The Monte Carlo code FLUKA in Ion Therapy: Status & Outlook

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on behalf of the FLUKA collaboration

PHYSICS FOR HEALTH IN EUROPE WORKSHOP

(Towards a European roadmap for using physics tools in the development of diagnostics techniques and new cancer therapies)

2-4 February 2010

Rationale for MC in hadron-therapy

- Biological calculations in tumour therapy with ions depend on a precise description of the radiation field.
- In ^{12}C ion irradiation, nuclear reactions cause a significant alteration of the radiation field.
- contribution of secondary fragments needs to be taken into account for accurate planning of the physical and biological dose delivery in the scheduled treatment.
- Treatment Planning Systems (TPS) for ion beam therapy essentially use analytical algorithms with input databases for the description of the ion interaction with matter.

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

Rationale for MC in hadron-therapy

- In practice MC codes can be used for:
  - startup and commissioning of new facilities
  - beamline modeling and generation of TPS input data
  - validate analytical TPSs in water/CT systems both for physical and biological aspects
  - Prediction/Analysis of in-beam PET application
  - Biological calculations for cell survival experiments

- Additional advantage to describe complex geometries (and interfaces between rather different materials!):
- Accurate 3D transport
  - Fully detailed description of the patient anatomy
    → CT image converted into a MC geometry

Model challenge: interface to radiobiological model to predict "biological dose" (→actual effect) and not only physical dose

The case of FLUKA

- FLUKA is a general purpose tool for the calculations of particle transport and interactions with matter ("condensed history MC")

  Applications: proton and electron accelerator shielding, target design, calorimetry, activation, dosimetry, detector design, Accelerator Driven Systems, cosmic rays, neutrino physics, radiotherapy etc.

  Owned by INFN+CERN http://www.fluka.org ~2000 users in the world
- Main design/development criteria:
  - Based on original and well-tested microscopic models.
  - Optimized by comparing with experimental data at single interaction level: ***"theory driven, benchmarked with data"***
  - Final predictions obtained with minimal free parameters fixed for all energies, targets and projectiles
- Since 2001 development oriented towards 2 main directions:

"High energy"
(LHC, HE cosmic ray physics…)

"Low energy"
(Medical application…)

The FLUKA international collaboration

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Main FLUKA developments in view of medical applications (and hadron therapy in particular)

- Models for nucleus-nucleus interactions :
  - 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
  - BME (Boltzmann Master Equation) for E < 0.1 GeV/n. FLUKA implementation of BME from E. Gadioli et al (Milan)
- Improvement of models for evaporation/fission/fragmentation used in fragment final de-excitation. Prediction of radionuclide production
- Improvement of dE/dx models (Z^2+Z^3 corrections, molecular effects, nuclear stopping power)
- Run time application of linear-quadratic models describing radiobiological effects
- Extensions and improvement of neutron library (thermal + ephithermal region)
- Voxel geometry
- Time-varying geometry
- Routines to import CT scans, material/density/composition assignment to CT

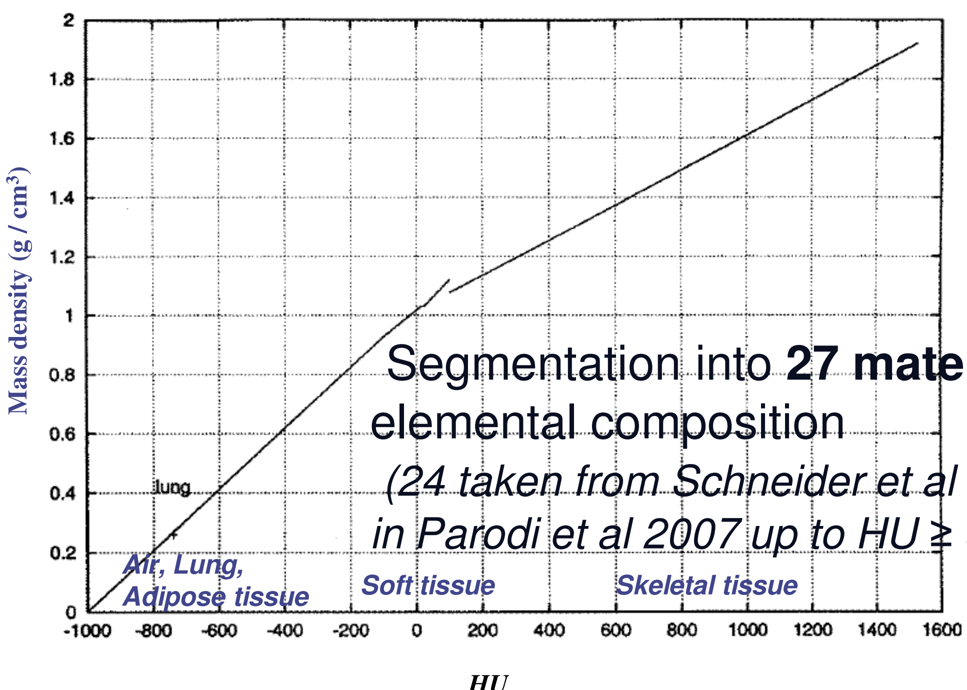
Main references to FLUKA in ion-therapy related matters:

1) F.Sommerer, K.Parodi, A.Ferrari, K.Poljanc,W.Enghardt and H.Aiginger, **Investigating the accuracy of the FLUKA code for transport of therapeutic ion beams in matter**, Phys. Med. Biol. **51** (2006) 4385–4398
2) K.Parodi, A.Ferrari, F.Sommerer and H.Paganetti, **Clinical CT-based calculations of dose and positron emitter distributions in proton therapy using the FLUKA Monte Carlo code**, Phys. Med. Biol. **52** (2007) 3369–3387
3) A. Mairani, **Nucleus-Nucleus Interaction Modelling and Applications in Ion Therapy Treatment Planning**, PhD Thesis, Univ. Pavia, 2007
4) G.B. et al. (FLUKA collaboration), **The FLUKA code and its use in hadron therapy**, Il Nuovo Cimento **31C**, no. 1 (2008) 69.
5) F.Sommerer, F.Cerutti, K.Parodi, A.Ferrari, W.Enghardt and H.Aiginger, **In-beam PET monitoring of mono-energetic 16O and 12C beams: experiments and FLUKA simulations for homogeneous targets**, Phys. Med. Biol. **54** (2009) 3979–3996
6) A.Mairani, S.Brons, A.Fassò, A.Ferrari, M.Krämer, K.Parodi, M.Scholz and F. Sommerer, **Monte Carlo based biological calculations in carbon ion therapy: the FLUKA code coupled with the Local Effect Model**, submitted to PMB 2010

FLUKA developments: CT geometry in the MC

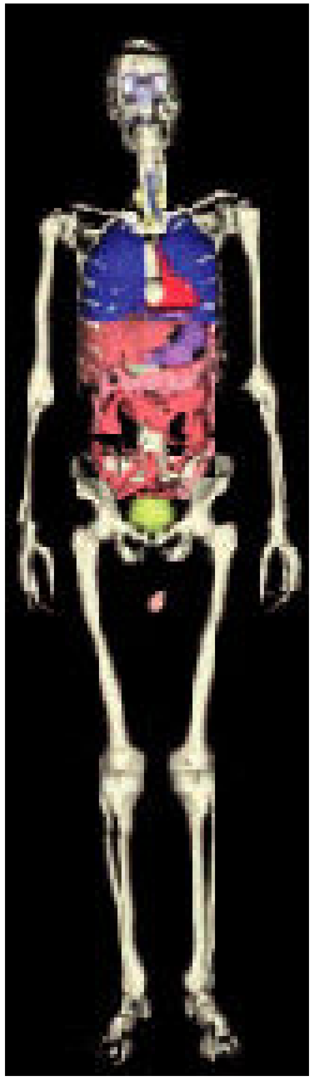
The Voxel Geometry

- 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



Segmentation into **27 materials** of defined elemental composition

(24 taken from Schneider et al 2000, extended in Parodi et al 2007 up to HU ≥ 3060 for Ti)

