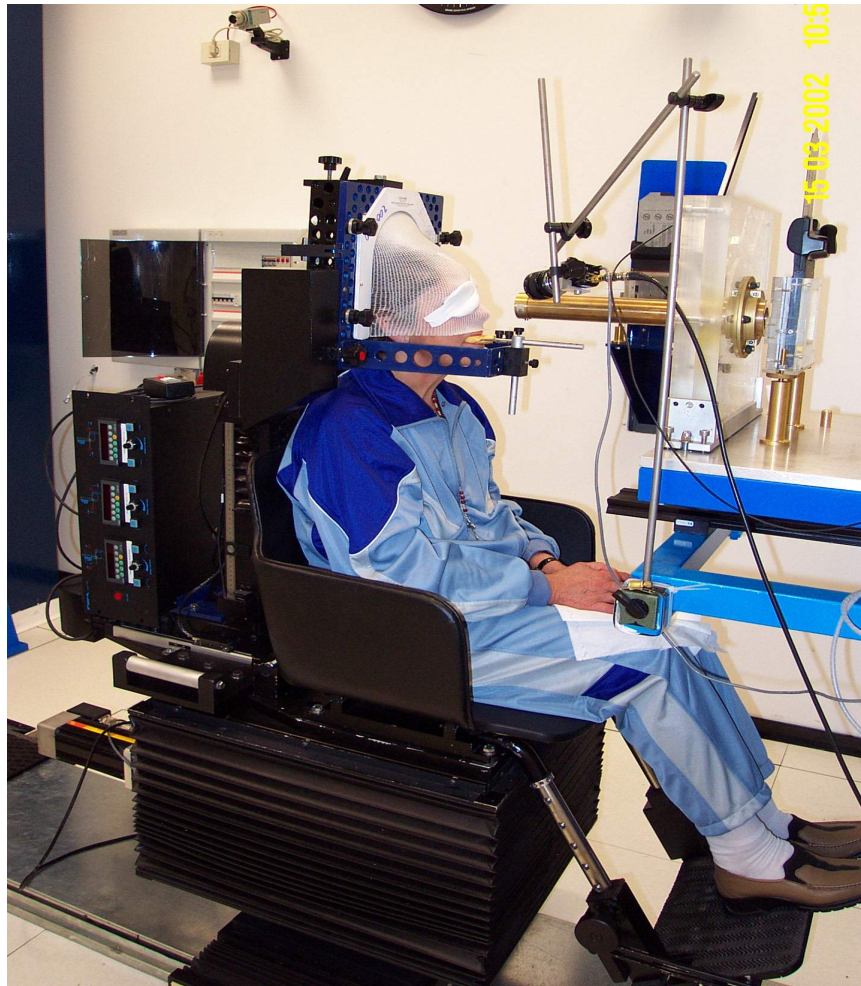


Particle Therapy in the world



Community looking at ^4He – ^{16}O beams: begin to be tested at clinical center
Piergiorgio Cerello – cerello@to.infn.it **Giornate di Studio sui Rivelatori** - Cogne, February, 23rd-26th 2016

Particle therapy in Italy: CATANA



INFN – LNS
62 MeV protons
Eye melanoma treatment
since 2002

Particle therapy in Italy: ATREP

ATreP

Agenzia Provinciale per la Protonterapia
Azienda Provinciale per i Servizi Sanitari
Trento, Italy
Since 2014

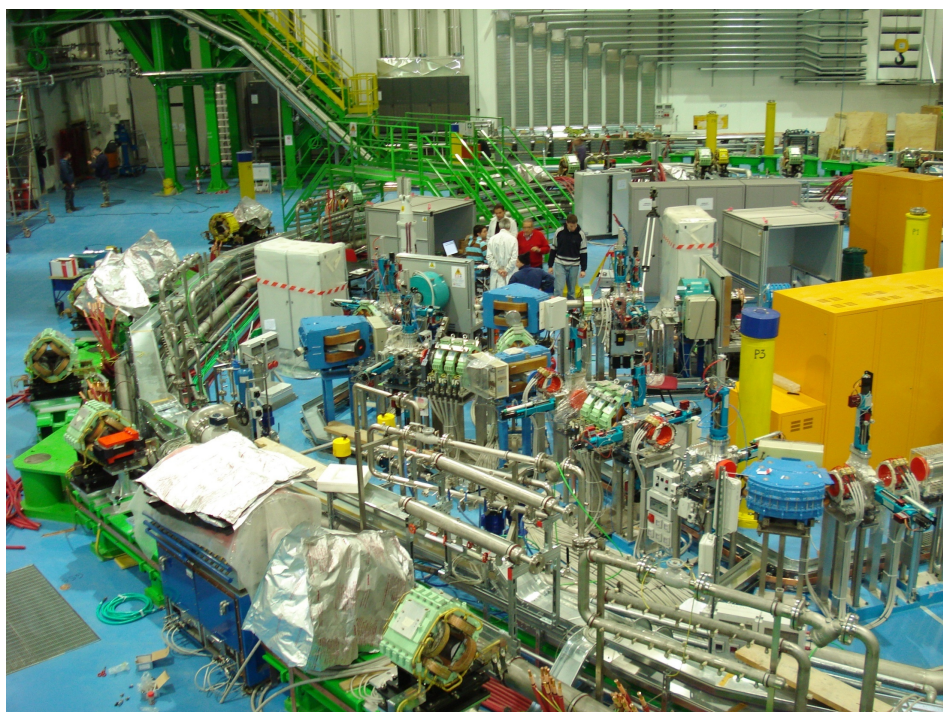


Cyclotron

Particle therapy in Italy: CNAO

Head & neck / pelvic tumours

Synchrotron



Treatment with
protons since 2011
Treatment with
carbon ions since 2012



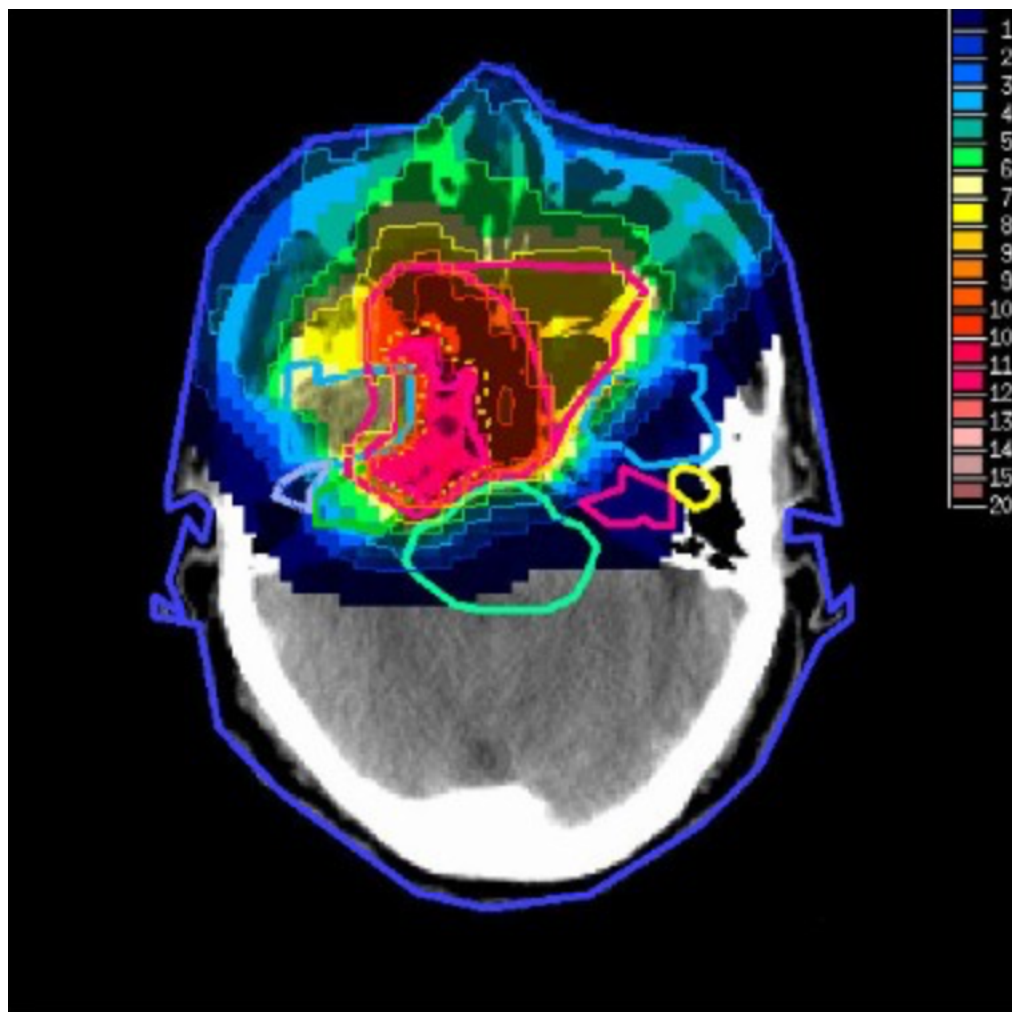
Particle therapy how-to

Diagnosis (& staging) CT – PET/CT



Particle therapy how-to

Treatment Planning



Particle therapy how-to

Pencil Beam

CNAO	
Energy Range (p)	60 – 250 MeV
Energy Range (^{12}C)	120 – 400 MeV/u
Energy Step	0.02 MeV
Beam size (mm)	4 – 10 FWHM
Beam position (xy)	< 0.05 mm
Maximum field size	20x20 cm ²
Beam Intensity (p)	$10^8 - 10^{10}$ /s
Beam Intensity (^{12}C)	$4 \times 10^6 - 4 \times 10^8$ /s
Time Structure	1s spills + 4s pause

Particle therapy how-to

2D beam monitor



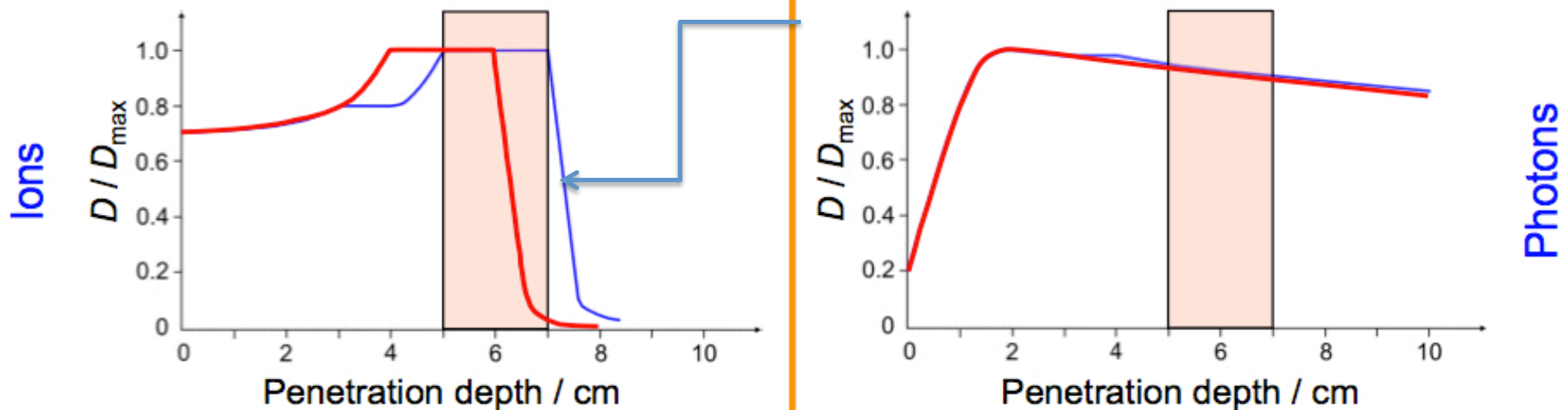
Range verification in Particle Therapy

AAPM 2012

What prevents particle therapy from becoming mainstream?

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

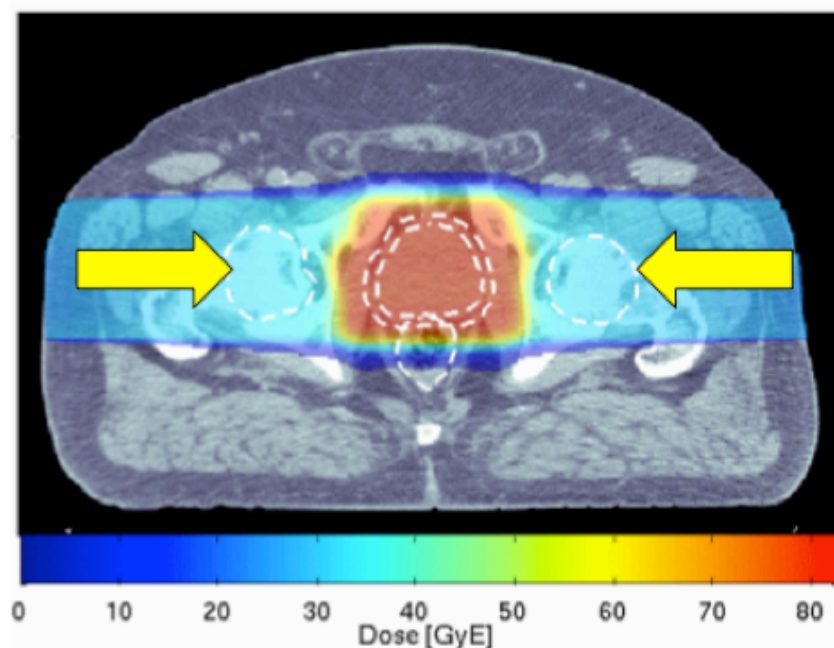
A little mismatch in density (by CT)
→ sensible change in dose release



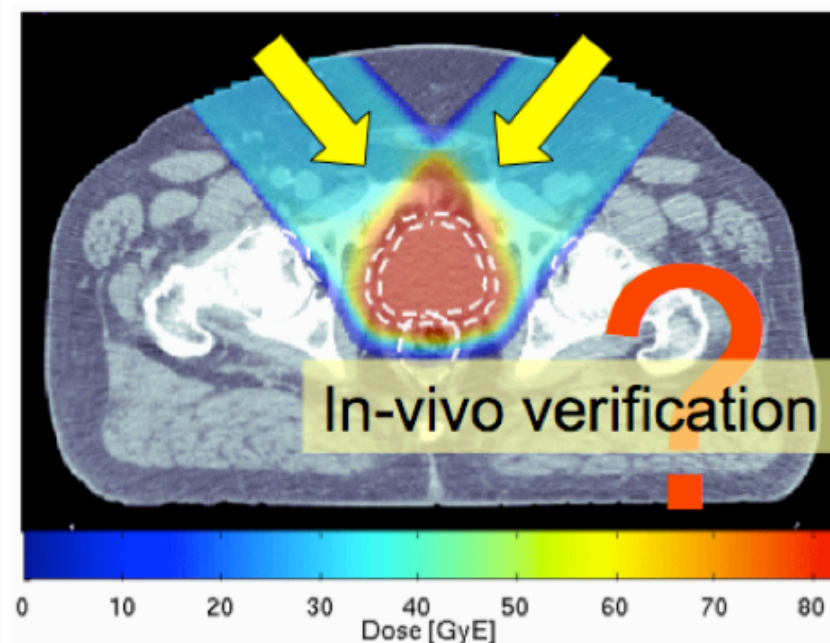
Particle Therapy: error sources

- Treatment planning (body density)
- Treatment delivery

Current approach:
*Opposed fields,
overshooting*



Desirable approach:
*Different beam angles and
no overshooting*

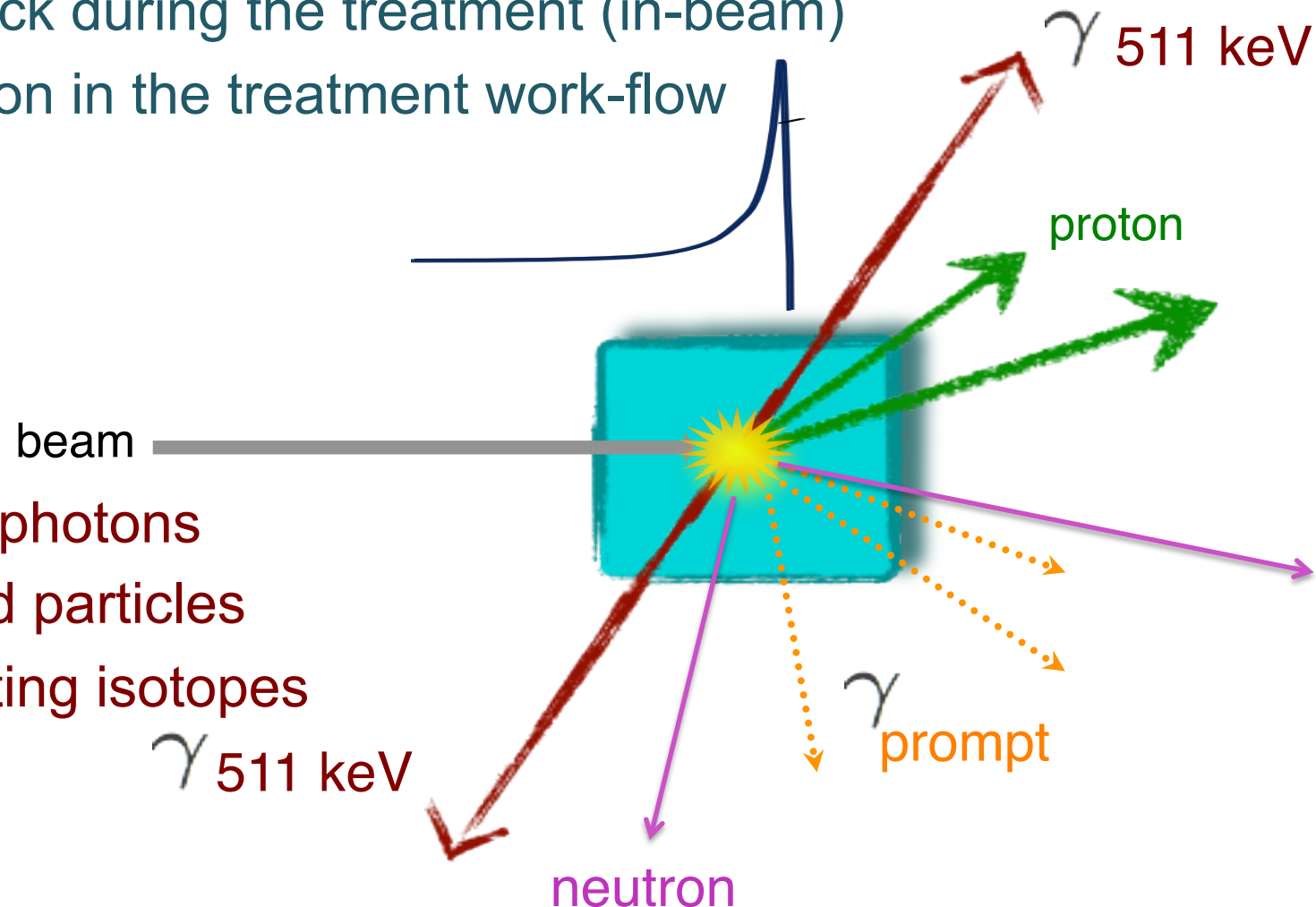


Protons

Range Monitoring in particle therapy

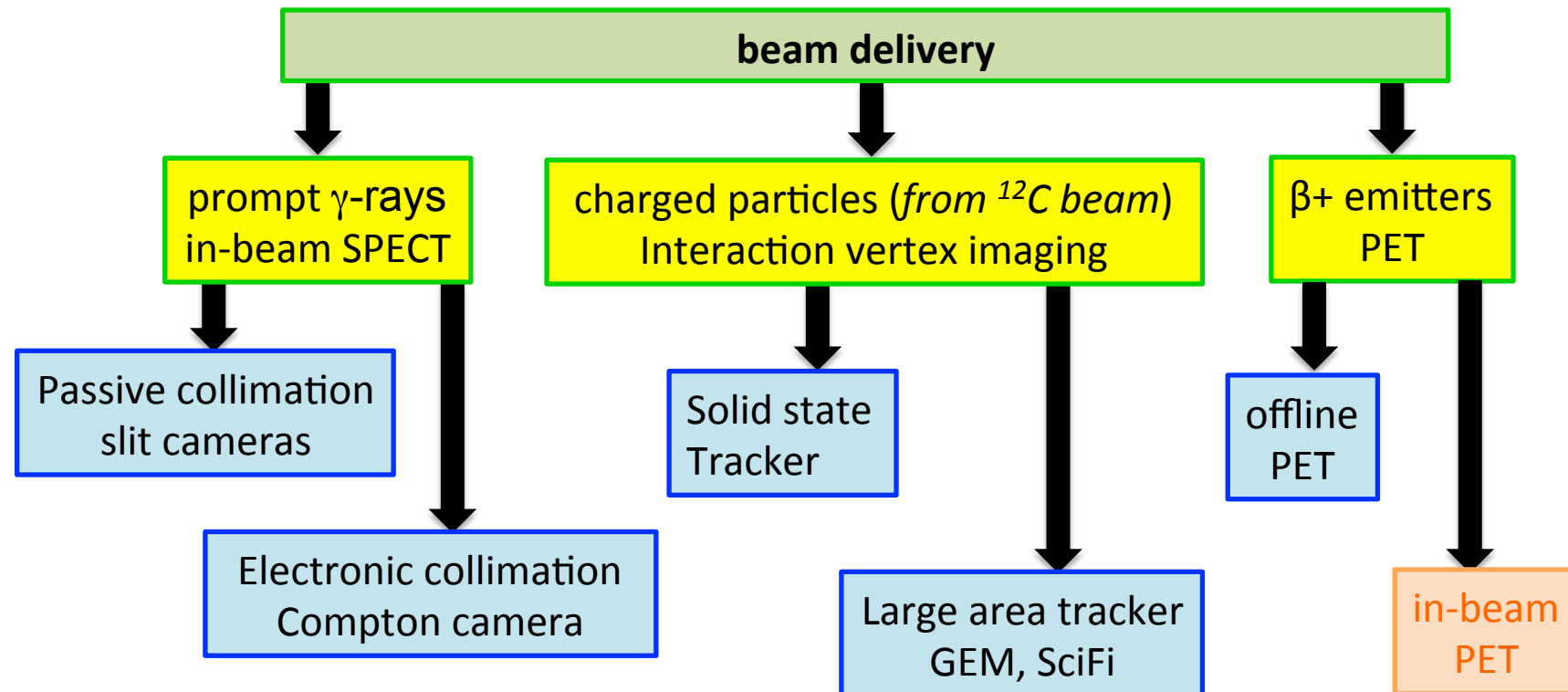
Secondary particles: a SIGNAL!

- Check of dose release shape
- Feed-back during the treatment (in-beam)
- Integration in the treatment work-flow



- Prompt photons
- Charged particles
- β^+ emitting isotopes

Secondary particles: a SIGNAL!



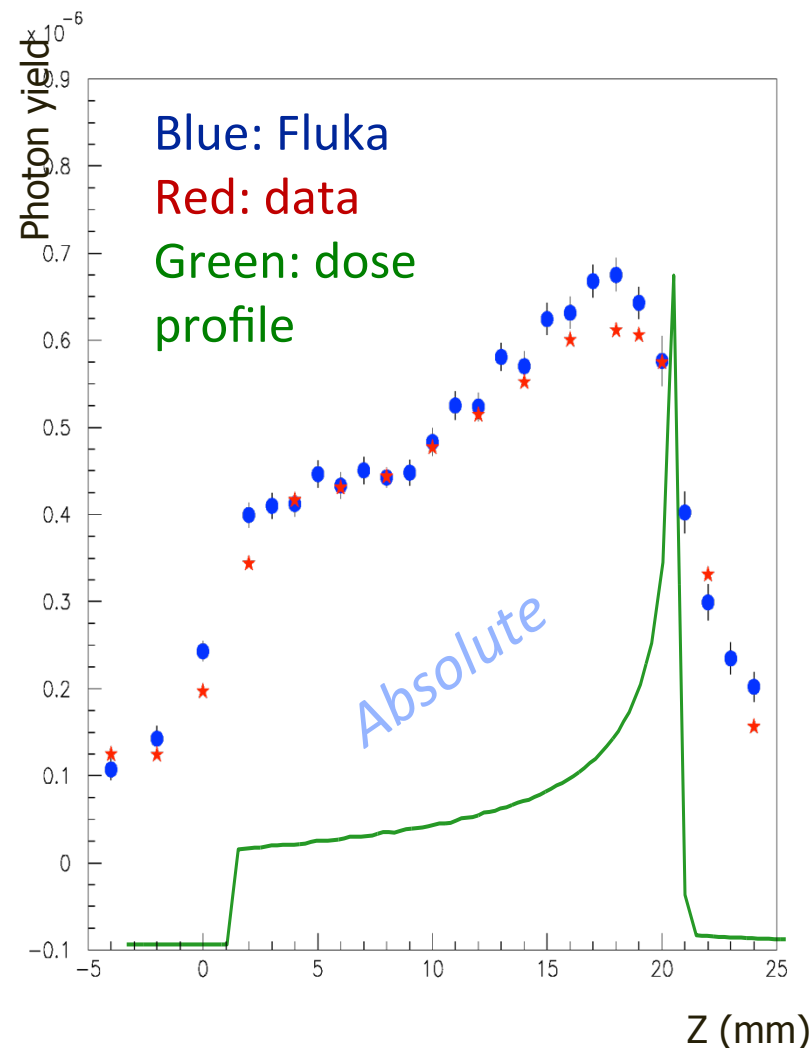
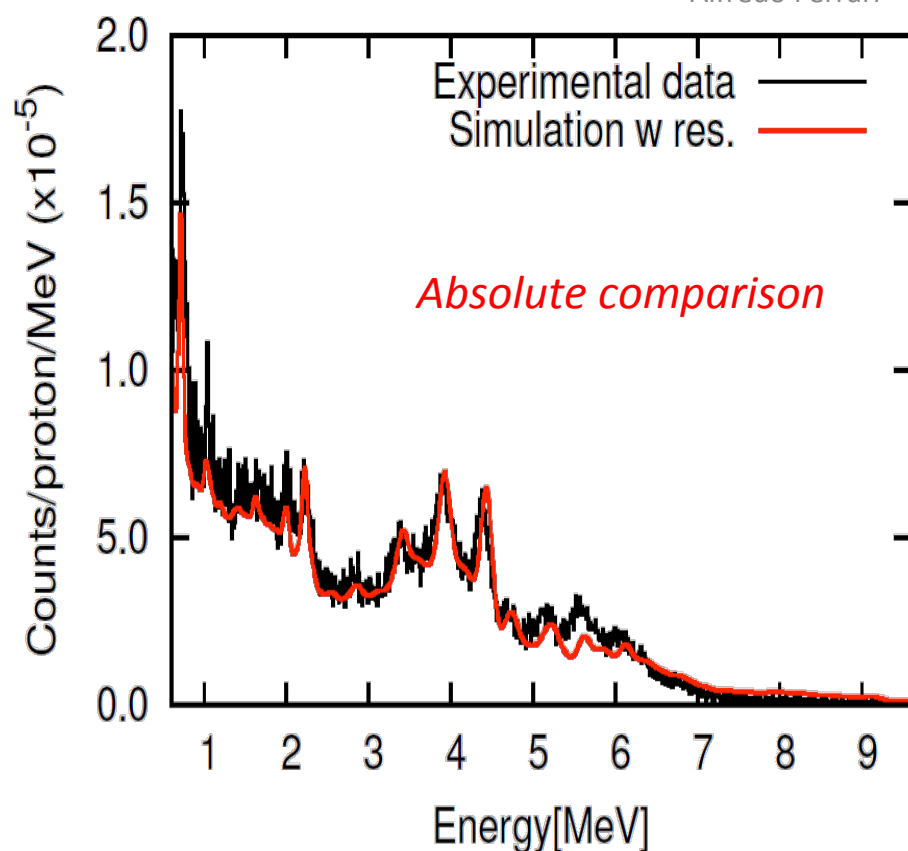
Goal:

<1 mm uncertainty on the Bragg peak position!

