

ONLINE RANGE MONITORING IN HADRONTHERAPY WITH THE INSIDE PET SCANNER

*PhD: Veronica Ferrero
Tutor: Dr. Piergiorgio Cerello
XXXI PhD cycle*



HADRONTHERAPY

“Radiation therapy is the medical use of ionizing radiation to treat cancer. When the irradiating beams are made of charged particles (protons and other ions, such as carbon), radiation therapy is called Hadrontherapy.”

*The European Network for LIGHT ion
Hadron Therapy*

CORRIERE DELLA SERA / SPORTELLLO CANCRO

NUOVI LEA

Adroterapia rimborsata dal Servizio Sanitario contro 10 tipi di tumori

Pubblicato in Gazzetta Ufficiale il decreto ministeriale sui nuovi Livelli Essenziali d'Assistenza: l'adroterapia, cura i per i tumori resistenti alla radioterapia tradizionale e non operabili, rimborsata in tutte le Regioni

18th March 2017

*~ 80 operating centers in the world
41 new centers in the next 2 years*



CNAO

CNAO - TERA Foundation, Pavia

Synchrotron

60-250 MeV/u protons

120-400 MeV/u carbon ions

Protons since 2011

Carbon ions since 2012



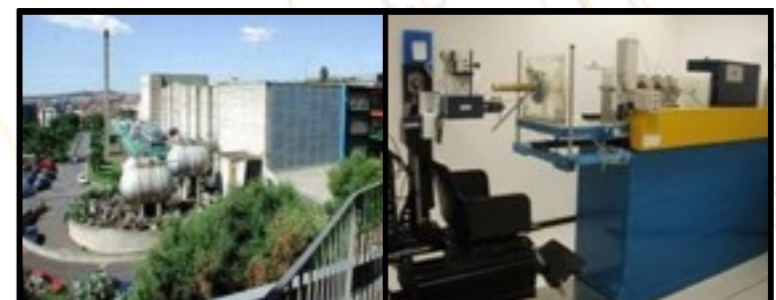
ATreP

ATREP, Trento

Cyclotron

220 MeV/u protons

Since 2014



CATANA

CATANA, Catania

Cyclotron

62 MeV/u protons

Since 2002

TREATMENT ACCURACY ASSESSMENT

BETHE-BLOCH EQUATION

$$-\frac{dE}{dx} = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

$$K = 4\pi N_A r_e^2 m_e c^2$$

Z Atomic number of absorber

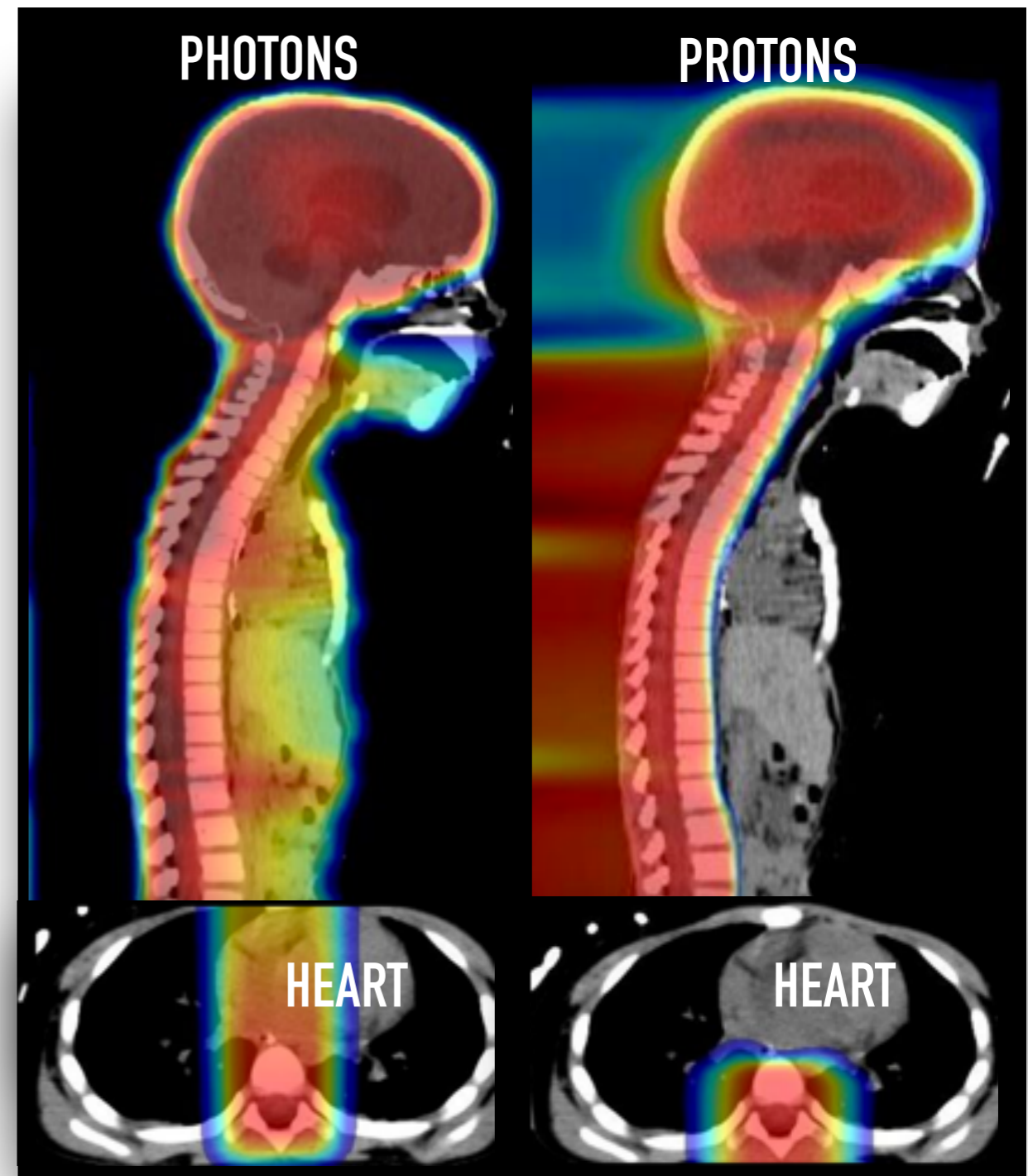
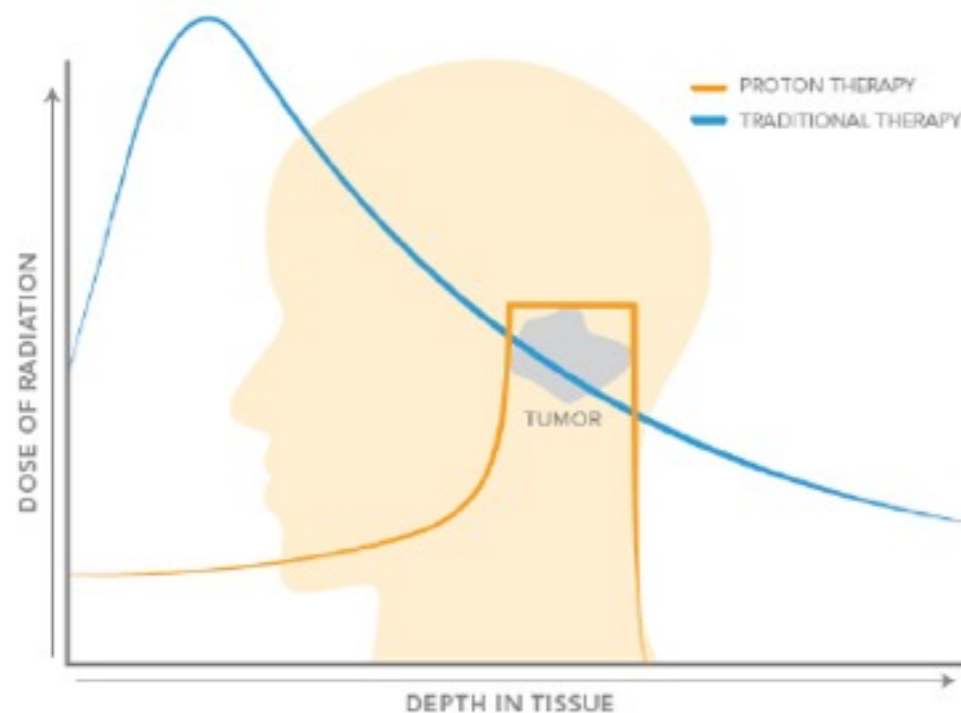
A Atomic mass of absorber

m_e Mass of an electron

r_e Classical radius of an electron

I Mean excitation energy

T_{max} Maximum Kinetic energy which can be imparted to a free electron in one collision



Mirabell R et al., Potential reduction of the incidence of radiation-induced second cancers by using proton beams in the treatment of pediatric tumor, Int. Jour. Rad. Onc. Phys. 2002, 54 (3) 824

TREATMENT ACCURACY ASSESSMENT

BETHE-BLOCH EQUATION

$$-\frac{dE}{dx} = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

$$K = 4\pi N_A r_e^2 m_e c^2$$

Z Atomic number of absorber

A Atomic mass of absorber

m_e Mass of an electron

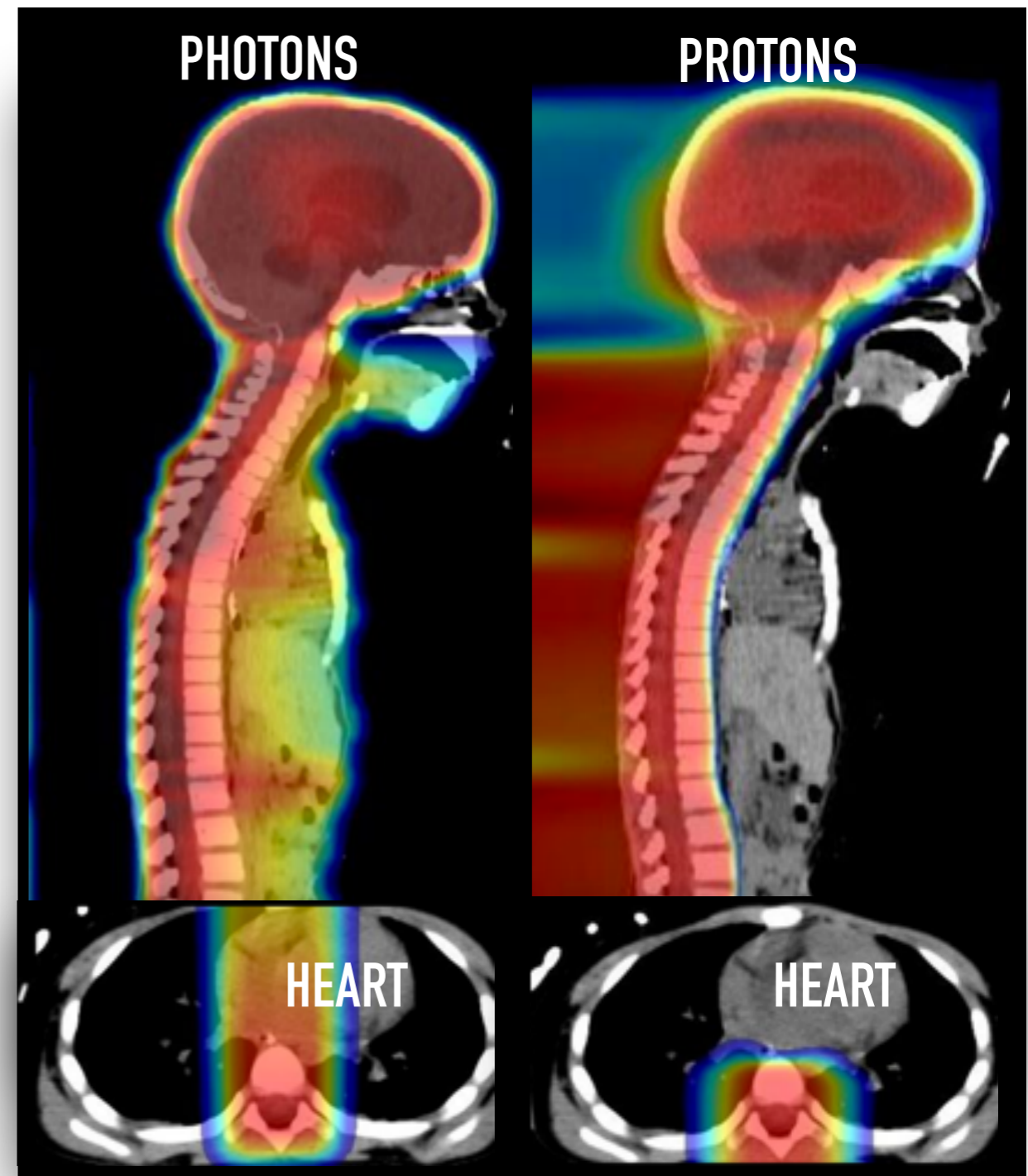
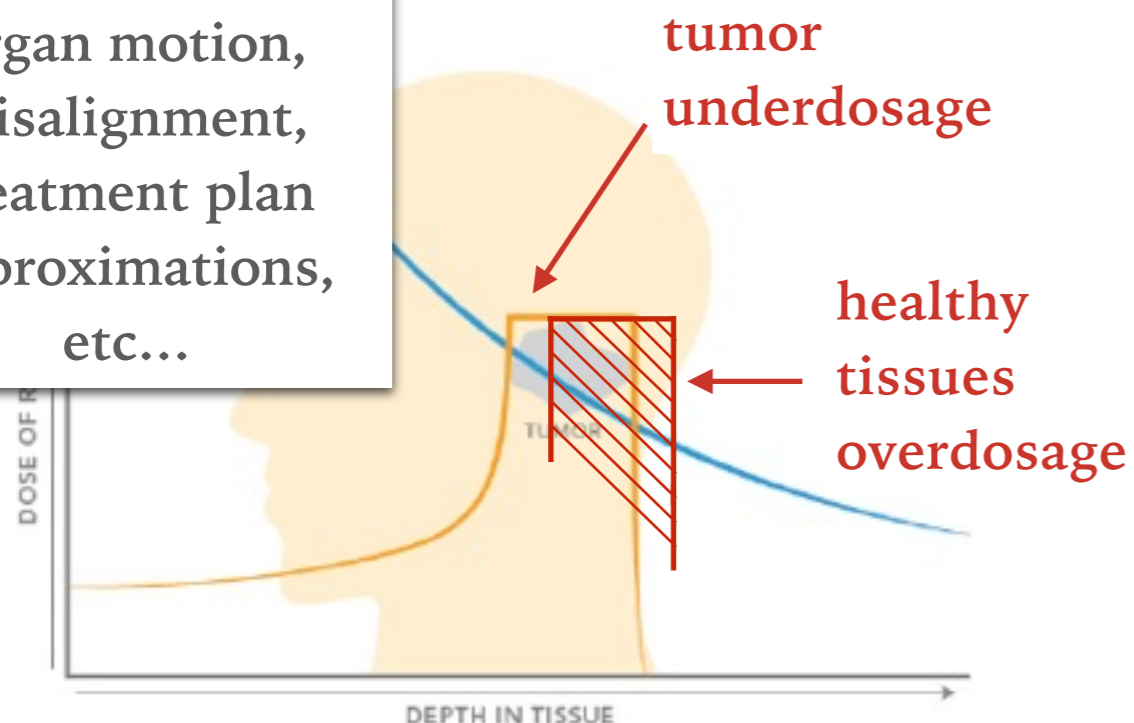
r_e Classical radius of an electron

I Mean excitation energy

T_{max} Maximum Kinetic energy which can be imparted to a free electron in one collision

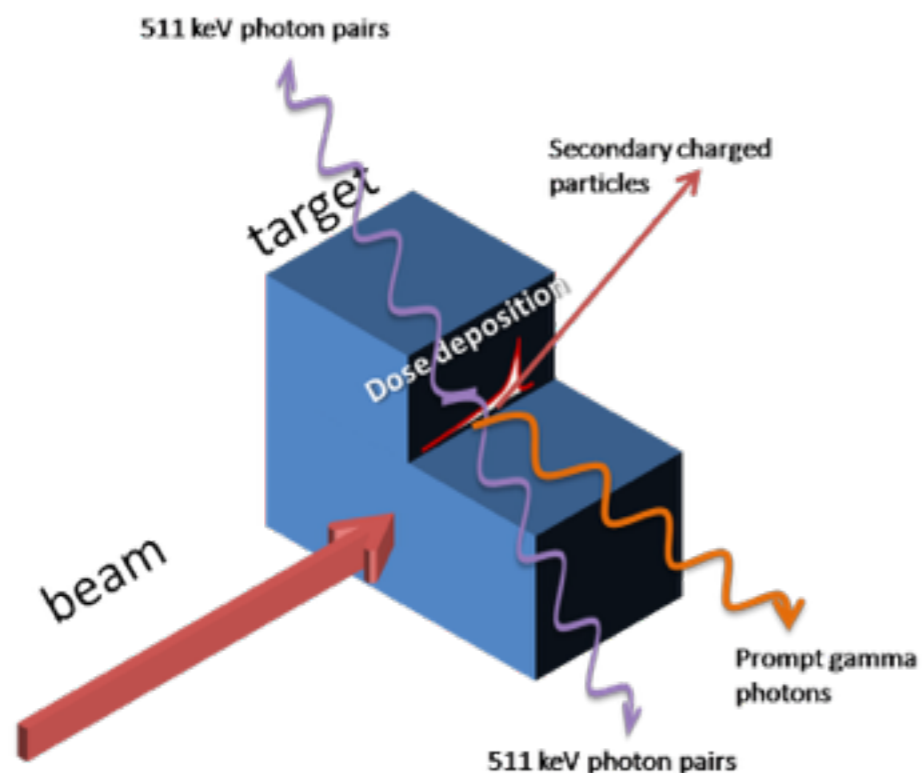
dose uncertainties:

organ motion,
misalignment,
treatment plan
approximations,
etc...



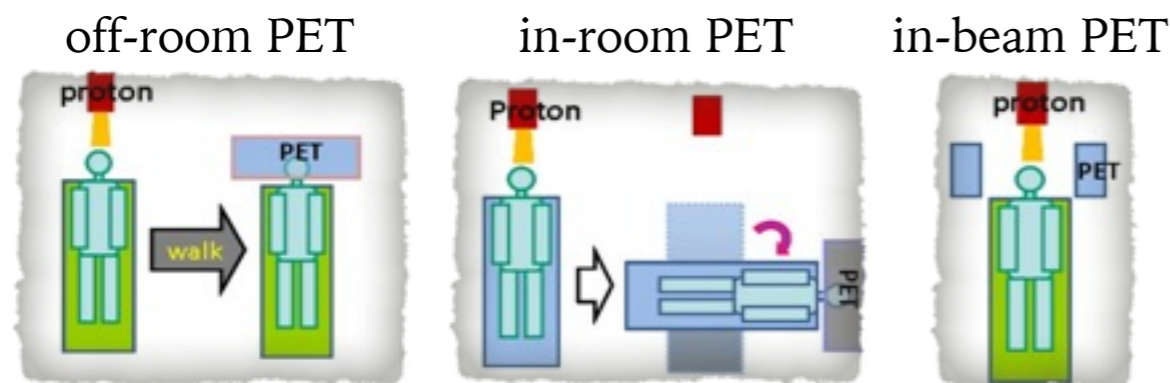
Mirabell R et al., Potential reduction of the incidence of radiation-induced second cancers by using proton beams in the treatment of pediatric tumor, Int. Jour. Rad. Onc. Phys. 2002, 54 (3) 824

PARTICLE RANGE VERIFICATION

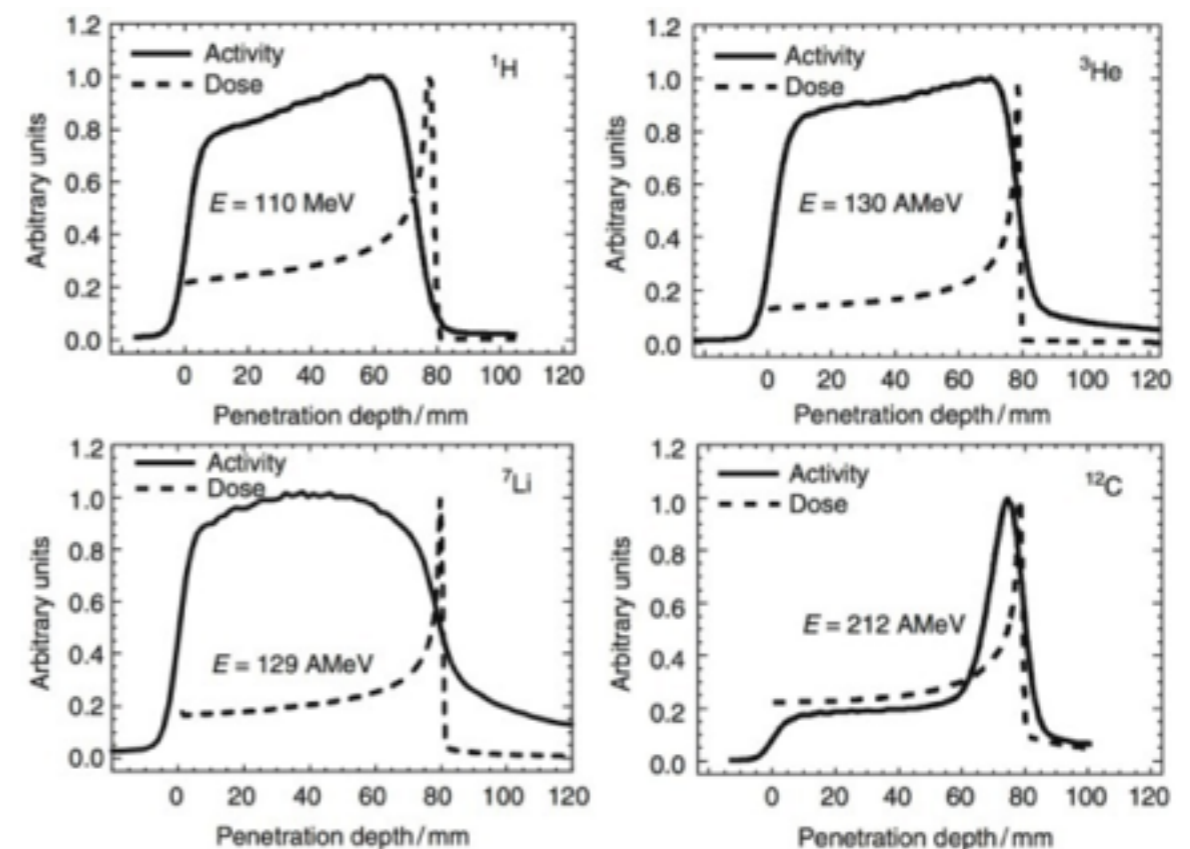


Target	β^+ isotopes	Half-life
C	^{10}C , ^{11}C	19.29 s, 20.33 m
N	^{13}N	9.96 m
O	^{14}O , ^{15}O	70.61 s, 122.24 s
P	^{30}P	2.50 m
Ca	^{38}K	7.64 m