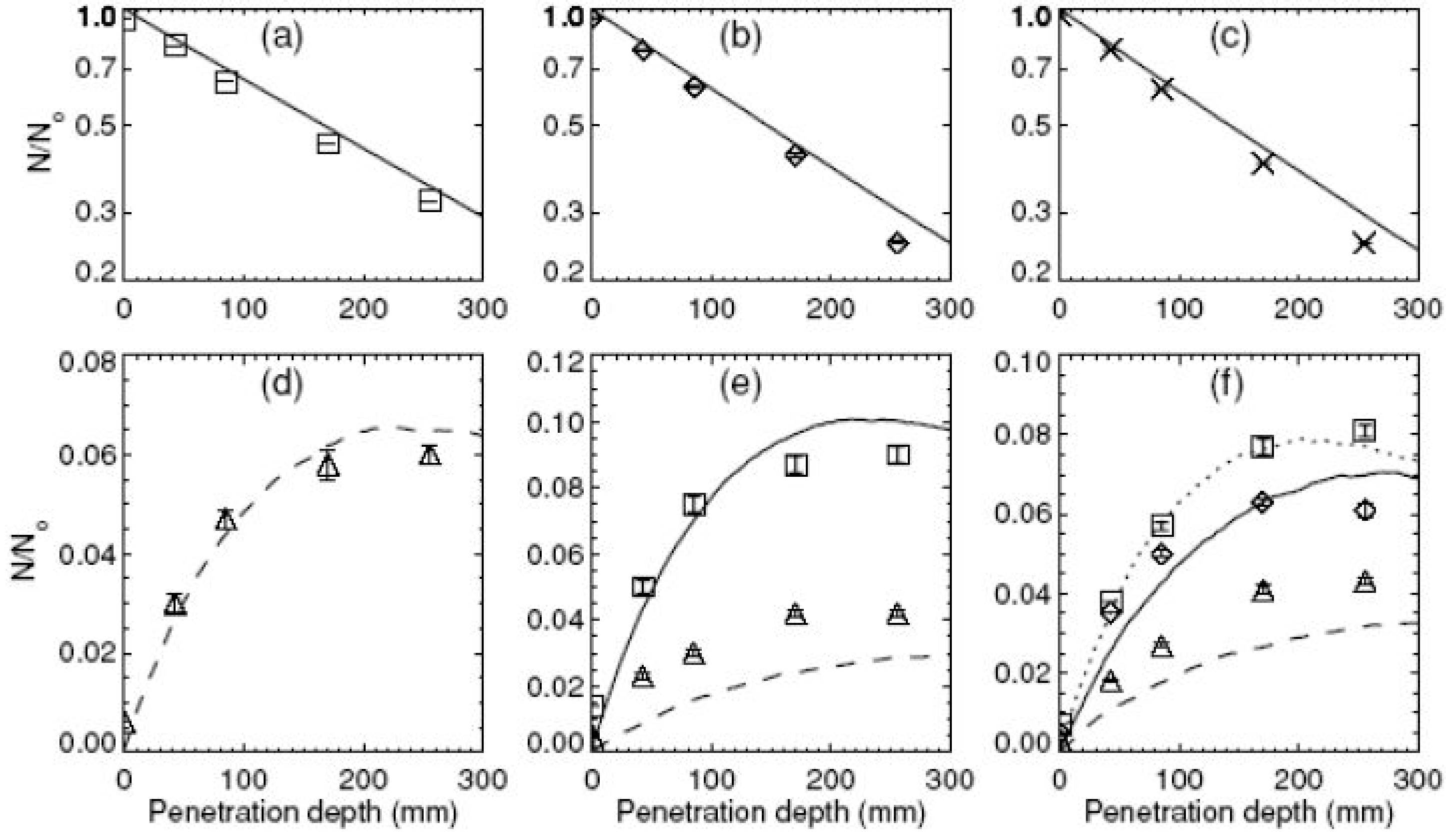


The **GOLEM phantom**

Petoussi-Henss et al, 2002

From Ref. 1)

Projectile Fragmentation: ^{12}C, ^{14}N, ^{16}O at 640 MeV/n



Attenuation of the primaries and fragment spectra obtained by FLUKA for ^{12}C (graphs (a) and (d)), ^{14}N (graphs (b) and (e)) and ^{16}O (graphs (c) and (f)) ions incident in water.

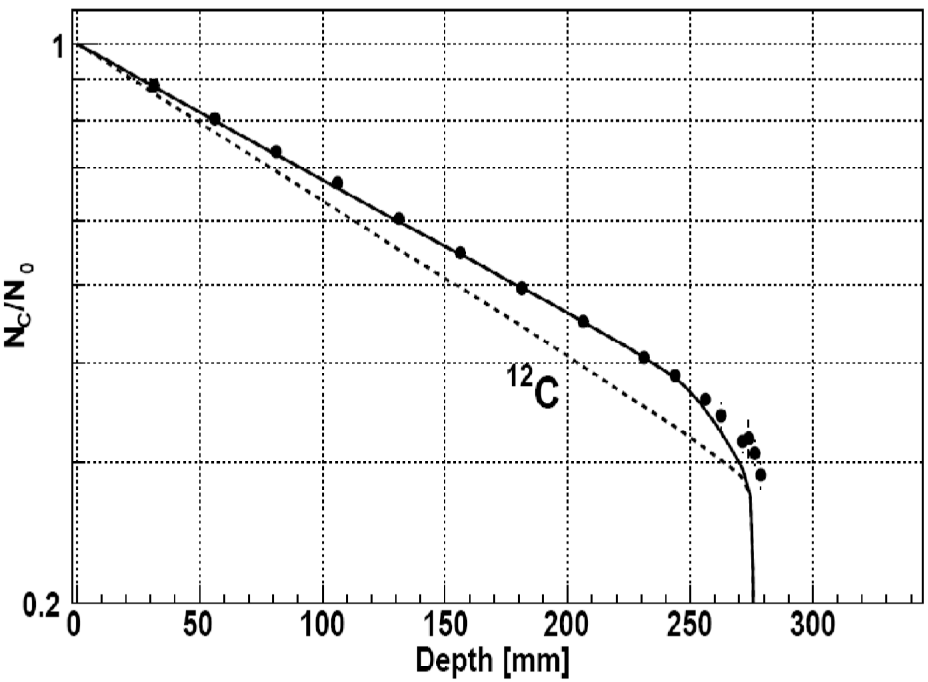
Sommerer et al PMB 51 2006

The lower row of graphs refers to projectile fragment spectra. The symbols indicate measured data from Schall (1996). depicts boron,carbon, ♦nitrogen and × indicates oxygen. The simulated boron fragments are depicted by dashed lines, carbon fragments by solid lines and nitrogen fragments by dotted lines.

