The use of FLUKA in hadron therapy

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On behalf of the FLUKA Collaboration

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Rationale

- At the moment, the long computational time prevents the use of MC codes in clinical routine

- However, MC codes can be very useful for:

  - validate analytical TPSs in water/CT systems both for physical and biological aspects
  - PET application
  - Biological calculations for phantom experiments

- Thanks to a more realistic representation of:

  - the physical interactions, especially the nuclear ones
    -> Mixed Field (especially in carbon ion therapy)
  - the patient anatomy
    -> CT image converted into a FLUKA geometry

FLUKA Description

- FLUKA is a general purpose tool for calculations of particle transport and interactions with matter

  Applications: proton and electron accelerator shielding, target design, calorimetry, activation, dosimetry, detector design, Accelerator Driven Systems, cosmic rays, neutrino physics, radiotherapy etc.
- 60 different particles + Heavy Ions
  - Hadron-hadron and hadron-nucleus interactions 0-10000 TeV
  - Electromagnetic and μ interactions 1 keV – 10000 TeV
  - Nucleus-nucleus interactions ~10 MeV/n-10000 TeV/n
  - Charged particle transport – ionization energy loss
  - Neutron multi-group transport and interactions 0-20 MeV
  - neutrino interactions
  - Transport in magnetic field
  - Double capability to run either fully analogue and/or biased calculations
  - Combinatorial (boolean) and Voxel geometry

Heavy ion interaction models

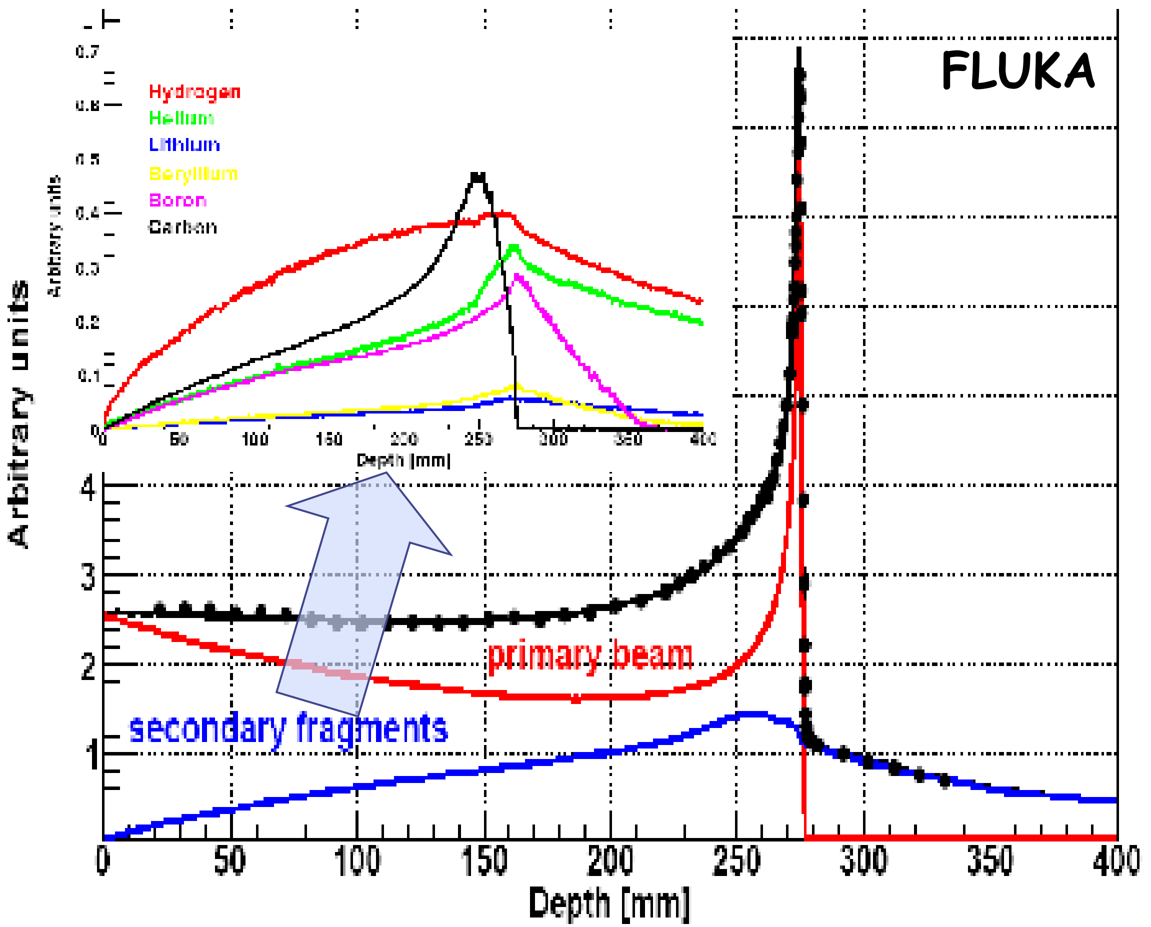
- DPMJET-III for energies ≥ 5 GeV/n
  - DPMJET (R. Engel, J. Ranft and S. Roesler) Nucleus-Nucleus interaction model
  - Energy range: from 5-10 GeV/n up to the highest Cosmic Ray energies (10^{18}-10^{20} eV)
  - Used in many Cosmic Ray shower codes
  - Based on the Dual Parton Model and the Glauber model, like the high-energy FLUKA hadron-nucleus event generator

- Modified and improved version of rQMD-2.4 for 0.1 < E < 5 GeV/n
  - rQMD-2.4 (H. Sorge et al.) Relativistic QMD model
  - Energy range: from 0.1 GeV/n up to several hundred GeV/n
  - Successfully applied to relativistic A-A particle production
- BME (Boltzmann Master Equation) for E < 0.1 GeV/n
  - FLUKA implementation of BME from E. Gadioli et al (Milan)

- Standard FLUKA evaporation/fission/fragmentation used in fragment final de-excitation
- Electromagnetic dissociation

