IFMP WORKSHOP IN IONIAN UNIVERSITY, CORFU, GREECE

Tuesday 7/11/201 11:00

FLUKA SIMULATION IN MEDICAL PHYSICS

Albana Topi

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Abstract: FLUKA is a general-purpose tool for calculations of particle transport and interactions with matter, covering an extended range of applications spanning from proton and electron accelerator shielding to target design, calorimetry, detector design, cosmic rays, neutrino physics, dosimetry, medical physics, radiotherapy etc. The FLUKA physical models are described in several journal and conference papers [1][2].

Over the last decades, developments in Monte Carlo radiation transport algorithms have had tremendous impact in different areas of radiation therapy. MC simulations are particularly important to improve the treatment planning algorithms and the quality assurance issues related to the outcoming dose deposition in the patient [3]. The aim of this talk is to give an overview of the FLUKA code and the application in medical physics, mainly in radiation physics.

My research project is focused on the use of FLUKA code for validation of monitoring techniques in proton therapy. This is a valuable method for treatment of radioresistant and deep-seated tumors due to the depth-dose distribution characterized by the Bragg peak. Nuclear interaction between the protons and the phantoms irradiated generate beta+ emitters during the treatment. The detection of this activity signal can be used to perform the validation of the monitoring techniques. FLUKA is used to calculate the expected activity distribution simulating the experimental conditions of irradiation. The data acquisition were performed in Trento proton therapy facility (IT), where a cyclotron of maximum energy of 230 MeV is installed. The activity signals were acquired with a PET system (DoPET) [4] based on two planar 16 cm x 16 cm LYSO-based detectors and designed to be installed along the beam line and acquire data also during the irradiation.

[1] A. Ferrari et al., FLUKA: a multi-particle transport code, CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773

[2] T.T. Boehlen et al., The FLUKA Code: Developments and Challenges for High Energy and Medical Applications, Nuclear Data Sheets 120, (2014)211-214

[3] G. Battistoni at al., The FLUKA Code: An Accurate Simulation Tool for Particle Therapy, Front. Onco (2016) 6:116

[4] L. Brombal et al., Proton Therapy treatment monitoring with in-beam PET: investigating space and time activity distributions, Nucl Instr Meth, A861, (2017), 71-76

Application of FLUKA code for medical physics

Albana Topi* & Silvia Muraro

11/10/17

The FLUKA code

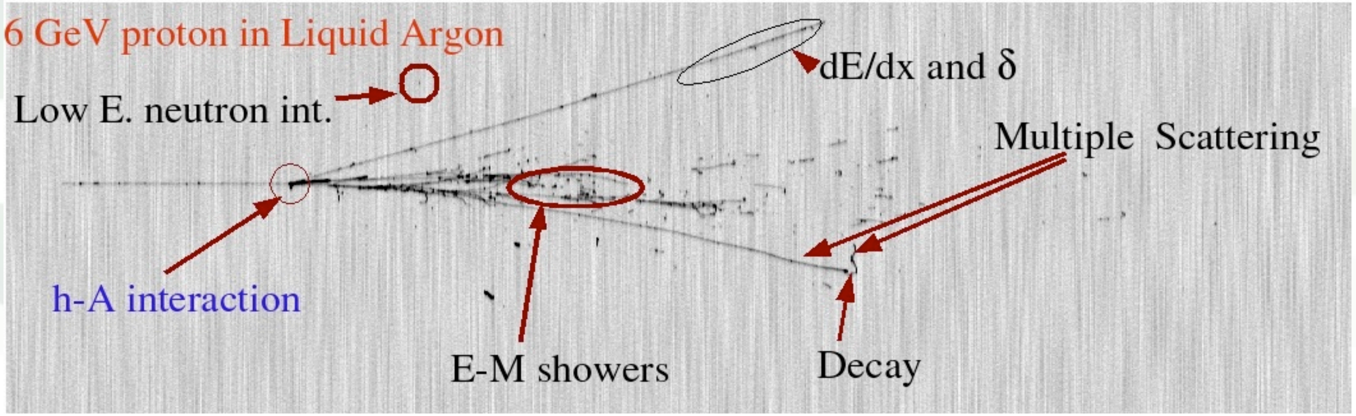
http://www.fluka.org

>8000 registered users

A general purpose tool for calculations of particle transport and interactions with matter: from LHC to microdosimetry *(developed in Fortran)*

Main authors: A. Fassò, A. Ferrari, J. Ranft, P.R. Sala

Contributing authors: G. Battistoni, F. Cerutti, M. Chin, T. Empl, M.V. Garzelli, M. Lantz, A. Mairani, S. Muraro, V. Patera, S. Roesler, G. Smirnov,F. Sommerer, V. Vlachoudis



- High accuracy physics models/"microscopic" approach. Benchmarked with exp. data
- Conservation laws implemented at the level of machine accuracy
- Continuous development
- Easy to use for basic applications

Courtesy G. Battistoni

The FLUKA International Collaboration

G. Aricò, C. Bahamonde Castro, M.I. Besana, M. Brugger, F. Cerutti, A. Cimmino, R. Dos Santos, L. Esposito, Alfredo Ferrari, R. Garcia Alia, J. Idarraga Munoz, W. Kozlowska, A. Lechner, M. Magistris, A. Mereghetti, E. Nowak, S. Roesler, F. Salvat-Pujol, P. Schoofs, E. Skordis, G. Smirnov, C. Theis, A. Tsinganis, Heinz Vincke, Helmut Vincke, V. Vlachoudis, J.Vollaire CERN

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A. Mairani, CNAO Pavia, Italy & HIT, Germany

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K.T. Lee, B. Reddell, E. Semones, N. Stoffle, N. Zapp NASA, Houston, USA
A.Bahadori Kansas Univ. USA M. Trinczec, A. Trudel TRIUMF, Canada

G. Dedes, S. Mayer, K. Parodi, LMU Munich, Germany Anna Ferrari, S. Mueller HZDR Rossendorf, Germany
S. Brechet, L. Morejon, N. Shetty, S. Stransky, S. Trovati, R. Versaci, ELI-Beamlines, Prague, Czechia
T.J. Dahle, L. Fjera, A. Rorvik, K. Ytre-Hauge , Bergen Univ., Norway
F. Belloni, T. Tessonnier INSTN-CEA, France

A. Fedynitch DESY Zeuthen, Germany T. T. Boehlen, Medaustron, Austria S. Rollet, AIT, Austria
C. Cuccagna, TERA Switzerland T.V. Miranda Lima Kantonhospital Aarau, Switzerland
M. Lantz, Uppsala Univ., Sweden F. Fiorini, Oxford Inst. Rad. Oncol., UK
P. Garcia Ortega IUFFYM, Spain I. Rinaldi, INP Lyon, France
M. Chin, Malaysia

A. Fassò, M.V. Garzelli, E. Gadioli, J. Ranft

The History

The early days

The beginning:

1962: Johannes Ranft (Leipzig) and Hans Geibel (CERN): Monte Carlo for high-energy proton beams

The name:

1970: study of event-by-event fluctuations in a NaI calorimeter (FLUktuierende KAskade)

Early 70's to ≈1987: J. Ranft and coworkers (Leipzig University) with contributions from Helsinki University of Technology (J. Routti, P. Aarnio) and CERN (G.R. Stevenson, A. Fassò)

Link with EGS4 in 1986, later abandoned

The modern code: some dates

Since 1989: mostly INFN Milan (A. Ferrari, P.R. Sala): little or no remnants of older versions. Link with the past: J. Ranft and A. Fassò

1990: LAHET / MCNPX: high-energy hadronic FLUKA generator *No further update*

1993: G-FLUKA (the FLUKA hadronic package in GEANT3). *No further update*

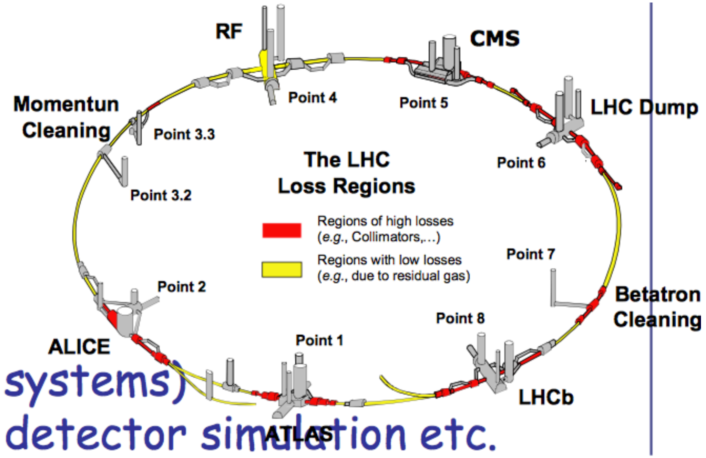
1998: FLUGG, interface to GEANT4 geometry

2000: grant from NASA to develop heavy ion interactions and transport

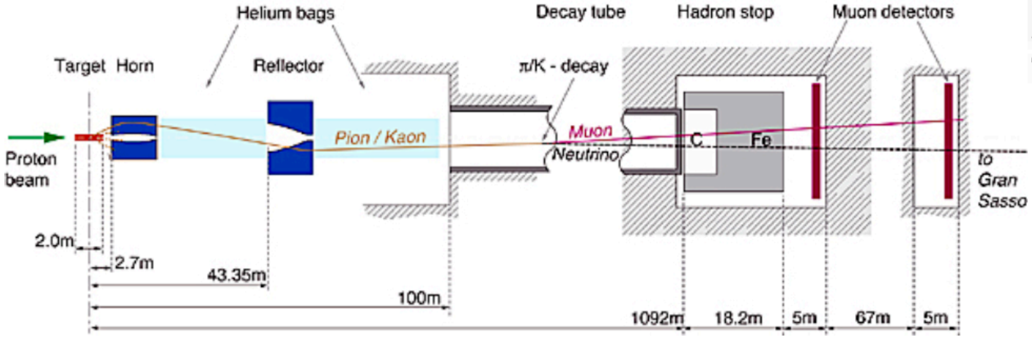
2001: the INFN FLUKA Project

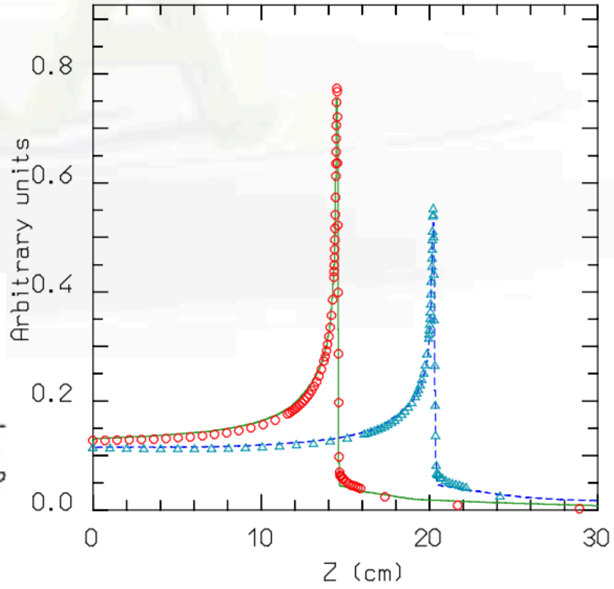
2003: official CERN-INFN collaboration to develop, maintain and distribute FLUKA

FLUKA Applications



- Cosmic ray physics
- Neutrino physics
- Accelerator design (→ n_ToF, CNGS, LHC systems)
- Particle physics: calorimetry, tracking and detector simulation etc. (→ ALICE, ICARUS, ...)
- ADS systems, waste transmutation, (→"Energy amplifier", FEAT, TARC,...)
- Shielding design
- Dosimetry and radioprotection
- Radiation damage
- Space radiation
- Hadron therapy
- Neutronics





E.M. Physics of FLUKA
(down to 1 keV for e^+e^-,100 eV for photons)

- Interactions of leptons/photons
  - Photon interactions
    - Photoelectric
    - Compton
    - Rayleigh
    - Pair production
    - Photonuclear
    - Photomuon production
  - Electron/positron interactions
    - Bremsstrahlung
    - Scattering on electrons
    - e^+ Annihilation
  - *(Muon interactions*
    - *Bremsstrahlung*
    - *Pair production*
    - *Nuclear interactions)*

Compton, Rayleigh: takes into account photon polarization atomic bonds and orbital motion

e^+ Annihilation: takes into account orbital motion of atomic electron

- Ionization energy losses
  - Continuous
  - Delta-ray production
- Transport
  - Multiple scattering
  - Single scattering

These are common to all charged particles, although traditionally associated with EM

Courtesy G. Battistoni

Nuclear environment in FLUKA: PEANUT

(PreEquilibrium Approach to NUclear Thermalization)

Target nucleus description (density, Fermi motion, etc)

↓

Glauber-Gribov cascade with formation zone

↓

Generalized IntraNuclear cascade

↓

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

↓

Evaporation/Fragmentation/Fission model

↓

γ deexcitation

t (s)

10^{-23}

10^{-22}

10^{-20}

10^{-16}

Courtesy G. Battistoni

Nuclear environment in FLUKA: PEANUT

(**P**re**E**quilibrium **A**pproach to **NU**clear **T**hermalization)

Target nucleus description (density, Fermi motion, etc)

↓

Glauber-Gribov cascade with formation zone

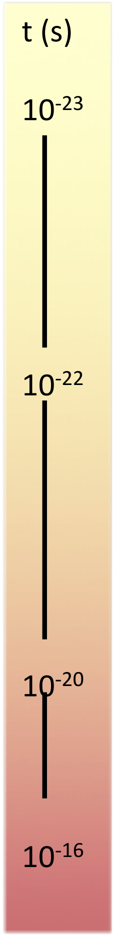
↓

Generalized IntraNuclear cascade

↓

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

↓

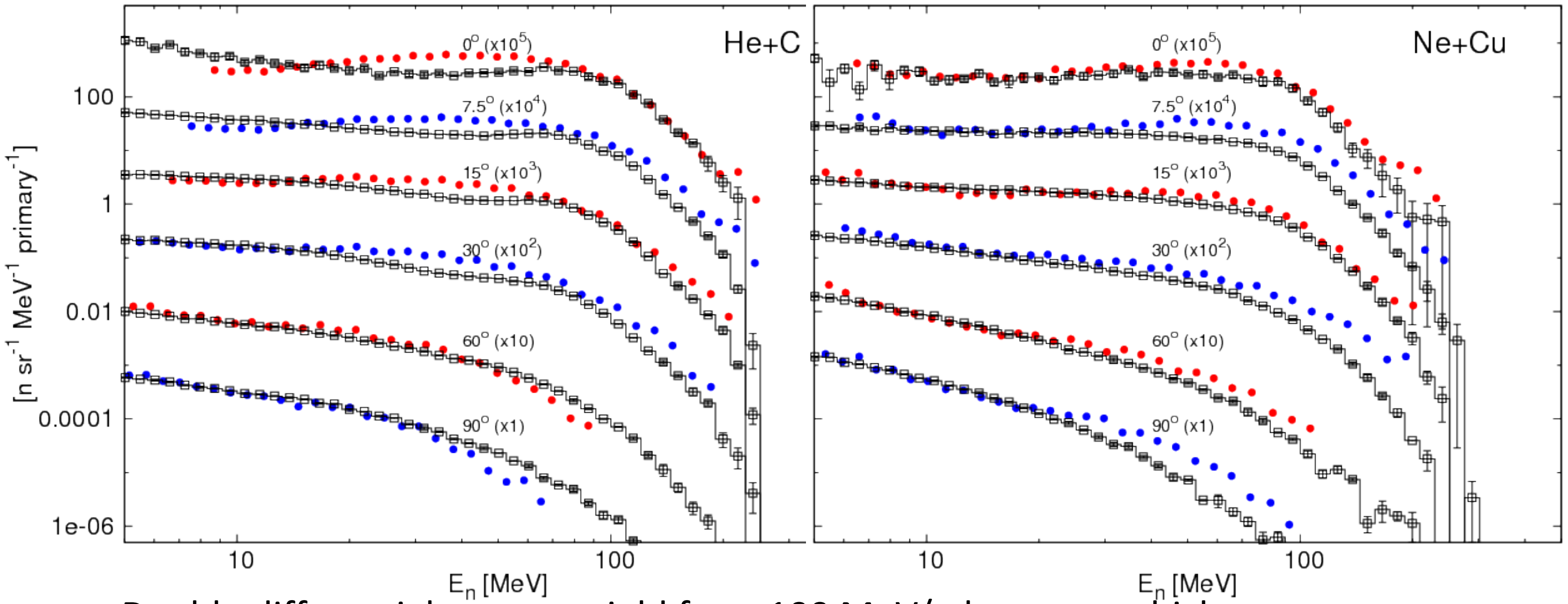


Recently, competition of gamma ray emission with particle evaporation has also been implemented.

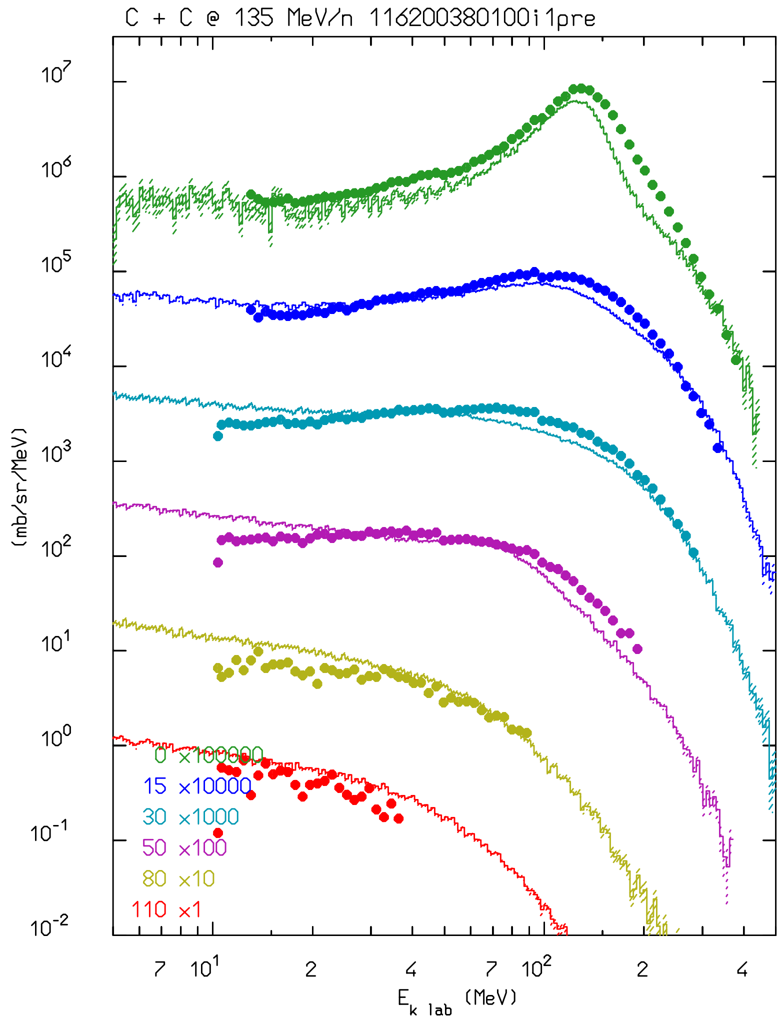
The low excitation stages of nuclear interactions are presently under strong development

Low energy ion interactions : BME

E < 0.15/0.12 GeV/n : Boltzmann Master Equation (BME) theory (E.Gadioli et al.)
thermalization of a composite nucleus by sampling from the results of the numerical integration of the BMEs. Recently interfaced with PEANUT in order to treat the first de-excitation stage of all nuclei for which BME information is not (yet) available: **particularly important for reactions induced by α.**



Double differential neutron yield from 100 MeV/n beams on thick targets
FLUKA vs experimental data from Nucl. Sci. Eng. 132, 30 (1999)



The rQMD model

relativistic **Q**uantum **M**olecular **D**ynamics

For ions in the few GeV/n energy range and down to 0.12-0.15 GeV/n, FLUKA uses an interface to a modified version of RQMD-2.4: a relativistic quantum molecular dynamics model that can also be run in intranuclear cascade mode. Excited fragments from RQMD are further processed by PEANUT.