E Palomares et al. Study of the reliability of the cross sections used to model the production of PET isotopes with proton beams. *Phys. Med. Biol.* 2011; 56:2687-98

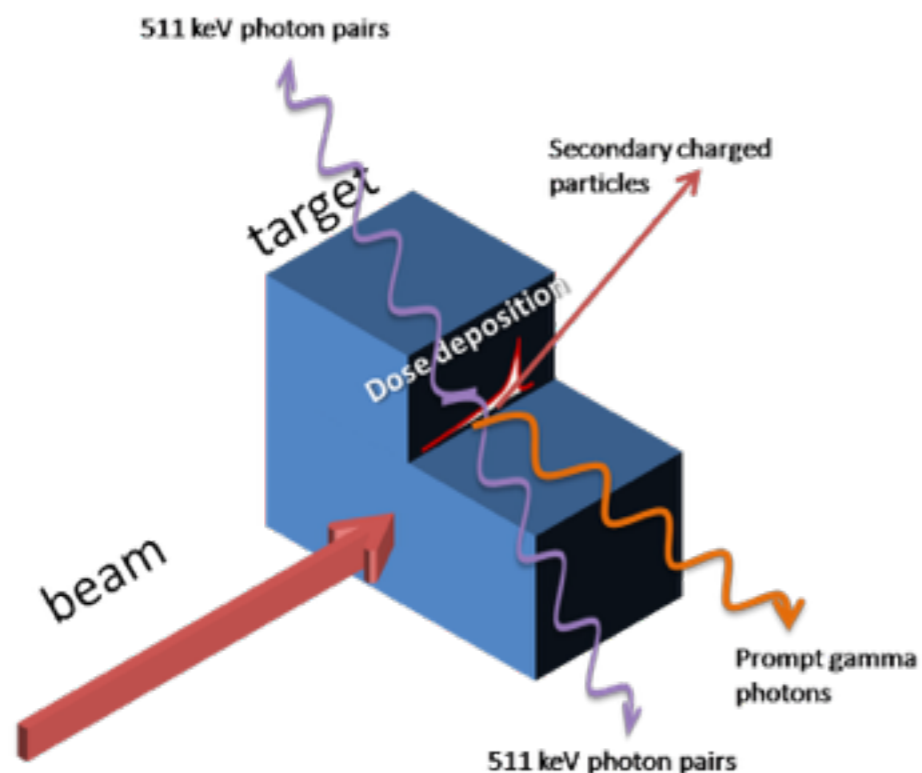


Zhu X, Fakhri GE. *Theranostics*. 2013;3(10): 731-740.



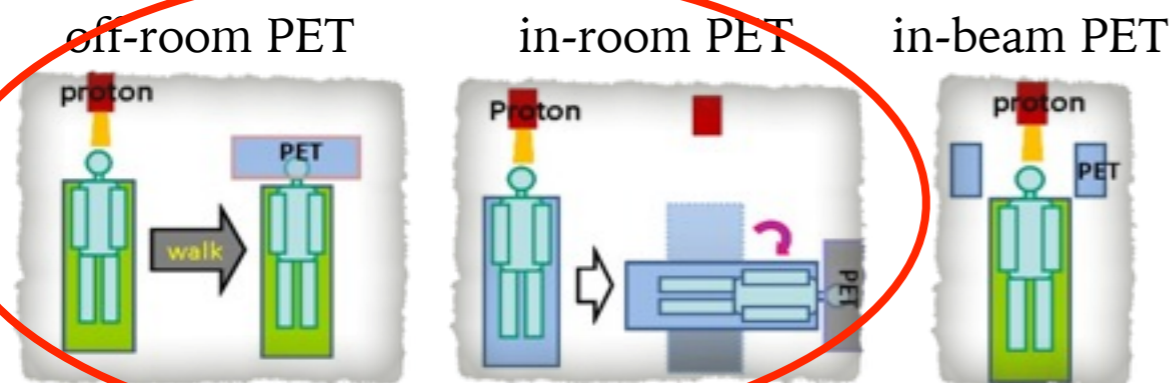
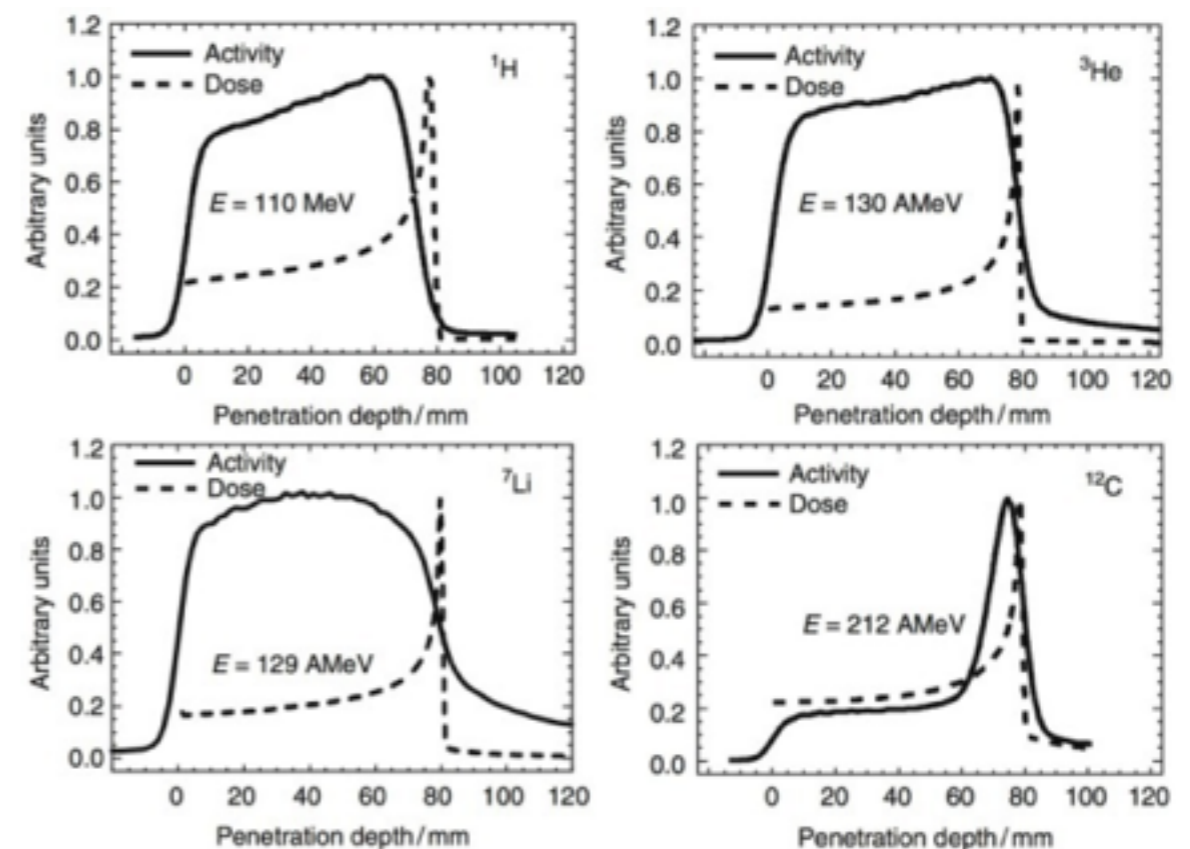
Fiedler F., et al. Online irradiation control by means of PET. *Ion Beam Therapy Fundamentals, Technology, Clinical Applications*. Berlin: Springer-Verlag (2012) p. 527-43

PARTICLE RANGE VERIFICATION



Target	β^+ isotopes	Half-life
C	^{10}C , ^{11}C	19.29 s, 20.33 m
N	^{13}N	9.96 m
O	^{14}O , ^{15}O	70.61 s, 122.24 s
P	^{30}P	2.50 m
Ca	^{38}K	7.64 m

E Palomares et al. Study of the reliability of the cross sections used to model the production of PET isotopes with proton beams. *Phys. Med. Biol.* 2011; 56:2687-98



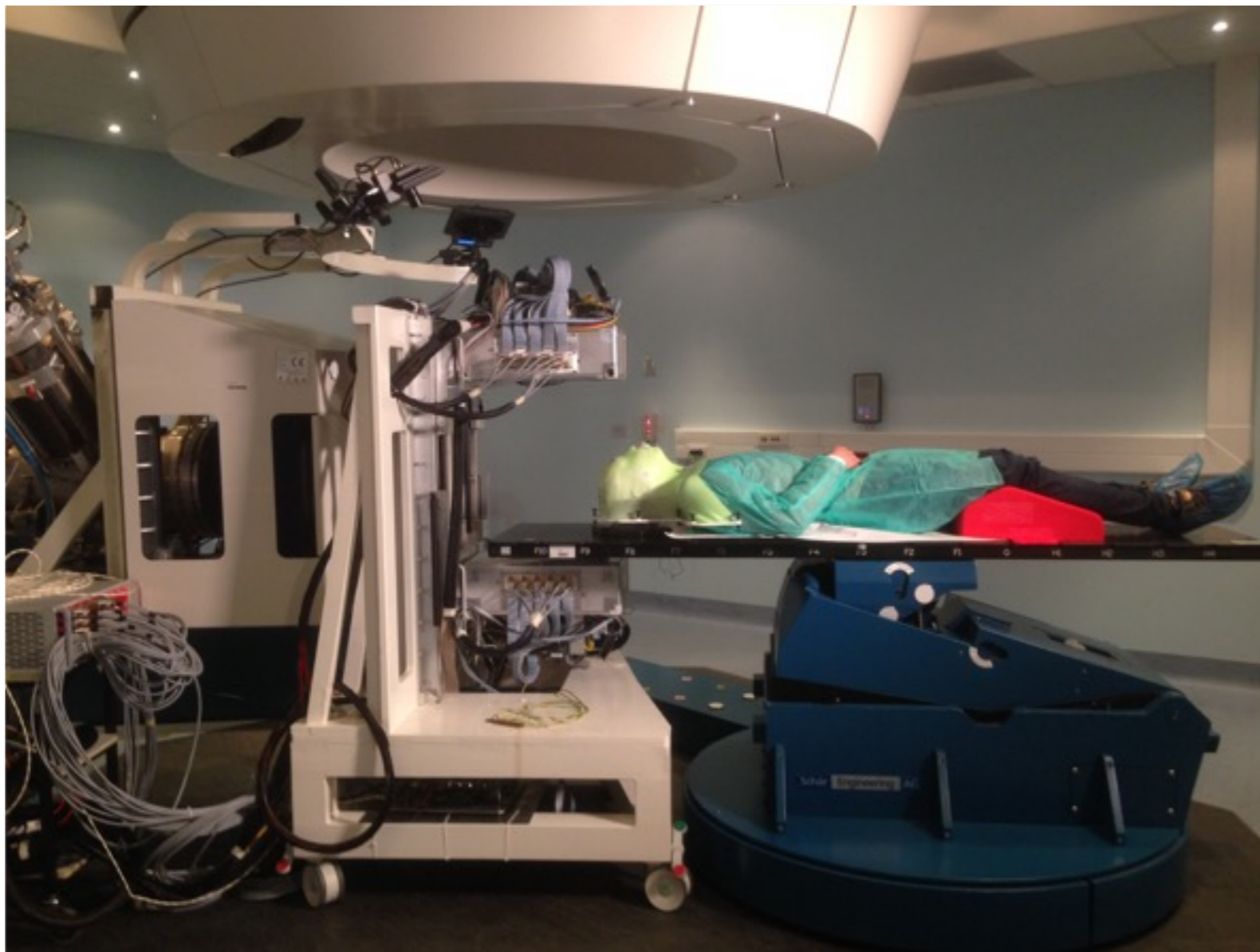
Zhu X, Fakhri GE. *Theranostics*. 2013;3(10): 731-740.

loss of signal due to short half lives, higher washout

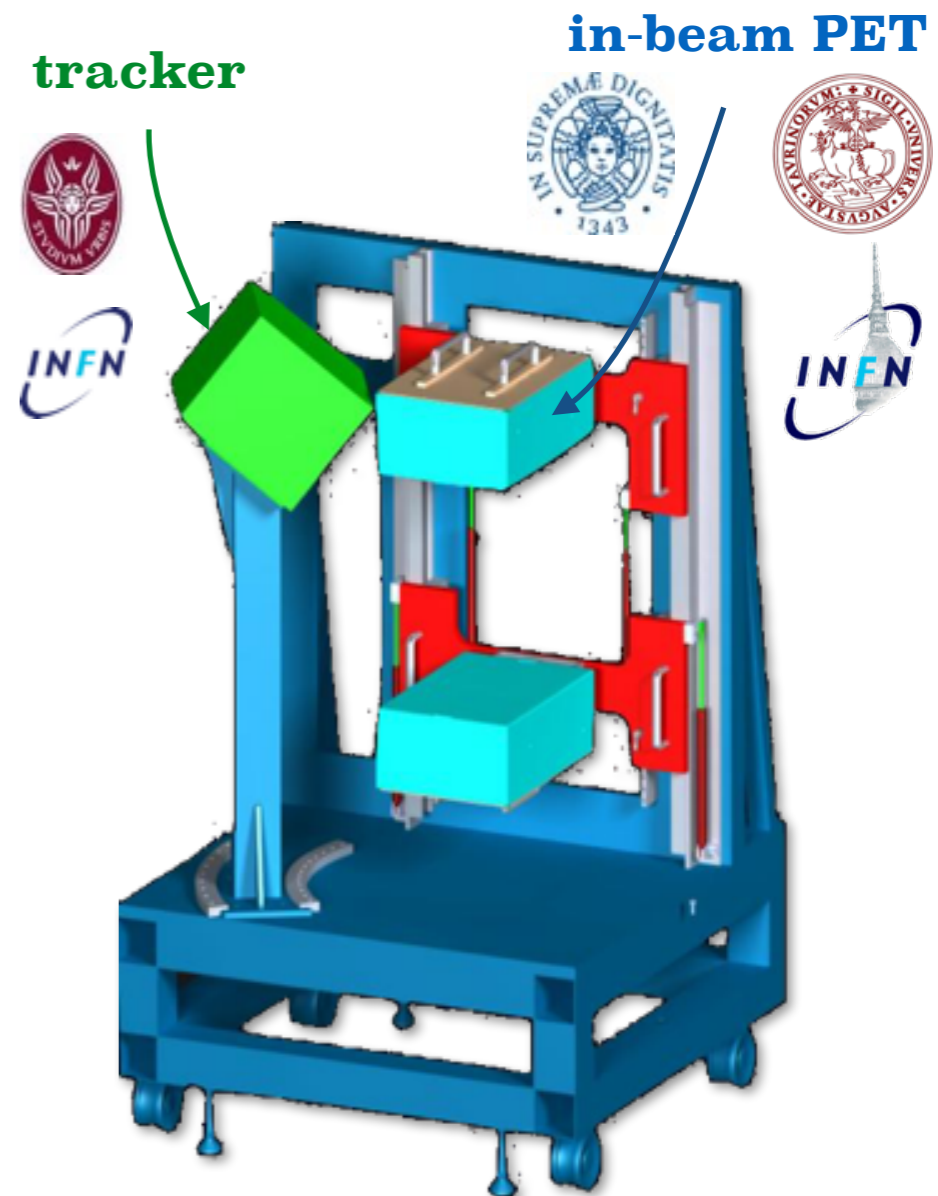
Fiedler F., et al. Online irradiation control by means of PET. *Ion Beam Therapy Fundamentals, Technology, Clinical Applications*. Berlin: Springer-Verlag (2012) p. 527-43

The *InSide* Project @ CNAO

INnovative Solutions for In-beam DosimEtry in Hadrontherapy



National Center of Oncological Hadrontherapy (CNAO), Pavia, Italy

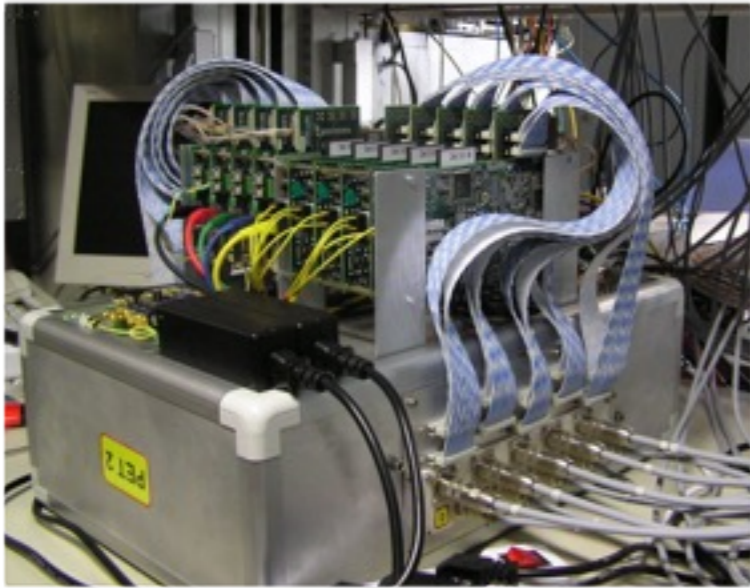


- ▶ Bimodal system (tracker under characterization, PET installed at CNAO)
- ▶ Integrated in the treatment room
- ▶ Provides a feedback during the treatment

THE INSIDE IN-BEAM PET

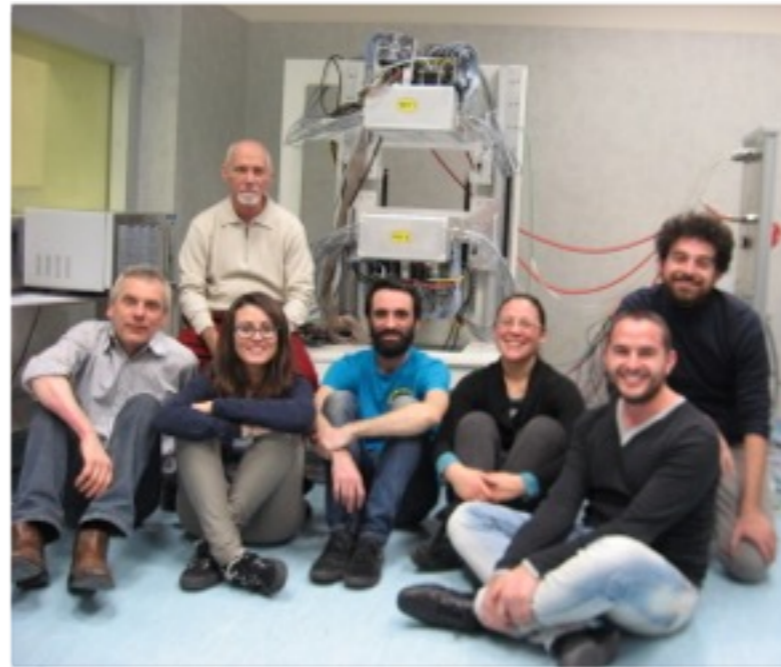
.....