Prompt photons

160 MeV proton beam
Energy spectrum of prompt “photons”
(J.Smeets et al., IBA)

Courtesy
Alfredo Ferrari



The energy spectrum is in the 1-10 MeV range

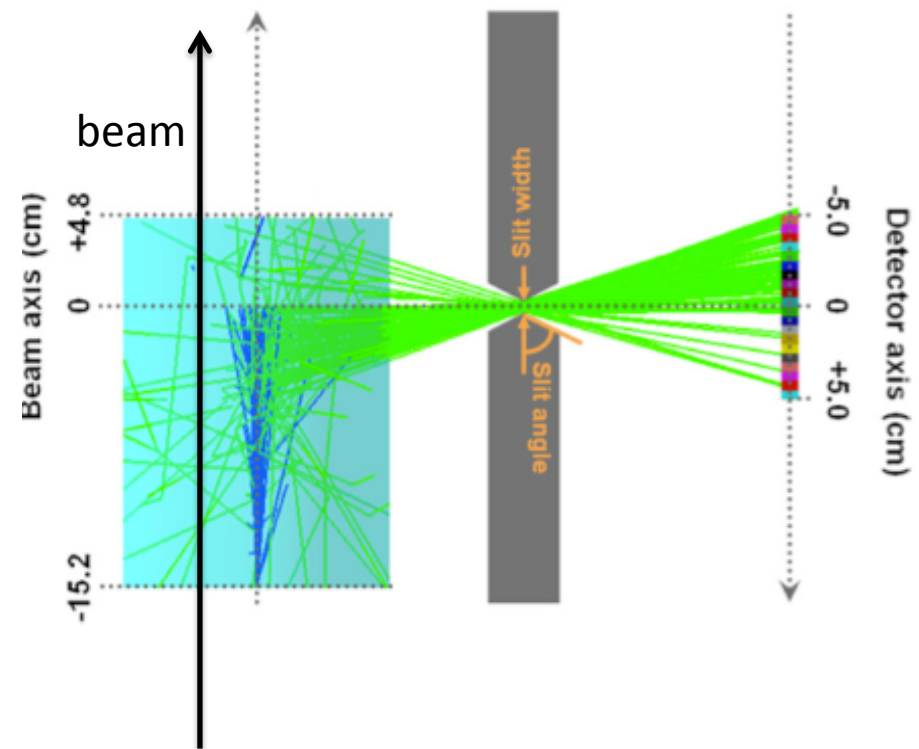
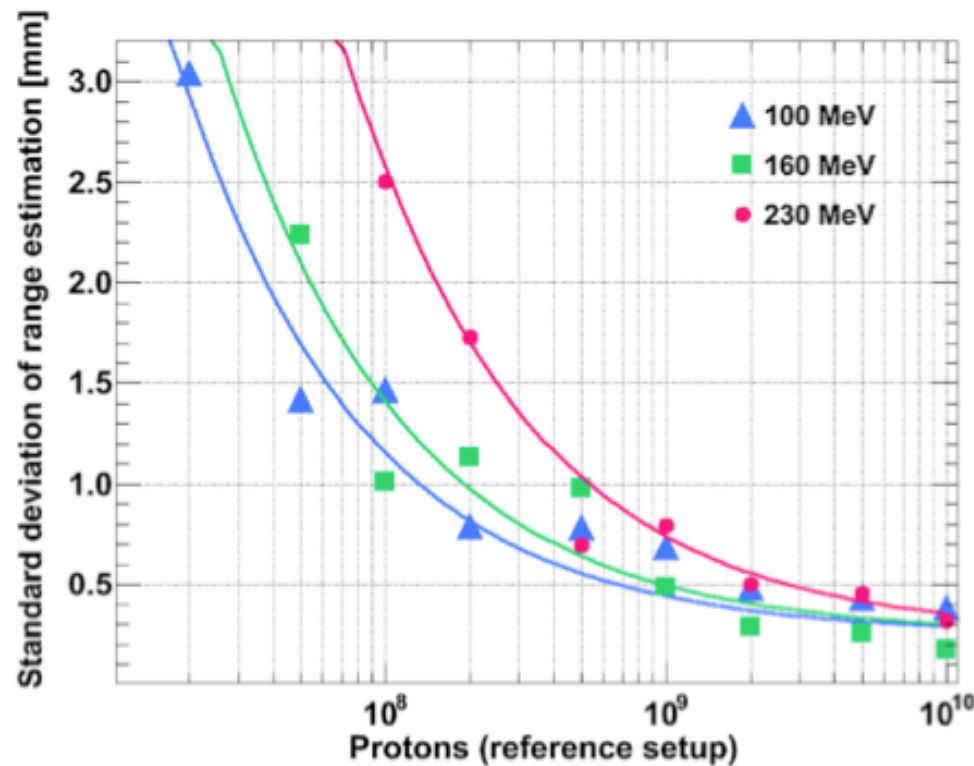
Piergiorgio Cerello – cerello@to.infn.it

Giornate di Studio sui Rivelatori - Cogne, February, 23rd-26th 2016

Prompt photons: slit camera

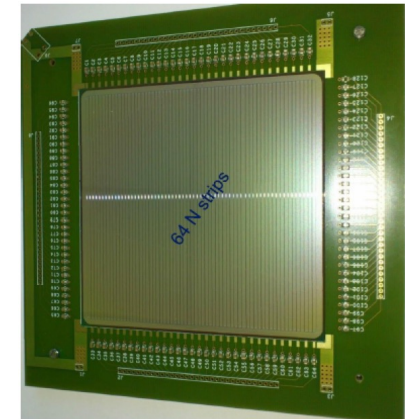
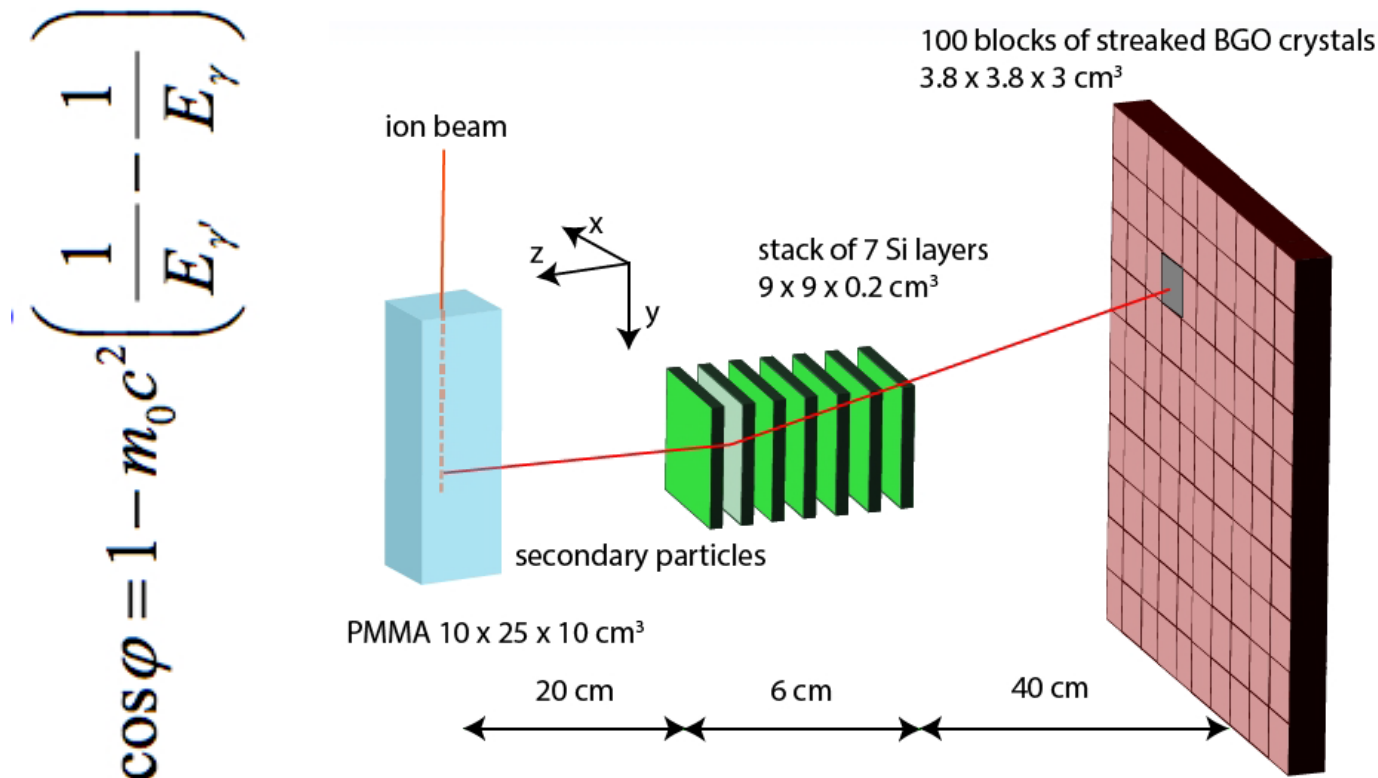
- Simple geometrical concept
- Optimized for range measurement on proton beam

IBA, Politecnico di Milano, Xglab



J Smeets et al. Phys. Med. Biol. **57**
(2012) 3371

Prompt photons: Compton camera



CNRS,
UCB Lyon

Absorber: Scintillator

- BGO 35 × 38 × 30 mm³
- 4 PMT



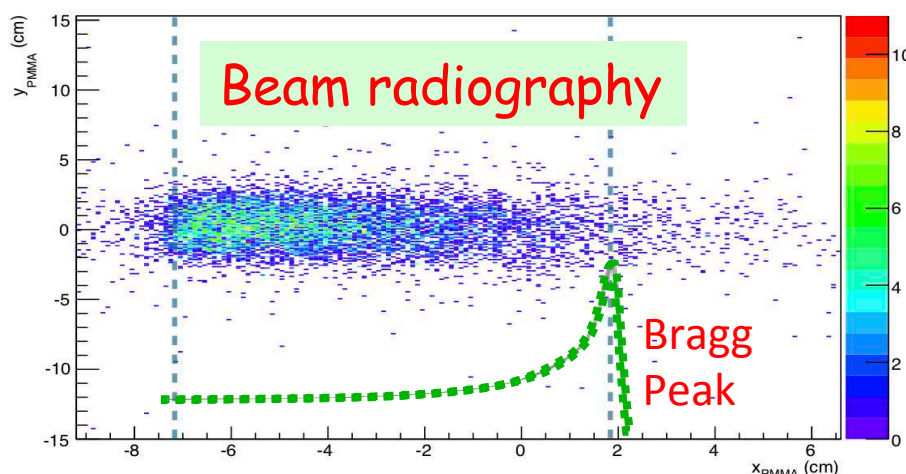
Scatterer: double-sided Si strip detectors

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



Charged particles

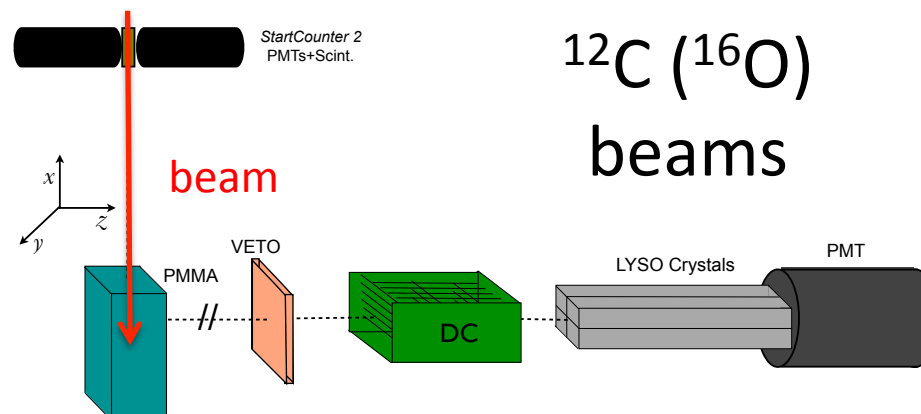
- detection efficiency $\sim 100\%$
- easily back-tracked to the emission point
- correlation to the beam profile



K Gwosch et al PMB 58 3755

C Agodi et al PMB 57 5667

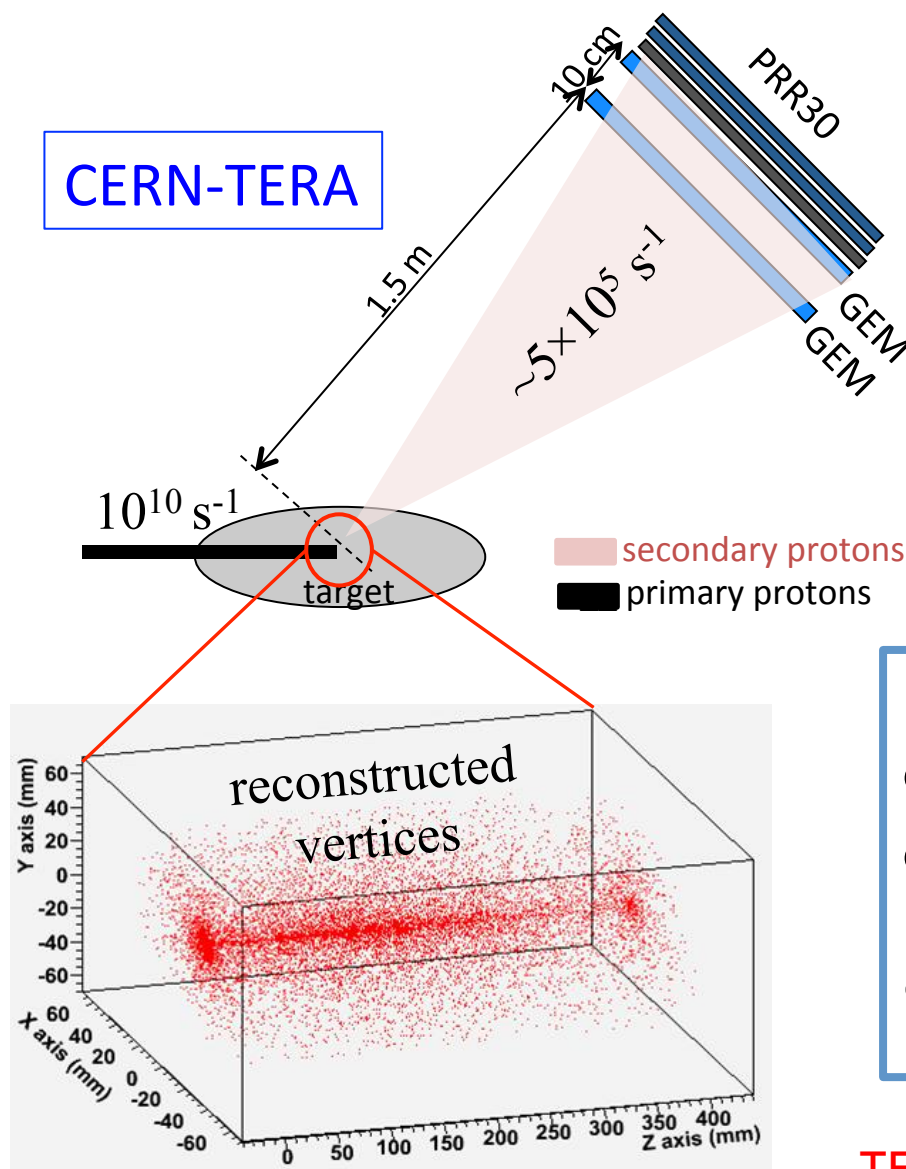
$\sim 10^3$ events required to achieve desired accuracy on the emission point distribution: detector size matters!



- Low emission rate
- Escape energy threshold ~ 50 -100 MeV
- multiple scattering inside the patient $\rightarrow$ 6-8 mm on single track back-pointing resolution
- MC highly unreliable

Charged particles: GEM tracker

CERN-TERA



- Large area gas (!) detector
- Acceptable solid angle even far away from the patient
- No need for TOF

Expected performance

$$\sigma_{\text{GEM-spatial}} \approx 400 \mu\text{m}$$

$$\sigma_{\theta} \approx 6 \text{ mrad} \quad \text{Angular resolution}$$

$$\Omega \sim 0.3\% \text{ (0.04 sr)} \quad \text{Solid angle}$$

Courtesy of
TERA Foundation

PET Radioisotopes: β^+ + emitters

Phantom vs Human Body composition

	P (g/cm ³)	C	O	H	N	others
PMMA	1.18	45%	48%	7%	-	-
Body	1.0	18.5%	65%	9.5%	3.2%	3.8%

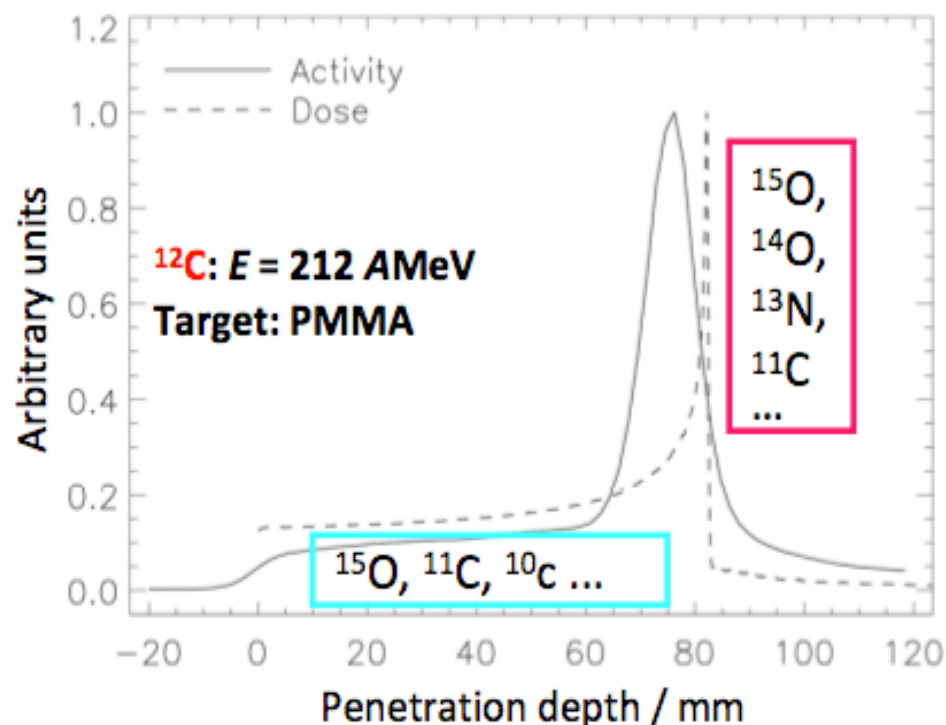
β^+ + emitters

Isotope	¹¹ C	¹⁵ O	¹³ N	¹⁰ C	¹² N
Half-life (s)	1223	122	598	19	11 x 10 ⁻³

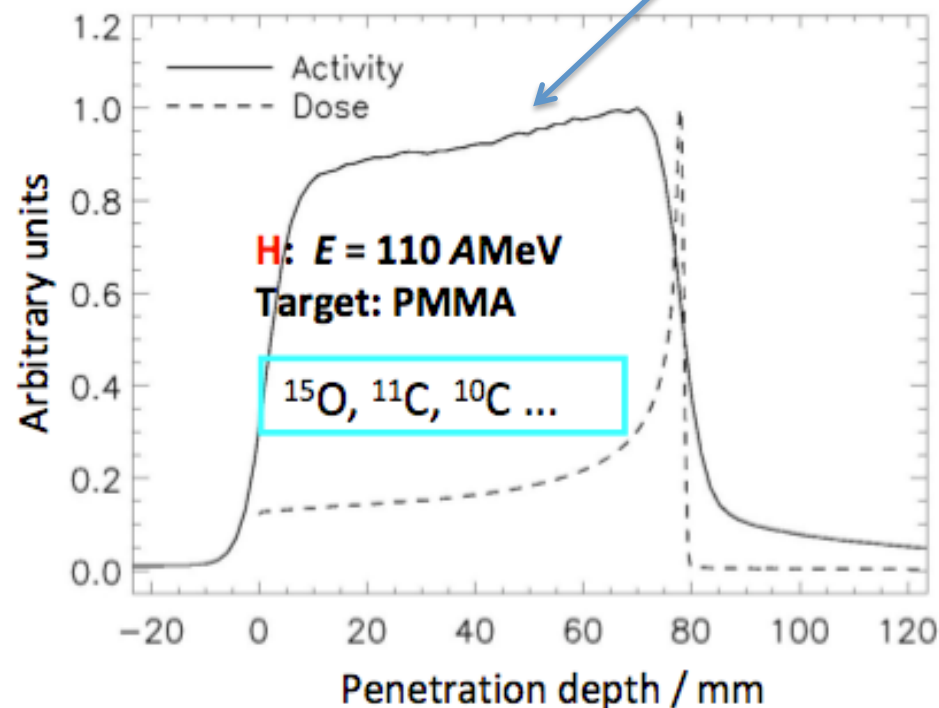
β^+ activity and dose: correlation

Isotope	^{12}C	^{16}O	Nuclear Medicine
Activity density	1600 $\text{Bq cm}^{-3} \text{ Gy}^{-1}$	1030 $\text{Bq cm}^{-3} \text{ Gy}^{-1}$	$10^4 - 10^5$ Bq cm^{-3}

Projectiles & target fragmentation



Target fragmentation measured



The *InSide* Project @ CNAO

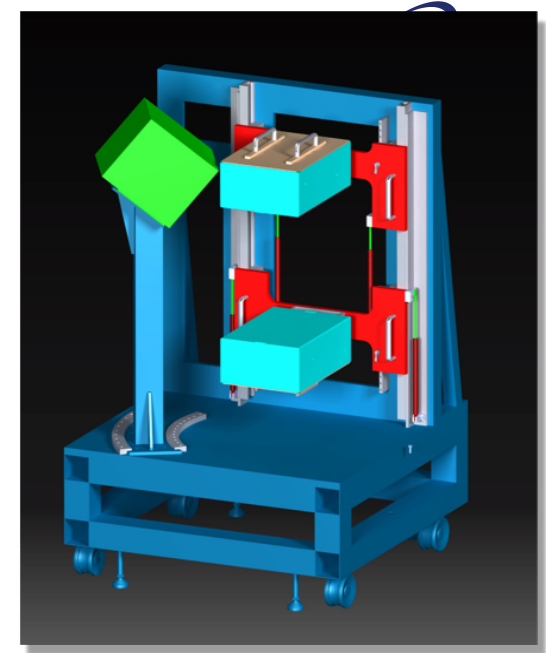
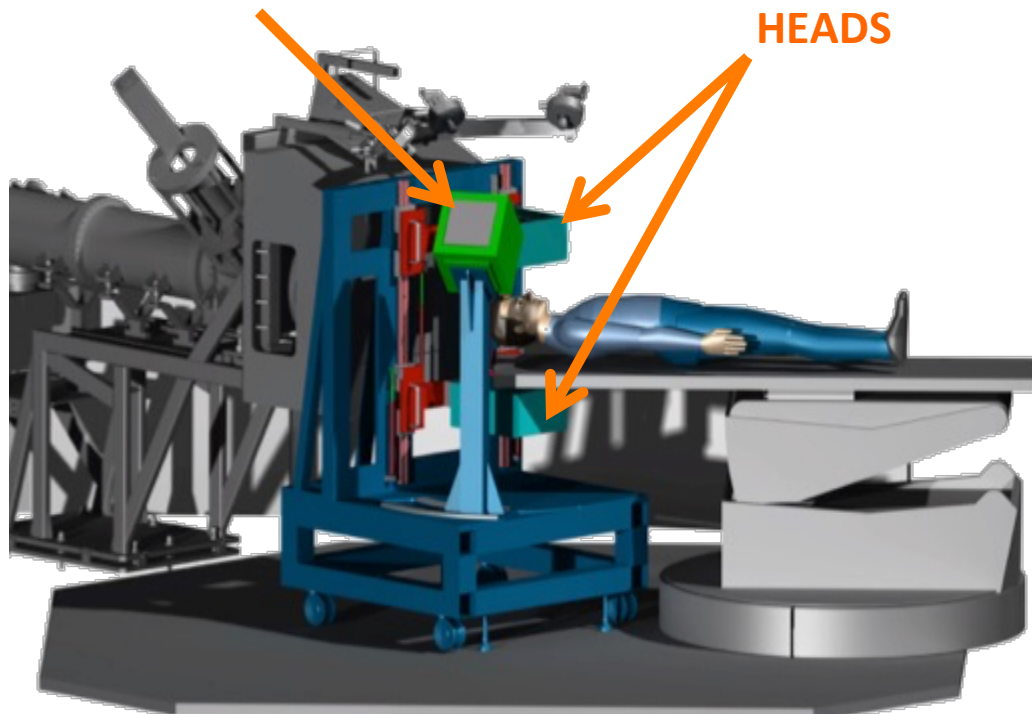
INnovative S**o**lutions for In-beam **D**osim**E**try in Hadrontherapy

Funding by: PRIN + Centro Fermi + INFN (RM1-TO-MI-PI)

proton emission

Tracker +
Calorimeter =
DOSE PROFILER

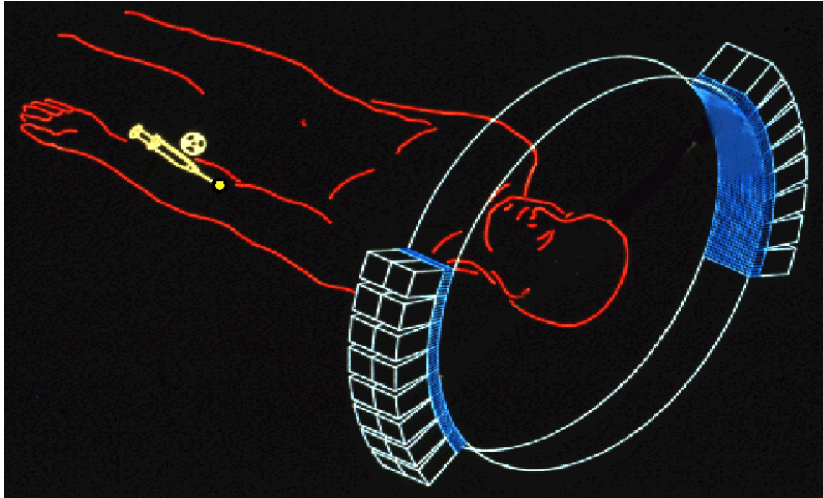
β^+ activity
distribution
IN-BEAM PET
HEADS



- ❑ Dual signal operation
- ❑ integrated in treatment room
- ❑ in-beam feedback
- ❑ Challenge: fusion of charged and PET information

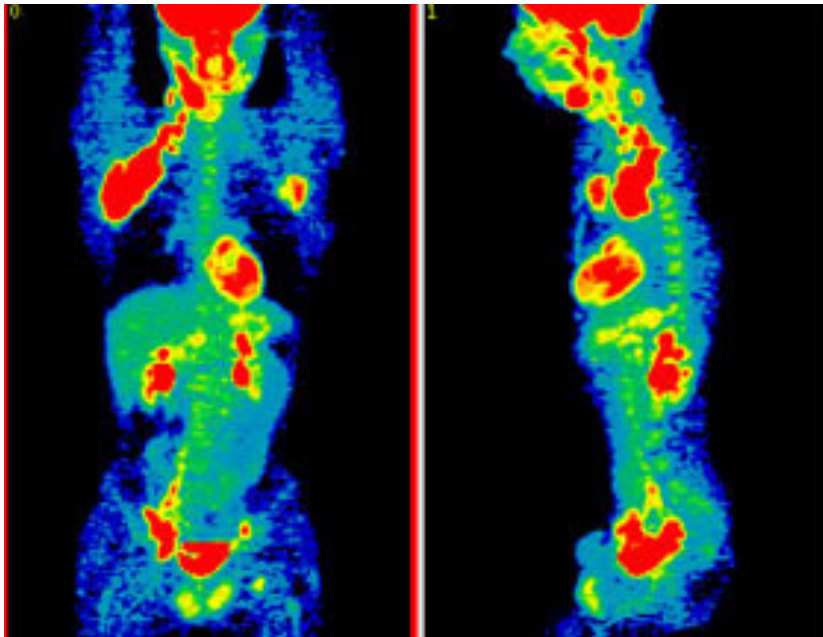
PET Imaging

PET Imaging: Ingredients



1) a β^+ decaying isotope bound to 'functionally-relevant' molecule

the emitted e^+ annihilates (almost at rest) close to the emission point into a (nearly) back-to-back 511 keV photon pair



