Ion- and proton-beams: Experience with Monte Carlo Simulation

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Workshop on Monte Carlo usage in the medical field
Rome, Italy, 07.12.2007
Overview

- The advantages of ion therapy
- Physical validation of the FLUKA MC tool
- Examples of clinical applications *(from dose calculations to PET monitoring)*
- Conclusion and outlook
The physical advantages of ion beams

The „Inverse“ depth-dose distribution (BP)
The physical advantages of ion beams

The reduced lateral scattering (for $Z > 1$)

Lateral Scattering

![Graph showing lateral scattering for different ions](image)

- **Proton**
- **Helium**
- **Carbon**

Initial FWHM = 4 mm

*Courtesy of T. Haberer, HIT*
The physical advantages of ion beams

IMRT

Protons

Courtesy of A. Trofimov and A. Chan, MGH Boston
The physical advantages of ion beams

IMRT: 9 Fields

Carbon ions: 2 Fields

Courtesy of O. Jäkel, DKFZ Heidelberg
The role of MC in ion therapy

- Long computational time 😞
- Realistic representation of physical interactions in complex targets, e.g., patient 😊

**In clinical practice:** validation of critical TPS dose calculations (e.g., inhomogeneous tissue, metallic implants)

**In commissioning of new facilities:** specification of the beam parameters and generation of TPS input data (✔ meas. time)

**In dedicated applications:** powerful tools for nuclear reaction related issues, like PET monitoring of ion treatment
The FLUKA MC code
(http://www.fluka.org)

- Reliable nuclear models
- Already applied to proton therapy for dosimetric and radiobiological studies (Biaggi et al NIM B 159, 1999)
- Huge efforts for ion transport in connection with NASA grant since 2000
- Promising results from initial studies of ion beam fragmentation in water (Sommerer et al PMB 51, 2006)
- Recent improvements for therapeutic ion applications: BME generator for low energy nucleus-nucleus reactions (Cerutti et al Proc. VII LASNPA Conf., Cusco, Peru, 2007)
Experimental validation: Protons

Protons (182 MeV/u) in Water

Exp. Data (points) taken at HIT(!):
D. Schardt, P. Steidl,
K. Parodi, S. Brons et al.

Protons (160 MeV/u) on MultiLayer Faraday Cup (CH₂)

Exp. Data (points):
H. Paganetti et al.,
Medical Physics, 2003
Simulations: A. Mairani, INFN Pavia
Experimental validation: $^{12}$C$^{6+}$

$^{12}$C ions @ 400 MeV/u in Water

Depth-dose distribution (BP)

Experimental validation: $^{12}\text{C}^{6+}$

$^{12}\text{C}$ ions @ 400 MeV/u in Water

Carbon Beam Attenuation  Build-up of secondary fragments

Simulations: A. Mairani, Ph.D. Thesis
Experimental validation: $^{12}\text{C}^{6+}$

$^{12}\text{C} @ 400 \text{ MeV/u in water}$

Carbon angular distribution at different depths

Preliminary exp. Data: E.Haettner (Diploma thesis) and D.Schardt, GSI
Simulations A.Mairani Ph.D. thesis
Experimental validation: $^{12}\text{C}^6^+$

$^{12}\text{C} @ 400 \text{ MeV/u in water}$

Heavy Fragment angular distribution at 31.2 cm

Preliminary exp. Data: E.Haettner (Diploma thesis) and D.Schardt, GSI
Simulations A.Mairani Ph.D. thesis

![Graphs showing angular distribution for Lithium, Beryllium, and Boron](image_url)
Two examples of clinical dose calculations

I. For protons @ MGH Boston

II. For $^{12}\text{C}$ @ GSI Darmstadt
I. Beam input information
Passively formed p treatments @ MGH

The general principles of Passive Modulation

Example of set-up (Tsukuba)

At MGH: FLUKA coupled with beam phase-space from a Geant4 MC-calculation of nozzle and beam modifiers

Paganetti et al, Med. Phys. 2004
I. Beam input information
Passively formed $p$ treatments @ MGH

Parodi et al, Med Phys 34 2007

SOBP
MC vs. IC meas.:
80% and 90% fall-off position agree within 1 mm
II. Beam input information
Active rasterscan system for $^{12}$C treatments @ GSI

Active variation of beam energy, focus and intensity from accelerator

Intensity- and Position- controlled magnetic scanning

Haberer et al, NIMA 1993
II. Beam input information

Active rasterscan system for $^{12}$C treatments @ GSI

FLUKA coupled with control file of raster scanning system and modeling ridge filter


**Experimental data (points) from S.Brons (HIT)**
**Simulations: A. Mairani, Ph.D. Thesis**
I-II. Using the information from the patient CT

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

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I-II. Using the information from the patient CT

Nominal mean density for each HU interval

(Jiang and Paganetti MP 31, 2004)

But real density varies continuously with HU value

\[ \rho \quad (g/cm^3) \]

\[ H \]

Schneider et al
PMB 45, 2000
I. Adaptation of FLUKA to follow the TPS (XiO/CMS) calibration curve for $p @ MGH$

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 PMB 52, 2007
II. Adaptation of FLUKA to follow the TPS (TRiP) calibration curve for $^{12}$C @ GSI

$^{12}$C (270 MeV/u) on CT phantoms


A. Mairani Ph.D. thesis
I. Proton therapy @ MGH: MC vs XiO/CMS
Clivus Chordoma Patient

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)