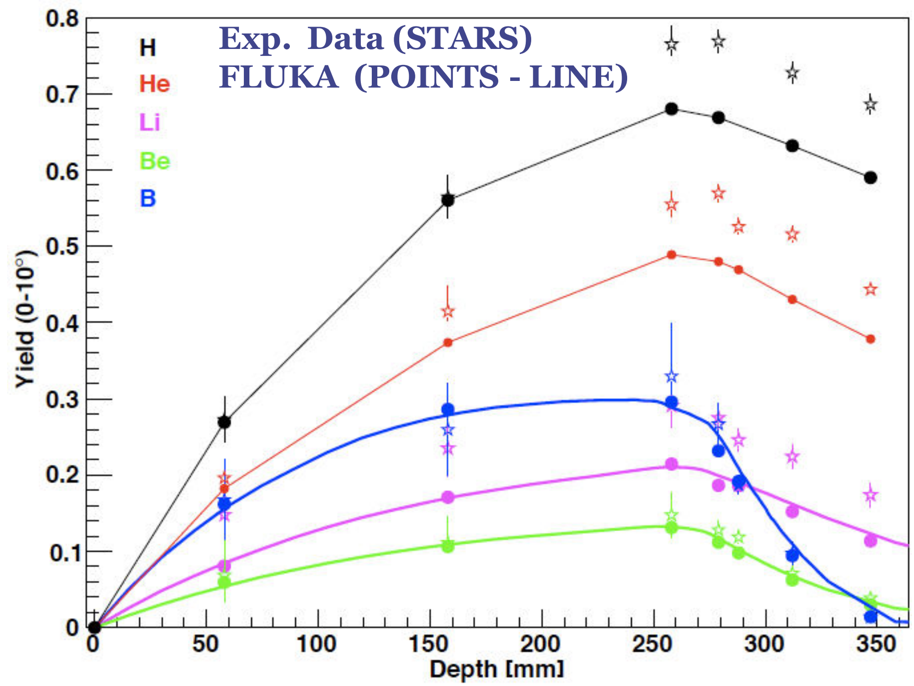
The experimental validation against mixed field measurements in Carbon Ion therapy

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

Carbon Beam Attenuation

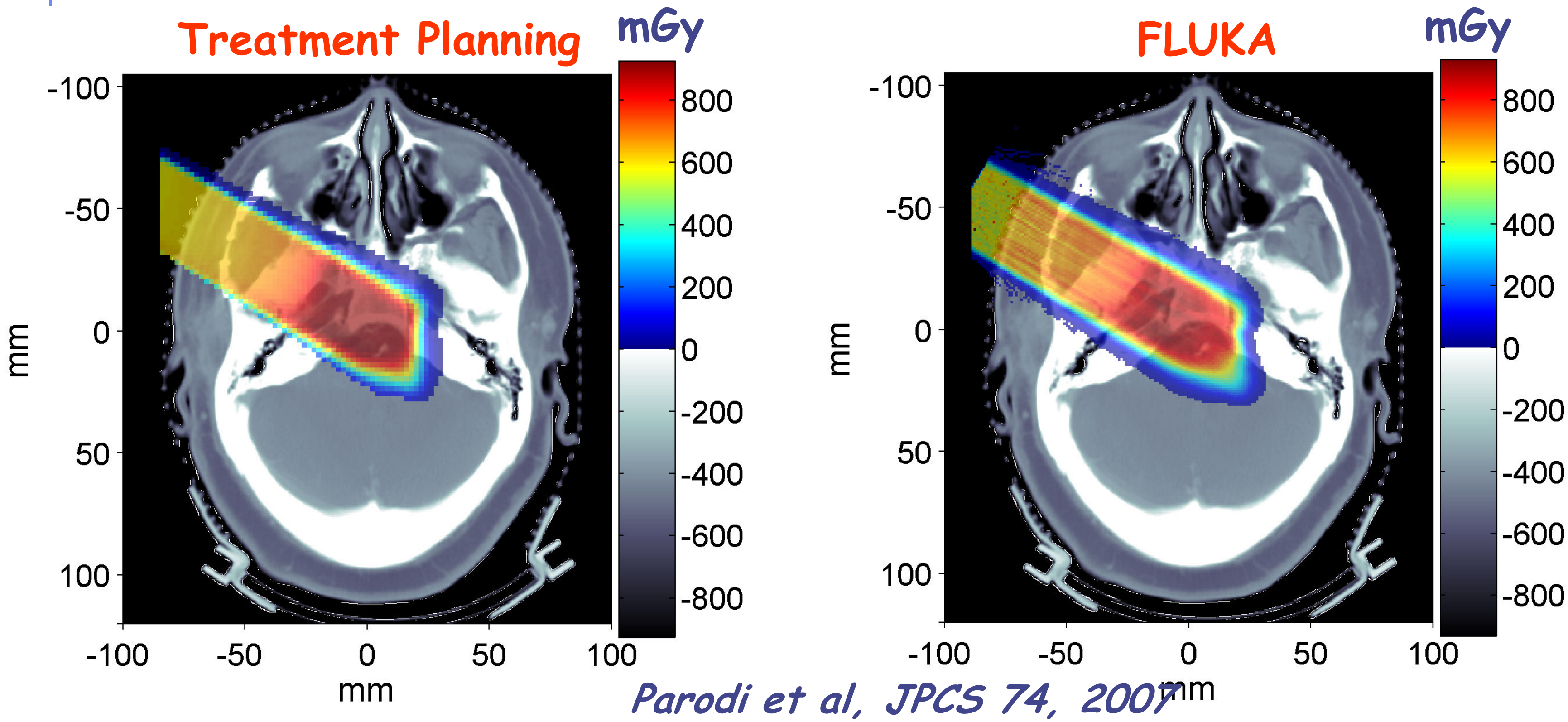


Build-up of secondary fragments



Exp. Data (points) from Haettner et al, Rad. Prot. Dos. 2006
Simulation: A. Mairani PhD Thesis, 2007, PMB *to be published*

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



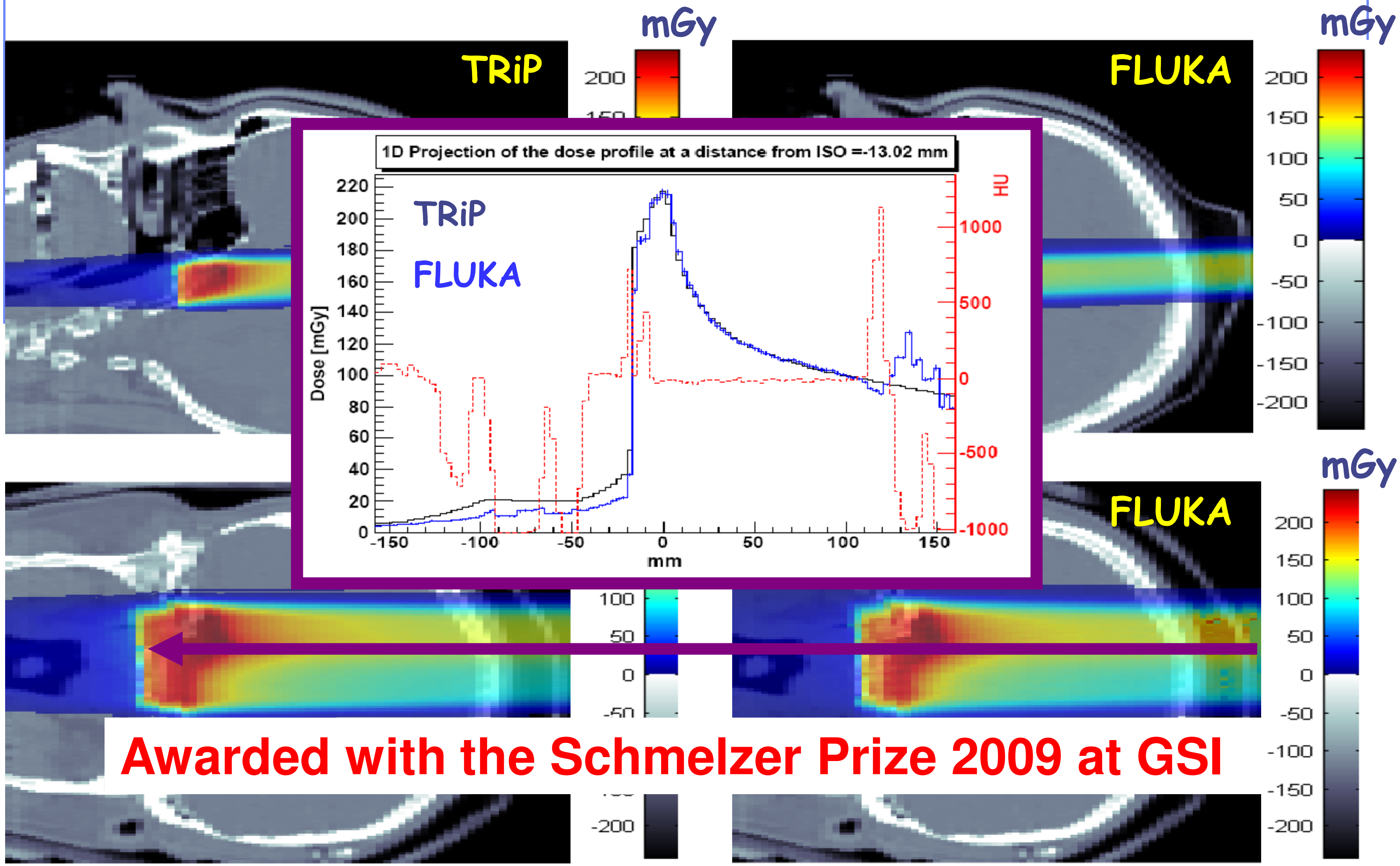
Parodi et al, JPCS 74, 2007

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)