The experimental validation against measured Bragg curve in Carbon ion therapy

^{12}C ions (400 MeV/u) in Water

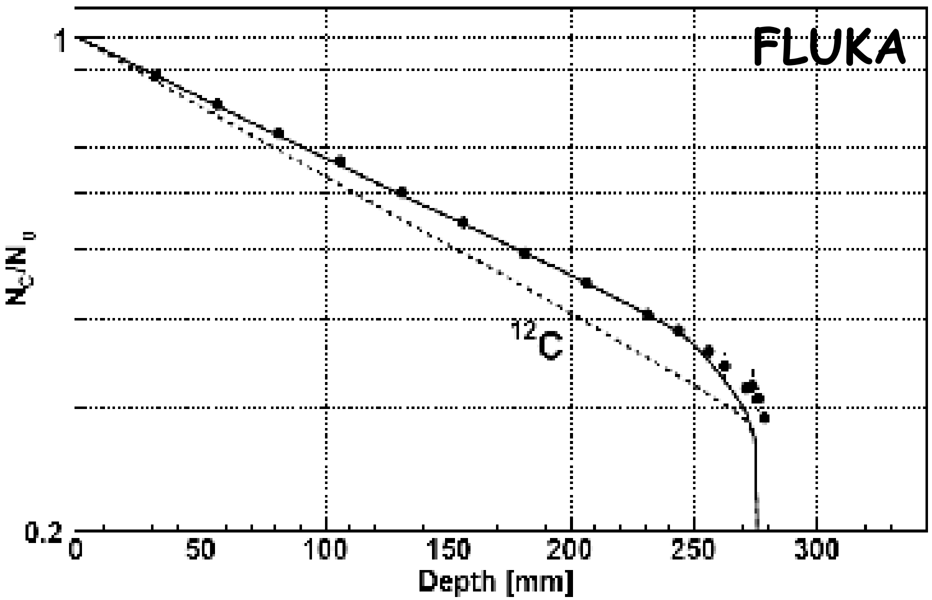


Exp. Data (points) from Haettner et al, Rad. Prot. Dos. 2006
Simulation: A. Mairani PhD Thesis, Pavia, 2007

The experimental validation against mixed field measurements in Carbon Ion therapy I

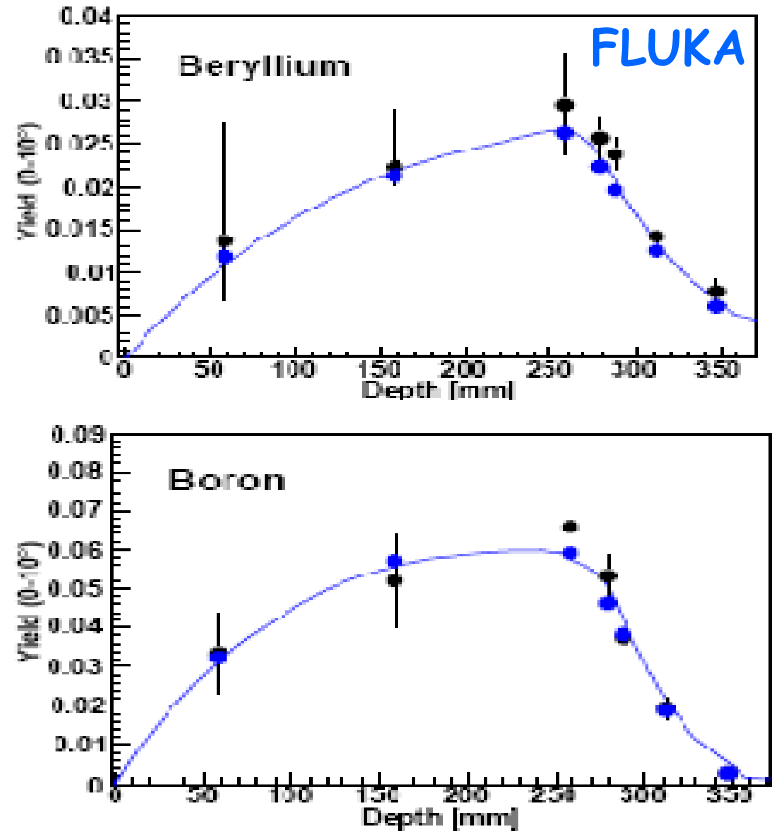
^{12}C ions (400 MeV/u) on Water phantoms

Carbon Beam Attenuation



Exp. Data (points) from Haettner et al, Rad. Prot. Dos. 2006
Simulations: A. Mairani PhD Thesis, Pavia, 2007

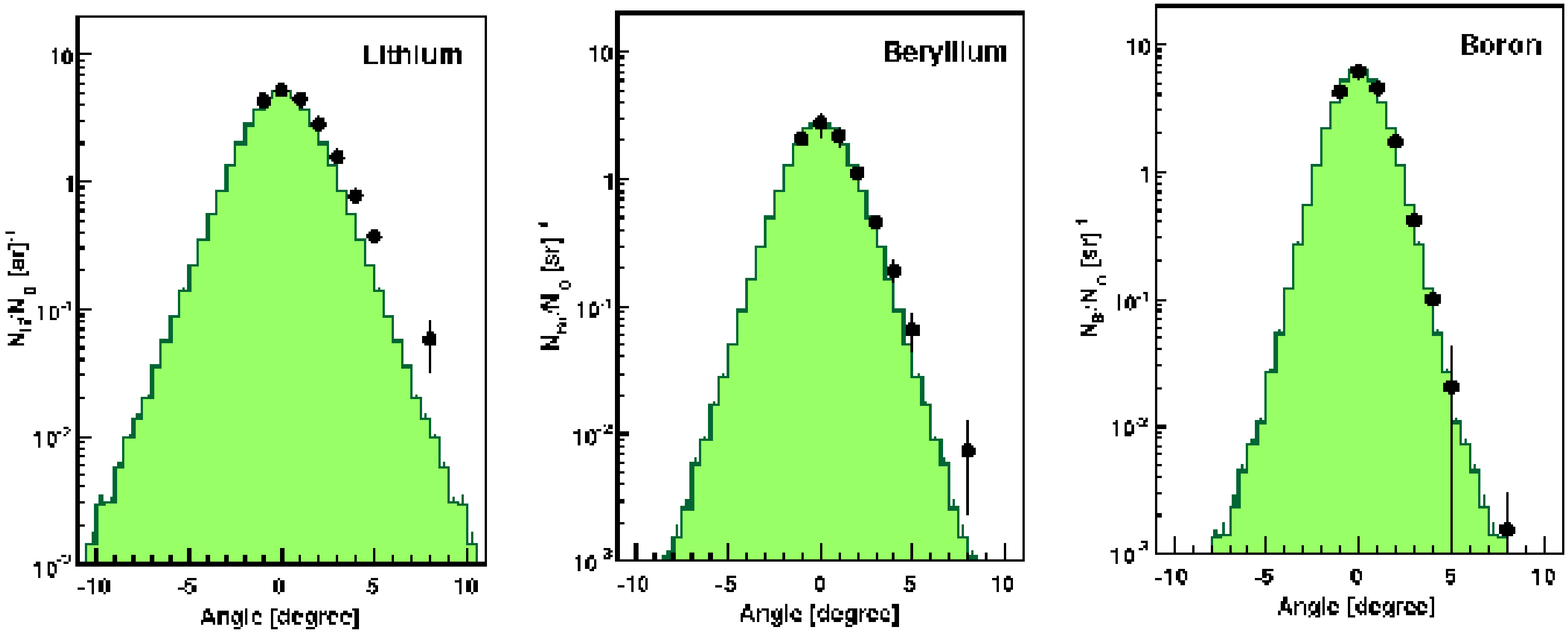
Build-up of secondary fragments



The experimental validation against mixed field measurements in Carbon Ion therapy II