2) a photon detector (typically a crystal)

generates a list of Lines Of Response (LOR)

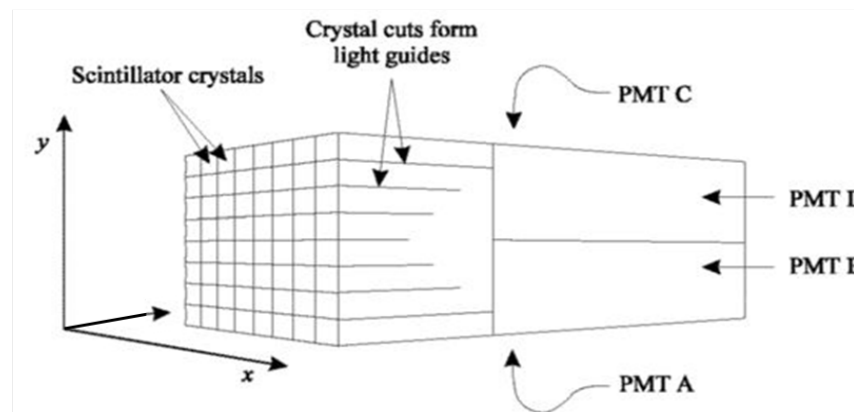
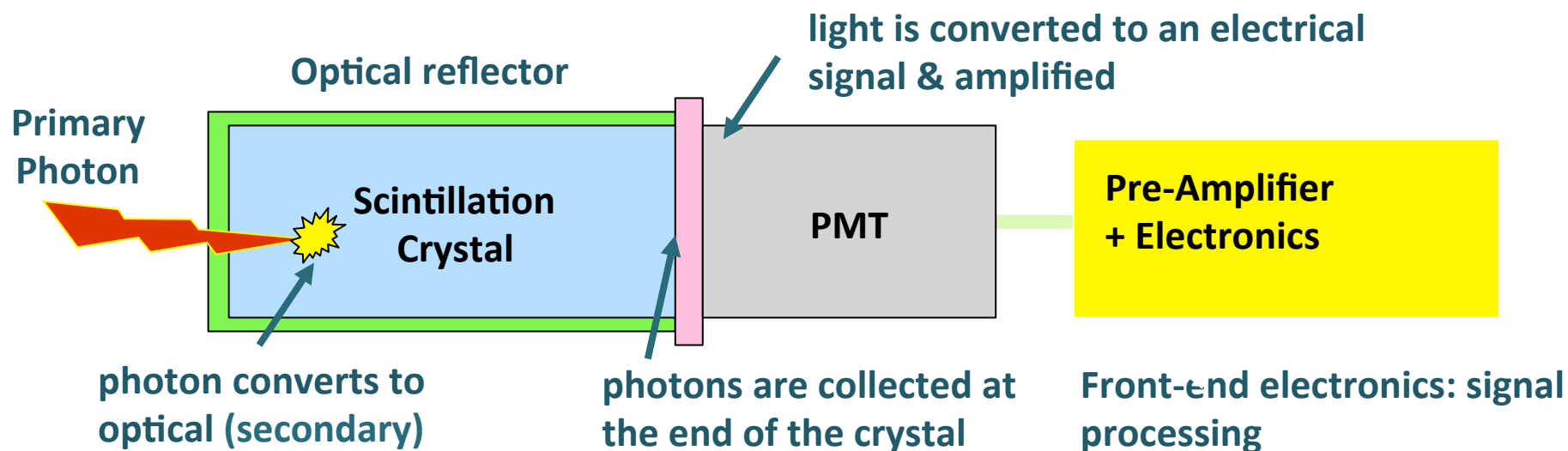
3) Reconstruction software

provides a 3D activity map

How do you design a PET System?

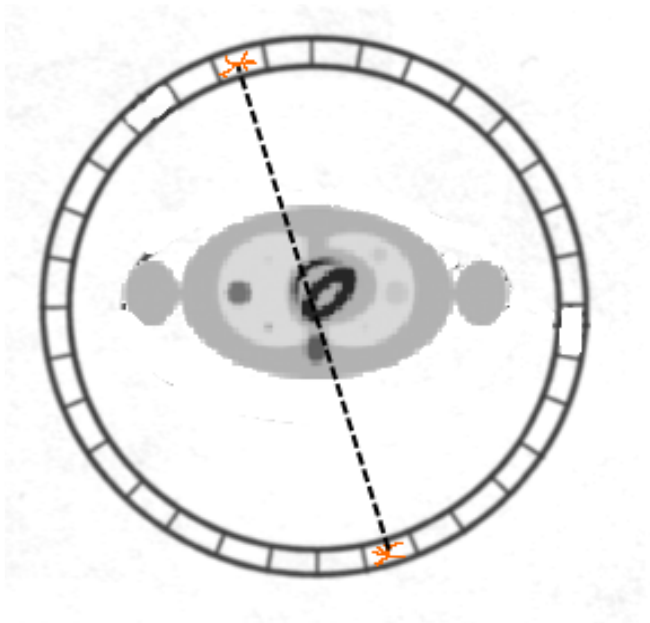
PET Imaging

Conventional PET detector



PET Imaging

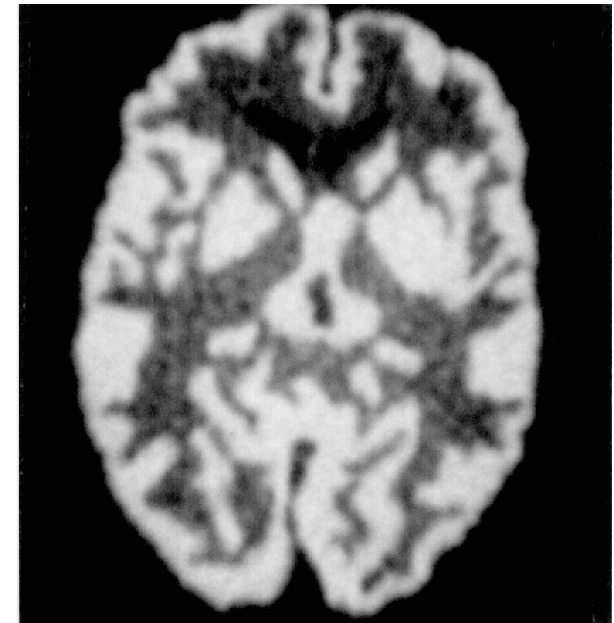
Line of Response



Sinogram



Image



What are the critical parameters of a PET system?

PET Imaging Parameters



Field Of View

Photon detection efficiency

Energy resolution

- Compton scattering vs. photopeak

Spatial Resolution

- positron path
- depth of interaction
- time of flight

Time Resolution

- Annihilation point along the LOR

PET Imaging: detection efficiency

Detection efficiency

(aka sensitivity, stopping power)

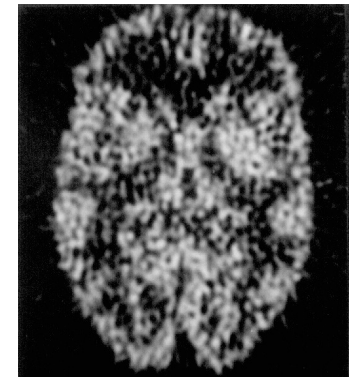
Reduces noise from counting statistics

Reduces dose

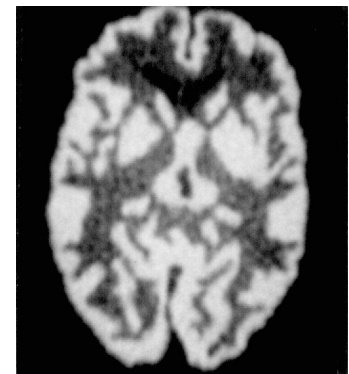
Example: 2cm of LSO

~ 82% (singles)

~ 67% (coincidences)

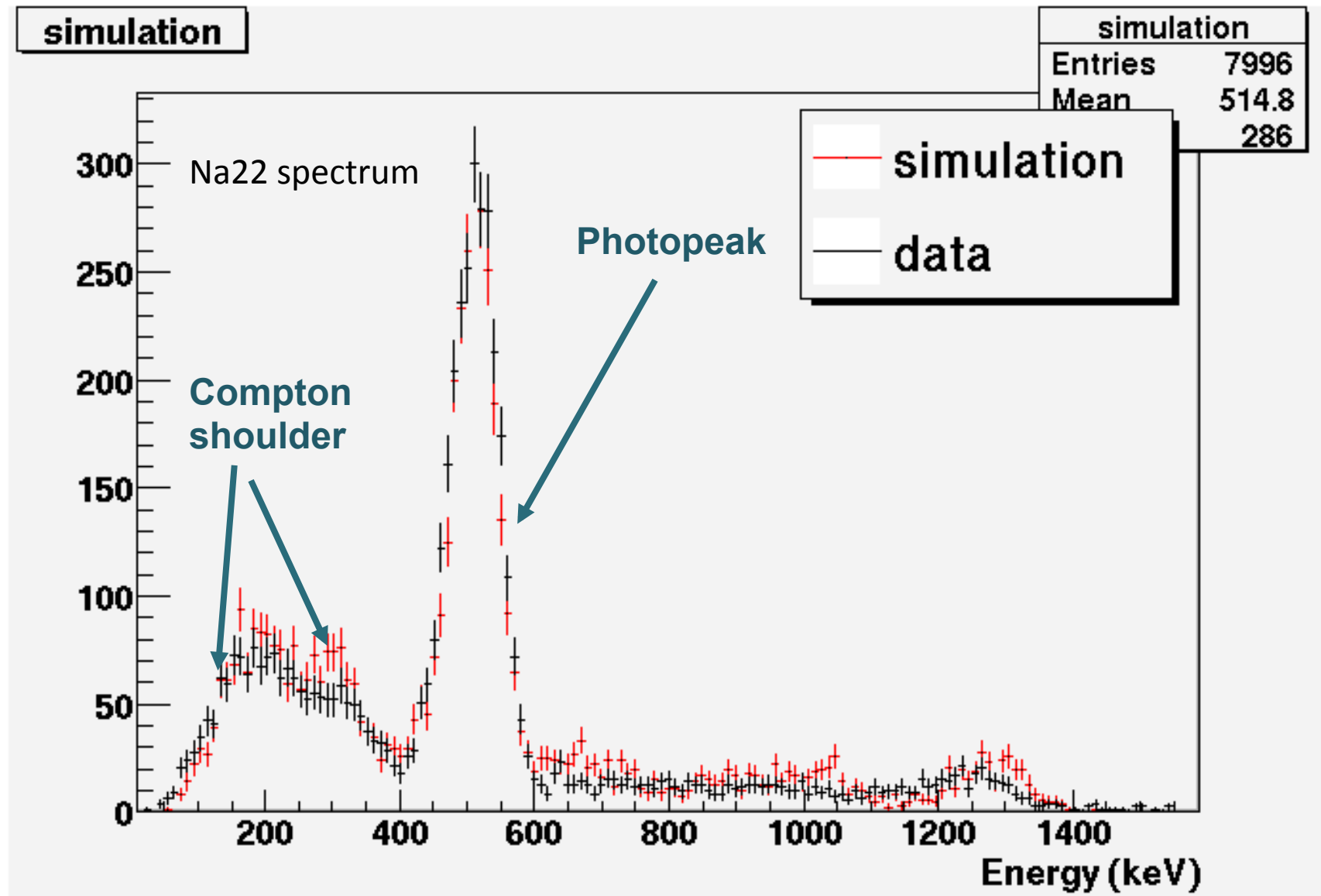


1M Events



55M Events

PET Imaging: Energy Spectrum



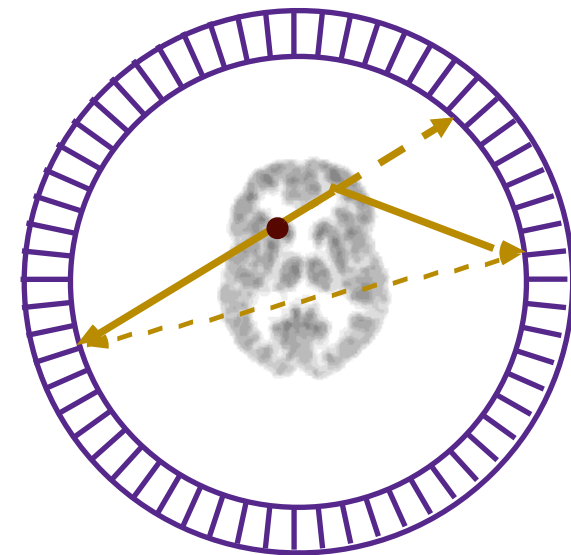
PET Imaging: Compton background

Energy resolution

Scattered photons change direction
AND lose energy

Affects acceptance of scattered
coincidences

Currently ~ 15 - 20%



Deadtime / Rate

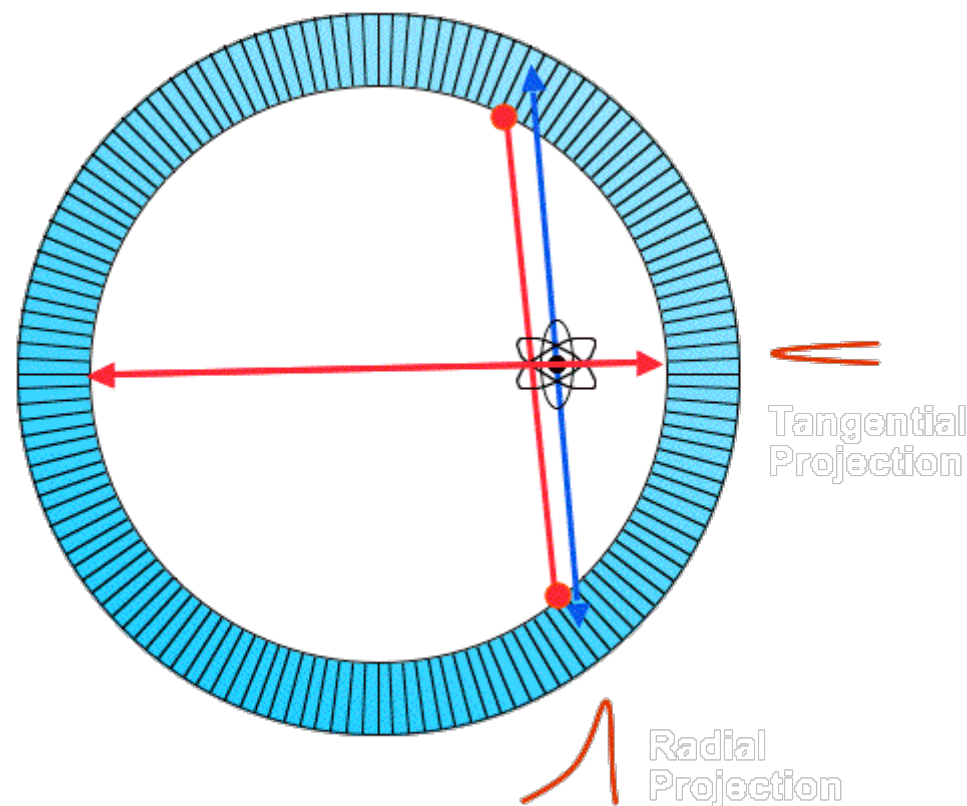
single channels must handle
MHz count rates!

multiple coincidences rejection

PET Imaging: Depth of Interaction

Depth Of Interaction

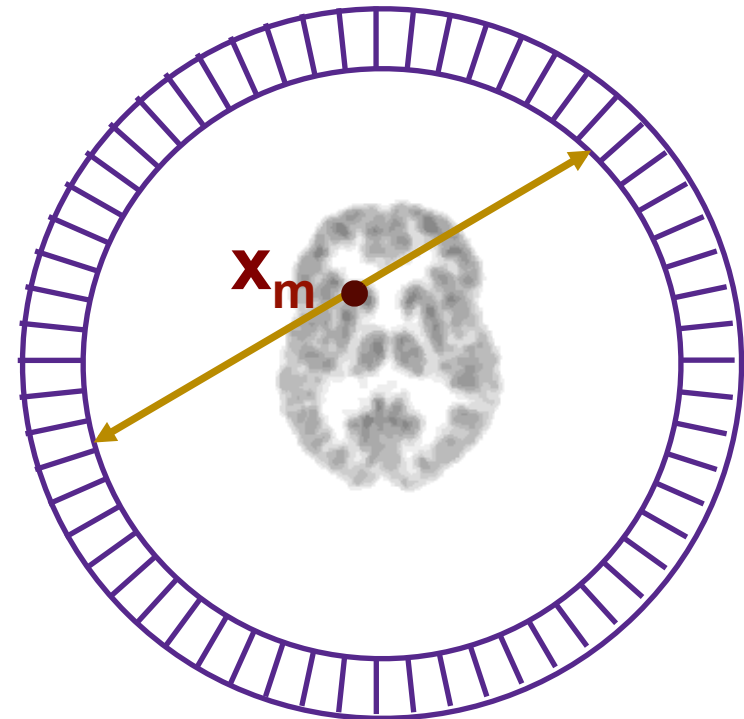
- parallax error
- goal ~ 1 mm



PET Imaging: Time of Flight

Time Of Flight

- more information on LOR
- less background
- Detection Quantum Efficiency
- present intrinsic limit: ~ 100 ps



$$P(x) \sim \exp(-(x - x_m)/2 \sigma^2)$$

$$\frac{\sigma(S/N_{tof})}{\sigma(S/N_{non-tof})} = \sqrt{\frac{2D}{c\Delta t}}$$

PET detectors

How to improve PET performance?

- 4D detectors with new design
 - **Depth of Interaction**
 - Parallax error
 - **Time Of Flight**
 - Weighted Line Of Response
 - **MR compatibility**
 - PET/MR Hybrid Imaging
 - **Compactness**
 - In-beam PET in Particle Therapy
 - **Cost & Scalability**



How to improve PET design?

- Scintillators
- Photon Detectors
- Front-End Electronics
- System Design & Integration

Scintillators

	NaI	BGO	GSO	LSO	LYSO	LGSO	LuAP	YAP	LaBr ₃
Light yield 10 ³ ph/MeV	38	9	8	30	32	16	12	17	60
Primary decay time	250	300	60	40	41	65	18	30	16
$\Delta E/E$ (%) at 662 keV	6	10	8	10	10	9	15	4.4	3
Density (g/cm ³)	3.67	7.13	6.71	7.35	7.19	6.5	8.34	5.5	5.08
Effective Z_{eff}	50	73	58	65	64	59	65	33	46
1/ μ @ 511 keV (mm)	25.9	11.2	15.0	12.3	12.6	14.3	11.0	21.3	22.3
PE (%) at 511 keV	18	44	26	34	33	28	32	4.4	14

Photon Detectors

Detector	PMT	APD	(d)SiPM	UFSD
Gain	10^5	50-1000	$\sim 10^6$	5-15
Rise Time (ns)	~ 1	~ 5	~ 1	~ 0.1
QE @ 420 nm (%)	~ 25	~ 70	$\sim 25-75$ (PDE)	~ 75
Bias (V)	> 1000	300-1000	30-80	100
Temperature sensitivity (%/K)	< 1	~ 3	1-8	Negligible
Magnetic field sensitivity	Yes	No	No	No

Front-End Electronics

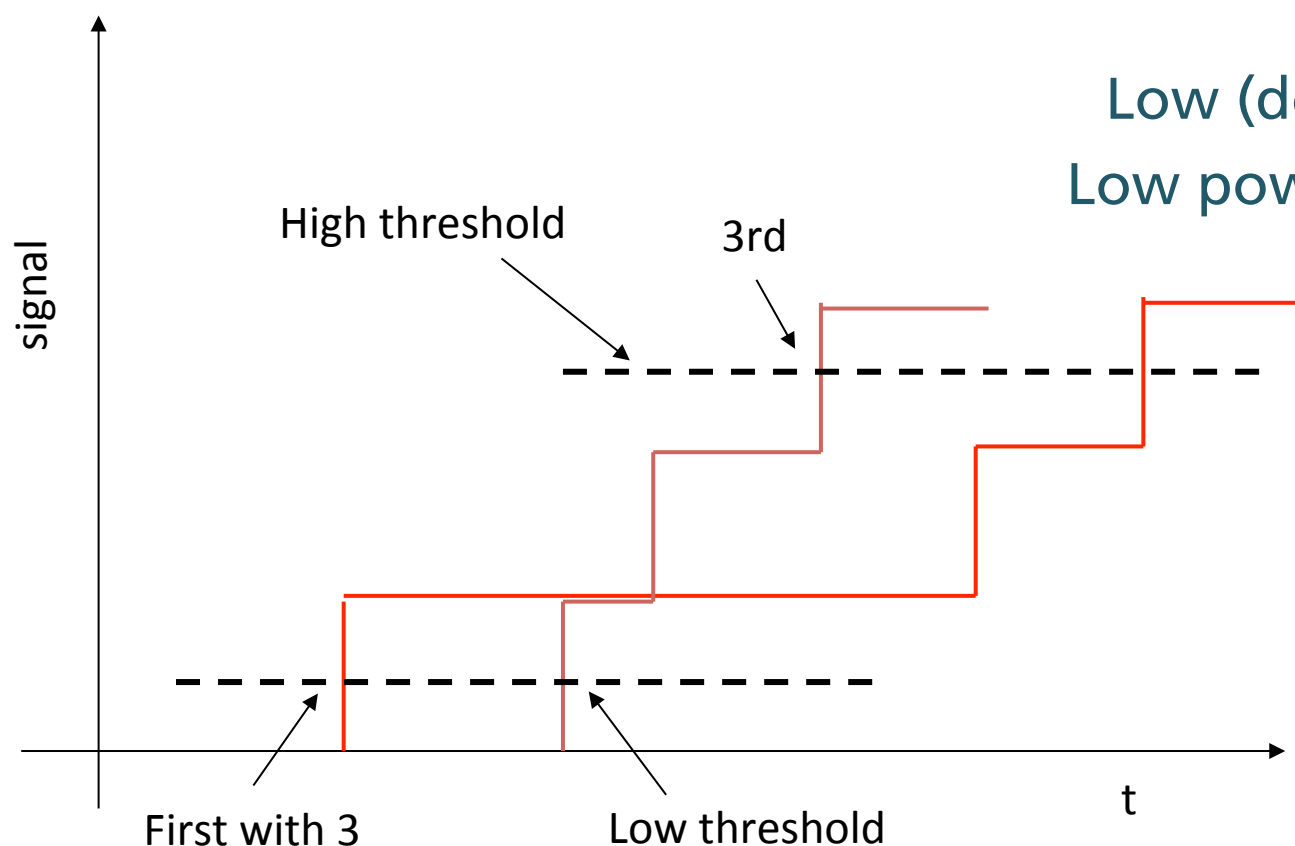
- “Catch the first de-excitation photon”

Speed

Low Noise

Low (double) threshold

Low power consumption



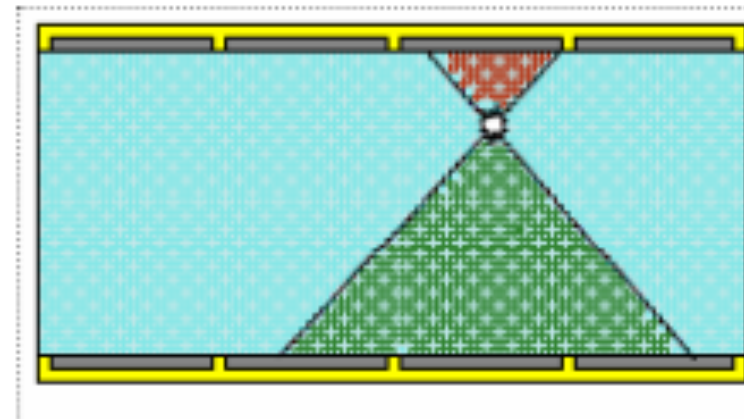
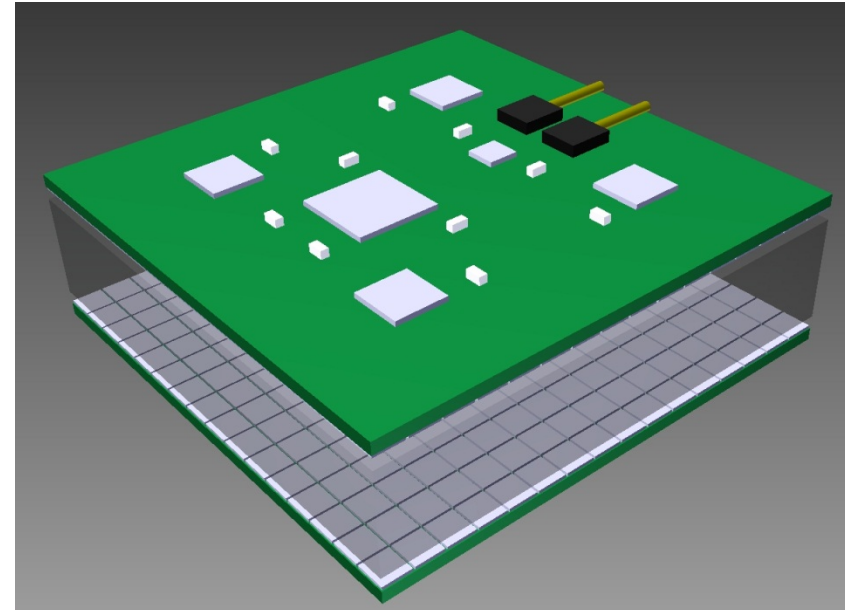
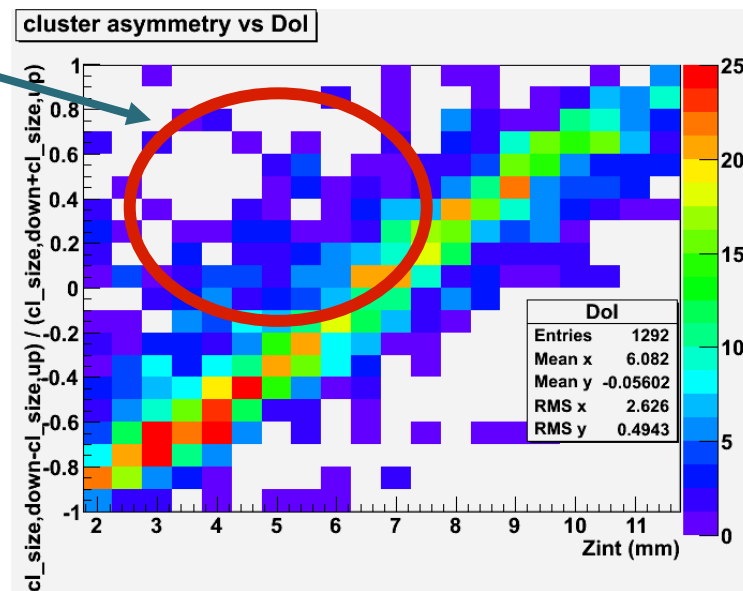
System Design

- **Segmented vs. Monolithic crystal**
Axial
Block
- **Time measurement strategy**
Single secondary photon detection
 - noise
 - dark counts

4DM-PET Detector Layout

- A. LYSO scintillator slab Size: $48 \cdot 48 \cdot 10 \text{ mm}^3$
- B. Top / bottom SiPM layers
 - 16x16 square pixels, 3mm pitch
- C. Independent identical readout boards
 - Depth Of Interaction
 - Size Asymmetry: $(t - b)/(t + b)$
 - Simulated FWHM: 1.0 mm