Carbon ion therapy: MC vs TRiP for a Clivus Chordoma Patient at GSI



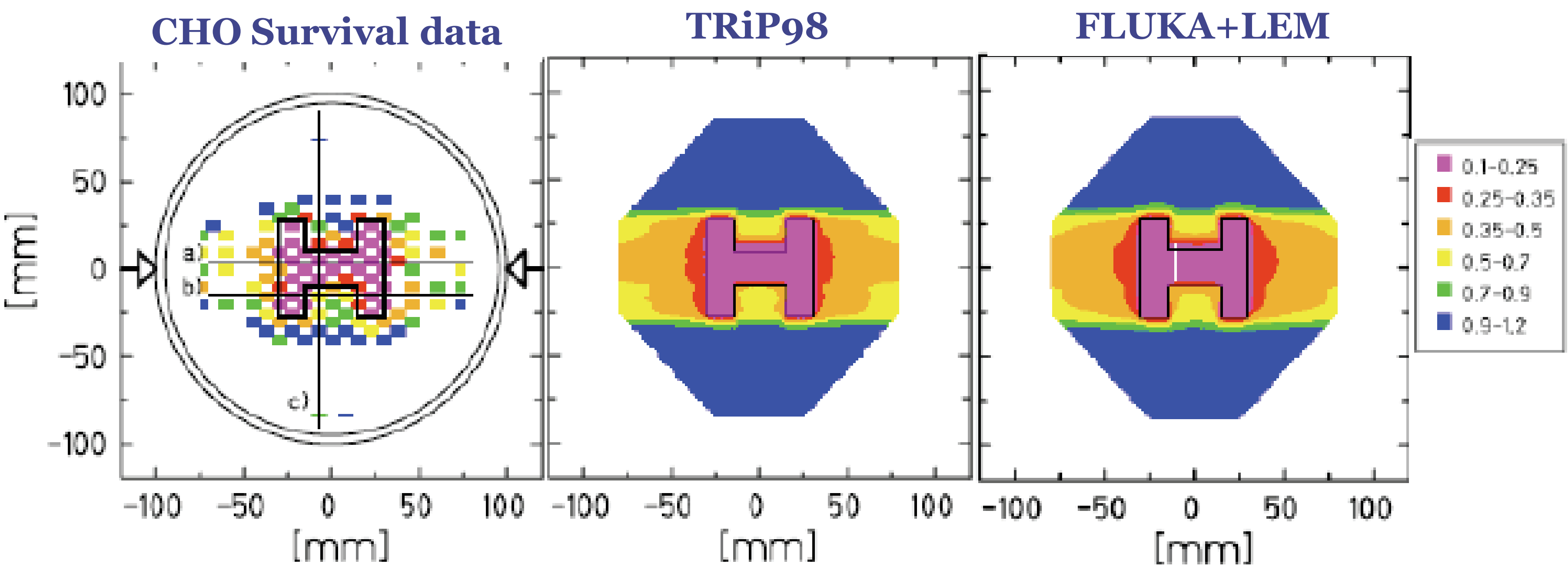
Awarded with the Schmelzer Prize 2009 at GSI

A. Mairani, PhD Thesis, Pavia, 2007, A. Mairani et al, IEEE 2008

MC Biological Calculations in Carbon Ion Therapy: FLUKA coupled with Local Effect Model (GSI)

Forward recalculation of a biologically optimized TRiP98 plan (GSI)

Two-Dimensional Cell Survival Distributions



Exp. data and analytical calculations from M. Krämer *et al*, PMB 48 2003
Simulation: *A. Mairani et al* PMB *submitted*

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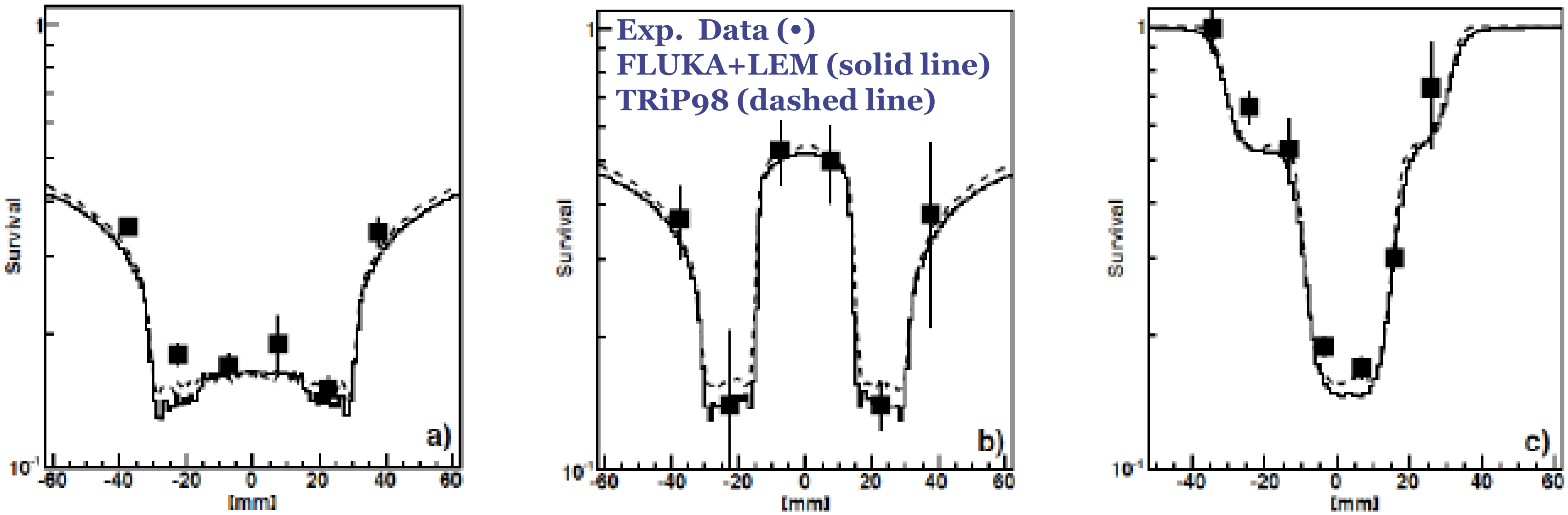
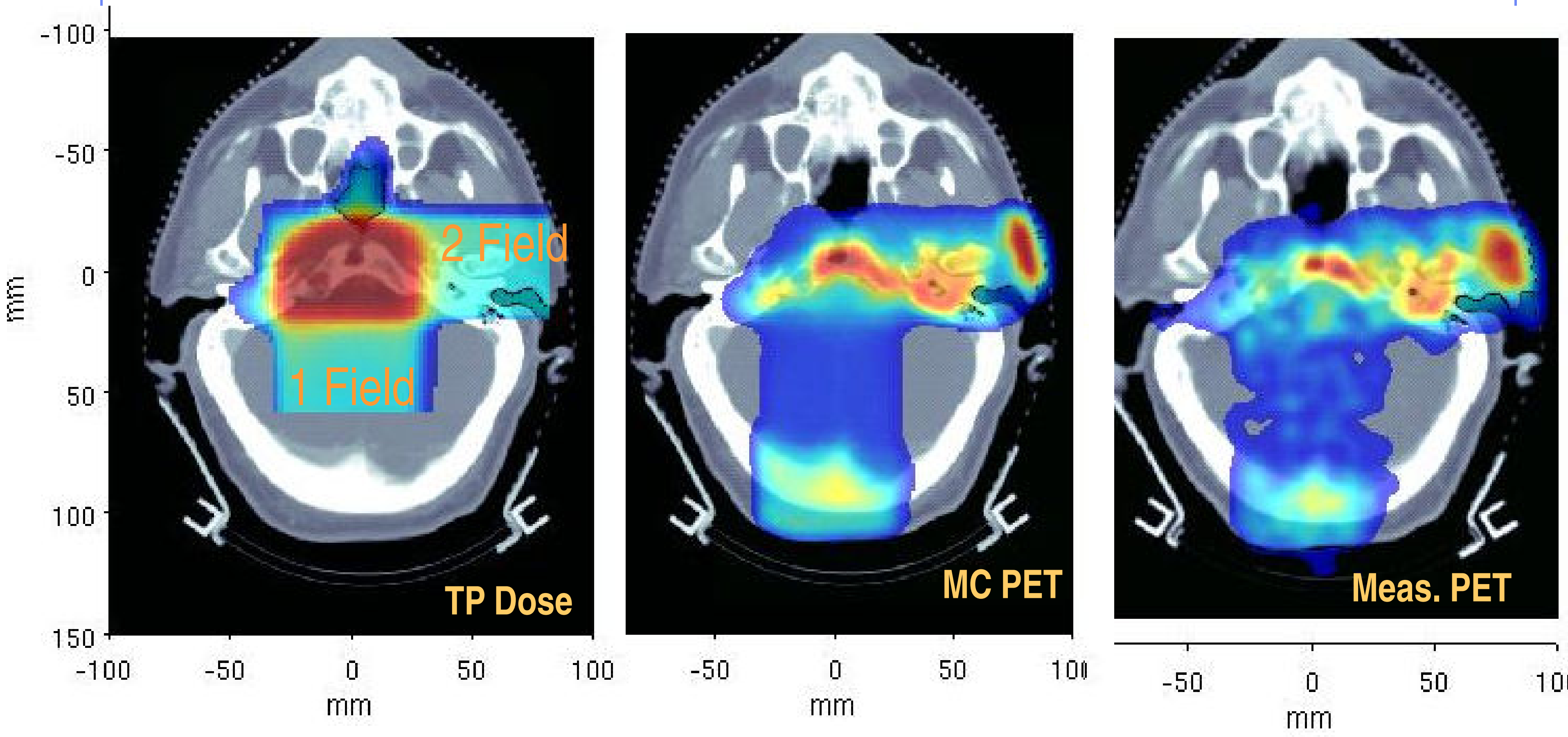