^{12}C ions (400 MeV/u) on Water phantoms

Angular Distributions at 31.2 cm

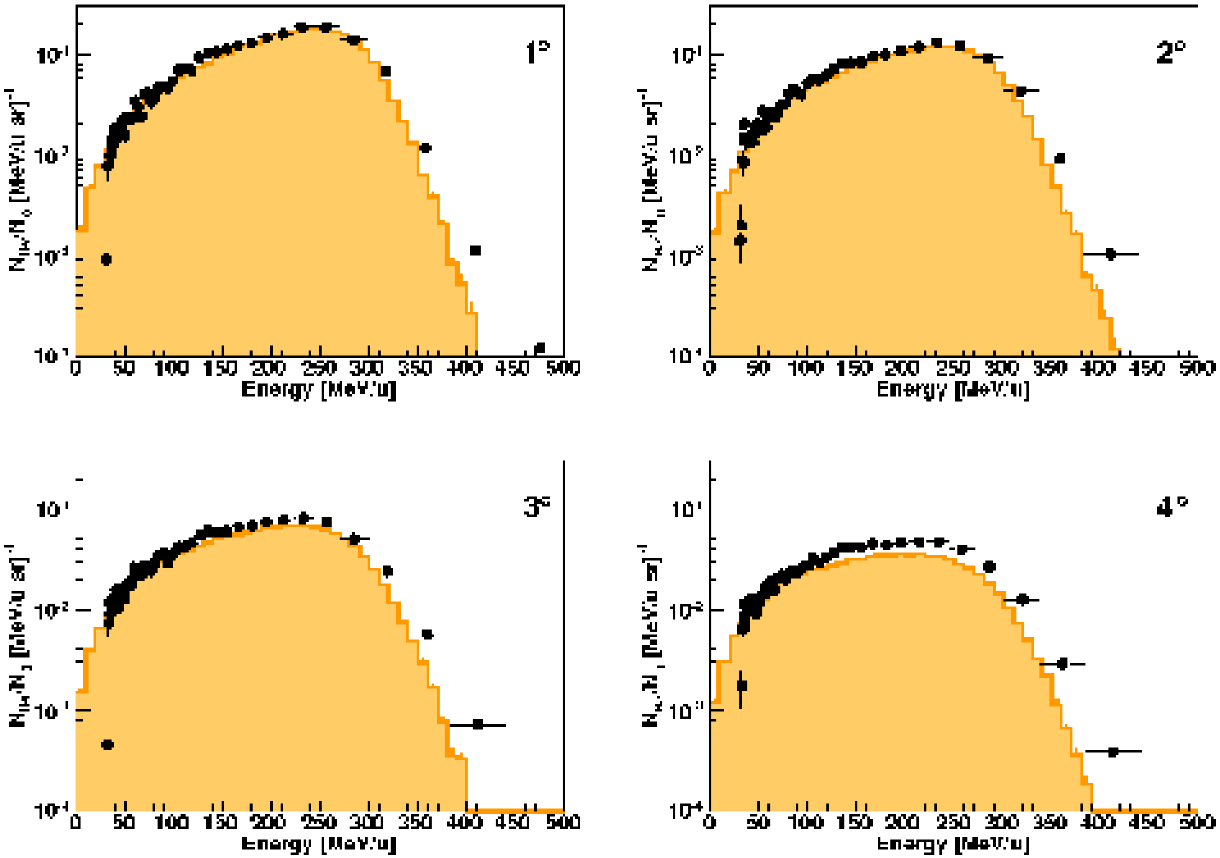


Exp. Data (points) courtesy of E. Haettner, D. Schardt, GSI, and S. Brons, K. Parodi, HIT.
FLUKA Simulations: A. Mairani, PhD Thesis, Pavia, 2007

The experimental validation against mixed field measurements in Carbon Ion therapy III

^{12}C ions (400 MeV/u) on Water phantoms

Alpha Energy-Angle Spectra at 28.8 cm



FLUKA

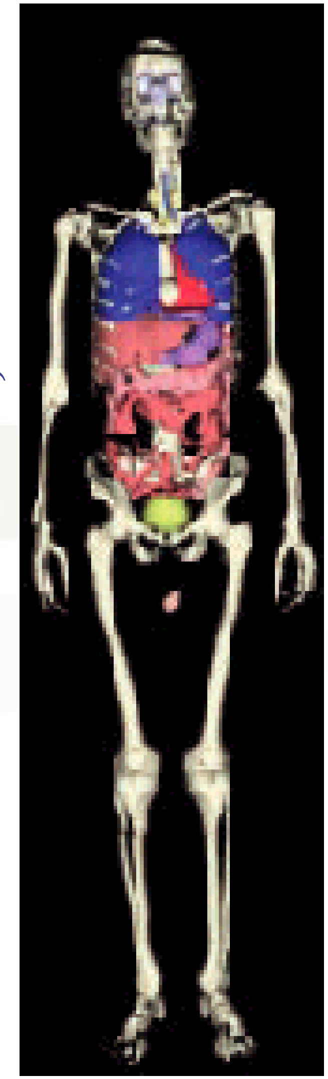
Simulation: A. Mairani, PhD Thesis, Pavia 2007

Preliminary data (points) courtesy of E. Haettner, D. Schardt, GSI, and S. Brons, K. Parodi, HIT.