January 2016, INFN Torino

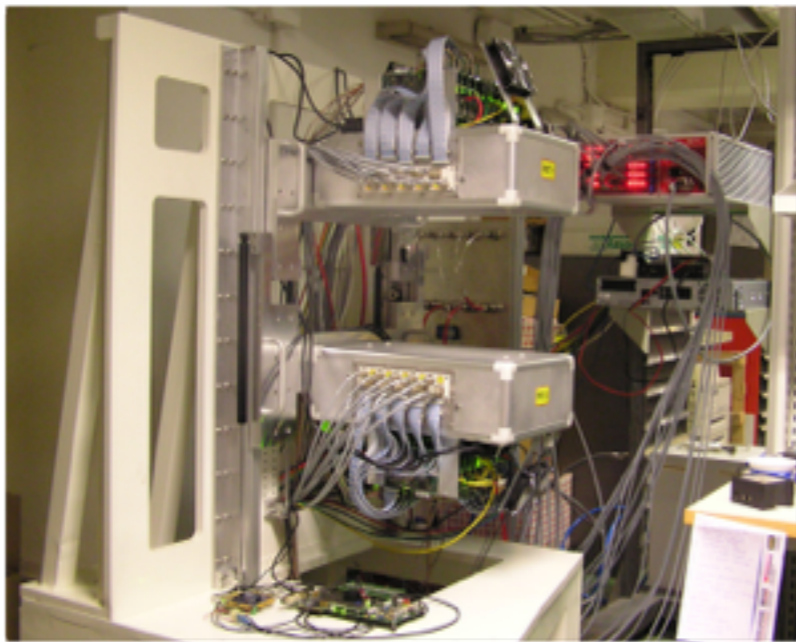


PET heads assembled and tested

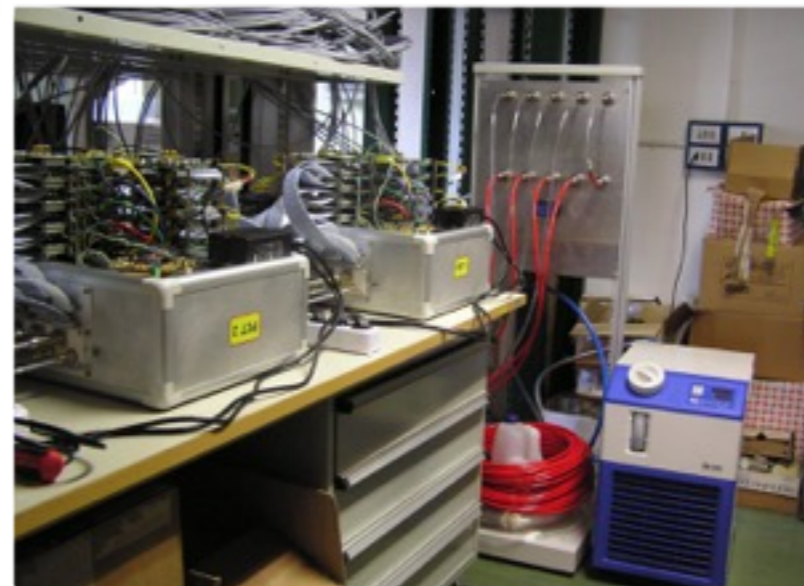
March 2016, CNAO, Pavia



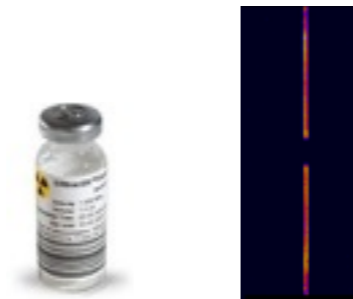
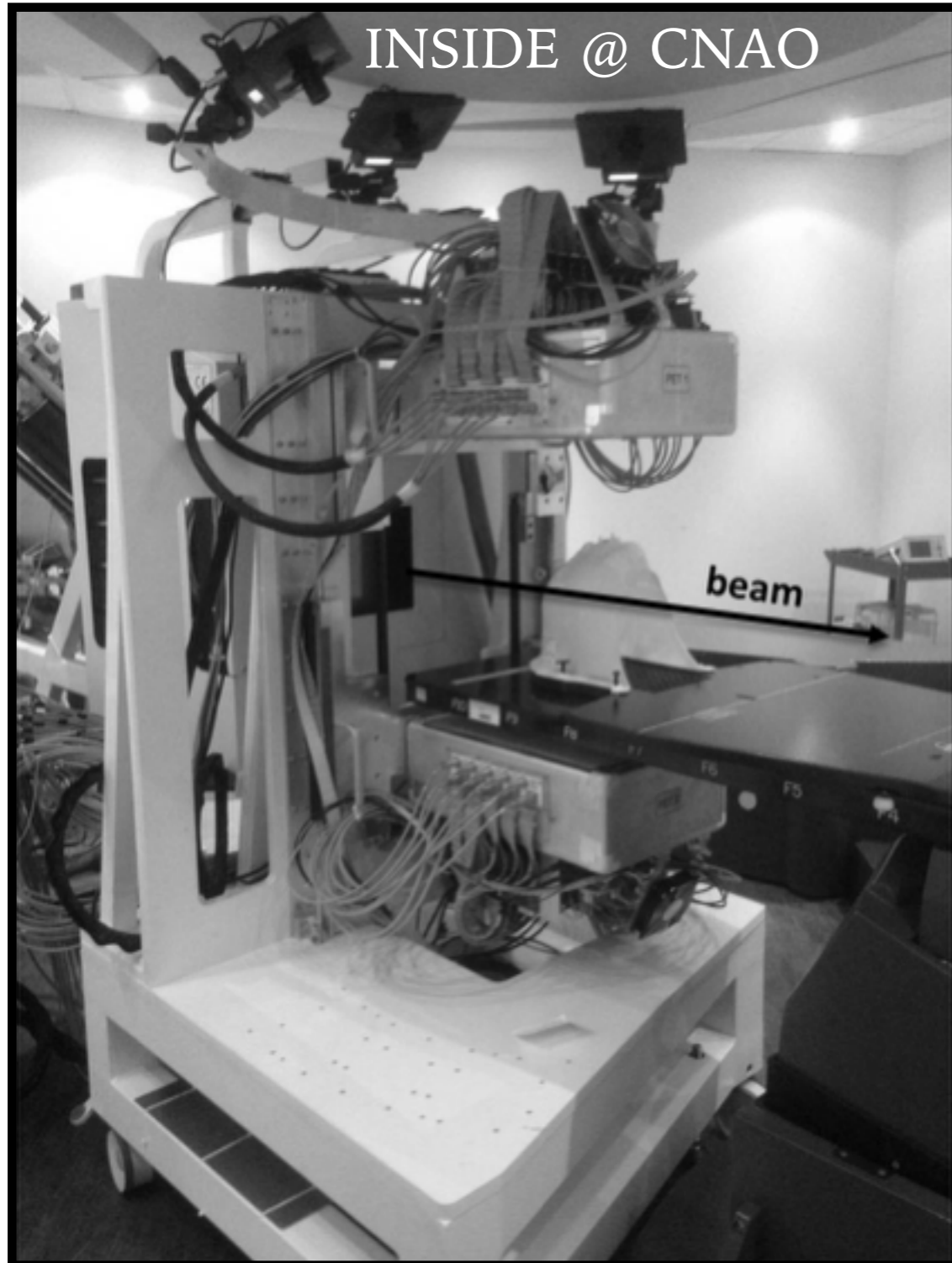
November 2017, INFN Torino



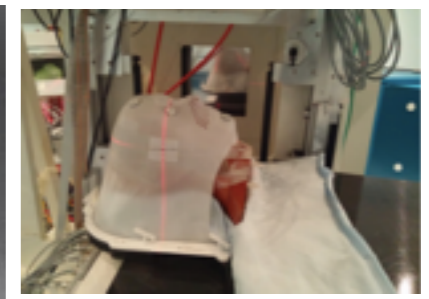
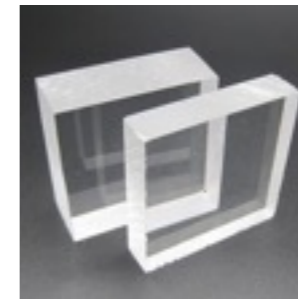
Completed PET detector (running)



CHARACTERIZATION TESTS



FDG, ^{68}Ge rods



PMMA, anthropomorphic phantom

JINST

First results of the INSIDE in-beam PET scanner for the on-line monitoring of particle therapy treatments

M.A. Piliero,^{a,b,1} N. Belcari,^{a,b} M.G. Bisogni,^{a,b} N. Camarlinghi,^{a,b} P. Cerello,^{b,c} S. Coli,^d A. Del Guerra,^{a,b} V. Ferrero,^{c,d} E. Fiorina,^{c,d} G. Giraudo,^d E. Kostara,^b M. Morrocchi,^{a,b} F. Pennazio,^{c,d} C. Peroni,^{c,d} G. Pirrone,^{a,b} A. Rivetti,^d M.D. Rolo,^d V. Rosso,^{a,b} G. Sportelli,^{a,b} R. Wheadon^d

JMI

INSIDE in-beam positron emission tomography system for particle range monitoring in hadrontherapy

Maria Giuseppina Bisogni,^{a,b,*} Andrea Attili,^{c,d} Giuseppe Battistoni,^e Nicola Belcari,^{a,b} Niccolò Camarlinghi,^{a,b} Piergiorgio Cerello,^d Silvia Coli,^d Alberto Del Guerra,^{a,b} Alfredo Ferrari,^f Veronica Ferrero,^{c,d} Elisa Fiorina,^g Giuseppe Giraudo,^g Eleftheria Kostara,^b Matteo Morrocchi,^{a,b} Francesco Pennazio,^e Cristiana Peroni,^{c,d} Maria Antonietta Piliero,^{a,b} Giovanni Pirrone,^{a,b} Angelo Rivetti,^c Manuel D. Rolo,^c Valeria Rosso,^{a,b} Paola Sala,^h Giancarlo Sportelli,^{a,b} and Richard Wheadon^d

JINST

The INSIDE project: in-beam PET scanner system features and characterization

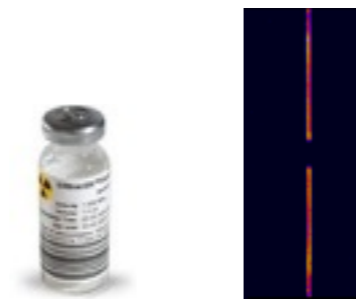
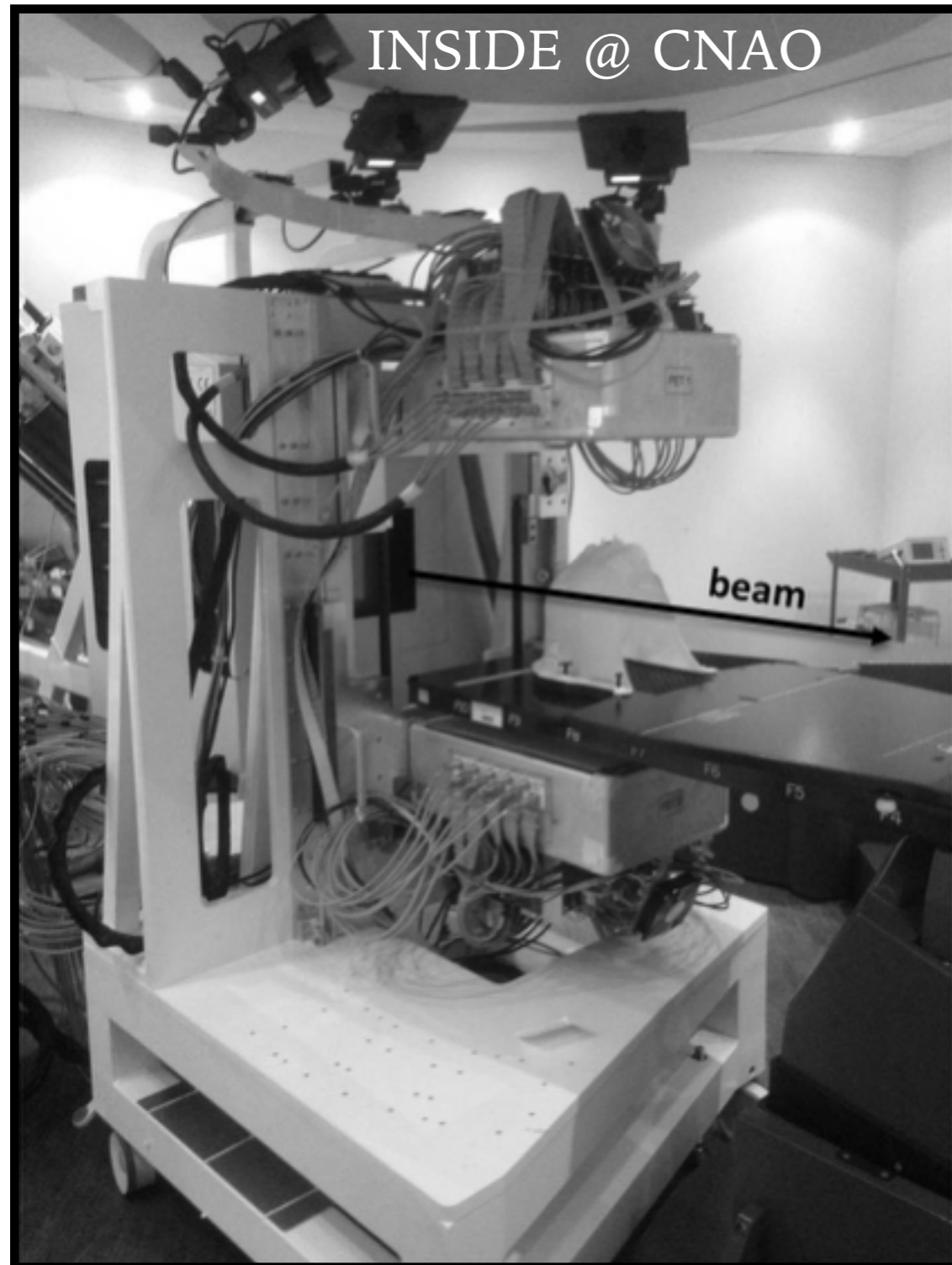
V. Ferrero on behalf of the INSIDE collaboration

JPCS

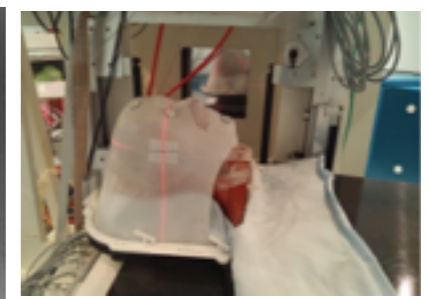
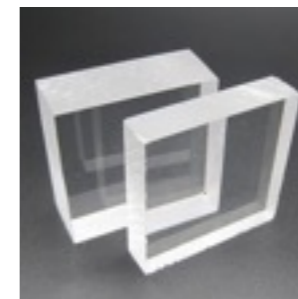
The INSIDE project: on-line monitoring and simulation validation with the in-beam PET scanner

V Ferrero^{1,2} on behalf of the INSIDE collaboration

CHARACTERIZATION TESTS



FDG, ^{68}Ge rods



PMMA, anthropomorphic phantom

JINST

First results of the INSIDE in-beam PET scanner for the on-line monitoring of particle therapy treatments

M.A. Piliero,^{a,b,1} N. Belcarì,^{a,b} M.G. Bisogni,^{a,b} N. Camarlinghi,^{a,b} P. Cerello,^{b,c} S. Coli,^d A. Del Guerra,^{a,b} V. Ferrero,^{c,d} E. Fiorina,^{c,d} G. Giraudo,^d E. Kostara,^b M. Morrocchi,^{a,b} F. Pennazio,^{c,d} C. Peroni,^{c,d} G. Pirrone,^{a,b} A. Rivetti,^d M.D. Rolo,^d V. Rosso,^{a,b} G. Sportelli,^{a,b} R. Wheadon^d

JMI

INSIDE in-beam positron emission tomography system for particle range monitoring in hadrontherapy

Maria Giuseppina Bisogni,^{a,b,*} Andrea Attili,^{c,d} Giuseppe Battistoni,^e Nicola Belcarì,^{a,b} Niccolò Camarlinghi,^{a,b} Piergiorgio Cerello,^d Silvia Coli,^d Alberto Del Guerra,^{a,b} Alfredo Ferrari,^f Veronica Ferrero,^{c,d} Elisa Fiorina,^g Giuseppe Giraudo,^g Eleftheria Kostara,^b Matteo Morrocchi,^{a,b} Francesco Pennazio,^g Cristiana Peroni,^{c,d} Maria Antonietta Piliero,^{a,b} Giovanni Pirrone,^{a,b} Angelo Rivetti,^g Manuel D. Rolo,^g Valeria Rosso,^{a,b} Paola Sala,^h Giancarlo Sportelli,^{a,b} and Richard Wheadon^g

JINST

The INSIDE project: in-beam PET scanner system features and characterization

IPRD, Siena (talk)

V. Ferrero on behalf of the INSIDE collaboration

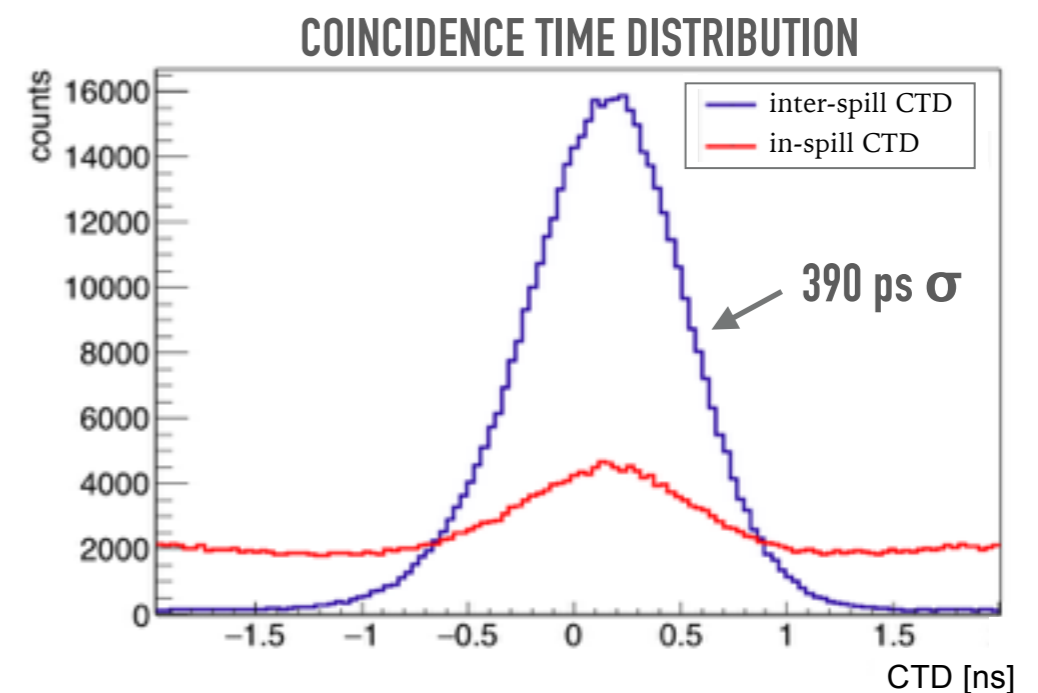
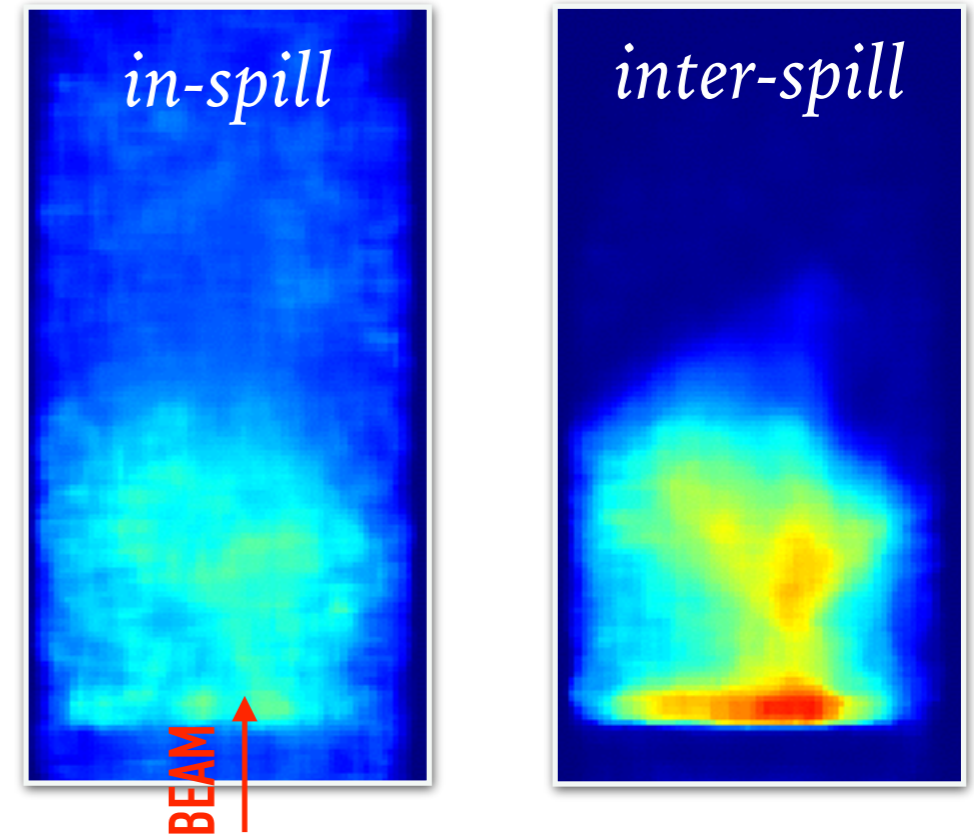
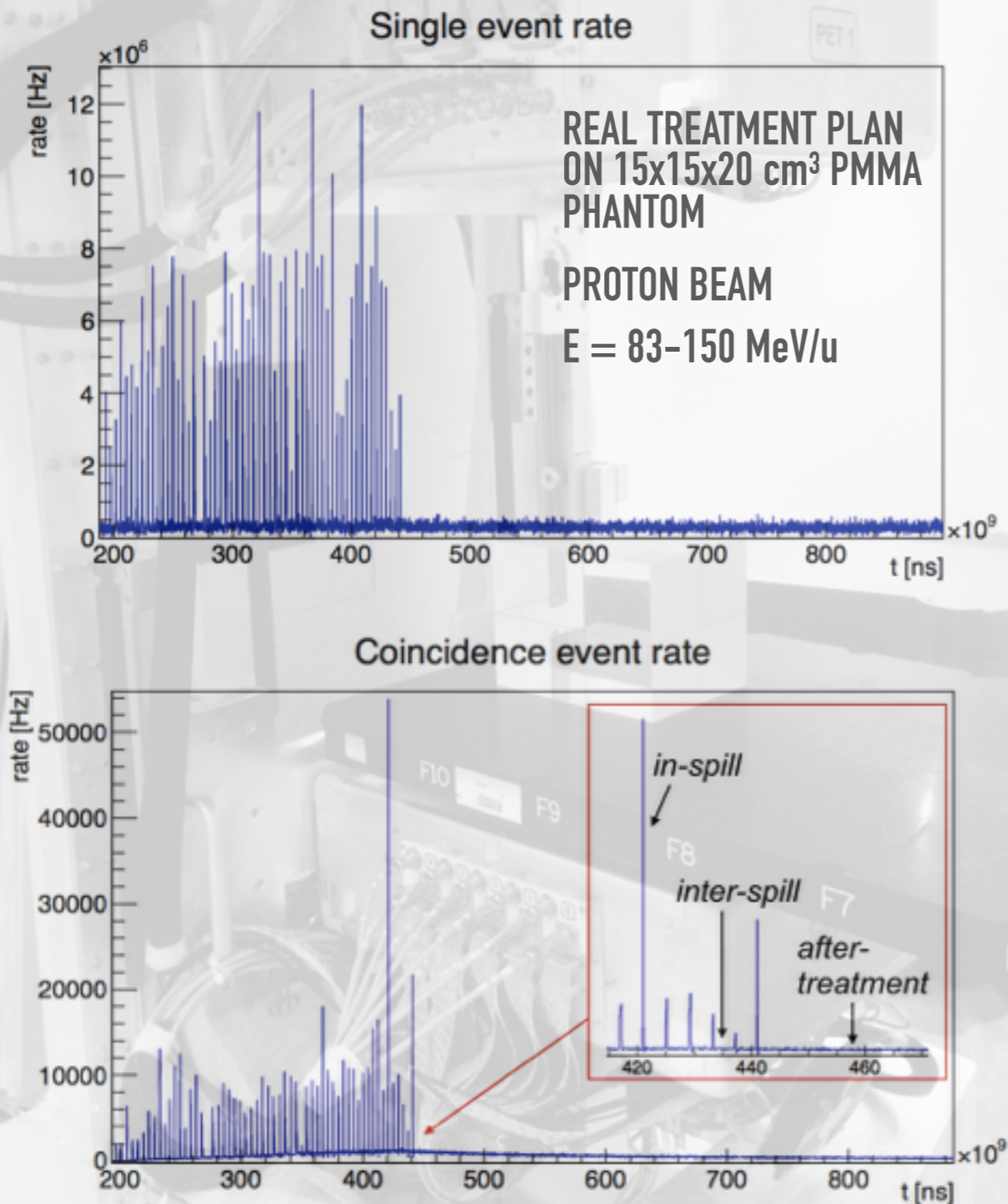
JPCS