Courtesy G. Battistoni

The importance of nuclear models

While nuclear recoils result typically in negligible spatial modifications of the delivered dose, secondary nucleons, particles, and fragments produced in nuclear reactions can considerably affect the spatial pattern of energy deposition and must be carefully taken into account.

In the case of heavy ions, nuclear fragmentation reactions are responsible for the deterioration of the physical selectivity in the longitudinal and transversal dimension especially around the Bragg peak region. The amount of fragments produced generally increases with the mass and charge of the primary particle.

/fleə(r)/ n [U,C] natural or instinctive ability (to do something well, to select or recognize what is best, more useful, etc.
[*Oxford Advanced Dictionary of Current English*]

FLUKA ADVANCED INTERFACE

[http://www.fluka.org/flair]

- User friendly graphical Interface (developed in python & C++)
- Minimum requirements on additional software
- Working in an intermediate level

Other Goodies:

- Access to FLUKA manual as hyper text
- Checking for release updates of FLUKA and flair
- Import export to various formats: MCNP/X, GDML,…
- Nuclear wallet cards
- Library of materials
- Database of geometrical objects
- Programming python API
- Everything is accessible with keyboard shortcuts

Flair
Front-End and Back-End interface

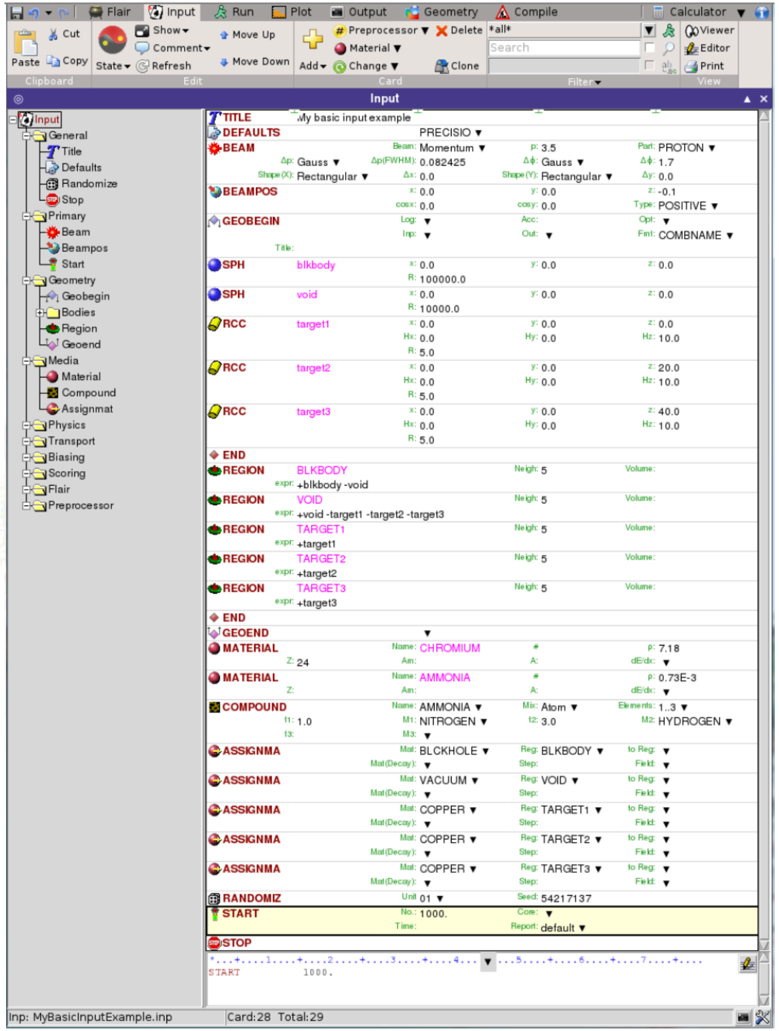
- Fully featured **Input file Editor**
  - Mini-dialogs for each card, allow easy and almost error free editing
  - Uniform treatment of all FLUKA cards
  - Card grouping in categories and card filtering
  - Error checking and validation of the input file during editing
- **Geometry:** interactive visualization editing, transformation, optimizations and debugging
- **Compilation** of the FLUKA Executable
- **Running** and monitoring of the status of runs

- Inspection of the **output files** (core dumps and directories)
- Output file(s) viewer divided in sections
- Post processing (merging) the output data files
- Plot generation through and interface with gnuplot

```
TITLE
My Basic Input example
* Set the defaults for precision simulations
DEFAULTS                                                              PRECISIO
* Define the beam characteristics
* ..+....1....+....2....+....3....+....4....+....5....+....6....+....7..
BEAM            3.5 -0.082425      -1.7       0.0       0.0          PROTON
* Define the beam position
* ..+....1....+....2....+....3....+....4....+....5....+....6....+....7..
BEAMPOS           0.0       0.0      -0.1       0.0       0.0
*
GEOBEGIN                                                              COMBNAME
    0    0
* Black body
SPH blkbody    0.0 0.0 0.0 100000.0
* Void sphere
SPH void       0.0 0.0 0.0 10000.0
* Cylindrical target
RCC target1    0.0 0.0  0.0 0.0 0.0 10.0 5.0
RCC target2    0.0 0.0 20.0 0.0 0.0 10.0 5.0
RCC target3    0.0 0.0 40.0 0.0 0.0 10.0 5.0
END
* Black hole
BLKBODY      5 +blkbody -void
* Void around
VOID         5 +void -target1 -target2 -target3
* Target
TARGET1      5 +target1
TARGET2      5 +target2
TARGET3      5 +target3
END
GEOEND
* ..+....1....+....2....+....3....+....4....+....5....+....6....+....7..
MATERIAL        24.0                7.18                             CHROMIUM
MATERIAL         0.0             0.73E-3                             AMMONIA
* ..+....1....+....2....+....3....+....4....+....5....+....6....+....7..
COMPOUND         1.0  NITROGEN       3.0  HYDROGEN                   AMMONIA
*
* ..+....1....+....2....+....3....+....4....+....5....+....6....+....7..
ASSIGNMA    BLCKHOLE   BLKBODY
ASSIGNMA      VACUUM      VOID
ASSIGNMA     AMMONIA   TARGET3
*
* ..+....1....+....2....+....3....+....4....+....5....+....6....+....7..*
ASSIGNMA    CHROMIUM   TARGET1   TARGET2       1.0

* Set the random number seed
* ..+....1....+....2....+....3....+....4....+....5....+....6....+....7..
RANDOMIZ         1.0 54217137.
*
* Set the number of primary histories to be simulated in the run
* ..+....1....+....2....+....3....+....4....+....5....+....6....+....7..
START          1000.
STOP
```

*.fluka *.inp

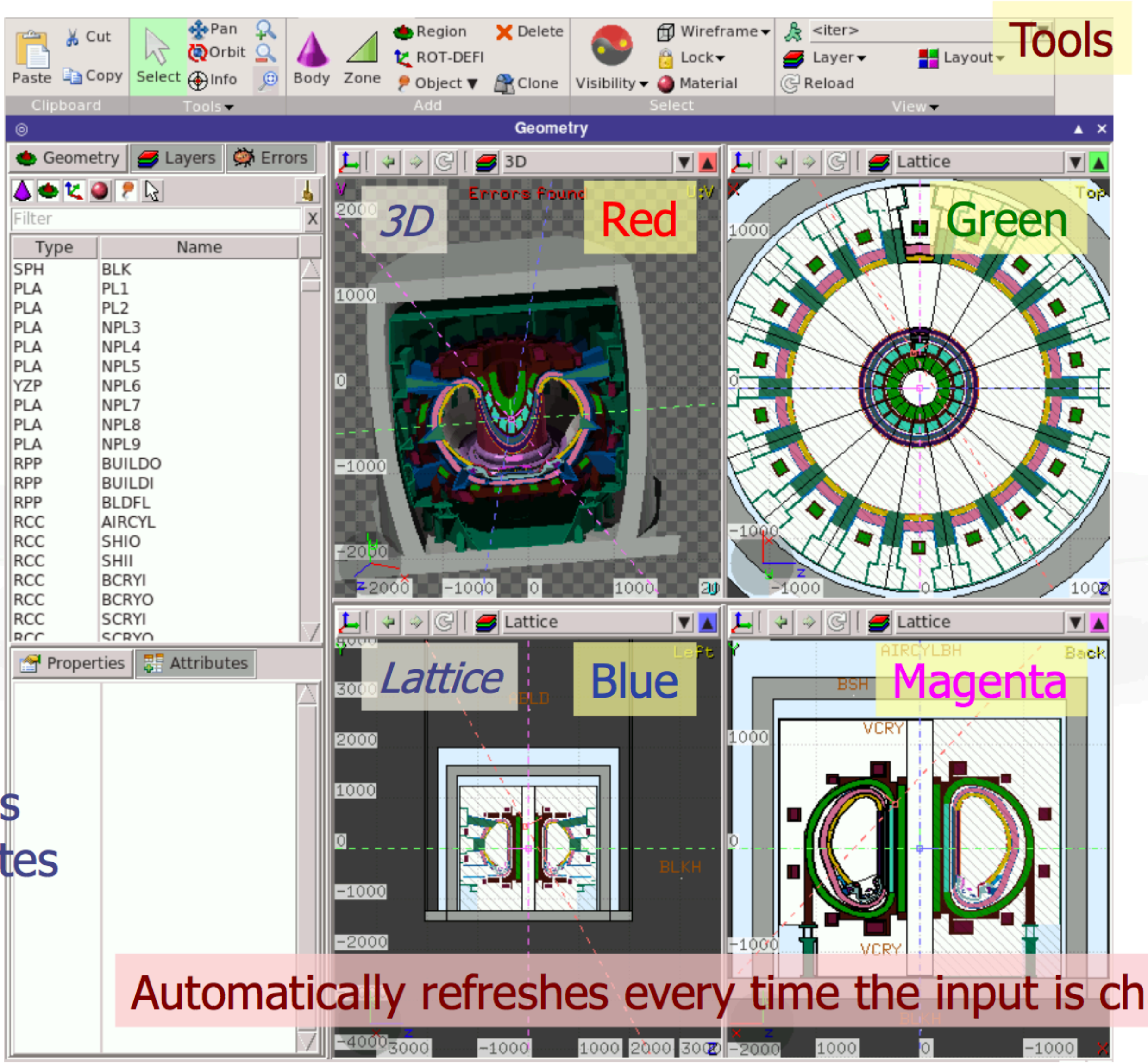


Geometry editor

Filter

Filtered Objects

Properties & Attributes



Automatically refreshes every time the input is changed

Applications in Medical Physics and related disciplines

Nuclear Medicine

- Dosimetry

Radiotherapy

- Simulation of therapy devices
- Simulations/Check of treaments

Hadrontherapy

- Shielding
- Commissioning of facilities
- Treatment planning and forward checks
- Predictions for monitoring applications (imaging for hadrontherapy)
- Design of instruments, dosimetry
- Calculation for shielding and rad. protection in facilities

Application in Nuclear Medicine

Radioactive source decay

FLUKA contains data about **decaying schemes of radioactive isotopes**, allowing to select an isotope as radiation source. Complete databases are generated from the data collected **from National Nuclear Data Center** (NNDC) at Brookhaven National Laboratory.

Phys. Med. Biol. 58 (2013) 8099–8120 doi:10.1088/0031-9155/58/22/8099

Use of the FLUKA Monte Carlo code for 3D patient-specific dosimetry on PET-CT and SPECT-CT images*

F Botta[1], A Mairani[2,10], R F Hobbs[3], A Vergara Gil[4], M Pacilio[5], K Parodi[6], M Cremonesi[1], M A Coca Pérez[7], A Di Dia[1], M Ferrari[1], F Guerriero[1], G Battistoni[8], G Pedroli[1], G Paganelli[9], L A Torres Aroche[7] and G Sgouros[3]

Application in Nuclear Medicine

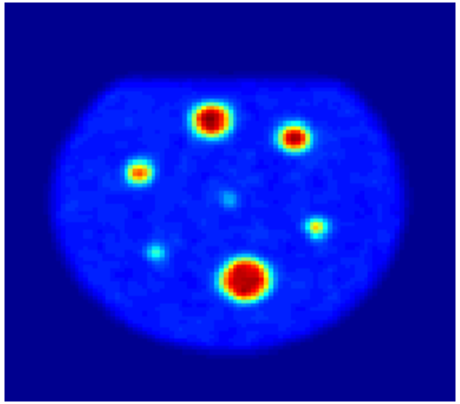
Calculation of absorbed dose at voxel level starting from 3D images of activity distribution (SPECT, PET images)

Simulations of hot sphere in homogeneous water

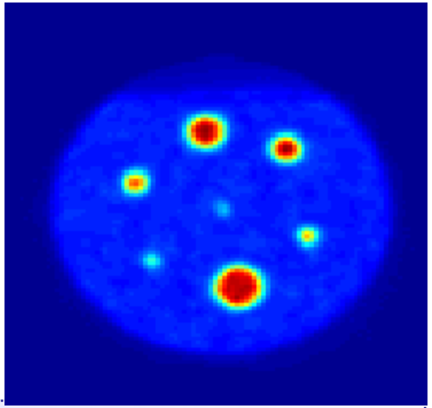
^{90}Y spectrum

Voxel-by-Voxel ratio
Integral DVH
Profiles

Dose Point Kernel
F. Botta et al.
INFN and IEO Collaboration, 2011



VOXEL Dosimetry



MONTE CARLO 10^9 particles

With 10^9 particles simulated, FLUKA and VOXEL DOSIMETRY (a standard analytic procedure in nuclear medicine) results in water agree within 5%

Rationale for MC in hadrontherapy

Biological calculation in tumor therapy with ions depend on a precise description of the radiation field.

In Carbon ion irradiation, nuclear reaction cause a significant alternation of the radiation field.

Contribution of secondary fragments need to be taken into account for accurate planning of the physical and biological dose delivery in the scheduled treatment.

Treatment planning system (TPS) for ion beam therapy essentially use analytical algorithms input database for the description of the ion interaction with mater.

Monte Carlo code with sophisticated nuclear models are more efficient (though slower) computational tools to handle the mixed radiation field.

Hadrontherapy

A long history of applications and developments for hadrotherapy
- FLUKA used at CNAO for TPS database generation, patient plan verification, forward calculation of patient plans, eye treatment studies, radio-biology related studies…etc
- At HIT for TPS database generation, patient plan verification, forward calculations of patient plans, imaging related studies…etc

frontiers in Oncology

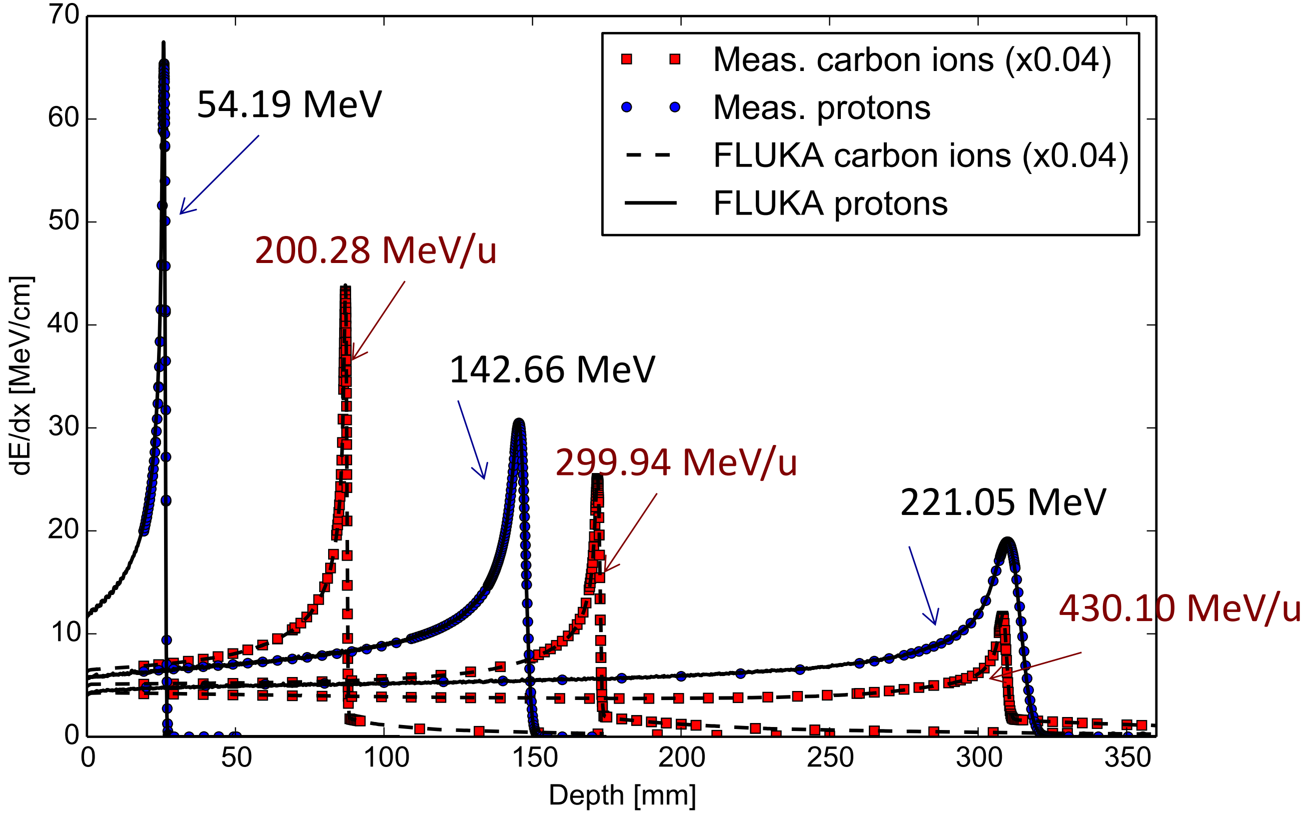
Front. Oncol. 6:116.
doi: 10.3389/fonc.2016.00116