Using the information from the patient CT in the MC I

The Voxel Geometry

- FLUKA can embed voxel structures within its standard combinatorial geometry
- Transport through the voxels is optimized and efficient
- Raw CT-scan outputs can be imported



The GOLEM phantom
Petoussi-Henss et al, 2002

Using the information from the patient CT in the MC II

CT segmentation into 27 materials (*Schneider et al PMB 45, 2000*, extended to include Ti in *Parodi et al, Med. Phys. 34, 2007*)

Air, Lung, Adipose tissue: rows −1000−−950 to −52−−23

Soft tissue: rows −22−−7 to 80−120

Skeletal tissue: rows 120−200 to 1500−1600

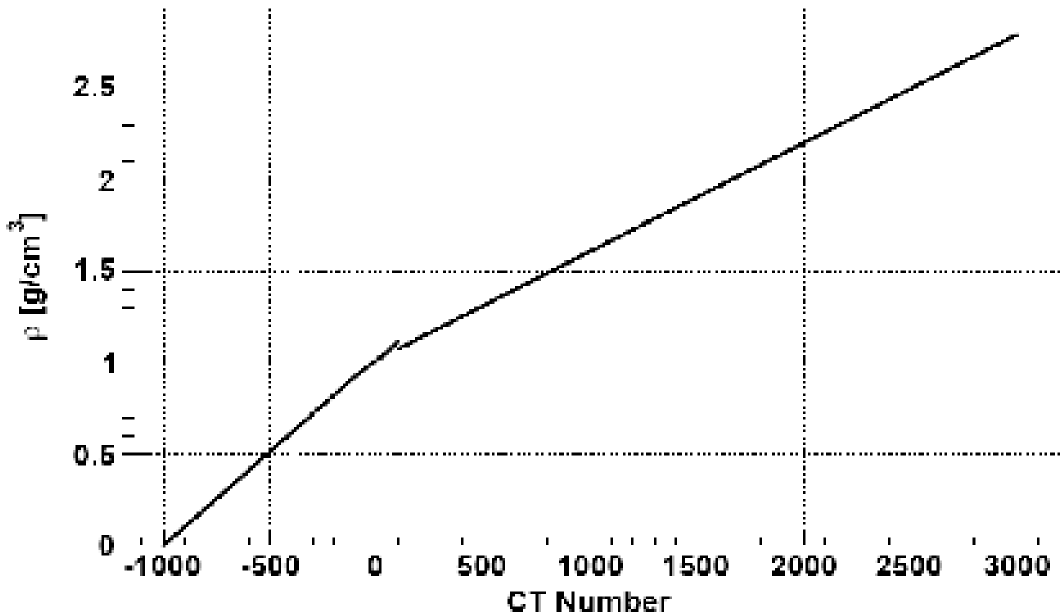
	w_i (pp)											
H	H	C	N	O	Na	Mg	P	S	Cl	Ar	K	Ca
−1000−−950			75.5	23.2						1.3		
−950−−120	10.3	10.5	3.1	74.9	0.2		0.2	0.3	0.3		0.2	
−120−−83	11.6	68.1	0.2	19.8	0.1			0.1	0.1			
−82−−53	11.3	56.7	0.9	30.8	0.1			0.1	0.1			
−52−−23	11.0	45.8	1.5	41.1	0.1		0.1	0.2	0.2			
−22−−7	10.8	35.6	2.2	50.9			0.1	0.2	0.2			
8−18	10.6	28.4	2.6	57.8			0.1	0.2	0.2		0.1	
19−80	10.3	13.4	3.0	72.3	0.2		0.2	0.2	0.2		0.2	
80−120	9.4	20.7	6.2	62.2	0.6			0.6	0.3			
120−200	9.5	45.5	2.5	35.5	0.1		2.1	0.1	0.1		0.1	4.5
200−300	8.9	42.3	2.7	36.3	0.1		3.0	0.1	0.1		0.1	6.4
300−400	8.2	39.1	2.9	37.2	0.1		3.9	0.1	0.1		0.1	8.3
400−500	7.6	36.1	3.0	38.0	0.1	0.1	4.7	0.2	0.1			10.1
500−600	7.1	33.5	3.2	38.7	0.1	0.1	5.4	0.2				11.7
600−700	6.6	31.0	3.3	39.4	0.1	0.1	6.1	0.2				13.2
700−800	6.1	28.7	3.5	40.0	0.1	0.1	6.7	0.2				14.6
800−900	5.6	26.5	3.6	40.5	0.1	0.2	7.3	0.3				15.9
900−1000	5.2	24.6	3.7	41.1	0.1	0.2	7.8	0.3				17.0
1000−1100	4.9	22.7	3.8	41.6	0.1	0.2	8.3	0.3				18.1
1100−1200	4.5	21.0	3.9	42.0	0.1	0.2	8.8	0.3				19.2
1200−1300	4.2	19.4	4.0	42.5	0.1	0.2	9.2	0.3				20.1
1300−1400	3.9	17.9	4.1	42.9	0.1	0.2	9.6	0.3				21.0
1400−1500	3.6	16.5	4.2	43.2	0.1	0.2	10.0	0.3				21.9
1500−1600	3.4	15.5	4.2	43.5	0.1	0.2	10.3	0.3				22.5

Using the information from the patient CT in the MC III

Nominal mean density for each HU interval

(*Jiang and Paganetti MP 31, 2004*)