The INSIDE project: on-line monitoring and simulation validation with the in-beam PET scanner

V Ferrero^{1,2} on behalf of the INSIDE collaboration

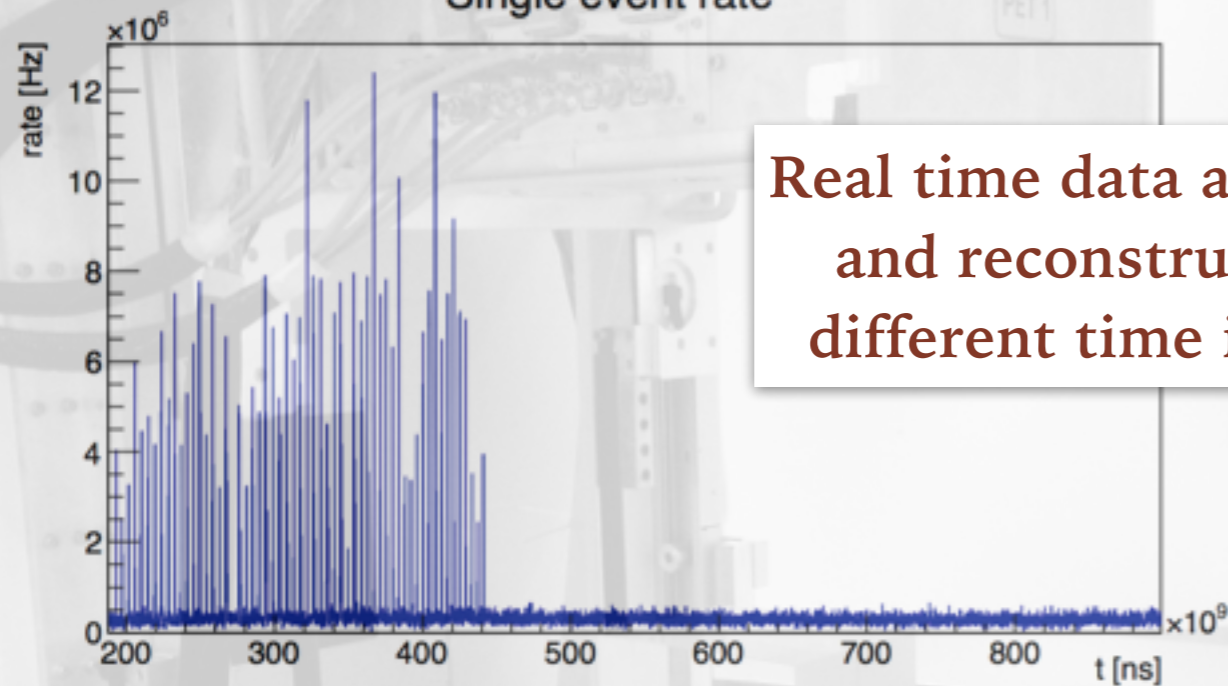
YRM, Torino (talk)

THE INSIDE PROJECT: IN-BEAM PET SCANNER SYSTEM FEATURES AND CHARACTERIZATION (14TH IPRD, SIENA)



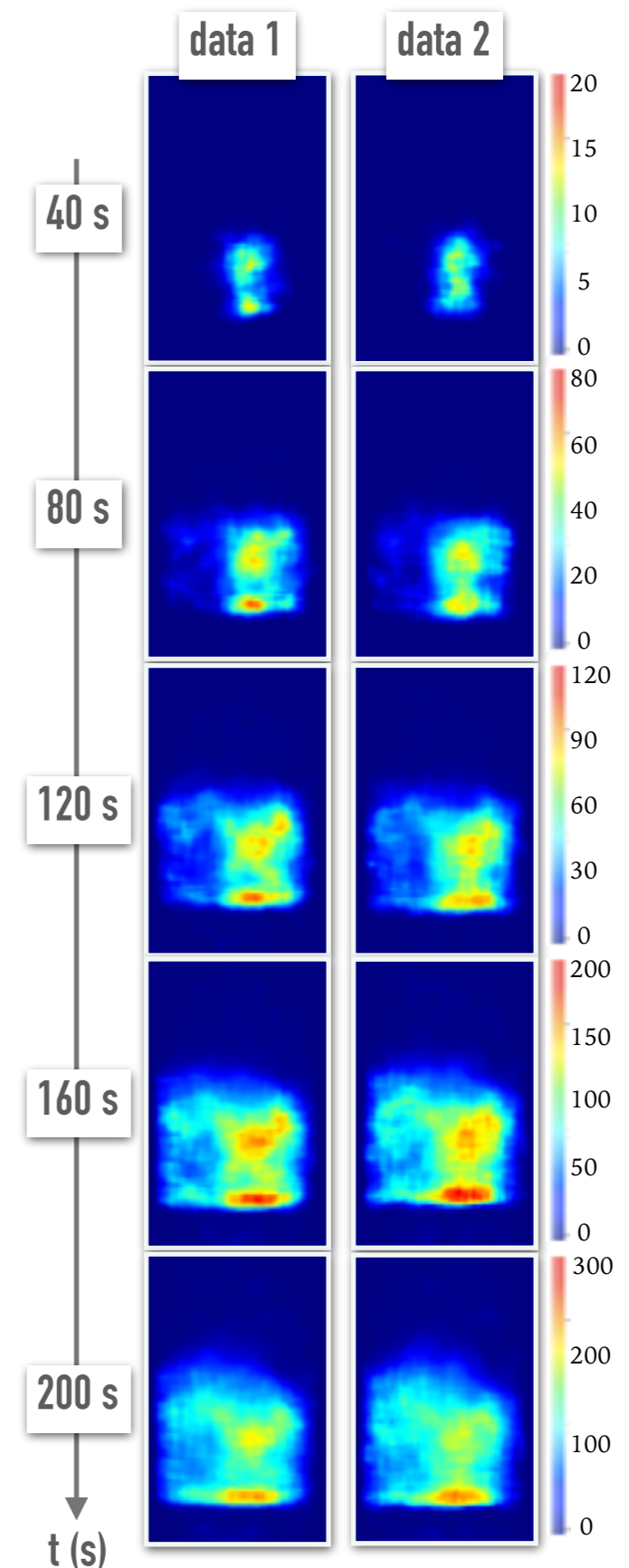
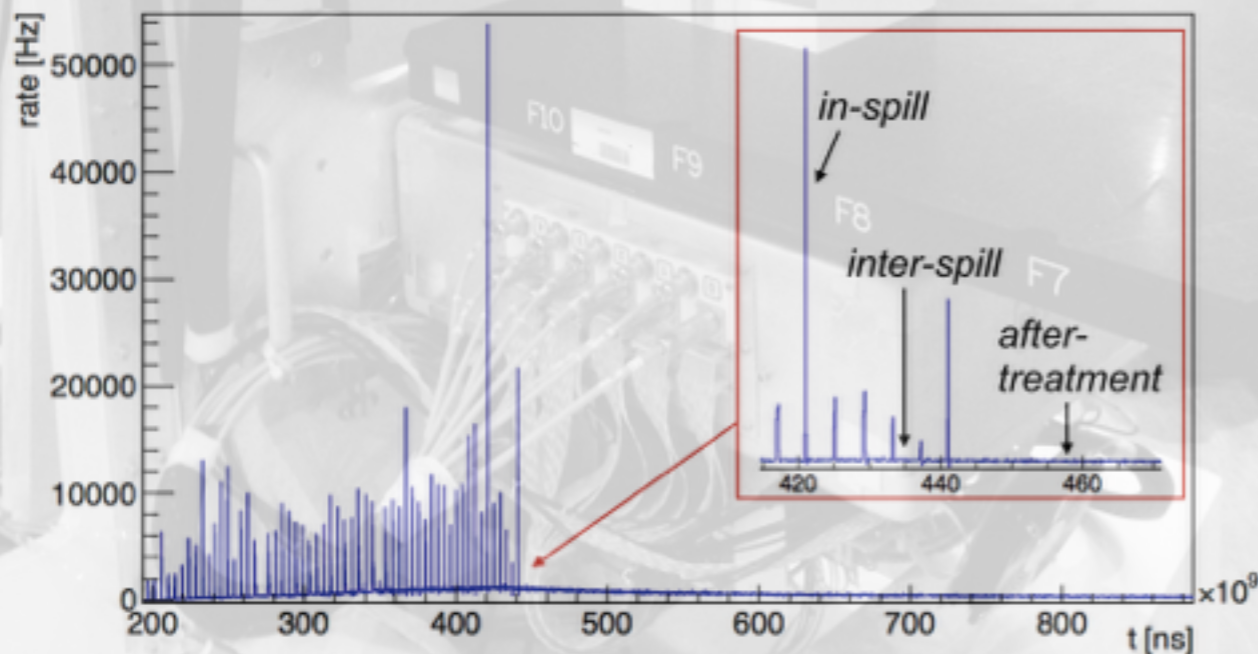
THE INSIDE PROJECT: IN-BEAM PET SCANNER SYSTEM FEATURES AND CHARACTERIZATION (14TH IPRD, SIENA)

Single event rate



Real time data acquisition
and reconstruction at
different time intervals

Coincidence event rate



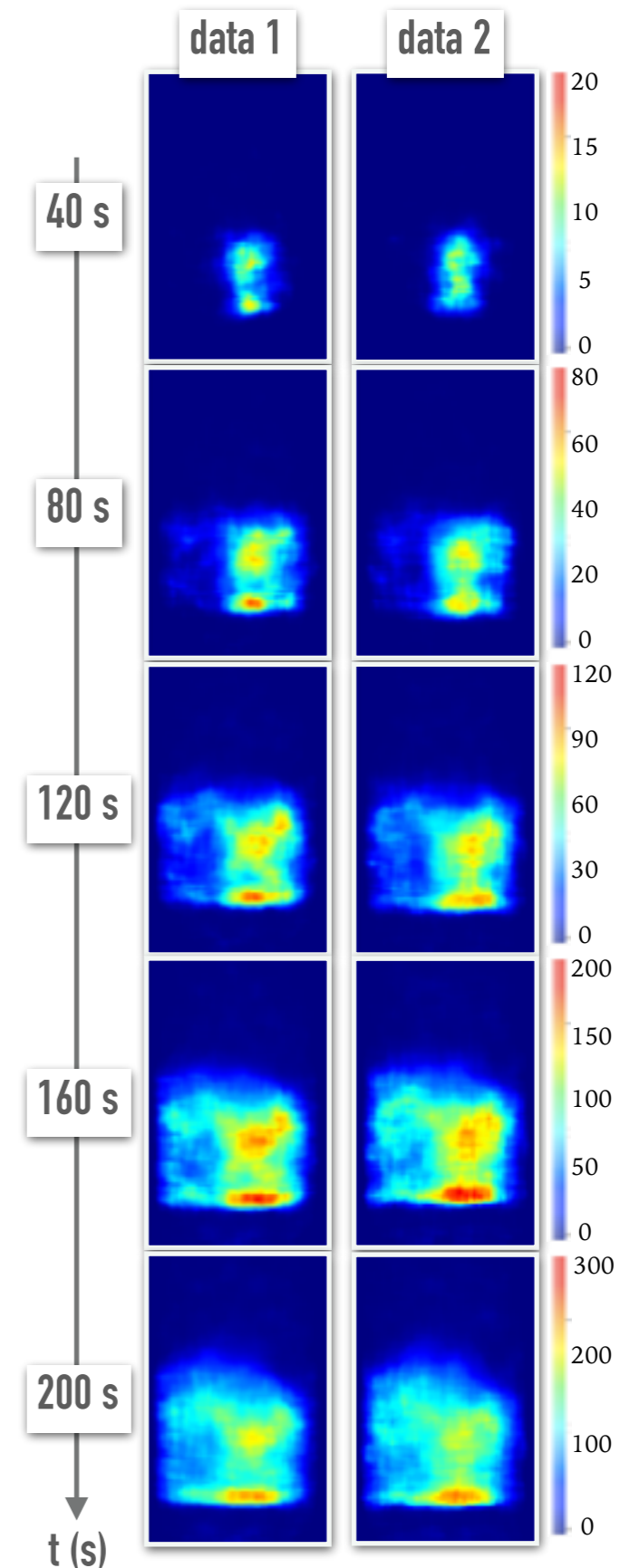
COINCIDENCES ANALYSIS

```

veronica@mag11x1:~$ INSIDEWriteLORfile
Program to analyse DAQ data and write LORfile for image reconstruction, usage:
-h [ --help ]                Produce this help message
-D [ --DataType ] arg        Data type permitted:
                              'w' binary file 20 modules, Clock 120 MHz,
                              beam test Feb 2016. Option -g needed for
                              this data type.
                              's' binary file 20 modules, Clock 120 MHz,
                              beam test Apr 2017 in/interspill selected by
                              server. NB if acquired data have a wrong
                              threshold, use data type 'w' to better
                              select in/interspill
-L [ --LORFile(s) ] arg      Input DAQ LORFile(s) (.bin)
-C [ --ChannelMap ] arg      /ChannelMap.txt
-g [ --RootFile ] arg        [DataType 'w'] GUI root file (forwarded
                              data) needed for inspill/interspill
                              selection (only for data type 'w')
-t [ --spillThreshold ] arg  [optional!] Threshold (Hz) to discriminate
                              in- and inter-spill data, default 450000 Hz
                              (only for data type 'w')
-b [ --BuildHisto ]          [optional!] Creates histogram.root file with
                              DAQ data
-i [ --startTime ] arg       [optional!] Cuts DAQ data from time
                              startTime (s)
-e [ --endTime ] arg         [optional!] Cuts DAQ data to time endTime
                              (s)
-j [ --nbinTime ] arg        [optional!] Number of bins in the time
                              histograms.
-w [ --coincWindow ] arg     [optional!] Sets coincidence window
                              (default: 2ns)
-r [ --EnergyWindow ] arg    [optional!] Applies new energy window to
                              data, /EnergyWindow.txt
-o [ --EnergyWindowOnBoard ] arg [optional!] Saves additional TOT shift in
                              histogram.root, /EnergyWindowOnBoard.txt
    
```

- Can be launched as soon as the server saves LOR files
- Finds and analyses coincidences over a certain time window
- Can apply time selection
- Produces a listmode coincidences file compatible with the reconstruction program

C++, ROOT/BOOST LIBRARIES

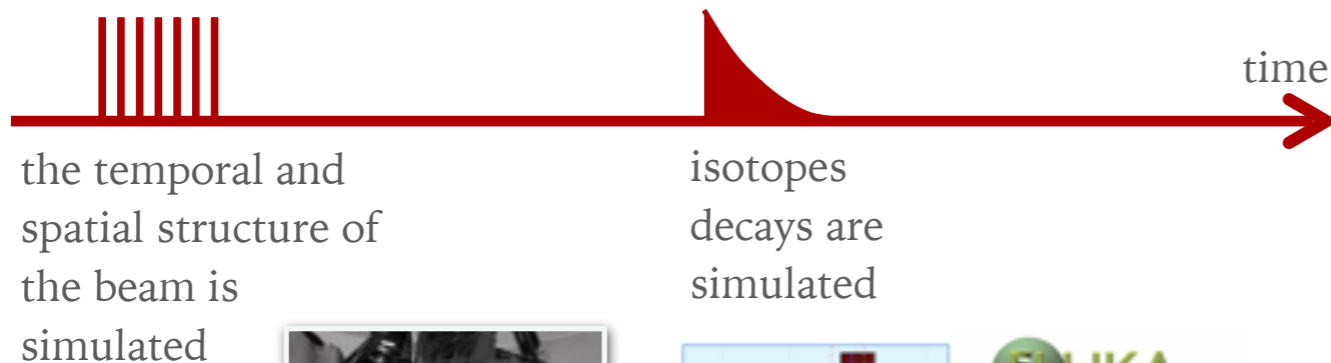


THE INSIDE PROJECT: ONLINE MONITORING AND SIMULATION VALIDATION WITH THE IN-BEAM PET SCANNER (7TH YRM, TORINO)

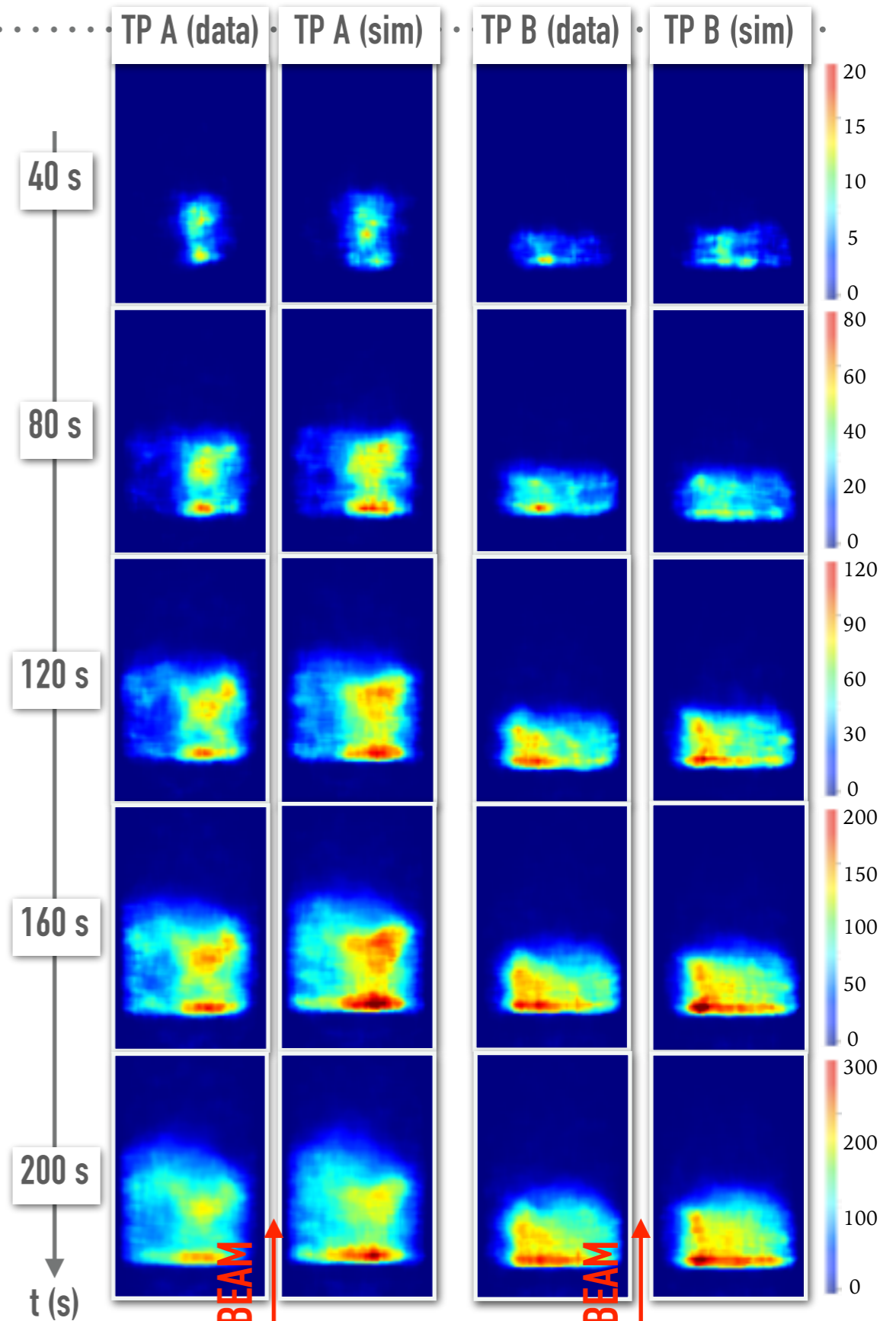
TP	E_{min} (MeV/u)	E_{max} (MeV/u)
A	83	150
B	62	129