The FLUKA Code: An Accurate Simulation Tool for Particle Therapy

Giuseppe Battistoni[1], Julia Bauer[2], Till T. Boehlen[3], Francesco Cerutti[4], Mary P. W. Chin[4], Ricardo Dos Santos Augusto[4,5], Alfredo Ferrari[4], Pablo G. Ortega[4], Wioletta Kozłowska[4,6], Giuseppe Magro[7], Andrea Mairani[7,8], Katia Parodi[5,8], Paola R. Sala[1,4], Philippe Schoofs[4], Thomas Tessonnier[2] and Vasilis Vlachoudis[4]*

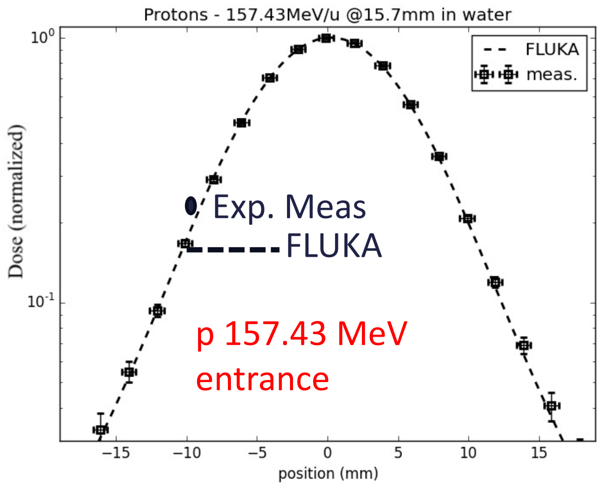
[1] INFN Sezione di Milano, Milan, Italy, [2] Uniklinikum Heidelberg, Heidelberg, Germany, [3] EBG MedAustron GmbH, Wiener Neustadt, Austria, [4] CERN, Geneva, Switzerland, [5] Ludwig Maximilian University of Munich, Munich, Germany, [6] Medical University of Vienna, Vienna, Austria, [7] Centro Nazionale di Adroterapia Oncologica, Pavia, Italy, [8] Heidelberger Ionenstrahl-Therapiezentrum (HIT), Heidelberg, Germany

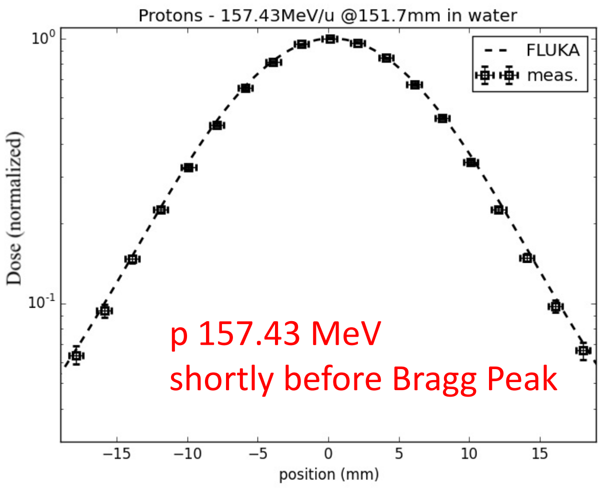
Comparing Predictions
Depth-Dose curves and Lateral Dose Profiles

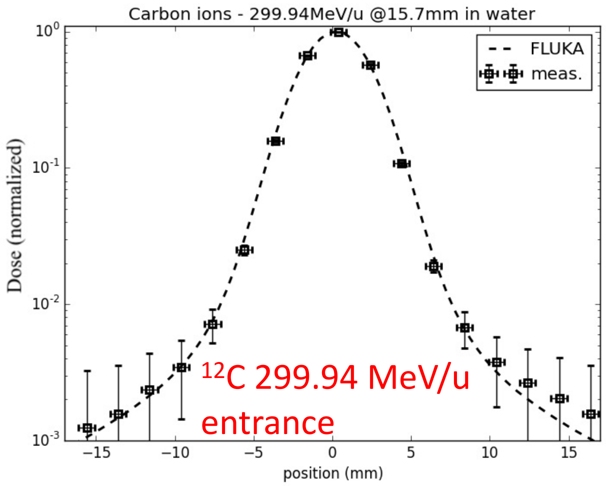


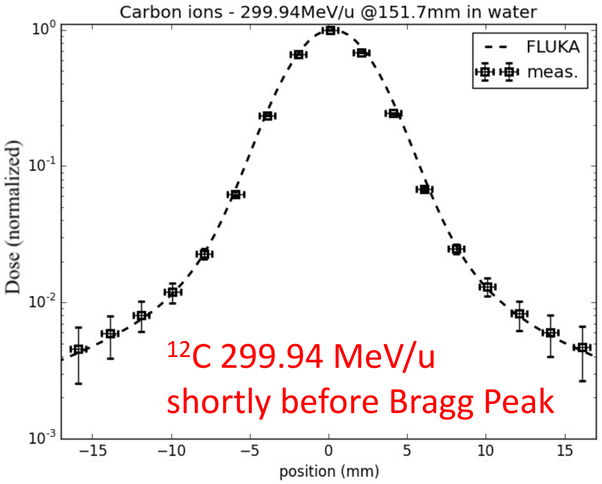
FlUKA simulations of depth–dose profiles of protons and carbon ions with therapeutic ranges in comparison with measured data at HIT.

Lateral profiles measured @HIT







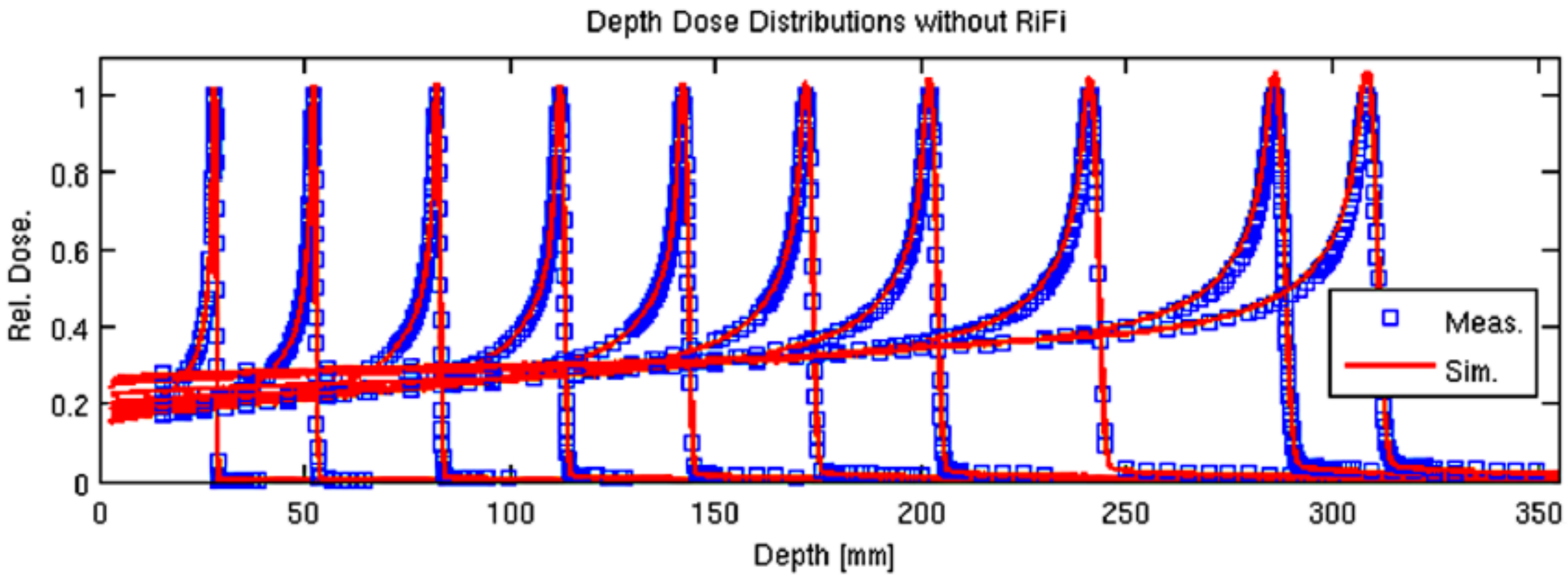


New ions for therapy

Helium ions at the heidelberg ion beam therapy center: comparisons between FLUKA Monte Carlo code predictions and dosimetric measurements

Phys. Med. Biol. **62** (2017) 6784–6803

T Tessonnier[1,4], A Mairani[2,3], S Brons[2], P Sala[5,6], F Cerutti[6], A Ferrari[6], T Haberer[2], J Debus[1,2] and K Parodi[1,4]



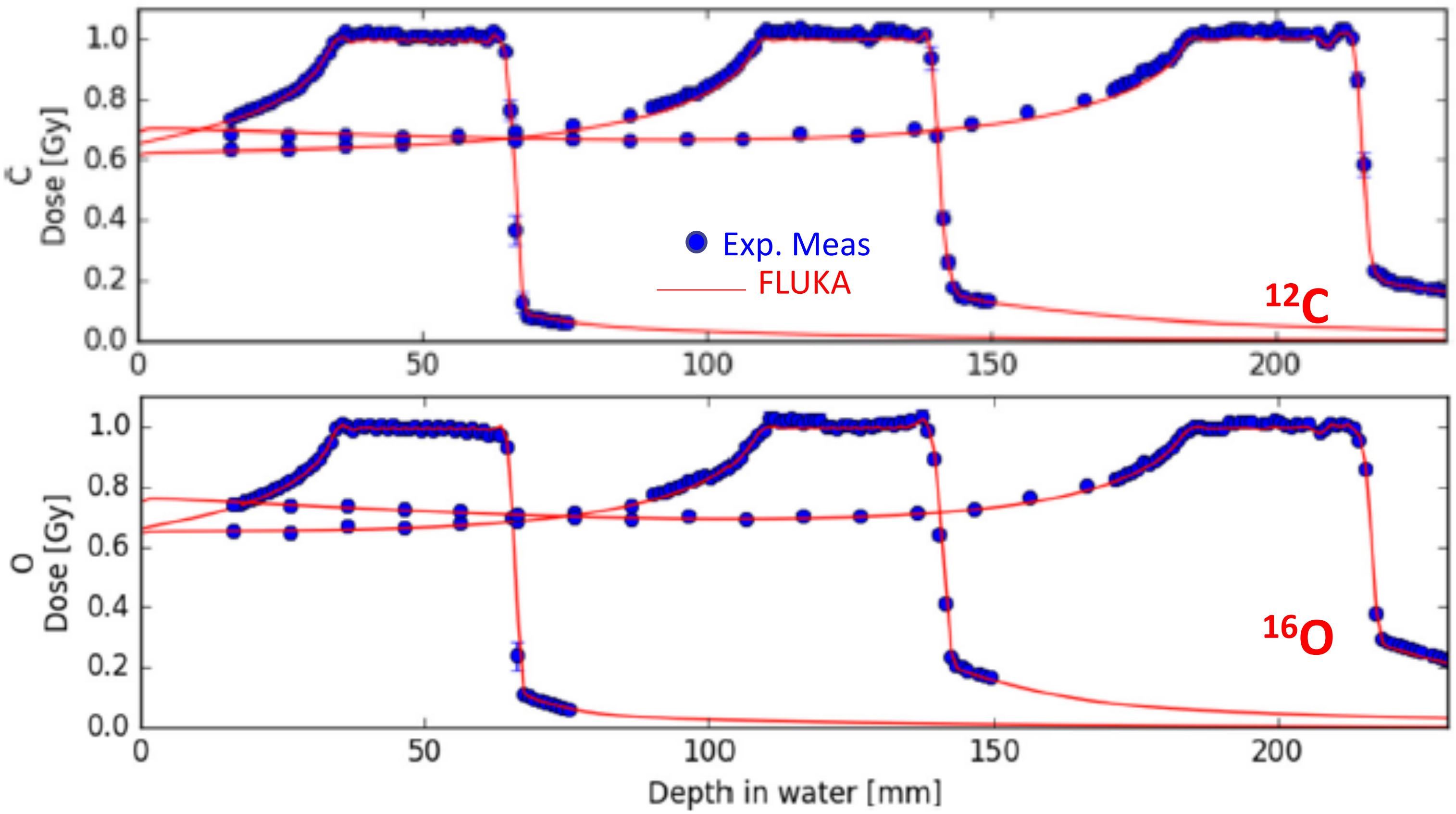
Dosimetric verification in water of a Monte Carlo treatment planning tool for proton, helium, carbon and oxygen ion beams at the Heidelberg Ion Beam Therapy Center

Phys. Med. Biol. **62** (2017) 6579–6594

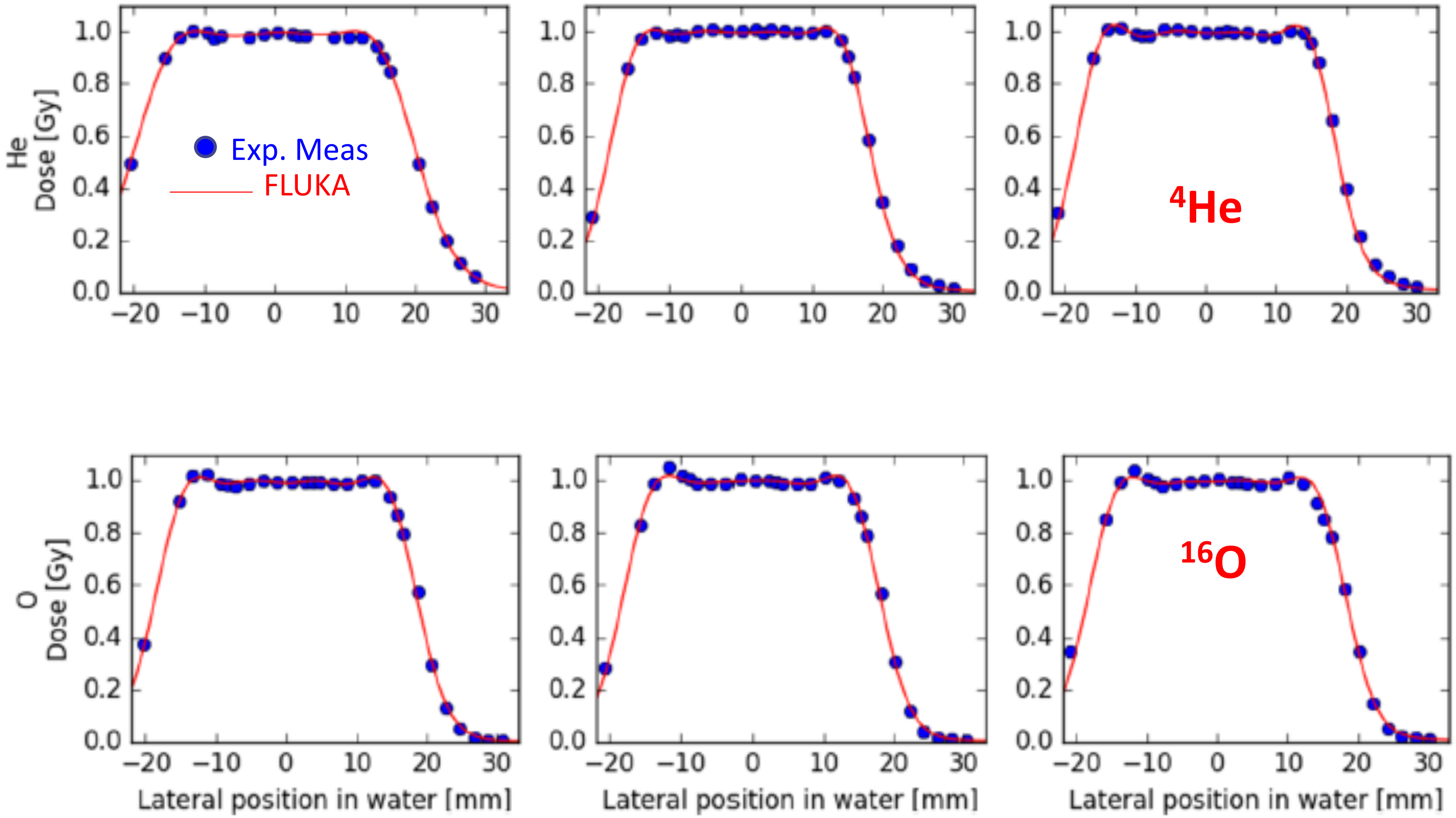
Physical Dose
in a cube in Water

T Tessonnier[1,2], T T Böhlen[3], F Ceruti[4], A Ferrari[4], P Sala[4,5], S Brons[6], T Haberer[6], J Debus[1,6], K Parodi[1,2] and A Mairani[6,7]

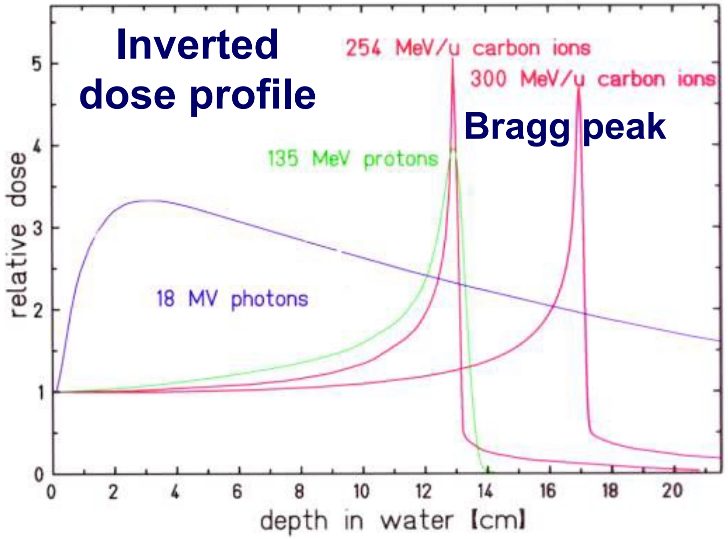
3 cm x 3 cm x 3 cm SOBPs



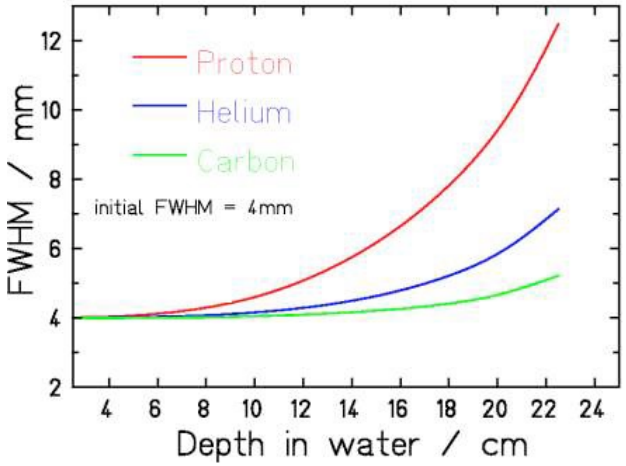
Lateral Dose distrib. for SOBs centered at 5, 12.5 and 20 cm



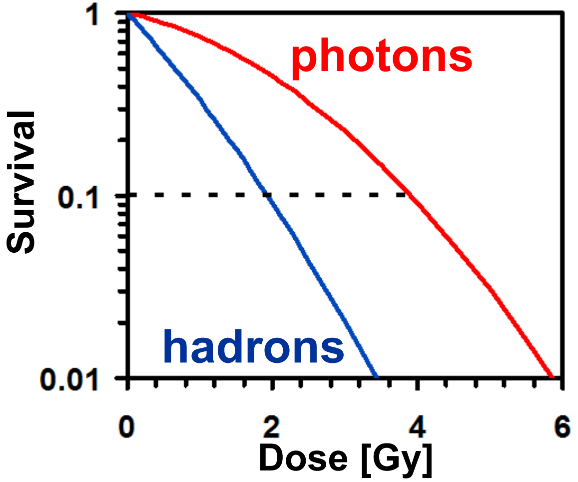
Physics



Lateral scattering



Biology



Courtesy A. Mairani

RBE (relative biological effectiveness):

RBE = D_{photon} / D_{hadron}
for the same biological effect

The RBE depends on:

- **particle type (p, ^{12}C, …), LET / local energy spectrum, dose**
- **tissue type, biological endpoint**

In clinic: p RBE = 1.1
^{12}C RBE models

Biologically Oriented Scoring in FLUKA

For each **energy deposition i,** FLUKA interpolates from the external database provided by the user the $\alpha_{D,i}$ **and** $\beta_{D,i}$ parameters for the specific ion with a certain charge at a certain energy.