Compton effect

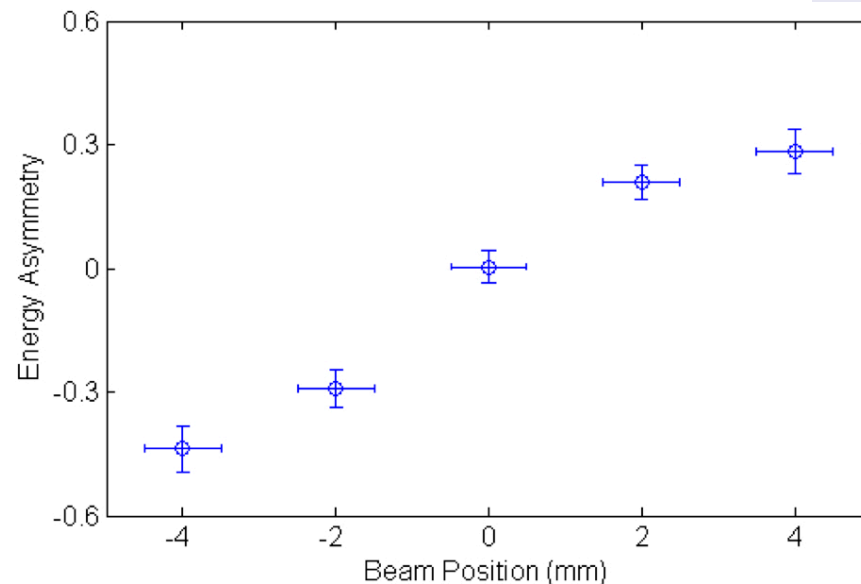
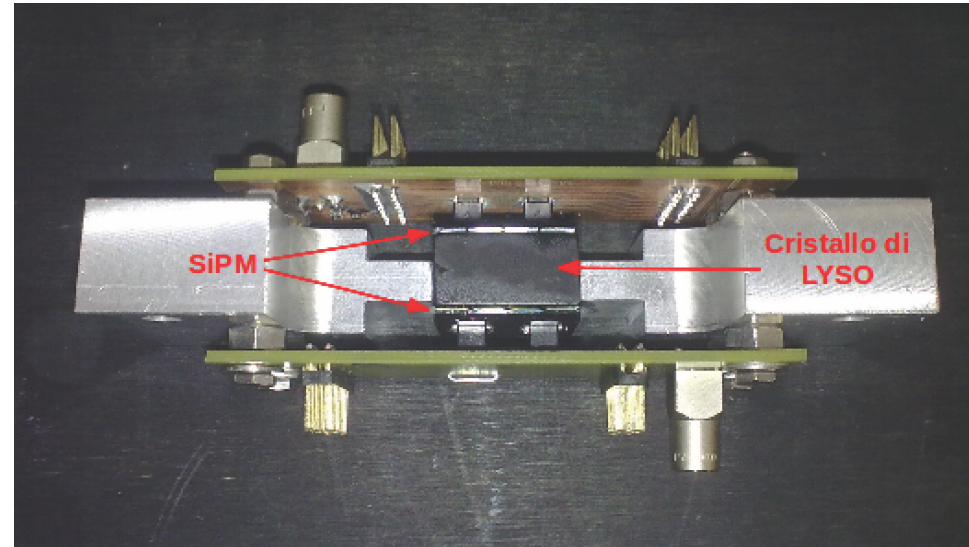


Courtesy of the 4DM-PET
Collaboration

4DM-PET DOI measurement

Preliminary DOI
measurement on a $5 \times 5 \text{ mm}^2$
detector with 4×4 channels

- "worst case scenario"
- 2 mm FWHM



16x16 module with TOF
capabilities under
construction

Courtesy of the 4DM-PET
Collaboration

new PET detectors



TOF-PET: crucial

real “phase transition”:
time resolution $\sim 10 - 20$ ps

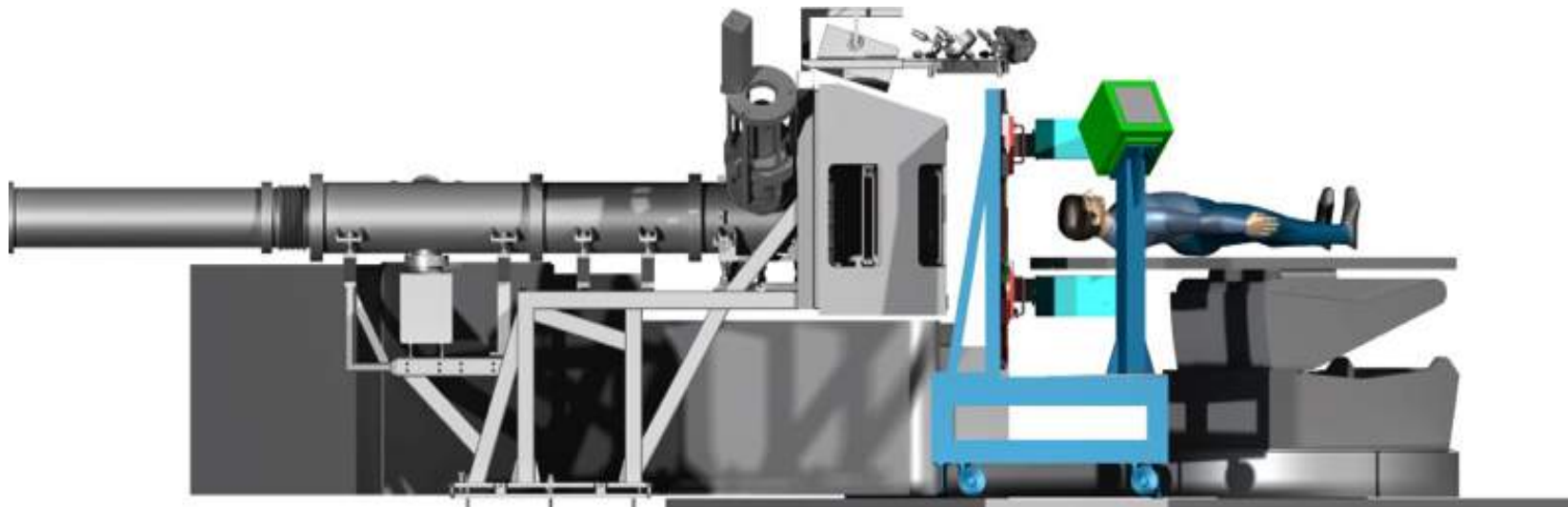
the challenge lies in the detector
rather than the electronics...

Any idea?

- **Why Particle Therapy?**
- **Why Range Verification?**
- **Why Positron Emission Tomography?**

INSIDE

The INSIDE Project



CNAO

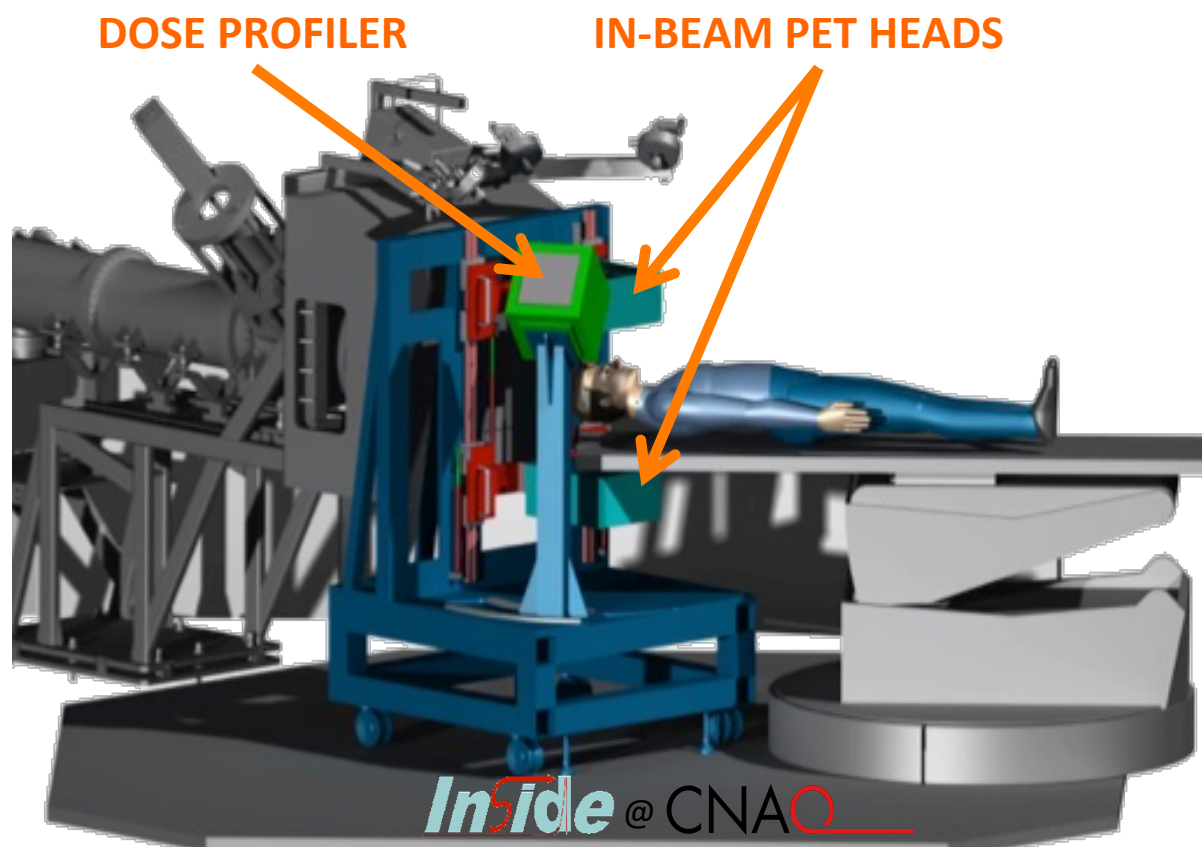
Piergiorgio Cerello – cerello@to.infn.it

InSide

Giornate di Studio sui Rivelatori - Cogne, February, 23rd-26th 2016

The INSIDE Project

INnovative **S**olutions for **In**-beam **D**osim**E**try
in particle therapy



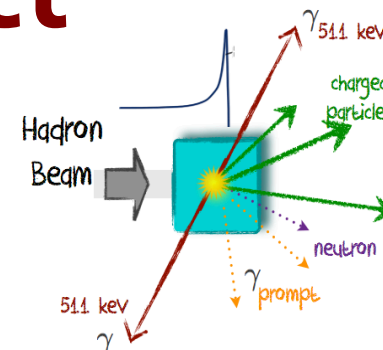
Designed to:

- ❑ integrate in the gantry
- ❑ operate in-beam
- ❑ provide an immediate feedback on the particle range

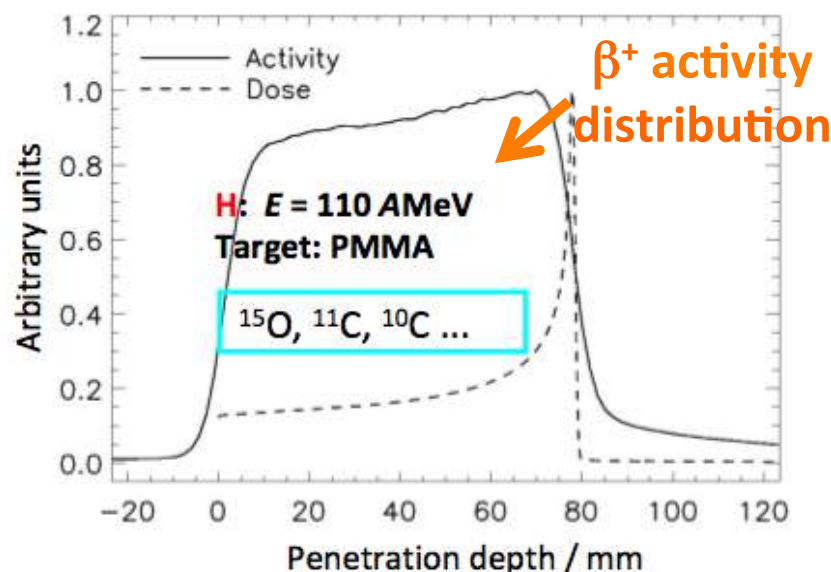
Inside

The INSIDE Project

Real time monitoring of Bragg Peak depth
with passive signals by secondary particles



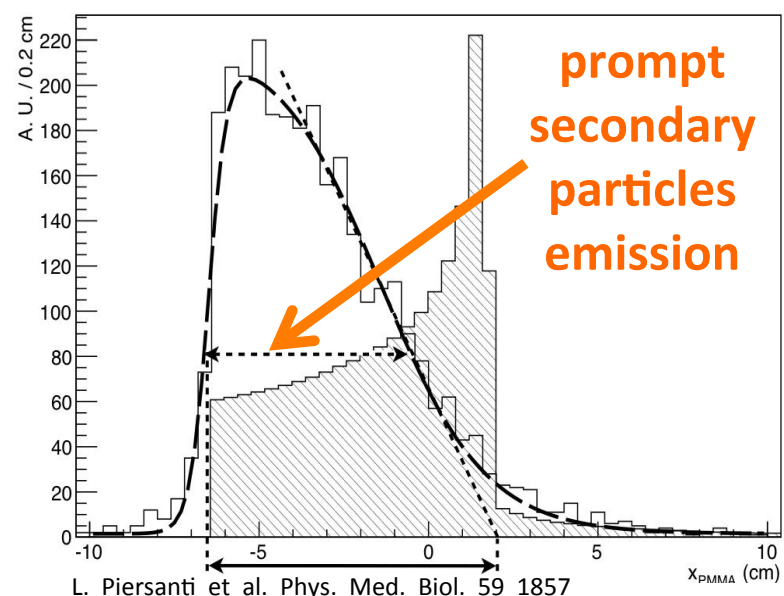
IN-BEAM PET HEADS



J Pawelke et al., Proceedings IBIBAM, 26.-29.09.2007, Heidelberg

PET image reconstruction

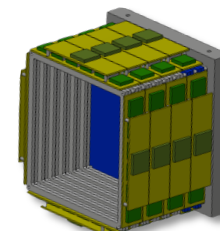
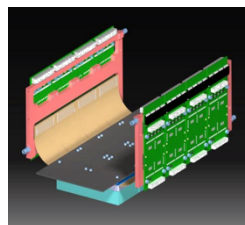
DOSE PROFILER



track and interaction point reconstruction

Inside

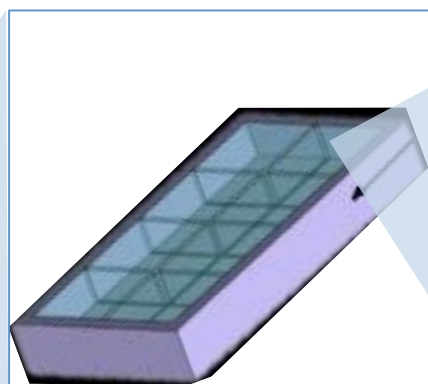
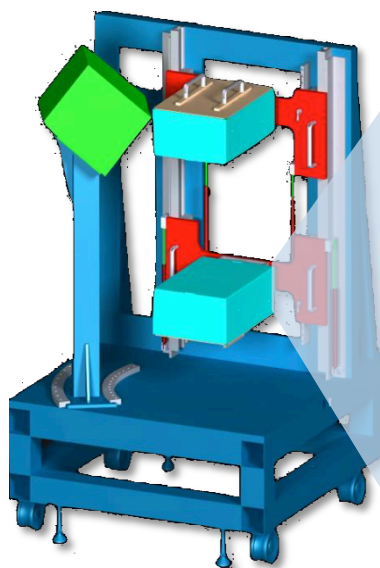
The INSIDE Concept



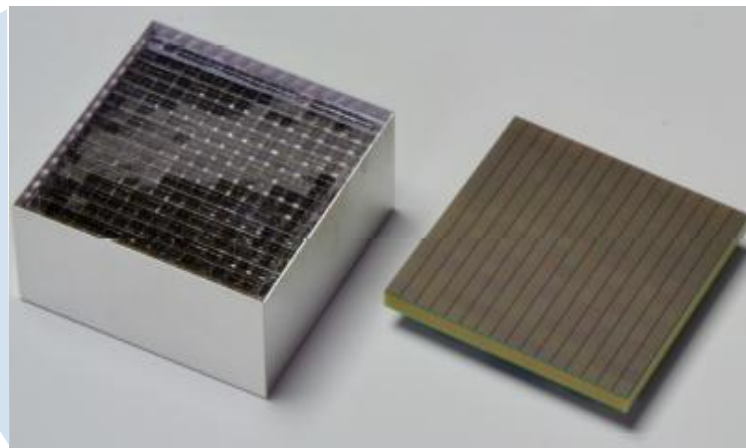
	IN-BEAM PET HEADS	DOSE PROFILER
Signal	β^+ decay	Secondary (charged) particles
Acquisition	In-spill, inter-spill, after-treatment	In-spill
Position	❑ heads face to face ❑ perpendicular to the beam axis ❑ fitted position wrt the isocenter	❑ forward direction ❑ 60° wrt the beam axis.
Distance from beam isocenter	25 cm	~ 40 cm
Output	3D activity map / profile	Emission point distribution

Inside

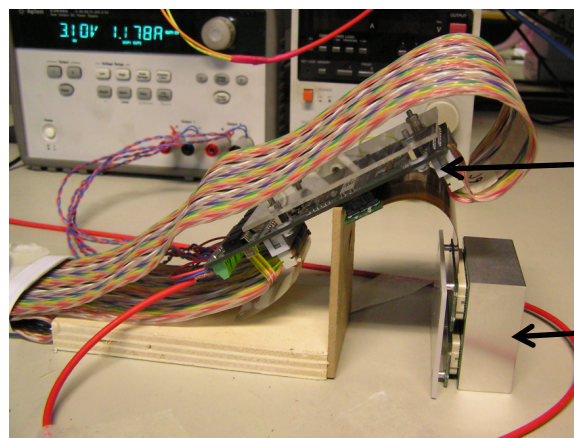
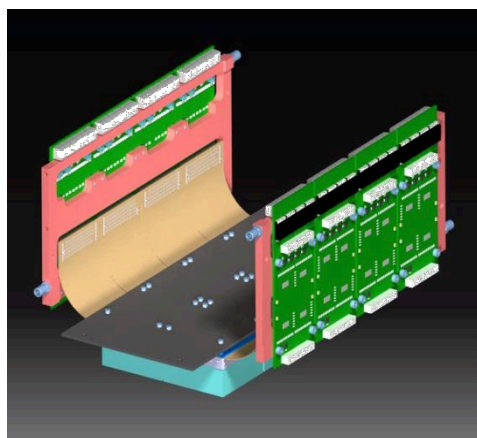
The INSIDE PET



10 x 20 (25) x 5 cm³
Distance from the
Isocenter = 25 cm



256 LFS pixel crystals (3x3x20mm³) coupled one to one to MPPCs (Multi Pixel Photon Counters, SiPMs).



FE board
(Tofpet ASIC)

In-beam PET
module

Inside

The INSIDE PET design: simulations

Beam delivery

Target (phantom, patient CT)

Activity generation

PET module structure

Signal generation

Electronics

DAQ

Reconstruction

Data Analysis

**GEANT4,
FLUKA**

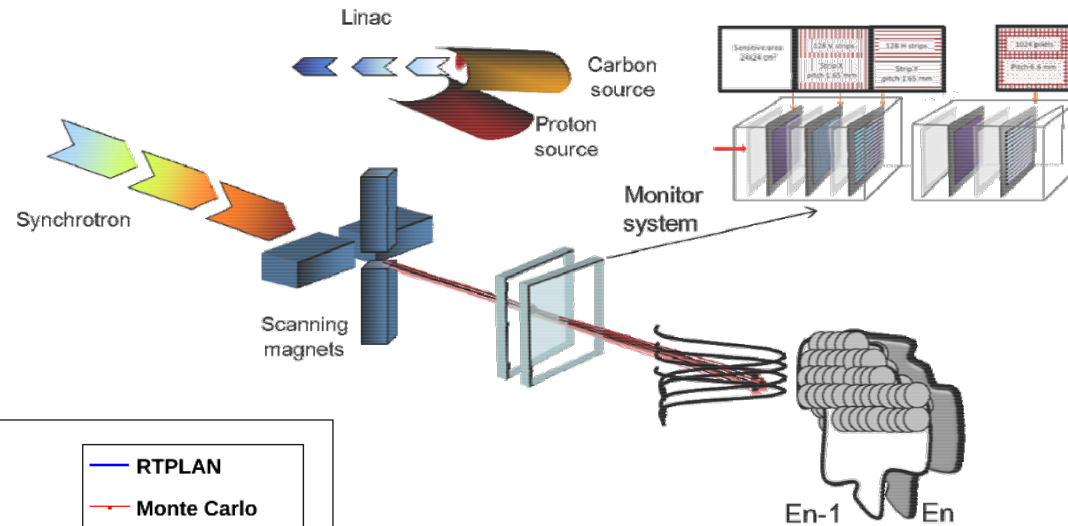
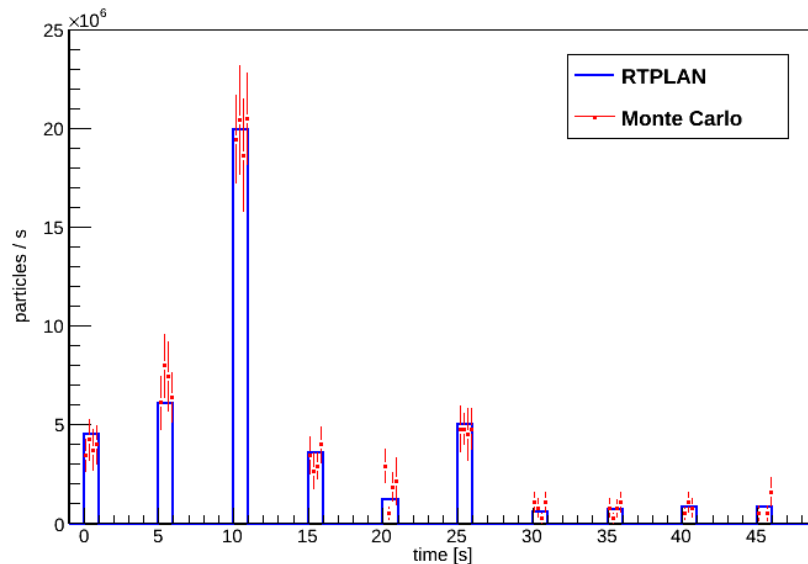
**Custom
development**

Inside

The INSIDE PET design: simulations

Beam delivery

CNAO beam
Time structure



<http://www.fluka.org>

Inside

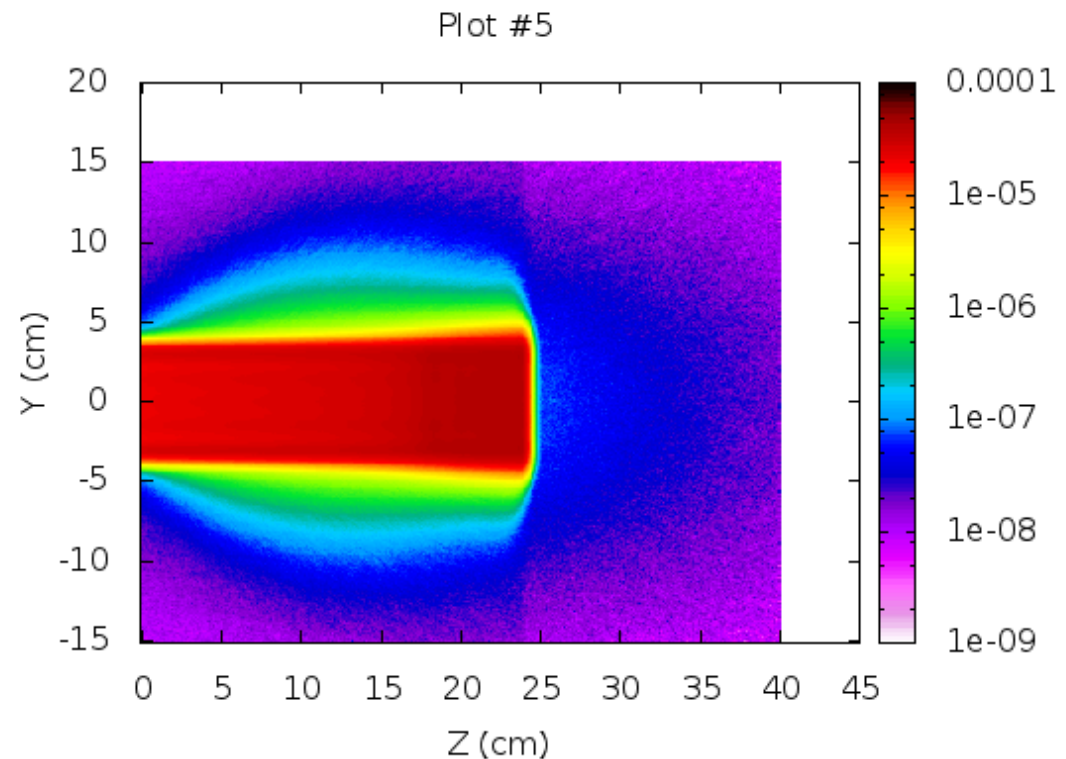
The INSIDE PET design: simulations

Target / Activity generation

Protons on a
 $5 \times 5 \times 40 \text{ cm}^3$
water phantom
simulated with



<http://www.fluka.org>



Inside

The INSIDE PET design: simulations

PET module structure

Lutetium Fine Silicate (LFS)

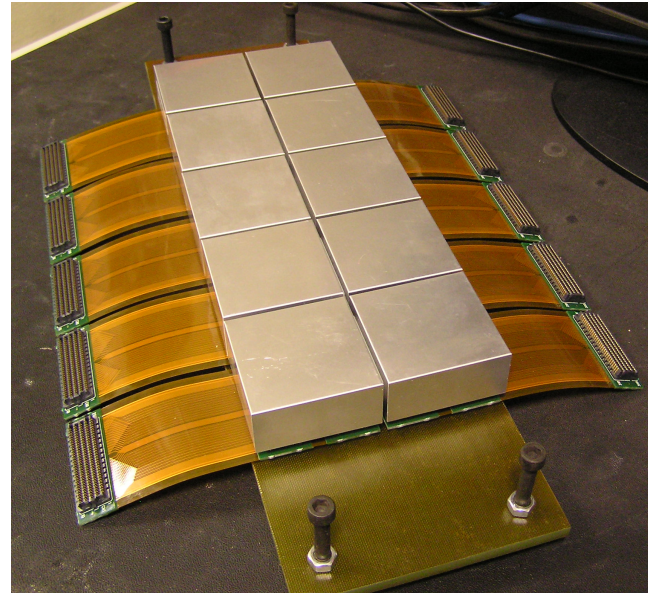
16 x 16 crystals / module

3 x 3 x 20 mm³ size

5 x 5 cm² module

25 x 10 cm² head

Coupling to SiPMs



Inside

The INSIDE PET design: simulations

Silicon PhotoMultipliers (SiPMs)

Avalanche Photo Diodes in Geiger (saturation) mode

50 x 50 μm^2 cells

- **single photon counting!**

Gain $\sim 10^6$

Risetime: $\sim 1\text{ns}$

Bias: 30-80 V

Temp. sensitivity: 1-8%/K

Compactness

Magnetic compatibility



Inside

The INSIDE PET design: simulations

Front-end Electronics

The TOF-PET ASIC

LIP (Lisbon)/INFN

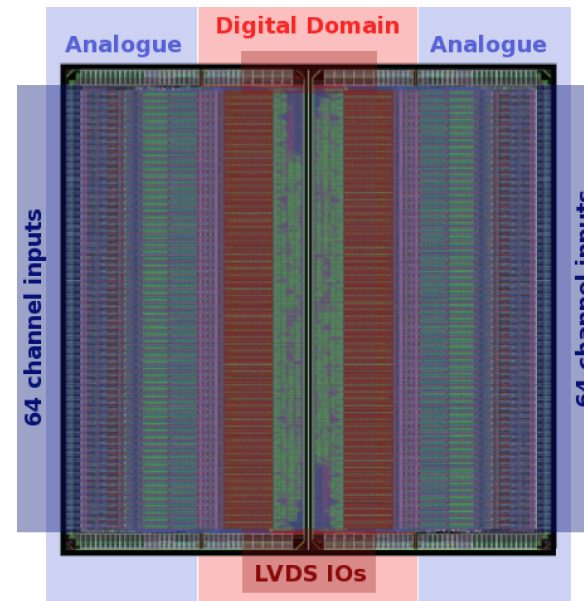
64 channels

100 kHz/ch

15mW/ch

Energy: ToT (not linear!)