MONTE CARLO SIMULATIONS

STEP 1 beam simulation	time-tagged activity scoring	STEP 2 PET simulation	image reconstruction
about 1/100 of primary hadrons are simulated	isotope production map	all positrons are simulated (x100)	same analysis chain as real data



the detector characteristics are simulated



THE INSIDE PROJECT: ONLINE MONITORING AND SIMULATION VALIDATION WITH THE IN-BEAM PET SCANNER (7TH YRM, TORINO)

TP	E_{min} (MeV/u)	E_{max} (MeV/u)
A	83	150
B	62	129

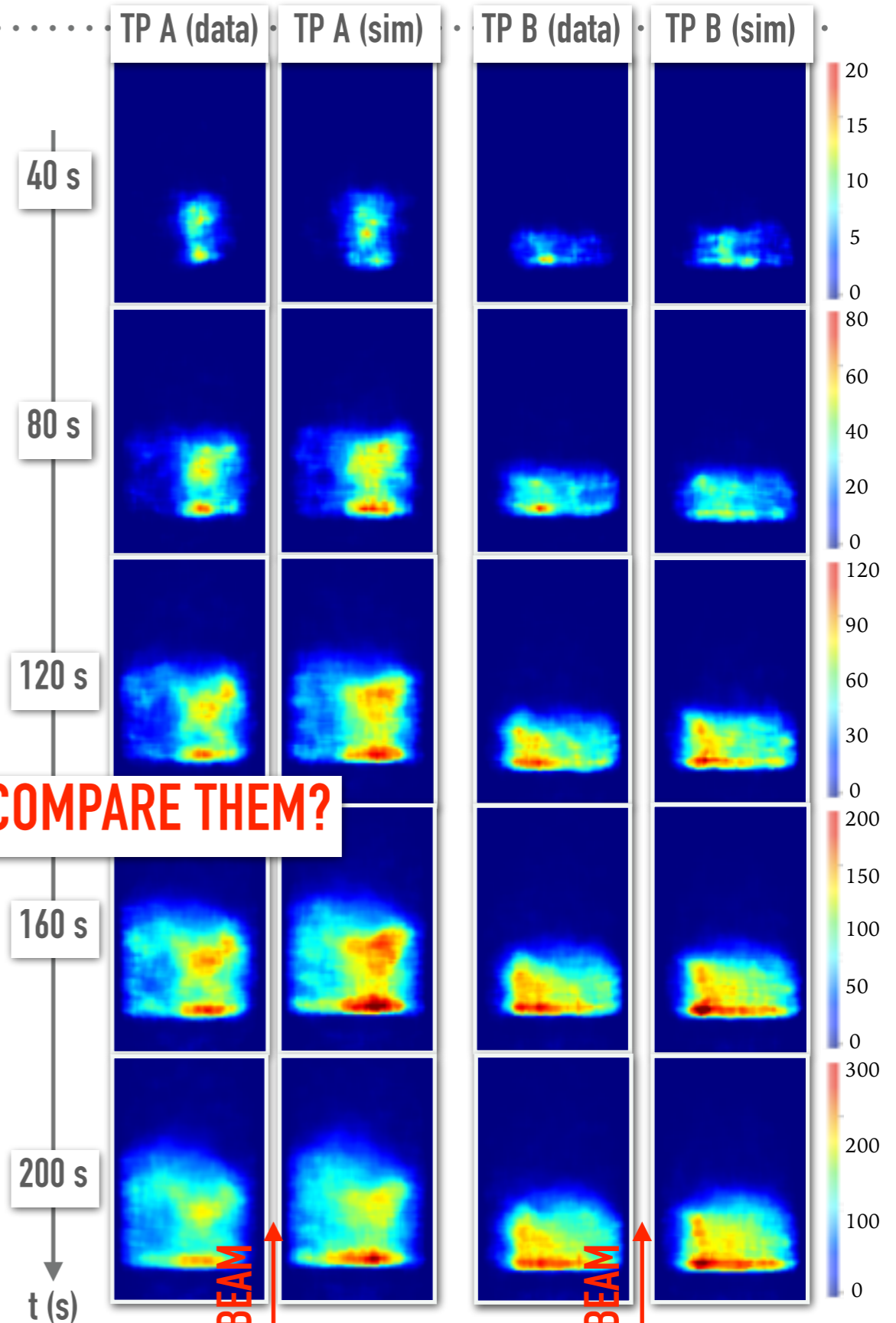
MONTE CARLO SIMULATIONS

STEP 1 beam simulation	time-tagged activity scoring	STEP 2 PET simulation	image reconstruction
about 1/100 of primary hadrons are simulated	isotope production map	all positrons are simulated (x100)	same analysis chain as real data



the detector characteristics are simulated

HOW DO WE COMPARE THEM?



ACTIVITY PROFILE

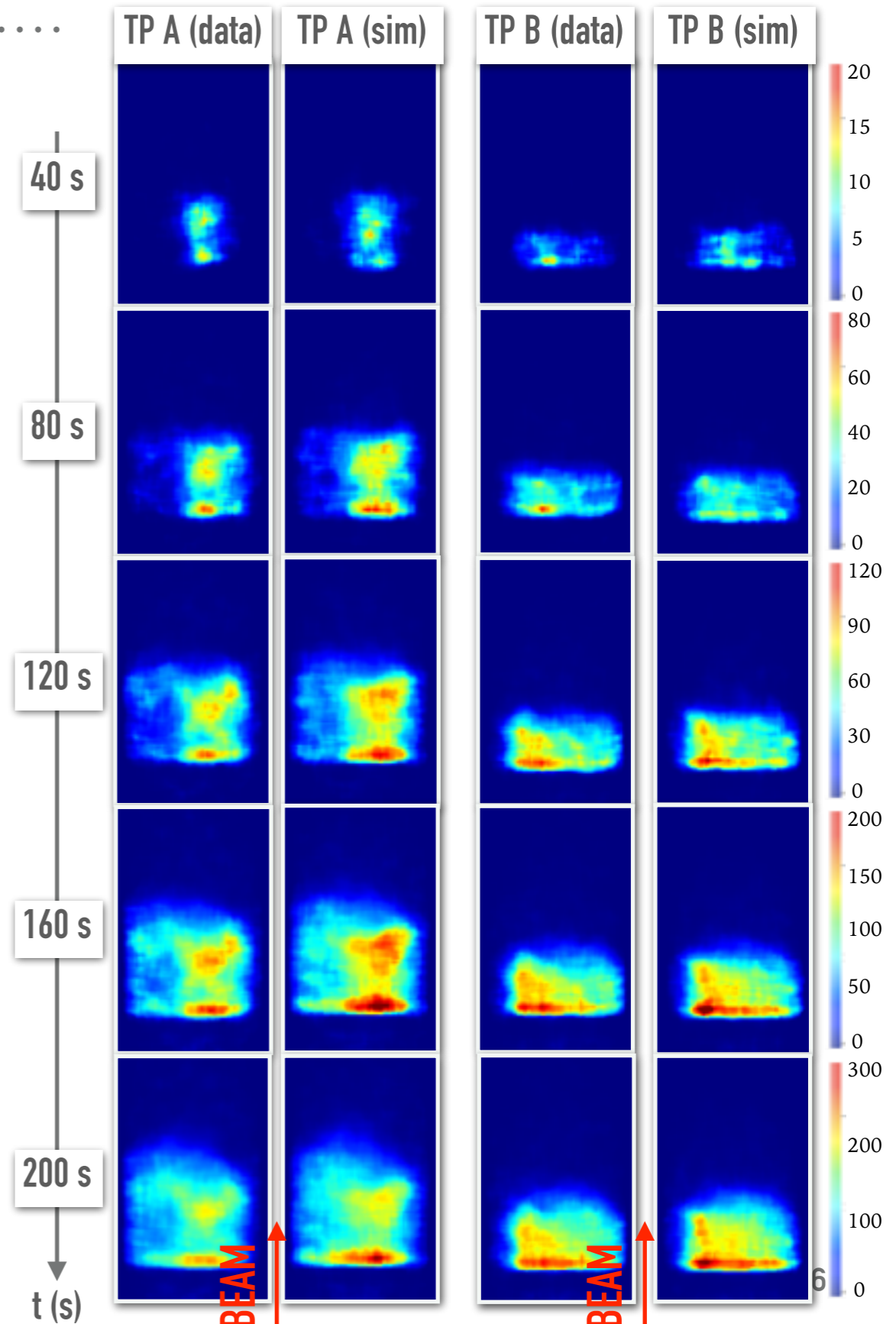
```

veronica@mag11x1:~$ INSIDEAnalyseImageProfile
Program to analyse reconstructed PET images, usage::
-h [ --help ]                Produce this help message
-R [ --ReconstructedImage(s) ] arg  3D PET reconstructed image(s) (.nii)
-L [ --Plane ]                Profile centered in (xIndex,yIndex),
                                along a plane in y (ROI width set by
                                opt j)
-P [ --Prism ]                Profile centered in (xIndex,yIndex),
                                prism with cubic base (ROI set by opt
                                1,j)
-i [ --Width_X ] arg          [optional!] Half number of voxels to be
                                considered for ROI calculation in the
                                profiles, X direction (default: 1)
-j [ --Width_Y ] arg          [optional!] Half number of voxels to be
                                considered for ROI calculation in the
                                profiles, Y direction (default:
                                ImgDimY/2)
-v [ --VoxelSize ] arg        [optional!] Voxel dimension (default:
                                0.16cm)
-x [ --xIndex ] arg           [optional!] x position (slice) to
                                calculate profiles (default: ImgDimX/2)
-y [ --yIndex ] arg           [optional!] y position (slice) to
                                calculate profiles (default: ImgDimY/2)
--axisY                       Select this to calculate the profile in
                                the Y direction [default: Z]
--axisX                       Select this to calculate the profile in
                                the X direction [default: Z]
-b [ --fitRangeBegin ] arg     [optional!] Initial z coordinate for
                                sigmoid fit
-e [ --fitRangeEnd ] arg       [optional!] Final z coordinate for
                                sigmoid fit
--gausFit                     Select this option to fit the selected
                                range with a gaussian [default is
                                sigmoid]
  
```

- Can compare several images
- Image profile on preferred direction in a selectable sub-image
- Calculates range with sigmoid or gaussian function in the interval specified by the user

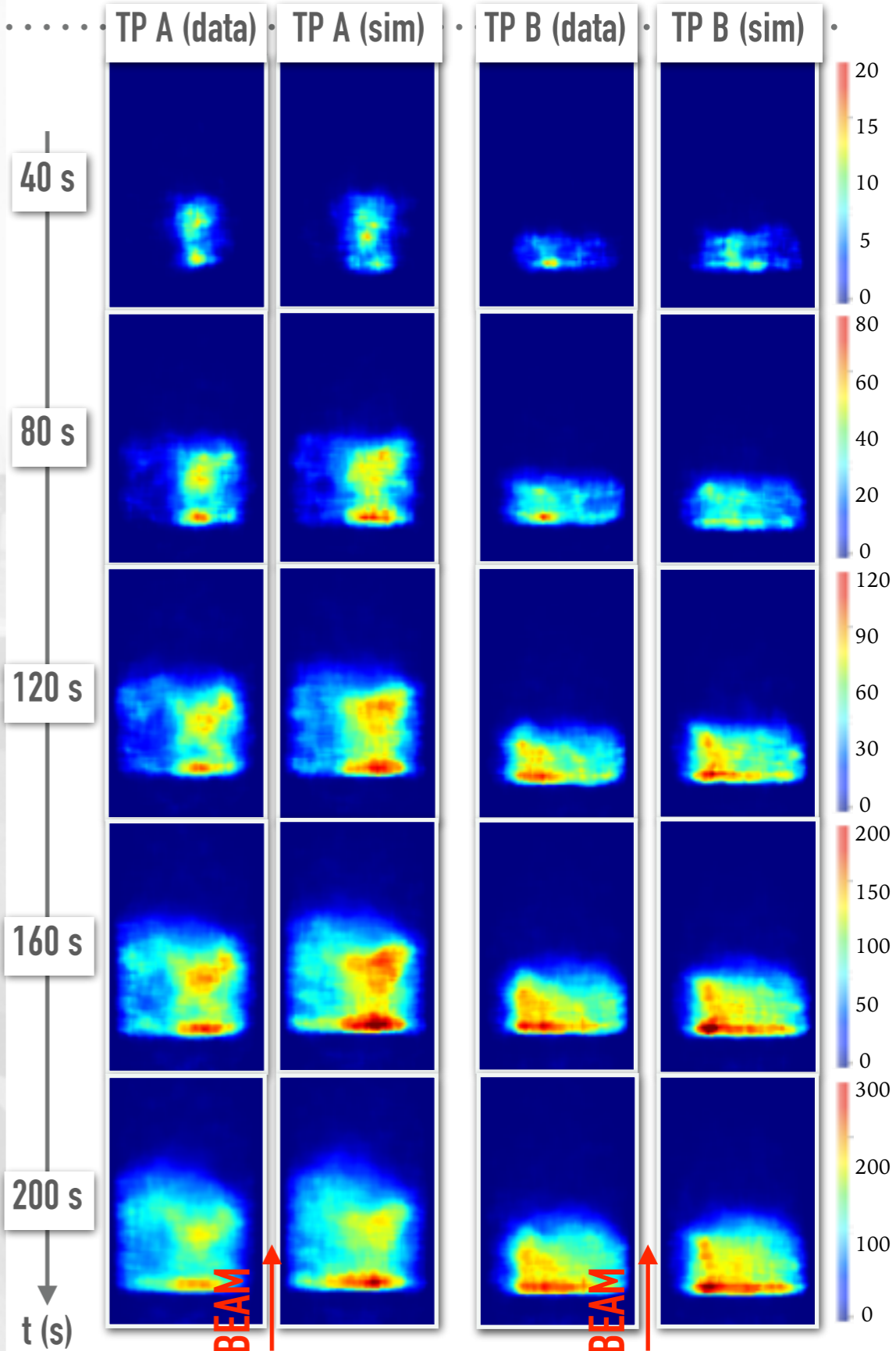
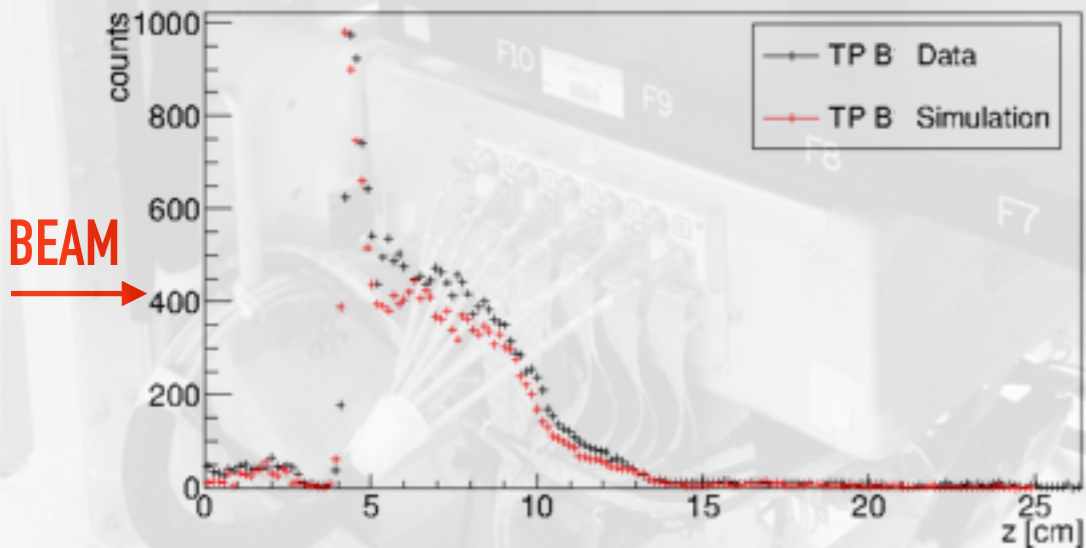
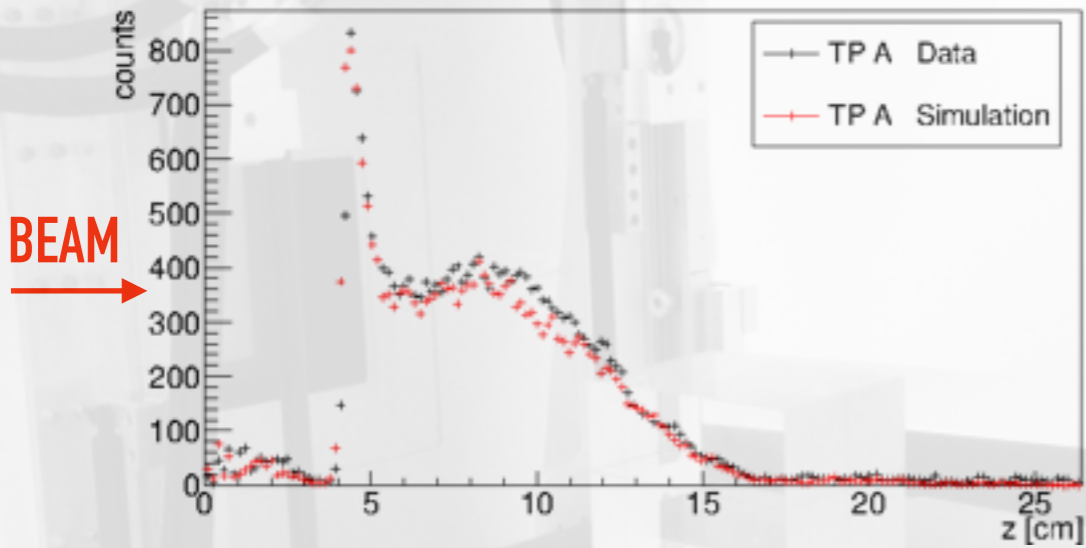
C++, ROOT/BOOST/ITK LIBRARIES

vferrero@to.infn.it, INFN and University of Torino



THE INSIDE PROJECT: ONLINE MONITORING AND SIMULATION VALIDATION WITH THE IN-BEAM PET SCANNER (7TH YRM, TORINO)