Exp. data and analytical calculations from M. Krämer *et al*, PMB 48 2003
Simulation: A. Mairani *et al* PMB *submitted*

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)

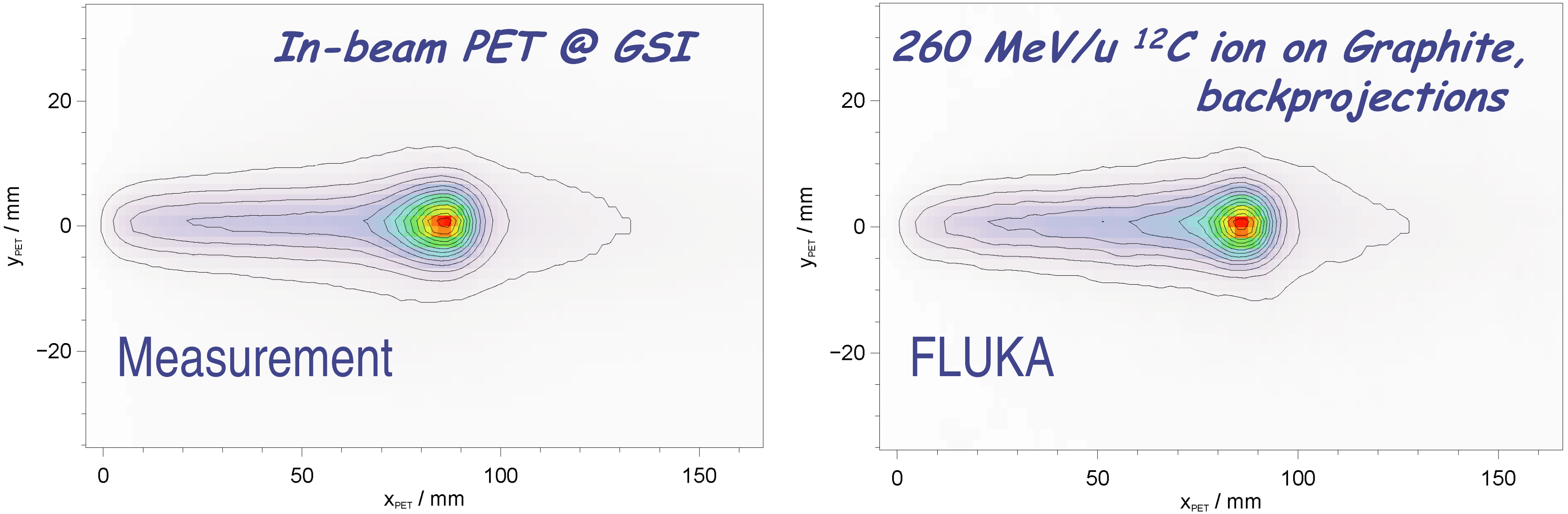
β^+ emitters for ion beams: phantom experiments

Application of FLUKA to PET monitoring of ion species (e.g. ^{12}C, ^{16}O) based on ***internal nuclear models***

Simulation of ***imaging process*** (β^+-decay, propagation of e^+ and annihilation photons, detection) same as for measured data

- ✓ Exact replica of the experimental setup, PET heads included
- ✓ FLUKA irradiation+decay features exploited
- ✓ MC γ's reaching PET heads converted to list-mode data by modified PETSIM[1]
- ✓ Backprojection with same routines as in experiment