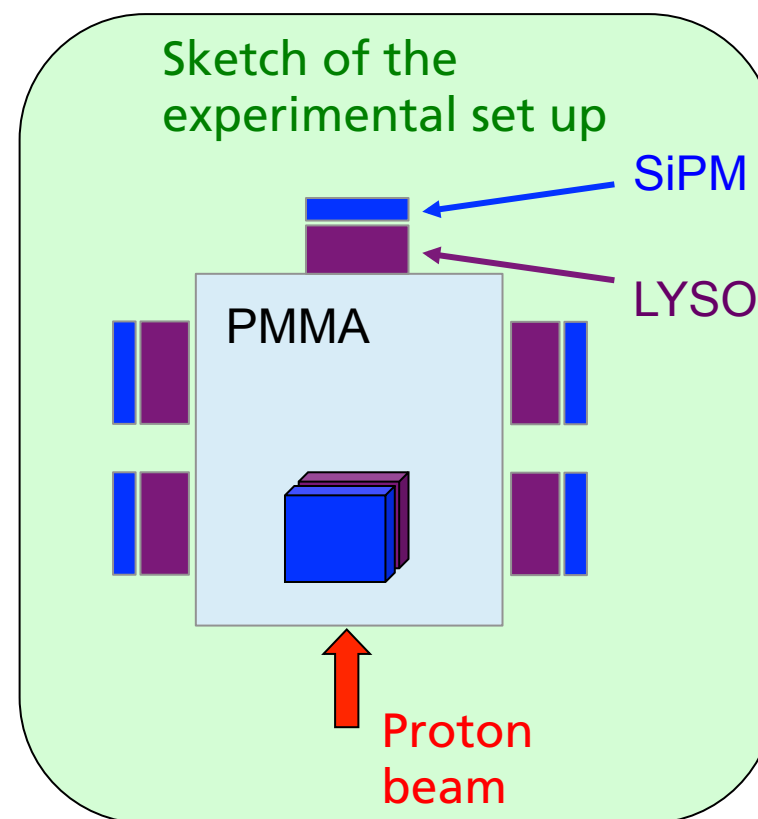
Time resolution: 150-200 ps



Inside

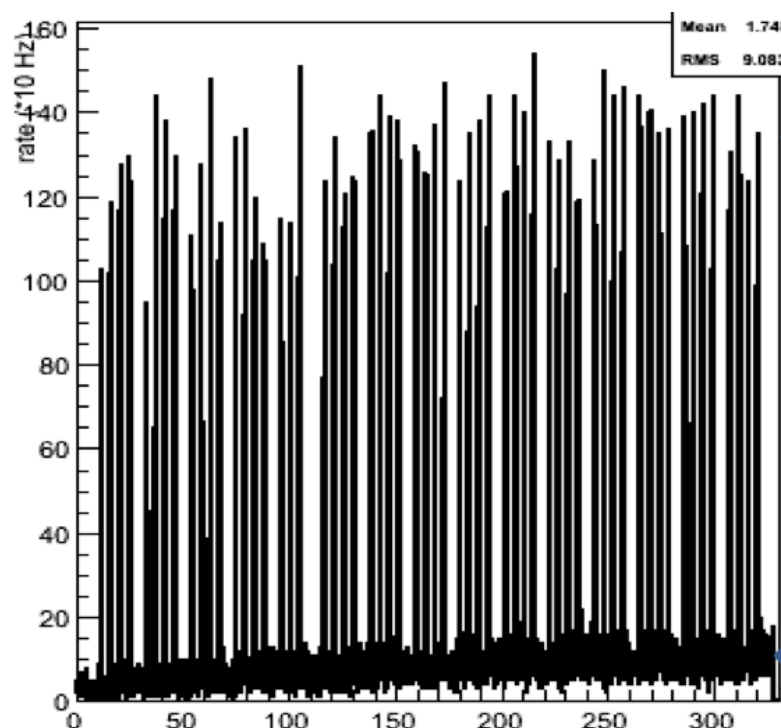
PET “prototype”: few channels

- **Beam**
 - Energy: 95 MeV
 - Intensity: $2 \cdot 10^9$ p/s
- **Target**
 - PMMA phantom $5 \times 5 \times 7$ cm³
- **Detectors**
 - LYSO crystal $3 \times 3 \times 10$ mm³
 - RGB SiPM from AdvanSid 3×3 mm²
 - Front-end ASIC: TOFPET

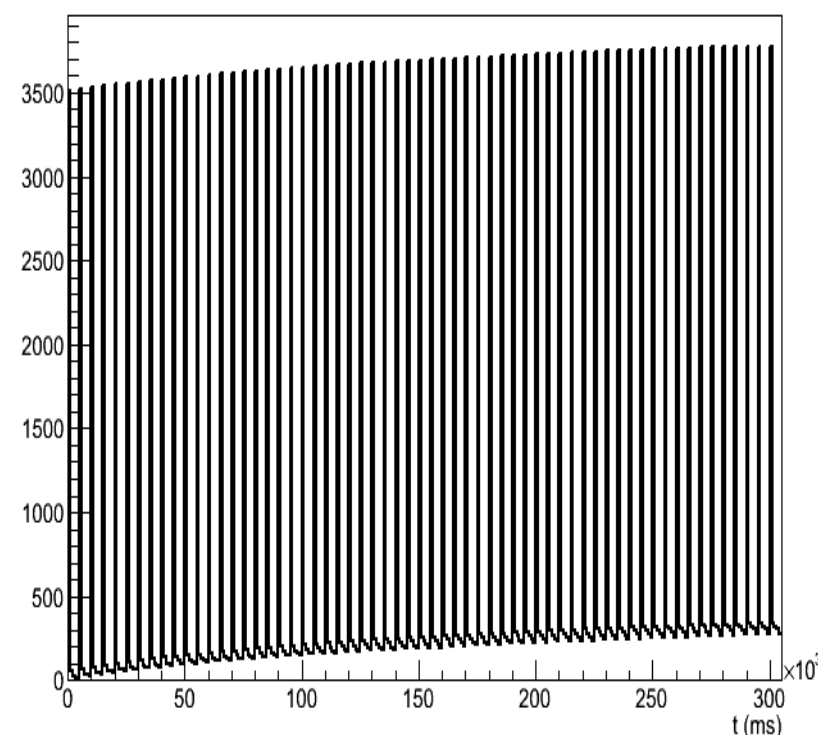


PET Single Trigger Rate

Raw Data



Simulation

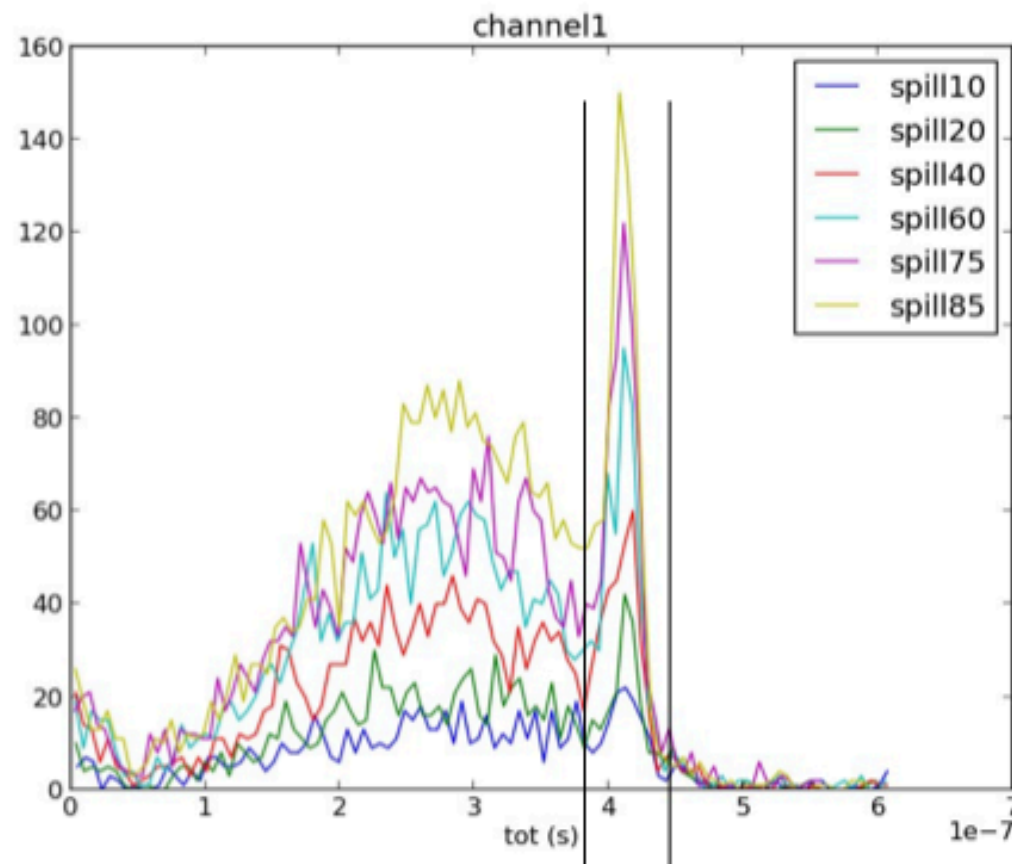


Peak to valley: ~ 15 (Raw Data), ~ 16 (Simulation)

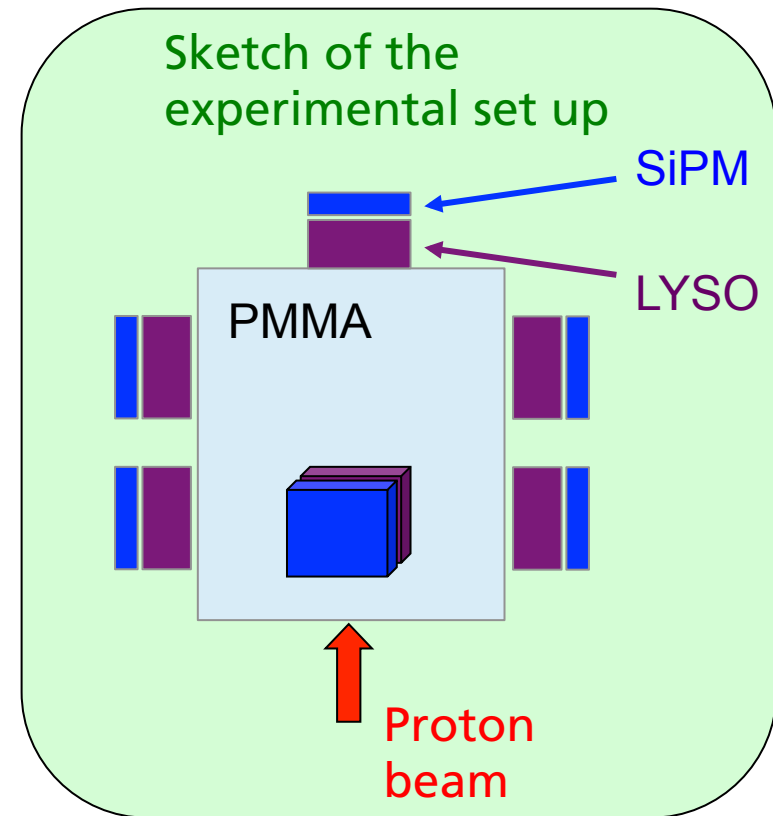
DAQ Rate and full beam/in beam structure under control



Test of PET system "prototype"



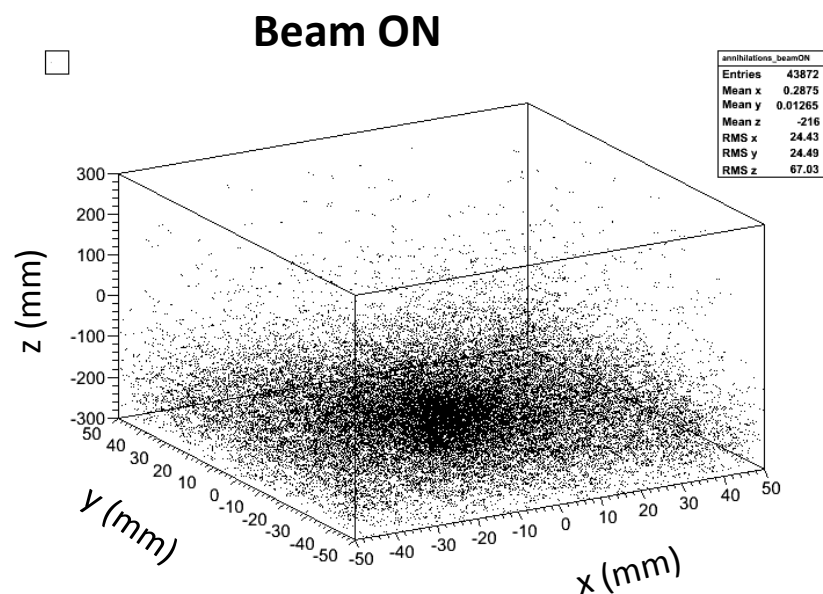
511 keV photopeak events



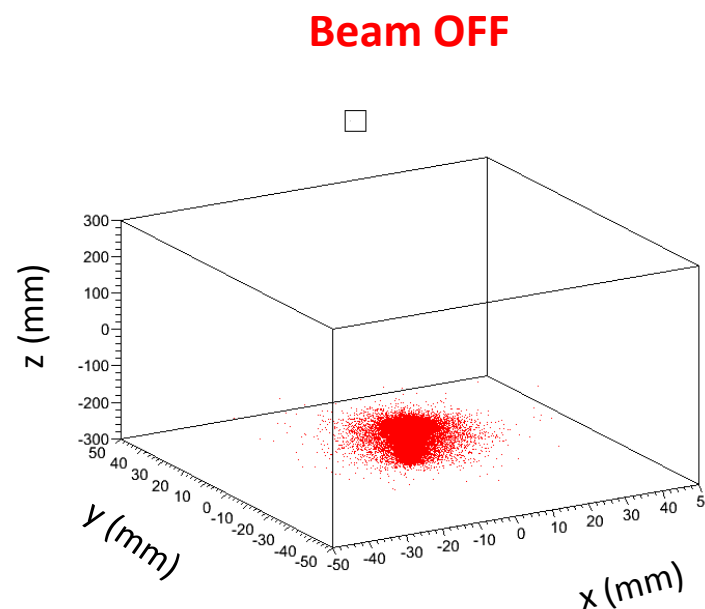
InSide

Annihilation position

- Simulation of the annihilation position :
 - 2 ms beam on + 300 s beam off
 - Plot of the (**known!!!**) annihilation positions



prompt annihilations
& β^+ decays

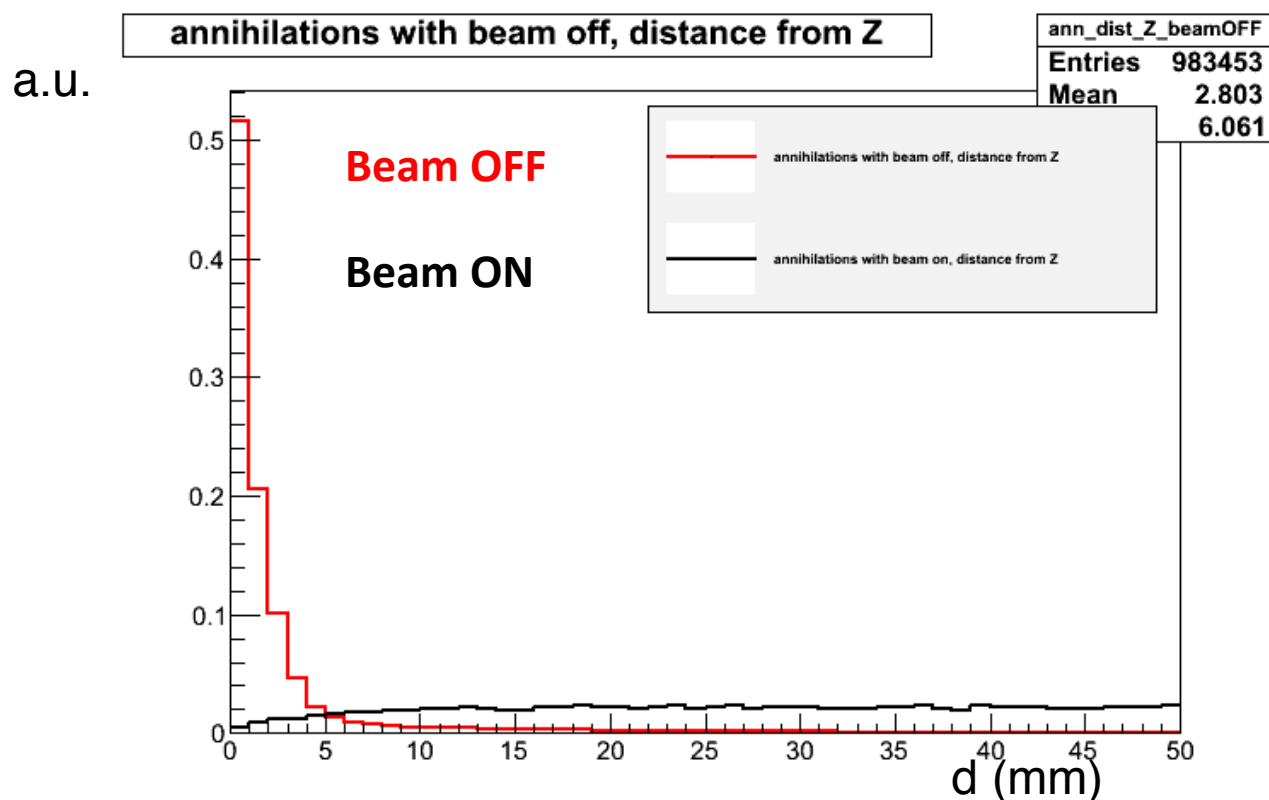


β^+ decays only

Inside

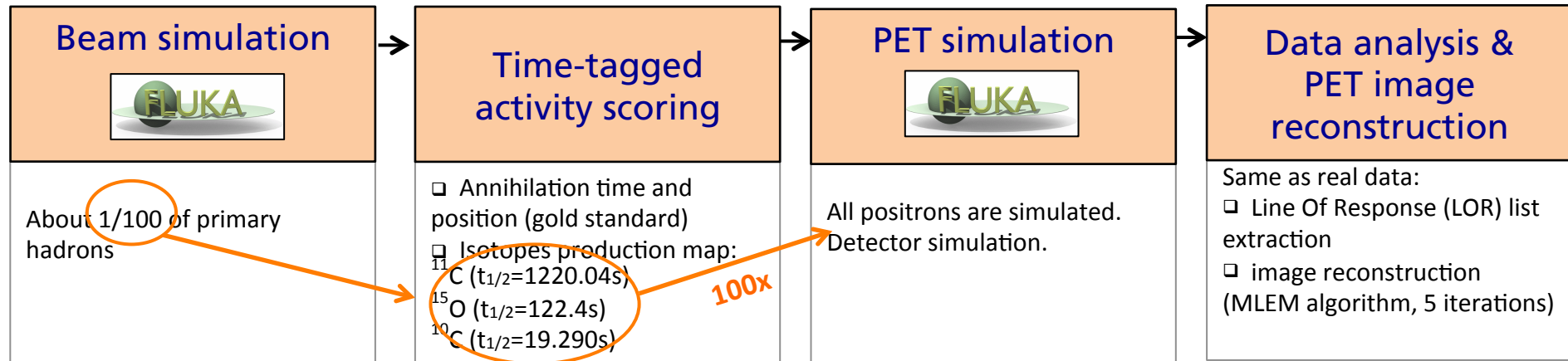
Annihilation position

- Simulation of the annihilation position :
 - 2 ms beam on + 300 s beam off
 - Plot of the (**known!!!**) annihilation positions



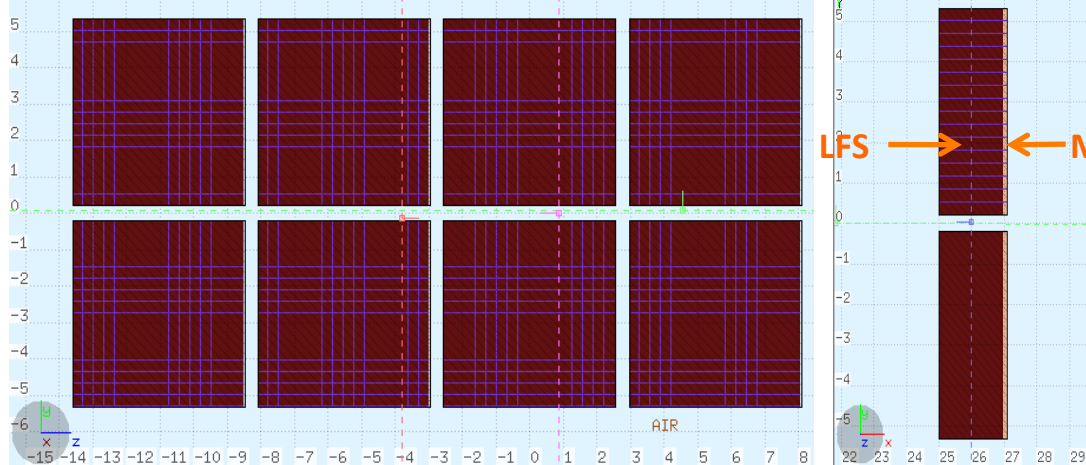
Inside

The INSIDE PET design: simulations



In-beam PET heads simulated geometry

LFS side

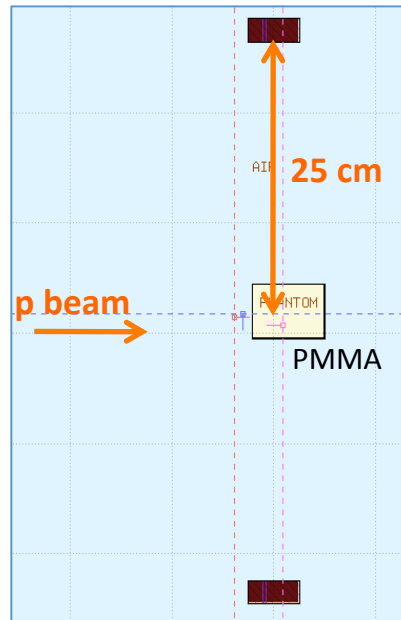


- ☐ Simulated detector:
 - ☐ 15% s DE/E
 - ☐ 600 ps time resolution
 - ☐ 2.5 ns coincidence time window

Inside

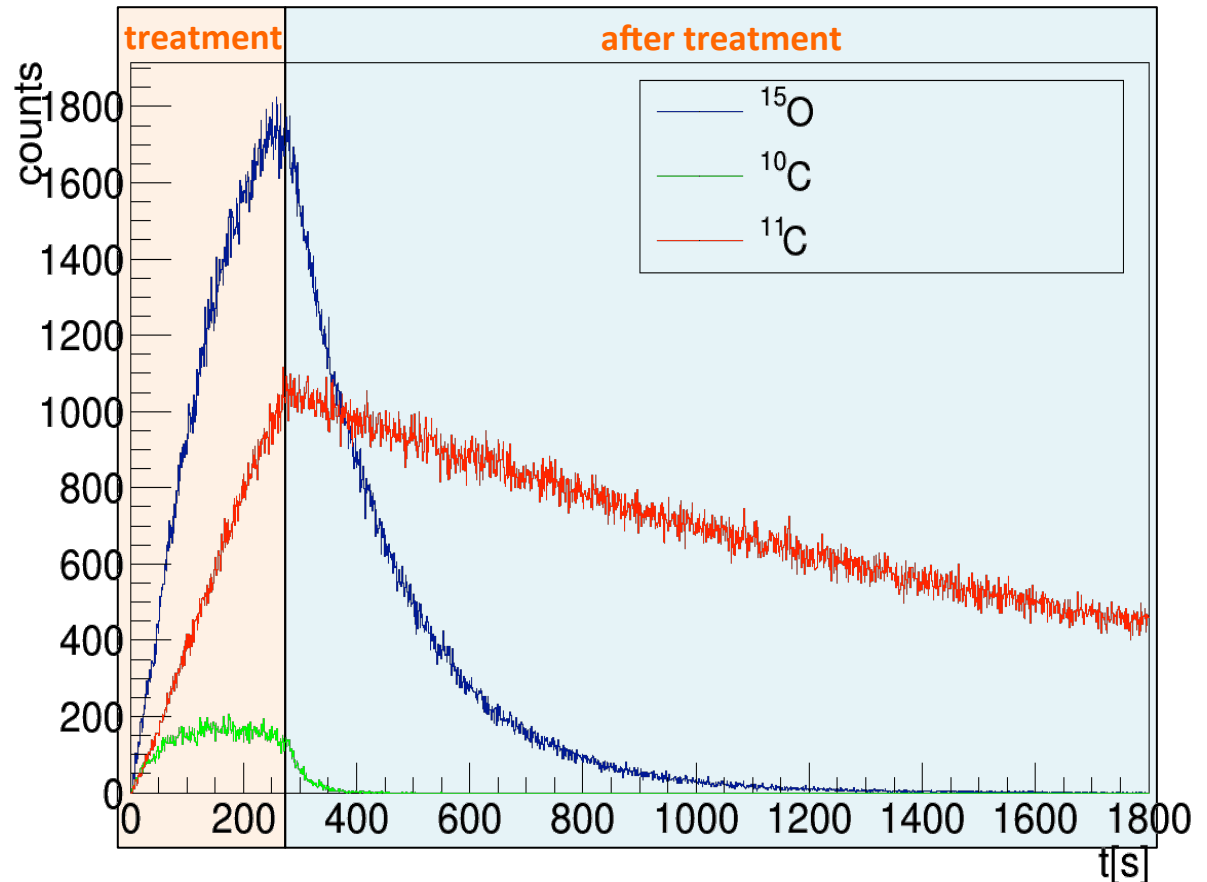
The INSIDE PET design: simulations

ANNIHILATION DISTRIBUTION



Monoenergetic 2D proton treatment:

uniform irradiation
4.5x4.5x0.3cm³ slice @ E=66.34 MeV
4.50E+10 protons
59 spill
7.63E+8 average protons/spill

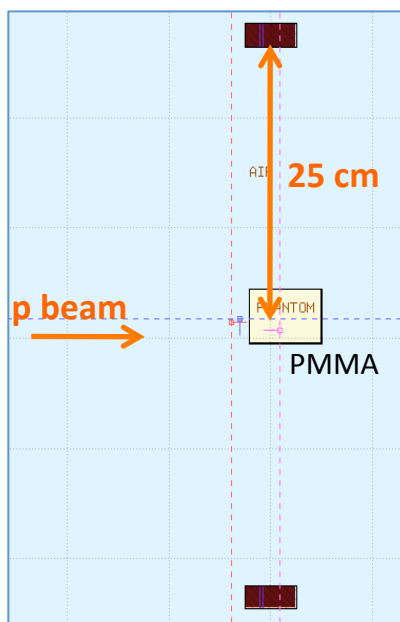


¹¹C, ¹⁰C and ¹⁵O simulated annihilations for the whole treatment plan = 3.2E+8 in 1800s.