Then **FLUKA sums up** properly **the mixed radiation effect** applying the Kellerer and Rossi theory of dual radiation action:

$$\sum \alpha_{D,i} D_i \qquad \sum \sqrt{\beta_{D,i}} D_i$$

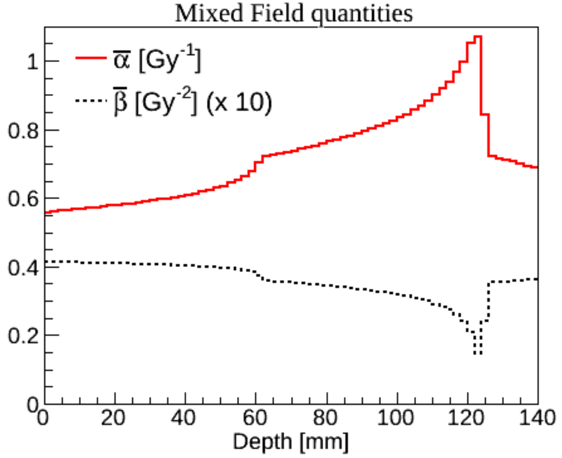
Then the **average biological parameters** can be calculated at the end of the FLUKA run:

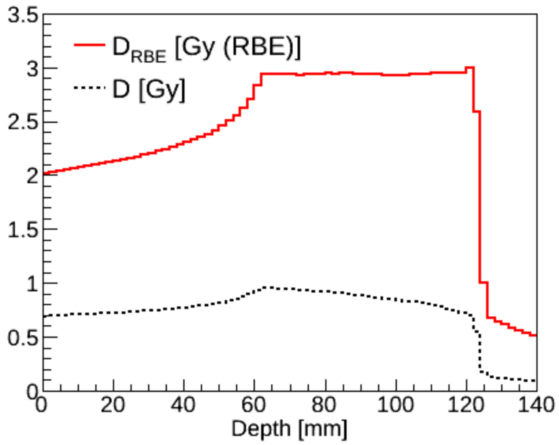
$$\bar{\alpha} = \frac{\sum \alpha_{D,i} D_i}{\bar{D}}$$

$$\bar{\beta} = \left(\frac{\sum \sqrt{\beta_{D,i}} D_i}{\bar{D}} \right)^2$$

$$\bar{D} = \sum D_i$$

For example the **cell survival** can be calculated: $S = \exp(-\bar{\alpha}\bar{D} - \bar{\beta}\bar{D}^2)$

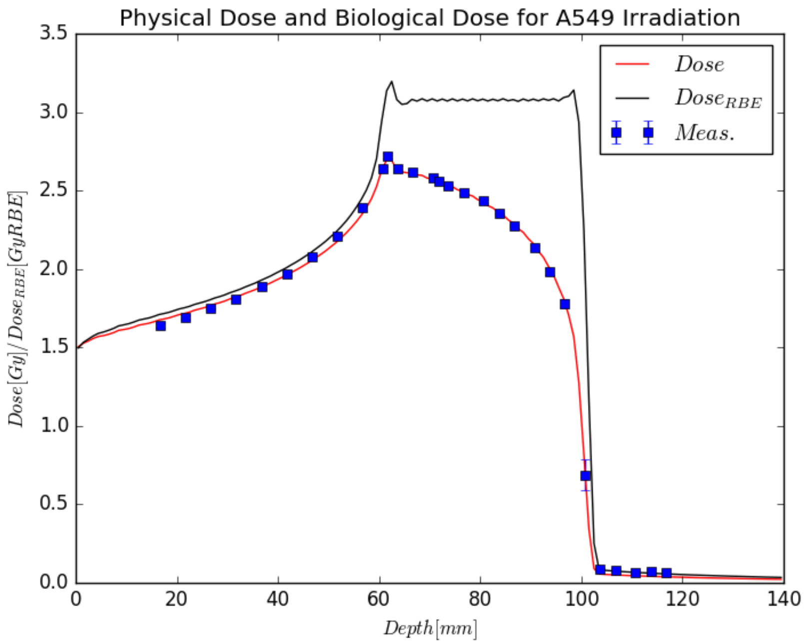


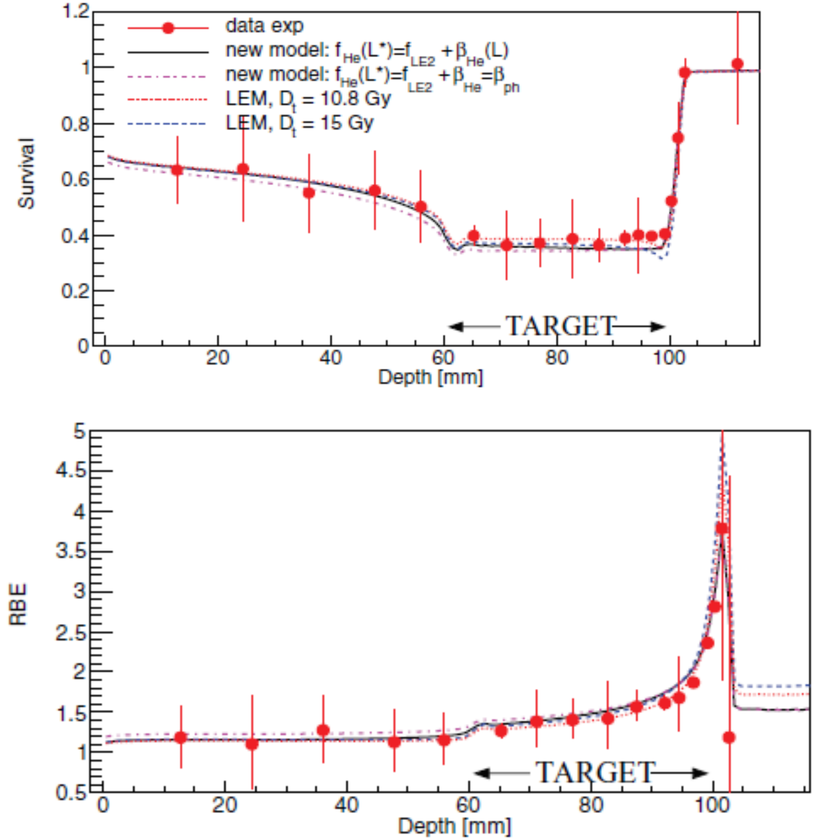


D_{RBE} = RBE x DOSE [Gy (RBE)]

G. Magro,…,A.Mairani Physics in Medicine and Biology 2017, 56, 3814–3827

RBE model validation





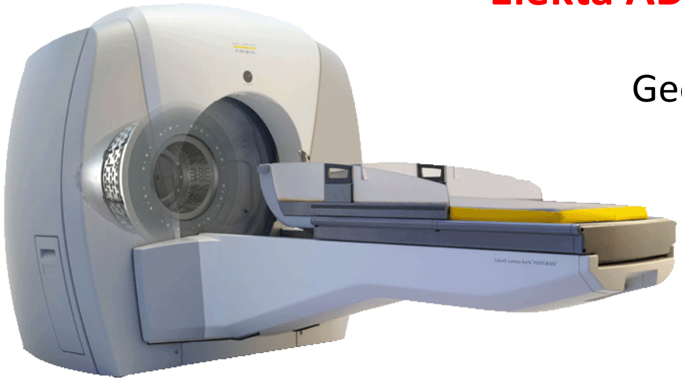
1 – Bio. Optimized SOBP
2 – Measurements verifications
3 – Cell Survival (A549) + RBE

→ **Validated in-house model for He (5%) and H (2%)**

Mairani et al 2016 PMB 61 4283

The Leksell Gamma Knife Perfexion:

The **Leksell Gamma Knife Perfexion** (LGK-PFX)
Elekta AB Instruments Stockholm, Sweden.



Geometry details provided by courtesy of Elekta

Physica Medica 29 (2013) 656–661

Contents lists available at SciVerse ScienceDirect

Physica Medica

journal homepage: http://www.physicamedica.com

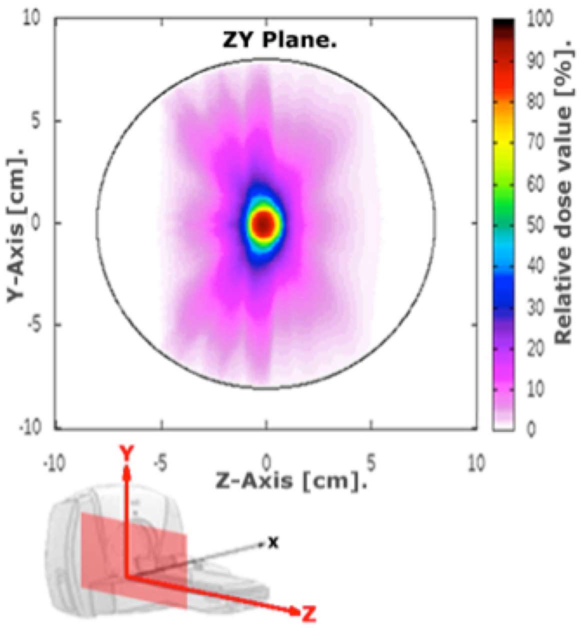
ELSEVIER

Original paper

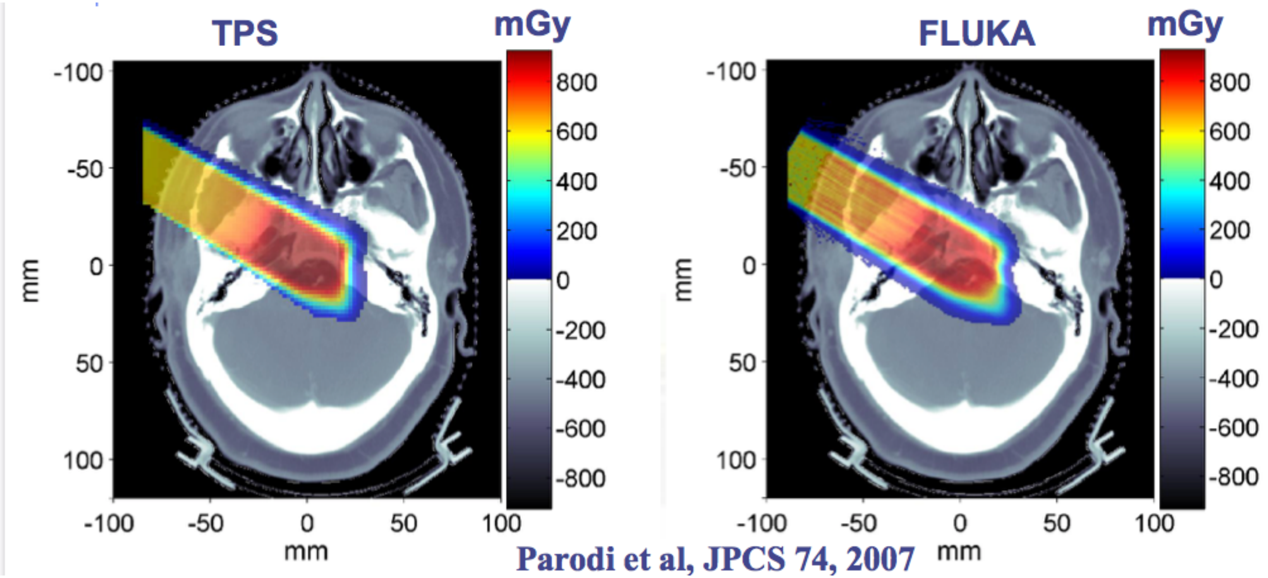
FLUKA Monte Carlo simulation for the Leksell Gamma Knife Perfexion radiosurgery system: Homogeneous media

Giuseppe Battistoni [a,1], Fabrizio Cappucci [a,*], Nicola Bertolino [b,2], Maria Grazia Brambilla [c,3], Hae Song Mainardi [c,4], Alberto Torresin [c,5]

[a] I.N.F.N. Section of Milan, Via Celoria 16, 20133 Milano, Italy
[b] Health Department, I.R.C.C.S. Neurologic Institute C. Besta, Italy
[c] Medical Physics Department, Niguarda Ca' Granda Hospital, Italy



Application of FLUKA to p- therapy @MGH



Input phase-space provided by H. Paganetti, MGH Boston

Prescribed dose: 1Gy

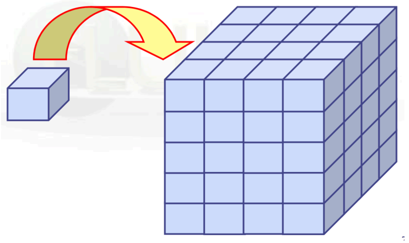
MC: ~5.5 10^6 protons in 10 indipendent runs

(11h each on Linux Cluster mostly using 2.2GHz Athlon processors

Rationale: Why FLUKA for PET

FLAIR Complete IDE* for all FLUKA simulation phases
(input, geometry editor, debugging, post-processing output visualization)

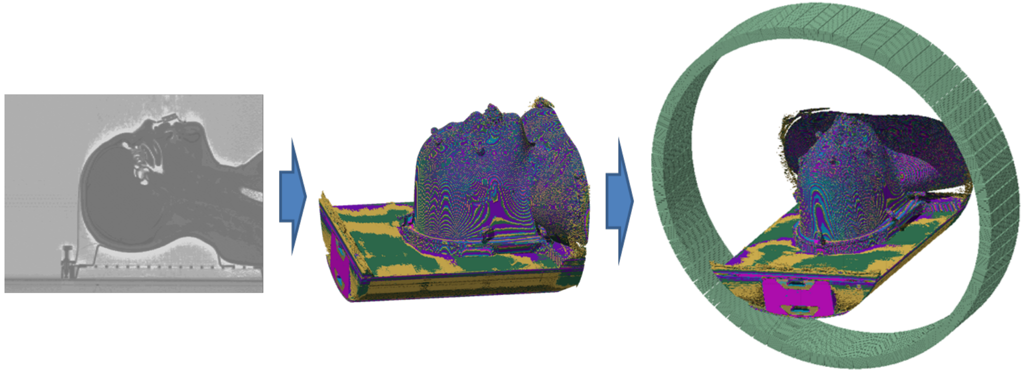
Integrated Development Environment



Voxel geometries

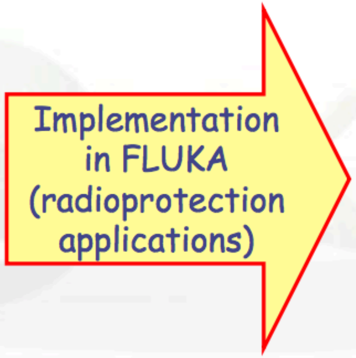
natively integrated with
FLUKA tools for QA MC-TPS

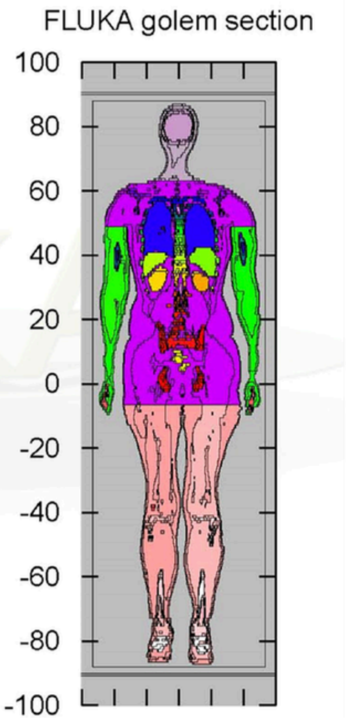
DICOM information from clinical
CT to FLUKA Voxel geometry