But *real* density varies continuously with HU value



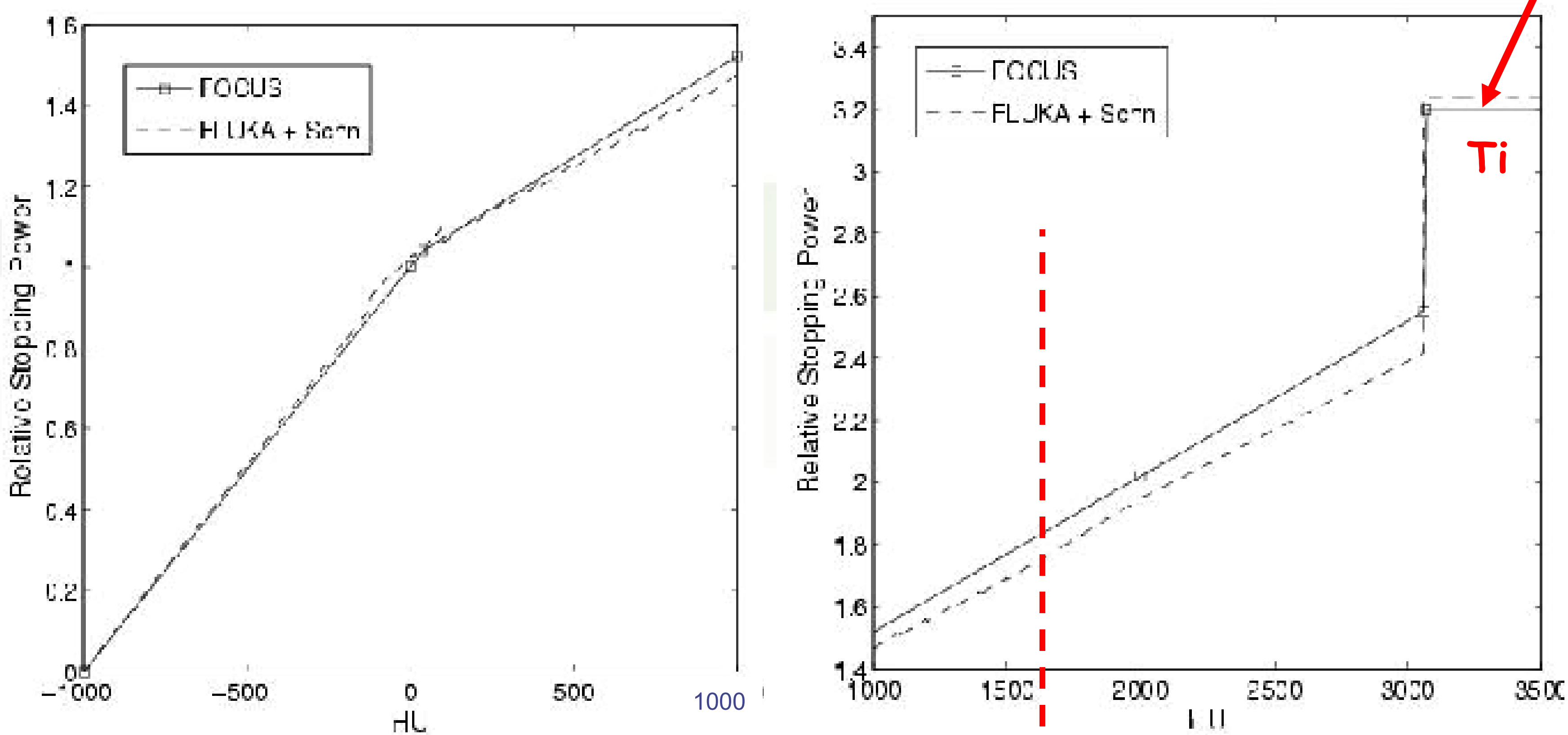
Conversion of CT numbers into mass density extending the original one proposed by *Schneider et al in PMB 45 (2000)* to HU > 1600

Parodi et al, Med. Phys. 34, 2007

Adaptation of FLUKA to follow the Focus/XiO TPS calibration curve for proton at MGH

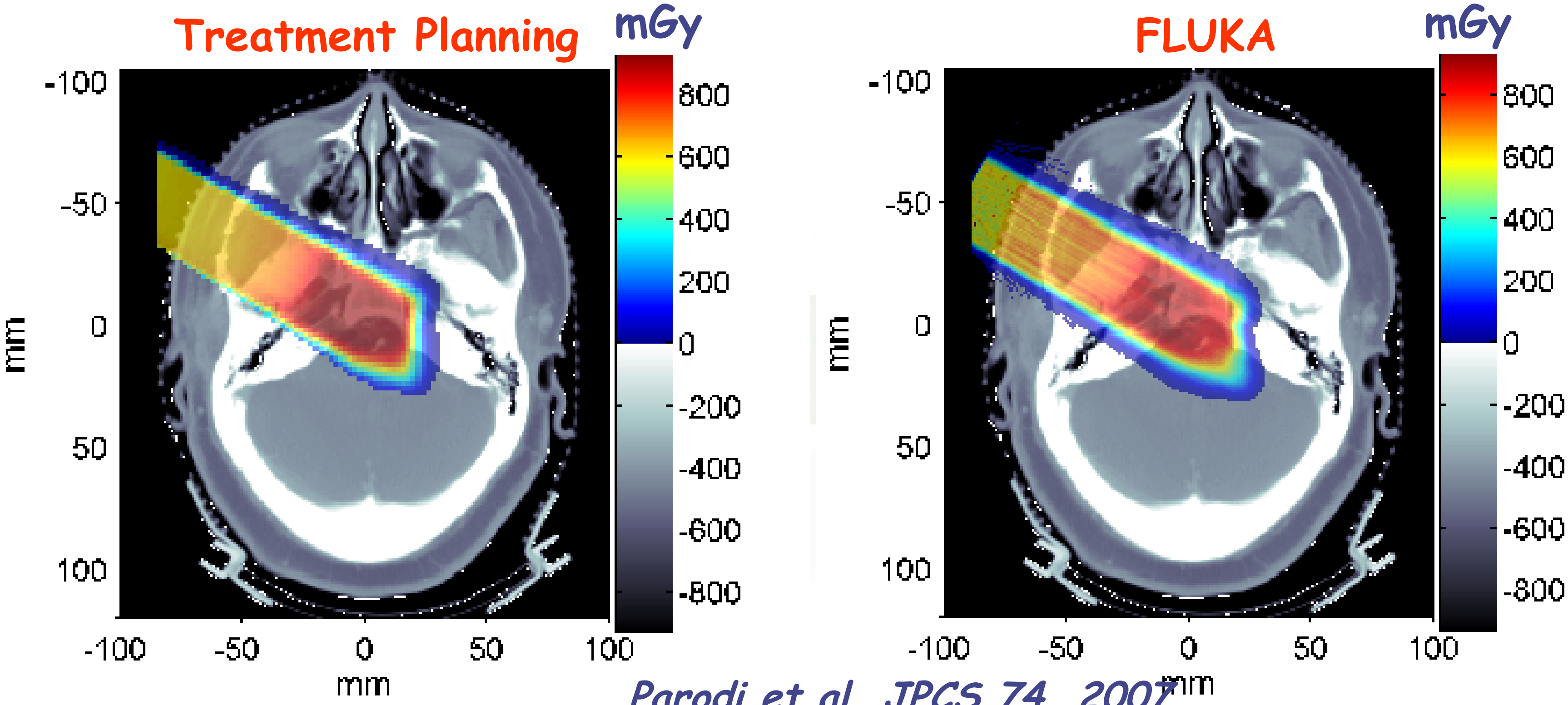
HU dependent adjustment of nuclear and electromagnetic processes, reproducing same calibration curve as TPS

(similar to *Jiang and Paganetti MP 31, 2004*)