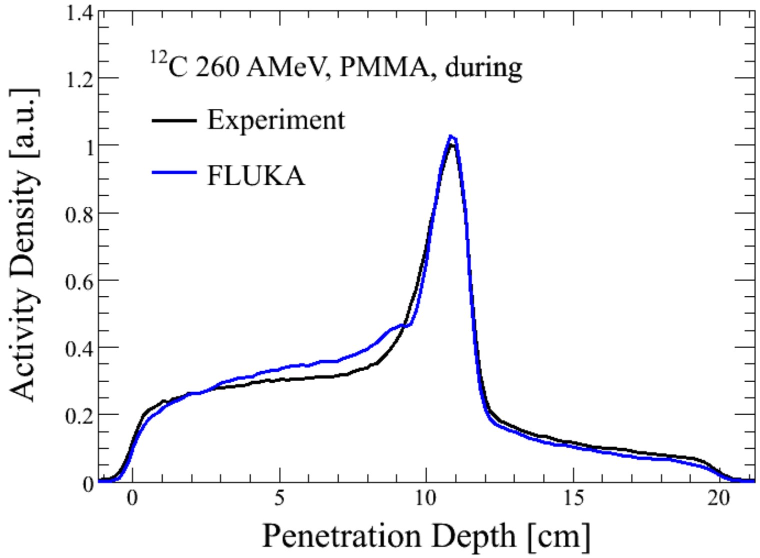
[1] Pönisch et al. PMB **49** 2004

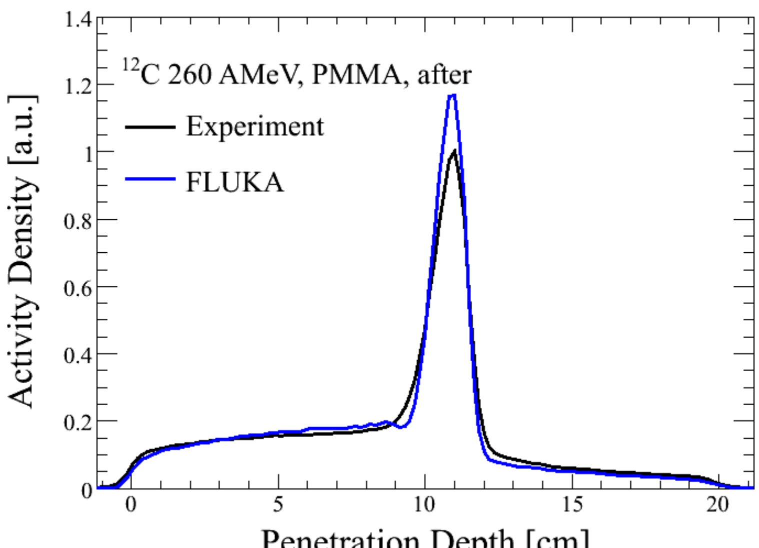


F. Sommerer PhD Thesis, 2007, F. Sommerer et al PMB 54 2009

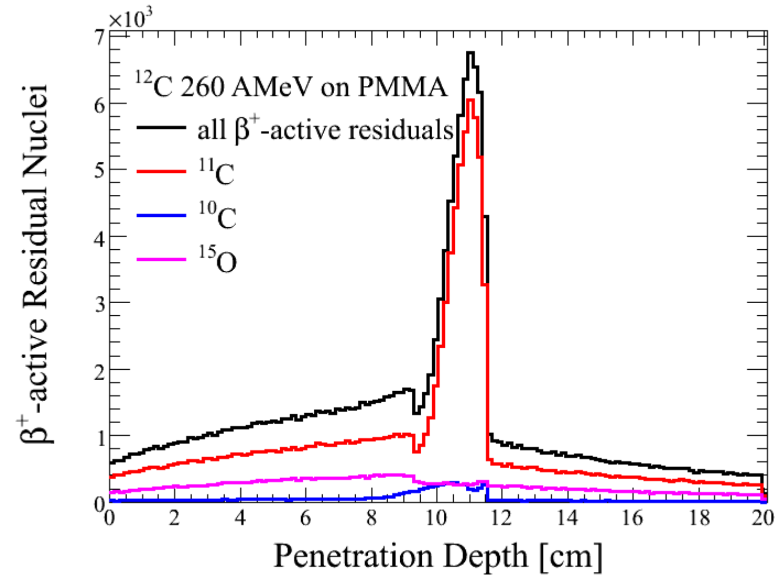
Backprojections: FLUKA vs Exp data

^{12}C 260 MeV/A on PMMA





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

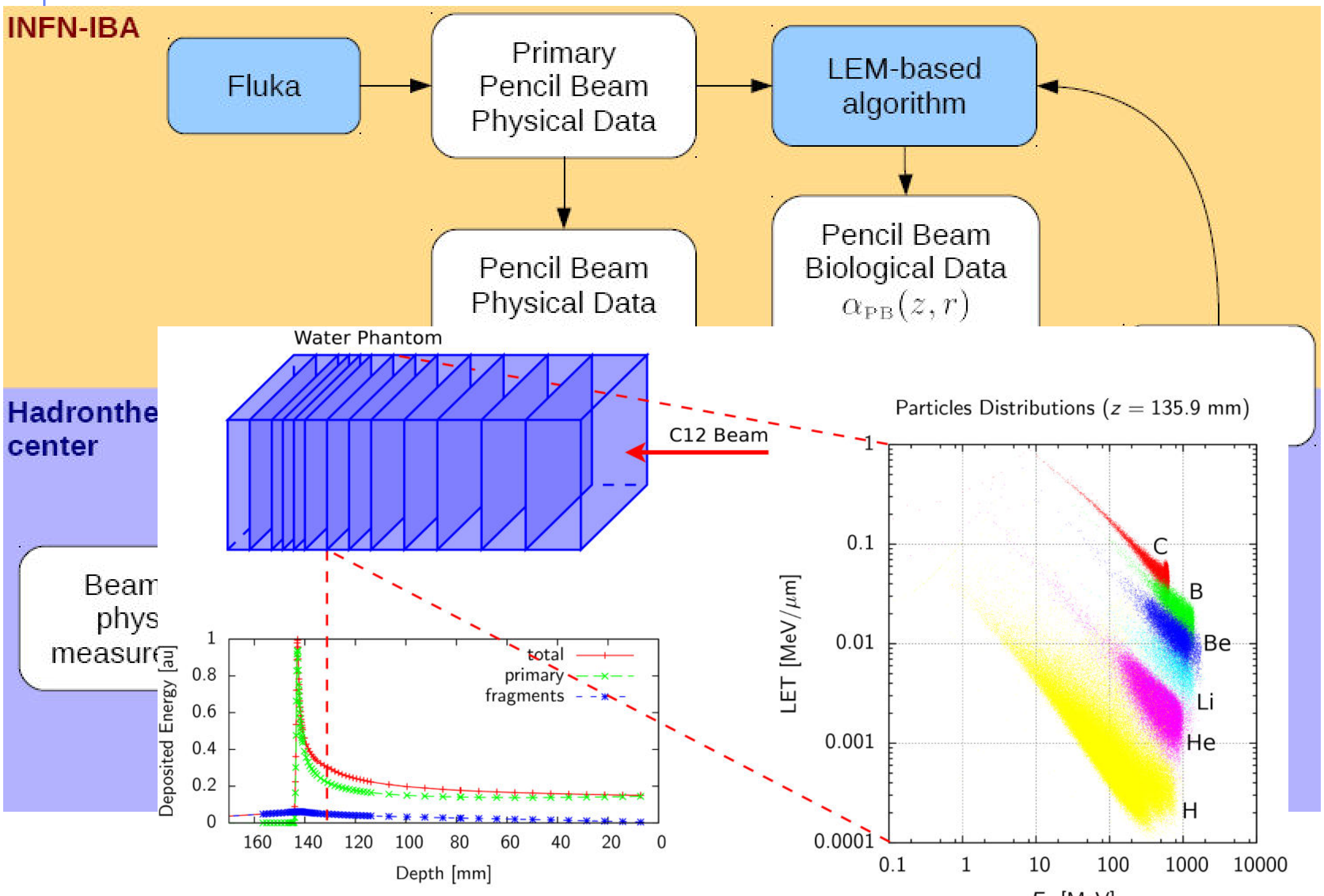


Both the data and the FLUKA calculations are normalized to the same area

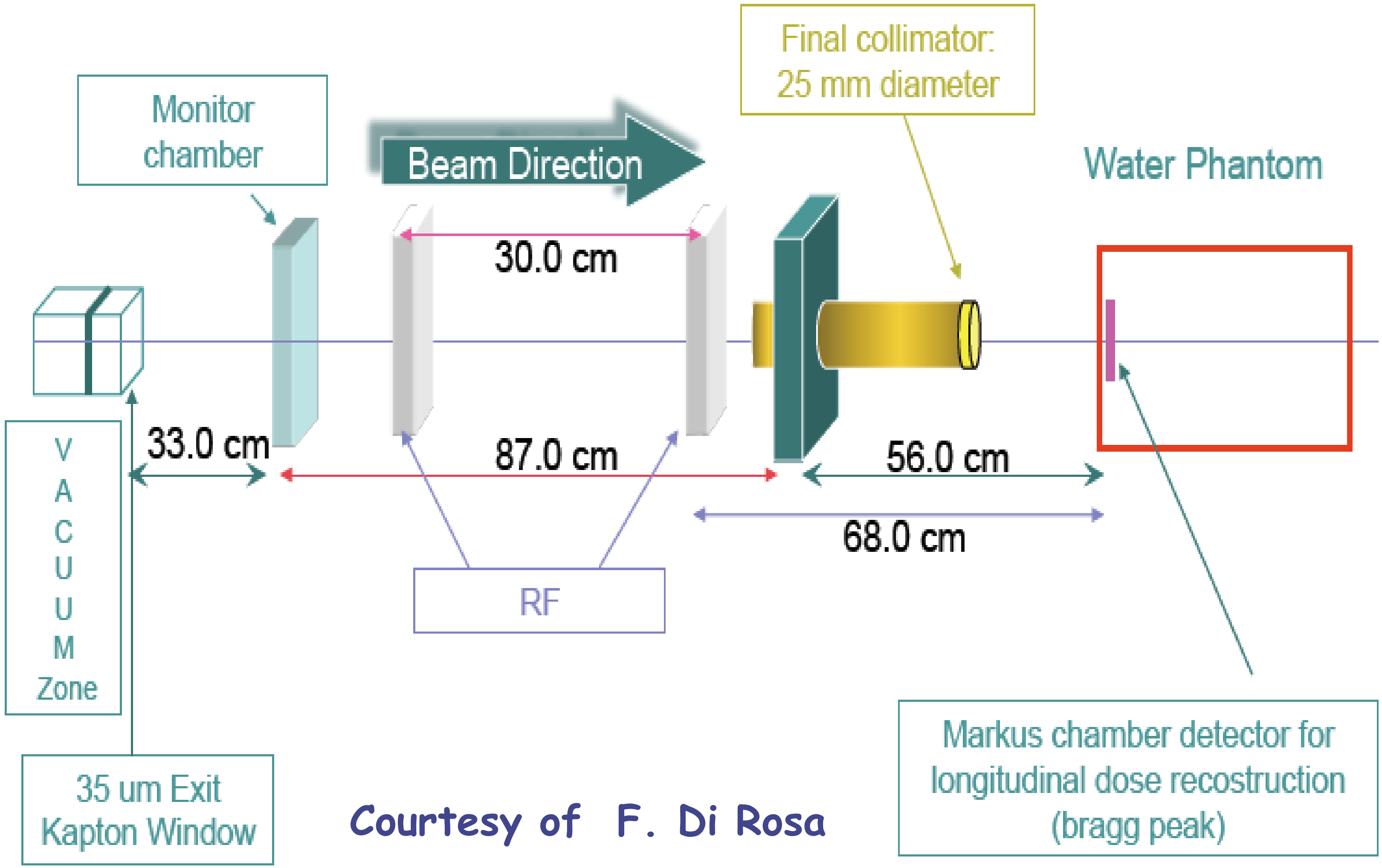
F. Sommerer PhD Thesis, 2007, F. Sommerer et al PMB 54 2009

Towards new development in TPS for ion therapy (INFN in collaboration with IBA)

(see talk by A.Attili)