Parodi et al, JPCS 74, 2007
I. Proton therapy @ MGH: MC vs XiO/CMS
Prescribed dose: 2 GyE
MC : \(\sim 7.4 \times 10^7\) in 12 independent runs
\(\sim 130\)h each on 2.2 GHz Linux cluster
II. Carbon ion therapy: MC vs TRiP
Clivus Chordoma Patient (physical dose calculations)

A. Mairani, Ph.D. Thesis
II. Carbon ion therapy: MC vs TRiP
Two examples of application at the upcoming Heidelberg Ion Therapy Center (HIT)

Ion species
- low-LET: Protons (later He)
- high-LET: Carbon (Oxygen)

Beam delivery
- Rasterscanning with active energy variation (like GSI)
- Required parameters:
  - 255 Energy steps
  - 4 (6) Foci
  - 10 Intensities

HIT, Heidelberg, Germany
Two examples of dedicated, fragmentation-related applications

I. PET/CT after proton therapy

PET/CT @ MGH Radiology

Siemens Biograph 16

II. In-beam PET during $^{12}$C therapy

In-beam PET @ GSI

FZ Rossendorf
The principle of PET monitoring in ion therapy

Production of positron emitters ($^{15}\text{O}$, $^{11}\text{C}$, $^{13}\text{N}$..., $T_{1/2} \sim 2, 20$ and $10\text{min}$...) as a by-product of irradiation

In-vivo, non-invasive detection of irradiation induced $\beta^+$-activity by means of PET

Courtesy of W. Enghardt, FZ Rossendorf
The motivation for PET and Monte Carlo

K. Parodi et al, IEEE MIC CR, 2002

\[ A(r) \neq D(r) \]

⇒ Measured activity compared with MC calculation as for \(^{12}\text{C}\) therapy at GSI Darmstadt, Germany (Enghardt et al, NIMA 525, 2004)
**I. PET/CT@MGH: β⁺-activity calculation**

**FLUKA simulations using**

1. Initial beam and CT information as for dose calculations
2. Runtime folding of experimental cross-sections with $p$ fluence
   
   $$N_Y \propto \int \frac{d\Phi(E)}{dE} \sigma_{X \rightarrow Y}(E)dE$$

4. Convolution of activity with 3D Gaussian kernel (~7mm FWHM)

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*(Diagram showing cross-section data, labeled as Parodi et al, PMB 45 2002, Data from IAEA Nuclear Data Section)*

+ other reaction channels on C, N, O, Ca yielding, e.g., $^{13}$N, $^{38}$K, …

*(Parodi et al PMB 52 2007)*
I. PET/CT@MGH: Head

Clival Chordoma, 0.96 GyE / field

**Planned dose**

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</table>
I. PET/CT@MGH: Head

Clival Chordoma, 0.96 GyE / field, $\Delta T_1 \sim 26$ min, $\Delta T_2 \sim 16$ min

Agreement within 1-2 mm
For position of distal max.
And 50 % fall-off

Parodi et al., IJROBP 68(3) 2007
I. PET/CT@MGH: Spine

T-spine Chondrosarcoma, 0.6 GyE, 1.2 GyE

Planned dose
I. PET/CT@MGH: Spine

T-spine Chondrosarcoma, 0.6 GyE $D_{T_1}$ ~ 22 min, 1.2 GyE $D_{T_2}$ ~ 16 min

Average Activity

Parodi et al., IJROBP 68(3) 2007
I. PET/CT@MGH: Spine

Activity evolution over time

Parodi et al.,
IJROBP 68(3) 2007
II. In-beam PET imaging of heavier ions

Ongoing work on:

- Application of FLUKA to PET monitoring of ions (e.g. $^{12}$C, $^{16}$O) based on internal nuclear models
- Simulation of imaging process ($\beta^+$-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 $\gamma$’s detection converted to list-mode data by modified PETSIM
  - Backprojection with same routines as in experiment

⇒ In-beam PET phantom experiments @ GSI

260 MeV/u $^{12}$C ion on Graphite, backprojections

II. In-beam PET imaging of heavier ions

Incorporating time course of irradiation and acquisition as in meas. … (F. Sommerer, PhD Thesis)

$^{12}$C 260 MeV/A on PMMA, during irradiation

$^{16}$O 350 MeV/A on PMMA, after irradiation

$^{12}$C 260 MeV/A on PMMA, during irradiation
Conclusion and outlook

MC tools are increasingly spread in ion therapy to support
- Analytical TPS (validation in water /CT, input data generation)
- Special applications (e.g., PET monitoring)

FLUKA is a good candidate
- Generally good agreement of \( p / ^{12}C \) dose calculations vs. experimental data and established TPS systems
- Differences to TPS mainly because of large inhomogeneities (e.g., metallic implants) and dose-to-water / dose-to-tissue
- Reasonable predictions of nuclear reactions and, in particular, fragmentation (key factor for heavier ions!)

Still ongoing...
- Several activities in connection with HIT / FLUKA team
- Optimization of computational time... MC TPS???
Acknowledgement

CERN Geneva:
   A. Ferrari, F. Sommerer, F. Cerutti

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   S. Brons, T. Haberer, P. Heeg, J. Naumann

INFN Pavia:
   A. Mairani

MGH Boston:
   H. Paganetti, T. Bortfeld, H. Shih

FZ Rossendorf:
   W. Enghardt