TP	E_{min} (MeV/u)	E_{max} (MeV/u)
A	83	150
B	62	129



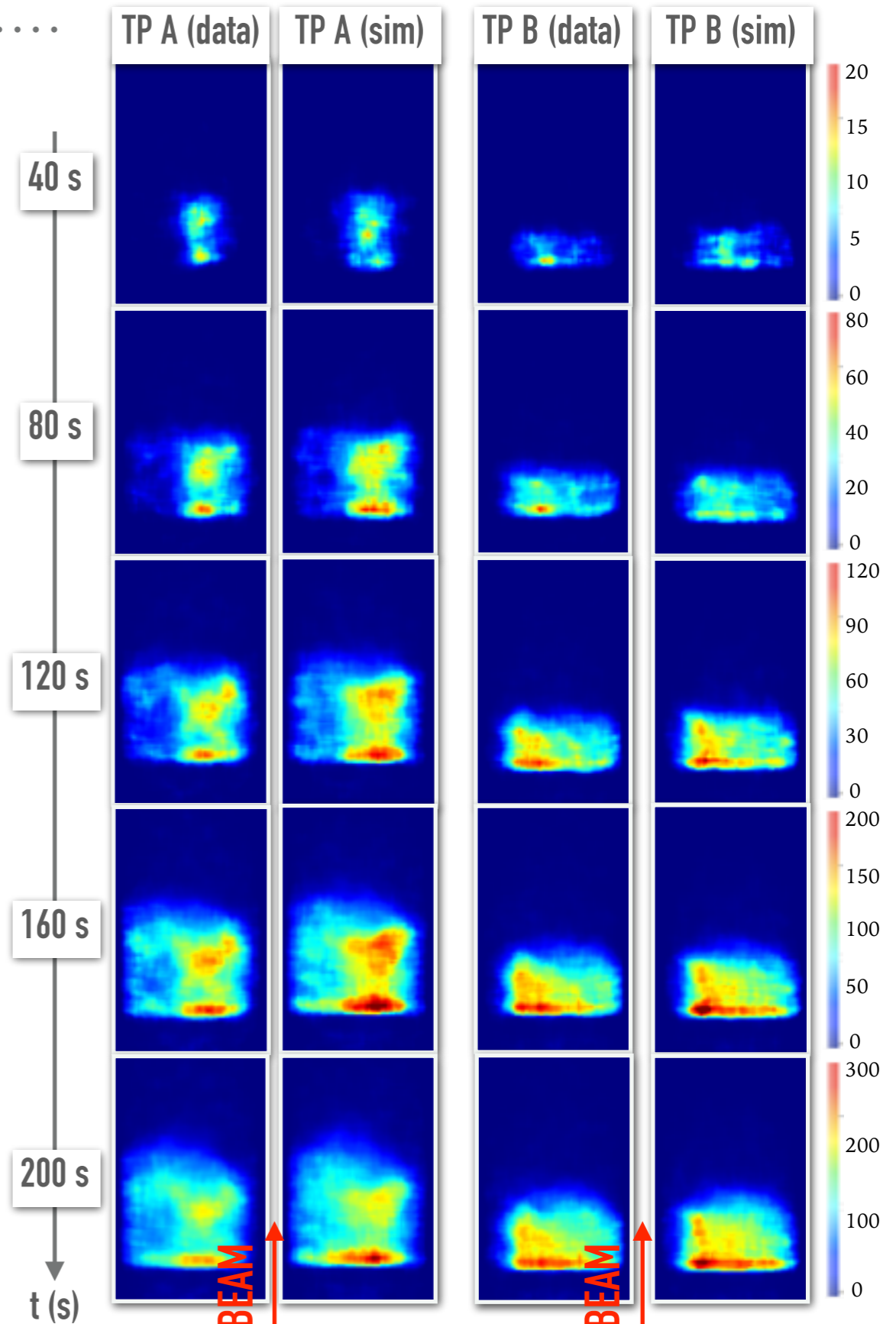
ACTIVITY COMPARISON

```

veronica@mag11x1:~$ INSIDECompareImage
Compares two images. Activity distributions are saved in root file INSIDECompareImage.root
Usage: image1 image2 [options]
Defalut analysis: image difference and activity masks and contours (.nii format), intensity
scatter plot:
-h [ --help ]                Produce this help message
--image1 arg                 3D PET reconstructed image (eg.
                             data.nii)
--image2 arg                 3D PET reconstructed image (eg.
                             simulation.nii)
-o [ --output-image ] arg    Output image: (image1-image2)/image2
                             [default name: diff_image.nii]
-t [ --mask-threshold ] arg  Mask threshold for the input images
                             (eg. 0.1 --> 10%). Gives .nii output
                             image [default: 0.1]
-c [ --mask-threshold2 ] arg Mask threshold for the second input
                             image. [default: same as mask-threshold].
                             NOT USED WITH DOUBLE FIELD
-k [ --median-kernel ] arg   Kernel to apply to the Median filter
                             used for image comparison [default: 5 mm]
-g [ --erode ] arg           Radius for image erosion (mm) [default:
                             5 mm]
-i [ --dilate ] arg          Radius for image dilation (mm) [default:
                             7 mm]
-e [ --equalize ]            Equalize first image to second (default
                             = no equalization)
-r [ --range-verification ] arg argument = Simona Giordanengo-like
                             logfile. With this option, the activity
                             range values of the two input images are
                             compared. Saves additional histograms in
                             INSIDECompareImage.root
-d [ --range-verification-dop ] arg argument = Treatment.txt. With this
                             option, the activity range values of the
  
```

- Compares two images
- Can be launched in time (bash script)
- Selects the activity through the application of image filtering and compares the images 3-dimensionally
- Can use the treatment plan spatial information to select a sub-image of activity

C++, ROOT/BOOST/ITK LIBRARIES



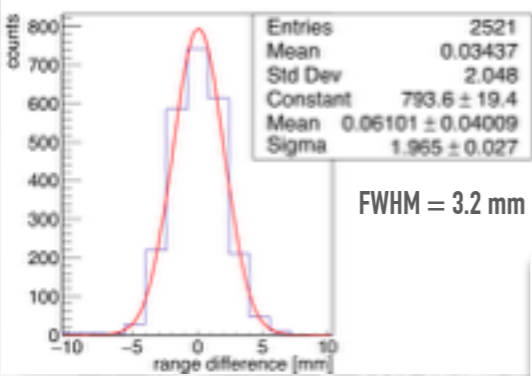
THE INSIDE PROJECT: ONLINE MONITORING AND SIMULATION VALIDATION WITH THE IN-BEAM PET SCANNER (7TH YRM, TORINO)

TP	E_{min} (MeV/u)	E_{max} (MeV/u)
A	83	150
B	62	129

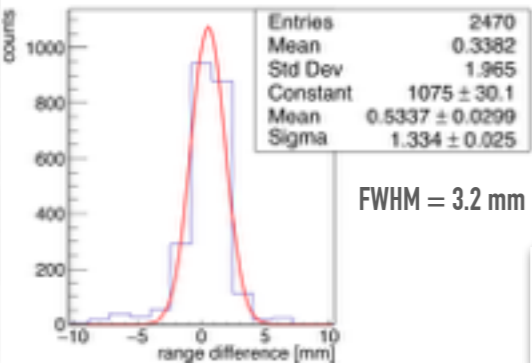
ACTIVITY SELECTION



BEAM'S EYE VIEW

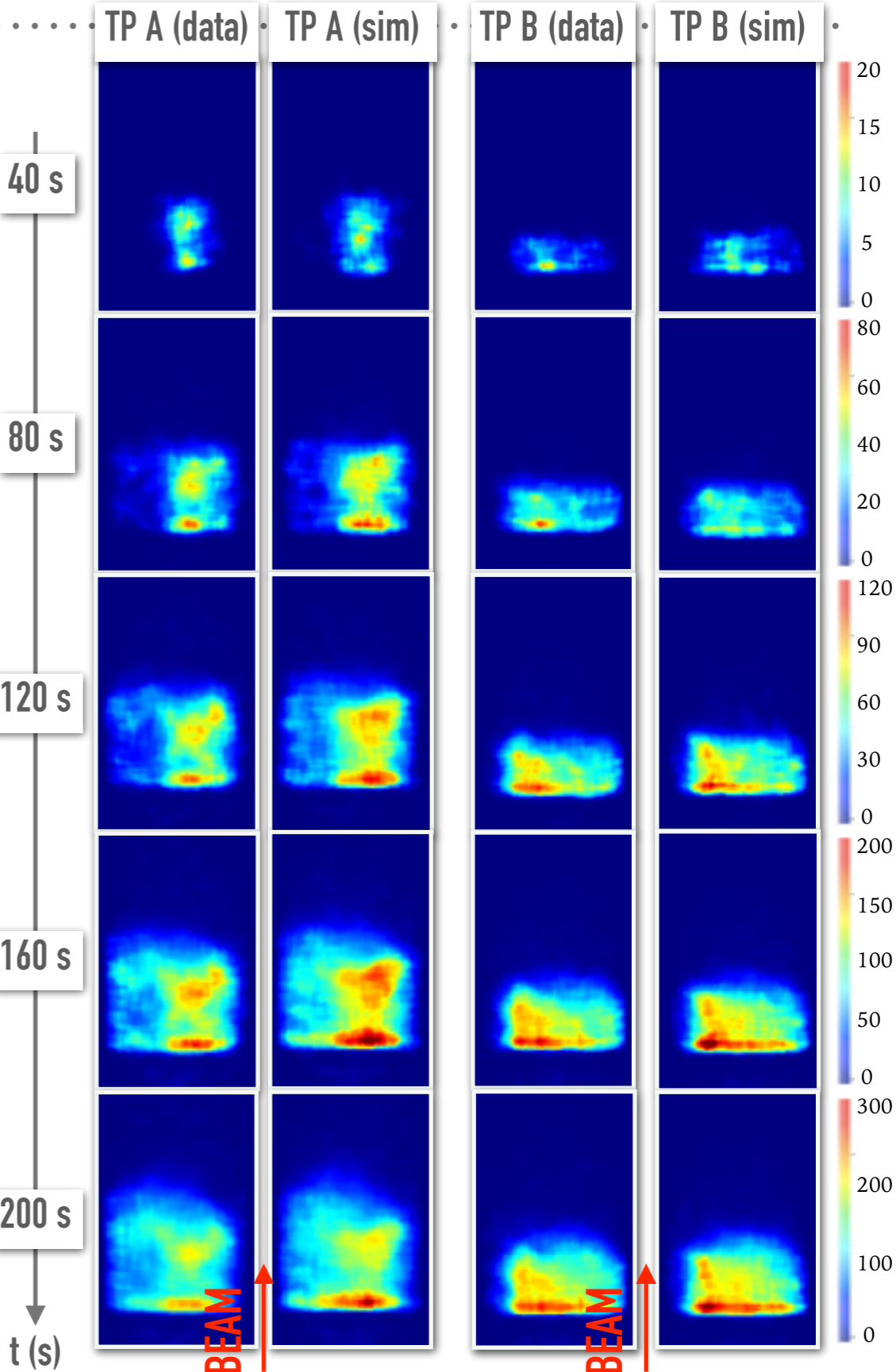
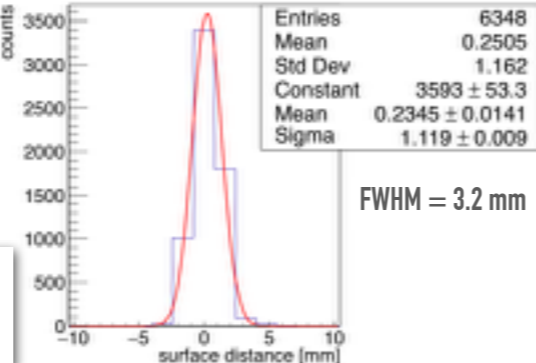
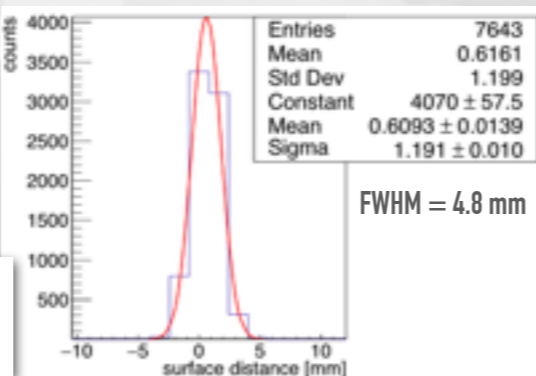


TP A 200s
(data vs sim)



TP B 200s
(data vs sim)

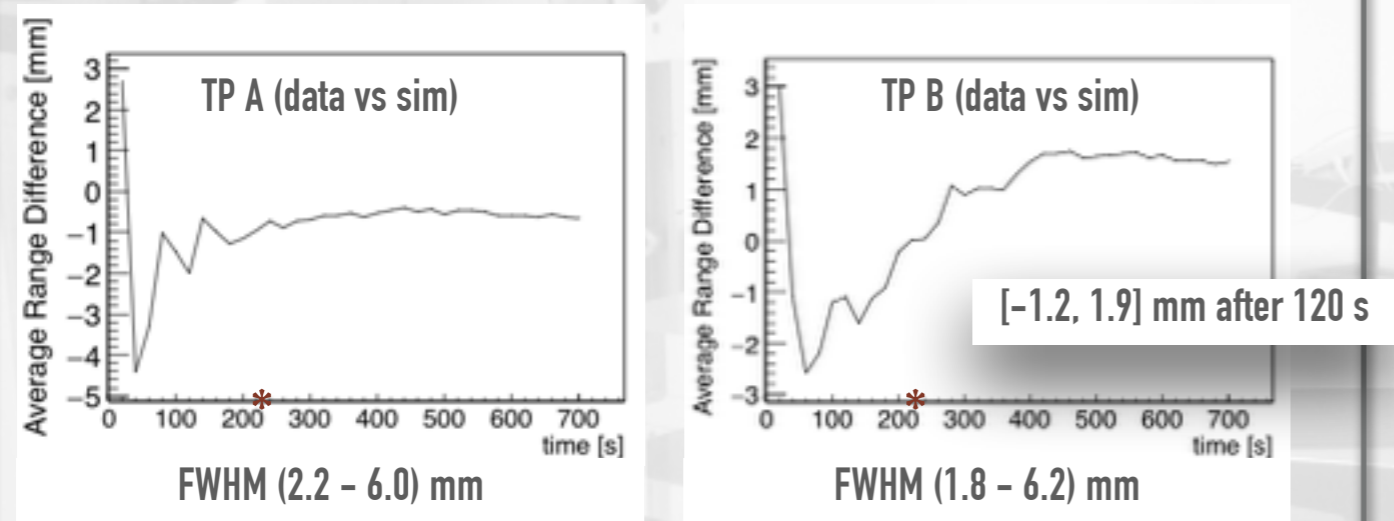
OVERALL VIEW



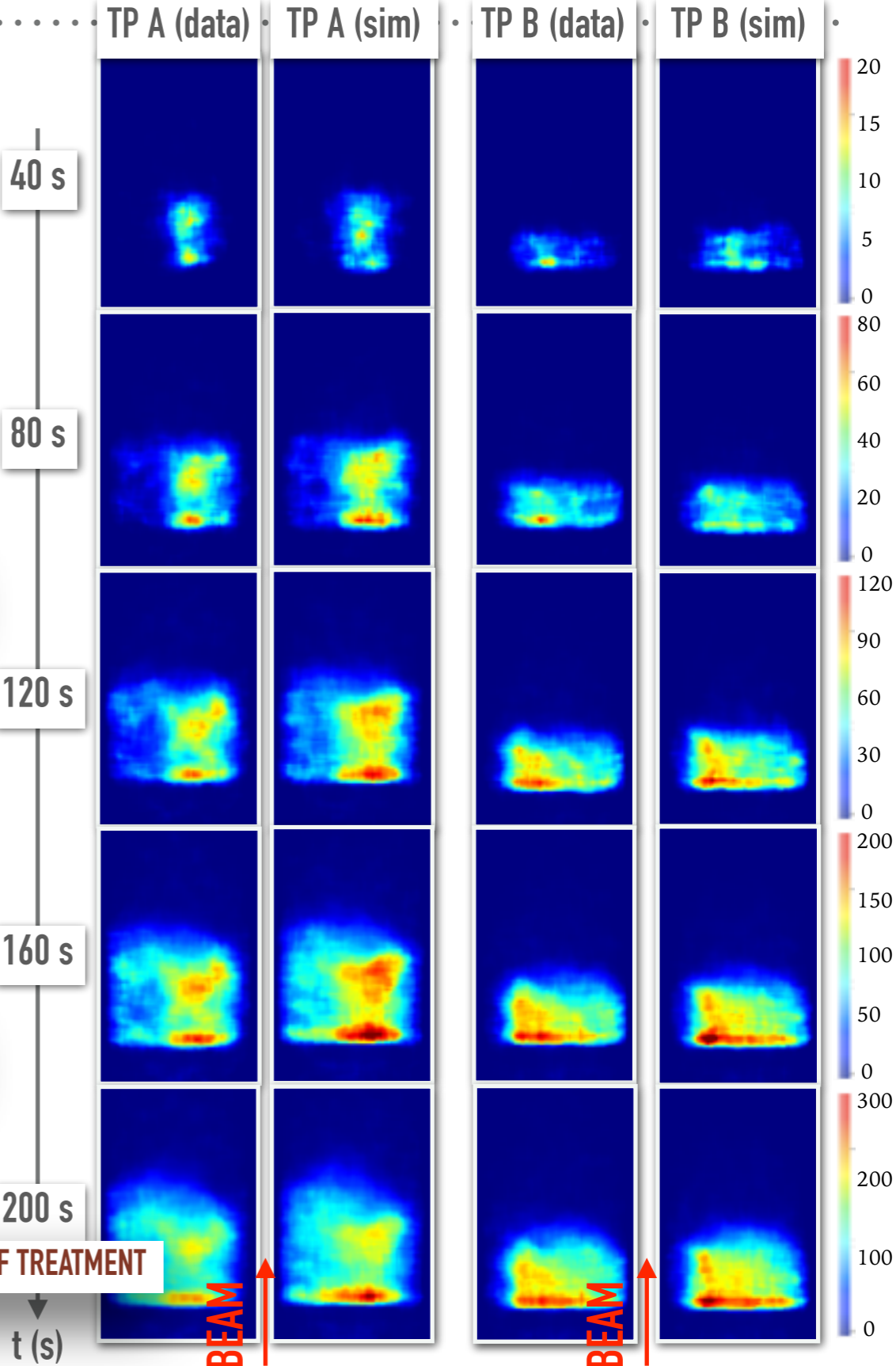
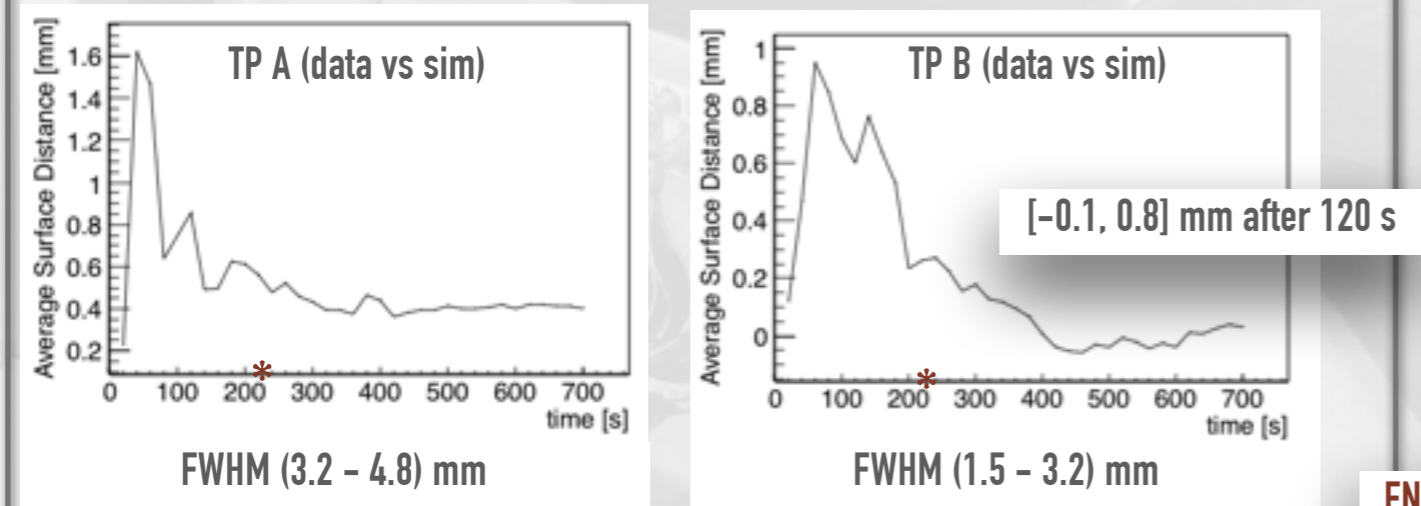
THE INSIDE PROJECT: ONLINE MONITORING AND SIMULATION VALIDATION WITH THE IN-BEAM PET SCANNER (7TH YRM, TORINO)