Inside

The INSIDE PET design: simulations

ACTIVITY PROFILE ANALYSIS



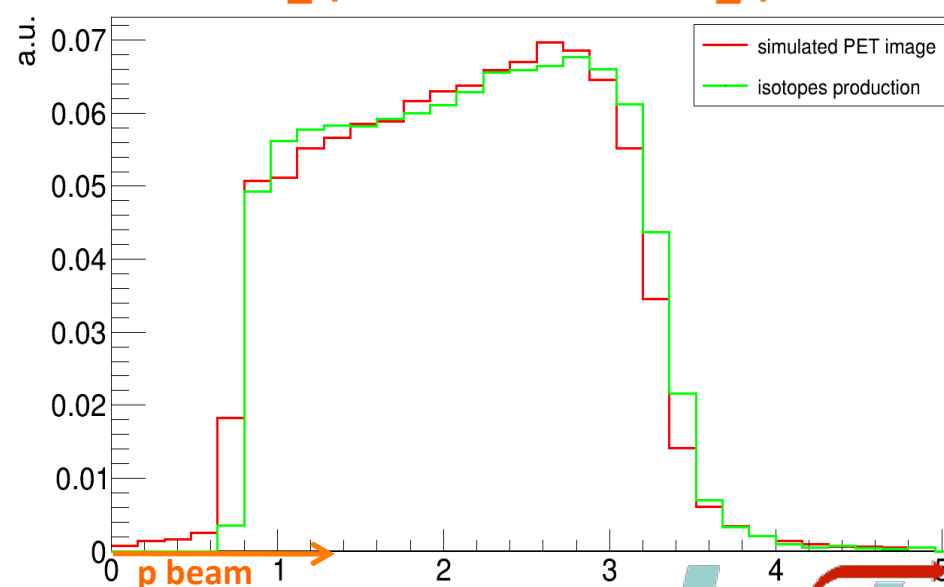
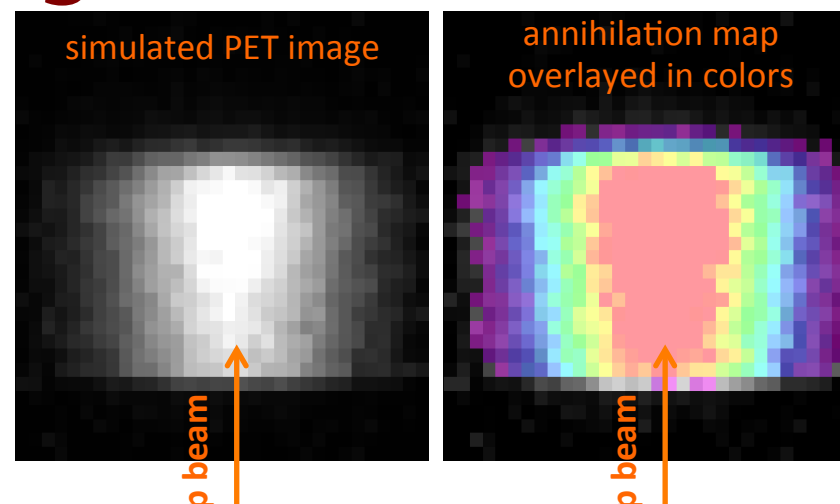
Monoenergetic 1D proton treatment:

single spot @ $E=68.3$ MeV

$2.E+11$ protons

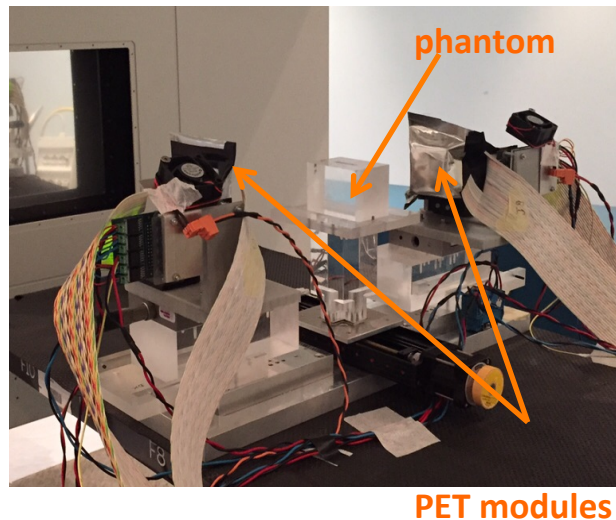
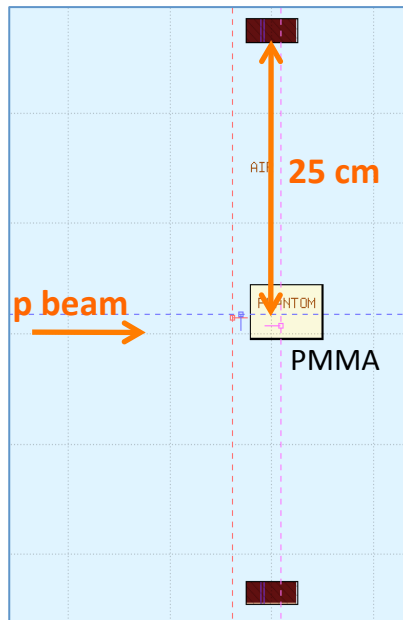
102 spill

$1.96E+9$ average protons/spill



Inside

Beam test May 2015 @ CNAO



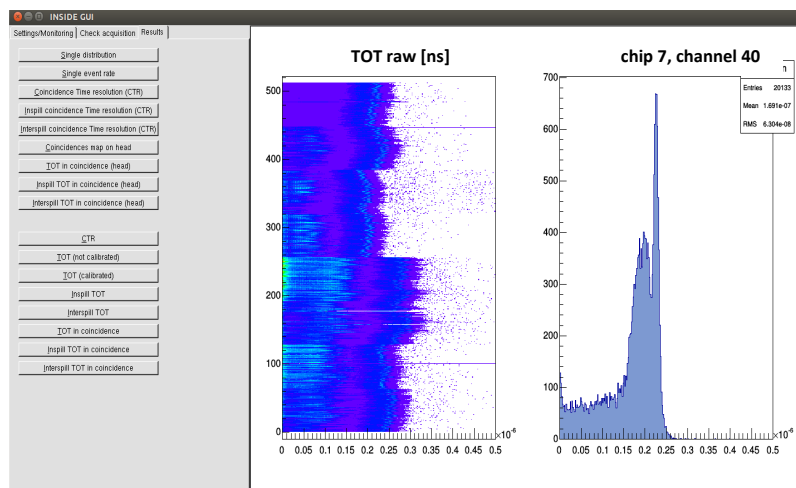
Monoenergetic 1D proton beam

Single spot @

$E=68.3 / 72.03 / 84.3$ MeV

$2E+11$ protons

100 spills instead of 10
(emulate 10 modules with
just 1)



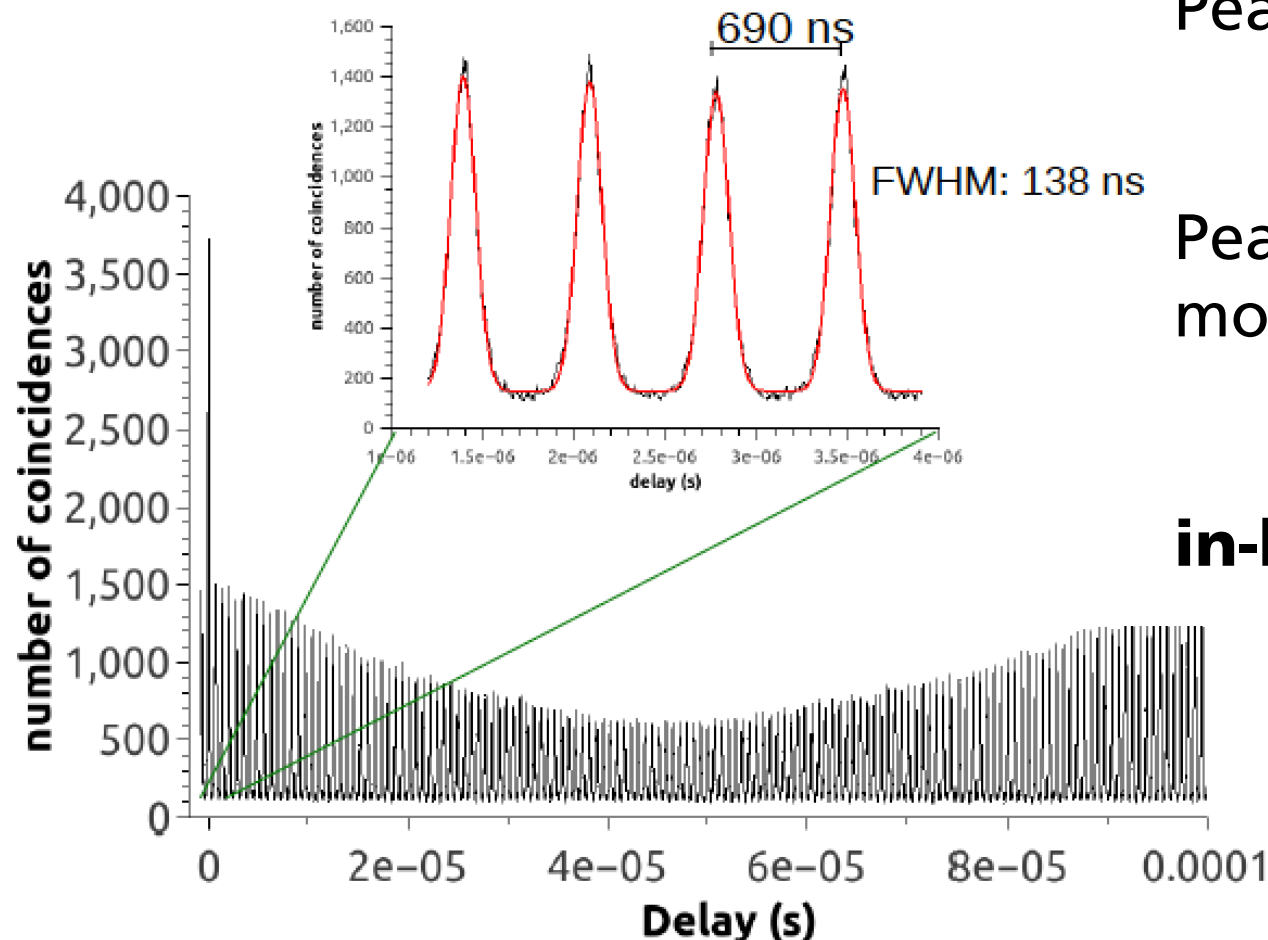
DATA ANALYSIS:

- ☐ Online/offline analysis
- ☐ Automated energy window selection for each channel
- ☐ Automated time delay calibration
- ☐ 3D PET image reconstruction
- ☐ Profile analysis

Inside

Beam test May 2015 @ CNAO

Is 'in-beam' really in-beam?



Peak-to-peak period:
690 ns

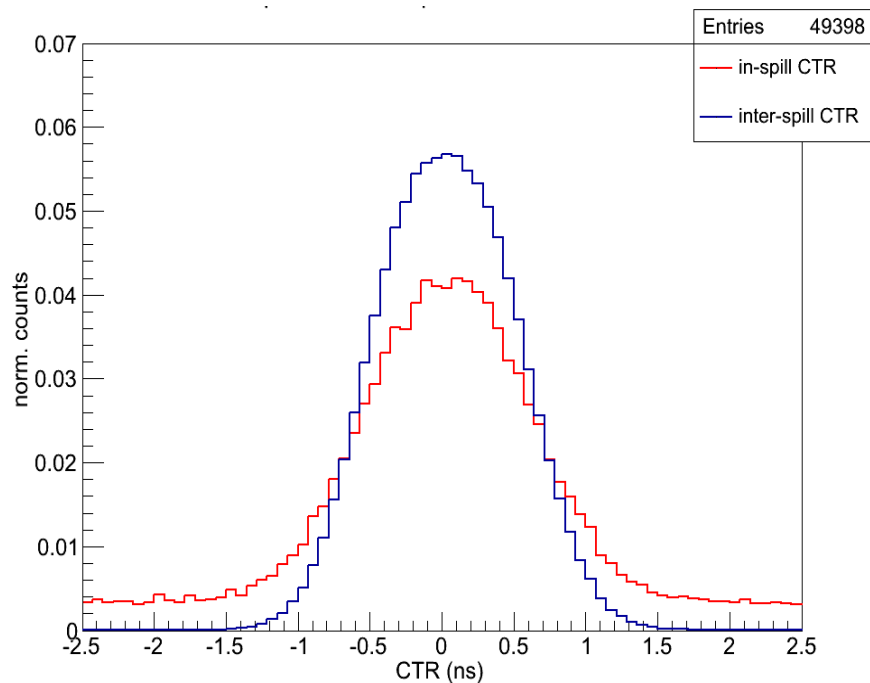
Peak amplitude
modulation
10 kHz

in-beam DAQ!!!

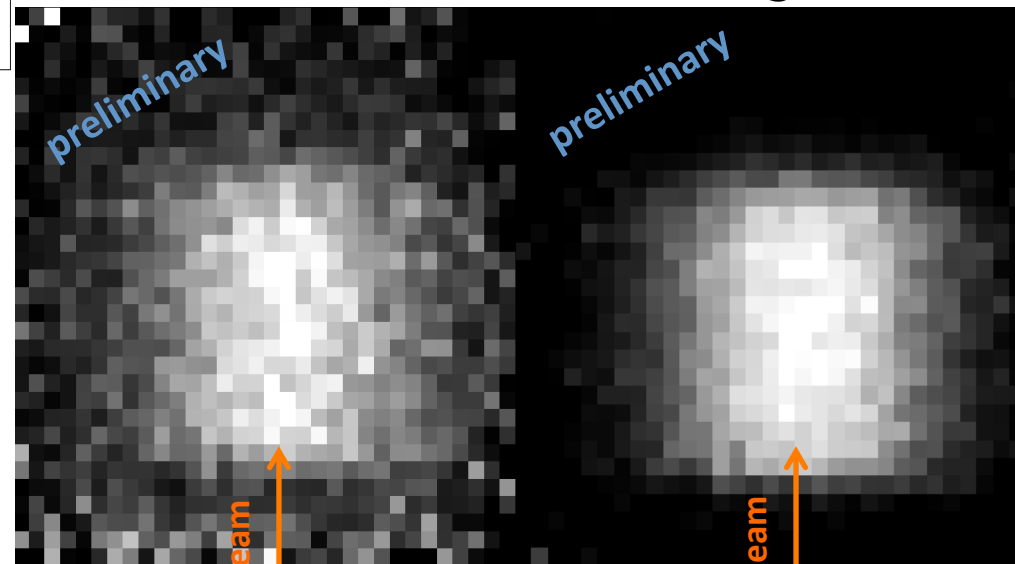
InSide

Beam test May 2015 @ CNAO

Monoenergetic 1D proton treatment @ 68.3 MeV



PET reconstructed images



in-spill

inter-spill

Coincidence Time Resolution (CTR)*

Interspill = 699 ps σ (blue)

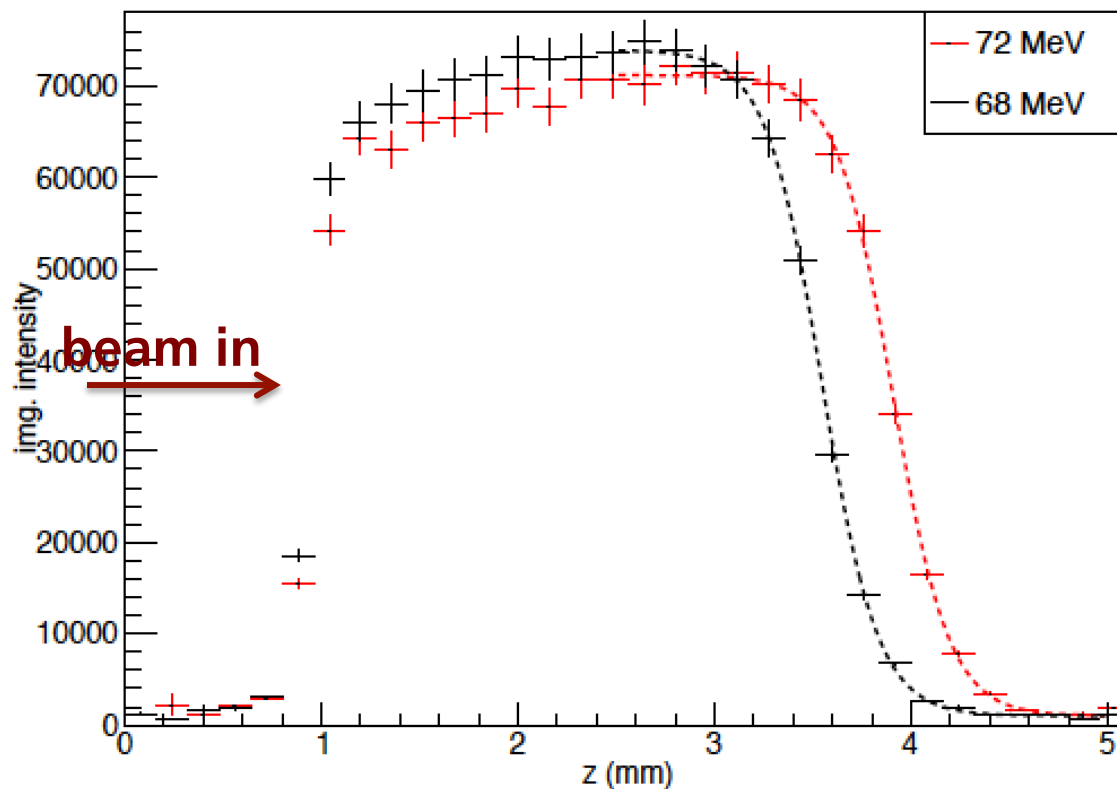
Inspill = 851 ps σ (red)

*detector calibration to be optimised

InSide

Beam test May 2015 @ CNAO

Activity profile / interspill data



PMMA phantom
Difference in the distal
fall-off

Expected:

3.7 mm

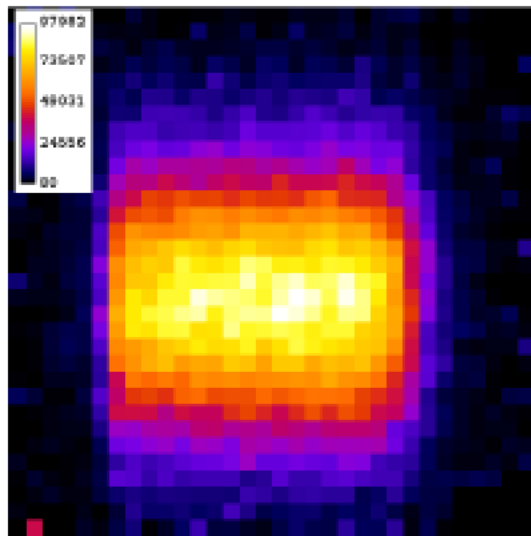
Measured:

(3.6 +/- 0.3) mm

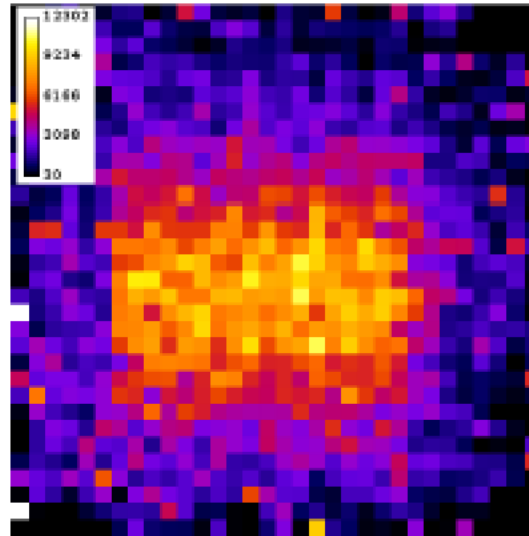
Inside

Beam test May 2015 @ CNAO

Reconstructed images

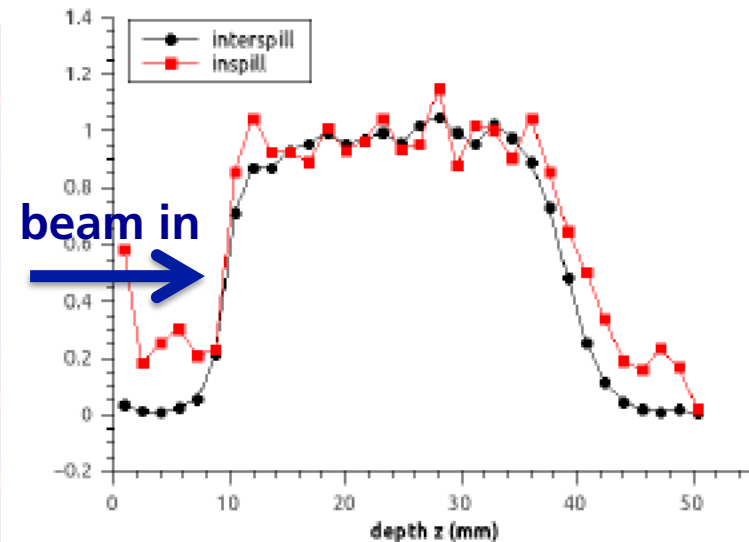


inter-spill



in-spill

Activity profile



Distal fall-off cleaner for inter-spill data
4x
no background from prompt events

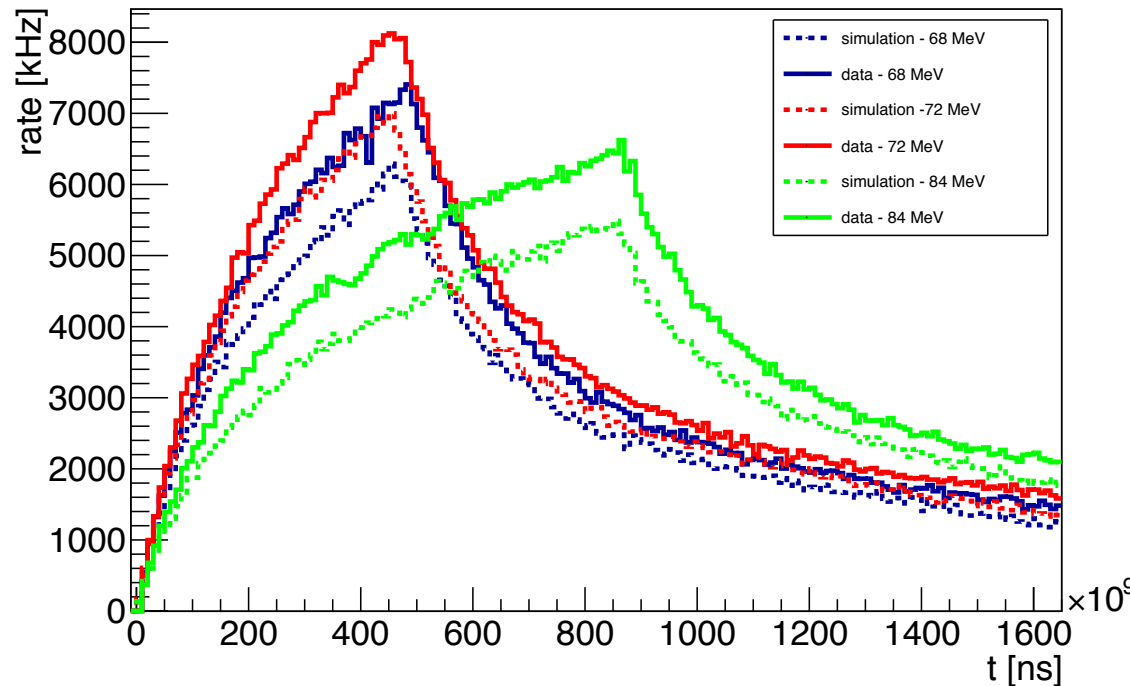
Inside

Beam test May 2015 @ CNAO

Collected events vs time

Single spot @ E=68.3 / 72.03 / 84.3 MeV, 2×10^{11} protons

Coincidence Rate: p @ 68/72/84 MeV/u



Simulations do not take into account all the produced isotopes!

^{11}C , ^{15}O , ^{10}C only

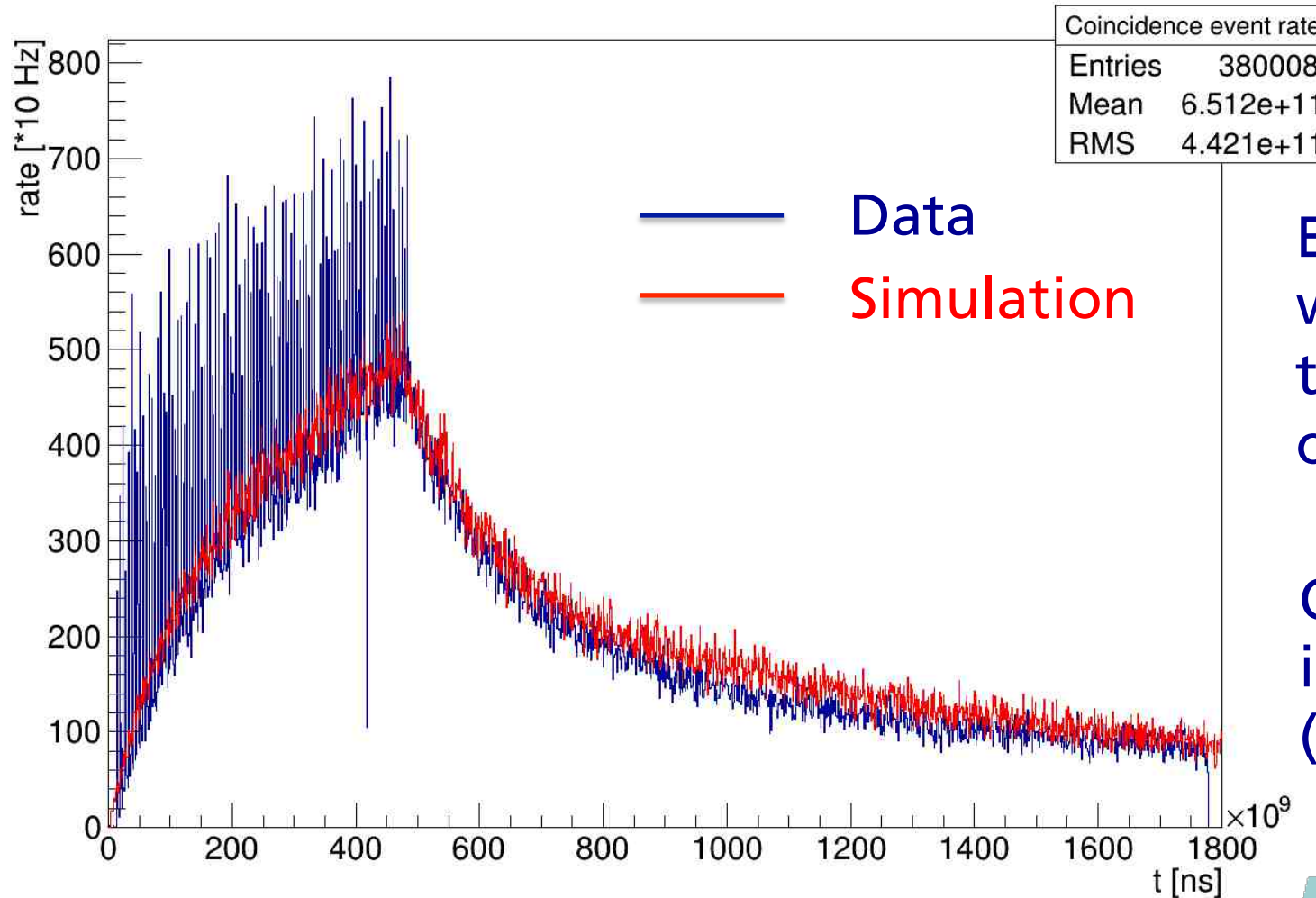
LFS absorption properties not well known

Isotope	^{11}C	^{15}O	^{13}N	^{10}C	^{12}N
Half-life (s)	1223	122	598	19	11×10^{-3}

Inside

Beam test May 2015 @ CNAO

Coincidence event rate



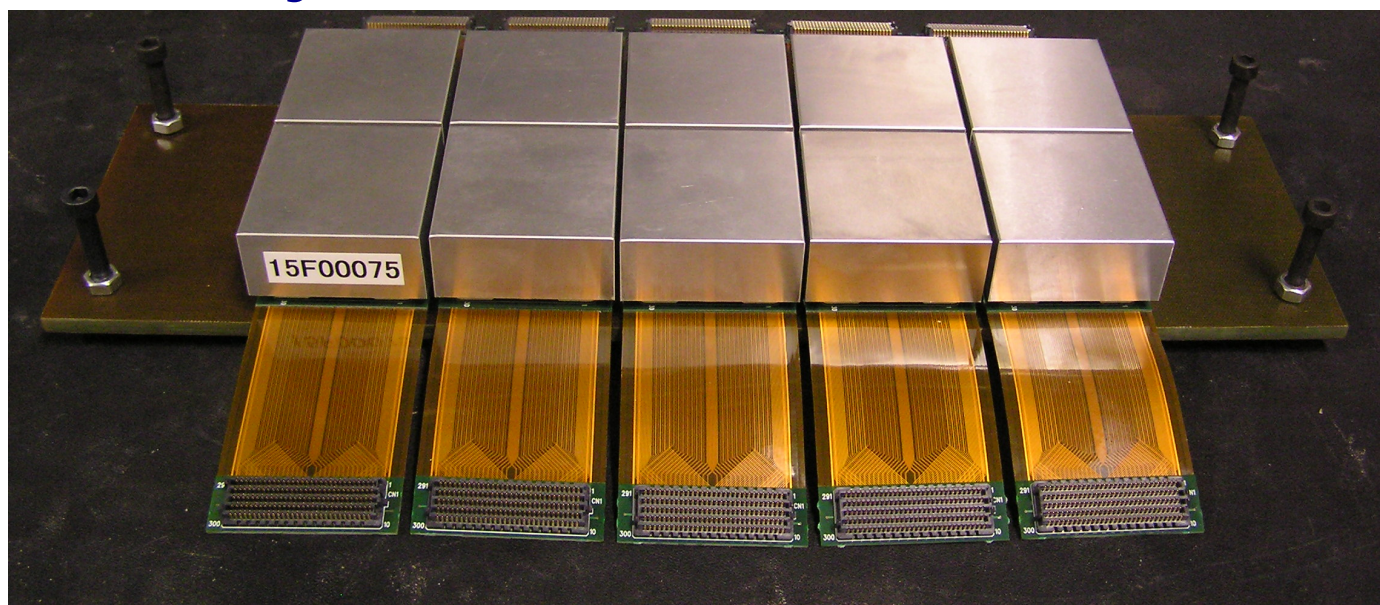
Energy
windows
to be
optimized?