Courtesy C. Cuccagna

The anthropomorphic
GOLEM phantom



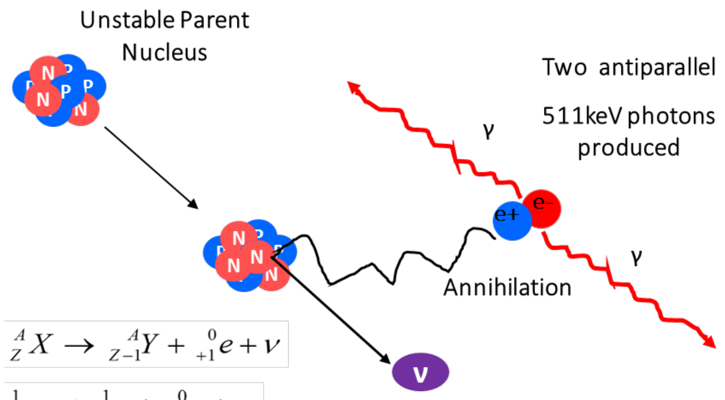


Petoussi-Henss et al, 2002

Rationale: Why FLUKA for PET

Most recent FLUKA code developments

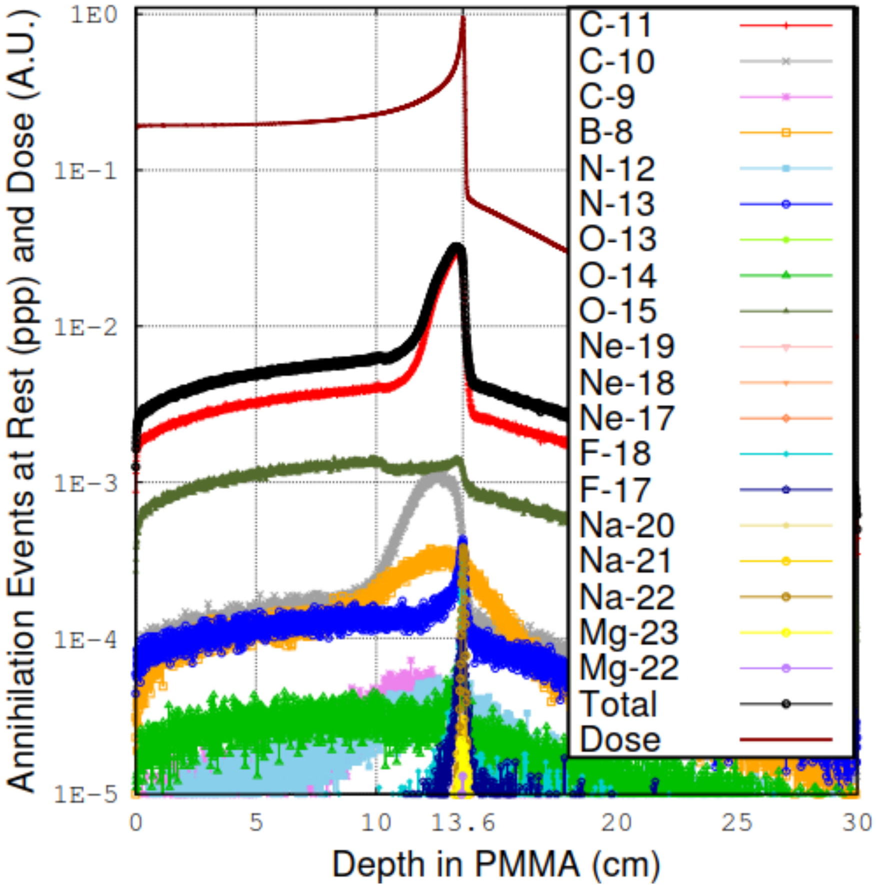
- Scoring annihilation at rest and activity binning
- New flag for keeping track for (parent) Isotope:



$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + {}^{0}_{+1}e + \nu $$

$$ {}^{1}_{1}p \rightarrow {}^{1}_{0}n + {}^{0}_{+1}e + \nu $$

Courtesy C. Cuccagna



NSS-MIC 2017,Atlanta

Rationale: Why FLUKA for PET

Most recent FLUKA application for in-beam PET

Protons in PMMA

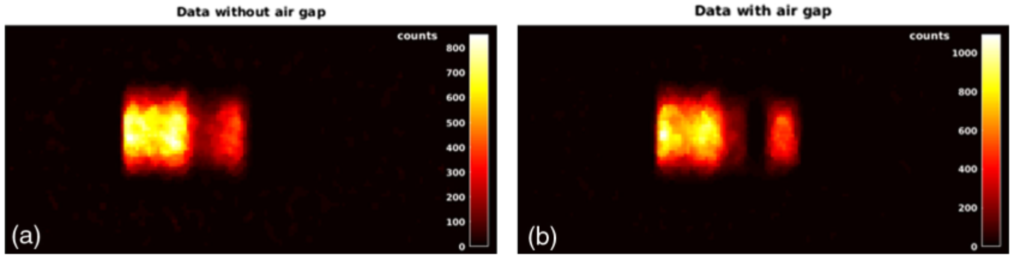
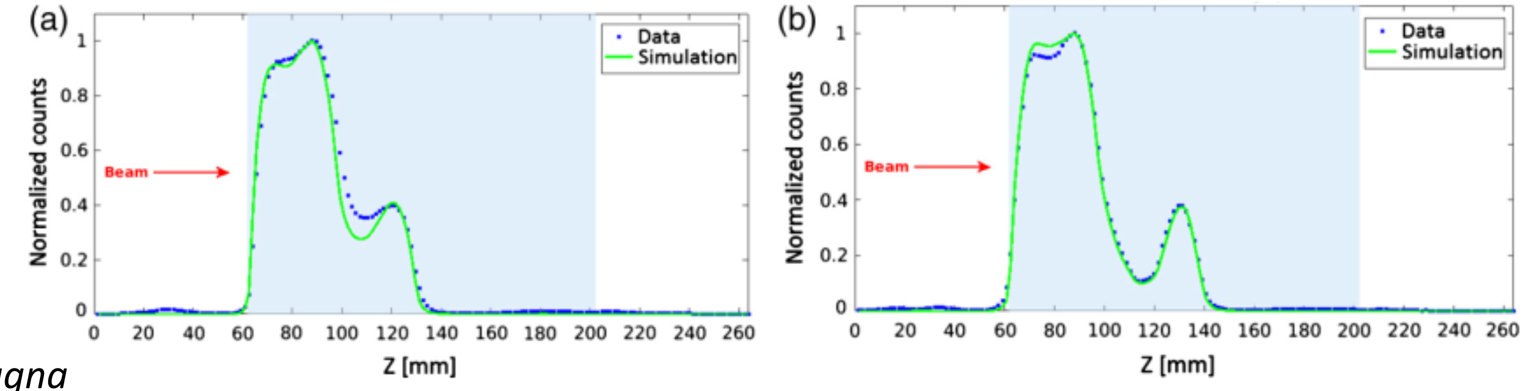


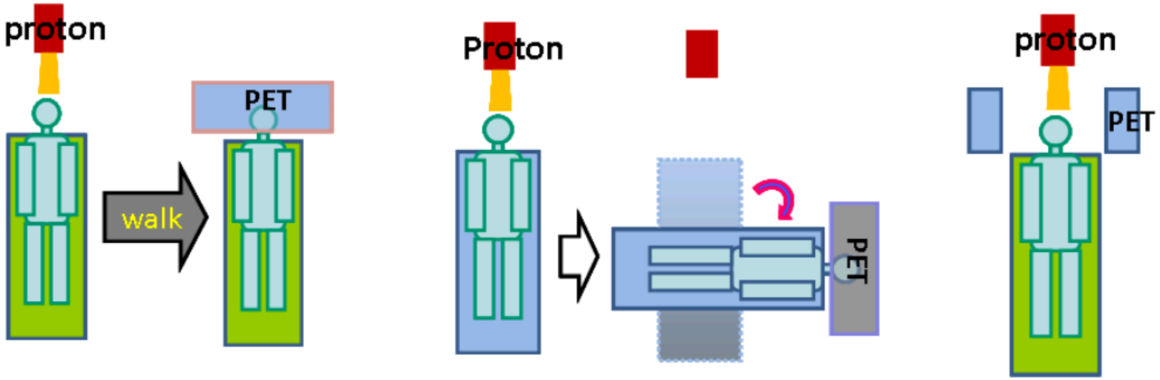
Fig. 8 (a) Image (central slice) of the phantom A obtained for an acquisition time of 519 s. (b) Image (central slice) of the phantom B obtained for an acquisition time of 485 s. In both acquisitions, only inter-spill and after-treatment data are considered.



Courtesy C. Cuccagna

M.G. Bisogni "INSIDE in-beam positron emission tomography system for particle range monitoring in hadrontherapy," J. Med. Imag. 4(1), 011005 (2017), doi: 10.1117/1.JMI.4.1.011005.

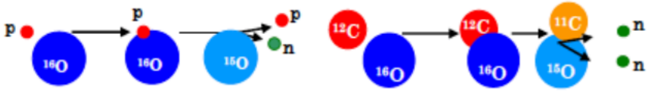
Operational modalities for PET verification of hadrontherapy



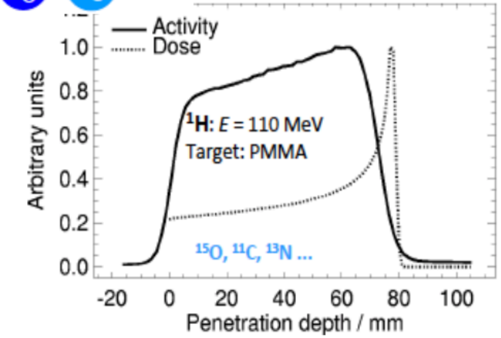
off-line in-room in-beam

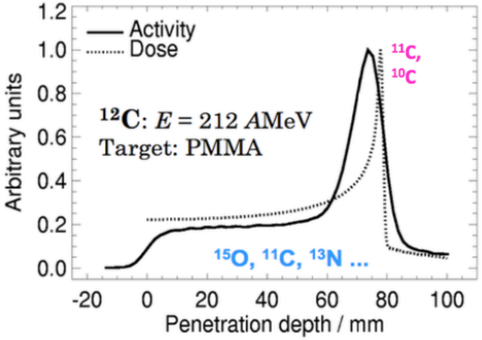
Xuping Zhu and Georges El Fakhri, Proton Therapy Verification with PET Imaging, Theranostics. 2013; 3(10): 731–740.

PET–based treatment verification

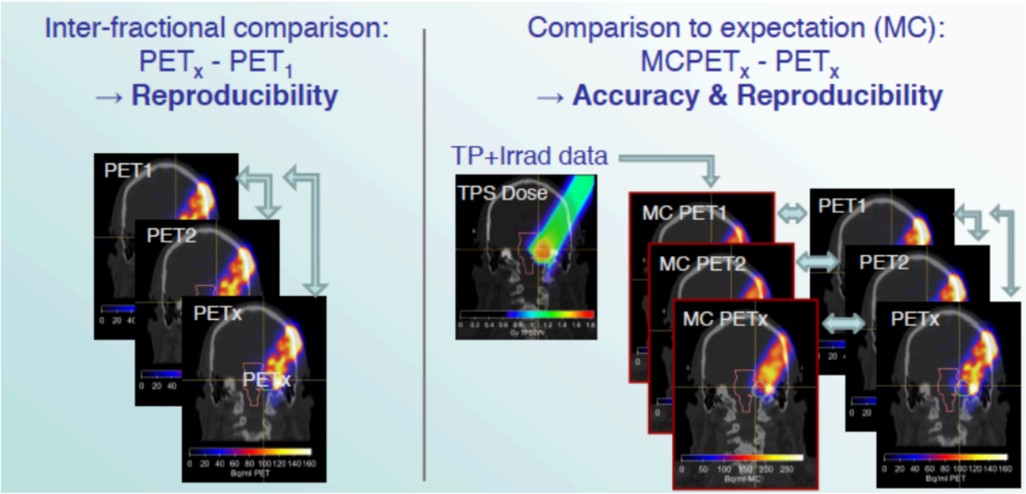


Main contribution:
^{11}C ($T_{1/2} \approx$ 20.3 min)
^{10}C ($T_{1/2} \approx$ 19.3 s)
^{15}O ($T_{1/2} \approx$ 2.0 min)
^{13}N ($T_{1/2} \approx$ 10.0 min)





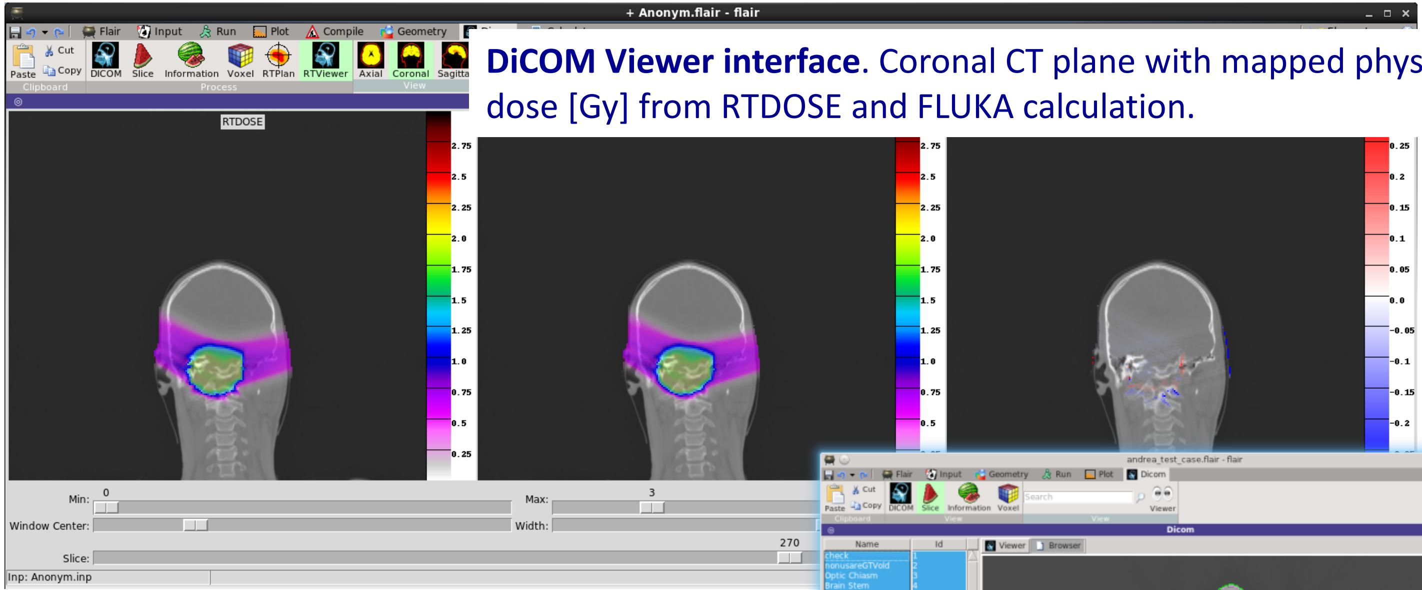
J Pawelke et al., Proceeding: Ion Beams in Biology and Medicine (IBIBAM), 26.-29.09.2007, Heidelberg, Germany



Courtesy of J. Bauer, HIT

Importing DICOM images into FLUKA geometry

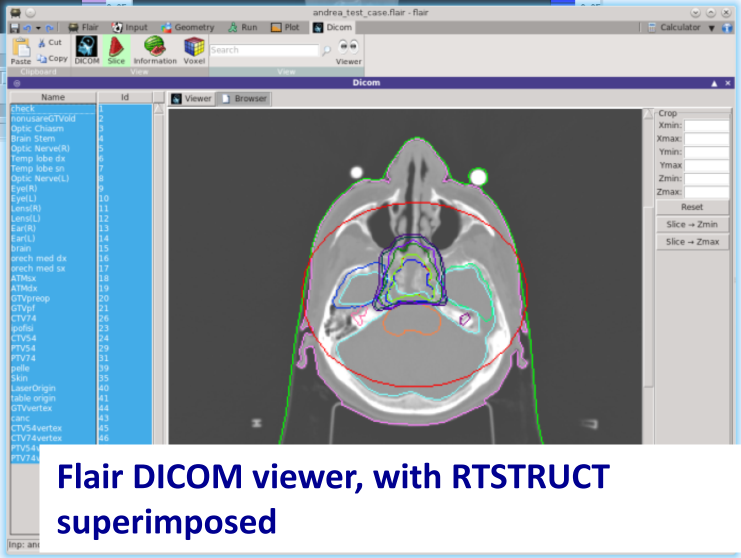
Handled by User Graphical interface: Flair (developed in python & C++)



DiCOM Viewer interface. Coronal CT plane with mapped physical dose [Gy] from RTDOSE and FLUKA calculation.

Based on Pydicom

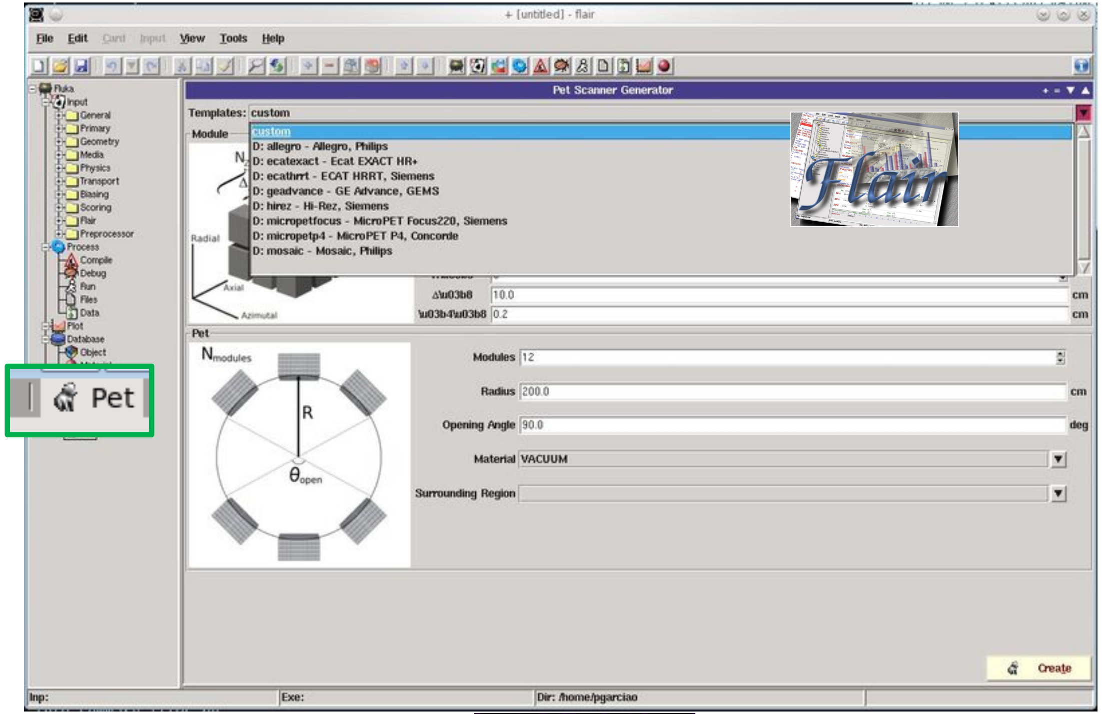
- DICOM CT, MR, importer
- Automatic material assignment using the Schneider parameterization
- Importing ROI RTstructures
- Importing RTPlan
- Generation of DVH plots and comparison plots with RTDOSE



Flair DICOM viewer, with RTSTRUCT superimposed

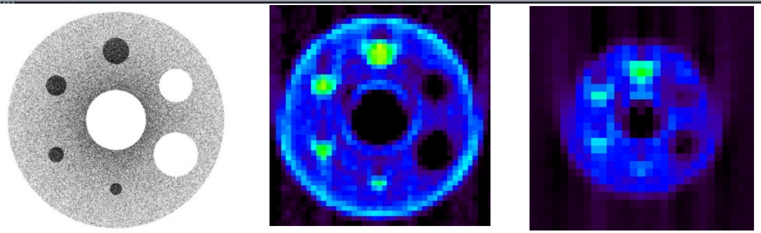
FLUKA PET tools : the Origins..