TP	E_{min} (MeV/u)	E_{max} (MeV/u)
A	83	150
B	62	129

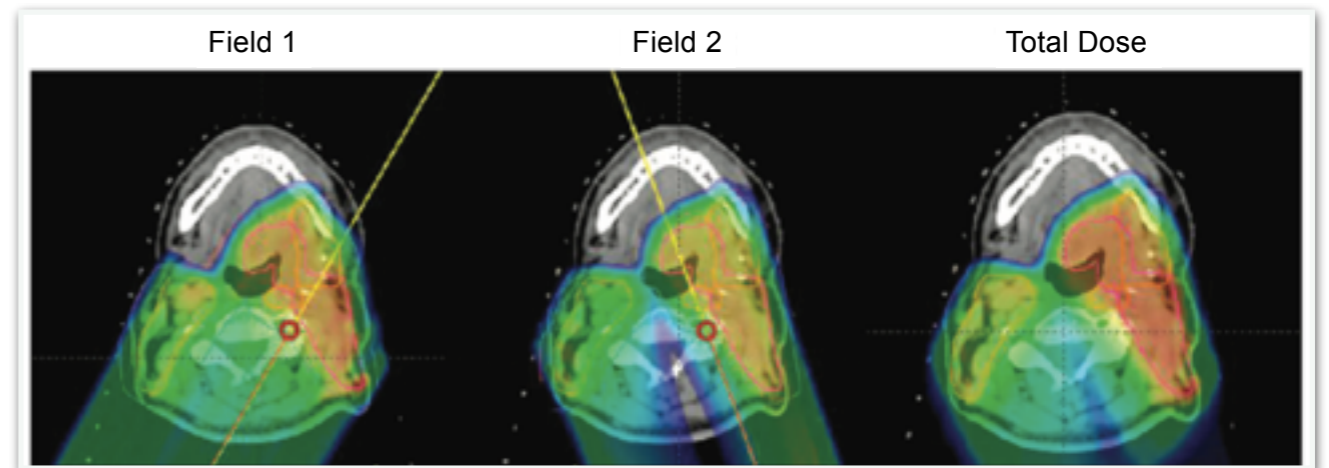
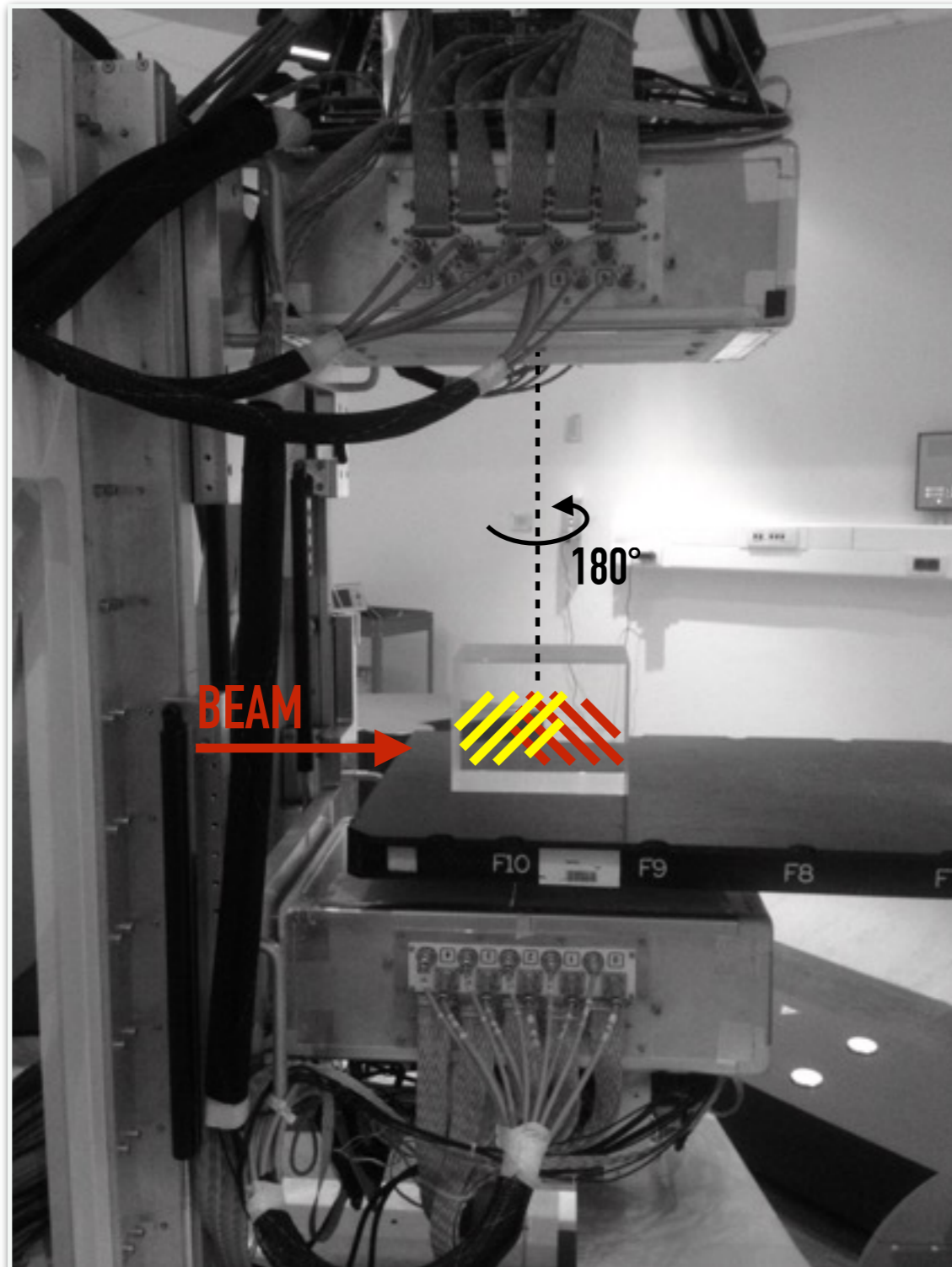
BEAM'S EYE VIEW



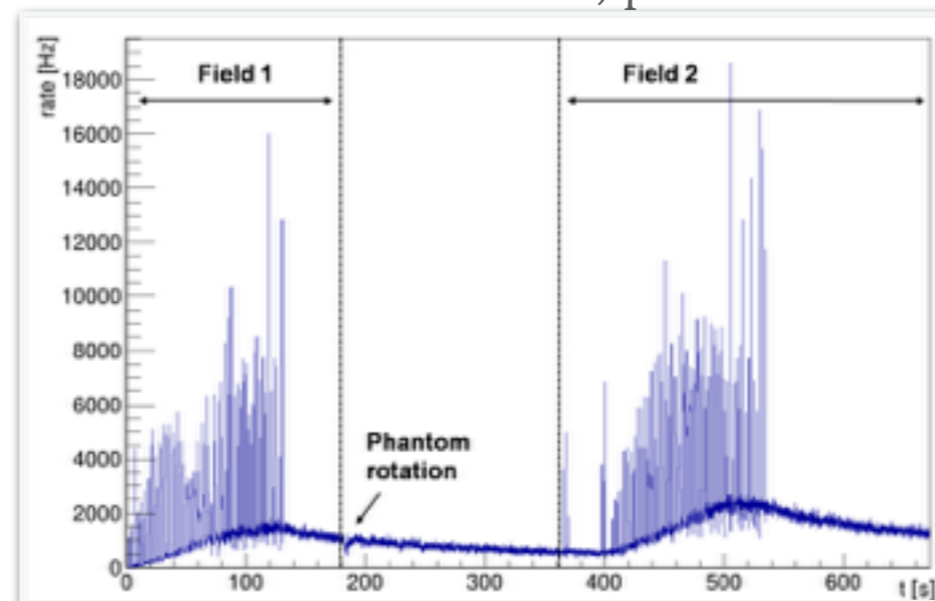
OVERALL VIEW



DOUBLE FIELD HADRONTHERAPY TREATMENT MONITORING WITH THE INSIDE IN-BEAM PET: PROOF OF CONCEPT ON PMMA PHANTOMS (IEEE NSS/MIC, ATLANTA, USA)



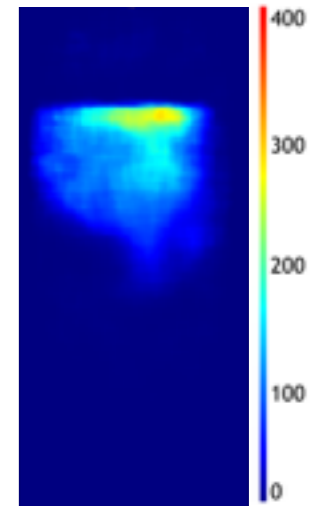
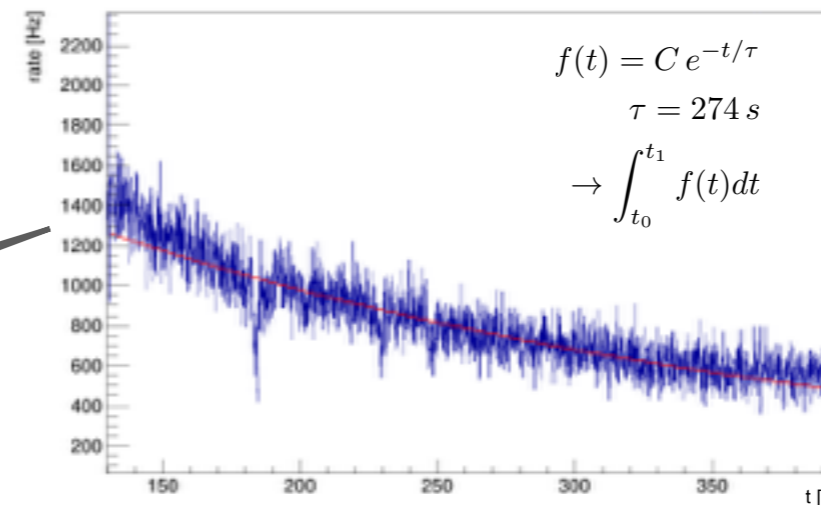
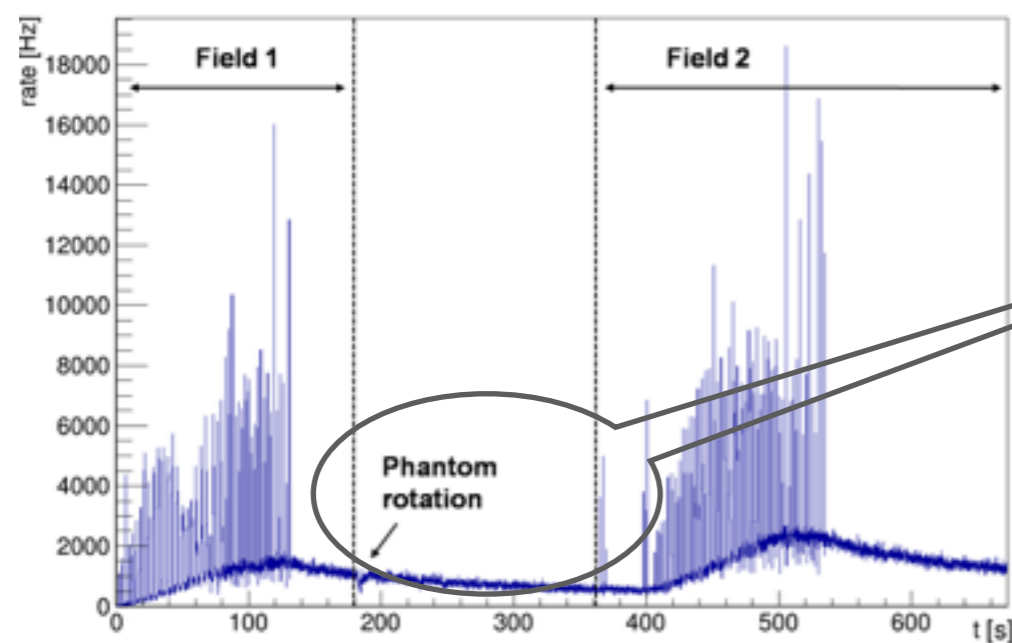
Coincidences event rate, proton beam



Treatment		E_{min} (MeV/u)	E_{max} (MeV/u)
Proton beam	Field 1	83	150
	Field 2	62	129
Carbon ion beam	Field 1	134	269
	Field 2	134	264

DOUBLE FIELD HADRONTHERAPY TREATMENT MONITORING WITH THE INSIDE IN-BEAM PET: PROOF OF CONCEPT ON PMMA PHANTOMS (IEEE NSS/MIC, ATLANTA, USA)

Coincidence event rate



PROTON BEAM TREATMENT PLAN

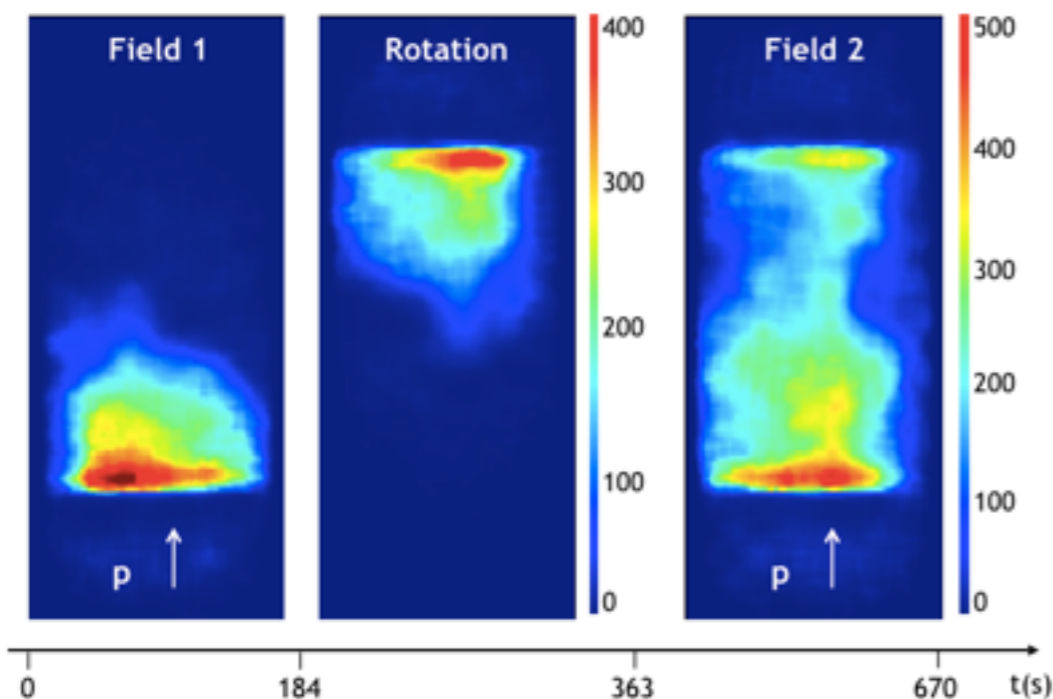
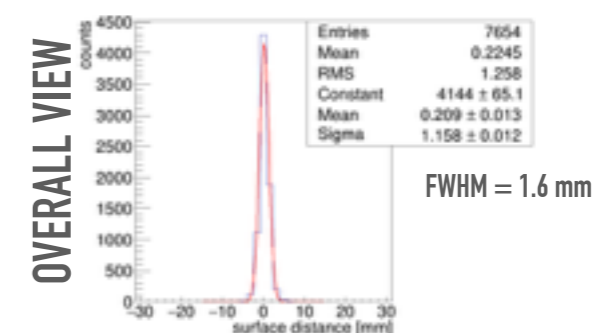
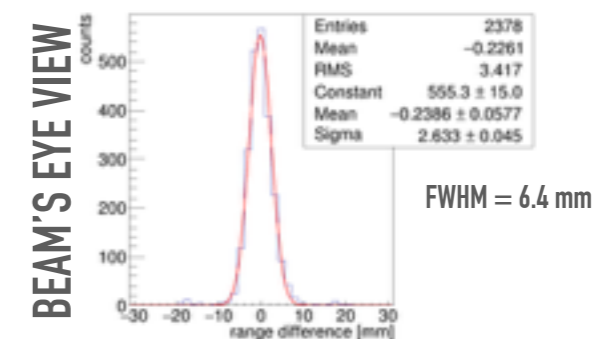
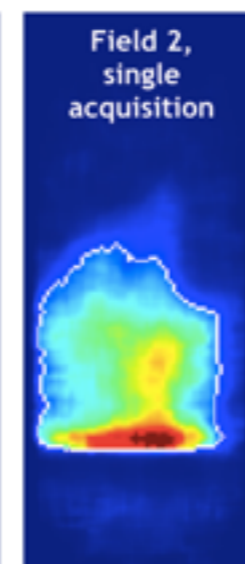
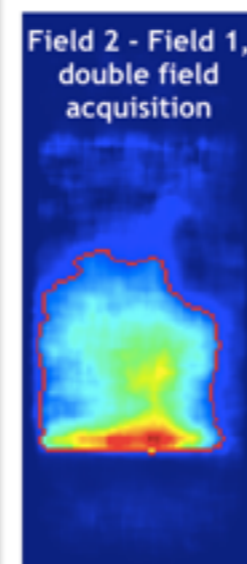
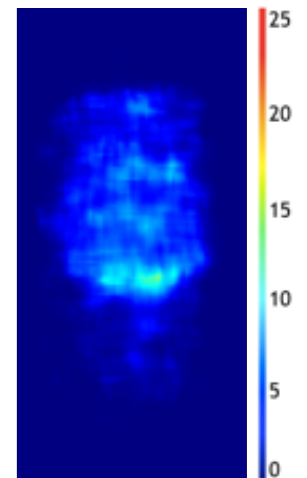
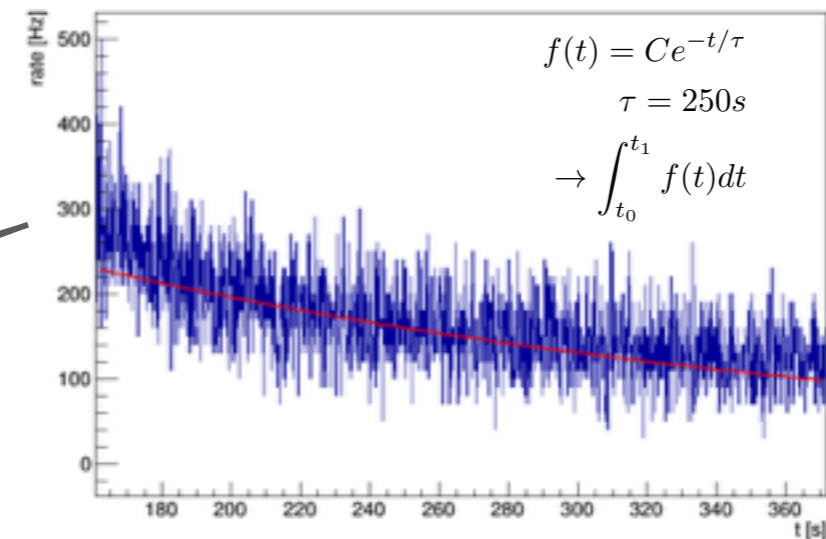
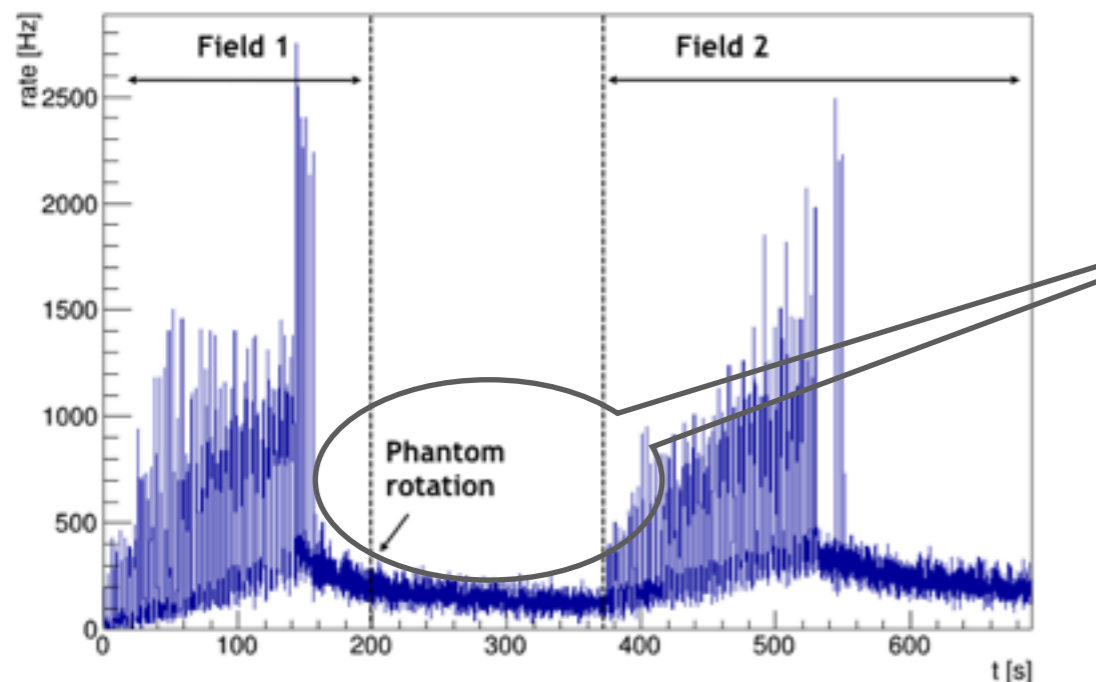


IMAGE COMPARISON



DOUBLE FIELD HADRONTHERAPY TREATMENT MONITORING WITH THE INSIDE IN-BEAM PET: PROOF OF CONCEPT ON PMMA PHANTOMS (IEEE NSS/MIC, ATLANTA, USA)