Parodi et al MP 34, 2007, Parodi et al PMB 52, 2007

Proton therapy: MC vs Focus/XiO for a Clivus Chordoma Patient at MGH



Parodi et al, JPCS 74, 2007

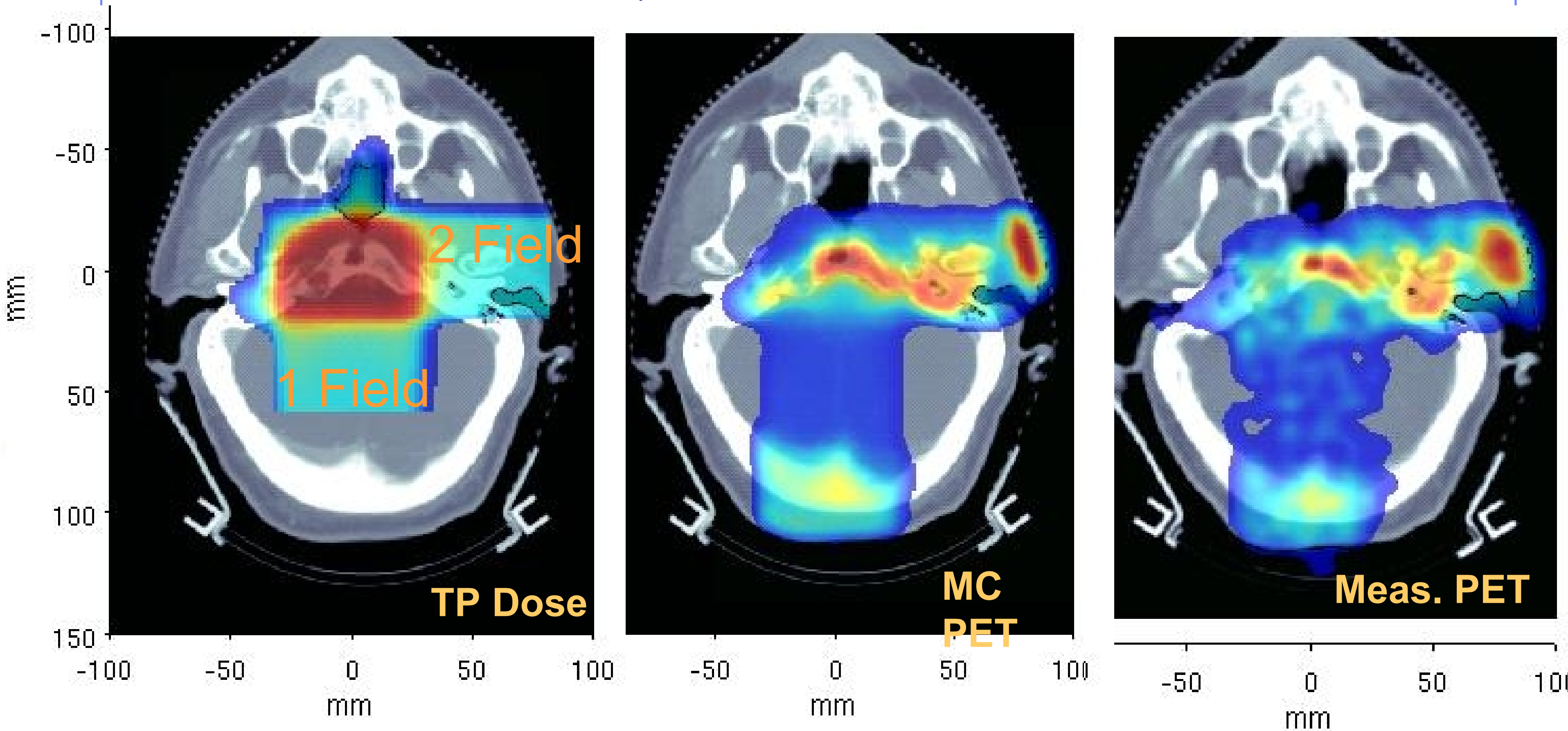
Prescribed dose: 1 GyE

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

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

PET/CT imaging after irradiation at MGH

Clival Chordoma, 0.96 GyE / field, DT_1 ~ 26 min, DT_2 ~ 16 min



K. Parodi et al., IJROBP 68 (2007)

β^+ emitters for ion beams: phantom experiments

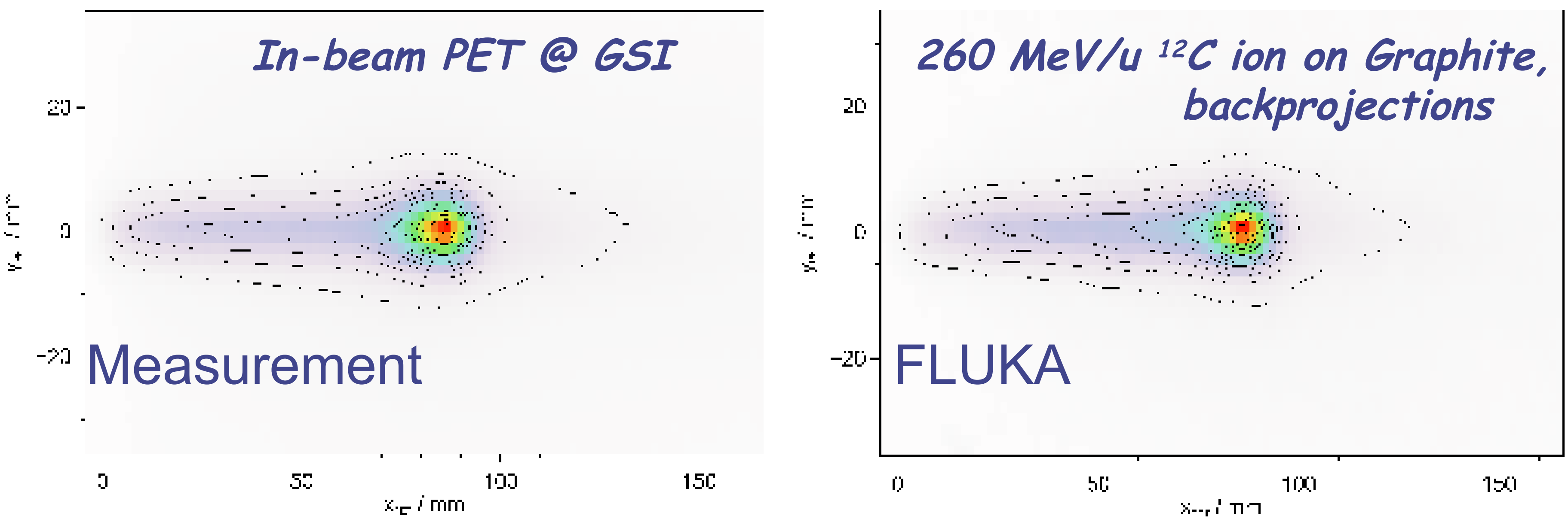
Application of FLUKA to PET monitoring of experiments with ^{12}C and ^{16}O