Other
isotopes
(^{12}N)?

Inside

building INSIDE...

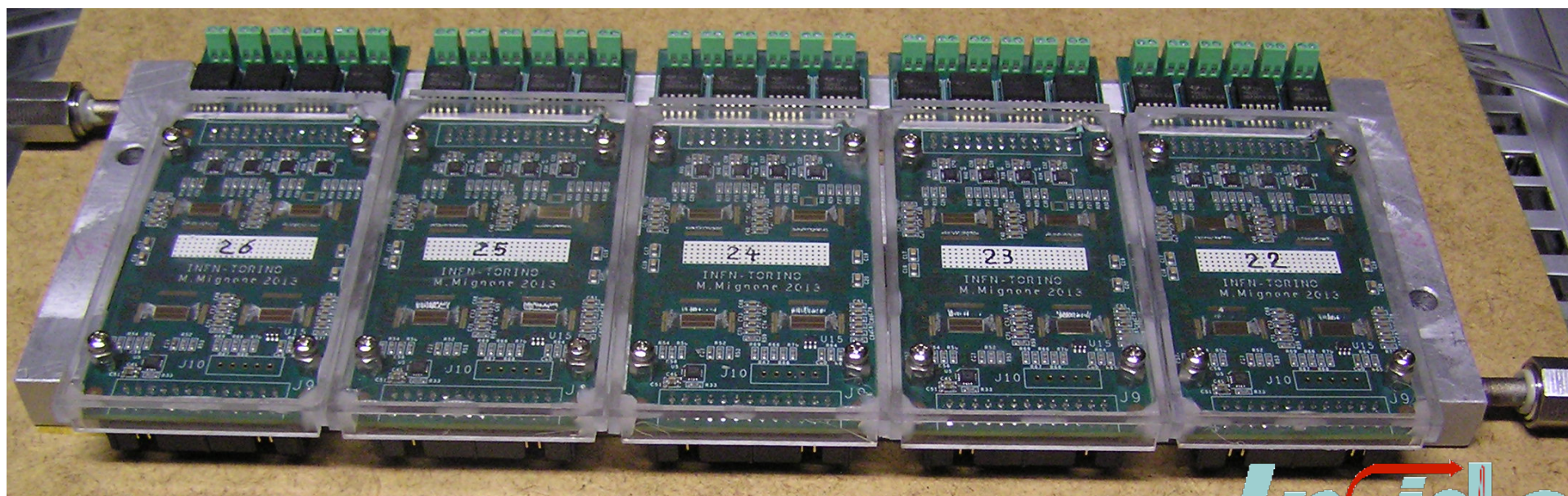
the crystals (+ SiPMs)



InSide

building INSIDE...

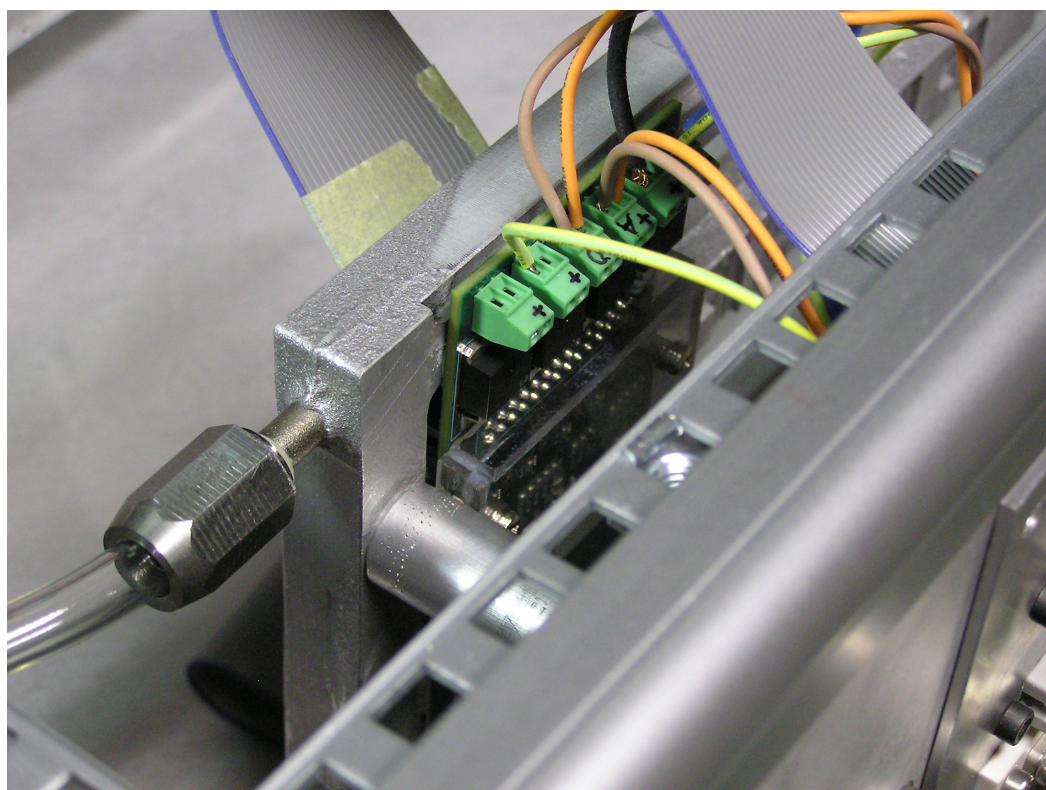
the front-end board... in the cooling plate



Inside

building INSIDE...

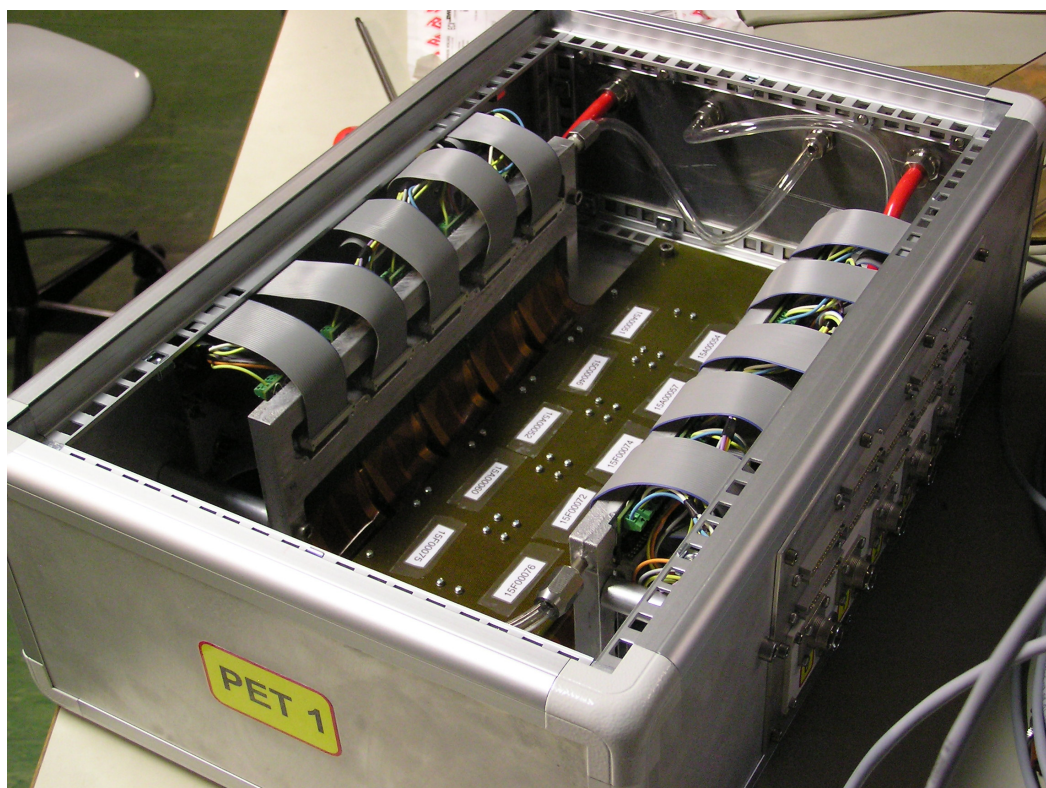
the cooling plate in the box



InSide

building INSIDE...

the boards in the box



InSide

building INSIDE...

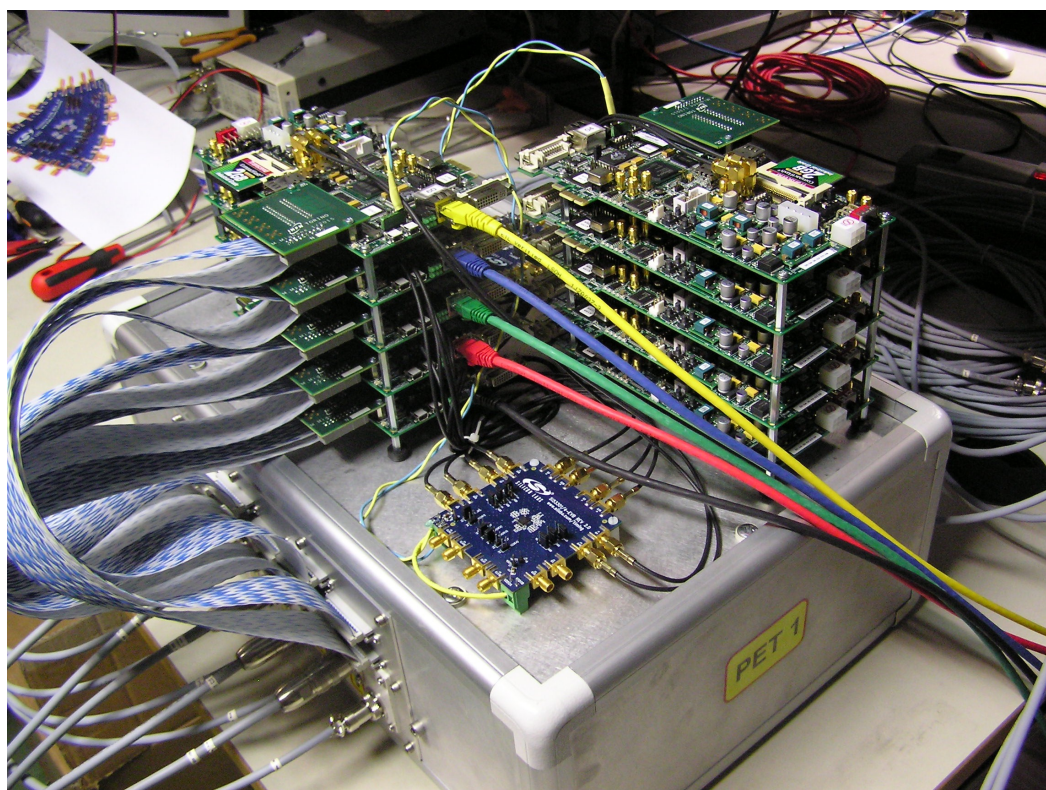
the boards (& their cables) in the box



InSide

building INSIDE...

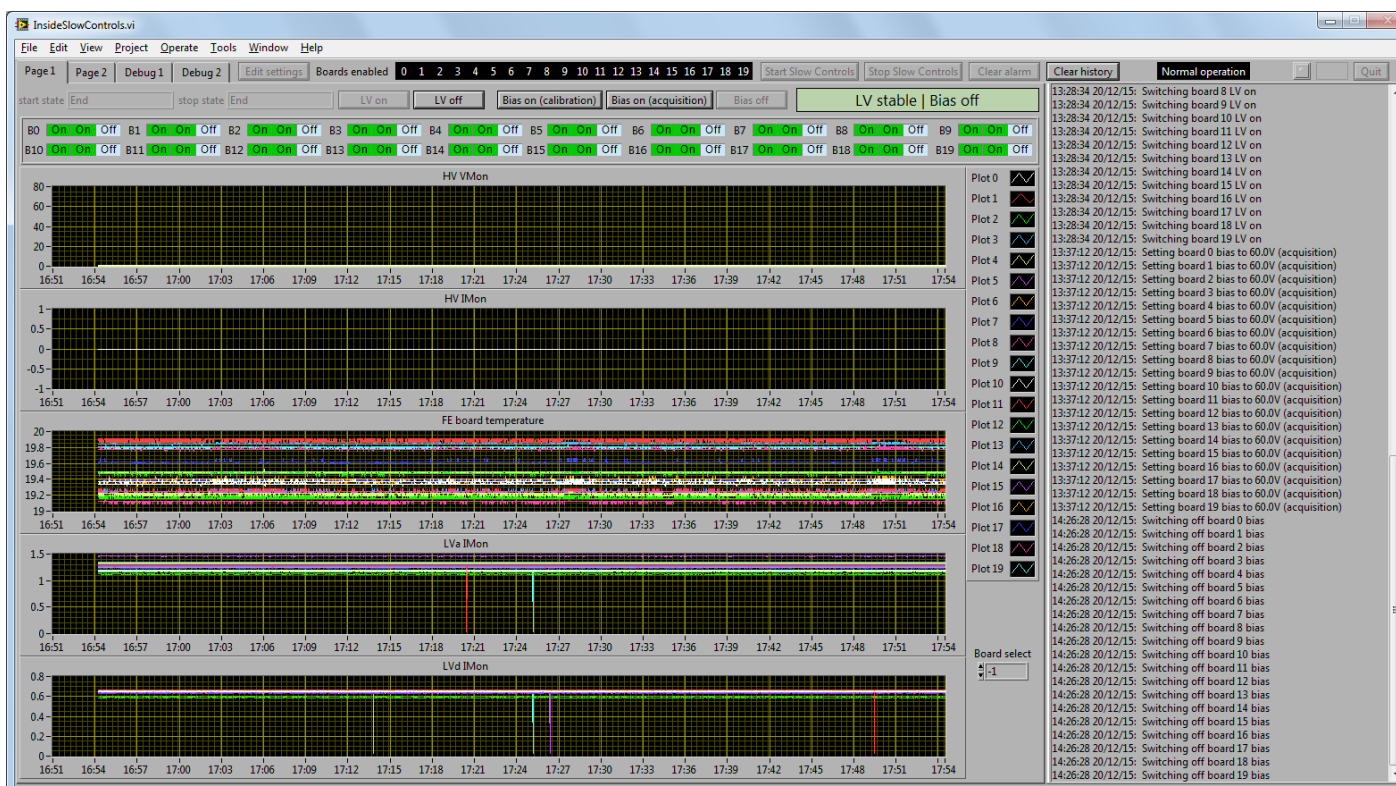
the FPGA boards



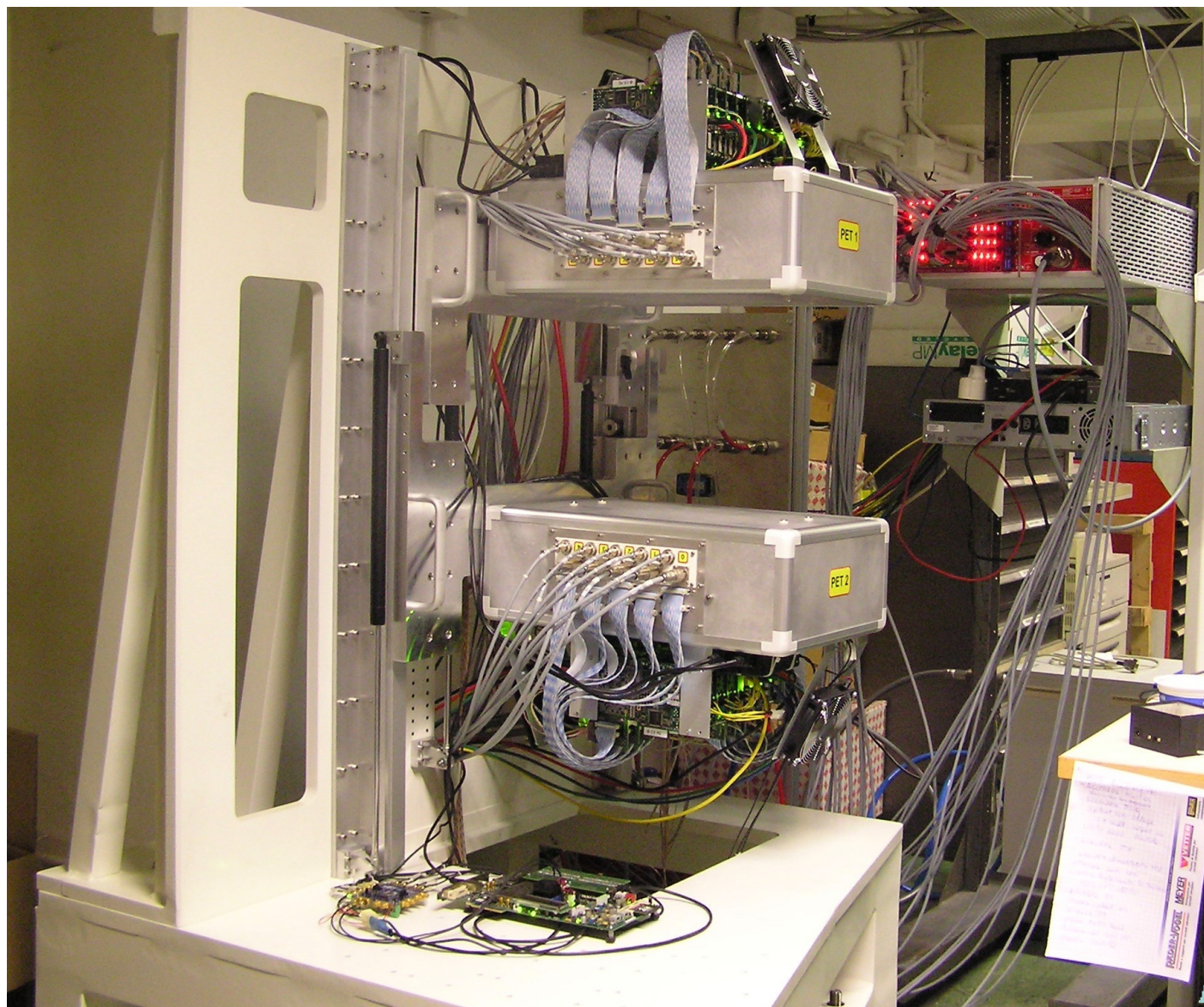
InSide

building INSIDE...

the slow control console: monitor T, V



INSIDE @ INFN - Torino: 01/2016



Inside

the INSIDE calibration

foreseen at IRCCS Candiolo (To) with ^{18}F -FDG
planar source

logistics (transportation) issues

what could we do?

problems with radiation protection

maximum activity that can be freely transported (1 MBq)

available from Ospedale S. Croce e Carle (Cuneo)



INSIDE

the INSIDE calibration

drive to Cuneo, come back with 1 MBq ^{18}F -FDG

point-like source (twice)

- channel map debugging + rates
- energy calibration

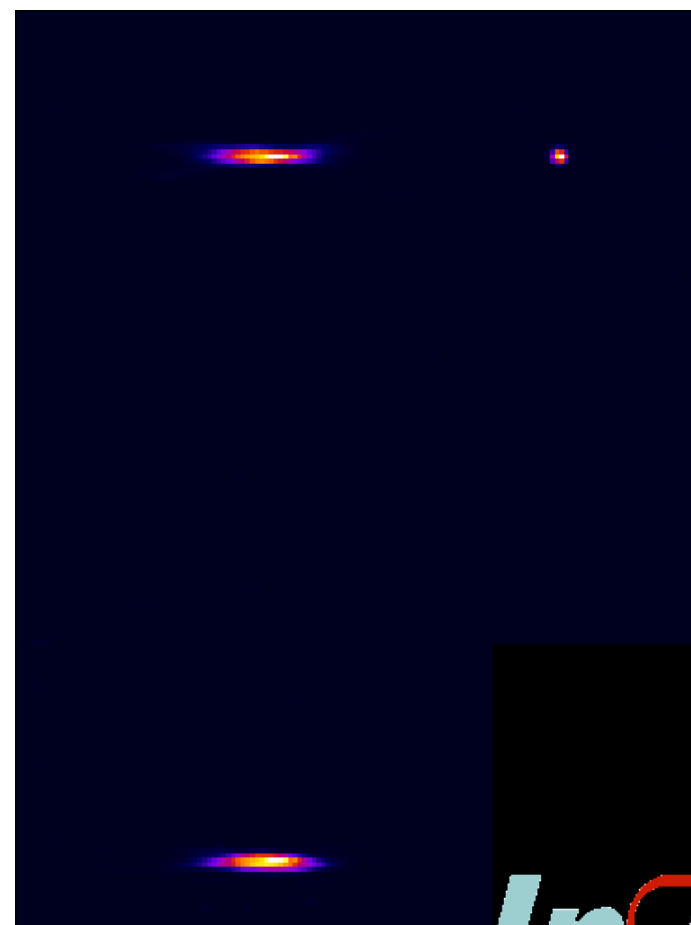
planar source (once)