- Integrated in FLAIR
- Developed in 2013
- Tested for conventional PET
- Generic Radioactive sources
- Example for small PET scanner
- Fixed position of the PET scanner
- Only one image reconstruction algorithm (FBP)



Useful for:

- Inferring the dose map from the β+ emitter distribution
- Test new PET design/options

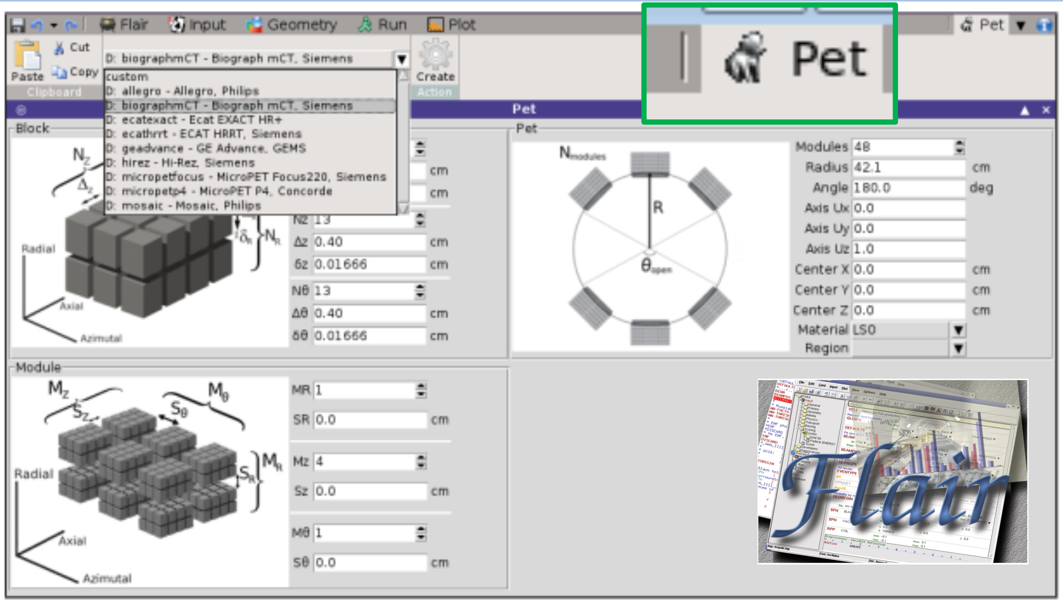


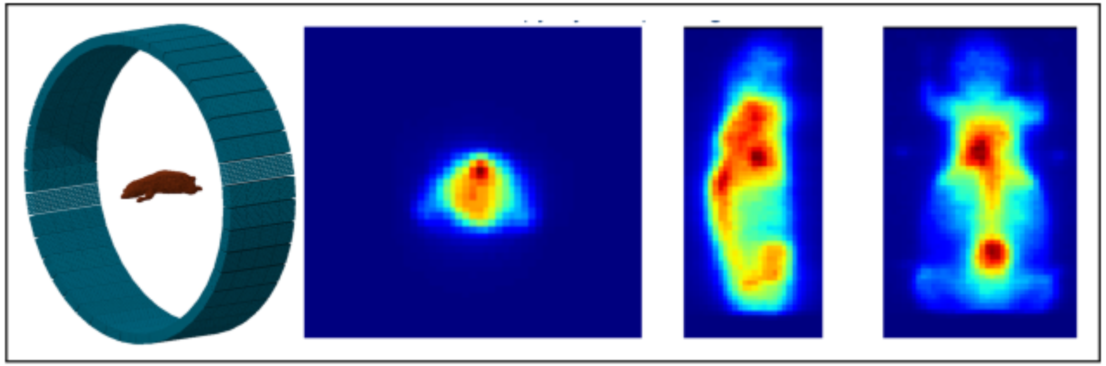
P. G. Ortega ANIMMA2013

Courtesy C. Cuccagna

FLUKA PET tools: today

- Rototranslations
- Integration of post processing and scoring routines in Fluka
- New PET scanners and validation with NEMA source
- In-beam PET , beam time structure and acquisition time
- Studies with RIB (Radioactive Ion Beams)
- MLEM code



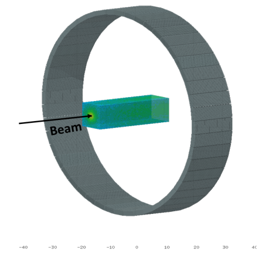


Courtesy C. Cuccagna

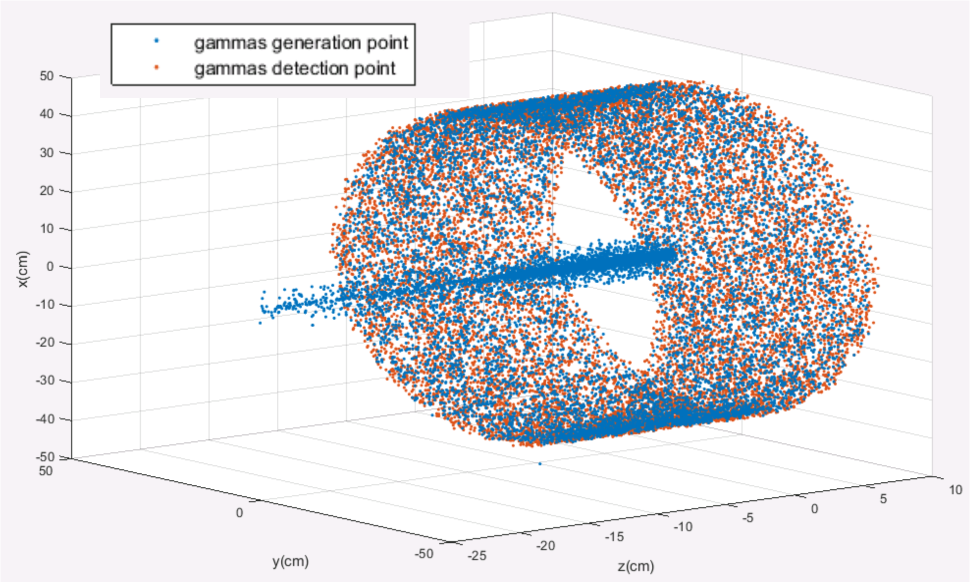
Coincidences file in list mode

Courtesy C. Cuccagna

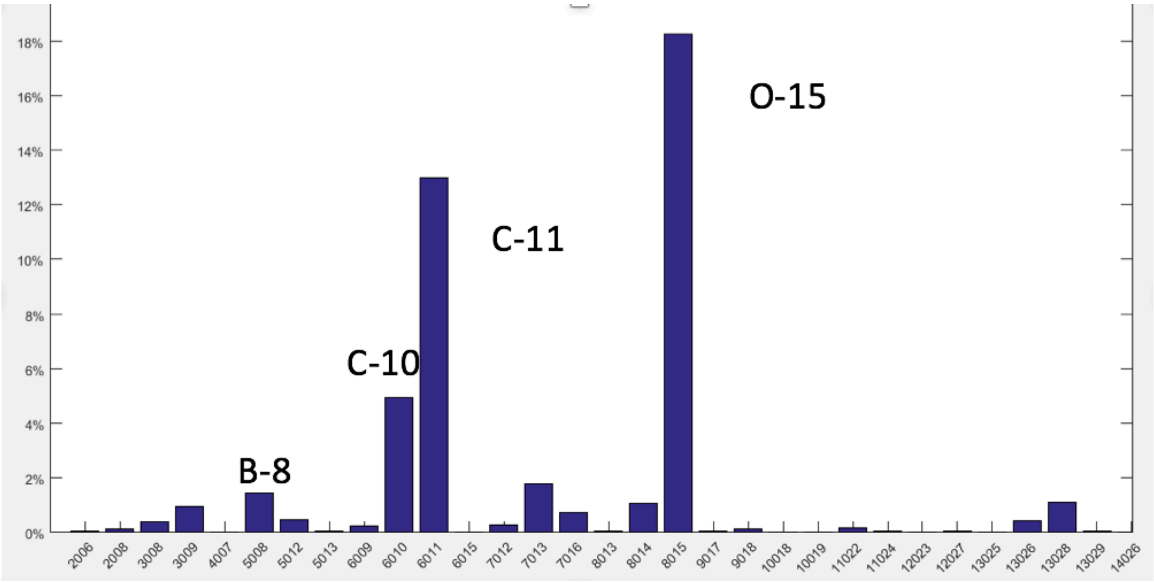
The user can perform several analysis :
Ex. For in-beam PET with a C12 ion beam



In space



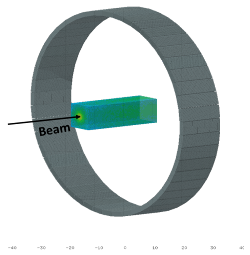
Parent Isotope studies



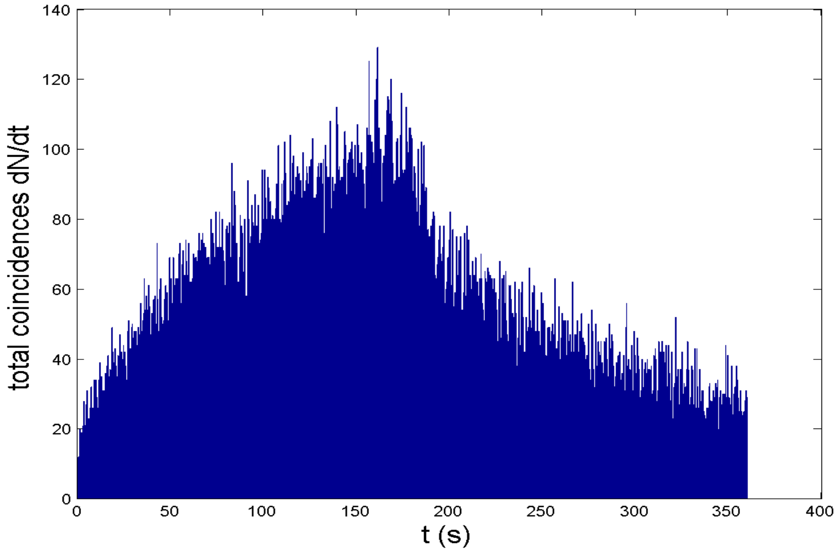
Coincidences file in list mode

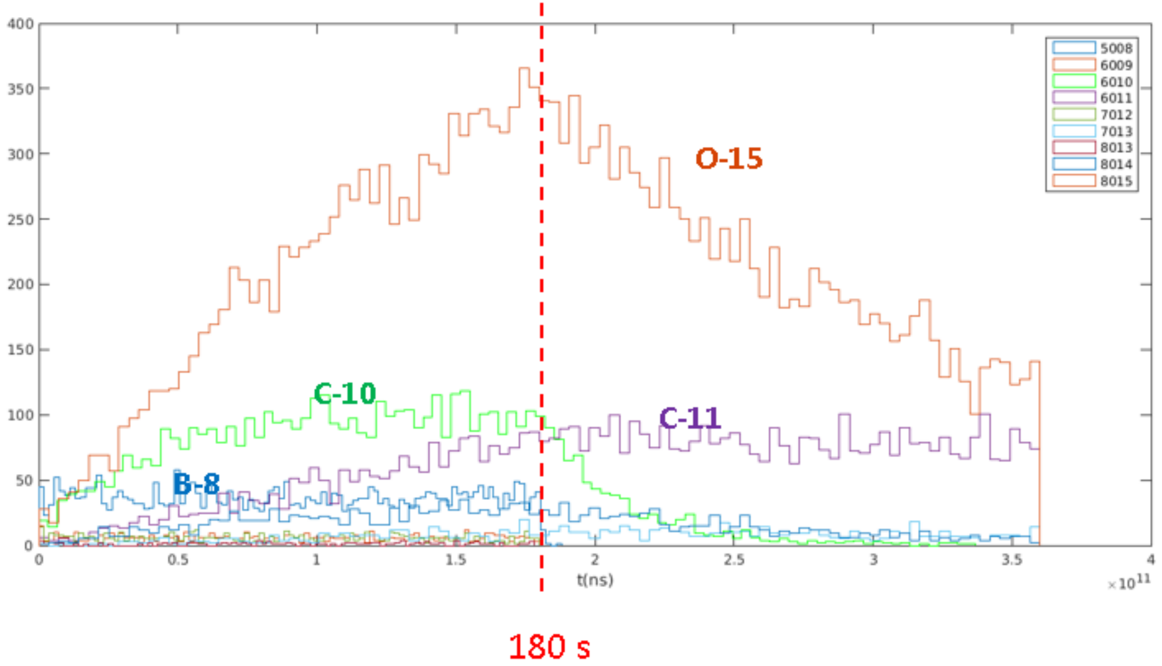
Courtesy C. Cuccagna

The user can perform several analysis on single hit:
Ex. For in-beam PET with a C12 ion beam



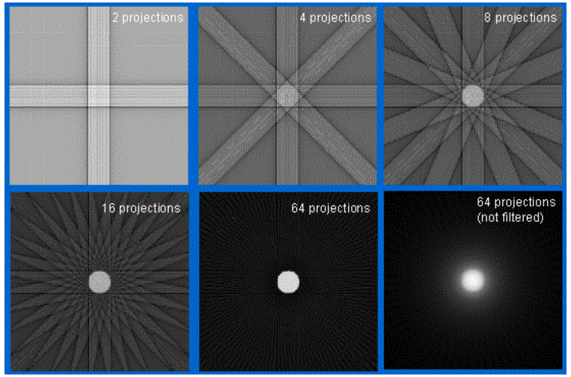
In time





Reconstruction codes

- FBP (python) Filtered Back Projection
  - Based on the **Fourier slice theorem**.
  - Simple, fast… not accurate enough
  - Available in **scikit-image** Python package.



- MLEM Maximum-Likelihood Expectation-Maximization
  - Best estimates the reconstruction image maximizing the *likelihood function*: Finds the mean number of radioactive disintegrations in the image that can produce the sinogram with the highest likelihood.
  - Iterative, more accurate

- Integration with STIR
  - Easy to implement Sinogram outputs to STIR
  - STIR Templates are ready for the users, to use different algorithms.