Simulation based on ***internal nuclear models*** (nuclear interaction, β^+-decay, propagation of e^+ and annihilation photons)

Time structure in simulation is exactly the same as for measured data

- ✓ Exact model of the experimental setup, PET heads excluded
- ✓ FLUKA irradiation and decay features exploited
- ✓ Response of detector is simulated by modified PETSIM[1]
- ✓ Backprojection with same routines as in experiment

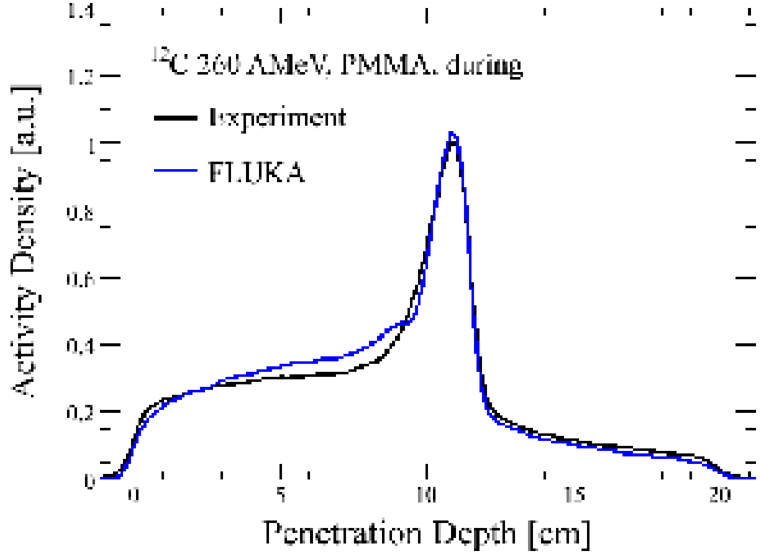
[1]Pönisch et al. PMB ***49*** 2004

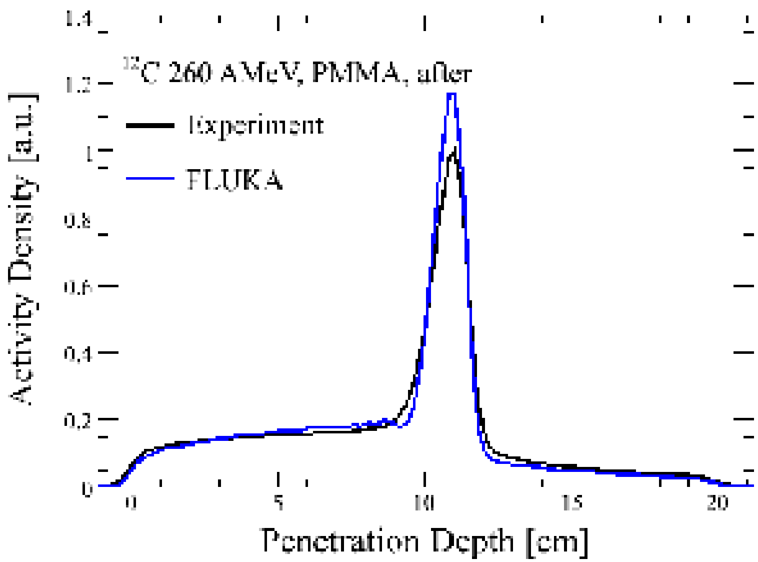


F. Sommerer PhD Thesis, 2007

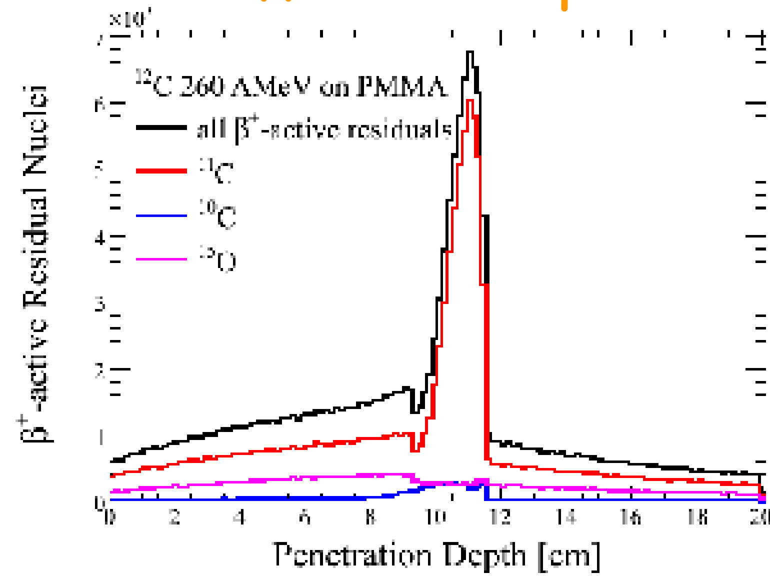
Backprojections: FLUKA vs Exp data

Backprojections 12C 260 MeV/A on PMMA PMMA





^{12}C 260 MeV/A on PMMA, simulated relative production rate of different isotopes



Backprojections on left side: Both the data and the FLUKA calculations are normalized to the same area

F. Sommerer PhD Thesis, 2007

Application of the FLUKA code in biologically based calculations

- Mixed radiation field: particle type, energy, etc.
- Patient CT images (density and elemental compositions)
- Coupling FLUKA with biological basis data is possible to evaluate the cell response in phantom experiments or in clinical CT-based calculations
- Input biological "database" is needed !?!
- Example of application:
- proton therapy at PSI (*Biaggi et al NIM-B, 1999,159*)

Coupling FLUKA with biological basis data

Given a biological model as a input of the simulation (in terms of particle type, energy or LET)

Whenever an energy *E* is deposited in a target voxel by a certain radiation type, the biological response is evaluated on-line taking into account the biological database.