- time calibration



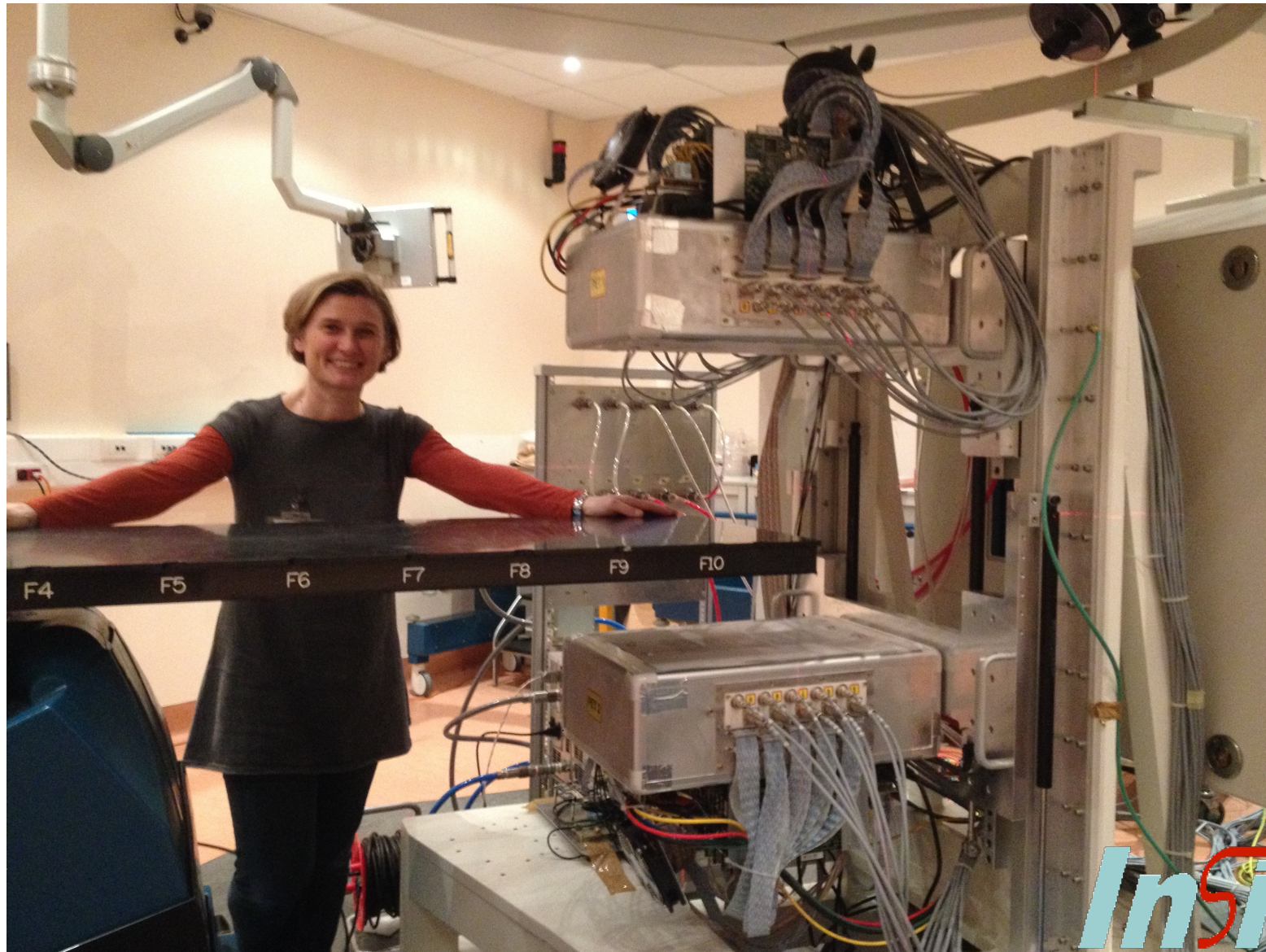
the INSIDE calibration

Point-like ^{18}F -FDG source



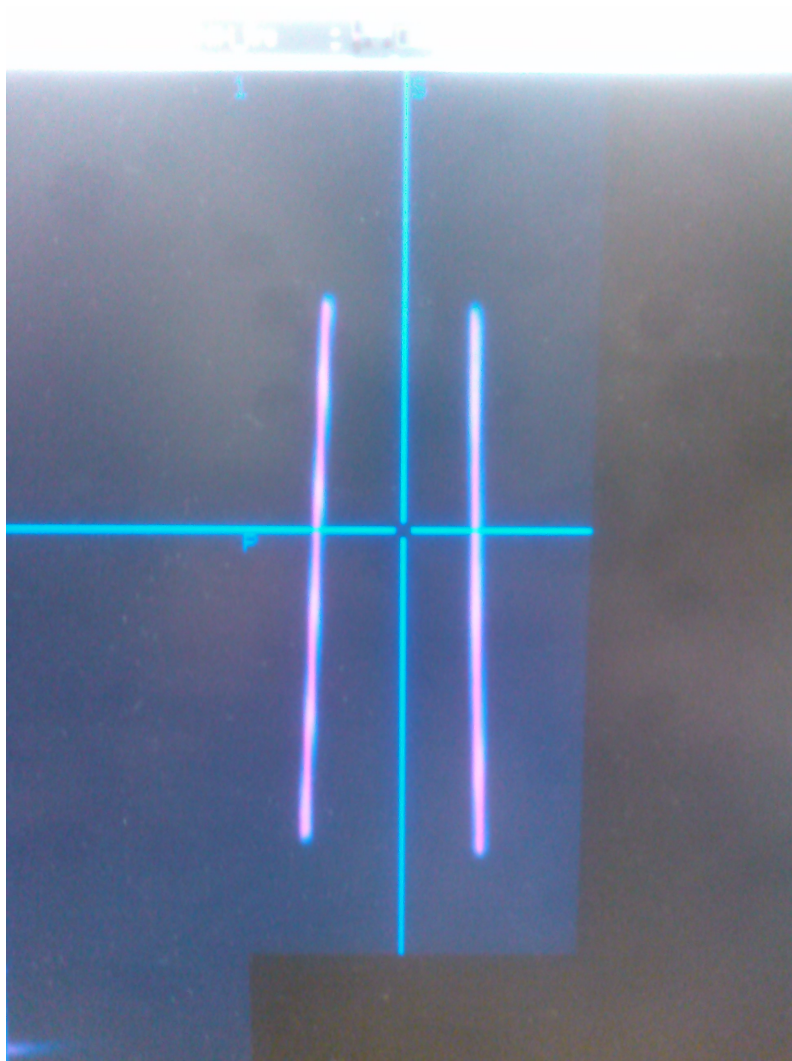
Inside

INSIDE @ CNAO: 07/02/2016



Inside

Calibration with ^{68}Ge rods

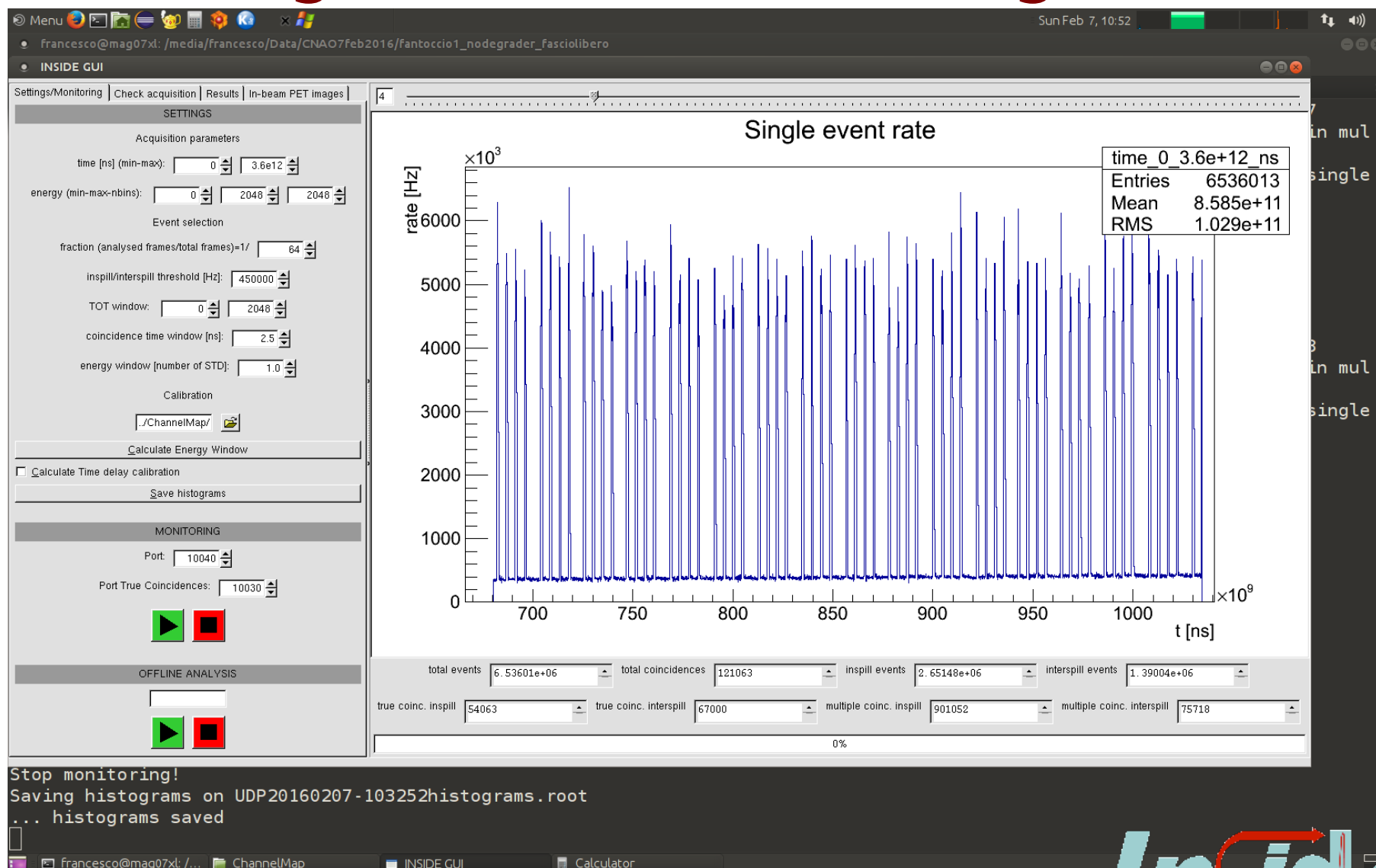


- Test of high rate DAQ
- Verification of channel map
- Energy calibration
- Time calibration

INSIDE @ CNAO: 07/02/2016



Turning on INSIDE: rate (singles)



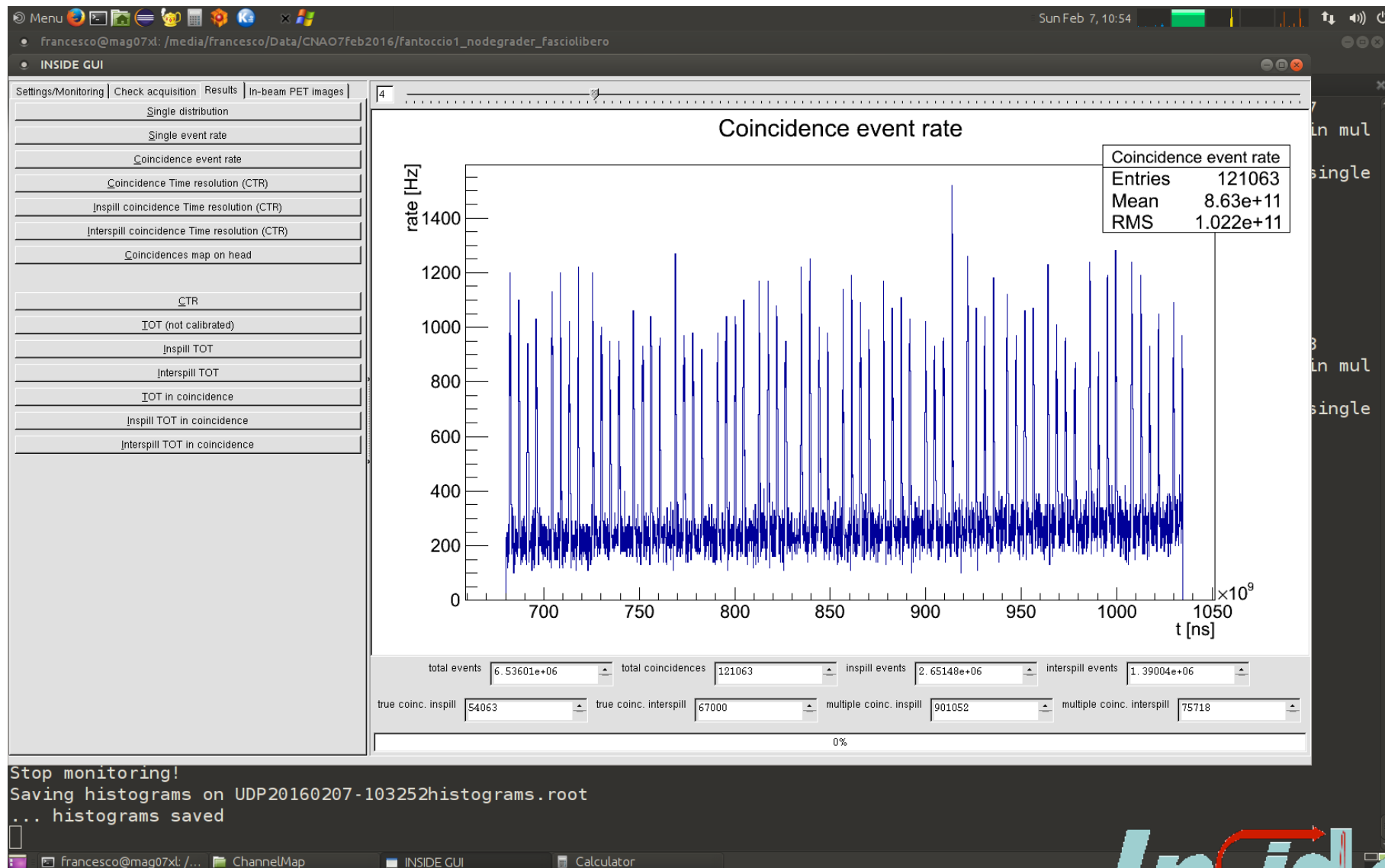
Peak to valley: 13

Piergiorgio Cerello – cerello@to.infn.it

Giornate di Studio sui Rivelatori - Cogne, February, 23rd-26th 2016

Inside

Turning on INSIDE: rate (coincidences)



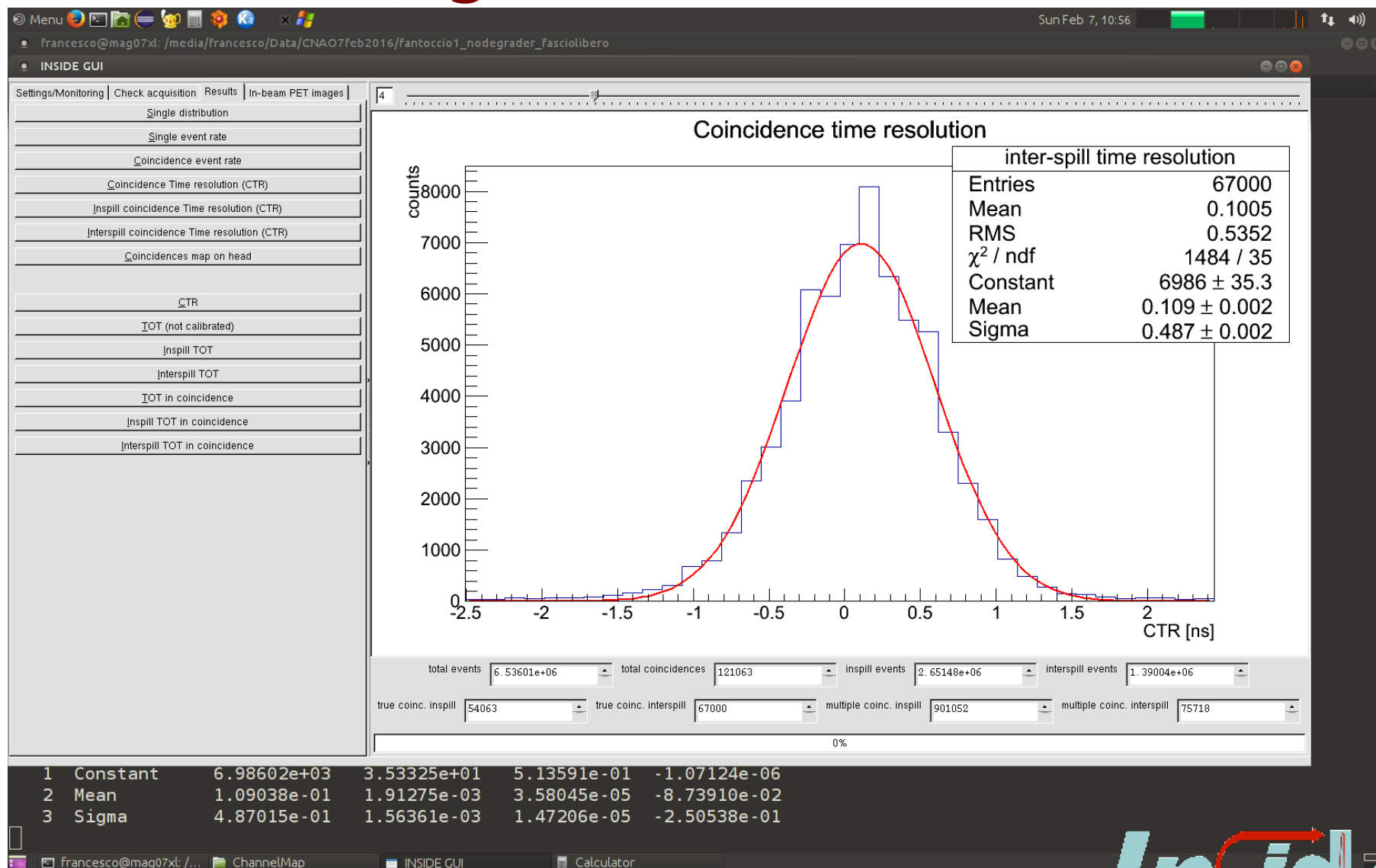
Peak to valley: 5

Piergiorgio Cerello – cerello@to.infn.it

Giornate di Studio sui Rivelatori - Cogne, February, 23rd-26th 2016

Inside

Turning on INSIDE: CTR



Intrinsic time resolution < 480 ps

Piergiorgio Cerello – cerello@to.infn.it

Giornate di Studio sui Rivelatori - Cogne, February, 23rd-26th 2016

Inside

Bragg peak depth validation

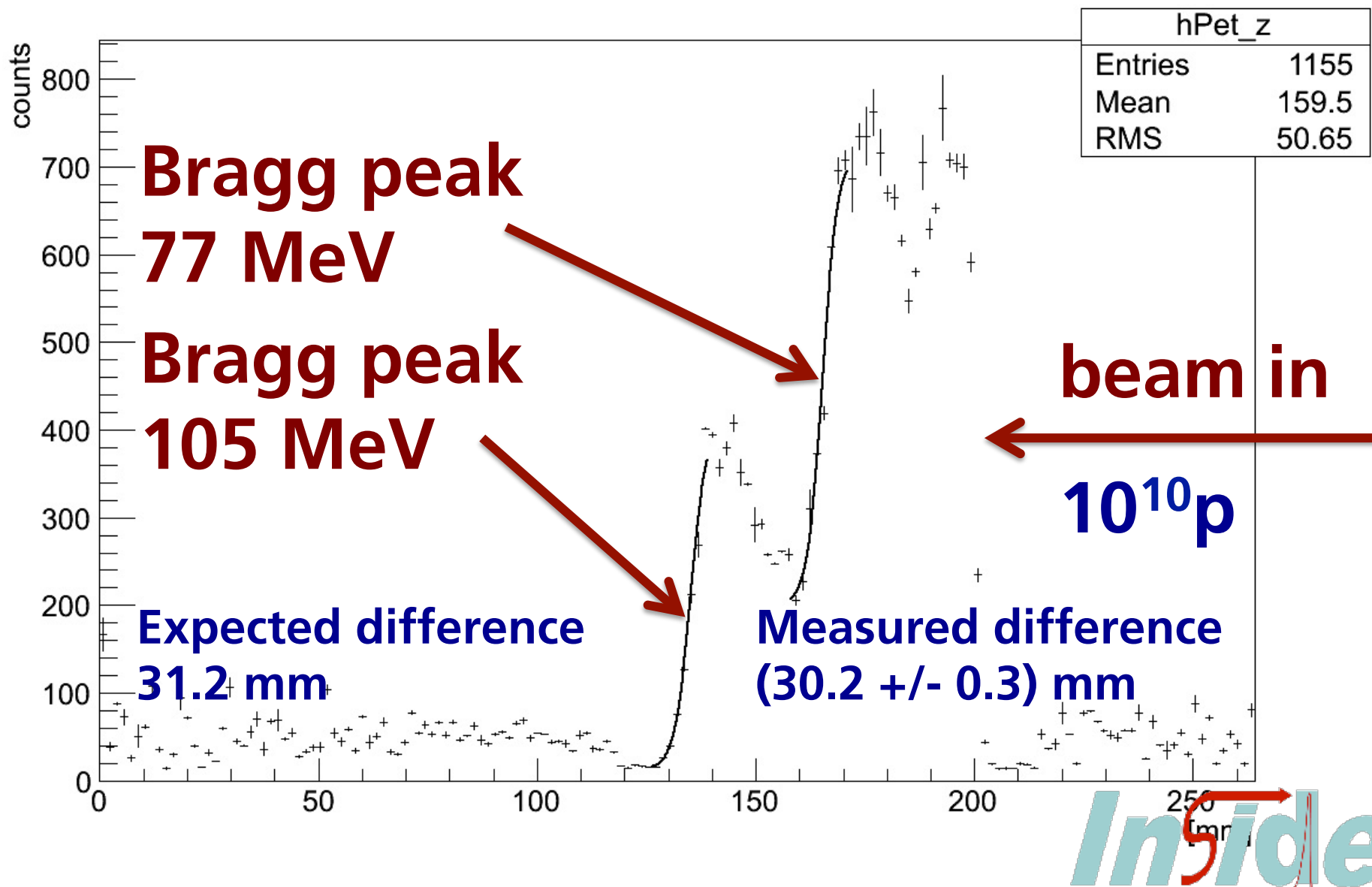
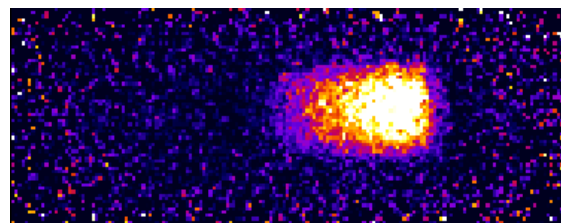


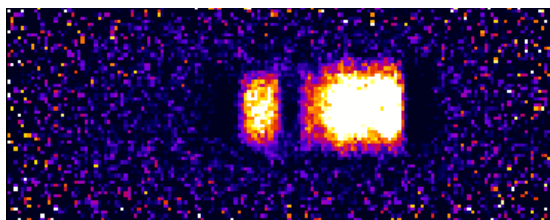
Image & Profile Reconstruction

Preliminary – 25/02/2016

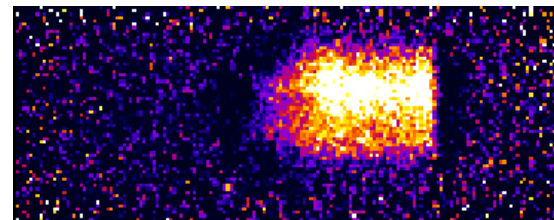
A



B



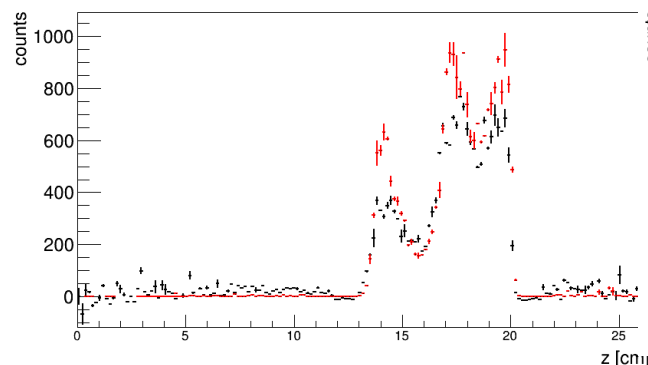
D



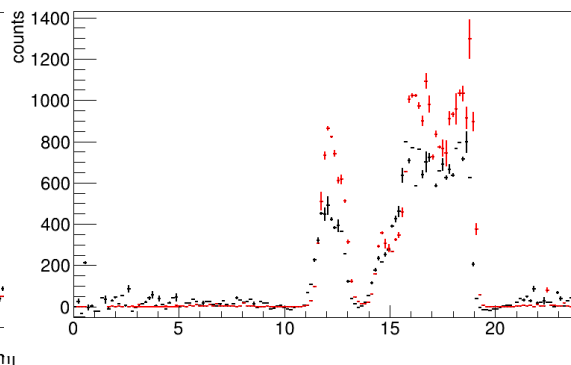
— Data

— Simulation

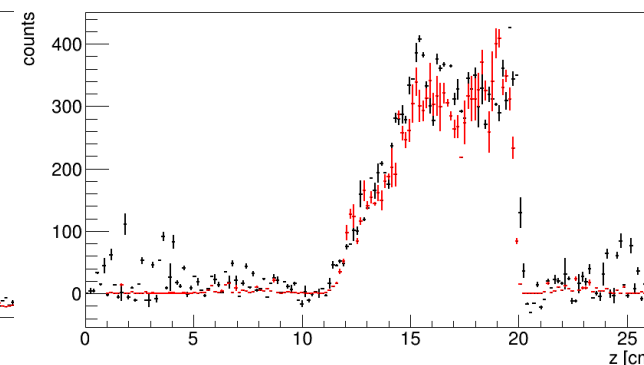
← beam



$E_1 = 75 \text{ MeV}$
 $E_2 = 103 \text{ MeV}$



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 $E_2 = 103 \text{ MeV}$



Treatment
plan

InSide

INSIDE: the future

- **Key results**
 - Successful data acquisition during beam delivery
 - Cyclotrons (Trento)!
 - Real time reconstruction and analysis
 - Real time Bragg peak position validation
 - Hypofractionation
 - Secondary tumour treatments
 - a new detector, with larger acceptance, to be operated in Trento?
 - agreement with IBA?



Inside



... the future ...

Range verification: summary

- The dose monitoring problem is a key issue to improve Quality Assurance in Particle Therapy
 - **in beam-PET**: metabolic wash-out and difficulty in quick feedback limitations might be overcome
 - **prompt photons**: can suffer from the presence of a huge neutral background
 - **light charged particles**: statistics could balance the absorption and scattering in the patient body

Can we still help in fighting cancer?

Cancer and efficiency of treatments

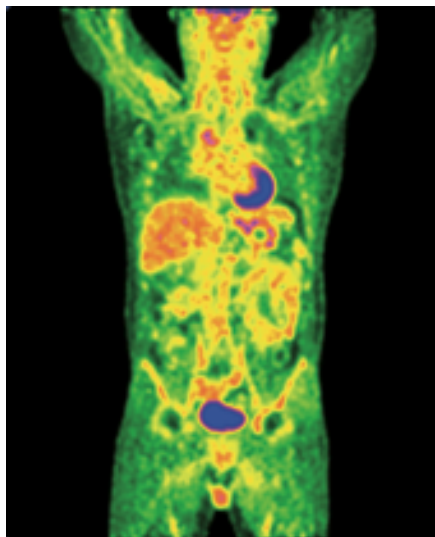
At time of diagnosis	Primary tumor	With metastases	Total
Diagnosed	58%	42%	100%
Cured by:			
Surgery	22%		
Radiation therapy	12%		
Surgery+radiation therapy	6%		
All other treatments and combinations incl. chemotherapy		5%	
Total cured	40%	5%	45%
Fraction cured	69%	12%	45%

Per year over **one million cancer deaths** in the EU.

⇒ improve early diagnosis

⇒ improve **systemic treatments**

... probably yes



Medical Imaging

will PET/CT replace CT as the standard in oncology?

what will the evolution of PET/MR be?

PET Time Of Flight resolution?



Particle therapy

real-time range monitoring?

hypofractionation?

how will particle therapy scale?

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Veronica Ferrero

Elisa Fiorina

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Cristiana Peroni

Maria Antonietta Piliero

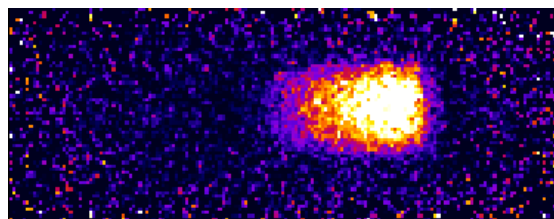
Giovanni Pirrone

Richard Wheadon

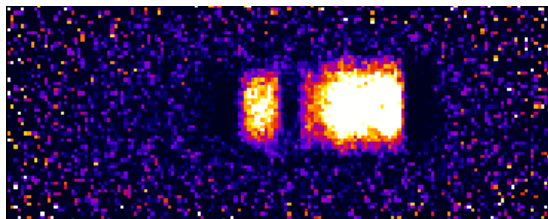
Image & Profile Reconstruction

Preliminary – 25/02/2016

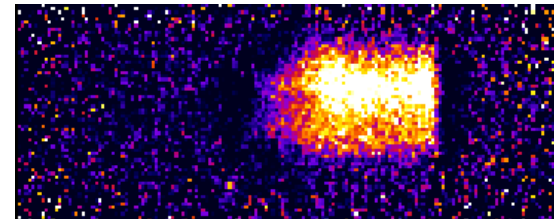
A



B



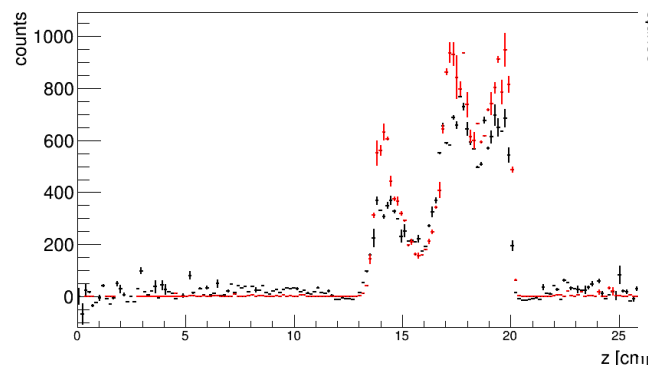
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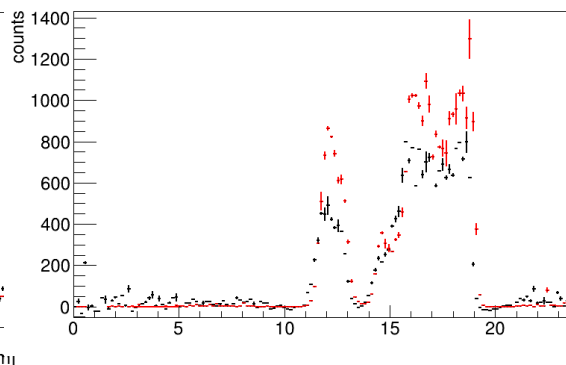
— Data

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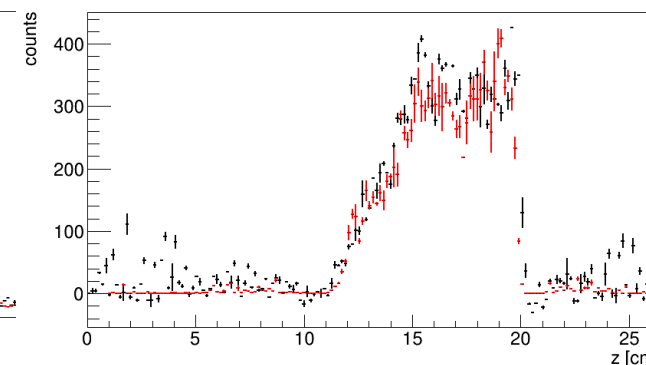
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