Coincidence event rate



CARBON ION BEAM TREATMENT PLAN

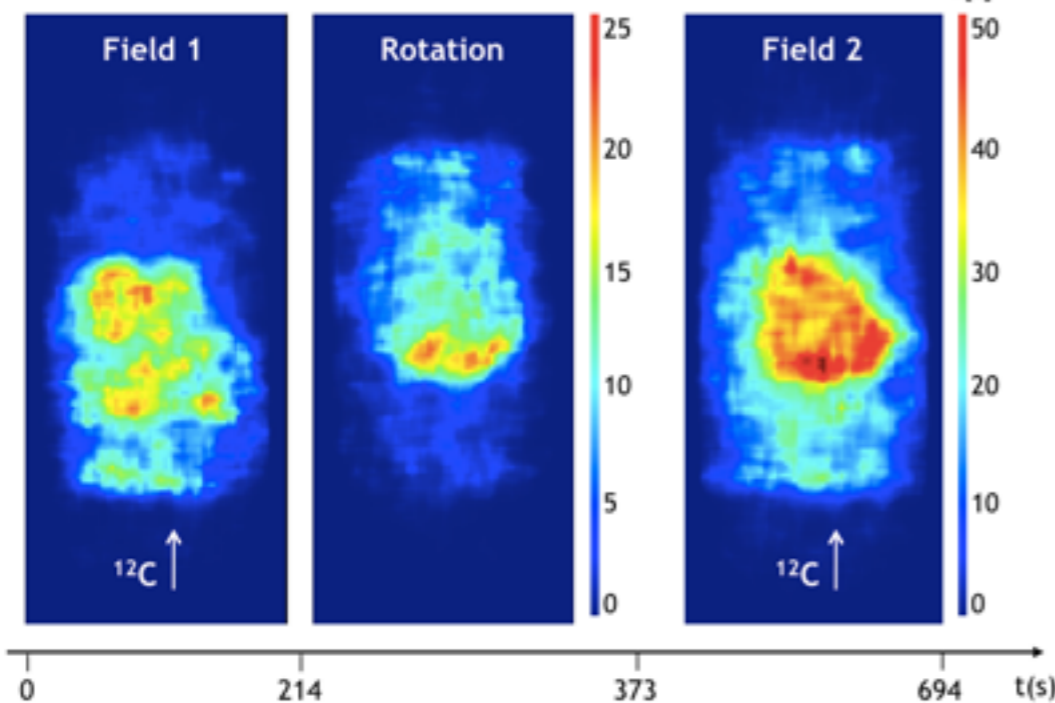
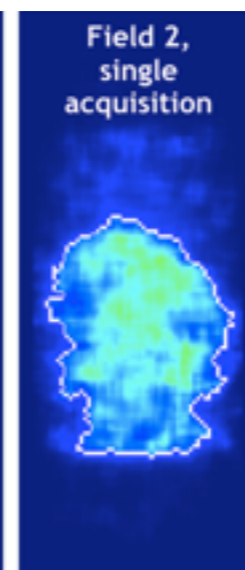
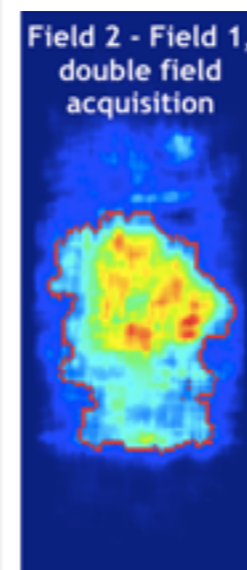
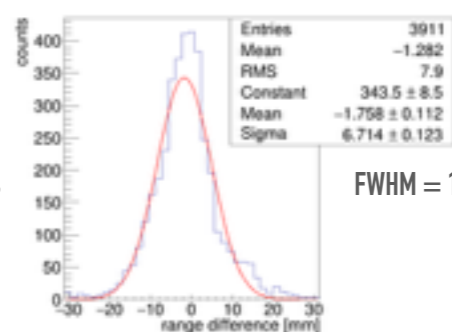


IMAGE COMPARISON

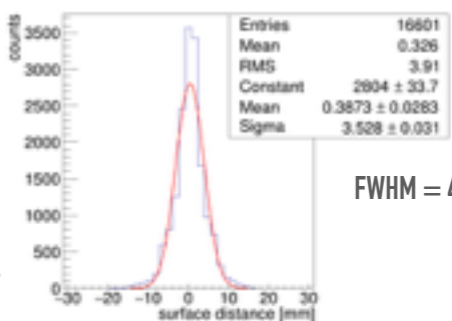


BEAM'S EYE VIEW



FWHM = 11.2 mm

OVERALL VIEW



FWHM = 4.8 mm

FIRST CLINICAL TEST



NEWSLETTER 30

Italian National Institute for Nuclear Physics

DECEMBER 2016



PHYSICS AND MEDICINE

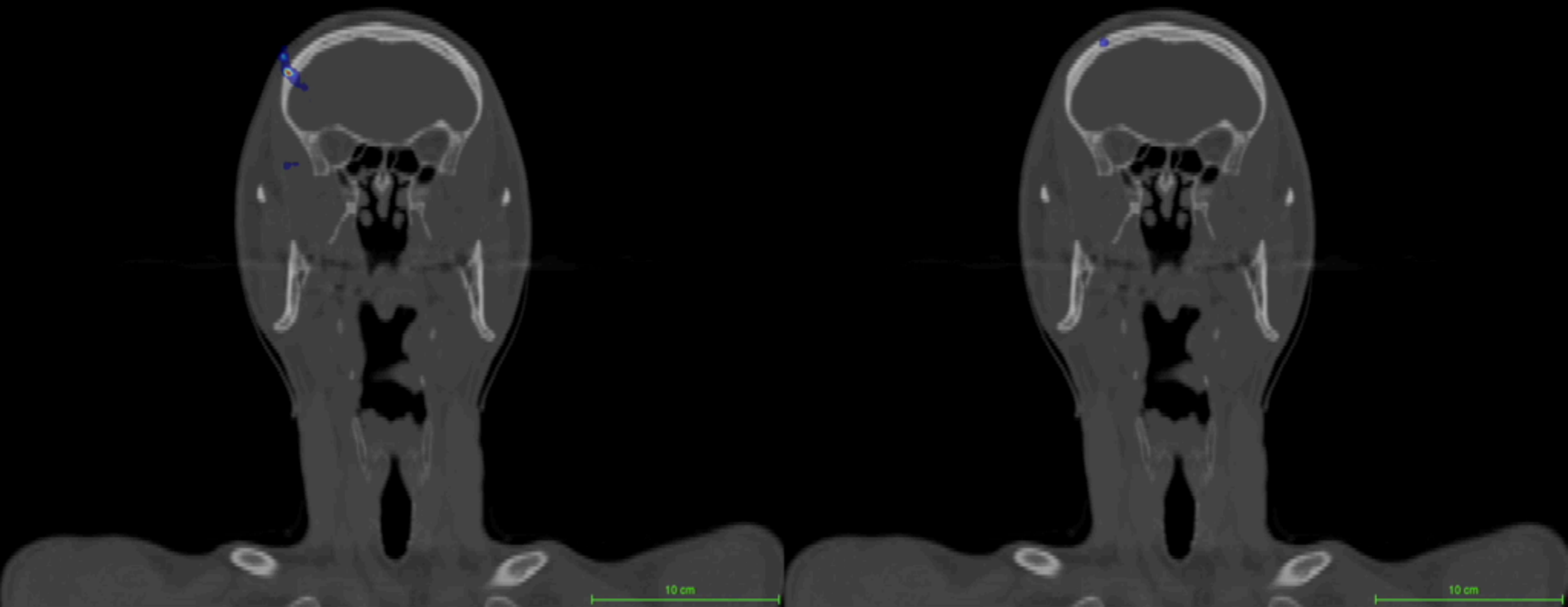
CANCER: INSIDE SYSTEM SUCCESSFULLY TESTED FOR THE FIRST TIME ON A PATIENT

INSIDE (Innovative Solutions for Dosimetry in Hadrontherapy) has been tested for the first time on a patient. This innovative imaging system, which uses particle accelerators, was built by the INFN in

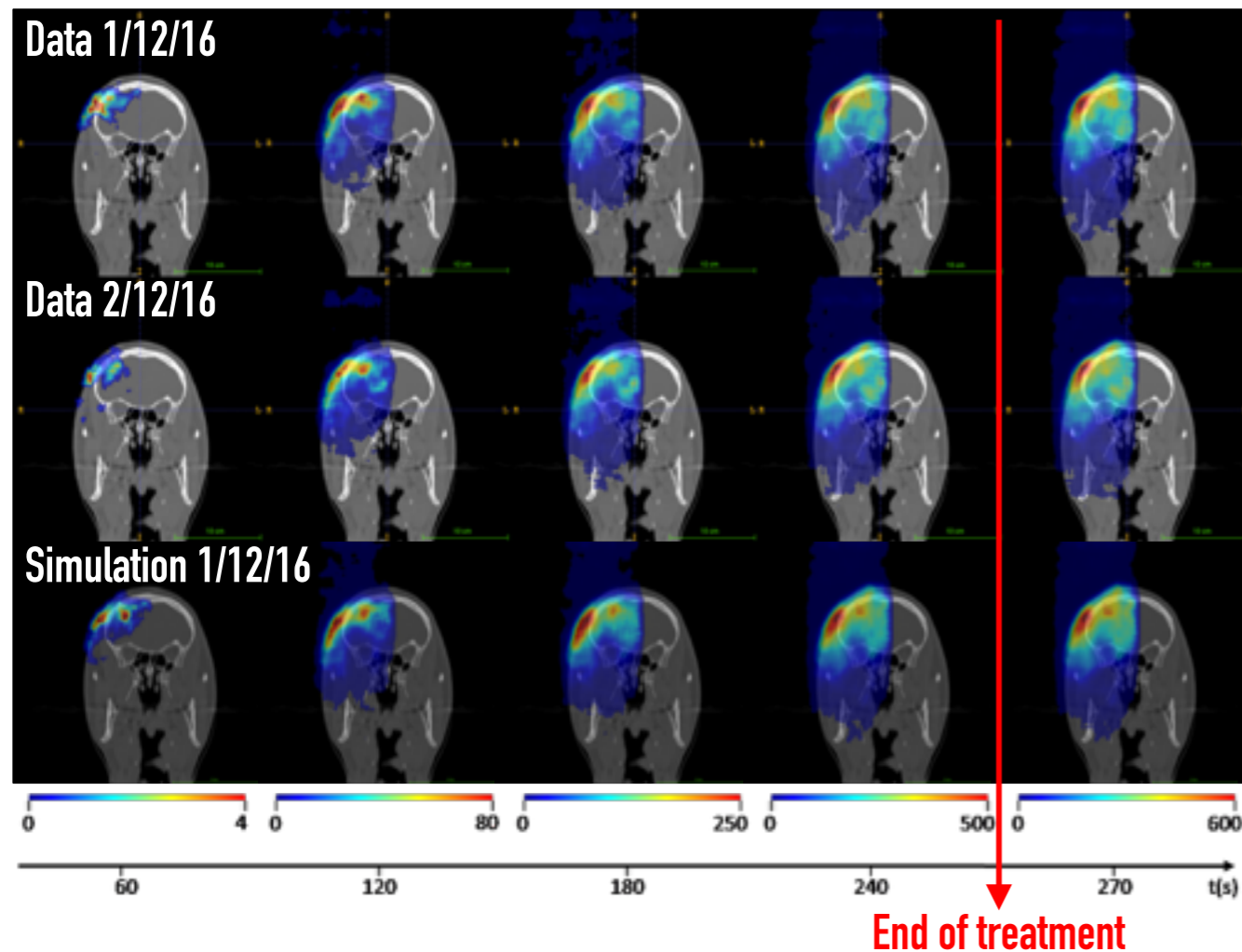
Turin to further enhance the efficacy of hadron therapy, used for the treatment of localised tumours. INSIDE, which received a € 1 million grant under the PRIN (Relevant National Interest Projects) program, is the result of a research project coordinated by the University of Pisa in collaboration with the Universities the universities of Turin and Sapienza of Rome, Bari Polytechnic University and INFN. For the trial phase, INSIDE was tested on the patient at the Italian National Centre for Oncological Hadron Therapy (CNAO), in Pavia. INSIDE is an innovative monitoring system, which uses detector technology to obtain images of what happens inside the patient's body during the hadron therapy treatment. In more detail, this bimodal imaging system combines a positron emission tomography (PET) scanner with a tracking system for charged particle imaging and is capable of operating during radiation delivery to treat head and neck tumours. ■

FIRST CLINICAL TEST

.....

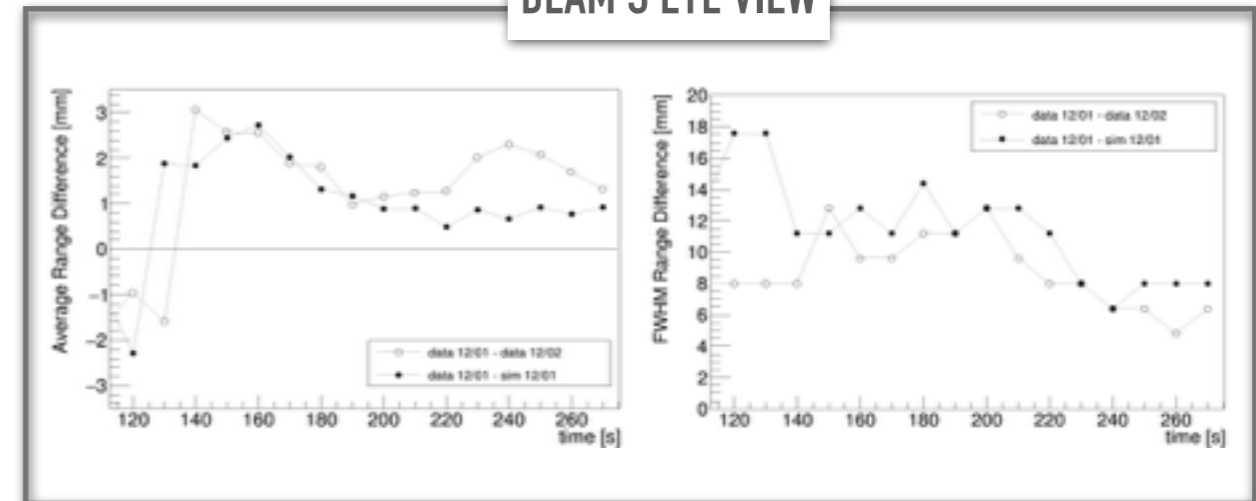


FIRST CLINICAL TEST

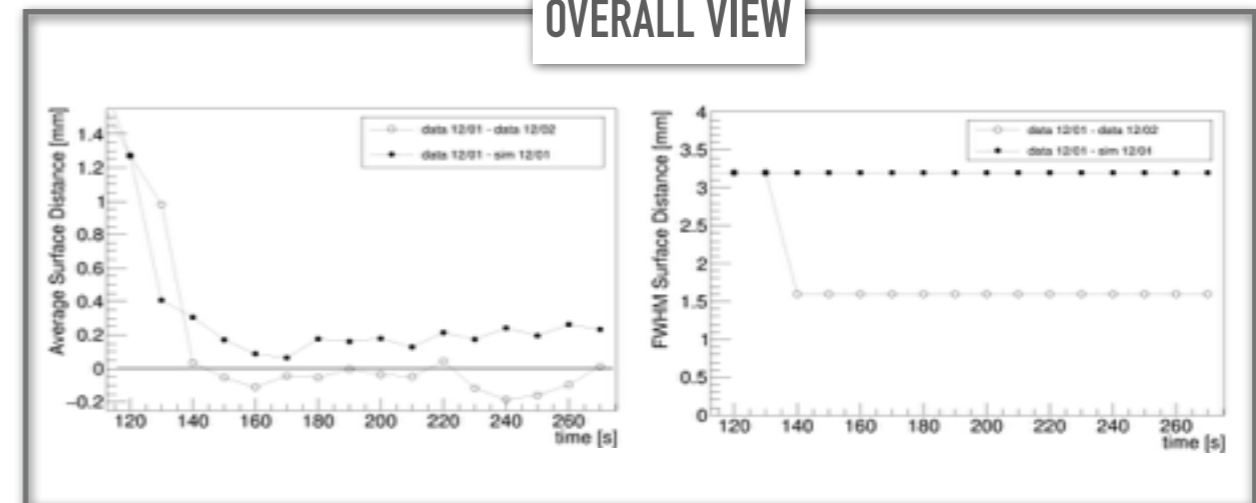


Comparison analysis of the experimental data acquired in the two consecutive days: *Ferrero V., Fiorina E., Morrocchi M., Pennazio F. et al, Online proton therapy monitoring: clinical test of a Silicon-photodetector-based in-beam PET, submitted to Nature Scientific Reports*

BEAM'S EYE VIEW



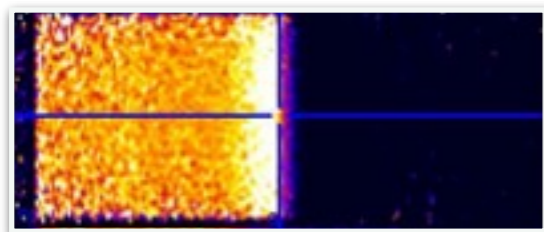
OVERALL VIEW



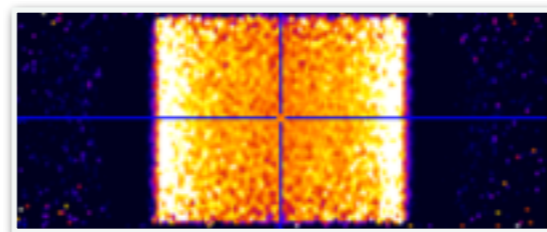
IN THE NEXT FUTURE: RECONSTRUCTION ALGORITHM

Simulation of a $10 \times 10 \times 12 \text{ cm}^3$ water phantom at different positions along z (beam axis)
30 kBq activity (^{18}F -FDG)

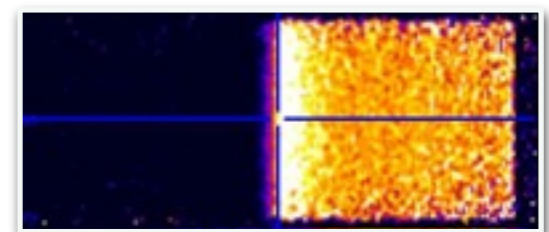
Maximum Likelihood Expectation Maximization (MLEM) reconstruction model with 5 iteration



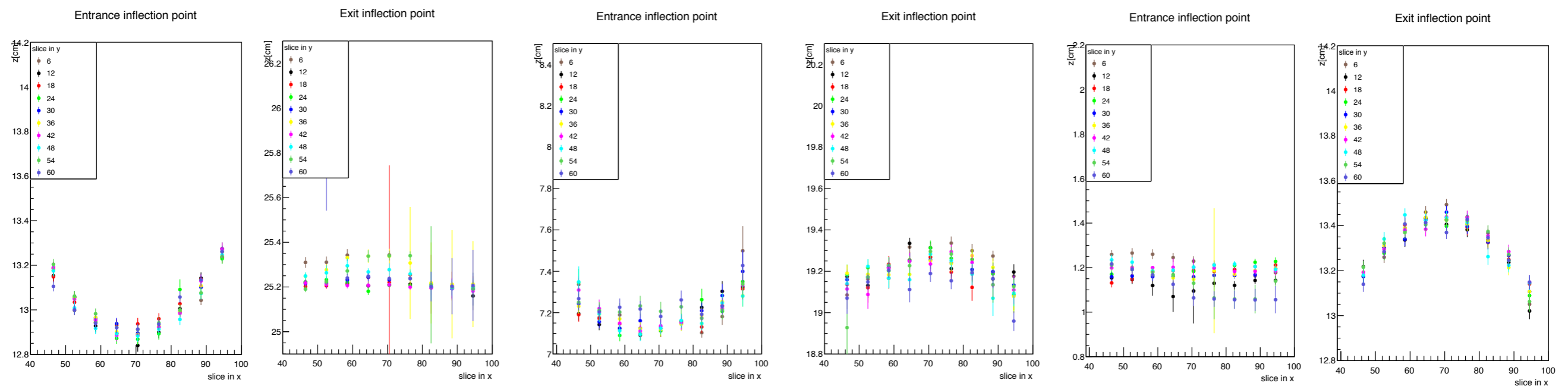
right side in FOV



central point in FOV



left side in FOV



The reconstruction algorithm is limited by the PET dual head geometry, but it could be optimized, e.g. by integrating the beam information → Visiting at Lübeck University, Germany, 2018



IN THE NEXT FUTURE

.....

- Mechanical cart upgrade
- PET/tracker combined acquisition tests
- Longitudinal clinical trials @ CNAO
- Image reconstruction algorithm: visiting period (3 months - Erasmus Traineeship grant) @ Lübeck University, Germany

fondazione **CNAO**
Centro Nazionale di Adroterapia Oncologica per il trattamento dei tumori



CONFERENCE AND WORKSHOP PRESENTATIONS

2017

IEEE NSS/MIC, Atlanta, Georgia, USA

Fisica e Informatica in Medicina, Monza, Italy

7th Young Researchers Meeting, Torino, Italy

2016

14th Topical Seminar on Innovative Particle and Radiation Detectors, Siena, Italy

102° Italian National Congress, Padua, Italy

PAPERS

PUBLISHED

The INSIDE project: in-beam pet scanner system features and characterization. Journal of Instrumentation, 12(03):C03051, 2017.

The INSIDE project: on-line monitoring and simulation validation with the in-beam PET scanner. Journal of Physics: Conference Series, 841(1):012011, 2017.

INSIDE in-beam positron emission tomography system for particle range monitoring in hadrontherapy. Journal of Medical Imaging, 4(1), 2016.

Full-beam performances of a pet detector with synchrotron therapeutic proton beams. Physics in Medicine and Biology, 61(23):N650–N666, 2016.

First results of the INSIDE in-beam pet scanner for the on-line monitoring of particle therapy treatments. Journal of Instrumentation, 11(12):C12011, 2016.

SUBMITTED

Online proton therapy monitoring: clinical test of a Silicon-photodetector-based in-beam PET, Nature Scientific Reports

WORK IN PROGRESS

Monte Carlo Simulations and data analysis of carbon ions beam therapy monitoring: a case study with the INSIDE in-beam PET

Monte Carlo simulation tool for online treatment monitoring in hadrontherapy with in-beam PET

Double-field hadrontherapy treatment monitoring with the INSIDE in-beam PET: proof of concept on PMMA phantoms