Courtesy C. Cuccagna

MicroPET

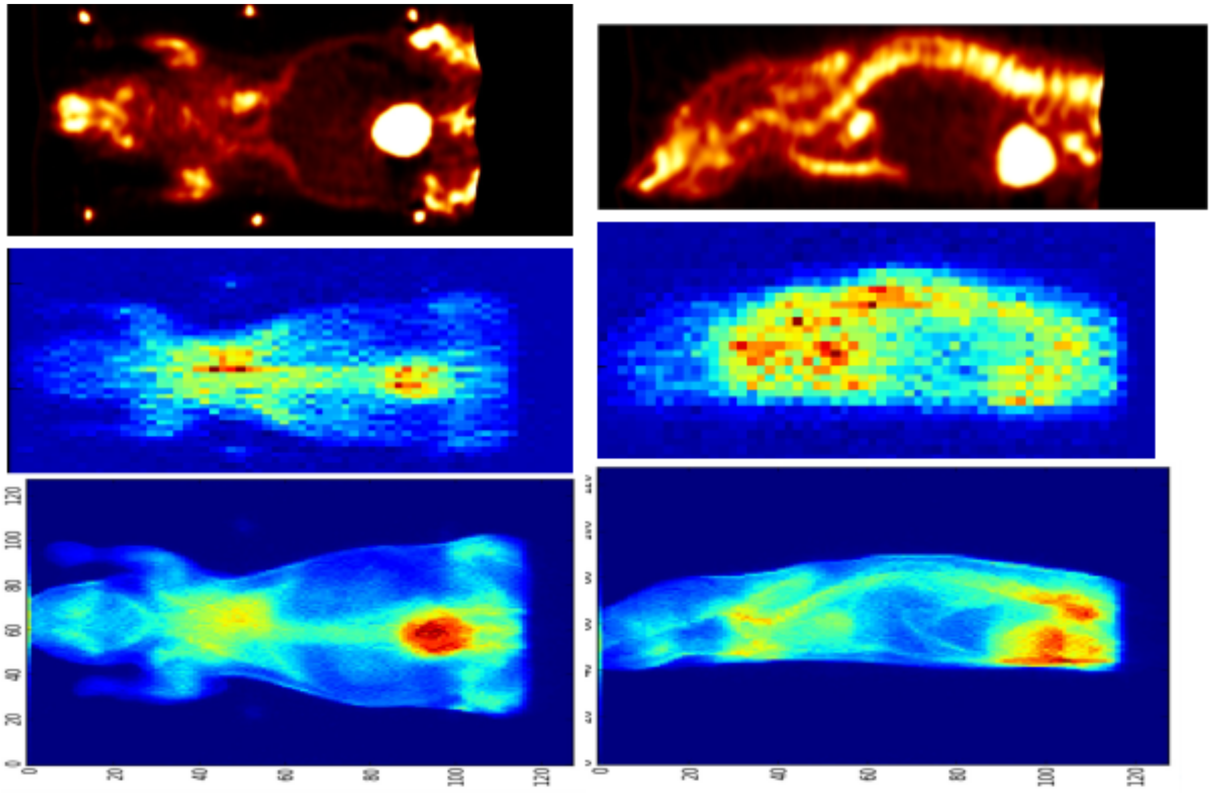
Reconstructed images

Mouse Phantom CT

neuroimage.usc.edu-Digimouse

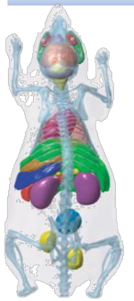
FBP (python)
Filtered Back Projection

MLEM
(new code!)
Maximum-Likelihood
Expectation-Maximization



Courtesy C. Cuccagna

MicroPET P4 scanner

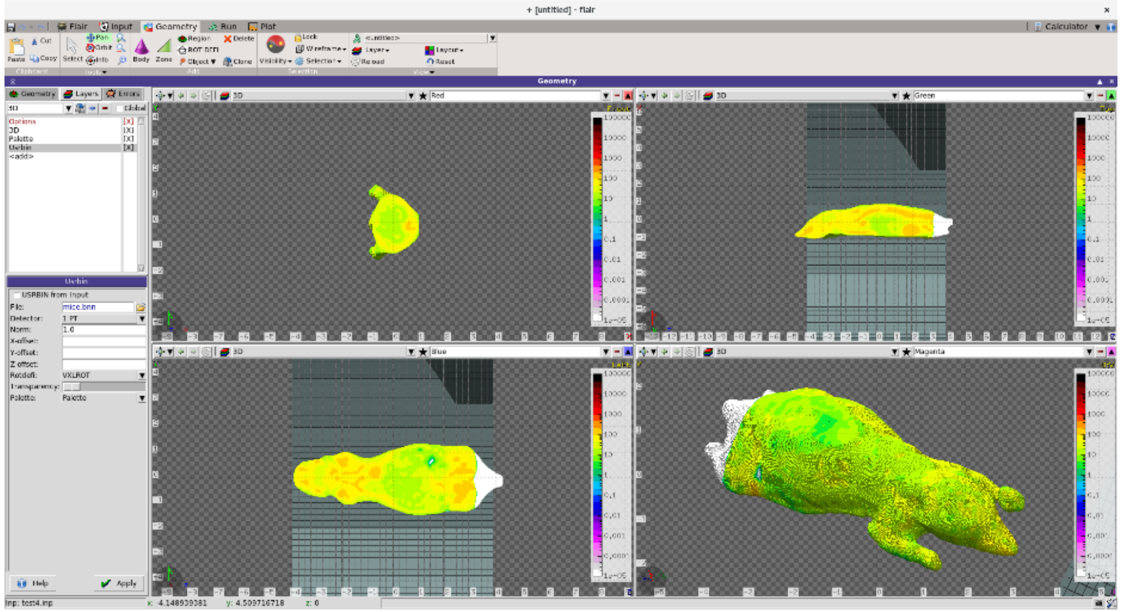


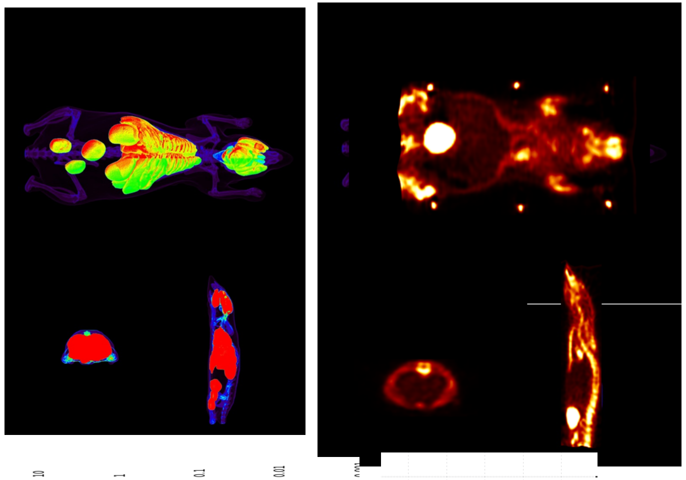
Voxelized phantom: Digimouse Atlas

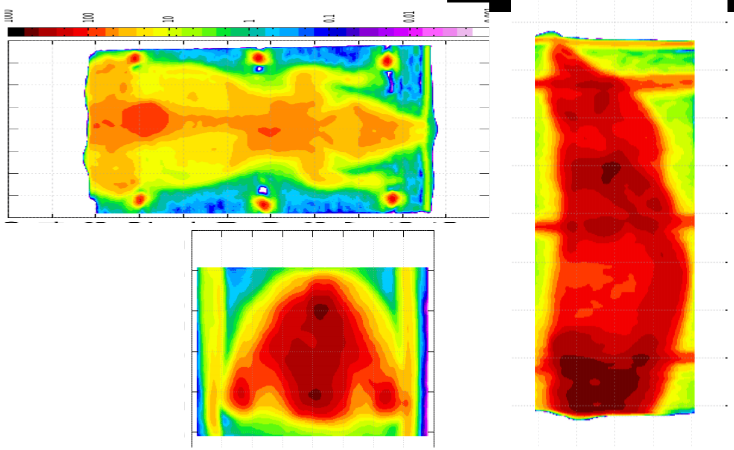
[neuroimage.usc.edu-Digimouse]()

Optimization for FLUKA courtesy of M.P.W. Chin

- *F-18 source*, generated from USRBIN of Mouse PET image

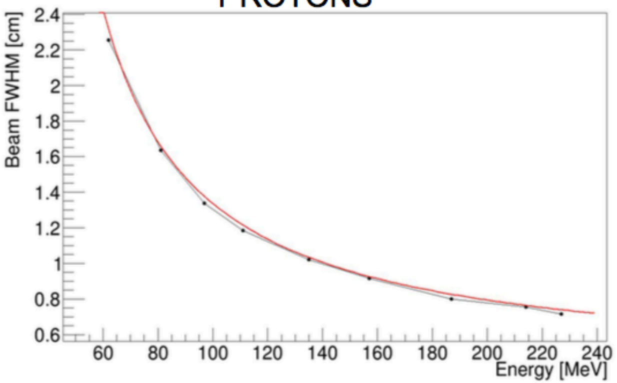






CNAO BEAM LINE

PROTONS

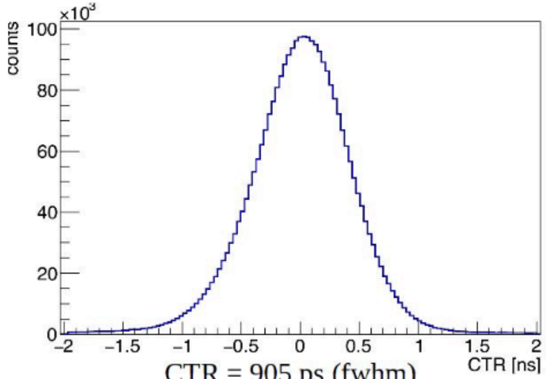


Model from Mirandola et al. Medical Physics 2015

- geometry
- materials
- beam size

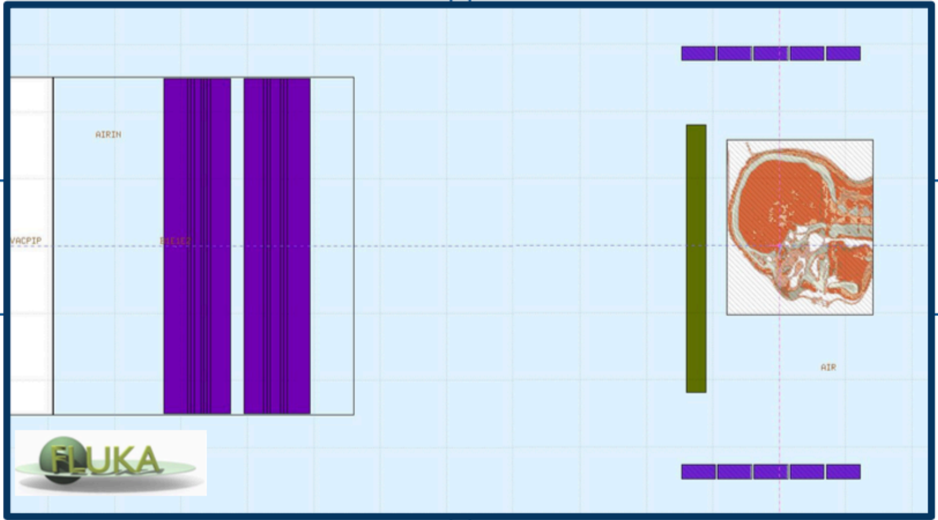
INSIDE IN-BEAM PET SCANNER

- geometry
- materials
- energy resolution
- time resolution

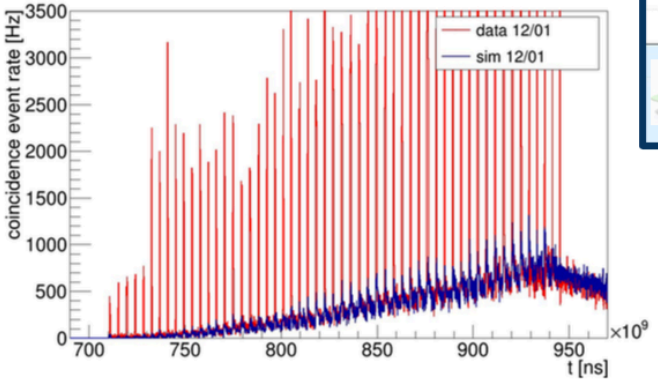


CTR = 905 ps (fwhm)

Time coincidence window = 2 ns

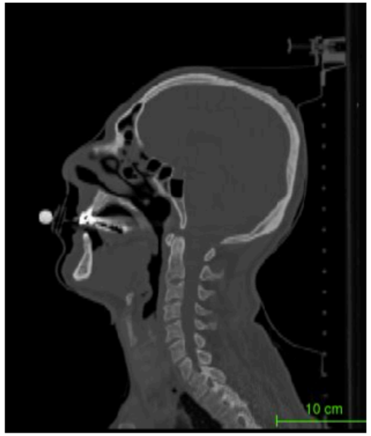


Courtesy E. Fiorina



- particle (p,C)
- spot position
- energy
- time structure

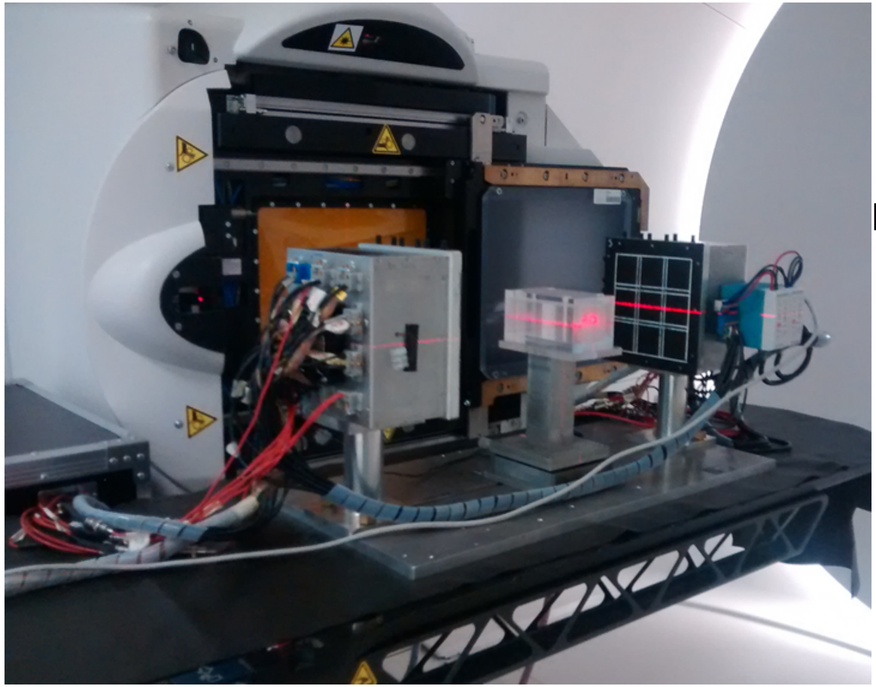
TREATMENT



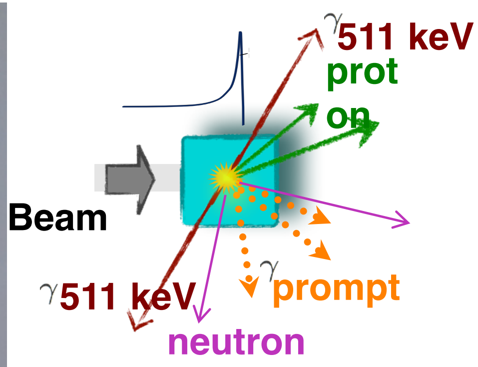
- geometry
- materials
- additional inserts

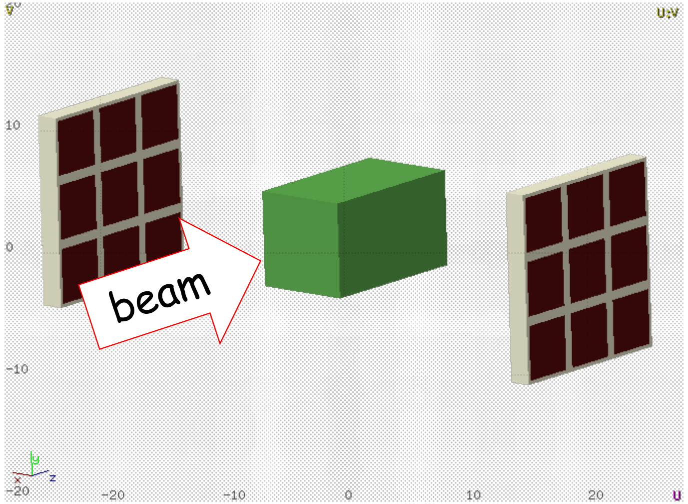
PATIENT

DoPET system for monitoring

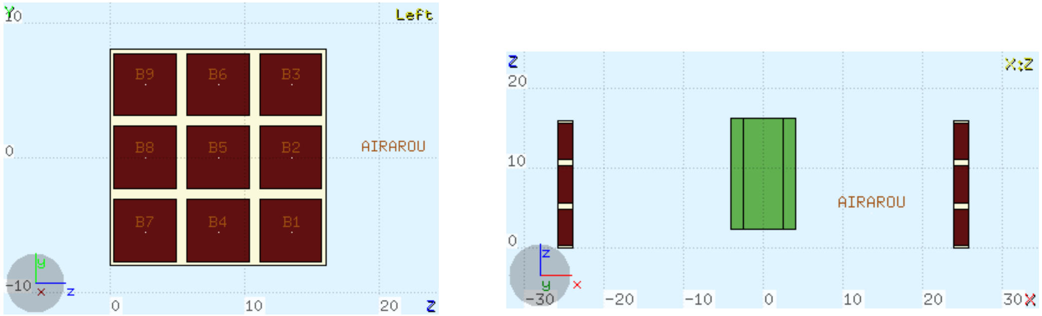


The DoPET prototype and the PMMA phantom positioned on the couch in use at the proton therapy center: behind the PET prototype the snout of the nozzle is well visible



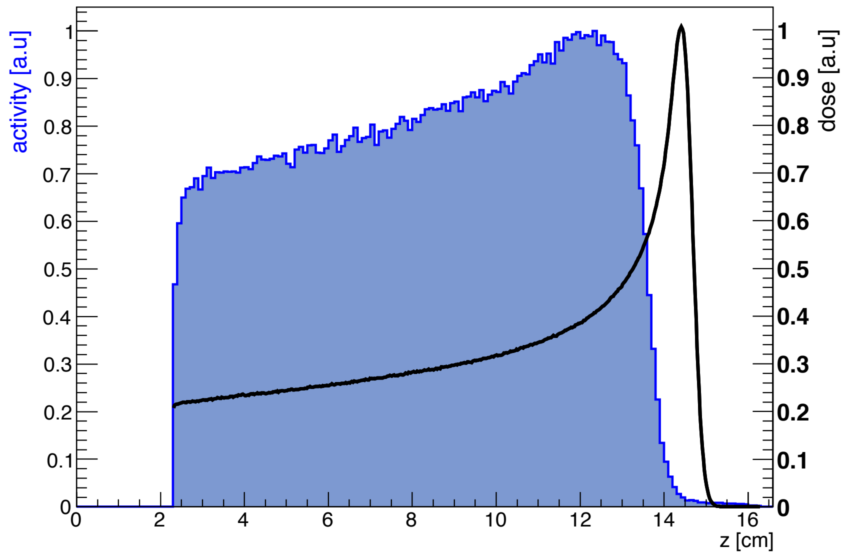


A sketch of the set-up

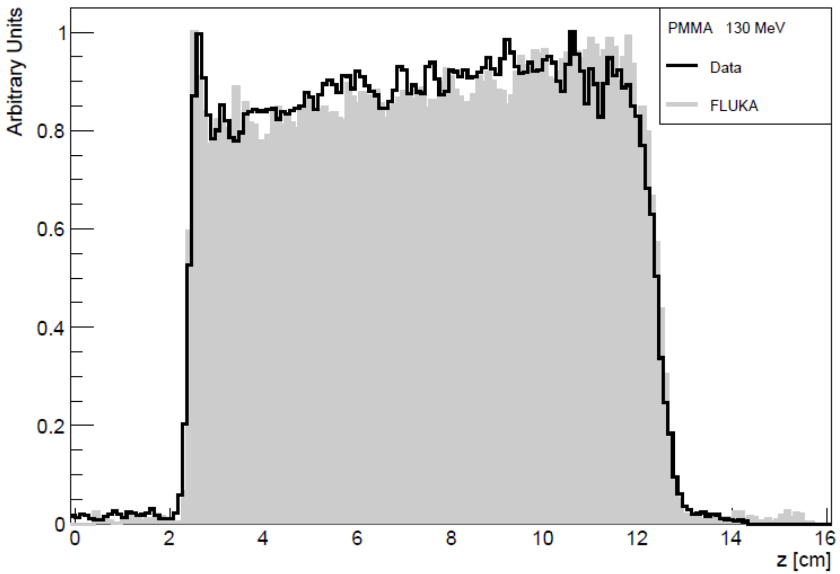


Geometry of DoPET in Flair

DoPET: Data analysis



Bragg peak and activity distribution for 100 MeV proton beam in w.eq. tissue

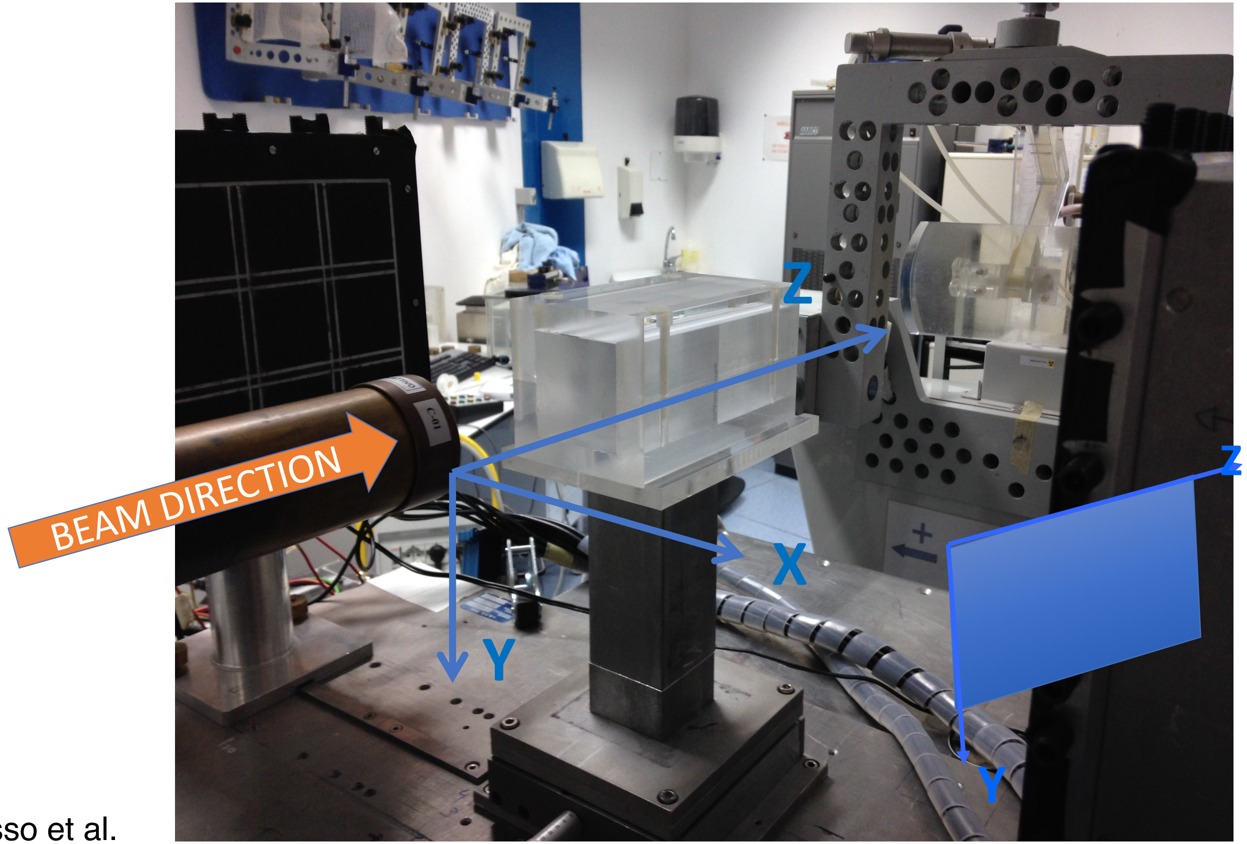


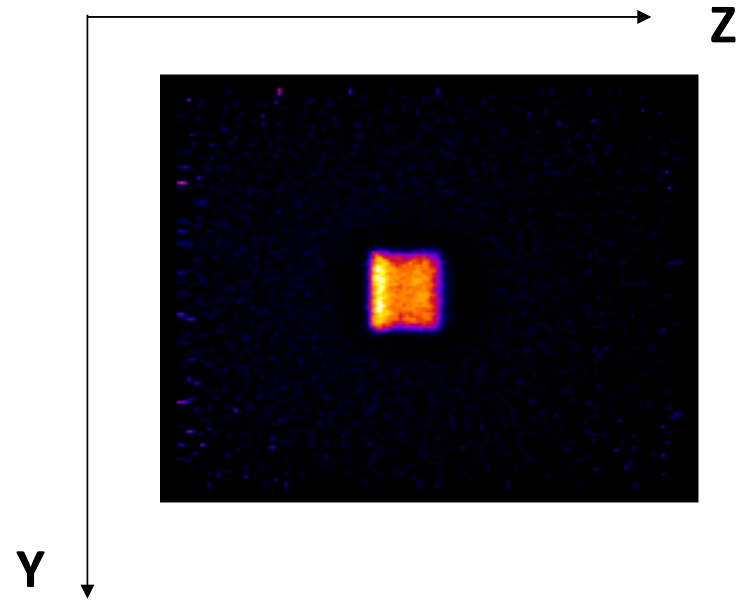
1-D activity profile (exp. data and MC)