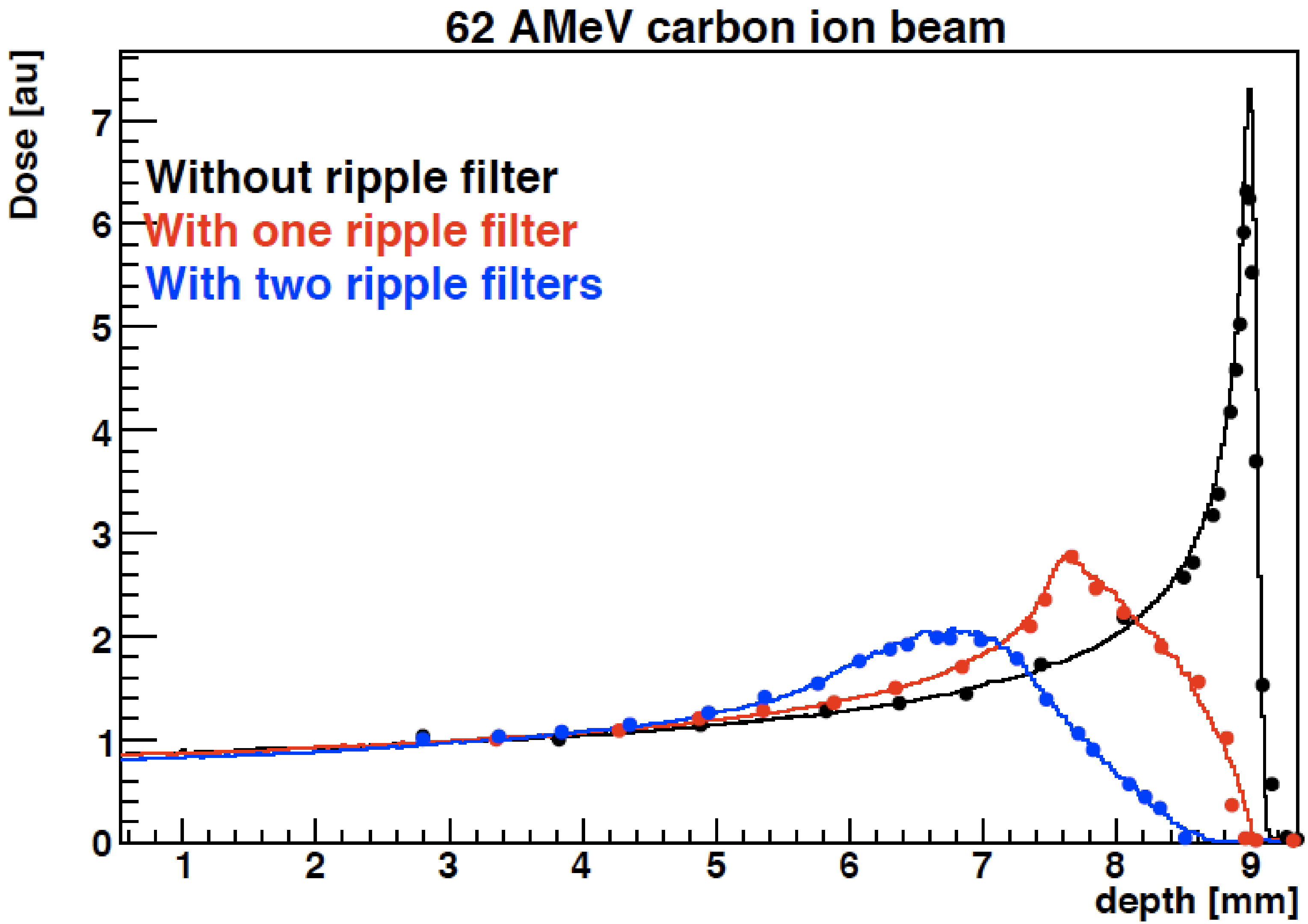


Characterization of LNS "Zero-Degree" beamline: 62 MeV/u Carbon ion beam



Courtesy of F. Di Rosa

Bragg peaks for 62 MeV/u Carbon ion beam in different conditions

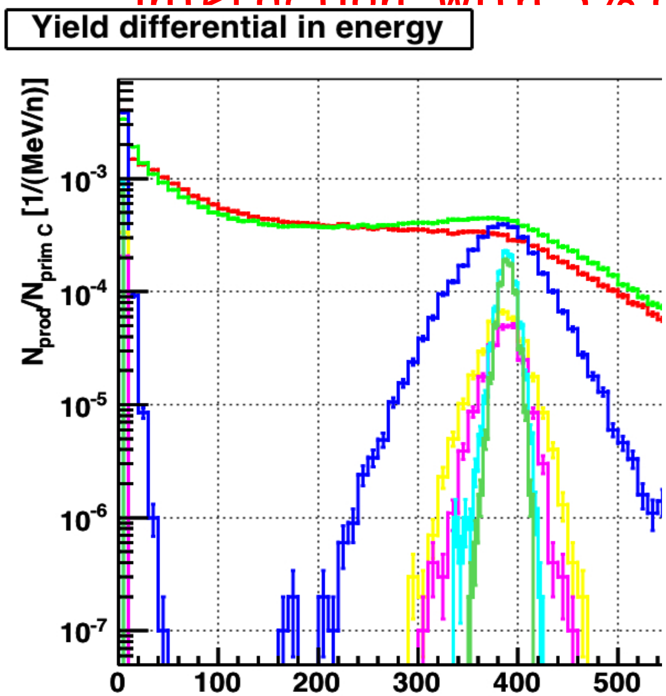


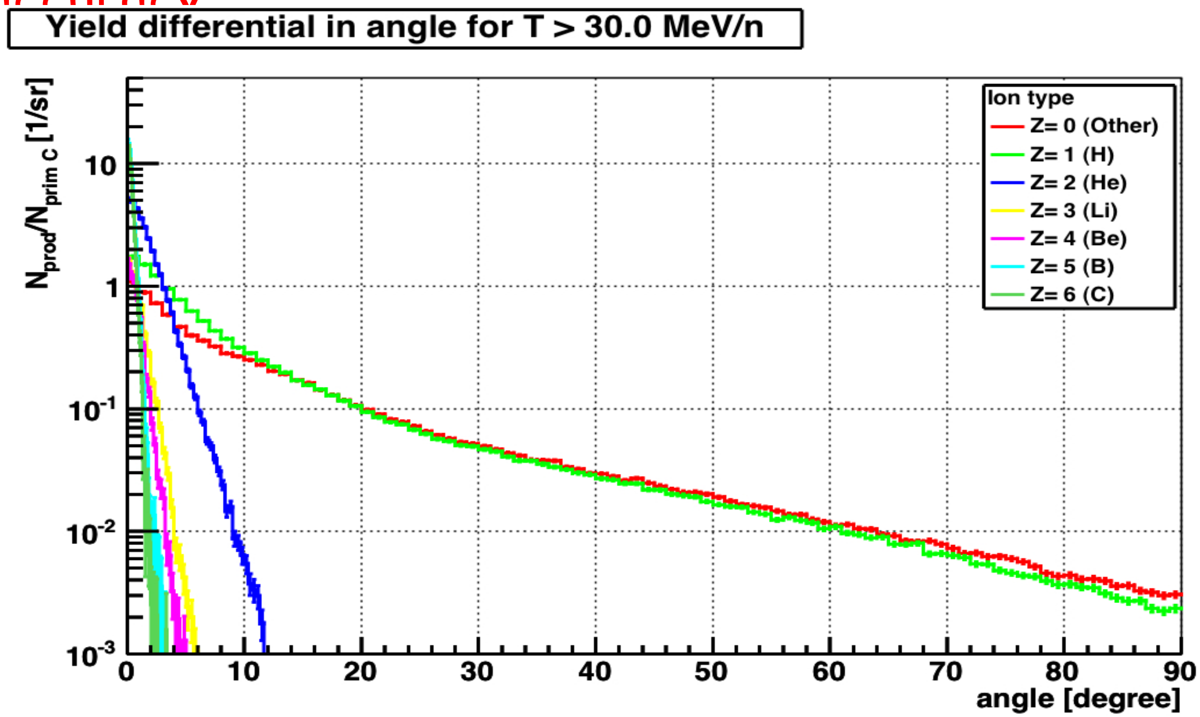
Data and calculations: TPS-INFN Collaboration

Directions for future developments: Physics models improvement

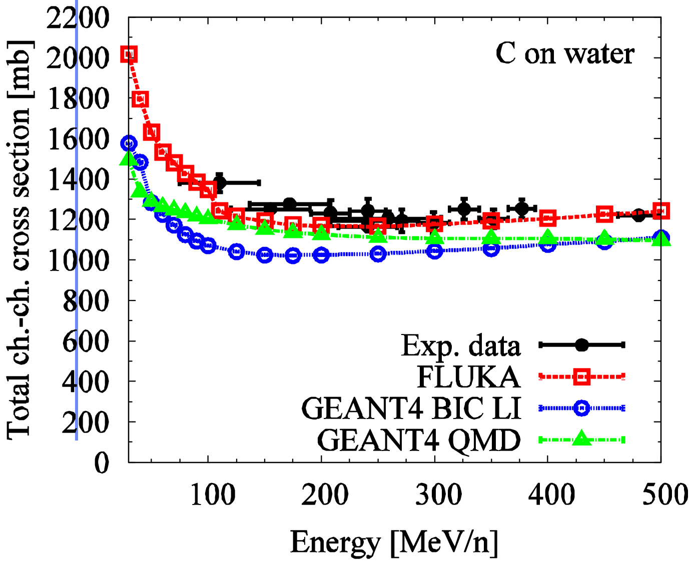
Critical point: assesment and validation of nucleus-nucleus cross sections. Participation in FIRST exp. at GSI *(INFN, GSI, DSM/IRFU/SPhN CEA Saclay, IN2P3 Caen, Strasbourg, Lyon, ESA)*

Aim: Double differential cross section (with respect to the emission θ and E) for each of the produced fragments in C-C, C-Au interaction with 3% accuracy





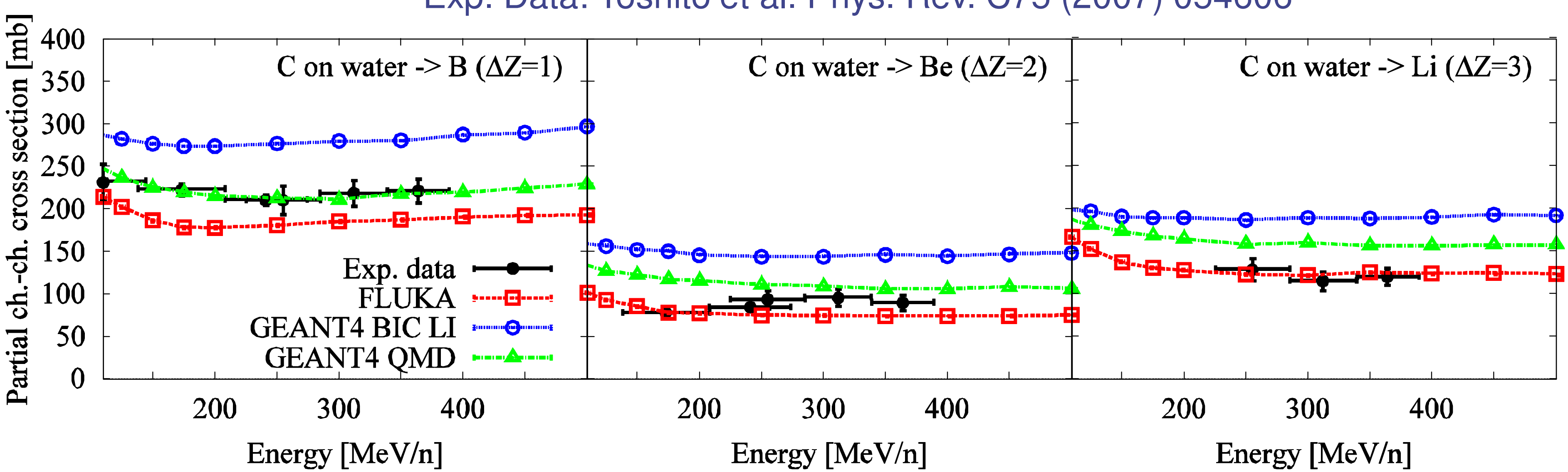
Example of comparison of data vs models. Charge-Changing Cross Sections in Water



See poster

From Till Böhlen (CERN)
Irena Gudowska (KI/SU)
Alfredo Ferrari (CERN)

Exp. Data: Toshito et al. Phys. Rev. C75 (2007) 054606



Other on-going applications and projects

- Beam-line characterization and generation of TPS input data (done at HIT, planned at CNAO)
- Validation and improvement of analytical TPSs in proton and carbon ion therapy for both physical and biological calculations (water/CT)
- Application Positron Emission Tomography and novel imaging techniques for ion beam therapy *(see the poster of I. Rinaldi)*
- Possible development of an interface library (similar to GATE with GEANT4)
- Further work for Nucleus-Nucleus interaction modeling

ENVISION

European NoVel Imaging Systems for ION therapy