For example: in case of the chromosome aberrations (lesion Y(D) = α D + β D^2) the TDRA (Theory of Dual Radiation Action) is applied in presence of **Mixed Radiation Field**

The sequential exposure to two doses D_1 and D_2 (with the subscripts referring to two different radiation types), gives the following yield of lesions:

$$Y(D_1, D_2) = \alpha_1 D_1 + \beta_1 D_1^2 + \alpha_2 D_2 + \beta_2 D_2^2 + 2(\beta_1 \beta_2)^{1/2} D_1 D_2$$

Generalizing:

$$\epsilon(D_1, D_2, ..., D_n) = \sum_{i=1}^{n} \alpha_i D_i + (\sum_{i=1}^{n} \sqrt{\beta_i} D_i)^2$$

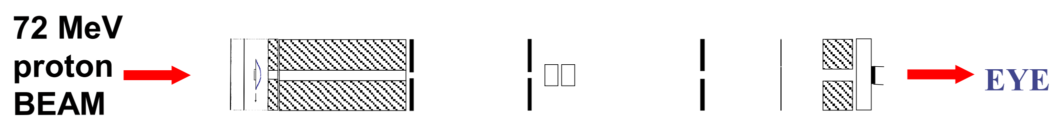
And the average parameters for a mixed field:

$$\alpha = \frac{\sum_{i=1}^{n} \alpha_i D_i}{\sum_{i=1}^{n} D_i},$$

$$\beta = (\frac{\sum_{i=1}^{n} \sqrt{\beta_i} D_i}{\sum_{i=1}^{n} D_i})^2.$$

Example I: in proton therapy

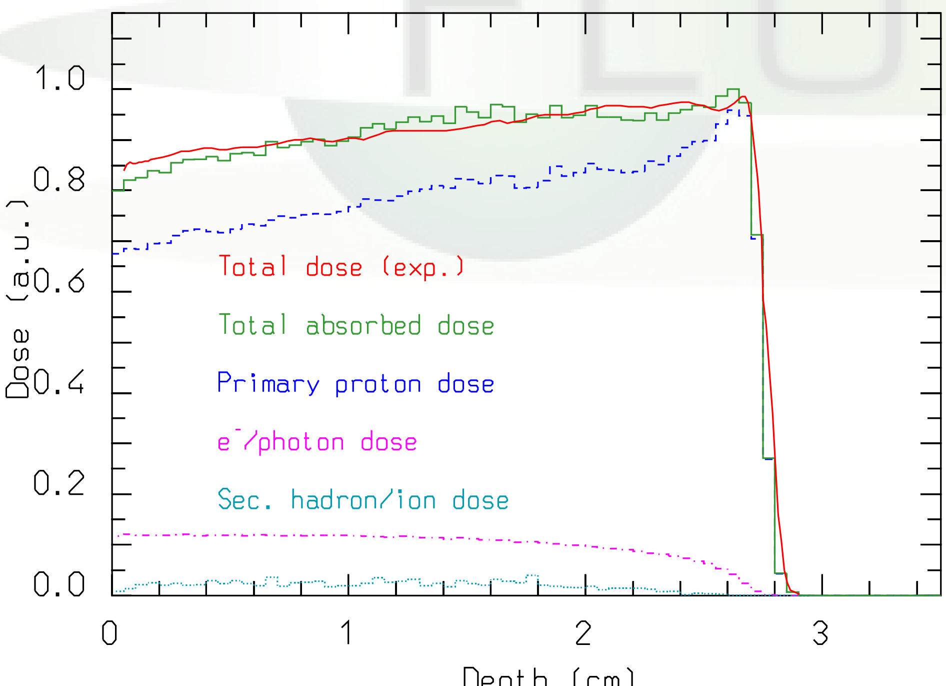
Geometry of the OPTIS therapy unit

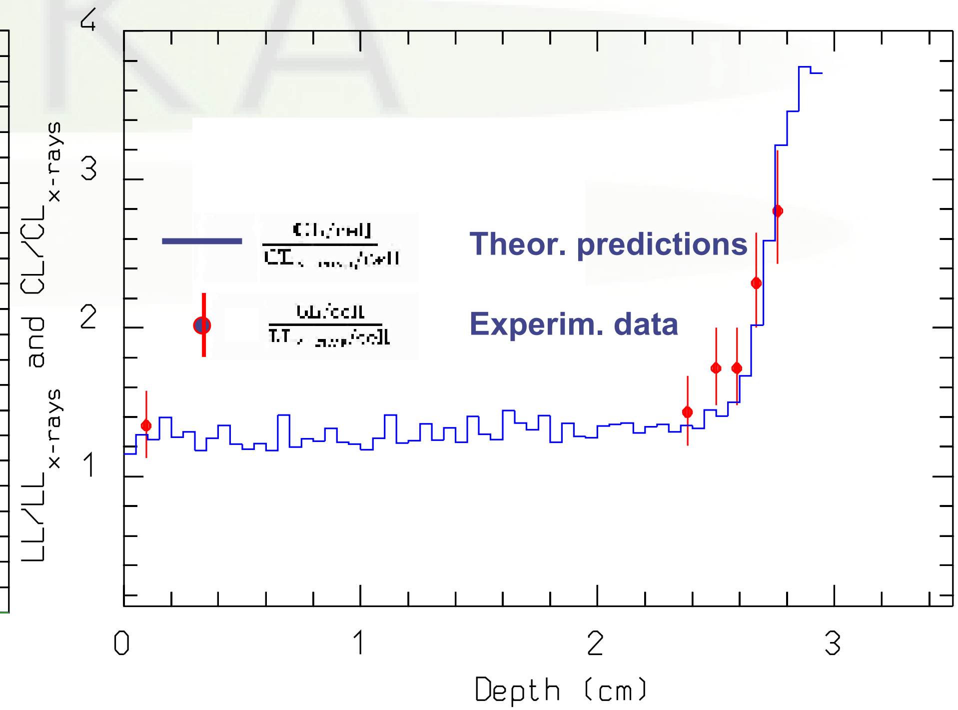


FLUKA code (extended)

Complex Lesions as a function of LET and particle type

A. Ottolenghi et al





Biaggi et al NIM-B, 1999, 159,89-100

Conclusions

FLUKA applications to Medicine/radiobiology:

- Validation and improvement of analytical TPSs in proton and carbon ion therapy
- PET

They are growing, thanks to

- ✓ Mixed field capability, including ion transport and interactions
- ✓ Voxel geometry (patient CT information)
- ✓ Coupling with radiobiological models

Improvements in a near future:

- New library for low-energy neutron transport
- Finalize the implementation of BME for low energy ion interactions

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