S. Muraro ,G. Battistoni, N. Belcari, M.G. Bisogni, N. Camarlinghi, L. Cristoforetti, A. Del Guerra, A. Ferrari, F. Fracchiolla, M. Morrocchi, R. Righetto, P. Sala, M. Schwarz, G. Sportelli, A. Topi, V. Rosso: "*Proton Therapy treatment monitoring with the DoPET system: activity range, positron emitters evaluation and comparison with Monte Carlo predictions*".

Presented at **19th** International Workshop on Radiation Imaging Detectors: Krakow (Poland), 2-6 July 2017 -Journal of Instrumentation, submitted

CATANA: set-up





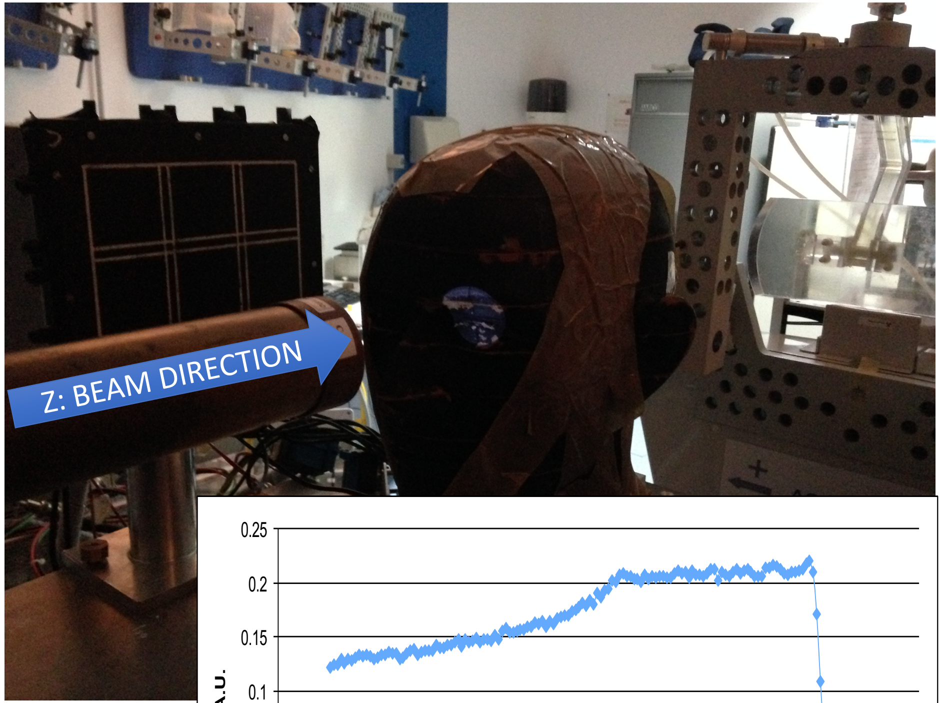
- 58 MeV protons on PMMA
- collimator: ∅ 30mm
- D= 15 Gy (5.7 Gy/min)

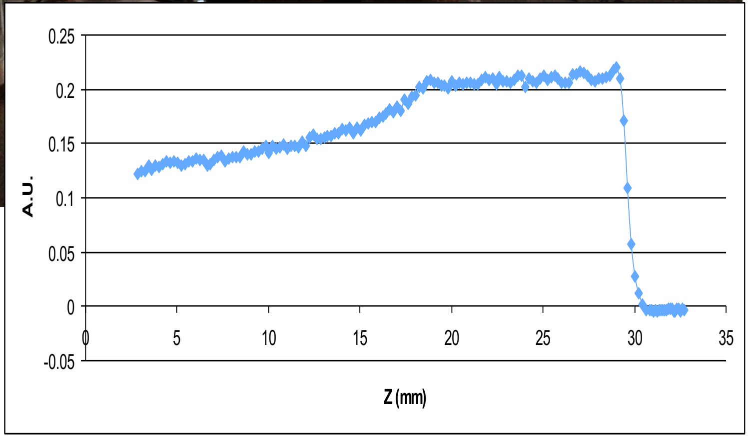
V. Rosso et al.
DoPET: an in-treatment monitoring system for proton therapy at 62MeV
Journal of Instrumentation, 11, C12029 (2016), 1-8
doi:10.1088/1748-0221/11/12/C12029

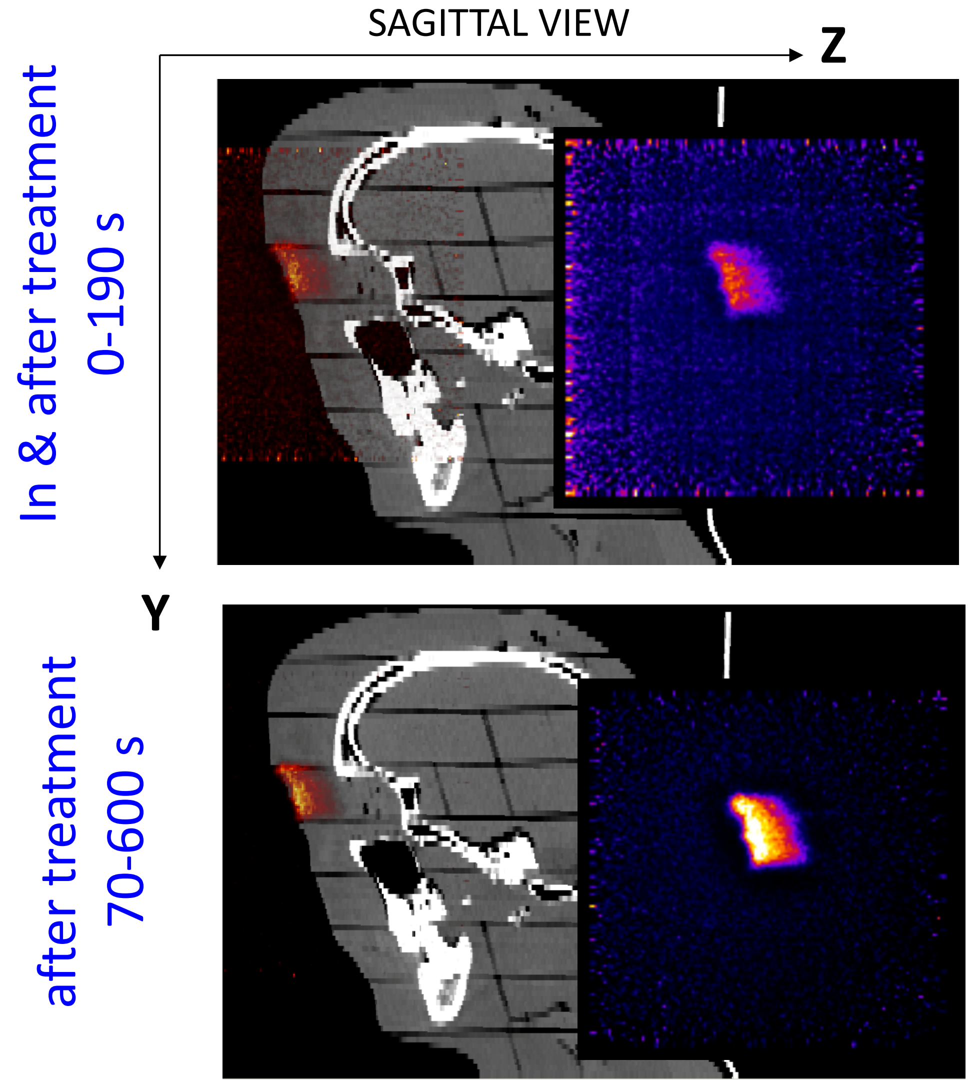
CATANA: an example of an antropomorphic phantom irradiation

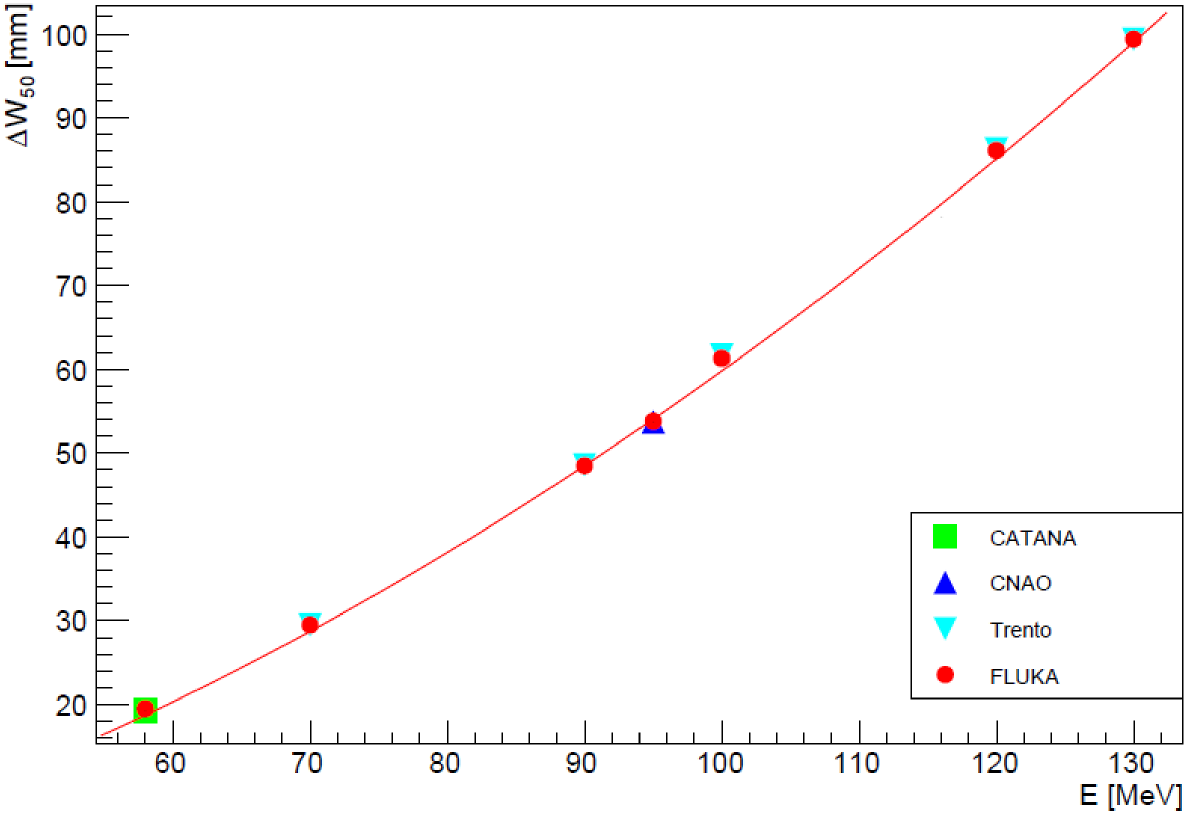
SOBP, collimator: Ø 3 cm, D= 15Gy

Δt in-treatment= 70s





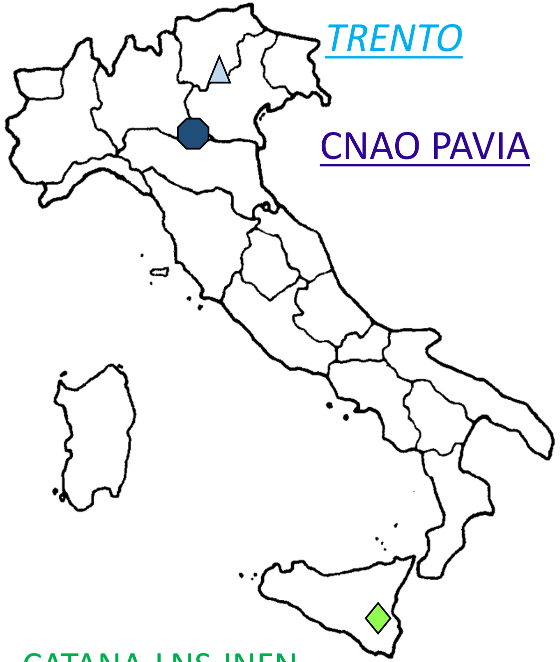




$$\Delta W_{50\%} = a + b\, E^{1.77}$$

a = -6.6 ± 1.9;
b = 0.0191 ± 0.0005
χ^2 / ndf = 5.008/2

The experimental data and the MC predictions relative to the data acquired in three Italian particle therapy facilities.



Many thanks:

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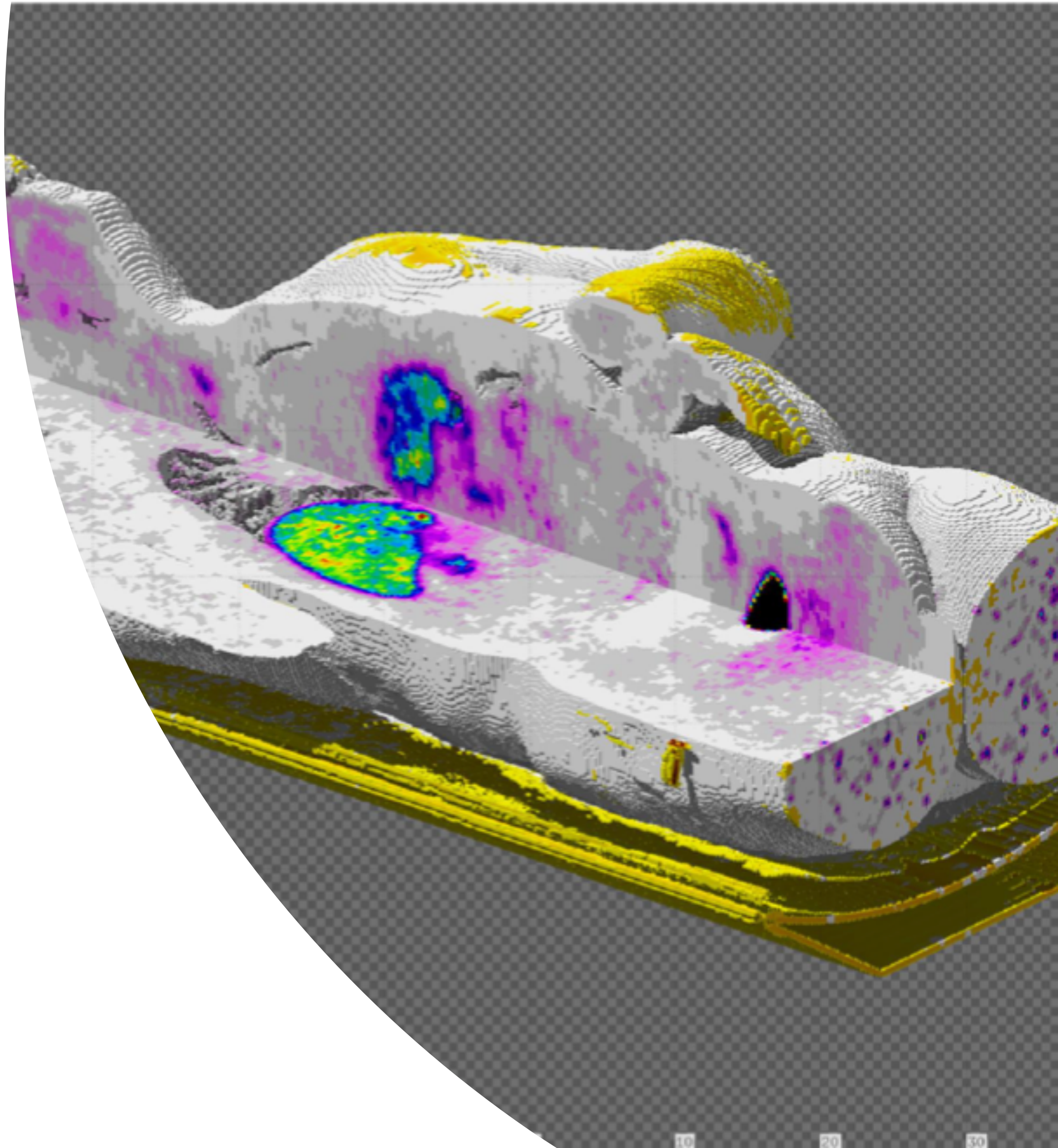
C. Cuccagna

E. Fiorina

Thank you for your attention



Questions ?